

2 SCIENCE GOALS AND TECHNICAL REQUIREMENTS

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Revision History

2001-July-25: Initial release
2001-Nov-12: Added Experiments
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2002-Mar-19: Added RFI section
2003-Sep-04: Reviewed and revamped requirements.

2.0 Summary

The scientific capability of the Very Large Array is severely limited by its 20-year-old technology. Virtually every experiment now scheduled on the VLA achieves far less than that which would be attained were the array outfitted with the instrumentation available today with current technologies.

The primary goal of Phase I of the VLA Expansion Project is to enable the array to achieve its full potential through implementation of modern technologies. The basic plan is to retain the antennas, array design, and infrastructure, and to replace the electronics (which in nearly all areas date to the late 1970s) with modern systems. This strategy is exceedingly cost-effective, since the cost of new interferometric facilities is dominated by the antenna and supporting infrastructure costs. For the VLA Expansion Project, this major cost is avoided -- it is already paid for and is part of the investment.

The implementation of modern technology on the VLA will increase its technical capabilities by at least an order of magnitude in **every** key observational area. This factor of improvement will enable new science which not only is currently unavailable on any existing telescope, but will enable areas of inquiry which could not have been anticipated when the telescope was first designed, nearly 30 years ago.

This chapter describes a number of key scientific experiments, along with the technical capabilities that are required to enable them. The top-level technical requirements are combined and summarized in Section 2.2. A key component of the EVLA is the correlator. Top-level requirements for this are in Section 2.3. The sensitivity and wide-bandwidth characteristics of the EVLA electronics system will make the array especially vulnerable to radio-frequency interference. An overview of the plan to handle this is given in Section 2.4. Along with all new telescopes, the EVLA will make extensive use of, and be dependent upon, computing software. Section 2.5 gives the top-level software requirements.

2.1 Illustrative Key Scientific Experiments

The order-of-magnitude improvement of the VLA's capabilities brought by the EVLA Project will enable a broad spectrum of original science. In the following sections, I briefly describe some examples of demanding experiments, while reminding the reader that long experience has shown that the most exciting new science from any order-of-magnitude improvement in scientific capability is rarely anticipated. Thus, the areas of most exciting scientific impact of the project will likely not be known until after the project is completed!

The reader should also keep in mind that the Very Large Array is fundamentally an extraordinarily flexible telescope, and was designed to enable research over a maximally broad range of astronomy. It is not a facility designed for a specific science goal, but is a facility intended to encourage research throughout all of astronomy. The EVLA Project will follow this same, successful, design philosophy.

2.1.1 Radio Observations of Gamma Ray Bursts

Long an enigma, GRBs are now known to be extremely distant and powerful explosions (10^{52} - 10^{54} ergs) probably announcing the birth of distant black holes. The study of this phenomenon has undergone a renaissance since the launch of the Italian-Dutch satellite BeppoSAX, and the subsequent discovery of long-lived X-ray, optical and radio 'afterglows' of these explosions. Radio observations are key to understanding the physics on these objects. The current VLA enables detection of a few GRBs per year. This detection rate will rise to about 100 per year with the improved sensitivity of the EVLA.

Observations of GRBs with the EVLA will permit:

- Determination of the complete spectral energy distribution. Combining EVLA data with that from the optical, submillimeter, infrared and X-ray portions of the spectrum will permit determination of the shape and evolution of the complete SED over ten orders of magnitude in frequency. This will be used to derive the total energy and ambient density of the surroundings, and to probe the physics of the particle acceleration in the expanding blast wave. As the radio portion of the SED is accessible throughout the expansion lifetime, it is particularly valuable in constraining theories. The sensitivity of the EVLA is expected to permit detailed study of dozens of GRBs per year.
- Determination of GRB sizes and expansion rates. The phenomenon of refractive interstellar scintillation (RISS) enables a size determination with a 'resolution' of a few microarcseconds, provided highly sensitive receivers are available at the appropriate radio frequency (which will be a function of the galactic latitude). With well-sampled, high SNR data, constraints on the geometry of the expanded emission region can also be placed. Polarization observations will also permit further constraints. The existing VLA can do this work on only one or two sources per year (and cannot detect their polarization). The EVLA should permit study of dozens of objects per year, with polarization information for most.
- The Geometry and Energetics of the Central Engines. Radio observations are needed on timescale of months to a year after a burst to discern the geometry of the outflow and to undertake unambiguous calorimetry of the afterglows. This will enable discrimination between wide-angle and narrow-angle jets. The long-lived nature of the radio afterglow will

also allow an accurate measure of the total energy after the blast wave has transitioned to a non-relativistic velocity.

- Unbiased Tracer of Star Formation. Fewer than half of all GRBs exhibit optical afterglows, despite deep searches, and many others show clear signs of reddening. Dust extinction, originating within the circumburst environment or along the line-of-sight to the GRB host galaxy is the most likely cause of these 'dark bursts'. If so, then we can use the dust penetrating ability of radio afterglows to detect and localize dark bursts and use them to probe obscured star formation in the early universe.

Technical capabilities needed for these studies:

- Maximum sensitivity within all EVLA bands.
- Wide frequency coverage -- needed both for the determination of the spectral distribution, and because observations of RISS will be made at the frequency where these refractive scintillations are strongest.
- Good polarization characteristics. Noise-limited polarization maps in the presence of a strong confusing background object are necessary.
- Rapid scheduling capability. The time and position of a GRB cannot be predicted. The array must be able to change programs and sources within a minute of the announcement of a new target of opportunity.

2.1.2. Separating starbursts from black holes in the early universe.

To be added

2.1.3 Observations of Magnetic Fields in Galaxy Clusters

Clusters of galaxies are filled with turbulent hot gas, relativistic particles, and magnetic fields. The hot gas is best observed by its thermal X-ray emission, but the relativistic components (fields and particles) are most readily observed at radio wavelengths. The role of the magnetic fields is potentially very important, as they affect energy transport, and may influence cluster evolution and dynamics. The only direct means of observing these fields is through radio polarimetric observations. Radio synchrotron emission and Faraday rotation measurements both indicate the presence of widely distributed magnetic fields within clusters. However, current instruments permit sufficiently sensitive observations on only a few, unusual, clusters -- those with unusually bright cluster synchrotron emission, and those with strong, extended, embedded radio sources. Are these known fields due to these embedded sources, or are they a general property of all clusters? Such questions can be answered only by an instrument of much greater sensitivity than those now available. The EVLA will vastly expand the number of clusters in which measures of the magnetic fields can be made, due to its order-of-magnitude improvement in sensitivity, and its outstanding polarimetric capabilities. These improvements will allow detailed imaging of the synchrotron cluster emission from hundreds of clusters, and will enable Faraday rotation studies using background sources seen through the clusters. The current VLA can achieve useful polarimetry on only one or two objects per cluster -- the EVLA will enable polarimetry on dozens of objects per cluster, thus allowing analysis on individual clusters.

Technical capabilities needed for these studies:

- $\sim 1\mu\text{Jy}$ sensitivity at the lowest four frequency bands (1.5, 3.0, 6.0, and 10 GHz bands).
- Noise-limited polarization imaging in the presence of a strong background object.

2.1.4 Imaging the Formation of High-Redshift Galaxies behind Dusty Screens.

2.1.5 Observing Ambipolar Diffusion and Thermal Jet Structures in Galactic Young Stellar Objects.

2.1.6 Measuring the three-dimensional motion of ionized gas and stars in the center of our Galaxy.

2.1.7 Unbiased Searches for Star-Forming Regions in Nascent Galaxies

Dust obscuration prevents optical studies of QSO absorption line systems with HI column densities $> 10^{22} \text{ cm}^{-2}$. These high column density systems provide the most detailed information on the dense, (pre-) star-forming ISM in nascent galaxies. The major difficulty in studying these high column density systems is finding them, since optical selection cannot be used. To date, only four such redshifted molecular absorption line systems are known, all seen toward 'red quasars', -- flat spectrum radio sources with faint, or absent, optical counterparts. Searches for molecular absorption line systems with the current VLA are essentially precluded due to the limited bandwidth (100 MHz) and number of spectral channels (16 at that bandwidth). The EVLA will provide the capability for such searches through very wide band spectroscopy with many channels – a capability enabled by the unique design of the WIDAR correlator. For example, in 24 hours with a single frequency the EVLA could survey the frequency range of 30 to 38 GHz with 16384 channels, corresponding to a velocity resolution of 5 km/s (characteristic of molecular absorption line systems), to an rms sensitivity of 0.16 mJy/channel. This corresponds to a 5-sigma detection of 30% absorption (again, characteristic of molecular absorption systems) towards 2.5 mJy sources, of which there are about 7 per square degree. Possible lines include the first order transitions of CO, HCN, and HCO+ at redshifts between 1.3 and 2.8.

The wide bandwidths of the EVLA's receiver bands, combined with the WIDAR correlator, will also enable searches for CO emission from high redshift galaxies, (corresponding to $z > 1.3$ for 1-0, and $z > 3.7$ for 2-1), and for water megamaser emission.

Technical capabilities needed for these studies:

- Addition of the 28 - 40 GHz band.
- LO/IF and receivers providing 8 GHz contiguous bandwidth in each polarization in the 18-26, 26-40 and 40-50 GHz bands..
- A correlator providing ~ 10 km/sec velocity resolution, over the 8 GHz bandwidth, for both parallel-hand correlations. This corresponds to 16384 channels.

2.1.8 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 EVLA will offer 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 ($> \sim 100$ Gauss), gyroresonance opacity is the dominant source of opacity in solar active regions. Radio waves with frequencies which are low integer multiples of the electron gyrofrequency may be resonantly absorbed and emitted by electrons gyrating in the local magnetic field. For example, the electron gyrofrequency in a 600 Gauss magnetic field is 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.

Coronal magnetography works because solar images made at a given frequency show the brightness at the level and temperature where the emission process becomes optically thick (due to gyroresonance absorption). The emission is typically at a brightness temperature which is similar to the effective temperature of the corona -- ~ 3 million degrees. At a higher frequency, the resonance condition is matched at higher magnetic field strength, which occurs at a lower height in the corona. At some critical frequency, this resonance condition is matched at the base of the corona. For frequencies above this, the brightness temperature drops precipitously as the resonance layer moves into the transition region and chromosphere where the effective temperature is much lower. High-resolution images made over a wide range of frequencies may therefore be converted into a map of the magnetic field 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.

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. 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 EVLA are essential to mapping out the detailed magnetic field structure of the corona.

Use of the EVLA to image solar phenomena presents is very challenging technically. The antennas, when pointing at the sun, will see their system temperatures rise from typically 30K to as high as 10^5 K (at 1.5 GHz). The active sun, which is of considerable scientific interest, will raise these temperatures to as high as 3×10^5 K. And powerful flares can raise the temperature to over 10^8 K – requiring a calibrated attenuation of over 60 dB, if good imaging is to be enabled.

Technical capabilities needed for these studies:

- Full frequency coverage between 1 and 20 GHz.
- Full polarimetry within these bands.

- The ability to reduce the system gain sufficiently (by more than 40 dB, and up to 60 dB) and accurately (so the true flux density of the solar activity can be recovered) to keep the solar emission from saturating the receivers.
- The ability to rapidly change antenna gain in response to solar flares.

2.1.9 Mapping the Changing Structure of the Dynamic Heliosphere

The heliosphere is a cavity, extending to perhaps 100 AU, which is inflated by the solar wind, and which is filled with a tenuous magnetized plasma called the interplanetary medium (IPM). Radio interferometers can deduce the solar wind speed and acceleration profile, measure properties of the turbulence and magnetic fields, and map large-scale structures by measuring the angular broadening, intensity scintillations and rotation measure fluctuations of background sources viewed through the IPM.

Currently, such studies are limited by the VLA's sensitivity – few background sources are strong enough to permit detailed study. The greatly increased sensitivity of the EVLA will provide access to large numbers of background sources strong enough to enable determination of the properties of the solar wind turbulence along many lines of sight over the course of a single observing run. More exciting still is the prospect of mapping the large-scale transient disturbances (coronal mass ejections -- CMEs) in the IPM. With the EVLA, a 10-minute observation would give on average five to twenty sources at 100 times the rms noise per primary beam in the 2 - 4 GHz band, while greater numbers will be available at lower frequencies.

Technical Capabilities Needed for This Work:

- Maximum sensitivity in the 1-2 and 2-4 GHz bands (1 microJy rms in 12 hours).
- A wide-band correlator, to provide full polarimetry over the entire bandwidths.
- Accurate noise-limited polarization imaging in the presence of strong background sources.

2.1.10 Bistatic Planetary Radar Observations

Bistatic radar observations offer a unique probe of material beneath the solid surfaces of planets, moons, and asteroids. The EVLA will offer 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 the combined Goldstone-VLA 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, the discovery that significant differences between the ice caps of Mars extend to large depths, the discovery of a huge region near the equator of Mars which reflects no detectable energy (dubbed "Stealth"), and the discovery that Titan has no deep global ethane/methane ocean, contrary to theoretical predictions. The EVLA will extend these impressive results to the other major planetary radar frequency (2.3 GHz) and will allow Doppler imaging of sources as small as the asteroids.

2.1.10.1 13 cm 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 interface) 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 (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.

2.1.10.2 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, this spread 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 spread scales 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 in frequency, 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 EVLA 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 telescope at 13 cm (2.3 GHz).

Key Capabilities Needed for this Science:

- The 2-4 GHz band with maximum sensitivity.
- A correlator providing:
 - 1024 channels with resolution as fine as 1 Hz in all four polarization correlations, and
 - The capability of simultaneously providing the high-resolution spectra and a broadband 'continuum'.

2.1.11 Structure and Orientation of the Galactic Center's Magnetic Field

A strong and highly ordered magnetic field pervades the central region of the Galaxy. This field is oriented vertically 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. 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 Expanded Very Large 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 within 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 that trace the ionized gas as a whole. Sensitive imaging of the broadening of OH masers near the galactic center will give direct information on the magnetic field structure and the nature of the scattering material. 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.

The increased sensitivity of the EVLA will allow a factor of >4 more sensitive imaging with complete polarization and spectral information of the filaments 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. 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.

Sensitive polarimetric studies of the filament emission within the 1.5 GHz band will allow determination of the rotation measure (RM) of the gas between us and the filaments, giving information on the longitudinal component of the magnetic fields and thermal gas density in the intervening material. Current studies are limited by the high rotation measure to the 5 GHz band, which limits the field of view to nine arcminutes. The EVLA will allow these studies to be undertaken

at the 1.5 GHz and, for which the field of view is 0.5 degrees -- encompassing the entire region of interest.

Recent VLA observations of the Zeeman splitting in spectral lines of H1 and OH in absorption have given direct measurements of very strong magnetic fields (1 – 5 milliG) 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. These measurements are at the limit of the current VLA's sensitivity. The EVLA will improve the current measurements and increase the number of detections substantially. The much-increased bandwidth will also allow simultaneous searches for, and measurement of Zeeman splitting in a large number of masers. Finally, the EVLA will for the first time allow the detection of the Zeeman effect in radio recombination lines -- giving critical information on the magnetic fields within the HII regions located in this region. 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 EVLA will give a factor of 5 - 10 improvement by allowing simultaneous observations of all or most of the RRLs within one band. Preliminary estimates indicate that the 3 GHz band, within which there are approximately 30 RRLs, is optimal for this study.

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. 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. Previous VLA work observed five masers per day, each requiring a separate frequency tuning of the array. The new correlator of the EVLA will allow the entire inner 30~arcminutes to be searched simultaneously for OH masers, with sub-km/sec channels, over a huge velocity range (3000 km/sec). This would map the sizes and orientations of the scattering disks across the entire region in a single observation, yielding direct information both on the magnetic field structure, and on the scattering material itself.

Technical capabilities needed to achieve these goals:

- Maximized sensitivity in all bands – noise limited in the presence of a strong background object.
- Accurate polarimetry across the full bandwidth in all bands.
- Correlator resolution sufficient to resolve H and OH maser lines.
- Correlator flexibility capable of simultaneous observation of at least 16 recombination lines within one frequency band, in both parallel-hand correlations.
- Addition of the 2-4 GHz band.

2.1.12 Large-Scale Mapping of Star-Forming Molecular Clouds

Submillimeter cameras on single-dish telescopes such as the JCMT are now being used to survey large areas of individual star-forming molecular clouds in order to provide a complete census of different phases of early protostellar evolution. Such studies are vital for understanding the formation of stars in molecular clouds, and rely on the thermal emission from dust as a tracer of protostars so deeply embedded in their natal cloud cores that they are often not detected in the infrared. However, the resolution provided by these telescopes, while representing a huge improvement over other survey

instruments sensitive to similar emission processes such as IRAS, is still 1000 AU or worse for even the nearest molecular clouds. This is many times the size of the Solar System, and is insufficient for investigating the formation of multiple protostellar systems, or for separating the emission from a forming proto-planetary disk from the more extended cloud core. Thus, the sub-arcsecond resolution provided by the submillimeter interferometers SMA and ALMA currently under development will be essential for investigations of stars and planetary systems. However, dust emission at submillimeter wavelengths can be optically thick -- particularly in the inner regions of circumstellar disks. Furthermore, submillimeter wavelengths are not useful for tracing the ionized gas in hyper- and ultra-compact HII regions associated with the earliest phases of massive star formation.

Without measurements at lower frequencies, the picture of star formation available to submillimeter instruments will be incomplete. In particular, surveys of star-forming molecular clouds at 8 GHz and at 45 GHz will be needed for establishing the relative contributions from ionized gas (both in HII regions and in jets and winds) and optically-thick dust. The EVLA will therefore be essential for providing the resolution and the sensitivity to the thermal emission processes associated with star formation. As star-forming molecular clouds are often very large, the ability to mosaic these regions is vital.

As an example, the Orion Molecular Cloud harbors the nearest region of massive star formation ($D \sim 450$ pc), and as such provides the highest spatial resolution for understanding the formation of stars of all masses in a cluster environment. The $10' \times 50'$ section of Orion A cloud recently mapped by Johnstone and Bally in 850 and 450 μm dust continuum emission contains IRC2, the BN object, many dense cores and embedded low-mass protostars, and also lies behind the Orion Nebula. The same area can be covered by the EVLA with a 3σ sensitivity to dust emission at 45 GHz of $0.1 M_{\odot}/\text{beam}$ in 80 hours of on-source integration incorporating ~ 2000 separate pointings. Observations at 8 GHz will also be needed to separate the contributions from ionized gas associated with the embedded protostars and the foreground HII region. A similar amount of time is sufficient to survey 1 square degree of the more nearby ($D \sim 140$ pc) low-mass, star-forming Taurus Molecular Cloud, to a sensitivity of $0.015 M_{\odot}/\text{beam}$. Such a survey would be complete for all embedded protostars in the cloud.

The Orion B region, on the other hand, is several arc minutes in extent and contains young stars at all stages of evolution, including a ridge of dense molecular cores some of which contain deeply-embedded protostars, and an infrared cluster associated with a spectacular HII region. The possibility that the molecular cores are protostellar or pre-protostellar in nature is extremely exciting: massive protostars evolve so quickly that they are usually observed only after they have already reached the main sequence. It has been suggested that the formation of the protostars in the dense molecular ridge may have been triggered by the expansion of the HII region into the surrounding cloud, an idea that has important implications for sequential star formation in stellar clusters and associations, and could also provide insight into star formation in starburst and interacting galaxies. The details of this process can only be tested through high-angular resolution ($\sim 1''$), high sensitivity ($\sim 1\text{K}$) observations of the molecular and ionized gas. The kinematics of the latter component can be studied using radio recombination lines in the 6 GHz band -- these observations would be used to look for evidence of expansion. The dynamics of the dense molecular gas associated with the protostars can be traced by the $J=1-0$ transitions of CS (49 GHz) and SiO (43 GHz) to search for evidence of cloud collapse or energetic outflow. However, as the VLA's primary beam at these frequencies is approximately $60''$, these observations must be done in mosaicing mode, which will require extremely good antenna pointing.

Often the EVLA's sensitivity will be such that scientifically productive work can be accomplished with integration times of a few seconds or less. At the same time, the angular sizes of target sources can be many times the angular size of the VLA's primary beam. This will especially be so for the high frequency bands, and invites the use of a rapid mosaicing mode – the capability of taking interferometric visibility data while the antennas are in constant motion. This technique, well known in single-dish work, is termed 'On the Fly Mapping'. Estimates are that the VLA's antennas will be able to track accurately (meaning both that they can move smoothly, and that the position of the antennas will be known) at a rate of up to ten times the sidereal rate – or 150 arcseconds/second of time. The scientific payoff of this is very valuable. If the antennas can move at ten times the sidereal rate using the 'On the Fly Mapping' technique in mosaicing mode, then the whole of the Taurus Molecular Cloud -- an area of approximately 25 square degrees -- could be covered in only 12 hours to a 3σ sensitivity limit of 2 mJy/beam at 45 GHz, corresponding to $0.2 M_{\odot}$ /beam.

Technical Capabilities Needed for this Work:

- Antenna pointing (via referenced pointing) with an r.m.s. accuracy of 3"
- An antenna tracking capability to permit interferometric observations while the antennas are moving ('On-The-Fly Imaging') at rates of up to ten times sidereal.
- 43 GHz point-source sensitivity of 0.4 mJy (1 K in a 1" beam) in a 1km/s channel in 12 hours.

2.1.13 Pulsar Science with the EVLA

2.1.13.1 Astrometry -- Proper Motions

For most pulsars, astrometry will move from 1.5 GHz to the 4 - 8 GHz band. This has many benefits, including reduced dispersion smearing and a narrower pulse which improves the gain from pulsar gating, less ionospheric distortion, a beam size reduced by a factor of four, reduced artifacts due to pulsar scintillation, and a larger available bandwidth. Even after considering that the typical pulsar has only 6% the flux density at 6 GHz that it does at 1.5 GHz, the EVLA positional sensitivity in the 4 to 8 GHz band will be a factor of about 80 greater than the VLA's current sensitivity at 1.5 GHz. To date, only about 100 of the 1200+ known pulsars have reliably measured proper motions, and most of these are the bright, nearby pulsars. By increasing the number of pulsar proper motions, especially those of distant pulsars, systematic studies of pulsar velocities become possible. With the EVLA, proper motions of 100 distant pulsars could be measured over a period of five years in three 50-hour observations with typical uncertainties of 0.5 mas/year. These data will allow questions of pulsar birth velocity distribution and the pulsar dipole magnetic field decay timescales to be addressed.

Key Technical Requirements for this project:

- Maximum sensitivity in the 4 - 8 GHz band.
- Correlator with 1024 phase bins with < 100 microsec resolution.
- Ability to phase the array with > 256 MHz bandwidth.

2.1.13.2 Pulsar Emission Mechanisms

One of the open questions in pulsar astronomy is the nature of the plasma processes giving rise to the observed radio radiation. Simultaneous monitoring of the pulsar magnetosphere at multiple frequencies provides a detailed look at the processes. Co-ordinated observing from multiple observatories is difficult, due in large part to instrumental differences. The unique capability of the VLA to observe

simultaneously multiple frequencies has provided unique information about the emission region. But the limited bandwidth (50 MHz) of the current VLA has constrained observations to time resolutions of 20ns. The wide bandwidth of the EVLA will allow both higher time resolution observations, and will enable single pulse detection at higher frequencies. The ability of the EVLA to be divided into simultaneous multiple phased subarrays will provide for true multifrequency observation.

Key Technical Capabilities required for this project:

- Up to 5 simultaneous subarrays
- Wide-band (1 GHz) phased array capability for each subarray.
- Continuous data acquisition (no periodic data interrupts).

2.1.13.3 Pulsar Timing Experiments

The timing of pulse arrival times from millisecond pulsars (MSP) provides a unique method to prove general relativity in the strong field regime. Measurements of Shapiro delay, perihelion shift and now spin-orbit coupling have been observed in a few binary MSPs, providing some of the best evidence that the theory of general relativity is correct. To date, the pulsar with the most stable timing is J0437-4715, with timing uncertainties of 100 nsec. With large bandwidths being opened to radio astronomy in this decade, the probability of discovering even stabler pulsars increases. In order for the EVLA to remain competitive in this science, the absolutely timing precision must be significantly better than 100 nsec.

Key Technical Capabilities required for this project:

- Correlator capable or providing ~ 1 nsec internal timing in phased array mode.
- Knowledge of absolute time accurate to 10 nsec.

2.1.14 The Structure of a Cluster of Galaxies, plus an HI Pencil Beam Survey

At a redshift of about 0.1, an entire cluster of galaxies can be observed with a single pointing of the VLA. A single 36-hour integration can then give the spatial and kinematic distribution of all the gas-rich objects in and around the cluster. Such an integration, using the C-configuration to provide some spatial resolution, would (at $z = 0.1$) allow a 6-sigma detection of 700 million solar masses of HI with a 100-km/sec line width. Half of the EVLA correlator would then provide 3.2-km/sec resolution in both parallel-hand polarizations, providing detailed kinematic information. This spatial and velocity distribution of the gas rich galaxies will provide information on the dynamical state of the cluster -- whether it is relaxed or still collapsing. This resolution will also enable absorption studies on the bright continuum background objects, as well as reveal subtle kinematics of the interaction between the IGM and ISM. The velocity coverage of 13,000 km/sec is twice that needed to cover a typical cluster rich cluster, so many foreground and background spirals will be detected.

The 3km/sec resolution will make it possible to derive useful Tully-Fisher distances to the galaxies, and thus to probe

Deviations from the Hubble flow out to many Mpc from the cluster. These observations will also provide a useful database to compare with cluster studies at higher redshifts aimed at determining the evolution of the gas content in clusters.

As the 1-2 GHz band will provide good sensitivity to frequencies below 1 GHz, and the entire band is always available to the correlator, the 'unused' half of the correlator from the observation described in the previous paragraph can be employed in analyzing the entire spectrum from 900 to 1400 MHz -- corresponding to redshifts out to ~ 0.6 . This will provide a resolution of ~ 40 km/sec, and with the same 36-hour integration, HI masses of 4×10^9 solar masses can be detected at $z = 0.2$, implying that galaxies with modest HI content can easily be detected. Each such integration should give detections of a few hundred galaxies in HI.

However, this part of the spectrum is heavily used by aeronautical systems, and very strong RFI is common. These strong signals (whose peak power exceeds that of the entire 1 GHz bandwidth noise by more than an order of magnitude) require a signal transmission system and a correlator with very high linearity, plus the ability to 'tune around' signals which drive the system outside its linear region.

Technical Requirements for this science:

- High sensitivity between 1 and 1.4 GHz.
- Instantaneous bandwidths > 512 MHz.
- 16000 channel correlator that can process 512 MHz of spectrum in two simultaneous modes.
- Very highly linear signal transmission system and correlator.
- A correlator that can avoid extremely strong spectral features.

2.2 Overall Technical Goals

To enable the scientific experiments listed above, the capabilities of the existing facility must be improved approximately ten-fold in all key technical areas.

Existing technologies can accomplish this. Below are listed the major technical goals that must be attained. In many cases, there are two goals listed. The first is the ‘Required Goal’ – giving the performance that is necessary for achieving the science goals listed above. The second is the ‘Target’, giving a performance goal that, if attained, will give good extra science return.

An explanation and justification for each of the goals listed below will be found in EVLA Memo (TBD – under construction in Sept. 2003)

2.2.1 Antenna – Mechanical

2.2.1.1 Pointing

These specifications apply to optimum observing conditions: wind less than 5 m/s, nighttime with the antenna near thermal equilibrium with the environment. The pointing error is defined as the root-mean-square of the difference between the actual and commanded positions, after a recent telescope model has been applied.

a. Blind Pointing

Required: 6” between 30 and 70 degrees elevation.
Target: 6” between 20 and 80 degrees elevation.

b. Referenced Pointing

The reference source is within 5 degrees (angle) and 15 minutes (time):

Required: 3” between 20 and 70 degrees elevation.
Target: 2” between 20 and 70 degrees elevation, and
3” between 70 and 80 degrees elevation.

c. Super-Sidereal Tracking (OTF Imaging)

All requirements are applied between 20 and 70 degrees elevation.

Required: 4” at drive rates up to 1 deg/min
8” at drive rates between 1 and 2.5 deg/min.
Target: 2” at drive rates up to 1 deg/min.
4” at drive rates between 1 and 2.5 deg/min.

2.2.1.2 Subreflector Positioning

All positioning requirements, unless specifically noted otherwise, are ‘repeatable’, meaning that the subreflector is to return to a previous position within the listed error. It is presumed that any offset error is calibrated out by application of a valid pointing model or local determination, and that this offset is itself stable within the given error. The first focus requirement is absolute, and is referenced to the best-fit paraboloid focus position for the band in use.

a. Focus

Required absolute: 0.6mm
Required repeatable: 0.3mm
Target repeatable: 0.2mm

b. Horizontal Positioning Stability

Required: 0.3 mm on timescales ~ 1 month
Required: 0.15 mm on timescales ~ 30 minutes.
Target: 0.1 mm on timescale ~ 30 min.

c. Tilt Positioning Stability:

Required: 24" on timescales ~ 1 month
Required: 12" on timescale ~ 30 minutes
Target: 8" on timescales ~ 30 minutes.

d. Rotation Positioning Accuracy

Required: 480" on 1 month timescales
Required: 240" on 30 min timescales.
Target: 180" on 30 min timescales.

e. Band Change Speed

Required: 20 seconds
Target 10 seconds

2.2.1.3 Antenna Slew and Settle Time

This requirement refers to the time taken to move and settle between two commanded positions.

Required: <5 seconds, when distance is less than 30 arcminutes.
Target: <3 seconds, when distance is less than 30 arcminutes.

2.2.1.4 Secondary Focus Feed Positioning

This requirement refers to the angular accuracy with which a feed at the Cassegrain focus can be aligned.

Required: 10 arcminutes, adjustable in the field.

2.2.2 Antenna – Electrical

2.2.2.1 On-Axis Efficiency

This includes the effects of aperture blockage, surface roughness, spillover, illumination taper, feed alignment, diffraction losses, and VSWR losses for both the feed and LNA.

Band (GHz)	Required	Target
1.2 – 2.0	0.50	0.55
2.0 – 4.0	0.62	0.68
4.0 – 8.0	0.60	0.66
8.0 – 12.0	0.56	0.61
12.0 – 18.0	0.54	0.59
18.0 – 26.5	0.51	0.56
26.5 – 40.0	0.39	0.43
40.0 – 50.0 (@ 43 GHz)	0.34	0.37

2.2.2.2 Main-Beam Efficiency

TBD

2.2.2.3 Antenna Primary Beam Power Pattern Similarity

Required: The normalized primary power pattern of any antenna must not vary by more than 0.03 (power units) from the average of all antennas, within the 3dB ellipse.

Example: At the 3dB angle defined by the mean power pattern, all antennas must have a power gain between 0.47 and 0.53 of the peak forward gain.

Required: The antenna voltage phase within the 3dB ellipse may not vary by more than 0.35 degrees w.r.t the on-axis value.

2.2.2.4 Feed Illumination

Required: The illumination centroid is to be within 5 cm of the antenna center.

2.2.2.5 Antenna Polarization Characteristics

a. Stability of Cross-Polarization

Required: Over an 8 hour period, and under stable weather, the RCP and LCP polarization ellipses shall be stable to:

- i) 0.002 in Axial Ratio
- ii) 2 degrees in position angle

within the inner 3dB (FWHP) of the antenna primary beam.

b. Limits on Ellipticity

Required: The RCP and LCP on-axis polarization ellipse axial ratios are to be between 0.9 and 1.0.

Required: The polarization ellipses axial ratios are to be the same for all antennas at a given frequency, to within the same tolerances as given above.

c. Circular Polarization ('Beam Squint') Stability:

Required: The angular separation between the R and L beams to remain constant to 6", over a period of 8 hours.

2.2.3 Receivers

2.2.3.1 System Temperature and Sensitivity

The requirements for each band for the total system temperature are listed below. The listed values apply to the middle 50% of each band, include atmospheric absorption and

emission, and are referenced above the atmosphere. See Table 3-2 for a breakdown of the contributions.

Band (GHz)	Tsys	Comments
1.2 – 2	30	
2 – 4	29	
4 – 8	30	
8 – 12	30	
12 – 18	40	
18 – 28	60	Under optimum conditions*
28 – 40	55	Under optimum conditions*
40 – 50 (low end)	80	Under optimum conditions*
40 – 50 (high end)	150	Under optimum conditions*

*‘Under optimum conditions’ means clear skies on a winter night, ZD = 0 degrees.

These requirements, when combined with the antenna efficiency requirements listed in 2.2.2.1, give the following system sensitivity requirements. These supersede both the efficiency and system temperature requirements.

Band (GHz)	Ae/Tsys (m ² /K)	SEFD (Jy)
1 – 2	8.2	335
2 – 4	10.6	260
4 – 8	9.9	280
8 – 12	8.6	320
12 – 18	6.5	425
18 – 28	4.1	680
28 – 40	3.3	835
40 – 50 (low end)	2.0	1350
40 – 50 (high end)	1.0	3000

Required: Degradation of receiver temperature within any band with respect to the mean defined in the central 50% is to be by less than 3dB at any frequency, by less than 1dB over the inner 85% of each band, and by less than 2 dB over 95% of the band.

2.2.3.2 Power Gain Linearity

This refers to the accuracy with which the flux density scale will be preserved when observing a source strong enough to increase the total system noise by the given ratio.

Required: Overall power gain linearity better than 0.5% over an input power range of 15 dB.

Required: Overall power gain linearity better than 2% over an input power range of 50 dB.

Required: The following table gives the headroom requirements for the signal delivered to the sampler.

Frequency Band (GHz)	Headroom (in dB) to 1 dB compression
1.2 – 2	36
2 – 4	35
4 – 8	34
8 – 12	34
12 – 18	31
18 – 26.5	31
26.5 – 40	31
40 -- 50	25

2.2.3.3 System Phase Stability (Temporal)

The listed values are after all round-trip corrections. For reference, we note that the phase error in degrees is the time error in picoseconds times the frequency in GHz, divided by 3.

Required: Variations $(1-\sigma) < 0.5\text{ps}$ on timescales less than 1 second.
 A slope $< 0.2 \text{ ps/min}$ over durations < 30 minutes.
 Variations about the slope $< 1.4 \text{ ps}$ over 30 minutes.
 Any phase change associated with antenna motion must be less than 0.7 ps for arbitrary change in pointing direction, and 0.07 ps for antenna pointing change less than 10 degrees.
 Note: These requirements apply to the system electronics, and do not include effects of atmospheric instability.

Required: R – L phase (difference between oppositely polarized signal channels) to be less than 0.5 ps, for all timescales.

2.2.3.4 Bandpass Characteristics

a. Amplitude Stability

Required: Variations in bandpass (power units) are to be less than 10^{-4} , on timescales of less than 1 hour, on frequency scales less than the band frequency/1000.

b. Phase Stability

Required: Phase variations within the bandpass are to be less than 0.006 degrees, on timescales less than 1 hour and frequency scales less than the RF frequency/1000.

c. Gain Slope

Required: The overall system power gain ratio across the full bandwidth of any band is to be less than 3 dB.

Required: The gain ratio is to be less than 0.3 dB on frequency scales less than:
0.5 MHz at L-band (i.e. gain slope is less than 0.6 dB/MHz);
1 MHz at S-Band; (0.3 dB/MHz)
2 MHz at C and X bands (0.15 dB/MHz); and
4 MHz at the other bands (0.1 dB/MHz).

d. Gain Ripples

Required: Power ripples in the passband are to be less than 0.25 dB on frequency scales less than those listed in c. above.

e. Bandpass Phase Structure

Required: Bandpass phase variations (differences between antennas) are to be less than 2 degrees in phase, on frequency scales less than those listed in c. above.

f. Phase Slope (Residual Delay Errors)

Required: Residual system delay errors must be less than 2.8 nsec.

2.2.4 Time

Required: System time must be accurate to 10 nsec.

2.3 Correlator Requirements

The capabilities of the 'WIDAR' correlator, being designed and built by the DRAO correlator group, are described in detail in Chapter Eight. The major requirements are summarized below:

- The capability to process at least 27 antenna inputs, and be expandable to at least 48, in anticipation of Phase II of the project.
- Instantaneous bandwidth for each antenna input of up to 16 GHz, nominally organized as four oppositely polarized pairs of signals of 2 GHz each.
- Full polarization capability, with the user specifying which combinations are desired.
- At least 16384 spectral channels/baseline for all input bandwidths.
- Spectral resolution ranging from a few MHz to less than one Hertz.
- The ability to 'target' up to 32 spectral transitions or narrow portions of the input bandwidth simultaneously, with velocity resolution of ~ 1 km/sec.
- The ability to avoid isolated strong RFI.
- At least 50 dB spectral dynamic range.
- A pulsar binning capability providing at least 2000 bins/baseline, with bin width 0.2 ms or less.
- A flexible subarraying capability, with at least 5 subarrays in cross-correlation modes.
- A phased-array mode, for up to 5 independent subarrays.
- A minimum data output integration time no greater than 100 msec with all spectral channels.
- VLBI-ready, such that recorded data (either by tape or disk) can be correlated with at least the capability of the current VLBA correlator.
- The ability to blank all correlations identified with potential RFI on an antenna input signal.

2.4 RFI Management Plan

Because of the wide utilized bandwidth (for the five lowest frequency bands, the entire received RF will be transmitted to and fully processed by the correlator), avoidance of strong RFI will generally not be possible. This means that non-cosmic signals with signal powers many orders of magnitude greater than the system noise power must be accommodated by the signal chain, which must then be designed to preserve gain linearity, and to avoid intermodulation products.

The external signals can be very strong – the environmental monitor system regularly detects signals from the 'DME' aircraft ranging system whose instantaneous power, as seen through the isotropic sidelobes of our 25-meter antennas, exceeds the total noise power within the 1 GHz bandwidth of the L-band system by 30 dB. These DME signals are pulsed – a pair of pulses of 3 μ sec width, separated by 9 to 45 μ sec, with a repetition rate of 10 to 150 Hz. Although these signals may represent an extremum in their characteristics, we must assume they are typical, and construct a plan to handle them.

The RFI environment is not static – strong signals come and go without warning, and overall it is clear that the usage of the spectrum is increasing with time. Undesirable signals can occur at any frequency – even within the protected radio astronomy bands. Our strategy for accommodating this changing environment must then be flexible.

The EVLA RFI Management Plan is based on the following foundations:

Measurement and Monitoring of man-made signals. Management must begin with knowledge of the dynamic RFI environment, and measurement of the strengths, characteristics, and origins of the RFI, both internal and external.

Linear and Flexible Design. Maximum linearity of all components in the signal-processing path is necessary to prevent saturation and intermodulation products. With input signal powers exceeding the total system noise power by 30 dB or more, we have established a 'headroom' requirement of at least this much for those bands where such signals strengths are anticipated. High bit-level quantization (up to 8 bits) must be used for bands with high RFI environment. Flexible design means the ability to tune the IF frequency around strong, isolated RFI, and to configure the correlator to avoid such RFI, either through tuning of its sub-bands, or by implementation of blanking, based on detection of strong input power. Finally, provision to insert stop-band filters is required for blocking signals strong enough to saturate secondary stages of amplification.

Suppression of man-made signals. It is obviously undesirable for the EVLA electronics to pollute the astronomical signals of interest. Thus, locally generated signals must be eliminated through design or suppressed through containment. Permitted maximum signal emission levels, based on the ITU standards and incorporating expected space attenuation and shielding capabilities must be set and followed by a rigorous testing procedure. Non-local signals should be minimized through identification and interaction with the agencies responsible for their generation.

Excision through post-correlation processing. To the correlator, a source of RFI is just another radio source, which can be distinguished from an astronomical source by its differing phase and phase rate. Provided the correlator can resolve the RFI in frequency and time, and that linearity in the signal chain (including the correlator) is maintained, post-processing will be able to effectively remove much or most RFI from the data, using methods similar to those employed now in removing unwanted background radio sources. Methods are being developed at many observatories to allow such removal, and the EVLA Project must ensure that the correlator and subsequent data processing not prohibit future effective methodologies. Although we are certain that the foundations of this method are sound, it is certain that such processing will be computationally intensive and expensive.

2.5 Overall Software Requirements

(To be contributed by Bryan Butler).