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THE EXPANDED VERY LARGE ARRAY: A NEW TELESCOPE FOR NEW SCIENCE

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ABSTRACT

Since its commissioning in 1980, the Very Large Array (VLA) has consistently demonstrated its scientific productivity. However, its fundamental capabilities have changed little since 1980, particularly in the key areas of sensitivity, frequency coverage, and velocity resolution. These limitations have been addressed by a major upgrade of the array, which began in 2001 and will be completed at the end of 2012. When completed, the Expanded VLA—the EVLA—will provide complete frequency coverage from 1 to 50 GHz, a continuum sensitivity of typically 1 μJy beam^{-1} (in 9 hr with full bandwidth), and a modern correlator with vastly greater capabilities and flexibility than the VLA's. In this Letter, we describe the goals of the EVLA project, its current status, and the anticipated expansion of capabilities over the next few years. User access to the array through the Open Shared Risk Observing and Resident Shared Risk Observing programs is described. The following papers in this special issue, derived from observations in its early science period, demonstrate the astonishing breadth of this most flexible and powerful general-purpose telescope.

Key words: telescopes

Online-only material: color figures

1. INTRODUCTION

The Very Large Array (VLA) is an imaging radio interferometer located in west-central New Mexico, operated by the National Radio Astronomy Observatory (NRAO).[1] It comprises 27 antennas of 25 m diameter positioned along three equiangular arms of length 21 km, nine antennas per arm. The array provides images of astronomical objects in all four Stokes parameters, with a diffraction-limited maximum resolution of 1.4 arcsec at 1.4 GHz and 40 milliarcs at 50 GHz, utilizing the well-established techniques of aperture synthesis, as described for example in Thompson et al. (2001). The VLA is an exceptionally flexible telescope, in part due to its ability to reconfigure—there are four standard configurations of maximum baseline lengths of 1, 3.4, 11, and 36 km, providing a wide range of resolutions and image surface brightness sensitivities. Descriptions of the VLA as originally designed are found in Thompson et al. (1980) and Napier et al. (1983). A picture of the VLA in its most compact configuration is shown in Figure 1.

The VLA was designed and built in the 1970s utilizing the best technology available at the time. Upon its completion in 1980, the array could observe in four frequency bands with a maximum bandwidth of 100 MHz per polarization. Its innovative digital correlator provided a maximum of 512 spectral channels, spanning a maximum of 3 MHz for each of the 351 baselines in a single polarization, or it could provide full Stokes visibilities for polarimetric imaging but without any spectral resolution. These capabilities were ground-breaking at the time and were well matched to the key science goals for the telescope, which included imaging the Doppler-shifted hydrogen emission from nearby galaxies and resolving the fine-scale structure of powerful radio galaxies, quasars, and supernova remnants.

With 27 antennas and a two-dimensional array, the VLA was designed for sensitivity, speed, and flexibility of operation. Besides the ability to change its physical scale, changes in frequency band and correlator mode could be effected in seconds, enabling astronomers to acquire a range of information on astronomical objects not possible on any other centimeter-wavelength radio telescope. These attributes encouraged users of the VLA to image radio emission from processes far removed from those given in the original proposal as science goals for the array—indeed, much of the VLA's most original and influential observations are in fields unanticipated or unknown at the time of construction.

Most components of the VLA's design remained unchanged for 20 years following its completion—in particular, the signal transmission and correlation capabilities remained at their 1980 levels, essentially freezing the array's bandwidth and spectral resolution. During this interval, and continuing on to this day, spectacular improvements in signal transmission and processing have taken place, making it clear that a minimum of an order-of-magnitude improvement in the array's sensitivity, frequency coverage, and spectral resolution could be obtained at modest cost by implementing these new technologies. During this same interval, the breadth and range of astronomical science had changed dramatically, with ever increasing emphasis on rapid time response, fast imaging, precision polarimetry, high sensitivity, wider frequency coverage, and higher spectral resolution. In response to these expanding needs, the NRAO proposed to the NSF in 2000 a far-reaching expansion of the VLA's capabilities, essentially marrying modern high-speed wide-band digital and wide-band receiver technologies to the sound infrastructure already in place. Following a high ranking by the 2000 Decadal Review National Research Council (2001), the Expanded VLA (EVLA) Project began in 2001 and will be completed by the end of 2012. The Expanded Very Large Array Project is a partnership among the U.S., Canada, and Mexico, with a total budget of $96M (inflation-adjusted, in 2011 dollars).

[1] The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Figure 1. Aerial photograph of the VLA in its most compact "D" configuration, with maximum baseline 1.0 km. The array can be reconfigured by moving the antennas to more distant pads via the rail lines visible in the photograph.

(A color version of this figure is available in the online journal.)

2. KEY EVLA GOALS AND CAPABILITIES

The technical goals of the EVLA are based on a comprehensive review of potential science enabled by a minimum tenfold increase in capabilities over the VLA. The identified science capabilities were organized into four major themes.

1. The magnetic universe: measuring the strength and topology of cosmic magnetic fields.
2. The obscured universe: enabling unbiased surveys and imaging of dust-shrouded objects that are obscured at other wavelengths.
3. The transient universe: enabling rapid response to, and imaging of, rapidly evolving transient sources.
4. The evolving universe: tracking the formation and evolution of objects in the universe, ranging from stars through nearby galaxies to galactic nuclei.

Within each theme, it was readily demonstrated that order-of-magnitude improvements in VLA performance would result in spectacular new science by the world-wide user community. Based on these conclusions, the fundamental goals of the EVLA project are as follows.

1. Complete frequency coverage from 1 to 50 GHz, via eight new or improved receiver bands, utilizing state-of-the-art technology. See Table 1 for basic characteristics.
2. New antenna electronics to process eight signal channels of up to 2 GHz each.
3. High-speed wide-band digital samplers within each antenna to sample up to 8 GHz bandwidth in each polarization.
4. A new wide-bandwidth fiber-optical data transmission system to conduct digital signals from the antennas to the correlator.
5. A new wide-bandwidth, full polarization correlator providing a minimum of 16,384 spectral channels per baseline.
6. A new real-time control system for the array, and new monitor and control hardware for the electronics.

Table 1
EVLA Band Characteristics

Band (GHz)	Letter Code	Available Bandwidth[b] (GHz)	Antenna SEFD[c] (Jy)	Sensitivity[a] Continuum (μJy beam^{-1})	Sensitivity[a] Line (mJy beam^{-1})
1–2	L	0.7	400	5.5	2.2
2–4	S	1.75	350	3.9	1.7
4–8	C	3.5	300	2.4	1.0
8–12	X	3.8	250	1.8	0.65
12–18	Ku	5.5	280	1.7	0.61
18–26.5	K	8	450	2.3	0.77
26.5–40	Ka	8	620	3.2	0.90
40–50	Q	8	1100	5.6	1.4

Notes.
[a] The expected rms noise in a 1 hr integration at high elevation and under good weather conditions. For the Continuum case, the bandwidth utilized is that listed in Column 5. For the Line case, a bandwidth corresponding to 1 km s^{-1} velocity resolution is assumed.
[b] An estimate of the effective bandwidth available, free of RFI.
[c] The System Equivalent Flux Density is a measure of the antenna sensitivity: SEFD $= 2kT_{\rm sys}/A_e$. It is the flux density of a source which doubles the system temperature.

7. New high-level software that provides easier and more flexible management of EVLA capabilities to its users.

2.1. The WIDAR Correlator

A key component of the EVLA is its new wideband digital correlator, known by the acronym WIDAR.[2] This is a 10 peta-32-bit ops/sec special-purpose computer which produces the cross-power spectral visibilities for all baselines in the array. A description of its design is given in Carlson & Dewdney (2000). Its key astronomical capabilities are summarized below.

[2] For Wideband Interferometric Digital ARchitecture.

Table 2
EVLA–VLA Performance Comparison

Parameter	VLA	EVLA	Ratio
Continuum sensitivity	10 μJy beam^{-1}	1 μJy beam^{-1}	10
Maximum BW, per polarization	0.1 GHz	8 GHz	80
No. of frequency channels at maximum BW	16	16384	1024
Maximum no. of frequency channels	512	4194304	8092
Coarsest frequency resolution	50 MHz	2 MHz	25
Finest frequency resolution	381 Hz	0.12 Hz	3180
No. of full-polarization spectral windows	2	64	32
Frac. frequency coverage (log scale)	22%	100%	5

1. 16 GHz maximum instantaneous input bandwidth.
2. A minimum of 16,384 spectral channels per baseline, and a maximum exceeding 4 million.
3. Full polarization capabilities on all baselines and channels. If full polarization is not needed for the science, correlator resources can be reallocated to provide higher spectral resolution for the parallel-hand correlations.
4. Generation of 64 independent "spectral windows,"[3] each of which is separately tunable in frequency and bandwidth. The spectral window width is variable, by factors of two, from 128 MHz down to 31 kHz.
5. The ability to improve spectral resolution by utilizing correlator resources freed up with a reduction of the spectral window width, or by reallocating resources from unneeded spectral windows or polarization products. The spectral resolution is adjustable from a maximum of 2000 kHz to a minimum of 0.12 Hz.
6. A minimum integration time of 100 ms with the standard minimum 16,384 spectral channels, and less with a reduced spectral resolution.

Besides these basic capabilities for regular observing modes, there are a number of specialty modes including:

1. A phased array mode, where the signals from all antennas are combined in phase, and made available for external capture and analysis, such as for VLBI applications and pulsar processing.
2. A specialized pulsar binning mode, providing up to 2000 phase bins with temporal resolution as short as 200 μs with all spectral channels, and as short at 15 μs with a reduced spectral resolution, enabling rapid imaging of objects such as globular clusters and the Galactic Center where multiple pulsars are expected to lie within the antenna primary beam.
3. Up to eight simultaneously operating subarrays, each with a different target point and correlator configuration.
4. An external data capture capability, allowing antenna or phased array outputs to be externally recorded for off-line processing.

The WIDAR correlator is Canada's contribution to the EVLA project, and was designed and built to meet or exceed the requirements of the EVLA by the HIA correlator group, located at DRAO near Penticton, BC, Canada.

A more thorough description of the EVLA's design, including that of its correlator, is found in Perley et al. (2009).

[3] A spectral window is a digitally defined frequency span, which is uniformly subdivided into spectral channels by the correlator.

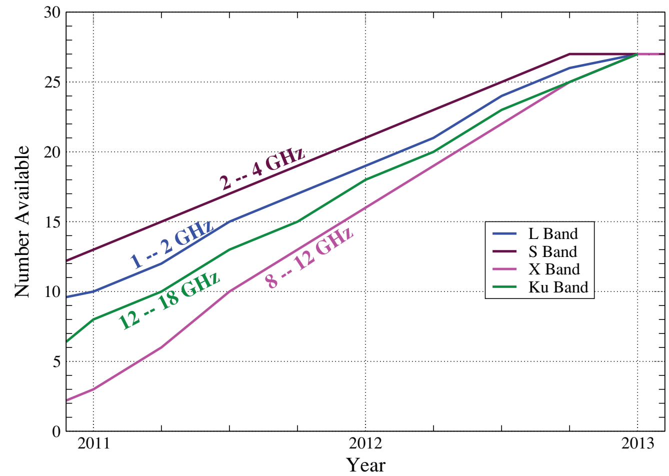

Figure 2. Predicted availability of wideband EVLA receivers for the remaining four receiver bands. The 4–8 GHz band and the three bands spanning 18 through 50 GHz are now fully outfitted.

(A color version of this figure is available in the online journal.)

3. EVLA CAPABILITIES GROWTH

A compact summary of the expansion in capabilities of the EVLA in comparison to those of the VLA is provided in Table 2

The conversion of the VLA into the EVLA was scheduled to take more than a decade. It was therefore considered vital to maintain operation as a productive scientific facility throughout the conversion process. This required designing in a backward compatibility between the newly converted antennas and the original correlator. This process has been very successful, enabling nearly seamless continuing observing, with the array only shut down for a single seven-week period between 2010 January and March in order to move hardware from the old VLA correlator to the WIDAR correlator upon the latter's implementation. This has enabled the NRAO to offer steadily increasing scientific capabilities to the user community ahead of the completion of the construction project. The growth in capabilities can be separated into two parts: that provided by the antennas, including the receivers and the data transmission system, and that provided by the correlator.

3.1. Antenna and Frequency Band Capabilities

Figure 2 shows the current and anticipated availability of the eight receiver bands. Full outfitting of four receiver bands are now complete—these are the 4–8 GHz band, and the three highest frequency bands, spanning 18 through 50 GHz.

A critical component, not illustrated in the figure, is the growth in data transmission capabilities. The current maximum total bandwidth which can be transferred from antenna to correlator is 4 GHz, available in two pairs of oppositely polarized signals of bandwidth 1 GHz each. Implementation of the full 16 GHz capability will not be available for science observing until at least mid-2012.

3.2. Growth in Correlator Capabilities

The WIDAR correlator is capable of a diverse range of observing modes. Following the decommissioning of the old VLA correlator in 2010 January, a basic set of WIDAR correlator capabilities were defined and offered for the first full EVLA standard configuration cycle that were modeled on the capabilities of the VLA, and in fact more than doubled the total available bandwidth per polarization, to 256 MHz, and dramatically increased the number of available spectral channels at the maximum bandwidth. At the same time the commissioning of the correlator proceeded to focus on delivering the maximum 2 GHz per polarization bandwidth currently available in preparation for the configuration cycle beginning in 2011 September in the most compact configuration. The jump from 256 MHz to 2 GHz marks a potential increase in data set size by a factor of eight, and with the total 8 GHz bandwidth expected in 2012, there will be a further increase. In its highest spectral resolution modes, with typically hundreds of thousands of channels per integration, visibility data set sizes will potentially be several terabytes. By the beginning of EVLA full operations in 2013 January, it is expected that up to 8 GHz bandwidth (for those bands supporting these bandwidths; see Table 1) will be available, with up to 4 million channels for spectroscopy.

3.3. Science Commissioning

The delivery of the full science capabilities of the EVLA, as opposed to the correlator modes and updated electronics and receivers, requires the development of new observing, calibration, and post-processing procedures compared with the VLA, plus the software to support them. The WIDAR correlator is fundamentally a spectral line correlator, so that even standard "continuum" observations of astronomical sources are carried out in a spectral line correlator mode. Furthermore, the vastly increased sensitivity of the EVLA provides new opportunities such as fast "on-the-fly" mosaics of large areas, large (in number) source surveys, and high time resolution observations. All these observing modes are new to the EVLA, and each will be commissioned by EVLA staff. At the time of EVLA full operations many new observing modes and capabilities are expected to be available, but some more specialized modes may take longer.

The wide bandwidths of the EVLA present a special problem at its lower frequencies ($\nu \lesssim 10$ GHz, although higher frequencies are also affected to some extent), for which the radio spectrum suffers considerable external interference (RFI) that is both temporally and spatially variable. The development of automated flagging and interference excision procedures and software is a key area of commissioning throughout 2011 and 2012.

3.4. EVLA Early Science Programs

EVLA Early Science Programs began in 2010 March with the array in its most compact, D-configuration, and will continue through the end of the EVLA construction project until full operations commences in 2013 January. It includes an Open Shared Risk Observing (OSRO) program for the general user community and a Resident Shared Risk Observing (RSRO) program. The OSRO program offers the correlator capabilities described in Section 3.2 above. The RSRO program offers participants full access to the growing capabilities of the WIDAR correlator for peer-reviewed science projects, in exchange for a period of residence at the Domenici Science Operations Center (DSOC) in Socorro to assist with the EVLA commissioning. It is intended to accelerate the development of the EVLA's full scientific capabilities by gaining enhanced resources and expertise through community participation, at the same time as more quickly optimizing the scientific productivity of the EVLA. To date, 27 individuals have passed through the DSOC as RSRO visitors. The papers in this special issue of *The Astrophysical Journal Letters* utilize data obtained through both of these Early Science programs.

4. USING THE EVLA

Observing time on the EVLA is open to all astronomers world-wide. There are no quotas or reserved blocks of time. Starting in 2011 time on the EVLA is scheduled on a semester basis, with each semester lasting six months. Proposal deadlines are 5 pm (1700) Eastern Time on February 1 and August 1.[4] The February 1 deadline nominally covers observing time in August or later, and the August 1 deadline nominally covers observing time in February or later. At either proposal deadline, requests for future array configurations may also be considered.

Astronomers prepare and submit observing proposals using the on-line Proposal Submission Tool (PST). The PST permits the detailed construction of a cover sheet specifying the requested observations, using a set of online forms, and the uploading of a scientific and technical justification to accompany the cover information. Funding opportunities are available for students at US institutions and may be requested via the PST. Proposal evaluation involves technical reviews by NRAO staff and panel-based science reviews by community members. The results of these reviews are cross-reconciled by the community-based Time Allocation Committee, leading to an approved science program.

Information from approved proposals flows to the Web-based Observation Preparation Tool (OPT), an online tool for creating observing scripts. Astronomers use the OPT to specify sources to be observed, instrumental setups, and timing information, all packaged as a Scheduling Block (SB). Astronomers also use the OPT to submit their SBs to a dynamic queue. NRAO staff use the Observation Scheduling Tool (OST) to examine the queue of pending scheduling blocks and the current observing conditions. The OST then applies heuristics to select the optimal scheduling block and send it off for execution by the monitor and control system. Such dynamic scheduling enhances science data quality and the array's ability to discharge time-sensitive science. The OST can also be used to execute a fixed-date scheduling block, as required for a coordinated observation with other telescopes.

As an observation progresses, NRAO staff monitor the array's health, maintain an observing log, and ensure that science data are being archived. At the conclusion of an observation the observing log is e-mailed to the astronomer. This log includes a link to the Archive Access Tool, an online search tool that the astronomer can use to locate and download the archived data. Those data are proprietary to the proposal's authors for a period of 12 months.

5. DATA POST-PROCESSING, PIPELINES, AND ALGORITHM DEVELOPMENT

It is clear that the data post-processing needs of the EVLA will far exceed those of the VLA. The salient features of the EVLA that will drive the post-processing software development are the capabilities to produce data covering: (1) a large instantaneous bandwidth (at the lowest three frequency bands the high-frequency end is twice the frequency of the low end) and (2) a large number of spectral channels (usually flexibly arranged in non-contiguous multiple spectral windows of varying width

4 It is also possible to obtain EVLA observing time by proposing to NASA missions, under joint agreements between NRAO and those missions. Such programs currently exist for the *Chandra* and *Fermi* missions; consult the relevant mission proposal calls for more information.

and frequency resolution). These two features result in high data rates (>5 MB s^{-1}) as a matter of course, with the WIDAR correlelator capable of producing much higher rates (up to 350 GB s^{-1}), and also therefore with the prospect of dealing with large (>1 TB) data sets. Therefore, calibration and imaging of the data from the EVLA will present problems that must be solved by a combination of a scalable post-processing package, algorithmic improvements, and processing and I/O speed gains.

A large fraction of data collected by the EVLA will be taken in one of a number of standard observing modes, for example, low frequency continuum, high frequency continuum, H I (neutral hydrogen) spectral line, or polarization. Given the considerable experience in reducing data taken in similar kinds of modes with the VLA, it is reasonable to assume that reduction of this type of data can be mostly automated. The post-processing package (see below), when combined with some information collected from the astronomer in the observation preparation stage (in the OPT—for instance what a particular source is meant to actually be used for in the post-processing), during actual observing, and with some heuristics (rules for what to do given certain situations) should be sufficient to complete such automatic reductions. While we are not currently providing an automated reduction pipeline for EVLA data, we plan to do so in the near future. When this occurs, all data taken in any of the standard modes on the EVLA will be processed with this pipeline, and the results (mainly so-called reference image cubes) made available via the science data archive, subject to proprietary constraints. While these reference image cubes may be sufficient to give the investigators (and others) an idea of data quality and crude source characteristics, there is some concern that it will be extremely difficult to ever provide completely reliable automatic pipeline products as a *final* data product from the EVLA. For that, some human intervention, either by NRAO staff or the astronomers themselves, may be needed. This is an active area of investigation within the observatory.

For all data which cannot be reliably reduced via a pipeline, or for astronomers who wish to modify or extend what is done within the pipeline, there must be a post-processing software package capable of performing all steps necessary to turn the measured visibilities into final image cubes. For the VLA, several packages have been used for data editing and calibration over the years, but for nearly the entire lifetime of the VLA, AIPS (Greisen 2003) has been the primary software package for data processing. There are problems with AIPS, however, that prevent its continued long-term use for EVLA data post-processing. The post-processing package of choice for the EVLA project is CASA (Common Astronomical Software Applications; see, e.g., McMullin et al. 2007), because of its scalability, ability to be parallelized, scriptability, expertise within NRAO, and commonality with ALMA. Not everything that is needed for EVLA data reduction (and certainly not for robust pipeline-reduction) is currently available within CASA, however, so there is a program of implementation of missing pieces within the package. In addition, a vigorous program of algorithm development within NRAO is ongoing, to address items that are not only implemented within CASA, but have no generally accepted algorithmic solution at all. Notably, automatic flagging of suspect data, wide-field wide-bandwidth full polarization imaging, RFI detection and excision, and ionospheric corrections are all areas of active research, and will be implemented within CASA as soon as possible after accepted algorithms are developed. Many of these areas of research are of course not unique to the EVLA, so developments at other observatories and telescopes are closely watched so that we can take advantage when appropriate.

Finally, in order to support the scale of computing that is needed for both pipeline and hands-on post-processing of EVLA data, we are planning to provide a mid-sized computing cluster (tens of nodes) for both the automatic pipeline reduction of standard mode observations and for somewhat more interactive reduction by astronomers. We believe this, along with improvements in the speed of the CASA code itself, is sufficient to support the needs of the astronomical community. We assume that most access to the cluster will be either by the NRAO-controlled automatic reduction pipeline or by batch jobs submitted by remote users. We are committed to remaining flexible in this plan, however, as this will be a new era for post-processing of interferometer data, and we must be able to react to new developments, pressure from the community, and other realities as we go forward.

6. SUMMARY

The EVLA is a major expansion to the highly flexible and productive VLA. By expanding the bandwidth to 8 GHz/polarization, adding receivers to provide full frequency coverage from 1 to 50 GHz, and implementing a new correlator with superb spectral resolution and flexibility, the EVLA will provide orders of magnitude improvement in scientific capability over the VLA—capabilities that will ensure that the EVLA will be the premier general-purpose centimeter-wave imaging radio telescope for at least the next decade, serving the world user community for investigations into, and understanding of, celestial radio transients, the evolution of radio-emitting objects in the universe, the structure and strength of celestial magnetic fields, and the dusty obscured regions opaque to most other wavelengths.

A project of this magnitude requires the talents and dedication of hundreds of individuals, far too numerous to list here. We acknowledge, with gratitude, the exceptional efforts by the members of the engineering, computing, and commissioning teams, both at the NRAO and at the DRAO, who have worked so long and hard over the past decade to make this project a success.

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Facility: VLA

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