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The Expanded Very Large Array

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Abstract: The Very Large Array is undergoing a major upgrade that will attain an order of magnitude improvement in continuum sensitivity across 1 to 50 GHz with instantaneous bandwidths up to 8 GHz in both polarizations. The new WIDAR correlator provides a highly flexible spectrometer with up to 16 GHz of bandwidth and a minimum of 16k channels for each array baseline. The new capabilities revolutionize the scientific discovery potential of the telescope. Early science programs are now underway. We provide an update on the status of the project and a description of early science programs.

1 Background

The Very Large Array has played a leading role in radio astrophysics over 30 years since it was completed in 1980. Since then, the capabilities of the VLA have changed very little. In order to continue the unparalleled scientific achievements of the telescope, a major expansion of its capabilities is currently nearing completion that improve radically the capabilities of the VLA. The key goals are to attain an order of magnitude improvement in continuum sensitivity (two orders in survey speed), complete frequency coverage from 1 to 50 GHz with vastly increased spectroscopic capability and correlator flexibility. Such improved specifications will greatly enhance the scientific discovery potential of the telescope, particularly in four science areas:

- the magnetic universe - the structure and topology of magnetic fields
- the obscured universe - enable unbiased imaging surveys of dust-enshrouded objects that are obscured at higher frequencies
- the transient universe - enable rapid response to transient events, and
- the evolving universe - tracking the formation and evolution of objects in the universe, from stars to galaxies to magnetic fields.

The key drivers within these broad science themes demand noise-limited, full-field imaging in all Stokes parameters, and point-source sensitivities of a few micro-Jy in an hour, leading to imaging dynamic ranges greater than 10^6, and a wide-range of spectroscopic ability. To attain such demanding specifications, several primary hardware areas have been upgraded:

- new broad-band receiver systems that provide continuous coverage between 1 to 50 GHz in eight different frequency bands, and superior sensitivity compared to the VLA systems (see Figure 1).

- new front-end electronics to digitize four 2-GHz-wide (R and L) frequency pairs at each antenna for a total of up to 8-GHz instantaneous bandwidth per polarization.
- new wide-band fiber-optic data transmission system to carry 16 GHz of signal bandwidth from each antenna to the correlator. This will eliminate stability and calibration challenges imposed by the analogue wave-guides of the VLA e.g. 3 MHz ripple and related spectral baseline instabilities.
- a new, highly-flexible, wide-band, full polarization correlator with at least 16k channels per baseline, and adjustable frequency resolution between 2.0 MHz and 0.12 Hz, using 64 independently tunable sub-bands, leading to an enormous range of potential correlator configurations, especially important for spectroscopy. Additionally, WIDAR has many specialized modes - e.g. phased-array, pulsar gating, pulsar binning etc, that increase greatly its scientific utility.

The EVLA project started in 2001 and is now nearing completion. The upgrade of all front-end electronics in the 27 antennas was completed in July 2009 and the WIDAR correlator began commissioning operations and early science in March 2010. The installation of the new receiver systems is on-going and will be completed in late 2012, and marks the completion of the EVLA. This $90 Million project is funded jointly by the US National Science Foundation (NSF), the Canadian National Research Council (NRC), and CONACyT, Mexico.

2 EVLA Performance

The upgrades in the EVLA system provide substantial improvement over the performance characteristics of the VLA (Figure 1 and Table 1)

Table 1: Comparison of overall EVLA and VLA performance characteristics

Parameter	VLA	EVLA	Factor
Continuum Sensitivity (1σ, 9 hr)	10 μJy	1 μJy	10
Maximum bandwidth in each polarization	0.1 GHz	8 GHz	80
Number of channels at maximum bandwidth	16	16,384	1024
Maximum number of frequency channels	512	4,194,304	8192
Coarsest frequency resolution	50 MHz	2 MHz	25
Finest frequency resolution	381 Hz	0.12 Hz	3180
Number of full-polarization sub-correlators	2	64	32
log (frequency coverage over 1-50 GHz)	22%	100%	5

A key element of the EVLA is the Wide-band Digital Architecture (WIDAR) Correlator, designed and built by NRC-HIA in Penticton. The major feature of this design is the correlation of the four 2-GHz IF bands (giving 8-GHz of bandwidth in each polarization) via 64 independently tunable sub-band pairs with 16,384 channels per baseline. There are 16 sub-band pairs associated with each 2-GHz IF band. Each pair effectively forms an independent "sub-correlator", and correlator configurations can be assigned to each pair independent of the other pairs. Each sub-band pair can have a sub-band width of any of 128, 64, 32...,0.03125 MHz, and through recirculation the number of spectral channels per baseline can be increased, using certain correlator configurations, up to a maximum of 4.2M channels.

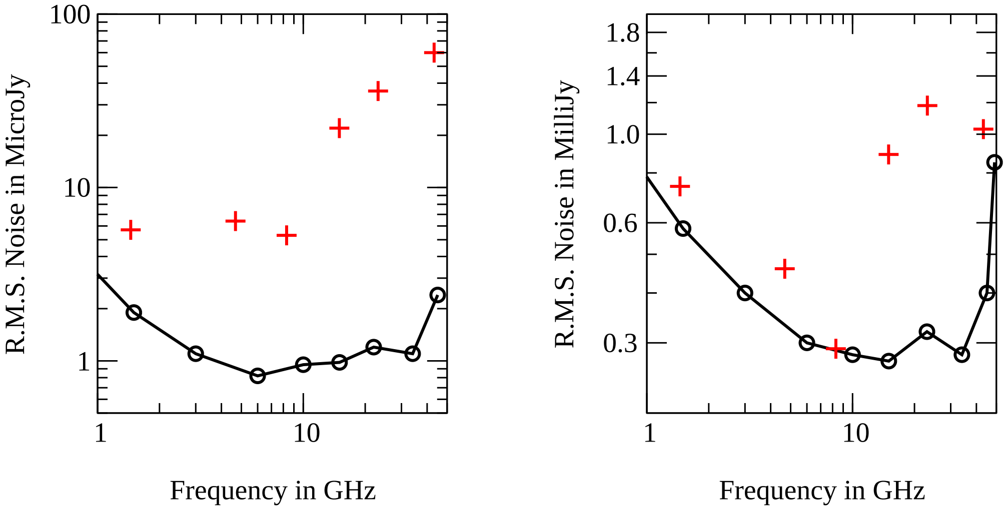

Figure 1: The continuum (left) and line (right) sensitivity of the EVLA (solid lines) compared to the VLA (crosses) (1σ in 12 hours). For the continuum sensitivity, the full available bandwidth at each band is assumed. For the spectral lines, the bandwidth adopted corresponds to a velocity width of 1 km s^{-1}. Note the EVLA will be continuously tunable over the entire frequency range.

2.1 Spectroscopy

The enormous flexibility in the configuration of the WIDAR correlator resources enables the EVLA to meet or exceed the demands of spectroscopic observations, and stands to revolutionize high-resolution centimetre wave spectroscopy.

An example of this flexibility is the simultaneous detection of multiple spectral lines. It is possible to target up to 64 lines simultaneously, and assign different spectral resolutions and sub-band widths for each sub-band pair, if desired. Taking recombination line observing at S band (2-4 GHz) as an example, there are 32 Hydrogen recombination lines that can all targeted independently with 2 kHz resolution and 8 MHz sub-band width (covering 1/8 the total bandwidth at S band), focusing correlator resources on the spectral regions of interest. For weak lines, subsequent stacking can be used to improve the signal-to-noise. More extensive examples of the efficiency of spectral line observing as a result of the WIDAR sub-band design come at K band (18-26.5 GHz), of particular interest to massive star research. Here, the EVLA could target the 32 molecular density and temperature indicator lines with a velocity resolution of 0.2 km s^{-1} e.g. including lines of NH_3, SO_2, H_2CS, H_2O, H_2CO, CH_3OH, OCS (Figure 2). With the remaining resources, 8 sub-bands could be tuned to each of the Hydrogen recombination lines in this frequency range, with the remaining 24 sub-bands covering 24×128 MHz (3 GHz) of continuum. Another advantage of the wide bandwidth, the continuum emission can be readily determined with the abundance of “empty” channels.

There are innumerable variants on the configuration of the WIDAR correlator, and potential users should consult the latest operational status summary for the availability of correlator configurations (http://science.nrao.edu/evla/proposing/obsstatsum.shtml).

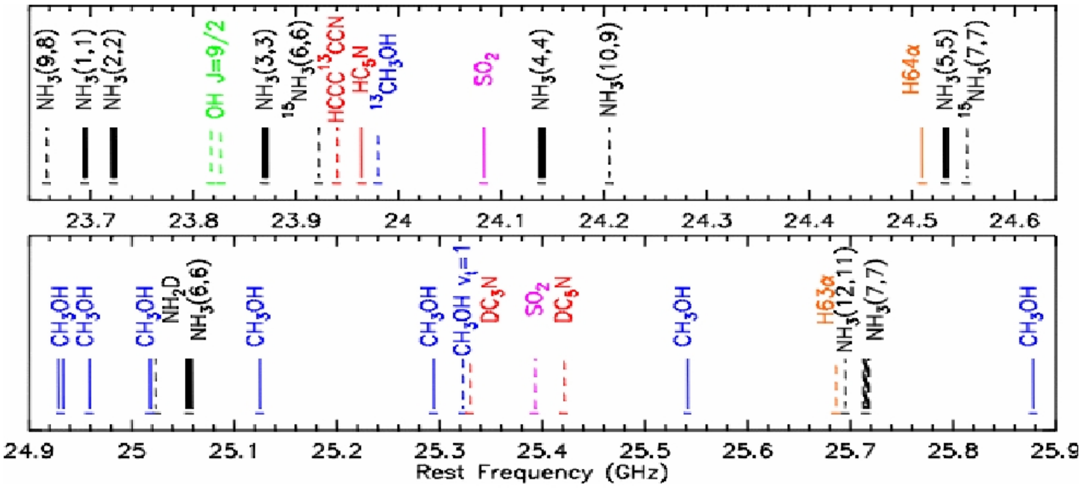

Figure 2: A multi-line spectroscopic setup example that can be attained with the WIDAR correlator, emplacing a sub-band at each of a series of 32 lines at K band (18-26.5 GHz). This example is taken from an RSRO experiment to study the conditions in a massive star forming region (Figure 3).

2.2 Continuum Imaging

The digital data transmission system leads to improved calibration of system gains, and together with the improved sensitivity of the new receivers greatly enhances the continuum capability of the EVLA. Typical image dynamic ranges used to be, at best, approaching 10^5, requiring major post-processing efforts. With the new system, dynamic ranges approaching 10^6 can be readily achieved with little effort, but reveal that more sophisticated processing methods are required to handle the residual image artifacts to attain the goal of greater than 10^6.

The large bandwidth provides two immediate advances of relevance to continuum emission studies. At full bandwidth the EVLA gives a factor of 10 improvement in sensitivity (0.1GHz vs 8 GHz), implying the potential to detect continuum sources out to $3\times$ greater distance at the same noise level, and hence flux limited sample sizes $\sim 30\times$ larger than available with the VLA. For massive stars, higher precision fluxes will lead to more precise mass-loss estimates across the entire range of massive star evolution. Another benefit is the vastly improved ability to determine the continuum spectra as a result of the large number of potential spectral fluxes that an be derived across each observing band and the improved ability to match spectra across adjacent observing bands. For stars, this will lead to improved understanding of, for example, the nature of the underlying emitting particle energy spectrum in non-thermal sources, and circumstellar envelope geometry of thermal emission sources.

3 Early Science programs

To make early and effective use of the new features of the EVLA as they are commissioned, early science with the EVLA is enabled through two observing programs - the Observatory-Shared Risk (OSRO) and Resident-Shared Risk (RSRO) observations.

OSRO: This program provides science capabilities that are similar to those to the VLA, utilizing capabilities in the EVLA system that were commissioned early in 2010, and is possible to access "at-home". Initially, up to 256 MHz of bandwidth is available through two independently tunable 128-MHz bands of 64 channels each, with both co- and cross-polarization products. For higher spectral resolution, the total bandwidth of the sub-bands can be reduced. Alternatively, 256 channels in one

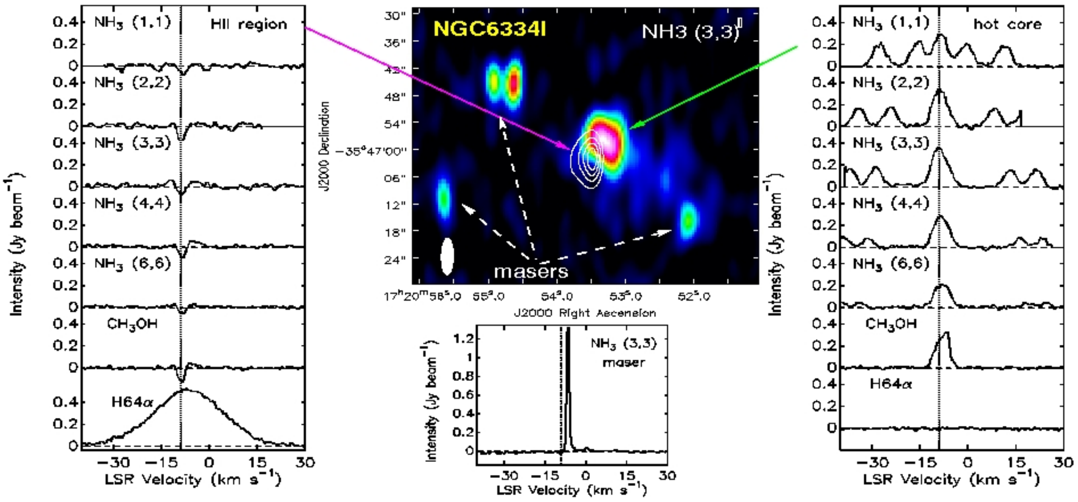

Figure 3: An example of Early Science enabled through the RSRO program, showing a K-band image of Ammonia in a massive star forming region obtained in 10 minutes using 8×8 MHz sub-bands. The contours are continuum emission from an HII region. Ammonia in absorption against the HII region (left panel) and in emission from one of the hot cores (right panel). The panel at bottom-centre shows an ammonia maser line.

128-MHz (or smaller) sub-band is available. The available bandwidth in OSRO is expected to grow in early 2011.

RSRO: Science programs that require access to the more extensive capabilities possible with the EVLA, particularly more sub-bands and broader bandwidths, come under the auspices of the RSRO program. These features are available to users in exchange for a period of residence at the Array Operations Centre to aid in commissioning. The goal is to accelerate the development of the scientific capabilities of the EVLA though the broad expertise of the user community. The current plan is for the RSRO program to run to the end of 2011. For those interested in participating in RSRO, a description of the current status is available at http://science.nrao.edu/evla/earlysicence/rsro.shtml.

4 Summary

Early science is already demonstrating the unprecedented potential of the EVLA system, especially the flexibility and range of configurations of the WIDAR correlator system. The science opportunities are tremendous and ensure the EVLA will be the pre-eminent centimetre-wave radio telescope over at least the next decade. Numerous challenges remain, particularly in data processing and calibration, before the full diversity of science goals can be achieved, but is it is through programs such as RSRO that these challenges can be met in collaboration with the broad community.

Acknowledgments

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