PROCEEDINGS OF SCIENCE

The Long Wavelength Array

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The Long Wavelength Array (LWA) is one of the next-generation radio telescopes. Operating at frequencies between 20 and 80 MHz ($3.75\,\mathrm{m} \leq \lambda \leq 15\,\mathrm{m}$) with a naturally wide field of view, the LWA will probe the long-wavelength sky at arcsecond resolution, an angular resolution that has heretofore not been available at these wavelengths. The LWA science case is varied, but a key component is searching for radio transients, and a variety of observations and theoretical expectations suggest that the long-wavelength sky will be rich with transients. Currently under development and prototyping in the U.S. state of New Mexico, the first step toward the LWA is the NRL-funded Long Wavelength Demonstrator Array, which is producing all-sky images and allowing us to develop the data analysis pipeline for future LWA observations.

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1. Introduction

The recognition that the Universe could be observed at wavelengths other than those in the visual spectrum began with Jansky's discovery of celestial radio emission at a wavelength of 14.6 m (20.5 MHz) [4]. Subsequently, the basis for much of modern astronomy was laid throughout the 1950s and 1960s by key discoveries and technological advances in radio astronomy—and particularly at long wavelengths—including:

- The recognition of non-thermal emission processes [1, 8, 16], motivated by 1.9-m wavelength (160 MHz) observations of the diffuse Galactic radio emission [12], though it took some time for the importance of non-thermal emission to be accepted widely;
- The discovery, at 3.7-m wavelength (81 MHz), of pulsars [3]; and
- The development, at 7.9-m wavelength (38 MHz), of aperture synthesis interferometry [15, 14, 10, 13].

Notably, two Nobel Prizes in Physics were awarded for work at long wavelengths (the discovery of pulsars and the development of aperture synthesis). By the late 1960s and early 1970s, however, interest was growing in obtaining high-resolution images. Producing images with sub-arcminute angular resolution (or sub-arcsecond resolution in the case of the VLA by the late 1970s), with dynamic ranges of several hundred or better, became routine at centimeter wavelengths by a variety of interferometers.

The primary impediment to comparable angular resolution at long wavelengths was the limited maximum baselines of the available instruments. In all cases, the maximum baselines was no more than about 5 km. The corresponding angular resolution was relatively poor ($\gtrsim 10'$), and the resulting high confusion levels meant poor sensitivities ($\gtrsim 1$ Jy). The primary constraint on baseline length was the phase distortion imposed by the Earth's ionosphere over the intrinsically wide fields of view and the lack of suitable algorithms to compensate for the ionospherically-imposed distortions. On baselines longer than a few kilometers, phase distortions are severe enough to cause decorrelation, making higher-resolution imaging difficult to impossible.

In the 1980s, the application of *self-calibration* techniques to radio wavelength observations was developed [11]. While the initial application of self-calibration was to centimeter wavelength imaging, it was recognized quickly this technique would also work to mitigate ionospheric phase corruptions at meter wavelengths.

Demonstration of the efficacy of self-calibration coupled with wide-field imaging for sub-arcminute resolution long wavelength astronomy occurred with the 90 cm (330 MHz) system on the VLA [2]. Later, this work was extended to 4-m wavelength (74 MHz). The prototype 4-m system consisted of eight of the VLA's 28 antennas equipped with receivers, and Kassim et al. [6] were able to produce images with sub-arcminute resolutions and sub-Jansky sensitivities, thereby demonstrating that these self-calibration techniques were able to correct for ionospheric phase errors on baselines at least as long as the longest VLA baselines (35 km) and, in principle, much longer. Because of the limited number of antennas, the prototype 4-m system had relatively poor *u*-*v* coverage, so only the strongest (≥ 500 Jy) sources, numbering a dozen or so, were imaged.

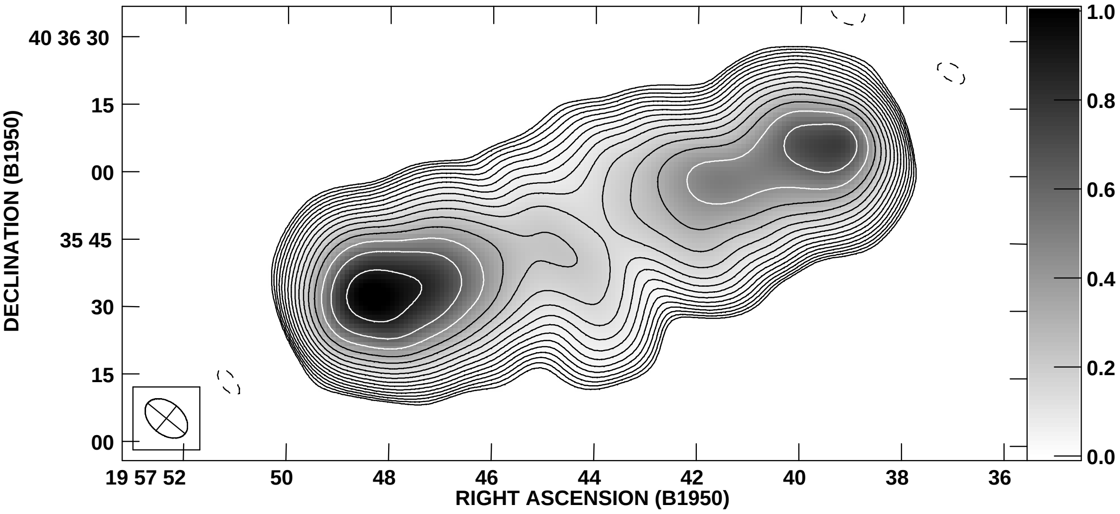

Figure 1: Cygnus A at 4-m wavelength with 10′′ angular resolution [9]. This VLA-Pietown link observation illustrates that ionospheric phase fluctuations can be mitigated to the level that high angular resolution observations longward of 2 m can be conducted. Because of the limited sensitivity of the VLA, only the strongest sources can be observed on the VLA-Pietown link. The LWA aims to provide arcsecond resolution imaging on a routine basis.

Subsequent developments have seen all 28 VLA antennas being equipped with 4-m wavelength receivers and the 4-m system becoming a part of the VLA facility [5]. The result is that the 4-m VLA is now the most powerful imaging instrument at wavelength longward of 2 m ($\nu < 150$ MHz). More recently, imaging extended to the "VLA-Pietown link," which results in baselines of approximately 70 km and 10′′ angular resolution [9, Figure 1].

2. The Long Wavelength Array

While the 4-m VLA has produced unprecedented angular resolutions and dynamic ranges at long wavelengths, it suffers from a number of limitations. Notably, it is narrowband, operating at only the wavelength of 4 m, and it has a relatively small collecting area. While broadband receivers and dipoles could be developed, the VLA antennas are, at best, only modestly efficient at these wavelengths. At 4-m wavelength, the antennas are only 6 wavelengths in diameter, and extending the wavelength coverage to longer wavelengths would lead to rapidly decreasing performance. More seriously, the high sky temperature at wavelengths longer than 2 m means that only significantly larger collecting areas will produce improved sensitivities.

The Long Wavelength Array (LWA) is motivated by the goal of constructing a high angular resolution, high sensitivity, broadband astronomical instrument operating longward of 3 m in order to capitalize on the lessons learned from the 4-m VLA; similar goals motivate the low-frequency component of the Low Frequency Array (LOFAR).

The science case for the LWA has four components:

Cosmic Evolution and the High-*z* Universe High-redshift radio galaxies, potentially to include those hosting the first supermassive black holes, are often distinguished by their steep radio spectra, which can be identified efficiently with long-wavelength surveys. Long-wavelength observations can also detect radio halos and relics within clusters of galaxies, which in turn serve to identify sites of merger activity and probe the formation of the largest objects in the Universe.

Particle Acceleration Cosmic rays have an energy spectrum extending from below 1 GeV to nearly 10^{20} GeV. The mechanisms by which particles can be accelerated over such a large range remains poorly understood. High angular resolution, long-wavelength observations probe particle acceleration in a variety of environments, including supernova remnants, radio galaxies, and clusters of galaxies. Moreover, ultra-high energy cosmic rays impacting the Earth's atmosphere (and potentially the lunar regolith) can produce a radio pulse from which various particle properties can be inferred. (See also "The Dynamic Radio Sky" below.)

Ionospheric and Space Physics The ionospheric phase fluctuations, so corrupting to astronomical observations, are the result of density fluctuations, which in turn reflect physical processes within the ionosphere. The same techniques used to calibrate and mitigate the ionospheric phase fluctuations therefore provide information on the ionosphere.

The Dynamic Radio Sky Coherent emission processes are marked by volumes within which the particles radiate in phase. At long wavelengths, the size of an emitting volume can become quite large, making for intense emission. Examples in the solar system include the electron cyclotron masers in the magnetic polar regions of the Earth and the giant planets; by analogy, extrasolar giant planets may also produce detectable amounts of long-wavelength radiation. More generally, the naturally large fields of view at long wavelengths make for efficient surveying of the sky and higher likelihoods of finding radio transients.

At long wavelengths, parabolic antennas become impractically large, and broadband dipoles are a more suitable option for obtaining collecting area. Dipoles have a number of additional advantages. Their collecting area scales as λ^2 while the temperature of the Galactic background scales approximately as $\lambda^{2.6}$, so that to first order they provide approximate wavelength-independent sensitivity. Moreover, dipoles are intrinsically low cost, suggesting that a substantial collecting area can be obtained relatively inexpensively.

For the LWA, the following architecture has been adopted. A dipole is mated with a balun, an active element providing impedance matching and increasing the wavelength range over which the dipole can operate. Current experience suggests that a spectral dynamic range of approximately 3.5:1 can be obtained. A *stand* consists of two dipoles, one for each linear polarization. A *station* consists of 256 stands, phased together, forming the equivalent of a single-dish reflector at shorter wavelengths. In order to obtain the requisite sensitivity and angular resolution, approximately 50 stations will be distributed over a region of approximately 400 km in the state of New Mexico (Figure 2).

The LWA is being designed and constructed by the Southwest Consortium—the University of New Mexico, NRL, the Applied Research Laboratory of the University of Texas at Austin (ARL:UT), the Los Alamos National Laboratory, Virgina Tech., and the University of Iowa. Funding for the initial stage of construction has been secured, design reviews are scheduled in 2008, and the goal is for construction of the first station beginning in 2009.

Figure 2: An illustration of how the LWA stations may be deployed across the state of New Mexico. Possible station locations are indicated as yellow dots, and the blue Y indicates the location of the VLA. Major highways and cities are also indicated, and the dotted lines indicate the state boundaries. While assessment of sites continues, this figure illustrates how 400-km baselines, producing arcsecond angular resolution, could be obtained.

3. Initial Results from the Long Wavelength Array

As part of the prototype activities for the LWA, NRL funded the Long Wavelength Demonstrator Array (LWDA), which was designed and constructed by ARL:UT. The LWDA consists of 16 dipole stands deployed near the center of the VLA (Figure 3). Their operational wavelength range is 3.75–5 m (60–80 MHz); the LWDA operational wavelength range is more limited than that intended for the full LWA, in part because an initial design goal was that the LWDA be slightly optimized toward use in conjunction with the VLA 4-m system.

The LWDA dipole antenna stands approximately 1 m high and is sloped at a 45° angle in order

Figure 3: The Long Wavelength Demonstrator Array. The dipoles are in the foreground and are approximately 1 m high. The LWDA electronics are housed in the shed in the background. The VLA antennas are in the distance.

to improve its wavelength coverage. The active antenna (dipole + balun) is sky-noise dominated by at least 6 dB over the range 3.75 to 6 m wavelengths.

The LWDA signal chain consists of the dual polarization active balun, providing 24 dB of gain at the antenna. A buried cable runs 50–60 m to a shielded hut where three stages of amplification and filtering occur: (1) A fixed 24 dB of additional gain; (2) Two stages of variable gain (in a total of 6 dB steps); and (3) An anti-aliasing filter in the 50–100 MHz passband. A receiver then digitizes, time-delays, and further filters the signal to a 1.6-MHz bandwidth. Adder boards then sum the signal for beamforming (e.g., for dedicated pulsar observations) or interleave the signals in order to obtain visibilities and all-sky imaging.

The LWDA achieved first light in 2006 October, and its images (Figure 4) illustrate the power of long-wavelength imaging for providing wide fields of view for transient hunting. In all-sky imaging mode, the LWDA cycles over the 120 pairs of dipoles to produce all unique visibilities once per 6 seconds. Instrumental phase and amplitude gain corrections, determined during the installation of the LWDA are applied, and the visibilities are then stored in FITS files. An AIPS-based pipeline reads the visibility data, does crude excision of radio frequency interference (RFI), images the sky, blanks the strongest sources, and identifies any extrastatistical peaks in the image (i.e., candidate transients). A second generation transient search program, utilizing background model subtraction, is being implemented to improve the sensitivity of the system.

While simplistic, simple considerations suggest that the LWDA images themselves may be useful for improving on current limits for radio-wavelength transients. The STARE campaign [7] was a year-long, all-sky monitoring program at 50 cm (610 MHz); it placed an upper limit of 27 *kJy* on the existence of any transients. For comparison, the flux density of Cyg A at 4-m wavelength is approximately 17 kJy, and the LWDA images (Figure 4) have a dynamic range of at least 10:1. Thus, a transient monitoring campaign with the LWDA alone has the potential to probe the transient sky, on a *wide-field* basis, to levels of 1000 Jy or better.

Indeed, since the LWDA first light, approximately 83 hr of observations from 2006 October

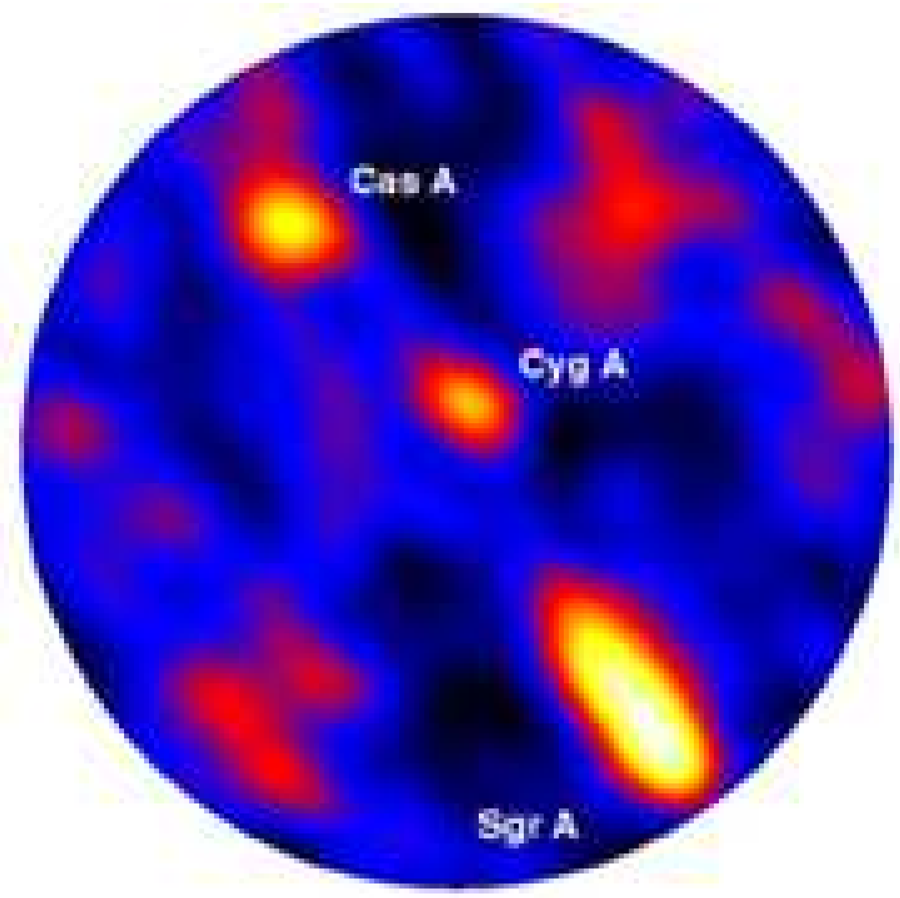

Figure 4: A still from the first-light movie of the sky above the Long Wavelength Demonstrator Array at 4-m wavelength (74 MHz). In this image, no image blanking is applied, and various well-known sources in the long-wavelength sky are labeled. Moreover, comparison of this image with those from shorter wavelengths indicates that much of the structure in the image is real and can be related to portions of the Galactic plane or other structures in the radio sky (e.g., Loop I).

to 2007 February have been collected. While analysis of these are continuing, there are no obvious transients above a level of 5000 Jy. The power pattern of the LWDA remains only partially known, so as a zeroth-order approximation, we take its effective sky coverage to be 10 000 deg.^{2}. Thus, our initial upper limit on the rate of transients stronger than 5000 Jy at 4 m is 10^{-2} deg.$^{-2}$ yr^{-1}.

Acknowledgments

The LWA project involves the dedicated efforts of many individuals. In particular, the LWDA first light and transient observations would not have been accomplished without P. Ray, D. Wood, and W. Lane.

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