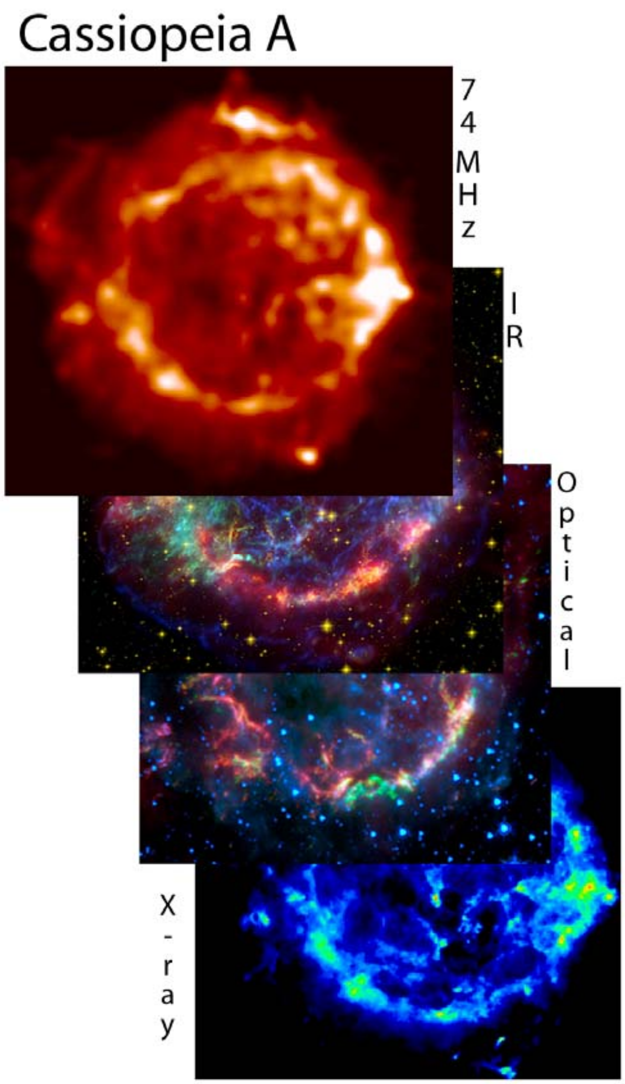
The Long Wavelength Array

Activity White Paper for the Astro 2010 Decadal Survey



(74 MHz VLA image: Kassim et al. 2007)

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Executive Summary

Observational capability at the lowest radio frequencies is a fundamental tool for a wide range of photon- and non-photon–based astrophysics. The Long Wavelength Array (LWA) will take advantage of emerging technologies in calibration, imaging and digital processing to surpass previous instruments by several orders of magnitude in resolution and sensitivity below 100 MHz ($\lambda > 3$ meters).

The LWA will consist of 53 phased-array "stations," each consisting of 256 pairs of crossed-dipole antennas, operating with Galactic noise-limited sensitivity over the frequency range 20–80 MHz. The stations will be distributed over the state of New Mexico, with maximum baselines (distances between stations) of up to 400 km, and nominally 16 stations in a 'core' within the central 10 km. Beam-forming (up to 4 simultaneous beams) will be done at the individual stations with the data then transmitted to a central correlator for image formation. The LWA will image wide fields of view with sufficient diversity of baselines to study both compact and complex sources in interferometric mode. The planned sensitivity in each beam will be a few mJy in 8 hours with a resolution of 8" to 2" (20 to 80 MHz).

The LWA's scientific frontiers include: (1) The radio-transient universe such as extra-solar planets, GRBs, ultra-high energy cosmic rays (CRs), and new sources of unknown origin; (2) The high-z universe, including distant black-hole-powered radio galaxies and clusters – tools for understanding proto-galaxy collapse in the early Universe and the cosmological evolution of Dark Matter and Dark Energy, respectively – and path-finding studies of the Dark Ages at $z > 30$ ($\nu < 50$ MHz), before stars turned on or galaxies formed; and (3) Acceleration, propagation, and turbulence in the ISM, including the space distribution of Galactic CRs and supernova remnants (SNRs) together with scattering- and absorption-based probes of the magnetized interstellar plasma. The LWA will have a strong synergy with exciting new X-ray and γ-ray measurements and, because the spectral region below 100 MHz has been so poorly explored, the potential for new discoveries is great. The LWA will also explore small-scale ionospheric structure, as part of its astrophysical calibration and imaging.

With a user-oriented operational concept and the goal to help stimulate University-based radio astronomy and hands-on student training, the LWA project embodies a science every step of the way approach. Prototype-based all-sky transient searches and an ongoing program to monitor the secular flux density decrease of Cassiopeia A reflect this philosophy.

Phase I of the LWA is underway, with construction of the first station (LWA-1) commencing in 2009. Utilizing modern FPGA computing, LWA-1 will form four independent (in both frequency and pointing) beams on the sky, with instantaneous bandwidths of 8 MHz per beam, spectral resolutions down to 100 Hz, and temporal resolutions to 0.1 ms. Its homodyne receiver architecture will allow direct beam-formation over the entire LWA bandwidth. Operating as a fully electronic, phased array, the beams can be cycled rapidly among many sources on millisecond timescales. LWA-1 will begin first science studies of the transient sky, radio recombination lines, and Solar and Jovian emission, and will be used to test methods for real-time calibration of the turbulent ionosphere which limits both resolution and sensitivity at low-frequencies.

The LWA Project is funded through a contract from the Office of Naval Research to the University of New Mexico, which partners with the Naval Research Laboratory, Virginia Tech, the Jet Propulsion Laboratory, Los Alamos National Laboratory, and the University of Iowa. \$10M has already been funded for FY07-10. The expected required funding profile for construction is ~\$10M/yr through FY19, for a total construction cost of \$97M. The estimated operations budget is ~\$10M/yr.

LWA Key Science Goals

The greatest discoveries in astronomy have often followed technical breakthroughs that expand astrophysical discovery space. The Long Wavelength Array (LWA) takes advantage of emerging innovations in calibration, imaging, and digital processing to achieve improvements of several orders of magnitude in resolution and sensitivity below 100 MHz. Notwithstanding key scientific leaps earlier in the last century, including the birth of radio astronomy, this regime remains one of the last, most poorly explored astrophysical frontiers. Given the versatility afforded by an electronic array with naturally wide fields-of-view and multiple, rapidly reconfigurable beams, the LWA's scientific potential is substantial. We discuss six astrophysical goals for the LWA posed as *frontier science* questions and include pertinent ***Astro-2010 science white paper*** (*Astro2010 WP*) references.

Q1: How can Galaxy Clusters Constrain the Cosmic Evolution of Dark Matter and Dark Energy?[1] *(Astro2010 WP1-4)*

The LWA will be uniquely sensitive to the merger-driven shocks and turbulence that heat the intercluster medium (ICM) and compress its magnetic fields (Fig. 1). By tracing merger-driven steep-spectrum emission from thousands of clusters over a wide range of redshifts, the LWA will accurately trace cluster number density and merger frequency, placing tight constraints on the cosmological evolution of the largest Dark Matter halos in the Universe. High quality LWA maps will also be able to differentiate magnetic-field configurations and particle-acceleration mechanisms in clusters.

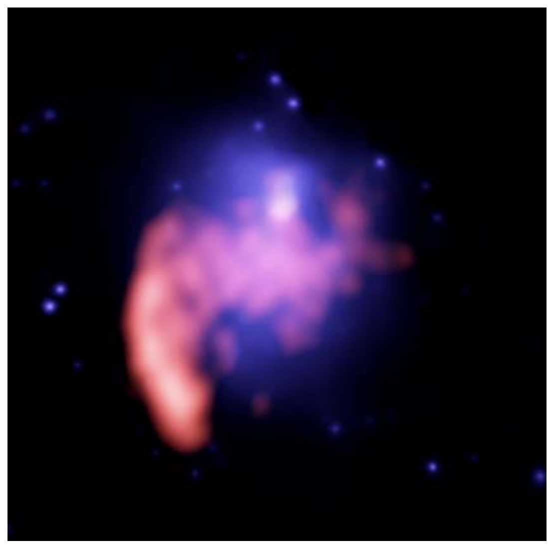

Figure 1: Red: Abell 521 radio halo (center) and relic (left) at 240 MHz, superimposed on Chandra X-rays (blue)[2]. The steep spectrum radio halo is undetectable at 1400 MHz.

X-ray observations of clusters probe the Dark Energy density and equation of state by measuring the baryonic mass fraction of the Universe[3], but they depend on the identification of a large, relaxed cluster sample, a costly and often ambiguous task at optical and X-ray wavelengths. LWA observations will be an efficient method for distinguishing a relaxed sample of galaxy clusters for Dark Energy studies.

Q2: What is the Impact of Relativistic Particle Acceleration?

In Supernova Remnants (SNRs): Galactic SNRs are responsible for cosmic-ray (CR) acceleration to at least 10^{15} eV. These CRs represent ~1/3 of the interstellar medium (ISM) energy density, and they drive Galactic chemistry through the ionization of atoms and molecules. Nearly all models for SNR CR acceleration by shocks or turbulent Fermi processes predict subtle radio spectral index variations. Sensitive images at LWA frequencies are required to measure the variations over a sufficient frequency space[4]. LWA surveys can also help achieve a complete census of Galactic SNRs[5], essential to understanding Galactic star formation history and ISM energy input, and for uncovering the rare sources tying CR acceleration from radio to γ-rays[6].

***Feedback in galaxies & clusters of galaxies** <u>(Astro2010 WP3-5)</u>:* Relativistic particle acceleration to ~10^{19} eV is prolific in radio galaxy jets and lobes. These particles extend through the intergalactic medium into the ICM, and only the lowest-energy, lowest-frequency emitting electrons may provide an accurate historical census of particle acceleration.[7] The paucity of sensitive low-frequency measurements has forced studies to rely entirely on extrapolation from high frequencies. Accurate low-frequency measurements are available only for a few powerful sources, from which have emerged exciting, unanticipated results such as the "heating flow" of Virgo A[8], an outer X-ray cavity in Perseus A[9], and the enormous past outbursts of Hydra A[10] (Fig. 2). The LWA will have the required sensitivity, resolution, and frequency coverage to study a large population of weaker and smaller radio galaxies, thus probing the feedback mechanisms whereby radio galaxies impact the formation and evolution of groups and clusters of galaxies, and potentially suppress star formation in large elliptical galaxies, leading to the observed exponential cut-off in the bright end of the luminosity function[13,14].

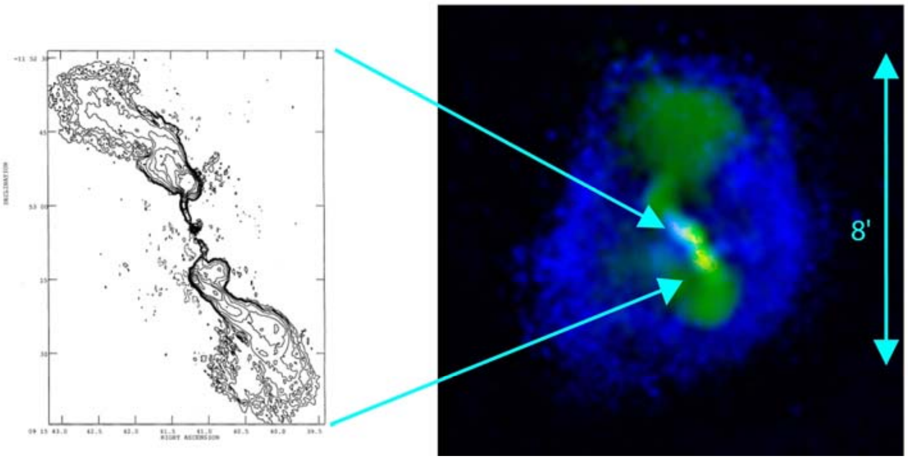

Figure 2: Right: 74 MHz radio (green) embedded in X-ray dominated ICM (blue) revealing its true size[11] compared with left: 4835 MHz radio image (contours)[12].

LWA studies of the low energy relativistic electron population in radio galaxies and clusters are critical to understanding many other important issues, including pressure balance with the ambient X-ray-dominated thermal ICM, inverse Compton emission, and galaxy formation[15].

Q3: What is the Nature of the Earliest Active Galaxies? <u>(Astro2010 WP6)</u>

Emission from the most powerful and distant high redshift-radio galaxies (HzRGs) is a critical signpost of the collapse of protogalaxies in the early Universe. HzRGs are among the most luminous, massive, and distant objects in the Universe, usually identified by steep-spectrum radio emission powered by super-massive black hole (SMBH) accretion. They are energetic sources across the whole electro-magnetic spectrum revealing diverse components in the proto-cluster environment and

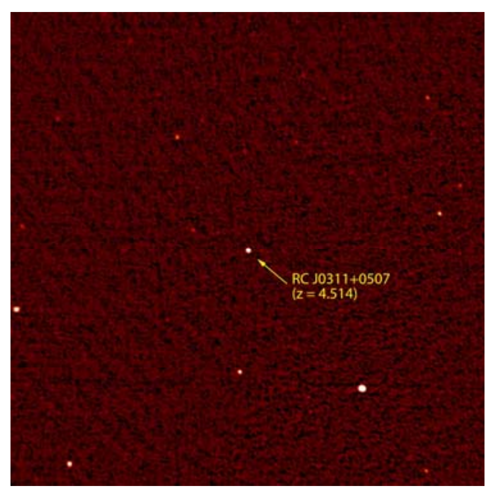

Figure 3: HzRG J0311+0507[16] at z = 4.514 detected at > 20σ in the relatively insensitive 74 MHz VLSS survey[17].

providing important diagnostics of key physical constituents in the early Universe, including relativistic plasma, hot and warm ionized gas, cool atomic gas, molecular gas, dust, old and young stellar populations, quasars and SMBHs. The most efficient way to identify possible HzRGs is to search for ultra-steep spectrum objects in low-frequency sky surveys (Fig. 3). The sensitivity of the LWA below ~100 MHz is crucial to identifying these objects at high redshifts, particularly if they exist beyond $z \geq 8$. As signposts of Dark Matter potential wells, LWA identifications invite natural optical/IR and radio line (e.g. CO) follow-ups to search for groups of galaxies.

Q4: What was the Universe like Before the First Stars Formed? *(Astro2010 WP 7-8)*

The so-called Dark Ages at $z>30$ ($\nu < 50$ MHz), before stars turned on or galaxies formed, can be uniquely studied at the LWA's low radio frequencies. Using a dedicated beam, the core of the LWA will pioneer deep and sensitive observations needed to measure statistical fluctuations in 21cm absorption and probe the standard cosmological models at a time when there are no astrophysical contaminants. Such studies will complement planned studies of the later Dark Ages ($30<z<6$) and Epoch of Reionization by higher-frequency instruments, building a complete picture of the early evolution of the Universe. Although the measurements are challenging, the LWA will certainly serve as a pathfinder for planning dedicated Dark Ages arrays.

Q5: What is the Role of Acceleration, Turbulence, and Propagation in the ISM of Galaxies and Intergalactic Space?

Thermal ISM Absorption: The LWA will spatially resolve thermal absorption against discrete nonthermal sources, first demonstrated with the 74 MHz VLA[18-21] (Fig. 4), from which the relative radial positions of thermal and nonthermal sources in Galactic complexes can be determined (and, e.g., SNR-molecular cloud interactions probed). By extension, this same technique can also be applied to ensembles of sources in nearby galaxies.

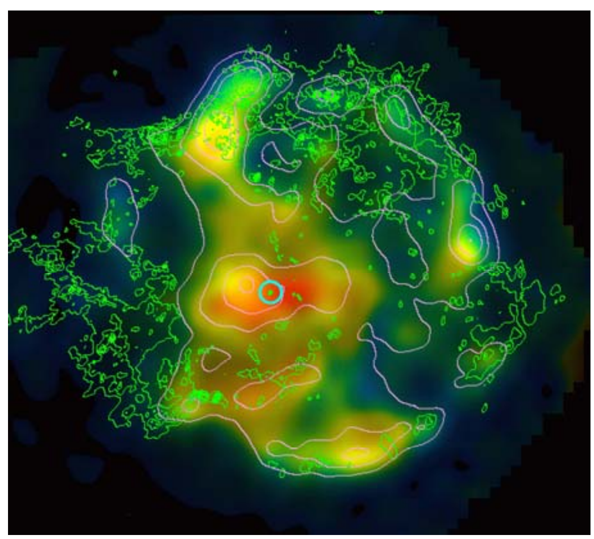

Figure 4: Unshocked ejecta in Cassiopeia A traced by 1) low frequency radio absorption[18] (74/330 MHz spectral index) in color and 2) SPITZER SII IR in purple & red contours[22]. Chandra X-rays including the compact central object (blue circle) in green contours[23].

Cosmic Ray Tomography: The LWA will observe thousands of HII regions in absorption at kinematically well-determined distances, providing a powerful 3D probe of the distribution and spectrum of Galactic CRs[24-26]. Comparison with diffuse Galactic γ-ray emission[27] will break the degeneracy of particle density and magnetic field in synchrotron measurements, permitting determination of the 3D distributions of the CR electrons and magnetic field. Low-frequency synchrotron studies with the VLA and GBT already challenge the paradigm of a strong, pervasive Galactic center magnetic field[28] and further broad-band studies will be greatly enhanced by the LWA.

Self-absorption processes: Intrinsic and extrinsic self-absorption processes are ideally probed in the LWA frequency range. Internal absorption by unshocked ejecta ionized by X-rays from the reverse shock in Cassiopeia A[18] (Fig. 4) was theoretically anticipated but undetectable before observations with sub-arcminute resolution below 100 MHz, while constraints on self-absorption in the hotspots of Cygnus A have helped differentiate between competing mechanisms of synchrotron self-absorption, electron-energy cutoff, and thermal absorption[29]. The LWA will pioneer broadband studies of thousands of much weaker sources.

Interstellar Scattering *(Astro2010 WP9)****:*** The λ^2 refractive index fluctuations in plasmas, most easily observed at low frequencies with the LWA, can be used to probe plasma physics in the interplanetary medium (IPM) and ISM. For example, the diffusion and propagation of charged particles are likely driven by turbulence-driven magnetic-field fluctuations that can be probed via pulsar scintillations currently too faint to detect. The first LWA station alone will detect ~80 pulsars[30], constraining their poorly determined low-frequency spectra. Additional LWA scattering frontiers encompass: 1) detecting scattering upstream of turbulence associated with SNR shocks; 2) extending studies of ionized gas in the "Reynolds layer" to much higher Galactic latitudes; 3) constraining the 3D distribution of scattering media through measurements along similar lines of sight to Galactic and extragalactic sources; 4) extending scattering studies to intergalactic space.

Q6: What Discoveries Lurk in the Radio Transient Universe? (Astro2010 WP10-12)

Figure 5: Wide-field low frequency Galactic center radio image (bottom panel) used to reveal new sources of transient emission[31]. Top and middle panels provide Galactic views at IR and optical wavelengths, respectively[32].

Studies of time-variable phenomena have remained relatively primitive, offering a new scientific frontier for next-generation wide-field, multiple-beam radio telescopes, such as the LWA, that naturally maximize field-of-view and observational dwell time. Existing data show that transient radio sources may originate from nearly all astrophysical environments on timescales from nanoseconds to years, providing insights into fundamental questions including the mechanisms of particle acceleration and the physics of the intervening medium.

At the low frequencies of the LWA, known transient phenomena include a new class of coherent emitters suggested by recently detected Galactic center radio transients (Fig. 5), giant flares from γ-ray repeaters, solar and Jovian bursts, and pulsars. By extrapolation we anticipate observing brown dwarfs, giant pulses from radio pulsars beyond the Crab, and flare stars, for which simultaneous observations anchored at LWA low frequencies are crucial for understanding the multiple physical processes, timescales, plasma-heating processes, and nonthermal-energy deposition. Furthermore, theoretical predictions suggest that supernovae, prompt emission from GRBs and radio emission from evaporating primordial black holes may also be observed at low frequencies. Improvements in time-domain processing coupled with the LWA's multiple wide-field beams, frequency range, sensitivity, and spatial resolution ideally position it for studying these transient phenomena. With the potential to detect coherent, low frequency emission from ultra-high-energy ($\geq 10^{21}$ eV) CR induced air-showers, currently detectable with a few dipoles[33], the LWA could join the revolution in non-photon particle astrophysics being led by the Pierre Auger observatory.

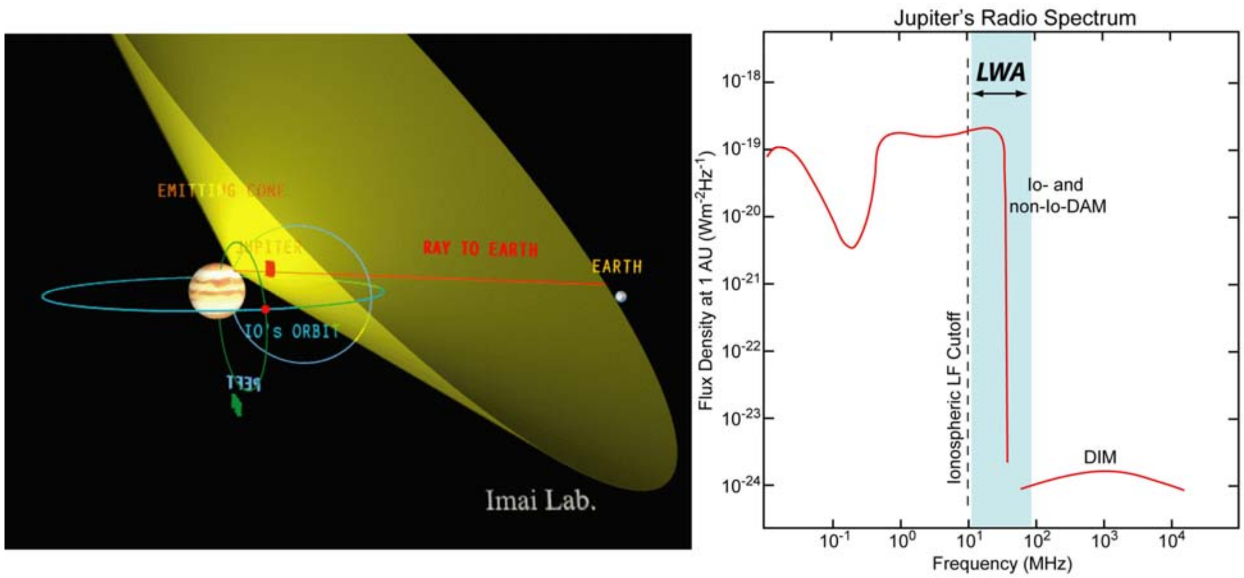

Figure 6: Left: Schematic of Jupiter's decametric emission (≤ 40 MHz)[34]; Right: Jovian radio spectrum[35].

Extra-solar planets *(Astro2010 WP13)**:*** The most exciting of the anticipated transients may be extra-solar planets. All solar system giant planets generate radio emission from the interaction between their magnetic fields and the solar wind. If magnetic fields are typical for giant planets, as indirect evidence suggests, extrasolar planets may be detectable with the LWA. Jupiter's decametric radio bursts, with their characteristic upper frequency cutoff near 40 MHz, are the prototype for such studies (Fig. 6). Current extra-solar planet searches below 100 MHz have been sparse, with observational limits at the most optimistic extreme of theoretical predictions. Allowing for anticipated variations of the magnetic fields and internal compositions of these planets, the LWA may directly detect them. CR-shielding planetary magnetospheres could be a prerequisite for life.

We also note that by routinely monitoring solar radio bursts (e.g., CMEs & flares) with a dedicated solar beam and through scintillation-based solar wind studies, the LWA will be a powerful tool for solar radio-physics and space weather (Astro2010 WP14). It will provide a beautiful complement to space-based radio instruments such as *STEREO/SWAVES*, by picking up in frequency space where they typically cut off (~15 MHz), as well as space-based optical and ultraviolet instruments such as *STEREO/SECCHI*. Finally, as a pre-requisite to ionospheric calibration, the LWA will naturally provide a sensitive, near real-time measure of turbulence and wave phenomena in the Earth's ionosphere.

LWA Technical Overview

Upon completion, the LWA will consist of 53 electronically-steered phased-array "stations," each consisting of 256 pairs of crossed dipole antennas, operating with Galactic noise-limited sensitivity over the frequency range 20–80 MHz, within a total range of 10–88 MHz. The stations will be distributed over the state of New Mexico (Fig. 7), with maximum baselines (distances between stations) of up to 400 km. 16 stations will be in a 'core', within the central 10 km. Beams formed by the stations will be transmitted to a central correlator and processed to form images. With 53 stations, the LWA will have sufficient diversity of baselines to image large fields and complex sources in interferometric mode. In addition, each station will also be capable of operating as an independent telescope.

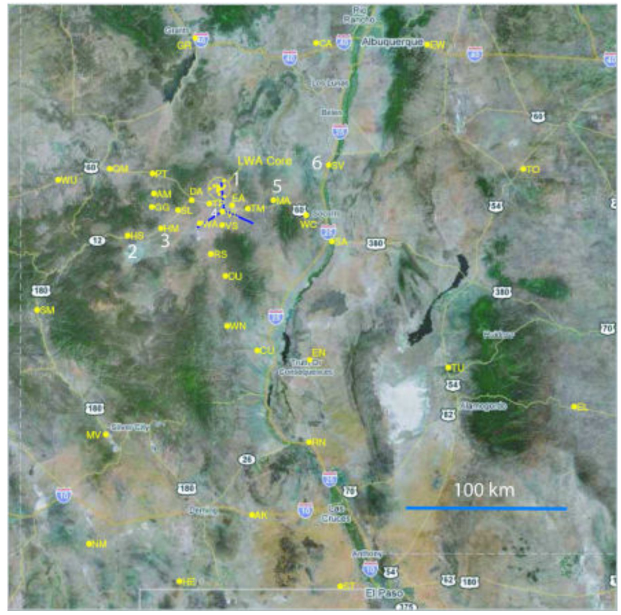

Figure 7: Nominal LWA station locations shown in yellow; location of the VLA is shown in blue.

Receiving Elements and Station Layout: The primary receiving element is a fixed stand that incorporates two broadband, crossed, linearly-polarized dipoles. A group of 256 stands will form a roughly 100-meter diameter station, with a pseudorandom distribution (Fig. 8) to prevent aliasing of the main lobe and to mitigate large sidelobes at higher frequencies where the aperture will be undersampled. The station beam can be steered to any point in the sky by adjusting the digital delays of the individual elements. Beam steering will be entirely electronic.

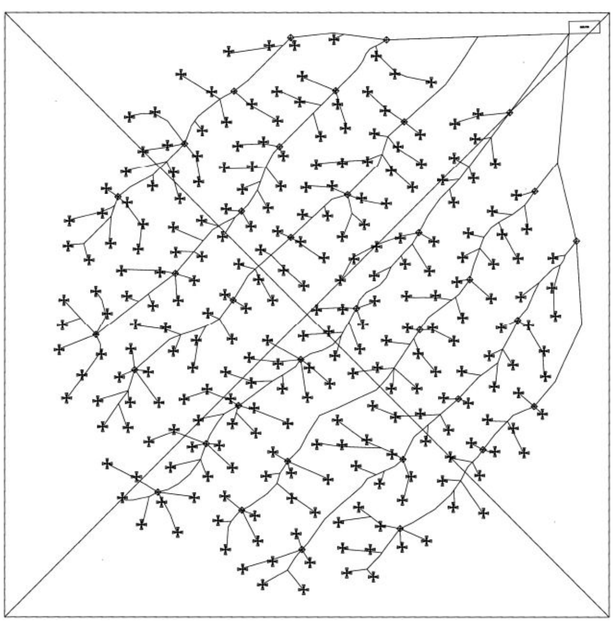

Figure 8: Stand layout within LWA-1, showing cabling and (upper right) electronics shelter.

Each dipole feeds a balun and low-noise amplifier (Fig. 9) to produce a balanced, single-polarization, Galactic-noise-dominated output signal. The front end electronics (FEE) uses commercial InGaP HBT MMIC amplifiers (Mini-Circuits GALI-74) in a differential configuration presenting a 100 Ω balanced load to the antenna. This is followed by a passive balun which produces a 50 Ω single-ended signal suitable for transmission over coaxial cable. The gain, noise temperature, and input 1-dB compression point are approximately 36 dB,

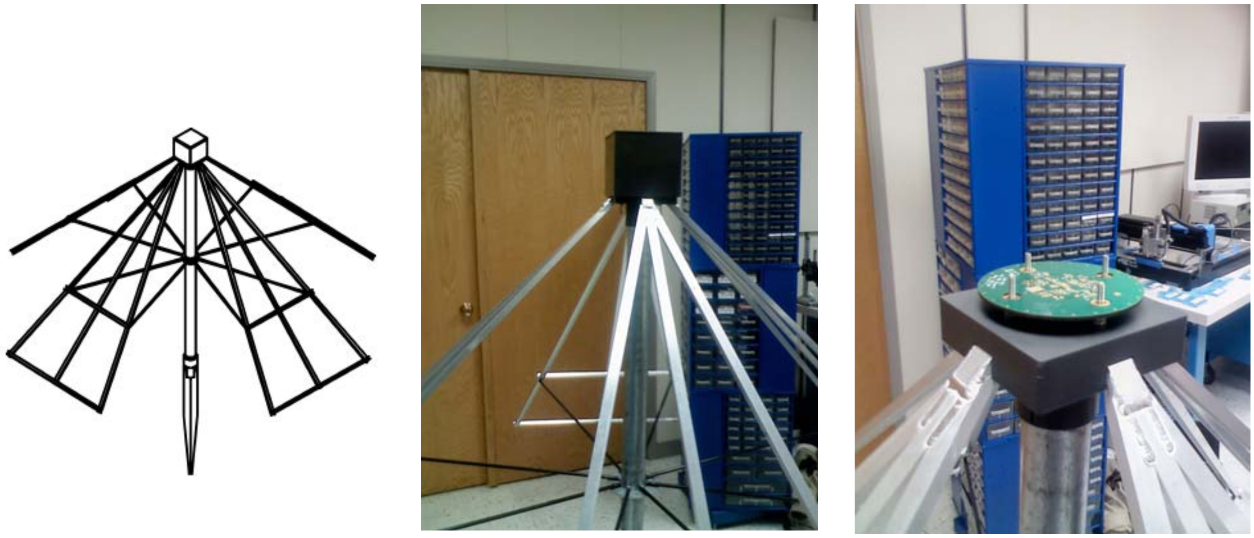

Figure 9: (left) Schematic view of a single stand; (middle) Photo of stand in lab, showing front end electronics (FEE) box; (right) View of FEE board.

250 K, and −18 dBm respectively, roughly independent of frequency over 10–88 MHz. A coarse-mesh ground screen underneath the stand will reduce ground losses and stabilize the antenna impedance.

The choice of 256 stands distributed over ~ 100m is driven by the anticipated need to rapidly image several hundred sources across the sky, to calibrate for ionospheric effects within the station field of view (FWHM ~ 8°[20 MHz/ν]). It meets the sensitivity goals of the science requirements while achieving a balance with classical and sidelobe confusion for 400-km baselines over plausible integration times. It also balances cost against quality of image calibration over a broad range of frequencies and zenith angles. Further details of the basic requirements and design arguments have been published[36].

Station Architecture and Electronics: Figures 10-13 summarize the architecture of the station; (10-12) are the basic signal path, and (13) is the common monitor and control system (MCS). In figure 10, signals from the 256 stands (STDs), each consisting of a pair of antennas (ANT) and front-end electronics (FEE) over a ground screen (GND), go by way of a common RF and power distribution network (RPD) to the signal-entry panel (SEP) of the electronics shelter (SHL). Inside, each polarization is filtered and amplified by an analog receiver (ARX) and then direct-sampled at 196 Msps by the A/D converter in figure 11. We are adopting a digitization scheme that enables us to fold the FM band

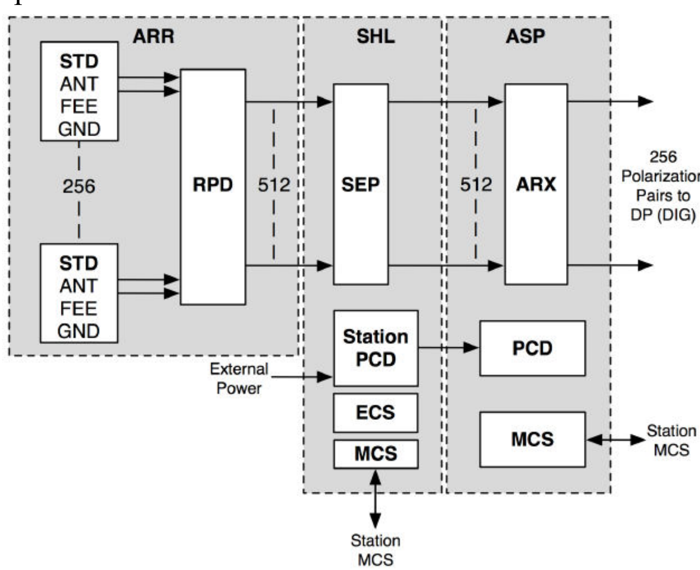

Figure 10: Architectural schematic of LWA from antennas through analog signal processing.

(88-108 MHZ) over on itself, substantially reducing its impact. This fixes a high-frequency limit of 88 MHz and a low-frequency limit of 10 MHz.

In figure 11, the beam-forming units (BFUs) employ a time-domain delay-and-sum architecture, which allows the entire 10–88 MHz passband from each antenna to be processed as a single wideband data stream. Delays are implemented in two stages: A coarse delay is implemented using a first-in first-out (FIFO) buffer operating on the A/D output samples, followed by a finite impulse response (FIR) filter for sub-sample delay. The signals are then added to the signals from other antennas processed similarly. Four dual-polarization beams of bandwidth 78 MHz, each capable of fully independent pointing over the visible sky, will be constructed in this fashion. Each full-bandwidth beam is down-converted by a digital receiver (DRX) and sent to a polyphase filter bank to channelize the beams into spectral channels. With 4096 channels, beam bandwidths up to 8 MHz and spectral resolution down to 61 Hz are achieved.

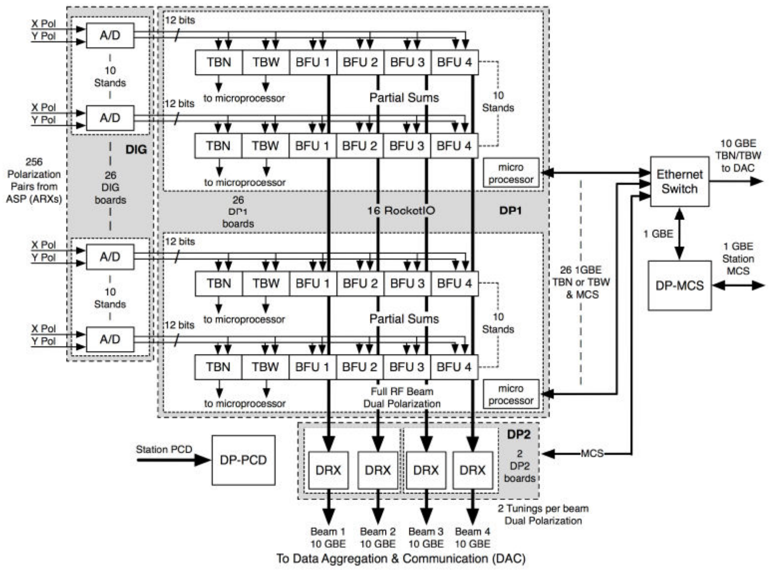

Figure 11: Architectural schematic of LWA electronics, from digitization through digital processing.

These beams will be available for various "backends" implemented at the station level, such as data recorders, wideband spectrometers, and pulsar machines. For interferometric imaging, two "tunings" will be extracted from any frequency in the 78 MHz-wide passband for each beam. These beams are the output to the LWA correlator. In addition, stations in the LWA core will output a wideband beam derived from one of the full-RF beams.

To facilitate commissioning activities, diagnostics, and certain types of science observations requiring all-sky fields of view, the station electronics will also have the capability to coherently capture and record the output of all A/Ds, where each A/D corresponds to one antenna. This will occur in two modes: the "transient buffer – wideband" (TBW) allows the raw output of the A/Ds to be collected continuously for 57 ms at a time. The "transient buffer – narrowband" (TBN) allows a single tuning of 1 kHz to 100 kHz bandwidth to be streamed continuously.

Data Handling and Correlator: For the first LWA station, the data streams will be handled by a set of data recorders (MCS-DR), as shown in figure 12. The MCS-DR consists of 5 identical computers, four of which receive data streams from the digital processor (DP) corresponding to the output of each of the four station beams. The fifth computer receives the DP output data streams corresponding to TBW/TBN outputs. All computers contain internal arrays of large hard drives, to which data can be streamed at the rate received from the DP.

The data aggregation and communication system (DAC) for the full LWA will be a Gigabit ethernet over optical fiber connecting stations to the correlator at a central location. For most stations, the output to the correlator will be both polarizations of 3 beams of 8-MHz bandwidth each, resampled to 8 bits at 1.5 times the Nyquist rate. This results in a data rate of 576 Mb/s. One of these beams will always be available to assist in measuring the ionosphere, as part of image calibration, whereas the other two can be used for simultaneous independent observing programs. Practical limitations in data transmission from the stations to the correlator constrain the immediate plan for multibeam operation to a bandwidth of 8 MHz (selectable within the tuning range). However beams will be formed at the station as “full RF”; i.e., with bandwidth equal to the tuning range. LWA core stations will also transmit a wideband beam (~56 MHz) to the correlator simultaneously with the three 8 MHz beams. This beam will be used primarily for solar science during the day and for early universe (“Dark Ages”) studies at night.

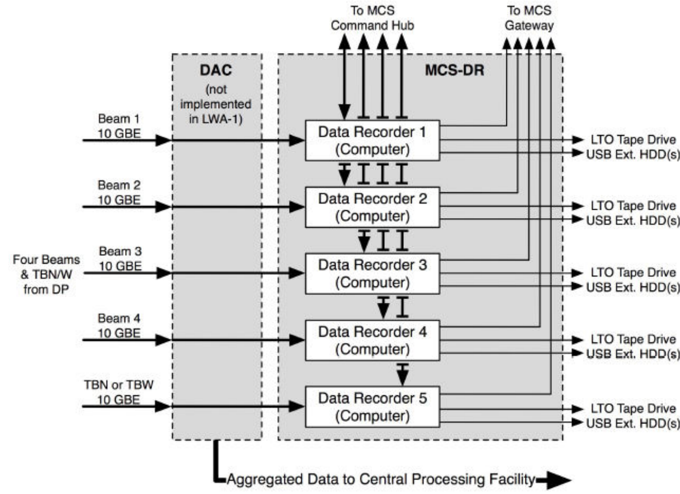

Figure 12: Architecture of LWA data recording.

The large number of high data-rate signals involved makes correlation extremely computationally-intensive, requiring dedicated equipment running in real time for the complete LWA. Development of this correlator has not yet begun. However, the LWA is to be built in stages (discussed below), with the number of stations available in the early stages being relatively small. During this time, we intend to simply capture the station outputs at a central location using disk buffers, and perform correlation in software using general-purpose computers, while developing the final correlator (which might be software based, e.g. DifX).

Control Systems: The station MCS (Fig. 13) is essentially the set of computers that controls the station, and provides status information. Various subsystems including the analog and digital processors also have MCSs, which are embedded computers subordinate to the station MCS. The subsystem MCSs are implemented to facilitate modularity in the station design and to facilitate independent development of subsystems. The Scheduler is a computer whose primary function is to issue commands and receive status from other LWA subsystems. It handles tasks that are extremely time sensitive and that must be coordinated on timescales down to milliseconds. The Executive is the computer which exercises top-level control over MCS as well as the station. It is responsible for interpreting observation requests and, from these, generating the data which becomes the content of command messages issued by the Scheduler. This includes numerically intensive operations such as computation of FIR-filter coefficients. The Executive manages tasks that are moderately time-sensitive and that must be coordinated on timescales down to seconds. The Task Processor is a computer which exists primarily to host applications that are not

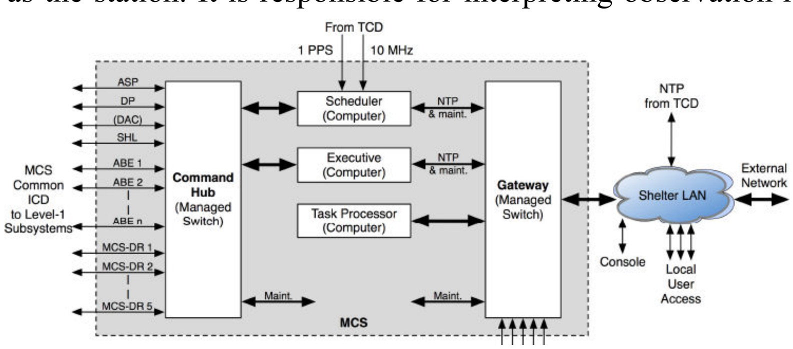

Figure 13: Architecture of LWA monitor and control system.

time critical (time resolutions > 1 sec), and therefore can be offloaded to reduce the processing burden of the Executive.

It is the primary interface with users, managing command line and GUI interactions. The Task Processor is also responsible for the scheduling and interpretation of internal diagnostics (both automatic or user-directed), and manages MCS-DR.

Radio Frequency Interference: A sense of the RFI environment is conveyed by figure 14, which shows the observed sky signal obtained in the field with prototypes of the antenna, front-end electronics, analog receiver, and digitizer, in this case the Analog Devices AD9230-250, 12-bit A/D. The result is sky-noise dominated by at least 6 dB over the range 20–80 MHz, and by at least 10 dB over 28–47 MHz, despite the presence of very strong in-band RFI. The system input 1 dB compression point, as configured for this measurement, was −45 dBm.

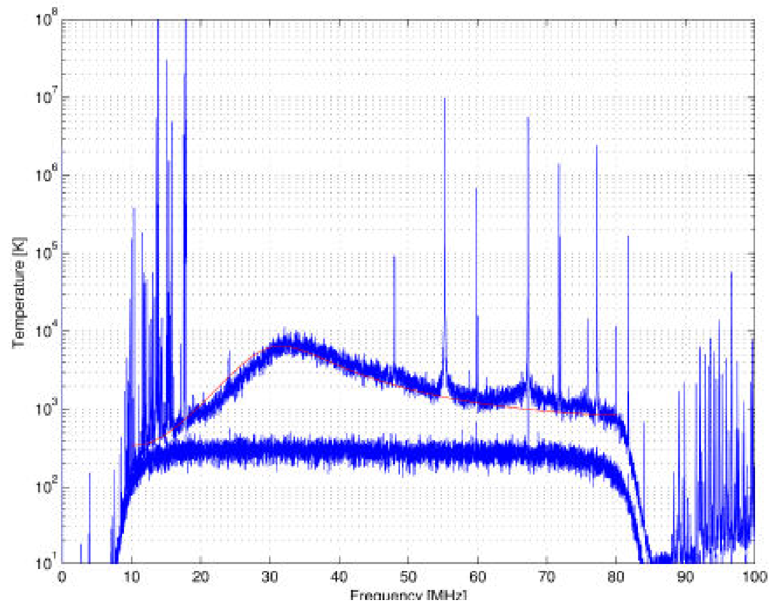

Figure 14: ***Top curve*****: Spectrum acquired in the field using an LWA prototype active antenna (similar to the one shown in Figure 3), with the FEE, ARX and A/D described in the text, with 1 s integration. Also shown overlaying the top curve is the result (red line) predicted from a sky model.** ***Bottom curve*****: Same measurement performed with a 100-ohm (matched) load replacing the dipole arms.**

Experience from the 74-MHz VLA system and other instruments has demonstrated that RFI from external as well as internal sources will be present at all levels throughout the spectrum. The primary difficulty posed by RFI, assuming it does not threaten linearity, is that it dramatically increases the amount of manual effort required to reduce data. A variety of solutions for automatic real-time mitigation of RFI are being considered for implementation. In the station electronics, this may include the ability to modify the responses of digital filters to suppress narrowband RFI, and pulse blanking to remove strong, bursty interference. Spatial or space-frequency nulling can be supported by the electronics architecture. For spectrometry, time-frequency blanking to resolutions of a few ms × a few kHz is supported. Other devices and backends may use additional application-specific methods, and the specific mix of techniques employed will depend on the observing mode and RFI present. Note that the transition from analog to digital TV in the U.S., to be complete by June 2009, will alter the RFI environment.

Technical Challenges: The pseudorandom antenna distribution is vulnerable to significant mutual coupling effects, which will be studied in work with the first station. The ability to calibrate out ionospheric effects has not been tested at the combination of LWA frequencies and baseline lengths. Indeed, the requirements for number of calibrators per beam and cycle times are extrapolated from experience with the VLA at 74 MHz, as are the requirements on software to image the large fields of view of the station beams. Without improved RFI mitigation, wide-field imaging, and ionospheric calibration, the LWA will fall far short of its full scientific potential, as will other next-generation large low-frequency arrays.

LWA Activity: Organization, Partnerships, and Current Status

The LWA Project is funded through a contract between the Office of Naval Research and the University of New Mexico. UNM engagement includes the Office of the Vice President for Research and Economic Development, and the Departments of Physics and Astronomy, Electrical and Computer Engineering, and Civil Engineering. The current development partners are the Naval Research Laboratory, Remote Sensing and Space Sciences Divisions; The Jet Propulsion Laboratory; Virginia Tech; Los Alamos National Laboratory, and The University of Iowa. In addition, the Air Force Research Laboratory and the National Radio Astronomy Observatory are members of the Executive Committee.

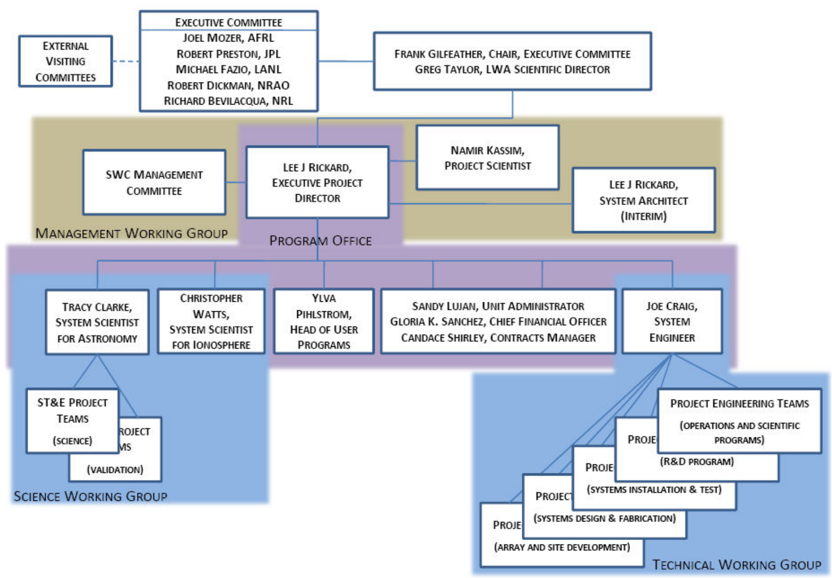

Figure 15: LWA project organization

Critical Design Reviews are scheduled for June and October 2009. Assuming successful completion of CDR1, construction of the first station (LWA-1) will start this summer, at the site near the VLA that currently hosts the Long Wavelength Demonstration Array (LWDA)[37]. Engineering and scientific commissioning will start by the end of 2009, with an interim digital backend, and full operation will begin by the end of 2010. The LWA will be an open skies user facility, scheduling time on the basis of scientific merit. We will begin this policy with LWA-1.

The science plan for LWA-1 focuses on (1) extension of pulsar spectra to low frequencies, including scintillation, scattering, and 'giant' pulse studies; (2) monitoring of all-sky data for transient events possibly associated with transients seen at other wavelengths, including, but not limited to, anticipated high-energy counterparts; (3) studies of low-frequency radio recombination lines, especially of carbon atoms distributed in the cold interstellar medium; (4) studies of the frequency structure of ionospheric transparency events, using LWA-1 in 'riometer' mode; and (5) studies of the fine-scale frequency structure of solar and Jovian radio bursts, especially solar bursts with concurrent higher frequency and high energy measurements. We have already begun our science at every step approach, using the LWDA for all-sky transient searches and for a study of the secular flux density decrease of Cassiopeia A[38,39].

The engineering plan focuses on (1) determining the effects of mutual coupling of antennas on the performance of the synthesized station beam, which has not been studied for pseudorandom configurations like that of LWA-1, and which will be important for understanding the performance of the full LWA; and (2) determining the ability to do long integrations on dark sky without limitations by systematic effects; which will have major implications for other high-profile low-frequency science projects involving studies of the high-redshift universe – especially the epoch of reionization and the 'Dark Ages'.

LWA Activity Schedule (Table 1)

Milestone	Date Complete	Funding (FY11 on)
<u>Short-Term (LWA-1 Implementation)</u>		
Initial Funding	4/6/07	
System Requirements Review	1/8/08	
Preliminary Design Review	3/20/09	
Site infrastructure work (surveying, trenching, etc.)	6/01/09	
Critical Design Review for non-digital system elements	6/01/09	
Critical Design Review for digital system elements	10/30/09	
Installation through analog receivers and related MCS	10/30/09	
Commissioning through analog receivers	2/01/10	
Installation of partial digital system	2/01/10	
Installation of remaining digital system and related MCS	10/29/10	
Begin LWA-1 science operations	11/01/10	
Begin LWA-1 automated operations	3/31/11	
<u>Medium-Term (LWIA Implementation)</u>		
Stations 2 and 3 – installation complete	11/01/11	$7.0M
Stations 4 to 7 – installation complete	11/01/12	$10.0M
Stations 8 to 11 – installation complete	11/01/13	$10.0M
Stations 12 to 16 – installation complete	11/01/14	$10.0M
Begin LWIA science operations	3/31/15	$12.0M
<u>Long-Term (LWA Implementation)</u>		
LWA Core installation (16 stations)	2017	$20.0M
Full LWA installation (remaining 28 stations)	2019	$17.5M
Nominal science operations (average annual cost)	2020-2034	@ $10.5M/yr

In table 1 above, we have shown the details of the development of the first LWA station, which should begin its scientific use in the fall of 2010. The next phases are the construction of the 16-station Long Wavelength Intermediate Array (LWIA), complete in 2015, and the construction of the final 53-station LWA, beginning operations in 2020.

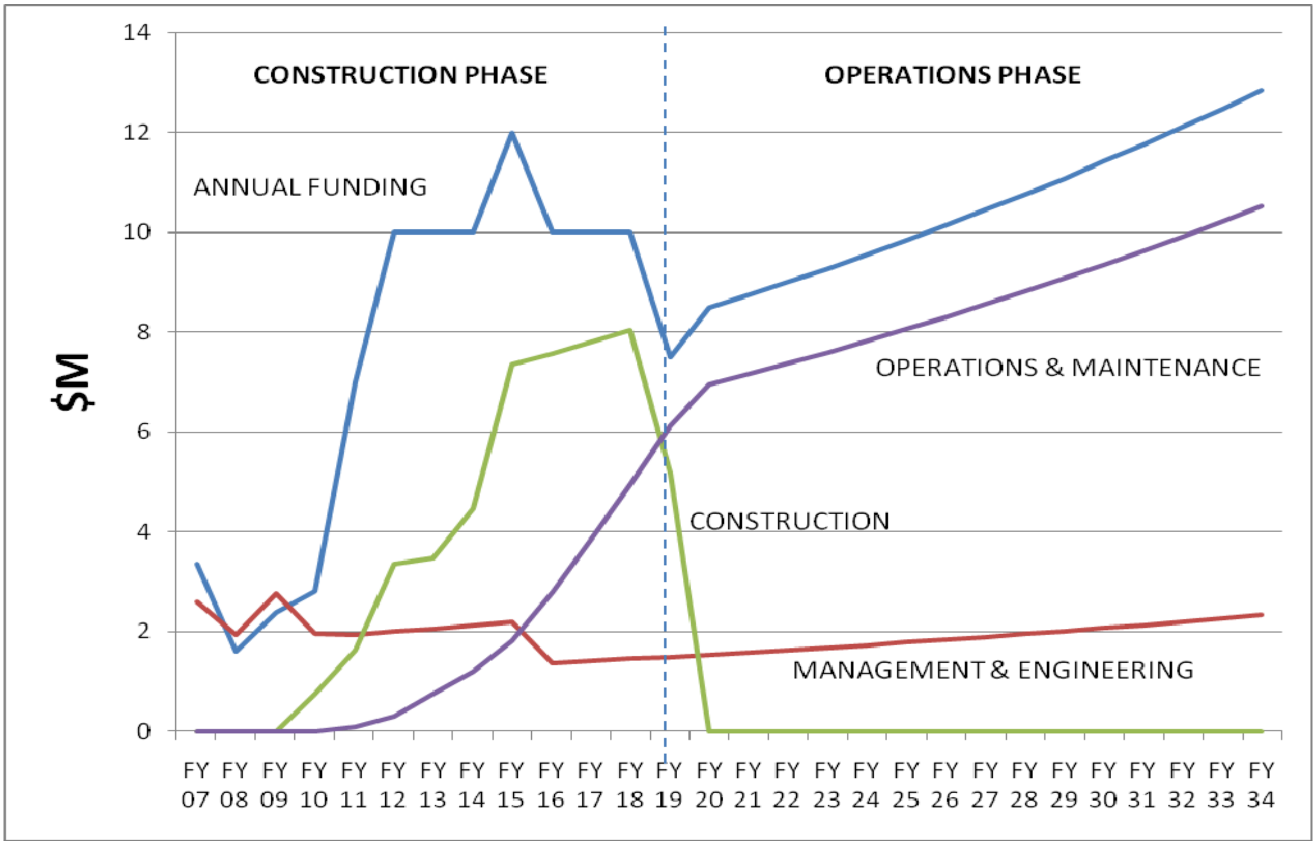

Figure 16: Financial Profiles for Full LWA Project

The anticipated financial requirements for the full development and operation of the LWA project are shown in figure 16. Note that the figures for FY07-10 are based on actual funding. The estimates are based on a construction pace of 4 stations per year to the completion of the LWIA, and 8 stations per year during the subsequent period, FY 16-19. (We have analyzed the variation of costs as a function of pace of construction, from a minimum of 4 stations per year throughout to a maximum of 12 per year. (The case used is a compromise between required level of funding and total construction cost.) The profiles are based on the estimates presented below for the costs of project management, support to engineering by the project partners, construction for LWA-1 and, separately, for LWA-2 through -53, operations (dominated by power and communications), and maintenance (estimated at an annual cost of 5% of the capital cost per station). Each station becomes operational upon completion of construction. An annual inflation rate of 3% is assumed beyond FY 10. In addition, we have adopted a management reserve of 5% on engineering and construction and a contingency of 10% on operations and maintenance, levels that are justified by the relatively low risk of the technical elements.

We have not incorporated any explicit program support to science. The assumption is that such support will be the responsibility of the user. There are no dedicated program science teams.

LWA Cost Estimates

Table 2, below, presents the basic cost analysis for construction of individual LWA stations, in current dollars. It is part of the cost model that was validated in Preliminary Design Review, March 2009, by an external Technical Advisory Committee (P. Napier, NRAO; D. Backer, J. Welch, U.C. Berkeley; R. Ferris, CSIRO; M. Davis, SETI Institute). The cost for stations after LWA-1 reflects some savings enabled by large orders. However, LWA-1 does not require the extensive data system and correlation (DAC), which renders subsequent stations more expensive. The final entry in the table (SIT) refers not to a subsystem, but rather to the work (mostly labor) required for the site infrastructure: surveying, trenching and laying cables, fencing, and so forth.

Table 2: Cost Breakout for Construction of LWA Stations (figures are in $)

			LWA-1			LWA-n	
Subsystem	Quantity		Unit Cost ($)	Subtotal ($)		Unit Cost ($)	Subtotal ($)
Stand and Antennas (STD/ANT)	256		243	62,241		218	55,841
Front-end Electronics (FEE)	256		130	33,280		100	25,600
Ground Screen (GND)	256		19	4,849		19	4,849
RF & Power Distribution Network (RPD)	1		52,352	52,352		52,352	52,352
Analog Receiver (ARX)	512		141	72,440		141	72,440
Digital Processing System (DP)	512		487	249,228		487	249,228
Data Aggregation and Communication (DAC)	1			0		51,775	51,775
Time Conditioning and Distribution (TCD)	1		9,000	9,000		9,000	9,000
Monitor and Control System (MCS)	1		10,000	10,000		10,000	10,000
Data Recorders (MCS-DR)	1		32,000	32,000		0	0
Power Conditioning and Distribution (PCD)	1		6,800	6,800		6,800	6,800
Electronics Shelter (SHL)	1		85,200	85,200		85,200	85,200
Site Infrastructure (SIT)	1		74,300	74,300		74,300	74,300
TOTAL				691,690			697,386
Cost per stand				2,702			2,724

In addition to the station construction, the LWA costs include: (1) A small program office with 6.7 FTE, incorporating management and engineering support, partial support to UNM faculty in the project, and support to postdocs/students. The fully loaded program office cost is $1.1M/year. (2) Engineering support provided by project partners, to complete development, over the period FY 11-15, at an annual cost of $0.7M. This period results in the completion of the Long Wavelength Intermediate Array (LWIA), and the initiation of construction of the full LWA. (3) Basic operations and maintenance costs for each station as it comes on line. The driving costs are for station power (currently estimated at 30 kW) and communications (currently estimated at 576 Mbps). We have estimated the resulting costs at $51K/station/year for operation and $38K/station/year for maintenance.

In summary, the cost breakout by development phase is shown in table 3 below. Figures are in $K. Funding for the LWA is assumed to come entirely from US federal sources. At the moment there are no international partners, or significant private sponsors. At present, the FY 07- 10 part of the project has been funded in the amount of $10.125M.

Table 3: Cost Totals for the LWA Project (figures are in $K)

Phase	FY	Management and Engineering	Construction	Operations and Maintenance	Total
Development of LWA-1	07 – 10	9,214	749	0	9,963
Development of LWIA	11 – 15	10,259	20,258	4,179	34,697
Completion of LWA	16 – 19	5,700	28,554	17,708	51,962
Initial Operation (annual cost)	20	1,533	0	6,957	8,490
Total Cost of Development and Construction	07 – 19	25,173	49,560	21,888	96,622
15 Years of Scientific Operation	20 – 34	28,521	0	129,386	157,907
Total Cost of LWA Project	07 – 34	53,694	49,561	151,274	254,529

Thus, the cost to complete the development and construction of the full LWA (which includes operation of the interim array), given the funds in hand, is $86.5M, of which 56% is purely for station construction. At the start of full operations (FY 20), the annual cost of operations corresponds to 8.8% of the total development and construction cost.

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Astro-2010 science white papers (note: bolded references explicitly cite LWA)

WP1: "Diffuse Baryonic Matter beyond 2020" – Markevich et al.

WP2: "The Evolution of Galaxy Clusters across Cosmic Time: A Science Working Paper for the 2010 Decadal Survey" – Arnaud et al.

WP3: "Clusters and Large-Scale Structure: The Synchrotron Keys" – Rudnick et al.

WP4: "Galaxy Cluster Astrophysics and Cosmology: Questions and Opportunities for the Coming Decade" – Myers et al.

WP5: "Cosmic Feedback from Supermassive Black Holes" – Fabian et al.

WP6: "High Redshift Radio Galaxies, Laboratories for Massive Galaxy and Cluster Formation in the early Universe" – Miley et al.

WP7: "Astrophysics from the Highly-Redshifted 21 cm Line" – Furlanetto et al.

WP8: "Cosmology from the Highly-Redshifted 21 cm Line" – Furlanetto et al.

WP9: "Plasma Physics Processes of the Interstellar Medium" – Spangler et al.

WP10: "The Dynamic Radio Sky: An Opportunity for Discovery" – Lazio et al.

WP11: "Mass-Loss and Magnetic Fields revealed by Stellar X-ray Spectroscopy" – Osten et al.

WP12: "Radio Detection of UHE Neutrinos" – Langston et al.

WP13: "Magnetospheric Emission from Extrasolar Planets" – Lazio et al.

WP14: "Solar and Heliospheric Physics with Low Frequency Arrays" – Kasper et al.

Additional references (note: LWA Tech. Memos are available at http://www.ece.vt.edu/swe/lwa/)

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