LWA Overview

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LWA Memo

Contents

Chapter 1

Introduction

The Long Wavelength Array (LWA) project will design, construct, and operate a next generation radio telescope with imaging power 2-3 orders of magnitude better than current or past capabilities at frequencies below the FM band. This document describes the organization of the effort and the development and construction issues for the overall instrument as well as the immediate effort based on initial funding.

We present an overview for a phased deployment of the LWA (a long term project) with a large field of view, excellent sensitivity, and high angular resolution. When completed the LWA will consist of 52 stations, where each station consists of 256 crossed-dipole antennas (see Fig. 1.1). Over the next 6-7 years we envision the immediate project (the Long Wavelength Intermediate Array or LWIA) to comprise about 16 stations and designed to provide a significant new capability to probe the ionosphere while also accomplishing important astronomy objectives.

A dedicated LWA science and engineering team will guide and oversee the effort with valuable contributions expected from all members of the Southwest Consortium (SWC) and other centers of expertise. Thorough reviews of the project will be held regularly and we anticipate annual funding for 6-7 years in order to complete the initial projoect which involves substantially completing the LWIA.

The LWA will be designed, constructed and operated with the guidance and support of the SWC, a group of universities and government laboratories currently consisting of the University of New Mexico, the Naval Research Laboratory, the University of Texas at Austin, and the Los Alamos National Laboratory. The SWC will play an active role in the LWA project through many inter-institutional activities, subcontracts and additionally funded efforts. The intent is that the LWA be seen as a SWC effort while contractually and legally it is represented by UNM.

This document is meant to be a planning document providing an overview of the implementation strategy for the Long Wavelength Array. Introductory material can be found on the web pages (`lwa.unm.edu`). More complete technical descriptions of subsystems can be found in the LWA memo series (`http://www.ece.vt.edu/swe/lwa/`).

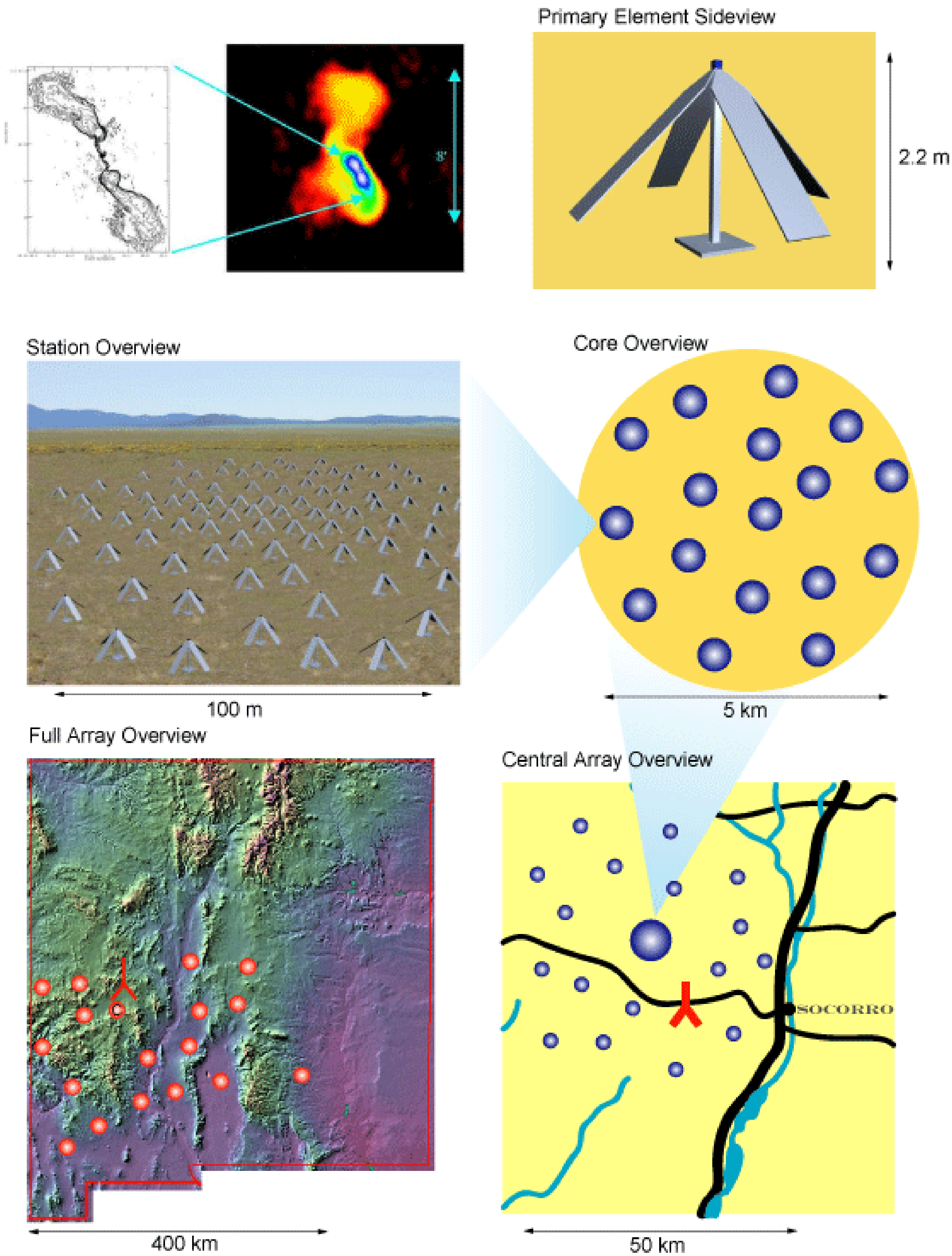

Figure 1.1: Top left: Hydra A as a sample Active Galaxy that has been imaged by the VLA at both short and long wavelengths. Top Right: sideview of a primary antenna element. Middle: schematic of an LWA station and core. Bottom: full array and central array overview. Station locations shown are not exact.

Chapter 2

Implementation Strategy

2.1 Implementation Plan

In order to meet the goals of the LWA effort, we envision a phased development effort. Thus, initial system-level issues (receiver designs, calibration, imaging, etc.) are addressed through implementations using minimum-risk, proven component technology. At the same time, development of new subsystems will be carried out to enable reaching the desired instrument performance (e.g., we plan to implement a narrowband beamformer and data recorder for the first LWA station, and to defer the full-bandwidth beamformer to the second station). When more capable subsystems are ready, the existing stations will be retrofitted.

A general philosophy of the project will be to retain operational capability at all times. That is we will operate the LWDA while we are building the LWA1. Then we will operate LWA1 while building LWA2. We will operate LWA2 while retrofitting LWA1, etc. This will be important for student training, software development, and continued scientific productivity.

2.1.1 Phased Station Deployment

The three initial phases of the LWA characterize the development timeline of the instrument and of necessity span multiple funding years (see Table 2.1).

Site selection is an important aspect of the implementation plan for each Phase of the LWIA. The basic procedure that we will use to evaluate and select sites is:

Identify candidate sites from maps showing available land and road access.

Evaluate available power and fiber access (see cost estimates below).

Evaluate the (u, v) coverage that the site will provide.

Perform a quick physical survey of the site to identify any obvious problems due to terrain, occupation and location.

Table 2.1: LWA Phased Development

Time	Phase	Description	Total Stations	Acronym
2006	0	Existing 74 MHz VLA and LWDA		VLA/LWDA
2006-2008	I	Long Wavelength Array Station 1	1	LWA1
2008-2009	Ib	Long Wavelength Array Station 2	2	LWA2
2009-2010	II	Long Wavelength Intermediate Array	9	LWIA
2010-2011	III	Add LWA Core to LWIA	16	LWIA
2010-2011	IIIb	LW Operations and Science Center		LWOSC
2011-2015	IV	Long Wavelength Array	52	LWA

Make a detailed physical site survey.

Conduct initial RFI monitoring (minimum 2 hours).

Conduct detailed RFI monitoring (minimum 24 hours, maximum TBD).

At this time we do not know if an Environmental Impact Statement (EIS) will be necessary for any station, or group of stations. A UNM lawyer is being engaged to look into this situation futher. It may be that an Environmental Assessment (EA) is sufficient. If an EIS is required then that may take three years or more and can be quite expensive. Determining what certifications are needed for the sites is an important task for the project office in year one.

A preliminary configuration study has recently been presented by Cohen et al. (2006; LWA memo No. 55). This study provides two possible configurations for the LWIA, and preliminary station locations for the LWA. The establishment of the LWA stations will be an iterative procedure.

Phase I: The implementation of the first two LWA stations occurs in the initial 18 to 24 months of the effort. Long Wavelength Array station 1 (LWA1) will benefit from experience developed on the LWDA, and have greater capabilities, in particular the antennas will be tunable over the band from 20-80 MHz, but with limited bandwidth. LWA2 will be a demonstration station using updated technology that has improvements over LWA1 such as increased bandwidth. The LWA1 and 2 will also work with the VLA operating at 74 MHz. These two elements will enable us to do the bulk of the validation of the LWA system concepts, and of the basic engineering designs.

Also during this phase, we will begin performing a limited set of experiments, including: 1) single-station based all-sky monitoring for anticipated radio transient phenomena including from ultra-high energy cosmic rays and gamma-ray bursts; 2) surveying the cold interstellar medium through low frequency radio recombination lines; 3) conducting deep integrations to verify the expected noise performance and to gauge the capability of subsequent phases to achieve much deeper thermal noise limited sensitivities. We will begin development of an angle-dependent ionospheric calibration method, wide field imaging, and will develop single-station based RFI avoidance and mitigation strategies. See also the science case for the various phases of the project presented in Appendix A.

In general we want to be developing several sites at once. In this way once we are ready to build the next station we will have options to choose from, even if a site is held up or is shown to be unacceptable for unforseen reasons.

LWA1 is being sited at the VLA, where the LWDA currently resides. An initial build of 16-32 "stands" (where a stand is a pair of crossed dipoles) may occur colocated with the LWDA. When we are ready to build out to 256 stands we anticipate removing the LWDA.

Site selection of LWA2 (with more than one possible option) should begin soon after the first year of ONR funds are available. For this second site we would like to push to baselines beyond A configuration, thus enabling new scientific projects beyond the capability of the current 74 MHz system on the VLA (including Pie Town). The addition of this station will also allow us to test the feasibility of going to 400 km baselines as planned. Having this data available will allow us to begin working on the software to handle long baselines. To complement the VLA+PT, a southern site is preferable (see Fig. 2.1). Sites that should be evaluated are those near Dusty and Horse Springs. Both sites have been considered for the EVLA-II. Further simulations of the (u, v) coverage, as well as RFI surveys, and assessment of the feasibility of obtaining power and communications to the sites, will be needed for the evaluation.

A possible location for LWA3 is at Sevilleta, a research property owned by UNM. This has the advantage of going to 100km baselines so that we can assess the number of compact, high brightness sources available for study. A preliminary analysis, based on VLA 74 MHz observations, suggests that there should be hundreds of extragalactic radio sources that are sufficiently strong and compact to be detected on baselines of order 100 km. A station at Sevilleta would allow us to validate this study and provide justification for further expansion of the LWA (or conversely indicating that a substantial review of LWA requirements is in order). Fiber and power are available at relatively low cost for this site, though studies are needed to understand the RFI environment, availability of suitable land, etc.

Sites that have a ready internet connection, such as perhaps a site near Water Canyon, or at Sevilleta should also be considered for early deployment. Finally, there are two prospective locations for the LWA core - one past the end of the North arm, and one past the end of the West arm. We may want to build an LWA station at one or both of these locations in order to gain familiarity and inform the choice for siting the core during Phase III. These could be possible locations for LWA4 and LWA5.

Phase II: Building to both long and intermediate spacings for the Long Wavelength Intermediate Array (LWIA) is the following 36 months of effort. At the completion of this phase, we expect between seven and nine stations operating in the frequency range 20 and 80 MHz, with a target bandwidth of 32 MHz. The LWIA should be able to operate in concert with some of the VLA antennas at 74 MHz in order to provide new scientific capability and allow for testing calibration algorithms. By the end of Phase II, the stations should also be capable of limited scientific operation independent of the VLA. Independence from the VLA will allow exploration of frequencies besides 74 MHz, and more flexible scheduling.

During this phase, we should be able to achieve sub-arcminute imaging at 60 MHz, and

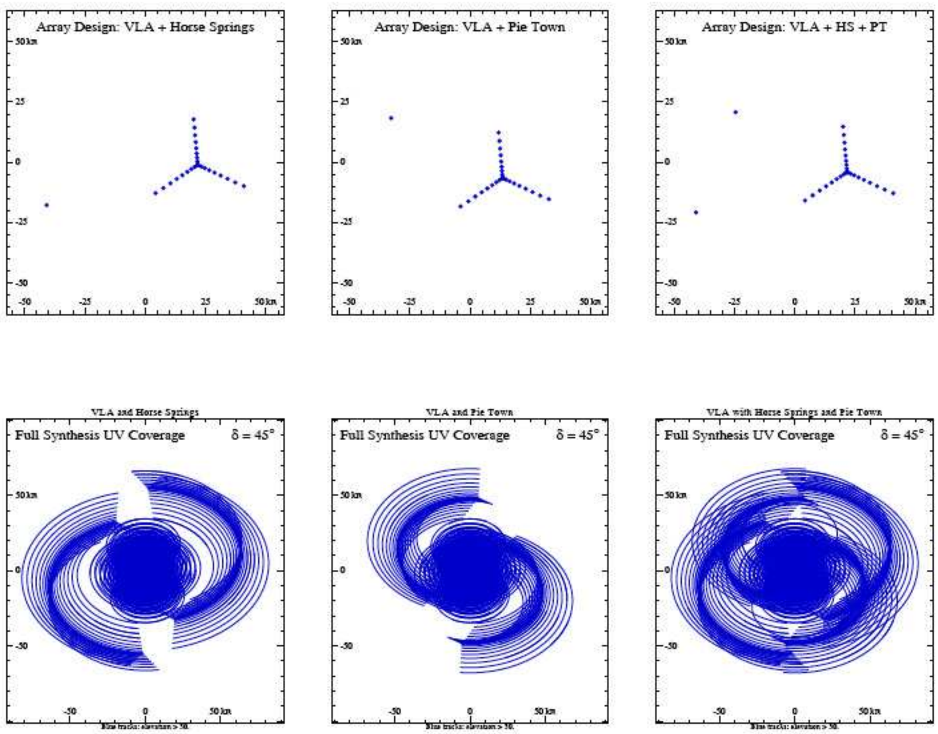

Figure 2.1: An illustration of the (u, v) coverage provided by an antenna station for a source at a declination of 45°. *Left* The VLA combined with a station at Horse Springs. *Middle* The VLA-Pie Town link for comparison. *Right* The VLA combined with stations at Pie Town and Horse Springs (Courtesy of A. Cohen).

will be able to begin investigating long-baseline (200 km) calibration. We expect to be able to explore acceleration physics in bright 3C objects including supernova remnants, radio galaxies, and clusters of galaxies, and to search for extra-solar planetary systems at low frequencies. In addition, we will test and evaluate long baseline ionospheric calibration methods, and will develop techniques for interferometer-based RFI mitigation to complement station-based techniques. Studies of ionospheric physics should begin to ramp up as data becomes available on new scales.

Phase III: Completion of the LWIA by the addition of the Long Wavelength Array Core (LWAC) begins in the final years of the LWIA project. With the partial completion of this phase, we expect to add seven stations with LWIA characteristics, bringing the total number of stations to between 14 and 16. This phase includes developing a centrally condensed (10 km) core of stations to remove the dependence on the 74 MHz VLA, which is used as a surrogate core in the earlier phases of the project.

In this phase, we should be able to achieve routine full-field imaging out to 200 km baselines at the full range of LWA frequencies. This will enable us to probe acceleration processes in larger samples of sources including moderate strength supernova models; study space weather and the radio characteristics of Coronal Mass Ejections, and other solar bursts and flares, complementing lower frequency, space-based measurements with the Solar TErrestrial RElations Observatory (STEREO); and explore capabilities for geomagnetic storm prediction based on ground-based, LWA observations. In order to do all this, we will develop techniques for ionospheric calibration and RFI mitigation that permit full field-of-view, near-thermal noise limited imaging across the LWA frequency band of remnants, radio galaxies, and diffuse emission from galaxy clusters; explore acceleration, turbulence and propagation physics of the interstellar medium; study Galactic center magnetic fields, and use HII region tomography to map the 3D distribution and spectrum of Galactic cosmic rays; perform deep, wide-field searches for transients (e.g., Galactic center and magnetar radio transients); study ionospheric waves, turbulence, and small-scale structure, probe capability of LWA real-time ionospheric model to test theater predictions of global ionospheric models.

Phase IV: Although beyond the scope of the first increment of funding and time, here we give a brief description of Phase IV. In this phase stations will continue to be added to the core. At the same time, more distant stations will be added, gradually increasing the maximum baseline length to 400km. The correlator will need to be increased in capability by an order of magnitude to handle the increase in stations from ∼16 to 52.

2.1.2 Correlator and Array Operations

During Phase I we plan to employ a software correlator, and will make limited use of the VLA correlator. Engineering tests making use of the VLA correlator will need to be coordinated with NRAO. Astronomical observations with the VLA correlator will need to be formally proposed to NRAO for. The details of these arrangements have not yet been established. The software correlator is likely to be implemented at the LWA site. In Phase II we will begin work on a hardware correlator that can handle the needs of the LWIA.

A control building connected by fiber to the LWIA stations will need to be established toward the end of Phase I. The control building will house the correlator, a small inventory of spare parts, and provide some workspace for basic repairs. To reduce communications costs and travel time, the control building should be fairly close (less then 30 km) to the center of the array, but it may be desirable not to locate it near the LWAC to avoid self-generated RFI (or to reduce the level of shielding required). The control building must also not produce any emissions that would be harmful to VLA antennas, or any other radio astronomy projects. Access to communications and power are essential, and good roads are highly desirable.

In 2010 we should consider the conversion of the project office at UNM into the Long Wavelength Operations and Science Center (LWOSC). The LWOSC might house the archive for the LWA and provide processing capabilities for routine pipeline calibrations. Alternatively it might be more practical to house the archive and a cluster at the High Performance Computing center at UNM.

2.2 LWA Cost Model Summary

Here we provide very rough estimates of the cost of:

a) Acquiring the land for a station (surveys, evaluation, etc.)

b) Infrastructure costs (power, fences, etc.)

c) Communication costs for the station (fiber)

d) The LWA station hardware

a-d scale up by N where for the LWIA+LWAC N=14-16, assume some average cost for the fiber run.

e) Correlator

f) Central Processing Facilities including archive

g) project management

h) operations (power, maintenance, etc.)

i) software

We estimate that LWA1, if designed/built according to the Strawman Design Document, will have a credible "pile of parts" cost somewhere between $836K and $997K (Ellingson 2006; LWA memo 45). The same analysis leads us to an estimate of about $723K for LWA2 assuming large-quantity pricing (which means we either buy large quantities or get equivalent discounts). These estimates assume no significant progress in cost reduction; however the analysis points to analog receivers (ARXs), digital receivers (DRXs), and antennas as items for which cost reduction could have significant impact. The biggest unknown uncertainty overall is the cost of digital receivers (DRXs). Development costs are not included in the above estimates.

The infrastructure for LWA1 is largely in place though it may cost another $25K for installation of antennas and cabling. For LWA2 the infrastructure costs are estimated at $60K (Gerstle 2006; LWA memo 48), but will depend on the distances required for roads, power, and fiber runs. Based on our experience with the LWA1 site, the cost is about $40K/mile with the breakdown being $32K/mile for power and fiber on overhead lines, and $8K/mile to grade a road.

2.3 Review Process

We plan for regular reviews, especially in the initial stages of the project. As a baseline schedule, we envisiage the following:
(IoF = Initiation of Funding)
LWA1
Requirements review - IoF + 1 month
CoDR - IoF + 3 months
PDR - IoF + 10 months
CDR - IoF + 20 months

LWA2
Requirements review - IoF + 24 month
CoDR - IoF + 27 months
PDR - IoF + 36 months
CDR - IoF + 48 months

More detailed review structures will be provided by the Project Office. As LWA2 would be close to the "final" design, additional station construction would proceed on a much more rapid pace, with less need for such reviews.

Figure 2.2: A big blade prototype at the LWA site for testing with the 16 LWDA stands in the background taken in August 2006 after a series of heavy rains watered the Plains of San Augustin.

Appendix A

LWA Milestones

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Milestones attached as pdf.

Long Wavelength Array (LWA) Milestones

LWA Phase I (LWA1 and LWA2): 2 stations - ≤ 100 km baselines.

- Technical approach/challenges/capabilities
  - Construct two dipole-based stations to gain experience
  - Single-station based all-sky transient monitoring
  - Conduct deep integrations to verify expected noise performance
  - Expected sensitivity & resolution: [20,80]MHz, [19,9] mJy, [31,8]”
- Scientific capabilities
  - Transients
    - Prompt emission from GRBs (Usov & Katz 2000, Sagiv & Waxman 2002)
    - Ultra-high energy cosmic rays (Falcke et al. 2005)
  - Radio Recombination Lines (RRLs) from the largest atoms (Payne et al. 1994)
  - With the VLA - high resolution imaging of isolated, bright sources at 74 MHz
    - Includes: Cyg A, Cas A, Tau A, Vir A, Per A, Her A (Gizani et al. 2005, Lane et al. 2004).

LWA Phase II (LWIA): ~6-7 stations - ≤ 200 km baselines [~9 total]

- Technical approach/challenges/capabilities
  - 6-7 new stations
  - Baselines ≤ 200 km
  - First sub-arcminute imaging below 74 MHz
    - Imaging comparable to VLBA, early 74 MHz system (Kassim et al. 1993)
  - With the VLA – first full-field mapping at 74 MHz out to 200 km.
  - Expected sensitivity & resolution: [20,80]MHz, [4,2] mJy, [15,4]”
- Scientific capabilities
  - Acceleration physics in bright 3C objects
    - Supernova remnants – shock acceleration (Anderson & Rudnick 1996, Frail et al. 1995), interaction with environment (Kassim et al. 1995, Bietenholz et al. 1997)
    - Radio galaxies – self-absorption processes.
    - Clusters – cooling flows or “heating” outflows? (Owen et al. 2001, Fabian et al. 2002), new relics & halos & related steep-spectrum emission (Lane et al. 2002, Cohen et al. 2005).
  - Transients
    - First deep integrations for extra-solar planetary systems (Lazio et al. 2004)
    - Increased cross-section for ultra-high energy cosmic rays

LWA Phase III (LWIA): Core - ~7 new stations inside 10 km baselines [~16 total]

- Technical approach/challenges/capabilities
  - ~15 new stations to form core within 5 km
  - Break dependence on 74 MHz VLA surrogate core
  - Routine full-field mapping with 200 km baselines at all frequencies
  - Expected sensitivity & resolution: [20,80]MHz, [2,0.7]mJy, [15,4]”
  - Significantly increased surface brightness sensitivity – key for Galactic & solar applications.

- Scientific capabilities
    - Probing acceleration processes in
        - Clusters – the diffuse radio emission/merger connection – precursor to Dark Energy (DE), Dark Matter (DM) studies (Kassim et al. 2001, Clarke et al. 2005)
        - Radio galaxies – powerful evolutionary studies – synchrotron aging (Carilli et al. 1991), pressure balance with X-ray gas (Krawczynski et al. 2003), first deep searches for high-Z radio galaxies (Rawlings et al. 1996)
    - Acceleration, Turbulence, & Propagation in the ISM
        - Full Galactic SNR census - find "missing SNRs", including sites of CR acceleration in youngest SNRs (Brogan et al. 2005a)
        - HII region tomography, deep, higher resolution core-based studies of RRLs from the cold ISM (Erickson et al. 1995)
        - ISM studies via scattering (Lazio et al. 1999) and thermal absorption (Lacey et al. 2001)
        - Galactic center magnetic field (LaRosa et al. 2005)
    - Transients
        - Deep, wide-field imaging searches, e.g. Galactic center transients (Hyman et al. 2002), magnetar radio flares (Gaensler et al. 2005)
    - Space Weather and Solar Radio Astronomy (Bastian 2004)
        - LWA ~20-80 MHz compliment to Solar TErrestrial RElations Observatory (STEREO) 10 KHz – 16 MHz range.
        - Coronal Mass Ejections, Solar Energetic Particle Events (SEPs), Solar bursts and flares (Bastian et al. 2001, Cane et al. 2002)
        - Solar radar: LWA receiver, Arecibo or HAARP transmitter
        - FASR – LWA triggered follow-ups, LWA based ionospheric calibration
    - Ionospheric Physics
        - Ionospheric waves, turbulence, & small-scale structure (Jacobson & Erickson 1992a,b)

LWA Phase IV (full LWA): ~ 34 new stations out to 400 km baselines [~50 total]

- Technical approach/challenges/capabilities
    - ~28 new stations to complete LWA: 52 total stations
    - 400 km baselines approach arc-second resolution at all frequencies
    - Full field, broad-band imaging across LWA frequency range.
    - Expected sensitivity & resolution: [20,80]MHz, [0.7,0.3] mJy, [8,2]"
- Scientific capabilities
    - Cosmic Evolution with
        - Clusters of Galaxies - Dark Matter and Dark Energy
            - Complete census of radio emission from clusters up to z = 1 and beyond.
            - Cosmological evolution of DM via z-dependence of cluster mergers
            - DE equation of state by defining statistical sample of relaxed clusters (Allen et al. 2004)
            - Evolution of radio galaxies & clusters – radio-X-ray connections (Cohen et al. 2003)
        - The High Redshift Universe – High-Z Radio Galaxies and the EOR
            - Detection and study of the first supermassive black holes (De Breuck et al. 2000, Jarvis et al. 2001)
            - Search for localized HI absorption during the Epoch of Reionization & beyond (Carilli et al. 2001, Barkana & Loeb 2005(a,b), Loeb & Zaldarriaga 2005, Sethi 2005)
    - Acceleration of Relativistic Particles

        - LWA-EVLA ultra-sensitive acceleration studies in:
            - Hundreds of SNRs & normal galaxies at energies up to 10^{15} eV (Bietenholz et al. 2001, Delaney et al. 2005).
            - In thousands of radio galaxies & clusters at energies up to 10^{19} eV (Feretti et al. 2004) - low-γ e^- population to test IC assumptions (Rudnick et al. 2005)
            - Test predictions of Fermi acceleration theory in all nonthermal sources (Reynolds & Ellison 1992)
            - Galactic center nonthermal filaments (LaRosa et al. 2004, Nord et al. 2004)
    - Ionospheric Physics
        - Real-time ionospheric modeling
        - Interface with Global Ionospheric models.
    - Planetary Science
        - Jupiter's nonthermal emission (dePater 2004)
        - Deep searches for extra-solar planets (Farrell et al. 2004)
        - Planetary radar with LWA receiver, Arecibo or HAARP transmitter
    - The interstellar medium (ISM) and beyond
        - Detailed probe of interaction between thermal and nonthermal sources in star-forming regions (Brogan et al. 2005b).
        - Resolve all Galactic SNRs and many in nearby galaxies.
- Opportunity: Astrophysical discovery space – what is left?
        - < 100 MHz is the last, poorly explored spectral region
        - LWA increases both resolution & sensitivity 2-3 OOM - like going from EINSTEIN to CHANDRA
        - Unprecedented volume of space sampled
        - New observing paradigms: multi-beaming
    - ***The LWA efficiently exploits the last remaining areas of exploration space for radio astronomy – new discoveries anticipated***
        - ***E.g. unexpected classes of coherent emitting sources (Hyman et al. 2005)***

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