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The Swarm Development Concept for the LWA

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Ground Based Project

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1. INTRODUCTION

We propose to develop what we call the Long Wavelength Array (LWA) Swarm telescope - a powerful instrument for investigating the Universe while engaging students at Universities and Colleges across the US. The highly regarded decadal surveys of prospective research are recommending telescope arrays that have significant capabilities, but also overwhelming complexity and costs. These barriers result in black-box instruments where students have little opportunity to understand the inner workings. We propose a novel model for realizing a continental scale telescope array that is accessible to anyone and everyone with interest. We will achieve this by deploying LWA stations to hosting universities and colleges that will operate the stations both independently for their own scientific interests, and jointly as part of the LWA Swarm through a very long baseline interferometry mode. This will energize a multi-disciplinary community, and result in increased opportunities for students to learn about instrumentation as well as science. At the same time, this will also result in a powerful instrument, the Long Wavelength Array Swarm, for exploring the Universe at low frequencies. The exploration of this electromagnetic window has recently led to a bonanza of exciting scientific results, including the discovery of cosmic dawn and radio afterglows from meteors.

While radio astronomy got its start at 15 m wavelengths with the pioneering work of Karl Jansky, researchers moved quickly to shorter wavelengths in order to increase angular resolution and reduce the sky background noise. Recently we have returned to the little explored region of the spectrum between the ionospheric cutoff and the FM band (10 to 80 MHz; 30 to 4 m in wavelength) and are making exciting discoveries regarding the nature of high energy cosmic rays (Falcke et al. 2005; Apel et al. 2013), radio afterglows from fireballs entering the atmosphere (Obenberger et al. 2014, 2015), pulsars (Stovall et al. 2015), and many other topics within and beyond our solar system (Taylor et al. 2012 and references therein); as of June 2019 the LWA has produced over 60 refereed publications. There are also now other passive uses such as studies of the ionosphere, lightning, solar and Jovian bursts, and space weather. The LWA provides access to the lowest frequencies observable from the ground, and has little overlap with the planned Square Kilometer Array (SKA) telescope in Australia.

Science at low frequencies has proved to be a remarkably interdisciplinary activity. This effort includes aspects relating to goals cutting across several disciplines including astrophysics, physics, geophysics, and ionospheric physics. This diverse nature makes it particularly amenable to distributing mini-stations among colleges and universities where there is likely to be a broad range of scientific interests.

2. LWA SWARM KEY SCIENCE GOALS

With many LWA stations working in concert as an interferometer there are a number of science topics that are approachable. Below we give examples of some high priority science objectives.

2.1. *Extra-Solar Planets*

Jupiter is well known to emit powerful bursts of coherent emission that can outshine all other sources below 40 MHz. In fact all of the planets in our solar-system with magnetic fields have been observed to produce coherent emission, with the maximum frequency linked to the field strength. This raises the intriguing possibility of not only detecting extra-solar planets by way of their low frequency emission, but also using the emission characteristics to measure the magnetic field strength (Lazio et al. 2019). Magnetic fields are of critical importance to the retention of planetary atmospheres and thus the development of life. Recent evidence from the MAVEN spacecraft suggests that Mars lost much of its atmosphere due to its lack of a significant magnetic field (Jakosky et al. 2017). From the modulation of the radio bursts it would also be possible to directly obtain the rotation period of the planet and infer the presence of an exo-moon.

While many searches have been carried out (e.g., Winglee et al. 1986; Lazio et al. 2004; Murphy et al. 2015; to name just a few), no radio bursts from exoplanets have yet been detected. However, almost all of these searches have been executed at frequencies well above Jupiter's cutoff at 40 MHz. Searches with the existing LWA1 facility have been plagued by high confusion noise causing a lack of sensitivity. We will address this through high resolution imaging with the LWA Swarm. We estimate our 10 minute sensitivity at 30 MHz at 25 mJy which should allow us to see a Jupiter-like planet out to $\sim$5 pc (but farther if the exoplanet is more luminous) assuming that we are inside the beaming cone. This is high-risk, high-reward science that relates to the successful Kepler mission and the ongoing TESS mission.

2.2. *Resolving Pulsar Scattering*

To date, LWA1 has been used to detect over 100 neutron stars (Stovall et al. 2015 and in prep.). The frequency range of the LWA, the lowest frequencies visible through the Earth's Ionosphere, makes it uniquely suited for studies of the effects of free electrons and magnetic fields on the pulsar signal as it travels from the pulsar to Earth. The influence of free electrons on the pulsar signal cause multiple effects, including dispersion and scattering. The dispersive delay as the pulse travels from the pulsar to the Earth is proportional to ν^{-2} and the effects of scattering are proportional to ν^{-4}, making the lowest frequencies optimal for detecting changes in these parameters. Of particular interest is gravitational wave detection using pulsar timing arrays (PTAs). The multi-path propagation effects strongly detectable at low radio frequencies at the wide LWA bandwidth will inform noise modeling in pulsar timing generally, as ultra-wideband receivers become the norm at all radio frequencies. Additionally, some PTA pulsars will be timed with the LWA-Swarm in order to characterize their particular lines-of-sight through the ISM.

The LWA Swarm will achieve sub-arcsecond resolution and thereby resolve the scattering disk for numerous pulsars revealing characteristics of the ISM and providing a new method for making distance measurements to pulsars. Recently, Popov et al.

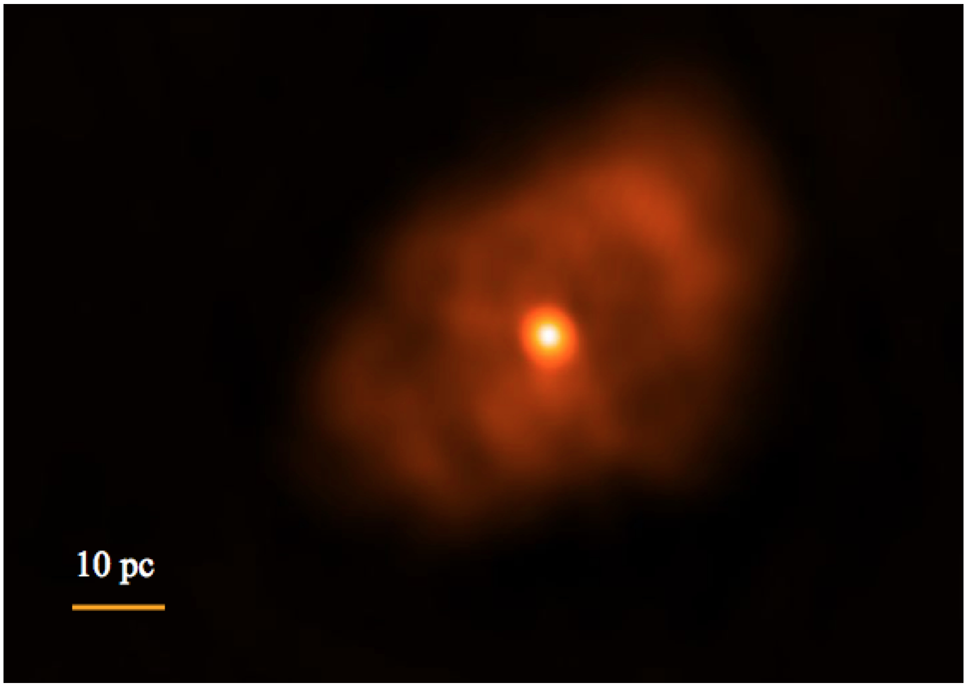

Figure 1. ELWA observations of the Crab pulsar obtained with the two LWA stations and 23 VLA antennas on Mar 26, 2018. The observing frequency was 74 MHz with an 8 MHz bandwidth and 4 hours on source. The peak flux density is 38 Jy and the rms noise in the image is ∼40 mJy/beam.

(2016) reported to have marginally resolved the scattering disk for PSR B0329+54 using RadioAstron at 324 MHz with baselines up to 330,000 km. Since the size of the scattering disk is proportional to the square of the wavelength, scattering disk observations in our frequency range can be done using significantly shorter baselines. As an example, taking the scintillation parameters for PSRs B2217+47 and B2303+30 (Lewandowski et al. 2015), the estimated scattering disk size for these two pulsars is 6 and 9 arcseconds, respectively, easily resolved by the LWA Swarm.

We will also make high resolution observations of the Crab pulsar and nebula (see Fig. 1). Such images would be of interest to compare the nebula at low frequencies to the extent in the x-rays ($7' \times 5'$). A good LWA image of the Crab would also strengthen limits, or possibly even detect, the long sought outer shell of the Crab associated with the original blast wave (Frail et al. 1995). Moreover, we expect to detect 20 - 40 giant pulses during a 4 hour integration on Tau A (Eftekhari et al. 2016). The expected duration of the pulse is 0.8 seconds at 74 MHz, so we will be able to image the pulse and look for a possible scattering disk or reflected echoes.

3. TECHNOLOGY

At UNM, we operate the LWA which currently consists of two stations, each with 256 dipoles separated by about 70 km. There is also an LWA station at Owens Valley operated by Caltech. The LWA thus far has had two primary modes of operation - (1) beamforming with between 1 and 4 beams, each 16 MHz wide with dual polarization and two tunings; and (2) continuous all-sky imaging in a narrow bandwidth (100 kHz). Recently we have developed a wide band (up to 40 MHz bandwidth and fully tunable) all-sky mode. Data can be either correlated to generate traditional visibilties on time scales of 10 seconds or, for imaging at a faster cadence, we can use the E-field Parallel Imaging Correlator (EPIC) framework based on the work of Morales (2011). EPIC has been implemented at LWA-SV and demonstrated to produce all-sky images at a 50 millisecond cadence (Kent et al. 2019; Thyagarajan et al. 2017; Beardsley et al. 2017). The LWA stations are also fully automated and remotely controlled.

We will take advantage of recent advances in digital processing that have dramatically reduced the cost to process large digital data streams. At the same time we can take advantage of the work at universities such as that at UNM, KU, Berkeley, and elsewhere, that have pioneered antenna designs and digital hardware development that makes the instrumentation required dramatically less expensive. **Over the past 7 years we have developed an extensive tool set for the analysis of long wavelength observations – the LWA Software Library** (LSL; Dowell et al. 2012). This software library includes routines to perform correlation, imaging, beamforming, calibration, de-dispersion, etc.. Most routines are written in Python and new scripts can be readily developed. Many tutorials already exist to help new users get started, and these have also been adopted for coursework ranging from signal procession to astrophysics.

4. COST ESTIMATES

We have gathered together a number of universities and colleges that are interested in hosting an LWA station or mini-station (see Table 1). These stations can be built by students and readily operated and maintained. Stations will be available for local experiments (e.g., meteors, cosmic rays, ionospheric measurements), and will swarm together into interferometric arrays to do collective scientific observations (transients, exoplanets, pulsars, etc.).

4.1. *Cost Model*

The materials cost for an LWA station is $600,000, not including the electronic shelter. We expect that most participating institutions will choose to deploy a mini-station for which the modest electronics required can be housed in an existing structure or even a do-it-yourself metal tool-shed. A rough estimate of the station cost can be obtained by taking the bill of materials cost and scaling this by the number of antennas desired. For example, a half-size LWA station with 128 antenna stands and associated electronics would cost roughly $300,000 and a quarter-size station $150,000. Simulations of baseline sensitivity needed for calibration suggest a minimum station size of 48 dipoles, which implies a cost of $112,500. With the minor exception of some station time-keeping equipment that can be built by UNM, all of the parts are available off-the-shelf. The most expensive parts are the ROACH2 boards which each handle 16 dual-polarization dipoles ($10,000 each), the analog re-

Table 1. Participating Institutions

Institute	Contact	Dipoles
UNM	G. Taylor	**256 x 2**
Caltech	G. Hallinan	**352**
Quest Univ.	I. M Hoffman	48
KU	D. Besson	48
ERAU	A. Gretarsson	48
TTU	T. Maccarone	48 × 2
ASU	J. Bowman	256
UTRGV	F. Jenet	48
UF	A. Gonzalez	48
UC Boulder	J. Burns	256
SUNY OW	M. Kavic	48
Hillsdale	T. Dolch	48

Note: The UNM and Caltech stations (indicated in bold) are already operational.

ceiver boards (ARX) that each handle 8 dual-polarization dipoles ($1,500 each), and the server/GPU nodes that can handle roughly 48 dipoles each ($7,000 each). The above estimates also assume quantity purchases which could be readily accomplished by consolidating purchases from multiple institutions.

Maintenance costs are dominated by power and data storage requirements. The cost for power to run a full LWA station is $1,500/month and again scales roughly linearly with the number of dipoles. Data storage costs will scale as the square of the number of dipoles for all-sky measurements, and independently of the number of dipoles for beam measurements. A decent rule-of-thumb for data storage is to use the same dollar amount as for power. Thus for a mini-station with 48 dipoles the expected annual power, disk and maintenance budget could be estimated at $7,000.

4.2. *Swarm Configuration*

As part of this project we will design and build an LWA mini-station at the LWA site at the end of the North Arm of the VLA. We will carefully cost and document this mini-station with the goal of providing this option to other Universities and colleges that are willing to host a station. The station will consist of 48 LWA dipoles (already on hand), six analog receiver boards, three ROACH2 boards for data capture, a computer for data acquisition and imaging, and various other array hardware. This array will be capable of imaging the sky (see Fig. 2), searching for cosmic rays and fireballs and the science objectives mentioned in section 2. We have done extensive simulations of various array layouts and found that 48 dipoles is the minimum useful number both for producing reasonable images of the sky (though with some loss in resolution) and adequate baseline sensitivity. The mini-station dipole configuration consists of a core having the same layout as the full 256 station plus a Gaussian tapered distribution of dipoles (Method #4; see Fig. 2[1]). Three other methods for distributing the antennas such as (1) a uniform spatial distribution over the entire 110 m by 100 m footprint of a full LWA station, (2) a distribution that preserves the (u, v) density of a full LWA station but limits the maximum baseline length, and (3) a hybrid of methods (1) and (2) were tried but found to produce inferior results. We note that with this central-core plus Gaussian configuration it should be relatively straight-forward to expand mini-stations to full stations if funding is available. Personnel from UNM and other interested Universities would travel to the sites to assist with the installation and commissioning.

Low frequency radio astronomy is very accessible in that the hardware costs required to build a single broad-band dipole antenna are now under $500. We note that many of the targeted users (undergraduate and graduate students) have access to machine shops where, guided by drawings, students can build their own antennas, as desired. The LWA antenna design has been of great interest to the Society of Ameteur Radio Astronomers (SARA). Members Reeve, Nelson, Heiterswil, Berlanga, and Fobes have all deployed LWA-style antennas (see Fig. 3). Other LWA antennas have been deployed by Stan Kurtz in Morelia, Mexico, and at Nancay, France. We will investigate cost-saving measures, and anticipate that the commodity hardware used will continue to fall in price and increase in capability.

These hands-on projects will directly encourage an understanding of engineering and design with college students. This is important given the increased weight given to STEM fields. This project would provide another avenue for creating and measuring the impact of engineering projects on science learning.

In addition to "stand-alone" operation of the mini-stations, we will implement a swarm mode which will incorporate the station into the larger Long Wavelength Array for maximal scientific capability. We will take advantage of the swarm concept for operation recently described by Dowell & Taylor (2018). These experiments, most likely planned at night when the RFI environment and the ionosphere are more benign and the stations are not being used for other purposes, will use the beam-forming mode to focus the station on one or more places in the sky. By recording data from all LWA stations distributed across the US for targets of special interest (e.g., an exo-planet candidate) this telescope will achieve an angular resolution of $\sim$0.5 arcsecond and $\sim$5 mJy-level sensitivity in a 4 hour observation. Using an extension of the EPIC approach it may also be possible to achieve high time resolution. The capabilities of the combined instrument will be superior to any other instrument currently operating in this frequency range.

By offering the "swarm-mode", Universities and Colleges will be part of a larger scientific effort and thereby also offer more powerful observations to their students. Data can automatically be uploaded into a central repository

[1] The antenna locations for the 48, 64, 96, and 128 element mini-stations can be found at http://www.phys.unm.edu/~lwa/memos/memo/mini-station-configs.tar.gz

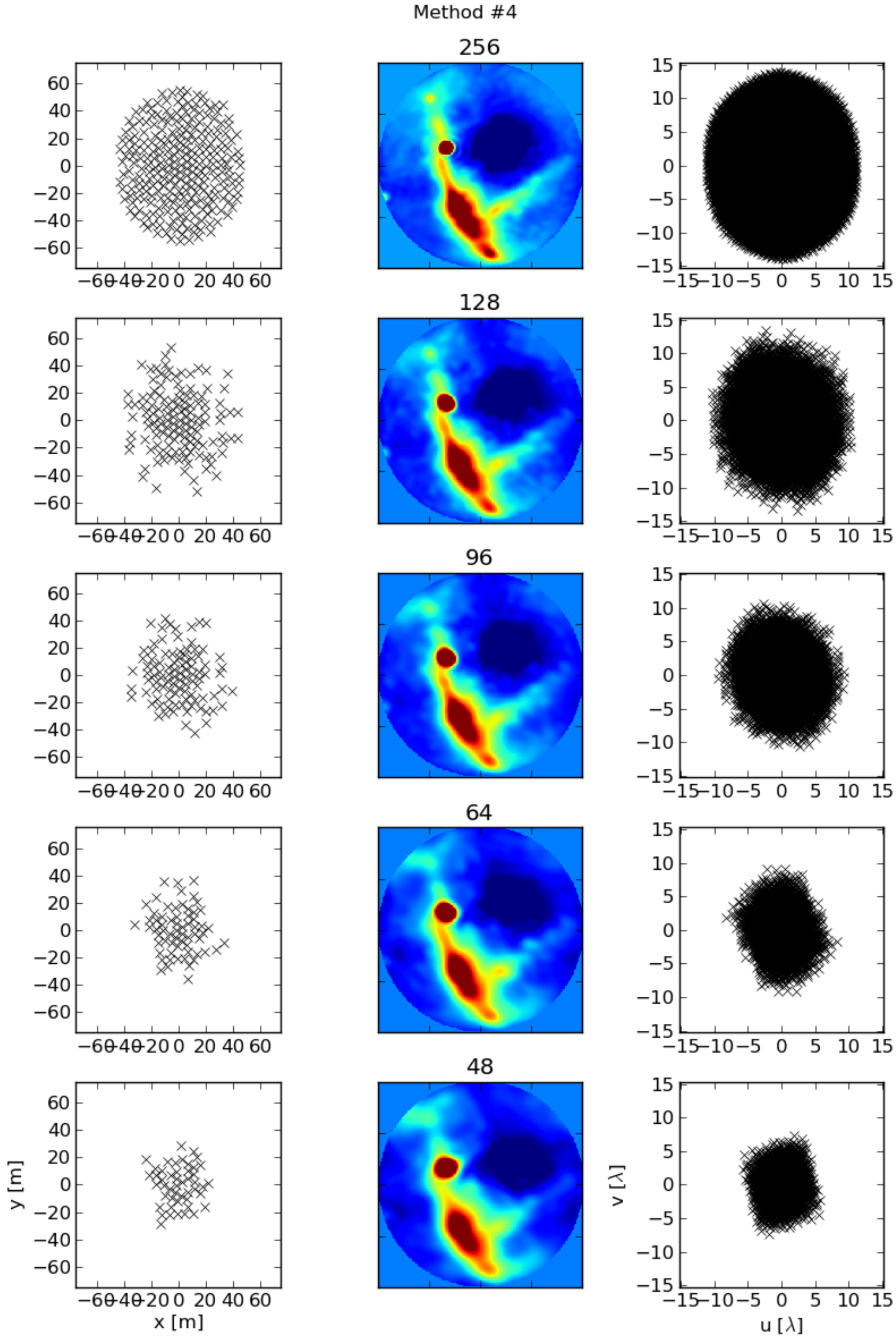

Figure 2. Example configurations and sky images for LWA mini-stations. Each row corresponds to dipole count and ranges from 256 at the top to 48 at the bottom. For each configuration, the left column shows the physical station layout while the right column shows the (u, v) coverage at 38 MHz. The center column shows the imaging fidelity and resolution at 38 MHz.

to allow each user to correlate their data with data obtained at another site. At the

Figure 3. LWA antennas around the world. (Top left) Stan Nelson's installation in Roswell, NM; (Top right) Ramon Fobes installation at Embry-Riddle University in Prescott, Arizona; (Bottom right) Christian Monstein installing LWA antenna at Sondrestrom Upper Atmospheric Research Facility in Kangerlussuaq, Greenland (credit: Christian Monstein); (Bottom Left): LWA antenna under construction at mountain site in Spain (credit: Courtesy of Space Research Group/University of Alcala).

same time, there will be forums for reporting on discoveries made of local fireballs and high energy cosmic rays detected by the individual stations. There will also be regular scientific meetings at the host institutions to share discoveries and discuss solutions to problems like radio frequency interference.

5. IMPACT

We anticipate many scientific discoveries could be made, increasing as the LWA is enhanced by the efforts of active collaborators. At the same time, We will increase the publics knowledge about the Universe at wavelengths other than optical, by connecting low-frequency radio phenomena to the familiar astronomical interests of Jupiter and meteors. Through this effort we will also learn about the spectral occupation (interference environment) in many locations. This is a key question for NSF Spectrum management. One of us (Taylor) was a member of the Committee on Radio Frequencies (CORF) for 6 years.

As the major part of this work we would engage a wide and interdisciplinary community. The strong engagement of students in all aspects of the project from construction through scientific investigations should have a very positive impact on encouraging students to pursue STEM careers. As currently planned this project would involve at least 3 minority serving institutions (UNM, TTU, and UTRGV).

The LWA project provides a live video feed of the sky at low frequencies as seen by LWA1 and LWA-SV. This live view, called LWA-TV (available from http://lwa.unm.edu), has grown in popularity from a few hundred viewers in its first years to almost 2,500 unique IP addresses during 2019. It has also been used in classrooms to show students the contrast between how we see the sky at low frequencies, compared to the naked eye. The LWA-TV viewers are spread around the world. We also have dedicated displays in the lobby of the Physics and Astronomy department at UNM, at ERAU, and at the NRAO Visitor Center (25,000 visitors per year) as well as the Sevilleta National Wildlife refuge visitor center (10,000 visitors per year). We plan to install another dedicated display at the Albuquerque Museum of Natural History, and at all the participating Colleges and Universities that do not already have one.

6. SCOPE AND EXPANSION

During the first stage of this project we would design and cost out the LWA mini-stations (48+ dipoles) and deploy several demonstration units that will allow us to characterize performance in a number of settings. The stations will be sufficiently portable that we can re-deploy if the interference environment is unworkable. Some attention must also be paid to the configuration deployed in order to obtain reasonable imaging characteristics for the combined array. Since the sky at low frequencies is rather complicated (Dowell et al. 2017; Eastwood et al. 2018), a minimum of 10 stations will be needed. Figure 4 shows a sample of the (u, v) coverage obtained on a source observed for 12 hours with the 3 existing LWA stations and 10 new stations distributed across the US (see Table 1). The total cost of this first stage of the LWA Swarm is estimated at $5M. This includes 2 more full stations at a cost of $1M each, 8 mini-stations costing a total of $1M, $1M for central infrastructure including the correlator, and $1M for labor.

If the impact is as great as we imagine we will partner with a number of colleges and universities to triple the number of stations in a subsequent expansion stage at a cost of $15M which could be funded by the Mid-Scale Innovations Program (MSIP). Science can already be carried out with the existing LWA stations, and will continue to grow along with the capabilities of the array. We will seek new partners through our growing LWA User community.

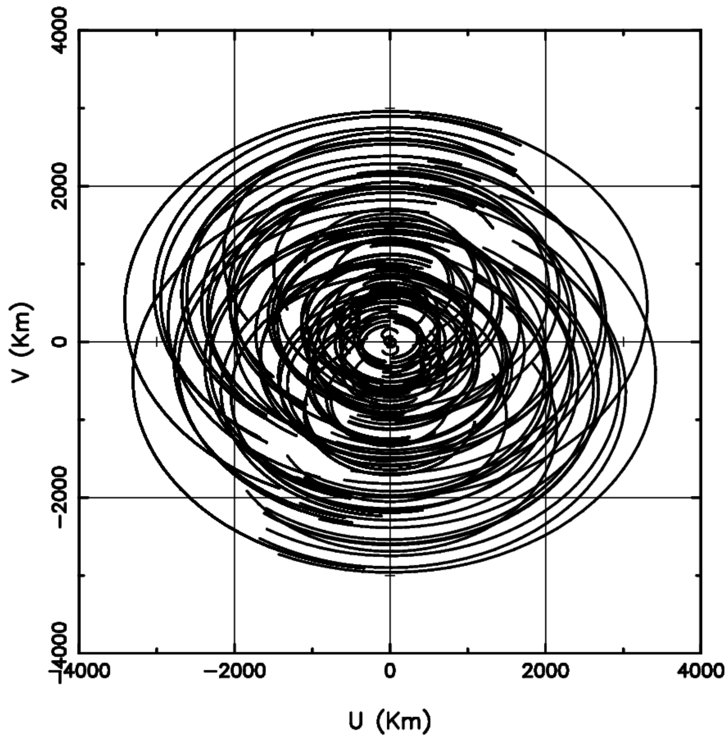

Figure 4. Simulated (u, v) coverage for the LWA observing a source at declination 47 degrees using the 3 existing LWA stations in NM and CA and adding an additional 10 stations distributed around the US (see Table 1). This configuration will achieve an angular resolution of 0.5 arcseconds at 74 MHz with a sensitivity of 5 mJy/beam in 4 hours of observing.

This project builds upon investments in the LWA ($12M), including hardware designs, software development, and expertise gathered over the past decade. Considerable support for LWA has come from the Department of Defense, whose interests include LWA-based ionospheric and space weather measurements. A current limitation of existing LWA assets is limited geographic distribution. The Swarm would directly mitigate that weakness and encourage further DoD investment over the longer term.

The radio astronomy community, unlike the optical astronomy community, has been highly centralized in the United States over the past generation, with the National Radio Astronomy Observatory having ownership of all the large-scale projects. The centralized approach has led to great efficiency in designing, constructing, and operating these facilities, but has not led to the same level of development of expertise in hardware among junior scientists. Projects like LWA-Swarm, which can greatly expand the base for talent development, while also doing unique science and costing a relatively small fraction of the radio astronomy budget, are thus of great value in their own right and are essential for maintaining a strong pipeline of talented experts in radio hardware both for the astronomical community and for commercial and defense work.

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