The Long Wavelength Array (LWA): A Large HF/VHF Array for Solar Physics, Ionospheric Science, and Solar Radar

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ABSTRACT

The Long Wavelength Array (LWA), currently under construction in New Mexico, will be an imaging HF/VHF interferometer providing a new approach for studying the Sun-Earth environment from the surface of the sun to the Earth's ionosphere. The LWA will be a powerful tool for solar physics and space weather investigations, through its ability to characterize a diverse range of low-frequency, solar-related emissions, thereby increasing our understanding of particle acceleration and shocks in the solar atmosphere along with their impact on the Sun-Earth environment. As a passive receiver the LWA will directly detect Coronal Mass Ejections (CMEs) in emission, and indirectly through the scattering of cosmic background sources as they propagate towards Earth. If coupled with a suitable transmitter, the LWA would be an excellent receiver for solar radar, potentially demonstrating accurate geomagnetic storm prediction from the Earth's surface. Both radar and passive receiving techniques could monitor the Sun-Earth environment during daytime as a compliment to nighttime space weather remote sensing techniques.

The LWA will also naturally provide a measure of small-scale spatial and temporal ionospheric structure, a pre-requisite for accurate calibration and imaging of solar and space weather phenomena. As a sensitive monitor of differences in total electron content (TEC) through the ionosphere, the LWA will provide an unprecedented characterization of ionospheric turbulence and waves, capable of testing predictions of global ionospheric models with an aim towards improving their accuracy through input to physics-based models. As a fully digital, multi-beaming instrument, the LWA can monitor the Sun daily with a dedicated solar beam, while simultaneously pursuing ionospheric and astrophysics science programs both day and night.

In this paper we present an overview of the LWA, currently under construction in New Mexico, and discuss the scientific goals of the project in the areas of solar, ionospheric, and solar radar applications.

1. INTRODUCTION

An emerging suite of large, dipole-based interferometers including the Long Wavelength Array (LWA) in the southwestern US, the Low Frequency Array (LOFAR) in Europe, and the Murchison Widefield Array (MWA) in Australia, are bringing powerful new imaging capabilities to the HF/VHF spectrum for a variety of solar, space science, and astrophysics applications. Our focus here is the LWA, optimized for exploring the lowest frequency regime (~10-88 MHz) between the ionospheric cutoff at low frequencies and the FM bands at high frequencies. The LWA follows the heritage of the 74 MHz system developed by the Naval Research Laboratory and the National Radio Astronomy (NRAO) for the Very Large Array (VLA) radio-telescope [1]. That system was the first connected element, imaging interferometer to demonstrate sub-arcminute resolution imaging below 100 MHz. This breakthrough was achieved based on innovations in *HF/VHF adaptive optics* required to accurately measure and model small scale (temporal and spatial) ionospheric-induced phase variations that become severe on antenna separations (or *interferometer baselines*) > 5 km. The LWA is designed to extend the maximum baselines available with the original 74 MHz VLA system (~35 km) by approximately one order of magnitude, and the available sensitivity by more than two orders of magnitude.

In the next section we provide a brief technical overview of the LWA and its current construction status. In Sections 3 and 4 we discuss solar and heliospheric imaging applications of the LWA, respectively. In Section 5 we review LWA ionospheric remote sensing applications afforded naturally through its requirement to calibrate against thousands of natural cosmic background sources. In Section 6 we discuss application of the LWA as a radar imaging receiver for detecting Earthward-bound Coronal Mass Ejections (CMEs) for geomagnetic storm prediction, and in Section 7 we present our concluding remarks.

2. LWA TECHNICAL OVERVIEW

LWA technical specifications are outlined in Table 1. The basic building blocks are broad-band, active antennas, 256 of which are grouped into ~100-m diameter "*stations*", each analogous to a single element in a dish-based aperture synthesis array. Within each station, the full 10-88 MHz bandwidth from each dipole antenna is direct-sampled (196 MHz A/D) allowing formation of 4 rapidly reconfigurable beams that can be steered independently both in frequency and on the sky. One of these beams will be dedicated to ionospheric calibration, naturally providing near real-time, full-sky ionospheric monitoring, while a dedicated solar beam will monitor the sun throughout each day. Each LWA station beam will be brought to a central location for cross-correlation, possibly with a software correlator. Although its 53 stations are fixed, the LWA will provide the full baseline set, measured in wavelengths, currently available by combining all configurations of the VLA. A fuller technical description of the LWA is provided in [2].

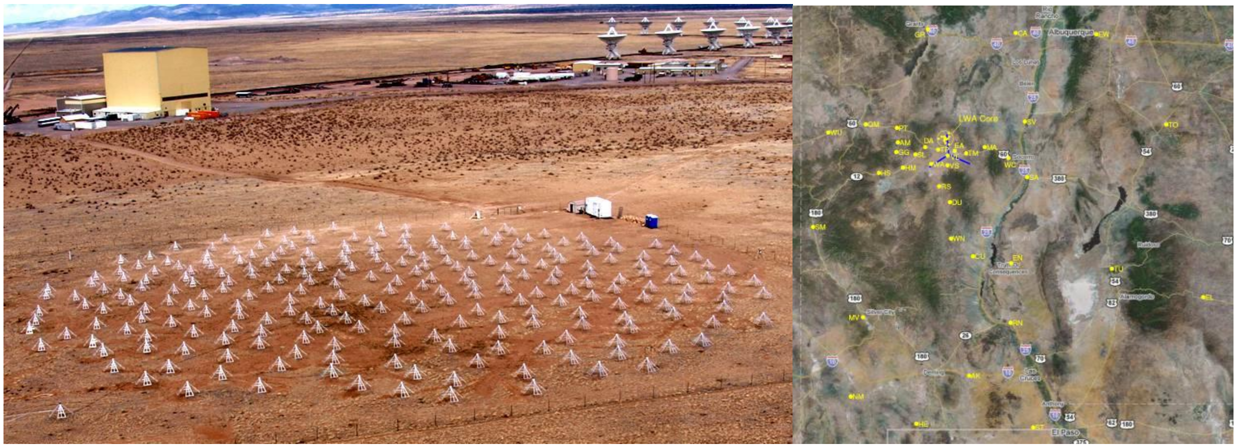

Fig. 1. Left - Aerial view of LWA-1 located near the center of the VLA site; parabolic VLA antennas appear in the background; right – yellow dots depict planned LWA station locations across New Mexico state; the VLA location appears as a blue "Y".

Table 1: LWA Technical Specifications

Frequency Range	10-88 MHz (20-80 MHz optimized)
Effective Collecting Area	10-30 MHz: ~10^5 m^2; 30-88 MHz: ~10^5 $(30\ MHz/\nu)^2$ m^2
Dipole Elements Total / Dipoles Per Station	~10^4 / ~256
Number of Stations / Station Diameter	~53 / ~100 m
Station Interferometer Baseline Range	0.1-400 km
Point Source Sensitivity (dual polariz., 1 hr, 4 MHz BW)	1.0 mJy @20 MHz, 0.5 mJy @80 MHz
Angular Resolution	15" @ 10 MHz; 5" @ 30 MHz; 2" @ 80 MHz
Field of View	~2º @ 80 MHz (proportional to ν)
Number of Independent FOV (beams)	4
Maximum Observable Bandwidth	~20 MHz/beam
Spectral Resolution	≤ 1 KHz
Image Dynamic Range	≥ 10^4
Digitized Bandwidth	Full RF

Construction of the 1st LWA station (or "*LWA-1*") is nearing completion with the remaining 52 stations planned for eventual deployment across New Mexico (Fig. 1). The antennas, front-end electronics, and cabling infrastructure for LWA-1 are fully in place, and initial commissioning with an interim receiver is underway. Installation of the dedicated LWA digital receivers is expected to commence in early 2011.

3. SOLAR PHYSICS WITH LWA

The LWA frequency range, optimized for 20-80 MHz, is the domain of the classic solar radio burst types: Type II bursts, generated by shocks in the corona, with their characteristic fundamental-harmonic split-band structure; Type III bursts, drifting rapidly in frequency as the electron beams that generate them propagate into the solar wind; and Type IV bursts, from trapped electrons producing broadband emission in long-duration flares. Examples of Type II and IV emission are shown in Fig. 2; on a plot like this a Type III burst appears as a brief nearly vertical feature. With its sensitivity, flexible frequency coverage and multibeam capability, the LWA will be a powerful tool for the study of these bursts. Each of them is believed to emit by the mechanism of plasma radiation, i.e., the conversion of electrostatic Langmuir waves into electromagnetic waves at the fundamental and second harmonic of the electron plasma frequency 9000 $n_e^{0.5}$ Hz, where n_e is the electron density (cm^{-3}). The frequency of plasma emission thus reveals the density in the source. Some examples of possible solar science topics are described below.

An important advance provided by the LWA is the ability to image at many frequencies across a significant bandwidth simultaneously. Previous imaging of, e.g., Type II bursts has been at fixed frequencies, and one then only has access to the phenomena that happen to be drifting through the observing frequency at any given instant. This is a disadvantage for Type II bursts because, as Fig. 2 shows, they typically consist of fundamental and harmonic bands, each of which is split. It is believed that the splitting may be due to emission coming from the upstream and downstream regions of a shock, with the differing densities in the two locations leading to different plasma emission frequencies. Previously it has never been possible to make an image of the two split bands simultaneously: the LWA, with its large instantaneous bandwidth and the ability to image anywhere in that bandwidth, will make that possible and thus provide a test of models that use the splitting to infer the shock Mach number.

Similarly, Fig. 2 shows that Type IV bursts exhibit strongly modulated emission. It is suggested that such emission comes from plasma emission that is broadband due to the range of densities experienced by electrons trapped in post-flare loops as they propagate along the length of the loops. The modulations then represent simultaneous injections of additional nonthermal electrons onto the loops. An alternative explanation is that the Type IV emission is composed of individual electron beams that drift rapidly over a finite height range. LWA-1, with its combination of exceptional sensitivity and time resolution, will be capable of looking for extreme drift rates in Type IV

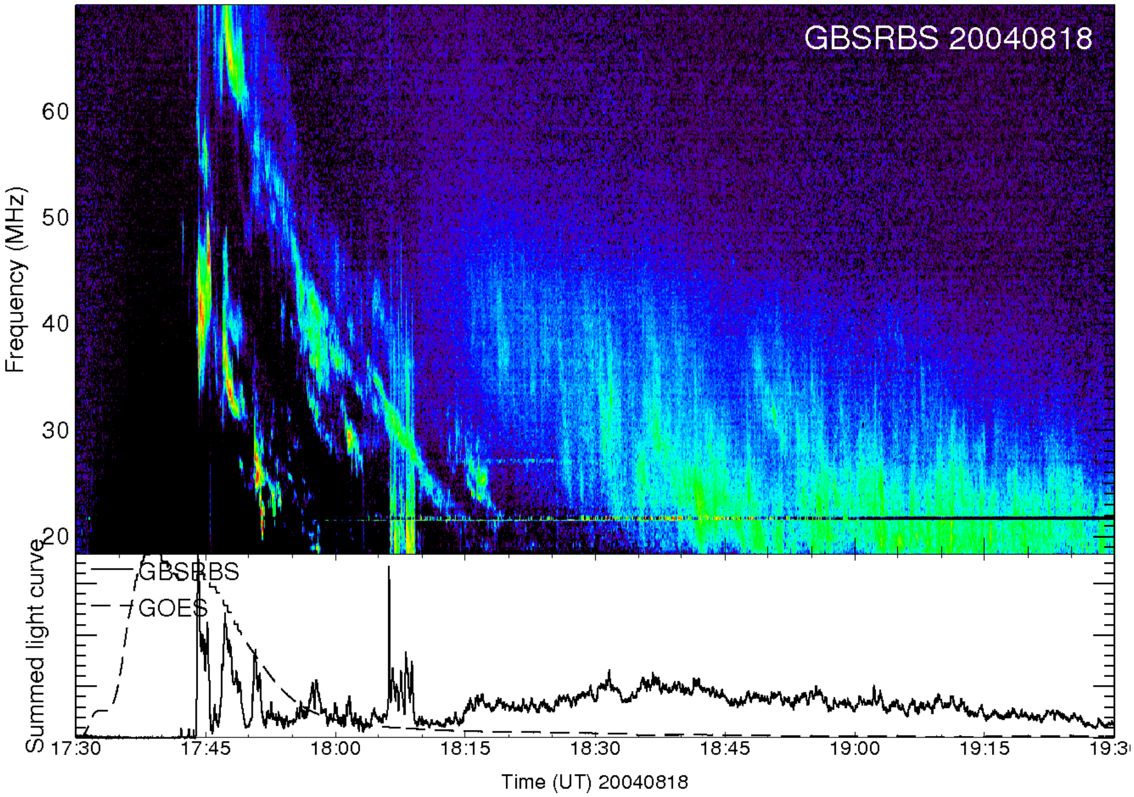

Fig. 2. Radio emission from a solar flare in the LWA frequency range, observed with the Green Bank Solar Radio Burst Spectrometer. The upper panel shows a dynamic spectrum (frequency vs. time plot) with harmonic bands of a Type II burst dominating from 17:45-18:00 UT, and the broadband continuum of a Type IV burst drifting gradually lower in frequency from 18:20-19:30 UT.

substructure across 8 or 16 MHz of bandwidth, while the full LWA system will be able to measure changes in source position with frequency and trace out the locus of the burst source.

In events in which the bright plasma emission sources are absent in some regions of the LWA's frequency coverage, it should be possible to detect CMEs directly via the synchrotron emission from electrons accelerated in the CME-driven shock above the solar corona. This has been demonstrated with Nancay Radioheliograph observations at 164 MHz by [3]. The emission by these electrons is generally weak relative to the bright coherent plasma emission of the classic large burst types, and does not show up on a dynamic spectrum such as Fig. 2, but imaging reveals a quasicircular arc of emission co-located with the CME front. The spectrum of this emission close to the Sun [3] appears to be consistent with a nonthermal spectrum suppressed at low frequencies by the Razin effect. The LWA will be able to trace such emission to much greater heights above the Sun thanks to its lower frequency range; Razin suppression will be less effective at greater heights due to the lower densities in the atmosphere there, and the emission should be very bright and easily observed in the LWA frequency range provided that it is not swamped by plasma emission sources. These observations have the potential to address a large number of important questions in shock physics, including:

- What is the relative effectiveness of quasi-perpendicular and quasi-parallel shock acceleration?
- What is the magnetic field geometry of the expanding CME structure?
- How does the rate of electron acceleration vary with height and what is their energy distribution?
- What is the energy distribution of the accelerated electrons?

Related to this topic is the observation of "moving Type IV" bursts. These are huge, rare broadband disturbances in the LWA frequency range observed historically by the Culgoora Radioheliograph and (on a few occasions) by Clark Lake Radio Observatory; they cannot easily be distinguished from normal Type IV bursts from dynamic spectra alone, and there is debate as to whether their emission mechanism is plasma radiation or synchrotron. They are seen to move out to great heights above the solar surface at speeds similar to fast CMEs. However, their exact relationship to CMEs is poorly understood because there was only a brief overlap between modern space-borne coronagraph imaging of CMEs and the operation of Culgoora: in the one well-studied case, the moving Type IV burst appeared to be lagging behind the leading edge of the associated CME, lying closer to the densest material in the ejection (probably the erupting filament) [4]. The LWA will permit the observation of moving Type IV bursts again, and the study of their relationship to other erupting phenomena, for the first time in 25 years.

The LWA will also be capable of mapping the quiet solar atmosphere once sufficient stations in the core are available to provide good *u-v* coverage for a source of dimension 1° such as the Sun. Observing the variation in the structure of the solar atmosphere in the 1-3 R_{sun} height range will be an important adjunct to ongoing studies of the formation and acceleration of the solar wind, which is believed to occur in that height range. Currently a large emphasis is placed on MHD modeling and magnetic field extrapolation techniques to study these topics due to the difficulty of obtaining suitable measurements: The LWA's frequency flexibility will permit mapping of the solar atmosphere from 20 to 80 MHz and reveal changes in structure with height that will strongly constrain these studies.

4. LWA HELIOSPHERIC SCIENCE

The LWA will be able to employ the well-established technique of interplanetary scintillation (IPS) to track regions of increased density associated with CMEs as they propagate through the interplanetary medium. This technique is being used by several groups around the world (e.g., see http://ips.ucsd.edu/). The method is to observe the level of fluctuations ("scintillations") in the signal from a bright background radio source as it passes through the solar wind: the fluctuations are produced by scattering and diffraction of the signal in the density fluctuations of the solar wind. The level of density fluctuations is generally found to be well correlated with the absolute density; a turbulent feature such as a CME-driven shock may well increase the level of scattering further.

IPS radio systems (e.g., STELab in Japan and Ooty in India, both at 327 MHz) generally employ large telescopes operated as single frequency 'transit instruments', where a set of strong compact radio sources is observed daily as the source transits the local meridian at the observing site. The advantage that the LWA possesses is that it has no moving parts: "pointing" is achieved electronically by phasing the signals from each of the 256 elements so that, when combined, they form a beam pointing at the source of interest. With up to 4 beams and its large collecting area, the LWA can observe 4 sources simultaneously with a time resolution of order milliseconds, opening up the possibility for unique data analyses. Since the LWA can switch to a new set of sources essentially instantaneously, it will be able to monitor the level of fluctuations in the solar wind with much denser time-and-space sampling than can be achieved with current instruments, with a consequent improvement in the ability to track the movement of discrete features in the solar wind such as CMEs. Furthermore, the LWA's ability to make measurements over a significant frequency range simultaneously allows the use of frequency-correlation techniques that can yield velocity information even with a single station. Initial work on IPS measurements can be carried out with LWA-1 using the classical IPS and frequency-correlation methods; once more stations are available, it will be possible both to add measurements of solar wind and density-structure velocities using the multi-station technique employed currently by STELab, and to use a denser array of scintillation sources thanks to the smaller beam of the multi-station array.

The ability to measure polarization adds an extra dimension to both IPS and other observations. The polarization of the CME synchrotron emission observed by [3] will be of great interest for revealing the structure of the magnetic field in an expanding CME front. Further into the heliosphere, Faraday rotation measurements can be used to infer magnetic fields: such measurements require measuring changes in the full polarization state of background radio sources as a CME passes in front of them, and the variation of the polarization with frequency. These are difficult measurements and this is not a prime goal of the LWA, but this technique will be explored once the LWA has sufficient sensitivity and has measured the polarization characteristics of its stations

5. LWA IONOSPHERIC MEASUREMENTS

The distribution of electric charge in the Earth's ionosphere perturbs the refractive index for radio waves passing through it, and these refractive index fluctuations change the phase velocity of the rays and thus introduce delays between different paths. This effect makes a multi-element low frequency array extremely sensitive to small *differences* in total electron content (ΔTEC) through the ionosphere, as defined by the separation of interferometer pairs sampling it [1]. Typical ionospheric remote sensing techniques sample ΔTEC at the 0.1 TECU level (1 TECU = 10^{12} electrons*cm^{-2}) and on spatial scales of ≥ 100 km. The VLA can measure ΔTEC at the milli-TECU level and on spatial scales approaching 100 m. The VLA has been used for 330 MHz-based studies of travelling ionospheric disturbances (TIDs) [5], while more recent studies have extended measurements to lower frequencies [6].

The LWA will be a far more powerful ionospheric probe than the VLA, coupling the technical advantages of much greater collecting area, spatial sampling, and broadband low frequency spectral coverage with electronic multi-beaming and continuous monitoring. While on the one hand the ionosphere will be a significant problem for the LWA astrophysical observations, this "problem" offers a tremendous opportunity for ionospheric science studies and serves as a major justification for the instrument. The electron content of the ionosphere above the LWA, varying with position, height and time, introduces phase delays in the signal paths from the sky to the telescope. These delays show up to lowest order as a simple position shift of a source on the sky, and to second order as a smearing of the source, but over the long baselines planned eventually for the LWA this is an inadequate description of ionospheric effects: they will be different in different parts of the sky, and for the same source viewed from different stations. The LWA can therefore provide an unparalleled measure of small-scale ionospheric structure as a pre-requisite for accurate calibration and imaging of the Sun and other cosmic radio sources. As a real-time ionospheric monitor, the LWA will test predictions of global ionospheric models with an aim towards improving their accuracy through input to physics-based models.

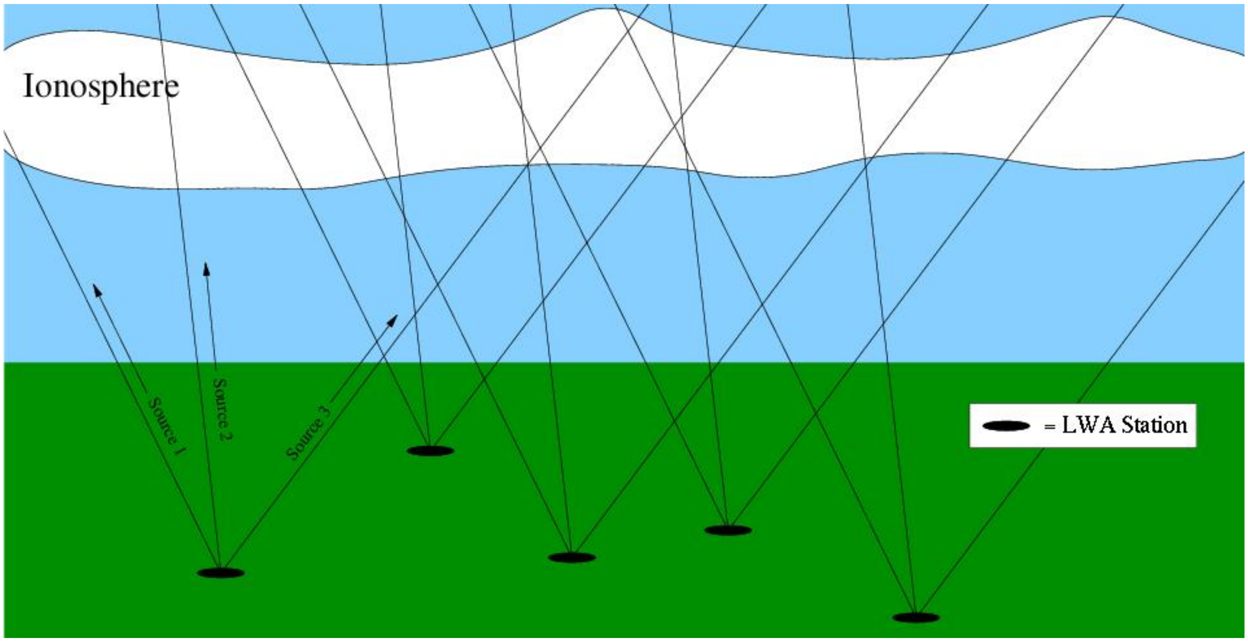

Fig. 3. A schematic illustration of LWA ionospheric tomography. With electronic steering, multiple beams and high sensitivity, the LWA can image 100 cosmic background sources within 5 seconds. This figure shows 5 stations and 3 sources corresponding to 15 lines of sight. 53 LWA stations will provide 5,300 pierce point samplings through the ionosphere.

From a single LWA station, the ionosphere can be studied by rapidly cycling through a set of strong compact sources that cover the sky down to some elevation and measuring the delay for each line of sight by established methods (Fig. 3). As for the IPS application, the fact that the LWA has multiple beams and no moving parts, so that repointing the beams can be achieved almost instantaneously, allows such studies to be carried out with unprecedented time sampling. Ionospheric perturbations such as "sudden ionospheric disturbances" can be detected as position-varying phase shifts depending on the electron content along each line of sight. Mapping these changes in electron content with time allows one to see the movement of features overhead.

With multiple LWA stations, measuring the electron content towards the same source in the sky from different stations introduces 3-dimensional information: the height distribution of the electron content can be studied from the differences of different lines of sight (Fig. 3). The baseline range of the full LWA, 400 km, is ideal for sampling the full height range of the ionosphere by this tomographic technique, potentially providing thousands of measurements through the ionosphere on timescales of seconds or less. The combination of measuring small and large spatial scales simultaneously, coupled with three-dimensional information and high time resolution, means that the LWA has the potential to improve greatly our understanding of the dynamics of the fine-scale structure of the ionosphere.

6. LWA SOLAR RADAR

As described earlier, the LWA is planned to be used for passive receiving studies of the low frequency solar radio spectrum. While we expect new discoveries to be made in solar radio emissions, the LWA also provides an important new capability as a receiving array for radar studies of the solar corona. The solar radar concept was first proposed as an approach to investigating the ionized structure of the solar corona [7,8]. Among the early experiments, echoes were reported both from Arecibo [9] and El Campo [10]. The El Campo campaign extended from 1961-1969, and its published reports are the main comprehensive description existing of solar radar echoes.

The El Campo solar radar operated at 38 MHz with a total power of 500 kW and used an array of antennas of about 18,000 m^2 in size, both to transmit and to receive. The fan-shaped beam of the El Campo radar was about 1° x 6° in the NS x EW direction, allowing only one transit experiment of the sun per day to be conducted. An experiment consisted of a coded waveform transmitted toward the sun for 16 minutes (the round-trip travel time of light) followed by 16 minutes of reception. The data recorded during the reception time interval were then correlated with the transmitted code to search for signals at time delays and frequency shifts expected for a solar echo at the reflection level of 38 MHz, expected at about 1.4 R_o (where R_o is the solar radius). From those cases in which an echo could be identified at some level of statistical probability, a radar cross section of the sun was calculated. The majority of radar cross sections had values about equal to or slightly larger than the solar geometric cross section. However, over the years of the El Campo experiments, there emerged a subset of cross sections that appeared at earlier time delays. It was suggested that these "high corona echoes" might be related to dense irregularities possibly associated with shock fronts in the corona [11].

Today we recognize that these high corona echoes were likely associated with large scale coronal disturbances such as Coronal Mass Ejections, a phenomenon that was unknown to solar physicists of the 1960s, but which today is recognized as a major driver of space weather at the earth. Thus, interest in the use of solar radars was revived in the 1990s [12] when it was recognized as a possible technique for early detection of earthward-moving CMEs.

Fig. 4 illustrates the concept of using a solar radar to detect an earthward-moving CME while it is still near the sun. The leading front of the CME is expected to cause a frequency shift in the radar echo proportional to the velocity of the CME, from which the travel time to the earth can be derived. However, today there is no extant solar radar comparable to El Campo, which was de-commissioned long ago (perhaps a memorial to being ahead of its time). Several high power transmitter facilities are in use today that approximate some characteristics of a solar radar. However, because these facilities were designed and built for a different purpose, they all lack some crucial aspect needed for a true solar radar. Among these existing facilities are Over-The-Horizon (OTH) radars, which have power levels and frequencies comparable to those of the El Campo radar, but have antenna beams that are hard-pointed at low elevation angles and azimuths and unable to illuminate the sun except on a few days of the year. Another class is the high power ionospheric heating transmitters, which have powers in some cases exceeding the power of the El Campo radar, but operate only at the low frequencies designed to maximize interaction with the earth's ionosphere. Only at special times when the ionospheric cutoff frequency is low enough are these transmitters able to illuminate the sun. Other high power ionospheric radars have fixed pointing directions or operate at frequencies too high for solar radar. Although these facilities were not designed to be solar radars, several experiments have been done with them anyway, in configurations that are as close as possible to the El Campo radar. Among these experiments, frequencies of 9 MHz, 25 MHz, 40 MHz, and 50 MHz have been used. However, the results have been somewhat disappointing, having null or marginal results, i.e., no evidence of a well-defined echo. The most recent solar radar experiments have been unable to clearly detect solar echoes [13]. Thus it remains an important task to understand the limitations that may have been significant in these various attempts to reproduce

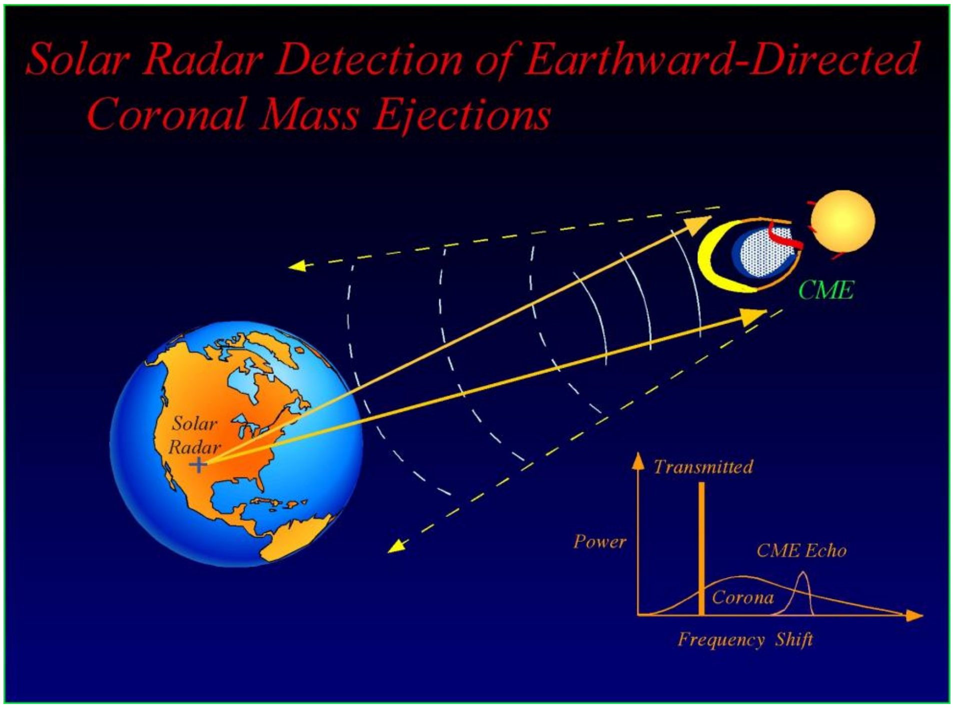

Fig.4. The concept of using solar radar to measure CME velocity and travel time to Earth.

the El Campo solar radar experiments. It is possible that solar radar experiments, already intrinsically difficult, are not adequately addressed with existing facilities and that a true solar radar is required.

While a solar radar demands high power transmission (radiated power up to 3 MW is desirable) due to the great distance to the sun and to the natural radio noise environment of the sun, it is just as important that the receiving array be well-matched to the angular size of the target and be able to resolve spatial and temporal variations in the echo and background emissions.

The LWA will receive frequencies in the range of 20 to 80 MHz and can provide several beams to receive several frequencies simultaneously, providing a significant improvement to the receiving component of a solar radar; all previous solar radars involved only one frequency. The LWA is being designed with solar studies in mind and will use modern techniques of digital signal processing of the data. The array will have electronic phasing of antennas in the various sub-arrays (or stations) situated over a large area. The spatial extent and phasing of the LWA bring about two important characteristics needed for a solar radar: beam sizes comparable to and smaller than the angular size of the solar disk (~ 30 arc-min) and the agility to form and track one or more beams to follow the sun across the sky. Neither of these capabilities existed in previous solar radars, including those of El Campo. All previous solar radar experiments have been done in transit mode in which the sun drifted across a stationary beam. The small beam size of the LWA will allow it to receive its signals from a solid angle that includes only the sun or to utilize smaller beam widths to map structure in the echo signal across the solar disk. The tracking capability expands the solar radar experiment to several hours, allowing more experiment cycles on a given day. The basic cycle is about one-half hour, composed of 16 minutes of transmission followed by 16 minutes of reception. As mentioned above, El Campo conducted only one experiment cycle per day. The experiment cycle time corresponds to an angular displacement of the sun by about 8°, requiring a stationary beam width to be broad enough to maintain sufficient antenna gain on the sun. The beam of the LWA phased array can be electronically steered to track the sun for several hours per day, thus making possible several experiment cycles per day. In addition, the LWA beam maximum response can be kept centered on the sun throughout the time of tracking. The additional cycles possible with the LWA can be used to help discriminate against solar radio noise that may resemble a radar echo.

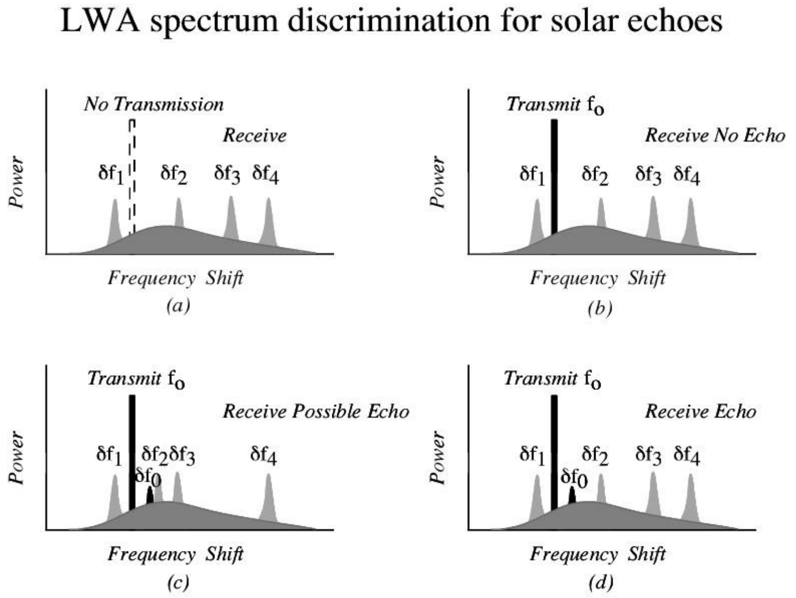

Fig. 5. LWA experiment cycles to discriminate a solar echo from radio bursts that may resemble an echo.

Fig. 5 illustrates a concept of how solar radar experiments might be carried out with the LWA. For this purpose, we are assuming that the appropriate high power transmitter facility is available near (but not too near) the LWA; in this discussion we take 28 MHz as the transmitted frequency (e.g., the OTH transmitters operate in the band 5 - 28 MHz). The four panels (a)-(d) may be thought of as slices of a three-dimensional plot of power, frequency shift, and delay time, where the delay time is the axis perpendicular to the plane of the page. The frequency shift is with respect to the transmitted frequency. In panel (a) we show a schematic of the power and frequency shift of the solar radio spectrum received by the LWA at a time when no transmission at 28 MHz occurs; i.e., the normal radio emission of the sun is observed, which may consist of a broad thermal noise component with several spectral peaks of sporadic emissions at given frequencies. For illustration, we take the peaks at δf_1, δf_2, δf_3, and δf_4 to be at the frequency shifts corresponding to 25 MHz, 38 MHz, 40 MHz, and 50 MHz. These latter frequencies have been used in solar radar experiments; 38 MHz is the El Campo frequency, and the other frequencies have been used more recently (with marginal results). The peaks shown in (a) are to illustrate a situation in which the spectrum has natural solar radio emissions that may resemble a radar echo; of course, because no transmission has occurred, we are certain that none of the peaks could be a radar echo. In panel (b) we show the case in which an actual transmission has occurred from earth at frequency f_0, which we assume to be 28 MHz. However, recall that during the reception cycle of the experiment, the transmitter is turned off, so that the high power of the transmitted frequency does not enter (and possibly saturate) the received spectrum; we show its location in the spectrum for reference only. If a new signal at some shift from 28 MHz appears in the received spectrum, we might be able to conclude that a solar echo was detected. If the frequency shift of the echo were sufficient to move it under one of the existing peaks, we may not be able to detect it and may have to conclude that there was no echo. In panel (c) we show a case in which several of the existing natural noise peaks have moved in frequency and we also see a new signal at a frequency δf_0; depending on the clarity of the measurement, we may be able to conclude that a solar echo has been detected. In panel (d) we show a case in which a new peak at δf_0 has appeared well-separated from the other peaks that we had previously identified as natural solar emissions. In this case we could conclude that a solar echo had likely been detected.

Panels (a) through (d) correspond to successive solar radar experiment cycles conducted on one day, with the LWA tracking the sun across the sky for about 2 hours (each experiment cycle is about one-half hour long). As many as 6 hours in one day may be available for solar radar experiments. At the location of the LWA, between 0900 and 1500 local time, the sun's midsummer elevation ranges from 45° to 80° to 45° and the midwinter elevation ranges from 20° to 32° to 20°. The number of experiment cycles would depend on the lower limit of the LWA beam elevations. Variations on the operations shown in the panels could be done, such as changing the values of δf_1, δf_2, δf_3, and δf_4 at which the LWA beams are receiving. Also, in successive experiment cycles, the transmitted frequency f_0 could be changed. For example, steps of ± 4 MHz between experiment cycles would give f_0 = 28 MHz, 24 MHz, 28 MHz, 24 MHz. Small changes in the delay time of an echo are expected as f_0 changes. If the received spectrum corresponds to successive cases of panel (d) with correlated changes in the time delays of δf_0, we then have evidence of an echo detection. Being able to conduct multiple solar radar experiments in succession on a given day becomes an important advantage of the tracking and multiple beaming of the LWA.

7. SUMMARY

The LWA is a large HF/VHF array currently under construction in New Mexico. It joins an emerging suite of powerful, multi-beaming dipole-based arrays that will provide modern probes of a region of the electromagnetic spectrum that has been relatively poorly explored at the levels of angular resolution and sensitivity typically probed by interferometers operating at higher frequencies. The LWA is unique in concentrating on the lowest observable frequencies accessible from the Earth's surface, coupled with its emphasis on solar, space weather, and ionospheric applications in addition to traditional astrophysics. See [14] for a review of all LWA science applications.

In this paper, we have described how LWA observations of solar and heliospheric phenomena could greatly improve our understanding of solar flares and related physical processes influencing the dynamic Sun-Earth environment. We have described how the LWA, by virtue of its ability to calibrate ionospheric phase effects against naturally occurring cosmic background radio sources, will provide an unparalleled and near real-time characterization of fine spatial and temporal scale ionospheric phenomena. We have also reviewed the potential for the LWA to serve as a receiver for solar radar capable of detecting Earthward-directed CMEs for accurate geomagnetic storm prediction. A clear demonstration of this technique could open a new field of space weather investigations. In summary, the LWA will serve as a powerful new tool to address key questions across, solar, ionospheric, and space weather science.

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