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A BROADBAND ALL SKY IMAGER FOR RIOMETRY, METEOR RADIO AFTERGLOWS AND TRANSIENTS

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A Broadband All Sky Imager for Riometry, Meteor Radio Afterglows and Transients

14. ABSTRACT
UNM owns and operates the Long Wavelength Array (LWA) stations for scientific research. Through this project we enabled a wide-band all-sky imaging capability at the LWA-SV station through the purchase of additional hardware and modifications to the networking on site. We also developed the software tools needed to calibrate the wide-band images. The images are automatically ingested into the LWA Data Archive and a sub-band image is displayed in real time. We used observations collected over many months to investigate the spectra of meteor radio afterglows. We anticipate that in the future these capabilities will be of use for image-based riometry as well as studies of sporadic-E.

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1. INTRODUCTION

Billions of meteoroid particles enter Earth's atmosphere everyday with velocities from 11-72 km/s, ablating and producing long columns of ionized plasma at altitudes between 60-130 km. The plasma trails of bright and large meteors can produce strong radio emission known as meteor radio afterglows (MRAs) at HF (3-30 MHz) and VHF (30-300 MHz) bands (Obenberger et al., 2014). The MRAs were initially detected with the LASI (LWA All-Sky Imager) correlator of the first station of the Long Wavelength Array (LWA1; Obenberger et al., 2015a). The detected radio emission was non-thermal, unpolarized and has characteristic light curve patterns with a fast rise of 10-20 seconds and a slow decay which can last up to couple of minutes (Obenberger et al., 2014). Also, the emission was smooth and broadband between 20-60 MHz and it has not been observed below a cutoff elevation of 90 km (Obenberger et al., 2015b, 2016a, 2016b). A recent study using LWA1 and the second LWA station located on the Sevilleta National Wildlife Refuge (LWA-SV) has revealed that the emission is isotropic (Varghese, Obenberger, Taylor, & Dowell, 2019).

The electrons in the lowest layer of the ionosphere, namely the D region, reside in a highly collisional environment. These collisions act as a damping force for any radio waves passing through this region. Relative Ionospheric Opacity meters (Riometers) are specially designed instruments which use the background radio sky to measure relative changes of D layer absorption of radio waves Little & Leinbach (1959). The amount of absorption is related to both the density of electrons in the D region as well as the observed frequency, where absorption is stronger at lower radio frequencies. Changes in the D region ionization are typically induced by particle precipitation and solar X-rays, where large solar events can create radio blackouts on the day-side of Earth, severely disrupting systems relying on HF radio wave propagation.

Generally speaking, riometers use a handful of antennas operating in the 30 to 40 MHz frequency range. Riometers are almost always built in high-latitude regions as they are an effective way to observe aurorae Hargreaves (1995). Mid-latitude absorption, while an important factor in radio communication, is poorly studied as it requires a great deal more sensitivity than the polar regions. With unparalleled all-sky imaging sensitivity, a wide-band all-sky imager on LWA-SV would provide an opportunity to characterize the absorbing environment and drivers at mid latitudes.

There is great interest in cosmic radio transient sources, especially at low frequencies where relatively little exploration has taken place. Expected sources of transient emission include flare stars and exo-planets with strong magnetic fields. Jupiter is well known to emit powerful bursts of coherent emission that can out-shine 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. 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.

2. BACKGROUND

The first station of the Long Wavelength Array (LWA1) is itself a fully capable HF array, located at the Very Large Array site, about 140 km from Kirtland AFB. The first station was completed in April 2011 and has been undertaking a wide variety of scientific investigations since November 2011. The instrument consists of 260 dual-polarization dipoles, which are digitized and combined into beams. Four independently steerable dual-polarization beams are available, each with two “tunings” of 16 MHz bandwidth that can be independently tuned to cover any frequency between 5 MHz and 88 MHz. The system equivalent flux density for zenith pointing is ~3 kJy and is approximately independent of frequency; this corresponds to a sensitivity of ~5 Jy/beam (5 sigma, 1 s); making it one of the most sensitive meter-wavelength radio telescopes. LWA1 also has two ``transient buffer'' modes which allow coherent recording from all dipoles simultaneously, providing instantaneous all-sky field of view. LWA1 provides versatile and unique new capabilities for ionospheric research, Galactic science, pulsar science, solar and planetary science, space weather, cosmology, and searches for astrophysical transients. LWA1 will provide excellent resolution in frequency and in time to examine phenomena such as solar bursts, and pulsars over a 4:1 frequency range that includes the poorly understood turnover and steep-spectrum regimes. Just a few seconds with the completed 260-dipole LWA1 provide the most sensitive images of the sky at 23 MHz obtained yet.

With support from AFOSR in 2014 we built a second LWA station at Sevilleta (LWA-SV; see ***Figure 1***). This second station is similar in design to LWA1, but had a commodity back-end for the all-sky modes and beamformer. This “off-the-shelf” hardware required considerably more software development to achieve matching capabilities of LWA1, but also having the ability to be adapted with new scientific capabilities such as a wide-band all-sky imager.

3. METHODS, ASSUMPTIONS, AND PROCEDURES

The new broadband imager at LWA-SV, known as Orville, can image the whole sky every 5 seconds with a bandwidth up to 20 MHz. This 200 times increase in bandwidth over the previous LWA all-sky imager (LASI), provides a factor of 15 increase in sensitivity, and the ability to characterize the spectrum of sources. The imaging is performed using w-stacking (Offringa et al., 2014) to correct for the noncoplanarity of the array. For each image, the sky is projected onto the two-dimensional plane using orthographic sine projection. To reduce the number of w-planes needed during w-stacking, the phase center is set to a location slightly off zenith that minimizes the spread in the w coordinate. The gridding operation is based on the Romein gridder implemented as part of the EPIC project (Kent et al., 2019, Romein, 2012). Every 5 seconds, the imager produces 4 Stokes (I, Q, U & V) images in 198 channels, each with 100 kHz bandwidth. This will roughly produce 1 TB of images every day and they are stored in the local disk.

Figure 1. The LWA-SV station located at the Sevilleta National Wildlife Refuge

The Orville broadband imager provides an opportunity to make broadband measurements of MRAs with a higher detection rate and to introduce better constrains on the spectral characteristics. In **Figure 2** we show a sample sub-band image from the Orville monitoring pages (https://lwalab.phys.unm.edu/SERFScreen/ss.php). These images are produced automatically in near-real time every 5 seconds, and spectrally averaged images are ingested into the archive.

To identify MRAs, the transient search pipeline is based on an image subtraction algorithm. In this method, an average of the previous 4-6 images within the last 30 seconds is subtracted from a running image. This will give a clean subtracted image removing the contribution from steady sources and the Galactic plane. Pixels with flux values greater than 6 sigma noise level are marked as transient candidates. This noise threshold varies as a function of the Galactic latitude. The transient search pipeline for the narrowband imager/LASI is described in more detail in Varghese et al. (2019b). The existing pipeline for the narrowband imager was modified to find transient sources from the new broadband images. The 198 channel images for each integration from the Orville system are averaged down to a single image in four Stokes parameters. The pipeline collects these averaged images for an hour and carries out a transient search in Stokes I and V on integration time scales of 5, 15 and 60 seconds. The transient search produces roughly 500-2000 transient candidates per day in Stokes I.

Most of the transient candidate events are false positives due to the scintillation of cosmic radio sources caused by the plasma irregularities in the ionosphere. The ionosphere contains an inhomogeneous magnetized plasma and density structures which acts as a screen causing refraction and scattering of the incoming radio waves from space. This results in rapid flux changes and position shifts of the observed sources by a couple of degrees. More details on scintillation and how it affects the transient search can be found in Varghese et al. (2019b). Two steps were carried out to reduce false positives due to scintillation in the pipeline. In the first step, we masked all transient candidates within 3 degrees of VLA Low Frequency Sky

Survey (VLSS) sources with flux density greater than 50 Jy at 74 MHz (Cohen et al., 2007, Lane et al., 2012). Scintillating sources have characteristic light curve patterns with rapid fluctuations and peaks over the period of half an hour to few hours. In that case signal to noise ratio of a scintillating source from the light curve will be lower. In the second step, light curves of the events over the duration of an hour was used to filter out low signal to noise ratio events which includes most of the scintillating sources.

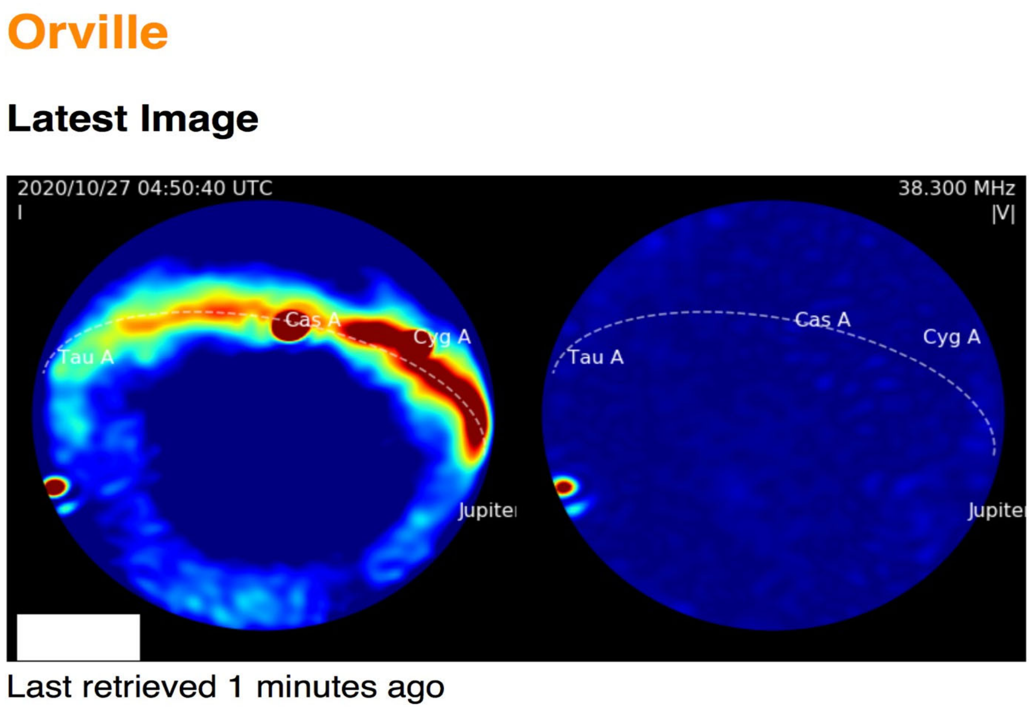

Figure 2. LWA-TV images using LW1 (left) and LWA-SV (right)

4. RESULTS AND DISCUSSION

From the perspective of science, this award has supported, directly or indirectly, 2 refereed publications and another publication about to be submitted. This work has also supported the PhD Thesis of Savin Varghese (graduating December 2020). The main thrust of the work has been research into meteors, although future work on riometry and searches for radio transients will certainly make use of the broadband imager developed. The first publication involved testing the isotropic nature of meteor radio afterglows. [1]

Using the radio data from the LWA-SV and optical data from the Widefield Persistent Train Camera (WiPT), Obenberger et al. [2] has shown that the MRAs are temporally and spatially correlated with the long-lasting emission in the optical and infrared known as persistent trains. This work demonstrates that persistent trains can provide enough suprathermal electrons to drive the MRA emission. Despite various efforts to characterize the properties of MRAs, the emission mechanism is still unknown. This work also involved UNM graduate student Savin Varghese, who under Ken's joint supervision with Greg Taylor, will complete his PhD this semester.

The spectrum of a radio source provides the energy distribution as a function of frequency. See Figure 3 on page 6. The shape of the spectrum can vary depending on the emission mechanism of the source. Since the emission mechanism of MRAs are poorly understood, broadband spectral measurements of the source provide insight into the emission mechanism. In future, developing theoretical models of emission mechanism requires observational constraints. Understanding the correlation between spectral parameters and physical properties of MRAs will help to identify the key parameters playing a significant role in the formation of MRAs.

A paper by Varghese et al on broadband observations of MRAs is in preparation for JGR. [3]

5. CONCLUSIONS

Low frequencies present a rich, and still relatively unexplored window on the ionosphere, space environment, and the cosmos. The exploration of this electromagnetic window has recently led to a bonanza of exciting scientific results including the discovery of radio afterglows from meteors. Through this award we developed new instrumentation and capabilities on the Long Wavelength Array Sevilleta Station for exploring meteor radio afterglows. We used this new broadband imager to make discoveries which were published in prominent refereed journals. The instrumentation developed under this award will be incorporated into future LWA stations.

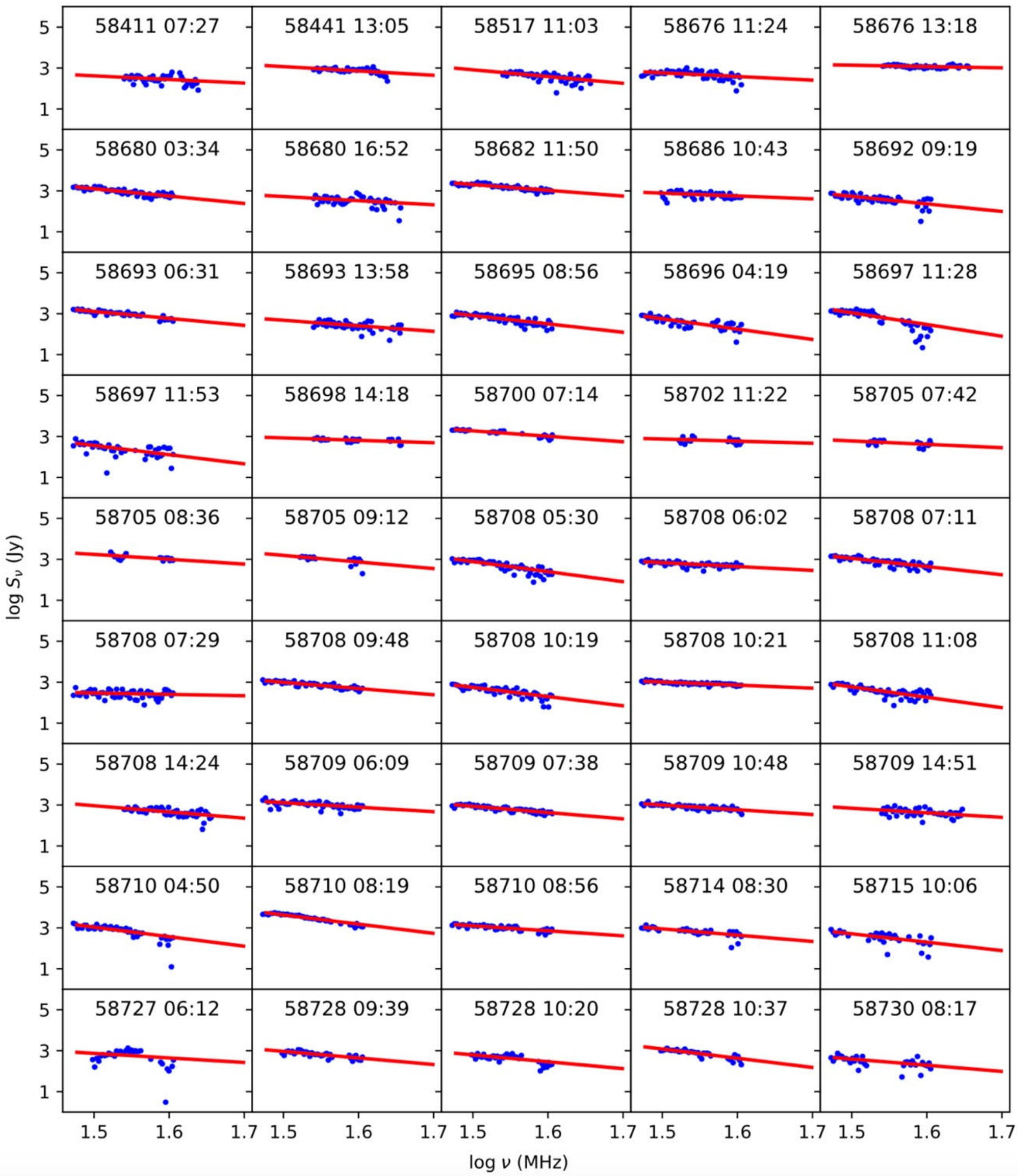

Figure 3. The log-log plots of MRA spectra fitted with a power law. Each subplot data is labelled with the MJD day and UTC hour at the time of occurrence. The frequency axis ranges from 30-50 MHz

6. REFERENCES

[1] Varghese, S.S., Obenberger, K.S., Taylor, G.B., & Dowell, J., “Testing the Radiation Pattern of Meteor Radio Afterglow,” *JGR Space Physics*, **vol 124**, issue 12, Dec 2019, pp. 10749-10759.

[2] Obenberger, K.S., Holmes, J.M., Ard, S.G., Dowell, J., Shuman, N.S., Taylor, G.B., Varghese, S.S., & Viggiano, A.A., “Association between Meteor Radio Afterglows and Optical Persistent Trains,” *JGR Space Physics,* **vol. 125**, issue 9, Aug 2020.

[3] Varghese, S.S., Obenberger, K.S., Dowell, J., & Taylor, G.B., “Broadband Imaging of Meteor Radio Afterglows,” (In preparation).

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