Imaging at Both Ends of the Spectrum: the Long Wavelength Array and Fermi

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The Long Wavelength Array (LWA) will be a new multi-purpose radio telescope operating in the frequency range 10-88 MHz. Scientific programs include pulsars, supernova remnants, general transient searches, radio recombination lines, solar and Jupiter bursts, investigations into the "dark ages" using redshifted hydrogen, and ionospheric phenomena. Upon completion, LWA will consist of 53 phased array stations distributed accross a region over 400 km in diameter. Each station consists of 256 pairs of dipole-type antennas whose signals are formed into beams, with outputs transported to a central location for high-resolution aperture synthesis imaging. The resulting image sensitivity is estimated to be a few mJy (5σ, 8 MHz, 2 polarizations, 1 h, zenith) from 20-80 MHz; with angular resolution of a few arcseconds. Additional information is online at http://lwa.unm.edu. Partners in the LWA project include LANL, JPL, NRL, UNM, NMT, and Virginia Tech.

The full LWA will be a powerful instrument for the study of particle acceleration mechanisms in AGN. Even with the recently completed first station of the LWA, called LWA1, we can begin spectral studies of AGN radio lobes. These can be combined with Fermi observations. Furthermore we have an ongoing project to observe Crab Giant Pulses in concert with Fermi. In addition to these pointed studies, the LWA1 images the sky down to declination −30 degrees daily. This is quite complimentary to Fermi's daily images of the sky.

I. INTRODUCTION

LWA1 originated as the first "station" (beamforming array) of the Long Wavelength Array (LWA). The LWA concept was conceived by Perley & Erickson [20] and expanded by Kassim & Erickson [10] and Kassim *et al.* [11]. It gained momentum with sub-arcminute imaging with the VLA at 74 MHz [9][13] and the project began in April 2007, sponsored primarily by the Office of Naval Research (ONR), with the ultimate goal of building an aperture synthesis radio telescope consisting of 53 identical stations distributed over the U.S. Southwest [6].

The LWA1 Radio Observatory is shown in Fig. 1. It is located on NRAO land within the central square mile of the EVLA, which offers numerous advantages. The project to design and build LWA1 was led by UNM, who also developed analog receivers and the shelter and site infrastructure systems. The system architecture was developed by VT, who also developed LWA1's monitor & control and data recording systems. Key elements of LWA1's design were guided by experience gained from a prototype stub system project known as LWDA, developed by NRL and the University of Texas at Austin [24]; and by VT's Eight-meter wavelength Transient Array (ETA; [4]). NRL developed LWA1's active antennas, and JPL developed LWA1's digital processing subsystem.

Institutions represented in the LWA (as determined by attendance at the May 12, 2011 LWA1 User Meeting) include U.S. Air Force Research Laboratory (AFRL), Arizona State University (ASU), Harvard University, Kansas University (KU), Long Island University, National Radio Astronomy Observatory (NRAO), NASA Jet Propulsion Laboratory (JPL), U.S. Naval Research Laboratory (NRL), New Mexico Tech (NMT), University of New Mexico (UNM), UTB, and Virginia Tech (VT). New institutions and individuals are invited to join the LWA and if interested should contact Namir Kassim (NRL) or Greg Taylor (UNM). The LWA1 has recently been established as a University Radio Observatory by NSF and as such will entertain regular calls for proposals from the astronomical community. The first of these widely open calls for the proposals is out with a **deadline of June 22, 2012**. Table 1 summarizes the capabilities of LWA1. For more details see the LWA web pages at `http://lwa.unm.edu` including the LWA Memo series.

II. CURRENT STATUS

At the time of writing, we are in the commissioning phase. We anticipate to reach IOC ("initial operational capability") – essentially the beginning of routine operation as an observatory – by April 2012. We now summarize some early results obtained during commissioning. In Fig. 2 we show a spectrogram obtained from the Transient Buffer Wideband (TBW) data taken over 24 hours for a 20-dipole zenith-pointing beam. The integration time of the individual captures is 61 ms, and one capture was obtained every minute. The frequency resolution is ∼10 kHz and diurnal variation of galactic noise is clearly evident. Strong RFI from the FM bands shows up as vertical lines at 88 MHz and above. Below 30 MHz there are a variety of strong communications signals. While there is abundant RFI visible in the spectrum, it is very narrowband, obscures only a tiny fraction of our band, and does not interfere with our ability to be sky-noise limited. More details about the RFI environment can be found in Obenberger & Dowell [19].

We have recently begun imaging the sky with

FIG. 1: Aerial view of the LWA1 radio observatory.

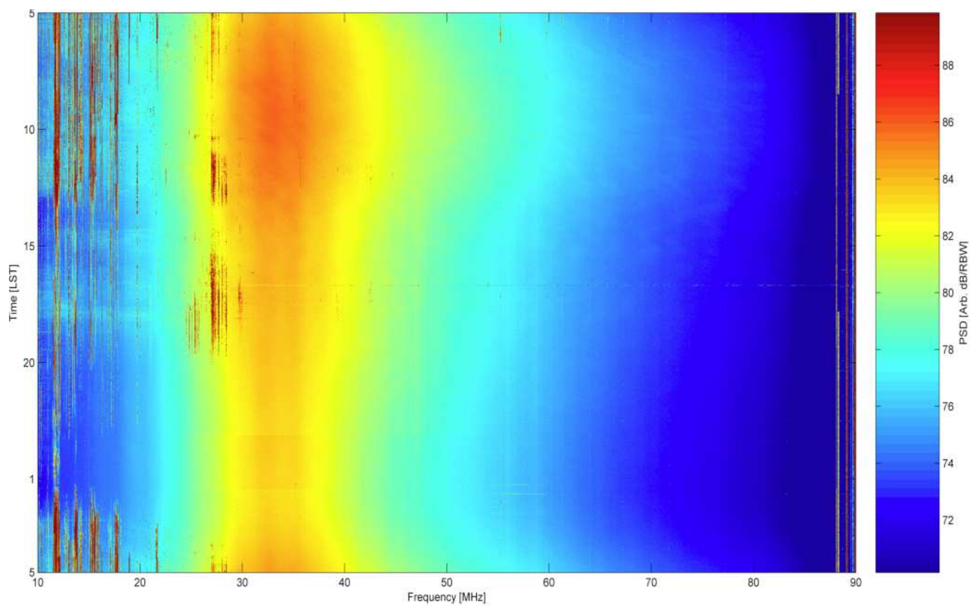

FIG. 2: Spectrum using the TBW capture mode for 20 dipoles phased at zenith for 24 hours. The time and frequency variation of the background are real; the contribution of the active antenna appears as a steep role-off below 30 MHz. Note that 30-88 MHz is always useable, and even frequencies as low as 13 MHz are usable for a few hours each day.

LWA1. In Fig. 3 we show four views of the sky taken with the TBN mode on May 16 using 210 stands (21945 baselines). In these Stokes I images one can see the Galactic plane, Cas A, and Tau A, and at the lowest frequency Jupiter is quite prominent. The LWA1 routinely images the sky in near real-time using the Transient Buffer Narrowband (TBN) cabability of the station and a modest cluster located at the LWA1 (see Hartman et al. 2012, in preparation, for more details). These images are shown live on "LWA-TV" which is available from the LWA web pages. Movies for each day are also available made from the individual 5 second cqptures.

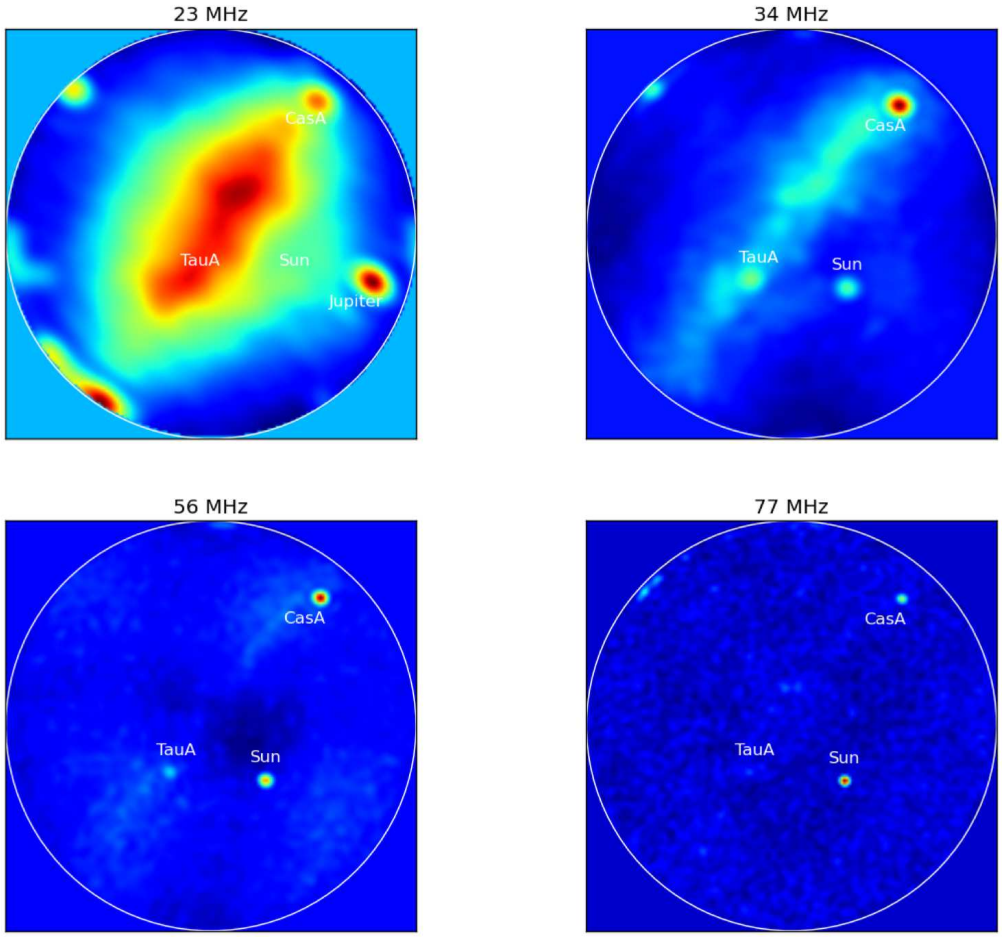

FIG. 3: Nearly-simultaneous all-sky images taken at 4 widely separated frequencies using LWA1's TBN mode. Absolute calibration is the same in all four images; the apparent decrease in sky brightness with increasing frequency is real, and the bright region near zenith is the Galactic plane. Clearly visible at 23 MHz is Jupiter, and the horizon "hot spots" in the 23 MHz image are ionospherically-refracted RFI. Note that Cas A and the Sun are visible in all images. Data was obtained for 10 seconds each, 50 kHz bandwidth, using 210 dipoles.

III. CONNECTIONS TO FERMI

A. Pulsars

Pulsars are fascinating objects with spin periods and magnetic fields strengths ranging over 4 and 5 orders of magnitude respectively. Though it is well accepted that pulsars are rotating neutron stars, the pulsar emission mechanism and the geometry of the emitting region are still poorly understood [5]. LWA1 will be an excellent telescope for the study of pulsars including single pulse studies, and studies of the interstellar medium (ISM). In fact, it is in the LWA1 frequency band range where strong evolution in pulsar radio emission can be observed, e.g, a turn over in the flux density spectrum, significant pulse broadening, and complex changes in the pulse profile morphologies [17]. And, although pulsars were discovered at low frequency (81 MHz), there is a remarkable lack of good observational data in the LWA1 frequency range. LWA1 observations should be able to detect dozens of pulsars (e.g., Fig. 4 and see [8]) in less than 1000 seconds.

LWA1 will be able to perform spectral studies of pulsars over a wide frequency range and with high spectral resolution. This will allow investigators to look for drifting subpulses. Strong notches have been seen to appear in the profiles of pulsars at low frequencies [7], but little progress has been made in understanding their origin. Some pulsars may reach 100% linear polarization at low frequencies (B1929+10; [16]). In addition to being intrinsically of interest (providing clues about the pulsar magnetospheric structure), such strongly polarized beacons can assist in probing coronal mass ejections and determining the orientation of their magnetic fields, which strongly affects their impact on Earth.

LWA1's large collecting area will be particularly useful for "single pulse" science, including studies of Crab Giant Pulses (CGPs) and Anomalously Intense

Pulses (AIPs). The Crab Pulsar intermittently produces single pulses having intensity greater than those of the normal periodic emission by orders of magnitude. Despite extensive observations and study, the mechanism behind CGPs remains mysterious. Observations of the Crab pulsar across the electromagnetic spectrum can distinguish between various models for GP emission such as enhanced pair cascades, radio coherence, and changes in beaming direction. We plan to coordinate low frequency observations of GPs with observations of GPs by Fermi. To date the study of the CGP emission at low radio frequencies is only very sparsely explored. Reported modern observations of CGPs in this frequency regime are limited to just a few in recent years including UTR-2 at 23 MHz [21], MWA at 200 MHz [3], and LOFAR LBA [22]. LWA1 will be able to provide hundreds of hours per year of sensitive observations of CGPs which will revolutionize our knowledge of the time- and frequency-domain characteristics of these enigmatic events. Combined with observations in other wavelength regimes (e.g., simultaneous L-band observations already planned in a current observing project) significant advances in understanding are expected.

We should be able to measure scattering for practically every good CGP detection (S/N $\sim$20 or better), and it is known that both the dispersion and scattering of the Crab emission can vary dramatically on short or long time scales. By observing over an extremely broad bandwidth, we may be able to better quantify the scatter broadening and thereby assess the level and importance of anisotropy. Furthermore, the broad bandwidth of the observations will be helpful in shedding light on the issue of the frequency scaling of the scattering (believed to be $\sim$3.6 compared to the canonical value of $\sim$4.4 for the general ISM), which is thought to be related to the nature of turbulence in the nebula.

Anomalous high intensity single pulses from known pulsars have been reported previously using the UTR-2 (Ulyanov *et al.* 2006) and LOFAR [22]. These anomalously intense pulses (AIPs) have many features similar to the giant pulse phenomenon, including emission in a narrow longitude interval and power-law distribution of the pulse energy. One distinctive feature of these AIPs, however, is that they are generated by subpulses or some more short lived structures within subpulses. The emission is seen to be quite narrow band, typically 1 MHz in bandwidth. The nature of such pulses is not yet understood. The LWA1 with its excellent sensitivity and large available bandwidth provides an opportunity to study these pulses.

Pulsars make up a significant component of the source population visible by both Fermi and the LWA1. The LWA1 is an excellent instrument for the study of pulsars as it offers good sensitivity, broad bandwidth, wide field-of-view for rapid survey speed, and precise timing capabilities. The LWA1 also records raw voltages, which allows for very flexible post-processing of the data (coherent dedispersion, fine time and frequency resolution, etc.). See Fig. 4 for the first light detection of pulsar 1919+21.

An immediate connection between LWA1 and Fermi is in the study of pulsars. In particular Fermi has recently discovered over 36 pulsars in the gamma-ray band. Only a few of these have been found to pulse in the radio at centimeter wavelengths. Low frequency searches are of considerable interest as pulsars are generally very steep spectrum and the beaming fraction is thought to be lower at low frequencies. A survey of gamma-ray pulsars will be carried out with the LWA1 in the near future.

B. Blazars

At high galactic latitudes 80% (106 of 132) of the γ-ray bright sources detected in the LAT Bright Source List (BSL) derived from the first 3 months of Fermi observations [1] are associated with known Active Galactic Nuclei (AGN). In the second LAT AGN catalog (2LAC; [2]) there are 1017 γ-ray sources associated with AGN. The vast majority of the Fermi γ-ray sources are blazars, with strong, compact radio emission. These blazars exhibit flat radio spectra, rapid variability, compact cores with one-sided parsec-scale jets, and superluminal motion in the jets [18]. Extensive studies of blazars are reported in these proceedings.

Due to the low angular resolution of LWA1, only a few blazars are bright enough to rise above the confusion noise. Fortunately, blazars are in general highly variable so it is possible to detect flaring sources with the LWA at low frequency. The all-sky images from the Prototype All Sky Imager (PASI) on LWA1 (see §3.3) can be compared to the daily all-sky images from Fermi. Strong flaring blazars can be detected in the all-sky images, and beams can be used to confirm detections. Measurements at low frequencies can help to constrain the particle acceleration mechanisms is the jets.

C. Transients

Astrophysical transient sources of radio emission signal the explosive release of energy from compact sources (see Lazio *et al.* 2010, Cordes & McLaughlin 2003 for reviews). Known types of radio transients include cosmic ray airshowers, solar flares (§2.5), Jovian flares and flares from extrasolar hot jupiters (§2.2), giant flares from magnetars (Cameron *et al.* 2005), rotating radio transients (McLaughlin *et al.* 2006), giant pulses from the Crab pulsar, and supernovae. The study of these sudden releases of energy allow us to recognize these rare objects, and yield insights to the nature of the sources including energetics, rotation rates, magnetic field strengths, and particle acceleration mechanisms. Furthermore, some radio transients remain unidentified such as the galactic center radio transient GCRT J1745−3009 (Hyman *et al.* 2005), and require further study.

PASI is a software correlator and imager for LWA1 that analyzes continuous samples from all dipoles with a 75 kHz passband placeable anywhere within 10–88 MHz. PASI images nearly the whole sky ($\approx 1.5\pi$ sr) every five seconds, continuously and in near realtime, with full Stokes parameters and typical sensitivities of $\sim$5 Jy at frequencies above 40 MHz and $\sim$20 Jy at 20 MHz. Candidate detections can be followed up within seconds by beamformed observations for improved sensitivity and localization. These capabilities provide an unprecedented opportunity to search the synoptic low-frequency sky. PASI saves visibility data for $\sim$20 days, allowing it to "look back in time" in response to transient alerts. The images generated by PASI will be archived indefinitely. The images of the sky from PASI are available "live" at the URL: `http://www.phys.unm.edu/~lwa/lwatv.html`.

Acknowledgments

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TABLE I: Summary of LWA1 Specifications

Specification	As Built Description
Beams:	4, independently-steerable, each dual-polarization
Tunings:	2 independent center frequencies per beam
Freq Range:	24–87 MHz (>4:1 sky-noise dominated); 10–88 MHz usable
Instantaneous bandwidth:	$\leq$16 MHz $\times$ 4 beams $\times$ 2 tunings
Minimum channel width:	$\sim$0 (No channelization before recording)
Beam FWHM:	[8,2]° at [20,80] MHz for zenith-pointing
Beam SEFD:	$\sim$3 kJy (approximately frequency-independent) zenith-pointing
Beam Sensitivity:	$\sim$ 5 Jy (5σ, 1 s, 16 MHz) for zenith-pointing
All-Dipoles Modes:	TBN: 67 kHz bandwidth continuously from every dipole
	TBW: Full band (78 MHz) every dipole for 61 ms, once every $\sim$5 min.

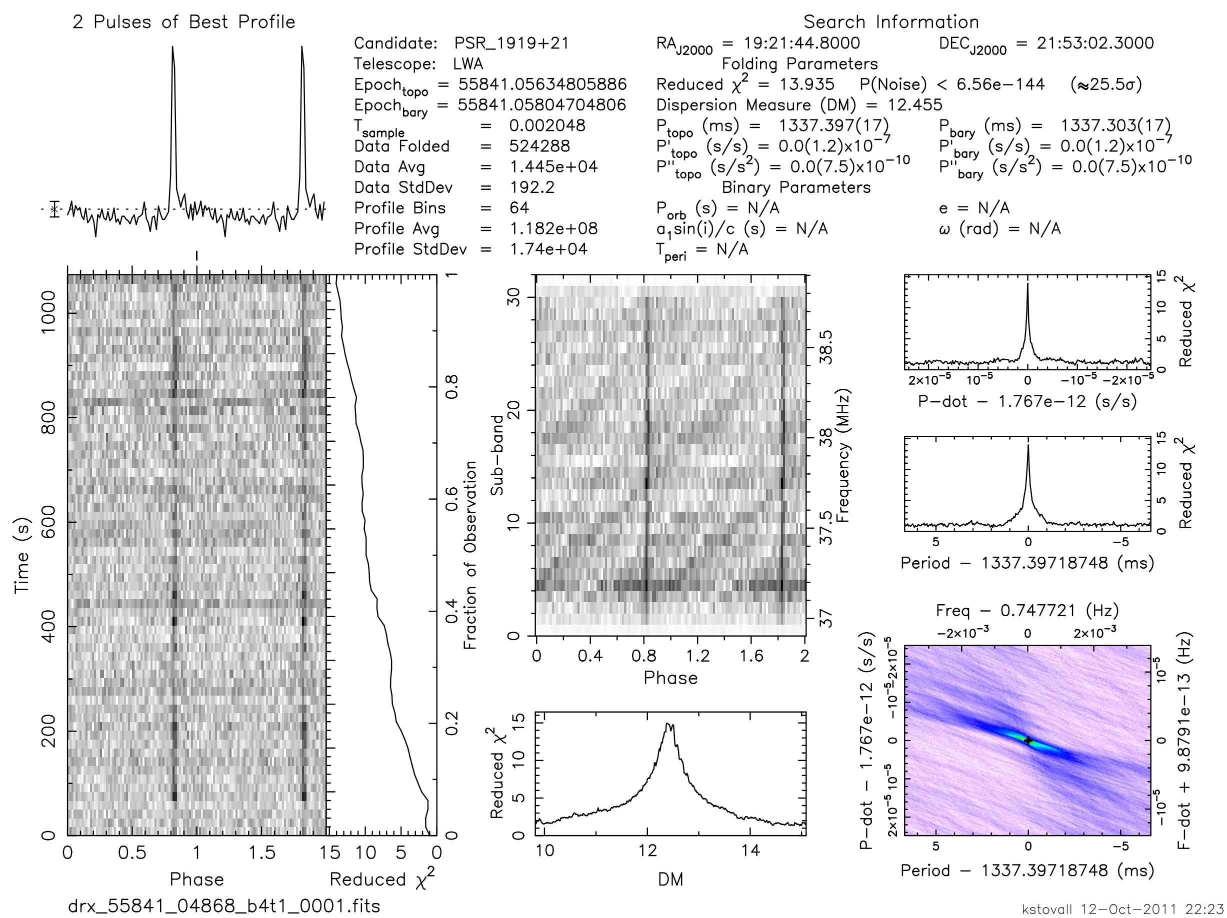
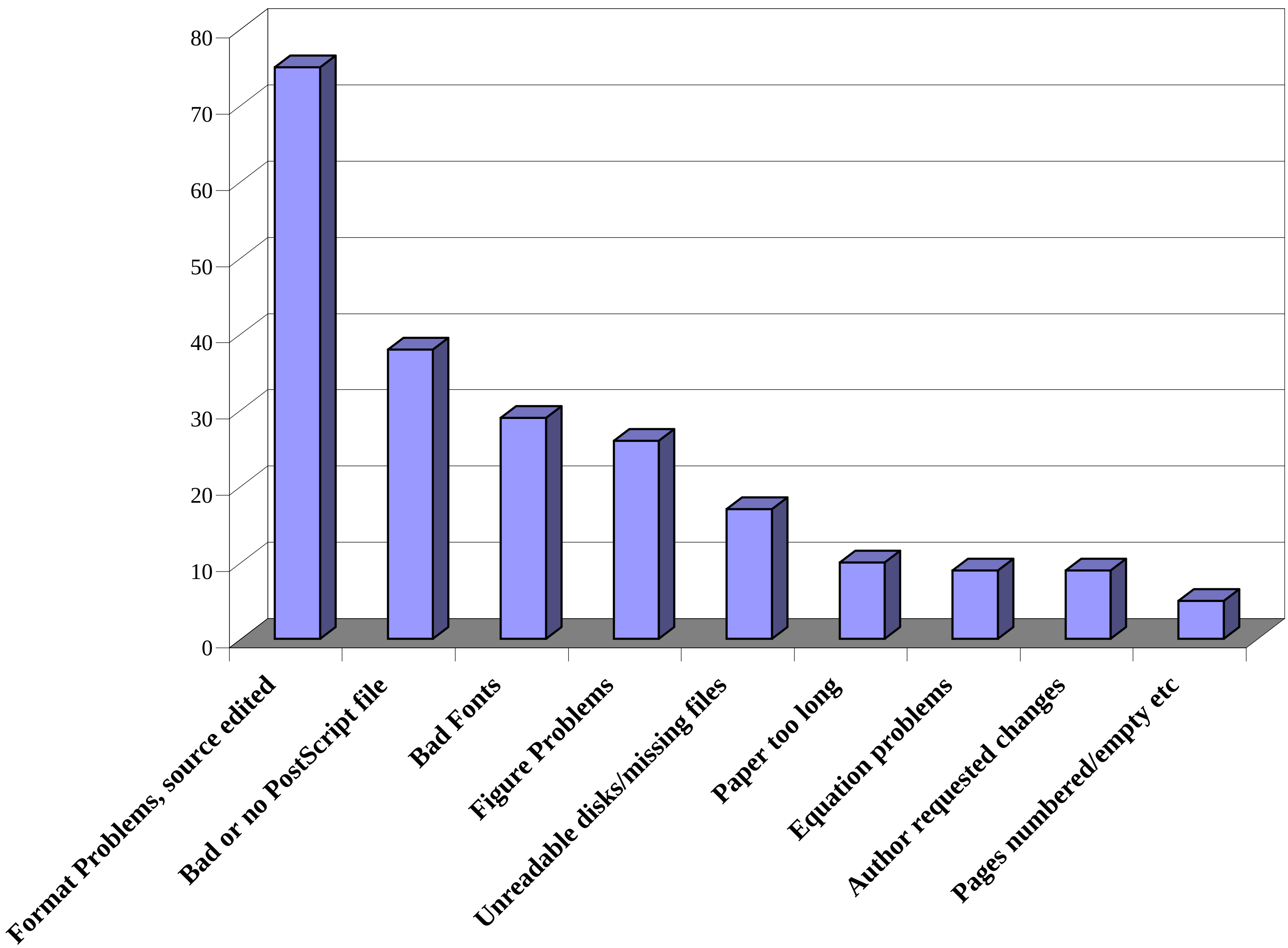


FIG. 4: First detection with LWA1 of the pulsar 1919+21 using a narrow (1 MHz) beam taken during commissioning observations.



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