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## OBSERVATIONS OF ROTATING RADIO TRANSIENTS WITH THE FIRST STATION OF THE LONG WAVELENGTH ARRAY

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### ABSTRACT

Rotating radio transients (RRATs) are a subclass of pulsars first identified in 2006 that are detected only in searches for single pulses and not through their time averaged emission. Here, we present the results of observations of 19 RRATs using the first station of the Long Wavelength Array (LWA1) at frequencies between 30 and 88 MHz. The RRATs observed here were first detected in higher frequency pulsar surveys. Of the 19 RRATs observed, two sources were detected and their dispersion measures, periods, pulse profiles, and flux densities are reported and compared to previous higher frequency measurements. We find a low detection rate (11%), which could be a combination of the lower sensitivity of LWA1 compared to higher frequency telescopes, and the result of scattering by the interstellar medium or a spectral turnover.

*Key words:* pulsars: general – radio continuum: stars

### 1. INTRODUCTION

Rotating radio transients (RRATs) are a subclass of pulsars whose emission is only observed intermittently, with only single pulses being detected. These single pulses can be separated from one another on timescales ranging from minutes to hours. In general RRATs are not detected through periodicity searches as is the case with other pulsars (McLaughlin et al. 2006). Therefore, single pulse searches are needed to identify them. However, the ability to detect RRATs depends upon the instrument, the frequency, and the length of the observations, and some RRATs may even be detectable as normal pulsars in periodicity searches for some combinations of parameters.

RRATs were first discovered in a re-analysis of data from the 1.4 GHz Parkes Multibeam Pulsar Survey (PMPS), which identified 11 RRATs with single pulses with pulse widths ranging from 2 to 30 ms, peak flux densities between 0.1 and 3.6 Jy, and detected pulses ranging from only 4 up to 229 (Manchester et al. 2001; McLaughlin et al. 2006). More than 100 RRATs have been discovered thus far with most being found in the blind pulsar surveys carried out by major radio observatories.<sup>7</sup> Some notable surveys include the Green Bank Telescope’s (GBT) 350 MHz Drift Scan Survey and its Northern Celestial Cap Pulsar Survey (Lynch et al. 2013; Karako-Argaman et al. 2015), the High Time Resolution universe Survey (Burke-Spolaor et al. 2011), Arecibo’s 327 MHz Drift-Scan Pulsar Survey (Deneva et al. 2013), as well as in subsequent re-analyses of the PMPS (Keane et al. 2010, 2011).

The mechanism behind the transient pulsing of RRATs has not yet been determined, with many models having been put

forth. The inferred periods of the still small fraction of RRATs that have measured periods are generally longer than the typical periods of canonical pulsars, with Karako-Argaman et al. tentatively finding some evidence that pulsars with periods longer than 200 ms are more likely to be detectable only in single-pulse searches than pulsars with shorter periods (McLaughlin et al. 2006; Keane et al. 2010; Karako-Argaman et al. 2015). It has been suggested that RRATs are old pulsars near the end of their pulsing lifetime and turn off in a sporadic manner (Zhang et al. 2007). Others suggest RRATs are pulsars whose emission is regulated by a surrounding debris field (Cordes & Shannon 2008), or that they are fundamentally similar to nulling pulsars (Burke-Spolaor & Bailes 2010). Another proposed model is that RRATs are pulsars which emit single bright pulses in addition to a distribution of weaker single pulses (Weltevrede et al. 2006).

If RRATs are actually a distinct type of pulsar that forms independently of regular pulsars, they should be counted in addition to the number of other pulsars. Given the need for the birth rates of the various populations of neutron stars to add up to the supernova rate in the Galaxy, the presence of RRATs would require a substantial increase in that supernova rate. Indeed, the maximum supernova rate was estimated by Keane et al. (2010) to be 3 century<sup>-1</sup>, whereas the neutron star birth rate required to account for RRATs alone as a distinct class was estimated to be 5.8 century<sup>-1</sup>.

Using the first station of the Long Wavelength Array (LWA1), we carried out observations of 19 RRATs at frequencies between 30 and 88 MHz. This is the first time that RRATs have been studied at such low frequencies, and their properties, including burst rates, flux densities, pulse shapes, and spectral indices are consequently all unknown. LWA1 possesses both high time and frequency resolution, thereby allowing the pulse properties and dispersion measures (DMs) of detectable pulses to be determined very precisely. For detected RRATs, LWA1 has more available observing time than many other instruments, so timing observations can be carried out readily.

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<sup>7</sup> See the RRATalog at <http://astro.phys.wvu.edu/rratolog/>.

We describe two observing campaigns and the data reduction in Section 2, followed by the details of the two detected RRATs individually in Section 3. We consider the implications in Section 4, with concluding remarks in Section 5.

## 2. OBSERVATIONS

The observations reported here were taken with LWA1 (Taylor et al. 2012). The observatory consists of two stations, LWA1 and LWA-SV. For this work we used LWA1, which is co-located with the Jansky Very Large Array. This station utilizes 256 stands of orthogonal dipoles and can observe at any frequency between 10 and 88 MHz with a bandwidth of 16 MHz. Four independent steerable beams have two frequency tunings each and a beamwidth of  $2.2^\circ$  at 74 MHz. With its high time and frequency resolution, LWA is particularly well suited to observations of time varying phenomena such as pulsars and RRATs. More than 60 regular pulsars have been re-detected with LWA with four of these being millisecond pulsars (Stovall et al. 2015). Given the observatory's low frequency range, where pulses will experience scattering and dispersion effects to a much greater degree than in higher frequency observations, LWA1 can make very accurate studies of the time-varying properties of the interstellar medium (ISM) with uncertainties for the DM values in the range of  $0.001 \text{ pc cm}^{-3}$ .

Two different observing campaigns of RRATs were carried out with LWA1, with the first taking place from mid-2013 to early 2014 and the second campaign taking place from 2014 August to 2015 March. In the first observing session (LWA project code LM002) we selected 10 RRATs with DMs less than  $50 \text{ pc cm}^{-3}$ , as the scattering timescale given by Bhat et al. (2004) at 64 MHz is over 100 ms at this DM, much larger than the typical width of an RRAT's pulse. These RRATs had also been confirmed in multiple observations with different telescopes. A single LWA1 beam was utilized, which provided an effective central frequency of 72 MHz and a bandwidth of 32 MHz. The bandwidth of the individual channels used for analysis was 4.8 kHz. Each observation was 2 hr in length and any detections were followed up with additional observations.

The second observing campaign (LWA projects DM001 and LM003) selected an additional nine RRATs to be observed along with the 10 from the first observing run with less stringent constraints on their DMs. All of these additional targets have DMs less than  $100 \text{ pc cm}^{-3}$ . While the first observing run selected RRATs without previous timing solutions, many of those in the second observing run have measured periods allowing for comparisons with higher frequency results. The nature of the observations was changed to more resemble the style utilized for LWA1's already successful pulsar observations. Two of the beams were used in the split filter setting with central frequencies of 35.1, 49.8, 64.5, and 79.2 MHz and an effective bandwidth after combination of 60 MHz. Each RRAT was observed with 1 hr observations and any detections were followed up with additional observations. All observations of this run were scheduled at night across transit to limit the level of radio frequency interference (RFI). All 19 RRATs targeted in either campaign are listed in Table 1 along with their measured DMs and periods from discovery, follow up, or from our observations. For the objects that we detect we also provide the low frequency burst rate.

The data reduction was carried out at LWA's User Computing Facility (LWAUCF), a computing cluster consisting of six nodes located at the nearby VLA control building, with the PRESTO software package<sup>8</sup> being used for the analysis (Ransom 2001). The raw data from each frequency tuning were first converted to Flexible Image Transport System (FITS) format using *write2psrfits.py* and the resulting files combined to yield a single FITS file for all frequency tunings (see Dowell et al. 2012). This combination of the beams provides an effective increase in bandwidth, thereby increasing the signal-to-noise ratio (S/N) of the pulses. RFI was then flagged utilizing *rfifind* and the data were dedispersed into 128 subbands at trial DMs spanning  $10 \text{ pc cm}^{-3}$  with a step size of  $0.001 \text{ pc cm}^{-3}$  centered on the DMs of their discovery detections. This large DM range was searched in order to ensure any real pulses were not missed due to a larger error than that which is reported in the discovery detection and to determine the false-positive detection rate resulting from any remaining RFI. Due to the low observing frequency of these observations, the dispersion of the pulses is significant even for low DMs, so a small step size is required. This results in a smearing due to an incorrect DM of roughly 1 ms across the band. The results were searched using both single pulse search and periodicity search techniques using the routines *single\_pulse\_search.py* and *prepfold* respectively.

Again, as a result of the  $\nu^{-4.4}$  frequency dependence of scattering effects of the ISM, pulses in LWA1's frequency band are scattered by a factor of 2000 times more than a pulse at 350 MHz (Cordes 2002). It is possible that the pulses from the RRATs might be too scattered to be detected by the standard match filtering. For this reason a modified version of *single\_pulse\_search.py*, which performs a matched-filter search using Equation (3) from Karuppusamy et al. (2013) with  $\tau_d$  values ranging from 2 to 42 ms, was also utilized to improve the chance of detection of some of the higher DM RRATs that were observed. This technique has also been successfully applied to detect giant pulses from the Crab pulsar as described by Eftekhari et al. (2016).

To estimate the flux density of the detected pulses we employed the radiometer equation which relates the S/N to the integration time, bandwidth, and system equivalent flux density (SEFD) of the telescope. The SEFD of LWA1 varies with observing frequency, projected area of the array as a result of the source's elevation, and the proximity to bright sources such as the Galactic Plane. We used the results of Schinzel & Polisensky (2014) to estimate the response of LWA1 at varying zenith angles, and from that derived the flux densities for measured pulses. The uncertainty we conservatively assigned to this method is  $\pm 50\%$  (Stovall et al. 2015).

## 3. RESULTS

Of the 19 RRATs observed with LWA, just two confirmed detections have been made, with one from the 2013 to 2014 observing run and one from the 2014 to 2015 observing run. The RRATs that were detected are J0054+66 and J2325-0530, both of which were originally discovered with the GBT in its 350 MHz sky surveys. These will be addressed individually below.

<sup>8</sup> <http://www.cv.nrao.edu/~sransom/presto>

**Table 1**  
RRATs Observed with LWA1

Source	DM ( $\text{pc cm}^{-3}$ )	Period (s)	Rate ( $\text{hr}^{-1}$ )	References	Frequency (MHz)	BW (MHz)	Time (hr)	Date <sup>a</sup> (YY MM DD)
J0054+69	90.3	...		1	57	60	1	2014 Nov 08
J0054+66	14.554	1.390	0.7	2, 3	57	60	1	2015 Jan 17
					57	60	3	2014 Dec 28, 23, 20
					57	60	2	2014 Dec 18, 17
					57	60	1	2014 Nov 26
J0103+54	55.605	0.354		1	57	60	1	2014 Oct 05
					57	60	1	2014 Nov 26
J0201+7005	19.998	1.349		1	72	32	2	2013 Oct 17
					72	32	2	2014 Jan 11
					57	60	2	2014 Dec 19, 2014 Oct 13
					57	60	2	2014 Nov 17, 13
					57	60	3	2014 Sep 29, 24, 21
J0332+79	16.67	2.056		1	72	32	2	2013 Oct 17
					57	60	1	2015 Jan 25
					57	60	1	2014 Oct 06
J0447-04	29.83	1.188		1	72	32	2	2013 Oct 17
					57	60	1	2015 Jan 24
					57	60	1	2014 Nov 10
J0628+09	88	1.241		4	57	60	1	2014 Nov 09
J0957-06	26.95	1.724		1	72	32	2	2014 Jan 08
					57	60	1	2015 Feb 06
					57	60	1	2014 Dec 27
J1439+76	22.29	0.948		1	72	32	2	2014 Jan 08
					57	60	1	2015 Feb 05
					57	60	1	2015 Jan 19
J1538+2345	14.909	3.449		1	72	32	2	2014 Jan 08
					57	60	1	2015 Feb 27
					57	60	1	2015 Feb 07
					57	60	1	2015 Jan 16
					57	60	1	2015 Jan 16
J1611-01	27.21	1.297		1	72	32	2	2014 Jan 08
J1610-17	52	...		5	57	60	1	2015 Feb 17
					57	60	1	2015 Jan 14
J1623-0841	60.42	0.503		6	57	60	1	2015 Feb 18
					57	60	1	2015 Jan 15
J1705-04	42.951	0.237		1	72	32	2	2014 Jan 08
					57	60	1	2015 Jul 18
J1753-12	73	0.405		5	57	60	1	2015 Feb 19
J1850+15	24	1.383		5	57	60	1	2014 Dec 21
J1944-10	31.01	0.409		1	72	32	2	2013 Jul 23
					57	60	1	2015 Jul 16
J2225+35	51	0.94		7	57	60	1	2014 Oct 18
					57	60	1	2014 Sep 19
J2325-0530	14.963	0.869	21	1, 3	72	32	2	2013 Jul 23
					72	32	2	2014 Jan 11
					57	60	2	2014 Dec 19, 2014 Nov 14
					57	60	3	2014 Oct 31, 26, 23
					57	60	3	2014 Oct 21, 20, 19

**Note.**

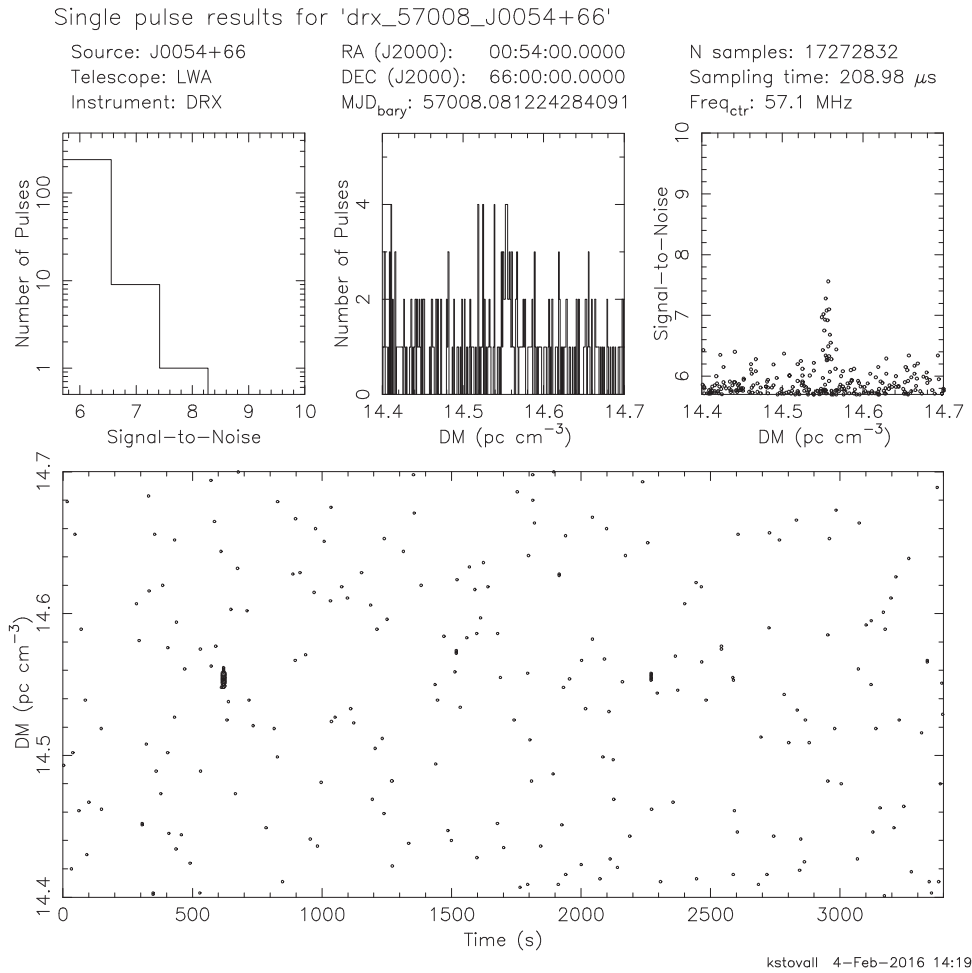
<sup>a</sup> Epochs in YY MM DD format with additional entries corresponding to days in the same month.

**References.** (1) Karako-Argaman et al. (2015), (2) Hessels et al. (2008), (3) this work (4) Deneva et al. (2009), (5) Burke-Spolaor & Bailes (2010), (6) Boyles et al. (2013), (7) Shitov et al. (2009).

### 3.1. J0054+66

This RRAT was one of the eight new RRATs selected for observing in the second observing session, and was discovered with the GBT in its Survey of the Northern Galactic plane for Radio Pulsars and Transients at 350 MHz. Its initial GBT detection DM was  $\sim 14.5 \text{ pc cm}^{-3}$  with no reported error, with a burst rate ranging from  $\sim 4$  to  $40 \text{ hr}^{-1}$ , and a period of 1.390 s (Hessels et al. 2008). The pulse profile from the GBT had a width on the order of 10 ms. A total of six observations of 1 hr

with LWA1 have been carried out on this RRAT, with three yielding detections and the others no observable emission. To be classified as a detection we required a minimum S/N of 6, and that the S/N versus DM peaked at a reasonable value for the DM. The flux density of the faintest detectable pulse for the combined 60 MHz band was  $\sim 50 \text{ Jy}$ . The number of detectable pulses in each of the observations varied, with two of the combined bandwidth (60 MHz) observations yielding only one detected pulse per observation and one detecting two pulses as

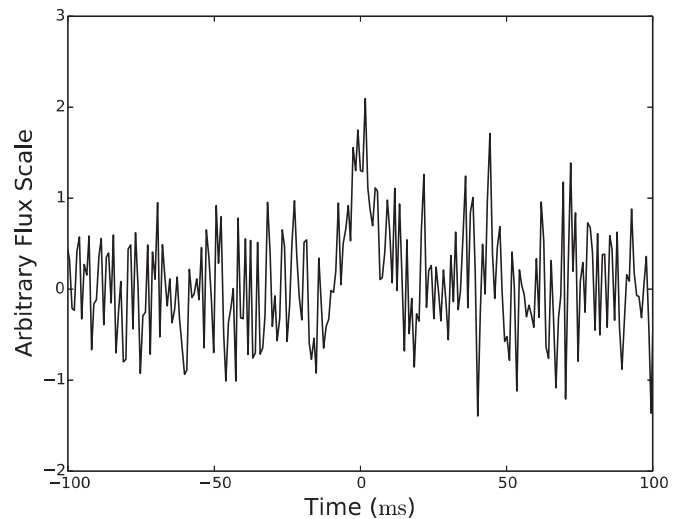


**Figure 1.** LWA1 detection of J0054+66 showing two pulses detected with the point size scaling with S/N on the bottom, distribution of the number of pulses (over a range of DM) with S/N at top left, the distribution of the number of pulses with DM in the middle, and the distribution of S/N with DM at top right.

is illustrated in Figure 1. We estimate the burst rate from these observations to be  $0.7 \text{ hr}^{-1}$ .

The detections at the other individual frequencies without the combined beam also vary in the number of pulses detected, with some finding none, whereas the 64.5 MHz tuning of the same observation that detected two pulses in the combined bandwidth also detected two pulses within the hour-long observation. The pulse profile for a single bright pulse observed with LWA1 is shown in Figure 2.

The DM measured with LWA1 did not change significantly from observation to observation or pulse to pulse in those observations that had multiple detections, with a DM of  $14.554 \pm 0.007 \text{ pc cm}^{-3}$ . To estimate the error we fit the S/N versus DM curve to Equation (12) from Cordes & McLaughlin (2003) and took the error to correspond to the range in which values are  $1\sigma$  below the peak. However, we note that significant profile evolution, whether it is intrinsic or due to scattering, would bias this DM value (e.g., Hassall et al. 2012). The average S/N, mean flux and pulse width for J0054+66 are listed in Table 2. The S/N in the individual tunings was not sufficient to allow measurements across the band. The variations in S/N are likely intrinsic to the RRAT and perhaps modulated by the ionosphere and/or ISM. The elevation angle of the RRAT was the same for all the observations, meaning that LWA1's sensitivity should have remained nearly constant



**Figure 2.** The pulse profile of a single bright pulse from J0054+66 at a center frequency of 57 MHz with a bandwidth of 60 MHz.

for each detection. The variations in S/N and pulse widths result in a derived peak flux density that is also variable, with values between about 100 and 160 Jy for the combined bandwidth.



**Table 2**  
Pulse Properties for J0054+66

Frequency (MHz)	FWHM (ms)	Peak Flux (Jy)	Mean Flux (Jy)	Max. S/N
57	$11 \pm 2$	$70 \pm 35$	$0.6 \pm 0.3$	8.3

PSR J0054+66 was not detected in any periodicity searches folded at the period known from the GBT observations with LWA1. An additional 2 hr observation was performed with the intention of improving the detectability in a periodicity search and to get a better estimate on the pulse rate, but no single pulse or periodic emission were detected in this longer session. However, the period derived from the lowest common denominator method is consistent with the period reported from the GBT detection.

### 3.2. J2325–0530

PSR J2325–0530 was the first RRAT to be detected with LWA and has been detected in both observing campaigns. Due to the wider bandwidth of the second campaign, the S/N and burst rate are much higher than in the first observing run, as is shown in Figure 3. This RRAT was originally found in the 2007 GBT’s 350 MHz Drift Scan Survey described previously, with a DM of  $14.966 \pm 0.007 \text{ pc cm}^{-3}$  at a discovery S/N of 13. The burst rate in the 350 MHz GBT and the 110 MHz LOFAR observations were  $46 \pm 9 \text{ hr}^{-1}$  and  $52 \pm 8 \text{ hr}^{-1}$ , respectively (Karako-Argaman et al. 2015). In comparison, LWA1’s detection DM was  $14.963 \pm 0.006 \text{ pc cm}^{-3}$ , with a peak S/N of 19. For the faintest detectable pulses using the combined bandwidth we used an S/N of 6 corresponding to a flux density of  $\sim 60 \text{ Jy}$ . The pulse rate was also much higher than for the detection of J0054+66, with the combined bandwidth observations yielding a rate of  $21 \text{ hr}^{-1}$ , compared to the first observing run’s  $12 \text{ hr}^{-1}$ . Individual pulses have similar shapes with a scattering tail out to  $\sim 30 \text{ ms}$  at  $35.1 \text{ MHz}$  as shown in Figure 4.

Pulse widths for a typical pulse in the individual frequency tunings (Figure 5) were found and are listed along with their S/N, pulse width, and flux density in Table 3. The spectral index of the mean flux density for the pulse shown in Figure 5 is  $\sim -0.7$ . J2325–0530 was not detected in the periodicity searches that were folded at the period from the GBT observations and carried out on each of the detection observations, despite its high pulse rate and S/N. A period of  $0.869 \text{ s}$  was found, however, by determining the least common multiple value between detected pulses. This agrees with the period found from timing observations given in Karako-Argaman et al. (2015).

## 4. DISCUSSION

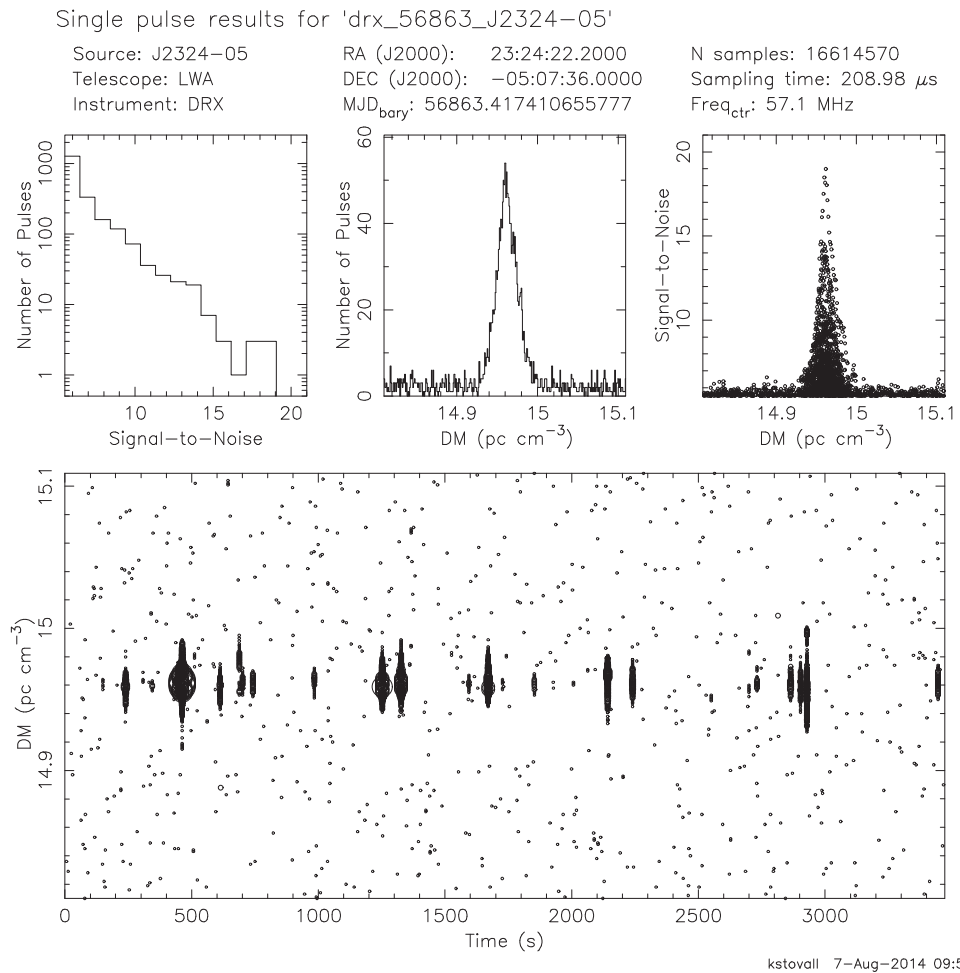
The detection of only two out of 19 RRATs observed is likely a result of the low observing frequency of the LWA1 station, which makes detections difficult due to the effects of pulse broadening by interstellar scattering, in addition to the spectral properties and burst rates of the targets, and the limited sensitivity of LWA1. We note that the faintest detectable pulses for LWA1 are at the level of  $\sim 50 \text{ Jy}$  compared to  $\sim 0.2 \text{ Jy}$  for the GBT at  $350 \text{ MHz}$  (Karako-Argaman et al. 2015). We do not believe that RFI was an issue, especially in the 2014–2015 observing campaign, where we carried out the observations at night-time and most runs were almost entirely devoid of interference other than some short duration burst-like signals across all DMs. The

rare unusable observations in the second run were simply re-observed as the RFI was not persistent. One observation of J0957–06 in the first run tentatively detected a pulse at nearly the correct DM, but the nature of the pulse could not be confirmed. The two observations of this RRAT in the second run did not detect any pulses at the DM of the pulse in the first run.

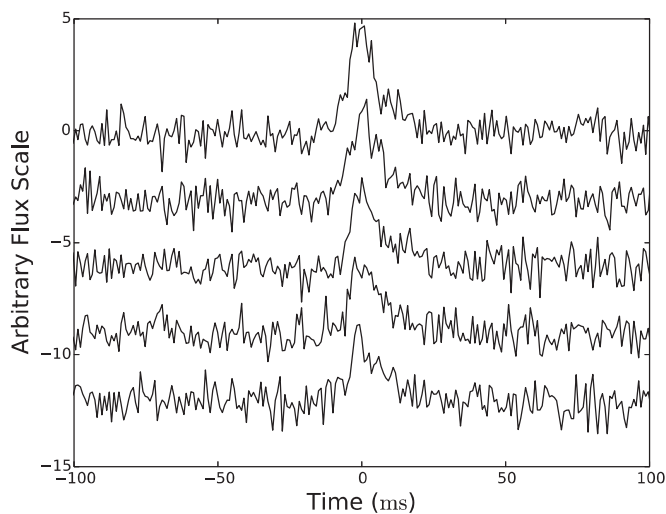
Reasons behind the non-detections can be inferred by investigating the properties of the RRATs that were observed. Both of the detected RRATs have DMs less than  $20 \text{ pc cm}^{-3}$  with somewhat low detected pulse rates compared to their pulse rates in the GBT detections. This suggests that, not surprisingly, RRATs with DMs greater than  $20 \text{ pc cm}^{-3}$  (which make up 14 of the 19 sources observed) will be difficult to detect at these low frequencies due to scattering by the ISM. The non-detections may also be explained by RRATs having flatter spectral indices, thus reducing the flux densities, and therefore observed burst rates, at these frequencies. The degradation in sensitivity with DM can be seen in Figure 6 in which we plot the detected flux density at  $57 \text{ MHz}$ , or the range of expected flux densities. To predict the range in flux density we assumed a spectral index of between  $-1$  and  $-3$ . Only five RRATs had reported flux densities from higher frequency observations. Over this we have plotted the sensitivity of LWA1 to a pulse with a width of 1, 10, or 50 ms assuming an SEFD for LWA1 of  $9100 \text{ Jy}$ , although in practice due to elevation effects the SEFD for our targets ranged between 6000 and 16,000 Jy. From this plot we can see that our two detections are both above the 10 ms sensitivity of LWA1. The predicted fluxes for the five non-detections for which flux measurements are available at high frequencies, however, fall below LWA1’s threshold, assuming a spectral index of  $-1.4$  (Bates et al. 2013) and scattering as predicted by the NE2001 model (Cordes & Lazio 2003). The spectral index must be much steeper, or scattering less significant, in order for these sources to be detectable with LWA1.

The idea of RRATs being too dim to be observed with LWA is somewhat supported by the low DMs of those that we actually detected, although DM is also correlated with scattering which is perhaps the more likely culprit. While pulsars of DMs up to  $50 \text{ pc cm}^{-3}$  have been detected with LWA (Stovall et al. 2015), these were with periodicity searches where the sensitivity is boosted through the folding of the data; no such sensitivity advantage exists for single pulse searches. With that said, none of the RRATs that have been observed in periodicity searches were detected either, including J1850+15 and J0628+09, both of which are now also classified as regular pulsars based on periodicity searches at higher frequencies. J0628+09 has a very high DM of  $88 \pm 2 \text{ pc cm}^{-3}$ , and a predicted scattering timescale of  $824 \text{ ms}$  (Cordes & Lazio 2003) making detection of either single or regular pulses with LWA1 unlikely. Although the DM of J1850+15 is less than  $10 \text{ pc cm}^{-3}$  higher than our detected RRATs, the steep dependence of scattering on DM (Bhat et al. 2004) implies a scattering timescale four times larger, suggesting that scattering could have prevented our detection of this pulsar.

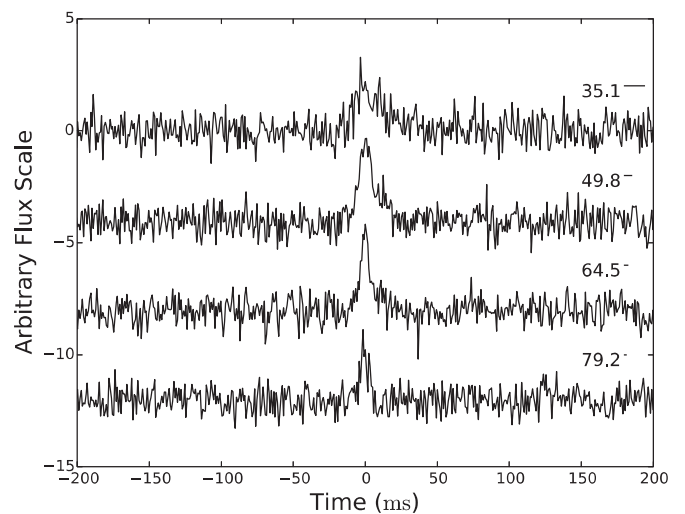
With few studies having been done at frequencies below  $200 \text{ MHz}$ , it is difficult to make conclusions about the intrinsic properties of RRATs at these low frequencies. However, there have recently been studies of normal pulsars at low frequencies, which provide a useful comparison. Normal pulsars often have spectral turnovers around  $100$  to  $200 \text{ MHz}$  and also have significant profile evolution. In some cases the profile evolution is intrinsic while in others it is due to scattering (e.g., Stovall



**Figure 3.** LWA1 detection of J2325-0530 showing pulse detection with the point size scaling with S/N on the bottom, distribution of the number of pulses with S/N at top left, the distribution of the number of pulses with DM in the middle, and the distribution of S/N with DM at top right.



**Figure 4.** LWA1 profiles at a center frequency of 57 MHz and with 60 MHz bandwidth for five strong pulses from J2325-0530 showing a scattering tail.



**Figure 5.** LWA1 profiles for a single pulse from J2325-0530 shown at four different frequencies. The line next to the frequency label indicates the timescale of the interchannel smearing due to dispersion.

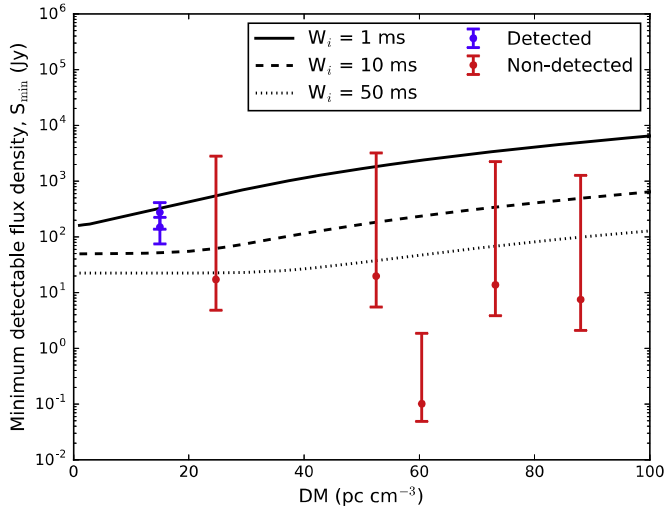
et al. 2015). It may be that some RRATs have a spectral turnover or a flatter than average spectrum, but it is also possible to attribute the non-detections to scattering in the ISM, given average spectral indices. Additional observations of low DM RRATs could help to see if some RRATs enter more active

phases. Also the addition of the LWA-SV station and VLA antennas would triple the sensitivity of LWA. Indeed, the largest difficulty currently in this study is characterized by the high errors on the measurements of the flux densities, pulse widths,



**Table 3**  
Pulse Properties for J2325–0530

Frequency (MHz)	FWHM (ms)	Peak Flux (Jy)	Mean Flux (Jy)	S/N
35.1	$23.1 \pm 2.2$	$150 \pm 75$	$3.9 \pm 1.9$	8.8
49.8	$12.8 \pm 0.9$	$250 \pm 125$	$3.8 \pm 1.9$	14.1
64.5	$7.8 \pm 0.6$	$300 \pm 150$	$2.8 \pm 1.4$	13.2
79.2	$6.8 \pm 0.9$	$240 \pm 120$	$1.9 \pm 1.0$	9.8



**Figure 6.** Peak flux densities at 57 MHz for the two detected RRATs in our sample (blue points) and estimated flux densities for non-detections (red points) calculated using published mean peak flux densities and assuming a spectral index of  $-1.4$ . The error bars shown for each non-detection represent the range of estimated flux densities corresponding to assumed spectral indices of  $-1$  to  $-3$ . Also shown are the sensitivity curves of LWA1 against DM for pulse widths of 1, 10, and 50 ms with the effects of scattering estimated as in Cordes & Lazio (2002).

and consequently the spectral indices. Improving upon both the accuracy of the fitting and the sensitivity would increase the value of these measurements.

## 5. CONCLUSIONS

We have observed 19 known RRATs at between 30 and 88 MHz with LWA1, substantially lower in frequency than their discovery observations. Of the targets observed and analyzed in both single pulse and periodicity search routines, only two RRATs were detected and the pulse widths and flux densities were estimated for each. We calculated the spectral index of J2325–0530 within the LWA band resulting in a value of  $\sim -0.7$ , which is somewhat flatter than for measurements of typical pulsars made at higher frequency (Bates et al. 2013), possibly indicating there may be a spectral turnover in J2325–0530 as is seen in many normal pulsars. We note that these measurements are taken from a small number of bright pulses, however they are in agreement with the spectral index distribution of pulsars reported by Stovall et al. (2015), which showed a spectral index distribution with a mean of  $-0.7$  and a standard deviation of 1.0. Both of these results indicate that for those RRATs LWA1 can detect, they are much brighter at these low frequencies. While the origin of the RRAT’s transient

pulsing nature cannot be significantly constrained by this study, we have demonstrated that RRATs do indeed continue to behave as transients in this little studied frequency band and that their pulse profiles are similar to those observed at higher frequencies. Both of the detected RRATs had DMs below  $20 \text{ pc cm}^{-3}$  while 14 of the 19 RRATs observed but not detected had DMs above this value, confirming the notion that scatter broadening of the pulses is an important factor at long wavelengths. Future studies of RRATs with LWA or other low frequency instruments will likely provide further clues into RRATs, their emission mechanisms, and their relation to the many other subclasses of pulsars.

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