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ALFABURST Initial

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ABSTRACT

The ALFABURST fast radio burst (FRB) survey has been observing commensally with other projects using the ALFA receiver since July 2015. We report on the non-detection of any FRBs from that time until June 2017. With current FRB rate models we expected to see multiple FRBs based on the total observing time, telescope sensitivity and beam size. We discuss the implications for this non-detection FRBs in the context of recent detections with other telescopes.

Key words: radio continuum: transients – methods: observational

1 INTRODUCTION

The first FRB (Lorimer et al. 2007) was detected in a reprocessing of data from a survey of the Magellanic Clouds (Manchester et al. 2006), with an estimated flux density of 30 ± 10 Jy. The detection of this event led to a spurt in single pulse searches, conducted on both archival data (burke-spolaor?) as well as data from surveys specially designed to look for such events. Siemion et al. (2012) conducted a wide-field survey using the Allen Telescope Array, in which each of the forty two antennas of the array was pointed in a different direction. Although this configuration rendered the limiting fluence high (~111 kJy μs), it allowed a large field of view (~147 deg^2). The survey resulted in no detection, and yielded an event rate of 2 sky^{-1} hr^{-1} for 10 ms-wide pulses with flux density greater than 44 Jy.

1.1 Repeater

FRB121102 was discovered in the Pulsar- ALFA (PALFA) survey as a highly disperesed bright single radio pulse in beam 4 with a dispersion measure (DM) of 559 cm^{-3} pc. The results of the single pulse detection were published in Spitler et al. (2014). The authors also compute a FRB rate based on the single detection. Based on the numerical model of the ALFA beams, they obtained a Field of View (FoV) weighted gain of the system and the instantaneous FoV. The total time on sky was computed as the difference of total observation time and total data masked due to Radio Frequency Interference (RFI). Thus, assuming Poisonnian statistics for the FRB rate, they compute the best FRB rate for the computed flux sensitivity of PALFA. They also report FRB rate for flux sensitivity corresponding to a gain greater than 0.4 K Jy$^-$1 which corresponds to the average gain of the Parkes multi-beam receiver. After the initial discovery, more radio follow-up was carried out with no detections at any of the epochs. The follow-up continued into the next year when Spitler et al. (2016) reported the discovery of 10 new bursts in 2015. The bursts had the same DM as the discovery burst and the detections were within a few arc seconds from the initial detection suggesting that the later pulses came from the same source. The authors were unable to find a period for the bursts and also discuss the possiblity that these could be RFI though all the observational evidence suggests that the source is astrophysical.

This discovery generated a lot of interest in multi-wavelength follow-up efforts. Scholz et al. (2016) report the first multi-wavelength follow-up results where seven more bursts were detected, all in radio and two from the Green Bank Telescope taking the total to 17 pulses. They reported an interesting frequency structure the pulses have which varies on a pulse to pulse basis. Spitler et al. (2016) had already showed that the pulses had peculiar frequency behaviour which cannot be explained by scintillation effects in the ISM and the IGM. This alongwith the large range of spectral indices (-13 – 5) observed in the bursts led the authors to believe that the emission variability is intrinsic to the source. The discovery of repeating bursts led to a massive campaign using the Very Large Array (VLA) in order to detect and localize the FRB to arcsecond precision. Chatterjee et al. (2017) reported a successful localization of FRB 121102 with the final position of the burst with an error of 100 mas. Such precise localization made discovery of a counterpart plausible. The paper also reports a discovery of a persistent radio source which is offset by ~12 mas from the point source. Marcote et al. (2017) make a strong argument for the association for the persistent radio source and the FRB based on high resolution European VLBI Network (EVN) observations and also report that the flux variation of the radio source are unlike what would be expected from an Active Galactic Nuclei. Tendulkar et al. (2017) presented the results of the detection of an optical counterpart associated with the radio source and thus with the FRB. Based on the spectrum of the optical source, tehy conclude that it is a mag 25.5AB starforming dwarf galaxy with a total mass of $7{\times}10^7$ M$_\odot$. They also argue that though the optical signatures are unlike any seen from an AGN with optical counterparts, a lot of AGNs are discovered where the optical counterpart is absent and hence no claims on the radio source can be made. They also suggest that localizing such repeater source would be easier if the field was searched for optical spectra similar to the one shown by this source. The big assumption here is that there is a strong relationship between the FRB and the type of hosts where they are found.

2 ALFABURST OVERVIEW

ALFABURST is an Fast Radio Burst (FRB) search instrument which has been used to commensally observe since July 2015 with other Arecibo L-Band Feed Array (ALFA) observations at Arecibo Observatory. This system is a component of the SETIBURST back-end (Chennamangalam et al. 2017) and uses ARTEMIS (Karastergiou et al. 2015) for automated, real-time detection. During this time period an Single Pulse Search (SPS) was performed from Dispersion Measure (DM) 0 to 10000, pulse width from $256\mu s$ to 16 ms, across a 56 MHz bandwidth for all 7 beams. Detections above an Signal-to-Noise Ratio (SNR) of 10 were recorded along with an 8.4 second dynamic spectrum window around the event. If multiple events were detected in the same time window, these events were pooled together. Approximately 150k windows were recorded between July 2015 and June 2017, the vast majority of which are false detections due to Radio-frequency Interference (RFI) signals passing through the real-time RFI exciser. We detect no FRBs in our commensal survey.

A wide-feature, learned model was used to classify the event windows in order to filter out RFI and create a priority queue for visual examination. This model and the post-processing procedures are discussed in Section 6. We discuss the expected event rates in Section 3 and consider possible explanations for our non-detection result in Section 7.

From the beginning of July 2015 to the end of June 2017 ALFA has been used for approximately 1400 hours of observing, with all seven beams functional. Due to pipeline development and hardware reliability ALFABURST was active and functional for, on average, 322 hours per beam. The current system is setup to be reliably in use for all beams any time ALFA is active and in the correct receiver turret position. Of the survey coverage, approximately 65% of the time has been in pointings out of the galactic plane ($|b| > 5°$). These pointings are primarily from to the ongoing AGES survey. Pointings in the plane are primarily from the PALFA survey. Since we are searching up to a DM of 10000 the survey is still sensitive to FRBs at cosmological distances when observing in the galactic plane. But, scintillation effects can reduce the overall FRB event rates (Macquart & Johnston 2015).

3 EXPECTED FRB EVENT RATES

As of this writing, only 23 FRBs have been reported. As these events vary significantly in DM, pulse width, and flux density we assume a simple model to derive an expected event rate with our survey. We use the a model (Lorimer et al. 2013) which assumes FRB sources are standard candles with a fixed spectral index, uniformly distributed in comoving volume. The events rates in this model are scaled to the event rates reported in Thornton et al. (2013).

We use two beam models to derive our expected rates. The first is a simple Full-Width at Half-Maximum (FWHM) beam size with a fixed sensitivity limit that allows us to sample a constant co-moving volume. We also use a model which accounts for the ALFA first side lobes. This results in a sky coverage and sensitivity which varies as a function of beam gain. This model results in a higher expected event rate than the simple FWHM model. We use this full beam model as the Arecibo dish provides high sensitivity at the cost of a smaller beam size. The side lobes of the ALFA feed would be sensitive to many of the previously detected FRBs. By including the full beam we improve our survey coverage while still being sensitive to these brighter FRBs.

3.1 FWHM Beam

An ALFA beam is approximately 3.8' x 3.3' at FWHM across the band. Given the average observing time per beam of 322 hours this results in a survey coverage of 6.2 deg^2 hours.

Using Equation 6 of Karastergiou et al. (2015), an SPS pipeline is sensitive to pulses with a minimum flux density (in Jy) of

$$S_{min} = \mathrm{SEFD}\frac{\mathrm{SNR}_{min}}{\sqrt{D\ \Delta\tau\ \Delta\nu}} \qquad (1)$$

which is a function of the telescope System Equivalent Flux Density (SEFD), the minimum SNR detection level SNR_{min} and the decimation rate D compared to the native instrumental time resolution τ, this comes from the search pipeline which averages together spectra to search for scattered pulses. ALFABURST has a native resolution of $\Delta\tau = 256\ \mu s$, effective bandwidth $\Delta\nu = 56$MHz, and $\mathrm{SNR}_{min} = 10$. The SEFD of the ALFA receiver is approximately 3 Jy across the band for all beams.

The SPS pipeline is configured to search for pulses from 256 μs to 16 ms. Assuming a matched filter this results in a sensitivity to pulses with a minimum flux of $S_{256\mu\mathrm{s}} = 250$ mJy to $S_{16\ \mathrm{ms}} = 31$ mJy. Figure 1 shows the peak flux density of using the standard candle FRB model as a function of source redshift for different model spectral indices. The dashed lines of constant flux is the sensitivity of the ALFABURST search pipeline to pulses of different widths. Assuming a positive spectral index model ($\alpha = 1.4$) results in a sensitivity out to the maximum redshift /DM for pulses with widths of at least 1 ms. A flat spectral index model results in sensitivity from $z \sim 1.5$ out to $z \sim 5$ depending of pulse width. A negative spectral index model ($\alpha \sim -1.4$) limits the survey to $z < 3$.

We will assume a simple model of $\alpha = 0$ as we have limited information about the source spectral index. And, we will use a pulse width of 4 ms as that is an approximate median pulse width of reported FRBs. This results in a maximum redshift of $z = 3.4$ (a co-moving distance of 6.8 Gpc) and a survey volume of 4.2×10^6 Mpc^3 when using all 7 ALFA beams. The number of galaxies sampled in this volume is 4×10^5 assuming a constant galaxy number density of 10^{-2} per Mpc^3. The volumetric event rate from Thornton

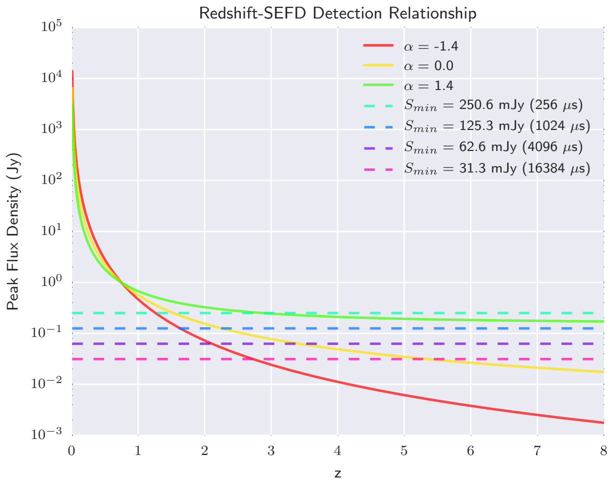

Figure 1. Sensitivity of the ALFABURST search pipeline (dashed) to FRB pulses assuming a standard candle model using different spectral index models (solid).

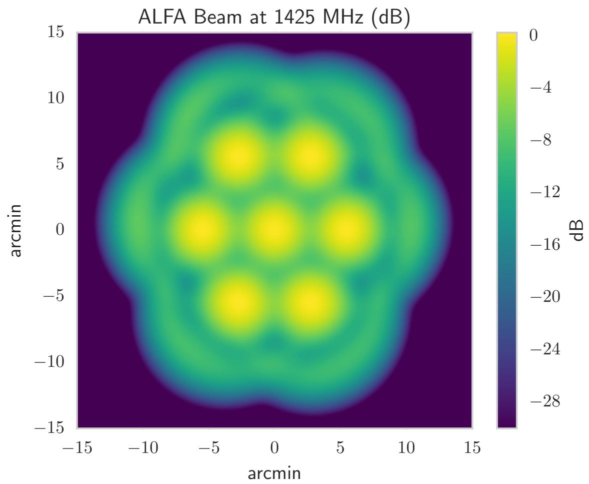

Figure 2. Primary and first side lobe model of the AFLA receiver in decibels, cut-off at −30 dB.The first side lobe peak at around −9 dB.

et al. (2013) is stated to be $R_{\rm FRB} = 10^{-3}$ FRBs per galaxy per year. We should expect to detect ~ 1.5 FRBs based on the current observation time.

3.2 Primary Beam and First Side Lobes

In Section 3.1 we are only take into account the beam size out to the FWHM. We can take into account the entire first side lobes of the beams as Arecibo would be sensitive to detect most previous FRBs in the first side lobes. Using the parameterized ALFA beam model (Figure 2) (Heiles 2004) we can compute the FRB survey metric and expected rates as a function of beam sensitivity. The first side lobes peak at around −10 dB and provide a significant increase in sky coverage compared to just the primary lobes.

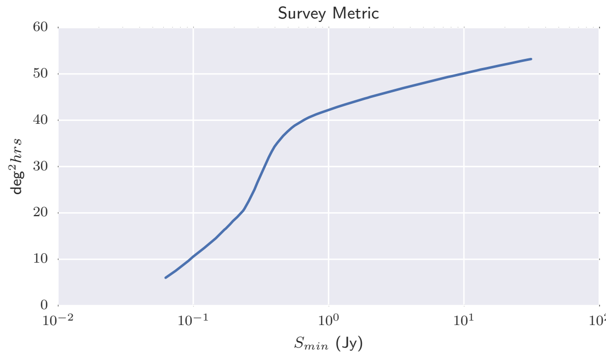

Figure 3. Survey metric as a function of the ALFA receiver minimum sensitivity using the ALFA primary and first side lobes.

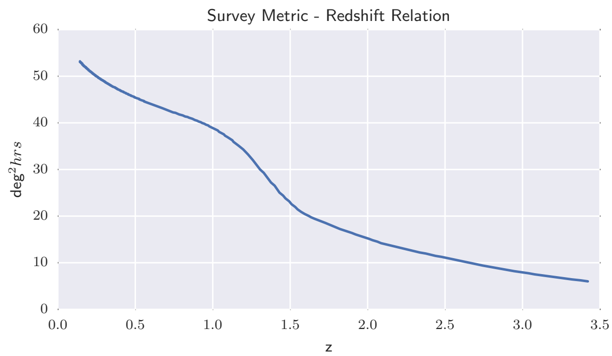

Figure 4. Survey metric as a function of redshift using the standard candle model with a flat spectral index ($\alpha = 0$) and pulse width of 4 ms. The bump out to $z = 1.5$ is due to the including the ALFA first side lobes.

The total survey metric can be computed as a function of the beam sensitivity by integrating over the beam (Figure 3). The flux threshold has been set by assigning the −3 dB the same sensitivity as the FWHM sensitivity. The segment which increased the survey metric to approximately 20 deg^2 hours is due to including more of the primary beam beyond the FWHM point. The steep increase in the survey metric is from including the first side lobes. The long tail is from the residual sensitivity by integrating over the remaining beam.

The significant increase in the survey metric only modestly improves our survey volume. Plotting the survey metric as a function of maximum redshift (Figure 4) shows that the full beam model increases the survey volume out to $z < 1.5$. Including additional ALFA side lobes would have minimal increase in the survey volume.

Accounting for this extra survey coverage results in an integrated survey volume of 5.8^6 Mpc^3. The expected number of FRBs in the survey is ~ 2 when using the same galaxy number density and $R_{\rm FRB}$ as Section 3.1.

3.3 Sensitivity Upper Limit

Part of the SPS pipeline is a parameterized RFI exciser. The choice of these parameters sets an upper limit on the flux of a pulse before it a portion of the flux is clipped and replaced. Individual frequency channels in a spectra are replaced when they exceed a threshold T_{chan} after the spectra is normalized ($\mu = 0$, $\sigma = 1$). And, entire spectra are clipped when the summed spectra exceeds a threshold T_{spectra}. For standard ALFABURST operation $T_{\mathrm{chan}} = 5$ and $T_{\mathrm{spectra}} = 10$.

For very bright, small DM pulses the RFI exciser will replace channels or spectra, reducing the overall flux or potentially removing the entire pulse. For bright, high DM pulses the spectra will likely not be replaced, but individual channels may be, resulting in a lower detected flux. The RFI exciser only works in the undecimated-in-time case ($D = 1$), that is the sensitivity that we are most concerned about when setting the RFI exciser thresholds.

FRBs detected at L-Band range between 200 mJy to a few Jy in flux density, typically on the order of 5-10 milliseconds. For the sensitivity of the ALFA receiver, individual channels of flux greater than 2.8 Jy will be flagged, this will not have an effect on our ability to detect even the brightest FRBs. The maximum integrated pulse flux (256μs width, DM= 0) is ~ 250 mJy before the pulse is clipped. The maximum detectable flux increases as the square-root of the pulse width. We see in verification observations of bright, low DM pulsars that individual pulses are often excised. But, as we are interested in detecting high DM FRBs we have a higher upper limit as the flux is spread over multiple spectra.

For reference the minimum DM of a pulse before the at least one channel is shifted to the next spectra in time is DM= 1.8 for the typical ALFABURST observing band (using Eq. 5.1 of Lorimer & Kramer (2004)). And, the minimum DM before each frequency channel is in a separate spectra is DM= 976. Most reported FRBs fall with in this DM range, so we consider an a test FRB with a dispersion measure of 250 and narrow pulse width of 256μs to report our survey upper-limit sensitivity. A DM of 250 results in approximately 1/128 of the pulse per spectra. A bright pulse (> 32 Jy) would be excised as RFI in this test case. This an extreme case, as most FRBs are wider in width and at higher DMs. Our pipeline would not excise all detected FRBs except the extreme FRB150807. This also assumes the FRB is detected at boresight, we would still be sensitive to such bright pulses in the side lobes.

4 SURVEY COVERAGE

Since ALFABURST was installed, the majority of ALFA observation time is allocated for the AGES (Auld et al. 2006) and PALFA (Cordes et al. 2006) surveys (Figure 5). The AGES survey pointing is off the galactic plane, thus there is little dispersion and scattering due to the galactic Interstellar Medium (ISM). PALFA is a pulsar search survey with pointings near the galactic plane. These lines of sight can introduce significant dispersion due to the ISM. We search out to a DM of 10000 which is well beyond the maximum galactic dispersion, even when Intergalactic Medium (IGM) dispersion is accounted for from sources of cosmological distances. The PALFA survey detected the repeating FRB FRB121102 (Spitler et al. 2014), the only FRB detected with Arecibo thus far. As ALFABURST has been running commensally with the PALFA survey since 2015 these two backends act as independent SPS pipelines, useful for detection verification.

5 SYSTEM VERIFICATION

PALFA survey scheduling includes regularly observing known pulsars to verify timing analysis, this provides a consistent verification of our SPS to detect pulses. As the PALFA survey is performed in the galactic plane a number of high DM pulsars were observed, single pulses from B1859+03 (DM: 402), B1900+01 (DM: 245), B2002+32 (DM: 234), B1933+16 (DM: 158), among others were detected.

6 EVENT PRIORITIZATION AND CLASSIFICATION

7 DISCUSSION

8 FUTURE WORK

The current SPS pipeline is undergoing a significant upgrade. The input bandwidth is limited to 56 MHz of the full 336 MHz digital band due to IO limitations. A new pipeline developed for Square Kilometre Array (SKA) Non-image Processing (NIP) will be used to process the full ALFA band. This will increase sensitivity, and improve detection rate if FRBs scintillate similar to FRB121102. An improved version of the real-time RFI exciser is currently being developed and will be deployed to reduce the false detection rate. The post-processing classifier and prioritizer model is being updated to make use of an auto-encoder to select deep features and auto-generate classes.

Over the time period ALFABURST has been active, the use of ALFA has decreased as the PALFA and AGES surveys end. The 327 MHz and L-band wide feeds are commonly used. We are generalizing the ALFA specific SPS pipeline to be used when these feeds are active, increasing our survey time and sampling a larger portion of frequency space. Additionally, our search pipeline will be duplicated for use on the Greenbank Telescope (GBT) to be commensally run with L-band observations.

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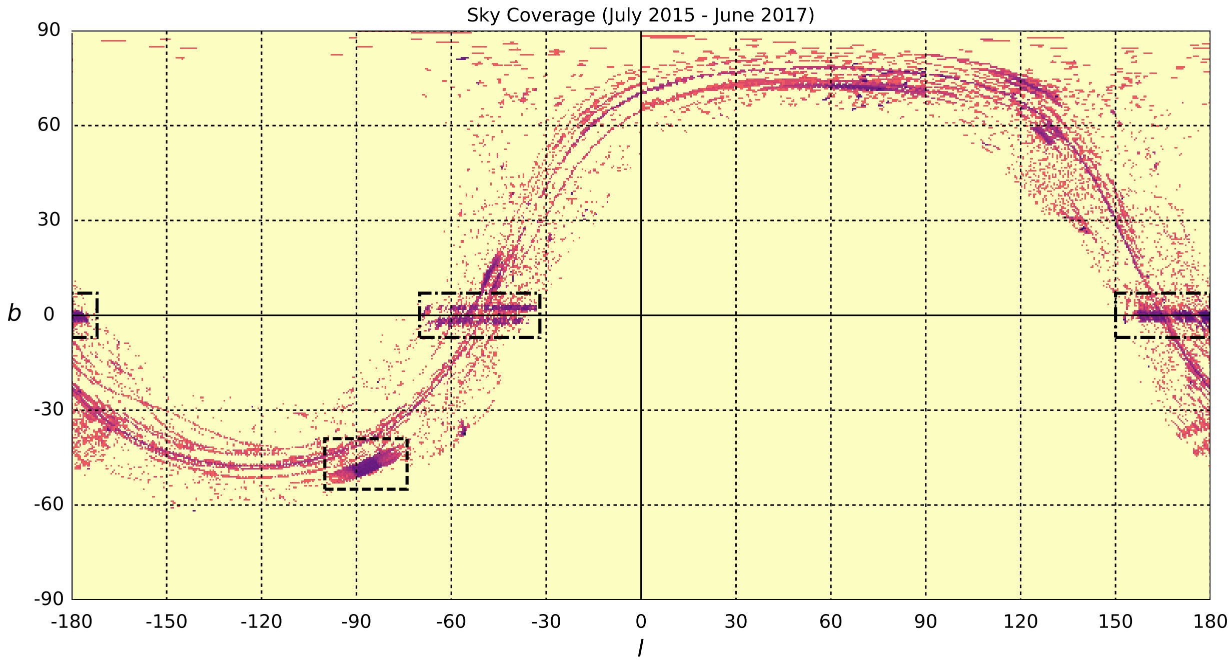

Figure 5. Sky coverage during ALFA usage between July 2015 and June 2017, shown in a Cartesian projection in galactic coordinates. Color represents total time pointing in a log scale. The majority of ALFA usage during this time was for the PALFA survey along the galactic plane (dot-dashed boxes) and the AGES survey (dashed box). The S-shaped arcs across the plot are due to fixed pointings in local azimuth and altitude.

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