MNRAS 000, 1–6 (2017) Preprint 4 August 2017 Compiled using MNRAS LATEX style file v3.0

ALFABURST Initial

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Accepted XXX. Received YYY; in original form ZZZ

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

As of August 2017, 23 Fast Radio Bursts (FRBs) have been reported (Petroff et al. 2016). The majority of which have been detected with the Parkes Radio Telescope at L-Band frequencies. FRB121102 was detected in the PALFA survey using Arecibo Observatory, showing FRBs are not a phenomenon local to the Parkes Telescope (Spitler et al. 2014). This FRB is the only known FRB to repeat (Scholz et al. 2016). FRB110523 was detected with the Green Bank Radio Telescope at UHF frequencies, confirming FRBs occur at other radio frequencies (Masui et al. 2015). Recently, a number of very bright FRBs have been detected with UTMOST (Caleb et al. 2017) and ASKAP (Bannister et al. 2017).

The population of FRBs varies significantly across the parameter space. The measured Dispersion Measures (DMs) varies from 278 (FRB160410) to 1629 (FRB121002), with pulse widths ranging from sub-millisecond unresolved to 10's of milliseconds, and apparent flux densities covering 4 orders of magnitude. The sky distribution of these sources is preferentially at high galactic latitudes (Macquart & Johnston 2015).

So far, FRBs have been poorly localized as most have been detected with single dish telescopes. The unknown detection position in the beam, and one-off nature of FRBs does not allow determination of the absolute flux or spectral index. Only the repeater FRB121102 has been localized using Very Long Baseline Interferometry (VLBI) (Marcote et al. 2017; Tendulkar et al. 2017). Localization is a key observable which needs to be improved in order to identify the source environment. Which requires use of interferometric arrays for arc-minute localization. Arrays such as CHIME, MeerKAT and ASKAP will provide such localization.

Other than localization, more of the frequency space is being searched. Low frequency searches with LOFAR (Karastergiou et al. 2015), MWA (Tingay et al. 2015), and the GBT (Chawla et al. 2017) have reported non-detections. No large surveys for FRBs have been done above L-band frequencies. This is, in part, due to the narrowing of beam size which limits sky coverage. Law et al. (2017) ran a coordinated-in-time, multi-telescope campaign of the repeater FRB. They report non-detection of pulses at VHF, C-band, Ku-band during periods of detected bursts in L-band and S-band.

For single dish telescopes there is a trade-off of sensitivity to sky coverage. Small beams, while providing a large sky coverage, have been unsuccessful at detecting FRBs. Conversely, Arecibo provides the highest sensitivity, but with a very narrow beam. Parkes appears to be near the optimal trade-off point between sensitivity and beam size. ASKAP dishes with Phased-Array Feedss (PAFs) provides a large sky coverage with a significant enough sensitivity to detect bright FRBs. Interferometric arrays such as CHIME and MeerKAT while provide both sensitivity and sky coverage.

2 ALFABURST OVERVIEW

ALFABURST is an 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 DM 0 to 10000, pulse width from $256\mu s$ to 16 ms, across a 56 MHz bandwidth for all 7 beams. We choose this DM limit as it can be approximately associated with a redshift that is far beyond our sensitivity limits as discussed in Section 4. The gain of Arecibo allows for the most sensitive FRB search to date.

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

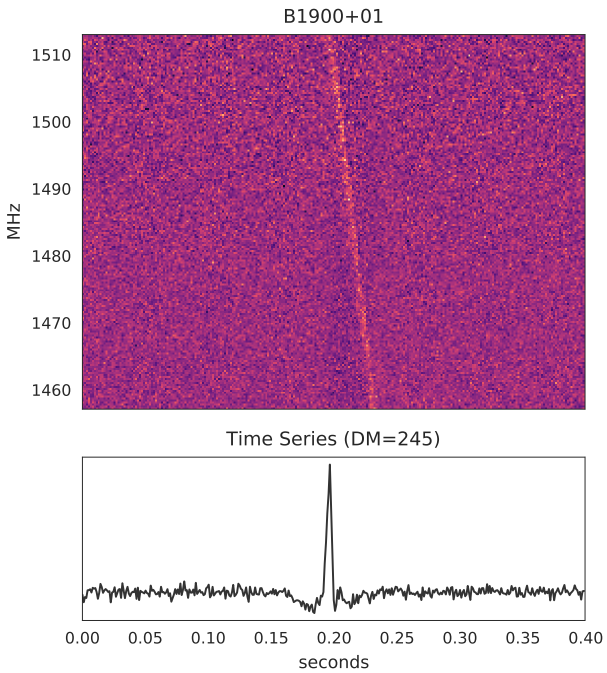

Figure 1. Detection of a single pulse from Pulsar B1900+01 (DM 245). The baseline dip before and after the pulse is due to zero-DM removal.

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 3. We discuss the expected event rates in Section 4 and consider possible explanations for our non-detection result in Section 5.

2.1 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) (Figure 1), B2002+32 (DM: 234), B1933+16 (DM: 158), among others were detected.

2.2 Observing Time

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. The PALFA continues to do a SPS for FRBs across the full band. This provides an independent search pipeline to ALFABURST for these observations. Since the beginning of ALFABURST observations no FRBs have been reported by PALFA. 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).

2.3 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 2). 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.

3 EVENT PRIORITIZATION AND CLASSIFICATION

4 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 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.

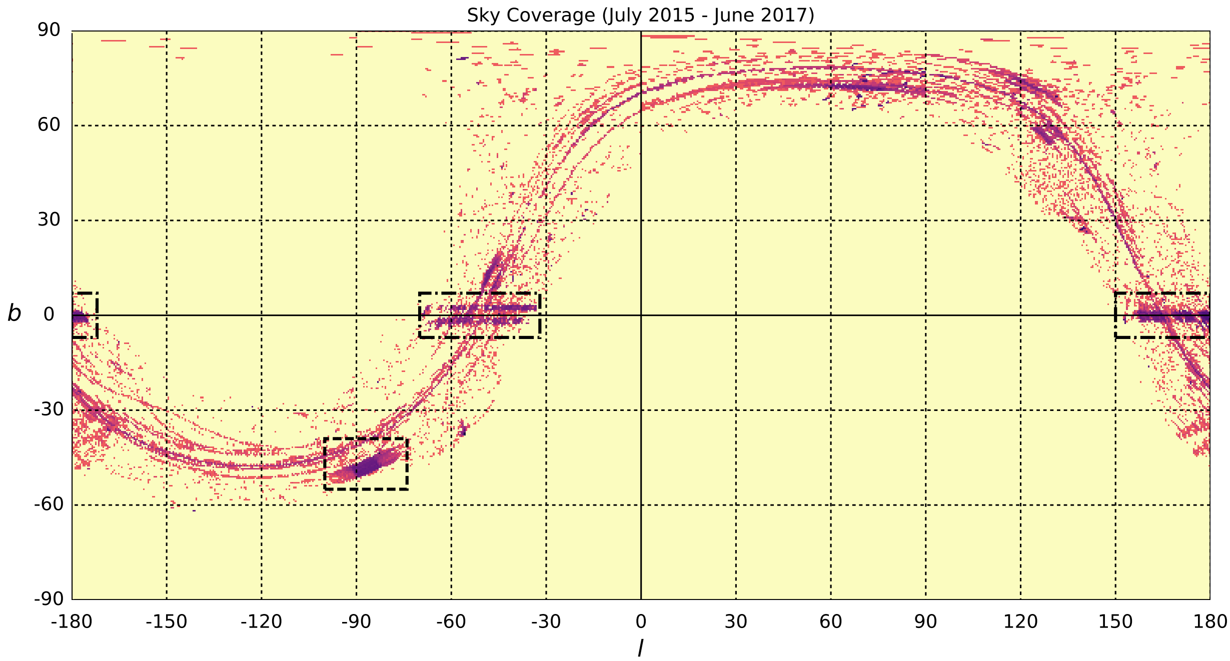

Figure 2. Sky coverage during ALFA usage between July 2015 and June 2017, shown in a Cartesian projection in galactic coordinates. Color represents total time pointing in a log scale. The majority of ALFA usage during this time was for the PALFA survey along the galactic plane (dot-dashed boxes) and the AGES survey (dashed box). The S-shaped arcs across the plot are due to fixed pointings in local azimuth and altitude.

4.1 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 when accounting for all 7 beams. This is a small survey coverage compared to most other FRB surveys, primarily due to the narrow beam size of Arecibo. ALFABURST does not compete with other surveys on sky coverage, rather it is the highest sensitivity FRB survey to date. Using Equation 6 of Karastergiou et al. (2015), an SPS pipeline is sensitive to pulses with a minimum flux density (in Jy) of

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

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 $\Delta\nu$ = 56MHz, and 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 3 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 et al. (2013) is stated to be $R_{\mathrm{FRB}} = 10^{-3}$ FRBs per galaxy per year. We should expect to detect $\sim$ 1.5 FRBs based on the current observation time.

4.2 Primary Beam and First Side Lobes

In Section 4.1 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 4) (Heiles 2004) we can compute the FRB survey metric and expected rates as a function of beam sensitivity. The first side lobes peak

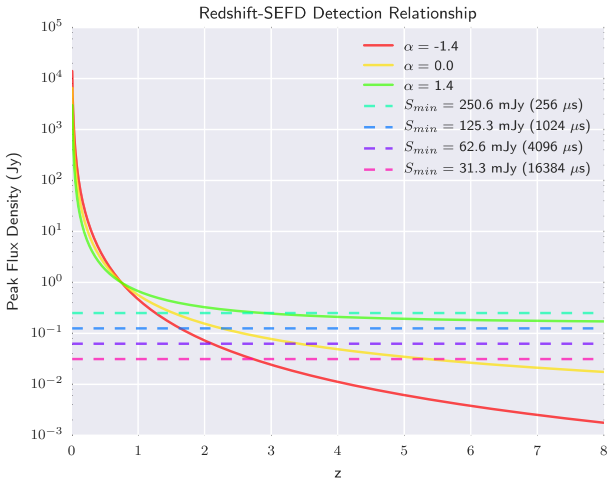

Figure 3. Sensitivity of the ALFABURST search pipeline (dashed) to FRB pulses assuming a standard candle model using different spectral index models (solid).

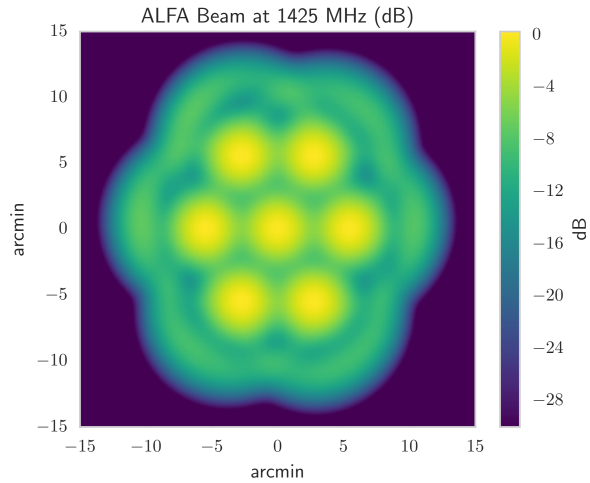

Figure 4. Primary and first side lobe model of the AFLA receiver in decibels, cut-off at −30 dB.The first side lobe peak at around −9 dB.

at around −10 dB and provide a significant increase in sky coverage compared to just the primary lobes.

The total survey metric can be computed as a function of the beam sensitivity by integrating over the beam (Figure 5). 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 6) shows that the full beam model increases the survey volume out to $z < 1.5$.

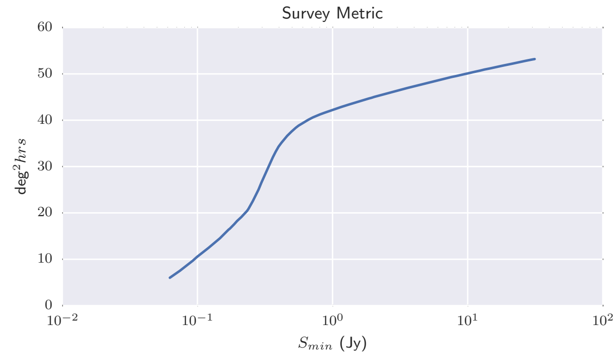

Figure 5. Survey metric as a function of the ALFA receiver minimum sensitivity using the ALFA primary and first side lobes.

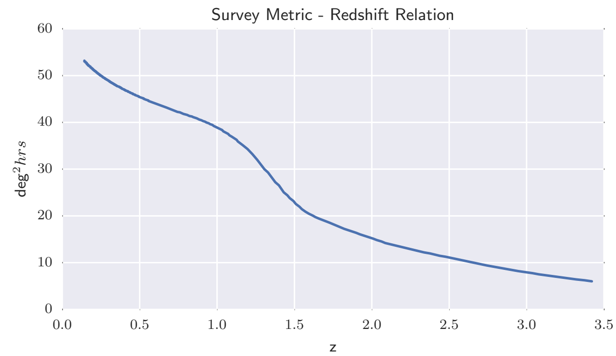

Figure 6. Survey metric as a function of redshift using the standard candle model with a flat spectral index ($\alpha = 0$) and pulse width of 4 ms. The bump out to $z = 1.5$ is due to the including the ALFA first side lobes.

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 4.1.

4.3 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 $T_{\rm chan}$ after the spectra is normalized ($\mu = 0$, $\sigma = 1$). And, entire spectra are clipped when the summed spectra exceeds a threshold $T_{\rm spectra}$. For standard ALFABURST operation $T_{\rm chan} = 5$ and $T_{\rm spectra} = 10$.

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 ($D = 1$),

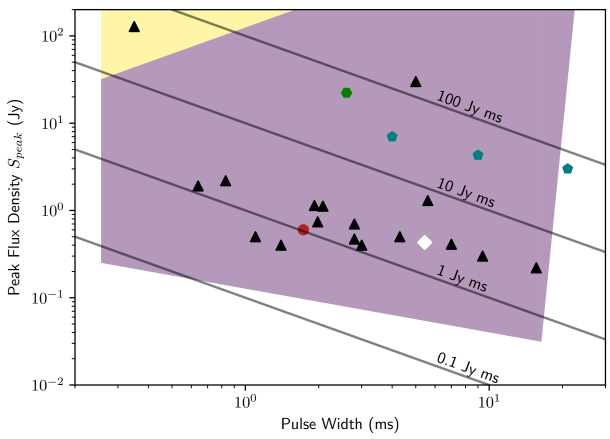

Figure 7. ALFABURST single pulse sensitivity (purple region) improves upon the sensitivity of all past FRB surveys. Automated RFI excision excludes narrow in width, bright FRBs such as FRB150807 (yellow region). Previously detected FRBs from Parkes (black triangle), GBT (red circle), Arecibo (white diamond), UTMOST (cyan pentagon), and ASKAP (green hexagon) are plotted for reference.

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 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. Figure 7 shows that ALFABURST sensitivity region based on pulse width and peak flux, assuming detection at boresight.

4.4 Fluence Rate

5 DISCUSSION

The limited processing bandwidth of ALFABURST may be a cause of the survey non-detection. Multiple detected FRBs show apparent scintillation and step spectral indicies. It is not possible to differentiate between an apparent spectral index induced by the beam or an absolute spectral index from the source. If an FRB did occur in the field of view of the telescope while ALFABURST was in operation we could have been unlucky and scintillation caused the pulse in the band to go below the detection threshold. An increase to the full ALFA band would result in a $\sqrt{6}$ increase in sensitivity, assuming no scintillation. This would increase our event rates to ~ 5 FRBs for the current amount of observation time.

6 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.

Jupyter notebooks are hosted on our public git repository[1].

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