Fast Radio Bursts - I: Initial Cogitation

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ABSTRACT

Fast radio bursts (FRBs) are millisecond-duration radio signals thought to originate from cosmological distances. Many authors are endeavouring to explain their progenitors, with others outlining their potential uses as cosmological probes. Here we describe some sub-optimal performance in existing FRB search software, which can reduce the volume probed by over 20%, and result in missed discoveries and incorrect flux densities and sky rates. Recalculating some FRB flux densities, we find that FRB 010125 was approximately 50% brighter than previously reported. Furthermore we consider incompleteness factors important to the population statistics. Finally we make data for the archival FRBs easily available, along with software to analyse these.

Key words: surveys — intergalactic medium — methods: data analysis

1 INTRODUCTION

Fast radio bursts (FRBs) are millisecond-duration jansky-flux density signals discovered by single dish radio telescopes operating at frequencies of \( \sim 1.4 \) GHz (Lorimer et al. 2007; Keane et al. 2011; Thornton et al. 2013; Spitler et al. 2014; Burke-Spolaor & Bannister 2014; Petroff et al. 2014b). All but one were detected with the 64-m Parkes Telescope; the other with the 300-m dish at Arecibo. The bursts exhibit a frequency-dependent time delay which obeys a quadratic form so strictly that the signals could only have traversed low density regions, such as the interstellar and intergalactic media, en route to Earth (Dennison 2014). The magnitude of this delay — parametrised by the dispersion measure (DM), which is the integrated electron density along the line of sight — is so large that cosmological distances are inferred for the sources of the FRBs (Ioka 2003; Inoue 2004).

There are two main questions of interest in relation to FRBs: (i) what are they? (ii) what can they be used for? The source of the FRB signals is hotly debated in the literature with suggested progenitors ranging from terrestrial interference and flare stars (Burke-Spolaor et al. 2011; Loeb et al. 2014) to neutron star-neutron star mergers, gamma-ray bursts and planetary companions to extragalactic pulsars (Totani 2013; Zhang 2014; Mottez & Zarka 2014). However, the two leading candidate theories are that FRB bursts are associated with giant magnetar flares (Kulkarni et al. 2014; Lyubarsky 2014), or that they are “blitzars” occurring when a neutron star just above the Tolmann-Oppenheimer-Volkoff limit collapses to a black hole (Fulcke & Rezzolla 2014). Amongst other observables which would distinguish between these two possibilities (see e.g. Ravi & Lasky 2014) we simply note that magnetar flares repeat whereas blitzars are one-off events. For an expansive discussion of FRB origin possibilities we refer the reader to Kulkarni et al. (2014).

The uses of FRBs are many: they have the potential to be used as astrophysical/cosmological tools to make several important measurements. FRBs can be used to weigh the ‘missing baryons’, as it is the ionised component of these same baryons which cause the dispersion of the FRB signal (McQuinn 2014). The measurement of the rotation measure of a linearly polarised FRB would tell us the magnetic field strength of the intergalactic medium, analogously to what has been done in the Milky Way using pulsars, see e.g. Noutsos et al. (2008). If a sufficiently large sample of FRBs were identified, with independent redshift measurements from observations at other wavelengths the distribution of the DM values as a function of redshift can be used as an independent measure of the dark energy equation of state (Gao et al. 2014; Zhou et al. 2014).

Determining progenitors and fully exploiting the exciting cosmological possibilities demands that we detect more FRBs. To do this we have undertaken a large-scale FRB search of existing archival data, which we will describe in a series of papers. In this first paper, we set the scene, by discussing, in § 2, commonly used search techniques including some flaws therein that can unnecessarily reduce the sensitivity of the search, and the impacts of this. In § 3 we discuss three known archival FRBs. In § 4 we discuss additional incompleteness factors one ought to consider when deriving population statistics. Finally, in § 5 we present our conclusions and highlight our online data and code repositories which we hope will encourage further FRB analysis.
2 SINGLE PULSE SEARCHES

FRBs are detected as follows: (i) Acquisition: Radio telescopes record incoherent filterbank data: these are time-frequency-flux density data cubes. Thus far the data wherein FRBs have been discovered have been centred at $\sim 1.4 \text{ GHz}$ with bandwidths ranging from $288 - 400 \text{ MHz}$, frequency resolutions ranging from $0.336 - 3 \text{ MHz}$ and time resolutions ranging from $0.064 - 1 \text{ ms}$; (ii) Cleaning: The data are cleaned of radio frequency interference signals in various ways; (iii) Dedispersion: The data are dedispersed at a number of trial dispersion measure (DM) values to remove frequency-dependent delays imparted by the interstellar and intergalactic media; (iv) Search: Each dedispersed time series is subjected to a single pulse (SP) search, which is a matched filter search to a number of trial boxcar widths. Usually events down to a level which is well within the noise floor are recorded; (v) Refinement: Upon detection optimised DM and width values of the pulse are derived.

In steps (ii)--(iv) there is the potential for a loss in sensitivity. All of these are avoidable, but accuracy is sometimes sacrificed for processing speed. The DM parameter is always covered in a ‘scalloped’ fashion, where the next DM trial is chosen so as to limit the sensitivity loss of a narrow pulse falling between DM trials. Typically the choice is to lose no more than $\sim 10\%$ of the sensitivity for bursts narrower than the sampling time. However FRBs are typically much wider than the sampling time, and the observed width is dominated by dispersion smearing so that the loss in sensitivity to FRBs is typically much less than this. As DM corresponds to the volume probed in a line-of-sight dependent way, the actual volume probed can be quite uncertain, especially for lines-of-sight closer to the Galactic plane.

The searching step can be subject to the ‘root 2 problem’, which manifests itself when performing a ‘decimation search’. This is a procedure in which a time series is searched for events of 1 sample in width. It is then down-sampled by a factor of 2, averaging adjacent samples. This process is repeated a number of times in order to search for a range of pulse widths (Cordes & McLaughlin 2003). However, this search method is not optimal. For example, let’s consider a time series with samples $i$, $i=1,2,3,4,...$, and a top-hat pulse which is 4 bins wide, occupying bins 3,4,5 and 6. This pulse is ‘out of phase’ with respect to the down-sampling procedure and it is clear that the derived S/N will be too low by a factor of $\sqrt{2}$. The optimal way to search a time series is to run a sliding boxcar along the time series.

Figure 1 illustrates this problem by showing the results of searching for a synthesised FRB as it is moved along a time series in single time sample steps up to one pulse width in total. The results of several commonly used SP search codes are shown. In particular these are HEIMDALL$^1$, DEDISPERSER_ALL$^2$, SEEK$^2$ DESTROY$^3$. Here a ‘typical’ FRB with an intrinsic pulse width of 2 ms (16 bins for the simulated time sampling value of 125 µs), a DM of 1000 cm$^{-3}$pc, and an injected S/N of 16, is used. The data are centred at a frequency of 1374 MHz with spectral resolution of 3 MHz meaning the dispersion smearing will make the observed pulse width 7.4 ms (59 bins). Thus, for a power-of-2 boxcar search the optimal S/N we expect to find is $16 \times \sqrt{59/64} = 16 \times 0.9375 = 15.4$.

We can see that DEDISPERSER_ALL reaches the maximum theoretical S/N when the pulse is ‘in phase’ and reaches a minimum S/N when the pulse is ‘out of phase’. SEEK has the same problem, although to a lesser extent, and is relatively rotated in phase and with a response curve which repeats at twice the frequency. These differences are because SEEK performs an extra 2-bin smoothing step to the data prior to each down-sampling step. HEIMDALL and DESTROY give the correct result for all ‘phases’. We have verified that the curves in Figure 1 scale directly with the injected S/N. One can quickly make a simple estimate of the effects of these results on a survey, e.g. for an $N \propto S^{-3/2}_{\text{min}}$ law SEEK probes 86% and DEDISPERSER_ALL only 78% of the volume probed by HEIMDALL and DESTROY. The true volume probed will be even lower than this however as here the exact DM of the pulse has been used, so that the ‘scalloping’ loss factor (which would effect all four codes equally) has been removed. Crucially this can mean that FRBs detectable in our data are never detected. Some of these errors can also result in incorrect flux density and volumetric rate estimates for those FRBs which are detected.

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1. http://sourceforge.net/projects/heimdall-astro/
2. See e.g. https://github.com/SixByNine/parsoft
3. https://github.com/evanocathain/destroy_gutted
3 ARCHIVAL FRBS

Here we look at the three archival FRBs reported so far in the literature. We do not examine the bursts reported by Thornton et al. (2013), Spitler et al. (2014) or Petroff et al. (2014b). The FRBs, which all occurred in 2001, are discussed in the chronological order of their discovery which, as it happens, is the reverse chronological order to when they actually occurred.

FRB 010724

FRB 010724, the so-called “Lorimer Burst”, the first FRB to be discovered, was by far the strongest of any FRB detection to date (see Figure 2). It saturated the 1-bit digitiser in the main beam in which it was detected, and was additionally detected in 3 other beams (Lorimer et al. 2007; Burke-Spolaor et al. 2011). Using DESTROY we determine the S/N value and corresponding width values to be \( \gtrsim 100 \) and \( \sim 20 \text{ ms} \) (beam 6), \( 16(1) \) and \( 9^{+12}_{-5} \text{ ms} \) (beam 7), \( 6(1) \) and \( 33^{+28}_{-28} \text{ ms} \) (beam 12), and \( 27(1) \) and \( 15^{+9}_{-5} \text{ ms} \) (beam 13), and \( < 5 \) over a wide range of widths in all other beams. The S/N estimate for beam 6 is a lower limit due to the digitiser saturation (Lorimer et al. 2007). The corresponding detected peak flux density values are \( > 1500 \text{ mJy} \) (beam 6), \( 357^{+73}_{-138} \text{ mJy} \) (beam 7), \( 83^{+24}_{-6} \text{ mJy} \) (beam 12), and \( 554^{+84}_{-85} \text{ mJy} \) (beam 13). The limits for the other beams are, assuming the same width as for the weakest detection in beam 6, \( < 54 \text{ mJy} \) (beam 1), \( < 58 \text{ mJy} \) (inner ring, \( \neq 6, \neq 7 \)) and \( < 69 \) (outer ring, \( \neq 12, \neq 13 \)). We note that we have not included the additional source of uncertainty (which is at the \( 20 \% - 30 \% \) level) which arises from the scaling to flux density units.

One can use the multiple detections to try to refine the localisation of the burst. Noting the beam configuration and invoking a simple Gaussian beam model (Staveley-Smith et al. 1996) it is straightforward to show that for two beams with relative detected flux densities \( f \), full-width half-maxima \( f \) and beam separation \( s \), the angular offset to the true position of the source, along the line joining the two beams, is given by: \( s/2 + (1/s)(f/2.355)^2 \ln r \). The offset in the perpendicular direction is unconstrained for a single pair. Using two pairs of beams one can define a point (or region, when the uncertainties are included). Using a third, or more, pairs gives a consistency check.

Applying this method, using the values quoted above, and ignoring the uncertainties in the flux densities, defines a region on the sky whose centre is at \( (\alpha, \delta) = (19.154, -75.155) \), where \( \alpha \) is in degrees of right ascension and \( \delta \) is in degrees of arc. The offset with respect to the centre of beam 6 is \( (\Delta \alpha, \Delta \delta) = (-0.371, 0.050) \), i.e. the position is WSW of beam 6. The errors on the position are large, i.e. of the same order as this offset. They are at least \( 5.1 \text{ arcmin} \) : \( (\sigma_{\alpha}, \sigma_{\delta}) = (0.332, 0.085) \), and are about double this if the uncertainty in the flux densities (mentioned above) are included. So it seems that FRB 010724 occurred somewhere within the full-width half-power range of beam 6. In comparison to the estimate of Burke-Spolaor et al. (2011) we are in agreement, with our uncertainties slightly larger\(^4\). Assuming our above position would imply a true flux density of at least \( > 1.5 \text{ Jy/G(6.4 arcmin)} > 2.7 \text{ Jy} \), where \( G \) denotes the angular response of the beam. Our estimate and that of Burke-Spolaor et al. (2011) differ from the kite-shaped region determined by Kulkarni et al. (2014), perhaps because that analysis did not include the detection in beam 12. In theory, with knowledge of the frequency-dependent beam response one could also estimate the true spectral index (which is highly degenerate with position) if sufficient S/N existed to measure the spectral index in multiple beams. We do not attempt this (and our analysis implicitly assumes a flat spectral index) as (i) we do not have such a beam response model; and (ii) our position is less localised than that of Burke-Spolaor et al. (2011), who determined a spectral index in the range \( \sim 2.5 \) to \( 0.6 \), the uncertainty we would obtain would therefore be worse than this. Clearly the uncertainty in FRB spectra is huge, and dramatically so for all FRBs detected in just one beam, as illustrated well in Spitler et al. (2014) where an uncertainty of an order of magnitude in the spectral index is noted.

We also note the existence of a previously unreported narrowband signal trailing the FRB (see Figure 2). This is seen in a single frequency channel only (between frequencies 1395 and 1398 MHz), is \( \sim 20(2) \text{ ms} \) in duration, and trails the FRB by \( \sim 46(2) \text{ ms} \). The S/N of this pulse is difficult to determine given the saturation, but is nominally \( \sim 10 \). This channel is not known to have been subject to radio frequency interference, e.g. in the Parkes Multi-beam Pulsar Survey (Manchester et al. 2001), which used this receiver over the course of several years around the time of the FRB. This pulse is not seen in any of the other 12 beams. On the face of it, this is statistically significant, although we can offer no explanation for its origin. To allow the reader make an informed assessment we have not removed the known ‘bad’ channels in Figure 2.

FRB 010621

FRB 010621 was the second FRB to be identified (Keane et al. 2011) and was a much weaker detection than FRB 010724. The S/N value and corresponding width values are \( 18(1) \) and \( 8^{+4}_{-3} \text{ ms} \) (beam 10) and \( < 5 \) over a wide range of widths in all other beams. The corresponding flux density values were \( 505^{+111}_{-117} \text{ mJy} \) (beam 10), \( < 111 \text{ mJy} \) (beam 1), \( < 118 \text{ mJy} \) (outer ring), \( < 140 \text{ mJy} \) (inner ring), \( < 140 \text{ mJy} \) (outer ring, \( \neq 10 \)), where again we do not include the flux density scaling uncertainty in this estimate. As per all flux density values based upon detections within a single beam, this is a lower-limit and the true value is larger by the inverse of the gain curve at the (unknown) offset position. As a single-beam detection the positional uncertainty can only be refined using its non-detection in the closest surrounding beams (3 and 4): this is a poor constraint which yields only that the pulse must be within a \( \sim 12.2 \text{ arcmin} \) radius of the centre of the beam in which it was discovered. The burst’s DM is nominally extragalactic but Keane et al. (2012) could only find Galactic solutions compatible with this burst, and Bannister & Madsen (2014) determined that there is a high probability that the electron density along this line of sight is underestimated (2011) was given in degrees of arc, rather than degrees of right ascension (Burke-Spolaor, priv. comm.).
The detected flux density-observed width parameter space. Lines of constant signal-to-noise (dashed) and constant fluence (solid) are shown. Events above the thick black flux density limit line are detectable at Parkes. In this case, and if all FRBs are less than some maximum putative width (here denoted by the thick vertical line), we only have completeness in terms of fluence above the thick black line. In the shaded triangle we have incomplete coverage of fluence. Note that here the Arecibo FRB (green triangle) is included for illustration only. The sensitivity curves from Arecibo differ to those from Parkes; different incompleteness regions apply to different observing configurations.

so that a Galactic source seems most favoured. The actual progenitor is unlikely to be definitively identified unless it is seen to repeat.

FRB 010125

FRB 010125 has recently been reported by Burke-Spolaor & Bannister (2014). The S/N value and corresponding width value is 25(1) and $10^{1.3}$ ms (beam 5) and < 5 over a wide range of widths in all other beams. The corresponding flux density values were 530 ± 85 mJy (beam 5), < 100 mJy (beam 1), < 106 mJy (inner ring, ≠ 5), < 125 mJy (outer ring), where again we do not include the flux density scaling uncertainty in this estimate. The non-detection in surrounding beams tells us only that the true position is no closer to the central beam than ~11.9 arcmin, and no closer to the closest inner (outer) ring beams than ~12.0 (~12.1) arcmin. The reported S/N by Burke-Spolaor & Bannister (2014) was 17(1) but our value is ~ $\sqrt{2}$ times higher. Our minimum flux densities are more so in disagreement, due to differing width estimates, although the appropriate width to use is vague: Burke-Spolaor & Bannister (2014) use the full-width at half the maximum value whereas we are essentially using the equivalent width. The true discrepancy is about a factor of $\sqrt{2}$, which we postulate to be due to the root 2 problem discussed in § 2.

4 SELECTION EFFECTS IN FRB SEARCHES

The estimate for FRBs detectable by the current setup at Parkes is ~ $10^4$ FRBs/(4π sr)/day (Thornton et al. 2013). This number is simply the observed rate of 4 FRBs in 23 days, extrapolated, from the ~ 0.55 deg$^2$ half-power field-of-view of the multi-beam receiver at Parkes (Staveley-Smith et al. 1996), to the entire sky. In addition to the obvious caveats of such an extrapolation, the meaning of this rate must be interpreted carefully, for a number of reasons.

Fluence & Width Incompleteness? One might suggest that the all-sky rate is that above the flux-density threshold at the half-power beam-width of Parkes. Using the system configuration relevant to the data wherein the 3 bursts discussed here were found this corresponds to flux densities of $1.01/\sqrt{W/\text{ms Jy}}$ (1.07/√W/ ms Jy or 1.27/√W/ ms Jy) for the central (inner or outer ring) receivers, for an 8-ω signal. Even though the physically relevant parameter is the fluence, i.e. the area under the pulse curve in the dedispersed time series, our sensitivity depends also on the pulse width. Thus, pulses with the same fluence but different widths (due to traversing different paths in the IGM/ISM) are not equally detectable. Figure 3 shows the sensitivity to bursts in the flux density-width plane. We are always incomplete to wide bursts. However if FRBs do not exist above some maximum width we are still left with an incomplete sampling of fluence. Such selection effects should be considered when determining population estimates, especially when extrapolating to lower frequencies where observed pulses are likely to be wider (Trott et al. 2013; Coenen et al. 2014).

Latitude dependence?: Some additional selection effects have been identified empirically, e.g. FRBs seem to be much more difficult to detect at lower Galactic latitudes, despite intensive efforts (Petroff et al. 2014a; Burke-Spolaor & Bannister 2014). This points towards a Galactic obscuration effect but at present none of the known possibilities are sufficient to explain the paucity of low-latitude detections. The possibility remains that the rate (extrapolated from 4 events, see above) is in fact too high.

What is an FRB?: There is also the question as to how
to algorithmically define what an FRB is, in contrast to a "RRAT"; pulsars which show detectable single pulses of radio emission only very occasionally (Keane & McLaughlin 2011). If we detect a single pulse from a RRAT how do we distinguish it from an FRB? A RRAT may eventually repeat but the main difference is that RRATs are Galactic whereas FRBs are believed to be extragalactic. We decide upon this based on the ratio of the $DM$ of a detected event to the maximum Galactic $DM$ contribution along the line of sight, $DM_{\text{max}}$. If $x = DM/DM_{\text{max}} > 1$ then the source is extragalactic, but the model we use to determine $DM_{\text{max}}$ is quite uncertain, especially at high Galactic latitudes (Cordes & Lazio 2002). This has resulted in ad hoc selection rules such as selecting events with $x > 0.9$ (Petroff et al. 2014a), but, as noted in Spitler et al. (2014) there is a rather wide ‘grey area’ in this parameter space. As the uncertainty on $x$ depends both on the $DM$ and the line of sight in very asystematic ways this is difficult to quantify and it is quite conceivable that many FRBs have already been detected and falsely labelled as RRATs, and the converse may already be the case for FRB 010621. In effect there is a low-redshift blindness to FRBs, analogous to the low-$DM$ blindness in Galactic SP searches (Keane et al. 2010).

5 CONCLUSIONS, DATA & SOFTWARE RELEASE

With so many selection effects evident, large uncertainties in flux density and fluence estimates (see § 3), essentially no knowledge of FRB spectra, and when dealing with such small number statistics, serious population analyses are precluded. These obstacles will be overcome only when a much larger number of FRBs are discovered. For example, to remove the fluence incompleteness one could simply discard all FRBs below the incompleteness value, but this is only practical (see Figure 3) when a much larger sample is obtained. To remove the low-redshift blindness we would benefit from independent distance estimates. New means of estimating the distance, such as the method of Bannister & Madsen (2014), could shed some light on this if they are applied to a large sample of RRATs and FRBs. The clear scientific potential of FRBs further motivates a search for more, and as such we are currently performing a large-scale search of the existing archival data, some of which has either never been searched previously, or has only been searched to a limited extent. We will present the results of this search in subsequent papers. Beyond that the only way to discover hundreds to thousands of FRBs is to use high sensitivity wide field-of-view telescopes with a large amount of on-sky time, e.g. through ‘piggy-back’ transient observations with MeerKAT and SKA1-Mid (Fender 2015).

We have made the data easily available for the three archival bursts discussed in this paper. The data can be accessed via a DROPBOX repository. Additionally analysis software is available and can be accessed via a GITHUB repository. These have been used in the preparation of this paper. It is our hope that others can use these to directly access and analyse the raw data collected at the telescope. In this way uncertainties and misinterpretations can be minimised, and new predictions and analysis tools can be quickly tested.

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5 https://www.dropbox.com/sh/16kr870xaxspxg367/AAAgdvv-ZdqcMpxOx2mfKOG3a
6 https://github.com/evanocathain/Useful_FRB_stuff