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Fast Radio Transient searches with UTMOST at 843 MHz

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ABSTRACT

We report the first radio interferometric search at 843 MHz for fast transients, particularly Fast Radio Bursts (FRBs). The recently recommissioned Swinburne University of Technology's digital backend for the Molonglo Observatory Synthesis Telescope array (the UTMOST) with its large collecting area (18 000 m^2) and wide instantaneous field of view (7.80 deg^2) is expected to be an efficient tool to detect FRBs. As an interferometer it will be capable of discerning whether the FRBs are truly a celestial population. We show that UTMOST at full design sensitivity can detect an event approximately every few days. We report on two preliminary FRB surveys at about 7 per cent and 14 per cent, respectively, of the array's final sensitivity. Several pulsars have been detected via single pulses and no FRBs were discovered with pulse widths (W), in the range 655.36 μs $< W <$ 41.9 ms and dispersion measures (DMs) in the range $100 < \mathrm{DM} < 2000$ pc cm^{-3}. This non-detection sets a 2σ upper limit of the sky rate of not more than 1000 events sky^{-1} d^{-1} at 843 MHz down to a flux limit of 11 Jy for 1 ms FRBs. We show that this limit is consistent with previous survey limits at 1.4 GHz and 145 MHz and set a lower limit on the mean spectral index of FRBs of $\alpha > -3.2$.

Key words: instrumentation: interferometers – methods: data analysis – surveys – pulsars: general.

1 INTRODUCTION

High time resolution astronomy over the last decade has led to the discovery of new classes of radio sources such as the Rotating Radio Transients (RRATs; McLaughlin et al. 2006) and Fast Radio Bursts (FRBs; Lorimer et al. 2007; Thornton et al. 2013; Burke-Spolaor & Bannister 2014; Spitler et al. 2014; Champion et al. 2015; Masui et al. 2015 ; Petroff et al. 2015; Ravi, Shannon & Jameson 2015; Keane et al., in preparation). The majority of the RRATs and all the FRBs are characterized by millisecond duration pulses implying coherent physical processes in their origin if they are compact sources. RRATs have been found to repeat on time-scales of a few pulses an hour to a few pulses a day while FRBs have not yet been seen to repeat. These elusive bursts have ∼Jy peak flux densities and dispersion measures that well exceed the contribution from the Milky Way along the line of sight indicative of a possible a cosmological origin. Only a handful of FRBs are known, and to date no transient event or afterglow has been seen at any other wavelength despite major efforts to do so (Petroff et al. 2015). Several cosmological and non-cosmological models for the origin of FRBs have been suggested, including radio emission from pulsars (Connor, Sievers & Pen 2015; Cordes & Wasserman 2015), collapsing gravitationally unstable black holes (Falcke & Rezzolla 2014), hyper flares from magnetars (Lyubarsky 2014) and dark matter induced collapse of neutron stars (Fuller & Ott 2015).

Caleb et al. (2015) have performed Monte Carlo simulations of a cosmological population of FRBs to study the distributions of their observed and inferred properties and their log$N$–log$\mathcal{F}$ curve. From comparison of the slope of the log$N$–log$\mathcal{F}$ curves of their simulations with the slope of the log$N$–log$\mathcal{F}$ curve of the observations they conclude that FRBs are consistent with being of cosmological origin. If FRBs are indeed cosmological in origin, they could be potentially used to probe the 'missing baryon problem' (McQuinn

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2014), obtain rotation measure of the intergalactic medium (IGM) along the line of sight (Zheng et al. 2014) and also as an independent measure of the dark energy equation of state (Zhou et al. 2014). Most of the FRBs that have been discovered to date i.e. between 2007 and 2015, have all been seen at 1.4 GHz using single dish antennas with relatively poor angular resolution. This means that their spatial localization is poor and lacks the precision required to unequivocally associate them with a possible host galaxies. Until 2013, FRBs had only been discovered in archival surveys, but since 2014 we have entered the era of real time detections with rapid multiwavelength follow-up with three already having been done at Parkes (Petroff et al. 2015; Keane et al., in preparation). Thornton et al. (2013) estimate the FRB event rate as $1.0^{+0.6}_{-0.5} \times 10^4$ sky^{-1} d^{-1}. Keane & Petroff (2015) have reanalyzed the Thornton et al. (2013) results and derive a fluence complete event rate of 2500 events sky^{-1} d^{-1} above a fluence of 2 Jy ms.

There is clearly a need to discover FRBs more efficiently as the present discovery rate is only of order 1 per ∼12 d on sky at Parkes. The 50 year old Molonglo Observatory Synthesis Telescope in Australia is currently being refurbished with a new digital backend system and increased bandwidth as part of an upgrade to transform it into a burst finding machine. This instrument being an interferometer will help discern if FRBs are truly a celestial population by measuring a parallax to the sources. In this paper, we introduce the Molonglo observatory synthesis telescope and discuss its single pulse sensitivity in Section 2. The first FRB survey at 843 MHz using the University of Technology's digital backend for the Molonglo Observatory Synthesis Telescope (UTMOST) instrument and limits on the detectability of FRBs is discussed in Section 3. We make estimates of the FRB rates we can expect with the UTMOST instrument, showing that at full sensitivity it is considerably more effective than Parkes for doing FRB surveys due to its large field-of-view and high observing duty cycle (Section 4) under conservative assumptions for the FRB spectral index. At full sensitivity we expect to detect an event every few days. We constrain the FRB event rate and mean spectral index based on the non-detection of FRBs in these pilot surveys and draw our conclusions in Section 5.

2 THE MOLONGLO OBSERVATORY SYNTHESIS TELESCOPE (MOST)

The Molonglo telescope was originally a 'Mills Cross' design, completed in 1967 (Mills 1981) and operating as a transit instrument at 408 MHz. It is located about 300 km south-west of Sydney, near Canberra, and is a field station of the University of Sydney. It played a crucial role in radio astronomy with the discovery of the Vela pulsar (Large, Vaughan & Wielebinski 1968) and 155 new pulsars in the second Molonglo pulsar survey (Manchester et al. 1978). It was substantially modified in the early 1980s to make the east–west (E–W) arms fully steerable and increase the operating frequency to 843 MHz and a 3 MHz bandwidth (Robertson 1991). The telescope was renamed the Molonglo Observatory Synthesis Telescope (MOST); it has a collecting area of 18 000 m^2, the largest in the Southern hemisphere.

The E–W arm consists of two collinear cylindrical paraboloids, each 11.6 m wide and 778 m long, separated by a 15 m gap (Bock, Large & Sadler 1999). Each paraboloid is divided into smaller sections called 'modules', each with a beam of order 4.64° × 2.14° (EW–NS). Four such modules were linked together digitally to form a 'bay' and 44 such bays constitute one arm. A line feed system of 7744 right circularly polarized dipoles (22 per module), in 352 resonant chambers each feeding a Low Noise Amplifier (LNA) means that the telescope is effectively an array of 352 receivers operating at a system temperature of ∼70 K (Campbell-Wilson, Davidson & Large 1997). The E–W arms can be tilted north–south (N–S), while E–W pointing is attained by differential rotation of the ring antennas (spaced at 0.54 λ) on the line feed. The telescope can access the whole sky south of $\delta = +18°$, although hour angle coverage is limited to an E–W tilt of ±60°.

Table 1. Comparison of Parkes multibeam (Manchester et al. 1978) and UTMOST (Bailes et al. in prep).

Parameter	Parkes	UTMOST
Field of view (deg^2)	0.55	4.64 × 2.14
Central beam gain (K Jy^{-1})	0.7	3.6
Central beam T_{sys} (K)	21	70
Frequency (MHz)	1352	843
Bandwidth (MHz)	340	31.25
Channel width (kHz)	390.625	781.25
No. of polarizations	2	1
Polarization feeds	Dual linear	Right circular
Fresnel limit (km)	∼40	∼14 000

The telescope is currently being upgraded both in the backend receivers and with the installation of a new graphics processing unit (GPU) based correlator, in a collaboration between Sydney and Swinburne Universities. The installation of high-performance GPUs at MOST has transformed it into a powerful instrument, the Swinburne UTMOST (Bailes et al. in preparation) and enlarged the field of view to twice that of the Sydney University Molonglo Sky Survey (SUMSS ; Bock et al. 1999) due to processing data from each 'module' rather than each 'bay'.

The sensitivity of UTMOST to FRB events (i.e. single pulse events) can be calculated using the radiometer equation,

$$S_{\rm min} = \beta \, \frac{{\rm S/N}\,(T_{\rm rec} + T_{\rm sky})}{G\,\sqrt{B\,t\,N_{\rm p}}}, \qquad (1)$$

where S_{min} is the minimum detectable flux for a given signal to noise (S/N), β is the digitisation factor, B is the bandwidth in Hz, N_p is the number of polarisations, t is the width in seconds, T_{rec} and T_{sky} are the receiver and sky temperatures in K, respectively, and G is the system gain in K Jy^{-1}. For a pulse with S/N of 10 and width of 1 ms at Parkes, the sensitivity is $S_{min} = 0.4$ Jy. At UTMOST, $S_{min} = 1.6$ Jy. Thus UTMOST is about four times less sensitive to individual FRB events than Parkes. This is more than compensated for with its 14 times larger field-of-view indicating that UTMOST can be a very effective FRB discovery machine. In practice the sensitivity at UTMOST degrades depending on the scattering from the ISM and possibly the IGM at the lower UTMOST operating frequency. Detailed calculations of the event rate at UTMOST, taking into account the system sensitivity, sky temperature at our operating frequency, scattering effects due to the ISM and IGM, DM smearing due to channel bandwidth, beam pattern of the telescope and adopted FRB comoving space density have been performed in a companion paper, Caleb et al. (2015).

The main properties of UTMOST and Parkes from the point of view of discovering FRBs are shown in Table 1.

3 FRB SURVEYS AT UTMOST

Two FRB searches have been performed at UTMOST at different fractional sensitivities during the ongoing upgrade. These two surveys are called V1.0 and V2.0 and the data processing pipeline is

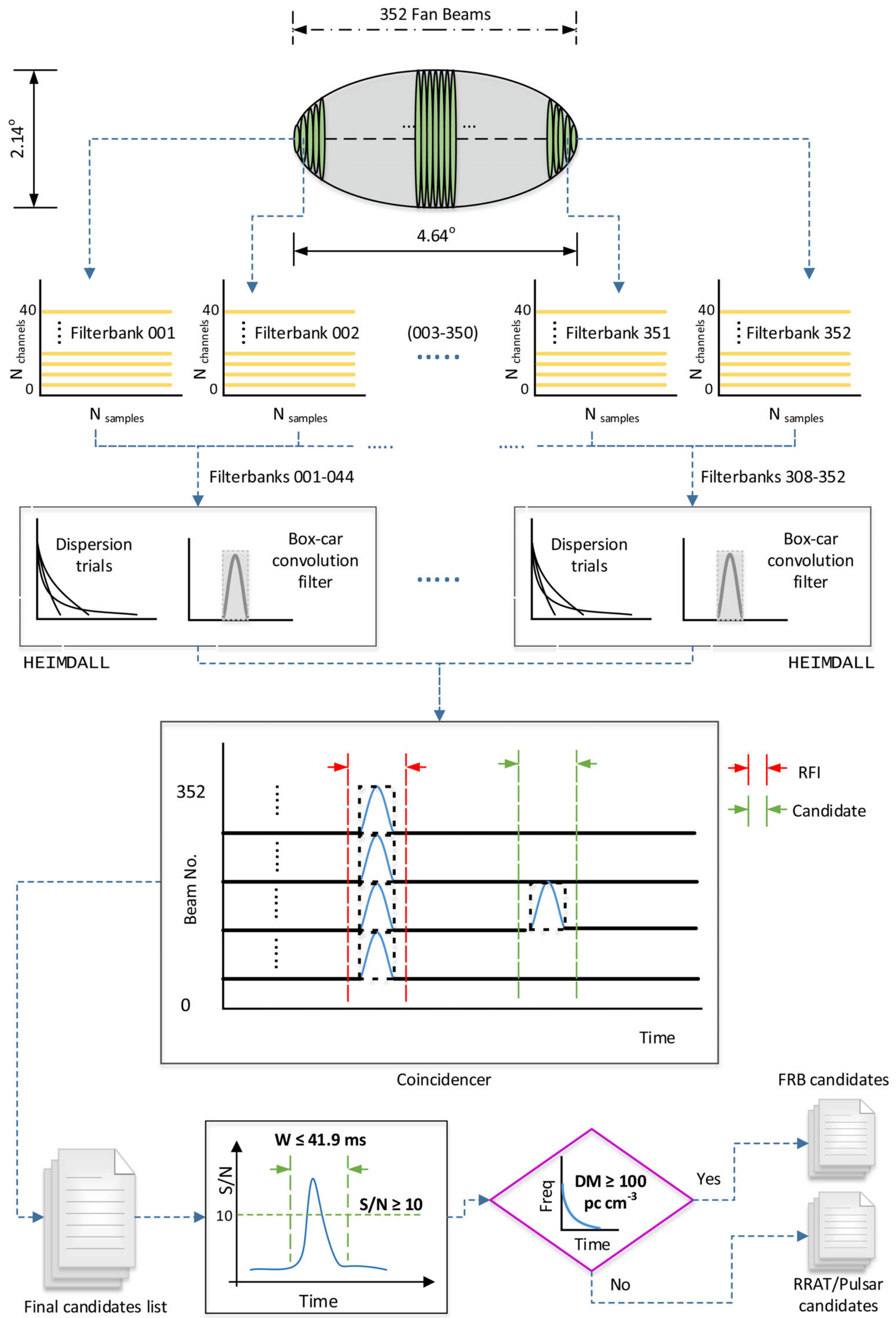

Figure 1. Fast transient search pipeline at UTMOST for FRB survey V2.0.

shown in Fig. 1. The antennas are aligned and fringe stopped to maintain stable and flat phases and then combined into a tied-array beam, centred on the primary beam boresight. This beam is then re-steered into 352 tied array beams called 'fan beams' that are 'tiled' across the 4 deg east–west axis of the primary beam. Time series from each fan beam are detected and integrated from 1.28 to 655.36 µs sampling and also requantised to 8-bits/sample.

The total data rate to the backend is 11 GBps, and the resulting output data rate from the 352 beams is approximately 10 MBps for both surveys. The input stream at UTMOST in FRB search mode is 16 MHz for survey V1.0 and 31.25 MHz for V2.0, of single polarization baseband data from 352 antennas, in 20 frequency channels produced in a polyphase filterbank (PFB). We upgraded to 40 coarse channels in FRB survey V2.0. After completion of V1.0, the rest of the GPUs were installed onsite (2015 May) so that the full 31.25 MHz could be processed for V2.0. As a consequence it is clear that roll-off at the edge of the bandpass is quite pronounced so that the extra bandwidth is not usable. We conservatively assume 16 MHz of final effective bandpass for all the results in this paper.

For both surveys the time-frequency data for each fan beam is initially dedispersed to trial DMs in the range 0 to 2000 pc cm^{-3}. Each dedispersed time series is then convolved with a series of box-car filters to maximize sensitivity to single pulses and optimised for processing on a GPU using HEIMDALL.[1] This package was originally designed for the program at the Parkes Observatory, and has been suitably modified to accommodate the specifications of UTMOST. HEIMDALL produces a list of candidates for each of the 352 fan beams, which are then carefully 'coincidenced', by rejecting events if they occur simultaneously in more than three fan beams (of the 352). The output of the coincidencer is a final list of candidates for human inspection. The candidate list is then further filtered to only retain events which have S/N $\geq$ 10 (to minimize the false positive rate) and $W \leq 41.943$ ms ($W = 2^{N} \times 0.655\,36$ ms, where N = 0,1,2...). For the purposes of labeling these as either RRAT, pulsar or FRB candidates we define all pulses with $W \leq 41.943$ ms and DM $\geq$100 pc cm^{-3}, as FRB candidates, the rest as RRAT/pulsar candidates.

A typical FRB search is made on the transiting sky, with the telescope being parked on the meridian at a declination of $\delta = -46^{\circ}$. This declination has the advantage of the bright Southern hemisphere pulsars PSR J0835−4510 (Vela) and PSR J1644−4559 transiting through the beam once per sidereal period, as well as a bright unresolved phase calibrator, the radio galaxy J1935−4620, so that the phases and delays on the array can be checked every 24 h. In practice, the array remains well phased over a few days, and the calibrator was merely used as a confirmation of phase stability. Individual pulses from both Vela and PSR J1644−4559 were routinely detected with each transit. The single pulses from PSR J1644−4559, with its rather high DM (478.8 pc cm^{-3}) and widely spaced pulses ($P0 = 455$ ms), and average pulse fluence (29 Jy ms) have rather similar properties to FRB pulses, making it an excellent daily validation of the system performance. Fig. 2 shows the passage of Vela (orange) and PSR J1644−4559 (magenta) through the 352 fan beams across the sky. Typically a few hundred candidates would be produced per 24 h, and further analyses of these candidates is performed to look for FRBs. The vast majority of the events in the search were radio frequency interference (RFI) due to mobile phone handsets, which operate on 5 MHz bands in our frequency range. The false positive rate is of order 10^{2} events per 12 h across all beams in transit mode. Tests have demonstrated that coincidencing is a very efficient means of rejecting RFI, primarily because UTMOST is an interferometer. Additionally techniques of spectral kurtosis and total power thresholding have been implemented to mitigate the RFI. The spectral kurtosis approach measures the similarity between the input signal and Gaussian noise. RFI typically is non-Gaussian and so this is useful in discriminating between the two (Bailes et al. in prep). The total power technique monitors and measures the median and median standard deviation for the preceding 8 s of data to determine when RFI causes the power levels to exceed pre-defined limits. The two techniques complement each other and result in relatively robust excision of transient RFI in an otherwise noisy environment.

Encouragingly, we redetected the bright pulsar PSR J1430−6623 in our FRB search V1.0, when the telescope was erroneously left surveying for 24 h at its declination ($\delta = -66^{\circ}$) in a true blind test of system performance. Pulse recovery tests were also performed by injecting fake FRBs by adding in total power at random positions into real filterbank data. The filterbank data chosen was RFI affected and contained bright pulses from the Vela pulsar. The fake events had injected S/Ns in the range 10–40, DMs in the range 300–2000 pc cm^{-3} and widths in the range 1–20 ms. Blind single pulse search techniques were used to process this fake data, identical to the method used for 'real' data processing. The injected FRBs were recovered with a success rate of order 95 per cent. All the injected FRBs with relatively high S/Ns (S/Ns $\gtrsim$ 15) were re-dectected successfully and only a few with S/N = 10 were missed due to being amidst RFI.

[1] http://sourceforge.net/projects/heimdall-astro/

3.1 FRB Survey V1.0

By 2015 April, our upgrade of UTMOST had reached a sensitivity where we could perform an FRB survey as part of commissioning science. FRB searches commenced, covering the full UTMOST primary beam area of 7.80 deg^{2}. The system was operated at only a fraction (~7 per cent) of its final sensitivity, as not all modules had been recommissioned, only half the bandwidth was available (16 MHz of a final system bandwidth of 31.25 MHz ; with 20 coarse channels), and the individual modules were still in the process of being brought to full sensitivity. The data processing described in Section 3 involving dedispersion and box-car convolution by the HEIMDALL single pulse search software was performed offline by processing one filterbank at a time on a single GPU. We typically see of order 100 pulses from PSR J1644−4559, with single pulse S/Ns of ~20, when it transits the search area. From S/N measurements of the correlation amplitude of the quasar 3C 273 used to phase the array, we estimate $T_{\rm sys} = 400 \pm 100$ K. This $T_{\rm sys}$ yields a single pulse sensitivity of 23 ± 6 Jy ms for a millisecond duration event in the V1.0 search with UTMOST for a S/N of 10, using a gain of 1.4 K Jy^{-1} for 140 modules and a bandwidth of 16 MHz. We have attempted to verify the $T_{\rm sys}$ from transits of Vela, J1644−4559, J1731−4744 and J1752−2806. The uncertain flux densities yield a rather poor $T_{\rm sys}$ constraint with an uncertainty of a factor of 2. We set the $T_{\rm sys} = 400 \pm 100$ K for this survey. At the time of FRB survey V1.0 the telescope was at about 7 per cent of its design sensitivity. The search is thus sensitive to the brightest FRB reported to date referred to as a 'Lorimer' type burst (Lorimer et al. 2007), but not yet to the brightest of FRBs reported in Thornton et al. (2013). Assuming a Euclidean universe, so that the cumulative number density of detectable events scales as $\mathcal{F}^{-3/2}$, we obtain an event rate estimate of about 300 d with an error margin of 50 per cent. With such a low sensitivity, our expectation of discovering an FRB was very low, but the survey allowed us to do many validation measurements on the FRB search pipeline. Our total search time on sky was 467 h. No FRBs were detected down to a fluence of 23 Jy ms and a lower S/N limit of 10. Fig. 3 displays this region (shaded in green) surveyed by UTMOST in survey V1.0. Assuming a 2σ upper limit of four events (Gehrels 1986) on this null detection, 467 h on sky and a search area of 7.80 deg^{2}, this yields a 2σ upper limit on the FRB rate at UTMOST, of not more than 1000 events sky^{-1} d^{-1} at 843 MHz with a fluence greater than 23 Jy ms.

3.2 FRB Survey V2.0

In 2015 September, we roughly doubled our search sensitivity by doubling the number of commissioned modules. In addition the installation of the second part of the GPU correlator in 2015 May enabled us to process 31.25 MHz in 40 coarse channels. $T_{\rm sys}$ remained at 400 ± 100 K. The single pulses from the pulsar J1644−4559

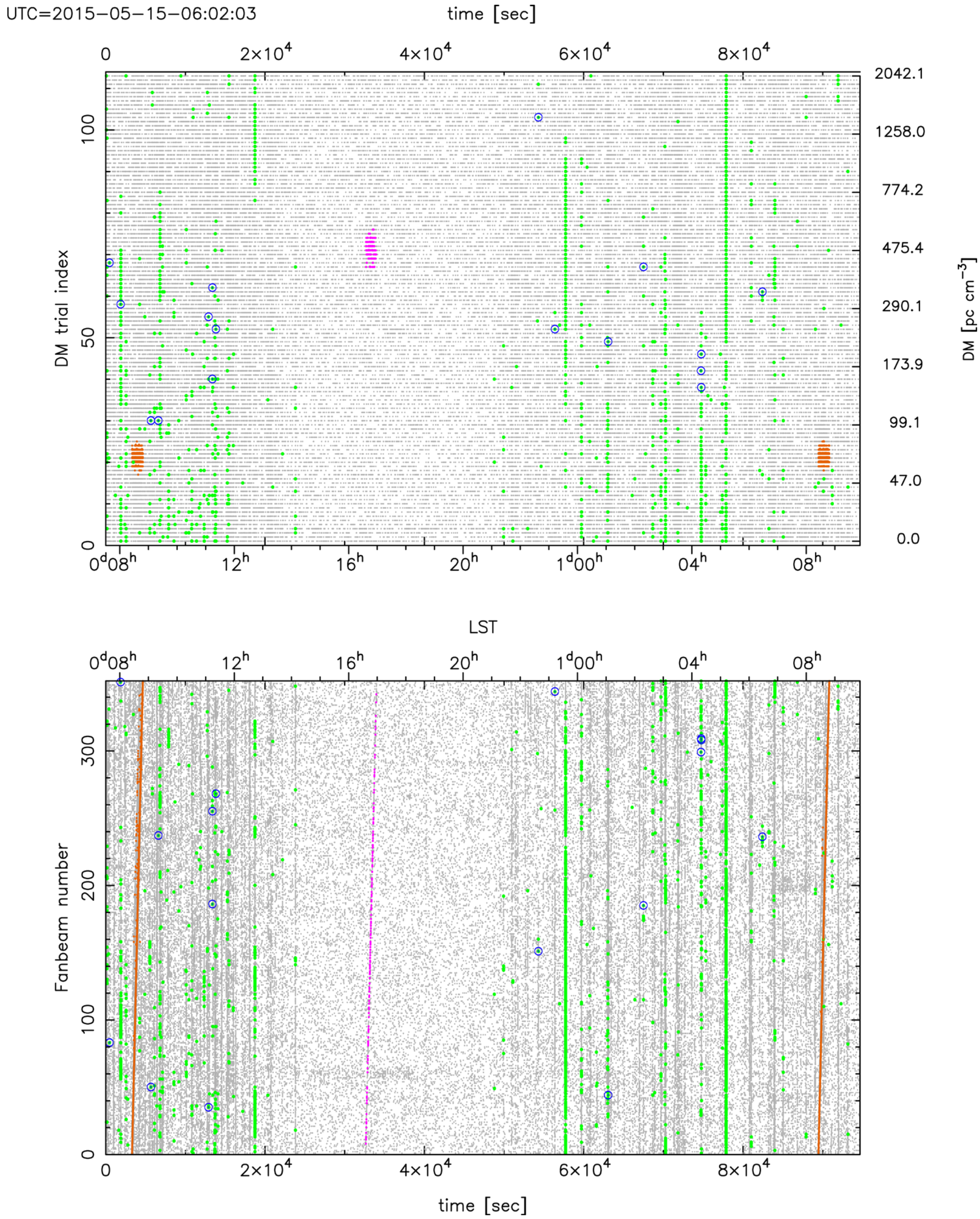

Figure 2. FRB transit search from survey V1.0 at UTMOST spanning 1.1 d, starting at UTC 2015-05-15-06:02:03. The telescope was parked on the meridian at $\delta = -46°$. Detections of the pulsars Vela and PSR J1644−4559 are shown by the orange and magenta points, respectively. The lines are slanted at the sidereal rate as the objects pass through the fan beams on the sky. Events with an S/N < 10 are marked in grey, and FRB candidates by blue circles. Events with a S/N > 10 but which can be removed because they occur in four or more fan beams at the same time are marked in green. These are dominated by mobile phone calls in our observing band. Indicative DM values, for the DM trial indices are shown on the right-hand side of the upper panel in pc cm^{-3}. All the FRB candidates turned out to be false positives from mobile phone calls, due usually to 20 ms narrow band emission. Events have been ignored if the total number seen in 10 second blocks exceeded 500 – this removes about half the events but only affects about 3 per cent of the survey time-on-sky.

were once again used to validate the system performance. On average we found the S/N of an individual pulse to be ∼40, a factor of 2 increase from the search V1.0, i.e. the searches were at about 14 per cent of the design sensitivity. As previously mentioned, even though we are able to process the full 31.25 MHz bandwidth in this search, only 16 MHz of usable bandwidth resulted due to a sharp roll-off at the edges of the bandpass. The 10σ, 1 ms single pulse sensitivity during this search was 11 ± 3 Jy ms for a gain of 3.0 KJy^{-1}, bandwidth of 16 MHz and $T_{\rm sys}$ of 400 ± 100 K.

The FRB survey V2.0 was performed simultaneously with a pulsar timing programme. Additional coincidencing was performed by rejecting RFI induced events if they occurred in groups of 500 or more in 10 s intervals across all beams. The processes of dedispersion and box-car convolution by HEIMDALL, was performed in real-time by processing all 352 filterbank files in blocks of 44 on 8 GPUs. This increased sensitivity has enabled us to detect single pulses from several more pulsars. The RRAT J1819−1458 ($S_{\rm peak} = 3.6$ Jy at 1.4 GHz) was also detected during

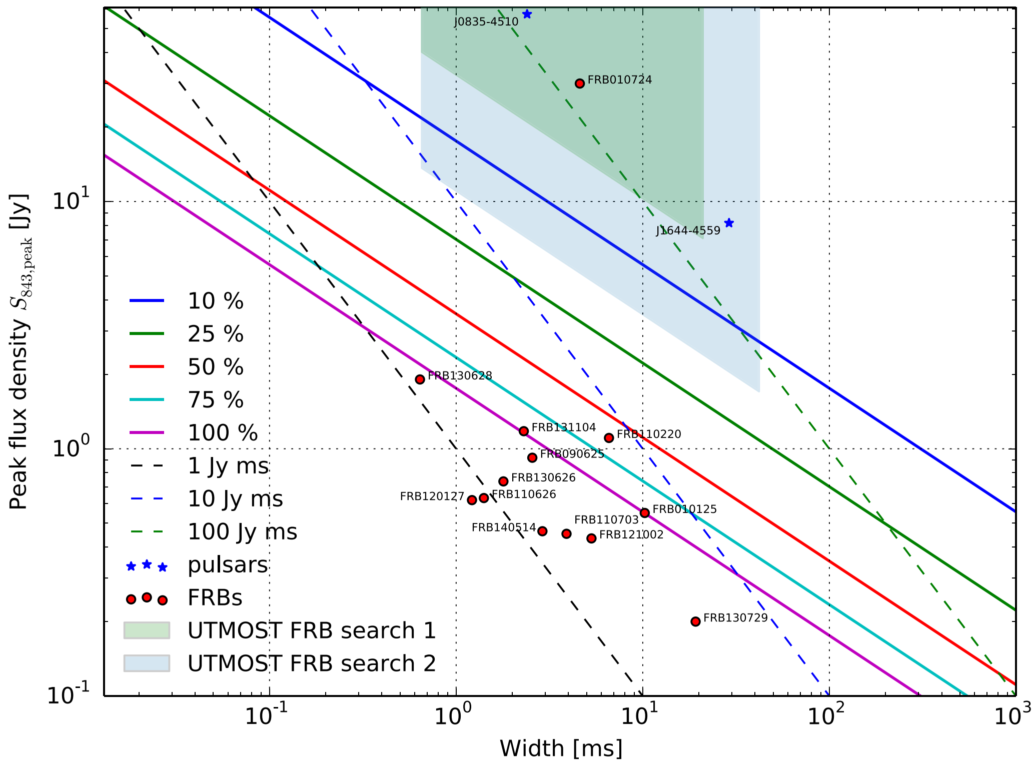

Figure 3. Single pulse sensitivities at UTMOST for FRB searches V1.0 (2015 April) and V2.0 (2015 September). Solid lines of constant S/N and dashed lines of constant fluence for different fractional sensitivities of the telescope are shown. Filled circles mark the FRBs and stars mark pulsars that have been detected through their single pulses. The green and blue shaded regions enclose the UTMOST surveys at the S/N limit for the sensitivities during the V1.0 and V2.0 surveys, respectively.

commensal observations with Parkes at 1.4 GHz, and UTMOST at 843 MHz.

Fig. 3 displays the area surveyed (blue and green) by UTMOST during the V2.0 FRB search with increased sensitivity. From Fig. 3 we see that we are still only sensitive to 'Lorimer' type bursts. We spent 225 h on sky and detected no FRBs down to the fluence limit of 11 Jy ms. From this null detection we obtain a 2σ upper limit of not more than 1000 events sky^{-1} d^{-1} at 843 MHz with a fluence greater than 11 Jy ms. We estimate the rate of FRBs given our current sensitivity at about 120 d with an error margin of 50 per cent.

Our non-detection is consistent with published FRB rate limits at Parkes, the Very Large Array (VLA) and the Allen Telescope Array (ATA) at 1.4 GHz, the Green Bank Telescope (GBT) at 800 MHz, the Low Frequency Array for Radio Astronomy (LOFAR) at 145 MHz and the Murchison Widefield Array (MWA) at 150 MHz (Fig. 4) assuming the Euclidean scaling and 1 ms duration pulses. For comparison, the current estimated rate at 1.4 GHz at Parkes is $\sim$200 events sky^{-1} d^{-1} down to a fluence of 11 Jy ms (green circle in Fig. 4) based on the rate of 2500 events sky^{-1} d^{-1} above 2 Jy ms by Keane & Petroff (2015). Using this scaled rate estimate at 1.4 GHz and our 2σ upper limit of 1000 events sky^{-1} d^{-1} at 843 MHz, we estimate the FRB spectra to be no steeper than a spectral index of -3.2 assuming FRBs were occurring during the duration of our observations. We have also included the Thornton et al. (2013) rate of $1.0^{+0.6}_{-0.5} \times 10^{4}$ events sky^{-1} d^{-1} at 3 Jy ms (magenta circle in Fig. 4) and a lower limit of $\sim$130 events sky^{-1} d^{-1} at 0.6 Jy ms (red circle in Fig. 4) which is the event with the lowest fluence in Thornton et al. (2013). The rate of 5×10^{3} events sky^{-1} d^{-1} above 1 Jy ms at 800 MHz from Masui et al. (2015) scaled to our 11 Jy ms fluence limit is $\sim$140 events sky^{-1} d^{-1}. From LOFAR at 145 MHz we estimate not more than $\sim$1800 events sky^{-1} d^{-1} down to 11 Jy ms based on the (Coenen et al. 2014) upper limit of 150 events sky^{-1} d^{-1} brighter than 71 Jy ms. We obtain another upper limit with LOFAR at 145 MHz of $\sim 1.5 \times 10^{4}$ events sky^{-1} d^{-1} down to a fluence of 11 Jy ms based on the Karastergiou et al. (2015) upper limit of 29 events sky^{-1} d^{-1} at 310 Jy ms assuming standard cosmological scaling for a fluence limited survey (viz. Section 4.3). The upper limit at 1.4 GHz at the VLA is $\sim 3.7 \times 10^{3}$ events sky^{-1} d^{-1} based on 7×10^{4} events sky^{-1} d^{-1} on 0.9 Jy ms events (300 mJy events of 3 ms width - their Fig. 4) (Law et al. 2015) and at the ATA is $\sim 7 \times 10^{4}$ events sky^{-1} d^{-1} based on an event rate of 48 events sky^{-1} d^{-1} above 440 Jy ms events (Siemion et al. 2012) scaled to the 11 Jy ms sensitivity at UTMOST. For the MWA we estimate a rate of not more than $\sim 3.5 \times 10^{5}$ events sky^{-1} d^{-1} down to a fluence of 11 Jy ms based on the upper limit of 700 events sky^{-1} d^{-1} at 150 MHz brighter than 700 Jy ms (Tingay et al. 2015).

4 ESTIMATES OF FRB RATES AT UTMOST

4.1 Extant estimates

Hassall, Keane & Fender (2013) have estimated FRB rates that might be seen at a wide range of radio telescopes operating over a wide range of frequencies. They assumed the bursts to be standard candles, to have a constant spectral index and a constant comoving space density. They estimated a detection rate of $\sim$3 d^{-1} at MOST, but this is an overestimate for the present system being installed. The MOST telescope specifications they adopt from Green et al. (2012) are for a more ambitious upgrade path than the current UTMOST

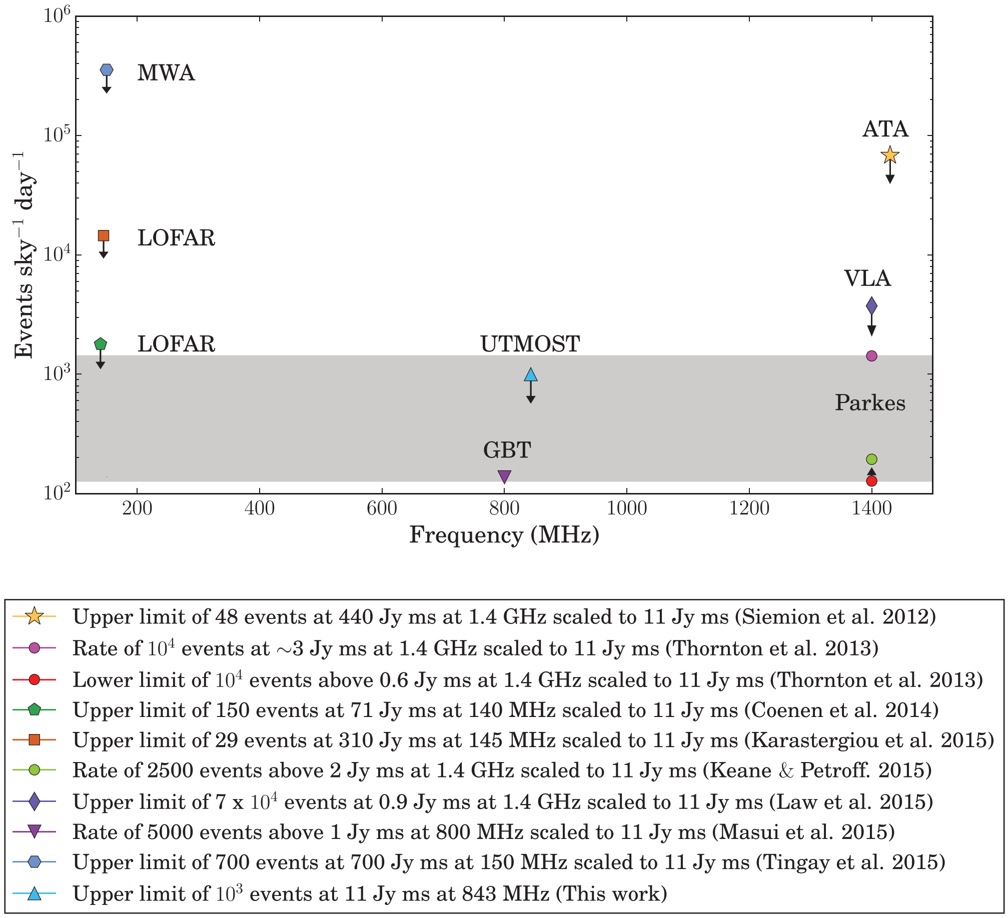

Figure 4. Comparison of the non-detection of UTMOST with the published rate limits at different frequencies scaled to 11 Jy ms. Using the scaled rate of ∼200 events sky^{-1} d^{-1} at 1.4 GHz down to a fluence of 11 Jy ms (green circle) and our 2σ upper limit of 1000 events sky^{-1} d^{-1} at 843 MHz (blue triangle), we set a lower limit on the mean spectral index of FRBs of $\alpha > -3.2$ over this frequency range.

design, which has a bandwidth a factor of 6 smaller and a field of view smaller by 60 per cent (Bailes et al. in prep). We now estimate the rate of FRBs for the current upgrade at UTMOST using two methods, in both cases scaling from the event rate at Parkes.

4.2 Empirical scaling from events at parkes

We compute what fraction of the Parkes FRBs would be detectable at UTMOST given its sensitivity for a pulse of S/N = 10 and $W = 1$ ms is $S_{\rm min} = 1.6$ Jy compared to $S_{\rm min} = 0.4$ Jy at Parkes. Thornton et al. (2013) discovered four FRBs in 24 per cent of the high latitude (Hilat) sub-survey of the high-time resolution Universe survey and estimated a rate of $1.0^{+0.6}_{-0.5} \times 10^4$ events sky^{-1} d^{-1}. Champion et al. (2015) have discovered five more FRBs in the remaining 75 per cent of the survey. Thus, nine of the known FRBs were discovered in the Hilat survey alone. To estimate their detectability at UTMOST, we reduce the S/Ns of these nine FRBs by a factor of 4 due to UTMOSTs lower sensitivity and account for reduction in their S/N by width-broadening due to the difference in observing frequency between Parkes and UTMOST. Only one Parkes event is found to be detectable at UTMOST.

The nine FRBs at Parkes were discovered after processing 100 per cent of Hilat. This corresponds to a rate of $R_{\rm Parkes} = 0.08 \pm 0.03$ events d^{-1}. Since only one of the nine Parkes FRBs is detectable at UTMOST, and the field of view is larger by a factor of 14, this yields an event rate estimate at UTMOST of $R_{\rm UTMOST} = 0.11 \pm 0.09$ events d^{-1}.

4.3 Event rate based on surveyed volume

Following (Hassall et al. 2013) we assume FRBs have flat spectral indices and are distributed through space in a Euclidean Universe, so that the cumulative number density of events with fluence $\mathcal{F}$, scales as $\propto \mathcal{F}^{\alpha}$, where $\alpha = -3/2$. Since the sensitivity of UTMOST is ∼0.25 times that of Parkes, the events are expected to occur $4^{3/2} = 8$ times less often at UTMOST than at Parkes. Since the area surveyed at UTMOST by the beam is 14 times that of Parkes, the overall rate is 2 times higher. Thus a rate of 0.08 ± 0.03 events d^{-1} at Parkes scales to a rate $R_{\rm UTMOST} = 0.16 \pm 0.06$ events d^{-1}. Caleb et al. (2015), show using Monte Carlo simulations of a cosmological population of FRBs, that the log$N$–log$\mathcal{F}$ relation for the Parkes events has a slope $\alpha \sim -1.0$, not as steep as the standard $\alpha = -3/2$ relation – adopting this shallower relation would elevate the rate at Molonglo, but we prefer to be conservative and use $\alpha = -3/2$, to estimate the UTMOST detection rate.

5 DISCUSSION AND CONCLUSIONS

The discovery of FRBs has opened up numerous exciting possibilities for the exploration of the extragalactic Universe. However, their extragalactic/celestial origin is yet to be decisively established. With the newly upgraded UTMOST array, we will be able to affirm if these sources are truly extraterrestrial when we detect one, as the array's Fresnel zone is at ∼14 000 km. FRB searches at two different fractional sensitivities (7 per cent and 14 per cent) were performed as part of commissioning science with the telescope parked at $\delta = -46^{\circ}$. The chosen declination was to allow the diurnal passage of bright southern pulsars Vela and PSR J1644−4559 and a bright calibrator, radio galaxy J1935−4620, so that the system performance, phases and delays could be monitored. No FRBs were detected down to fluence limits of 23 Jy ms and 11 Jy ms after spending 467 and 225 h on sky, respectively.

We estimate FRB rates at UTMOST by scaling from the observed events at Parkes and by assuming an Euclidean flux distribution. Most importantly we assume a flat spectral index for both methods. The rates from the two methods at full sensitivity: 0.11 ± 0.09 events d^{-1} and 0.16 ± 0.06 events d^{-1}, are consistent within their uncertainties. We have used the simplest assumption sets one can apply to yield a rate at UTMOST which shows that at full sensitivity it will detect FRBs at twice the rate as at Parkes, and yet more effective still because of our near 24×7 access to the telescope. Given the duty cycle of Parkes and the estimated event rate, only a fully dedicated survey will be capable of detecting FRBs in sufficient numbers for interesting science to be performed. UTMOST is potentially the FRB discovery machine which will do this.

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