GBTrans: A commensal search for radio pulses with the Green Bank twenty metre telescope

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ABSTRACT
We describe GBTrans, a real-time search system designed to find fast radio bursts (FRBs) using the 20-m radio telescope at the Green Bank Observatory. The telescope has been part of the Skynet educational program since 2015. We give details of the observing system and report on the non-detection of FRBs from a total observing time of 503 days. Single pulses from four known pulsars were detected as part of the commensal observing. The system is sensitive enough to detect approximately half of all currently known FRBs and we estimate that our survey probed redshifts out to about 0.3 corresponding to an effective survey volume of around 124,000 Mpc$^3$.

Modeling the FRB rate as a function of fluence, $F$, as a power law with $F^{-\alpha}$, we constrain the index $\alpha < 2.5$ at the 90\% confidence level. We discuss the implications of this result in the context of constraints from other FRB surveys.

Key words: radio continuum: transients – methods: observational – methods: data analysis

1 INTRODUCTION
Pulsar searches and their need for high time and frequency resolution have opened new windows on the transient Universe. The best example of this so far is the discovery of fast radio bursts (FRBs; Lorimer et al. 2007; Thornton et al. 2013). FRBs are very bright transient radio pulses that occur on short (millisecond) timescales, but emit about as much energy as the Sun produces in a month. At the time of writing, sixty-five FRBs are in the public domain (for an up-to-date list, see Petroff et al. 2016). Although this sample is currently not large enough to unambiguously characterize their origin and emission mechanism, it is clear that they form a cosmological population (see, e.g., Caleb et al. 2016; Tendulkar et al. 2017). Though most FRBs have been detected as one-off events, a few have them have shown repetitions (Spitler et al. 2016; CHIME/FRB Collaboration et al. 2019b). FRB 121102 was localized to a star-forming region in a dwarf galaxy, using the Karl G. Jansky Very Large Array (VLA) acting jointly with single-dish observations using the 305-m William E. Gordon Telescope at the Arecibo Observatory (Chatterjee et al. 2017). The redshift measurement to the host galaxy of 0.19 (Tendulkar et al. 2017) makes this the only FRB so far with a direct distance determination. Follow-up studies showed a large and variable rotation measure towards this source, suggesting that FRB 121102 is in an extreme and dynamic magneto-ionic environment. A neutron star origin is consistent with both such an environment and the short burst durations (Michilli et al. 2018). FRB 180814.J0422+73 was recently discovered by CHIME (Canadian Hydrogen Intensity Mapping Experiment CHIME/FRB Collaboration et al. 2019b). This detection, along with 12 other FRBs detected by CHIME (CHIME/FRB Collaboration et al. 2019a), strongly suggests the existence of a second population of FRBs. For further discussion of this possible second population, see Caleb et al. (2019). Further discoveries with CHIME and other instruments are greatly anticipated.

Over the past decade, many different hypotheses for the

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origin of FRBs have been suggested, from which some could be tested based on data observed from FRBs (Katz 2016). The main proposed models include giant pulses from pulsars (Cordes & Wasserman 2016; Lyutikov et al. 2016), magnetar giant flares (Nicholl et al. 2017; Metzger et al. 2017), merging or colliding neutron stars (Falcke & Rezzolla 2014), interaction of a pulsar with its environment (Zhang 2017), primordial black holes falling into neutron stars (Abramowicz et al. 2018), and coalescing white dwarf binaries (Kashiyaama et al. 2013).

Because of the large number of unanswered fundamental questions regarding FRBs, a number of surveys designed to increase the size of the sample have been carried out. ALFABURST uses the Arecibo L-band Feed Array (ALFA) to search for FRBs commensally among with other projects (Foster et al. 2018; Chennamangalam et al. 2017). The High Time Resolution Universe (HTRU) high-latitude surveys used the Parkes 64-m radio telescope and the Effelsberg 100-m radio telescope (Champion et al. 2016) to cover the sky in three regions for different Galactic latitude ranges. SUPERB (Survey for Pulsars and Extragalactic Radio Bursts) is an ongoing real-time fast transient and pulsar survey at Parkes (Keane et al. 2018; Bhandari et al. 2018) that conducts extensive and rapid multi-messenger post-burst follow-ups at radio, optical, X-ray, neutrino, and gamma-ray facilities.

CHIME operates in the 400–800 MHz band, and also has a large field of view as well as good sensitivity which makes this instrument unique for real-time FRB search purposes (The CHIME/FRB Collaboration et al. 2018). Rajwade & Lorimer (2017) predicted that CHIME will be able to observe ~30 or more FRBs per day which is the highest predicted event rate among current FRB surveys, and it appears that this prediction is confirmed through the first months of CHIME operation. The Commensal Real-time ASKAP Fast Transients (CRAFT) survey uses the Australian Square Kilometer Array Pathfinder (ASKAP) dishes to search for fast transients (Macquart et al. 2010). CRAFT provides a large sky coverage while only sensitive enough to detect bright FRBs, unlike Arecibo and the Five Hundred metre Aperture Spherical Telescope (FAST) which have much higher sensitivity and a very narrow beam1. The Swinburne University of Technology’s digital back-end for the Molonglo Observatory Synthesis Telescope array (UTMOST), with the telescope’s large collecting area as well as its wide instantaneous field of view, searches for FRBs at 843 MHz. As an interferometer it is capable of localize FRBs (Farah et al. 2018). MeerTRAP (Mee: more, TRAnsients and Pulsars) project, a real-time commensal pulsar and FRB search using the MeerKAT telescope (Stappers 2016), benefits from the excellent sensitivity and sky coverage of MeerKAT, which could result in detecting hundreds of well-localized FRBs and their associated hosts. Rane et al. (2016) reported a radio transient and FRB search in Parkes archival data sets. The LOFAR Pilot Pulsar Survey (LPPS), conducted around 140 MHz (Coenen et al. 2014), ARTEMIS (Advanced Radio Transient Event Monitor and Identification System), a real-time search backend at 145 MHz (Karastergiou et al. 2015), and ALERT (The Apertif LOFAR Exploration of the Radio Transient Sky), a real-time search with Apertif phased array system (Maan & van Leeuwen 2017), are three FRB surveys using LOFAR (The Low-Frequency Array). V-FASTR (VLBA Fast Radio Transient) commensal experiment, used the Very Long Baseline Array in Socorro, New Mexico in order to search for FRBs (Wayth et al. 2011). Tingay et al. (2015) did a pilot study for FRBs using the Murchison Widefield Array (MWA) in Australia at low frequencies (139–170 MHz). Law et al. (2015) attempted the first millisecond timescale radio interferometric FRB search at L-Band the VLA. Finally, Realfast is real-time, commensal fast transient surveys with the VLA for imaging and FRB detection (Law et al. 2018).

The Green Bank Northern Celestial Cap (GBNCC) Pulsar Survey (Stovall et al. 2014) and GREENBURST (Surnis et al. 2019) are the two main FRB surveys with the Green Bank Telescope. The GBNCC survey started in 2009 with the goal of searching for pulsars and RRATs (Rotating Radio Transients). This survey focuses on 350 MHz, which can provide strong constraints on the FRB rate and spectral index due to its low frequency range (Chawla et al. 2017). GREENBURST is searching for FRBs at a central frequency of 1.5 GHz with a bandwidth of 800 GHz. It is designed to use a parallel tap to the L-band receiver in order to be able to search for FRBs even if other receivers are in focus.

Although many of the above experiments use telescopes with large collecting areas and high sensitivities, motivated by the relatively large flux densities of some FRBs (see, e.g., Shannon et al. 2018), we have developed a real-time FRB detector on the 20-m telescope at the Green Bank Observatory, taking advantage of the extensive sky coverage available (approximately 80% of the sky) and a large field of view of this smaller dish. This experiment, which we call GBTrans, is a synergistic effort partially supported from the Skynet Robotic Telescope Network Project2. The 20-m telescope is also being used in a companion project (Gregg et al. 2019) which focuses on coordinated observations with Swift. The plan for the rest of this paper is as follows. In §2, we describe the GBTrans system and detection pipeline. In §3, we summarize the observations carried out and present the results of the survey including detected single pulses and giant pulses from known pulsars and candidate astrophysical pulses. In §4 we explain the method we used to estimate the FRB rate and survey volume for this survey and possible explanations for our non-detection of FRBs so far and speculate on future developments, and finally, in §5, we draw conclusions and make suggestions for future work.

2 GBTRANS DESCRIPTION

The 20-m telescope at the Green Bank Observatory in Green Bank, WV, has been in operation since late 1994. Originally funded by the US Naval Observatory, it was part of the National Earth Orientation Service telescope network, and participated in a global program of Earth Orientation VLBI measurements in cooperation with the International Earth Rotation Service, and with the NASA Space Geodesy program. Following a shut down in 2000, the telescope was

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1 Typically, for small single dish telescopes, there is a trade-off of low sensitivity for large sky coverage.

2 http://skynet.unc.edu
Figure 1. Block diagram showing the downstream electronics and data acquisition system summarising the existing system architecture developed for GBTrans.

restored, automated, and made accessible as part of Skynet (Smith et al. 2016; Hosmer et al. 2013). The main receiver currently in use operates at 21 cm wavelength and provides a cryogenically cooled dual-polarization channel input for pulsar and spectral line work. Although varied a lot, the typical system temperature is about 40 K. In particular there were quite a few warm-ups due to problems associated with cryogenics failure and also Skynet users spending telescope time on super-bright sources which caused the system temperature to increase. The frequency bandwidth is about 80 MHz, centred at 1400 MHz.

A block diagram summarising the signal path from the sky to the data acquisition system developed for GBTrans is shown in Fig. 1. The signals are down-converted to a centre frequency of 750 MHz and digitized at 1 GHz before being converted to incoherent fully-polarimetric dynamic spectra using a ROACH-I FPGA-based spectrometer. The spectrometer output is 2048 frequency channels with spectral resolution of 244 kHz and time resolution of 131 µs, represented as 8-bit integers for all four Stokes parameters. The resulting data stream is slightly greater than 500 Mb/s, including meta-data.

Real time analysis and detection is implemented on a GPU-equipped Dell R720 rack mount server using purpose-built software developed by Virginia Tech. The server consists of dual Intel Xeon E5-2640 2.5 GHz 6-core CPUs, 32 GB RAM, 4 x 1 TB hot-pluggable hard drives, and an Nvidia Tesla K10 Graphics Processing Unit (GPU). Data analysis software is implemented in C and was developed to run on a Linux platform. The principal software components include a ring buffer, an executive processor, and a GPU-based processor. The ring buffer transfers data arriving synchronously from the spectrometer into shared memory, which allows the executive processor to operate asynchronously. The executive processor operates on arriving dynamic spectra in contiguous 13.1-s segments. Each segment is examined for data integrity (e.g., checking for correctly-ordered frame counters). As a diagnostic, spectra and total power for all four Stokes parameters are integrated over the segment and recorded.

We take the 13.1-s data segments and use a GPU to produce de-dispersed total power time series using a brute-force algorithm for 531 trial DMs spanning the range 0–9900 cm$^{-3}$ pc. Each time series is subsequently box-car averaged in powers of 2 to search for single-sample pulses with widths in the range 131 µs to 268 ms. The resulting detection metrics are saved, and any data segments containing pulses with signal-to-noise (S/N) ratios exceeding 10 and DM > 10 trigger a data-preservation protocol which causes a block of data to be written which we henceforth refer to as an event. Each event consists of the raw segment of full-Stokes data as well as all available meta-data which is saved on a post-processing cluster for long-term storage and follow-up analysis.

3 OBSERVATIONS AND DATA PROCESSING

We have collected data with the aforementioned system from the beginning of December 2014 to the beginning of March 2018. Taking into account the days in which the system was down due to maintenance on the telescope or equipment failures, where no events were recorded, GBTrans was in operation for 503 days. Fig. 2 shows the distribution of events over the entire duration.

For each event, we applied a post-detection pipeline where the data were processed using the heimdall$^3$ single-pulse software package. The generated candidates were clustered using the “friends-of-friends” algorithm (Huchra & Geller 1982) in which groups of events were identified with the same DM within a tolerance of 20 cm$^{-3}$ pc, a time of arrival within 32 raw samples, and associated with an event of the highest S/N and pulse width. The resulting candidates were then appended to the output list and tested against the following criteria: Pulse widths shorter than 33.5 ms and S/N above 10. For each event that met these constraints, a diagnostic plot was generated which contained the original dynamic spectrum, the de-dispersed dynamic spectrum using the DM at which the pulse was detected with the highest S/N, along with a frequency collapsed time series of the detection which is equal to twice the dispersion delay, and were

$^3$ https://sourceforge.net/projects/heimdall-astro
Figure 2. Histogram of the number of events versus date. There is very little data available before January 2016 (Seven epochs containing 27 events at MJDs from from 56998 to 57121). Most of our observations occurred between January 2016 and September 2017 (MJD range 57400—58000).

Table 1. Parameters for known pulsars detected by GBTrans. From left to right, we list pulsar name, mean flux density at 1400 MHz, catalogue DM, number of detected single-pulses, and maximum single-pulse S/N. The mean flux density at 1400 MHz and DM were obtained from the ATNF pulsar catalogue (Manchester et al. 2005).

| PSR           | $S_{1400}$ (mJy) | $DM_{cat}$ (cm$^{-3}$ pc) | $N_{pulses}$ | $S/N_{max}$ |
|---------------|------------------|---------------------------|--------------|-------------|
| J0332+5434    | 203              | 26.76                     | 344          | 13.05       |
| J0534+2200    | 14               | 56.77                     | 22117        | 88.69       |
| J0835—4510    | 1050             | 67.97                     | 13           | 10.51       |
| J1644—4459    | 296              | 478.80                    | 318          | 34.38       |
| J2022+5154    | 27               | 22.55                     | 1633         | 13.09       |

4 DISCUSSION

4.1 Expected FRB Rate

When this experiment was being designed in 2013, the all-sky FRB rate, $R$, was thought to be much higher than current estimates which are now based on larger samples of FRBs. Recent studies (see, e.g., Lawrence et al. 2017) now show that the event rate is almost an order of magnitude lower than previously thought (see, e.g., Thornton et al. 2013). With this in mind, the lack of FRB detections in the survey, while disappointing, can be understood yet still provides useful constraints on the rate–fluence distribution. In our analysis below, we first determine the instantaneous sensitivity and field of view of our experiment to FRBs. We then adopt a recent determination of the all-sky FRB rate $R_{ASKAP} = 37 \pm 8$ bursts per sky per day with 1.4 GHz fluences above 26 Jy ms which was found from an analysis of ASKAP detections (Shannon et al. 2018) to determine realistic expectation times needed to make a detection.

To compute the sensitivity and sky coverage of GB-Trans, we take the measured gain of the 20-m telescope, $G = A/2k$, where the effective surface area $A = 237 \text{ m}^2$ as-

4 http://www.atnf.csiro.au/research/pulsar/psrcat


\[ F_{\text{min}} = \frac{T_{\text{sys}} S/N}{G} \sqrt{\frac{W}{2B}}. \]

where the typical system temperature \( T_{\text{sys}} = 40 \) K and the bandwidth \( B = 80 \) MHz. For consistency with the ASKAP survey, we adopt their minimum FRB pulse width \( W = 1.26 \) ms, and a S/N threshold of 10. This gives \( F_{\text{min}} \approx 6 \) Jy ms. The minimum detectable fluence at the full-width half maximum (FWHM) of the main beam of GBTrans is therefore about 12 Jy ms. Fig. 5 shows the survey sensitivity among with previously detected FRBs. It appears that more than half of the current FRBs are detectable with GBTrans.

Having found the sensitivity out to the beam FWHM, we next need to compute the corresponding solid angle, \( \Omega \), which represents the instantaneous amount of sky sampled at this limit. For a gaussian beam response (for a discussion, see Condon & Ransom 2016) we have \( \Omega = 1.133 \) FWHM$^2$.

\[ T = \left( \frac{R(\Omega)}{2.2}\right)^{-1} \left( \frac{1600 \pm 350 \text{ days}}{2.2} \right). \]

In Fig. 6 we show Eq. 4 alongside these various values of \( \alpha \) from earlier studies and our experimental limit on \( T \). To be consistent with our experimental results, \( T > 503 \) days. From this, as shown in Fig. 6, we estimate that \( \alpha < 1.7 \).

Care should be taken when interpreting this simple point estimate of the upper limit because there is no confidence interval associated with it. To demonstrate this, assume that FRBs as a population follow Poissonian statistics in their event rate, the probability of finding at least one FRB in our data set \( P_1 = 1 - \exp(-\mathcal{R}\Omega T) \). Setting \( \alpha = 1.7 \) in Eq. 3 to find \( \mathcal{R} \) and \( T = 503 \) days, we find \( P_1 = 70\% \). To set a robust limit on \( \alpha \), we can repeat this calculation to find \( P_1 \) as a function of \( \alpha \). Requiring \( P_1 \geq 0.9 \), we find that we should have detected at least one FRB with 90% confidence if \( \alpha > 2.5 \). We therefore conclude that \( \alpha < 2.5 \) at the 90% confidence level.

Table 2 summarizes different \( \alpha \) constraints reported in literature. There is currently a wide range of \( \alpha \) values that are quoted. An Euclidean rate–fluence distribution would therefore lead to \( T \approx 1 \) yr. Macquart & Ekers (2018) estimate, based on a recent maximum likelihood analysis on the Parkes FRBs, that \( \alpha = 2.6 \pm 0.7 \). For this range of \( \alpha \) values, we would expect waiting times in the range \( 58 < T < 436 \) days. In contrast, Li et al. (2017) estimate \( \alpha = 0.14 \pm 0.20 \). This would correspond to \( 956 < T < 2044 \) days.

| Source count index, \( \alpha \) | Reference |
|---------------------------------|-----------|
| \( 2.6 \pm 0.3 \)              | Macquart & Ekers (2018) |
| \( 2.2 \pm 0.6 \)              | Bhandari et al. (2018) |
| \( 2.2 \pm 0.47 \) (ASKAP) \( < 2.5 \) | GBTrans — this paper |
| \( 1.18 \pm 0.24 \) (Parkes)   | Lawrence et al. (2017) |
| \( 0.91 \)                      | Caleb et al. (2016) |
| \( 0.8 - 1.7 \)                | Vedantham et al. (2016) |
| \( 0.9 \pm 0.3 \)               | Li et al. (2017) |
| \( 0.5 - 0.9 \)                | |
| \( 0.14 \pm 0.20 \)            | |

where for an observing wavelength, \( \lambda = 0.2 \) m,

\[ \text{FWHM} = 1.2 \sqrt{\frac{\lambda}{4A/\pi}} = 48'. \]

From this, we find that the beam solid angle at the FWHM, \( \Omega = 2.2 \times 10^{-4} \) sr or \( 1.7 \times 10^{-5} \) of the whole sky.

We model the rate–fluence distribution as a power law such that

\[ \mathcal{R}(> F) = \mathcal{R}_{\text{ASKAP}} \left( \frac{F}{26 \text{ Jy ms}} \right)^{-\alpha}. \]

where the index \( \alpha = 1.5 \) for Euclidean geometry. Keeping \( \alpha \) as a free parameter but setting \( F = F_{\text{min}} \), then we find an expression for the mean “waiting time”, \( T \), to detect a pulse. Since this is just the reciprocal of the rate scaled by the solid angle coverage, we find that

\[ T = (R\Omega)^{-1} = \left( \frac{1600 \pm 350 \text{ days}}{2.2\alpha} \right). \]
4.2 Survey Volume

Assuming a pulse width of 1 ms (consistent with the ASKAP FRB rate assumption), our nominal fluence limit discussed above corresponds to a peak flux limit of about 12 Jy. Adopting the standard candle model discussed by Lorimer et al. (2013) which gives a peak flux-redshift relationship (see their Eq. 9), we find a maximum redshift reached by GBTrans to be approximately $z = 0.3$. Given the beam solid angle computed in the previous section, the comoving volume corresponding to this limit assuming a standard set of cosmological parameters for a flat universe (Bennett et al. 2014) is 124,000 Mpc$^3$. As expected, this is substantially less than what Foster et al. (2018) reported ($z \approx 3.3$ and 600,000 Mpc$^3$) for the more sensitive ALFABURST survey even with its smaller field of view.

5 CONCLUSIONS

GBTrans was an automated system that searched for FRBs commensally for over 500 days on a 20-m class telescope at Green Bank. The observations were nominally sensitive to FRBs with redshifts out to about 0.3. Our non-detection during this experiment leads to an upper limit on the power law index of the event rate–fluence exponent, $\alpha < 2.5$ with 90% confidence. With the torrent of discoveries expected from CHIME and ASKAP in the near future, the brightness distribution will undoubtedly be well probed by these and other experiments.

Our detection of numerous pulses from known pulsars has validated the observing system. In addition to a forthcoming publication concerning giant pulses from the Crab pulsar found during the course of this project, future uses of the 20-m in the FRB field are migrating to targeted searches such as the Swift survey described in the companion paper by Gregg et al. Ongoing work aims to adapt the system to operate as a rapid response observer of radio transient signals associated with gamma-ray bursts.

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