The High Time Resolution Universe Pulsar Survey – III. Single-pulse searches and preliminary analysis

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ABSTRACT
We present the search methods and initial results for transient radio signals in the High Time Resolution Universe (HTRU) survey. The HTRU survey’s single-pulse search, the software designed to perform the search and a determination of the HTRU survey’s sensitivity to single pulses are described. Initial processing of a small fraction of the survey has produced 11 discoveries, all of which are sparsely emitting neutron stars, as well as provided confirmation of two previously unconfirmed neutron stars. Most of the newly discovered objects lie in regions surveyed previously, indicating both the improved sensitivity of the HTRU survey observing system and the dynamic nature of the radio sky. The cycles of active and null states in nulling pulsars, rotating radio transients (RRATs) and long-term intermittent pulsars are explored in the context of determining the relationship between these populations and of the sensitivity of a search to the various radio-intermittent neutron star populations. This analysis supports the case that many RRATs are in fact high-null-fraction pulsars (i.e. with a null fraction of \( \geq 0.95 \)) and indicates that intermittent pulsars appear distinct from nulling pulsars in their activity cycle time-scales. We find that in the measured population, there is a deficit of pulsars with typical emission time-scales greater than \( \sim 300 \) s that is not readily explained by selection effects. The HTRU low-latitude survey will be capable of addressing whether this deficit is physical. We predict that the HTRU survey will explore pulsars with a broad range of nulling fractions (up to and beyond 0.999), and at its completion is likely to increase the currently known RRATs by a factor of more than 2.

Key words: methods: data analysis – surveys – stars: neutron – pulsars: general.

1 INTRODUCTION
Radio single-pulse (SP) searches within the last decade have revealed a number of fascinating objects within and outside of our own Galaxy. Pulsed radio emission originating from other galaxies could give an estimate of the combined free electron content of their host galaxies and of the intergalactic medium; thus far, searches have detected SPs from neutron stars in two close satellites of our Galaxy, including giant pulses from B0540 – 69 in the Large Magellanic Cloud (Johnston & Romani 2003) and a probable transient neutron star in the sculptor spheroidal dwarf galaxy (Rubio-Herrera 2010). A number of other nearby galaxies have been the target of SP searches, showing only sparsely detected events of inconclusive origin (e.g. galaxies M33 and M31, searched by McLaughlin & Cordes 2003; Rubio-Herrera 2010, respectively). The discovery by Lorimer et al. (2007) of a seemingly dispersed, 30-Jy impulse [at a dispersion measure (DM) of 375 pc cm\(^{-3}\)] appeared to represent the first discovery of an extragalactic pulse with high significance that was of non-neutron star origin. However, the recent discovery of pulses of ambiguous terrestrial origin with frequency sweeps that mimic the cold plasma dispersion relation and primarily appear around DM \( \sim 375 \) pc cm\(^{-3}\) has cast some doubt on the Lorimer et al. pulse as being extragalactic and provided an additional, terrestrial target for SP searches (Burke-Spolaor et al. 2011).
The most frequently detected sources of transient radio emission are pulsars. SP searches in recent years uncovered what was labelled the ‘rotating radio transient’ (RRAT) phenomenon (McLaughlin et al. 2006), which encapsulates sparsely radio-emitting neutron stars, that due to their sporadic emission were undetectable by the Fourier-based search techniques currently in standard use for pulsar surveys. It has recently been established that in fact the term ‘RRAT’ is a ‘detection label’ rather than a description of a physical phenomenon: Keane (2010a) noted that whether a discovery is considered ‘RRAT’ is highly dependent on both the survey length and an object’s rotational period. This and other mounting evidence indicate that RRATs are unlikely to have a physically distinct origin from radio pulsars. This includes, for instance, that RRAT pulse energy distributions tend to obey lognormal distributions similar to both non-nulling and nulling pulsars (e.g. Cairns, Johnston & Das 2001; Keane 2010b; Miller et al. 2011) and that there is a lack of distinction between RRAT and pulsar Galactic distributions and pulse width distributions (Burke-Spolaor & Bailes 2010, hereafter BSB). Additionally, if RRATs were a distinct phenomenon unrelated to other neutron star populations in an evolutionary sequence, the implied birthrate of neutron stars would far exceed the rate of supernovae that produce them (Keane & Kramer 2008). As such, the current understanding of the objects discovered preferentially in SP searches is that they are a mix of both modulated pulsars with long-tailed pulse energy distributions (Weltevrede et al. 2006) and pulsars at the most extreme end of the nulling pulsar population (BSB; Keane 2010b; Miller et al. 2011).

However, the following questions remain. Why do the objects appear to have a period-derivative and/or magnetic field distribution that sits higher than the average pulsars of the same period range (McLaughlin et al. 2009)? What are the statistics of peculiar phenomena in these extreme-nulling objects such as the RRAT-pulsar mode switching of PSR J0941−39 (BSB), the multimodal (and latitude-dependent) behaviour of PSR J1119−6127 (Weltevrede, Johnston & Espinoza 2011) or the glitch activity of PSR J1819−1458 (Lyne et al. 2009)? What causes nulling and what is the distribution of pulsar nulling fractions (again holding implications for the neutron star birthrate)? And finally, do (and if so, how do) the most extreme-nulling pulsars fit into an evolutionary progression between average radio pulsars, nulling pulsars, radioquiet neutron stars and the magnetar population (e.g. Lyne et al. 2009; McLaughlin et al. 2009; BSB; Keane 2010b)? Acquiring a larger statistical sample of these objects is among the next essential steps in understanding RRATs and transient radio neutron star phenomena (currently a total of ~40 such objects are known; Hessels et al. 2008; Deneva et al. 2009; Keane et al. 2010; Rubio-Herrera 2010; BSB).

The High Time Resolution Universe (HTRU) survey is the first digital, all-southern-sky survey for pulsars and fast (sub-second) transients, covering declinations δ < +10° (Keith et al. 2010, hereafter HTRU Paper I). The survey employs a new digital backend, the ‘Berkeley–Parkes–Swinburne Recorder’ (BPSR), that has been installed at the Parkes Telescope for the 20-cm multibeam receiver (Staveley-Smith et al. 1996). BPSR allows improved digitization levels, frequency and time resolution over the previous analogue instrument that has been used for previous southern SP searches and studies (i.e. McLaughlin et al. 2006; Keane et al. 2010; BSB). This affords the HTRU survey unprecedented sensitivity to sub-second duration, dispersed single impulses of radio emission in the southern sky. This paper describes the techniques used in the survey to search for SPs.

As an all-sky survey, the HTRU survey is sensitive to terrestrial, Galactic and extragalactic sources of radio pulses. The HTRU intermediate- and high-latitude surveys will cover Galactic longitudes −120° < l < 30° and latitudes |b| < 15°, and declinations δ < +10° (not covered by intermediate pointings), respectively. Although no processing has yet commenced for the HTRU low-latitude survey, this survey will cover areas |b| < 3.5 and −80° < l < 30°, with 70 min per pointing. A parallel northern effort is underway at Effelsberg Radio Telescope, affording a full sky survey for pulsars and transients. The low- and intermediate-latitude surveys share common areas of sky coverage to previous surveys which employed the analogue filterbank installed on the Parkes 20-cm multibeam receiver. The ‘Parkes Multibeam Survey’ (Manchester et al. 2001) covered |b| < 5° with 35-min pointings and was searched for SPs by McLaughlin et al. (2006) and Keane et al. (2010), revealing the bulk of the currently recognized RRATs. Hereafter, we refer to these two searches collectively as the PKSMB searches. At higher Galactic latitudes, an SP search was performed on the Edwards et al. (2001) and Jacoby et al. (2009) surveys by BSB. Despite the common sky coverage and high success rate of the BSB and PKSMB searches, we nevertheless expect to discover new sources of pulsed radio emission in these areas; some pulsing radio sources may not have been previously detected due to the source’s low event rate, insufficient sensitivity in previous surveys or the improved dynamic range of the BPSR observing system over the previous analogue filterbank system installed on the Parkes multibeam receiver, whose dynamic range was diminished by √N statistics (explored in more detail in Section 2.2).

In this paper, we present the search methods, sensitivity and current status of the HTRU survey SP search (Section 2). Because this survey required concurrent searches using periodicity and SP techniques, it affords the opportunity to explore efficient modes of search operation, attempting to perform these techniques in parallel with a minimum of duplicated computing effort. We also report on initial discoveries in the intermediate- and high-latitude surveys (Section 3). In Section 4, we explore the detectability of our discoveries in previous surveys of overlapping regions, present our new discoveries in terms of the windowing description of pulsar intermittence presented in BSB and make predictions for the sparsely emitting radio neutron stars that the full HTRU survey will uncover.

2 HTRU SURVEY’S SINGLE-PULSE SEARCH

2.1 Data analysis pipeline

Thus far, all processing and analysis have been carried out using the ‘Green Machine’ supercomputer at the Swinburne Centre for Astrophysics and Supercomputing. The pipeline employs several standard search techniques (e.g. dedispersion and boxcar-matched filtering, multibeam coincidence matching; Cordes & McLaughlin 2003; Deneva et al. 2009; BSB; Keane et al. 2010) and several novel techniques (e.g. independent-event identification and inspection). The basic methodology of the SP search is based on that described by BSB.

There are two main bottle-necks in the HTRU survey’s SP search. The first is the computational load demanded by the dedispersion of our data and the second is the number of candidates which need to be manually assessed. The SP data reduction pipeline design includes schema that aim to abate both of these. First, we minimize the net computational time of the periodicity and SP searches by integrating the SP search into the HTRU processing pipeline introduced in HTRU Paper I. By doing this, the interference excision
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2.1.1 Single-beam processing

For each observation, a multibeam monitor is initiated and the available beams for this pointing are submitted in sequence for processing on the supercomputer, each processed independently using the HTRU pipeline. For this pipeline, we begin with 2-bit filterbank data with the sampling properties that are summarized in Table 1. Pre-analysis radio frequency interference excision is done first, as detailed in HTRU Paper I. In brief, this excision creates and uses both a frequency and a time mask that flags periodic-interference-affected channels and time samples with a DM = 0 pc cm$^{-3}$ signal above a signal-to-noise ratio (S/N) of more than 5. Flagged time samples are replaced in the filterbank file with noise drawn from adjacent unflagged samples, while offending frequency channels are replaced in the filterbank file with noise drawn from adjacent unflagged samples.

Table 1. HTRU survey observing parameters and an indication of the processed portion of the survey. Full survey parameters are given in HTRU Paper I.

| Parameter | Intermediate | High |
|-----------|--------------|------|
| Avg. pointing duration (s) | 540 | 270 |
| Total time processed | 3490 h | 140 h |
| Total area processed | 7671 deg$^2$ | 591 deg$^2$ |
| Fraction of total survey | 23.5 per cent | 0.39 per cent |
| Centre frequency (MHz) | 1352 | 1352 |
| Total bandwidth ($B$, MHz) | 340 | 340 |
| Typical usable $N_{\text{chan}}$ | 870 | 870 |
| Sampling time ($t_{\text{samp}}$, 1s) | 64 | 64 |

The typical single-beam field of view is calculated within the average half-maximum beamwidth ($\sim$0.04 deg$^2$).
are blanked. While the time-domain interference excision reduces
the S/N of bright signals of DM < 0.12(\mu s/64 \mu s) pc cm\(^{-3}\), where
\(w\) is the pulse’s width, it allows us to produce and inspect candi-
dates down to DM \(\sim 1\) pc cm\(^{-3}\) while maintaining a manageable
false detection rate at the manual inspection stage.

We perform dedispersion at 1196 trial DMs over the range of
0–1000 pc cm\(^{-3}\) using the \texttt{DEDISPERSE\_ALL} program.\(^1\) After reading
the input filterbank data into computer memory, time series are
formed for each DM trial; the efficient dedispersion aspect of the
\texttt{DEDISPERSE\_ALL} code is described in detail in HTRU Paper I. As the
time series data stream at each DM trial is produced, it is searched
for SPs with parameters as in BSB. Our input search parameters
differ only in that the boxcar filter used in our search ranges in size
\(N_b = 1\) to 512 samples and that events separated by more than 10
samples (640 \mu s) were considered independent. All significant (as
defined by our pre-set S/N threshold, \(m_t > 6\), detailed below) events
in each boxcar and DM trial are recorded and stored in a database.

At the completion of dedispersion of all trial DMs, \texttt{DEDISPERSE\_ALL}
performs a temporal coincidence matching [similar to the ‘friends-
of-friends’ method developed by Huchra \\& Geller (1982) and used by
Deneva et al. (2009) and BSB to identify time-coincident event
clusters]. Each event is defined by the parameters (DM, boxcar
filter, width and time) at which the S/N is found to be the greatest
and consists of members at other DM and boxcar trials found to be
coincident.

The presence of man-made interference (i.e. radar communica-
tions, satellite and aircraft transmissions, on-site hardware and
a number of other sources) during observations causes the noise in
our time series data to follow a non-Gaussian distribution. These
signals are typically either not dispersed or dispersed to a level that
is undetectable in our data, and therefore the zero-DM time se-
ries interference mitigation performed before processing removes
the bulk of these signals. After interference pre-removal, however,
some low-level interference signals remain, and we employ pre-set
search thresholds to balance the false detection rate. For most data,
the interference pre-removal allows time series at trials above DM =
\(1.5\) pc cm\(^{-3}\), in the absence of our target astrophysical signals, to
be roughly Gaussian-distributed. At lower dispersion trials, the
false detection rate becomes unmanageable, and we therefore set a
dispersion-based threshold to reject all events found with a peak S/N
at DM \(\sim 1\) pc cm\(^{-3}\). For each 9-min intermediate-latitude beam,
we produce 1196 dedispersed time series of \(N_s \geq 845\) 0000 samples.
Our total number of searched data points for each file therefore con-
sists of \(1196 \times \sum_{n=0}^{12}(N_s/2^n) = 2.02 \times 10^{19}\). In Gaussian-distributed
data, at our S/N threshold of \(m_t = 6\) we would expect approximately
50 independent random noise detections per file. We attempt to filter
these events by automatically rejecting events which have less than
three associated members. This is an effective method of Gaussian
event rejection; noise peaks at an S/N of 12 or below are not likely to
exhibit S/N > 6 in more than two trials, assuming the peak’s signal
between DM steps and boxcar trials drops by at least \(\sqrt{2}\). Further-
more, the number of statistically random events above S/N = 12 is
negligible, even when considering analysis of the full HTRU
intermediate-latitude survey. This strategy impacts weakly on our
sensitivity to events of \(w = N_d\) that have S/N \(< 12\). However,
in concert this event-match-based candidate rejection typically re-
duces the number of candidates by a further factor of \(~100–1000\)
and much more for data badly affected by interference. In Fig. 2,
we show the two visual inspection plots used for manual candidate
discrimination. For the observation displayed, the telescope was
pointed at PSR J1129–53, a known RRAT (BSB). The six pulses
emitted by the pulsar in this pointing were correctly discriminated
by the software from zero-dispersion interference and from spurious
peaks in the data.

All non-interference events are then written to disc by \texttt{DEDIS-
PERSE\_ALL}, producing one file per event, in which the properties of
all members of that event are listed. At this stage, the SP events
for the beam are gathered by the multibeam data monitor associ-
ated with the beam’s pointing. The time series are written to disc,
stored for use in the periodicity search and for later access by the
multibeam data monitor.

### 2.1.2 Multibeam data monitor

As SP events are produced for all the beams associated with one
pointing, the multibeam monitor for that pointing collects the events
and performs a temporal coincidence match of an identical form to
that done by \texttt{DEDISPERSE\_ALL}; however, it is performed for events
from different beams.

The Parkes 20-cm multibeam receiving system allows the simul-
taneous observation of 13 positions on the sky with \(~30\) arcmin
between beam positions, and each beam has a sensitivity fall-off on
scales of \(< 30\) arcmin from its pointing centre (Staveley-Smith et al.
1996). Point-like radio sources boresight to the telescope pointing
direction will therefore typically be detected in a maximum of three
beams of the receiver. Particularly luminous objects such as the Vela
Pulsar, which emits SPs with peak flux densities of up to \(~60\) Jy,
may be detected in up to approximately seven beams when ideally
positioned in the multibeam field. Typically, signals of sufficient
brightness to appear in all beams at similar intensity, i.e. through
a far sidelobe of the telescope, are generated by terrestrial or near-
Earth sources (such as satellites or aircraft). Therefore, as in BSB,
we do not inspect candidates which were detected in more than nine
of the 13 beams. This filter decreases our sensitivity to the terres-
trial ‘Perytons’ of Burke-Spolaor et al. (2011); however, there is
significant benefit gained through a decrease in the false detection
rate per pointing. A search of the data aimed specifically at detect-
ing Perytons is planned for the near future. All events occurring in
nine beams or less are imaged as described in BSB, collecting the
relevant filterbank and time series data from the original off-disc
location of the single beams. When both SP and pulsar searches
have been completed, the data are freed for removal from the disc.

Finally, a pointing’s result plots (i.e. those for individual beams and
events as in Fig. 2) are manually assessed to determine whether
they contain a detection of interest. The ‘beam summary’ plot has
superior sensitivity to objects emitting multiple pulses with signals
at or just exceeding the detection threshold, while the single-event
plots allow a user swift discrimination between interesting candi-
dates and falsely identified interference or noise. During the manual
inspection stage, results are also compared with the most up-to-date
version of the Australia Telescope National Facility Pulsar Cata-
logue originally published by Manchester et al. (2005).

### 2.2 Search sensitivity

The sky coverage of the HTRU survey includes regions covered
by previous surveys that have been searched for SPs. Particularly

\(^1\) This software and the C++ \texttt{GTOOLS} library, which is drawn from \texttt{DEDIS-
PERSE\_ALL} for SP functionality and contains the SP search algorithms, can-
didate matching functions and SP candidate type classes, are available from
http://www.github.com/swinlegion

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Figure 2. Example diagrams used in the manual inspection stage. (a) Following Cordes & McLaughlin (2003), a single-beam summary diagram showing a position near PSR J1129−53. 13 such plots are made for each pointing. Here events are coloured according to their autoidentified event type, as determined by the process described in Section 2.1.1. Events flagged as zero-DM interference are black, those identified as Gaussian peaks are red crosses and candidate events are highlighted in blue/grey. The upper middle panel shows the S/N of each event plotted against DM and the left-hand panel shows a histogram of the net number of candidate (blue/grey) and all (black) detected event members in the pointing. The bottom panel shows the DM versus time, with each member’s S/N coded in the size of the plot point. In this example, six candidate pulses from PSR J1129−53 have been correctly discriminated from the noise and interference in the observation. (b, c) Here we show single-event plots that correspond to the second and third pulses detected from PSR J1129−53 in panel (a). Panels show (clockwise from top left) the dedispersed time series in 13 beams, the S/N versus DM (left-hand subpanel) and boxcar filter trial (right-hand subpanel) of the event; a false-colour image representing the signal power over frequency (MHz) and time since the beginning of the file (s); dedispersed time series at DM = 0 pc cm$^{-3}$ (bottom subpanel), and three DM trial steps around the brightest detected DM (upwards from the bottom subpanel). The structural deviations in the S/N versus DM curves in (b) and (c) from the predicted Cordes & McLaughlin (2003) curves are the combined result of noise, and both time- and frequency-dependent pulse structure.
for the HTRU intermediate-latitude survey, we have direct overlap with the areas searched by BSB and PKSMB. Here we calculate our sensitivity to transient events and make a comparison to these surveys.

Instrumental and interstellar pulse broadening serves to weaken the S/N of the pulse from its signal at the pulse’s intrinsic width, $w_i$. All instrumental broadening effects are in principle avoidable; therefore, the backend design of any observing system aims to reach the scatter-broadening limit, as this is the theoretical best that a pulsar/transients survey can achieve. As noted in HTRU Paper I, for a large range in DMs the improved time and frequency resolutions of the HTRU survey cause pulse broadening from interstellar propagation to dominate over intrachannel dispersion broadening ($t_{scat}$). Using the empirical DM–scatter broadening relation given by Bhat et al. (2004), scatter broadening ($t_{scat}$) typically dominates over hardware-induced smearing above a DM of $\sim 230$ pc cm$^{-3}$ for the HTRU survey (note, however, that the scatter of individual pulsars in the Bhat et al. relation means that individual objects may deviate by up to an order of magnitude). To calculate our sensitivity to SPs, we take these pulse-scattering and broadening effects into account.

Following for example Lorimer & Kramer (2005), the observed pulse width depends on $w_i$ and various pulse-broadening effects by $w = (w_i^2 + t_{scat}^2 + t_{inter}^2 + t_{w}^2)^{1/2}$. Note that our step size between DM trials is chosen such that the broadening due to an error in DM is small compared to other broadening effects. If the observed peak flux density for a pulse is given by $S_{peak}$, our sensitivity limit for the intrinsic peak flux density of SPs with observed duration $w = N_e \times t_{w}$ is then

$$S_{lim} \geq S_{peak} \frac{w}{w_i}; \quad S_{peak} = \frac{m_T \beta}{G \sqrt{N_e M_B}}$$

(cf. Lorimer & Kramer 2005), where $T_{sys} \approx 23$ K is the system temperature of the multibeam system, $G$ is the telescope gain (ranging from 0.735 to 0.581 K Jy$^{-1}$, from the central to outer beams) and $N_p = 2$ is the number of summed polarizations in the data. $\beta$ is a factor of the order of ~1 that is included to represent signal losses due to system imperfections (for BPSR’s 2-bit digitization, $\beta \approx 1.07$, following from Kouwenhoven & Voute 2001). In Fig. 3, we indicate our sensitivity to SPs of various durations as a function of DM and in comparison to the sensitivities of PKSMB and BSB.

The 2-bit digitization levels of the BPSR instrument and large number of frequency channels result in the increased dynamic range capabilities over the previous Parkes analogue filterbank. We made empirical measurements of the mean ($\mu$) and standard deviation ($\sigma$) of HTRU survey data judged by eye to not be strongly affected by interference. Using these values, we calculate the highest achievable S/N in the HTRU survey data for pulses with $w = t_{w}$ to be 41.5. This is in good agreement with the S/N of saturated interference pulses observed in DM = 0 pc cm$^{-3}$ time series. For the 1-bit, 96-channel analogue filterbank, the maximum S/N may be calculated analytically, using a binomial probability distribution. The theoretical maximum S/N of this system at $w = t_{w}$ is then 9.6; again, this agrees with saturated interference signals observed in data from this system. The differences in dynamic range for these observing backends do not strictly impact the flux sensitivity of an SP search; however, the HTRU survey’s increase in dynamic range will affect the manual inspection stage by allowing detections of potentially very bright, narrow pulses to be more clearly discernible from noise or non-Gaussian statistics in the observation. This effect is more acute for pulses of width close to the sampling time of each survey.

The improved time and frequency resolutions and dynamic range of the HTRU survey are clearly beneficial for the detection of the narrow SPs of pulsars and RRATs, and extragalactic pulse emitters with durations $w_i \lesssim 10$ ms and DMs of $\lesssim 360$ pc cm$^{-3}$. For a DM of $>360$ pc cm$^{-3}$, we do not expect to see a large number of new RRAT discoveries for several reasons; first, we do not have a considerable increase in sensitivity over the previous surveys for these DMs, and the number of known RRATs above this DM represents only ~10 per cent of the known population. Additionally, for $|b| < 5$, the 35-min pointing duration of PKSMB searches affords a greater probability of detection of low-pulsation rate events over our 8.5-min observations of these areas, and we offer minimal improvements for the capability of detection of these objects. At higher latitudes, for the bulk of pointing positions in the HTRU survey the number density of electrons in the Galaxy is insufficient to produce a DM much greater than 360 pc cm$^{-3}$ (Cordes & Lazio 2002). For these reasons, we expect most new RRAT and high nulling-fraction pulsar discoveries to be at a DM of $<360$ pc cm$^{-3}$. As detailed in Sections 3 and 4.1, this is true for the initial discoveries.

### 2.3 Current processing status

The current status of the HTRU survey’s processing is summarized in the upper panel of Table 1. The processing reported in this paper includes only pointings from the HTRU intermediate- and high-latitude surveys. The survey coverage to date is not contiguous over all Galactic regions. We indicate the total observation time of the processed pointings as a function of sky position in Fig. 4. In total, 22 273 and 1718 beams have been processed out of the 95 056 and 443 287 total beams of the intermediate- and high-latitude surveys, respectively. Approximately 160 incomplete survey pointings of shorter duration have also been processed. As implied by Fig. 4, the bulk of observing time reported in this paper has been spent at Galactic latitudes $|b| < 15$. 

![Figure 3. The HTRU survey's SP search sensitivity to pulses of various intrinsic widths, compared to the performance of the Parkes 20-cm analogue filterbank used by BSB (note that PKSMB had $t_{w} = 250$ µs whereas BSB had $t_{w} = 125$ µs; thus, the PKSMB curve lies slightly above BSB’s). BPSR’s higher frequency resolution most markedly improves our sensitivity to narrow pulses at low DMs; above DM $\approx 450$ pc cm$^{-3}$, the Bhat et al. (2004) model for interstellar scattering dominates the instrumental broadening for both surveys. Because of our limited search range in boxcar-matched filter sizes, there is a sharp decrease in our sensitivity for pulses of a duration of $>32$ ms.](https://academic.oup.com/mnras/article-abstract/416/4/2465/974351)
2.4 Candidate ranking and follow-up strategy

We employ a follow-up prioritization scheme for our SP candidates to provide maximum scientific return with available observing time. Based on the strength of the candidate in various panels of the manual inspection plots and the number of detections at a similar DM in a pointing (Fig. 2), candidates are ranked as multipulse (two or more strong pulses detected at similar DM), strong (≥2 weak pulses, or one convincing pulse detected, that is with an S/N > 7 and exhibiting a characteristic signature in the S/N versus DM plot, e.g. as explored by Cordes & McLaughlin 2003) or weak (a DM > 0 pc cm$^{-3}$ detection appearing pointlike in the multibeam field, but poorly supported by other inspection panels and/or has S/N < 7). Weak candidates outnumber those ranked strong and multipulse by a factor of more than 2. All candidates that are not found in available archival data with pointings near the discovery position are reobserved for a duration equal to that of the discovery pointing. If weak detections are not seen in the initial follow-up pointing, they are not tracked in further follow-up observations. We do not include these detections in this report due to their highly uncertain nature; however, we preserve them in a data base for posterity, considering that borderline detections in future surveys of the same sky area could cross-correlate their findings with our weak, unconfirmed detections. This will be possible with the HTRU low-latitude survey and potentially with future Australian Square Kilometre Array Pathfinder/Square Kilometre Array surveys. Multipulse and strong candidates not seen in initial follow-up are observed again for a duration of three times the discovery pointing. Our ranking levels are set such that the strong and multipulse categories are highly unlikely to contain detections of spurious noise. We include all such candidates here, with objects not detected in follow-up observations distinguished in Table 2 by an upper limit on the objects’ pulsation rate ($\dot{\chi}$, quoted as the number of pulses per hour); this reflects that non-detections of these discoveries are used only to place limits on $\dot{\chi}$ for the object. While the limits are well within the range of pulsation rates for known RRATs, these objects essentially remain unconfirmed, and care must be taken in including these objects in statistical or categorical transient studies [note, however, that PSR J1424−56 is confirmed by the reported detection of PSR J1423−56 by Keane (2010b), as discussed below].

3 EARLY DISCOVERIES AND DETECTIONS

3.1 New discoveries

Table 2 lists the basic parameters of the 13 new and confirmed objects discovered thus far using the HTRU survey’s SP pipeline. There are several objects worthy of specific note.

PSR J0410−31, at Galactic coordinates $l = 230.6, b = -46.7$, is the only confirmed SP discovery arising thus far from the high-latitude survey. The DM of this pulsar is low, with DM = 9.2 pc cm$^{-3}$, lower than 98.9 per cent of known radio pulsars. Estimating distance to the new discoveries using their DMs and the Cordes & Lazio (2002) electron density model for the Galaxy (henceforth NE2001), we find that this is also the most nearby object discovered in our search ($d = 0.51$ kpc).

PSR J0912−38 was also detected in the HTRU survey’s Fourier-domain search. Bright SPs were only detectable above the noise for $\lesssim 30$ s in both the discovery and follow-up observations. When the data are folded over pulses not detected by the single-event search, the pulsar remains detectable with an S/N of >5; this behaviour is not consistent with scintillation. The abrupt change in flux density and the occurrence of these short-duration flares in both observations lead us to suggest that they are intrinsic to the star.
Table 2. Properties of the objects discovered in this search. The columns are as follows: (1) name based on the J2000 coordinate. († indicates a candidate from which only one clear pulse detection has yet been made. Such objects must be interpreted with care; see notes on these and the objects with limits only on $\dot{\chi}$ in Section 2.4.) PSRs J1307–67 and J1423–56 indicated with * are believed to be confirmations of PSRs J1308–67 and PSR J1424–56, respectively, of Keane (2010b); see notes on these objects in Section 3. (2, 3) J2000 right ascension and declination of the pointing centre for detected beam. Only for J1854–1557, the position is as derived from the pulsar’s timing solution. (4) The best-fitting period, where measurable, with the error on the last digit in parentheses. (5) Pulsation rate $\dot{\chi} = N_0 h^{-1}$. (6) Best-fitting DM and error in pc cm$^{-3}$. (7) Observed pulse width at half-maximum of the brightest pulse. (8) Peak flux density of the brightest detected pulse (calculated using $S_{peak}$ in equation 1).

| PSRJ | RA(J2000) | Dec(J2000) | $P$ (s) | $\dot{\chi}$ (h$^{-1}$) | DM (pc cm$^{-3}$) | $w_{eff}$ (ms) | $S_{peak}$ (mJy) |
|------|-----------|------------|---------|-------------------------|------------------|----------------|------------------|
| J0410–31 | 04:10:39 | -31:07:29 | 1.8785(2) | 107 | 9.2(3) | 18 | 470 |
| J0837–24 | 08:37:44 | -24:47:48 | - | 5 | 142.8(5) | 1 | 420 |
| J0912–38 | 09:12:27 | -38:48:34 | 1.5262(1) | 32 | 73.3(5) | 6 | 190 |
| J1014–48 | 10:14:18 | -48:49:42 | 1.5088(2) | 16 | 87(7) | 21 | 140 |
| J1135–49† | 11:35:56 | -49:25:31 | - | $\leq 1.3$ | 114(20) | 9 | 120 |
| J1216–50 | 12:16:20 | -50:27:01 | 6.355(9) | 13 | 110(20) | 9 | 130 |
| J1307–67† | 13:07:41 | -67:03:27 | 3.651(8) | 11 | 47(15) | 32 | 70 |
| J1424–56† | 14:24:23 | -56:40:47 | - | $\leq 1.3$ | 27(5) | 22 | 110 |
| J1541–42† | 15:41:55 | -42:18:50 | - | $\leq 1.3$ | 60(10) | 4 | 150 |
| J1549–57 | 15:49:05 | -57:21:37 | 0.7375(3) | 73 | 17.3(5) | 4 | 210 |
| J1709–53† | 17:09:47 | -53:45:43 | - | $\leq 7$ | 228(20) | 3 | 240 |
| J1854–1557 | 18:54:53.6 | -15:57:22(20) | 3.4532(1) | 25 | 160(25) | 65 | 50 |
| J1925–16 | 19:25:06 | -16:01:00 | 3.8858(2) | $\leq 6.5$ | 88(20) | 10 | 160 |

The pulses of PSR J1014–48 were only detected in one cluster spread over 16 rotations of the neutron star. Like PSR J1825–33 of BSB, no outbursts have yet been detected in follow-up observations.

We are confident that PSR J1307–67 is the PSR J1308–67 of Keane (2010b), who reported a solitary pulse discovery at DM = 44 ± 2 pc cm$^{-3}$ and a position with errors in agreement with our pointing position. Upon searching the archival data closest in position to our discovery, we found seven pulses with an S/N of >5, from which the period reported in Table 2 was determined. Similarly, we are confident that PSR J1424–56 is the PSR J1423–56 of Keane (2010b), who reported DM = 32.9 ± 1.1 pc cm$^{-3}$ and $\dot{\chi} = 3.4 h^{-1}$, both consistent with our findings. Timing solutions will solve the positional and naming ambiguities of these objects.

Broad-bandwidth amplitude modulation features are seen in the frequency-dependent structure of the SPs of PSR J1549–57 (see Fig. 5), the bandwidth of which is inconsistent with the predicted scintillation bandwidth of NE2001 by 4 orders of magnitude. The origin of this feature is unknown; however, despite the significant disagreement with the NE2001 prediction, it is likely to be scintillation if the detected emission is produced by a neutron star.

The predicted scatter broadening of PSR J1709–53 (130 ms at 1.375 GHz for the NE2001 model) is much greater than the half-maximum pulse width detected here. The SP from this object had an S/N of 10, a visible dispersion curve, an S/N versus DM curve well fitted to the model of Cordes & McLaughlin (2003) for a genuinely dispersed pulse and exists in a relatively interference-free observation. These conflicting properties indicate that either the impulse’s origin is not celestial or the NE2001 scattering model for this Galactic position is incorrect; the latter is highly possible to be the case here, as scattering is highly dependent on line of sight. A redetection of this candidate would conclusively clarify the nature of this candidate; however, follow-up has not yet been performed.

PSR J1854–1557 appears to be exhibiting periodic nulling, drifting and mode-changing behaviours (Fig. 6). Despite a high nulling fraction, this object’s relatively frequent emission renders it detectable in a Fourier search with an S/N of ~17 in the 8.5-min survey and follow-up pointings. This object was also detected in the Fourier pipeline, as reported in HTRU Paper I.

3.2 Redetections of known pulsars and RRATs

The SP pipeline has detected approximately 55 per cent of the known pulsars that could be detected through Fourier searches of the HTRU survey data. This is an unexpectedly large fraction, and it offers improvements over the SP detection rates presented in BSB.
Figure 6. A pulse stack showing SPs of the periodically nulling pulsar J1854−1557.

and PKSMB, perhaps a testament to the increased sensitivity to faint and narrow SPs that this survey’s hardware affords. The SP properties of these objects will be analysed in future work, so we will not detail them here.

We have processed 24 observations with pointing positions within 6 arcmin (our approximate half-power beamwidth) of published RRAT positions (i.e. from McLaughlin et al. 2006, 2009, BSB; Keane et al. 2010). Of these 24, 13 RRATs were redetected. For 22 of 24 observations, the number of pulses seen from each object was consistent with the expected number based on previously published pulsation rates in the discovery observations of these objects (again, as drawn from the BSB and PKSMB publications) and the observation length in our data. The two notably different detection rates were of RRATs J1753−38 (BSB; four expected and >15 seen) and J1819−1458 (McLaughlin et al. 2006; three expected and 10 seen). PSR J1819−1458 is known to exhibit small variations in the pulsation rate (and larger ones associated with glitches; Lyne et al. 2009), and the detection rate observed here is consistent with the range in $\chi$ reported by Lyne et al. (2009). For PSR J1753−38, the higher detection rate, detectability in a Fourier search with an S/N of ~13 (whereas it was undetectable in a Fourier search of its original discovery data) and the slight increase in $S_{\text{max}}$ exhibited in our observations indicate that (1) this pulsar’s emission appears to simply be highly modulated rather than nulling and (2) our observing position of the source is improved from that reported by BSB. Our positional offset was 0.1, suggesting an improved position of right ascension and declination 17:53:09, −38:52:13 (J2000).

4 DISCUSSION

4.1 Our discoveries in archival pulsar surveys

All of our discoveries except for PSR J0410−31 and PSR J0837−24 lie in regions previously covered by the surveys of Jacoby et al. (2009), Edwards et al. (2001) and Manchester et al. (2001). The presence of pulses in archival data can add valuable information about pulse rate changes over time and potentially add data points to their timing if a phase-coherent timing solution is obtained. The detection of J1307−67 and J1424−56 in archival data has already been discussed in Section 3.1. We inspected data in the archival surveys within one half-power beamwidth of our other objects’ positions to determine the detectability of our discoveries in the archival data. None of our objects was detected in these pointings in SPs. However, while PSR J1854−1557 is not detectable in a Fourier search, it is marginally detectable when the archival data are folded over the period given in Table 2.

We investigate the reason for the non-detection of the remaining objects by first estimating the signal loss due to the use of the analogue multibeam filterbank system used by BSB and PKSMB and then calculating the S/N that a pulse of equivalent width, DM and $S_{\text{peak}}$ (as listed in Table 2) would have shown in the archival data. This analysis suggests that even the brightest detected pulses in our data would result in only a marginal (S/N < 6) detection in the analogue filterbank data for PSRs J1135−49, J1541−42 and J1709−43. For two out of four of the remaining objects at $|b| > 5^\circ$, for which the archival data length was 4.4 min, the non-detections are accounted for by the low probability that a pulse would occur during the time-span of the observation. The remaining $|b| > 5^\circ$ objects, PSR J0912−38 and PSR J1014−48, had clusters of sequential pulses rather than a smooth distribution of SPs. Although the per-hour pulsation rate is high for these objects, the duration of on-activity is short, and the spacing between sequential pulse outbursts is $\geq 8$ min. This indicates that the non-detection of pulses is consistent with a decreased probability of the occurrence of a pulse outburst during the archival observations. The effect of on- and off-time-scales on object detectability will be discussed further in Section 4.2.

The only remaining undetected object is PSR J1549−57. We have not yet performed follow-up observations on this object, and so the archival data, in which we would have expected to see detections of S/N > 7, serve only to place limits on the pulsation rate and duration of off-activity in these objects. The non-detection in two archival pointings places a strong limit (zero pulses in $\geq 70$ min) on these values.

4.2 Activity time-scales in sparsely emitting neutron stars

Approximately one-third of our SP pipeline discoveries exhibit distinct periods of on-activity, marked by bright sequential pulses that are separated by longer intervals of either genuine nulls or a decrease in the intensity level sufficiently large that the object is undetectable through SP or periodicity search techniques during the null state. The pulsation rate, $\dot{\chi}$, that is typically quoted for SP discoveries poorly represents the emissivity of such objects. It provides insufficient information to assess the probability either of discovering such a neutron star in a given observation or of detecting such an object during a reobservation.

Considering this and the significant capability of the HTRU survey to discover new genuinely sparsely emitting objects (see Section 4.4), we seek to more accurately incorporate our discoveries and RRAT populations in general into the range of nulling and emissivity time-scales exhibited by radio pulsars. We explore a relevant...
'intermittence parameter space' here and review in Section 4.3 what effect survey parameters have on the selection of various populations in this space.

We note that the on- and off-states of nulling pulsars typically show characteristic lengths (Herfindal & Rankin 2007; Wang, Manchester & Johnston 2007; Redman & Rankin 2009), parametrized below by $t_{\text{on}}$ and $t_{\text{off}}$, respectively. This description of neutron star intermittence is more physically representative for pulsars of various nulling fractions, better reflects the time-scales associated with possible windowing phenomena and allows a more accurate exploration of selection effects for surveys of various lengths (see Section 4.3). Here we use a definition of $t_{\text{off}}$ that is similar to the ‘null length’ of Wang et al. (2007). We define $t_{\text{off}}$ as the average time between the first pulse whose signal drops below a set threshold (we use $S/N > 5$) and the next above that threshold. We define $t_{\text{on}}$ as the average number of pulses ($N_{\text{on}}$) above the same threshold times the rotational period of the object. Obviously, such values are only valid for genuine nulling pulsars, that is this analysis is inappropriate for highly modulated pulsars with long-tailed pulse energy distributions (e.g. Weltevrede et al. 2006). Uninterrupted data spans of $T \gg t_{\text{on}} + t_{\text{off}}$ containing SP detections of high significance (i.e. where the SP energy distribution of the on-pulses is such that all pulses exceed the threshold) would provide the most accurate measurements of these quantities; for our discoveries, most observations provide robust SP detections, although we are insensitive to time-scales of $\gtrsim 9$ min. We nevertheless make estimates of (or place limits on, in observations where no time-scales are measurable because they appear greater than our data span) the average $t_{\text{on}}, t_{\text{off}}$ for our discoveries based on all available data.

The nulling fraction of a pulsar is only valid in this analysis when measured over a time-scale far exceeding one activity cycle of the object, which is given by a length $T_A = t_{\text{on}} + t_{\text{off}}$. Below we generically represent the nulling fraction measured over ‘infinite time’ as $f_{\infty}$, where accordingly, the pulsar’s on-fraction measured over a time $T \gg T_A$ is given by $\xi = 1 - f_{\infty}$. As an example, the pulsar PSR B1931+24 exhibits periods of activity lasting for $\sim 5$–7 d, separated by nulls of $\sim 30$ d (Kramer et al. 2006). While the nulling fraction measured over short observational time-scales is therefore typically either 0.0 or 1.0, we find that $f_{\infty} \approx 0.85$.

In Fig. 7, we plot $\xi$ as a function of $t_{\text{off}}$ for the SP discoveries from HTRU, PKSMB, BSB and Deneva et al. (2009). We also plot all nulling pulsars analysed by Wang et al. (2007) that have a non-zero nulling fraction. The Wang et al. sample was selected from the periodicity-discovered pulsars of the same survey as the PKSMB searches and has poor sensitivity to nulls of $\lesssim 30$ s due to the averaging performed over 10–30 s time-scales. The dashed grey lines in this figure show contours of constant $t_{\text{on}}$. For a pulsar of period $P$, it is not straightforward to identify on- or off-activity time-scales of duration $t < P$; the shaded region below $t_{\text{on}} = 100$ ms indicates the area for which $t_{\text{on}}$ is shorter than the period range of SP search discoveries that emit at $N_{\text{on}} = 1$.

One critical point illustrated by this plot is the continuous transition between the Wang et al. (2007) nulling pulsars and the population discovered by SP searches. McLaughlin & Cordes (2003) derived that neutron stars of period $P$ will be more readily discovered in a single-pulse search (i.e. having $S/N \gg m_{\text{sp}}/m_{\text{ppq}} > 1$) when $\xi < 2\sqrt{P/T}$, leading Keane (2010a) to note that this effect causes $\xi$- and $P$-based selection effects for SP searches.

**Figure 7.** The on-fraction, $\xi$, against the mean null length for SP search discoveries and the pulsars of Wang et al. (2007). All elements highlighted in maroon indicate relevance to the HTRU intermediate-latitude survey; the squares show SP pipeline discoveries, while points enclosed by maroon circles indicate previously known objects which were redetected in the HTRU intermediate-latitude survey data (Section 3.2). Points with arrows designate an object for which $t_{\text{on}}$ has been measured but only a lower limit on the null time-scale is known, and points with flat-headed arrows represent objects for which only one pulse has been detected (we have assumed $P > 8.5$ s for these objects; therefore, the plotted point is an upper limit to $\xi$ and a lower limit to $t_{\text{on}}$). The solid green lines indicate lines of constant nulling fraction as measured over infinite time ($f_{\infty}$, see Section 4.2), and the dashed grey lines show constant contours of $t_{\text{on}}$. The vertical dotted lines show the single-pointing observation length for the survey of PKSMB and for the HTRU high (hi), intermediate (med) and low (lo) latitude surveys (see Section 4.3). The shaded region below $t_{\text{on}} = 100$ ms indicates the area for which $t_{\text{on}}$ is shorter than the period range of SP search discoveries and is therefore ill-defined. B1931+24 is the ‘intermittent pulsar’ published by Kramer et al. (2006) and discussed in Section 4.3.
HTRU intermediate-latitude survey pointings, pulsars with periods \( P < 6 \text{ s} \) should therefore be discovered more readily in the Fourier pipeline at \( \xi > 0.2 \), and thus it is not surprising that no HTRU intermediate-latitude survey points lie above this line in Fig. 7. For the \( T = 35\text{-min} \) pointings of the Parkes Multibeam survey (Manchester et al. 2001), \( r > 1 \) when \( \xi < 0.02–0.11 \), considering a period range from 200 ms to 6 s. Appropriately, this appears to be the region in Fig. 7 where the nulling pulsars give way to the SP discoveries. It is clear here that the on and off time-scales, and the nulling fractions of the radio pulsars discovered in SP searches exhibit a smooth distribution over many orders of magnitude with no obvious distinction of the RRAT population represented by the SP discoveries. A rigorous nulling-fraction analysis for bright pulsars in the HTRU intermediate-latitude survey is planned for the near future and is capable of addressing whether the objects discovered by SP searches represent a smooth extension in the probability density function of pulsar nulling fractions.

### 4.3 Detectability of intermittent neutron star populations

The distribution of objects in Fig. 7 is influenced by a number of selection effects, which we explore here both to investigate the underlying distribution of activity cycles in neutron stars and to determine the population to which the three HTRU survey components will be sensitive.

Considering the general detectability of pulsars in this phase space, the probability that at least one pulse will be emitted by a bright pulsar during an observation of length \( T \) is given by

\[
P_{\text{em}} = \begin{cases} 
0 & \text{for } f_{\infty} = 1 \\
1 & \text{for } T > t_{\text{off}} \\
(T - \xi T + \xi t_{\text{off}})/t_{\text{off}} & \text{for } T \leq t_{\text{off}}.
\end{cases}
\]

Equation (2) indicates that on average for \( t_{\text{off}} < T \), the probability that a source would be detected is 1, and for \( t_{\text{off}} > T \), it is directly proportional to \( \xi \). It is apparent in Fig. 7 that there is a drop in the neutron star population for objects with \( t_{\text{off}} \geq 9 \text{ min} \) to objects with \( t_{\text{off}} < 9 \text{ min} \). We point out that the object of the highest \( t_{\text{off}} \) discovered in each of the PKSMB, BSB and HTRU intermediate-latitude surveys is roughly a factor of 3 greater than the corresponding survey’s length. This corresponds to \( P_{\text{em}} \gtrsim 0.33 \). At null lengths greater than the observing time for these surveys, the probability of detection quickly decreases. Accordingly, a population of pulsars with a flat underlying distribution in \( t_{\text{off}} \) or \( \log(t_{\text{off}}) \), we would expect to have a higher discovery/detection rate of objects with \( t_{\text{off}} < T \). Focusing on the objects detected by the HTRU intermediate-latitude survey (highlighted in maroon in Fig. 7), the distribution is roughly consistent with a flat distribution in \( \log(t_{\text{off}}) \), with a ratio of 7:13 for objects with \( t_{\text{off}} \geq 9 \text{ min} \) to objects with \( t_{\text{off}} < 9 \text{ min} \). We point out that the object of the highest \( t_{\text{off}} \) discovered in each of the PKSMB, BSB and HTRU intermediate-latitude surveys is roughly a factor of 3 greater than the corresponding survey’s length. This corresponds to \( P_{\text{em}} \gtrsim 0.33 \).

Note, however, that this probability is generally representative and will hold for a sample of many sources but will not always be strictly true for an individual source as the distribution of \( t_{\text{off}} \) and \( t_{\text{off}} \) for a single object is not a delta function. Following this equation, the vertical lines in Fig. 7 mark the null length below which a sufficiently bright emitter has a probability of unity that it will be detected in the Parkes Multibeam survey, the HTRU intermediate-latitude survey and the (recently commenced) low-latitude survey, respectively. At null lengths greater than the observing time for these surveys, the probability of detection quickly decreases. Accordingly, given a population of pulsars with a flat underlying distribution in \( t_{\text{off}} \) or \( \log(t_{\text{off}}) \), we would expect to have a higher discovery/detection rate of objects with \( t_{\text{off}} < T \). Focusing on the objects detected by the HTRU intermediate-latitude survey (highlighted in maroon in Fig. 7), the distribution is roughly consistent with a flat distribution in \( \log(t_{\text{off}}) \), with a ratio of 7:13 for objects with \( t_{\text{off}} \geq 9 \text{ min} \) to objects with \( t_{\text{off}} < 9 \text{ min} \). We point out that the object of the highest \( t_{\text{off}} \) discovered in each of the PKSMB, BSB and HTRU intermediate-latitude surveys is roughly a factor of 3 greater than the corresponding survey’s length. This corresponds to \( P_{\text{em}} \gtrsim 0.33 \) at all nulling fractions.

4.4 Discovery forecast for the full HTRU survey

The rate of new SP discoveries in the HTRU survey, particularly those in overlapping regions of previous surveys, hints at the potential for the full HTRU survey to uncover many new examples of sparsely emitting neutron stars. For the intermediate-latitude survey, we have detected a total of 26 new and known SP emitters, suggesting detection rates on the order of \( 3 \times 10^{-3} \text{ deg}^{-2} \) at these latitudes. We have processed roughly 23.5 per cent of the intermediate-latitude survey to date, and if our discovery rate continues, the full HTRU intermediate-latitude survey data should contribute an additional estimated \( \sim 50 \) new discoveries of transient neutron stars. We note that the sky distribution of neutron stars should have a higher density at lower Galactic latitudes, and as seen in Fig. 4 we have not yet processed most of the pointings at latitudes closest to \( b = 0 \). At higher latitudes we have only processed a small fraction of the survey, and while it is tempting to take an extrapolated value as an upper limit, we note that our single discovery in only 0.39 per cent of the high-latitude survey implies a sky density of \( \sim 2 \times 10^{-3} \text{ deg}^{-2} \), higher than expected when compared to the sky density at lower
latitudes. Therefore, the detections are expected to be less than 250.

Finally, the explorations of Sections 4.2 and 4.3 have accented the time-scales of neutron star intermittence accessible by the HTRU survey. In particular, the HTRU low-latitude survey (with its 70-min pointing length) will mark a significant increase in the detection rate over the PKSMB survey for objects with $35 < t_{\text{eff}} < 70$ min, and may be realistically expected to discover objects with null lengths up to $t_{\text{eff}} = 3.5$ h, if such objects exist (as deduced in Section 4.3, in which it was noted that transient surveys have all been able to discover objects with $t_{\text{eff}}$ values of up to three times the survey pointing length; see also Fig. 7). The low-latitude survey will also provide data that may be used to investigate the possible deficit of low-nulling-fraction objects with $t_{\text{off}} > 300$ s. Care must be taken during both the SP and periodicity searches, analysis and follow-up, such that if these objects do exist, they are not selected against. This will involve, for one, appropriate follow-up monitoring of the stronger Fourier candidates that are undetected in initial follow-up pointings.

5 SUMMARY AND CONCLUSIONS

We have presented the methods of and initial discoveries for the SP analysis of the HTRU survey. We outlined the design of the HTRU survey’s SP pipeline, which functions efficiently alongside the Fourier-analysis pipeline; the SP analysis furthermore employs a ‘friend-of-friends’ single-event recognition algorithm and performs automated interference rejection based on the dispersive and multibeam signature of single events. The new digital backend used to collect HTRU survey data has afforded a factor of up to $\sim$5 times improvement in sensitivity over previous surveys in overlapping Galactic regions and offers the most significant improvements for short (sub-ms duration) pulses at low ($\text{DM} < 360$ pc cm$^{-3}$) DMs.

Analysis of 23.5 and 0.39 per cent of HTRU intermediate and high Galactic latitude survey data, respectively, has resulted in the discovery of 12 and one new neutron stars. Much of the survey pointings covered Galactic regions that were previously surveyed and searched for SPs (McLaughlin et al. 2006; BSB; Keane et al. 2010); 11 of our new discoveries lie within these regions, and for the nine of these that were not visible in the archival data, their non-detection was consistent either with the signal degradation due to the use of the previous wider channel analogue backend or with the improbability of a pulse being emitted in the archival survey due to a long null cycle.

Finally, we investigated the distribution of nulling and emissivity time-scales for the new SP neutron star discoveries and redetections in the HTRU survey data and for the RRAT/nulling population in general. We found that periodicity-discovered nulling pulsars and SP search discoveries exhibit a continuous distribution across null/activity time-scales and nulling fractions, building on evidence that many RRATs represent a tail of extreme-nulling pulsars. We found that there is an apparent decrease in objects with emissivity cycles longer than $\sim$300 s at intermediate and low nulling fractions which is not readily explained by selection effects, and note that the HTRU deep low-latitude survey will be capable of exploring whether this deficit is natural or an effect of selection. Finally, we estimated that the full HTRU survey is capable of more than doubling the known extreme-nulling pulsar population and will explore the neutron star population with nulling fractions exceeding 99.99 per cent and null lengths lasting for up to 3–4 h.

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