The Northern High Time Resolution Universe pulsar survey – I. Setup and initial discoveries

E. D. Barr,1,2,3 D. J. Champion,1 M. Kramer,1,4 R. P. Eatough,1 P. C. C. Freire,1 R. Karuppusamy,1,4 K. J. Lee,1 J. P. W. Verbiest,1 C. G. Bassa,4 A. G. Lyne,4 B. Stappers,4 D. R. Lorimer5 and B. Klein1,6

1Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
2Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Mail H30, PO Box 218, Hawthorn, VIC 3122, Australia
3Australian Research Council Centre of Excellence for All-Sky Astrophysics (CAASTRO), Mail H30, PO Box 218, Hawthorn, VIC 3122, Australia
4Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy, The University of Manchester, Manchester M13 9PL, UK
5Department of Physics, West Virginia University, White Hall, Morgantown, WV 26506, USA
6University of Applied Sciences Bonn-Rhein-Sieg, Grantham-Allee 20, D-53757 Sankt Augustin, Germany

ABSTRACT
We report on the setup and initial discoveries of the Northern High Time Resolution Universe survey for pulsars and fast transients, the first major pulsar survey conducted with the 100-m Effelsberg radio telescope and the first in 20 years to observe the whole northern sky at high radio frequencies. Using a newly developed 7-beam receiver system combined with a state-of-the-art polyphase filterbank, we record an effective bandwidth of 240 MHz in 410 channels centred on 1.36 GHz with a time resolution of 54 µs. Such fine time and frequency resolution increases our sensitivity to millisecond pulsars and fast transients, especially deep inside the Galaxy, where previous surveys have been limited due to intrachannel dispersive smearing. To optimize observing time, the survey is split into three integration regimes dependent on Galactic latitude, with 1500, 180 and 90-s integrations for latitude ranges |b| < 3.5°, |b| < 15° and |b| > 15°, respectively. The survey has so far resulted in the discovery of 15 radio pulsars, including a pulsar with a characteristic age of ∼18 kyr, PSR J2004 +3429, and a highly eccentric, binary millisecond pulsar, PSR J1946 +3417. All newly discovered pulsars are timed using the 76-m Lovell radio telescope at the Jodrell Bank Observatory and the Effelsberg radio telescope. We present timing solutions for all newly discovered pulsars and discuss potential supernova remnant associations for PSR J2004 +3429.

Key words: pulsars: general – pulsars: individual: J1946 +3417 – pulsars: individual: J2004 +3429.

1 INTRODUCTION
It could be argued that no other astrophysical object has the ability to provide insight into as many fields of physics and astrophysics as the pulsar. The extreme conditions found in and around these objects make them unique natural laboratories for the study of subjects such as the equation of state of supranuclear matter (Demorest et al. 2010; Antoniadis et al. 2013), the behaviour of gravity in the strong-field regime (Kramer et al. 2006; Freire et al. 2012), the formation and evolution of binary systems (Stairs 2004) and the existence and properties of gravitational waves (Hellings & Downs 1983). Therefore, the discovery of new pulsar systems, through targeted or blind surveys, holds great scientific potential.

Pulsar surveys will in general always increase our understanding of the underlying source distribution and its properties, but it is the potential for the detection of rare and exciting systems, such as a hypothesized pulsar black hole system (Narayan, Piran & Shemi 1991), that is the major driving force behind modern-day pulsar surveys. Several examples of such exciting discoveries can be found in surveys conducted within the last two decades. These include the discovery of the so-called Double pulsar, PSR J0737 −3039A/B (Burgay et al. 2003; Lyne et al. 2004), which consists of two pulsars orbiting each other in a highly relativistic binary system; PSR J1903 +0327 (Champion et al. 2008), a rapidly rotating pulsar in a highly eccentric orbit, which has shed light on the evolution of hierarchical triple systems (Freire et al. 2011); the ‘Diamond-planet
pulsar, PSR J1719–1438 (Bailes et al. 2011), with its Jupiter-mass CO white dwarf companion; and most recently of J2222–0137 (Boyles et al. 2013), a rapidly rotating pulsar with a massive companion, whose proximity to the Earth (∼300 pc) makes it an exciting system, both for the measurement of post-Keplerian parameters and for the multiwavelength study of pulsar emission physics.

While targeted pulsar surveys, such as those that observe globular clusters (e.g. Ransom et al. 2005) or γ-ray point sources (e.g. Keith et al. 2011; Barr et al. 2012) tend to have a high discovery rate, they cannot produce an unbiased sample of the underlying population. To achieve a more complete picture of the true population distribution and the exotic systems it may contain, we must perform all-sky surveys.

In the past, blind surveys have been successful in detecting many new and exciting pulsar systems. Good examples can be found in many surveys (e.g. Edwards et al. 2001; Manchester et al. 2001; Burgay et al. 2006) conducted using the 20-cm multibeam receiver system of the Parkes Radio Telescope over the last 10 years. These surveys have been remarkably successful, not only in discovering almost 60 percent of all known pulsars, but also some unique and fascinating objects. As well as the discovery of the aforementioned Double pulsar, these surveys have discovered 6 of the 10 known double neutron star systems, pulsars with massive stellar companions (Johnston et al. 1992; Stairs et al. 2001) and the pulsar with the largest glitch (Manchester & Hobbs 2011). Furthermore, reprocessing of these data has led to the discovery of Rotating Radio Transients (McLaughlin et al. 2006), a new class of pulsars that display bursty radio emission on varying time-scales (see Keane et al. 2011 for a recent review).

The original Parkes multibeam surveys used a 96 × 3-MHz channel analogue filterbank with a 250-μs sampling time. This relatively coarse frequency and time resolution resulted in a reduced searchable volume for narrow-pulse-width transients and millisecond pulsars (MSPs) due to dispersive smearing within individual channels (see Section 6.3.1). These limitations were compounded by a 1-bit digitization scheme employed by the analogue filterbank. The limited dynamic range of 1-bit digitization, although less sensitive to radio–frequency interference (RFI), acts to decrease the signal-to-noise (S/N) ratio of any pulsed or transient signal by ∼20 per cent (Kouwenhoven & Voûte 2001). While these surveys were state of the art at their conception, affordable technology now exists for the multiwavelength study of pulsar emission physics.

In Section 2, we describe the observing strategy used in the HTRU-North survey. In Section 3, we describe the frontend and backend systems used at the Effelsberg radio telescope. In Section 4, we present analytical and empirical estimates of the survey sensitivity. In Section 5, we consider the expected pulsar yield as determined through Monte Carlo simulations of the Galactic pulsar population. In Section 6, we describe the data processing pipeline from acquisition to candidate selection. In Section 7, we present the timing solutions for all newly discovered pulsars and discuss potential supernova remnant (SNR) associations for PSR J2004+3429. In Section 8, we present our conclusions.

2 SURVEY STRATEGY

The HTRU-North survey will be comprised of more than 1.5 million observed positions on the sky. To optimize the usage of our observing time, the HTRU-North survey is split into three complementary parts based on Galactic latitude (see Fig. 1).

The high-latitude section covers the sky at Galactic latitudes of |b| > 15° with short integrations of 90 s. The majority of sky covered by the high-latitude section has remained unsurveyed for more than 20 years, and so with the technical advances implemented in the HTRU-North survey we expect to discover many bright pulsars, which do not require long integration times to detect, and both Galactic and extragalactic transients (see Section 6). The near-isotropic distribution of MSPs expected to be discovered in this region will be of great use to current and future pulsar timing arrays for gravitational-wave detection (Foster & Backer 1990).

The mid-latitude section covers Galactic latitudes of |b| < 15° with 180-s integrations. This section of the survey probes the regions of the Galaxy most likely to contain undiscovered bright MSPs (again, vital for pulsar timing arrays). In the mid-latitude section, we also perform a shallow sweep of the Galactic plane. These observations are expected to discover any bright, longer period pulsars.

Finally, the low-latitude section covers Galactic latitudes of |b| < 3.5 with long integrations of 1500 s. These long

Figure 1. A Hammer projection of the Galaxy showing the survey area for all three regions of the HTRU-North survey. Note that the mid-latitude portion of the survey also incorporates the low-latitude survey region. For information on the parameters of each latitude region, see Table 1.
3 INSTRUMENTATION

All searching was performed using the 100-m Effelsberg radio telescope of the Max-Planck-Institut für Radioastronomie. Below, we describe the receiver and backend systems used to acquire observational data.

3.1 The 21-cm Effelsberg multibeam receiver

The 21-cm Effelsberg multibeam receiver consists of seven horns at the prime focus of the Effelsberg telescope. The horns are arranged in a hexagonal close-packed pattern around the central beam, with a beam separation of 0.25. The central beam is circular with a beamwidth (full width at half-maximum, FWHM) of 0.16, while the outer beams have slight ellipticity with a corresponding circular beamwidth of 0.166. Each of the seven horns has a bandwidth of 255 MHz centred on 1360 MHz and two polarization channels, left- and right-hand circular for the central horn and orthogonal linear for the outer horns. Signals from the 14 channels are amplified in low-noise amplifiers, before undergoing down-conversion to an intermediate frequency of 150 MHz via heterodyning. After hardware RFI rejection we recover 250 MHz of useable band. This figure typically drops to ~240 MHz after software RFI rejection (see Section 6.2).

During the course of an observation the parallactic angle of the beam pattern on the sky changes with the telescope’s azimuth-elevation position. To keep the outer beams at constant Galactic latitude, the receiver box is rotated to maintain a constant parallactic angle.

The laboratory-measured receiver temperature of the central horn is 21 K, with the outer horns having temperatures between 13 and 18 K. The layout of the beam pattern on the sky and the tessellation unit for the survey can be seen in Fig. 2.

3.2 The PFFTS backend

The Effelsberg Pulsar Fast Fourier Transform Spectrometer (PFFTS) backend was specially developed to meet the requirements of searching for pulsars with a wide-band, multibeam receiver. The PFFTS is based on the Array Fast Fourier Transform Spectrometer (AFFTS; Klein et al. 2012) – an FFT spectrometer originally designed for spectral line observations. The backend combines seven identical electronic boards, each equipped with a high-speed analog-to-digital converter and a high-performance FPGA. In ‘pulsar search’ mode, the signal from each beam of the receiver is sampled by an analogue-to-digital converter (ADC) clocked at 600 MHz with 8-bit resolution. Following the ADC, the signal is processed by a 512-channel polyphase filterbank implemented on 1 The receiver temperatures for each horn, plus further information about the receiver system, can be found at http://www.mpifr-bonn.mpg.de/effelsberg.

| Region   | High | Mid | Low |
|----------|------|-----|-----|
| $|b| > 15^\circ$ | $|b| < 15^\circ$ | $|b| < 3.5^\circ$ |
| $t_{\text{obs}}$ (s) | 90   | 180 | 1500 |
| $N_{\text{beams}}$ | 1066 135 | 375 067 | 87 395 |
| $t_{\text{samp}}$ (µs) | 54.61 | 54.61 | 54.61 |
| $\Delta v$ (MHz) | 240  | 240 | 240 |
| $\Delta v_{\text{chan}}$ (kHz) | 585.9 | 585.9 | 585.9 |
| $N_{\text{chans}}$ | 410  | 410 | 410 |
| $G_{\text{central}}$ (K Jy$^{-1}$) | 1.5  | 1.5 | 1.5 |
| $G_{\text{outer}}$ (K Jy$^{-1}$) | 1.3 | 1.3 | 1.3 |
| $N_{\text{samples}}$ ($\times 10^5$) | 1.6 | 3.3 | 27.4 |
| $S_{\text{min}}$ (mJy) | 0.17 | 0.14 | 0.05 |
| Data/beam (GB) | 0.8 | 1.6 | 13.4 |
| Data (total) (TB) | 818.1 | 575.6 | 1117.8 |
4 SENSITIVITY

4.1 Analytic sensitivity

To estimate the minimum pulsed flux density, \( S_{\text{min}} \), observable by our survey, we use the modified radiometer equation (see e.g. Lorimer & Kramer 2005),

\[
S_{\text{min}} = \beta \frac{S/N_{\text{min}} T_{\text{sys}}}{G \sqrt{n_{\text{pols}} \Delta f}} \left( \frac{W_{\text{eff}}}{P - W_{\text{eff}}} \right)^{1/2},
\]

(1)

where the constant factor \( \beta \) denotes signal degradation caused by digitization, which for 8-bit sampling is \( \sim 0.01 \) per cent, giving \( \beta = 1 \) (Kouwenhoven & Voûte 2001). The system temperature, \( T_{\text{sys,i}} \), is the sum of the receiver temperature, \( T_{\text{rec}} \), and the sky temperature \( T_{\text{sky}} \).

Other parameters in this expression are the total integration time, \( t_{\text{obs}} \); the effective bandwidth of the receiver, \( \Delta f \); the number of polarizations summed, \( n_{\text{pols}} \), which for this survey is always two; the pulsar period, \( P \); the effective pulse width, \( W_{\text{eff}} \); and the minimum \( S/N \) ratio with which we can confidently make a detection, \( S/N_{\text{min}} \).

Based on false alarm statistics (see e.g. Lorimer & Kramer 2005), \( S/N_{\text{min}} = 8 \). Due to intrachannel dispersive smearing the effective pulse width increases with DM\(^2\) as

\[
W_{\text{eff}} = W_{\text{int}} + \left( k_{\text{DM}} \Delta f_{\text{chan}} f^{-s} \right)^{1/2} + t_{\text{amp}}^{1/2},
\]

(2)

where \( W_{\text{int}} \) is the intrinsic pulse width, \( t_{\text{amp}} \) is the sampling interval of the observation, \( f \) is the observing frequency, \( \Delta f_{\text{chan}} \) is the bandwidth of a single frequency channel and \( k_{\text{DM}} = 8.3 \times 10^{-1} \) s. While scatter broadening will likely be the limiting factor on the DM depth to which we can detect short-period pulsars, the large uncertainty on its relationship with DM (Bhat et al. 2004) means that we disregard it when calculating expected sensitivities. For this reason, the sensitivity calculations here represent a best-case scenario. Fig. 4 shows sensitivity curves for each region of the survey for a selection of DMs.

4.2 Pulsar redetections

Thus far, observations have been concentrated on the mid-latitude portion of the HTRU-North survey. Processing of the first 13 per cent of these observations has led to the redetection of 93...
known pulsars. To obtain an empirical confirmation of our survey sensitivity, observed S/N ratios were compared to S/N ratios predicted using published flux densities taken from the Australia National Telescope Facility (ATNF) pulsar catalogue.\footnote{http://www.atnf.csiro.au/research/pulsar/psrcat/ (Manchester et al. 2005)}

Using the sky temperature model of Haslam et al. (1982), scaled with a spectral index of $-2.6$ (Lawson et al. 1987), and published pulsar positions taken from the ATNF pulsar catalogue, we calculated the expected S/N ratio for all redetections through rearranging equation (1). As the redetections did not lie in the centre of their discovery beam, S/N values were multiplied by a Gaussian offset factor, $\Omega = \exp\left(-\theta^2/\phi^2\right)$, to correct for off-axis gain decreases. Here, $\theta$ is the pointing offset in degrees and $\phi$ is the beam half-width at half-maximum.

To make the comparison more robust, only redetections that were within one beamwidth of the observed position were used. Redetection observations were also cleaned of RFI prior to S/N measurement (see Section 6.2). Fig. 5 shows the observed S/N versus the expected S/N for the remaining sample of redetections.

As an independent test for sensitivity losses in the backend, timing observations from the Lovell telescope were also used to obtain S/N ratio measurements for the newly discovered pulsars from this survey. In all cases, the S/N ratio measurement from the Effelsberg discovery observation agreed with the distribution of S/N ratio measurements obtained from the Lovell telescope timing data to within 1σ.

To verify that no pulsar had been missed by the survey, all pointings for which a known pulsar was within one beamwidth were examined. S/N ratios for these pulsars were estimated using the method outlined above. Of the pulsars with estimated S/N ratios above 8, five were undetected in the initial processing of the data. Folding the data for these pulsars with published ephemerides led to detections for two of the pulsars with S/N ratios below our detection limit. The three remaining undetected pulsars all have periods in excess of 2.5 s. Long period systems such as these are often difficult to detect in short observations, as wider Fourier bins and large low-frequency components in the data act to suppress the pulsar signal.

It should be noted that although these three pulsars were undetected in periodicity searches, one was detected through single-pulse analysis. These results confirm that the observing system is performing as expected, with no loss of sensitivity.

5 SIMULATIONS

To estimate the expected detection rate of the HTRU-North survey, Monte Carlo simulations of the Galactic MSP and normal pulsar populations were performed using the model outlined in Lorimer et al. (2006), with the PSRPOP\footnote{http://psrpop.phys.wvu.edu/} software. To simulate the normal pulsar population, input model parameters were chosen as follows.

(i) Empirical period distribution taken from the probability density function of the known population.

(ii) A log normal pseudo-luminosity distribution, defined at 1.4 GHz, with mean and standard deviation in log space of $-1.1$ and 0.9, respectively (Faucher-Giguère & Kaspi 2006).

(iii) An exponential distribution for the height above the Galactic plane, with a scaleheight of 330 pc (Lorimer et al. 2006).

(iv) A radial distribution as described in Lorimer et al. (2006).

(v) A 6 per cent duty cycle with dither given in Lorimer et al. (2006).

(vi) The NE2001 Galactic free electron density model (Cordes & Lazio 2002).

The number of pulsars to be simulated was chosen such that the discovery rates of simulated versions of the Parkes Multibeam Pulsar Survey (Manchester et al. 2001), the Swinburne Intermediate Latitude Pulsar Survey (Edwards et al. 2001) and its extension (Jacoby et al. 2009) and the Parkes High Latitude Survey (Burgay et al. 2006), matched those of their real counterparts.

To estimate the number of MSP detections expected from the survey, we used model ‘A’ of Lorimer (2012). This model updates the results of Lorimer et al. (2006) by taking into account Galactic MSPs found through recent high time- and frequency-resolution pulsar searches. Table 2 shows the results of the simulations and the expected discovery count for each region of the HTRU-North survey. The simulations suggest that the HTRU-North survey will detect $\sim 1657$ normal pulsars and $\sim 153$ MSPs, after taking into account pulsars co-detected in both the mid- and low-latitude portions of the survey. However, recent work on determination of the MSP luminosity distribution using pulsar detections from the HTRU survey (Levin et al. 2013) has suggested that larger MSP yields may be expected.

| Region    | Detections | Discoveries |
|-----------|------------|-------------|
|           | Non-MSPs   | MSPs | Non-MSPs | MSPs |
| High-lat  | 145        | 28  | 29       | 7    |
| Mid-lat   | 784        | 66  | 142      | 41   |
| Low-lat   | 1123       | 81  | 642      | 64   |

Table 2. Simulated results for the total number of pulsars detected in each latitude region of the HTRU-North survey. To estimate the number of new discoveries from each region, the number of known pulsars expected to be detected in that region was subtracted from the simulated detection count.
6 DATA ANALYSIS

Processing of data collected for the HTRU-North survey is currently performed both on-site at the Effelsberg observatory and at the Max-Planck-Institut für Radioastronomie in Bonn. Data undergo pre-processing and RFI treatment before being processed twice, once in a ‘quick-look’ pipeline that operates on reduced time- and frequency-resolution data and is sensitive to the majority of isolated pulsars in the data, and once in a full pipeline that incorporates searches for pulsars in compact binary systems. Below we describe all stages in the processing and archiving of data from the HTRU-North survey. It should be noted that the data analysis procedure reported here is only valid for mid- and high-latitude pointings from the survey. The analysis procedure for the low-latitude pointings will be presented elsewhere.

6.1 Pre-processing

Initially, data written in 32-bit format by the PFFTS backend are down-converted to 8-bit format for storage, transportation efficiency and software compatibility. During the conversion, the data in each frequency channel are clipped at the 3σ level, allowing the data to be mapped to 8 bits with minimal loss in dynamic range. A by-product of this process is that the bandpass shape is removed from the data, as noisy channels are down-weighted and quiet channels are up-weighted with respect to one another. For purposes of RFI mitigation and completeness in the data archiving system, the original 32-bit data bandpass shape is stored.

6.2 RFI excision

Before the data are searched for pulsars, they are treated with several RFI excision methods to remove spurious signals of man-made origin. In the first stage of RFI removal, frequency channels with average power levels 3σ or more above the normalized mean across the original 32-bit bandpass are replaced with zeros. This reduces our sensitivity to weak, persistent, narrow-band RFI. The multibeam nature of the receiver allows for the application of a spatial filtering system to mitigate impulsive RFI in the data. Assuming all RFI that enters the multibeam receiver is temporally coherent, we may apply a simple thresholding scheme to each data point to identify interference which appears in multiple beams.

The PFFTS is an adapted version of the AFFTS backend (Klein et al. 2012) used for H I observations at Effelsberg. As H I observations with the multibeam receiver do not require the high time resolution of pulsar observations, the AFFTS was not designed to have accurate synchronization between individual beam servers. This can result in lags of up to a few milliseconds between the start of recording between different beams of the same pointing. Therefore, to perform multibeam impulsive RFI excision, data must be cross-correlated to determine the absolute time offset. This process inherently relies on the presence of a multibeam signal in the data which will produce a strong feature in the cross-correlation. In the cases where no such signal exists the impulsive masking section of the RFI excision is bypassed.

After an absolute reference has been determined for each pointing, each data point is compared across the seven beams. If the data point has a significance of 1.5σ in four or more beams, it is replaced with Gaussian noise indistinguishable from the surrounding data and is logged for further analysis. Assuming that each channel is composed of Gaussian noise, the chance probability of removing a single ‘good’ data point is 0.000 13 per cent. The value of 1.5σ as with all threshold values used in the RFI mitigation procedure, was chosen based on empirical tests of the mitigation procedure.

Once all beams have been compared, histograms of the RFI-flagged data points are created, both by time sample and frequency channel. By examining the number of RFI-affected data points in each frequency channel, we can isolate channels which have persistent impulsive noise. If the percentage of RFI-affected data points in a given channel is greater than 0.2 per cent, the data in that channel are replaced by zeros. Similarly, if more than 10 per cent of the channels in a given time sample are RFI-affected, then all channels in the time sample are replaced by Gaussian noise, unless they have been previously replaced by zeros. An example of the zero-DM time series for each beam of the receiver before and after impulsive RFI excision can be seen in Fig. 6.

To identify periodic signals in the pointing, the ‘clean’ data are collapsed along their frequency axis, with the resultant ‘zero-DM’ time series analysed in the Fourier domain (see Section 6.3.2). Fourier frequencies which appear in four or more beams with a 2σ significance or greater are written to a ‘zaplist’ file that is used during periodicity searching and candidate sorting in the processing pipelines.

Typically, the RFI excision process removes ~4 per cent of the raw data. The majority of this is due to removal of the band edges and suppression of noisy frequency channels. After removal of these channels we recover an effective bandwidth of ~240 MHz.

6.3 Processing pipeline

Here, we cover the main stages of the full processing pipeline used to analyse HTRU-North data. The pipeline is built around the PRESTO
data analysis package (Ransom 2001). The quick-look pipeline is described in Section 6.4.

6.3.1 De-dispersion

Broad-band electromagnetic signals propagating through the interstellar medium are subject to group-velocity dispersion. This results in a frequency-dependent time delay in the signal, with components at higher frequencies arriving at the observer before those at lower frequencies. As the degree to which the signal from an unknown pulsar is dispersed (its DM), is not known a priori, we search 3240 trial DMs in the range 0–978 pc cm$^{-3}$. Such a large number of trials allows for retention of the data’s highest possible time resolution at all DMs, as the minimum time delay between adjacent trials is limited only by the sampling rate and time delay between the top and bottom of a single frequency channel. It should be noted that to account for high-DM pulsars and transients the quick-look pipeline searches up to a maximum DM of 3000 pc cm$^{-3}$ (see Section 6.4). At this stage in the analysis, the data are barycentred to remove the effects of the Earth’s rotation and motion in the Solar system.

6.3.2 Periodicity searching

Each of the 3240 time series created in the de-dispersion stage of the pipeline must be searched for periodic signals from isolated pulsars and pulsars in binary systems. To this end, the time series are discrete-Fourier-transformed to create a power spectrum for each DM trial. Often the power spectra contain strong low-frequency noise from long-period RFI or gain fluctuations in the receiver. To mitigate this, the power spectra are de-reddened through subtraction of an interpolated red noise curve (Israel & Stella 1996). At this stage, Fourier frequencies which have been found to contain RFI through the excision process are suppressed in the spectra.

To re-concentrate power distributed through harmonics in the Fourier domain, the process of incoherent harmonic summing is used. Here, the spectrum is summed with a stretched copy of itself such that all second harmonics are added to their corresponding fundamentals. This process is repeated four times such that all power distributed in even harmonics up to the 16th harmonic may be added to the fundamental (see e.g. Lorimer & Kramer 2005). To identify non-accelerated signals in the data, the spectra from fundamentals. This process is repeated four times such that all power distributed in even harmonics up to the 16th harmonic may be added to the fundamental (see e.g. Lorimer & Kramer 2005).

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To determine if a candidate is truly a pulsar, the data are phase-folded and de-dispersed at the period and DM of the candidate. After the data are folded, both the period and the DM of the candidate can be optimized through searching a small range of values around the discovery values. The optimization is tailored such that for faster period candidates, smaller ranges in DM and period are searched. To reduce sensitivity to RFI, long-period candidates do not undergo DM optimization.

All candidates with greater than 8σ significance are folded. In beams where there are less than 50 candidates above 8σ significance, candidates with greater than 6σ significance are also folded such that there is a minimum of 50 folds. Limiting the number of folds in this way reduces the probability of missing pulsars in observations strongly affected by RFI, as all candidates with a significance above our detection threshold are folded.

6.3.5 Candidate viewing and ranking

To deal with the >80 million candidates the survey will produce, a suite of interactive plotting software coupled with a MySQL database has been developed. For each folded candidate, the data base stores all the relevant statistics of that candidate. Through use of the viewing software, users may query the data base to select candidates which satisfy certain criteria, before viewing those candidates in the parameter space of their choice. User rankings of each candidate are stored in the data base, with highly ranked candidates marked for re-observation.

For someone with experience in candidate selection, taking on average two seconds to view each candidate, it would take five years without pause to view all candidates produced by the survey. To reduce the volume of candidates that must be inspected, we implement both an artificial neural network (ANN) and an automatic ranking algorithm in post-processing.

6 www.mysql.com
The Pulsar Evaluation Algorithm for Candidate Extraction (PEACE) software package (Lee et al. 2013) is used to generate automatic rankings for each candidate. Here, the software weights and combines a selection of scores, determined through analysis of the folded data, to generate an overall ‘likelihood-of-pulsar’ measure for each candidate. As the PEACE software is designed to detect pulsars that display expected properties, it is subject to selection bias against atypical systems.

ANNs are a class of computational techniques which attempt to emulate the decision making behaviour of a human mind. ANN have been successfully applied to candidate selection (e.g. Eatough et al. 2010; Bates et al. 2012) and have been shown to reduce the number of candidates required to be looked at by several orders of magnitude. To train the ANN, it is provided with a vector of ‘scores’, in this case generated by the PEACE software, for each candidate from a selection of both real and simulated pulsar signals and RFI. The use of ANNs must also be treated with care, as their sensitivity to pulsars which do not exhibit typical behaviour (e.g. pulsars which are intermittent, in binary systems or highly scintillating) is dependent on the composition of the data set used in training. Although both ANNs and PEACE are effective in determining whether a candidate is a pulsar or not, direct visual inspection of the candidate is still the primary method of pulsar identification. The rankings generated through visual inspection act as an absolute reference for all automatic ranking systems.

6.4 Quick-look pipeline

The aim of the quick-look pipeline is to perform a reduced version of the full pipeline that is capable of processing all acquired data between observing sessions. By keeping up-to-date with the observed data, we are able to monitor the performance of the receiver and backend systems, as well as maintain up-to-date knowledge of the RFI environment at the Effelsberg telescope.

Data passed to the quick-look pipeline are initially downsampled by factors of 4 and 2 in time and frequency, respectively. Although downsampling reduces our sensitivity to short-period/high-DM pulsars, it increases the throughput of the pipeline by a factor of 8, allowing processing to be performed with limited resources at 1.6 × real time. The data are de-dispersed to 406 trial DMs in the range 0–3000 pc cm$^{-1}$. To perform multiple de-dispersions efficiently, we employ the method outlined in Keith et al. (2010), with the caveat that we must first reduce the data to 7-bit resolution to avoid integer overflow in the output data.

For each trial DM, two searches are performed: a Fourier-domain search for periodic, unaccelerated signals and a time-domain search for isolated pulses. The Fourier-domain search closely follows the methodology outlined for the full pipeline with the exception that no acceleration searching is performed.

6.4.1 Transient searching

To search for isolated pulses in the time domain, we follow a similar methodology to that outlined in Burke-Spolaor & Bailes (2010). Here, we use matched filtering to identify significant impulsive signals of varying widths. Signals with significance greater than 4σ are collated and compared across all DMs to determine whether a candidate obeys the cold plasma dispersion relation and to determine that candidate’s optimal DM. As the data have already undergone spatial coincidence filtering during pre-processing, no event matching is required across beams.

Candidate detections from the transient search are viewed on a pointing-by-pointing basis, with interesting signals being followed-up using software that provides tools for interactive manipulation and viewing of the filterbank data. Follow-up in this manner is vital in determining if a signal is of astrophysical origin or is simply RFI. Although the transient search has detected many known pulsars, no previously unknown transients have so far been discovered.

The remaining steps of the quick-look pipeline follow the same process as the full pipeline, with the exception that candidates are stored independently of the MySQL database.

7 NEW PULSAR DISCOVERIES

Here, we present the initial pulsar discoveries of the HTRU-North survey. So far the survey has discovered 15 pulsars including one MSP. All discoveries originate from the processing of the first 13 percent of the mid-latitude region of the survey.

Upon discovery, each new pulsar is timed by the Lovell radio telescope at Jodrell Bank observatory and the Effelsberg radio telescope. Pulse times of arrival (TOAs) are analysed with the TEMPO2 software package (Hobbs, Edwards & Manchester 2006) to create phase-connected timing solutions for each pulsar. Tables 3 and 4 show the new pulsar discoveries with current timing solutions and derived properties. In the case of PSR J0555+3948 the short timing baseline precludes the accurate determination of both position and flux density. In this case, the position error is assumed to be equal to the half-width half-maximum of a single beam and the flux density measurement assumes the discovery position to be the true position. As period derivative ($\dot{P}$) and position are covariant over short timing baselines, the $\dot{P}$ measurement for all pulsars with data spans smaller than one year should be treated with caution. Fig. 7 shows integrated pulse profiles from coherently de-dispersed observations with the Lovell telescope. All timing observations are conducted in the 21-cm band with centre frequencies of 1.36 and 1.53 GHz, and bandwidths of 400 and 200 MHz for the Lovell and Effelsberg radio telescopes, respectively.

Observations with the Lovell are performed ~2 to 3 times per week until a preliminary timing solution for the pulsar can be determined. The cadence of observations is then reduced to ~1 observation every three weeks. After the pulsar’s position has been improved through continued timing with the Lovell, higher precision timing observations with Effelsberg begin. Effelsberg observations for each pulsar occur on a monthly basis.

7.1 Orion-spur observations

To achieve complete coverage and statistics for a sample portion of the survey, mid-latitude pointings were targeted on the region 64.1° $< l <$ 71.9°, |$b$| < 15°. In this direction the line of sight lies along the axis of the Orion spur up to a distance of ~3 kpc, and intersects with the Perseus arm and Outer arm at distances of ~6 and ~10 kpc, respectively. These hydrogen-rich regions are known for star formation, and as such make excellent targets for pulsar searches.

The only survey of comparable sensitivity to have covered this area is the on-going P-ALFA survey (Cordes et al. 2006). Although the P-ALFA survey discovered five new pulsars in the region, the declination limit of +38° imposed by the Arecibo telescope limited its coverage. The Effelsberg telescope has no upper declination limit and so is capable of observing the entire Orion-spur region.

Data were processed in both quick-look and full pipelines and all candidates with folded profile significance greater than 6σ were...
that three of the newly discovered pulsars have DMs greater than $100 \pm 30$ pc cm$^{-3}$, which is the free electron density in the line of sight. This results in DM-derived distances that place the candidate in the full processing pipeline, discovered as a $7\sigma$ candidate in the full processing pipeline, which stresses the importance of using backends with high frequency resolution.

Of the high-DM pulsars discovered in the survey, PSRs J2005+3552 and J2319+6411 have DMs that are larger than the NE2001 Galactic free electron density model's (Cordes & Lazio 2002) expected maximum DM contribution along their respective lines of sight. This results in DM-derived distances that place the pulsars outside of the Galaxy. However, in both cases the DM excess in the line of sight ($75$ and $13 \text{ pc cm}^{-3}$ for PSRs J2005+3552 and J2319+6411, respectively) falls within the expected uncertainties for the NE2001 model (Deller 2009).

### 7.2 PSR J1946+3417

Discovered as a $\sigma$ candidate in the full processing pipeline, PSR J1946+3417 has the honour of being the first MSP

### Table 3.

Timing solutions for the first discoveries of the HTRU-North survey. Numbers in parentheses represent twice the formal 1σ uncertainties in the trailing digit as determined by TEMPO2. Here, $\dot{P}$ is the first derivative of the pulsar's spin period. All parameters are measured w.r.t. reference epoch MJD 56100, unless otherwise stated. These parameters were determined with TEMPO2, which uses the International Celestial Reference System and Barycentric Coordinate Time. Refer to Hobbs et al. (2006) for information on modifying this timing model for observing systems that use TEMPO format parameters.

### Table 4.

Further parameters for the first discoveries of the HTRU-North survey. Here, $D_{\text{DM}}$ is the DM-derived distance, $B_{\text{surf}}$ is the characteristic surface magnetic field strength, $r_c$ is the characteristic age, $E$ is the spin-down luminosity and $l$ and $b$ are the Galactic longitude and latitude, respectively. All DM-derived distances were calculated using the NE2001 Galactic free electron density model (Cordes & Lazio 2002), giving a likely uncertainty of $\gtrsim 20\%$ (Deller 2009).

| RA (h:m:s) | Dec. ($^\circ$: $^\prime$: $^\prime\prime$) | $D_{\text{DM}}$ (kpc) | Mean flux density at 1.5 GHz (mJy) | $\log_{10}(\tau_c)$ (yr) | $\log_{10}(B_{\text{surf}})$ (Gauss) | $\log_{10}(E)$ (erg s$^{-1}$) |
|------------|---------------------------------|-----------------|---------------------------------|------------------------|----------------------|--------------------------|
| J0212+5222 | 02:12:52.26(3) | +52:22:45.13 | 376.386292(1) | 6.6(3) | 38 | 17 | 563 73–564 77 | 73 |
| J0324+5239 | 03:24:55.46(4) | +52:39:31.32 | 336.620230(3) | 0.38(1) | 119 | 64 | 559 77–564 78 | 309 |
| J0426+4933 | 04:26:06.81(1) | +49:33:38.46 | 922.474730(5) | 39.34(4) | 88 | 101 | 558 44–564 78 | 240 |
| J0555+3948 | 05:55:5(5) | +39:48:5(5) | 1146.9058(2) | 10.14 | 8.03 | 33.65 | 563 73–564 74 | 2004 |
| J1905−0056b | 19:05:27.9(1) | −00:56:37.5 | 214.394341(3) | 1.07(7) | 227 | 13 | 563 56–564 82 | 115 |
| J1913−3732 | 19:13:27.887(3) | −37:32:12.30 | 851.078948(2) | 1.3792(7) | 69 | 77 | 559 77–564 79 | 321 |
| J1946+3417 | 19:46:25.13182(6) | +34:17:14.67(1) | 3.17019278(6) | 0.000037(2) | 110 | 156 | 560 89–564 77 | 75 |
| J1959+3620 | 19:59:38.03(2) | +36:20:29.13 | 406.081181(1) | 0.036(1) | 273 | 116 | 558 39–564 81 | 3069 |
| J2004+3429 | 20:04:46.97(3) | +34:29:17.5(5) | 240.9526419(3) | 206.8254(5) | 351 | 90 | 560 69–564 82 | 3476 |
| J2005+3552 | 20:05:47.50(6) | +35:52:24.3(1) | 307.9429046(2) | 2.99(1) | 445 | 55 | 560 93–564 80 | 512 |
| J2036+2835 | 20:36:46.363(5) | +28:35:10.44(7) | 1358.726763(5) | 2.09(2) | 99 | 97 | 558 73–564 80 | 509 |
| J2206+6151 | 22:06:11.19(6) | +61:51:58.10(3) | 322.673549(8) | 3.9765(6) | 167 | 47 | 560 28–564 78 | 230 |
| J2216+5759 | 22:16:05.22(3) | +57:59:53.7(3) | 419.10226464(2) | 60.94(2) | 176 | 97 | 558 38–564 78 | 3710 |
| J2316+6411 | 23:16:35.210(2) | +64:11:25.575(7) | 216.018278401(6) | 0.1632(5) | 246 | 56 | 560 01–564 75 | 75 |
| J2333+6145 | 23:33:19.448(5) | +61:45:30.09(3) | 756.899832059(7) | 1.1761(6) | 125 | 94 | 558 38–564 75 | 412 |

"a"Co-discovered with the GBNCC survey (Lynch 2013).
"b"Parameters measured w.r.t. reference epoch MJD 56375.
Figure 7. Integrated pulse profiles for the 15 newly discovered pulsars of the HTRU-North survey. The y-axes show the flux density of each pulsar on arbitrary scales. For the mean flux density of each pulsar, refer to Table 4.

Figure 8. Comparison of the known pulsar population in the Orion-spur region, to pulsars discovered in this work. Grey circles show previously known pulsars with measured flux densities at 1.4 GHz. Black squares show pulsars discovered in this work.

7.3 PSR J2004+3429

PSR J2004+3429 was initially discovered as an 1σ candidate in a 3-min pointing analysed with the quick-look pipeline. The pulsar has a spin period of 241 ms and a DM of 352 pc cm$^{-3}$. The radio profile of PSR J2004+3429 shows two components separated by 180° (see Fig. 7), suggesting that the pulsar may be an orthogonal rotator. Using the NE2001 Galactic electron density model (Cordes & Lazio 2002) we estimate a distance to the pulsar of $\sim$12.5 kpc. Analysis of pulsar distance measures by Verbiest et al. (2012) suggests that this distance is likely overestimated, with the real distance lying closer to 10 kpc. Timing with the Lovell radio telescope has led to a phase-coherent timing solution for PSR J2004+3429 that shows it to have a large period derivative of $2 \times 10^{-13}$. For spin-down caused purely by the emission of magnetic dipole radiation, we find the pulsar to have a characteristic age of $\sim$18 kyr.

7.3.1 SNR association

Considering the young age of PSR J2004+3429, it is highly likely that the pulsar is associated with an SNR. Using the SIMBAD astronomical data archive, we find three published SNRs within a 2° radius of PSR J2004+3429: SNRs G069.7+01.0 (Kothes et al. 2006), G070.7+01.2 (Kulkarni et al. 1992; Cameron & Kulkarni 2007) and G069.4+01.2 (Yoshita, Miyata & Tsunemi 2000). The field also contains the candidate SNR G070.0+02.0 (Mavromatakis et al. 2009).

Small distance estimates to SNRs G070.0+02.0 (<1 kpc; Mavromatakis et al. 2009), G069.4+01.2 (~2.5 kpc, Yoshita et al. 

An in-depth discussion of the possible origins of PSR J1946+3417 will be presented in Barr et al. (in preparation).
Gamma-ray observations

PSR J2004+3429’s high spin-down luminosity ($\dot{E} = 5.7 \times 10^{35}$ erg s$^{-1}$) marks the pulsar as a potential gamma-ray emitter (The Fermi-LAT collaboration 2013). To search for gamma-ray pulsations from PSR J2004+3429, Fermi LAT photons recorded between 2008 August 4 and 2013 May 10, with energies above 0.1 GeV, and from a $3^\circ$ region of interest (ROI) around PSR J2004+3429 were phase-folded using the ephemeris shown in Table 3 and the Fermi plug-in distributed with the TEMPO2 package (Ray et al. 2011). To improve the chance of a detection, the phase-folded LAT data were restricted to ‘Source’ class events of the P7_V6 instrumental response functions. Furthermore, data taken during times when the rocking angle of the LAT exceed $52^\circ$ or the Earth’s limb infringed on the ROI were rejected.

To determine if a statistically significant signal was present, a range of different angular and energy cuts was applied to the data in order to optimize the $H$-test parameter (de Jager & Büsching 2010). We tried maximum angular separation values between 0.1 and 3°, and minimum photon energies ranging from 0.1 to 1 GeV. None of the cuts applied resulted in a greater than $3\sigma$ significance. To remove any error introduced by uncertainties in our ephemeris, the same procedure was repeated using only data which were taken during the validity interval of our ephemeris. Again, no signal of greater than $3\sigma$ significance was found. Considering the large distance to the pulsar, it is feasible that the pulsar will become detectable when more LAT data are available.

8 CONCLUSION

We have described the instrumentation, observing strategy, sensitivity and expected results of the HTRU-North pulsar survey, the first major search for radio pulsars conducted with the 100-m Effelsberg radio telescope and the most sensitive survey ever to observe the entire region above +30° declination. The survey has thus far resulted in the discovery of 15 radio pulsars, of which 13 have been found above +30° declination.

Of the newly discovered pulsars, two are of particular note. PSR 1946+3417 is a highly eccentric MSP binary located in the Galactic field. This system will be presented in detail in a future paper. PSR J2004+3429 is a young pulsar with a characteristic age of $\sim 18$ kyr. We currently rule out that PSR J2004+3429 is associated with near-by SNR G069.7+01.0, due to the high transverse velocity required to place the pulsar at its current position with respect to the remnant in the time-scale suggested by its characteristic age. Despite its high spin-down luminosity, we find no evidence of gamma-ray emission from PSR J2004+3429. This is most likely due to the large distance to the pulsar.

ACKNOWLEDGEMENTS

This work was carried out based on observations with the 100-m telescope of the MPIfR (Max-Planck-Institut für Radioastronomie) at Effelsberg.

Pulsar research and observations at Jodrell Bank Observatory have been supported through Rolling Grants from the UK Science and Technology Facilities Council (STFC).

JPWV acknowledges support by the European Union under Marie-Curie Intra-European Fellowship 236394.

PCCF and JPWV acknowledge support by the European Research Council under ERC Starting Grant Beacon (contract no. 279702).

DRL acknowledges support from WVEPSCoR and the Research Corporation for Scientific Advancement.

KJL acknowledges support from the ERC Advanced Grant ‘LEAP’, Grant Agreement number 227947.

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