Pulsar Searches — Tricks of the Trade

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Abstract. The study of pulsars has come a long way since their accidental discovery as “scruff” on pen chart recordings of the radio sky at 81 MHz by Jocelyn Bell and Anthony Hewish at Cambridge some thirty years ago. The present sample of almost 800 objects is the result of an immense amount of observing time at the largest radio telescopes around the world. This article highlights the most exciting finds, and summarises the most commonly used, yet relatively simple, techniques which continue to be most efficient at finding weak periodic signals hidden in noisy time series.

1 Preamble

Following the initial discoveries at Cambridge [20, 13, 12], a number of pulsars were unearthed by groups around the world in the next few years. As in the Cambridge survey, many of these early discoveries were made by visual inspection of pen chart recordings collected from the detected output of a large radio telescope. By definition, this method selects against those objects too faint to be detected from their individual pulses. To find such sources, which are likely to make up the bulk of the potentially observable sample, we require a more sophisticated search algorithm which can search for a priori unknown periodic signals in a longer time series. Following some success using algorithms developed to fold data in the time domain [50], it was realised that a more efficient method is to take the Fast Fourier Transform (FFT) of the time series. A periodic signal is then easily identified by a characteristic set of harmonics in the power spectrum. An additional complication arises when searching for more distant pulsars whose pulses become smeared across a finite receiver bandwidth as a result of their passage through the ionised component of the interstellar medium. As we shall see (§3) this can largely be removed by splitting the passband up into a finite number of channels and applying appropriate time delays to each channel before summing over the channels. Since the magnitude of this effect is unknown a priori, a number of time series are formed and FFTed. This basic two-dimensional approach, which has been used almost exclusively in all searches since the early 1970s, will be described in detail in the following.

2 A Potted History of Pulsar Searching

One means of summarising the history of progress in pulsar searches is the cumulative number distribution in Fig. 1. This shows, amongst other things, where
landmark discoveries of exciting pulsars have been made, and their impacts on subsequent searches. Perhaps the most famous discovery of all of these is the original binary pulsar, PSR B1913+16\(^1\), discovered by Hulse & Taylor in 1974 in a survey of part of the galactic plane visible from the giant 305–m Arecibo radio telescope [21, 22]. This relativistic binary system, which consists of a pair of neutron stars, has been shown to be a truly remarkable natural laboratory for tests of general relativity [53, 54] — certainly more than ample reward for the initial outlay of telescope time in the survey and subsequent off-line processing. Fascinating accounts of the discovery and study of this system can be found in the 1993 Nobel lectures given by Hulse and Taylor [23, 55].

Figure 1: The cumulative number of pulsars known as a function of time. This diagram captures some of the “thrill of the chase”, as well as the continued motivation to initiate new searches following significant technological advances and conceptual innovations. See text for discussions of individual objects.

In 1977 Dick Manchester and colleagues used the Molonglo radio telescope in Canberra to survey the sky with declinations \(-85^\circ \leq \delta \leq +20^\circ\) (\(\sim 8.4\) sr). This monumental effort [36] discovered no less than 155 pulsars, thereby doubling the observed pulsar population known at that time (the 1977/8 leap in Fig. 1). The new discoveries included one more binary system PSR B0820+02 — an ordinary 0.865 s pulsar in a wide orbit around a white dwarf star [37]. Together with the results of contemporary searches using northern hemisphere telescopes [14, 13], a fairly well-understood sample of pulsars over the whole sky was available for studying the statistical properties of the Galactic population [42, 58, 35]. These studies suggested a total population of \(\sim 10^5\) active radio pulsars in the Galaxy.

\(^1\)Pulsars are conveniently named with a PSR prefix followed by their celestial coordinates.
Data acquisition and processing limitations during the 1970s and early 1980s limited the sampling rates of surveys conducted during this era to $\gtrsim 20$ ms. The corresponding sensitivity to short-period objects, such as the 33 ms pulsar in the Crab nebula, was thus far from ideal suggesting that the true population of short-period pulsars was being underestimated in the observed sample. This was dramatically confirmed in 1982 with the discovery by Backer et al. of “the millisecond pulsar” B1937+21 [3, 4]. With a period of 1.56 ms and a corresponding rotation frequency over 20 times larger than the Crab, this remarkable object is still the most rapidly rotating neutron star known to man. Subsequent timing observations of B1937+21 soon showed that it is an extremely stable celestial clock on time-scales $\sim$ years [15] having a host of astrophysical applications including the detection of long-period gravitational waves from the early Universe [15]. In addition, PSR B1937+21 is a bright source, having a mean luminosity roughly 240 times that of the original Cambridge pulsar, B1919+21. It thus seemed natural to suppose that B1937+21 was just the tip of the iceberg of a larger population of rapidly rotating neutron stars missed by previous searches.

The large increase in computing power and data storage requirements in a search for millisecond pulsars meant that most early search efforts had only limited sensitivity to millisecond pulsars. This problem is highlighted by the fact that only 4 millisecond pulsars were found in the galactic disk prior to 1990 which, in turn, hampered early attempts to determine their galactic population [28]. Surveys conducted during this period were, however, very successful at discovering young pulsars along the galactic plane [11, 26] (see $\S$ 4).

Following initially unsuccessful searches of globular clusters prior to the discovery of PSR B1937+21 [19], search systems armed with faster sampling rates returned to globular clusters — where low-mass X-ray binaries, the probable progenitors of millisecond pulsars [1], were already known to exist [10]. This approach circumvents the need to cover large areas of sky, since each cluster can be observed with one telescope pointing, thereby greatly reducing the total amount of data to process. Searches soon proved fruitful, with the discovery of PSR B1821–24, a 3.1 ms pulsar in the globular cluster M28 [32]. Searches of other clusters have since been very successful, discovering over 20 millisecond pulsars. Notable highlights were the discovery of an eclipsing binary system in Terzan 5 [13], 11 millisecond pulsars in 47–Tucanae [38, 46], and a neutron star–neutron star binary in M15 [44, 2].

Advances in low-cost computing power and data storage capabilities towards the end of the 1980s meant that a return to galactic disk surveys with much improved sensitivity was possible. The breakthrough was made by Wolszczan in a search of just 200 deg$^2$ of sky away from the galactic plane during an upgrade period at Arecibo [60]. The survey found the millisecond pulsar planetary system B1257+12 [54, 61], and yet another neutron star–neutron star binary system PSR B1534+12 [60]. A statistical analysis by Johnston & Bailes [24] demonstrated that a large number of millisecond pulsars would be found by an all-sky search of similar sensitivity to Wolszczan’s survey.
Large-area searches began in earnest in the early 1990s at Parkes \[33, 34\], Jodrell Bank \[11\], Arecibo \[17, 15, 3, 7\], and Green Bank \[7\]. With the exception of the Arecibo surveys, these have now been completed. The great success of these surveys can be seen by the sharp rise in Fig. 1 during the mid 1990s, and also in Fig. 2 which compares the sky distributions circa 1990 with the present situation in which the sources are much more uniformly distributed on the sky. Over 30 millisecond pulsars have so far been discovered by these searches as well as many more low-luminosity ordinary pulsars. Notable highlights include PSRs J0437–4715 \[27\] and J1713+0747 \[18\] — bright, nearby millisecond pulsars which are already proving to be more stable clocks than PSR B1937+21. A future application of such an “array” of clocks will be as a very sensitive detector of long-period gravitational waves \[16\].

Although no further pulsar planetary systems like B1257+12, or relativistic binary systems like B1534+12, have thus far been found, many of the newly discovered millisecond pulsars have white dwarf companion stars which can be studied optically \[57, 31\].

3 Practical considerations in pulsar searches

Having gotten a flavour for the potential rewards gained in finding new pulsars, let us turn our attention to the specific problems involved in the search. As mentioned in \[4\], for any given point on the sky, our two basic unknown parameters are the pulse period and the amount of dispersion across the receiver bandwidth. A powerful technique to search for unknown periodicities, that is now the “industry standard”, is to take the Fast Fourier Transform (FFT) of the noisy time series. For any periodic signal with a small duty cycle (5–10% is typical of most pulsars), the resulting amplitude spectrum from the FFT consists of a family of harmonic spikes with the fundamental corresponding to the signal frequency. Having identified the fundamental, the original time series can be folded at the apparent pulse period to form an integrated profile with a high signal-to-noise ratio (SNR).
By considering the train of weak pulses in the time series to be a set of equally-spaced delta functions convolved with a simple boxcar function as the pulse profile, the number of harmonics in the power spectrum of the FFT can be shown to be equal to the inverse of the pulse duty cycle. Thus, much of the total power of a narrow pulse is distributed in its higher order harmonics, rather than just the fundamental. In this case, we can improve greatly on the sensitivity by adding higher harmonics onto the fundamental. For example, to add all 2nd harmonics onto their corresponding fundamentals, we stretch the lower half of the amplitude spectrum by a factor of two and add this to the original unstretched spectrum. An example of such a “harmonic summing”

![Power Spectrum: Incoherent Harmonic Fold Example](image)

Figure 3: The process of harmonic summing illustrated in the power spectrum on test data collected for PSR B2303+30, collected with the Ooty radio telescope at 327 MHz. Figure kindly provided by Dipankar Bhattacharya.

process is shown graphically in Fig. 3. Note that, whilst the summation process naturally increases the noise in the folded spectrum by a factor of $\sqrt{2}$, the amplitude of the signal may increase by a larger factor thus giving a net increase in the observed SNR. The action of repeating this process several times (in typical pulsar searches usually three further operations are done) is to effect a search in pulse duty cycle. Typically, the majority of weak signals with small duty cycles are only apparent in the harmonically folded spectra.

The group velocity of the pulsed radiation through the ionised interstellar medium is frequency dependent: pulses emitted at higher radio frequencies travel faster and arrive earlier than those emitted at lower frequencies. This dispersion process has the effect of “stretching” the pulse across a finite receiver bandwidth, thereby reducing the SNR. The delay $\Delta t$ in arrival times between a
high frequency $\nu_{hi}$ (MHz) and a low one $\nu_{lo}$ (MHz), can be shown to be

$$\Delta t = 4.15 \times 10^6 \text{ ms} \times (\nu_{lo}^{-2} - \nu_{hi}^{-2}) \times \text{DM}, \quad (1)$$

where the dispersion measure DM (cm$^{-3}$ pc) is the integrated column density of free electrons along the line of sight to the pulsar. Pulsars at large distances have higher column densities and therefore larger DMs than those pulsars closer to Earth so that, from Eq. [1], the dispersive delay across the bandwidth is greater. A measurement of the DM, together with a suitable model for the Galactic distribution of free electrons, can provide estimates for the distances to pulsars [72]. The DMs in the present sample of pulsars range between 2.4 cm$^{-3}$ pc (roughly 100 pc distant) out to 1074 cm$^{-3}$ pc (roughly the distance of the Galactic centre) with a median value of 82 cm$^{-3}$ pc (roughly 2 kpc).

![Figure 4](image_url)

**Figure 4:** *Pulse dispersion and the process of de-dispersion. The effect of simply summing the pulse train over a finite bandwidth is to significantly broaden the observed pulse (left panel). By dividing the passband into smaller bandwidth channels and applying the appropriate delay to each channel considerably reduces the broadening and increases the pulse signal–to–noise ratio (right panel).*

In the extreme case, if we naïvely neglect this effect in our search algorithm, then there is a limiting DM above which the pulse from a pulsar is stretched across the receiver bandwidth by an amount greater than one period so that, regardless of flux density, such a dispersed pulsar would be undetectable. To see this quantitatively, we can rearrange Eq. [1] for a bandwidth $\Delta \nu = \nu_{hi} - \nu_{lo}$ about a centre frequency $\nu = \frac{1}{2}(\nu_{lo} + \nu_{hi})$ to obtain the “dispersion broadening” relation (for $\nu \gg \Delta \nu$) as:

$$t_{DM} = 8.3 \times 10^6 \text{DM} \frac{\Delta \nu}{\nu^3} \text{ ms}, \quad (2)$$

where the centre frequency $\nu$ and bandwidth $\Delta \nu$ are measured in MHz and the DM is in units of cm$^{-3}$ pc. For example, the first pulsar to be discovered, PSR B1919+21, has a relatively low DM of 12.4 cm$^{-3}$ pc. Over the 1 MHz bandwidth of the original Cambridge equipment observing at 81 MHz, the dispersion
broadening is $\sim 190$ ms — quite unacceptable for millisecond pulsar hunters!
Since this pulsar has a period of 1337 ms it was (fortunately) detected. To compensate for this effect, modern searches divide the full pass-band into a number of smaller bandwidth channels, over which the dispersion broadening is correspondingly less (see Fig. 4). By applying appropriate time lags to each channel (usually in software), the time series can be de-dispersed for large number of trial DM values. During the Parkes Southern Sky Survey \cite{39,34}, for example, each time series was de-dispersed for 738 DMs between 0 and 768 cm$^{-3}$ pc.

As well as the dispersion broadening effect, free electrons in the interstellar medium can scatter the pulses causing an additional broadening due to the different arrival times of scattered pulses. A simple scattering model is shown in Fig. 5 in which the scattering electrons are assumed to lie in a thin–screen between the pulsar and the observer \cite{48}. At observing frequencies $\lesssim 400$ MHz, scattering becomes particularly important for pulsars with DMs $\gtrsim 200$ cm$^{-3}$ pc, where the increased column density of free electrons can cause a significant tail in the observed pulse profile as shown in Fig. 5, reducing the SNR. Thus, high frequency ($\gtrsim 1$ GHz) surveys are much less prone to scattering than $\sim 400$ MHz searches.

To summarise our discussion on pulse broadening, we may consider the observed pulse width $W$ as being the convolution of the intrinsic width $W_{\text{int}}$ emitted at the pulsar with additional broadening functions due to dispersion, scattering, and by the post-detection integration performed in the receiver. This can be expressed approximately by the following quadrature sum:

$$W^2 = W_{\text{int}}^2 + t_{\text{samp}}^2 + t_{\text{DM}}^2 + t_{\text{scatt}}^2,$$

where $t_{\text{samp}}$ is the data sampling interval, $t_{\text{DM}}$ is the dispersion broadening across one filterbank channel and $t_{\text{scatt}}$ is the interstellar scatter broadening.

Figure 5: Diagram showing the “thin–screen” model of pulse scattering. The difference in path lengths and therefore in arrival times of the scattered rays result in a “scattering tail” in the observed pulse profile.
4 Search Sensitivity and Optimisation

The limiting flux density, $S_{\text{min}}$, required to detect a pulsar with a radio telescope can be written as:

$$S_{\text{min}} \simeq \frac{10 T_{\text{sys}}}{G \sqrt{n \Delta \nu \tau}} \left( \frac{W}{P - W} \right)^{1/2}.$$  \hspace{1cm} (4)

Here $G$ is the forward gain of the antenna (K/Jy); $n$ is the number of polarisations summed (usually 2); $\Delta \nu$ is the observing bandwidth (MHz); $T_{\text{sys}}$ is the system temperature (K) — essentially the sum of the thermal noise in the receiver (25–50 K is typical for modern systems) and the excess noise from the radio continuum background along the Galactic plane (see below); $\tau$ is the integration time (s); $P$ is the period of the pulsar (s) and, as defined in §3, $W$ is the observed width of the pulse (s). The additional factor of 10 is approximate, and takes into account a limiting SNR required for a detection ($\sim 8$ for typical pulsar searches), as well as losses in sensitivity due to hardware limitations. With this choice of units, $S_{\text{min}}$ is in mJy ($1 \text{ mJy} \equiv 10^{-29} \text{ W m}^{-2} \text{ Hz}^{-1}$).

To get a feel for the numbers, consider the Jodrell Bank 400 MHz search system used in a recent northern sky survey for millisecond pulsars [41]. Here $G = 1.0 \text{ K/Jy}$, $n = 2$, $\Delta \nu = 8 \text{ MHz}$, $T_{\text{sys}} \gtrsim 70 \text{ K}$, which gives $S_{\text{min}} \simeq 5 \text{ mJy}$ for an integration time of 5 minutes. Although the situation improves as $\tau^{1/2}$ for longer integration times, a price is ultimately paid through loss of sensitivity to pulsars in short-period ($\lesssim $ few hr) binary systems (§5), not to mention rapid loss of popularity with the telescope’s time allocation committee!

When planning a pulsar survey, we are faced with a number of combinations of observing parameters which can significantly effect the ultimate success/failure of the experiment. Before embarking on a search, we should perhaps first ask ourselves: What sort of pulsars are we interested in finding and where’s the best place to look for them? Broadly speaking, pulsar surveys to answer these questions fall into one of three main categories:

— A large area search for old and/or nearby low-luminosity pulsars.
— A galactic plane search for young and/or distant luminous pulsars.
— A targeted search towards supernova remnants, globular clusters etc.

Let us consider the first two cases (the third category depends on the location of the target objects with respect to the Galactic plane), assuming that we have got observing time on a large radio telescope equipped with a system that can sample fast enough to detect short-period pulsars, and that we have settled on an integration time that allows us to cover our search area within the time allocated to us by the committee.

Initially, we may choose to survey exclusively at 400 MHz. This does not seem unreasonable, particularly since pulsar flux density spectra are rather

\footnote{Observed 400 MHz flux densities vary between 0.1 and 5000 mJy, the median is 12 mJy.}
steep, with typical spectral indices of $-1.6$ and are known to turn over at frequencies below 400 MHz. For large area surveys, this spectral consideration is the main factor since the larger solid angle of the telescope beam at low frequencies allows a faster rate of sky coverage than a single beam higher frequency system. In surveying the galactic plane at 400 MHz, however, we immediately run into two big problems:

(i). The system temperature, $T_{\text{sys}}$, becomes dominated by the sky background radiation: From the combined all-sky 408 MHz radio continuum survey [19], we infer extremely large values: $\sim 900$ K in the direction of the galactic centre, and $\sim 300$ K along the galactic plane.

(ii). The observed pulse width $W$ in Eq. 3 becomes dominated by the $t_{\text{DM}}$ and/or $t_{\text{scatt}}$ terms due to excessive scattering and/or dispersion of pulses by free electrons in the interstellar medium. In the extreme case $W \gtrsim P$, so that such a pulsar would no longer be detectable by a time series analysis. For dispersion, it may be possible, at a cost of additional processing time, to increase the number of channels in the filterbank.

Fortunately all these effects diminish strongly when we choose a higher observing frequency: The spectral index of the radio continuum emission is roughly $-3$, so that the sky background temperatures quoted above are reduced by more than an order of magnitude for high frequency ($\gtrsim 1$ GHz) surveys. As mentioned in §3, dispersion and scattering scale as $\Delta\nu/\nu^3$ and $\nu^{-4}$ respectively thus becoming negligible when moving to high frequencies.

Clifton et al. [11] were the first pulsar hunters to really exploit this approach, finding 40 new young pulsars in a 1400 MHz survey of a thin strip of 200 deg$^2$ along the galactic plane. All of these pulsars were missed by a previous 390 MHz survey [51] which overlapped the same region which had twice the nominal sensitivity of the Clifton et al. survey. Many of the pulsars discovered in the high frequency survey are simply not observable at frequencies much below 600 MHz due to a combination of the sky background, dispersion and scattering effects mentioned above. A complementary survey of the southern Galactic plane using the Parkes radio telescope at 1520 MHz [26] also found 46 pulsars that were missed by previous lower frequency searches covering this region [36].

The main disadvantage of the high frequency surveys was always the rate of sky coverage which scales with the inverse square of the observing frequency. The current generation of 1400 MHz searches at Parkes and Jodrell Bank are addressing this problem by installing multi-beam receivers. At Parkes, a 13-beam system can cover the sky at the same rate as the recent Parkes 430 MHz survey [39] [43]. A 4-beam system is presently being installed at Jodrell Bank. With large bandwidths, and integration times of 35 minutes, the nominal sensitivity of these systems is about 7 times better than their predecessors [11, 26]; they are thus expected to discover several hundred new pulsars. Indeed, the Parkes multibeam survey has got off to a flying start, discovering over 60 pulsars in the first 5% of the survey [8].
5 Short-Period Binary Pulsars

As pointed out by a number of authors [29, 25, 4], searches with longer integration times begin to lose sensitivity to pulsars in tight binary systems relative to a solitary pulsar. In a short-period binary system, the apparent pulse frequency may become significantly Doppler shifted during the integration. Thus, rather than each harmonic being a single spike in the power spectrum, the power may be deposited into a number of spectral bins resulting in a net reduction in SNR.

At the cost of additional computing time, it is possible to counter this effect by quadratically stretching or compressing the de-dispersed time series for a number of constant trial accelerations before rebinning and FFTing the data [40]. In radio pulsar searches, this technique has to date mainly been used in globular cluster experiments where integration times may be as large as 1 hour or more [2]. Acceleration searches have so far not been employed in any untargetted survey with integration times \( \lesssim 10 \) min. In such cases, good sensitivity is maintained to most binary systems with orbital periods greater than 1–3 hr.

As mentioned in §4, the new multi-beam surveys have integration times \( \sim 35 \) min. Here the effects of Doppler shifting across several spectral bins can become significant. As an example, I generated a fake time series containing a pulsar with similar parameters to B1913+16 for a number of initial orbital phases and fed it through a search code with similar characteristics to the multi-beam searches. Depending on the orbital phase, the performance of the search code was down by typically 60\% (and in the extreme case 90\%) relative to tests on fake data for a solitary pulsar with the same pulse period as B1913+16.

To increase the sensitivity to such binary systems (which are, after all, the most interesting ones to detect!), an acceleration search is currently being implemented in the multi-beam searches (A. G. Lyne, private communication). Rather than a rebinning scheme outlined above, the time series will be split into a number of segments, across which the drift due to binary motion is reduced and the corresponding width of frequency bins in the Fourier domain is increased. By shifting and stacking these segments for a number of trial shifts, it is possible to recover much of the sensitivity to short-period binary pulsars with only a modest amount of additional computing cost.

6 Sub-millisecond Pulsars

PSR B1937+21 still holds the record for the pulsar with the shortest rotation period (1.56 ms), despite subsequent searches that are theoretically sensitive to even shorter period objects. The neutron star equation of state is currently not well constrained. As a consequence, the limiting spin period, below which centrifugal forces would rip the neutron star to shreds, may vary anywhere between 0.5 ms and just below the present period of B1937+21. Present limits on the existence of sub-millisecond pulsars are rather poor, since signals just
above the Nyquist period of the surveys (e.g. \( \gtrsim 0.6 \) ms for the Parkes Southern Sky survey) are significantly affected by dispersion broadening across individual filterbank channels, with only the very nearby (DM \( \lesssim 10 \) cm\(^{-3}\) pc) bright pulsars being theoretically detectable. Practically, the difficulty of fishing out such candidates, which look essentially like sinusoidal sources of interference, means that the effective sensitivity to sub-millisecond pulsars is presently negligible \( \text{[6]} \).

The future prospects of finding such pulsars look set to improve, however, through new surveys with ever faster sampling rates and narrower filterbank channels \( \text{[6]} \). In a novel 430 MHz survey, Bailes et al. (private communication) are presently using an S2 system to record baseband data. Subsequent off-line processing has been developed to simulate a filterbank in software! The present configuration samples 1024 \( \times \) 15.625 kHz channels every 64 \( \mu \)s, giving much better sensitivity to sub-millisecond pulsars than the Southern Sky Survey. With continual improvements computing power, it seems likely that the existence of such exotic objects will be settled in the coming years — hopefully pinning down our knowledge of the neutron star equation of state.

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