OPTIMIZING PULSAR SEARCHES AGAINST PROPAGATION EFFECTS *

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Abstract. Propagation effects are well known to limit the sensitivity of pulsar searches based on periodicity detections. I define several regimes for pulsar searches that are based on whether the search sensitivity is *luminosity limited, dispersion limited* or *scattering limited.* Consideration of these regimes allows general statements to be made about pulsar searches in and out of the Galactic plane. Telescope size matters, but only to a point. Once scattering becomes important it is better to search more sky (in a blind survey) than to integrate longer on a given sky position. Example surveys are described.

1. Pulsar Surveys

There are $\sim 10^5$ active radio pulsars in the Galaxy and about 20% are beamed toward us. Given the success of the Parkes Multibeam survey and the prospects for deeper surveys using existing or forthcoming telescopes (e.g. the upgraded Arecibo Observatory [AO], the Green Bank Telescope [GBT]) and future very large aperture telescopes (FAST, SKA), it is reasonable to consider the issues that optimize survey sensitivities.

The single-harmonic threshold, $S_{\min_1}$, is the minimum amplitude that a single FFT component must have to be considered a detection:

$$S_{\min_1} = \frac{m S_{sys}}{(n_{pol} \Delta\nu T)^{1/2}}, \tag{1}$$

where m = number of σ corresponding to the detection threshold: $S_{sys} = T_{sys}/G$; T_{sys} = system temperature; G = gain (K Jy^{-1}); $n_{pol} = 2$ if two polarization channels are used in the search; $\Delta\nu$ = total bandwidth; and T = total integration time. For a pulsar with period-averaged flux density S at distance D, the maximum distance that the pulsar is detectable is

$$D_{\max} = \left(\frac{L_p \sqrt{N_h}}{S_{\min_1}} \right)^{1/2} = D \left(\frac{S}{S_{\min_1}} \right)^{1/2} N_h^{1/4} \tag{2}$$

where $L_p = D^2 S$ is the 'pseudo luminosity' and N_h is the number of harmonics that maximizes the harmonic sum in a periodicity search.

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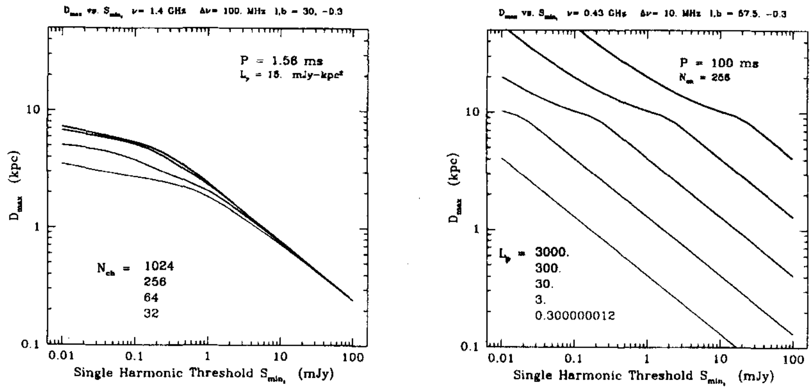

Figure 1. Left: $D_{\max}$ plotted against single harmonic threshold, $S_{\min_1}$, for a 100 MHz bandwidth at 1.4 GHz, a direction $\ell, b = 30°, -0.3°$, $P = 1.56$ ms, and $L_p = 16$ mJy kpc^2. The different curves correspond to different numbers of spectrometer channels (heaviest line = 1024 channels, lightest line = 32 channels). At high thresholds, $S_{\min_1} \gtrsim 1$ mJy, $D_{\max}$ is *luminosity limited*, i.e. $D_{\max} \propto S_{\min_1}^{-1/2}$. For lower thresholds and small numbers of channels, it is *dispersion limited*. For large numbers of channels, dispersion smearing is negligible and $D_{\max}$ becomes *scattering limited* at low thresholds. These curves apply to *post-detection* search systems. For predetection ('coherent') dedispersing systems, the search can still be scattering limited. Right: $D_{\max}$ vs. $S_{\min_1}$ for $P = 100$ ms and a series of pseudoluminosities, as labelled. The curves apply to a 10 MHz bandwidth at 0.43 GHz and a direction $\ell, b = 57.5°, -0.3°$.

The number of harmonics that optimizes the sum is determined by the sharpness of the pulse. If propagation effects – namely dispersion smearing and pulse broadening from scattering – are important, N_h can be much less than otherwise and vanishes when the smearing exceeds the pulse width by a large factor. The dispersion and scattering* broadening times are (for dispersion measure DM in pc cm^{-3}, scattering measure SM in kpc m$^{-20/3}$, D in kpc, $\Delta\nu$ in MHz, ν in GHz)

$$\begin{aligned} \Delta t_{\rm DM} &= 8.3\mu s {\rm DM} \Delta\nu N_{ch}^{-1} \nu^{-3} && \text{dispersion} \\ \Delta t_{\rm ISS} &= 1.1 {\rm ms} {\rm SM}^{6/5} \nu^{-11/3} D && \text{scattering.} \end{aligned} \tag{3}$$

Figure 1 shows $D_{\max}$ plotted against $S_{\min_1}$, calculated by using the electron density model of Taylor and Cordes (1993) to calculate dispersion and scattering as a function of distance.

In considering how $D_{\max}$ varies with $S_{\min_1}$, we define three regimes:

1. *Luminosity limited*: $D_{\max} \propto S_{\min_1}^{-1/2}$, i.e. the inverse square law.
2. *Dispersion limited*: $D_{\max}$ varies more weakly with $S_{\min_1}$ because at greater distances and hence larger DM, the pulse is smeared more, yielding fewer

* The scaling law for the pulse broadening time $\Delta t_{\rm ISS}$ assumes a Kolmogorov wavenumber spectrum for the case where contributing irregularities are between the inner and outer scales. For intense scattering (distant pulsars and/or very low frequencies), the scaling becomes $\Delta t_{\rm ISS} \propto {\rm SM}\nu^{-4}\ell_1^{-1/3}D$, where ℓ_1 is the inner scale. See Cordes and Lazio (1991) for details.

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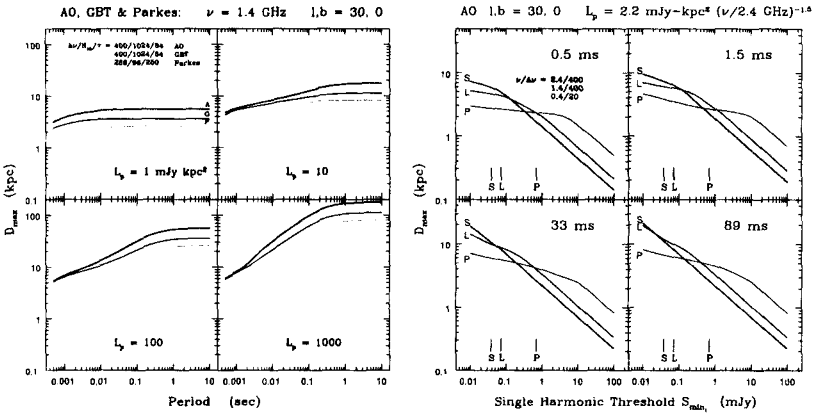

Figure 2. Left: $D_{\rm max}$ vs. P for AO, the GBT, and Parkes at 1.4 GHz and $\ell, b = 30°, 0°$. For AO and the GBT, spectrometers with 400 MHz total bandwidth, 1024 channels, and 64 μs time resolution are assumed while parameters of the multibeam survey are assumed for Parkes (288 MHz, 96 channels and 250 μs resolution). The four panels are for four different pseudoluminosities. For larger P and L_p, $D_{\rm max}$ extends beyond the nominal disk of the Galaxy. However, high velocity pulsars (e.g. $V > 1000$ km s^{-1}) can reach > 30 kpc in their ratio emitting lifetimes. Right: $D_{\rm max}$ vs. $S_{\rm min_1}$ for Arecibo at 0.4, 1.4 and 2.4 GHz, labelled as P, L and S, respectively and using the scaling $L_p \propto (\nu/2.4\ {\rm GHz})^{-1.5}$. The assumed total bandwidths are 400 MHz at L and S and 20 MHz at P. The tick marks along the horizontal axis, also labelled as P, L and S, indicate the thresholds expected at the three bands. The curves indicate that 1.4 GHz is the best of the three frequencies when surveying the Galactic plane.

harmonics. In this case, $D_{\rm max}$ is a sensitive function of the number of spectrometer channels used in the dedispersion process. As N_{ch} increases, $D_{\rm max}$ also increases until scattering dominates the pulse broadening. $D_{\rm max}$ is also a strong function of frequency in the dispersion-limited regime.

3. *Scattering limited*: $D_{\rm max}$ varies more weakly with $S_{\rm min_1}$ because scattering broadens the pulse and reduces the number of harmonics. In this case, $D_{\rm max}$ increases quickly with increasing frequency until either the dispersion or the luminosity limited regime is reached.

The *search volume* quantifies a telescope survey's performance:

$$V_s = \frac{1}{3}\Omega_s D_{\rm max}^3, \tag{4}$$

where Ω_s is the total solid angle covered and we assume (only for simplicity here) that $D_{\rm max}$ is the same in all directions. Note that some of the search volume can be empty if $D_{\rm max}$ extends past the pulsar population.

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2. Guidelines for Optimizing Surveys

By considering the distribution of pulsars in the Galaxy along with the role of propagation effects in searches, a number of basic guidelines emerge:

1. For equal time-bandwidth products, aperture efficiencies, and system temperatures, the larger of two telescopes searches the greatest volume in a single beam.
2. For fixed total survey time, maximizing the number of independent pointings also maximizes the volume surveyed. It is more efficient to increase the volume by adding new pointings rather than increasing the integration time per pointing, which increases $D_{\max}$ fairly slowly.
3. When pulses are smeared by distance dependent propagation effects, building a better telescope and backend produces diminishing returns. The total volume surveyed then increases much more strongly with number of pointings (for fixed total time).
4. When searching by tracking a grid of positions, the slewing overhead time determines the optimal integration time per pointing and thus the solid-angle coverage of a survey with fixed total integration time. Note this conclusion holds only if all directions and locations are equally good for discovering objects.
5. When searching the galactic disk, the number of pointings is bounded, thus determining the survey depth as a function of the total survey time.
6. When searching a subpopulation located at some distance from the observer, the integral time is set by the need to reach this distance.
7. It is suboptimal to use telescope time to integrate longer in a given direction than the time it takes to reach a distance such that pulse broadening becomes important. It is better to move to another sky position unless a subpopulation's distance requires a longer integration time.
8. The number of spectrometer channels should be optimized so that pulse broadening from dispersion smearing is smaller than the pulse width for all spin periods of interest.
9. For a disk population with scale height H, it is optimal to (i) choose an integration time per pointing that reaches the edge of the distribution at distance $H/|\sin b|$; and (ii) If the entire volume cannot be searched, then the search should start at $|b| = 90°$ and work downwards in $|b|$.

3. Survey Examples

Galactic Plane Surveys: The Parkes Multibeam (PMB) survey (Manchester, this proceedings) has been extraordinarily successful in discovering new pulsars at 1.5 GHz, owing to the greater $D_{\max}$ afforded by the lessening of propagation effects. Results presented above confirm that 1.5 GHz is the best among 0.4, 1.5 and

2.4 GHz for searching the furthest. Arecibo can search $\sim$ 480° of the Galactic plane with $|b| \leq 5°$. Scaling from the PMB survey by solid angle only, we estimate that 240 pulsars could be discovered. However, Arecibo can search to significantly greater D_{max} and thus greater volume. For $L_p \lesssim 10$ mJy kpc^2, Arecibo can 'see' about 2.2 times further than Parkes for $P \gtrsim 10$ ms, corresponding to $\sim$ 10 volume. For millisecond pulsars (MSPs), Arecibo can see factors of 3 to 5 further than the PMB survey, owing the anticipated narrower bandwidths and shorter dump times of Arecibo spectrometers. About 2000–4000 pulsars, mostly new, could be found using Arecibo in a 7-beam multibeam survey, requiring a total bandwidth of 400 MHz with 1024 channels and 3000 hr of telescope time divided into 300 s per beam. The proposed FAST telescope with much greater zenith angle coverage could expand the population of known objects by comparable amounts. The uncertainty in predicted numbers arises from our lack of knowledge of the spatial distribution of pulsars in the Galaxy.

High Latitude Searches for MSPs, NS-NS and NS-BH Binaries, and High-velocity Pulsars. Looking out of the Galactic plane, propagation effects are smaller and it is advantageous to search at lower frequencies in order to exploit the larger pulsed flux. MSPs have a scale height $H \sim 0.5$ kpc, so out of plane searches can be designed that search out to $H/|\sin b|$. The greatest volume available to be searched is at small $|b|$, where propagation effects are greatest. Thus the optimal latitude is roughly 10 to 20 deg. NS-NS binaries have sufficiently large space velocities that their scale height is expected to be about 5 kpc. This also favors a high-latitude search. NS-BH binaries also should have a sizable scale height though not as great as NS-NS binaries, since the BH formation process may not yield a kick and also because such binaries are more massive than NS-NS binaries. Isolated pulsars with high space velocities extend to very large $|z|$. About 25 to 50% of all NS will escape the Galaxy (Arzoumanian, Chernoff and Cordes, in preparation) and can reach $> 10^3$ km s^{-1} $\times$ 10 Myr = 10 kpc in their typical radio-emitting lifetimes. A deep, low frequency search is clearly appropriate for discovering members of this population.

The Galactic Center (GC): The star cluster may contain as many as 10^7 NS; most will be radio quiet though there are probably many MSPs in the star cluster. A star burst within the last 10 Myr may have produced a significant population of active radio pulsars. Pulse broadening is notoriously large for pulsars near Sgr A*: $\tau_d \sim 300$ s at 1 GHz (Cordes and Lazio, 1997). Exploiting the strong frequency dependence ($\tau_d \propto \nu^{-4}$), a search at 10 GHz is suggested. Some known pulsars placed at the GC are detectable at this frequency. Payoff includes study, through pulse timing, of the ISM in the GC and the gravitational potential in the star cluster and, possibly, near Sgr A*.

Extragalactic Giant Pulses: The Crab pulsar sporadically emits large amplitude ('giant') pulses that are hundreds to thousands of times the mean pulse amplitude (Hankins and Rickett, 1975; Lundgren *et al.*, 1995). The pulse amplitude distribution is a power law such that, at 0.4 GHz, the largest pulse seen at roughly one-hour intervals is visible to $\sim$ 1 Mpc using an Arecibo-sized telescope. The giant-pulse phenomenon is poorly understood but it may be associated with pulsars having small light cylinders, i.e. young pulsars and MSPs. Searches for giant pulses from pulsars in nearby galaxies may be made either through blind searches or through targetting of known supernova remnants in those galaxies. The payoff is greatest if an ensemble of pulsars can be found in a given galaxy so that the contributions of the intergalactic medium and the ISMs of the Galaxy and the host galaxy can be disentangled.

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