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An efficient search for the faint population of long period pulsars

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Abstract

The conventional periodicity search, based on the fast Fourier transform (FFT) of the time series, has two major drawbacks while searching for long period pulsars. Long period pulsars often have short duty cycles and the FFT based search with harmonic summing over a limited harmonic space is less sensitive for short duty cycles. The FFT search is also highly vulnerable to rednoise in the radio telescope data, reducing its sensitivity for longer periods. Since the current population of radio pulsars is mostly discovered by the FFT based search, there is a strong possibility of a missing population of long period and short duty cycle pulsars. An alternative search method for non-accelerated periodic signals is the fast folding algorithm (FFA), which has a uniform response for all periods and duty cycles. The FFA search provides an unbiased way to search for periodic signals with superior sensitivity. Though sufficiently bright population of long period pulsars can be discovered in single pulse searches, a suitable periodicity search along with an increase in integration time per pointing is required in major pulsar surveys to discover the fainter population of long period pulsars.

1. Introduction

Pulsars are highly magnetized rotating neutron stars. The rotation period of the known pulsar population ranges between 1.4 ms and 76 s. There are four known pulsars with periods greater than 10 s, all of them discovered in the last five years. Two of these pulsars (J0901-4046, the 76 s pulsar[1], and J2251-3711, the 12.12 s pulsar [2]) were detected in single pulse searches and the other two were found in periodicity search. The 23.5 s pulsar (J0250+5854 [4]) was discovered in an FFT based search in the LOTAAS(LOFAR Tied-Array ALL Sky) survey which has a long integration time of one hour[4]. The 14 s pulsar (J1903+0433g [3]) was discovered by the extremely sensitive Galactic Plane Pulsar Snapshot (GPPS) survey, in an FFT search at the 15th harmonic of the true fundamental frequency. Another pulsar in the same survey with a period of 9.8 s (J1856+0211g [3]) was discovered in a single pulse search. So, we see that most of the ultra long period pulsars are either found in single pulse searches, or in a periodicity search with a very long integration time.

All the major pulsar surveys have been using conventional FFT based search along with only a few minutes of integration time per pointing. It has been theoretically demonstrated that the FFT search sensitivity falls for small duty cycle signals, due to harmonic summing over a limited harmonic space[5]. Long period pulsars are expected to have small duty cycles due to the period dependence of the opening angle of the radio beam. This reduces the FFT search sensitivity for long period pulsars even in ideal white noise conditions. The real telescope data has rednoise and RFI (radio frequency interference) contributions in it. The rednoise is a low frequency noise dominant only at lower modulation frequencies. The rednoise is introduced by the slowly varying instrumental gain. The presence of rednoise in real noise heavily impacts the sensitivity of FFT search for longer periods[6,7]. It has been shown by van Heerden et al.[6] that the frequency domain spectral whitening does not help FFT search to improve its sensitivity towards long period signals. The FFA is now established as a more sensitive search method for non-accelerated signals in ideal white noise[5]. Theoretical analysis also shows a uniform response of FFA search for all periods and duty cycles, unlike the FFT search, where sensitivity is a function of the duty cycle[5]. All the theoretical predictions are only valid in the case of ideal white noise and tests are needed to establish the behavior of FFA search in real telescope noise conditions. In this work, we establish the behavior of FFA search in both ideal noise and real telescope like conditions and present results of FFA search processing of the GMRT High Resolution Southern Sky (GHRSS) survey data. The GHRSS survey is a time-domain survey for pulsars and transients in band-3 (300-500 MHz)[7].

In sections 2 and 3, we test the sensitivity of the FFT and FFA search over a range of signal parameters (period and duty cycle) in both ideal white noise and real telescope noise conditions. We compare the performance of these two search methods using the redetected pulsars in the FFA processing of the GHRSS survey data in section 4. In section 5, the results of the survey processing are presented. We summarize the work and discuss the scope of FFA search to discover the missing population of faint long period pulsars in section 6.

2. FFT search performance in ideal white noise and real telescope noise

To search for periodic signals in this method, an FFT of the time series is taken to generate the power spectra. Any periodic signal will manifest itself as peaks at the fundamental and subsequent harmonics in the power spectra. The power distribution in power spectra depends on the signal's duty cycle (i.e. fraction of the period containing the signal from the pulsar). The power in fundamental and subsequent harmonics is added together to increase the detection significance, but in practice, only a limited number of harmonics are added due to limitations on computation power.

In this section, we study the behavior of the FFT search over a range of periods and duty cycles in both white noise and real GHRSS noise. Figure 1 shows the FFT detection S/N as a function of the period of the signal. The curves are individually normalized to the unit maximum.

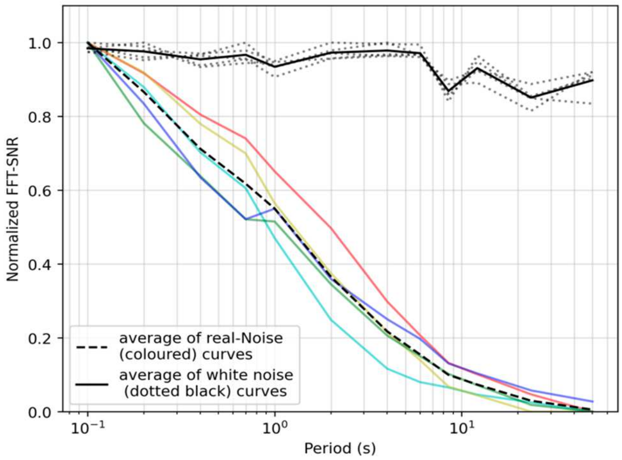

Figure 1. Variation of FFT detection S/N as a function of period. The dotted black curves are the results in white noise cases and the solid black curve is the mean of these curves. The colored curves are the results of the GHRSS noise conditions. The dashed black curve is the mean of all real noise cases.

We find that the FFT search has a uniform response to all periods in the case of ideal white noise but the FFT S/N falls rapidly with the increasing period in the real noise cases. The degradation in the FFT S/N is caused by the extra noise power at lower modulation frequencies in the power spectra, contributed by rednoise. This extra noise heavily reduces the significance of fundamental and subsequent harmonics of the long period signals located in the rednoise dominated frequencies. A 50% reduction in the FFT S/N is seen even at a period of 1 s, and it's more than 90% for periods greater than 10 s for the GHRSS noise conditions.

Figure 2 shows the variations in FFT S/N as a function of the duty cycle. The y-axis values represent the fraction of injected S/N recovered by the FFA search. We see an increase in the FFT detection S/N with the increasing duty cycle in white noise cases. This behavior is expected in an FFT search with harmonic summing. As the duty cycle increases, the fraction of total power in the lower harmonics increases, and an FFT search only summing a few initial harmonics gets more power. The white noise curves agree with the theoretical predictions by Morello et al. 2020[5]. But in the presence of rednoise in the real noise cases, initial harmonics are inside the rednoise-dominated frequencies and any increase of power in these harmonics gets suppressed by the rednoise. We see almost flat or even decreasing curves with the increasing duty cycle for real noise cases in figure 2. The recovered S/N remains below 20% of the injected S/N for all duty cycles (for an injected period of 2 s).

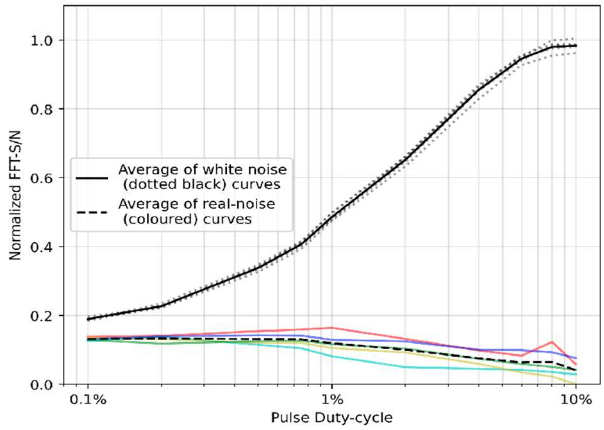

Figure 2. Variation of FFT detection S/N as a function of duty cycle. The color scheme for different noise cases is the same as figure 1.

3. FFA search performance in ideal white noise and real telescope noise

To search for periodic signals in the FFA search, the time series is folded at a number of closely spaced trial periods and folded profiles are then evaluated based on their S/N in a process called matched filtering. In this section, we evaluate the performance of the FFA search over a range of periods and duty cycles in both ideal white noise and real telescope noise.

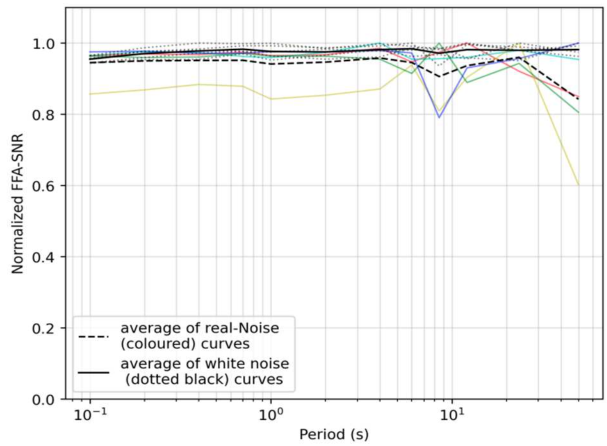

Figure 3. Variation of FFA detection S/N as a function of periods. The color scheme for different noise cases is the same as figure 1.

Figure 3 shows the FFA detection S/N as a function of period. The curves are individually normalized to the unit maximum. The FFA S/N remains constant for periods in both ideal white noise and real GHRSS noise conditions. This validates the use of FFA search to find long period pulsars.

The variation of FFA S/N as a function of the duty cycle is shown in figure 4. The y-axis values represent the fraction of injected S/N recovered by the FFA search. We see that the FFA search has a uniform response for all duty cycles in both real and ideal white noise conditions. The FFA search recovers more than 90% of injected S/N in the white noise and around 70% of the injected signal in the real GHRSS noise conditions. These findings validate the use of FFA search to discover short duty cycle pulsars.

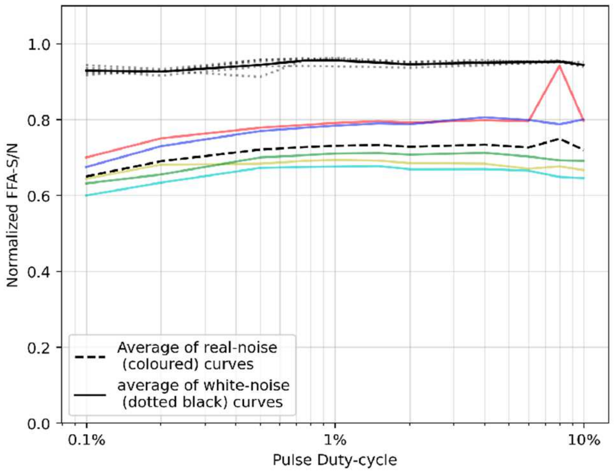

Figure 4. Variation of FFA detection S/N as a function of duty cycle. The color scheme for different noise cases is the same as figure 1.

4. Performance of the FFA and FFT search on redetected pulsars

We have established the following in sections 2 and 3: the FFT search sensitivity falls rapidly with increasing period and has poor sensitivity (below 20% of injected S/N) for all duty cycles at a period of 2 s in the real noise conditions, while FFA search shows a uniform response for all periods and duty cycles and recovers 70% of the injected power in the real noise conditions.

We performed FFA and FFT search on 48 redetected pulsars in the FFA processing of the initial 1500 square degrees of the sky coverage. Figure 5 shows the FFA S/N versus FFT S/N of these pulsars. All the pulsars are either on or above the 1:1 line, showing that these are better detected in the FFA search. The figure clearly shows that the ratio of FFA to FFT S/N is larger for longer periods. We find no such dependence of the ratio of FFA and FFT S/N on the duty cycle. These findings perfectly agree with the behavior of FFT and FFA search in real noise cases discussed in sections 2 and 3. At this point, we are convinced that the FFA search is well suited for searching long period and short duty cycle pulsars.

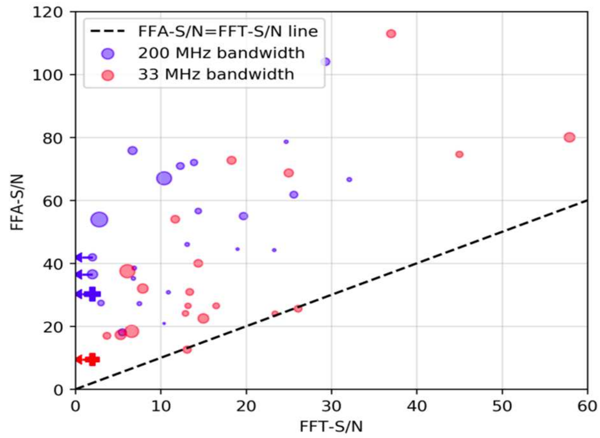

Figure 5. FFA S/N versus FFT S/N of redetected known pulsars. The black dashed line is a 1:1 line. The blue and red markers are for pulsars detected in narrowband (33 MHz bandwidth) and wideband (200 MHz bandwidth) data respectively. The marker size is scaled according to the period of the pulsar.

5. Discoveries

We are processing the GHRSS survey data with a newly implemented FFA based search pipeline. We have processed a total of 2800 square degrees of sky coverage and discovered 6 new pulsars. The periods of these pulsars range between 0.14s to 1.67 s, and DM values range between 42 to 108 $pc - cm^{-3}$. Figure 6 shows the FFA vs FFT detection S/N of these new pulsars. The survey sensitivity is 0.3 mJy at 7 sigma significance for a 5% duty cycle and DM less than 150 $pc - cm^{-3}$. The FFA detection S/N of these pulsars is ranging between 10 to 50 sigma, while the FFT detection significance is less than 14 sigma. Two of the new pulsars were missed by the FFT search even at 2 sigma significance (marked by 2 sigma upper limits in figure 6).

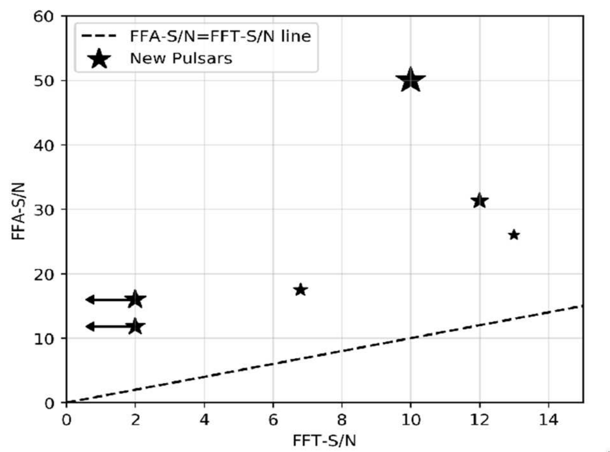

Figure 6. FFA versus FFT S/N of the new pulsars. Two pulsars were missed by the FFT search even at a 2 sigma threshold (marked by the 2 sigma upper limit of FFT S/N).

All of the FFA discovered pulsars are faint and five out of six new pulsars are having a flux density smaller than 1 mJy. One interesting aspect of these pulsars is their duty cycle. Three out of 6 new pulsars have a very narrow duty cycle, placing them on or below the observed lower boundary line in the duty cycle versus period plot (see figure 7). This demonstrates the capability of the FFA search to recover the missing population of long period and short duty cycle pulsars.

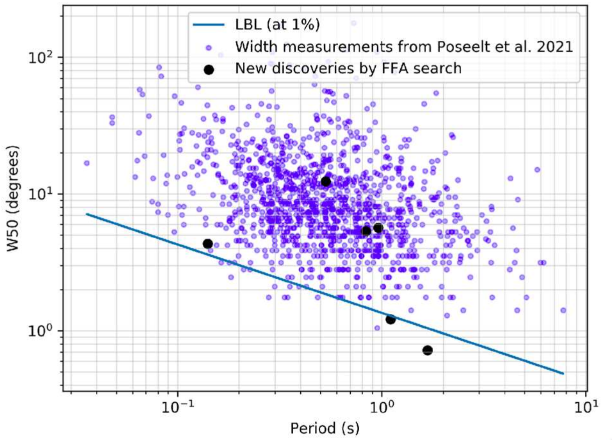

Figure 7. Location of new pulsars on duty cycle versus period plot. The black points are GHRSS pulsars found in the FFA search and the blue points are width measurements from Posselt et al. 2021[8]. The line is the lower boundary allowing only one percent of the population to be located below it.

6. Discussion

The discoveries of ultra long period pulsars in the past few years have strengthened the possibility of a missing population of long period pulsars. The brighter part of this population is being discovered in the single pulse searches and periodicity searches in pulsar surveys but a focused effort is needed to recover the fainter population of long period pulsars. The faint long period pulsars are unlikely to be detected either in a single pulse search or a periodicity search on a few minutes long time series. Since FFA search has a superior sensitivity for non-accelerated periodic signals and performs much better than the conventional FFT based search for long periods and small duty cycles, an FFA search implementation along with a significant increase in the integration time per pointing is the ideal combination to search for the fainter population of long period pulsars. In our GHRSS processing with FFA search, we are finding an increase of detection S/N by ~2 times compared to the FFT search. Aided by the discoveries from the FFA search, the population of long period pulsars in the GHRSS survey enhanced from 10% to 20% of the total discovery.

7. Acknowledgements

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8. References

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