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Search for long-period pulsars with the GMRT: Discovery of nulling in two pulsars

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Abstract

The process of coherent radio emission from pulsars poses many important questions in the field of astrophysics that are not fully understood yet. Features seen in the pulsed emission are the main probes to the actual physics of radio emission from these objects. Nulling is one of these important emission features in which radio emission from pulsars stops for a duration ranging between a few periods to a few tens of minutes or even hours and then starts again. Any emission model that attempts to explain pulsar radio emission has to explain this peculiar phenomenon of stopping and restarting radio emission. In this paper, we present nulling in two long period pulsars discovered in the GHRSS survey with the uGMRT. One of these pulsars, PSR J1937-2937 shows long nulls. We test the effciency of periodicity search methods to find pulsars with long nulls using several epochs of observation of PSR J1937-2937. We also present the nulling properties of pulsar J1244-4708.

1 Introduction

Since the discovery of the first pulsar, there has been a consistent effort to understand the radio emission physics from these objects. Even after decades of rigorous work on both the theoretical and observational front, there are still many questions regarding radio emission physics that are not completely answered. Backer (1970) [1] was the first to report the nulling phenomena in pulsars. Till now, over 200 pulsars are known to show nulling [2]. A careful investigation and search for nulling over the whole known pulsar population is required to truly estimate the number of nulling pulsars [2]. Discovering new nulling pulsars also poses significant challenge. Some nulling pulsars show very long nulls lasting for few tens of minutes, that is larger than the integration time per pointing in many major pulsar surveys. There is also a question of suitable search method for nulling pulsars, especially for pulsars with long nulls. Sufficient bright pulsars can be found in single pulse search, but periodicity search will be needed for fainter population of pulsars with long nulls. Fast Fourier Transform (FFT) based periodicity searches (e.g. PRESTO [4]) require signal to be consistently periodic. While, the Fast Folding Algorithm (FFA) [8] search method searches for periodic signal by folding the time seires at trial periods and can capture any signal that appears in the folded profile. A detailed comparison of these two periodicity search methods is required to select the best suited search method to search pulsars with long nulls. The nulling phenomena is often characterized by three parameters: nulling fraction, null and burst lengths, and periodicity of nulling [3]. The nulling fraction measures the fraction of observation time, when there is no signal from the pulsar. The null and burst lengths try to measure the typical timescales of the nulling and continuous emission. Sometimes nulling appears to be quasiperiodic and an approximate period of the nulling can be measured. These inputs from nulling phenomena are crucial to evaluate the radio emission models.

We describe the target pulsars in section 2 of this paper. Observations and data reduction is discussed in section 3. We present the nulling properties of the two pulsars in the sections 4 and 5. We summarise the results in section 6.

2 GHRSS survey and target pulsars

GMRT High Resolution Southern Sky (GHRSS) survey is a survey for pulsars and radio transients with the uGMRT. The survey uses band-3 of uGMRT with a bandwidth of 200 MHz (300-500 MHz) and targets sky away from the galactic plane. This survey is in its final stages and has discovered 28 pulsars and 2 RRATs.

Table 1: pulsar parameters of the target pulsars

Name	Period (s)	DM ($pc\text{-}cm^{-3}$)	duty-cycle (%)	Flux (mJy)
J1244-4708	1.411	74.9	5	1.4
J1937-2937	1.675	42.2	0.8	0.8

We are using a Fast Folding Algorithm (FFA) [8] based search pipeline to efficiently search for long period pulsars

[6]. The discoveries from the GHRSS survey include six long period pulsars with periods larger than 1 s. Two out of these six pulsars show clear nulling. Table 1 lists the basic parameters of these two pulsars.

3 Observations and data reduction

The observations were taken with uGMRT in the follow up observations after the discovery and timing campaign of these pulsars. We observed PSR J1244-4708 in band-3 (300-500 MHz) and band-4 (550-750 MHz) to investigate the wideband nulling properties of this pulsar. For PSR J1937-2937, we had many observations with duration ranging between 30 minutes to 2 hours in band-3 from the timing campaign. We recorded filterbank data with 4096 channels and 81.92 or 327.68 micro-sec time resolutions. We used pulsar data analysis softwares (SIGPROC[1] and PRESTO[2]) for the data reduction and analysis.

4 Periodicity search for nulling pulsars with long nulls

The FFA search is known to be good for long periods and small duty cycle pulsars. FFA search can capture anything that appears in the folded profile. Usually a periodic signal is the one to appear in the folded profile, but any periodic signal that is appearing and disappearing throughout the observation duration also can be captured in the folded profile. On the other hand, if the signal is not consistently present throughout the observation, FFT based searches can also capture it but will lose the detection significance due to inconsistency in periodicity. Nulling pulsars often show null phases, when signal from the pulsar is absent; and burst phases, when pulsar signal is consistently present. Such signals can be efficiently found in single pulse searches, but the fainter signals that are not detectable in single pulse searches, need a periodicity search. The FFA search is expected to be the suitable search method to search for such signals. But a detailed comparison is needed to assess the efficieny of the two periodicity search methods to search for nulling pulsars with long nulls.

J1937-2937 is a GHRSS pulsar discovered in the FFA search [7]. This pulsar is one of the exciting pulsars discovered with FFA search in the GHRSS survey. This pulsar has a period of 1.675 s and a very small duty-cycle, possibly the smallest duty cycle in the currently known pulsar population. This pulsar shows nulling with an extreme nulling fraction of ~90%. Only 5 other pulsars from the currently known population show such extreme nulling fraction [2]. This pulsar shows long nulls having a consistent length close to 30 minutes, separated by few minutes long bursts. The long period, small duty cycle, and long nulls from the PSR J1937-2937 make it an ideal case study for FFA search. Here we present the results of FFA and FFT based searches on different observation epochs of this pulsar (see figure 1 for pulse sequences).

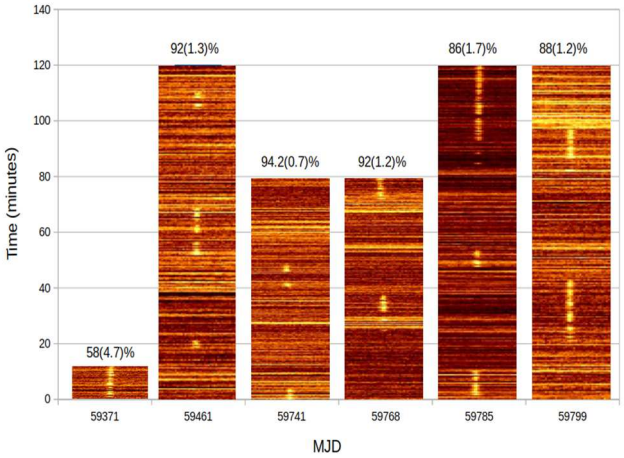

Figure 1: Pulse sequences from PSR J1937-2937. The null and burst phases can be seen in the figure along with nulling fraction written on top of each pulse sequence. This figure is a part of Singh et al. (2023a) [7].

Table 2 lists FFA and FFT detection S/N for different epochs of observation along with harmonic number at which signal was detected. We can notice that for epochs where burst lengths are very small (59461, 59741, and 59768), FFT search has completely missed the signal, while FFA search is performing well. FFT search is doing well for the epochs where burst are long (5971, 59785, 59799).

Table 2: FFA and FFT detection S/N for PSR J1937-2937 on different epochs of observation.

Epoch (MJD)	FFA-S/N	FFT-S/N	detected harmonic in FFT search
59371	50	15	5th
59461	11	-	-
59741	20	-	-
59768	28	2.09	11th
59785	20	9	8th
59799	32	9	7th

Overall, FFA search is detecting the signal and performing better than the FFT based search for all these epochs. Single pulse searches also can be very useful to search for such small bursts. A comparison between single pulse search and FFA search for the short bursts is required to choose the best method to search for such signals.

[1] https://github.com/SixByNine/sigproc

[2] https://github.com/scottransom/presto

5 Nulling properties of PSR J1244-4708

We discovered nulling in the Phased Array (PA) beam observation on this pulsar after determining its accurate localization. The nulling fraction was close to ~70% for the epoch in which nulling was discovered. The pulsar showed clear nulls of size up to ~ 300 pulses. The bursts were regularly separated by 50-70 pulses nulls. We observed this pulsar in band-3 (300-500 MHz) and band-4 (550-750 MHz) in a follow up observation.

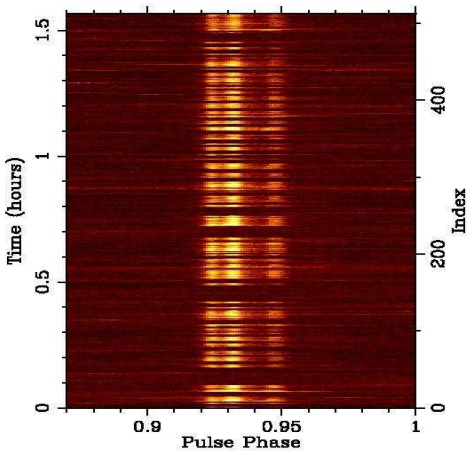

Figure 2: Pulse sequence from the band-3 observation of PSR J1244-4708. The plot is zoomed around the on pulse phase.

We observed this source for 1.6 hours (~4000 pulses) with uGMRT in band-3 on 15 Nov 2022 (see figure 2 for pulse sequence from this observation). The time and frequency resolution was kept 327.68 micro-secs 48.8 kHz. We use the method described by Wang et al (2020) [5] to compute the nulling fraction. We first subtract a running median from the time series to remove the baseline variations. Then, the significance of on pulse and off pulse region (by selecting the on pulse phase range and an off pulse phase range of the same length) of each pulse is calculated. Then histogram of off pulse significance is plotted. The off pulse significance follows Gaussian distribution with mean at zero. A Gaussian is fitted to this distribution to derive amplitude (A0) and standard deviation of the distribution. Now, histogram of the on pulse significance is plotted. The negative part of the on pulse significance histogram is fitted with a Gaussian having the standard deviation derived from the off pulse significance histogram. The amplitude of the fitted Gaussian (A1) is noted. The ratio of amplitudes of two Gaussians (A1/A0) gives us the nulling fraction. The nulling fraction tells us that in what fraction of the total number of pulses, there was no signal from the pulsar. The nulling fraction for 15 Nov 2022 observation was 57% with an error of 2.6% (see Figure 3).

We also search for periodicity in the nulling from this pulsar. We generated a series of zeros and ones for the pulse train, zeros for pulses where detection significance of the pulse was less than 5 sigmas and ones for the cycles where pulse had a detection significance of more than 5 sigmas. We then subtract the mean value from this series, and use python module *scipy.signal.periodogram* to generate a periodogram of this series.

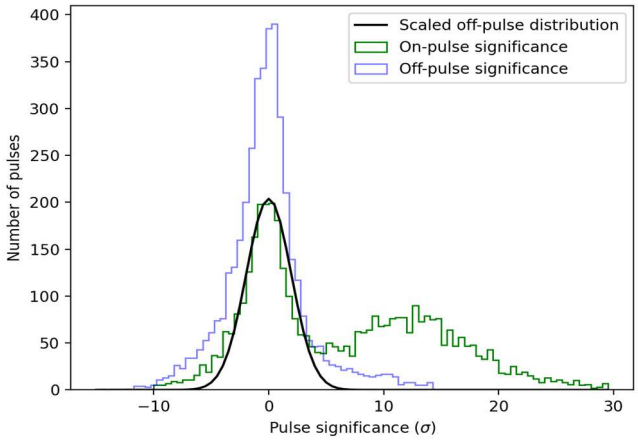

Figure 3: Pulse energy histogram of band-3 observation of J1244-4708 on 15 Nov 2022. The on pulse significance histogram clearly shows bimodal distribution. The nulling fraction derived from this histogram is 57 (2.6)%.

Figure 4 shows this periodogram. The periodogram has two periodicities of nulling, one corresponding to ~250 pulses and the second one corresponds to 60-70 pulses. These timescales are also visible in the pulse sequence shown in figure 2.

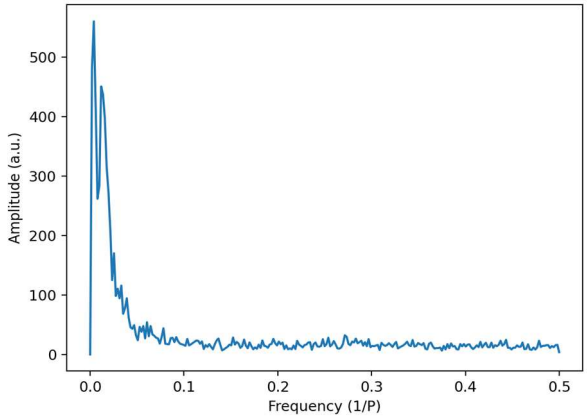

Figure 4: Nulling periodicity in band-3 observation of J1244-4708 on 15 Nov. The pulsar shows two timescales in the periodicity; first one with a period of ~250 pulses and the second one one with a period of ~70 pulses.

We observed this pulsar for 1.3 (3328 pulses) hours in band-4 of uGMRT (550-750 MHz). The time and frequency resolution were again kept at 327.68 micro-secs 48.8 kHz. We did similar nulling analysis for this

observation also. We found a nulling fraction of 55.1(8)% in this observation. The periodicity analysis showed two timescales of periodicity; first one with a period of 430 pulses and second with a period of 60 pulses.
We also observed this pulsar, simultaneously in band-3 and band-4 of uGMRT for 1.1 hour (2805 pulses). Figure 5 shows the pulse sequence from both band-3 and band-4. The pulse sequences are broadly identical, the only difference is the brightness of the pulses in two bands. This confirms the broadband nature of the nulling.

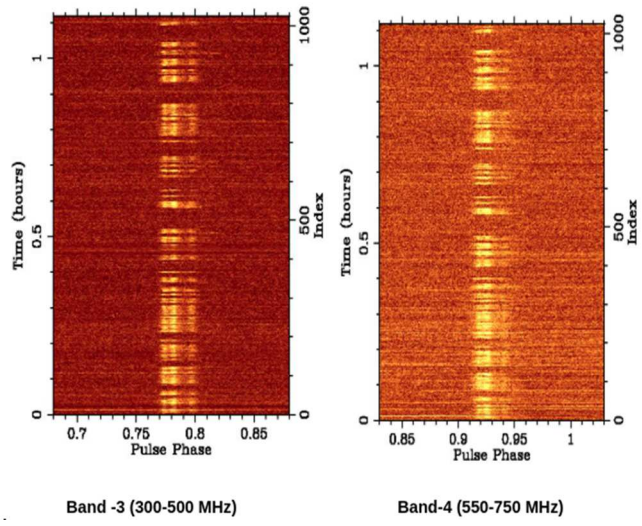

Figure 5: Simultaneous observation of PSR J1244-4708 in band-3 (300-500 MHz) and band-4 (550-750 MHz).

6 Summary

In the first part of the paper we show the performance of periodicity search methods (FFA and FFT based searches) on an extreme nulling pulsar J1937-2937 with long nulls. This pulsar shows null lengths consistently close to 30 minutes. We see that FFT based periodicity search performs well if the pulse sequence has long burst phases with consistent signal, but looses detection significance and even misses the signal in the epochs which have small burst phases. The FFA search detects signal and performs better than the FFT search for all epochs. A comparison between the single pulse search and the FFA search is required to select the best method to search for nulling pulsars with long nulls.
In the second part of the paper, we present the nulling properties of a recently localized GHRSS pulsar J1244-4708. We determined the nulling fraction of this pulsar close to 55%. The pulsar shows periodic nulling with two timescales of periodicity, one corresponding to few hundreds of pulses and second one corresponding to 60-70 pulses. A simultaneous dual frequency observation was used to confirm the broadband nature of nulling from this pulsars.

Acknowledgements

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