Detection of Dispersed Pulsars in a Time Series by Using a Matched Filtering Approach

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ABSTRACT

Pulsars are fast spinning neutron stars in the galaxy. Pulsars are the result of imploding stars where the matter of the core is condensed into a super dense neutron star. Charged particles are accelerated at it's magnetic poles causing radio beams. Pulsars spin with a frequency between 0.12Hz and 642Hz and causes their radio beams to periodically hit the Earth. These periodic signals are highly stable over time and are therefore suitable for use as a clock signal. The PulsarPlane project aims to utilize these signals for navigation purposes. Signal powers from pulsars are very low resulting in the need for a large amount of signal processing. When the radio waves from the pulsar pass through interstellar medium they get distorted and dispersed. For high bandwidths this dispersion is quite substantial. It is normally required to dedisperse the signal before detection. However if the dispersed pulse shape is known, a matched filtering technique could be used to still detect the pulsar in a noisy time series. This paper will show the effect of dispersion on the pulsar signal at the PulsarPlane's measurement bandwidth. Dispersion decreases the energy contained in the signal causing the signal-to-noise ratio to decrease. By making use of matched filtering and folding the original dispersed pulsar signal can be recovered when the dispersion is low enough. It will be shown that dispersion can make some pulsars undetectable. ■

1. INTRODUCTION

Navigation is a very important part of life in this modern age. Almost every vehicle is equipped with some kind of satellite navigation. A commonly used system is the Global Positioning System (GPS) developed by the United States, but other systems are becoming popular as well like GLONASS(Russian) and Beidou(Chinese). These systems have a limited operating lifetime of the satellites and the satellites are operated by the countries that developed them. This means that theoretically a country can make it inaccessible to other countries in case of a political conflict.

GPS works by accurately keeping time and sending this time information to the GPS receivers. This information is then use to calculate the distance between different satellites and hence provides position information. To keep the time information precise, atomic clocks are used in the GPS satellites.

Recently a new type of navigation system is being researched that makes use of pulsars to determine the position on earth. This project is called PulsarPlane and makes use of pulsars as clock sources[1]. A pulsar is a periodic radio source in our universe, some of them are found to be as stable as atomic clocks[2].

Section two will give some background information about the pulsar phenomenon. Section three will describe the theory of dispersion as well as the theory of the methods used for signal-to-noise ratio(SNR) enhancement. Section four will show and discuss the effects of the SNR enhancements methods on dispersed pulsar data. Section five will show and discuss the effect on real radio telescope data. Finally, section six will give the conclusions of this research and section seven the recommendations.

2. BACKGROUND INFORMATION

This section will first give a brief overview of the pulsar phenomenon. After this, the pulsar navigation system PulsarPlane is explained. Next, the effects of the interstellar medium(ISM) on the pulsar signal are described and how traditional pulsar detection works. Finally, the problem description and the research question is stated.

2.1 The pulsar phenomenon

The Handbook of Pulsar Astronomy[3] describes the pulsar phenomenon and characteristics. A short summary of the most important background information is presented here.
Pulsars are celestial bodies that are the result of the death of a star where the outer layers explode into a supernova while the inner core collapses into a neutron star consisting of very dense matter. The radius of the neutron star is smaller than the original star, however it's angular momentum is conserved causing the neutron star to spin rapidly.

A simplified schematic of a pulsar is shown in Figure 1. The neutron star can be seen as a highly magnetized superconducting sphere. The magnetic field of the pulsar focuses the radiation in the direction of the magnetic poles along the magnetic axis. This radia-

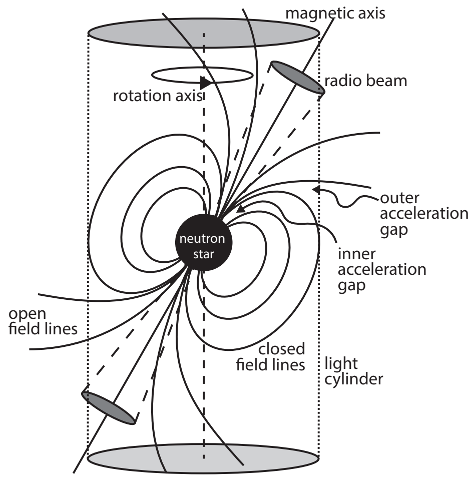


Fig. 1: **Simplified schematic model of a pulsar**

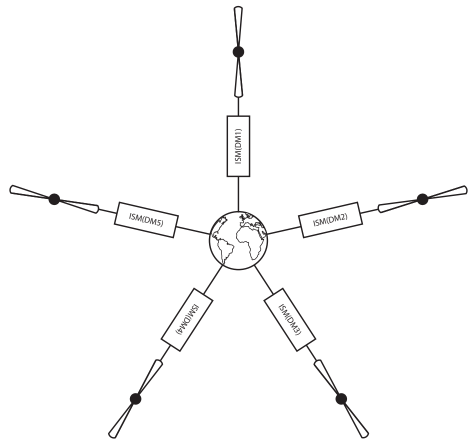


Fig. 2: **Model of the pulsar navigation system, five pulsars are used as time references. The pulsar signals are distorted by the interstellar medium and received in a single receiver.**

tion will travel through space and hit the Earth. As the pulsar spins, the radio beams spin with the same spin period. The magnetic field is typically not in the same direction as the rotation axis causing the beams to hit the earth periodically causing a "lighthouse" effect when observing them. Radio signals from pulsars are subjected to the interstellar medium causing distortion and attenuation. These signals are very faint(their average flux density can be found in the pulsar catalog of the Australia National Telescope Facility database [4]) and require sensitive equipment and post-processing to detect them. For navigation purposes, the pulsars need to be detected by using equipment that can be fitted to vehicles. This equipment is therefore limited in size and had to extract the signal in real time. Real time detection is needed to guarantee a fixed latency between detected pulses so it is usable for navigation. For navigation it is also required to track multiple sources.

2.2 Pulsar navigation system

A proposal for a pulsar navigation system has been described in the PulsarPlane documentation from ASTRON[1, 5, 6]. It makes use of a flat phased array antenna with beam forming to look at multiple different pulsars at the same time. The phased array antenna will have an area of about 100m^2 and will use beam forming to track the several pulsars at the same time. Furthermore the operating bandwidth will be 400MHz, from 1.2GHz to 1.6GHz. This document assumes that the pulsars have a flux density greater than 100mJy, which would limit the choice to only 4 pulsars [4]. PulsarPlane assumes a 10dB SNR is needed for good detection.

This project will focus on the signal processing part, so it is assumed that the signal is correctly received and amplified. The system will look like the diagram in Figure 2. There are five pulsars in different locations of the galactic plane each affected by the ISM medium wit a dispersion measure (DM). A priori knowledge of the pulsars will be used to enhance the detection of the pulsars via signal processing.
This research will look at five pulsars that are received simultaneously and are combined in one time signal. They are assumed to be always visible and are listed in Table 1, their information is gathered from [4, 5, 7]. All these pulsars are distorted by the interstellar medium differently because they are located in different parts of the galaxy. Hence they also have different dispersion measures. The timing signals from the pulsars need to be extracted from the noisy time series in order to properly use them for navigation.

Table 1. : **List of pulsars used in this research**

Pulsar name	Dispersion Measure $[cm^{-3}\ pc]$	Rotational period [s]
B0329+54	26.7641	0.7145811
B1937+21	71.0227	0.0015578
B0355+54	57.1420	0.1563824
B0531+21	56.791	0.0333924
B1933+16	158.521	0.3587439

2.3 Effect of the movement of the observation antenna

For long observations of pulsar signals it is necessary to correct for the movement of the observation antenna due to the earths rotation and the solar system. This can be done by correcting the topocentric data (data captured at the observation point) to the solar system barycenter[3]. Also, the antenna is strapped to an airplane so the movement of the plane also needs to be accounted for. Typically for astronomical observations the time of arrival of a pulsar is estimated using TEMPO2 software[8], then using this information further signal processing is required. These corrections are outside the scope of this thesis but are mentioned because they are important to incorporate in the PulsarPlane project. This research assumes a constant pulsar period for all pulsars because the aim is to see the effect of dispersion only.

2.4 The effect of the interstellar medium

Before pulsar signals reach the Earth, they pass through interstellar medium (ISM). This medium is basically everything that exists between the pulsar and earth. This medium consists of ionized gasses and tenuous plasma. This has several effects on the pulsar radio signal as explained in [9]. This research will only take into account the effect of dispersion.

2.4.1 Dispersion. The first effect of the interstellar medium is the dispersion it adds to the signal. The pulsar signal can be considered as a plane wave with multiple frequency components (wideband) in the observed bandwidth. The group velocity of the pulsar signal has a frequency dependence caused by the interaction with the ionized component of the ISM. The frequency dependence of these wave causes higher frequencies to arrive earlier than lower frequencies. To amount of dispersion of a pulsar signal is defined by the dispersion measure(DM), and is the integrated column density along the line of sight. The DM is proportional to the distance of the pulsar[3][9]. All these signals are added in the receiver so the peeks of the different frequency components are misaligned when dispersion isn't removed. This causes the pulse to be spread in time making it wider and decrease it's amplitude.

2.4.2 Scintillation. The second effect of the ISM is scintillation of the signal. The ISM is a turbulent plasma and is non-homogeneous causing the pulsar signal to experience phase modulation. This results in a change in the received intensity of the pulsar signal intensity that varies over time [3]. The effect of scintillation is shown in a 10 second frame of a real observation of the B0329+54 pulsar by the Westerbork Radio Synthesis Telescope (WSRT) in Figure 3.

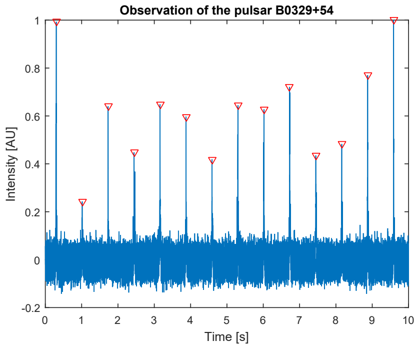


Fig. 3: **Observation of the B0329+54 pulsar at 1.4GHz by the WSRT on the 2nd of February 2012. There is no signal processing in this with the exception of down sampling (averaging). As shown the peeks of the pulsar (marked with red triangles) vary in intensity over time. This is the effect of scintillation.**

2.4.3 Scattering. The third effect is scattering. When the pulses pass through the ISM they get scattered by irregularities. The scattered parts of the signal arrive later and will hence broaden the pulse with an exponential tail. This effect of scattering is inversely proportional to the observing frequency. So it can be avoided by choosing a higher observing frequency[3].

2.5 Traditional pulsar detection

Detecting pulsars in radio data is very common in astronomy. There are a lot of techniques to find a pulsar but this research assumes that a priori information about the pulsar is available. The general block diagram for detection of pulsars is shown in Figure 4. First the signal is down converted from the band of interest to base band and detected. After this, the signal is digitized and can be seen as a time series of antenna voltages of both X and Y polarization. Then the dedispersion of the pulsar signal is applied, this is dividing the frequency domain data into small bins. Then each bin is time delayed corresponding to the dispersion measure. This causes the summed pulse to have more power and have a narrowed pulse width in time domain.

After dedispersion, the time series is folded with the known period of the pulsar. This is calculated from previous measurements by using the Modified Julian Date (MJD) compensating for spin down and doppler shifts, TEMPO2 is used for these estimations[8]. Folding the data will make the pulse profile increase in power while the noise stays the same level, this causes the signal to noise ratio (SNR) to increase. To further increase the output SNR, the resulting folded profile could be down sampled. This is done by dividing the folded profile into bins and averaging the data in those bins. When white Gaussian noise is averaged it will converge to a mean value while the signal will converge to its integrated pulse profile.

Instead of down sampling, a matched filter can be used as well. Matched filtering uses a template with the same pulse shape as the pulsar. By convoluting the folded time signal with the template, the pulsar signal is recovered. This is computationally intensive but is an optimal linear filter when detecting a known signal in white Gaussian noise [10].

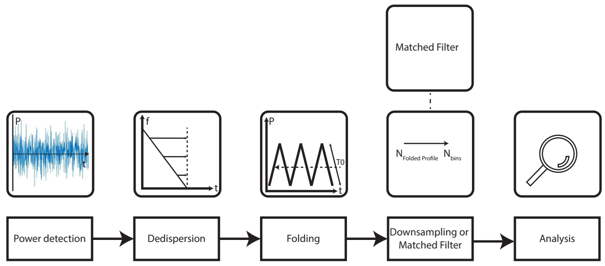


Fig. 4: **Signal flow of processing raw data to detect a pulsar in a noisy time series**

2.6 Problem description and research question

This research focuses on the dispersion that is present in the pulsar signal. The pulsar signals in the received time series are from five different sources that are all dispersed with a different dispersion measure and have a different rotational period. Due to the dispersion, the pulse shape is smeared in time which changes the pulse shape. If the template will be smeared with the same amount as the estimated dedispersed signal it might be possible to detect the signal from the time series without applying dedispersion. The main research question will hence be:

Is it possible to distinguish and detect multiple known pulsar signals from a time series of an antenna signal by using matched filtering with a dispersed pulsar template?

3. THEORY

This section briefly describes the theory that will be used in this research. First the signal characteristics of a pulsar and their quality will be described. To see the effect of the dispersion on the pulsar signal, dispersion will be added to a pulsar signal to emulate the effect of the ISM. The theory of adding dispersion will be discussed.

3.1 Pulsars in question

For this research a data set with 5 pulsars has been supplied by ASTRON. For tests, these pulsars are first modeled with MATLAB by using their undispersed pulse profile from the pulsar database. The list of pulsars was already given in Table 1 with some of their properties. The shape of the pulsars is displayed in Figure 5a and 6a. These shapes are extracted from the European Pulsar Network (EPN) database [7]. In these figures the pulses are dedispersed and folded hence they are an estimation of the exact pulse profile of the pulsar as measured by a radio telescope. This is sometimes called the integrated pulse profile[3].

3.2 Modeling dispersion

The primary effect that is researched in this project is dispersion in the pulsar time series. Dispersion measures of pulsars are really well know because they are used to study the ISM. Using the dispersion measure one can also determine the difference in arrival time between the highest frequency and the lowest frequency in the band of interest. The relation between this difference in arrival time and the frequency is shown in Equation 1 [3][9]. Here DM is the dispersion measure of the pulsar in cm^{-3}pc, f_{lo} is the lowest frequency in the measurement band and f_{hi} the highest frequency in the measurement band, both in GHz.

$$\Delta t = 4.148808 \cdot 10^{-3} \cdot \left[\left(\frac{f_{lo}}{[GHz]} \right)^{-2} - \left(\frac{f_{hi}}{[GHz]} \right)^{-2} \right] \cdot \frac{DM}{[cm^{-3} pc]} \tag{1}$$

The maximum difference in arrival time is calculated for the case of 400MHz bandwidth (PulsarPlane) and 20MHz bandwidth (real radio telescope data). The 400MHz data will be used for the simulations in this research while the 20MHz data will be used for the WSRT data. Maximum dispersion for the pulsars in question is calculated and displayed in Table 2. For each of the pulsars the time delay as a function of frequency (displayed over the frequency band) is displayed in Figure 7. Dispersion for both the 20MHz and 400MHz bandwidth case are displayed. For the 20MHz bandwidth this shows almost linear behavior while for 400MHz it's not the case anymore. Now a dispersed pulse can be made using this information and a undispersed pulse profile that is gathered from the EPTA[7].

Table 2. : **List of pulsars used in this research**

Pulsar name	DM[cm^{-3} pc]	$\Delta t_{max}[400MHz]$	$\Delta t_{max}[20MHz]$
B0329+54	26.7641	33.7ms	1.58ms
B1937+21	71.0227	89.5ms	4.19ms
B0355+54	57.1420	72.0ms	3.37ms
B0531+21	56.791	71.6ms	3.35ms
B1933+16	158.521	200ms	9.35ms

To generate the dispersion it is required do the exact opposite as dedispersion. The process is explained graphically in Figure 8. First the frequency band will be divided into a number of frequency bins(N_{bins}). The highest bin number is the highest frequency component (undelayed) while bin zero will contain the lowest frequency component (maximum delay). Each bin will be delayed with it's calculated delay value (see 1 and Figure 7). Then all frequency bins are summed resulting in a dispersed profile. Finally to compare the dispersed profile to the undispersed profile, it is normalized by dividing by the number of bins used. If the DM is zero, the resulting "dispersed" profile will be the same as the pulse profile again. This dispersion mimics what happens in a radio receiver trying to detect a pulsar, the different frequency components are not detected at the same time so the pulse widens. In this method it is assumed that the pulse profile does not evolve in shape over the frequency band, which can be safely said for the band between 1200MHz and 1600MHz [3].

Using this method, dispersion is generated for both 20MHz bandwidth (WSRT) and 400MHz (PulsarPlane). Although the sample rate is kept at 40MHz to limit the amount of data in the simulation. The results are shown in Figure 5b and 6b. These graphs show exactly one pulse period of the pulsar. Everything is made using a sample rate of 40MHz, hence pulsars with a lower amount of samples are faster pulsars. As seen in these graphs, the dispersion has a large effect to some of the pulsars. The pulse widens and the amplitude decreases. Also dispersion is only dependent on the ISM so the a faster pulsar is more heavily affected by it than a slower pulsar if they are the same DM. In some pulsars with a short rotation period, the dispersion measure is larger than the period itself resulting in an extra DC component being generated. This reduces the AC energy in the signal and makes it harder to detect. The most dispersed pulsars are displayed in Figure 9. In the next subsection it will be shown what the effect of this dispersion is on the signal quality.

3.3 Quality of pulsar signal

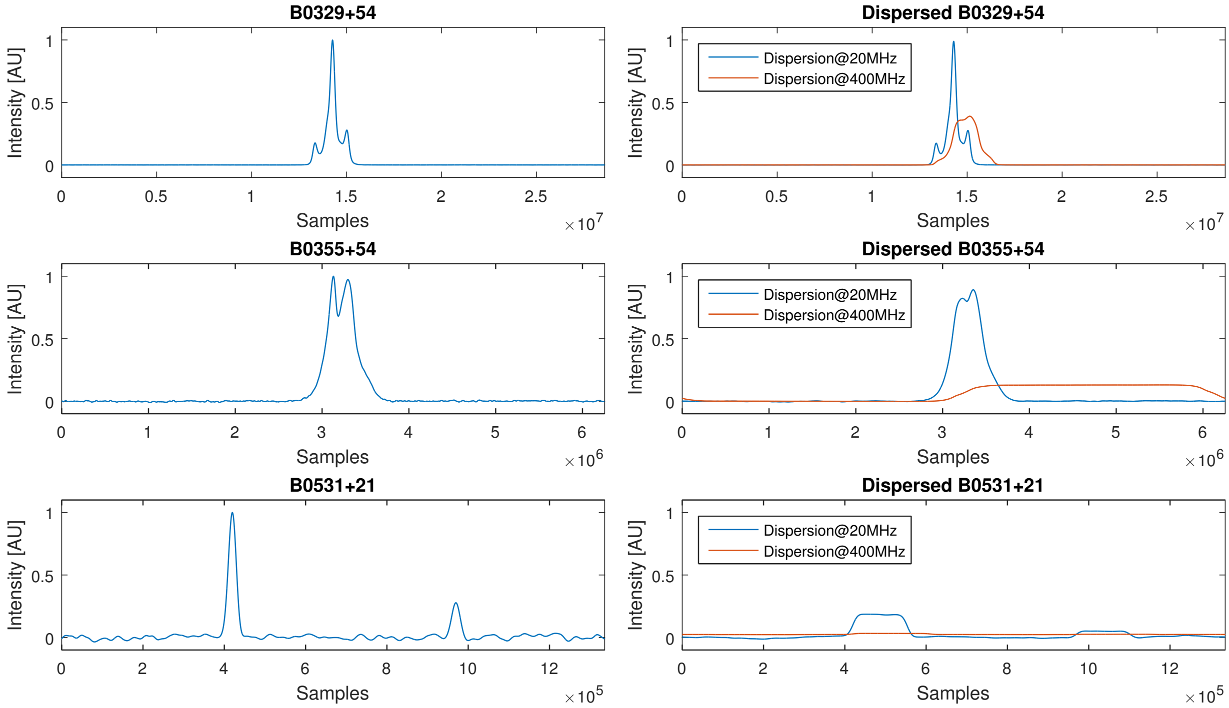
This subsection will describe how the pulsar signal can be analyzed for quality. A good way to give a qualitative figure of merit of the signal is to see how much energy is contained in one pulse period. The energy in a discrete signal can be calculated using Equation 2[11].

$$E \equiv \sum_{-\infty}^{\infty} |X(n)|^2 \tag{2}$$

For all the pulsars the energy within one period is calculated both with and without dispersion and displayed in Table 3. To make a fair comparison only the AC energy is taken into account. The energy is calculated from the data used in simulations.

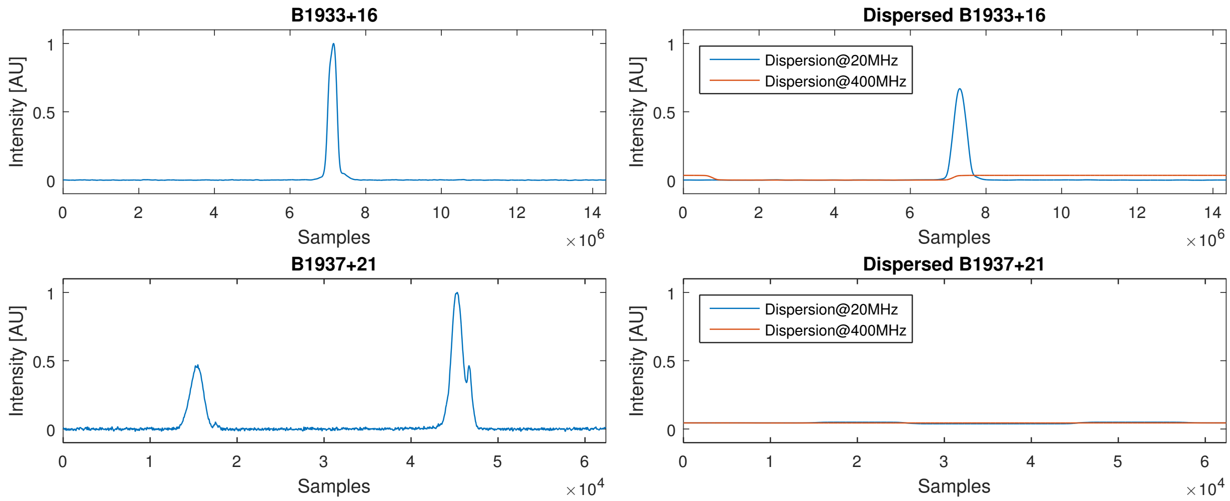
From this table it can be concluded that the signals undergo a large decrease in signal energy when enough dispersion is present in the signal. The reason for choosing a large bandwidth in the PulsarPlane project is to decrease integration time. However if dedispersion is not applied, the energy will lower. To analyze it further, the theoretical SNR for each pulsar signal is calculated. The SNR of a pulsar can be calculated using Equation 3 obtained via [12][5]. Where k is Boltzmann's constant, A_e is the effective aperture of the antenna, T_{sys} is the system temperature (receiver noise temperature plus sky noise temperature) and $S_{v,T}$ is the average pulsar power spectral density as measured by a radio telescope and can be obtained via the pulsar catalog [4].

$$SNR = \frac{1}{2k} \cdot A_e S_{v,T} T_{sys}^{-1} \tag{3}$$



(a) **Undispersed pulse profiles of pulsars** (b) **Dispersed pulse profiles of pulsars**

Fig. 5: **One period of 3 of 5 pulsars used in this research**

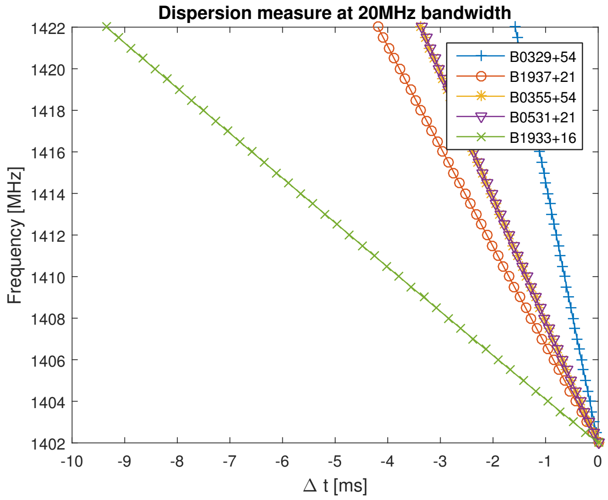


(a) **Undispersed pulse profiles of pulsars** (b) **Dispersed pulse profiles of pulsars**

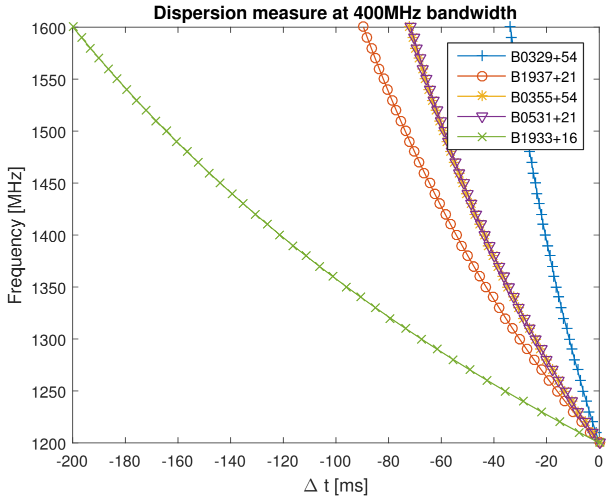
Fig. 6: **One period of the 5 pulsars used in this research**

In the PulsarPlane documents the T_sys is assumed to be 15K for a cooled system and 100K for an uncooled system, in the ESA document [12] it is assumed around 50K on average. For this research 50K is assumed.

The size of the phased array is not mentioned in the documentation however it will be assumed to be 100m^2. All the signal to noise ratios are calculated for the pulsar signals using information from [4]. The power of a periodic signal in signal processing is defined as the energy in one period divided by the number of samples[11]. The number of samples and sample rate is constant for the individual pulse profiles (dispersed and undispersed). Because this is constant, the deterioration of the SNR due to dispersion can be estimated by using the percentages in Table 3. Table 4 shows the SNR of each pulsar before and after dispersion.



(a) **Dispersion at 20MHz bandwidth.**



(b) **Dispersion at 400MHz bandwidth.**

Fig. 7: **Pulsar dispersion for different bandwidths. The highest frequency component in the measurement bandwidth arrives first while the lowest frequency component arrives last (0ms delay)**

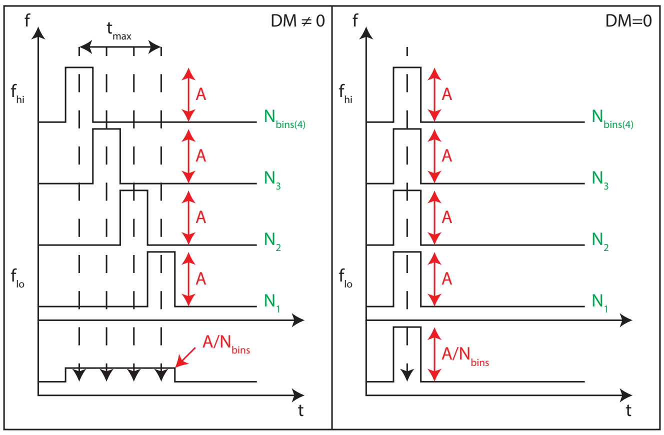


Fig. 8: Simplified schematic model of a radio pulsar

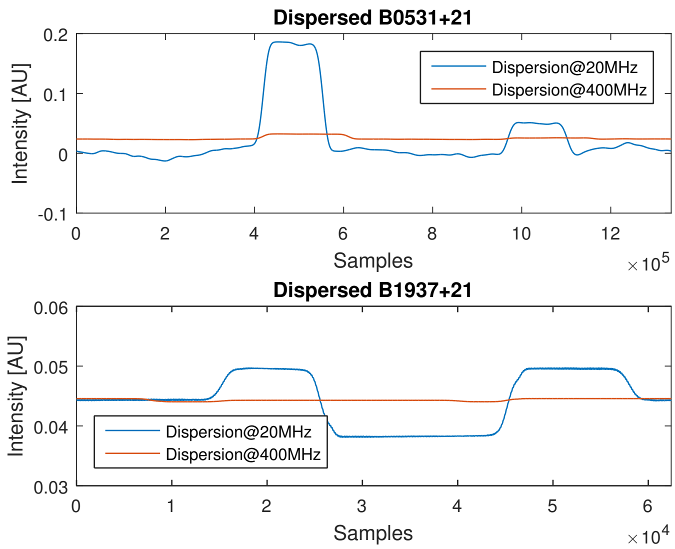


Fig. 9: A zoomed in picture of the most heavily dispersed pulsar.

The SNR reduction as a result of dispersion varies from pulsar to pulsar but is the higher for faster pulsars. Also if the dispersion measure is higher than the rotational period it will generate an extra DC component. The SNR reduction means that more effort has to be done in order to recover the signal in the signal processing stage.

3.4 Matched filters

A well known technique to increase the SNR of a signal that is buried in white Gaussian noise in communication systems is to use a matched filter. The theory behind the matched filter and it's derivation is described in [13, 10]. The matched filter is the optimal linear filter to maximize the output SNR by using knowledge of the wanted signal. It essentially correlates the received signal polluted by noise with a template of the wanted signal. This results in a SNR increase. The optimal template is essentially the time reverse of the known pulsar signal: $h_{opt}(t) = x(\tau - t)$. To compute the output, the noisy signal is convoluted with the template resulting in an increase in SNR. This is shown in Equation 4 for a discrete time signal.

$$y[n] = \sum_{k=-\infty}^{\infty} h[n-k]x[k] \tag{4}$$

To check the increase of SNR through a matched filter a known signal is passed through the filter. This process is repeated with the same signal but with added noise. The outputs are compared to determine the SNR. This can then be compared to the input SNR to determine the SNR gain. This process is shown in Figure **??**. In [10] research is already done about how much SNR increase can be obtained at a certain sample-rate with a matched filter. The

Table 3. : Calculated energy of the dispersed and undispersed pulsars

Pulsar name	Undispersed energy	Dispered energy at 20MHz BW (**remaining engergy**)	Dispered energy at 400MHz BW (**remaining engergy**)
B0329+54	$2.92 \cdot 10^5$	$2.90 \cdot 10^5$ (**99.44%**)	$1.67 \cdot 10^5$ (**57.41%**)
B0355+54	$2.31 \cdot 10^5$	$2.19 \cdot 10^5$ (**94.66%**)	$2.31 \cdot 10^4$ (**10.01%**)
B0531+21	$1.79 \cdot 10^4$	$3.72 \cdot 10^3$ (**20.74%**)	11 (**0.064%**)
B1933+16	$1.93 \cdot 10^5$	$1.27 \cdot 10^5$ (**65.63%**)	$4.02 \cdot 10^3$ (**2.080%**)
B1937+21	$1.41 \cdot 10^5$	12.14 (**0.086%**)	$2.19 \cdot 10^{-3}$ (**0.0002%**)

Table 4. : Theoretical SNR of the dispersed and undispersed pulsars

Pulsar name	Undispersed SNR	Dispered SNR (20MHz BW)	Dispered SNR (400MHz BW)
B0329+54	$-38.4dB$	$-38.4dB$	$-40.8dB$
B0355+54	$-47.8dB$	$-48.0dB$	$-57.8dB$
B0531+21	$-50.0dB$	$-56.8dB$	$-81.9dB$
B1933+16	$-45.2dB$	$-47.0dB$	$-62.0dB$
B1937+21	$-50.2dB$	$-60.9dB$	$-107.2dB$

resulting graph in the paper is replicated using MATLAB and the process described above and is shown in Figure 10.

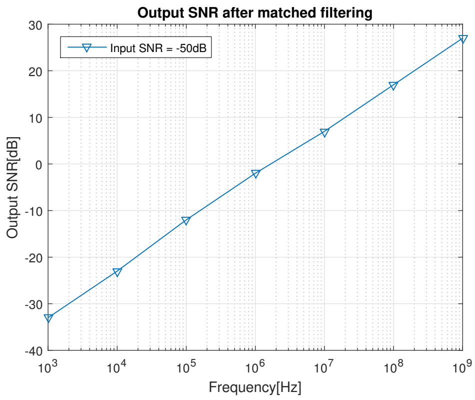


Fig. 10: **Graph showing the relation between the SNR increase of a matched filter versus sampling frequency**

Using the graph the estimation of SNR gain at 40MHz is about 62dB at 40MHz sampling rate and a 73dB at 1GHz sampling rate.

3.5 Epoch folding

Epoch folding is a technique that is widely used in pulsar research to increase the SNR of a periodic signal[3]. This technique uses knowledge about the period of the pulsar. If the exact period of the pulsar is known, the time series can be folded on itself using that period (also called folding period). This causes the pulsar signal to increase while the noise (assumed additive white Gaussian noise)

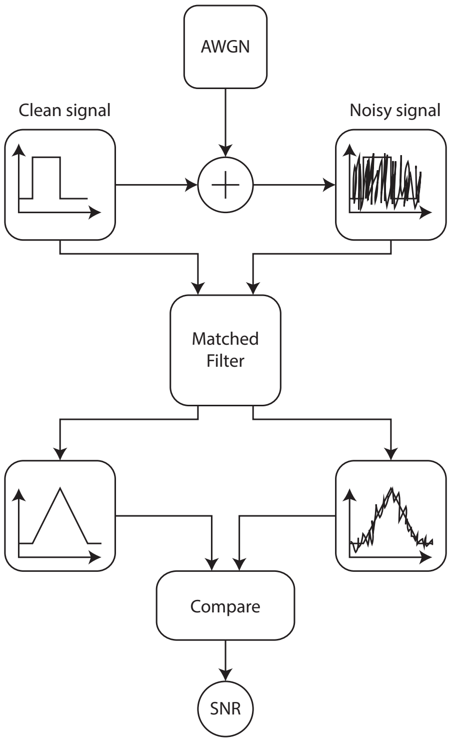


Fig. 11: **Diagram of how the simulation of SNR is performed.**

decreases. Folding results in a time signal exactly one pulsar period long. To further enhance the detection of the pulsar this time signal can be down sampled. This is done by dividing the signal into N bins and averaging all the samples per bin into one point. Another possibility is to use folding and matched filtering. This is proposed in the PulsarPlane project. Folding is shown in Figure 12.

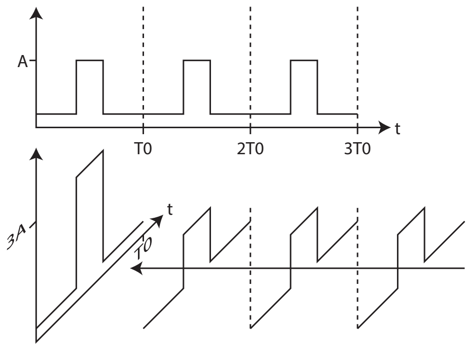


Fig. 12: **Graphical diagram of epoch folding.**

If the folding period of the pulsar is estimated correctly, folding will increase the signal to noise ratio per amount of folded profiles. A graph of the amount of folded periods versus the output SNR is shown in Figure 13.

The above graph only holds when the folding period is correctly estimated. If the folding period is not correct, the folded pulses will

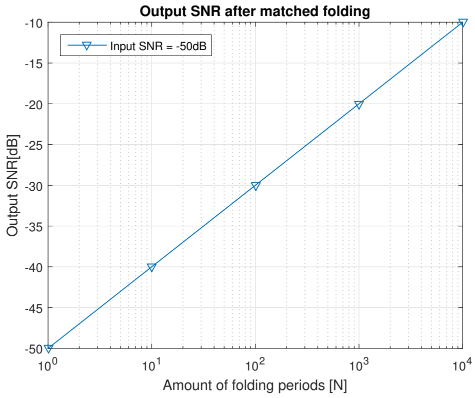


Fig. 13: **Graph showing the relation between the SNR increase of folding versus amount of folded periods**

be misaligned and will essentially be the same as adding dispersion. To illustrate this effect a pulsar is folded with the correct period and a slightly wrong period, the result is shown in Figure 14

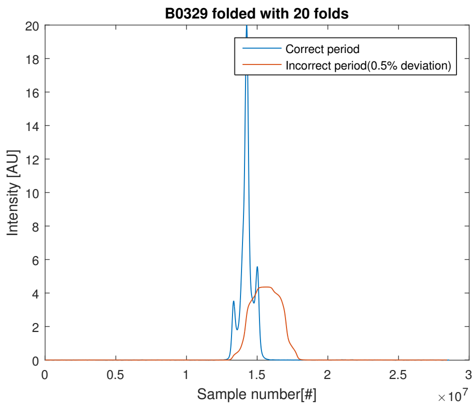


Fig. 14: **Pulsar signal that is folded with the correct period and a slightly incorrect period**

Getting the folding period right proves to be tricky and in astronomy data software is used to estimate it [8]. Furthermore, if a large number of folds is needed, the folding period cannot be assumed constant [3]. Folding large amounts of periods might therefore not be suitable for PulsarPlane. Next to instability in period, a large number of folds will increases the time needed for detection of the signal.

3.6 Conclusion

This section showed the theory behind pulsar dispersion and how to model it. Next to this the theoretical signal to noise ratios were calculated of the undispersed pulsars. By adding dispersion to them it was shown that the SNR of the pulsar signal is reduced and will therefore need more signal processing to recover the signal. Also it was shown that matched filtering can produce a theoretical SNR gain of 64dB at 40MHz sample rate and a gain of 76dB at 1GHz sample rate. Further increase in SNR can be obtained by folding the pulsar signal in time. This needs to be done with the correct folding period because minor deviations will decrease the performance substantially. Next section will show some simulations of pulsars signals generated in MATLAB but using the pulse shapes extracted from EPTA[7].

4. SIMULATIONS

For the simulations, a sample rate of 40MHz will be used because this will generate lower data amounts so that it can still be managed by MATLAB. Theoretically the matched filter will improve the SNR by 62dB. When looking at Table 4, it should be possible to directly detect B0329+54 and B0355+54. The other pulsars would need folding in addition to matched filtering. In order to test the theory from last section, pulsar signals will be made and noise will be added according to their signal to noise ratio. Then these pulsars will be subjected to matched filtering and their output SNR will be checked. After this, the combination of matched filtering after folding will be checked. Finally the effect of a combined pulsar signal will be used to evaluate its effect on the detection performance.

4.1 Signals containing a single pulsar with matched filtering

This subsection shows if the matched filter theory gives the noise reduction that was predicted in the theory. For this the pulsars are generated in MATLAB by taking real pulse profiles from the EPTA database and adding AWGN noise and dispersion of a 400MHz bandwidth. For each pulsar signal, ten periods are generated. The diagram for checking the SNR is shown in Figure **??**. To check the increase in SNR, the signal is passed through the matched filter without noise (uncorrupted). Then the signal is passed through the matched filter with noise. They are then compared by the MATLAB SNR measure function which also calculates the SNR in dB at the output of the filter. At the sample rate of 40 MHz this should give an increase of 64dB. The results are shown in Table 5.

Table 5. : **Simulated SNR's pulsars after matched filtering**

Pulsar name	Dispered SNR (400MHz BW)	Output SNR of matched filter	SNR increase
B0329+54	−40.8 dB	20.25 dB	61.05 dB
B0355+54	−57.8 dB	4.83 dB	62.63 dB
B0531+21	−81.9 dB	−20.81 dB	61.09 dB
B1933+16	−62.0 dB	7.12 dB	69.12 dB
B1937+21	−107.2 dB	−59.21 dB	49.99 dB

These simulation results show that the theoretical increase of 64dB matches the simulations very good. Although still only B0329+54 has a high enough output SNR to match the 10dB specification of PulsarPlane. The output of the matched filter for B0329+54 is shown in Figure 15. To further increase the SNR of the other pulsars, folding is required at this sample rate. At the 1GHz sample rate of PulsarPlane, theoretically B0355+54 and B1933+16 could also be detected without folding as the matched filter would have.

4.2 Signals containing a single pulsar with matched filtering and Folding

Now folding with matched filtering will be tested on the dispersed pulsar signal for those that need it to get to a 10dB output SNR. Using Table 5, an estimate can be made to see how many pulses need to be folded. The results are shown in Table 6.

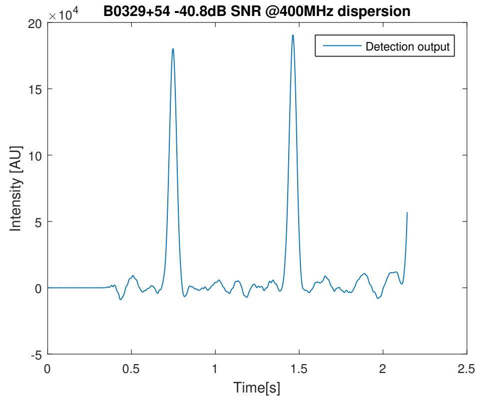


Fig. 15: **Output of the matched filter for B0329+54 with a samplerate of 40MHz and 400MHz dispersion**

Table 6. : **Simulated SNR's of pulsars after matched filtering and folding**

Pulsar name	Dispered SNR (400MHz BW)	Output SNR of matched filter with folding	Number of folding periods
B0329+54	-40.8 dB	20.25 dB	N/A
B0355+54	-57.8 dB	12.71 dB	10
B0531+21	-81.9 dB	9.90 dB	1000
B1933+16	-62.0 dB	19.32 dB	10
B1937+21	-107.2 dB	-17.29 dB (-6.87 dB)	10000 (100000)

This shows that folding and matched filtering can increase the SNR ratio of four of the five pulsars to the required specification. The pulsar B1937+21 is unrecoverable in this case. It should be noted that increasing the number of folds will increase the time span for detection of the signal. In case of B0531+21 the span will be 33.4s if it's folded a 1000 times and might therefore be potentially unsuitable for navigation. The resulting matched filter outputs are displayed in Figure 16b. Their corresponding uncorrupted input is shown in Figure 16a. Next section will explore a combined signal of all five pulsars. It will be tested if having multiple pulsars in one time signal will deteriorate the detection performance.

4.3 Signals containing multiple pulsars with matched filtering and Folding

In the last subsection test pulsar signals were used that contained the correct pulsar signal but did not contain the other signals that are simultaneously received. These tests were done on 4 out of the 5 pulsars since B1937+21 already proved to be unrecoverable. However the test signal contains all 5 pulsars with their amplitude scaled to their power ratios. The result of matched filtering after folding for these signals is shown in Table 7
Overall the SNR decreases when other pulsar signals are present in the time series. This is the result of the pulsars not having a zero mean and wont be averaged out by the matched filtering process. Folding does help in spreading the energy because pulsars are that are not meant to be detected are folded with an incorrect period. Only B1933+16 shows a radical decrease in SNR when other pulsars are present, this is probably due to the fact that its period is almost exactly half of B0329+54 (0.502 times). Hence when folded

Table 7. : **Simulated SNR's pulsars after matched filtering and folding while other pulsar signals are present**

Pulsar name	Output SNR with single pulsar	Output SNR with multiple pulsars	Difference
B0329+54	20.25 dB	12.55dB	-7.70dB
B0355+54	12.71 dB	3.10dB	-9.61dB
B0531+21	9.90 dB	7.19dB	-2.71dB
B1933+16	19.32 dB	-1.22dB	-20.54dB
B1937+21	-17.29 dB	N/A	N/A

it will have a deviation with the correct B0329+54 period of about 0.4%. Figure 14 shows that when the deviation of the folding period is low, the energy of the pulsar is not dispersed enough by the folding process. Also, the signal of B0329+54 is much stronger causing it to pollute the folded profile of B1933+16. The energy of this pulsar is not decreased enough during the folding process. For the other pulsars the SNR decrease can be reduces by using more folding periods, though more folding periods will results in a longer time span for detection.

5. REAL DATA TESTS

To mimic the a signal that could be received by PulsarPlane, the WSRT was aimed at the five different pulsars to receive their signal simultaneously. An attempt was made on trying to recover the signals of each of the five pulsars. The data of WSRT was first folded (with the exception of B0329+54) and then matched filtered with a dispersed pulse profile. The results of these operations are shown in Figure 17. B1937+21 once again proved to yield no results and is hence left out of the Figure. Unlike the simulations, there is no data available that does not have noise in it because it's real astronomical data. Therefore no quantitative analyses can be done of the signal to noise ratio. However when looking qualitatively at these plots, B0329+54 is detected very well even without folding (because of its high flux density). B0355+54 also shows an increasing slope but there is no clear peak that could be used for detection. B0531+21 does not show a clear correlation peak and it is therefor uncertain it is detected correctly. B1933+16 shows a clear peak in the output and is hence detected correctly.

6. CONCLUSION

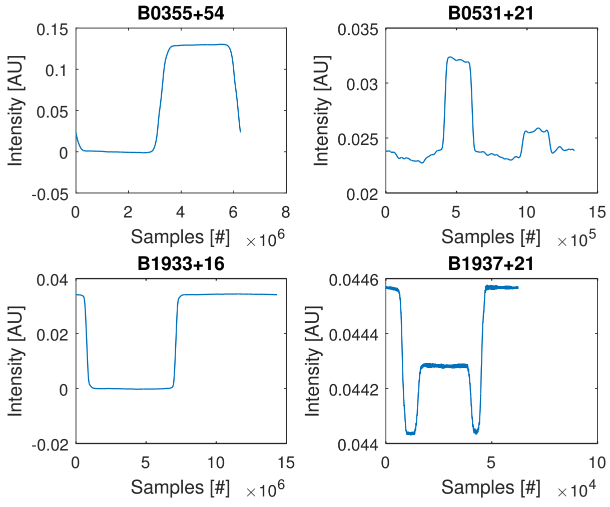
The aim of the research was to see if detection of pulsars was possible without the use of dedispersion.

First the research question is restated:

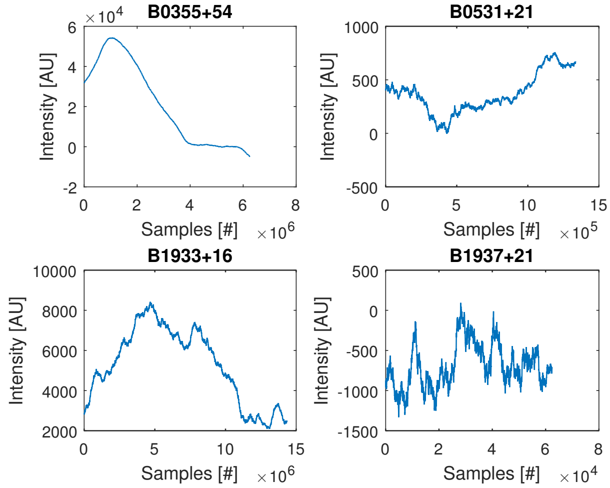
Is it possible to distinguish and detect multiple known pulsar signals from a time series of an antenna signal by using matched filtering with a dispersed pulsar template?

Sometimes it is possible to use matched filtering to detect and distinguish pulsar signals without using dedispersion. However dispersion deteriorates the signal to noise ratio, which has to be compensated with extra folding.

If the dispersion becomes too high such as in B1937+21, the signal will become irrecoverable. This is partly due to the fact that the dispersion measure is larger than the pulsar period itself and will generate an extra DC component reducing the energy



(a) **Uncorrupted input to the folding and matched filter process**



(b) **Output after matched filtering and folding**

Fig. 16: **Effect of folding and matched filtering on the pulsar signal**

contained in the AC component. It can also be concluded that having more pulsars in the same time series deteriorates the detection performance too. This is very clear when the pulsar periods are approximately an integer of each other such as in the case of B1933+16 and B0329+54.

Furthermore it can be concluded that the signal shape is heavily distorted by the dispersion. When the bandwidth becomes larges so does the dispersion. Signals will lose their narrow pulse shape.

7. RECOMMENDATIONS

This research only took into account the quantitative measure of SNR to assess if matched filtering without dedisperion is a possibility. However it was shown that the signal shape is also heavily distorted by the process. At this point it is unclear how this affects the the quality of the signal when it is used for navigation purposes. If this is no problem, it can be beneficial to skip dedispersion to save computational time. However research should still be done if using this method is still usable for navigation despite the widened pulse shapes.

Choosing a high sample rate only gives about 10dB (in case of 40MHz vs 1GHz) increase in SNR gain when using matched filtering while the SNR decrease by the dispersion is sometimes more than that. Therefore choosing a high bandwidth in combination with dispersed pulsars is not beneficial. It is recommended to find a good trade off between the bandwidth and dispersion measure.
Dispersion also gets a more serious issue when the pulsar period gets smaller because it is measured in time delay between the highest and the lowest frequency component. Pulsars with a longer rotational period are less affected by dispersion than pulsars with a shorter rotational period with the same dispersion measure. It is therefor recommended not to chose millisecond pulsars with high dispersion measures.

Folding pulsars should be limited to as low as possible to limit the detection time for the navigation signal. Also to avoid adding too much dispersion when an incorrect folding period is used.

The bottom line is that it's always recommended to do dedispersion of the time series. However it might be avoided by selecting low dispersion pulsars so distortion increase and pulse shapes deterioration are kept minimal.

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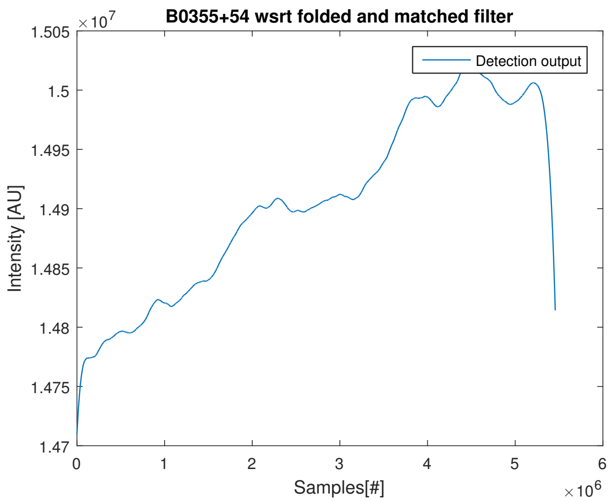
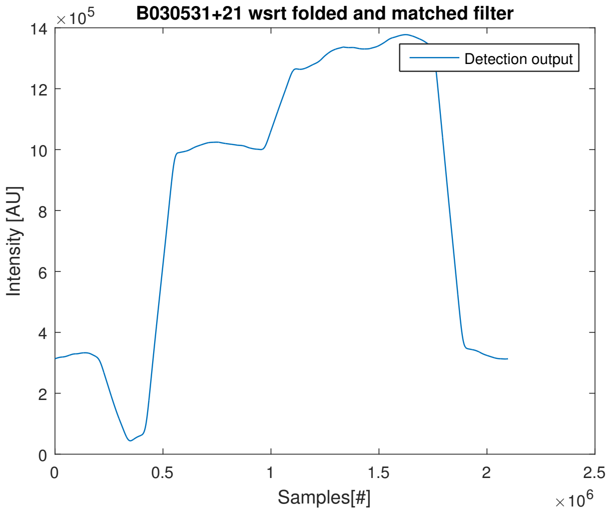
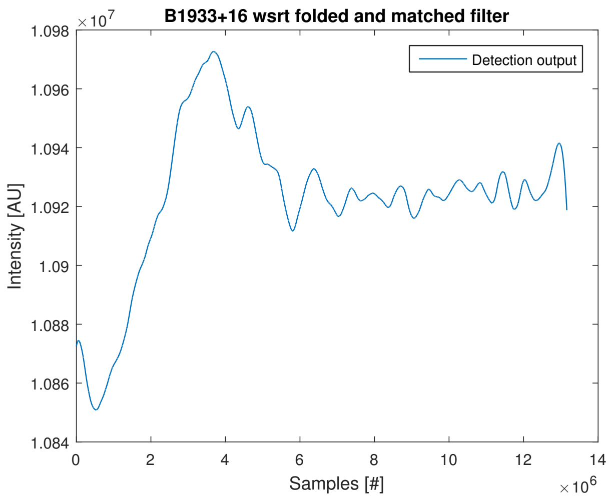


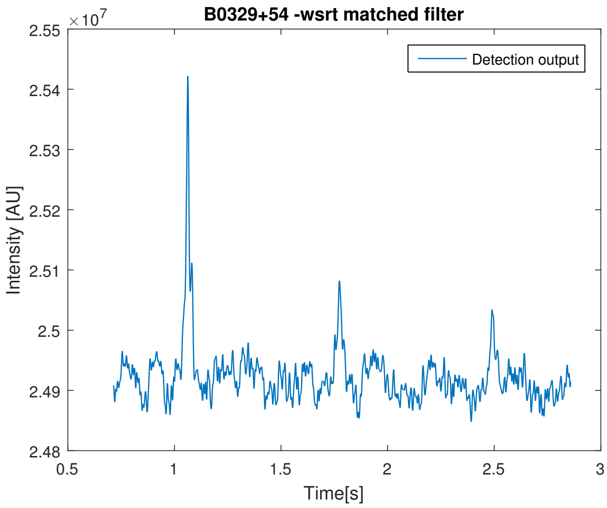
(a) **Pulsar B0355+54 after folding 50 periods and matched filtering**



(b) **Pulsar B0531+21 after folding 100 periods and matched filtering**



(c) **Pulsar B1933+16 after folding 100 periods and matched filtering**



(d) **Pulsar B0329+54 after folding 100 periods and matched filtering**

Fig. 17: **Output of WSRT data after folding and matched filtering for different pulsars**

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