A 350-MHz Drift-Scan Survey for Pulsars with the Green Bank Telescope

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Nederlandse Samenvatting

De 350MHz drift-scan zoektocht naar pulsars met de ‘Green Bank Telescope’ is een samenwerkingsproject waar dit bachelor project onderdeel van uit maakt. In plaats van de telescoop in verschillende richtingen te laten observeren, maakt de drift-scan techniek gebruik van het draaien van de Aarde om de hemel af te zoeken.

Pulsars zijn ronddraaiende neutronensterren die ontstaan na een supernova explosie. Ze worden gedetecteerd via hun radio beams die worden uitgestraald over de magnetische as. Deze as maakt een hoek met de rotatie-as, waardoor de beams van sommige pulsars over de aarde zwiepen, net als het licht van een vuurtoren.

De enorme hoeveelheid data van de telescoop is geanalyseerd met behulp van slimme computer algoritmes en snelle processoren. Een computer script (pipeline) is geschreven om alle onderlinge operaties aan elkaar te koppelen, waardoor de data-analyse sneller verloopt. Het zoeken naar pulsars komt overeen met het zoeken naar periodieke signalen van astronomische oorsprong. Doordat de straling in het interstellaire medium vervormd wordt (verstrooiing en dispersie) door interacties met electronen en stof, komt het signaal ‘uitgesmeerd’ aan. Voor dispersie moet gecorrigeed worden, want het signaal van een pulsar zou anders niet zichtbaar zijn boven de ruis.

De pipeline maakt een grote hoeveelheid pulsar candidaten in de vorm van ‘diagnostic plots’. Een diagnostic plot is een verzameling grafieken en diagrammen die duidelijk moet maken of het om een pulsar gaat of om een Aards signaal. Verreweg de meeste candidaten zijn gerelateerd aan óf Aardse bronnen, zoals de radar van een vliegveld, het stopcontact, en andere Aardse radiobronnen, óf statistische fluctuaties.

Met dit project zijn drie pulsars opnieuw gedecteerd. Dat wil zeggen dat ze al gevonden waren. Dit toont aan dat de zoekmethode goed werkt. Daarnaast zijn twee pulsar candidaten uit de pipeline goed genoeg bevonden om over een paar maanden met de telescoop te verifiëren of het inderdaad nieuwe pulsars zijn. Als het pulsars blijken te zijn, dan gaat het om zogenaamde milliseconde pulsars, wat heel snel ronddraaiende pulsars zijn.

Abstract

The drift-scan survey for pulsars with the Green Bank Telescope at 350MHz is a collaborative project, of which this bachelor project is a part. The data is analyzed using the software package PRESTO, which is installed on a computer cluster at ASTRON. A pipeline script combined the different steps of the data processing and produced a large number of pulsar candidates. The diagnostic plots of the candidates were examined individually and this has resulted in a number of interesting candidates, including three re-detected pulsars. In addition, two millisecond pulsar candidates have been considered worthy of a re-observation. This follow-up observation will hopefully confirm the discovery of two pulsars.

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Chapter 1

Introduction

1.1 This Project

This bachelor project is about a small portion of 1491 hours of observations with the Green Bank Telescope (approximately 1.5 TB of a total of 134 TB of data). By studying the periodicities in the data as well as strong peaks of intensity, it is hoped to find new pulsars. Members of other universities that are part of the project have already detected 25 new pulsars; perhaps one or two new pulsars are added to this total as a result of this bachelor project.

Shortly after the discovery of the neutron in 1932, Baade and Zwicky theorized the possible existence of a neutron star. This theoretical star was predicted to be very dense and extremely small compared to a Sun-like star, with a radius of only about 10km. In 1968, when Jocelyn Bell Burnell was trying to explain the source of her very periodic signal in the data from the Cambridge dipole array, she considered extraterrestrial life sending signals to Earth, white dwarf vibration, and the theoretical neutron star as possible explanations. Because of the strict periodicity of the signal, the source was not believed to come from extraterrestrial life, and the period of approximately one second was too small for white dwarf vibration, leaving her with the groundbreaking discovery of the neutron star.

A neutron star is a final life stage of select massive stars. When it is formed during a supernova, conservation of angular momentum and the asymmetric shape of the supernova cause the star to spin up to a few tens of milliseconds rotation rate. The combination of fast rotation and a very strong, usually misaligned magnetic field, results in a beam of electromagnetic radiation. This is observed on Earth as a periodic pulse as the beam sweeps past our line of sight.

A pulsar can be described as a rotating magnetic dipole, see Figure 1.1. The magnetic field co-rotates with the star. At a certain distance from the magnetic axis the point is reached where the co-rotation speed equals the speed of light. This sets a natural limit to the size of the magnetosphere and defines a so-called “light cylinder”. The radius of the light cylinder is inversely proportional to the beam width, and thus, millisecond pulsars often have a wider pulse profile.

Only a small portion of the neutron star population in our galaxy is detectable, for the following reasons. Firstly, the neutron star has to be a pulsar (or orbiting a pulsar so that due to Doppler shift a companion star can be identified as a neutron star). Secondly, the geometry has to be in such a way that the magnetic axis, which is at an angle with the rotational axis, sweeps over the Earth when the star rotates. In addition, the pulsar has to be bright enough as telescopes are limited in their sensitivity. Obviously, it is impossible to detect all of the likely few tens of thousands of neutron stars in our galaxy, although future, more sensitive telescopes will see an ever increasing fraction of the total population.

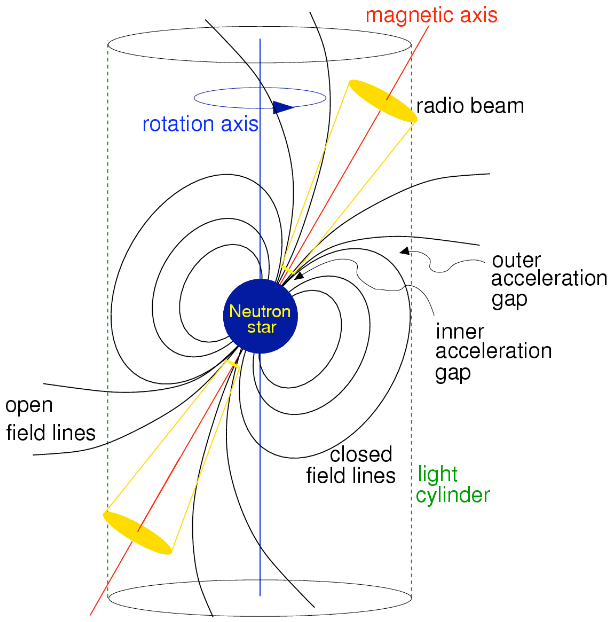


Figure 1.1: *Pulsar model (from Handbook of Pulsar Astronomy by Lorimer and Kramer).*

1.2 Pulsars as Tools for Studying Physics

Since the discovery of the first pulsar, the hunt for these rapidly rotating, highly magnetized neutron stars has begun. So far, the chase has resulted in several Hunting Lodges spread over the world, such as ASTRON, where plans are made and tools designed to successfully catch the most fascinating among the pulsar species: millisecond pulsars and pulsars orbiting another pulsar or a black hole. Pulsar science has become one of the larger research areas in radio astronomy, for numerous reasons, some of which are briefly described in this section.

1.2.1 Gravitational Physics

The Solar System has proved to be a good laboratory for testing General Relativity. However, in the strong field regime, the study of pulsars is one of the few ways of testing theories of gravity. The Nobel Prize in physics in 1993 was awarded to Russel A. Hulse and Joseph H. Taylor Jr. for the discovery of the binary pulsar B1913+16 and the indirect detection of gravitational waves indicated by the decrease in the system's orbital period [Weisberg and Taylor, 2005]. Another exciting example is J0737-3039, a double pulsar system. General Relativity was tested even more precisely in this system [Kramer et al., 2006].

One could imagine directly observing gravitational waves using a number of clocks distributed over a huge volume of space, for example pulsars in our Galaxy. Especially the group of pulsars that have a spin frequency of more than 100Hz, called millisecond pulsars, is interesting for this endeavor, because the time of arrival of the pulses can be measured more accurately, due to the high spin frequency. Pulsar astronomers may well be the first scientists to directly detect gravitational waves. The theoretical possibility of this justifies every attempt and all effort to find more and more millisecond pulsars (e.g. [Manchester et al., 2001]).

1.2.2 Matter at Extreme Density

One of the research areas in pulsar astronomy is studying the equation of state of neutron stars. Unfortunately the equation of state of matter at super nuclear density is not very well determined. If this problem were solved, astronomers would know a lot more about the internal structure of the neutron star, including the structure of its magnetic and electric fields. The density of a neutron star is not at all reachable in laboratories on Earth. Pulsar astronomy is one of the few ways of doing observational research on super dense matter.

Another area of concentration related to dense matter is glitches. The phenomenon of a sudden spin up, a glitch, is still poorly understood theoretically. To successfully explain the glitch, a model of the neutron star structure is necessary. So far the outcome of the debate is a superfluid component in the pulsar where quantized vortices are pinned to the crust.

1.2.3 Direct Environment of the Pulsar

The radio emission process is not at all understood in full detail. However, the beams of the pulsar interact strongly with the pulsar's direct environment; a companion star or maybe orbiting planets, but for some young pulsars also the supernova remnant is influenced by the emission of the pulsar. This provides the possibility to study ionized gases under extreme conditions as an effect of the presence of a pulsar.

Chapter 2

Observations

Observations were taken with the Green Bank Telescope in the summer of 2007, using the drift-scan technique. For an unusually long period of two months the telescope was available for a drift-scan, due to the GBT Azimuth Track Replacement Project. The drift-scan technique means that the telescope itself does not move, but is instead kept stationary and uses the Earth's rotation to search the sky. The surveyed area is shown in the plot. A large portion of the area between declinations of -21° and 26° was covered.

Initially the time resolution of the raw data is on the order of nanoseconds, but to observe in a bandwidth -which is important for many reasons- 1024 frequency channels are created resulting in a bandwidth of 50MHz and a centre frequency of 350MHz. This relates to a frequency resolution of $\sim$48.8kHz per spectral channel. With 350MHz as the centre frequency, it will be impossible to detect pulsars at large distance in the galactic plane, because at such a low observing frequency scattering becomes important. After the transformation to frequency channels, the resulting time resolution is 82 microseconds, which is still more than sufficient. With these parameters the survey is highly sensitive to detect nearby millisecond pulsars.

The method used to transform the time-intensity data to time-intensity-frequency data is the autocorrelation spectrometer. The idea is to multiply the signal with a delayed version of itself to obtain lagged products. The lagged products form the so-called autocorrelation function. The power spectrum can easily be obtained from this function, because it is related as a Fourier transform pair.

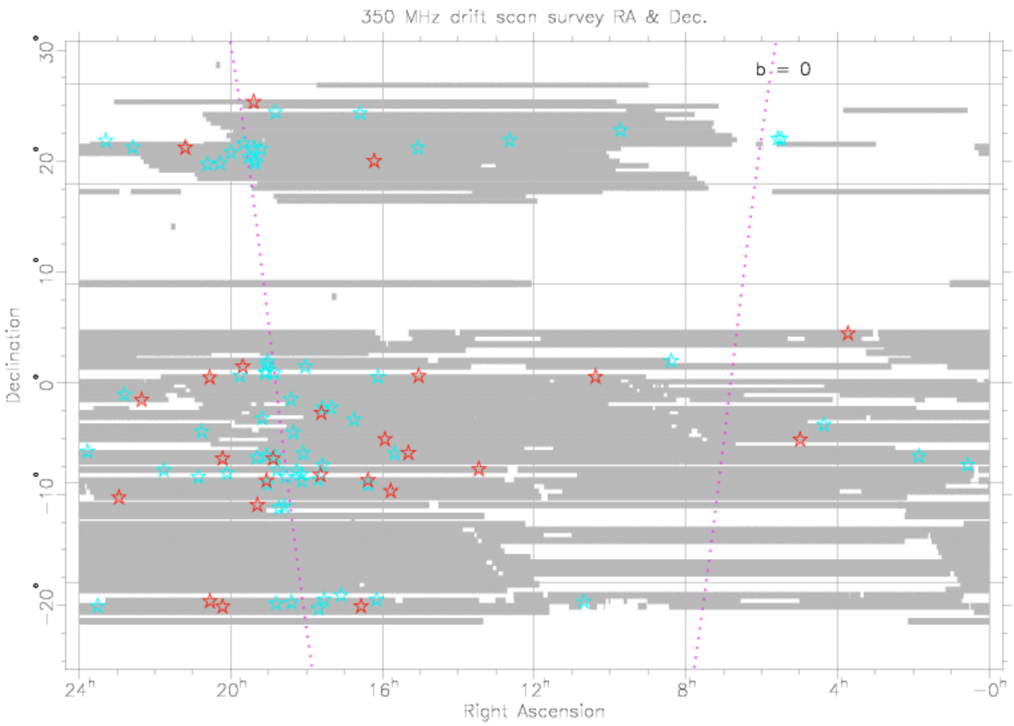


Figure 2.1: *Surveyed area. Grey indicates areas covered by the survey. Red stars represent newly discovered pulsars; blue stars represent re-detected pulsars (courtesy Vlad Kondratiev)*

Chapter 3

Analysis

The radio waves from the pulsar undergo all sorts of transformations when propagating through the interstellar medium, such as scintillation, scattering and Faraday rotation. However, the most important effect to take into account when searching for pulsars is dispersion. Dispersion is the effect that the speed of light in the interstellar medium is frequency dependent: low frequency waves are delayed more than high frequency waves. This section will discuss the method for searching for a dispersed, periodic signal.

3.1 The concept of dispersion

The following derivation of the dispersive delay is in essence taken from and similar to paragraph 4.1.1 of the Handbook of Pulsar Astronomy [Lorimer and Kramer, 2005]. Consider an electromagnetic wave propagating through the interstellar medium. To determine the time delay, the group velocity $v_g = c\mu$ is required, where c is the speed of light and μ is the refractive index, given by:

$$\mu = \sqrt{1 - \left(\frac{f_p}{f}\right)^2} \tag{3.1}$$

where f_p is the plasma frequency ($= \sqrt{\frac{e^2 n_e}{\pi m_e}} \sim 8.5\text{kHz} \sqrt{n_e}\ \text{cm}^{3/2}$). Noting that $f_p \ll f$, (3.1) can be written as

$$\mu \approx \frac{1}{1 + \frac{f_p^2}{2f^2}} \tag{3.2}$$

The time delay t is the difference between the time it takes for a wave traveling at the speed of light to reach the observer and the time of a wave traveling at the group velocity:

$$t = \left(\int_0^d \frac{\mathrm{d}l}{v_g} \right) - \frac{d}{c} \tag{3.3}$$

Combining equations (3.3) and (3.2) gives the desired result

$$t = \frac{1}{c} \int_0^d \left[1 + \frac{f_p^2}{2f^2} \right] \mathrm{d}l - \frac{d}{c} = \mathcal{D} \times \frac{\mathrm{DM}}{f^2} \tag{3.4}$$

where $\mathcal{D}$ is the dispersion constant ($\equiv \frac{e^2}{2\pi m_e c}$) and DM the dispersion measure

$$\mathrm{DM} = \int_0^d n_e \mathrm{d}l \tag{3.5}$$

It is clear from (3.4) that the time delay, caused by interactions with free electrons between the source and the observer, is frequency dependent, see Figure 3.1.

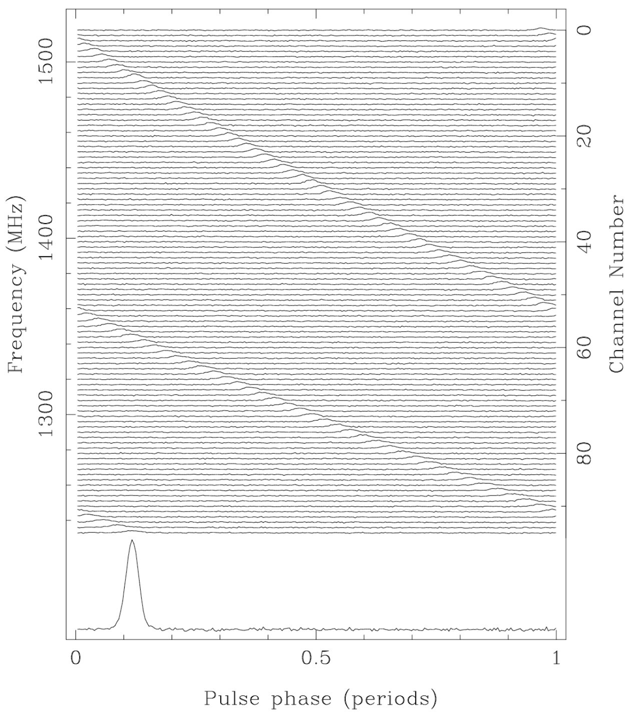


Figure 3.1: *Dispersed pulses. The bottom pulse profile is obtained by de-dispersing and somming the individual pulses (from the Handbook of Pulsar Astronomy, by Lorimer & Kramer).*

Although correction for dispersion greatly increases the computational burden of searching for pulsars, a great deal can be learned from it as well. When the position of different sources is independently determined from the DM, it gives the electron density in different directions and thus provides information on the matter distribution of the Galaxy. Although the electron number density strongly fluctuates throughout the Galaxy, a typical value is 0.03 cm^{-3}. This number can give a first estimate of the distance in parsecs of the newly discovered pulsar when dividing the DM by 0.03, provided the DM is given in cm^{-3} pc. Using a model for matter distribution in our Galaxy, such as "NE2001", one can even more accurately determine the position in different directions [Cordes and Lazio, 2002].

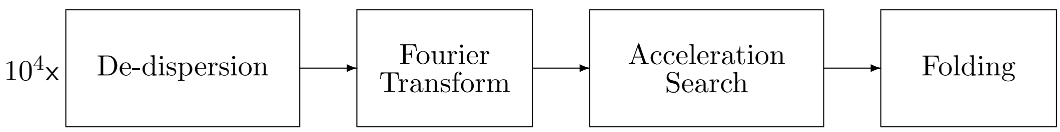
3.2 Data processing

Only a small group of pulsars is discovered by their individual pulses and this does not include millisecond pulsars. The majority of the pulsars are discovered by their highly periodic nature. However, because some pulsars only pulsate occasionally, it should be noted that not all pulsars can be found using the method described below.

Pulsars are weak sources, therefore pulsar surveys require sensitive telescopes and clever computer algorithms. ASTRON has a computer cluster, called DROP, which consists of seven 8-core computers. The software package PRESTO [Ransom, 2001], which is designed for pulsar surveys, is installed on DROP. Because of the large amount of data, a pipeline was written by other members of the collaboration to automate the data analysis. The input of the pipeline is the frequency-time-intensity data from the telescope; the output are the so-called diagnostic plots of potential pulsar candidates, which are examined with the human eye (an example of which is given in Figure 3.3).

3.2.1 Pipeline

A schematic of the pipeline is shown in the diagram. Apart from bookkeeping operations, such as creating arrays, reading out data, making directories, and deleting data, the fundamental steps of the pipeline can be explained easily. It should be noted that the pipeline is highly parallelizable, since this is not suggested by the flow diagram.



The first operation uses the PRESTO program “prepsubband”. This corrects the data for a range of dispersion measures from 0 to 1000 cm^{-3} pc with a minimum step size of 0.03 cm^{-3} pc. The output is a large number ($\sim 10^4$) of de-dispersed time series. This has to be done, since the DM is not known a priori. Each DM trial needs to be searched individually.

There are two ways of searching for periodic signals in the de-dispersed time series. The first makes use of the fast folding algorithm. Folding is the addition of pulses to make the accumulative pulse visible above the noise. To do this, the period of the signal is required. However, if this is yet unknown, one method of searching for pulsars is to fold the de-dispersed time series using many trial periods. The next step would be to plot the S/N as a function of trial period. If a peak occurs in this plot, this may well be caused by a pulsar. Unfortunately, to find millisecond pulsars, this method would be computationally too expensive. A better method for finding millisecond pulsars is to perform a fast Fourier transform on the de-dispersed time series and search the power spectra for candidates. The pipeline's next step is indeed the PRESTO program “realfft”, which creates for each de-dispersed time series a power spectrum.

Most millisecond pulsars are in binaries, which affects the pulsar's signal in the power spectrum. This significantly washes out the signal in the power spectrum, but can partly be overcome by searching for shapes in the power spectra associated with period derivatives due to the Doppler effect. The next step of the pipeline is therefore an acceleration search which performs such a search over all power spectra. The PRESTO program “accelsearch” is used for this purpose and is sensitive to both peaks and Doppler shifted signals. The output is a list of candidates per power spectrum with information such as S/N, period and period derivative. Candidates only visible at just one or a few discrete DMs are not considered further, because a pulsar is expected to be visible in a range of DMs. This DM test decreases the number of pulsar candidates significantly.

The final operation of the pipeline is folding. Each candidate that passes the DM test will be folded using the information from the acceleration search, such as period, period derivative, and DM. The folding program “prepfold” has the same input data as “prepsubband”, the first operation. First the data is de-dispersed for a range of DMs, then synchronously averaged at a range of trial periods and period derivatives. The best DM and combination of period and period derivative with respect to reduced χ^2 will be used to make two integrated pulse profiles. The motivation for creating two integrated pulse profiles is to always obtain at least one continuous pulse, see Figure 3.2.

The plot with the two integrated pulse profiles together with a number of other informative plots are combined into a so-called diagnostic plot, see Figure 3.3. For each candidate, a diagnostic plot is created and stored in a directory. This is the end of the pipeline.

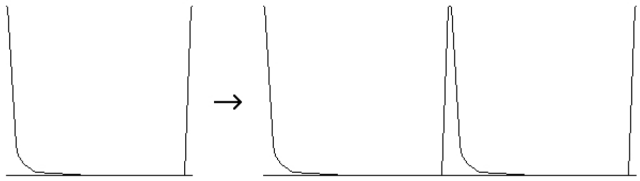


Figure 3.2: *The reason to repeat the fold twice.*

3.2.2 Examining the output of the pipeline: diagnostic plots

An important part of the analysis is the examination of the diagnostic plots, which are produced for the best candidates. Although there are some clever ways to handle the large amount of candidates [Keith et al., 2009], for a first pulsar survey project it is probably better to study the large number of diagnostic plots before using clever tricks. There is no better way to get an idea of the whole data-set than to go through a large amount of candidates. In this paragraph the figures of the diagnostic plot are discussed using the re-detected pulsar PSRJ1841+0912 as an example, see Figure 3.3.

The plot at the top left of Figure 3.3 should show two clear pulses in the case of a pulsar. The one component, sharp bright pulses of PSRJ1841+0912 are typical. Especially the non-millisecond pulsars often have a similar integrated pulse profile. Nevertheless, multiple-component pulse profiles have been found as well. Below the two pulse profiles, the pulse intensity is shown as a function of rotational phase and time. Apart from possible pulse nulling and eclipses, there should be two continuous straight lines in this diagram. A slightly different folding period would result in two skew lines and a lower S/N of the cumulative pulse profile. If a pulsar is observed long enough and is part of binary system, a sine (or part of it) can be seen.

The plot in the middle shows the intensity as a function of rotational phase and frequency. The frequency band is divided into 32 sub-bands. Each sub-band consists of (1024/32=) 32 frequency channels. At first, the data is de-dispersed per sub-band, and, secondly, the sub-bands are de-dispersed with respect to each other. This is done to speed up the creation of many thousands of trial time series with different DMs. In the case of a pulsar, this results in two continuous, vertical lines, since the pulsar emits radiation over the whole bandwidth. Below this diagram, a graph of the DM as a function of reduced χ^2 can be seen. An astronomical source is expected to show a peak in this graph, in this case at a DM of 48.5 cm^{-3} pc. This is natural; when folding at a different DM, the pulse is broadened and the signal intensity is reduced, depending on how greatly this incorrect DM differs from the true DM.

To the right are the graphs showing the search over the period and period derivative. The period as a function of reduced χ^2 and the period derivative as a function of reduced

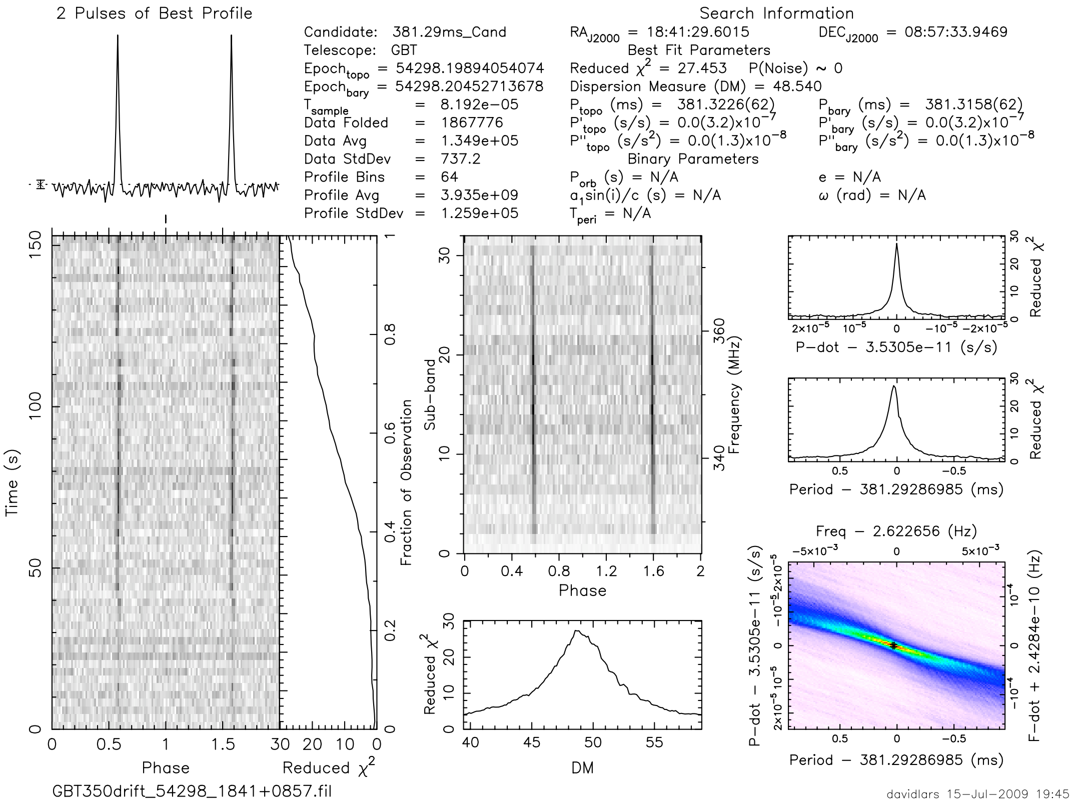


Figure 3.3: *Re-detected pulsar PSRJ1841+0912.*

χ^2 should both show a clear peak, because a pulsar has simply one combination of both. When folding at slightly different values, S/N reduces significantly. The result of the search for the best combination of these parameters with respect to signal strength is shown in the colored plot, where the colors indicate how strong the signal is for all combinations in a certain range. In the case of a pulsar, a well defined island should be visible here.

3.3 Radio Frequency Interference (RFI)

In analyzing the diagnostic plots, a few difficulties may arise. RFI is by far the most important concern. Despite the RFI filters created for each time series, most candidates are related to terrestrial sources, instead of astronomical ones.

Communication systems, such as the nearby airport radar, are often present in the data.

Fortunately, many such signals are only visible at DMs of 0 cm^{-3} pc or close to 0 cm^{-3} pc and can be filtered out easily. However, the mains AC frequency (60Hz in the US) will often be visible over a wide range of DMs. Sometimes a mains AC signal is pulsar-like, which makes it difficult to filter out a real pulsar with a spin frequency of 60Hz (or some simple integer fraction multiple of 60Hz). Also, sources at the observatory can interfere with the data. For example, computers are known to radiate in the radio spectrum. Electric storms can also badly disturb the data.

Despite the usually striking appearance of a diagnostic plot related to a pulsar, it is better to not really know what to expect when beginning with examining the plots. The interesting candidates are the ones that are somehow different from the rest. In what way candidates can be different is not defined beforehand. Therefore, the person analyzing the diagnostic plots should not necessarily be searching only for certain shapes and characteristics. Of course, there are many restrictions to astronomical signals (as discussed in 3.2.1). However, pulsars come in great diversity and it is wise to realize the extent of this when analyzing the plots.

Chapter 4

Results

For each time series of 150 seconds the pipeline produced ∼20 diagnostic plots, which are predominantly due to RFI and statistical fluctuations. There are a few exceptions, which form the results of this project and can be divided into re-detected pulsars, “A” candidates (candidates worthy of re-observation), and “B” candidates (slightly less interesting candidates).

4.1 Re-detected pulsars

The re-detection of pulsars, see Figure 4.1 was an important part of this project, because it proves that the method is working. In addition, since they were all found without knowing they were in the data, it gave added confidence that new pulsars would not be missed, although this is never totally beyond doubt.

The first re-detected pulsar was PSRJ1543+0929 and appeared faintly in this survey. The faintness is not an intrinsic property of the pulsar; the pulsar was simply pulsating at the edge of the field of view. The same is true for PSRJ1956+0838. By far the brightest re-detection was PSRJ1841+0912.

4.2 A candidates

Two candidates have been selected to this group and will be re-observed. The diagnostic plots are shown in Figure 4.2 and Figure 4.3.

The 8.03ms candidate is a weak signal, but the graphs in the diagnostic plot show similar characteristics compared to real pulsars. The pulse is quite clear above the noise. In the phase-time diagram and the phase-frequency diagram two straight lines are clearly visible. In the phase-time diagram, the pulsar seems weaker during the first tens of

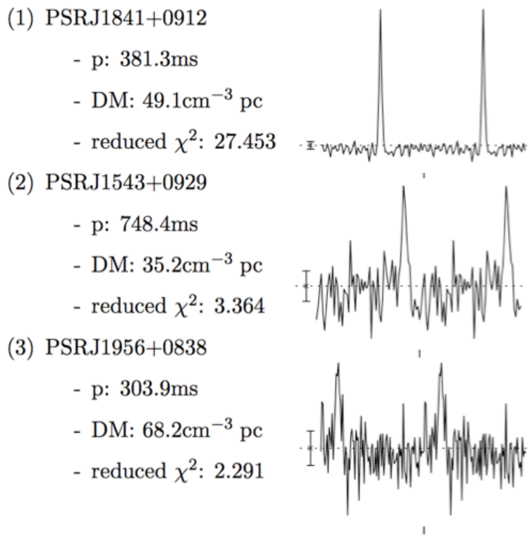


Figure 4.1: *Re-detected pulsars. Two integrated pulse profiles are shown per pulsar as they appear in the data.*

seconds, which can also be seen from the increase in the adjacent plot of reduced χ^2 as a function of time. If this is a pulsar, maybe it was not in the field of view to be easily visible. The graphs of DM, period, and period derivative as a function of reduced χ^2 all show a peak, although they are not very convincing. This is probably a result of the faintness of the signal. The best DM found is 43.8 cm^{-3} pc, the best period found is 8.033430(15)ms, and the best period derivative found is -2.2(7.5)e-10 s/s, consistent with zero period derivative, and, thus, unclear whether this candidate would be in a binary system or not. Despite the weakness of the signal, the overall appearance of this diagnostic plot is interesting, and stands out compared with the many thousands of candidates which were examined by eye.

Compared to the 8.03ms candidate, the 1.72ms candidate is slightly stronger. The three component pulse-shape is very different from all the other candidates, which makes this candidate very interesting. The three pulses seem glued together. An explanation may be DM smearing (explained in section 4.3), whose effect can be decreased by observing at a higher frequency or with a higher frequency resolution (more channels across the bandwidth). The three component pulse profile can be explained with different pulse beam models (see for example [Rankin, 1993] for a discussion of profiles assuming the nested cone model). Again, two straight lines are visible in both phase diagrams. Reduced χ^2 grows steadily with integration time. The DM peaks at a well defined value of 42.3 cm^{-3} pc, the period at 1.7264845(15)ms, and the period derivative at -2.041(74)e-9, which indicates if real this pulsar would be in a compact binary system. The island in the period-period derivative diagram is very clear. Although the independent plots in the diagnostic plot are all quite good, the candidate is especially interesting for the fact that the pulse shape differs strongly from all the other candidates which were observed.

4.3 B candidates

The 33 candidates placed in this category are not considered convincing enough to deserve a re-observation. For example, the S/N is too low, the plot of DM as a function of reduced χ^2 does not show a clear peak, or the lines in the phase-time diagram are not straight enough, indicating that the source is not strictly periodic, as is often the case with RFI. However, the main problem with B candidates is that they show a peak in the pulse profile that is narrower than the time resolution indicated by the horizontal bar below the pulse profile; see for example Figure 4.4. This effective time resolution depends on how well dispersion was corrected for, which is in turn dependent on the number of frequency channels over the 50MHz bandwidth. The frequency channels each have a finite bandwidth of 48.8kHz in which dispersion cannot be corrected. This causes "DM smearing" of the signal. Due to the quadratic frequency dependence of dispersive delay, this effect becomes less when observing at a higher frequency, because the dispersive delay would be smaller.

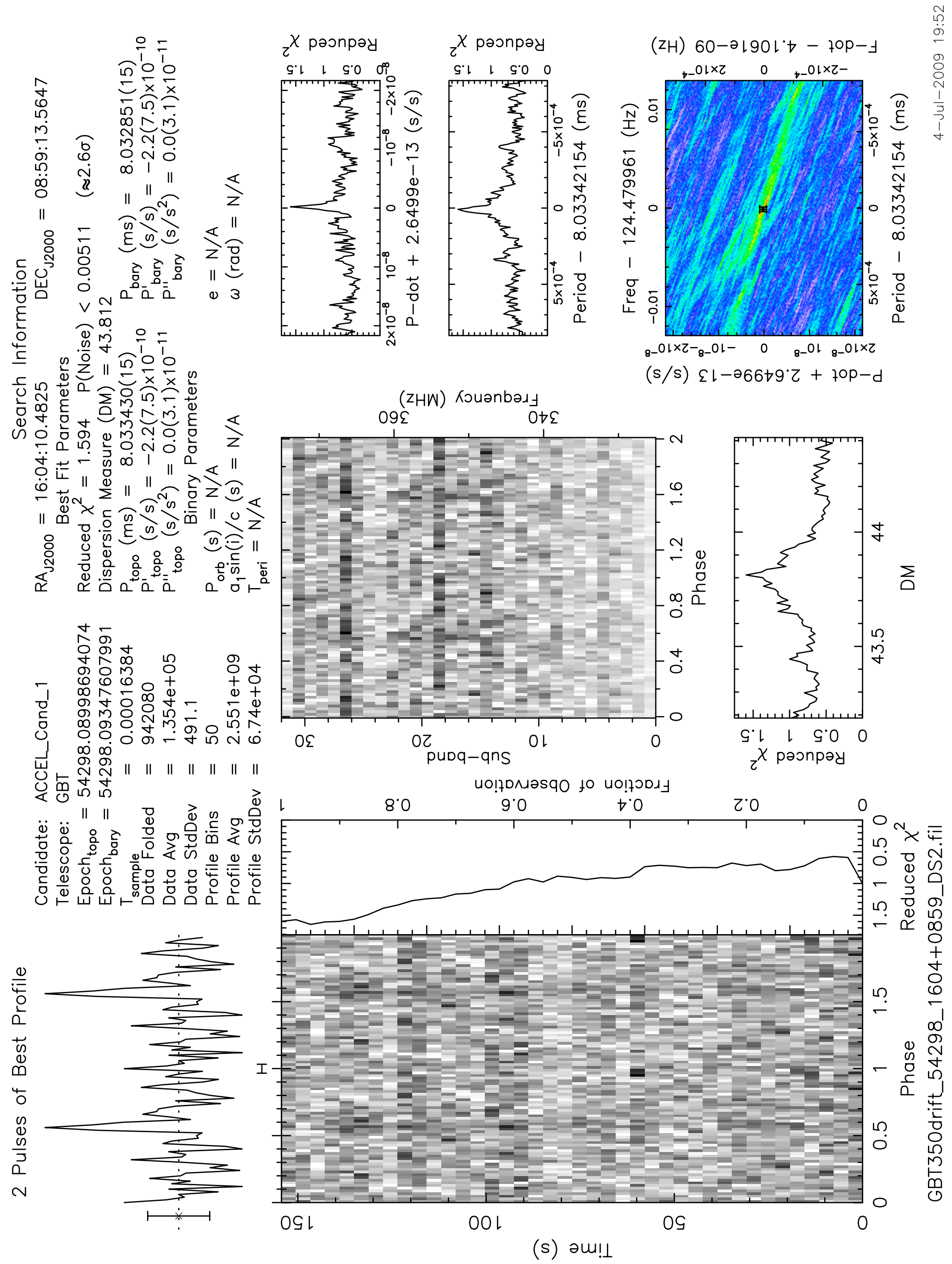


Figure 4.2: *8.03ms candidate.*

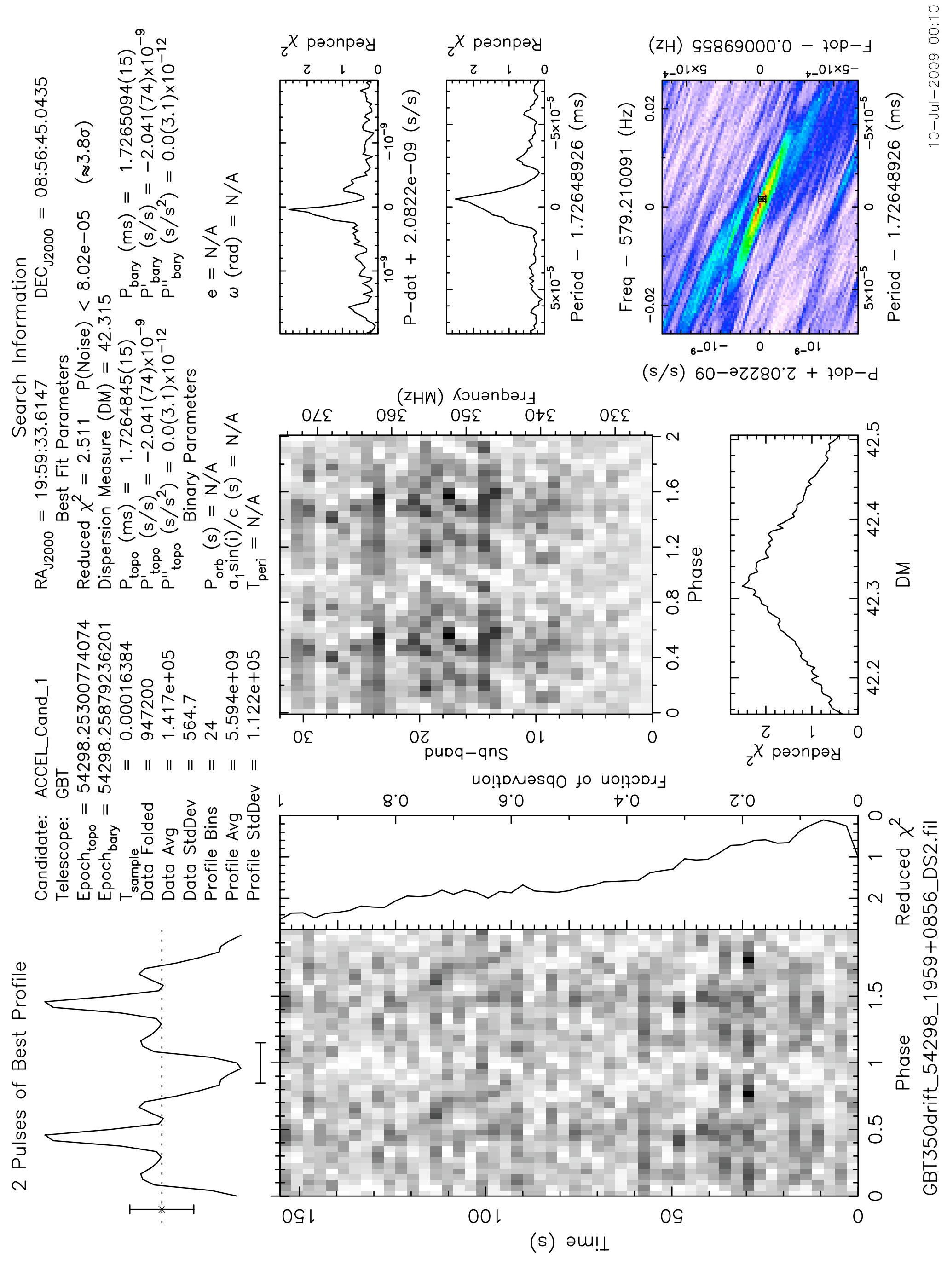


Figure 4.3: *1.79ms candidate.*

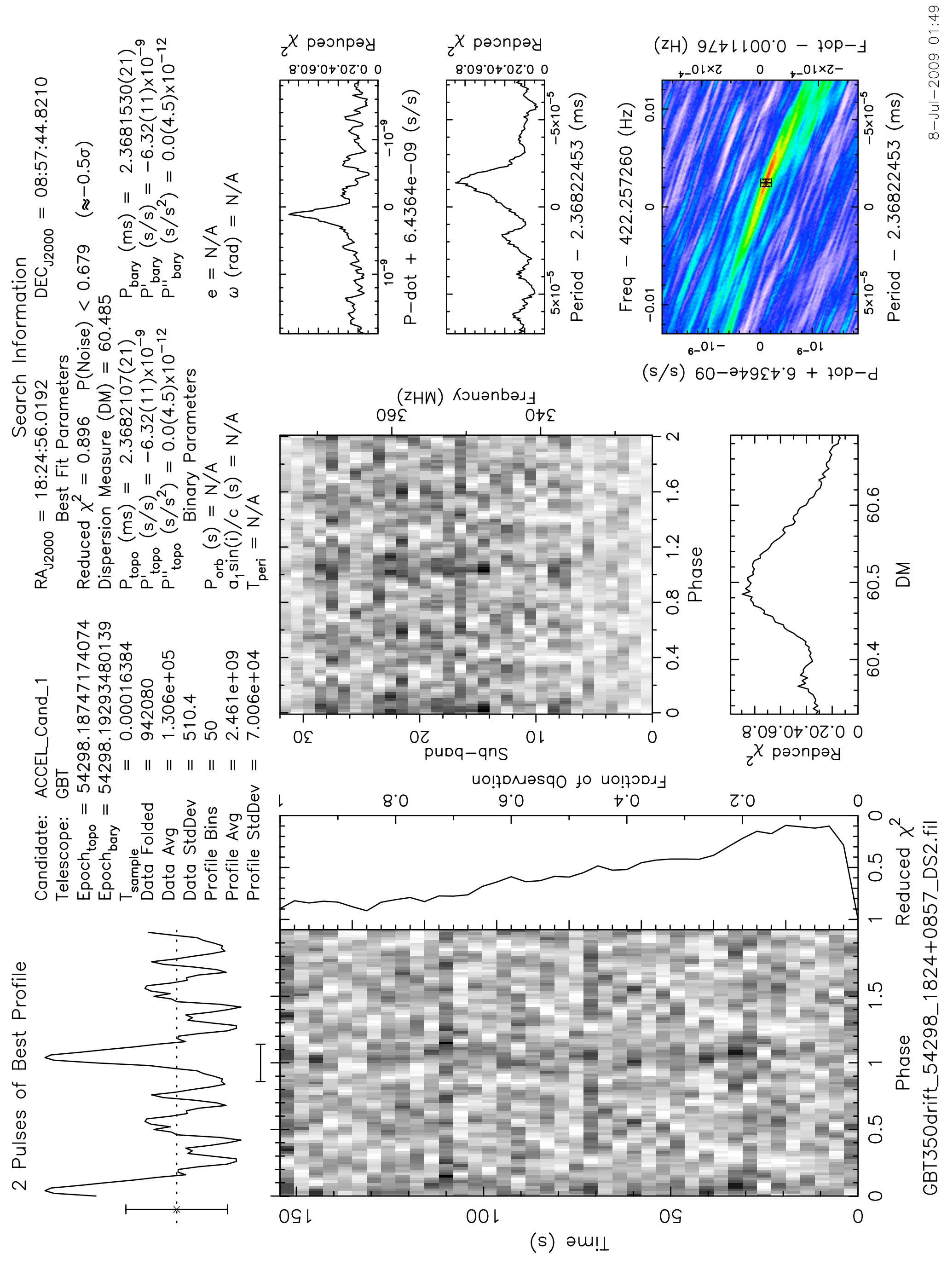


Figure 4.4: *A typical B candidate.*

Chapter 5

Discussion

The re-detected pulsars were important for this bachelor project. It is interesting to note that they were not included in the list of 459 pulsars that are in the surveyed area. On the other hand, PSRJ1947+0915 could have been detected considering the coordinates, but was not. This pulsar has a DM of 94 cm^{-3} pc, which is quite high for this survey. This DM implies a large distance (or at least a large amount of matter over the line of sight) and thus the signal may be scattered significantly at 350MHz. It is also possible that the radiation of the pulsar is equally strong at all frequencies, instead of stronger at lower frequencies, which is more common. Among the other re-detected pulsars thus far, a few have a considerably higher DM; B1829-08 has a DM of 301 cm^{-3} pc. Therefore, the intrinsic properties of the pulsar in combination with the search method and parameters determine whether or not the pulsar can be re-detected.

The average DM of the 25 newly discovered pulsars in the survey is 38.6 cm^{-3} pc, the largest being 67 cm^{-3} pc. The two A candidates both have a DM very close to the average (43.8 and 42.3 cm^{-3} pc). In a few months a re-observation should make clear whether or not the signals represent pulsars. At this stage the signals are too weak to be certain. If a candidate appears to be a pulsar, it will be observed on a monthly basis to determine the position precisely. This is especially important since both candidates may be millisecond pulsars and could therefore contribute to the Parkes Pulsar Timing Array [Manchester et al., 2001]. In addition, the properties of a possible companion can be studied.

Although the B candidates are not satisfying enough to be A candidates, they represent an important sub-group between clearly RFI and A candidates. It is this group that makes the analysis of the diagnostic plots difficult, because it is difficult to trace back the origins of the signals. However, when considering the high resolution of the data in combination with the modification of the data due to de-dispersion, it is statistically possible that a lot of pulsar-like candidates will appear that are not really pulsars. As the pipeline continues producing candidates it becomes more and more interesting to use techniques to sort candidates (see for example [Keith et al., 2009]), that is, to make the process more automated, and less subjective.

With 25 new pulsar discoveries, the drift-scan proves there are still many pulsars waiting for detection. This motivates technological advances to increase the sensitivity of future pulsar surveys. In addition, since drift-scans with different observing parameters are sensitive to different pulsars, those surveys are likely to detect pulsars as well. A good example of a project where technological advances and different observing parameters are combined is LOFAR, which is sensitive to a mostly unexplored spectral window [Hessels et al., 2009].

Chapter 6

Conclusion

RFI and statistical noise come in great diversity, which makes it difficult to distinguish between astronomical and terrestrial signals. Despite this difficulty, three pulsars have been re-detected as the result of analyzing $\sim$1.5 TB of data of a drift-scan with the Green Bank Telescope. In addition, two pulsar candidates are targets for follow-up observations. If these candidates are pulsars, they belong to the group of millisecond pulsars. Considering the growing number of candidates it becomes more interesting to use automated techniques for sorting pulsar candidates.

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