

Searches for Radio Transients using the Long Wavelength Array

Jr-Wei Tsai

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John Simonetti, Chair
Nahum Arav
Michael Kavic
Leo Piilonen
Mark Pitt
Uwe Täuber

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Abstract

We used the first station of the Long Wavelength Array (LWA) to observe giant pulses (GPs) from pulsars and search for other radio transients. Using the LWA with a bandwidth of 16 MHz at 39 MHz, we made a 24-hour observation of pulsar radio pulses from PSR B0950+08. The average pulse flux density and pulse width (dominated by “normal” pulses) are consistent with previous studies by others. Using techniques we developed for searching for radio transients, in this observation we detected 119 giant pulses (with signal-to-noise ratios 10 times larger than for the mean pulse). The giant pulses have a narrower temporal width (17.8 ms, on average) than the mean pulse (30.5 ms). Giant pulses occur at a rate of about 5.0 per hour, or 0.035% of the total number of pulse periods. The strength and rate of giant pulses is less than observed by others at ~ 100 MHz. The probability distribution of the cumulative pulse strength is a power law, but deviates from the Gaussian distribution of normal pulses. These results suggest PSR B0950+08 produces less frequent and weaker giant pulses at 39 MHz than at 100 MHz. We detected no other transients in this observation within a dispersion measure (DM) range from 1 to 90 pc cm^{-3} .

Furthermore, we conducted observations of giant pulses from PSR B0950+08 in a separate set of observations of 12 hours made simultaneously at 42 and 74 MHz. In these observations we detected a total of 275 at 42 MHz and a total of 465 giant pulses at 74 MHz. Giant pulses with double-peak temporal structure have a shorter peak-to-peak separation compared to the average pulse. Once again, PSR B0950+08 appears to produce less frequent and weaker giant pulses than reported at 100 MHz. Giant pulses are identified with signal-to-noise ratios 10 times larger than for the mean pulse, and the probability distribution of the cumulative pulse strength is a power law, but deviate from the Gaussian distribution of normal pulses, for both frequencies. There were only 128 giant pulses detected simultaneously at 42 and 74 MHz, which implies that more than half of them are narrow-band radio pulses. Using these observations we analyzed the effect of scattering due to the interstellar medium on pulses with signal-to-noise ratio > 7 and the average pulse using a CLEAN-based algorithm, assuming a thin-screen scattering model. The scatter-broadening time constant $\tau \propto \nu^\alpha$, where ν is the observing frequency. The resulting α as calculated from pulses with signal-to-noise ratio > 7 and for the average pulses is found to be $\alpha = -1.45 \pm 0.14$ and -0.14 ± 0.03 , respectively. These results indicate differences along the line of sight from a Kolmogorov spectrum for electron density fluctuations. We calculated the altitude of the emission region for the pulsar using the dipolar magnetic field model. We found a similar magnitude for the emission region altitudes of normal and giant pulses. We detected no other transient pulses

in a wide DM range from 1 to 4990 pc cm⁻³.

We also conducted another a 12-hour observational study of PSR B0031–07 at 38 and 74 MHz, simultaneously. Giant pulses were identified with flux densities of a factor of ≥ 90 and ≥ 80 times that of an average pulse, at 38 and 74 MHz. The cumulative pulse strength distribution follows a power law, and has a much more gradual slope than a Gaussian distribution for the normal pulses. We found 158 of the observed pulses at 38 MHz qualified as giant pulses. At 74 MHz a total of 221 of the observed pulses were giant pulses. Only 12 giant pulses were detected within the same pulse period at both 38 and 74 MHz, meaning that the majority of them are narrow-band radio pulses. No other radio transients were detected within a DM range 1 to 4990 pc cm⁻³.

We used the same data processing pipeline for observations of pulsar GPs to search within the pulsar observations for fast radio bursts (FRBs). We did not detect any non-pulsar signals with signal-to-noise ratio larger than 10. When the radio transient signals propagate through the interstellar medium, they are affected by propagation effects such as dispersion and scattering. Scattering may limit the detectability of radio transients.

By examination of archived pulsar profiles, we investigated the impact of scattering on observed pulses. We utilized a CLEAN-based strategy to decide the scatter-broadening time, τ , under both the thin-screen and uniform-medium scattering models and to determine the scatter-broadening time frequency scaling index, α , where $\tau \propto \nu^\alpha$. In most cases the scattering tail was not large compared to the pulse width at half maximum. Still, we deconvolved 1342 pulse profiles from 347 pulsars assuming a Kolmogorov spectrum of the interstellar medium turbulence. For a subset of 21 pulsars the scattering-broadening tails were sufficiently long to be estimated at the lowest frequencies. Since the scatter-broadening times were only determined distinctly for the subset of pulsars at the lowest observed frequency, we were restricted to utilizing upper limits on scatter-broadening times at higher frequencies for the assessment of the scatter-broadening-time frequency dependence. We include three new direct scatter-broadening time measurements at low frequencies and they are consistent with previous studies which were scaled from higher frequencies. Our findings are consistent with a relationship between the DM and scatter-broadening time which can range over more than two orders of magnitude in DM. One of the potential reasons that we did not detect FRBs is that transients may be highly scatter-broadened at low frequencies for high DM values.

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Chapter 1

Introduction

Parts of this chapter are paraphrased or taken from [1–4]. For these papers the author of this thesis wrote the code for data collection, data processing, analysis, and figures. He wrote the first drafts, then collected comments from the coauthors, then revised the papers. Lastly, he used the referee reviews to finalize the published version of the papers.

Astrophysics is built first and foremost on observations. Before the convenience of the electric light bulb, light pollution at night was not severe and people could easily make “naked eye” observations of the splendors of the night sky in the visible part of the electromagnetic spectrum. The records of naked eye observations of stars can be traced back to a very long time ago. Regular observations of changes in location or intensity of astrophysical objects became a means of fortune telling, time keeping, and the establishment of a calendar.

Isaac Newton (1642–1726) said [5]

I do not know what I may appear to the world, but to myself I seem to have been only like a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me.

And so it is for the astronomer. Mysteries can be found up ahead, but not unless we have the means to observe them. Two individuals made it possible to “see” more than visible light when observing the universe. William Herschel (1738–1822) discovered the invisible infrared with a thermometer when studying the spectrum of sunlight [6]. Karl G. Jansky detected the first cosmic radio emission coming from the center of the Milky Way Galaxy while investigating background noise interfering with trans-Atlantic radio telephone calls for Bell Telephone [7]. Just like for recent discoveries of pulsars and the first fast radio bursts (FRBs), these were major discoveries were made by accident. There are countless discoveries waiting

for us. All we have to do is simply look up. This is why I find astrophysics so attractive.

When we began research on detecting transients such as FRBs, only a handful of FRBs had been discovered. And most of FRB detections came from the same telescope: the Parkes Observatory radio telescope in Australia. Some of the observations were disputed and thought to be due to terrestrial phenomena, earning the nickname “perlytons.” These perlytons were then identified with the use of microwave ovens at the Parkes Observatory [8]! But FRBs are now acknowledged to be a cosmic phenomenon needing much more study to understand. To further investigate the nature of FRBs, using the the Long Wavelength Array (LWA), we first designed and tested a data-reduction pipeline that is capable of catching giant pulses from pulsars, which have some similarities to FRBs but are produced by known physical objects, pulsars, at random moments, but at a substantial rate. Much of this thesis is devoted to the details of that pipeline and its testing through observations of pulsar giant pulses.

We had a prime opportunity to study FRBs and giant pulses at low frequencies using a newly commissioned and suitable radio telescope (LWA), which was built through a collaboration involving Virginia Tech, plus a relatively new supercomputing cluster available at Virginia Tech (see Chapter 3), which could be used to analyze the huge raw data files produced by our observations using the LWA. The high-resolution observations in both the frequency and the temporal domains make it difficult to process data in a reasonable time if not for using a supercomputing cluster. The bottleneck in data processing is dedispersion, which involves loading a $\sim$ terabyte (TB) of dynamic spectra (spectrograms) into memory, displacing in time the frequency channels according to a trial dispersion delay (determined by a trial dispersion measure), then summing across frequencies to produce a time series. The process is repeated for each dispersion measure trial. For 4 hours of observation, using 72 parallel threads with 4TB of memory and on 100,000 different dispersion measure trials, it takes about 2 days to complete the job. After we have a dedispersed time series, potential signals will hopefully have a high signal-to-noise ratio (SNR), but so does residual radio frequency interference. Residual radio frequency interference is usually narrow band and of short duration, while astrophysical signals usually have a spectral dependence across the frequency band. We must examine the spectrum of those candidates from time series to filter out false-positive detections. We hope in the future to adopt machine learning to accelerate the process and reduce errors.

1.1 Pulsars

A pulsar is one possible endpoint to the life cycle of stars. When interstellar gas and dust condenses gravitationally to form a star of total mass larger than about 0.08 solar masses ($0.08M_{\odot}$), thermonuclear reactions forming helium from hydrogen can start in the star’s

core and enable a star to remain relatively stable mechanically. From there the general understanding of the star's evolution is well established and summarized here (see [9], for example). The initial stage of hydrogen “burning” for a star on the so-called main sequence lasts for a finite amount of time, until hydrogen is significantly depleted in the stellar core. More massive stars have a shorter main sequence lifetime. A star like our Sun will evolve off the main sequence in about 10^{10} years. In post-main-sequence evolution, the stellar core shrinks in size while its temperature increases as larger and larger nuclei are produced by nuclear reactions. Stars of mass $\gtrsim 10M_{\odot}$ lead, ultimately, to reactions producing iron-56 ($^{56}_{26}\text{Fe}$) in their cores at which point the core becomes unstable to collapse with the release of a large amount of gravitational potential energy (much in the form of neutrinos) leading to the explosive outward propulsion of the outer layers of the star in a core-collapse supernova explosion. If the remaining mass of the core is greater than the Chandrasekhar limit of $1.4M_{\odot}$ (which it will be for these supernova end products) and less than about $3M_{\odot}$, the Tolman-Oppenheimer-Volkoff limit, the gravitational pressure inside the object is balanced by the Fermi pressure originating in Pauli exclusion, producing a “degenerate” pressure from the free neutrons inside the object, resulting in a gravitationally stable object, a neutron star. For cores less massive than the Chandrasekhar limit (and produced by less explosive events than a supernova) the final object is a white dwarf made stable by electron degeneracy. For objects of mass greater than about $3M_{\odot}$ the core collapse cannot be stopped and the product is expected to be a stellar-mass black hole. It is thought that most neutron stars are highly magnetized and rotate at a high rate, due to conservation of magnetic flux and angular momentum during the core collapse. A quickly rotating, highly magnetized neutron star has the potential to be observed as a pulsar.

The first pulsar was discovered in 1967 by Jocelyn Bell Burnell [10] while she was observing radio galaxies looking for scintillation (varying brightness) due to radio wave scattering in the ionized interplanetary medium. The pulse production mechanism for pulsars is still an open subject of study but it is generally thought that the observed pulsing is the result of the rotation of the pulsar and a misalignment of the rotation axis and magnetic axis of the (approximately) dipole magnetic field of the neutron star [11]. The radiation is preferentially emitted in a cone aligned to the magnetic axis. We observe a pulse when the beam of radiation sweeps the line of sight, like a lighthouse. Indeed, this is called the “lighthouse model.” We only know of some tens of pulsars out of ~ 2000 known pulsars which emit giant pulses. The emission mechanics for the regular pulses is not well understood; giant pulses are less understood.

The favored model for the regular pulse emission mechanism is a rotating neutron star with a magnetic axis that is not parallel to the rotation axis. The pulse period is equal to the rotation period of the neutron star. The very consistent pulse period, over years, is accounted for by the near conservation of angular momentum of the almost isolated, rotating neutron star. The very slight increase in period over time occurs as the neutron star gradually loses angular momentum to its surroundings through its electromagnetic emission.

The nominal neutron star has a radius of 10–13 km and a mass $\approx 1.4M_\odot$. The escape speed at the surface of such a neutron star is $\sim 70\%$ of the speed of light. If a neutron star is the result of a core-collapse supernova and angular momentum and magnetic flux are assumed conserved during the collapse the resulting star will have a very strong magnetic field and high rotation rate. In the basic model of [12] given the strong magnetic field and high rotational speed, the space surrounding the neutron star can not be a vacuum. In this model, they considered a simplified case of a neutron star rotating about the magnetic dipole axis, where the neutron star is a conducting sphere. At any point $\vec{r}$ inside the sphere (measured from the center of the star), for the conducting sphere rotating in the magnetic field, the induced interior electric field $\vec{E}$ satisfies

$$\vec{E} = (\vec{\Omega} \times \vec{r}) \times \vec{B} \quad (1.1)$$

where $\vec{\Omega}$ is the angular speed. So the charge density distribution at $\vec{r}$ in the neutron star given by

$$\rho = \epsilon_0 \vec{\nabla} \cdot \vec{E} \quad (1.2)$$

is [13]

$$\rho = -2\epsilon_0 \vec{\Omega} \cdot \vec{B} = \epsilon_0 \Omega B_s \frac{R^3}{r^3} (3 \cos^2 \theta - 1) \quad (1.3)$$

where B_s is the magnetic field at the surface of the neutron star and θ is the angular position measured from the pole. Notice that the density changes sign at $\cos \theta = \sqrt{1/3}$. Under a boundary condition that there is a continuous tangential electric field at the surface of the neutron star they solved Laplace's equation for the vacuum static-external electric potential Φ [12, 13] as

$$\Phi = -\frac{\Omega B_s R^5}{6r^3} (3 \cos^2 \theta - 1). \quad (1.4)$$

Therefore, the extraction force on the surface charge is $eE_\parallel$ where [12, 13]

$$E_\parallel = \frac{\vec{E} \cdot \vec{B}_s}{B_s} = -\Omega B_s R \cos^3 \theta \quad (1.5)$$

is the electric field strength parallel to the magnetic field. Thus, they obtained an electrical force on the charged particles at a neutron star surface which is 10 or more orders of magnitude larger than the gravitational force. So electrons would be ripped easily from the surface of the star producing a charged medium constrained by the strong magnetic field to rotate at the same as angular speed as that of the star. At the distance $R_{LC} = c/\Omega \approx P \times 4.77 \times 10^4$ km where P is the pulsar's period in units of seconds, the corotating medium will reach the speed of light (LC stands for "Light Cylinder"). That is the maximum distance the magnetic field lines can remain closed. Beyond that distance the relativistic particles will escape as shown in figure 1.1. At the polar cap, electrons emit curvature radiation when accelerated to relativistic speed along the curved and open magnetic field line. A cascade reaction occurs near the magnetic polar cap as the high energy photons of the curvature radiation create electron-positron pairs and the electrons and positrons produce more curvature radiation.

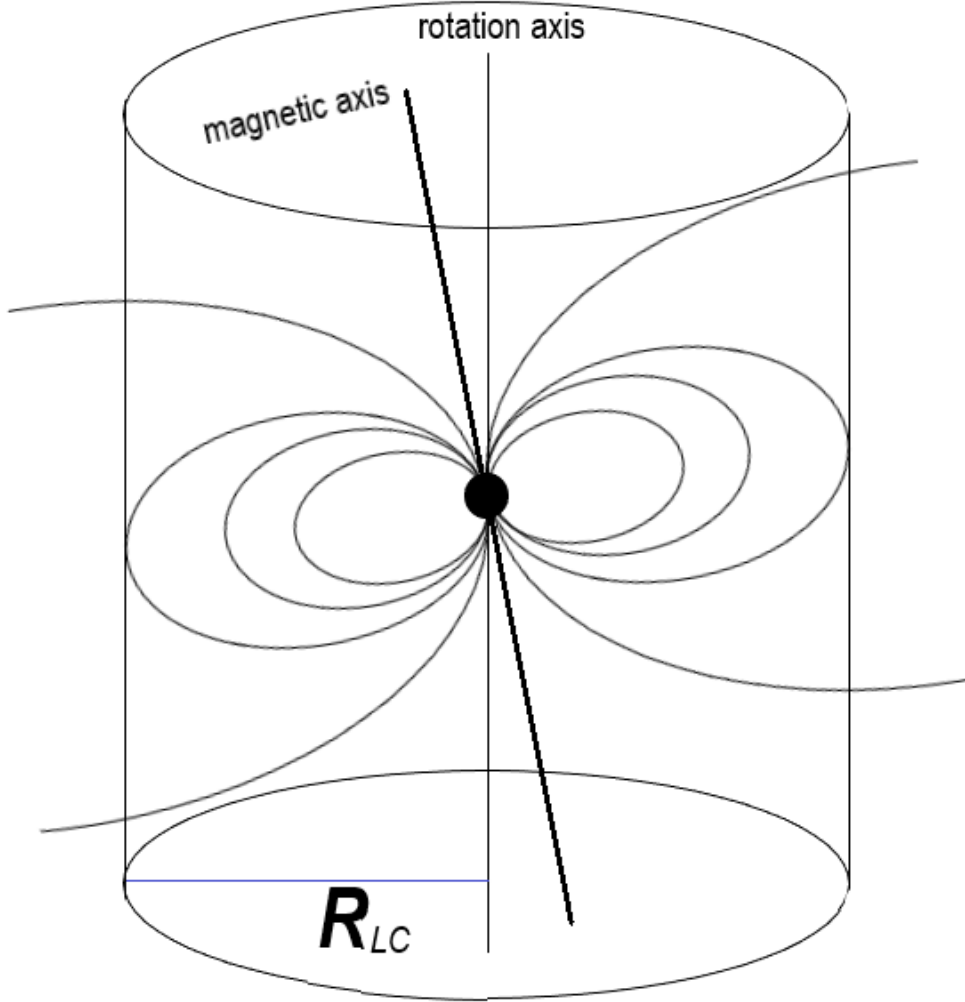


Figure 1.1: A sketch of the standard pulsar model.

In the rest frame of a charged particle, the direction of curvature radiation is perpendicular to direction of acceleration. Following the discussion from [14], a narrow beam of radiation is produced in the direction of motion of the charged particle as a result of the relativistic motion of the charged particle in the observer's frame of reference. Considering the rest frame of the particle to be the prime frame and the observer's frame to be unprimed, let a charged particle be moving in the y direction in the observer's frame, with the speed $v \sim c$, while accelerating in the x direction. A photon of curvature radiation emitted at an angle θ' from y' axis has projection speeds along the x' axis and y' axis of

$$v'_x = c \sin \theta', v'_y = c \cos \theta' \quad (1.6)$$

while these projections in the observer's frame are

$$v_x = c \sin \theta, v_y = c \cos \theta. \quad (1.7)$$

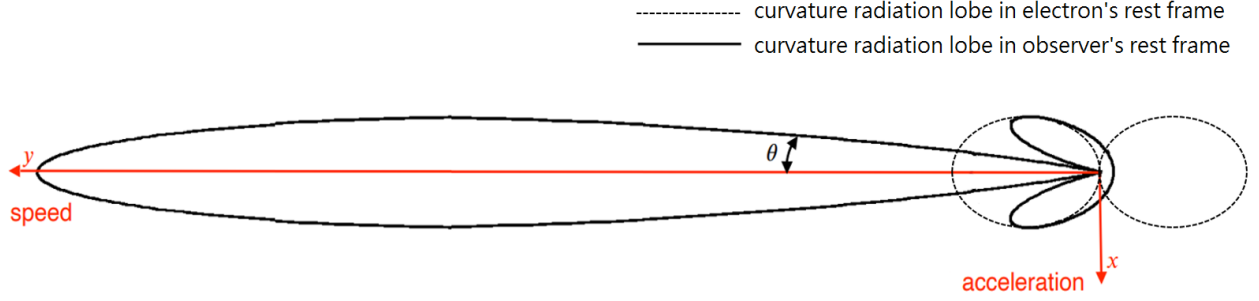


Figure 1.2: A sketch of the curvature radiation lobe profile in the rest frame of an electron and in the frame of the observer.

From the Lorentz transform on the velocities, we have

$$\sin \theta = \frac{\sin \theta'}{\gamma(1 + \beta \cos \theta')} \quad (1.8)$$

where $\gamma = 1/\sqrt{1 - \beta^2}$ and $\beta = v/c$ from [14]. From the Larmor equation [14], the power function $P(\theta')$ is null at $\theta' = \pm\pi/2$. In the observer's frame the curvature radiation is sharply beamed within a beam of angular width 2θ where θ is, for $\theta' = \pm\pi/2$ and $\gamma \gg 1$, is given by

$$\sin \theta = \frac{\sin \theta'}{\gamma(1 + \beta \cos \theta')} \approx \frac{1}{\gamma} \approx \theta \ll 1, \quad (1.9)$$

as shown in figure 1.2. Thus the curvature radiation produced near the magnetic pole is sharply beamed along the magnetic field axis, and if this beam sweeps along our line of sight to the star as the neutron star rotates, we observe a pulse of electromagnetic radiation.

1.2 Pulsar Giant Pulses

The first pulsar observed to produced giant pulses (GPs) was the Crab pulsar (PSR B0531+21) in 1968 [15], a year after the discovery of pulsars. GPs, or anonymously intense pulses (AIPs), have been observed in only a handful of pulsars. The Crab Pulsar was actually discovered through the observations of its GPs [15]. There is some ambiguity in the definition of GPs

and AIPs. In a recent paper, Karuppusamy et al. [16] defined GPs as pulses with at least 10 times the flux densities of the mean pulse, having a much narrower temporal width than the mean pulse, and a power-law pulse intensity distribution [16]. Singal and Vats, in a paper on GPs from B0950+08, define GPs as having flux densities exceeding ten times the mean pulse. Ulyanov & Zakharenko discussed the difference between GPs and AIPs, with AIPs appearing at lower frequencies, and exhibiting narrower-band emission than GPs [17]. We will discuss observations of pulses from PSR B0950+08 of large intensity relative to the mean (SNRs at least 10 times that of the mean pulse). For simplicity and brevity we will refer to our large intensity pulses as GPs.

Although GPs have been widely detected and discussed in the literature [18–21], the mechanism for GP production remains unclear. Petrova suggests that GPs are created by induced scattering of pulsar emissions by particles of ultra-relativistic plasma in the magnetic field [22], possibly explaining the observations of Smirnova [23]. Other proposed mechanisms aim to explain the observed power-law statistics through wave collapse [24], though concerns have been raised about the potential of the wave collapse model [25]. Cairns argues for stochastic growth theory, though he admits it is not favored. It is still to be determined whether the power-law features observed in GPs are intrinsic or due to convolution effects. There is broad consensus in the literature that more observations at various frequencies are required to reduce the list of possible mechanisms. Studies of giant pulses may provide another window on the pulsar surface and local electromagnetic field structure around the beam, since giant pulses may be generated at different altitudes and therefore at locations of different strength of magnetic field than for normal pulses. Reference [26] categorized plausible mechanisms of giant pulses into three main groups:

1. Perturbations in the production of the energetic electron-positron plasma near the light cylinder of the pulsar.
2. The induced Compton scattering of normal pulses within the magnetosphere of the strongly magnetized and relativistic plasma.
3. A mechanism involving thermal waves and uniform secular growth, that was reviewed in [27].

The bottom line is that what makes only a few pulsars out of thousands produce giant pulses, is still an open and interesting question.

The search for radio transient pulses from astrophysical phenomena, including GPs, has benefited from additional instrumentation with the development of new low-frequency arrays, such as the first completed station of the LWA [28] and the Low-Frequency Array (LOFAR) [29]. These arrays possess the capability to observe astronomical sources at frequencies that have not yet been explored in great detail. Notably, LWA has been shown to be capable of detecting giant pulses emitted by the Crab Nebula pulsar between 20 and

80 MHz [30]. LOFAR has also been active in finding GPs at low frequencies; [31] report detections of bright single pulses in, e.g., PSR B0950+08. Also, a prior measurement of the polarization of average pulses from PSR B0950+08 was conducted at 39 MHz [32]. An additional motivation for our current work is to prepare for using the LWA in searches for single dispersed pulses (fast transients) from a variety of sources, including the possible radio pulse produced by a binary neutron star merger. Such mergers are a prime target of the Laser Interferometry Gravitational-Wave Observatory and the counterpart Virgo observatory (LIGO-Virgo) collaboration [33]; a coincident observation of a prompt radio pulse from a merger could help in understanding the astrophysical origin and environment of the gravitational wave (GW) signal from the event [34].

1.3 Interstellar Radio Wave Scattering

A major issue in observations of transient pulses, whether from pulsars or otherwise, is the effect of interstellar scattering. Observations at low frequencies could be particularly affected by scattering. Interstellar scattering of radio waves is due to spatial irregularities in the free electron number density in the interstellar medium (ISM). The irregularities are often assumed to be described by a Kolmogorov spatial power spectrum which is consistent with pulsar observations of angular broadening and scintillation (e.g., [35] for distances $\lesssim 1$ kpc). However, there are also observations of pulsars which imply a departure from the Kolmogorov spectrum of irregularities. Studies of pulsars with large dispersion measures (DMs) [36] show a flattened dependence of pulse-width scatter-broadening on observing frequency. The analysis described in this thesis was performed by combining the CLEAN-based algorithm at high frequencies and the converted scatter-broadened times from correlative bandwidths caused by scintillation at low frequencies. It has been suggested that the effect of scattering for some pulsars is highly dependent on the line of sight (LOS) [4, 37–39].

While spatial variations in the interstellar free-electron number density are accountable for the scattering and scintillation of all radio waves propagating through the ISM, pulsar observations are particularly useful for measuring the effects of interstellar scattering, and thus can be used to characterize the interstellar electron-density irregularities.

Analysis of interstellar scattering often uses a thin screen between the source and observer. Observations have suggested that viable spatial electron-density irregularity spectra are limited to (approximately) power-law spectra,

$$P_{n_e} = C_n^2 q^{-\beta}, \quad (1.10)$$

for spatial wavenumber q between the outer and inner scales of the irregularities, q_o and q_i , i.e., $q_o \ll q \ll q_i$, with the exponent β ranging from 11/3 to 4.3 [40]. C_n^2 is the fluctuation strength of the irregularities.

A parameter commonly used to characterize the strength of plasma irregularities along a given line of sight is the scattering measure

$$SM = \int_0^D C_n^2(s) ds \quad (1.11)$$

where the integral is along the line of sight and D is the distance to the source.

To understand how spatial irregularities in the electron density cause scattering and produce a scattering-broadened pulse width, we follow discussions from [14, 41]. Consider a plane wave propagating through a tenuous interstellar plasma. The dipole moment per unit volume $\vec{P}$ induced by the electric field $\vec{E}$ of the wave is

$$\vec{P} = \epsilon_0(\epsilon - 1)\vec{E}, \quad (1.12)$$

where ϵ_0 is the permittivity of free space and ϵ is the relative permittivity of the medium. The equation of motion of the electron oscillation around a proton ($x = x_0 e^{ift}$) is

$$Ee = m_e \ddot{x} = -m_e f^2 x. \quad (1.13)$$

From equation (1.12) and $\vec{P} = n_e \vec{p}$ where $\vec{p} = \vec{x}e$ is the dipole moment for one electron-proton pair, we can calculate the relation between the relative permittivity of the medium and frequency as

$$\epsilon = 1 - \frac{n_e e^2}{4\pi^2 \epsilon_0 m_e f^2}. \quad (1.14)$$

From equation (1.12) and the Maxwell equation

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t} = \frac{\epsilon}{c^2} \frac{\partial \vec{E}}{\partial t}, \text{ where } J = \frac{\partial P}{\partial t} \quad (1.15)$$

the index of refraction of a radio wave depends on frequency as

$$n = \sqrt{\epsilon} = \sqrt{1 - \frac{f_p^2}{f^2}} \quad (1.16)$$

where

$$f_p = \frac{1}{2\pi} \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}} \approx 9 \left(\frac{n_e}{\text{cm}^{-3}} \right)^{1/2} \text{ kHz}. \quad (1.17)$$

For a typical line of propagation through our Galaxy, the interstellar medium n_e is ~ 0.025 electrons cm^{-3} [42], thus $f_p \sim 1.4$ kHz. For $f < f_p$, there is no propagation. The phase velocity is $c/n > c$, but information is not propagated at the phase velocity so there is no violation of relativity; the group velocity is $nc < c$. (Phase velocity and group velocity are

obtained from ω/k and $\partial\omega/\partial k$ by equation (1.16) and later equations (1.23), and (1.24) with the approximation $f_p/f \ll 1$.)

Two propagation effects of interest can be calculated from equation (1.16), the dispersion and scattering effects. The dispersion effect is a phenomenon in which a low-frequency pulse propagates more slowly than a high-frequency pulse. Pulses travel with speed equal to the group velocity. Thus, the time for a pulse to travel a distance D between the source and telescope is

$$t = \int_0^D \frac{dx}{n(x)c}. \quad (1.18)$$

Taking the approximation that $f \gg f_p$, the delay time between a finite frequency f and infinite frequency is

$$\tau = \frac{e^2}{8\pi^2\epsilon_0 m_e c} \frac{1}{f^2} \int_0^D n_e(x) dx. \quad (1.19)$$

We can express equation (1.19) as

$$\tau = 4.15 \times 10^3 \frac{1}{f_{\text{MHz}}^2} \text{DM seconds}, \quad (1.20)$$

where

$$\text{DM} = \int_0^D n_e(x) dx, \quad (1.21)$$

where the number density of free electrons n_e is expressed in the units of cm^{-3} and the distance to the source is measured in parsecs. Here $1 \text{ parsec} = 1 \text{ pc} \approx 3.1 \times 10^{16} \text{m}$ is an astronomical length unit based on stellar parallax methods. We mention frequently this dispersion measure DM, and dispersion, throughout this thesis because interstellar dispersion is one of the properties that distinguishes cosmic signals from terrestrial radio frequency interference (RFI). A dispersed astrophysical signal will produce a signal where the higher-frequency pulse will reach the telescope earlier than the lower-frequency pulse (as shown in figure 4.1), and the time lag is given by equation (1.20) with a certain DM value, the DM value differing for different sources. For example, the pulsar PSR B0950+08 has $\text{DM} \approx 2.97 \text{cm}^{-3} \text{pc}$, while PSR B0031-07 has $\text{DM} \approx 10.92 \text{cm}^{-3} \text{pc}$. Extragalactic sources may have DM values of hundreds of pc cm^{-3} .

The other propagation effect of interest is scattering. While a short duration and broad-band radio wave propagates through the non-uniform interstellar medium, initially plane (or spherical) waves will become “corrugated” as they pass through regions of greater and lesser refractive index. For a thin-screen scattering model (figure 1.3), a short pulse is broadened in time upon arrival at an observer’s position, with an intensity as a function of time $I(t)$ that has an exponential tail,

$$I(t) \propto e^{-t/\tau_s}, \quad (1.22)$$

where τ_s is the scattering time constant. At the location of the telescope, the first part of the pulse to arrive would be along the “ray” that follows the straight line-of-sight (LOS) from the source to the observer. Then parts of the signal that follow rays of greater and greater scattering angle arrive later and later. The corrugation of the initial plane waves is caused by the differing phase speed for passage through the medium. For an electromagnetic wave crossing the screen, the phase change per unit length is given by the wavenumber k , where

$$k = \frac{2\pi}{\lambda} = \frac{2\pi}{c}nf. \quad (1.23)$$

Variations in index of refraction along the path cause a variation of the phase per unit length $\Delta\phi$. For a path through a density irregularity of length a (along the ray path) $\Delta\phi = a\Delta k$ where Δk is the wave number variation in that irregularity. From equation (1.16) and for $f_p/f \ll 1$, equation (1.23) can be rewritten as

$$\Delta k = \frac{2\pi}{c}\Delta n f = \frac{e^2}{4\pi\epsilon_0 m_e c f} \Delta n_e. \quad (1.24)$$

The corresponding phase variation is $\Delta\phi = a\Delta k \propto 1/f$. Let us assume the transverse size of the density irregularities in the screen is also a . Then the transversely varying $\Delta\phi$ produces the corrugated wavefront with associated scattered rays (perpendicular to the wavefront), with typical scattering angle shown in figure 1.3,

$$\theta \approx \frac{\Delta\phi/k}{a} \propto \frac{1}{f^2}. \quad (1.25)$$

Therefore the typical geometric delay in arrival time of rays at the telescope is

$$\tau_s(\theta) = \frac{d}{c}(1 - \cos(\theta)) \approx \frac{\theta^2 d}{2c}, \quad (1.26)$$

where d is the distance to the thin scattering screen and $\theta \ll 1$. From equations (1.22), (1.25) and (1.26), we conclude that the scattering time constant $\tau_s \propto f^\alpha$, where $\alpha = -4$ for a thin screen model with irregularities in the screen of a specific size. For a Kolmogorov spectrum of density irregularities the ($\beta = 11/3$) the expected index is $\alpha = -4.4$ [36]. An example of the scatter broadening of a pulse at different frequencies is shown in figure 1.4.

While the Kolmogorov value of $\beta = 11/3$ appears to fit at least some of the observed results, it is an open question as to whether a turbulent process is producing the electron density irregularities (as would be suggested by labeling the spectrum as “Kolmogorov”).

The value of $\alpha = -4.4$ for a Kolmogorov spectrum comes from the following argument [44–46]. Figure 1.3 shows the geometry of the thin screen model. We define a coordinate system such that locations on the screen are given by x, y (or vector $\vec{x}$). The direction of propagation of the plane waves from the pulsar is the direction of the z axis. Let $z = 0$

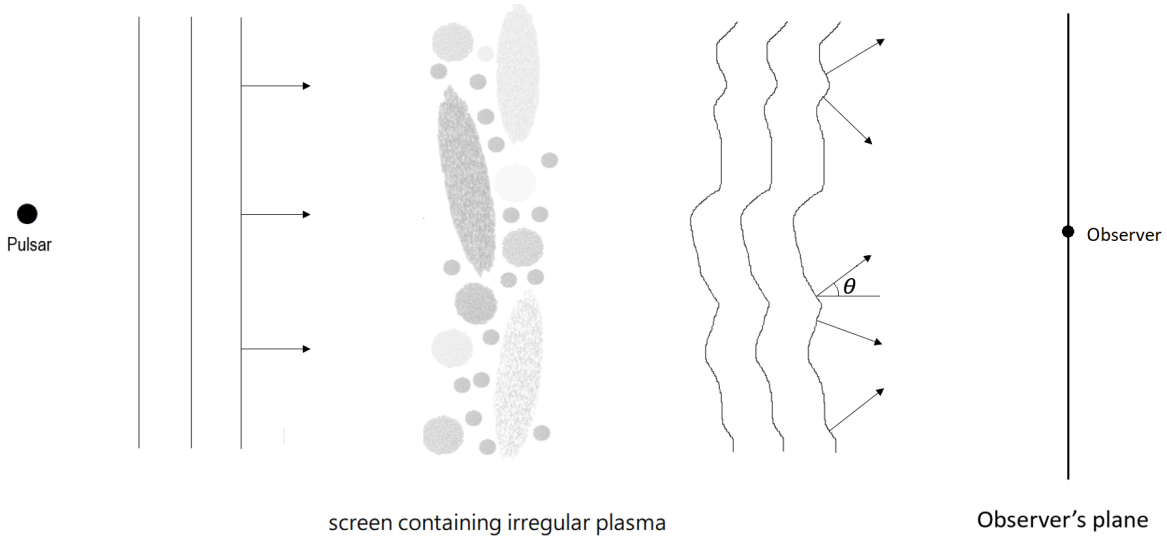


Figure 1.3: A sketch of a commonly discussed model for interstellar scattering. Initially plane-parallel waves from a pulsar are distorted by passage through a “screen” containing a plasma of non-uniform density and thus non-uniform index of refraction. Waves exiting the screen are no longer plane-parallel. Rays are shown on the exiting wavefronts. The typical scattering angle θ is shown. A diffraction pattern appears on the observer’s plane. If the screen, pulsar, or observer has any transverse velocity then variations in the brightness of the source are observed. Furthermore, a point-source pulsar now has a finite angular diameter $\approx 2\theta$ and different delays in the arrival of rays at the observer’s location produce the pulse broadening displayed in Figure 1.4.

be the location just after the thin screen. The distance to the observer from the screen is $z = L$. Let the complex amplitude of the wave emerging from the thin screen be given by

$$A(\vec{x}) = e^{i\phi(\vec{x})}. \quad (1.27)$$

Then, the “visibility function” of the emerging complex amplitude (i.e., the amplitude autocorrelation function) is

$$V(\vec{b}) = \langle A(\vec{x})A^*(\vec{x} + \vec{b}) \rangle = \langle e^{i[\phi(\vec{x}) - \phi(\vec{x} + \vec{b})]} \rangle. \quad (1.28)$$

Assuming many independent phase shifts along a ray within the screen, by the central limit theorem the phases ϕ are Gaussian distributed, so we can write

$$V(\vec{b}) = \exp\left(-\frac{D_\phi(\vec{b})}{2}\right) \quad (1.29)$$

where

$$D_\phi(\vec{b}) = \langle [\phi(\vec{x}) - \phi(\vec{x} + \vec{b})]^2 \rangle \quad (1.30)$$

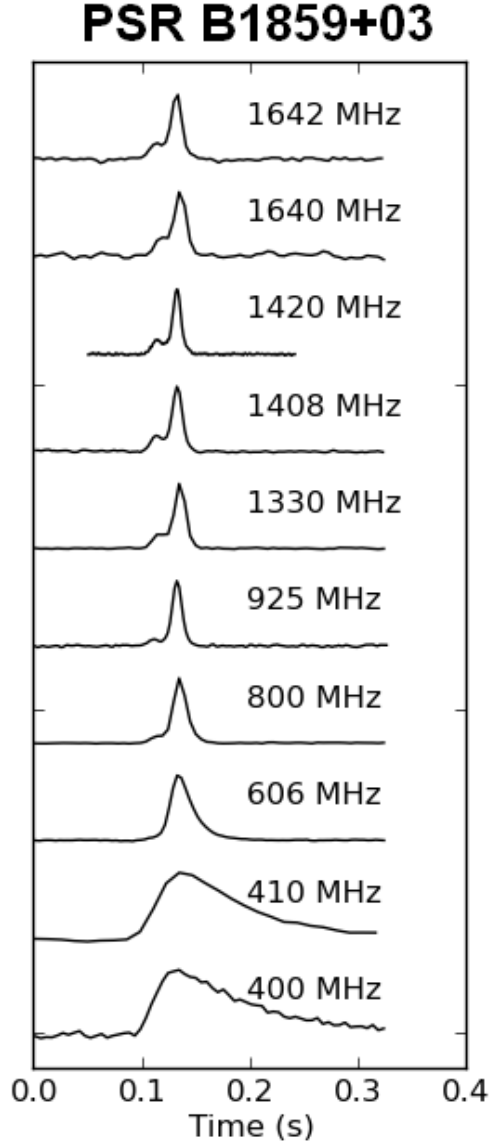


Figure 1.4: The pulse profiles for pulsar PSR B1859+03, showing the effect of scattering at different observing frequencies. Data to make this plot are available from European Pulsar Network [43]

is the phase structure function.

For a homogeneous, isotropic, power spectrum of electron density irregularities, equation (1.10), we have

$$D_\phi(\vec{b}) = 2 \left[\langle \phi(\vec{x})^2 \rangle - \langle \phi(\vec{x})\phi(\vec{x} + \vec{b}) \rangle \right] = 8\pi^2 \lambda^2 r_e^2 L \int dq \, q [1 - J_0(qb)] P_{ne}(q) \quad (1.31)$$

since the autocorrelation function is the Fourier-Bessel transform of the (isotropic) power spectrum, and where λ is the wavelength of the plane waves entering the screen and r_e is the classical electron radius.

Assuming $2 < \beta < 4$, and $q_o \ll b^{-1} \ll q_i$, the integral for $D_\phi(b)$ produces

$$V(b) = \exp \left[-(b/b_c)^{\beta-2} \right]. \quad (1.32)$$

The angular intensity spectrum emerging from the screen is the Fourier transform of the visibility function, so for $\theta_c = \lambda/2\pi b_c$ where

$$b_c = \left[4\pi^2 \lambda^2 r_e^2 L C_n^2 f(\beta) \right]^{\frac{-1}{\beta-2}} \quad (1.33)$$

where $f(\beta)$ is an order-unity function of the exponent β . Since the scatter-broadening time scale is $\tau \propto \theta_c^2$ (given the geometry in figure 1.3) we have

$$\tau \propto \lambda^{\frac{2\beta}{\beta-2}} \quad (1.34)$$

or $\tau \propto \lambda^{4.4}$ for $\beta = 11/3$.

There are observations of pulsars over a wide range of dispersion measures (DMs) which exhibit a departure from the thin screen model with a Kolmogorov density fluctuation spectrum. For example, a small group of pulsars with a high DM range (582–1074 pc cm⁻³) were observed to have an average $\alpha = -3.44 \pm 0.13$ [47]) and $\alpha = 3.49$ for DM > 500 pc cm⁻³ [39]. A larger group of low galactic-latitude pulsars were observed to have an average $\alpha = -3.9 \pm 0.2$ [36].

Several studies of the scattering spectral index [36, 39, 47–49] revealed that only a handful of pulsars have their scaling indices close to the theoretical value of $\alpha = -4.4$ [36, 49] and have therefore explored several plausible scenarios for the departure from $\alpha = -4.4$. In order for $\alpha = -4.4$ all four of the following conditions must be fulfilled.

1. The electron density spectrum is of the Kolmogorov form.
2. Only a thin screen or a homogeneous thick bulk lies in the LOS.
3. The wavenumbers sampled by the observations fall in the range between the inner and outer scales.
4. The turbulence is isotropic.

If condition number 1 is not true then α will be determined by β as in equation (1.34). If conditions 2, 3, and/or 4 are not satisfied, then the structure function of the phase would not be given by equation (1.31) and would have to be evaluated numerically, which could result

in α less than 4.4 or greater than 4.4, depending on the details of the medium. Numerical simulations of radio wave scattering in various scenarios would be helpful in investigating possible results.

Thus there are a variety of deviations from these conditions which could explain the departure from $\alpha = -4.4$. Some pulsar observations which deviate from Kolmogorov results have been attributed to deviations from the assumptions summarized above. For example, some atypical geometries, such as the truncated screens [50] may also affect the observed index of the scatter-time frequency relationship. It has also been proposed that observations that sample a spatial scale smaller than the inner turbulence scale can cause a deviation from Kolmogorov resulting in an $\alpha > -4.4$ [40].

1.4 Fast Radio Bursts

There have been hundreds of fast radio bursts (FRBs) reported since the first detection by [51] [52]. FRBs were first detected at the Parkes Radio Telescope [51, 53–59], and more detections came from other observatories, including the Green Bank Telescope [60], Arecibo [61] and the Canadian Hydrogen Intensity Mapping Experiment (CHIME) [62].

Statistically, FRBs have an average dispersion measurement above five hundred pc cm^{-3} , and the average pulse width is about 2 ms at GHz frequencies. But the FRB 160920 [63] had a pulse width of about 5000 ms, the FRB 160102 [64] had a DM as large of about 2600 pc cm^{-3} , and the FRB 190523 [65] had a flux density of about 670 Jy. Not all FRBs are single-peak profiled; the FRB 121002 [66] had a double peak width of 5 ms and two peaks separated by 5 ms. More than 5 repeating FRBs have been observed [65]. One of the repeating FRBs, 121102 [67], has a period of 157 days, during 90 of which it is radio loud; the rest of the time it is radio silent. FRB 180916 has a period of about 16 days [68]. FRB 160920 and FRB 170606 were discovered in archived data and appear to come from the same source (i.e., direction) [63], but they have different DMs of 1767 and 247 pc cm^{-3} , respectively; both pulse widths were relatively broad at 5s and 3s respectively. If both of these FRBs share the same source, the interstellar medium evolution along the LOS can be violent, based on the difference in DM, and the outlier of wide pulse widths may indicate that the source(s) of FRB 160920 and FRB 170606 may differ from most other FRBs. But the author of the paper on FRB 160920 and FRB 170606 pointed out that the direction of two FRBs may be different, given the angular uncertainty for the observations [63].

All of the FRBs have been detected at frequencies above 300 MHz with dispersion measures (DMs) larger than 103 pc cm^{-3} , some of which are more than thirty times larger than predicted from the Galactic electron density model NE2001 [69, 70]. There are at least three types of FRBs based on properties of repeating. There are one time bursts, non-periodic re-

peaters, and periodic repeaters. Since there are repeaters and non-repeaters, there should be at least two main categories of sources/mechanisms, including, perhaps, a one-time model involving a collision of compact objects. It has been suggested that supernovae could be a likely source [71]. Other source candidates include compact object mergers such as binary neutron star (BNS) mergers, and mergers of neutron star—white dwarf systems (NS-WD) [72]. One perhaps even more exotic mechanism that has been suggested is the radiation produced at the cusp of a cosmic string [73]. Mergers and cosmic string sources are also expected to generate GWs, which have been detected in the case of a compact object mergers, potentially providing additional mechanisms and environmental information outside of the electromagnetic spectrum [74–76]. To date, however, no coincident GW and FRB signals have been found [77], although it has been shown that there may be compatibility between the rate of BNS mergers and FRBs [78].

There may be more than one kind of emission mechanism for FRBs because single, periodic and sporadic FRBs have been observed. Reference [79] provided an online forum of up-to-date FRBs mechanisms, including compact object merging/interacting, giant emission from pulsars, magnetars, or other possibilities. CHIME detected FRB 200428 [80] on 28 April 2020, which appears to be associated with the soft gamma repeater SGR 1935+2154. This soft gamma repeater produced an X-ray burst detected with space-borne telescopes [80] coincident with the FRB. SGR 1935+2154 is thought to be a magnetar (an especially high magnetic-field neutron star). The coincident detection of FRB 200428 and an X-ray burst from the direction of SGR 1935+2154 suggests an emission mechanism for FRBs associated with an active magnetar. In this mechanism a super-active, and ultra-fast rotation, young magnetar injects a flare into the surrounding nebula which is the remnant shell from a supernova, producing an FRB by the synchrotron maser process [81]. This synchrotron maser emission is powered by intense magnetic flares from a magnetar with a hyper-strong magnetic field, which causes synchrotron radiation that is absorbed in the nebula around the magnetar, inverting the electron population to higher energetic states. Such a distribution is unstable and causes coherent radio emission [81].

1.5 Outline of the Thesis

This thesis is about work done in preparation for searching for Fast Radio Bursts (FRBs) and other radio transients perhaps associated with GW bursts identified by the LIGO-Virgo collaboration. We first describe a series of observations mainly of giant radio pulses from pulsars, using the first station of the LWA. The data from these observations were reduced using a software pipeline we developed to detect radio transients at very low frequencies. Techniques to detect FRBs and other radio transients (repeating or singular) are similar. Using this pipeline we were able to detect sporadic giant pulses (GPs) from a number of different pulsars. We discuss LWA and its sensitivity in chapter 2. Details about data

processing and pipelines are elaborated in chapter 3. The results from our first observations of a pulsar, follow-up observations of pulsars and the scattering effect analysis results from archival pulsar data are detailed in chapters 4, 5, 6, and 7. We introduce our method for searching for FRBs in chapter 8, where we also discuss the FRBs event rate. We discuss possible future work in chapter 9.

Chapter 2

The Long Wavelength Array

Parts of this chapter are paraphrased or taken from [1]. For this paper the author of this thesis wrote the code for data collection, data processing, analysis, and figures. He wrote the first draft, then collected comments from the coauthors, then revised the paper. Finally, he used the referee review to finalize the published version of the paper.

The LWA is an interferometric radio antenna array located in the high desert outside of Socorro, New Mexico (see figure 2.1). The main site of the LWA, LWA1, is located near the center of the Very Large Array (VLA). The LWA1 consists of 258 dual-polarization dipole antennas (see figure 2.2), spread out in pseudo-random pattern across a roughly circular area approximately 100 meters in diameter. For more information please refer to [82].

Virginia Tech (VT) was one of the institutions responsible for the construction of the LWA1. Professor Steve Ellingson from the Electrical & Computer Engineering department of VT contributed the monitor, control and data recording systems that were developed as part the Eight-meter wavelength Transient Array (ETA; [84]), a path-finder instrument for the LWA1. The ETA was constructed and operated by Ellingson, Professor John Simonetti of the VT physics department and Simonetti's graduate student, Sean Cutchin. Cutchin's thesis was focused on analyzing and reducing ETA data. The observational efforts described in this thesis were initially focused on data recorded by Sean Cutchin, to study the efficiency of the so-called cumulative summation RFI mitigation method.

The LWA1 has two primary observing modes, beamforming observations and all-sky observations, each of which makes use of different backend processors. The all-sky backend is called the Prototype All-Sky Imager (PASI) which can run independently and simultaneously with beamforming observations. PASI provides a live image of the entire sky which helps users monitor their observational efforts and recorded PASI data can be analyzed to search for unusual transient phenomena such as radio flares caused by meteors [85]. Figure 2.3

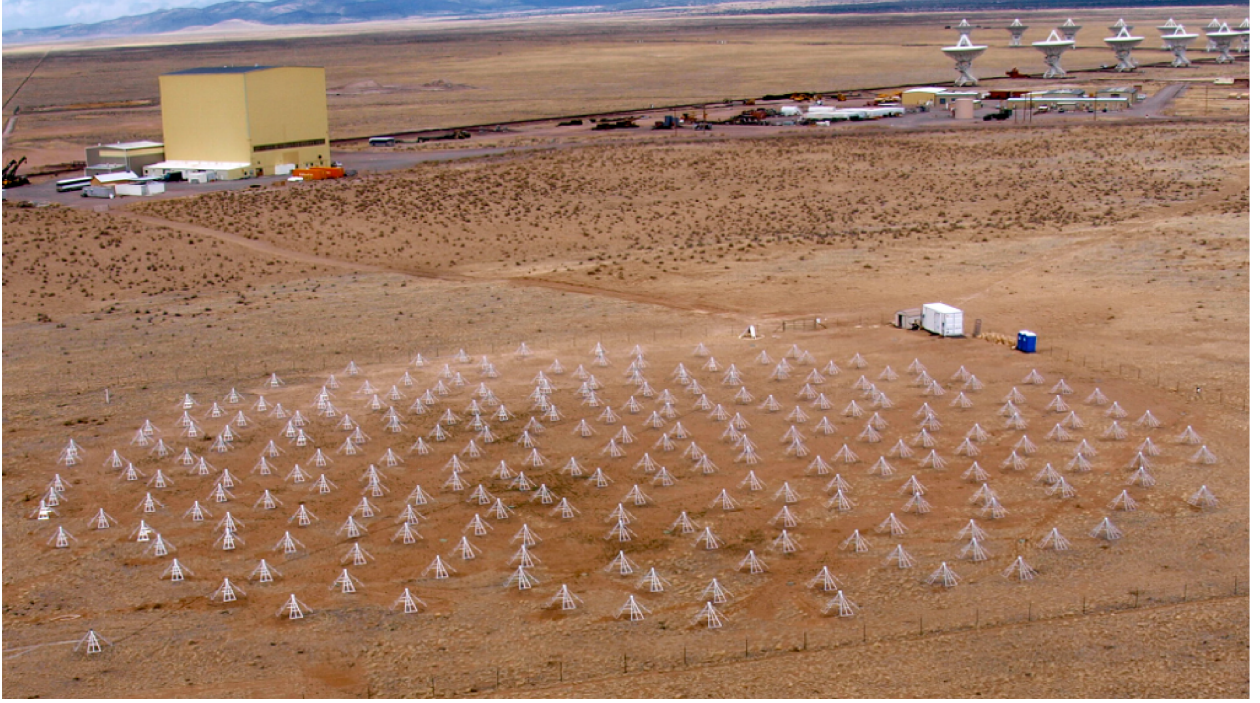


Figure 2.1: The site photo of LWA1 from Taylor et al. [83] (used with permission). The background is the center of the VLA.

shows a screenshot of the PASI monitor. The observations detailed in this thesis were made with the LWA1 in beamforming mode (DRX). The observed sources were primarily pulsars. The analog radio signals detected by each antenna are sent via underground cables to an onsite shelter, which has an analog-to-digital converter sampling at 196 million samples per second. The onsite shelter houses the two major backends, noted above, which process digital signals into beams and sky mapping simultaneously. To form beams, digital signals are delayed and summed from the antennas. There are two frequency tunings available for each beam and for each tuning the central frequency is selected by the user. The LWA provides a list of ‘filter codes’ corresponding to different choices of frequency and temporal resolution. The need to choose a frequency and temporal resolution is due to computational and storage limitations in the onsite shelter. We typically chose the extensively tested and vetted filter code ‘7’ which has a maximum available sampling rate of 19.6 MS/s.

The raw observations are recorded in binary data files. Making use of the LWA Software Library (LSL) [86], which is a collection of Python scripts, users are able to convert the binary data to spectrograms. LSL can help users with a variety of tasks including accessing raw data, obtaining antenna locations positions, producing data files in various formats, making plots of the spectra, and basic calculations for time series and spectra. It also possesses a graphical user interface (GUI) to schedule observations. However, for single dispersed pulse



Figure 2.2: LWA1 antennas, photo by author

searches it has certain limitations, especially in regards to complex dedispersion trials and removal of scattering. A significant portion of this thesis work focused on developing a code built on the LSL framework to process the data after the spectrograms were made that allowed our research group to accomplish its observational objectives which could not be achieved by using only LSL. This code accomplished a few essential primary tasks. These included: RFI and bandpass removal, dedispersion, and the creation of time series and diagnostic plots.

A computer cluster blade called a “data recorder storage unit” (DRSU), weighing about 10 kg, was used to store the observing data and even to physically transport the data (see

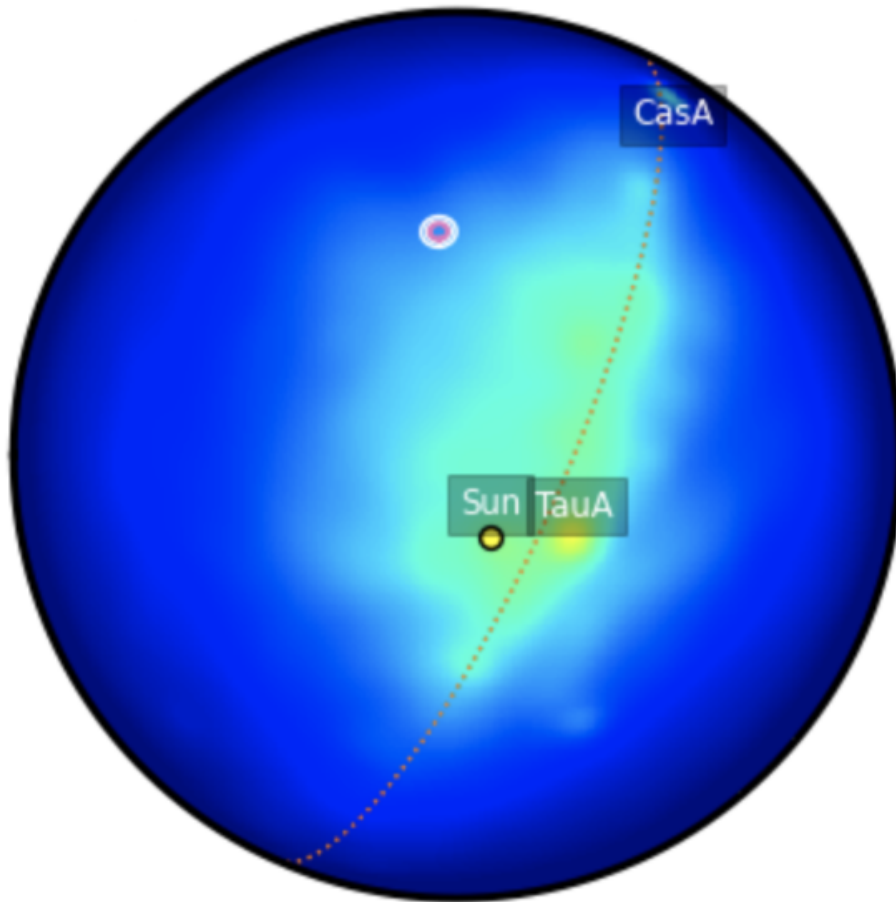


Figure 2.3: The screenshot of a video from <https://lwalab.phys.unm.edu/OpScreen/os2.php> showing an all-sky map made by the PASI system at LWA1.

figure 2.4 for configuration). A DRSU can hold five 3.5 inch traditional hard disks. If five 1 TB hard disks are loaded in the DRSU, a 5 TB DRSU can store about 18 hours of observation at maximum beam bandwidth. More recently the internet connection of the LWA site was upgraded and is capable of transferring data without having to transport DRSUs.

The RFI environment at the LWA1 site is favorable. The major RFI sources which can be identified and eliminated on the LWA site are from local power lines or nearby VLA facilities. The remaining RFI in the spectrum can be effectively removed. In figure 2.5 you can see that narrow horizontal features appear in the spectrogram. These are narrow-band RFI features. One can identify them by averaging across the spectrum (i.e., in time) which will produce an intensity vs. frequency graph, within which these narrow-band features will be clearly



Figure 2.4: Two stacked DRSUs. Photo by author..

apparent. One effective means of removing this RFI is blanking any frequency channels associated with the narrow-band RFI (by clipping at a 3σ level in the intensity vs. frequency graph), and replacing those spectrogram values with the surrounding average value. A similar procedure can be applied to vertical features in the spectrogram (impulsive RFI). RFI is more common at low frequencies around 28–35 MHz. Observations below 45 MHz usually have many frequency channels associated with narrow-band or impulse RFI. At higher frequency, 65–85 MHz, the spectrum is relatively clean. RFI is severe at frequencies above 88 MHz due to local FM broadcasts. The residual RFI remaining after the process outlined above can cause false-positive transient detections. Identification of these false-positives requires direct inspection of transient candidates. False positive transient candidates tend to be impulsive and consist of a few vertical, nearly lined-up features in the spectrogram. Dedispersing

a spectrogram which still contains this sort of impulsive RFI features can produce a time series which inadvertently yields a false positive transient detection in the final time series, since the separate vertical features could be lined up in the dedispersion process producing a spike in the time series of strength $> 5\sigma$. A promising future possibility is to apply machine learning techniques on large data sets such that the algorithmic code “learns” to differentiate between these false positives and astrophysical transients.

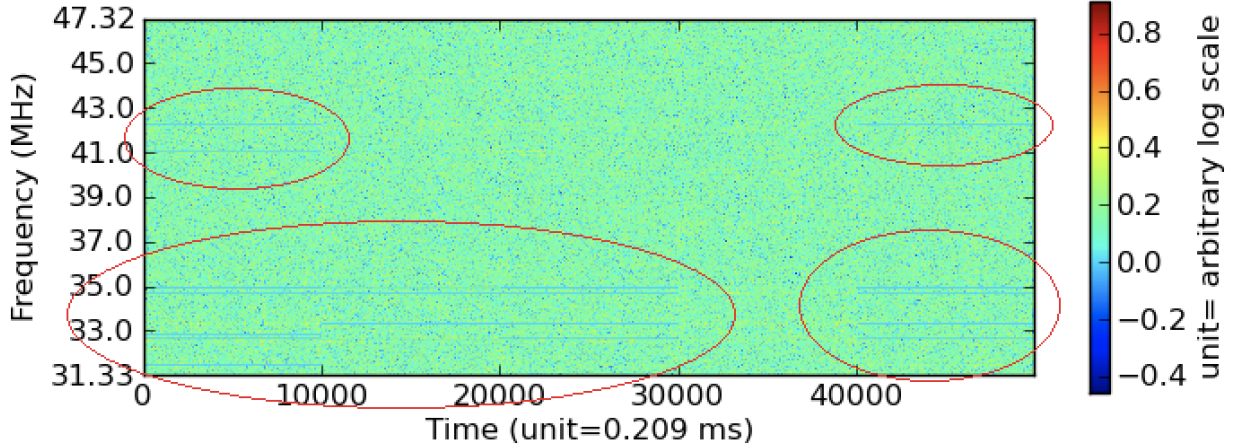


Figure 2.5: The clipped RFI section is shown in red circles. The spectrum is from a pulsar observation with giant pulses.

The LWA possesses unique capabilities for detection of radio transients, such as giant pulses from pulsars, and FRBs. It is also quite useful for studying scattering in the interstellar scatter medium. The relatively low observing frequency between 10–88 MHz (most radio observations are conducted at GHz frequencies), large collecting area and sensitivity make it ideal for transient detection and/or setting new constraints on astrophysical transient sources. The observational efforts described here involve using LWA1 to search for giant pulses from pulsars, transient-follow-up observations and probing of interstellar scattering. Specifically, we used the LWA to observe pulsar pulse profiles, by a technique called “folding” where the time series is broken into a set of series, each of length equal to the pulse period, and this set is summed after carefully lining up the set in terms of pulse phase. Once a stable average pulse profile is determined, we can study the spectral index and pulse profile evolution below 100 MHz. Giant pulse emission lacks a well-motivated theoretical explanation, and so innovative observational efforts could provide a great deal of illumination. To that point, we observed giant pulses from two pulsars over a relatively long observing program, and with high temporal resolution in order to obtain relatively precise giant pulse profiles. In addition to pulsar studies, due to interstellar dispersion which delays the arrival of radio waves relative to GWs (which travel at the speed of light), we can pursue triggered LWA observations of GWs sources discovered by the LIGO-Virgo collaboration. We can also use LWA to observe repeating FRBs discovered by CHIME [62]. The goals of this latter study

include investigating the spectral index of FRBs.

2.1 The Detectability of Transient Radio Signals using LWA1

We now wish to consider the sensitivity of LWA1 to a transient radio pulse. The level of noise after beam forming is difficult to estimate theoretically for LWA1. However, Ellingson [87] constructed a model to determine a system equivalent flux density (SEFD), which we will use in this discussion. One SEFD equals a flux density which produces unity signal-to-noise ratio (SNR), for a 1-Hz bandwidth and 1-second integration time, and takes account of all noise sources. To construct this model Ellingson [87] adopted a uniform brightness temperature for the sky of T_b , due to emission from our Galaxy. This temperature will dominate over any other sources of temperature in the system, due to the great strength of the galactic emission at low frequencies, and so it will dominate the production of system noise. The galactic brightness temperature depends on observing frequency ν , where

$$T_b = 9751 \text{ K} \left(\frac{\nu}{38 \text{ MHz}} \right)^{-2.55}. \quad (2.1)$$

For comparison the receiver noise is ~ 250 K; any ground temperature contribution is even smaller since the antennas are not sensitive to directions toward the ground and $T_{\text{ground}} \approx 300$ K. When Ellingson [87] applied this model to LWA1, incorporating the beam pattern of the individual antennas, and he showed that the sensitivity is highest when we observing in a direction at the zenith. When making a beam-forming observation that points away from the zenith, the sensitivity decreases significantly. The model's dependence of SEFD on zenith angle is shown in figure 2.6.

Ellingson's model implies that for an observation of a source producing flux density S_ν the SNR that would be obtained is

$$\text{SNR} \approx \frac{S_\nu}{\text{SEFD}} \sqrt{B \Delta t}, \quad (2.2)$$

where B and Δt are the bandwidth and the integration time used in making the observations, respectively. The typical bandwidth of LWA1 observations is $B \approx 20$ MHz. We take SEFD $\approx 15,000$ Jy at 38 MHz (with an uncertainty of $\sim 50\%$). The square-root dependence on B and Δt is the standard “radiometer equation” result [14]; the product $B \Delta t$ is essentially the number of independent samples in a series of observations. Note that a lower SEFD is better for sensitivity. Figure 2.7 shows comparisons of the model and the measured SEFD of LWA1. A sensitivity comparison between LWA1 and other instruments is shown in figure 2.8.

As stated at the beginning of this section, the galactic noise will be the main factor in limiting detectability of signals when observing below 100 MHz, as in our observations.

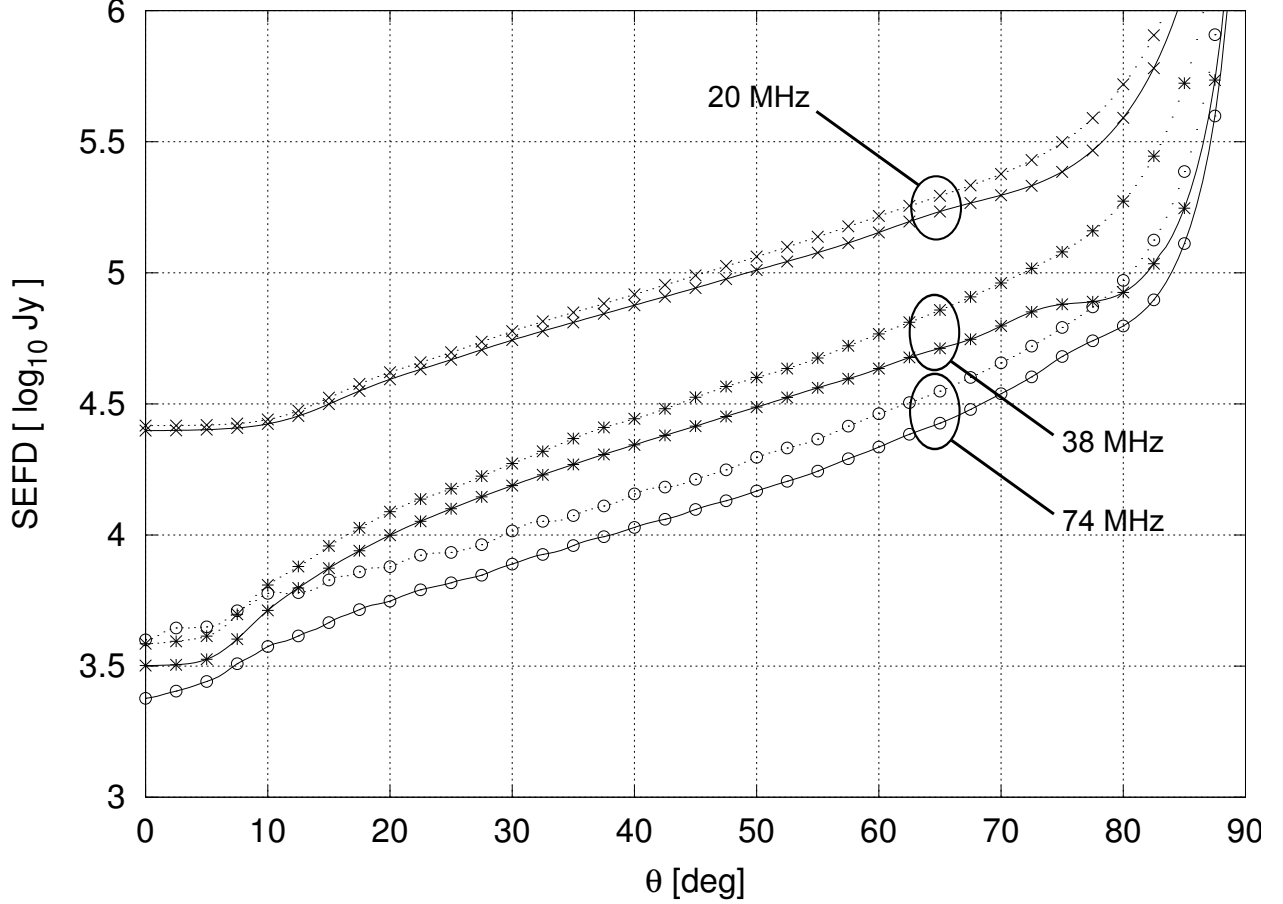


Figure 2.6: SEFD of LWA1 as the function of zenith angle, from Ellingson [87] (©2011 IEEE). Results are for 1 Hz bandwidth and 1 second integration time. For each frequency, the upper dotted curve and lower solid curves are the results for simple and optimal beamforming, respectively, as defined by Ellingson. The difference between these beamforming results is small compared to other uncertainties apparent from a comparison of these model results with actual observations.

The SNR depends on the integration time Δt , which, for best results in detecting a pulse is chosen to approximately match the pulse width (much larger integrations smooth out a pulse, much smaller integrations do not smooth out the noise sufficiently). In practice, a range of possible Δt can be employed in a search for any pulses in the observed data. A Δt that matches the actual pulse width will produce the highest SNR for that source. So, a discussion of what physical factors affect the pulse width is important to any discussion of sensitivity to pulses. In our observations a number of effects can broaden the pulse before it arrives at the telescope and data reduction can also affect the pulse width obtained.

For any temporally broadened pulse we observe, the broadening time can be expressed

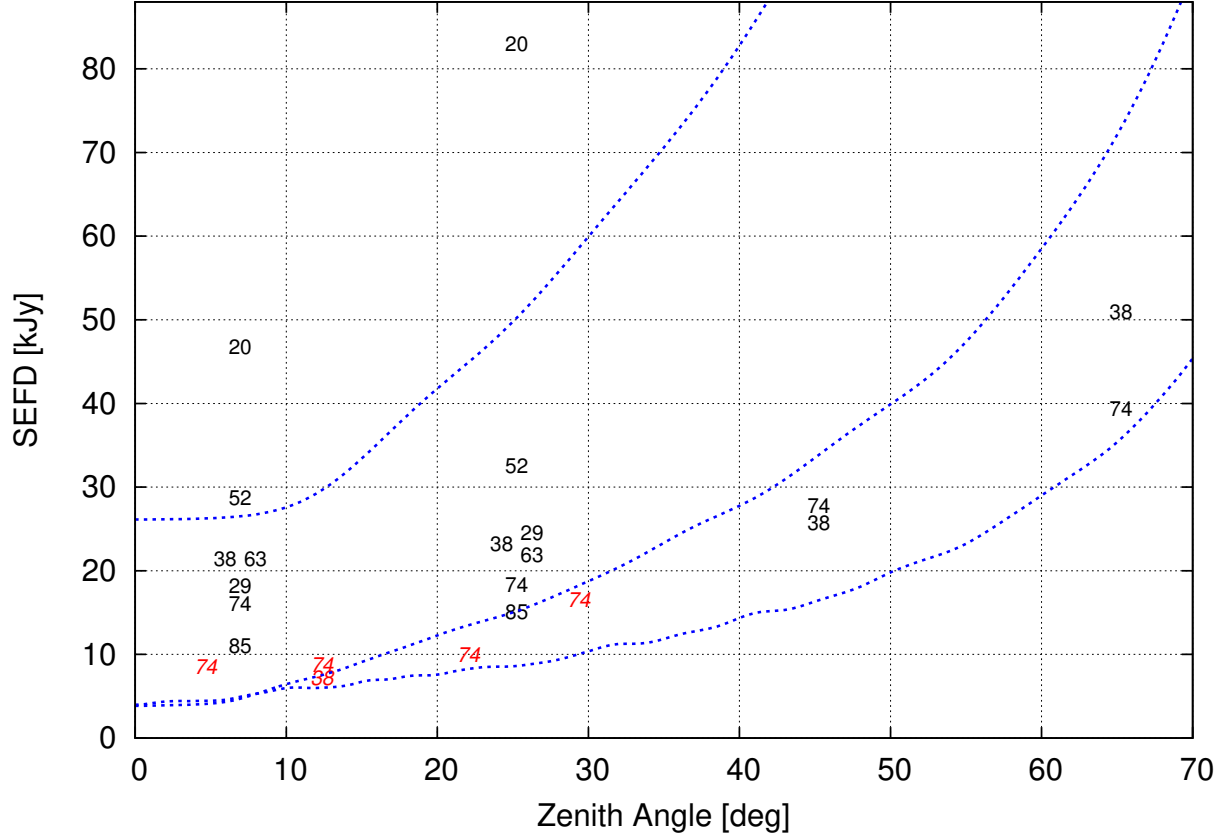


Figure 2.7: Sensitivity (SEFD combining both polarizations) vs. zenith angle obtained from drift scans by Ellingson et al. [88] (©2013 IEEE). The number data-point markers indicate the approximate observing frequency in MHz. Red markers represent observations of the different sources at different zenith angles. All the black markers are from observations of the source Cyg A. The dashed-lines are fits for 20, 38, and 74 MHz (top to bottom) in figure 2.6.

as due to a mix of effects by [89]

$$\Delta t = [\Delta t_{\text{intrinsic}}^2 + \Delta t_{\text{DM}}^2 + \Delta t_{\delta\text{DM}}^2 + \Delta t_{\Delta\nu}^2 + \tau_d^2]^{1/2} \quad (2.3)$$

where $\Delta t_{\text{intrinsic}}$ is the original pulse width, and Δt_{DM} is the temporal smearing due to interstellar dispersion (which can be removed by dedispersion techniques). The term $\Delta t_{\delta\text{DM}}$ is the residual smearing due the dispersion time-lag across one frequency channel (this dispersion smearing can not be removed by our dedispersion techniques); it depends on the DM and the frequency channel width $\Delta\nu$. The term $\Delta t_{\Delta\nu} \approx 1/(\Delta\nu)$ is the receiver filter response time. Finally, τ_d is the scatter-broadening term. After removal of Δt_{DM} this scatter-broadening term dominates the result for extragalactic sources, in which case, the result is very much simpler and is

$$\Delta t = \tau_d. \quad (2.4)$$

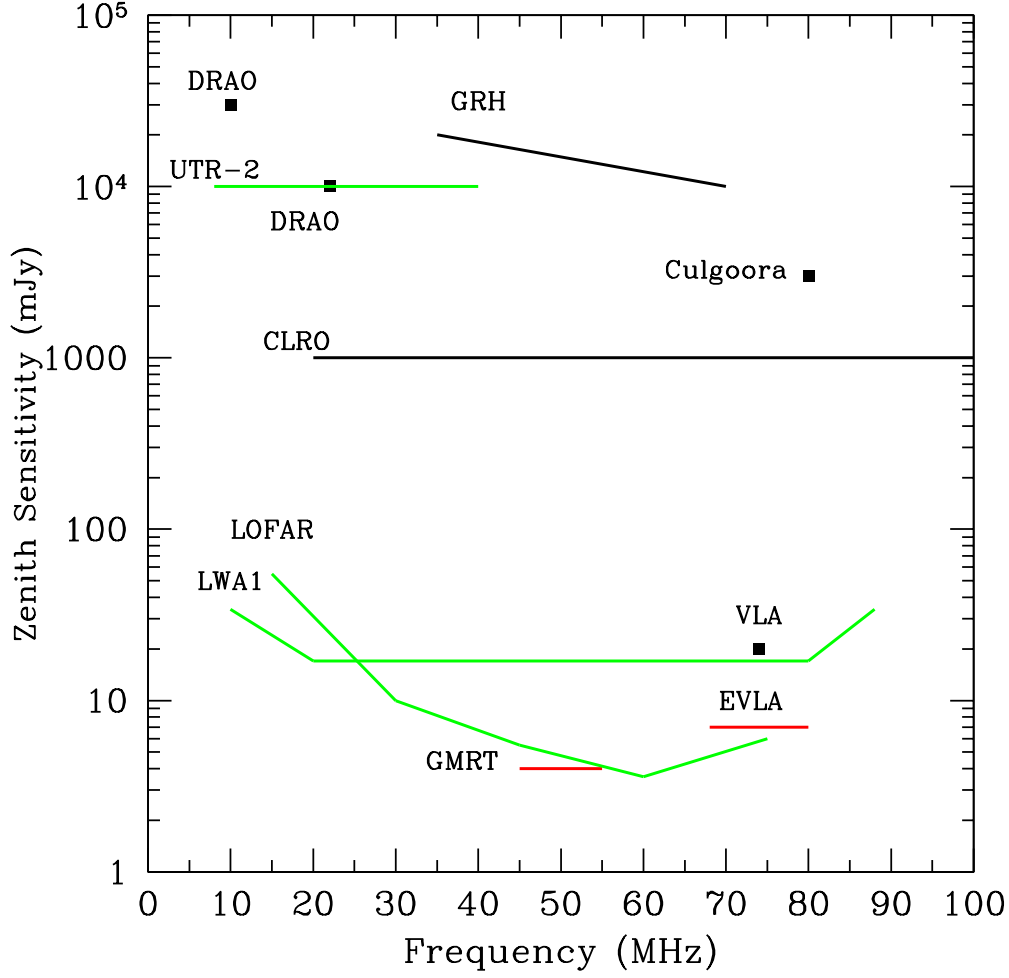


Figure 2.8: Sensitivity of the LWA1 compared to other instruments by Taylor et al. [83] (used with permission). Here the integration time is one hour for all instruments. Bandwidths are as follows: LWA1: 16 MHz, VLA: 3 MHz, LOFAR: 16 MHz, UTR2: ~ 3 MHz and GMRT: 10 MHz for planned (red) and current (green) instruments.

The scatter-broadening term requires more discussion, which we now undertake. For the observations of pulsars in our Galaxy, the scatter-broadening time τ_d is a simple function of the scattering measure SM for that pulsar, namely

$$\tau_d \propto SM^{6/5} D \quad (2.5)$$

where D is the distance to the pulsar [89]. The distance to the pulsar can be obtained from the DM (line-of-sight integral of the electron number density, provided by various models (e.g., [69])). Furthermore, we will be restricting our pulsar observations to pulsars with giant pulses we should easily detect. Thus a full analysis of the sensitivity of LWA1 to such pulsars will not be necessary.

On the other hand, estimating the limiting flux density of FRBs we can detect is an interesting question. In addition, estimating the scatter-broadening time for an extragalactic source is more complicated than for pulsars in our Galaxy, given there is a host galaxy through which the pulse travels, and the scattering in the host galaxy and our Galaxy are at vastly different distances from the observer. To estimate τ_d for an extragalactic source (e.g., an FRB), one can use the scatter-broadening model of [89] which is

$$\frac{\tau_{dxgal}}{\tau_{dGal}} \approx 3.7 \left(1 + \frac{SM_{xgal} D_{xgal}}{SM_{Gal} D_g} \right)^{6/5} \left(\frac{D_g}{D} \right)^{1/5}. \quad (2.6)$$

This equation describes how the scatter-broadening time τ_{dxgal} of an extragalactic source in the same direction as a source in our Galaxy would be increased over the scatter-broadening time τ_{dGal} experienced for the source in our Galaxy. The difference is caused by the effect of additional scattering in the source's host galaxy, and as a result of the different distances involved. In this equation SM_{xgal} and SM_{Gal} are the scattering measures for this line of sight in the host galaxy and in our Galaxy, respectively; D_{xgal} is the path length through the host galaxy, D_g is the path length through our Galaxy, and D is the distance to the extragalactic source. For a simple model, one might assume that SM_{xgal} is the same regardless of which galaxy the source is located in, and is the same as in our Galaxy (clearly quite a simplified model); furthermore, one could take $D_{xgal} \approx D_g$. In that case

$$\frac{\tau_{dxgal}}{\tau_{dGal}} \approx 8.5 \left(\frac{D_g}{D} \right)^{1/5}. \quad (2.7)$$

The typical path length through our Galaxy for a line of sight is ~ 1 kpc. From an empirical fit to pulsar data for a typical line of sight by [69], we have $\tau_{dGal} \sim 0.5$ s at an observing frequency of 38 MHz, with an uncertainty of $\pm$ a factor of roughly 4 (the pulsar data results have considerable scatter). The empirical results in [69] are given in terms of DM; we used the result for a DM of 50 pc cm^{-3} . The DM one would obtain looking out of the Galaxy is approximately $30/\sin|b|$ in units of pc cm^{-3} , where b is the galactic latitude of the line of sight. For a more typical line of sight we take $DM \approx 50 \text{ pc cm}^{-3}$. The estimate we will use as the typical scatter-broadening time for an extragalactic source is therefore

$$\tau_d(s) = \tau_{dxgal}(s) \sim 4 (D_{\text{kpc}})^{-1/5} \sim (D_{\text{Gpc}})^{-1/5}. \quad (2.8)$$

To obtain the distance D to an extragalactic source, we proceed as follows. We interpret DM as an indicator of distance in the following manner. Assuming a universe in which the “baryonic” matter (i.e., the matter comprised of elements in the periodic table—“baryonic” is how this is referred to by astronomers) is totally ionized and uniformly distributed, then the number density of free electrons at low redshift z would be $3H_o^2\Omega_b/8\pi Gm_p \approx 2 \times 10^{-7} \text{ cm}^{-3}$ [90,91]. Then, for a length D along the line of sight, the contribution to the DM of a source by the intergalactic medium is

$$DM_{\text{intergalactic}}(\text{pc cm}^{-3}) = \frac{D}{5 \text{ Mpc}}. \quad (2.9)$$

For a simple model, we assume that the total DM only receives contributions from the host galaxy, our Galaxy, and the intergalactic medium, or, in other words that there is no other galaxy located between the host and our Galaxy. Thus the total DM becomes

$$\text{DM} = \text{DM}_{\text{host galaxy}} + \text{DM}_{\text{intergalactic}} + \text{DM}_{\text{our Galaxy}}. \quad (2.10)$$

As stated above the we chose the typical DM due to the insterstellar medium along a line of sight to be 50 pc cm^{-3} . Furthermore, we also assume that the DM through the host galaxy and our galaxy are the same. Therefore the total DM for an extragalactic source is

$$\text{DM}(\text{pc cm}^{-3}) = 100 + 200 D_{\text{Gpc}} \quad (2.11)$$

where D_{Gpc} is the distance to the source in Gigaparsecs. Or,

$$D_{\text{Gpc}} = \frac{\text{DM}(\text{pc cm}^{-3}) - 100}{200}. \quad (2.12)$$

If we assume a DM for a typical extragalactic source (e.g., an typical FRB), we can compute its distance. Similarly, if we *measure* a specific DM for a source, we can compute its distance. FRBs have typical DMs of $\sim 500 \text{ pc cm}^{-3}$. Thus, for this simple model, a typical FRB has $D_{\text{Gpc}} \approx 2$.

We can now put together these results to predict the pulse flux density of an extragalactic source that will be detectable by LWA1. The equations that need to be used are eq. (2.2) for the signal-to-noise ratio for a source of a given flux density, and eq. (2.8) for the pulse width for an extragalactic source determined by scatter-broadening, which is matched by the integration time. For a typical distance to an FRB of $D \approx 2 \text{ Gpc}$, we find that to obtain a signal-to-noise ratio of 5 or greater a source must have a flux density greater $\sim 10 \text{ Jy}$. Most of the FRBs discovered have peak flux densities at 400 MHz to 1 GHz sub-Jy to 10s of Jy, or higher (see https://en.wikipedia.org/wiki/List_of_fast_radio_bursts for an up-to-date listing). The spectra of FRBs across the radio band are not well established, and flux densities could be larger at lower frequencies, such as ours, than at those frequencies at which FRBs have currently been observed (as is the case for many radio sources).

Chapter 3

Detecting Radio Transients in Observations using LWA1

Parts of this chapter are paraphrased or taken from [1]. For that paper the author of this thesis wrote the code for data collection, data processing, analysis, and figures. He wrote the first draft, then collected comments from the coauthors, then revised the paper. Lastly, he used the referee review to finalize the published version of the paper.

3.1 Overview

We have analyzed 120 hours (over 400 TB) of data using the pipeline developed by the author of this thesis (codes available in Appendix A). The raw data were stored in Data Recorder Storage Units (DRSUs). These consisted of a 1U rack-mount RAID enclosure, and 5 streaming-tuned hard disk drives and a regular 3.5 inch hard disk. We connected the DRSU to a personal computer (PC) as a file server to distribute the Fourier Transformed spectrograms to clusters for further data processing. We used two parallel-processing clusters in the Advanced Research Center (ARC) at Virginia Tech. The DRSU and the PC are connected to the ARC clusters by intranet to maximize the transfer speed. The most powerful cluster available to our research group was Blueridge, which allows for access to up to 1024 cores/64 nodes/4 TB of memory. For the purpose of debugging we made use of a smaller cluster called Hokieone. Both Hokieone and Blueridge share the same file system so we do not need to transfer the spectrograms between clusters. The Hokieone job system is similar to that of Blueridge so we were not required to modify the code to run on both clusters.

In searching for fast radio bursts at observing frequencies less than 100 MHz, the effect of dispersion is larger than for L-band observations (GHz). The temporal dispersion delay

is proportional to the square of the wavelength, which causes a transient pulse of lower frequency to arrive later. A pulse originating at a distant source, as a transient signal emitted simultaneously at all frequencies, traverses space and arrives at Earth as a “chirped” pulse. Initially it arrives at the highest frequencies in the observed band and then later at the lowest frequencies in the band. The observed, dispersed signal needs to be dedispersed to increase its SNR in a time series — a summation over a spectrogram’s frequency axis. The dispersion time is linearly related to the electron density line integral along the LOS, which is called dispersion measure (DM). We do not know the DM in advance and thus a wide range of DM trials are necessary in searching a given spectrogram for pulses. Thus we put the whole spectrogram into memory to improve I/O efficiency. To load a TB-scale raw spectrogram into memory we use the Message Passing Interface (MPI) which integrates the memory between nodes, and the system handles the separation of the spectrogram into individual nodes. The other benefit of dealing with a spectrogram as a whole is that we do not lose the full signal of a highly dispersed pulse across separated temporal chunks of a spectrogram when computing a time series.

Note that the intrinsic temporal resolution is 0.209 ms for LWA1. For searches with large DM trials we can choose a larger temporal resolution because of the finite frequency channel width, which causes a dispersion time lag across the frequency channel that can not be removed. Computational efficiency can also be improved by using a larger temporal resolution. This is particularly helpful while dedispersing large DM trials.

3.2 Data Analysis

The raw observed data is stored in DRSUs. A typical 6-hour-long observation occupies 2.5 TB of hard disk space. Before further analysis, routines from the LWA Software Library (LSL) [92] are used to convert the binary raw data into floats. Then a FFT is performed on the data stream to produce a spectrogram. To create the spectrogram, the data is partitioned into 4096 time-samples. Each of them are converted into the frequency domain by the FFT. The temporal resolution is 0.209 ms, as noted above, and the frequency resolution is 4.79 kHz. The total bandwidth is 19.6 MHz. Among 4095 frequency bins usually only the 360th to 3700th bin are reserved for further calculation involving the bandpass as shown in figure 3.2.

3.2.1 Initial Data Processing

While observing with radio frequency below 100 MHz, the system noise is dominated by the galactic temperature. We can see the background changing when the galactic plane approaches or recedes from the zenith, as shown in figure 3.1.

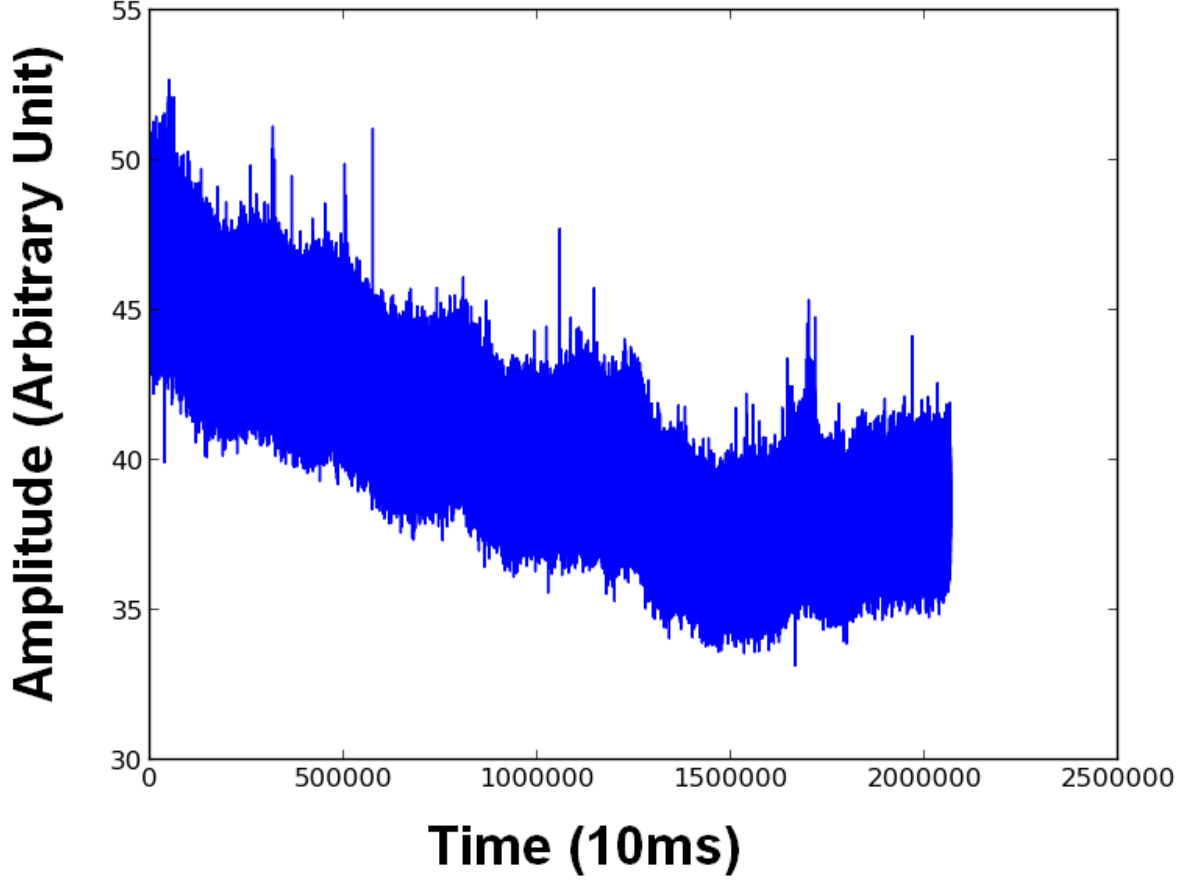


Figure 3.1: This plot shows the background level shifting in a time series of a ~ 6.5 hour observation.

The baseline in time series and bandpass will bias the signal detection or even result in no detection. Thus we will remove the baseline shifting by dividing the raw data with a fitting curve. Also RFI would induce false high SNR signal detections in a time series. We will discuss how to remove baseline and RFI in the next section.

3.2.2 Radio Frequency Interference Masking

RFI is a growing problem for observational radio astronomy. There are sophisticated RFI removal methods such as singular value decomposition and basic threshold cutting (e.g., [93]). The majority of RFI in our observations are narrow band and their duration can be a few minutes. More discussion of the RFI environment of LWA1 can be found in [94]. We found

that a simple threshold test for RFI detection and masking is good enough to suppress false detection for dispersed signals to an acceptable level. To mask out narrow-band RFI, we first cut a spectrogram into 2.09 s chunks. Then the intensity values in each chunk are summed along the time axis, resulting in an intensity vs. frequency series for that 2.09 s of data. Now, if a particular frequency bin in this series is more than 3σ above the local average value, this frequency bin is masked-out in the original spectrogram for that 2.09 s of duration.

To reiterate, the RFI mitigation procedure used is summarized as follows:

1. Cut a spectrogram into 2.09 s chunks.
2. For each chunk, determine the shape of the bandpass by summing in time the 2.09 s duration chunk, for each frequency bin.
3. Fit a 16th order polynomial to the shape of the bandpass for that 2.09s-chunk (the shape of the intensity vs. frequency curve for that 2.09s-chunk). The use of a 16th order polynomial is dictated by the shape of the bandpass experienced in LWA1 data (see figure 3.2).
4. Divide the 2.09s piece of the spectrogram by the fitted polynomial to remove the remove the shape of bandpass during that 2.09s of data, resulting in a bandpass with a flattened shape (see figure 3.3).
5. If a frequency bin's value is greater than 3σ from the mean, the frequency bin will be masked as containing RFI.
6. Replace masked bins with the mean value of the flattened bandpass.

Examples of the RFI mitigation masks are shown in figure 3.4. In these examples, the maximum percentage of pixels (time bins $\times$ frequency bins) masked as RFI in an observation is 0.87%, and the average is 0.61%.

3.2.3 Removal of the Temporal Baseline

During the RFI mitigation procedures, we have divided each sub-spectrogram by the shape of its bandpass to flatten the spectrogram in frequency space.

To flatten a spectrogram in both the frequency and the temporal domain, we then remove the drifting temporal baseline by dividing each 5-minute sub-spectrogram by its average value. Some smoothing across 5-minute boundaries is also done with a moving boxcar average. The temporal baseline is dominated by the radio emission from the galactic plane in the MHz frequency range, as shown in figure 3.1 (note the hours-long time-scale decrease

and increase in the signal, which corresponds to the passage of the galactic plane overhead). The 5-minute sub-spectrogram duration is chosen so the variation of the Galactic background is not very extreme.

We use different fitting methods for determining and removing the temporal baseline and the shape of the bandpass. A moving box-car is used for the temporal smoothing and utilizes a median when smoothing (not a mean). Polynomial fitting is used for the bandpass and is

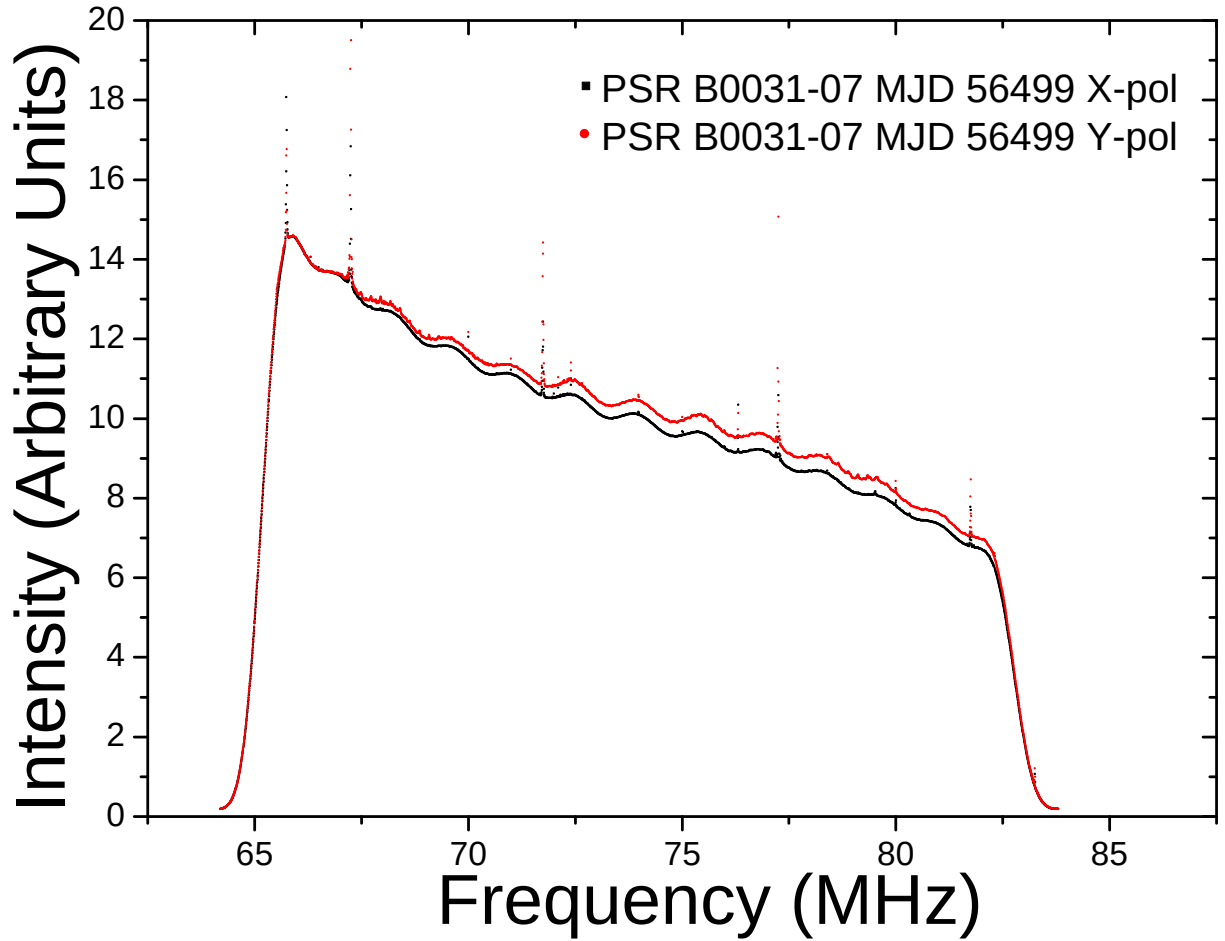


Figure 3.2: This plot shows the bandpass for an observation of 4 hours duration, targeting pulsar PSR B0031–07. The plot shows two different curves which represent the two different polarizations observed by the LWA1. The sensitivity drops to zero at the high and low frequency ends of the bandpass. Thus we removed the low and high frequency portions, keeping only the 16 MHz spanning the central frequency range. The vertical dots above each curve are created by RFI. Note that there is a ripple structure in both bandpass curves. This ripple effect can be minimized by repeating the baseline removal process three times.

not as sensitive to local extreme values as is a moving box-car smoothing, allowing for the detection and removal of narrow band RFI when masking is done.

3.2.4 Dedispersion

After RFI masking and baseline removal, the resulting spectrogram is ready for dedispersion. When an electromagnetic wave propagates through the interstellar plasma, different frequencies in the wave packet have different group speeds. This effect is known as dispersion. The lower frequencies arrive later at the detector. The time lag between two frequencies is given in equation (1.20). This dispersion helps distinguish RFI from astrophysical signals because most RFI possess no dispersion. However, in some instances RFI can also exhibit similar characteristics to a dispersed signal increasing the difficulty in identifying astrophysical signals (see the discussion of “perrytons” in Chapter 1). Anti-coincidence searching for corresponding signals in two distant observatories, can help to identify such false-positive detections.

Because of dispersion the original signal’s intensity is smeared out in a final time series unless we “dedisperse” the data. In the work presented here, we use “post detection dedis-

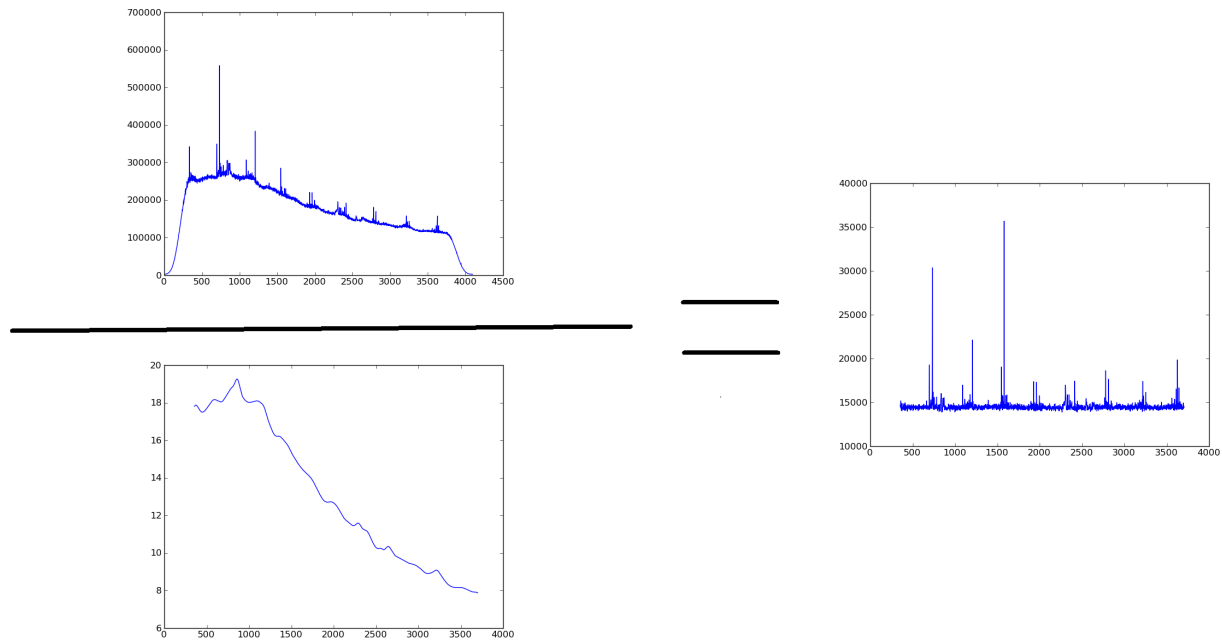


Figure 3.3: An example of bandpass removal. The shape of the original bandpass is divided by a fit to that bandpass.

persion,” which differs from “coherent dedispersion.” For dedispersion, we test a series of dispersion measures (DMs) on the observations; the intensity value in the final time series will be maximum, for a pulse, if the DM matches the actual DM of the source. To illustrate, in figure 3.6 we display a simulated spectrogram containing random noise with intensity from 0 to 1, spanning 34 MHz to 44 MHz, for 9 seconds, with a dispersed signal added in from 3 second to 4.5 second with an intensity that is normal-distributed, centered at a intensity value of 1 across the bandpass. The DM of the simulated pulse is 1 pc cm^{-3} . Figure 3.6(a) shows the spectrogram before dedispersion. Figure 3.6(c) shows the final time series for this simulated observation, made by summing along the frequency axis in the spectrogram. Clearly, before dedispersion, we can not detect the pulse in the final time series shown in figure 3.6(c). After dedispersion, when the trial DM matches the simulated DM, the signal across the bandpass lines up at the same time stamp, as shown in 3.6(b). Most dramatically, we can see an obvious peak in time series for the dedispersed spectrogram, as shown in figure 3.6(d).

In practice, the DM search range is chosen to be 1 to $5000 \text{ cm}^{-3} \text{ pc}$. The maximum value of the DM search range is chosen so that the dispersion time-lag cutoff in the time series after dedispersion is not too large (compared to duration of the observation).

The spacing of DM trials is chosen so that the time-smearing of a pulse is not large compared to the temporal resolution of the observations. From equation (1.20), the first-order approximation of the pulse time-lag across the bandwidth B_{MHz} is

$$\Delta t_{\text{dispersion}} = 8.3 \times \text{DM} \times B_{\text{MHz}} \times \nu_{\text{GHz}}^{-3} \mu\text{s}. \quad (3.1)$$

The change in pulse time-smearing for a change in DM is

$$\delta \Delta t_{\text{dispersion}} = 8.3 \times \delta \text{DM} \times B_{\text{MHz}} \times \nu_{\text{GHz}}^{-3} \mu\text{s}. \quad (3.2)$$

In our analysis we choose the DM trial-spacing so that the time smearing is not greater the minimum time smearing we can not erase across an frequency channel $\Delta \nu_{\text{MHz}}$:

$$\Delta t_{\text{dispersion}} = 8.3 \times \text{DM} \times \Delta \nu_{\text{MHz}} \times \nu_{\text{GHz}}^{-3} \mu\text{s}. \quad (3.3)$$

That gives

$$\frac{\delta \text{DM}}{\text{DM}} = \frac{\Delta \nu}{B}. \quad (3.4)$$

Note that this kind of spacing is proportional to the DM itself: the larger DM, the larger difference between DM and next DM trial.

3.3 Signal Detection

An astrophysical pulse is smeared in time due to propagation effects in space, such as dispersion, scattering, etc., and instrumental effects due to finite frequency binning and temporal

binning. We use post-dedispersion techniques to reduce the temporal broadening and produce an observed pulse in a time series. We dedisperse the observed data to retrieve the signal intensity, but because of finite temporal binning there is some unavoidable temporal smearing. As an example, a delta-function-shaped astronomical signal will be detected with a finite duration due to propagation influence and instrumental limitations. The approximate observed time resolution $\Delta\tau_r$ is described by Cordes and McLaughlin [89] as

$$\Delta\tau_r = (\Delta t_{\text{dispersion}}^2 + \Delta t_{\delta\text{dispersion}}^2 + \Delta t_{\text{scattering}}^2 + \Delta t_{\text{response}}^2)^{\frac{1}{2}}, \quad (3.5)$$

where each term is due, respectively, to dispersion smearing in a finite frequency channel width, error in dedispersion (i.e., incorrect DM), smearing due to scattering, and the filter response of an individual frequency channel. The dispersion smearing due to a finite frequency channel width is the time-broadening across the frequency channel. The dispersion error is caused by DM error in dedispersion process. The scattering smearing effect came from multipath scattering during the propagation. The last term, filter response, is due to the effect of a finite frequency channel width in the Fourier transform, which is $\approx 1/\Delta\nu$.

To identify the signals, we dedisperse the spectrogram, trying a series of DMs. The approximately correct DM will reduce the contribution to the smearing time from $\Delta t_{\text{dispersion}}$ to $\Delta t_{\delta\text{dispersion}}$. But there are still uncertainties in matching the temporal duration to the actual pulse width, attempting to maximize the SNR. To improve the SNR of a signal, we attempt pulse-width matching by using a series of temporal-averaging trials. The trials range from $2^0 \times 0.209 \text{ ms} = 0.209 \text{ ms}$ to $2^{15} \times 0.209 = 6.8 \text{ s}$ to search for a pulse which has a duration within that range. Each such time series is decimated so that a true pulse is represented in the final smoothed time series by 1 temporal sample, matched in width and location, with the highest SNR possible for that pulse. Decimation can be best described by an example. Imagine we have a time series of 1000 samples at the original temporal resolution of the data (e.g., 0.209 ms). Now, imagine that a true pulse in the time series is of approximate temporal width 2.09 ms and occurs at a specific time, of course. A time-averaging window of about 10 samples will best match the true width of the pulse and produce the greatest SNR for that pulse, compared to other time-averaging windows. In addition, the highest SNR in the time-averaged series will occur at the time sample at the center of the pulse. The other time samples before and after the center of the pulse will have smaller SNR values. Keeping every 10th sample in the final smoothed series removes redundant values and speeds the analysis. The pulse-width matching through time-series averaging and decimation, reduces signal smearing due to an incorrect temporal resolution. For each DM trial and for each temporal averaging, we record the SNR, time, time resolution, and DM trial when the $\text{SNR} > 5$ in the decimated, dedispersed time series, for further analysis. More details about further analysis will be discussed in chapter 8.

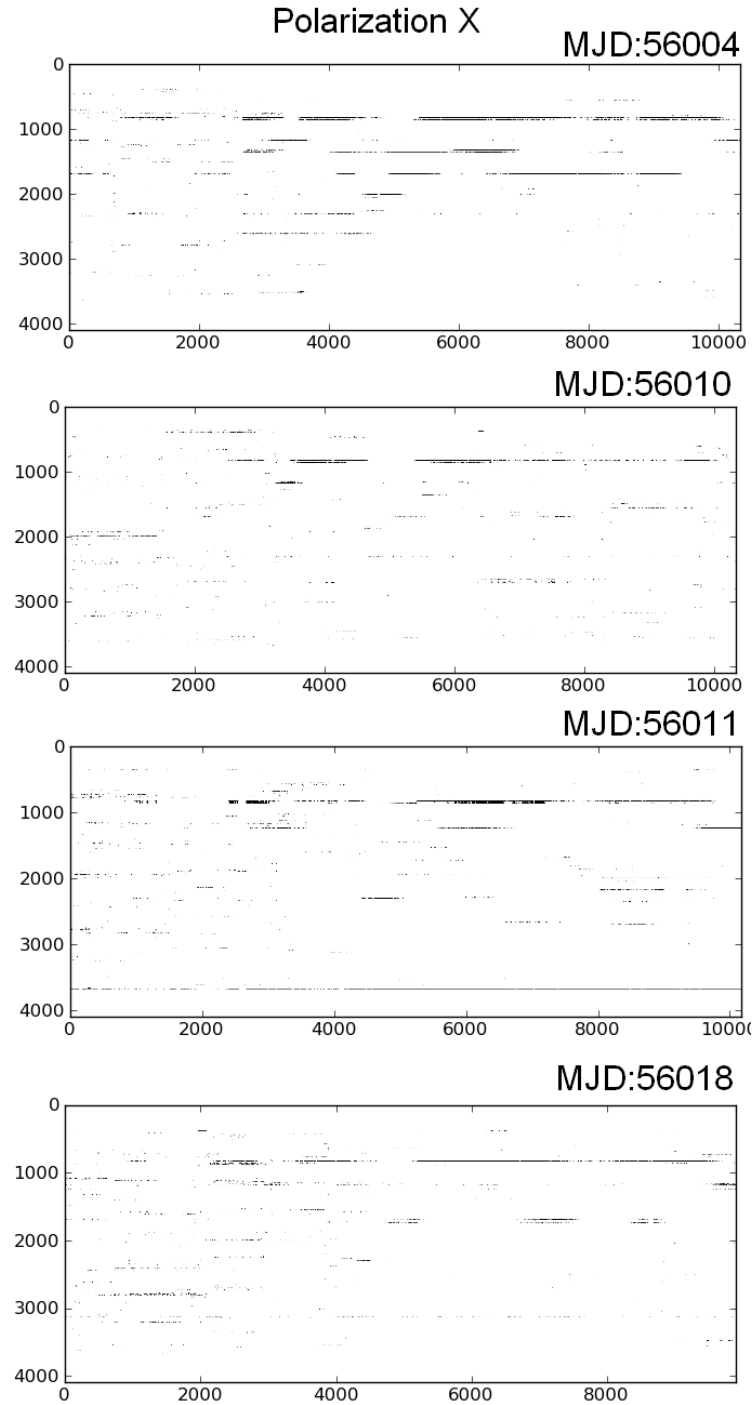


Figure 3.4: This panel shows RFI masks of polarization X for two polarizations, $4 \times$ six hours. The vertical axis is frequency bin number with frequency bin resolution of 4.7 kHz. The horizontal axis is the time bin number, a time bin resolution is 0.21 ms.

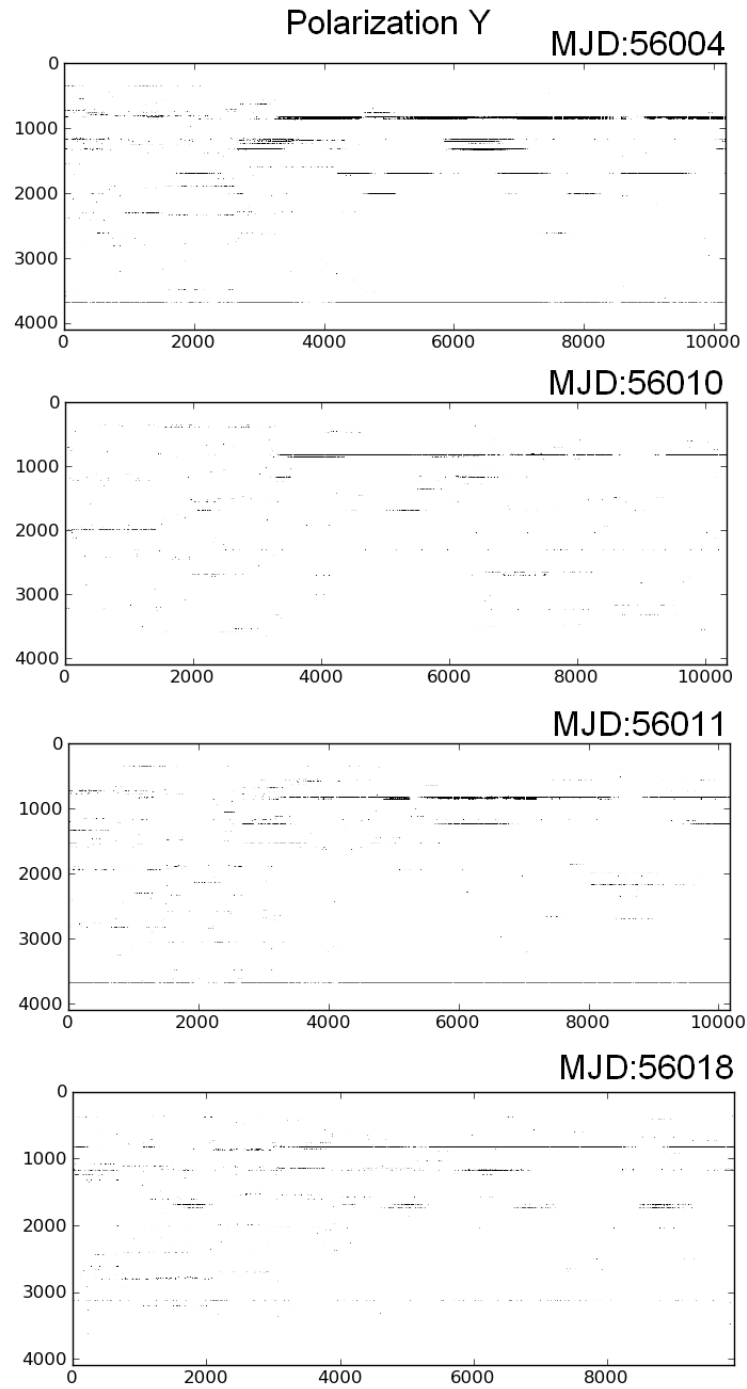


Figure 3.5: This panel shows RFI masks of polarization Y for two polarizations, $4 \times$ six hours. The vertical axis is frequency bin number with frequency bin resolution of 4.7 kHz. The horizontal axis is the time bin number, a time bin resolution is 0.21 ms.

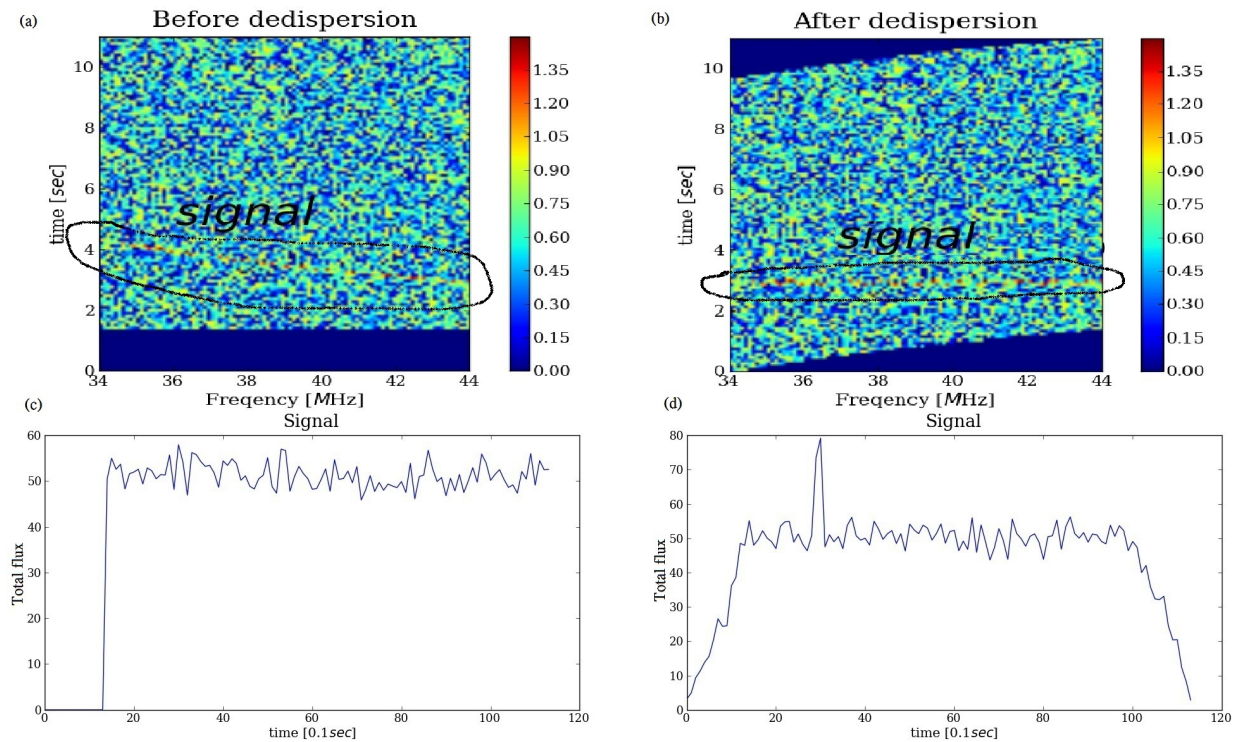


Figure 3.6: Simulation of dedispersion. (a) Random noise with an artificial dispersed narrow-width signal from 3 to 4.2 second. (b) After dedispersion, the spectrogram has been shifted in time as a function of frequency determined by the simulated dispersion. (c) The flux for all frequency bins in (a) are summed and plotted on the time axis. (d) After dedispersion, the flux for all frequency bins in (b) are summed and plotted on the time axis.

Chapter 4

Observations of Giant Pulses from the Pulsar PSR B0950+08

This chapter has been published in [1] (©2015 American Astronomical Society). The author of this thesis wrote the code for data collection, data processing, analysis, and figures. He wrote the first draft, then collected comments from the coauthors, then revised the paper. Lastly, he used the referee review for the submitted paper to finalize the published version of this work.

4.1 Introduction

Singal and Vats [95] define GPs as pulses with flux densities greater than ten times the mean pulse, for PSR B0950+08. In this chapter we present observations of pulses from PSR B0950+08 with large intensity relative to the mean pulse, i.e., pulses with SNR at least 10 times that of the mean pulse, equivalent in practice to the GP definition adopted by [95]. For simplicity, brevity, and comparison with previous work on PSR B0950+08, we will refer to our large intensity pulses as GPs.

GPs have been associated with PSR B0950+08 in previous observations [23, 25, 95]. Reference [23] has observed GPs for this pulsar at 112 MHz, during observing sessions of 3 minutes, over 22 days, finding pulses with strengths up to two orders of magnitude larger than the mean pulse strength. Reference [95] observed this pulsar at 103 MHz daily for half an hour over ten months. They found that $\sim 1\%$ of the total pulses had a strength greater than 20 times the mean flux density, and $\sim 0.01\%$ were greater than 100 times the mean flux density. Their observations also suggested that the GP temporal distribution is not uniform, with extremely active and silent days. Reference [95] defined GPs in their observed data as

pulses with flux densities at least ten times as large as the mean pulse flux density, while reference [23] uses a factor of 5 as the threshold for GPs. We will adopt 10 times the mean pulse strength as the threshold for GPs in our data.

In this chapter we discuss 39.4 MHz observations we made of pulses from PSR B0950+08 using LWA1. In section 4.2 we discuss the LWA1 and our observations. Section 4.3 details how we produced spectrograms from the data, and conducted a preliminary search for individual pulses across a large range of dispersion measures (DMs), finding statistically significant pulses only at the DM of PSR B0950+08. Then, in section 4.4, we explain how we performed a detailed search of our full data set for pulses at the DM of the pulsar, and measured the strength of each pulse; we specify pulse strength by SNR relative to the SNR of the mean pulse. We also discuss the statistics of our observed pulses in that section. In section 4.5, we assign approximate flux densities to the mean pulse and GPs, and compare these results to those of previous studies. Finally, we present our conclusions in section 4.6.

4.2 Observations, Data Processing & Preliminary Pulse Search

We used LWA1 to observe PSR B0950+08 for 30 hours, in 6-hour blocks, over 5 days during late March and early April 2012. Observations were started about 45 minutes before the transit of PSR B0950+08 in each observing session. We tracked the pulsar with 2 beams. Each beam had 2 frequency tunings, yielding observations centered at 19.8 MHz, 39.4 MHz, 59.0 MHz, and 73.7 MHz, each with a bandwidth of 19.6 MHz (the useful bandwidth is 16 MHz after data processing). The observations were done during the commissioning period for LWA1. In the end, only 24 hours of observations (4 six-hour observing blocks) for one beam, centered on 39.4 MHz, were analyzed. The observing sessions analyzed here are for the observing dates March 18, 24, 25, and April 1. These were the cleanest data, and, by using them, we avoided some pointing-error issues which influenced the results at higher frequencies. These observations were made before Initial Operating Capability was reached on April 24, 2012; thus the current instrument now has better sensitivity and the pointing issues have been fixed.

Using routines from the LSL [86], we performed a 4096-channel Fast Fourier Transform (FFT) on each 0.209 ms of raw data, dividing the 19.6 MHz observing bandwidth into channels of 4.785 kHz. Radio Frequency Interference (RFI) mitigation was performed on the data set using the following procedure. First, we obtained the average spectrum for each 2.09-s interval (each set of 10,000 consecutive spectra). Next, we fit a 16th order polynomial to the 2.09-second average spectrum, and divided that average spectrum by the polynomial. The 16th order polynomial is the lowest order that fits the approximately 16 ripples in the bandpass, without undue suppression of narrow-band RFI. Finally, any frequency bin

in the 2.09-s average spectrum that was greater than 3σ above the mean was masked as contaminated by RFI in all the corresponding 0.209-ms spectra.

The shape of the observed bandpass is not constant in time, and this variation must be removed to allow for an effective search for transient pulses. The variation in the spectrum is dominated by the diurnal variation of the galactic background. Once the RFI-contaminated frequency bins were identified and masked, we determined and removed the varying shape of the bandpass using the following procedure. First, for each 2.09 s of data, we computed a median spectrum for the 10,000 RFI-masked spectra. Then, we used 150 such spectra to compute the median spectrum for approximately 5 minutes of observations. The 5 minute duration was chosen so the diurnal variation of the Galactic background was effectively smoothed out. To further smooth the 5-minute spectrum, we performed a moving boxcar average across the 5-minute median-spectrum; the boxcar length used was 101 frequency channels. Finally, we divided each 0.209-ms spectrum by the boxcar-smoothed spectrum corresponding to its epoch. To prepare for further analysis we removed the first 360 channels and the last 395 channels from each spectrum, removing any end effects, and leaving a final bandwidth of 16.0 MHz. The final spectra were arranged into spectrograms of frequency (vertical axis) and time (horizontal axis). Reference [30] were able to visually identify Crab GPs in spectrograms. Figure 4.1 shows a portion of a full spectrogram (only 2.4 MHz, not the full 16 MHz, and only a few seconds of data) displaying one of our stronger GPs, along with the corresponding time series obtained by dedispersing the displayed data at the DM of PSR B0950+08.

Cordes and McLaughlin [89] describe in detail a technique suitable for searching for individual pulses of various origins, including pulsar giant pulses, in time-frequency data such as ours. As a first look, we used this method on our data, taken in chunks of 5-minute duration. In essence, the technique consists of constructing dedispersed time series for a range of candidate DMs and smoothing each individual time series with effectively larger and larger averaging-boxcars to search for pulses of temporal width matched to the smoothing time — which yields the best SNR for a candidate pulse. Pulses of strengths and numbers larger than expected for the (assumed) Gaussian noise in our data are pulses of possible astrophysical origin. (Another possibility is that they are RFI or other transient non-astrophysical events, but candidate pulses of the correct DM for PSR B0950+08 are more likely to be our sought-after pulsar pulses.) We performed incoherent dedispersion (summing intensities) in our spectrograms. We searched through time series for 15,030 candidate DMs in this manner, ranging from 1.0 to 89.9 pc cm⁻³. The DM spacing is given by

$$\delta\text{DM} = \text{DM} \frac{\Delta\nu}{B}, \quad (4.1)$$

where B and $\Delta\nu$ are the bandwidth and channel-width respectively. Thus the temporal smearing due to DM spacing is equal to temporal smearing across a frequency channel, which can not be removed. The time series was smoothed in steps by averaging a moving boxcar of width equal to 2 time samples, and then removing one of the resulting time samples.

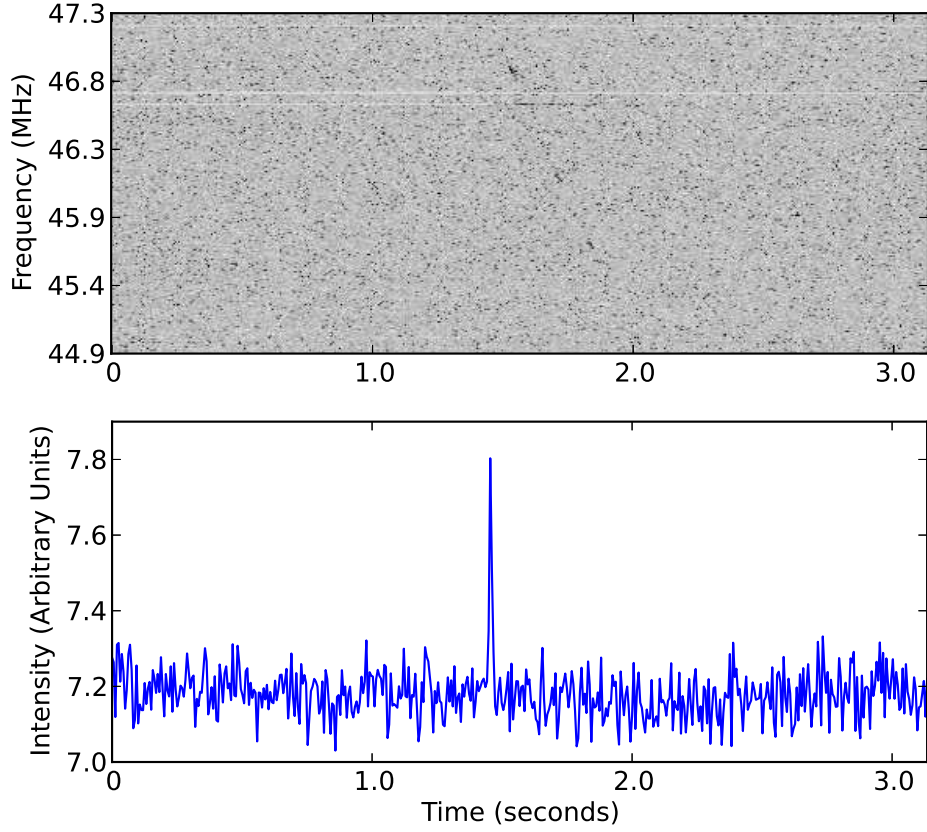


Figure 4.1: A portion of a full spectrogram chosen to show a detected giant pulse, accompanied by the dedispersed time series constructed from the data displayed, for $DM=2.97 \text{ pc cm}^{-3}$. The pulse can be seen in the displayed spectrogram as a series of narrow linear features running along a sloping, slightly curved path from earlier arrival times at high frequency (starting at $\sim 1.4\text{s}$) to later arrival times at low frequency (ending at $\sim 2\text{s}$). The dedispersed time series is constructed by summing the displayed spectrogram values in frequency, after shifting each frequency in time to compensate for the later arrival time of lower frequencies. Horizontal features can be seen in the spectrogram; these features are frequency bins masked due to RFI contamination. The SNR of the pulse in the displayed time series is about 8.8 (treating the pulse as an isolated event). In the time series constructed from the full 16-MHz spectrogram, this pulse has $SNR=21.7$. The ratio of this pulse's SNR to that of the mean pulse is 16.4.

Repeated smoothing and decimating in this manner efficiently produces a set of time series of increasing smoothness. At each smoothing and decimation step the resulting time series was searched for pulses. We performed 15 such steps for each dedispersed time series. Thus, the final time sample duration in the last-smoothed time series was $2^{15} \times 0.2089\text{s} = 6.85\text{s}$.

A representative 5-minute result of this DM-space search is shown in figure 4.2. In the entire search we found transient events in the resulting time series with SNRs $\gtrsim 6.5$ were for a DM of 2.97 pc cm^{-3} , the DM for PSR B0950+08. No such strong pulses were found at other DMs. Furthermore, as indicated in the figure (and as explained by Cordes and McLaughlin), the expected number of transient events due to Gaussian noise matches well our numbers of events at $\text{SNR} < 6.5$, but events of $\text{SNR} > 6.5$ are more numerous than expected from Gaussian noise alone, and appear at the DM of the pulsar. Thus we are confident that by focusing on transient events that have a $\text{SNR} > 6.5$, determined through this procedure, we are selecting pulses produced by PSR B0950+08.

We note here that the SNR determined for a pulse by the Cordes-McLaughlin procedure is computed in the time series smoothed to the temporal width of the pulse. This is a precise means of quantifying the SNR of a temporally-isolated *single, dispersed pulse*, and, as such, is perhaps reasonable for describing anomalously intense pulses or giant pulses, which tend to be isolated. But, it should be noted that quoted pulsar flux densities are averages in time, including both energy received during pulses, *and* between pulses, i.e., effectively zero. Thus, when we measure the SNR of our large pulses and compare them to the SNR of the mean pulse, we will adopt the more conventional time-average throughout a pulse period.

We searched through time series for 15,030 candidate DMs in this manner, ranging from 1.0 to 89.9 pc cm^{-3} . To further explore the parameters necessary to conduct an effective and efficient search for large individual pulses from PSR B0950+08, we searched one 5-minute sequence of bandpass-corrected 0.209 ms spectra using an incoherent dedispersion routine with trial DMs within 2.965 to 2.975 pc cm^{-3} . The transient time-sample events with highest SNR in the resulting time series were obtained for a $\text{DM} = 2.970\text{ pc cm}^{-3}$. Thus, we narrowed our subsequent search for GPs within the entire data set to this value of DM.

4.3 Pulses from PSR B0950+08

4.3.1 The Mean Pulse

The mean pulse profile is an average of the “folded” time series for the entire 6-hours. The folding occurred at the pulse period (253.077573 ms) and was optimized by using PRESTO [96] after converting the data into the PSRFITS format. This pulse profile is also smoothed such that there are 64 time bins across the pulse period (each time sample is about 4 ms).

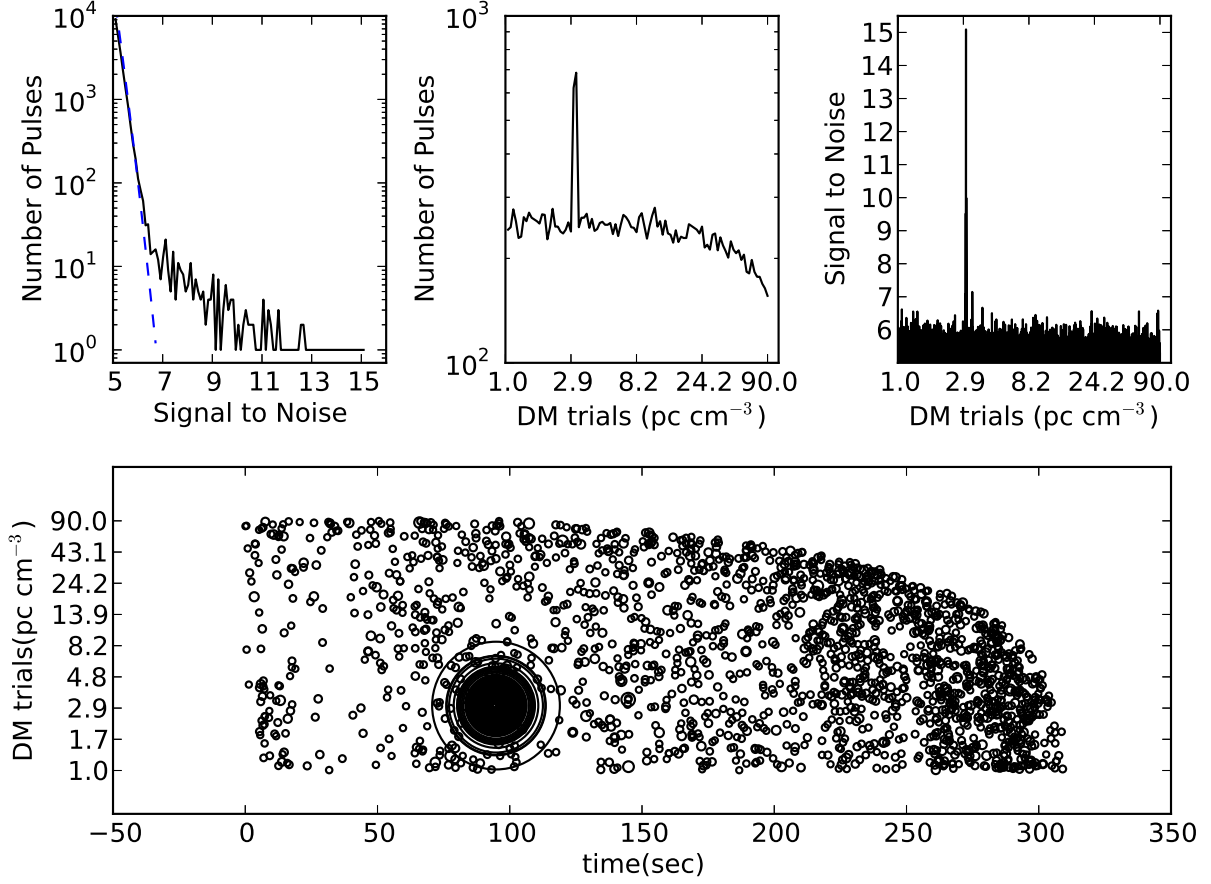


Figure 4.2: A representative result from a large DM-space search for transient pulses in one of the 5-minute subsets of data, following the method of [89]. Only events (generically called “pulses” by [89]) in the time series with $\text{SNR} > 5$ are displayed. The upper left panel shows that the number of pulses versus SNR deviates from the result expected in the case of Gaussian noise (the dashed blue line), only for $\text{SNR} > 6.5$. Thus events with $\text{SNR} < 6.5$ cannot be distinguished from Gaussian noise in the time series, and should not be construed as actual pulses from PSR B0950+08. A single giant pulse in this 5-minute observation will produce multiple events in the search across DMs similar to the pulsar’s DM. The upper middle and upper right panels show a peak appearing at the appropriate DM for PSR B0950+08. The upper middle panel displays the number of events found (with $\text{SNR} > 5$) versus DM. The upper right panel is a plot of events found with $\text{SNR} > 5$ versus DM. The lower panel shows a strong pulse appearing (as the large blackened circle) in the dedispersed time series for the appropriate DM; the radius of the circle shown is proportional to the SNR. The absence of circles in the upper right of that lower panel is due to the time shifting inherent in the dedispersion procedure, applied to a data set of finite temporal duration. Due to limited resolution, not all pulses at the DM of PSR B0950+08 with $\text{SNR} > 6.5$ can be seen in the lower panel.

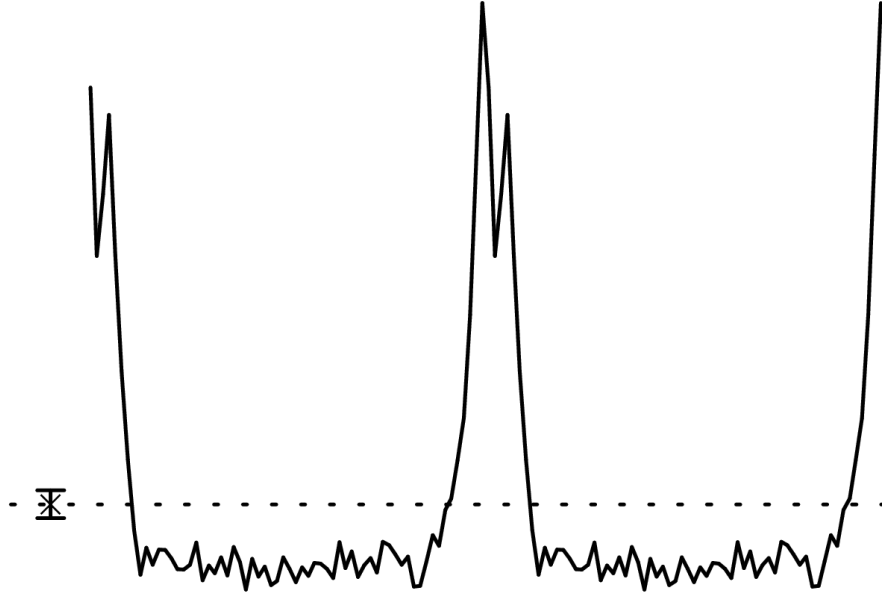


Figure 4.3: The mean pulse profile obtained from PRESTO [96], for one of the 6-hour observing sessions. Note that the time span displayed is two pulse periods. The dashed line is the average intensity in the profile, the error bars represent the rms of all the intensity values.

The normal pulses would be undetectable individually (in the sense discussed in the previous section), but the mean pulse is detectable due to a huge amount of possible folds in the data set. This mean profile is in agreement with the normal pulse profile for PSR B0950+08 in pulse period, pulse width, and pulse shape [31]. The main purpose in running PRESTO independently on our data was to verify the data processing software used for this work. For subsequent analysis, we used programs we wrote, for increased flexibility in analysis. Our mean pulse profiles are consistent with the PRESTO result, as discussed below. In the PRESTO mean pulse profile, and in our mean profiles, it is apparent that there are two components. These components are closely separated in time. We characterize the strength and width of the mean, and giant pulses, by fitting a single Gaussian to a pulse. This is justified in part by the lack of scatter broadening observed in the giant pulses with a single peak. This especially simplifies the analysis of *single* giant pulses, where the noise in the baseline is stronger relative to the peak of a pulse, than in the case of the mean pulses shown in figure 4.3 and figure 4.4.

The PRESTO output indicated that the strength of the pulsar appeared to systematically decrease throughout the 6-hour observing session. We investigated this behavior more carefully by writing a program to fold and sum the data in 5-minute chunks throughout the observing sessions, without smoothing the time series, using the pulse period optimized

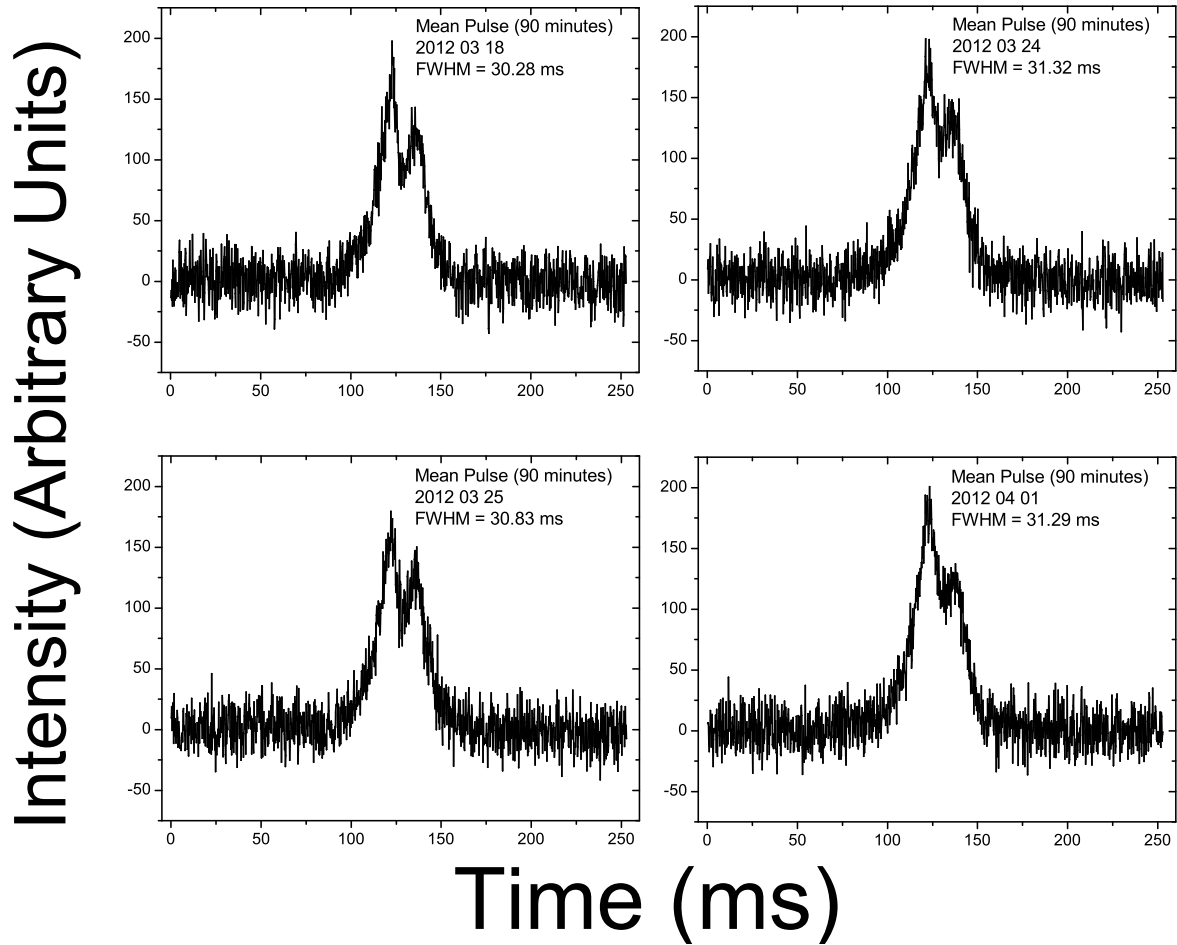


Figure 4.4: Mean pulse profiles from the first 90 minutes of each of the four observing sessions, when PSR B0950+08 was near transit. The time span displayed is one pulse period. The average FWHM pulse width is approximately 30.5 ms, as determined by fitting a single Gaussian to each of these profiles.

by using PRESTO. Figure 4.5 shows the resulting average SNRs during a pulse period as a function of time, for three of the 6-hour observing sessions. The systematic behavior in each observing session is the same, peaking about 40-45 minutes after the start of a session, corresponding to the transit of PSR B0950+08. We interpret this behavior as indicating a decrease in beam sensitivity as a function of increasing zenith angle. Note that by watching the behavior of the SNR, we automatically include both the decreased effective collecting area of the array with increasing zenith angle, and the increased system noise with increasing zenith angle (see Section 5). We fitted a third-order polynomial through these data, and normalized the SNR and polynomial values to unity at the maximum of the polynomial; we used this normalized curve to systematically correct all SNR measurements determined by subsequent analysis (multiplying pulse strengths by the appropriate factor which would make the SNR in the figure equal to the typical SNR at transit).

The mean pulse profiles determined from folding our data during the first 90 minutes of each of the four observing sessions, are shown in figure 4.4. Note the fairly consistent shape and strength of these mean pulse profiles; the consistent mean-pulse strength is apparent, by comparing the height of each pulse to the rms in each panel. A fitted Gaussian shape is used to measure the mean pulse strength and width for each panel. The mean pulse has a FWHM of about 30.5 ms. The SNR of each displayed mean pulse is clearly quite high. We took the average SNR throughout the full pulse period for each of these displayed pulses (signal = sum of the fitted Gaussian values, rms = rms in the baseline), and averaged the four results (which were within 10 percent of each other), then reduced the average by $\sqrt{N_{\text{folds}}}$, where N_{folds} is the number of folds necessary to produce the profiles shown, obtaining the SNR of the mean pulse for our observations, $\text{SNR}_{\text{mean pulse}}$. This is the SNR that can be assigned to a *single, typical pulse*, and can be used to characterize the SNR of any individual large pulse we detected, through the ratio $\text{SNR}/\text{SNR}_{\text{mean pulse}}$. Even in the absence of accurate flux density values for the mean pulse and individual large pulses, this ratio is a reasonably precise characterization of an individual large pulse's strength.

4.3.2 Individual Large Pulses

Four six-hours dedispersed time series ($\text{DM}=2.9702 \text{ pc cm}^{-3}$), with 0.209 ms time samples, were constructed by averaging the time series for the two orthogonal polarizations. Reading data, and a few other organizational steps, were carried out using LSL routines [86]. These time series were searched for individual large pulses using the following procedure. First, we found each individual time sample with a $\text{SNR} > 3.5$. Then, we fitted a Gaussian to the 1000 time samples centered on the $>3.5\sigma$ sample, and obtained the FWHM of the resulting Gaussian. We isolated the subset of time samples of total duration equal to 2000 FWHM as the baseline, which centered on the candidate pulse. Next, we decimated this time series by computing average values in intervals of length equal to the FWHM, making sure one interval was centered on the $>3.5\sigma$ peak. Then, we computed the SNR of the potential GP

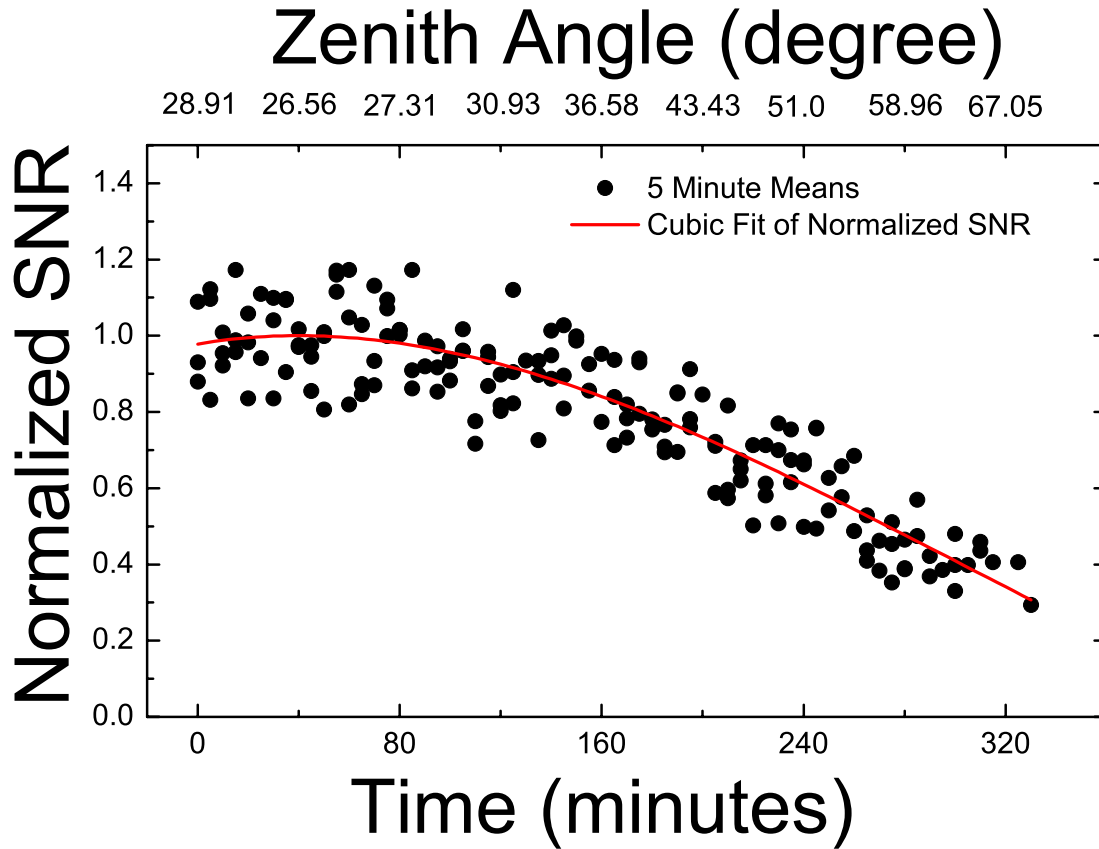


Figure 4.5: The average SNR in 5-minute intervals, during three of the 6-hour observing sessions. A few 5-minute averages were removed since they deviated significantly from the typical result, due to the presence of especially strong GPs. A third-order polynomial fit to the data is shown. The SNRs have been normalized, such that the fit peaks at a value of 1, which occurred at about the transit time of PSR B0950+08. The PSR B0950+08 passed the meridian with a zenith angle = 26.15 at 48 minutes after the first frame of observation.

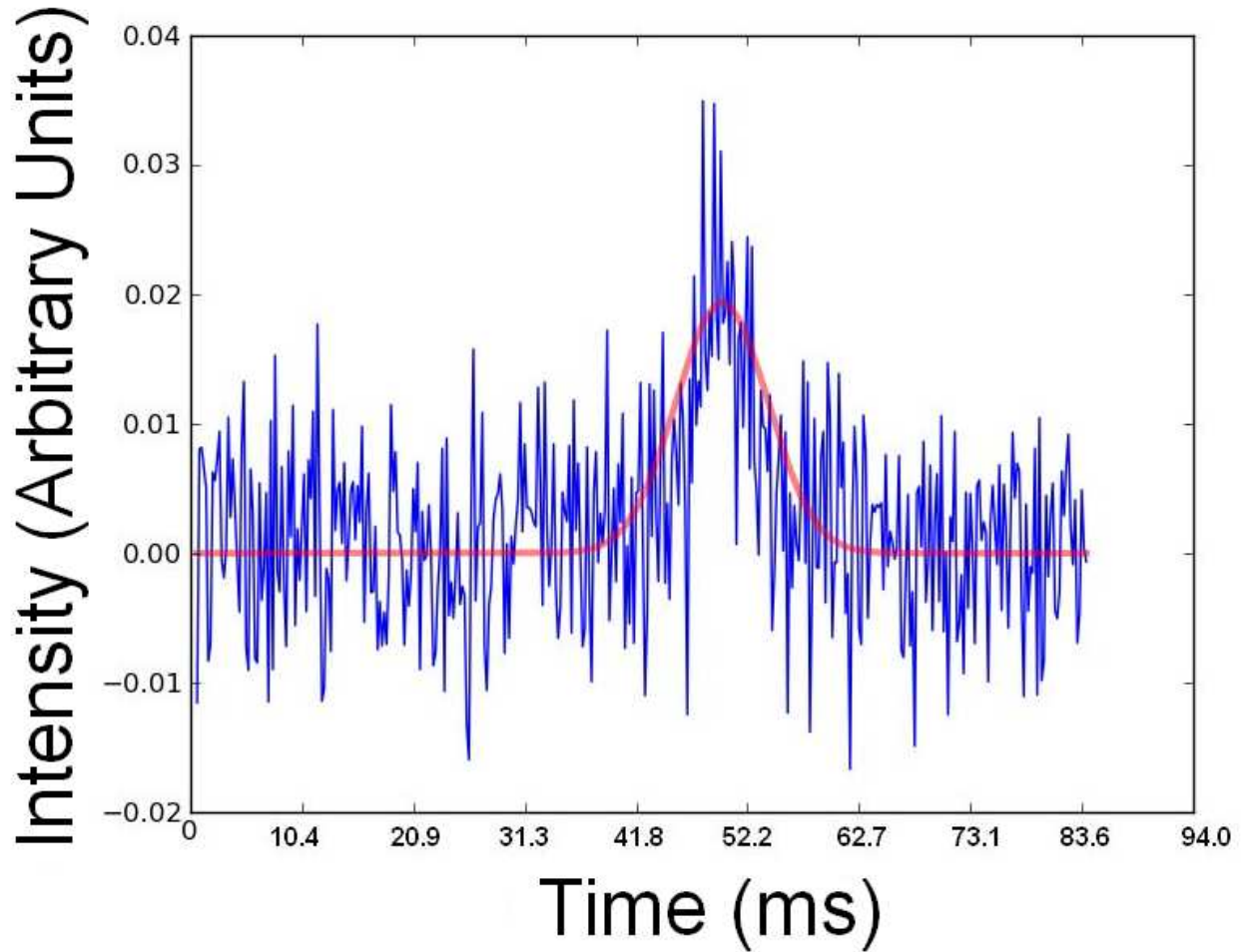


Figure 4.6: A dedispersed time series at the pulsar’s DM. Also shown is a Gaussian fit, clearly matching a pulse.

in the decimated time series. If this SNR was >6.5 , we recorded this event as a pulse. Note here the SNR for the event is taken to be the SNR in the decimated time series, in the sense used in the Cordes-McLaughlin technique, ensuring we are capturing pulses that are not part of the Gaussian noise in our time series data. As a further check on the reality of each pulse detected in this manner, we only kept candidate pulses with a FWHM that fell in a nominal range of 4.178 ms to 41.78 ms (20 to 200 of the 0.209-ms time samples); this pulse width range includes the width of the best candidate pulse in the initial 5 minutes of data we searched, and the duration of the double-peaked pulses we found in those data. Finally, we avoided double counting GPs by keeping only candidates that were at least 40 ms away from any other candidate pulse. An example pulse is shown in figure 4.6. Some dual-peak pulses are shown in figure 4.7.

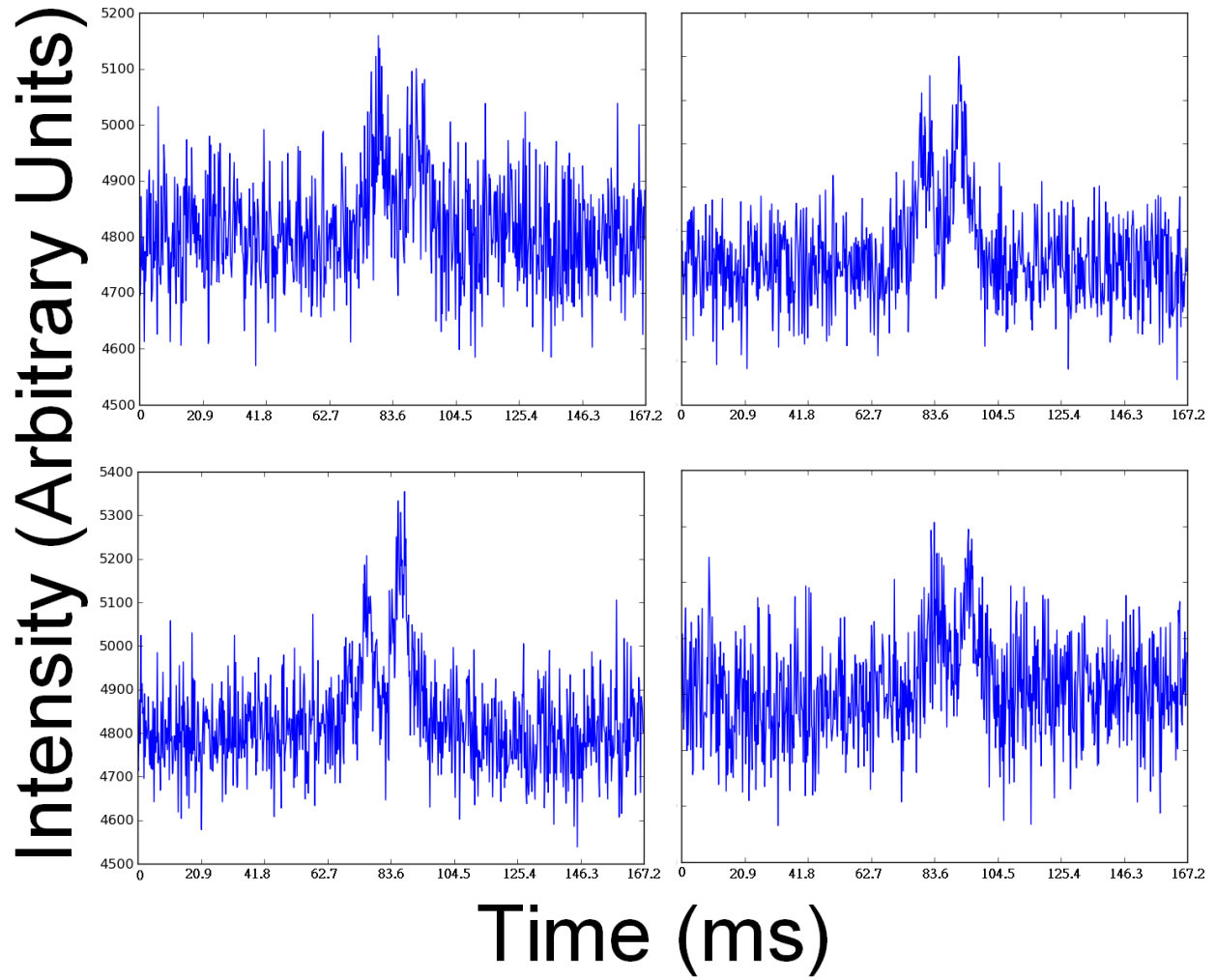


Figure 4.7: Examples of GPs with double peaks in the dedispersed time series. The typical time difference between peaks is about 10 ms.

4.3.3 Results

Using the methods discussed above, we detected 398 individual pulses in the 24 hours of observed data; these are pulses that are strong enough to not be considered part of the Gaussian noise in the time series data. Using the definition of [95] for giant pulses ($\text{SNR}/\text{SNR}_{\text{mean pulse}} > 10$), the number of such GPs is 119, or about $119/(24 \times 3600/0.253) \approx 0.035\%$ of the total number of pulses that occur in the 24 hours. The maximum value of $\text{SNR}/\text{SNR}_{\text{mean pulse}}$ for an individual pulse in our data set is 28.2, corresponding to a pulse of temporal width 19.6 ms (FWHM), considerably narrower than the pulse width of the mean pulse (30.5 ms).

Nearly all the GPs have a double-peaked profile. It may be that all are double-peaked, but one peak may be hard to discern given the noise in the single-pulse profile. To measure GP pulse strength and width, we fit a single Gaussian to the profile, as we did for the mean pulse, which simplifies the analysis and allows for a valid comparison of the GPs with the mean pulse. Figure 4.7 shows some GP profiles displaying two peaks.

Figure 4.8 displays a histogram of the detected pulses, in terms of $\text{SNR}/\text{SNR}_{\text{mean pulse}}$. GPs are those with $\text{SNR}/\text{SNR}_{\text{mean pulse}} > 10$. The number of GPs decreases sharply with increasing strength. Figure 4.9 shows a histogram of the GP widths. The average GP width (FWHM) is 17.8 ms, about half the width of the mean pulse.

Figure 4.10 shows the cumulative pulse strength $N(> S)$ distribution, where the strength S is the relative SNR, i.e., $S = \text{SNR}/\text{SNR}_{\text{mean pulse}}$. The figure shows a power-law fit to the GPs only ($S > 10$) which yields $N(> S) \propto S^{-4.7}$. It is apparent that the GPs we observed have a different distribution than pulses with relative $\text{SNR} < 10$. The distribution for the GPs is not as steep as would occur for normal pulses in the tail of a Gaussian distribution. For a Gaussian probability distribution, the fraction $f(> z)$ of pulses with strength greater than $z\sigma$ from the mean is given by

$$f(> z) = \frac{1}{2} \operatorname{erfc} \left(\frac{z}{\sqrt{2}} \right). \quad (4.2)$$

To obtain $f(> z) = 0.00035$, requires $z = 3.39$, and $d \log f / d \log z \approx -12.4$ at $z = 3.39$, much steeper than our value of -4.7 . Thus, the observed $N(> S)$ power-law implies the GPs are not in the tail of a Gaussian distribution of normal pulses.

Interestingly, a -4.7 power-law is steeper than found by [95] (-2.2) or [23] (-1.84 at the steepest), at frequencies just over 100 MHz. Their observations also show PSR B0950+08 to be stronger (larger mean flux density), to produce stronger GPs (as discussed in the next section), and to produce GPs at a higher rate than for our observations at 39.4 MHz (reference [95] report $\sim 1\%$ of the pulses in their observing period were GPs). All these results, taken as a whole, may indicate PSR B0950+08 is a weaker producer of GPs at 39.4 MHz, than at ~ 100 MHz. Reference [95] found there was a large day-to-day variation

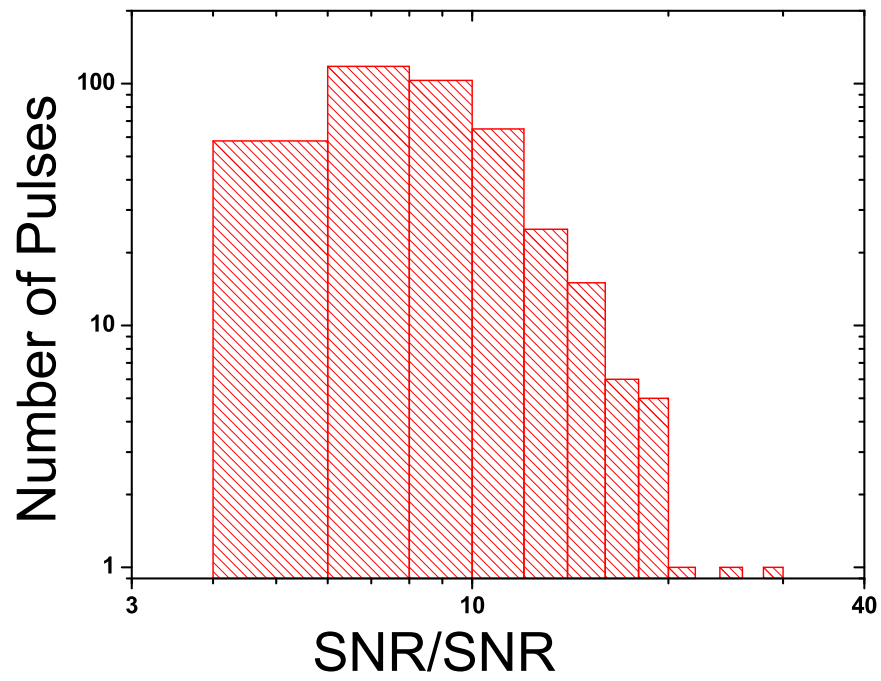


Figure 4.8: The histogram of detected pulses, given in terms of pulse SNR relative to that of the mean pulse. Giant pulses are those that have SNRs that exceeded that of the mean pulse SNR by at least a factor of 10.

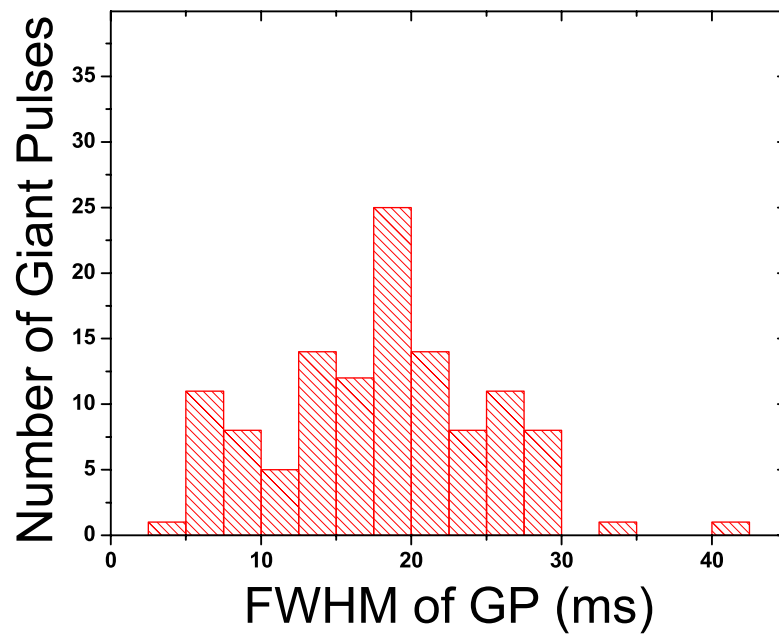


Figure 4.9: The histogram of temporal widths (FWHM) for single-Gaussian fits to the individual giant pulses. The average value is 17.8 ms. For comparison, the FWHM value for a Gaussian fit to the mean pulse is 30.5 ms.

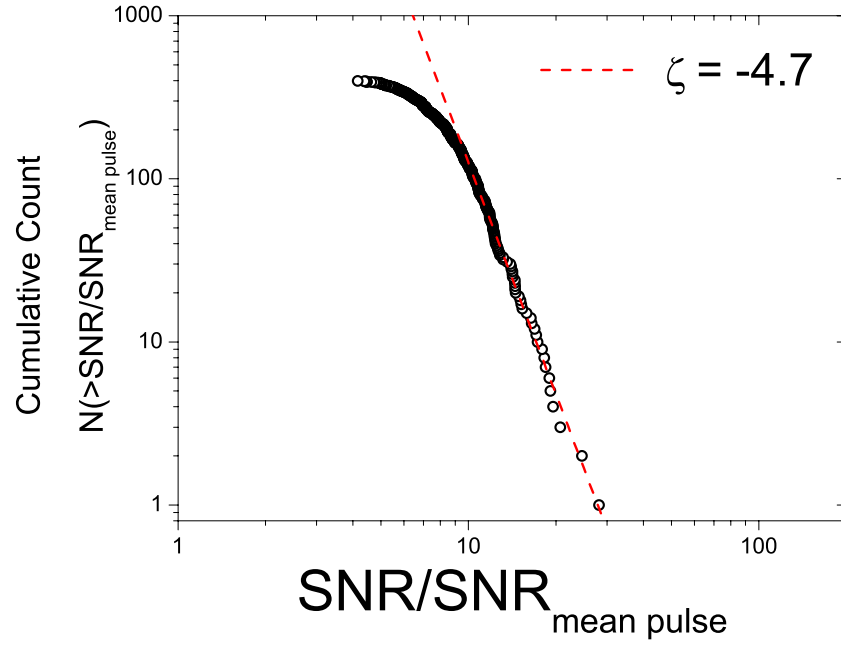


Figure 4.10: The cumulative number of pulse strength $N(> S)$ where S is the SNR relative to the mean pulse SNR, i.e., $S = \text{SNR}/\text{SNR}_{\text{mean pulse}}$. The number of pulses per hour with relative SNR exceeding the value S can be determined by dividing $N(> S)$ by 24 hours. A power-law fit to GPs only ($S > 10$), yields $N(> S) \propto S^{\zeta}$, where $\zeta = -4.7$.

in the rate of GPs they observed with more than 99% of their GPs occurring during $\sim 25\%$ of their observing sessions. By contrast, the number of GPs we observed over the four separate 6-hour observing sessions were 11, 41, 31, and 36, thus the same (to within root N) for three of the four observing sessions. Apparently, PSR B0950+08 is also less variable in its GP output rate at 39.4 MHz, according to our observations.

4.4 Flux Densities

Our observations did not include any drift scans of strong flux density sources, so we obtain rough flux densities for the mean pulse and our individual larger pulses using an estimated SEFD. One SEFD is the flux density a source in a beam needs, in order to produce a SNR of unity for an observation of 1 Hz bandwidth and integration time of 1 second. The system noise is overwhelmed by the emission from the Galaxy below 100 MHz. Ellingson created a model to assess the SEFD, which takes account of all sources of noise [97]. Ellingson [87] adopts a uniform brightness temperature of sky T_b in his model, determined by observing frequency ν , where

$$T_b = 9751\text{K} \left(\frac{\nu}{38\text{MHz}} \right)^{-2.55}. \quad (4.3)$$

The ground temperature and the receiver noise is negligible. This model when applied to LWA1 shows that beams are less sensitive when pointing away from zenith. Reference [28] checked this model with observations of strong flux density calibrators, finding the results roughly correct. Based on the model of Ellingson and his drift scan results, and given our observations of PSR B0950+08 at transit are for a zenith angle of about 26° , we estimate that an appropriate SEFD to use for our observations at transit is 15,000 Jy, with an uncertainty of roughly 50%. The SNR of pulses away from the moment of transit are corrected by a factor which compensates for decreasing effective collecting area and increasing SEFD, with increasing zenith angle.

Thus, the flux density we assign to a pulse, as averaged across the entire pulse period, is

$$S_\nu = \frac{\text{SEFD}}{\sqrt{2B\Delta t}} \frac{1}{N_{\text{bins}}} \sum_{i=1}^{N_{\text{bins}}} \frac{I_i}{\text{rms}} = \frac{\text{SEFD}}{\sqrt{2B\Delta t}} \text{SNR} \quad (4.4)$$

where $\text{SEFD} = 15,000$ Jy, $B = 16 \times 10^6$ Hz is the bandwidth, $\Delta t = 0.2089 \times 10^{-3}$ s is the duration of a time sample, $N_{\text{bins}} = 1211$ is the number of time samples (bins) in a pulse period of 253 ms, the sum is over the full pulse period, the I_i are the intensity values (arbitrary units) in the Gaussian pulse profile fitted to a pulse (a baseline average was already subtracted from the data), rms is measured in the baseline, and the average SNR during the pulse period. Taking the bandwidth as a full 16 MHz is appropriate, despite the masking of RFI in the spectrograms, since less than 1% of the data were lost to RFI.

In determining pulse flux densities we made no corrections for the LWA1 pointing errors known to be present at the time of the observations. Reference [98] indicates that telescope operators were making manual adjustments to pointing in late March 2012, and then starting on April 4, 2012, corrections were made automatically before running any observing file. These corrections were -7 minutes in RA and $+1^\circ$ in declination; at the declination of PSR B0950+08 this amounts to a total correction of about 2° . Assuming those pointing corrections may not have been applied during our observations (and should have been), we can estimate the resulting decrease in flux density that would have resulted. Assuming a beam FWHM of $4.3^\circ \times (39.4/74)^{-1.5}$ [28], or $\approx 11.1^\circ$, and a Gaussian beam shape, the measured flux density would be 98% of the true flux density, a negligible difference, especially given our 50% uncertainties in flux density.

The mean pulse for our observations has a flux density of 1.5 ± 0.75 Jy. Since our “threshold” for declaring the detection of a giant pulse is set at $\text{SNR}/\text{SNR}_{\text{mean pulse}} > 10$, the corresponding flux density is 15 ± 7.5 Jy. Our pulse with the largest $\text{SNR}/\text{SNR}_{\text{mean pulse}} = 28.2$ has a flux density of 42.3 ± 21 Jy.

Figure 4.11 shows flux densities for normal pulses from PSR B0950+08 at frequencies of 408 MHz and above, along with observations of the mean and giant pulses by [95] at 103 MHz and [23] at 112 MHz. In addition, we have added data points for the mean and giant pulses we observed. The error bar on our mean pulse flux density indicates our 50% uncertainty. The range of our GPs are indicated by a solid red vertical line, with upper and lower error bars indicated. Apparently our mean pulse and giant pulses are weaker than those found by [95] at 100 MHz, and [23] at 112 MHz. This is consistent with the work of [99] where it was found that the mean flux density at 39.4 MHz appears to deviate more from the power law fit to higher frequencies than occurs at ~ 100 MHz. As we noted in Section 4.3, the cumulative pulse strength $N(> S)$ distribution has a steeper power-law for the GPs than found by [95], and [23]. All these results perhaps indicate that PSR B0950+08 is weaker, and produces less frequent and less intense giant pulses at 39 MHz than at 100 MHz.

4.5 Scatter Broadening

Spatial variations in the interstellar free-electron number density are accountable for the scattering and scintillation of radio propagating through the interstellar medium. Pulsar observations are particularly useful for measuring the effects of interstellar scattering, and therefore characterizing the interstellar electron-density irregularities.

Analysis of interstellar scattering often uses a thin screen between the source and observer, containing electron number-density fluctuations with a power-law spatial power spectrum [104]. For wavenumbers q between the outer and inner scales of the irregularities, q_o and q_i ,

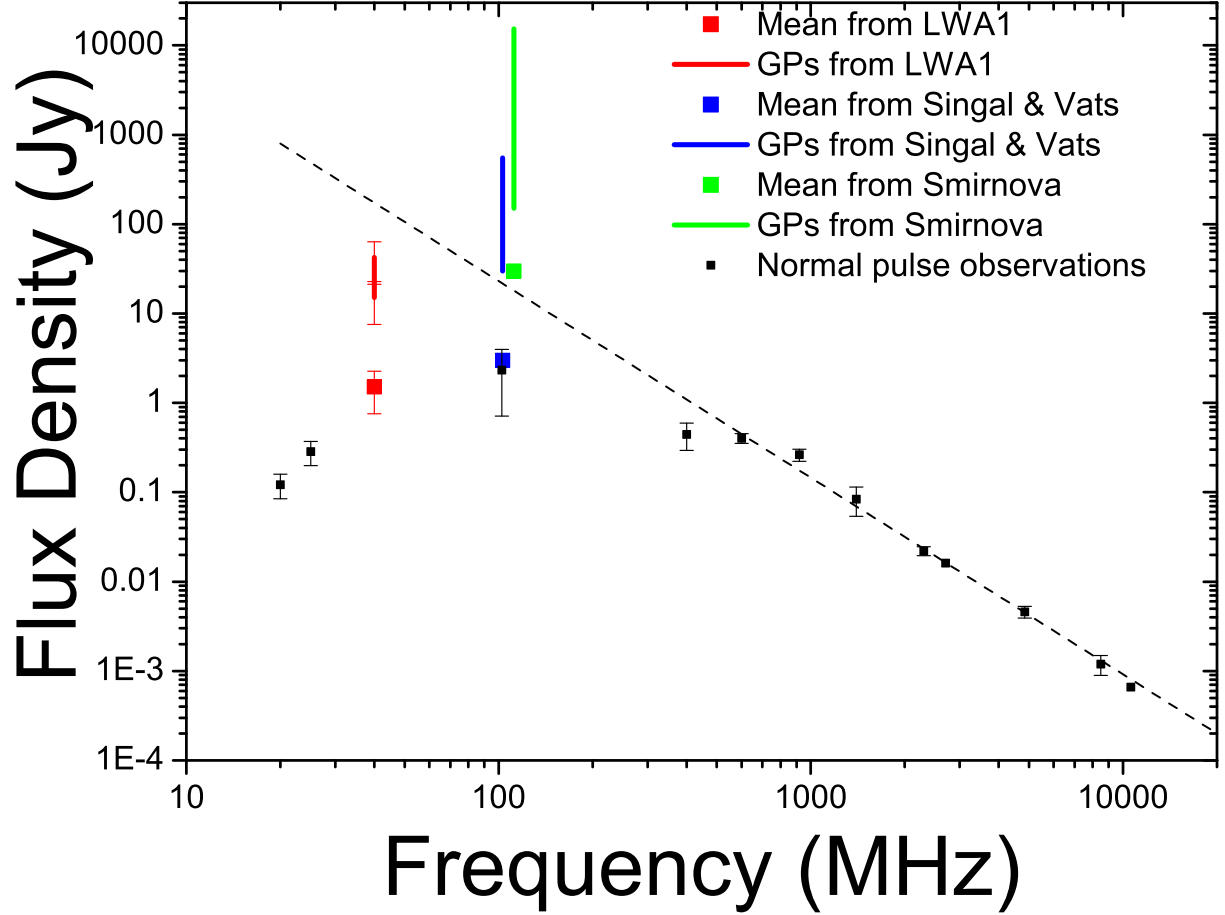


Figure 4.11: Observed flux densities for PSR B0950+08. Red symbols are for LWA1 at 39.4 MHz (this work); the red square is for the mean pulse, with 50% error bars. The thick red vertical line indicates the range of GP values; the thin error bars extending above and below indicate the 50% error associated with the lowest GP and highest GP flux density. Blue and green symbols similarly represent observations by [95] at 103 MHz, and by [23] at 112 MHz. The normal pulse observations (black squares) are from left to right: points 1–3, [100]; points 4–6, and 9, [101]; point 7, 10, and 12, [102]; points 8 and 11, [103]. The dashed black line is a fit through the normal pulse observations, of spectral index -2.2 .

i.e., $q_o \ll q \ll q_i$, the power-spectrum for the electron-density irregularities is often expressed as a power-law,

$$P_{n_e} = C_n^2 q^{-\beta}, \quad (4.5)$$

where C_n is the fluctuation strength for a given LOS. For a Kolmogorov spectrum $\beta = 11/3$ and the scattered-broadened pulsar pulse-width depends on observing frequency as (e.g., [40]),

$$\Delta t_{\text{scattering}} \propto \nu^{-\alpha} \propto \nu^{-2\beta/(\beta-2)} \propto \nu^{-4.4}. \quad (4.6)$$

A Kolmogorov spectrum is often assumed, and is consistent with many pulsar observations. However, there are observations of pulsars over a wide range of DMs which exhibit a departure from Kolmogorov. For example, a small group of pulsars with a high DM range (582-1074 pc cm⁻³) were observed to have an average $\alpha = 3.44 \pm 0.13$ [47]), a larger group of low galactic-latitude pulsars were observed to have an average $\alpha = 3.9 \pm 0.2$ [36]. The PSR B0950+08 was found to exhibit an exceptionally small $\alpha = 0.55$ [105], below 300 MHz.

References [36] and [49] explored several plausible scenarios for the departure from $\alpha = 4.4$. In order for $\alpha = 4.4$ all four of the following conditions must be fulfilled.

1. The electron density spectrum is of the Kolmogorov form.
2. Only a thin screen or a uniformly thick bulk lies in the LOS.
3. The wavenumbers sampled by the observations fall in the range between the inner and outer scales.
4. The turbulence is isotropic and homogeneous.

Thus there are a variety of deviations from these conditions which could explain the departure from $\alpha = 4.4$. Some pulsar observations which deviate from Kolmogorov results have been attributed to deviations from the assumptions summarized above. For example, a truncation of the electron-density power spectrum has been proposed as a cause [50]. It has also been proposed that observations on a spatial scale smaller than the inner turbulence scale can cause a deviation from Kolmogorov resulting in an α less than 4.4 [40].

We folded the 4×6 hours of observations of the mean pulse, as shown in figure 4.4. We then fit the folded mean pulse profile by assuming a Gaussian function which yielded an average FWHM pulse width as 30.5 ± 5.5 ms from the 4 observations, centered at 39.4 MHz with the bandwidth of 16 MHz. We find a temporal scatter-broadening spectral index of $\alpha = 0.43 \pm 0.078$ when our observations are placed in the context of other observations of this pulsar at frequencies from 25 MHz to 410 MHz, as shown in figure 4.12. Our results are consistent with other observations of the effect of scattering on pulses from PSR B0950+08. Perhaps the most plausible reasons for the small α for PSR B0950+08 is the peculiar distribution of the electron density along the LOS. This was discussed in [70]. They argued

that PSR B0950+08 has such a low scattering measure due to the path length being predominantly through the Local Hot Bubble (LHB) and the Local Super Bubble (LSB), which have small electron densities and small fluctuation parameters. Perhaps the explanation for the low value of α for PSR B0950+08 would be the peculiar LOS which is through a region that has an inhomogeneous scattering screen, anisotropic turbulence or an uncommon wavenumber spectrum. Further observations of PSR B0950+08 could help illuminate the circumstances that cause the observed deviation from the Kolmogorov result.

4.6 Conclusions

We observed PSR B0950+08 for 24 hours at 39.4 MHz with a bandwidth of 16 MHz, using the LWA1, determined a mean pulse profile, and detected 398 pulses strong enough to not be part of the tail of Gaussian noise in our data. Of these pulses, 119 have a SNR greater than 10 times the SNR of the mean pulse. Reference [95] considered such strong pulses “giant pulses” in their observations of B09050+08 at 103 MHz. For a large number of giant pulses, we observed a double-peak structure, similar to that observed in the normal pulses for this pulsar. The mean pulse profile (found by folding) has a FWHM of about 30.5 ms. The giant pulses are almost all narrower, having a FWHM, on average, of 17.8 ms. These 119 giant pulses are about 0.0035% of the total number of pulses that occur in the 24 hours. The rate of the GPs we observed is about 5.0 per hour. The cumulative distribution of giant pulse strength, $N(> S)$, follows a power law with power -4.7 . We assigned a rough flux density of 1.5 ± 0.75 Jy to the mean pulse, and our largest giant pulse is 28.2 times stronger than the mean pulse. No other transients were observed in a DM range from 1 to 90 pc cm $^{-3}$. Given that all transients were observed at the known DM of the pulsar there is a high degree of certainty that all observed transients were associated with the pulsar itself. The absence of transients allows for a limit to be set on the agnostic transient rate in this range of DMs, during our 24 hour beam on PSR B0950+08.

Our mean pulse flux density and giant pulse flux densities are weaker than observed by [95] at 103 MHz, and [23] at 112 MHz. The GPs observed by [95] were $\sim 1\%$ of the pulses that occurred over their total observing time, a rate much higher than ours. In combination with the steeper power-law cumulative distribution of giant pulse strengths we found for GPs at 39.4 MHz, we conclude we may be seeing a weaker and less active pulsar at 39.4 MHz than was observed at ~ 100 MHz. Further observations of PSR B0950+08 at low frequencies would be useful. Observations of the Crab pulsar demonstrated that the strongest GPs tend to have a shorter duration [113]. We did not see this trend in GPs from PSR B0950+08 in the frequency range observed.

Additional work of interest would include sensitive enough observations of PSR B0950+08, and other pulsars which exhibit pulses of large strength, to simultaneously explore the de-

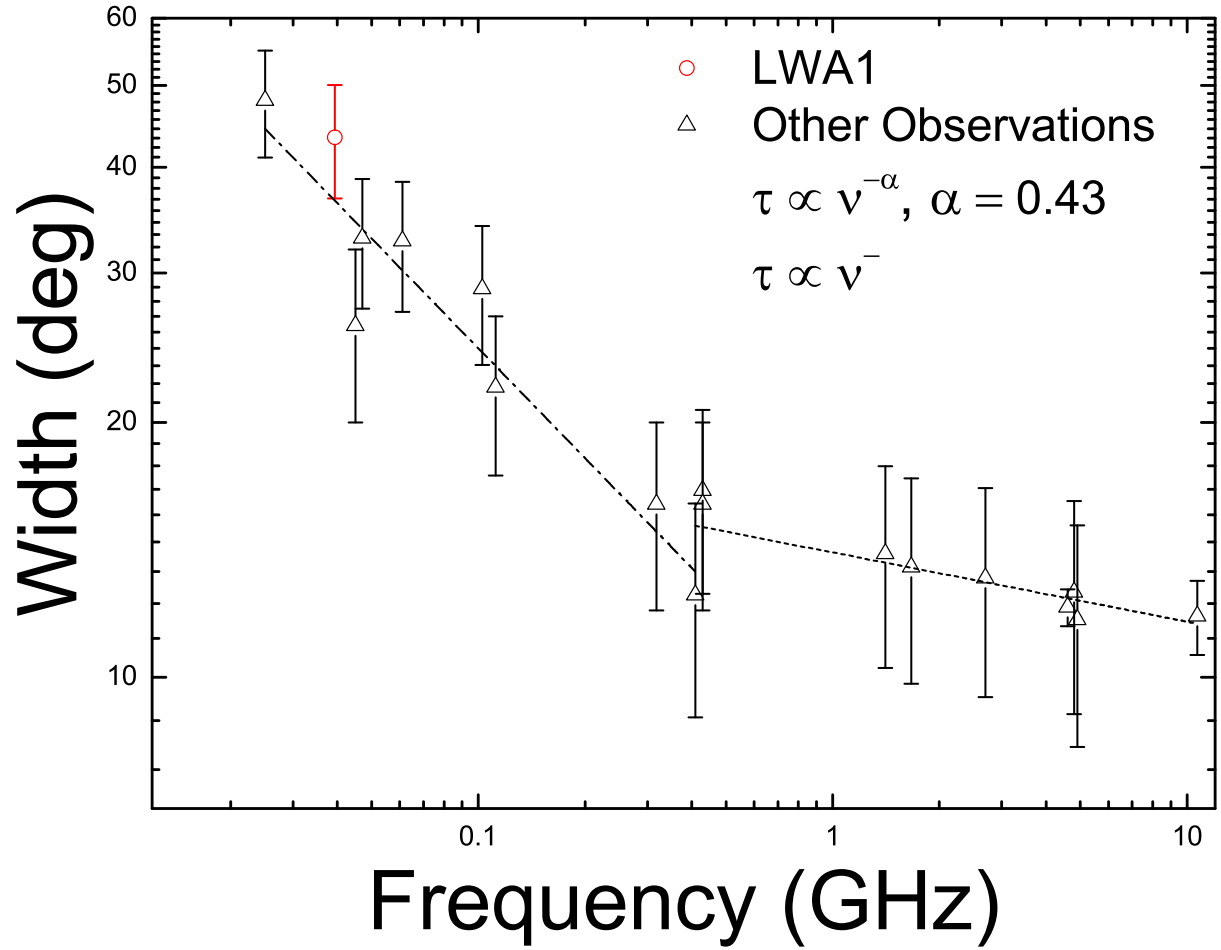


Figure 4.12: The spectra of pulse widths observed for PSR B0950+08 normalized to have a period of 360° with the current observation at 39.4 MHz included. We fit the spectral index for two frequency ranges, above and below 430 MHz. The vertical error bar is one σ assuming Poisson statistics unless otherwise specified in references for the observations cited. [106]: 0.41GHz, 1.665GHz. [107]: 2.7GHz, 4.9GHz. [108]: 61MHz, 102.5MHz. [109]: 430MHz. [110]: 4.6GHz, 10.7GHz. [111]: 25MHz, 47MHz, 112MHz, 430MHz, 1408MHz, 4800MHz. [112]: 45MHz. This work: 39.4MHz.

tailed statistical distributions of normal pulses and giant pulses. Such studies could put the observational identification of giant pulses on a firmer footing, and advance the theoretical modeling of giant pulses.

These observations demonstrate the usefulness of LWA1 in searches for transient pulses. In particular, agnostic searches would be valuable, in addition to targeted work such as reported here. Wide-area LWA1 searches could also be leveraged to enable more sensitive LIGO-Virgo searches for gravitational-wave events, triggered by the detection of radio transients. The benefits of such collaborative work will be described in another publication.

Chapter 5

Simultaneous Observations of PSR B0950+08 at 42 and 74 MHz

This chapter has been published [2] (©2016 American Astronomical Society). The author of this thesis wrote the code for data collection, data processing, analysis, and figures. He wrote the first draft, then collected comments from the coauthors, then revised the paper. Lastly, he used the referee review for the submitted paper to finalize the published version of this work.

5.1 Introduction

Observations of GPs can illuminate the underlying pulsar pulse production mechanism and can serve as an effective probe of the interstellar medium. Moreover, simultaneous observations at multiple frequencies allow for a more nuanced investigation of these phenomena. In this chapter we perform such an analysis using simultaneous observation of PSR B0950+08 at 42 and 74 MHz. These observations were conducted using the LWA1 [28].

Only a small minority of pulsars emit GPs. Initially, all pulsars observed to emit GPs were found to possess a very strong magnetic field in the region of the pulsar's light cylinder, with $B_{LC} > 10^5$ G [18]. This changed with the observations of PSR B0950+08 by [114], indicating $B_{LC} \sim 150$ G. Reference [115] suggested that there are two subgroups of GPs distinguished by the strength of the B_{LC} . GPs from pulsars with $B_{LC} > 10^2$ G have a narrow pulse profile compared to normal pulses and are detectable in a wide range of radio frequencies (e.g., 40-8300 MHz). For pulsars with $B_{LC} < 10^2$ G, the widths of the GP profiles are typically comparable to that of the normal pulses. Another common property of GPs is that they exhibit a non-Gaussian power-law distribution in the peak flux density. GP observations of PSR B0950+08 over the frequency range 39-111 MHz indicate further that the rate and

strength of GP emission is reduced at ~ 39 MHz as compared to ~ 100 MHz [1, 23, 95]. In this chapter we extend the previous study of PSR B0950+08 by [1] with simultaneous observations at two frequencies at 42 and 74 MHz. We detected 275 and 465 GPs at 42 and 74 MHz, respectively. The rate and strength of these GPs is less than has been observed at ~ 100 MHz. This indicates that this pulsar is weaker and produces less frequent GPs below 100 MHz, than above 100 MHz. We found the average pulse (AP) has a width which is consistent with previous observations. We detected no other transient pulses in a wide DM range from unity to five thousand pc cm^{-3} .

Simultaneous observations of pulses at multiple frequencies can be used to investigate the pulsar's beam structure. In particular it is possible to determine the emission altitude difference for the simultaneous observations. We can infer emission altitude from the peak-to-peak separation of double-peaked pulses at different frequencies, assuming a dipolar magnetic field of the pulsar. We determined the emission altitude in the context of a dipolar magnetic field for our set of observations for both GPs and APs. We found the emission regions to be $r(42 \text{ MHz}) = 29267 \pm 36$ m and $r(74 \text{ MHz}) = 29013 \pm 17$ m for APs and $r(42 \text{ MHz}) = 29106 \pm 11$ m and $r(74 \text{ MHz}) = 28950 \pm 3$ m for GPs. GPs have smaller peak-to-peak separation compared to APs for both frequencies.

As discussed in the Introduction, observations of pulsars have been used to probe the spatial spectrum of irregularities in the interstellar medium. Temporal pulse widths, at different frequencies, can determine the spectral index of a power law describing the interstellar irregularities. The most commonly discussed power law is for a Kolmogorov spectrum. Our previous observations of PSR B0950+08 suggested that the spectrum along this LOS deviates from Kolmogorov [1]. In this work, we explore the question further by using our simultaneous observations at two frequencies as well other observations of pulses from PSR B0950+08 and conclude the deviation from a Kolmogorov spectrum appears to be true. To analyze the effect of scattering we adopted the CLEAN-based algorithm [116] to determine the scatter-broadening time constant τ for APs and pulses with $\text{SNR} > 7$, and the found scattering spectral indices $\alpha = -0.14 \pm 0.03$ and -1.45 ± 0.14 for APs and pulses with $\text{SNR} > 7$, respectively, where $\tau \propto \nu^\alpha$.

We discuss the observations and processing in section 5.2. Next, we explain the scattering model used as well as the method for determining flux densities. We describe the pulse behavior determined from the observations in section 5.3. We then discuss scattering in section 5.4 and the interpretation of the observations in the context of the cone-structure beam-model in section 5.5. Lastly, we summarize findings in section 5.6.

5.2 Observations and Data Processing

Observations of PSR B0950+08 were conducted using LWA1 in beamforming mode from January 25 through January 27, 2014. The observation set is composed of 4 consecutive hours of data from each day beginning 2 hours before the pulsar passed the meridian. Observations were made at two frequencies simultaneously, centered at 42 and 74 MHz, each with a bandwidth of 16 MHz (after data processing). Two polarizations were recorded.

We carried out the same data processing steps described in Chapter 3 on the data collected for this chapter. We performed incoherent dedispersion (summing intensities) in our spectrograms. We searched through time series for 28,451 candidate DMs in this manner, ranging from unity to five thousand pc cm^{-3} . In the entire search we found all transient events in the resulting time series with SNRs $\gtrsim 6.5$ were for a dispersion measure of 2.97 pc cm^{-3} , the DM of PSR B0950+08. No such strong pulses were found at other DMs. Furthermore, the expected number of transient events due to Gaussian noise matches well our numbers of events at $\text{SNR} < 6.5$, but events of $\text{SNR} > 6.5$ are more numerous than expected from Gaussian noise alone, and appear at the DM of the pulsar. Thus we are confident that by focusing on transient events that have a $\text{SNR} > 6.5$, determined through this procedure, we are selecting pulses produced by PSR B0950+08.

Finally, to further explore the parameters necessary to conduct an effective and efficient search for large individual pulses from PSR B0950+08, we searched one 5-minute sequence of bandpass-corrected 0.209 ms spectra using an incoherent dedispersion routine with trial DMs between 2.965 and 2.975 pc cm^{-3} . The transient time-sample events with highest SNR in the resulting time series were obtained for a $\text{DM} = 2.97(02) \text{ pc cm}^{-3}$. Thus, we narrowed our subsequent search for GPs within the entire data set to this value of the DM.

5.3 Behavior of Pulses

To study the flux density and phase position of pulses we fit multiple Gaussians to both APs and GPs as both exhibited multiple-peak profiles. The multiple Gaussian fits at both frequencies enable a comparison of the pulses at both frequencies. Because the two observing frequencies were recorded simultaneously the relative phase position can be determined after dedispersion. We dedispersed the two frequencies independently using the same DM and produced separate dedispersed time series.

The flux density and phase positions of peaks were determined from the fitted Gaussians. The flux density is calculated by converting the area under the fitted curves to the SEFD. Flux density ratio of a GP and the AP is the ratio of area under fitted curves, while the area of the AP was divided by the folding number.

5.3.1 Flux density

Our observations did not include any drift scans on other objects for calibration, so we obtain rough flux densities for the AP and GPs using an estimated SEFD. One SEFD is the flux density a source in a beam needs to produce a SNR of unity, for an observation of 1 Hz bandwidth and integration time of 1 second. The system noise is overwhelmed by the emission from the Galaxy below 100 MHz. Ellingson created a model to assess the SEFD, which takes account of the combined all sources of noise [97]. Ellingson uses a model where the sky brightness temperature T_b is spatially regular, and depends on observing frequency ν , where

$$T_b = 9751\text{K} \left(\frac{\nu}{38\text{MHz}} \right)^{-2.55}. \quad (5.1)$$

The ground temperature and the receiver noise is negligible. This model, when applied to LWA1, shows that beams are less sensitive when pointing away from zenith. Reference [28] checked this model with observations of strong flux density calibrators, finding the results roughly correct. Based on the model of Ellingson and his drift scan results, and given our observations at transit are for a zenith angle, we can estimate an appropriate SEFD to use for our observations, with an uncertainty of roughly 50%. The SNR of pulses away from the moment of transit are corrected by a factor which compensates for decreasing effective collecting area and increasing SEFD, with increasing zenith angle.

Thus, the flux density we assign to a pulse, as averaged across the entire pulse period, from equation (4.4) using [28] we assume the same SEFD is 15,000 Jy ($\pm 50\%$) for both observing frequencies while transiting at a zenith angle of about 26° .

The sensitivity of LWA1 is also dependent on the altitude of the target. To correct for this effect we calculated sequences of 24 minute averages of the pulse flux densities and fit the variation with a polynomial function, with a maximum value of unity at or near the meridian, as shown in figure 5.1. Then the flux of any particular pulse was divided by the polynomial to remove the zenith angle dependence for future analysis.

5.3.2 Pulse Profile of PSR B0950+08

An adequate fit to the pulse profiles required three Gaussian components, as demonstrated in figure 5.2. While comparing the AP profile at two frequencies, we noted that the leading peak position does not shift more than a temporal bin, while the second peak's shift is more obvious.

The *full* temporal spread of the AP profile measured at half the maximum intensity, W , is 25.6 ms and 17.8 ms at 42 and 74 MHz respectively. Figure 5.3 shows W for frequencies above 20 MHz. We find a temporal broadening spectral index of $\xi = -0.49 \pm 0.064$ when

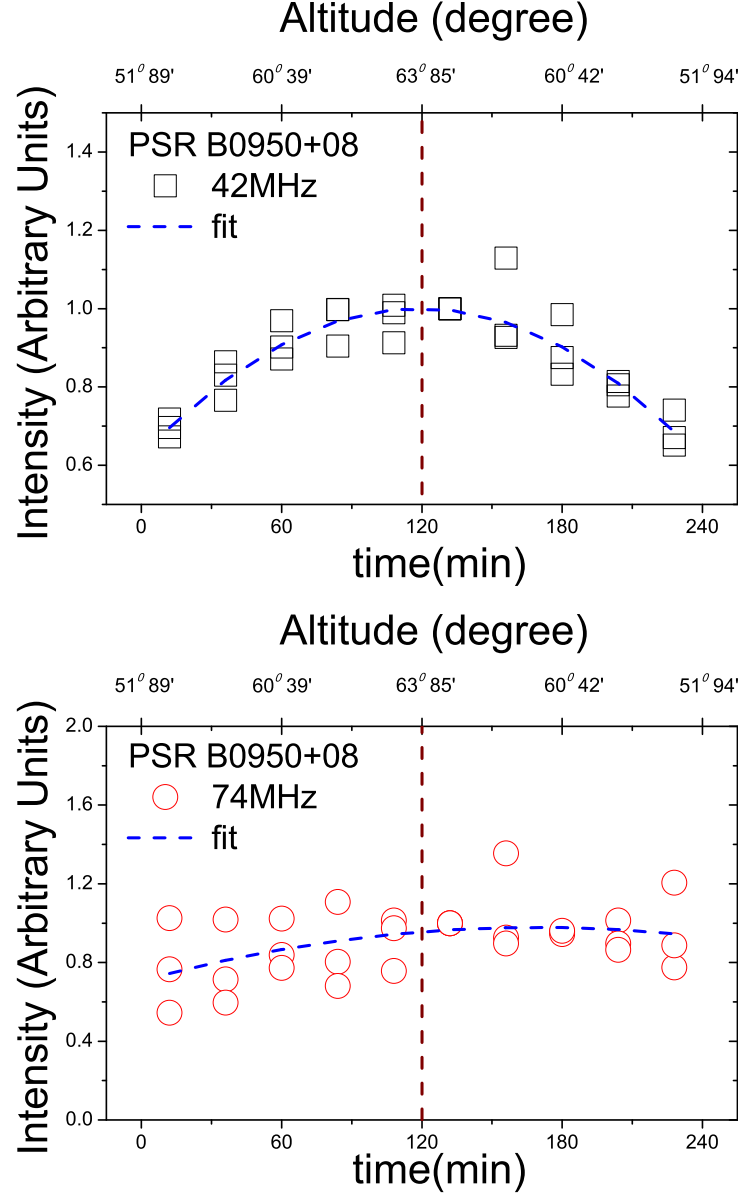


Figure 5.1: The flux density of different altitudes at two frequencies. PSR B0950+08 passed the meridian at 120 minutes after the first observing frame, with an altitude = 63.85° . The two panels demonstrate the sensitivity dependence on a target's zenith angle and the observing frequencies of LWA1 in beam-tracking mode. We corrected for these systematic effects when calculating the intensity of GPs. Each data point is the 24-minute averaged intensity. There are three observations from different dates in each panel.

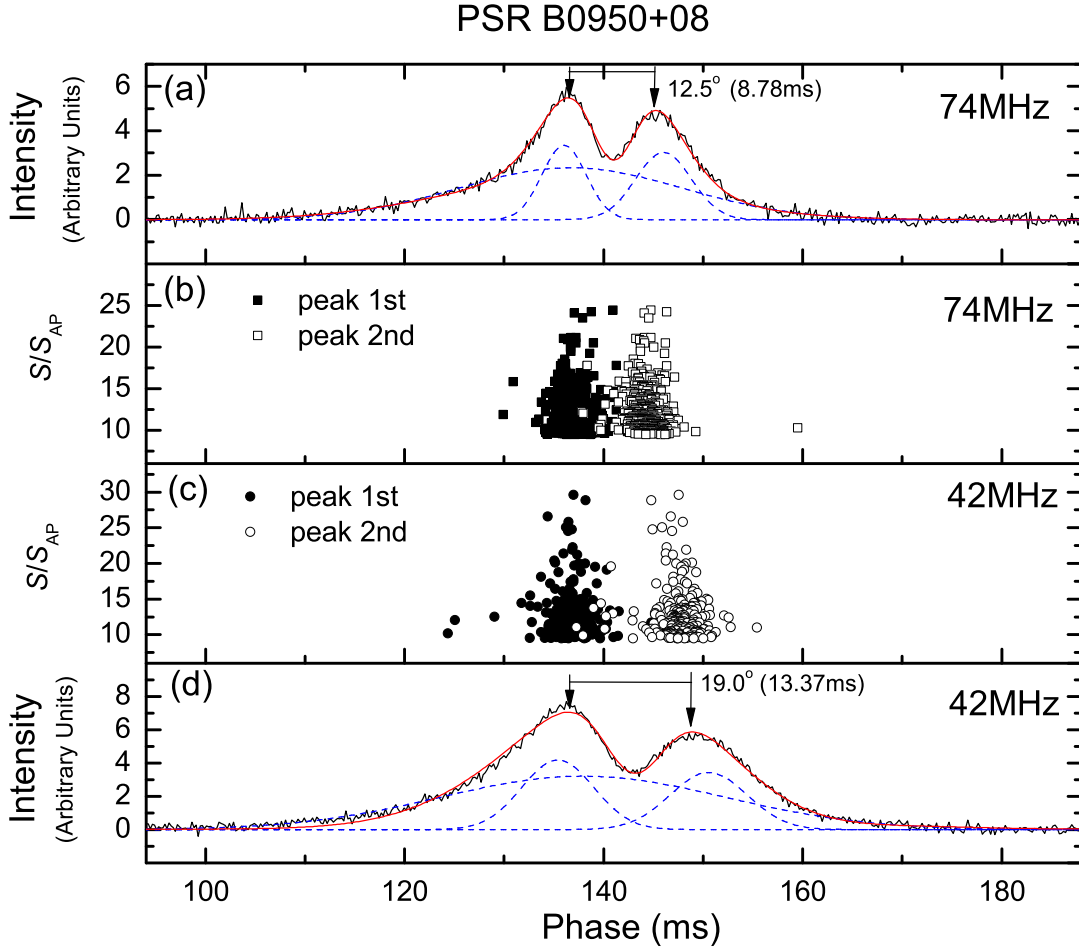


Figure 5.2: The AP profiles and GP peak phase positions at two frequencies. Panels (a) and (d) show the profile of the AP at each frequency, the three dash lines are Gaussian fit to the profile. The red solid curve is the summation of three Gaussians. Panels (b) and (c) show GP peak phase positions and flux density at each frequency compared to the flux density of the AP. A GP is defined as a pulse with flux density ratio (S/S_{AP})>10 in this study. The pulsar's period is 253.06 ms.

our observations are placed in the context of other observations of this pulsar at frequencies from 20 to 410 MHz, as shown in figure 5.3. The spectral index seems to change at about 0.5 GHz.

The period-averaged flux densities are 2.8 Jy and 2.4 Jy at 42 and 74 MHz, respectively. Figure 5.4 shows flux densities for APs at frequencies of 20 MHz and above, along with observations of GPs by [95] at 103 MHz and [23] at 112 MHz. In addition, we have added data points from this work. The error bar on our AP flux densities indicates our $\sim 50\%$ uncertainty. The figure shows that both APs and GPs have lower flux density below ~ 100 MHz.

5.3.3 GPs from PSR B0950+08

The cumulative distribution of pulses with flux density ten times larger than that of the AP (S_{AP}) was found to follow a power law $N(> S/S_{AP}) \propto S^\zeta$, where $\zeta = -4.09$ and -5.06 for 42 and 74 MHz respectively, as shown in figure 5.5. This supports our use of the definition of GPs as 10 times the AP's flux density for PSR B0950+08 as found in [95]. The strongest GP at 42 MHz had a flux density 29 times larger than the AP's, while at 74 MHz the strongest one was found to be 24 times larger. The statistical properties of GPs from the Crab pulsar found by [113] indicate that the strongest GPs have a shorter duration than other GPs. We did not see this trend in GPs from PSR B0950+08.

The cumulative pulse strength distribution has a steeper power-law for the GPs than found by [95] and [23], but much less steep than would be expected if we were observing the tail of a Gaussian distribution of normal pulses. All these results indicate that PSR B0950+08 is weaker, and produces less frequent and less intense GPs at low frequency than at 100 MHz. All GPs have double peaks structures and the phase position of GPs drifts through the range of the AP profile, as shown in figure 5.2.

If each GP is an independent event with a uniform probability for pulse generation at any given time, we expect the distribution of intervals between GPs to exhibit an exponential functional dependence. For simplicity, we will use the number of accumulated pulse periods, p , as a time measure. Then, the interval distribution for a single event as a function of the number of periods is given by

$$I_1(p) = r \exp(-rp), \quad (5.2)$$

where r is the average event rate (GPs per period). The observed distribution is shown in figure 5.6, which indicates that the GPs are indeed independent events.

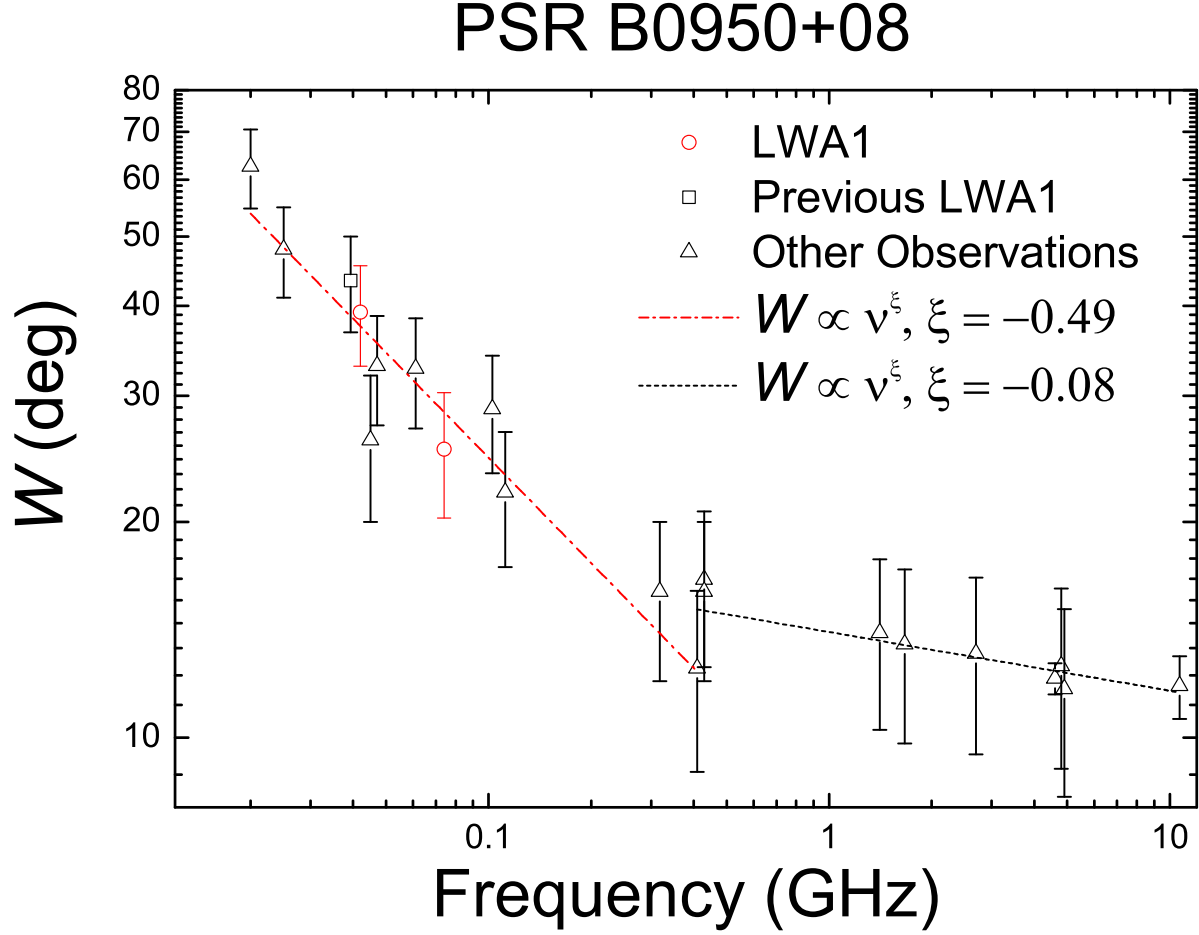


Figure 5.3: The spectra of pulse widths observed for PSR B0950+08 normalized to the period of 360° . The pulsar’s period is 253.06 ms. We fit the spectral index for two frequency ranges, separated at 410 MHz. The vertical error bar is one σ assuming Poisson statistics unless otherwise specified in references for the observations cited. Observations are from [1]:39.4 MHz; [106]:0.41 GHz, 1.665 GHz; [107]:2.7 GHz, 4.9 GHz; [108]: 61 MHz, 102.5 MHz; [109]: 430 MHz; [110]: 4.6 GHz, 10.7 GHz; [111]: 25 MHz, 47 MHz, 112 MHz, 430 MHz, 1408 MHz, 4800 MHz; [112]: 45 MHz and this work: 42 MHz, 74 MHz.

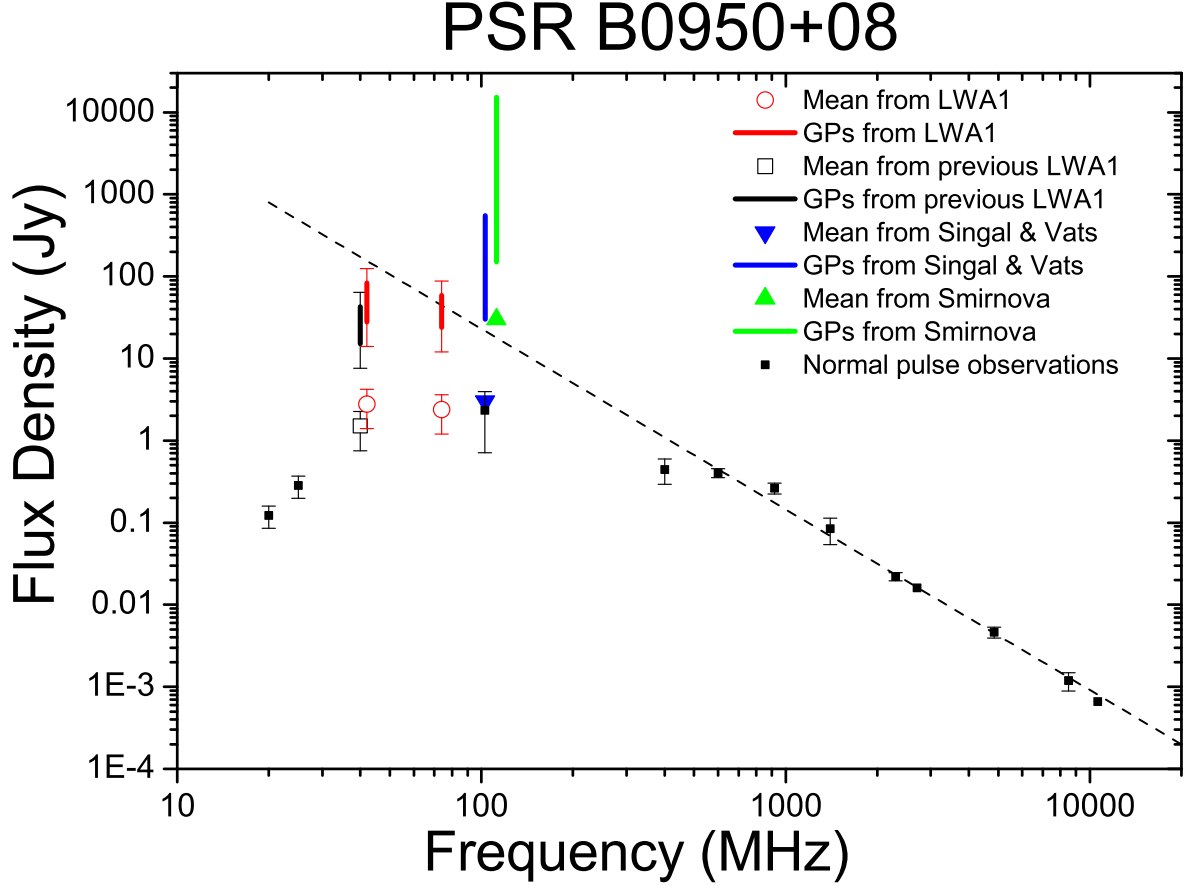


Figure 5.4: Observed flux densities for PSR B0950+08 for different observing frequencies are shown here. The AP flux density data points have 50% error bars unless otherwise specified in references for the observations cited. The vertical line indicates the range of GP values. The thin error bars extending above and below indicate the 50% error associated with the lowest GP and highest GP flux density. The black solid square represents the flux density for the AP. Red halo circles are for LWA1 at 42 and 74 MHz (this work). The thick red vertical line indicates the range of GPs' values. The black halo square represents previous LWA1 observation at APs and GPs by [1] at 39.4 MHz. Blue down triangle and green up triangle similarly represent observations by [95] at 103 MHz, and by [23] at 112 MHz respectively. The AP observations (black squares) are from left to right: points 1–3, [100]; points 4–6, and 9, [101]; point 7, 10, and 12, [102]; points 8 and 11, [103]. The dashed black line is a fit through the AP observations, of spectral index -2.2 .

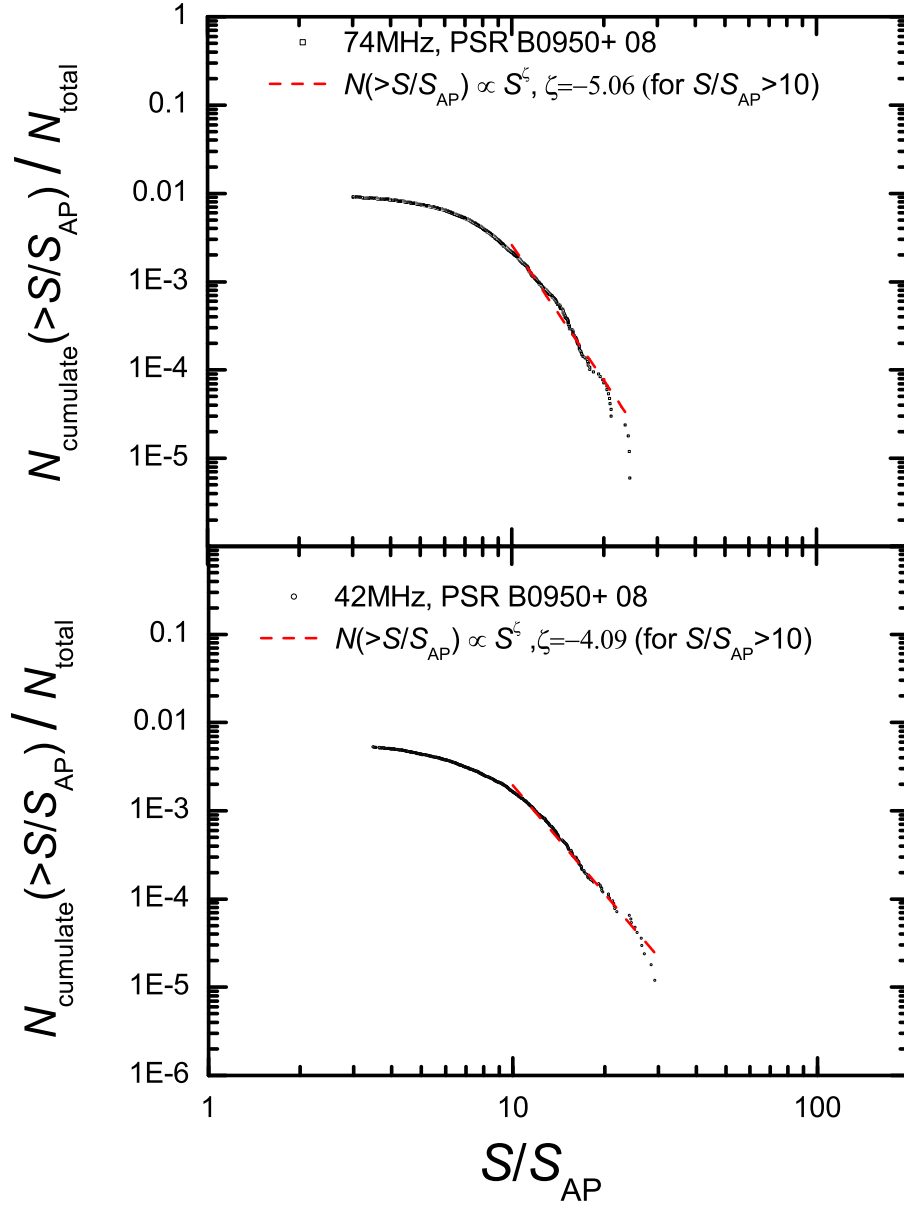


Figure 5.5: The pulse cumulative number $N(> S/S_{\text{AP}})$ plotted versus flux density. The red dashed line in both panels is the power-law fit for $S/S_{\text{AP}} > 10$.

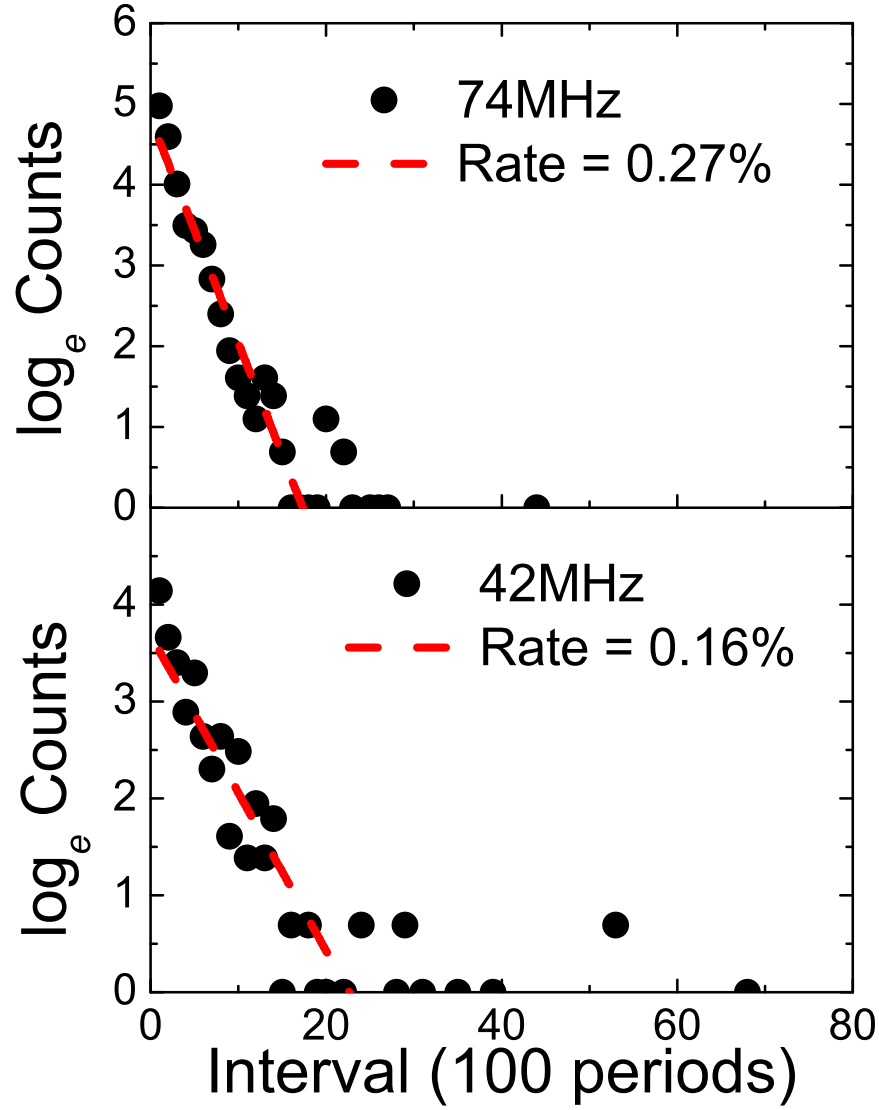


Figure 5.6: GP interval distributions at both frequencies. Intervals on the horizontal units are in units of 100 periods. The rate shown is the slope of a fit from 0 to 2800 periods and 0 to 1900 periods for 42 and 74 MHz, respectively. We did not find interesting clustering or periodic behaviors regardless of the chosen binning interval.

5.4 Scattering Analysis

We made use of the CLEAN-based algorithm [116] to deconvolve the effect of scattering from the observations of PSR B0950+08. The observed pulses are composed of the intrinsic pulse convolved with propagation effects and instrumental response. The CLEAN-based algorithm utilizes an accumulated delta-like signal to restore the intrinsic pulse. This approach allows for the deconvolution of various profile shapes without knowledge of the intrinsic profile. The recorded signal P_{obs} is

$$P_{obs}(t) = I(t) \otimes \text{PBF}(t) \otimes r(t) \quad (5.3)$$

where $I(t)$ is the pulse inherent profile, $\text{PBF}(t)$ is the pulse-broadening function and $r(t)$ is a function which gives the combined instrumental responses including effects due to data processing.

We applied this algorithm to data from the LWA Pulsar Data Archive [117] for observations from 25 to 75 MHz and the EPN data archive ([43], [118], [119], [120], [121], [122]) for 102 MHz to 10.6 GHz, and this work. We include as part of the instrumental responses the effect derived from setting the bin size of the time series to be the same as the temporal resolution and a similar effect for the frequency channel width. For simplicity, we compare only the scattering time constant from a thin screen model for APs in figure 5.7 with results for pulses with $\text{SNR} > 7$ in figure 5.8.

We found the scattering time constants from pulses with $\text{SNR} > 7$ centered at 42 and 74 MHz indicate a relatively flat spectral index of -1.45 ± 0.14 which differs from the Kolmogorov spectrum of -4.4 . The spectral index calculated from the APs, and over a much wider range of frequencies, see figure 5.7, is -0.14 ± 0.03 , which also greatly differs from the Kolmogorov spectrum. Both these results indicate that the free electron density irregularity spectrum along the LOS to PSR B0950+08 is not Kolmogorov.

5.5 Pulse Emission Altitude

Observations of GPs can be used to probe a pulsar's emission region. This can be done in a more subtle fashion if simultaneous observations at different frequencies are taken for a given pulse. Of particular importance is the observed separation in time between the two peaks in a GP or AP profile at the two observing frequencies. We consider the difference in the altitude of emission at the two observing frequencies. We do this both for APs and GPs and find a similar difference in emission altitude between the two frequencies. In analyzing the difference in the altitude of the emission region for the two frequencies observed we made use of the dipolar magnetic field model, as discussed in [123]. We will briefly summarize the basic features of this model that were used to calculate the altitude difference.

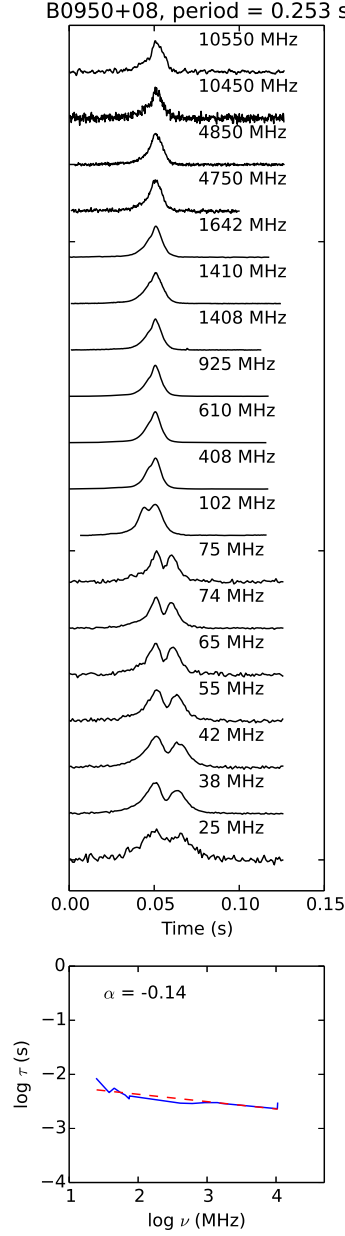


Figure 5.7: Profiles and scattering time constants for different observing frequencies. The data with frequency range from 25 to 75 MHz is from LWA Pulsar Data Archive [117], the rest are from European Pulsar Network (EPN) data archive (contributors: [43], [118], [119], [120], [121], and [122]). Below the profile panel are the scatter-broadening time constants τ of the profiles, assuming a thin screen model. The derived spectral index is $\alpha = -0.14 \pm 0.03$ for $\tau \propto \nu^\alpha$. Profiles are not aligned since the observations were taken at different facilities.

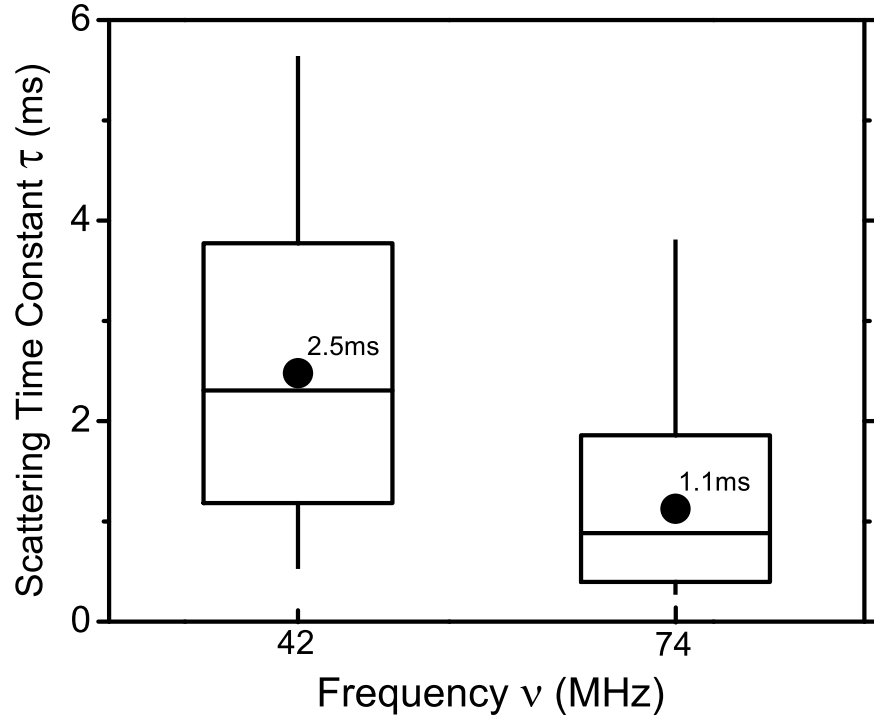


Figure 5.8: The distribution of scattering time constants from pulses with $\text{SNR} > 7$ at 42 MHz and 74 MHz. The solid circle represents the mean. The large box is divided by a median and bounded by the mean $\pm 1\sigma$ (standard deviation). The top and bottom vertical lines extend to the extreme values. The mean scattering time constant from pulses with $\text{SNR} > 7$ is smaller than that of the AP as shown in figure 5.7, which is 5.55 ms and 3.52 ms at 42 and 74 MHz respectively. The scattering spectral index is $\alpha = -1.45 \pm 0.14$ where the constant $\tau \propto \nu^\alpha$.

In the dipolar magnetic field model the field geometry is described using polar coordinates such that the ratio between $\sin^2 \theta$ and a radius r is fixed along a given magnetic field line. So, we can connect a point at (r, θ) along the last open field line of a dipole at the radius of the light cylinder r_{LC} by

$$\frac{\sin^2 \theta}{r} = \frac{\sin^2 90^\circ}{r_{LC}}. \quad (5.4)$$

The opening angle ρ is the half-width of the beam; it can be related to θ as

$$\tan \theta = -\frac{3}{2 \tan \rho} \pm \sqrt{2 + \frac{9}{4 \tan^2 \rho}} \quad (5.5)$$

if the emission cone is confined by the last open magnetic field line [124]. From equations (5.4) and (5.5), the opening angle ρ can be related to the emission height r as

$$\rho = 86^\circ \left(\frac{r}{r_{LC}} \right)^{\frac{1}{2}}, \quad (5.6)$$

using the small-angle approximation for both ρ and θ . The opening angle is also related to the observed pulse component separations $\Delta\phi$ as [125]

$$\cos \rho = \cos \eta \cos(\eta + \psi) + \sin(\eta) \sin(\eta + \psi) \cos \left(\frac{\Delta\phi}{2} \right), \quad (5.7)$$

where η is the angle between rotational and magnetic axes, and ψ is impact parameter, which is the nearest angle of the LOS to an observer and the magnetic axis. Given the component separations $\Delta\phi = 19.0^\circ \pm 0.75^\circ$ and $12.5^\circ \pm 0.54^\circ$ at 42 and 74 MHz, respectively, for the APs from figure 5.2, and $\eta = 5.9^\circ$ and $\psi = -4.2^\circ$ for PSR B0950+08 from [126], we find that the emission altitudes of both frequencies are $r(42 \text{ MHz}) = 29267 \pm 36 \text{ m}$ and $r(74 \text{ MHz}) = 29013 \pm 17 \text{ m}$, and the altitude difference is $254 \pm 53 \text{ m}$. For GPs, given the component separations as $10.3^\circ \pm 0.13^\circ$ and $15.2^\circ \pm 0.30^\circ$ for 42 and 74 MHz, respectively, the altitude is $29106 \pm 11 \text{ m}$ and $28950 \pm 3 \text{ m}$ for 42 and 74 MHz, respectively, and the altitude difference is $156 \pm 14 \text{ m}$. Because the uncertainties are not available on η and ψ from [126], the uncertainties noted above in altitudes r are solely calculated from uncertainties of $\Delta\phi$. Note that the peak separation is less for the GPs than the APs. Analysis of this pulsar at 111 MHz by [127] also indicated that higher intensity GPs have a narrower profile width.

5.6 Conclusions

We observed PSR B0950+08 simultaneously at 42 and 74 MHz detecting GPs and APs. Our study shows GPs and APs from PSR B0950+08 are much weaker than at $\sim 100 \text{ MHz}$. This indicates a turn-over in the spectrum of GPs between 74–100 MHz which is consistent

with previous observations [1]. We analyzed the effect of scattering using the CLEAN-based algorithm [116] to determine the scatter-broadening time constant τ and found the scattering spectral indices $\alpha = -0.14 \pm 0.03$ and -1.45 ± 0.14 for APs and pulses with SNR > 7 , respectively. This confirms a previously observed deviation from a Kolmogorov spectrum.

We determined the emission altitude in the context of a dipolar magnetic field for our set of observations for both GPs and APs. We found the emission regions to be $r(42 \text{ MHz}) = 29267 \pm 36 \text{ m}$ and $r(74 \text{ MHz}) = 29013 \pm 17 \text{ m}$ for APs and $r(42 \text{ MHz}) = 29106 \pm 11 \text{ m}$ and $r(74 \text{ MHz}) = 28950 \pm 3 \text{ m}$ for GPs. The difference in emission altitudes of GPs is similar to that of the APs. Most GPs can only be detected at one frequency which implies that the emission of GPs is localized within a small region and drifts within the emission region of the APs. The average component separation of the GP is smaller than that of the AP, and the component separation of the GP is closer to the average with larger intensity.

Chapter 6

Simultaneous Observation of PSR B0031–07 at 38 and 74 MHz

This chapter has been published [3] (©2016 American Astronomical Society). The author of this thesis wrote the code for data collection, data processing, analysis, and figures. He wrote the first draft, then collected comments from the coauthors, then revised the paper. Lastly, he used the referee review for the submitted paper to finalize the published version of this work.

6.1 Introduction

The pulsar emission from PSR B0031–07 exhibits many unusual properties, such as systematically drifting sub-pulses across the profile of an observed average pulse (AP) (e.g. [128], [16]) and the emission of GPs with a relatively low magnetic field at the light cylinder (B_{LC}) [129]. Perhaps most notably, the DM of PSR B0031–07 shows an unexpectedly large variance from 10.89 to 11.38 pc cm⁻³ [16, 100]. Reference [100] argued that at low frequencies the DM can be determined with higher accuracy given that dispersion is proportional to the inverse square of frequency. Observations of pulsar pulse emission can be used as an effective probe of the interstellar medium. However, the effect of interstellar scattering along the LOS to this pulsar is relatively unexplored. In the current work we analyze simultaneous observations of PSR B0031–07 at 38 and 74 MHz. Our results include observations of GPs, a determination of the DM of the pulsar, and a measurement of the scattering time constant for the interstellar medium along the line of sight (LOS) to the pulsar. These observations were conducted using the LWA1 [28].

GPs have been detected from PSR B0031–07 at 40 MHz [130] and 1.54 GHz [131], with a similar power law index of the cumulative number distribution. However, the ratio of GP

intensity with AP intensity is much weaker at 1.54 GHz than at frequencies below 100 MHz. Our observations show a similar intensity and power law distribution for GPs when compared to other observations below 100 MHz, which indicate that GPs maintain a similar intensity ratio to APs between 38 and 74 MHz. We detected 158 GPs (0.35% of the pulse periods) at 38 MHz and 221 GPs at 74 MHz (0.49% of the pulse periods). No other transient pulses were detected in a wide DM range from unity to five thousand pc cm^{-3} . For the observations detailed here the DM value which resulted in the largest SNR for dedispersed pulses was fixed for further analysis; this was $\text{DM} = 10.8(95) \text{ pc cm}^{-3}$.

Pulsar observations allow for study of the interstellar free electron density distribution. In particular, the temporal behavior of pulse widths can often be attributed to a Kolmogorov power-law spatial power-spectrum of density irregularities. Here, we combine our simultaneous, two-frequency observations with other known observations of pulses from PSR B0031–07 in order to analyze the effects of scattering and conclude that the spectrum is not consistent with a Kolmogorov spectrum. We determined the scatter-broadening time constants τ for both APs and individual pulses with $\text{SNR} > 5.5$ using the CLEAN-based algorithm [116]. For APs, the scattering spectral index was found to be $\alpha = -0.18 \pm 0.06$ and for individual pulses with $\text{SNR} > 5.5$, the scattering spectral index is -1.5 ± 0.2 , where $\tau \propto \nu^\alpha$.

This chapter is organized as follows. We detail observations, data processing in section 6.2., and pulse behavior in section 6.3. We then explain the scattering model we used as well as the method for determining flux densities in section 6.4. Finally, we discuss and summarize our main findings in section 6.5.

6.2 Observations and Data Processing

The LWA1 was used for observations of PSR B0031–07 over the span of three days, for 4 consecutive hours each day. These observations were performed from July 26 through July 28, 2013, with each observation beginning 110 minutes before the pulsar passed the meridian. These observations were made at two frequencies simultaneously, centered at 38 and 74 MHz, each with a bandwidth of 16 MHz (final bandwidth after data processing). These observations recorded both polarizations.

We carried out the same data processing steps described in Chapter 3 on the data collected for this chapter. Spectrograms were then incoherently dedispersed (summing intensities) and searched over various time series for a total of 28,454 candidate DMs in this manner. These data sets ranged from one to five thousand pc cm^{-3} in DM. The only DM for which the resulting time series produced transient events with $\text{SNRs} \geq 5.5$ were for a DM of $10.8(95) \text{ pc cm}^{-3}$, which is the DM for PSR B0031–07. The number of transient events

that we found with $\text{SNR} < 5.5$ are consistent with what would be expected from Gaussian noise. The number of events of $\text{SNR} > 5.5$, however, are both greater than expected from Gaussian noise alone, and appear at the DM of the pulsar. We are therefore confident that using this method of analysis and focusing on transient events with $\text{SNR} > 5.5$ results in the selection of pulses produced by PSR B0031–07.

Finally, as an additional test of the parameters discussed here, we used an incoherent dedispersion routine to vary the DM in a range from 10.845 to 10.945 pc cm^{-3} while searching one bandpass-corrected 0.209 ms spectra for large individual pulses from PSR B0031–07. The results of this search showed that a $\text{DM} = 10.8(95) \text{ pc cm}^{-3}$ produced the highest SNR. Thus, this DM was chosen for the search for GPs for the remainder of the data set.

6.3 Behavior of Pulses

Both APs and GPs, which exhibited multiple-peak profiles, were fit with multiple Gaussians. This allowed us to study both their flux density and phase position. Gaussians were fit at both frequencies, therefore it enabled a simple comparison of the pulse. As the two observing frequencies were recorded simultaneously, the relative phase position was determined after dedispersion. The two frequencies were dedispersed independently using the DM of the GP with the largest SNR.

Using the fitted Gaussians, the flux density and phase positions of peaks were determined. Simply, the flux density is calculated by converting the area under the fitted curves to the SEFD. Flux density ratio of a GP and the AP is ratio of area under fitted curves. The area of the AP was divided by the folding number.

6.3.1 Flux density

Rough flux densities for the AP and GPs were obtained by using an estimated system equivalent flux density (SEFD); drift scans on other objects were not used for calibration. For an observation of 1 Hz bandwidth and an integration time of 1 second, the SEFD is the flux density a source in a beam needs to have in order to produce a signal-to-noise ratio (SNR) of unity. System noise at low frequencies is dominated by emission from the Galaxy. The model established by Ellingson for estimating the SEFD, which takes account of all sources of noise [97], uses a spatially uniform sky brightness temperature T_b , depends on observing frequency ν , following equation 4.3 and neglects the receiver noise which is at a temperature 250 K, and does not contribute much to the SEFD. When applied to LWA1, this model shows that beams are less sensitive when pointing away from zenith. Using strong flux density calibrators, [28] checked this model and found the results roughly correct. Given

that our observations at transit are for a not-zero zenith angle and using Ellingson’s model and drift scan results we can estimate an appropriate SEFD for use in our observations, with an estimated an uncertainty of 50%. The SNR of pulses away from the moment of transit are corrected by a factor which compensates for decreasing effective collecting area and increasing SEFD, with increasing zenith angle.

Therefore, we assign the flux density to a pulse, as averaged across the entire pulse period, from equation 4.4 using [28]. We assume the SEFD is 15,000 Jy ($\pm 50\%$) for both observing frequencies while transiting at a zenith angle of about 26° .

It should be noted that the sensitivity of LWA1 depends on the target altitude. This effect was corrected by calculating sequences of 24 minute averages of the pulse flux densities and fitting the variation with a polynomial function, with a maximum value of unity at or near the meridian, as shown in figure 6.1. As such, the flux of any particular pulse was divided by the polynomial to remove the zenith angle dependence for future analysis.

6.3.2 Pulse Profile of PSR B0031–07

Three Gaussian components were required for an adequate fit to the pulse profiles (figure 6.2). Comparing the AP profile at two frequencies reveals that both components more shifted away from the center for the lower frequency. The *full* temporal spread of the AP profile, W , is 181.4 ms and 127.5 ms at 38 and 74 MHz respectively, measured at half the maximum intensity. Figure 6.3 shows W for frequencies above 20 MHz. In the context of other observations of PSR B0031–07 at frequencies from 38 MHz to 10.7 GHz, we observed a temporal broadening spectral index of $\xi = -0.37$ (figure 6.3). It should be noted that the spectral index appears to change at 38 MHz.

The period-averaged flux densities are 1.28 Jy and 1.27 Jy at 38 and 74 MHz, respectively. The flux densities for APs at frequencies of 20 MHz and above are shown in figure 6.4, along with observations of GPs by [130] at 40 and 111 MHz and [132] at 1.54 GHz. For comparison, we have added data points from this work. The error bar on our AP flux densities indicates our $\sim 50\%$ uncertainty.

6.3.3 GPs from PSR B0031–07

GPs, compared to strong pulses, are defined as pulses that follow a power law in cumulative distribution. The cumulative ratio of GP peak flux density to the AP peak flux density of all observed pulses is shown in figure 6.5. The distribution obeys a power law when the flux density ratio $\gtrsim 90$ at 38 MHz and $\gtrsim 80$ at 74 MHz. As such, a GP is defined by the two different flux density ratio ranges over which the two power laws apply. The index

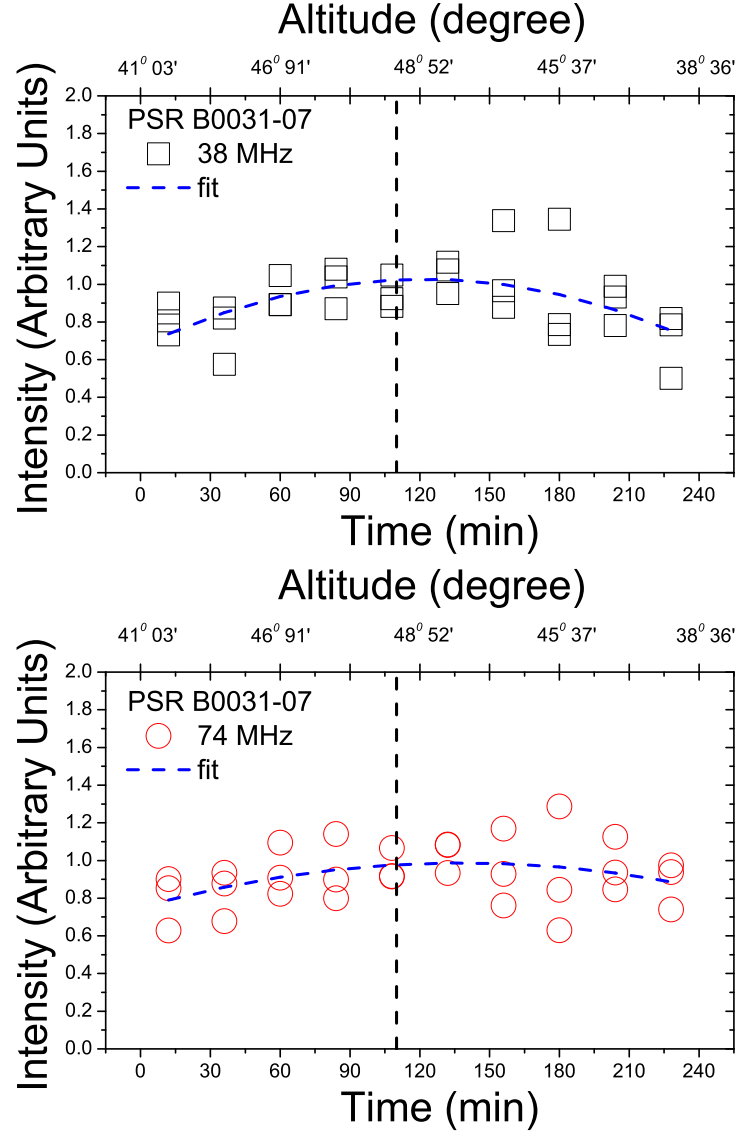


Figure 6.1: The flux density of the pulsar PSR B0031–07 as a function of time for the LWA observations at frequencies of 38 MHz (top) and 74 MHz (bottom). These data were collected for a duration of 4 hours on three consecutive days in beam tracking mode. The observations began each day 110 minutes before PSR B0031–07 passed the meridian at an altitude of 48.58° . Each individual data point represents an average intensity over a time duration of 24 minutes and there are three data points plotted for each observation time corresponding to three consecutive days of observation. The intensity signals show a clear dependence on the target’s zenith angle for both observation frequencies. These systematic effects were accounted for when calculating the intensity of GPs.

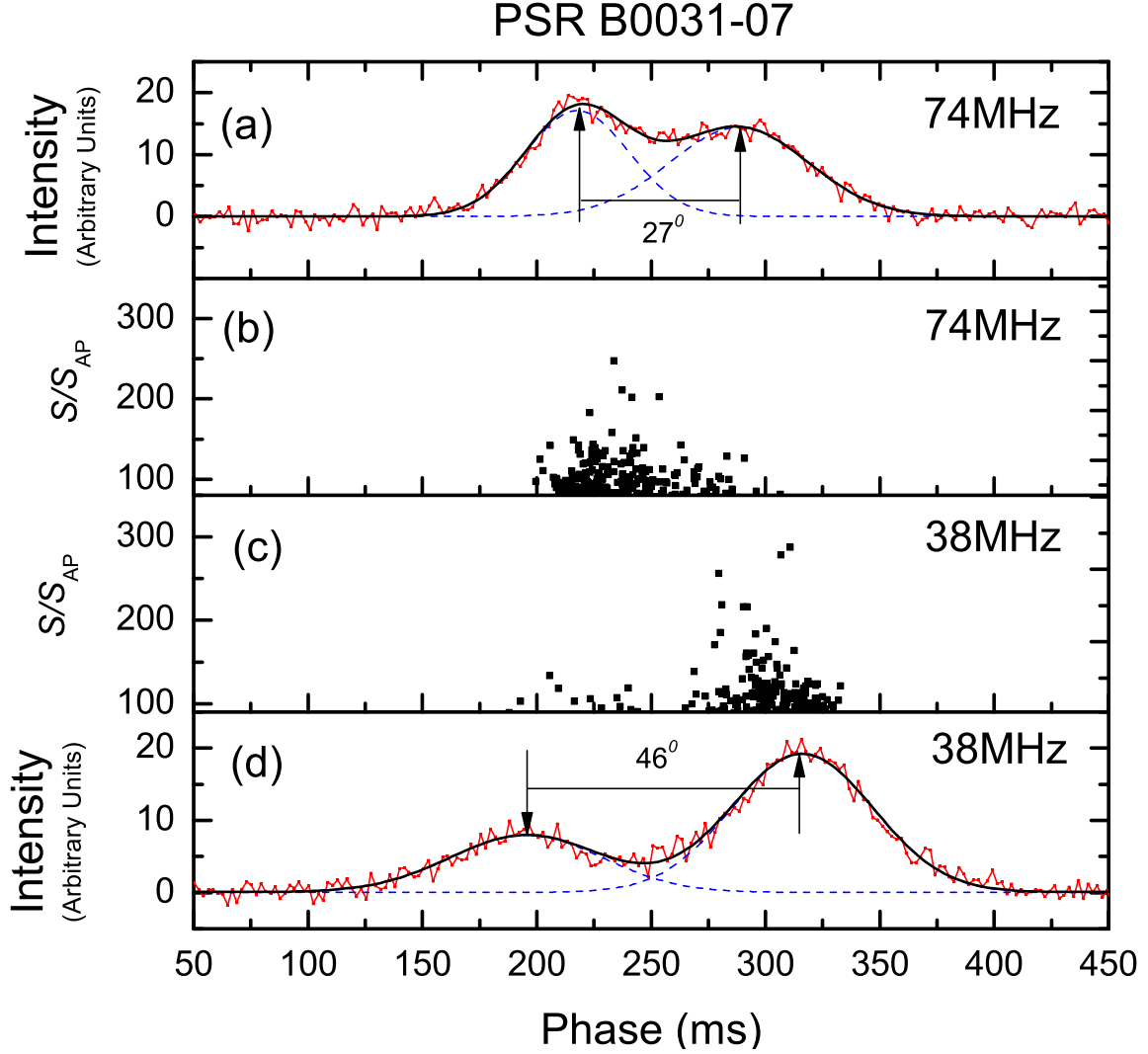


Figure 6.2: Plot of the AP profiles and GP peak phase positions for frequencies of 74 MHz and 38 MHz. Panels (a) and (d) show the profile of the AP at 74 MHz and 38 MHz respectively, with dashed lines to represent the two individual Gaussian fits to the profile. The black solid curve is then the summation of the two Gaussian curves. Panels (b) and (c) show GP peak phase positions and flux density at frequencies of 74 MHz and 38 MHz respectively compared to the flux density of the AP. A GP is defined as a pulse with flux density ratio (S/S_{AP}) > 90 at 38 MHz and (S/S_{AP}) > 80 at 74 MHz. The pulsar's period is 942.87 ms.

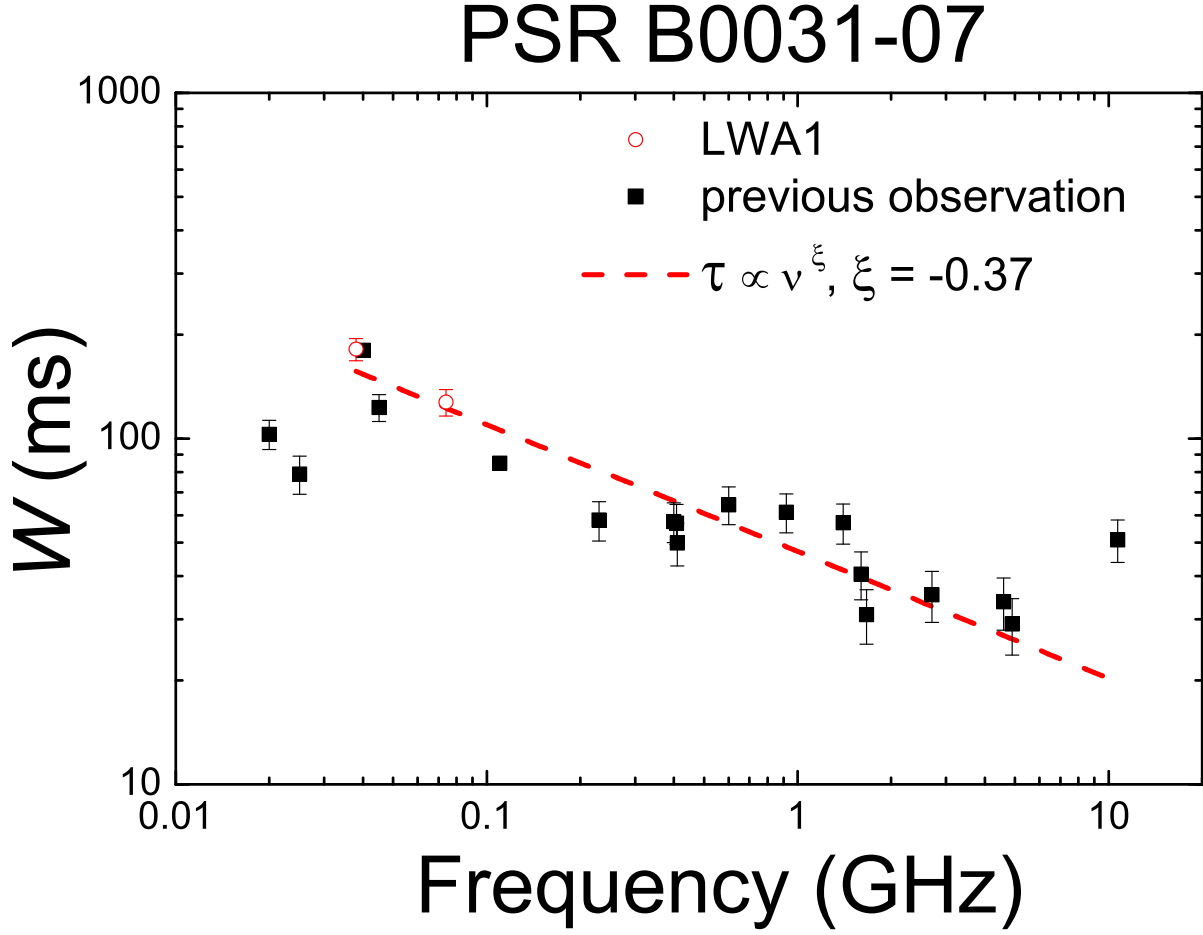


Figure 6.3: The collection of pulse widths observed for PSR B0031–07 includes both data included in this work and data from the literature. The pulsar’s period is 942.87 ms. The error bar is specified along with the references for the observations cited. The red dashed line is fitted from 38 MHz. Observations are from [106]:0.41 and 1.665GHz. [107]:2.7 and 4.9 GHz. [108]: 61 and 102.5 MHz. [109]: 430 MHz. [110]: 4.6 and 10.7 GHz. [111]: 25, 47, 112, 430, 1408 and 4800 MHz. [112]: 45 MHz. [100]:20 and 25 MHz. and this work: 38 and 74 MHz.

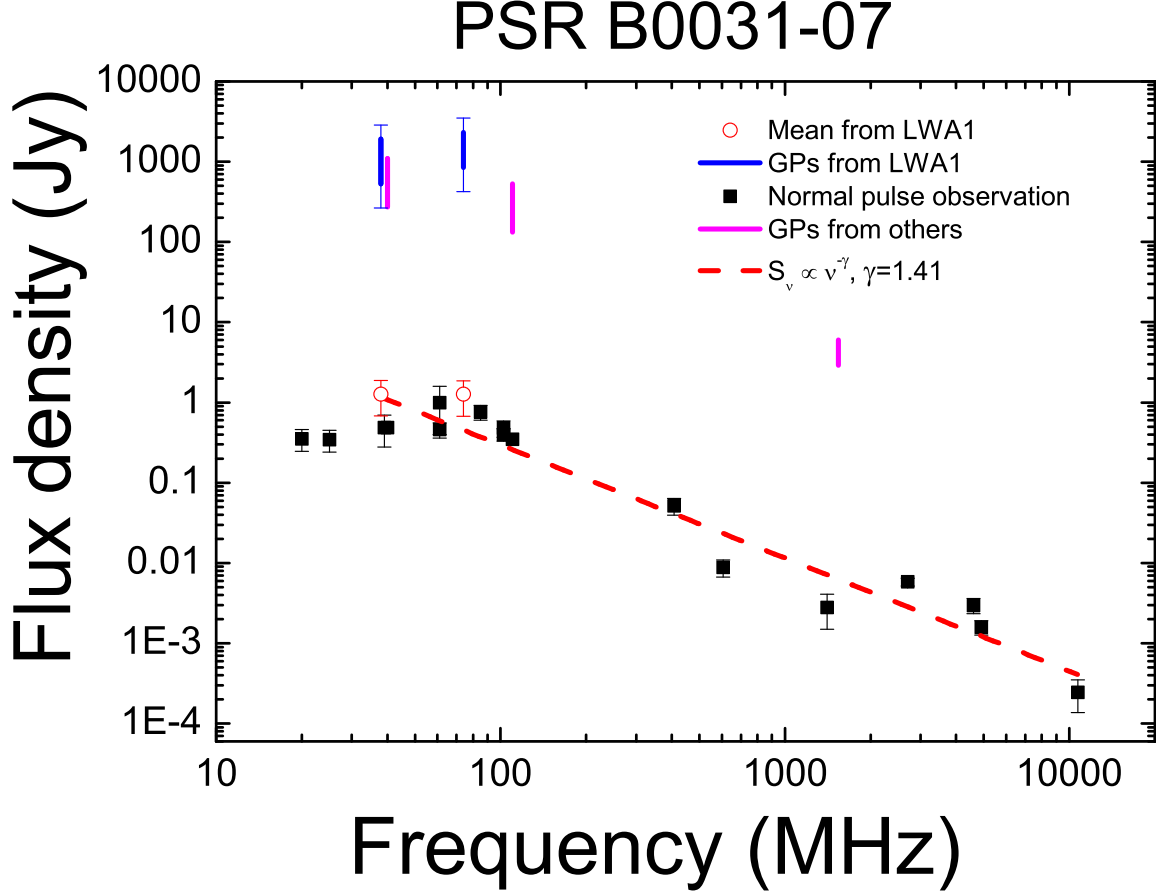


Figure 6.4: A collection of observed flux densities from the literature and current data from this work for PSR B0031–07 at different observing frequencies are shown here. Unless otherwise specified in the cited reference, errors of 50% have been assumed for all AP flux density points. The black solid squares represent the flux density for the AP. The red halo circles represent the values for LWA1 at 38 and 74 MHz (this work). For the GP data, the thick vertical line indicates the range of observed values and the thin error bars extending above and below indicate the 50% error associated with the lowest GP and highest GP flux density. The dashed red line is a fit through the AP observations, of spectral index -1.41 . Observations include [132]:1.54 GHz, [106]:0.41 and 1.665 GHz. [107]:2.7 and 4.9 GHz, [108]: 61 and 102.5 MHz, [130]:40 and 111 MHz, [109]: 430 MHz, [110]: 4.6 and 10.7 GHz, [111]: 25, 47, 112, 430, 1408 and 4800 MHz, [112]: 45 MHz, [100]:20 and 25 MHz, and this work: 38 and 74 MHz. Note that the GP flux densities from ([132] and [130]) at 40, 111 and 1540 MHz are peak averages. In order to compare to their results, we multiplied our period averaged result with the ratio of period and width to obtain the peak averaged flux density.

was found to be $= -4.2$ at 38 MHz and -4.9 at 74 MHz respectively. Therefore, our use of the definition of GPs for PSR B0031–07 as found in [130] is supported while the GP’s cumulative distribution index they found for 40 MHz is -4.5 [130].

The strongest GP at 38 MHz had a flux density 287 times larger than that of the AP, while at 74 MHz the strongest GP was found to be 247 times larger than for the AP. We detected only 2 and 19 double-peaked GPs at 38 and 74 MHz respectively, while the majority of the GPs have a single peak. Only 12 GPs were detected in both frequencies within the same pulse periods. The rest of GPs were only detected in one frequency. The AP profiles and GP peak phase positions are shown in figure 6.2. The average FWHM of the GPs is 10.7 ms at 38 MHz and 5.4 ms at 74 MHz. While the FWHM of the APs is 181.4 ms at 38 MHz and 127.5 ms at 74 MHz. The average FWHM of GPs is only 1/17 and 1/24 of that for the AP at 38 and 74 MHz, respectively.

The statistical properties of GPs from the Crab pulsar found by [113] indicate that the strongest GPs have a shorter duration than other GPs. Our observations of GPs from PSR B0031–07 show that a GP with stronger peak flux density could have shorter duration at 74 MHz, but this trend can not be seen at 38 MHz.

We expect the distribution of intervals between GPs to exhibit an exponential functional dependence if each GP is an independent event with a uniform probability for pulse generation at any given time. For simplicity, the number of accumulated pulse periods, p , will be used as a time measure. Therefore, the interval distribution for a single event as a function of the number of periods is given by equation 5.2. Figure 6.6 shows that the GPs are independent events.

6.4 Scattering Analysis

Pulsar observations allow for studies of the interstellar medium (ISM). We attempted to determine the scatter-broadening time (or scatter time) τ_d for both APs and individual pulses with $\text{SNR} > 5.5$ using the CLEAN-based algorithm [116]. The observed pulses are composed of the intrinsic pulse convolved with profiles for propagation effects and instrumental response. Because the CLEAN-based algorithm utilizes an accumulated delta-function-like signal to restore the intrinsic pulse, it allows for the deconvolution of various profile shapes without knowledge of the intrinsic profile.

The recorded signal P_{obs} is the convolution defined as 5.3 where $I(t)$ is the pulse inherent profile, $\text{PBF}(t)$ is the pulse-broadening function, and $r(t)$ is a function which gives the combined instrumental responses including effects due to data processing. We include as part of the instrumental responses the effect derived from setting the bin size of the time series to be the same as the temporal resolution and a similar effect for the frequency channel

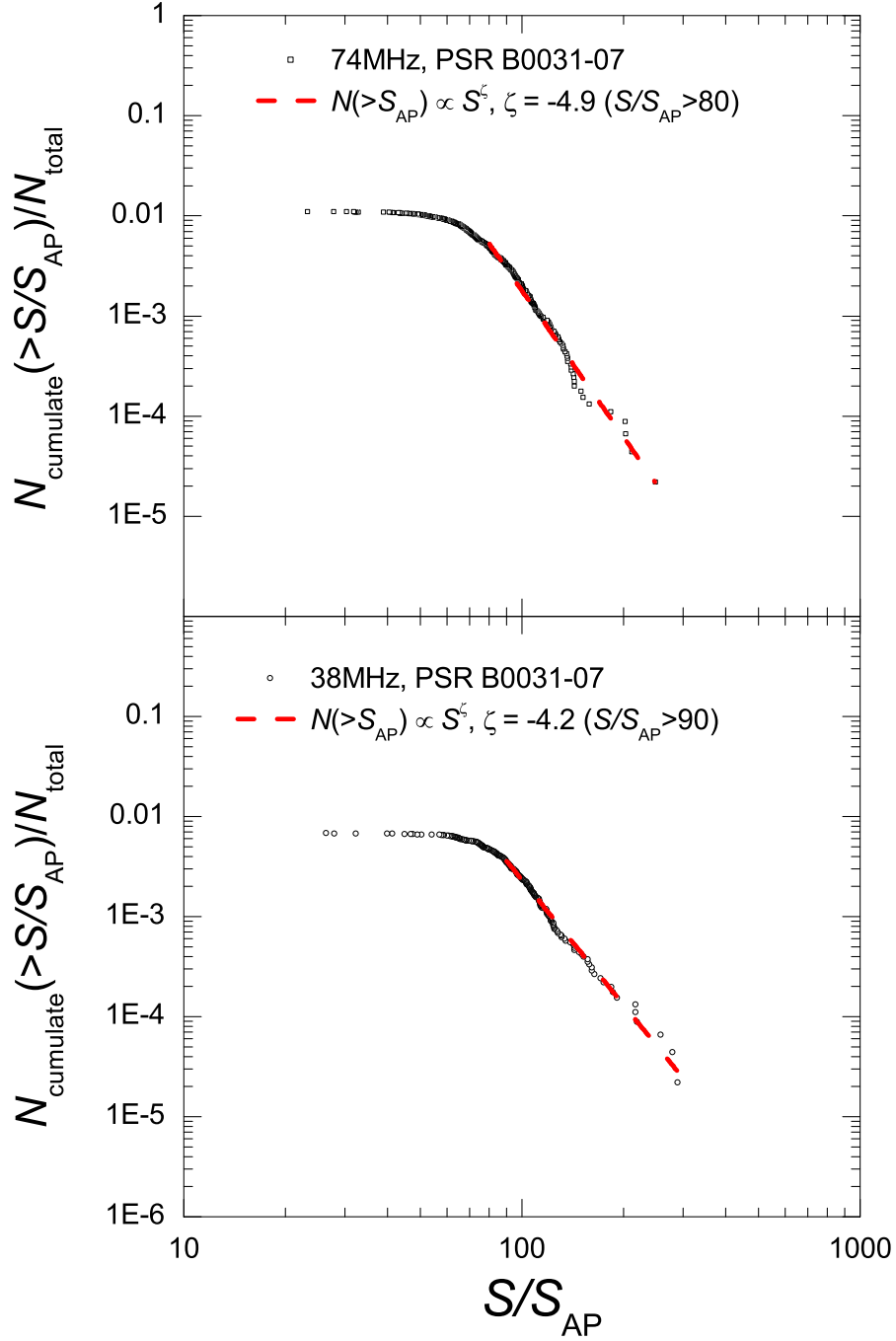


Figure 6.5: (Top) The pulse cumulative number $N(> S/S_{AP})$ for observation frequency 74 MHz as a function of flux density is plotted as black squares, with the power-law fit for $S/S_{AP} > 80$ included as a red curve. (Bottom) The pulse cumulative number $N(> S/S_{AP})$ for observation frequency 38 MHz as a function of flux density is plotted as black circles, with the power-law fit for $S/S_{AP} > 90$ included as a red curve.

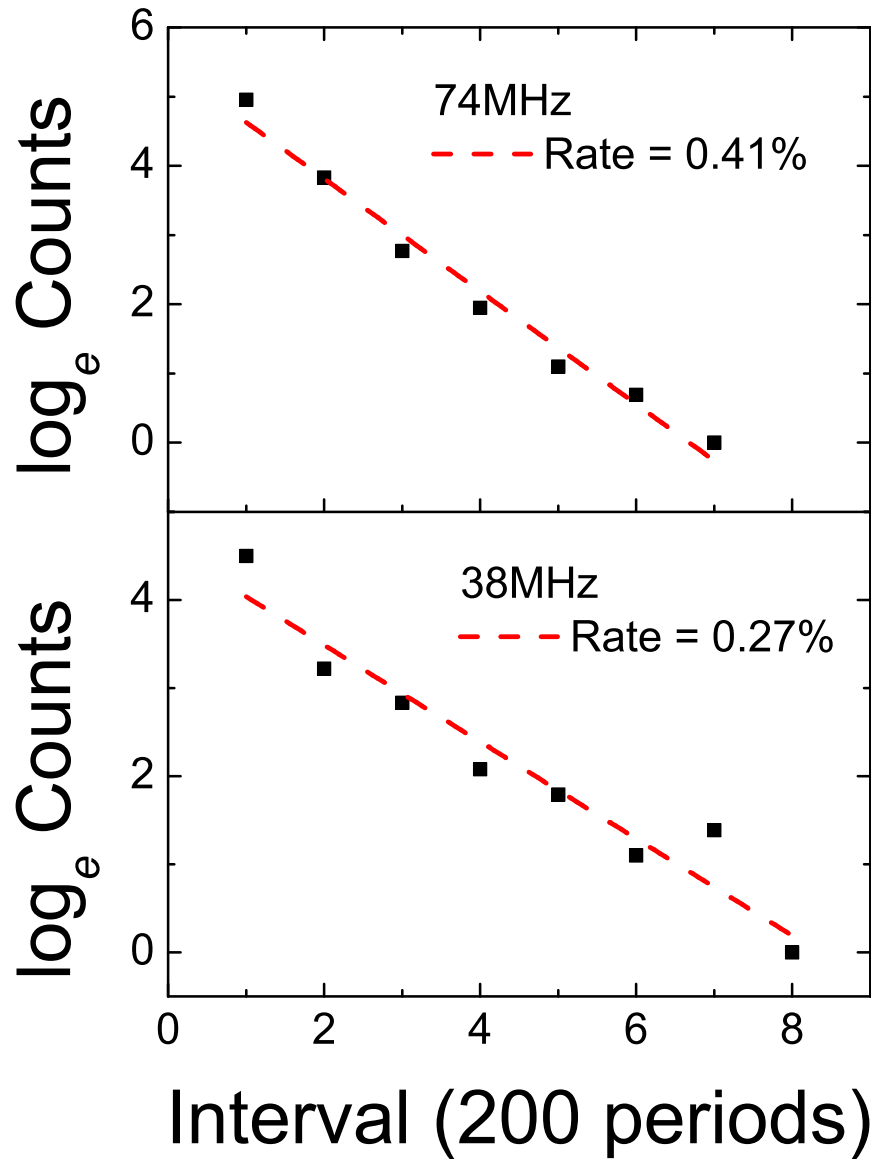


Figure 6.6: The top panel is the plot of the GP interval at a frequency of 74 MHz with a horizontal scale consisting of individual units of ten periods. The rate is the slope of the dashed line fit from 200 to 1400 periods. The bottom panel is the plot of the GP interval at a frequency of 38 MHz with the same ten period units for the horizontal scale. The rate is the slope of the dashed line fit from 200 to 1600 periods. We did not find interesting clustering or periodic behaviors regardless of the chosen binning interval.

width. For simplicity, we compare only the exponential decay time for APs, τ_d from a thin screen model, $\text{PBF}(t) = \exp(-t/\tau_d)$, with results for pulses with $\text{SNR} > 5.5$.

We found the exponential decay time from individual pulses with $\text{SNR} > 5.5$ is 6.1 ± 2.2 ms and 3.9 ± 1.4 ms for 38 and 74 MHz, respectively. For the APs we found 39 ± 7.6 ms and 36 ± 8.8 ms for 38 and 74 MHz, respectively. The scatter time frequency scaling index was found to be $\alpha = -0.18 \pm 0.06$ for APs, and -1.5 ± 0.2 for individual pulses with $\text{SNR} > 5.5$. The scatter time frequency scaling index is α , where $\tau_d \propto \nu^\alpha$. However, these measured values of α most likely do not reflect the actual scattering index as scatter-broadening should be a property of the interstellar medium through which the pulse is traveling, and therefore should be the same for all types of pulses from a given pulsar. The inconsistency between the values for τ_d for APs and for those with $\text{SNR} > 5.5$ is most likely a result of evolution of the profiles at different frequencies, such as radius-to-frequency mapping [133, 134], rather than the scattering effect from ISM. Also, as [49, 135] argued, one can obtain reliable values of τ_d only when the scatter time is significantly larger than the width of the profile. The exponential decay time derived from CLEAN method is much smaller than the profile width. Thus the interstellar medium scattering effect is not strong enough to be measured at the frequencies that we observed along the LOS to PSR B0031–07.

Furthermore, several studies of the scatter time frequency scaling index [39, 47–49] revealed that only a handful of pulsars have their scaling indices close to the value of -3.0 . All of these extremes happen only for high DM pulsars for which the interstellar medium can be expected to have some extreme scattering geometry which causes the scaling index to flatten [136]. PSR B0031–07 is not a high DM pulsar so this should not apply.

6.5 Conclusion

GPs and APs were detected while observing PSR B0031–07 simultaneously at 38 and 74 MHz using the LWA1. Notably, we have shown that GPs and APs from PSR B0031–07 are weaker than at ~ 100 MHz. The rate and strength of GPs are comparable with other observations at 111 MHz and 40 MHz by [130]. Most GPs were only detected at one frequency which implies that most of the detected GP emission is not a wide band. We found that a $\text{DM} = 10.9 \text{ pc cm}^{-3}$ produced the highest SNR for observed pulses. The CLEAN-based algorithm [116] was used to analyze the effect of scattering. It was determined that the scattering effect can not be detected because it is small compared to the effect of profile broadening.

Chapter 7

Scattering Effect Survey

This chapter has been published [4]. The author of this thesis wrote the code for data collection, data processing, analysis, and figures. He wrote the first draft, then collected comments from the coauthors, then revised the paper. Lastly, he used the referee review for the submitted paper to finalize the published version of this work.

7.1 Introduction

As discussed in the Introduction, there are scattering observations of pulsars which exhibit a departure from the Kolmogorov spectrum. Studies of pulsars with large dispersion measures (DMs) by [36] show a flattened scattering spectral index, and it has been suggested that the effect of scattering for some pulsars is highly dependent on the line of sight (LOS) [37–39]

These results suggest it may prove futile to attempt to formulate a general relationship between scattering at a specific frequency and DM (e.g. [39]). A comprehensive study of the effect of scattering on the emission from many pulsars at various DMs and with different lines of sight could be used to clarify this issue. A critical amount of archival pulsar data is available for such an analysis. Here we report results from a survey of the scattering effect of 1342 pulsar profiles from 347 pulsars that came from the LWA Pulsar Data Archive [117] and European Pulsar Network (EPN) data archive.

The majority of profiles do not show a significant scattering tail. Thus the deconvolved exponential decay time of the majority of the pulsars provides an upper limit on the scatter time. A subset of 21 pulsars showed a significant scattering tail in the lowest frequencies compared with higher frequencies. Because we did not find any pulsars for which two recorded profiles at different frequencies both showed a significant scattering tail, it remains difficult

to interpret a non-Kolmogorov spectrum of the free electron turbulence along the LOS from our results.

Assuming a scatter time frequency scale index $\alpha = -4.4$ for

$$\tau \propto \nu^\alpha, \quad (7.1)$$

where τ is scatter time and ν is frequency, we scaled the deconvolved scatter time assuming the thin screen scattering model to the frequency of 1 GHz and placed our results in the context of other studies. Our results support a broad relation between the scatter time and DM. The scatter time value is as wide as two orders of magnitude for a given range of DM, and the range could be wider for DMs larger than 100 pc cm⁻³. We found a mean value upper limit of $\lesssim -3.8$ for the thin screen scattering model from a subset of 21 pulsars.

7.2 Observations and Data Processing

Pulsars provide a great tool to probe the effect of scattering along different lines of sight, with different frequencies and DMs. We conducted a survey of the effect of scattering which included 1342 profiles from 347 pulsars to determine the best-fit scatter time in the thin screen and uniform medium scattering models. The pulsar profiles used were drawn from the LWA Pulsar Data Archive [117] and the European Pulsar Network (EPN) data archive¹. The analysis covers a frequency range from 25 MHz to 43 GHz and DMs from 2.38 to 780 pc cm⁻³.

We made use of the CLEAN-based algorithm [116] to deconvolve the scattering effect on the pulsar profiles. Each recorded pulsar profile is composed of the averaged intrinsic pulse convolved with propagation effects and instrumental responses. The CLEAN-based algorithm utilizes an accumulated delta-function-like signal to restore the intrinsic pulse. This approach allows for the deconvolution of various profile shapes without knowledge of the intrinsic profile. It does, however, make an important assumption; it assumes that all scatter-like features in the profile (i.e., an asymmetry that makes the right hand side slope of the profile flatter than the left) are indeed coming from scattering.

The observed signal P_{obs} is

$$P_{obs}(t) = I(t) \otimes \text{PBF}(t) \otimes r(t), \quad (7.2)$$

where $I(t)$ is pulse inherent profile, $\text{PBF}(t)$ is the pulse-broadening function, and $r(t)$ is a response function which gives the combined instrumental responses including effects due to data processing.

¹www.jb.man.ac.uk/pulsar/Resources

We deconvolved the profile using two scattering models, the thin screen model, and the thick-medium or uniform-medium model. As their names suggest these models make different assumptions about the distribution of the scattering medium between source and observer [137, 138]. For the majority of the distant pulsars the thin screen model provides a good approximation of the effect of scattering. The amount of scattering depends on the magnitude of density fluctuations in the ionized interstellar medium (ISM). The fluctuations may be greatest in high electron density regions, such as HII regions or supernova remnants. Within these regions the electron density may be a few orders of magnitude larger than in an average interstellar medium region. Thus the density fluctuations could be larger as well. When one considers that the size of such regions is at most a few tens-of-parsecs, compared to the kilo-parsec distances to many pulsars, the concept of a thin screen seems appropriate. The situation is a bit different for nearby pulsars, where the existence of such scattering screens along the LOS may be unlikely. Thus we also analyze the effect of scattering using the “uniform medium” model. As the name suggested this model assumes the density fluctuations are spread uniformly along the entire LOS.

The normalized pulse-broadening functions for these two models are given by

$$\text{PBF}_{\text{ts}}(t) = \tau_{\text{ts}}^{-1} \exp(-t/\tau_{\text{ts}}) U(t) , \quad (7.3)$$

$$\text{PBF}_{\text{um}}(t) = (\pi^5 \tau_{\text{um}}^3 / 16 t^5)^{1/2} \exp(-\pi^2 \tau_{\text{um}} / 4t) U(t) , \quad (7.4)$$

where PBF_{ts} and τ_{ts} are the pulse-broadening function and scatter time for the thin screen model, and PBF_{um} and τ_{um} are the pulse-broadening function and scatter time for the uniform medium model. The function $U(t)$ is a Heaviside step function where $U(\geq 0) = 1$ and the rest is $U = 0$ for all other times.

The choice of $r(t)$ affects the shape of the restored profile and may affect the scatter time measurement. The function $r(t)$ usually is chosen to be a Gaussian because $r(t)$ is a convolution of several step functions [116]. To choose a proper FWHM of $r(t)$, we first consider that some of the older profiles from the EPN database had poor time resolution yielding time constants that were larger than the sampling time and resulting in a broader instrumental response function. Also, dispersion smearing was a factor in data processing as only incoherent dedispersion was applied and at low frequencies, of the order of a few tens of MHz. This was the case for most of the older profiles included in the EPN database, since most of these observations were made using wide-band filterbank receivers. Thus in some cases where $r(t)$ is assumed to be a Gaussian with a small FWHM the restored profiles can contain a collection of narrow spikes. Here we simply assumed $r(t)$ to be a Gaussian with a FWHM that was equal to the $4 \times$ temporal bin width and iteratively subtracted the trial $\text{PBF}(t) \otimes r(t)$ from $P_{\text{obs}}(t)$.

We tried scatter times which ranged from 0.2 temporal bin widths to the observed profile width. In each trial we iterated by subtracting scattered bins [116] until the resulting average of the profile was smaller than the average of the time series outside the profile, or the

standard deviation of the profile was smaller than the standard deviation of the time series outside the profile. We thus identified the scatter time as the time constant which had the smallest ratio of residual standard deviations between the outside and inside of the profile.

The CLEAN-based method can be used to extract information about the effect of scattering only if one assumes that the intrinsic pulsar profile does not contain other features that may resemble scattering. This is also the case for other scatter time estimation methods [49]. If we imagine that the pulsar has an intrinsically asymmetric profile which is not scattered but which contains a feature that mimics the appearance of a scattering tail (see the profiles of the Vela pulsar at > 1 GHz for example), when the CLEAN method (or any other) is applied to extract the scatter time from such a profile a non-zero value of τ will be found. One can obtain reliable values of τ only when the scatter time is significantly larger than the width of the profile at higher frequency [49, 135].

When we apply this method to a given profile of the sort described in the previous paragraph, the value of α derived is most likely a result of evolution of the profiles at different frequencies dominated by effects unrelated to scattering. In such cases τ shows some kind of frequency evolution of this “fake” scatter time. This fake-scatter tail will lengthen, yielding larger values of the fake-pulse broadening time at lower frequencies. Since most of the profiles become broader at lower frequencies (due to radius-to-frequency mapping), this fake scatter time will in most cases also increase, mimicking the “real” scattering evolution, although usually with much flatter slope, yielding in turn fake values of α considerably larger than -4.4 .

7.3 Results

We carefully examined all profiles from each pulsar at all available observing frequencies from the EPN and LWA Pulsar Data Archive. We found a subset of 21 pulsars which significantly showed a scattering tail in the profile at lower frequencies compared with higher frequencies. From the subset of 21 pulsars we assume that the scattering effect dominated the profile tail and deconvolved the effect making use of the two scatter scenarios: the thin screen and uniform medium models, as shown in figures 7.1 and 7.2. The individual scatter times are shown in the table 7.1. For the sake of comparison we list the values of τ_{ts} at similar frequencies from previous works [47, 49, 139] in table 7.2. We scaled τ_{ts} to 1 GHz assuming a $\alpha = -4.4$ along with other works [36, 70] in figure 7.3. Note that our results include three new direct scatter time measures of low DM ($< 100 \text{ pc cm}^{-3}$) pulsars, which are not converted from measurements of the decorrelation bandwidth. Other values of τ_{ts} shown in figure 7.3 which were not calculated from the lowest available frequency of the subset of 21 pulsars we used to estimate scatter time upper limits. Our results support a broad relation between scatter time and DM. In figure 7.3, we can see that the scatter time generally spans

two orders of magnitudes for $\text{DM} \lesssim 100 \text{ pc cm}^{-3}$, and spans over even larger orders for $\text{DM} \gtrsim 100$, within a range of DM.

The scatter-time frequency index, α , can be calculated for observations at two different frequencies by using the following relationship

$$\alpha = \frac{\log \tau_{\text{high}} - \log \tau_{\text{low}}}{\log \nu_{\text{high}} - \log \nu_{\text{low}}}, \quad (7.5)$$

where we make use of the two respective scatter times and observing frequencies. Given that the scattering effect is not observed in the next to the lowest available frequency of the 21 pulsars, we can make use of the above expression to set an upper limit on α which we list in table 7.1. The mean values of the upper limit on α are -3.8 and -4.8 (from 13 pulsars) from the thin screen and the uniform medium scattering models, respectively.

We excluded results using the uniform medium scattering model for a subset of 21 of the pulsars because this model is not appropriate for those profiles, based on the deconvolved results which show an obvious scattering tail or a collection of narrow spikes that are not expected in a natural pulsar profile.

Note that we deconvolved the scatter time from the profile assuming an intrinsic profile composed of Gaussian components. However, this will not necessarily be the case for all intrinsic pulsar profiles. Thus the departures from the Kolmogorov scaling index we found for some pulsars should not necessarily be inferred as anomalies of the free electron turbulence along the lines of sight.

7.4 Conclusions

We used the CLEAN-based method to deconvolve the effect of scattering for 1342 profiles from 347 pulsars to derive the spectral index and time constant within a broad range of frequencies and DM, assuming the thin screen and uniform medium scattering models. Many scatter times were not significant compared to the profile widths but nonetheless provide bounds on the effect of scattering at higher frequencies.

A subset of 21 pulsars showed significant effects of scattering at the lowest available frequency, and were used to calculate upper limits on α . We found a mean value for the upper limit of $\alpha \lesssim -3.8$ using the thin screen scattering model from 21 pulsars. We also calculated a mean value of upper limit of α as $\lesssim -4.8$ using the uniform medium scattering model from 13 pulsars. Our results include three new direct scatter time measurements of low DM ($<100 \text{ pc cm}^{-3}$) pulsars.

It is difficult to infer a non-Kolmogorov spectrum of the free electron turbulence along

the LOS from our results. The scaled, deconvolved time constant supports broad relations between the DM and scatter time, which can span over two orders of magnitudes given a range of DMs.

Table 7.1: The scatter time and the upper limit value of α from the CLEAN-base method. The subscript “ts” and “um” indicate the thin screen scattering model and uniform medium scattering model, respectively. Note that for some of the pulsars the τ_{um} is not available because the phases of deconvolved peak components are outside of the range of the profile due to limitations of our data processing algorithm. The error is the step size during the deconvolution trial. (*Archive data from LWA Pulsar Data Archive, others are from EPN. **The CLEAN-base method is not valid due to improper clean bin phase position.)

PSR	ν (MHz)	τ_{ts} (ms)	τ_{um} (ms)	error (ms)	α_{ts}	α_{um}
B0329+54*	45	35.73	15.63	0.56	< -4.68	< -5.13
B0329+54*	55	< 13.96	< 5.58	0.56		
B1714-34	606	134.44		1.08	< -3.34	
B1714-34	1408	< 8.08		0.35		
B1737-30	408	37.89		0.9	< -4.64	
B1737-30	610	< 5.87		0.28		
B1753-24	606	78.44	39.22	0.68	< -4.06	< -4.13
B1753-24	925	< 14.07	< 6.85	0.38		
B1805-20	606	236.34		1.13	< -3.67	
B1805-20	925	< 54.09		0.67		
B1815-14	925	54.47	22.66	0.33	< -2.95	< -3.48
B1815-14	1408	< 15.78	< 5.26	0.38		
B1821-11	925	43.13	22.23	0.33	< -3.79	< -4.39
B1821-11	1408	< 8.77	< 3.51	0.35		
B1821-19	408	19.17	8.22	0.68	< -3.85	< -4.68
B1821-19	610	< 4.06	< 1.25	0.42		
B1822-09*	35	116.55	88.32	0.6	< -3.86	< -5.04
B1822-09*	49	< 31.84	< 16.22	0.6		
B1826-17	408	28.82		1.31	< -3.41	
B1826-17	610	< 7.3		0.41		
B1831-03	408	19.43	8.64	0.72	< -3.24	< -5.68
B1831-03	610	< 5.27	< 0.88	0.44		
B1834-04	606	31.25		0.43	< -4.92	
B1834-04	925	< 3.9		0.24		
B1834-10	408	128.16		1.91	< -4.46	
B1834-10	610	< 21.33		0.59		
B1838-04	606	22.94	11.47	0.6	< -3.61	< -4.41
B1838-04	925	< 4.99	< 1.78	0.18		

Continued on next page

Table 7.1 – continued from previous page

PSR	ν (MHz)	τ_{ts} (ms)	τ_{um} (ms)	error (ms)	α_{ts}	α_{um}
B1855+02	606	63.97		0.94	< -3.43	
B1855+02	925	< 15		0.28		
B1859+03	410	70.28	26.66	2.42	< -4.86	< -6.33
B1859+03	606	< 10.51	< 2.25	0.75		
B1900+06	408	60.57	25.5	3.19	< -3.86	< -6.37
B1900+06	610	< 12.84	< 1.97	0.99		
B1913+10	408	22.21	7.4	1.48	< -3.47	< -5.18
B1913+10	610	< 5.5	< 0.92	0.46		
B1929+20	410	10.16	2.54	1.27	< -3.67	< -2.94
B1929+20	610	< 2.36	< 0.79	0.39		
B1946+35	408	15.75	5.51	0.39	< -3.5	< -4.34
B1946+35	610	< 3.85	< 0.96	0.48		
B2217+47*	49	51.32		0.42	< -3.16	
B2217+47*	79	< 11.36		0.42		

Table 7.2: This table shows the comparison of scatter time from this work and previous works. (¹ [49], ² [139], ³ [47])

PSR	this work		previous works	
B1815–14	1.4 GHz	15.78 ± 0.38	1.4 GHz	15.3 ± 2.0^1
B1834–04	606 MHz	31.25 ± 0.43	610 MHz	33 ± 5^1
B1929+20	610 MHz	2.36 ± 0.39	610 MHz	1.71 ± 0.21^2
B1805–20	606 MHz	236.34 ± 1.13	0.6 GHz	259 ± 47^3
B1821–11	925 MHz	43.13 ± 1.34	0.9 GHz	40 ± 12^3

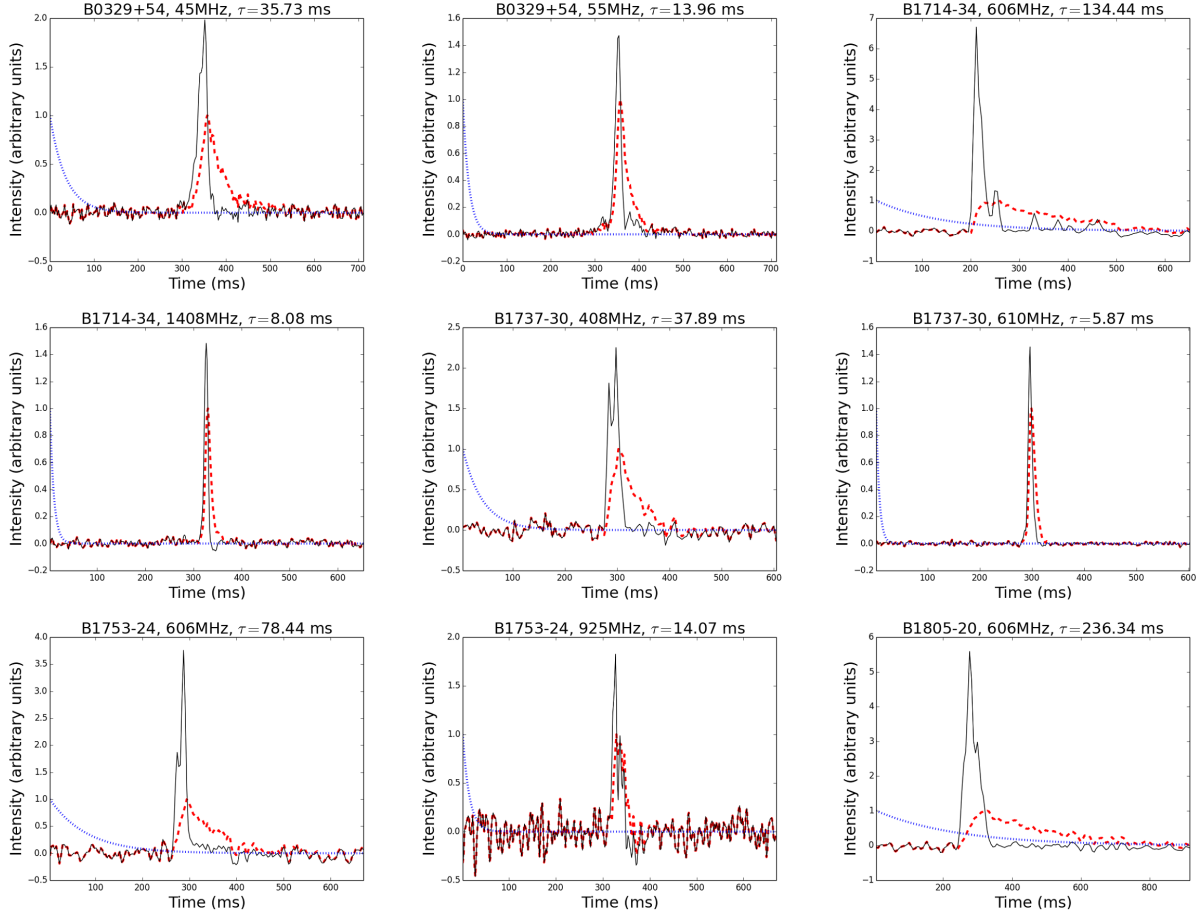


Figure 7.1: The deconvolved scatter time and clean components of 21 pulsars assuming the thin screen model is shown. The red thick dashed line is the average profile of a each pulsar. The blue thin dashed line is the scattering function. The black solid line is clean components with noise deconvolved from the profile. Clean components mathematically represent the intrinsic profile before scattering, but due to poor temporal resolution after data processing certain unphysical features such as collections of narrow spikes appearing in some clean components.

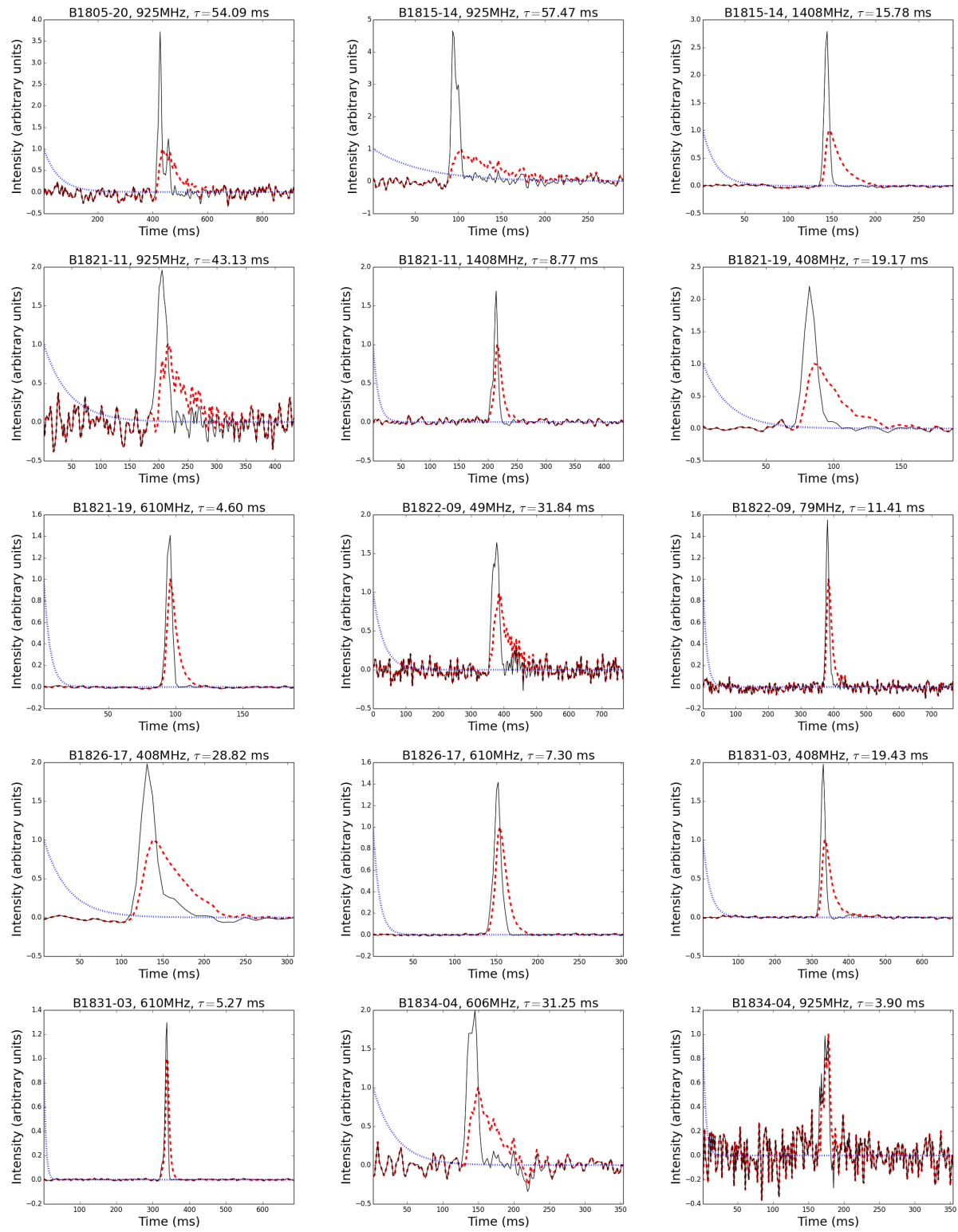


Figure 7.1: Cont.

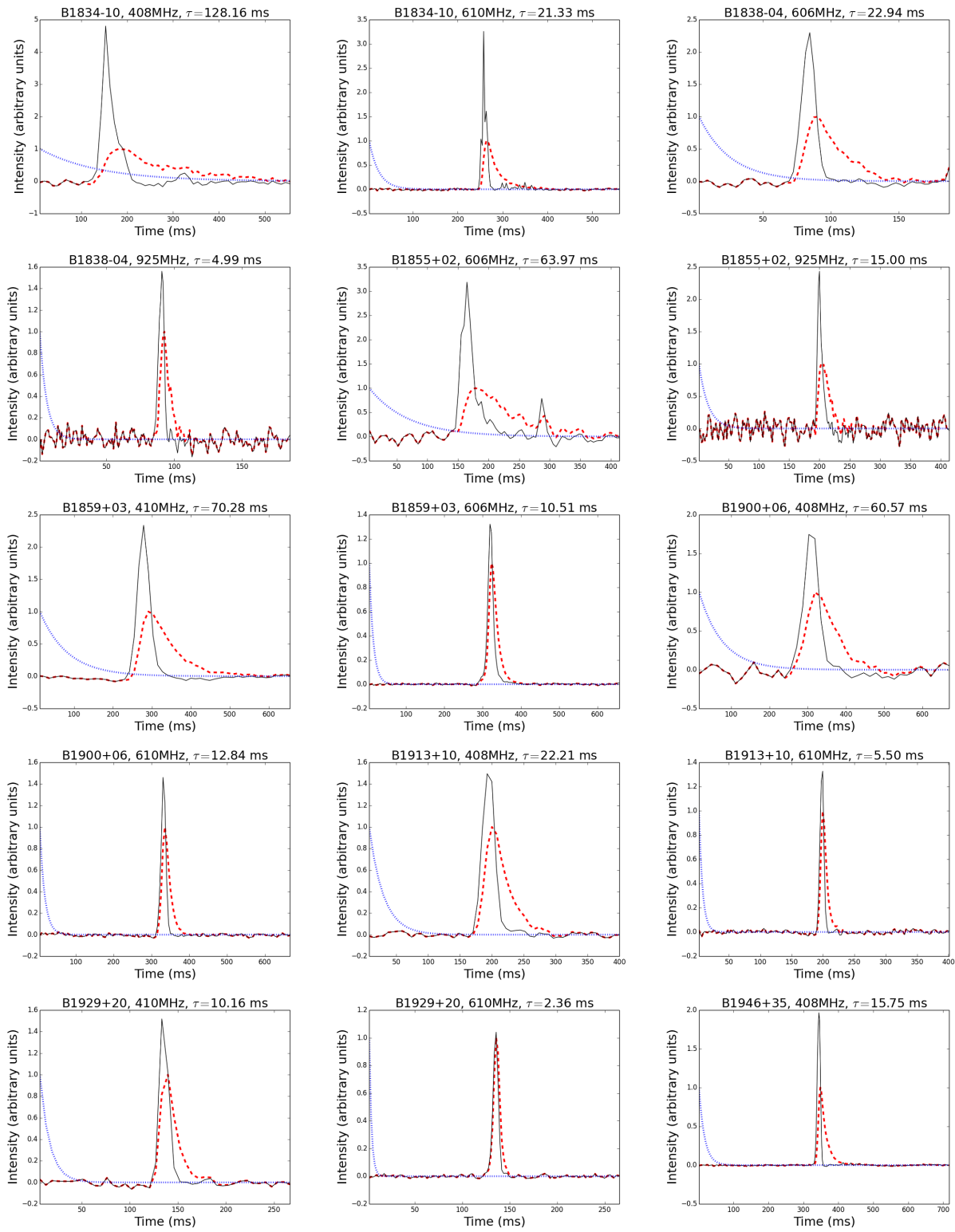


Figure 7.1: Cont.

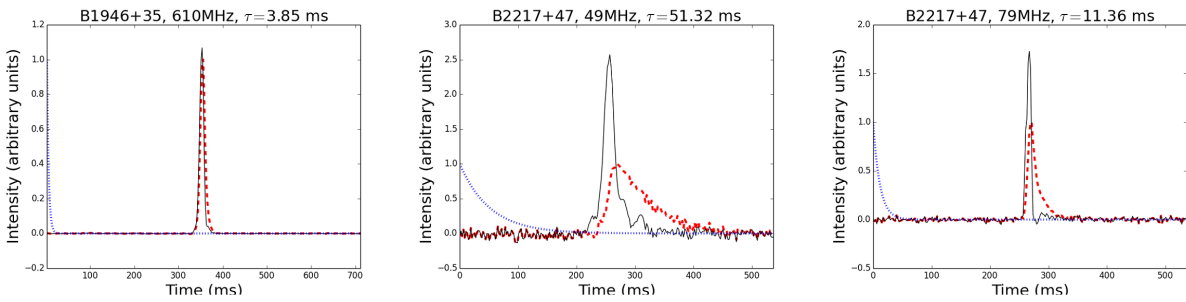


Figure 7.1: Cont.

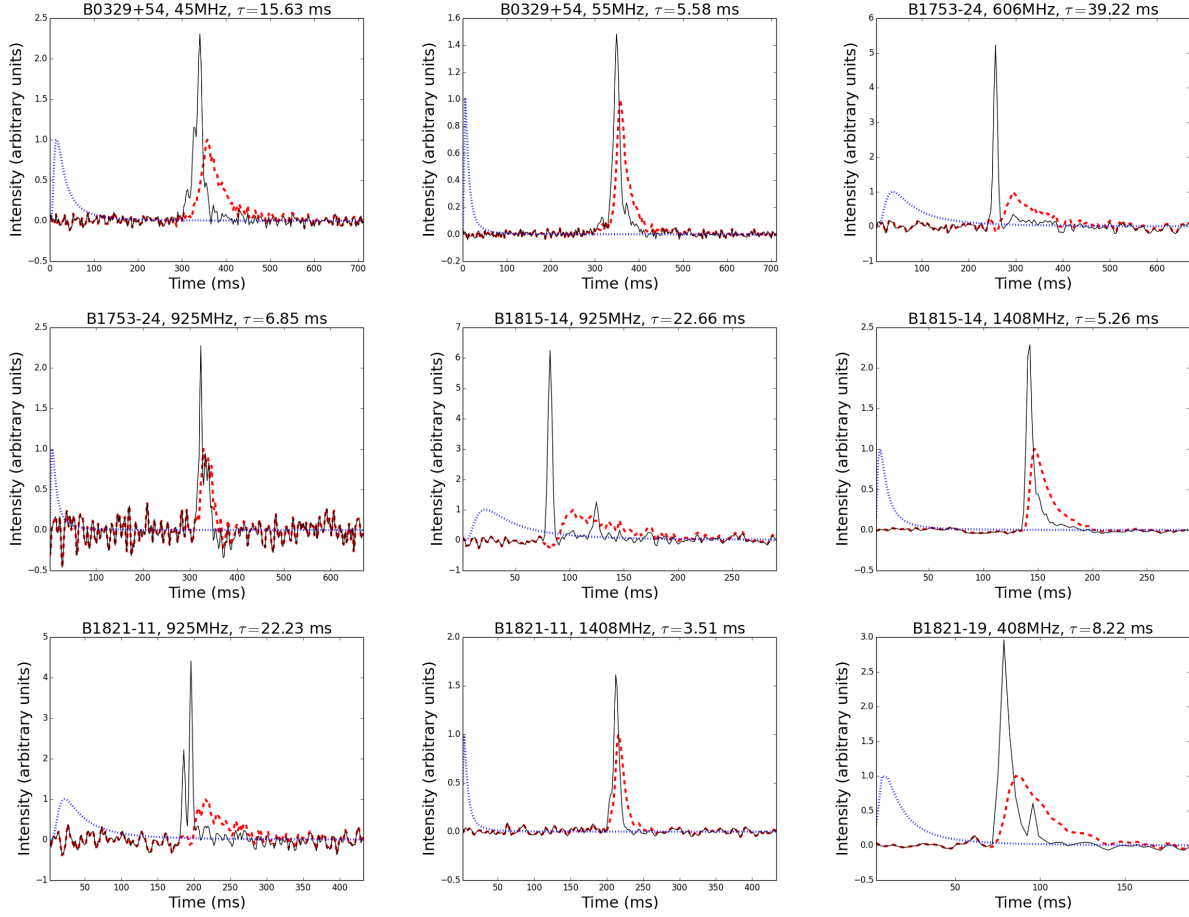


Figure 7.2: The deconvolved scatter time and clean components of 13 pulsars assuming the uniform medium scattering model is shown. The red thick dashed line is the average profile of each pulsar. The blue thin dashed line is the scattering function. The black solid line is clean components with noise deconvolved from the profile. Clean components mathematically represent the intrinsic profile before being scattered but due to poor temporal resolution after data processing certain unphysical features such as collections of narrow spikes appear in some clean components.

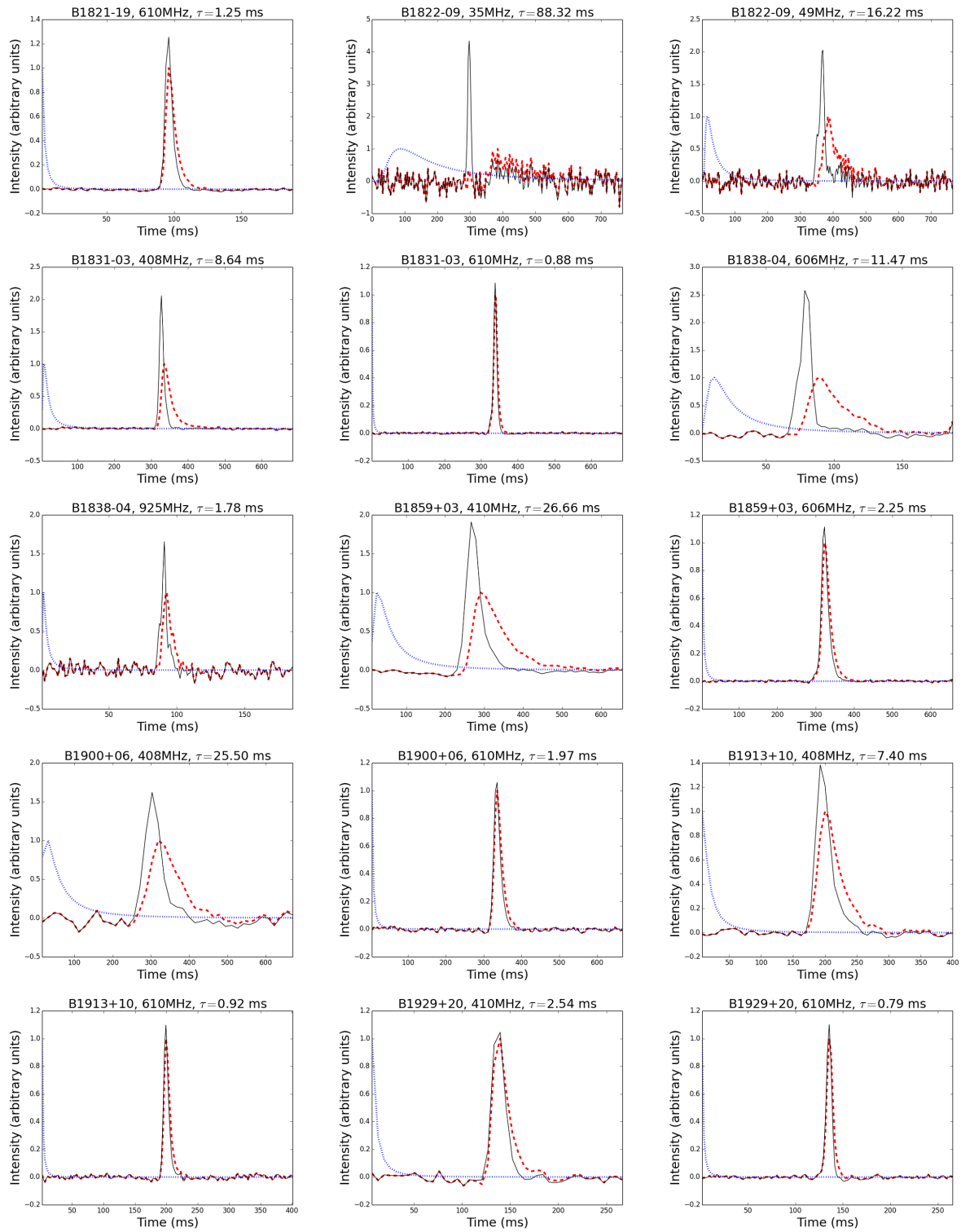


Figure 7.2: Cont.

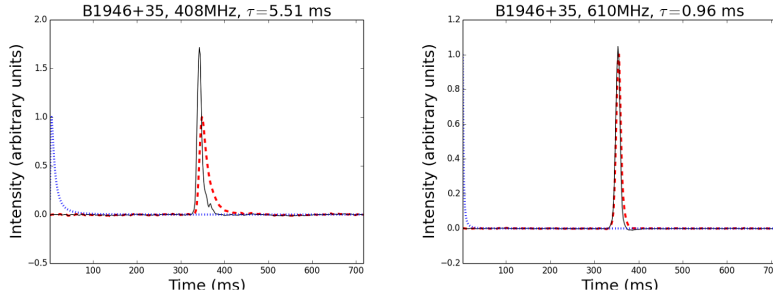


Figure 7.2: Cont.

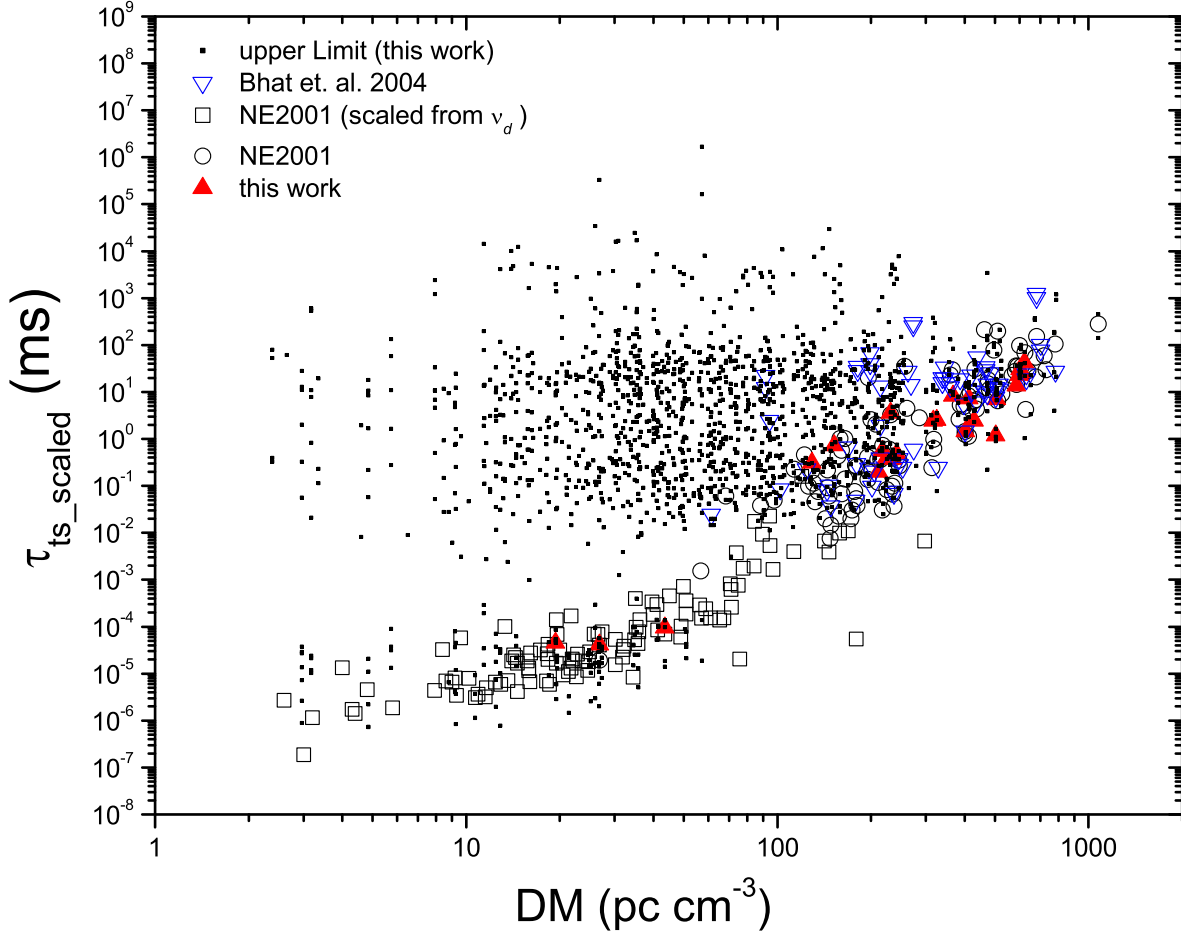


Figure 7.3: The scaled τ_{ts} at 1 GHz assuming $\alpha = -4.4$, where $\tau \propto \nu^\alpha$. Some of τ_{ts} are converted from ν_d by $\tau\nu_d = C_1/2\pi$, assuming $C_1 = 1$.

Chapter 8

Searches for Radio Transients

The algorithms used to search for single dispersed radio transients are identical to those used for pulsar giant pulse searches in many aspects. Examples are searching a range of DM trials and decimating the time series. But most radio transients do not repeat, which makes them difficult to detect. We follow the techniques described by Cordes and McLaughlin [89]. We did not find other signals with $\text{SNR} > 10$ in our observations of giant pulses for 120 hours with DM trials over a range $1\text{--}5000 \text{ pc cm}^{-3}$. In this chapter we detail how we deployed techniques described in [89] on the observations using LWA1. Then we discuss the relation between the FRB event rate and their spectral index based on our null detection.

8.1 DM Matching

It may take weeks to search over a large range of DM trials for dispersed radio transients in a 4 hour observation, given data files on the order of a terabyte in size. The bottleneck is that we can not cut the full spectrogram up into smaller parts and search for signals independently within those parts. And we need to design a parallel computation algorithm that can hold a TB of data in memory which can produce a full time series after dedispersion. One way to improve the computational efficiency is to flexibly change the spacing of DM trails determined by current DM trials, so we can predict the SNR smearing across a range of DM trials. Because a coherent dispersion method is not suitable for our study, we used incoherent dedispersion, which allows for a finite bandwidth so there is a finite dispersion time lag across the bandwidth. And this un-dedispersable time lag will increase as the DM trial increases, so the DM spacing is incremental and this is more efficient compared with a fixed DM spacing (eq. (3.4)).

To estimate the impact of a mismatched DM trail on SNR obtained for a pulse, we follow

the method developed in [89], which calculates the ratio of peak flux with an error in DM, S_{err} , versus the true peak flux S , for a rectangular band pass function, as

$$\frac{S_{err}}{S} = \frac{\sqrt{\pi}}{2} \zeta^{-1} \text{erf} \zeta \quad (8.1)$$

where

$$\zeta = \delta \text{DM} \times \frac{\Delta \nu_{\text{MHz}}}{W_{\text{ms}} \nu_{\text{GHz}}^3} \times 6.91 \times 10^{-3}, \quad (8.2)$$

and W_{ms} (FWHM) is a Gaussian profile width in milliseconds. In our case of the LWA1 with a total bandwidth of 16 MHz with 2 tuning frequencies centering at 38 MHz and 74 MHz, we show 4 examples of the signal strength ratio with DM error in figure 8.1. This estimation helps us to filter out RFI from astronomical signals, since most RFI do not show a similar decay in SNR when DM changes.

8.2 Thresholding

In each DM trail, after dedispersion, we decimate the time series by a factor of 2, then record the SNR for each potential pulse, DM, temporal resolution, and temporal position in the time series, as long as the pulse (time sample) has $\text{SNR} > 5$. Then we plot the results from these results of data processing (hereafter called a CM-plot). As an example we will explain the characteristics in figure 4.2 which has a giant pulse detection in an observation of the known pulsar B0950+08.

In the figure 4.2, the top left panel shows the number of signals vs. SNR. The blue dashed line shows the theoretical result for Gaussian noise detections per bin size in ΔSNR [89], namely

$$\Delta N_{\text{detection}} \approx \sum_{j=0}^{j_{\text{max}}=15} 2^{-j} N N_{\text{DM}} \Delta f(\text{SNR}), \quad (8.3)$$

for a time series with N samples, total N_{DM} trials of DM values, and 15 time decimation, where $f(\text{SNR})$ is a normalized Gaussian probability density function. For no true signal pulse and, therefore, only Gaussian noise, we expect the results will follow the blue dashed line. In this example (figure 4.2), the top left panel shows how a true signal at $\text{SNR} > 6.5$ differs from the Gaussian noise.

The top middle panel shows the number of signals vs. DM trial. The blue dashed line is the number of detections in a number of DM trials for $\text{SNR} > 5$, or

$$\Delta N_{\text{detection}} \approx \sum_{j=0}^{j_{\text{max}}=15} 2^{-j} N \Delta N_{\text{DM}} f(5), \quad (8.4)$$

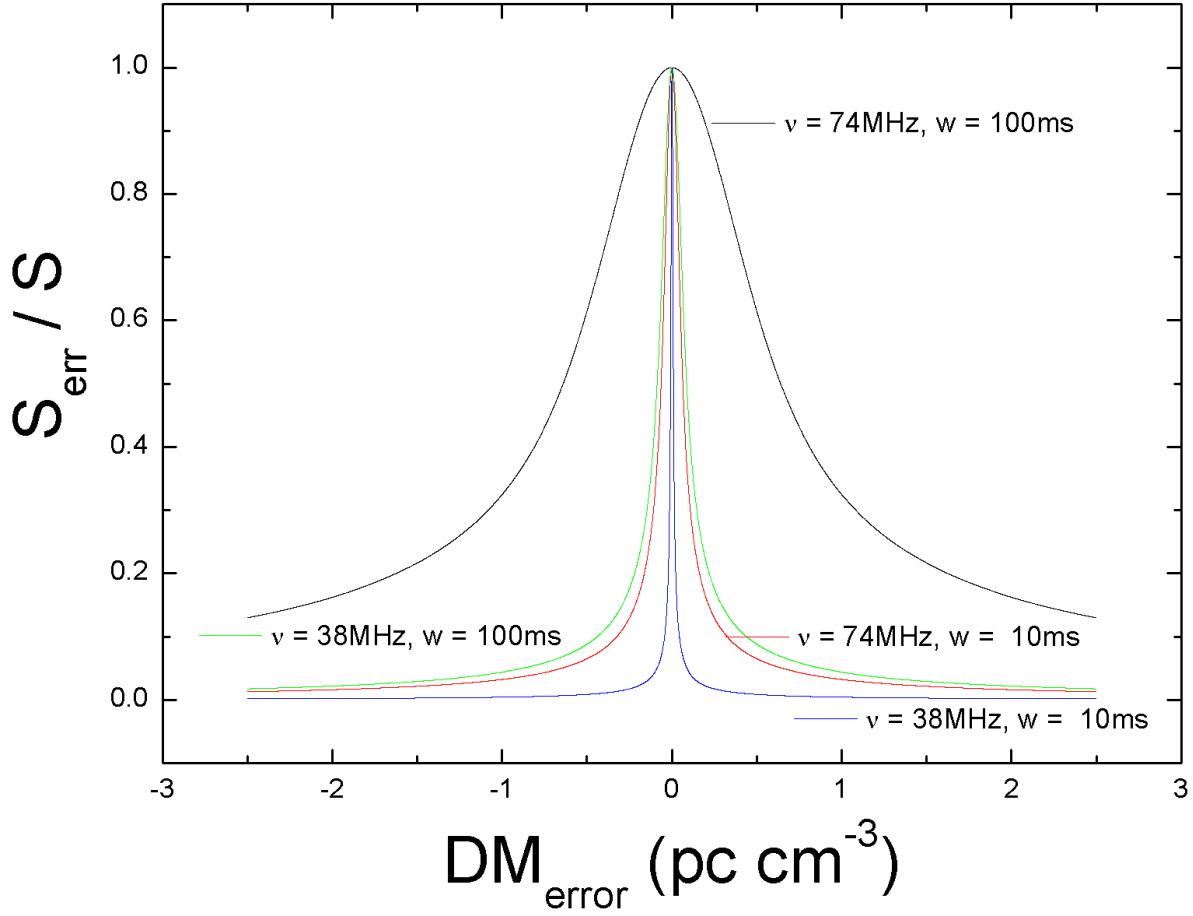


Figure 8.1: Ratio of detected to true flux density as a relation of DM errors for a dedispersed pulse. The error = 0 is for the ideal situation. The total bandwidth is 16 MHz. In the 74 MHz tuning with a pulse width of 100ms, the signal strength drops to half when the DM error is $\pm 0.76 \text{ pc cm}^{-3}$. Each example assumes the decimated time resolution is matched to pulse width.

for a time series with N samples, ΔN_{DM} trials of DM values in the bins, and 15 time decimations, and where $f(\text{SNR} = 5)$ is a normalized Gaussian probability density function. For no true pulse with pure Gaussian noise, we expect the records will follow the blue dashed line. In this example (figure 4.2), the top middle panel shows the result for a true pulse at $\text{DM} \approx 2.9$ as it departs from the Gaussian noise (the dashed blue line).

In the top right panel, we can see the highest signal peaks at a $\text{DM} \approx 2.9 \text{ pc cm}^{-3}$. Note that for a temporal-width matched situation, the pulse strength will drop to half if the DM error rises to $\pm 0.05 \text{ pc cm}^{-3}$ which can not be seen here. In the bottom panel, we can see

the scatter plot for the GP, where the size of the points is proportional to the SNR. The different point sizes show the different SNR for different resolutions (with decimation) of the dedispersed time series. If the resolution matches the duration of pulse, the SNR will be the maximum. For true (therefore positive) dispersed peaks in the time series, we expect that they will produce distributions different from Gaussian in top left and right panels, plus peaks in top right panel with a larger SNR (larger than the SNR where deviations occur in the top left panel), and multiple concentric circles in bottom scatter plot panel.

The other CM-plot with positive detections is shown in figure 8.2 with 3 different bottom scatter-plot panels showing concentric circles. The 3 different bottom panels show the results for only the top 1/1000, 1/100, 1/10 values of the SNR. This way we can now see the details that would have been obscured (covered) by symbols (circles) of large radius r ($r \propto \text{SNR}$).

In figure 8.3 we show another case to differentiate RFI from astrophysical signals. The residual RFI peaks are narrow in the lower frequency channel, so they are drifting to an earlier time with higher DM trials that can be seen in the bottom panel in figure 8.3. The 3 top panels show the cumulative number of pulses over the SNR threshold.

8.3 The Search Results

Using the algorithms described above, we searched ranges of DM trails and temporal resolutions in radio observation tracking the pulsars PSR B0950+08 and PSR B0031-07, and nearby galaxies to find FRBs. For the observations which targeted PSR B0950+08, we searched the 15,000 DM trails from 1.0 to 100.0 pc cm^{-3} with 12 temporal resolutions from 0.209 ms to 1 s. For the observations which targeted PSR B0031-07 and M31, we searched a larger set of 25000 DM trials which ranged from 100 to 5000 pc cm^{-3} with temporal resolutions from 2.09 ms to 10 s. We chose the beginning DM trial of 100 pc cm^{-3} from considering:

1. Narrowband, burst-like RFI was smeared out at higher DM trials, which helps in reducing false detection.
2. The reported FRBs show high DM ($> 100 \text{ pc cm}^{-3}$).

Generally, after data processing we needed to examine the CM-plots in smaller ranges of DM trials and time because RFI residuals would overwhelm the detail if plotting the whole searched parameter space in one plot. We designed a transient radio query system interface (which we will discuss more in the next section) to help us in plotting a valid range of DM trials, time, SNR, etc. To systematically examine the result of data processing, we followed these steps:

1. Plot the whole duration of a data set to find the regions that have $\text{SNR} > 10$, then zoom in to examine details of time, DM, and SNR distributions if there are RFI or potential astrophysical signals.
2. If the data set did not have records with $\text{SNR} > 10$, we checked the regions with $9 < \text{SNR} < 10$ from the start time to the end time.
3. Checked regions with $8 < \text{SNR} < 9$, etc., until reaching $\text{SNR} = 5$, because we record only with $\text{SNR} > 5$.

We did not find fast radio transients with $\text{SNR} > 7$. We found two potential signals in the 74 MHz tuning only from observations at UTC 2013 09 22 03:44:16.364 tracking at PSR B1937+21. The first one has $\text{DM} = 180 \text{ pc cm}^{-3}$, $t = \text{UTC 2013 09 22 06:36:34.3}$ with maximum $\text{SNR} = 6.5$. The second one has $\text{DM} = 126 \text{ pc cm}^{-3}$, $t = \text{UTC 2013 09 22 06:36:08.3}$ with $\text{SNR} = 5.5$. Both signals have a full-width-half-maximum magnitude (FWHM) pulse width of 0.1 s, the pulse shape is too weak to be seen in the spectrogram, and neither show signals in the corresponding records in the low frequency tuning. So we suspect these are the effects of residual RFI.

Date of First Frame (UTC)	Duration (hour)	Tuning Frequencies (MHz)	Target
2012 03 31 03:40:29.000	6.0	39 , 74	PSR B0950+08
2012 03 24 04:07:59.000	6.0	39 , 74	PSR B0950+08
2012 03 25 04:07:31.000	6.0	39 , 74	PSR B0950+08
2012 04 01 03:36:32.000	6.0	39 , 74	PSR B0950+08
2013 07 26 09:37:08.182	4.0	38 , 74	M31
2013 07 26 09:37:08.183	4.0	38 , 74	PSR B0031−07
2013 07 27 09:33:12.273	4.0	38 , 74	M31
2013 07 27 09:33:12.274	4.0	38 , 74	PSR B0031−07
2013 07 28 09:29:16.364	4.0	38 , 74	M31
2013 07 28 09:29:16.365	4.0	38 , 74	PSR B0031−07
2013 09 21 03:48:12.273	4.0	45 , 74	M31
2013 09 21 03:48:12.273	4.0	45 , 74	PSR B1937+21
2013 09 22 03:44:16.364	4.0	45 , 74	M31
2013 09 22 03:44:16.364	4.0	45 , 74	PSR B1937+21
2014 01 25 06:45:00.000	4.0	42 , 74	PSR B0950+08
2014 01 25 06:45:00.000	4.0	42 , 74	Ursa Major
2014 01 26 06:41:04.091	4.0	42 , 74	PSR B0950+08
2014 01 26 06:41:04.091	4.0	42 , 74	Ursa Major
2014 01 27 06:37:08.182	4.0	42 , 74	PSR B0950+08
2014 01 27 06:37:08.182	4.0	42 , 74	Ursa Major
2015 04 27 02:15:00.000	4.0	42 , 74	PSR B1112+50
2015 04 27 01:00:00.000	4.0	42 , 74	M81
2015 04 28 02:11:00.000	4.0	42 , 74	PSR B1112+50
2015 04 28 00:56:00.000	4.0	42 , 74	M81
2015 04 29 02:07:00.000	4.0	42 , 74	PSR B1112+50
2015 04 29 00:52:00.000	4.0	42 , 74	M81
2015 04 30 00:48:00.000	4.0	42 , 74	M81

8.4 The Transient Radio Query System

After the data processing, we generate a database which contains time tag, time resolution, SNR, and DM trails for each observation epoch. To enhance the accessibility of this database, we designed an online transient radio query system, which can be used to generate CM-plots with parameter ranges of interest, so the user can look for details of SNR evolution with different DM trials, temporal resolutions, etc., to determine if a signal is astrophysical or RFI. The query system is written in Python with the Structured Query Language (SQL) library.

Every observation can be selected by target, SNR, temporal resolution, time location,

etc. By using a single interface, a user can choose the interesting observation time duration in coordinated universal time (UTC), minimum SNR, and target, and submit these choices to the query system to produce a CM-plot containing only the results of interest. As a demonstration we show in figure 8.4 and figure 8.5, the results if a user wants to examine the time range 2013/7/27 08:33:12 to 2013/7/27 09:23:12 (UTC) with $\text{SNR} > 5$ for observations pointing at M31, with a DM range from 100 to 200 pc cm^{-3} and a temporal resolution from 0 to 1 second. The input parameters should be submitted as 8.4, then a window will pop up showing the query result in a CM-plot shown in figure 8.5.

The query system helps the user in signal identification. For example, from Equation (8.1) assuming a Gaussian-shaped, flat-spectral-index pulse width of 100 ms centered at 74 MHz, if a user sees a maximum SNR of 8 across a range of DM trials of size 10 pc cm^{-3} , it would be an RFI instead of an astrophysical signal. This is so because a dispersed astrophysical signal will be only half the strength when the DM trials are off $\pm 1 \text{ pc cm}^{-3}$, which means a user should expect the data points in the scatter plot would span less than $\pm 1 \text{ pc cm}^{-3}$ in the bottom panel of the CM-plot. In the future, we hope to develop the system so a user can correlate different observations such as the GRB, GW, etc., with our growing query system.

8.5 The FRB Event Rate

The discovery event rate for FRBs is not large, using conventional instruments (e.g., [51, 54, 60, 140, 141]). Since the event number is low, to estimate the events across different observing frequencies, we follow the discussion in Lorimer et al. [142] that assumes the four events from Thornton et al. [54] as standard candles to estimate the FRB event rate. Then we use the co-moving distance in the calculation of event distance since FRBs have large DMs which imply cosmological distances. Lorimer et al. [142] assume the pulse has a flat temporal shape with a finite pulse width. To derive the flux density-redshift relationship, they used the Λ CDM model [143] which assumes a flat space curvature. So they obtained a flux density $\bar{S}$ for the source at the comoving distance redshift z as

$$\bar{S}(z) = \frac{L(1+z)^{\alpha-1}}{4\pi D(z)^2(\nu'_{\text{high}}{}^{\alpha+1} - \nu'_{\text{low}}{}^{\alpha+1})} \left(\frac{\nu_2^{\alpha+1} - \nu_1^{\alpha+1}}{\nu_2 - \nu_1} \right), \quad (8.5)$$

where L is the luminosity of source, α is the spectral index, D is the comoving distance at redshift z , and ν'_{high} and ν'_{low} are the highest and lowest emission frequencies of the source, ν_1 and ν_2 are the lowest and highest observing frequencies.

Lorimer et al. [142] discussed two possible luminosities of FRBs based on different spectral indices with an observed flux density $\bar{S} = 1 \text{ Jy}$ at $1.4 \text{ GHz} \pm 200 \text{ MHz}$ and $z = 0.75$. Then, for FRBs with a flat or similar spectral index as pulsars (~ -1.4 [144]), the luminosity L can be derived as $\simeq 1.5 \times 10^{44} \text{ erg/s}$ or $\simeq 7.8 \times 10^{44} \text{ erg/s}$ for $\alpha = 0$ or -1.4 , respectively.

To estimate the event rate, Lorimer et al. [142] used the results of Thornton et al. [54] and scale the event rate with redshift z as

$$R(z) = R_{0.75} \frac{V(z)}{V_{0.75}}, \quad (8.6)$$

where $R_{0.75} \sim 1.0 \times 10^4$ per day per sky at $z = 0.75$ by Thornton et al. [54] and $V_{0.75}$ is the corresponding comoving volume.

We can see that from equations (8.5) and (8.6) the values of R and $\bar{S}$ can be determined given a redshift z . We plot $R(z)$ and $S(z)$ as in figure 8.6. For observations using LWA1, we have zero events with $\text{SNR} > 10$ during 120 hours of observation with a mean FOV $\sim 5^\circ$, which gives an upper event rate of $\sim 10^{-3} \text{ hr}^{-1} \text{ deg}^{-2}$ ($\sim 10 \text{ day}^{-1} \text{ sky}^{-1}$). For a pulse width $\sim 10 \text{ ms}$, the flux density is $\sim 237 \text{ Jy}$ with $\text{SNR} = 10$. From figure 8.6, we expected to detect a couple of such events if the spectral index $\alpha = -1.4$. Possible reasons for our null FRB detection would be interstellar scattering, or if there is a turnover of FRB spectral index for our low frequencies (lower than previously considered). Of course, the low number or expected events means we could have simply missed those few events we might have detected. We expect to analyze more data to develop greater confidence in our implied low frequency event rates.

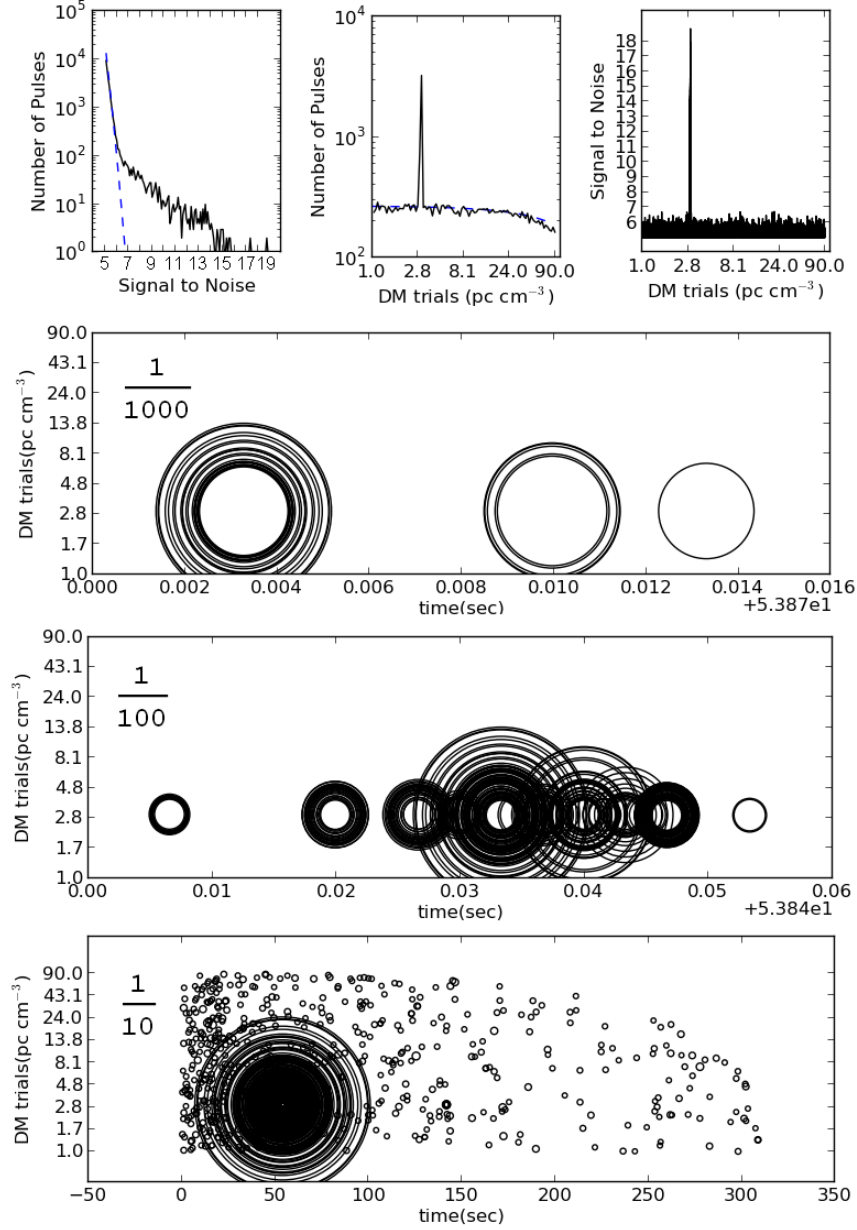


Figure 8.2: The CM-plot for a 5-minute analysis, but showing only the top 1/1000, 1/100, and 1/10 SNR values in the time-series vs. DM trial. In this manner, we can see the details of time positions which are overlapped by large SNR. In the plot, there is a repeating pulse signal for PSR B0950+08 with period 0.2530s, DM = 2.97 pc cm^{-3} , and we can tell from 1/100 or 1/1000 panels that it is a single pulse detection with a fine structure of multiple peaks in a pulse period.

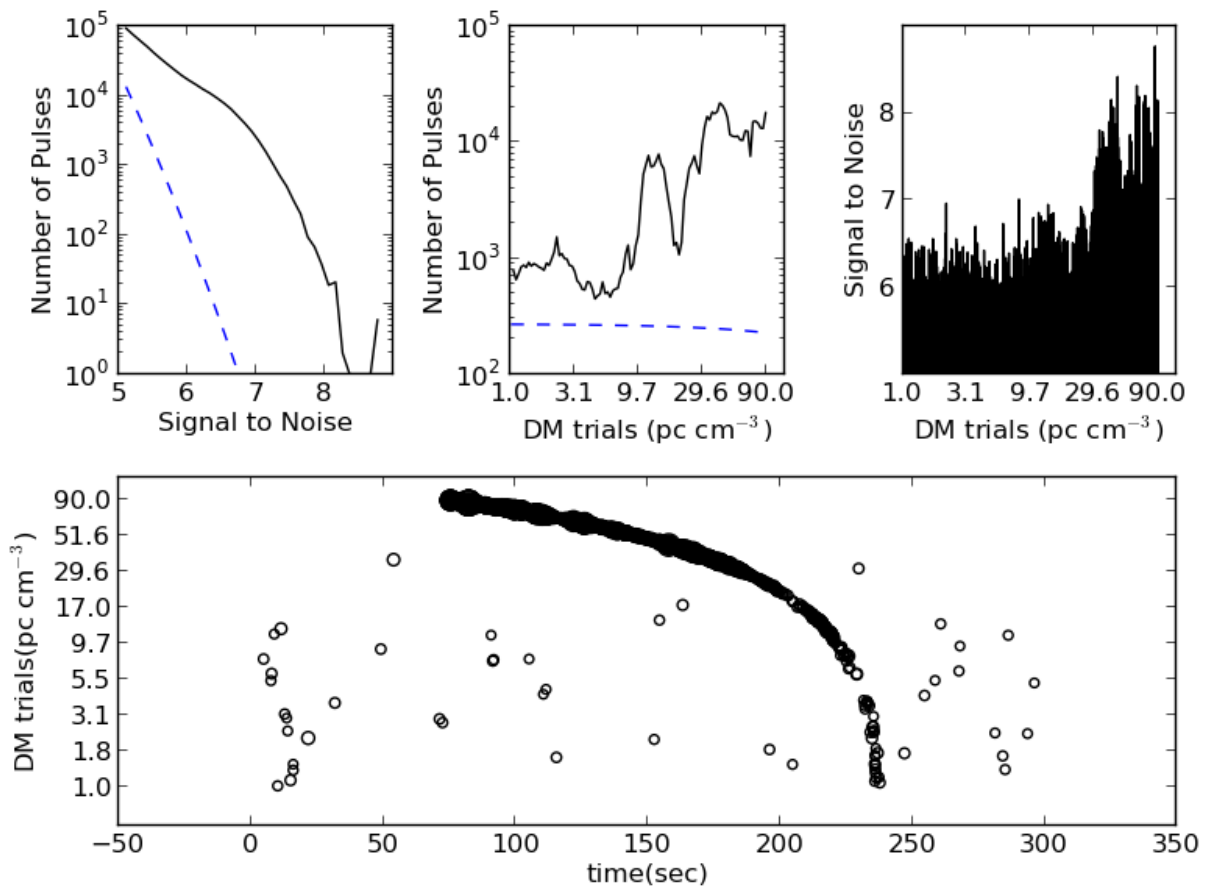


Figure 8.3: A 5-minute example with residual RFI. The distributions in the top left and middle panels deviate from Gaussian distribution due the RFI.

time (in seconds > -1hr) Low	0
time (in seconds < 4hr) High	3000
SNR minimum (> 5)	5
DM trials (in pc cm⁻³ > 100) Low	100
DM trials (in pc cm⁻³ < 5000) High	200
resolL (in s > 0) Low	0
resolH (in s < 10.0) High	1
mjd	366

Figure 8.4: The query table of the library system. The number for the “mjd” entry is a personal identification number for the user, with no other importance.

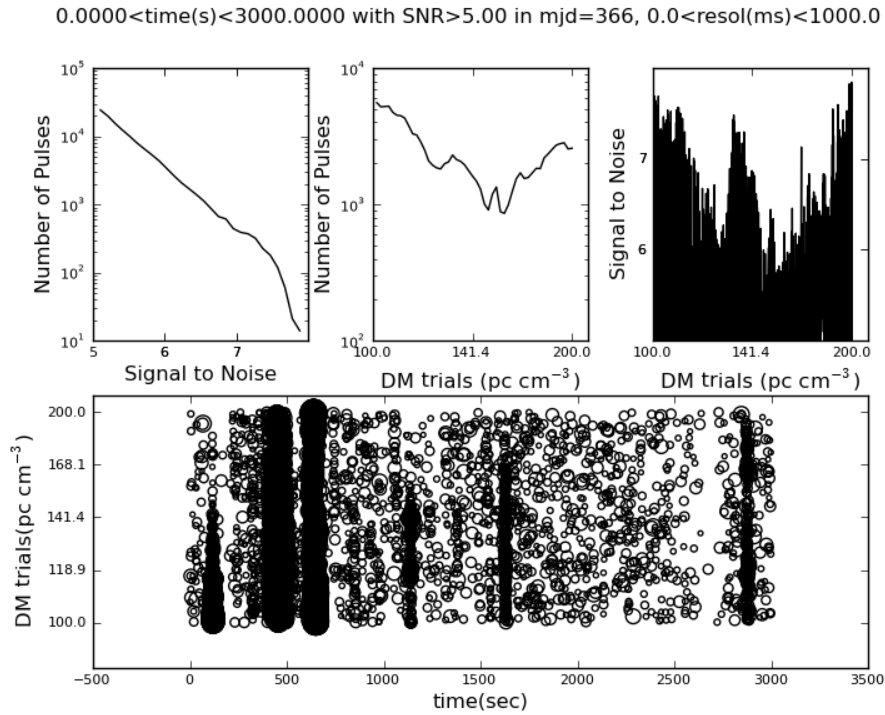


Figure 8.5: The query result of library system from table as shown in figure 8.4.

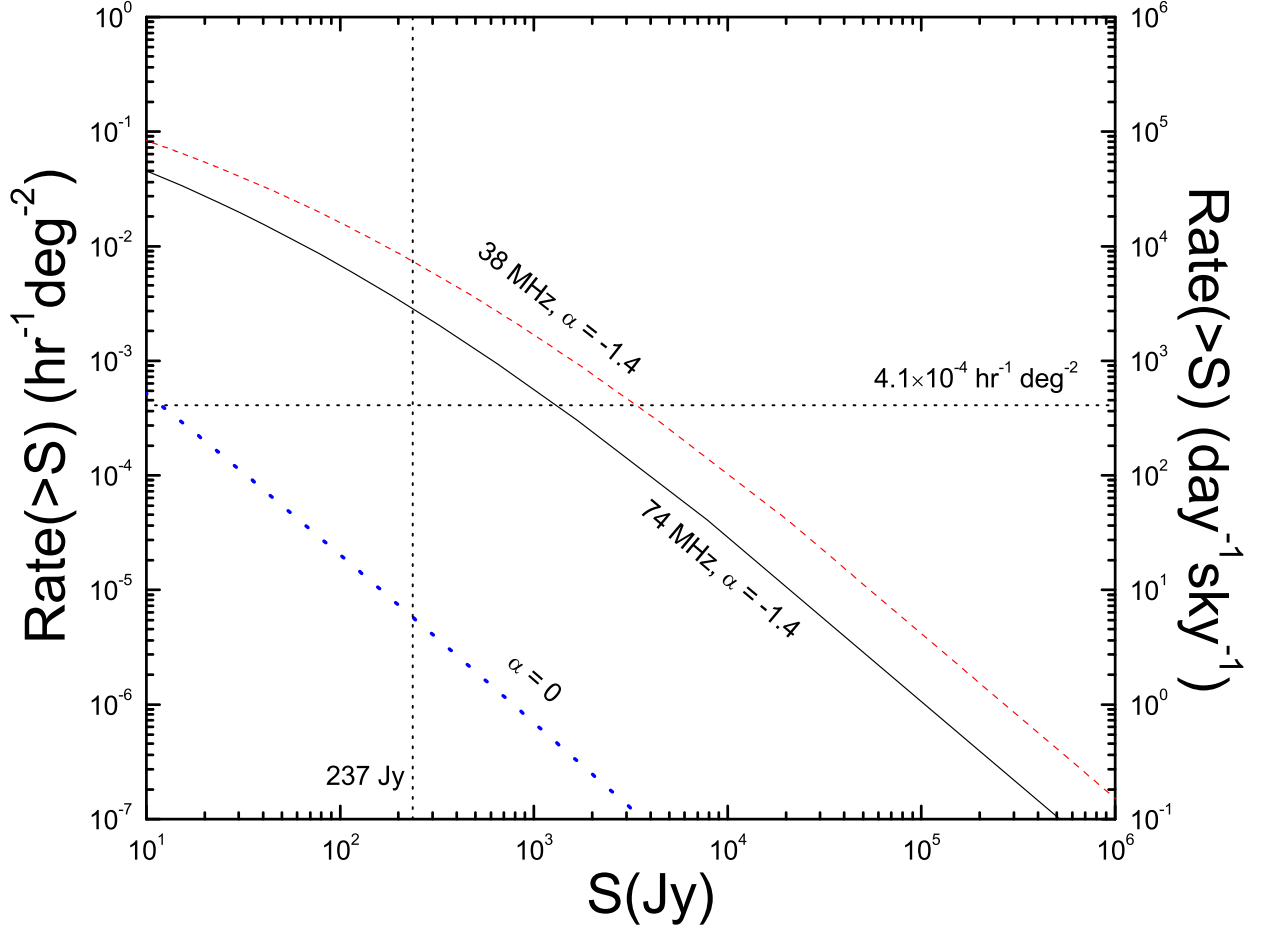


Figure 8.6: The expected event rate predicted by [54]. The vertical axis is the observed flux density of dedispersed pulse with matched temporal resolution. From equation 4.4, a SNR = 10 pulse with width ~ 10 ms has flux density of 237 Jy. From this extrapolated event rate plot we expect to observe a couple of events with SNR > 10 if spectral index $\alpha = -1.4$.

Chapter 9

Conclusion

Parts of this chapter are paraphrased or taken from [1–4]. For these papers the author of this thesis wrote the code for data collection, data processing, analysis, and figures. He wrote the first drafts, then collected comments from the coauthors, then revised the papers. Lastly, he used the referee reviews to finalize the published version of the papers.

The aim of this thesis was to explore techniques for searching for low-frequency radio transients from pulsars and sources of fast radio bursts, and to carry out such searches. This work required extensive development of a data reduction software pipeline. In addition, as a byproduct of such investigations, we also investigated radio wave scattering in the interstellar medium, using archival data for pulsars. In this chapter we summarize the results and discuss possible avenues of exploration for the future.

We used the first station of the LWA to search for low-frequency radio transients from pulsars and FRBs. The LWA is a relatively new instrument with the potential to enlarge this field of astrophysical research. Virginia Tech participated in the design of the LWA hardware architectures. The result is an array of 256 crossed-dipole antennas in a pseudo-randomly distributed array covering an area 110-by-100 m² near the center of the Very Large Array in central New Mexico. The LWA operates in the frequency range of 20–88 MHz in a variety of interferometric modes including beam-forming (which we used extensively for this work).

Searching for a radio transient (or radio pulse) of astrophysical origin requires obtaining high-temporal and high-spectral resolution data over an extended observing program. These data are often analyzable as spectrograms (or dynamic spectra), as was done in this thesis. A radio transient usually is not immediately detectable in a spectrogram due to interstellar dispersion, which is a phenomenon that causes a temporal delay depending on frequency while an EM wave propagates through the tenuous interstellar plasma. This dispersion spreads a pulse in time rendering the pulse undetectable in a simple time series of the signal

strength recorded by the telescope. The amount of temporal delay at a given frequency is proportional to the square of the frequency. If one knows the proportionality constant (the dispersion measure, or DM) one can dedisperse the signal in a spectrogram to compensate for the delay as a function of frequency and produce a time series (summed in frequency space) within which it might be more likely to detect a transient pulse. Furthermore, the dispersion of a pulse is one of the features that can help distinguish an astrophysical transient from a man-made transient (a pulse of radio frequency interference, or RFI).

To help in using this dispersed-signal characteristic to find astrophysical pulses, and to identify RFI, we designed and implemented a software analysis pipeline with a graphically-interactive querying system that allows the user to visually inspect potential astrophysical signal candidates. While the majority of RFI shows no signal smearing in time, we identified most of the candidate astrophysical transients as the residual RFI, and the rest of candidates are coincident narrow band-short duration RFI that stacked up in the dedispersed time series.

Because the LWA is operated at relatively low frequency compared with other major facilities, using the LWA provides a window on scatter-broadening for radio astronomy at low frequency. We explored theoretical pulsar beaming models using LWA at ≈ 40 and ≈ 70 MHz, while most similar work was done above 500 MHz. Benefits of low frequency include a longer delay time allowing for triggered observations of sources detected by other instruments (e.g., by LIGO), and expressly studying the interstellar scattering effect.

One benefit of conducting multi-messenger follow-up observations at low frequencies occurs because low frequency signals are delayed in their arrival when compared to GW signals, higher frequency radio signals, or signals in other wavebands. GW signals travel at the speed of light, while low frequency radio signals are delayed by interstellar dispersion. Thus, a transient radio signal may be emitted simultaneously with a GW signal, but would arrive at the Earth minutes or 10s of minutes later than the GW signal. This delay makes the need for immediate radio telescope system response times less critical.

9.1 Development of a Data-Reduction Pipeline

We developed a data-reduction pipeline that we used to detect dispersed transient radio signals using the LWA. The LWA is operated at low frequencies from 28 MHz to 88 MHz. At such low frequencies, a transient radio signal is subject to substantial propagation effects such as dispersion and interstellar and intergalactic scattering. The dispersion time delay is inversely proportional to frequency squared. A transient radio pulse with a dispersion measure of $DM \sim 100 \text{ pc cm}^{-3}$ observed at 48 MHz would have a differential time delay across a 16 MHz bandwidth on the order of hours. To dedisperse such a transient radio signal requires analyzing a spectrogram with a duration of hours, occupying about a terabyte of disk

space. To efficiently search for a dispersed transient radio signal with unknown dispersion measure we developed a pipeline, utilizing parallel computing, and capable of dedispersing a spectrogram with terabyte size.

To test the ability of our algorithms on detecting radio transients, we use the same algorithm that aims to detect FRBs on giant pulses from known pulsars. Our observation process algorithm has proved to be able to detect dispersed giant pulses from two known pulsars and also normal pulses after folding the time series for each pulse period. Our algorithms are able to parallel process an observation of 4–6 hours with effective DM trials from 1 to 5000 pc cm^{-3} .

Our results show that the average pulsar profiles and intensities are compatible with other observations at similar frequencies. We also utilized our pipeline in searching for radio transients from different lines of sight including pulsars and nearby galaxies. We used the same data processing pipeline to search within the pulsar observations for fast radio bursts (FRBs). We searched 120 hours of observations for FRBs from the directions of three pulsars and three nearby galaxies and we did not detect any non-pulsar signals with SNR larger than 7 with DM trails from 1 to 500 pc cm^{-3} .

When the radio transients propagate through the interstellar medium, there are propagation effects such as dispersion and scattering. The scattering effect on radio transients limits their detectability. A null detection over 120 hours of observations without other signals except from known pulsars sets an upper FRB rate limit of $\lesssim 10 \text{ day}^{-1} \text{ sky}^{-1}$ at our observing frequencies. Generally, others have set limits on FRB rates $\gtrsim 10^3 \text{ day}^{-1} \text{ sky}^{-1}$ [145]. One of the possible reasons that we did not detect FRBs is that signals are highly scattered at very low frequencies with high DM values.

When we started searching for FRBs in 2010, only a handful had been detected. Currently many more FRBs have been detected. Among them, some are repeaters. Only two have a known periodicity, while the other repeaters seem to be erratic. The majority of FRBs are observed with a mean pulse duration $\approx 3 \text{ ms}$, mean DM $\approx 500 \text{ pc cm}^{-3}$, and mean flux density of $\approx 1 \text{ Jy}$. One of the FRBs is associated with a magnetar (and is a soft gamma repeater). There are different theories for the emission models to explain various periodicities, such as compact objects mergers, and giant pulses from neutron stars (specifically magnetars).

Although we did not find signals with SNR larger than 7, we report two suspicious signals. The first one, with a SNR = 6.5 at DM = 180 pc cm^{-3} was found in a tracking observation in the direction of PSR B1937+21 at UTC 2013 09 22 03:44:16.364. The other one, with a SNR = 5.5 at DM = 126 pc cm^{-3} was found in the same tracking observation in the direction of PSR B1937+21 at UTC 2013 09 22 06:36:34.3. Both suspicious signals had a FWHM of 0.1 s and were only detected in the frequency tuning centering at 74 MHz. Compared with the observed FRB database, these two suspicious signals have relatively low DM values,

wider pulse width and the SNR is not very strong. We visually inspected the spectrogram for both suspicious signals, but the pulses were not apparent, and are probably too weak to be seen in the spectrograms by direct inspection.

9.2 Observations of Giant Pulses from B0950+08 and B0031–07

Using techniques we developed in searching for radio transients, we report the detection of giant pulses (GPs) from two known pulsars. The emission mechanism for GPs is not well understood, and observations at low frequencies are nearly nonexistent. Our GP detections are among some of the lowest frequencies detections reported. Our observations put limits on the “turnover frequency” below which a GP mechanism may be less effective.

From observations of PSR B0950+08 over 12 hours, we detected 465 GPs (in 0.27% of the pulse periods) and 275 GPs (in 0.16% of the pulse periods) at 74 and 42 MHz, respectively. We only detected transient pulses with the DM value of the PSR B0950+08 after searching a DM range from 1.0 to 5000 pc cm⁻³. The majority of the GPs have double peaks which have a smaller peak-to-peak separation compared to the average pulse. Less than 0.1% of the GPs were detected within the same periods at both 42 and 74 MHz, which means the majority of them are not generated in a wide band. This pulsar produces less frequent GPs and is weaker at our frequencies than at 100 MHz. One of the common properties of GPs is that the cumulative distribution of intensity ratio between GPs and the average pulse follows a power-law. The minimum GP intensity ratio to average pulse that follows the power law could be different for different pulsars. Pulses with the flux density ≥ 10 times of an average pulse exhibit a cumulative distribution obeying a power law with different values of index at 42 MHz and 74 MHz. From the much less steep slope of the power law cumulative distribution, compared to a Gaussian distribution, we conclude that the detected GPs are not the tail of a Gaussian distribution of normal pulses. We calculated the altitude r for the average pulse and GPs using the dipolar magnetic field model, and we found that the difference of r from the average and GPs is not significant.

We observed PSR B0031–07 for a total of 12 hours at both 38 MHz and 74 MHz. We found 221 GPs (in 0.49% of the periods) and 158 GPs (0.35%), at 74 MHz and at 38 MHz, respectively. Most GPs show a single peak. We only detected transients with the DM value of the PSR B0031–07 after searching a DM range from 1.0 to 5000 pc cm⁻³. Less than 0.03% of the GPs were detected within the same period at both frequencies, which indicates that most of these GPs are narrow-band emission events. We did not calculate the height where pulses are generated, due to the fact that both the impact parameter and the angle between magnetic axes and rotation used in the dipolar magnetic field model are not available for PSR B0031–07.

Most of the giant pulses observed for PSR B0950+08 and B0031–07 show narrow-band profiles. In other words, most of the giant pulses can only be detected in one of the observing frequencies in the same period. The narrow-band giant-pulse profile behavior implies that they are generated at a limited region based on the dipolar magnetic field model [2]. This result can help constrain the model.

Observations by Singal & Vats [114] had no giant pulse emission from PSR B0950+08 during some stretches of time. We wonder if this effect is related to the nature of giant pulse emission. If giant pulses are independent events with a uniform probability in time, we expect to see an exponential dependence of the distribution of temporal intervals between pulses. Our results show just such an exponential dependence for giant pulse observations of PSB B0950+08 [2] and B0031–07 [3], as shown in figures 5.6, 6.6. Figure 5.6 shows a long tail distribution of intervals. These results suggest zero detections of the GP could occur in short duration observation programs. Our observation programs of PSR B0950+08 [2] were much longer than described in the work by Singal & Vats [114].

9.3 Interstellar Scattering

When radio transients propagate through the interstellar medium, there are propagation effects such as dispersion and scattering. Scattering limits the detectability of radio transients. To explore general relations between the scattering time constant, observing frequency, and DM, we studied the interstellar scattering effects on pulsar profiles [4] using two on-line pulsar data archives, and using the CLEAN-based method [2].

We found that the relationship between scattering time constant (or scattering time scale), observing frequency, and DM are highly dependent on the line of sight (LOS) [4], which was also reported in the work of others. Our survey calculated directly the scattering time-scale from pulsar profiles at very low frequency and our result agrees with other studies using other methods for determining the scattering time-scale (i.e., not the CLEAN-based method).

Some benefits of using the CLEAN-based method [2–4] are that it does not require the assumption of a specific un-scattered profile, and it works on profiles with multiple peaks. There are possible errors from the CLEAN-based method survey, such as (i) low SNR peaks or wide (compared with period) peaks in profiles will cause the CLEAN-methods to be unable to distinguish signals from noise, and (ii) we use averaged profiles instead of a individual pulse to measure the scattering time constant, but a pulsar with drifting individual pulses may produce an average profile that mimics scattering tails in the average profile.

Because the interstellar scattering effect on a radio pulse profile is particularly strong at long wavelengths, we studied the interstellar scattering effect on radio transients using

pulsar survey data from the LWA and the European Pulsar Network (EPN).

Using the CLEAN-based method to determine the scattering time-scale τ from archived pulsar profiles under both the thin screen and average medium scattering models, we calculated the scattering index α , in $\tau \propto \nu^\alpha$, where ν is the observing frequency. For a Kolmogorov spectrum of interstellar density irregularities $\alpha = -4.4$.

We calculated the scattering time constant from thousands of profiles among ≈ 400 pulsars over a broad range of frequencies and DMs. Scattering time scales at our frequencies are consistent with other studies. In our analysis, the majority of scatter times are not large compared to the pulse profile temporal width (scattering was not significant). We chose 24 pulsars which showed significant scattering at the lowest available frequencies and calculated an average $\alpha = -3.7 \pm 0.41$ and $\alpha = -4.3 \pm 0.98$ for the thin screen and average medium models, respectively. We found that the scattering time scale, assuming an exponential decay on pulse profiles, depends on not only the observing frequencies but also the lines of sight.

9.4 Potential Improvements for the Future

9.4.1 Using Graphics Processing Units

In FRB searches, we blindly searched a large parameter space which included DM trials with temporal decimation. The bottleneck in data processing is the input and output (I/O). The first issue is the memory size. Because of limited computer memory size, we needed to figure out an efficient algorithm to read and store the data. There are no heavy calculations in shifting the frequency bin in a spectrogram (i.e., dedispersion) and time series summation, so the processing speed is not as important in single tasks. The Graphics Processing Unit (GPU) is designed for highly parallel computation. The major difference between the GPU and central processing unit (CPU) is the number of processes; nowadays a typical GPU can handle ten times more processes than a CPU, though the efficiency of each process in the GPU is less than half of that in the CPU. But the number of processes will more than compensate, so the spectrogram can be searched in a large parameter space using a GPU instead of a CPU, if there is enough GPU-accessible memory. Researchers from different facilities have noted the advantage of parallel GPUs, and libraries are under development for high performance GPU calculations. We expect in the near future the memory needs will be met so that we do not need additional techniques such as sub-band processing (which results in a slight sensitivity loss) [146] for GPU dedispersion.

9.4.2 Machine Learning in Transient Detection

There are many applications of machine learning in helping with tasks that humans are not good at handling systematically, consistently and automatically. Recently, deep learning algorithms such as CNN-LSTM (Convolutional Neural Network, Long Short-Term Memory), etc., show great flexibility and are more accurate than traditional machine learning algorithms (for example, Support-Vector Machines (SVM), and Random Forest). Machine learning, applied to RFI removal and transient signal detection, could be very productive in the future.

One of the challenges to detecting FRBs is to filter RFI out from true astrophysical signals. Machine learning can be one of the tools to filter out RFI without human intervention. To utilize machine learning for detecting FRBs, there are three issues to resolve:

1. How to transfer domain/insightful knowledge on detecting FRBs to characters in formats that the machine can process.
2. How to explain the decision making, confidence interval, limitations and predictions in machine learning.
3. To provide enough training data, including false and positive signals from pulsar data, available FRB data, and RFI.

Many public, already-written machine learning models are easy to acquire. These are well documented and can be modified. Researchers can define suitable features to use in training a model to distinguish astrophysical transients from RFI. To obtain a low false-alarm rate, researchers need to adjust these features to fine-tune a model.

Besides universal characters related to the SNR smearing at different DM trails and temporal decimation, there should also be a set of unique characters that only work at the individual observatory, handling the local RFI environments.

Most machine learning models are black boxes, and it is difficult to explain how a prediction is processed and decided. When applied to practical cases, an open and hot issue is how to determine a reasonable explanation and confidence interval for a detection or null result. One way to work around this is to use machine learning as a tool to get rid of most false detections caused by RFI, and leave only a few candidates that are worthy of detailed analysis by other processing means.

A supervised machine learning model needs a certain amount of labeled data, including true signals from pulsars or FRBs and false signals from RFI. A fine-tuned model relies on quality and quantity of data for training. For an observatory, collecting signals from pulsars with different profiles and a wide range of DMs would be a practical way to start. Then a

certain amount of false detection caused by RFI should be a supplemental set of training data. Then users need to engineer out the characters that are able distinguish true and false detection. The character engineering can be from dedispersed time series, raw spectrograms and/or combinations of both. It is plausible that the RFI mitigation process can be skipped. Though the RFI mitigation must be consistently on or off for both training and testing, and, if there are changes/upgrades in RFI mitigation, the training data collection and model training needs to be done over, because the characters may change dramatically and are no longer suitable for distinguishing the false and true detections.

9.4.3 All-Sky Observations

Our LWA1 observations were made in beam-forming mode, which has a limited field of view (FOV) ($\propto \nu^{-1}$). LWA1 has the capability to produce an all-sky map by using the Prototype All Sky Imager (PASI), which has a FOV of $\sim 2\pi$. But currently PASI has a total bandwidth of only 75 kHz [147]. Since the frequency bandwidth for PASI is much narrower than for the beam-forming mode so a weak transient will be relatively more difficult to detect with PASI than in the beam-forming mode. If we can obtain an all-sky map in high temporal resolution, high angular resolution, and wide bandwidth, the data size and data processing will be a challenge to computer science. But the greater detectable event rate of an all-sky observation is worth the effort. GPU calculations could be one of the best options for carrying out all-sky imaging and analysis processes. New time series analysis algorithms may be also required from the machine learning efforts.

9.5 Collaborative Observations with Gravitational-Wave Observatories

With the first gravitational wave (GW) detection [74], the rise of GW astronomy has opened a new window to investigate the universe, in particular by the LIGO-Virgo collaboration [33]. Collaborating radio astronomy observatories such as the LWA present an ideal source of observations that can help in the discovery and analysis of GW signals from transient astrophysical events. There are several advantages to coupling radio transients with GW detection [76,148]. One of the key advantages is that the theoretical models of radio transient sources exist which say that radio transients may accompany gravitational wave bursts. For example, both radio transients and GW transients are thought to be caused by core collapse supernovae, and the merger of compact object binaries [149].

Another advantage is that interstellar dispersion of the radio signal yields temporal and distance information about the source. This can be compared against the time of the GW

signal to provide timing information about processes occurring in the source during the event. Additionally, the strength of the GW and the masses determined from the GW signal can be used to perform a consistency check of the distance to the source.

A third advantage is that performing a joint observation with radio waves and GWs does not require active schedules. Both radio and GW detectors cache and store their data for later offline analysis. During this offline analysis, regions of the sky can be selected in software to scan for data containing GW signals that are coincident with transient events found in the radio data. Two caveats are that both the GW detector and the radio observatory are required to actively collect data in roughly the same time period and the location of the source in sky is not out of the radio observing field of view.

The final advantage is the ability of radio observatories to view simultaneously very large regions of the sky. This is a necessity for observing transient events as they can occur anywhere at any time, and they do not last for sufficiently long time periods to allow for more traditional sky surveys at shorter wavelengths. Additionally, the interferometric radio observatory is capable of segmenting the sky into a number of more localized beams that can independently scan the sky for astrophysical events. This makes radio observations most similar to GW detection, which is an all-sky observing mode, in terms of ability to scan the sky for events.

The work in this thesis is a prelude to more extensive observing programs in collaboration with GW observatories.

9.6 The Current Status of Pulsar Giant-Pulse and Fast-Radio-Burst Investigations, and Future Possibilities

The mechanisms for the production of GPs from pulsars, and FRBs, remain a mystery. Much more observational work must be done to help in determining the correct production mechanisms.

Although there are studies of observations of known pulsars in multiple bands, there has been no definite conclusion as to the origin and mechanism of giant pulses. Here we summarize the current discussion of giant-pulse models. There are extended and modified models based on the work of Lyutikov [150], Istomin [151] and Weatherall [152] on the mechanism where the GPs are generated in the magnetosphere of pulsars [153]. In the most recent models it is generally depicted that giant-pulse broadband characteristics are closely related to the yield of positrons and electrons above the polar crown. They also suggest that giant pulses may be a class of cyclotron resonance radiation generated near the location of

the light cylinder. Our results discussed in Chapter 5 imply altitudes at which giant pulses are generated in the magnetosphere of PSR B0950+08, perhaps having some bearing on these models. Other interesting models concern the self-focusing [154] or the amplification of the radiation [155].

Regarding the discussion of the environment in which giant pulses are generated, Istomin [151] suggested in 2004 that the GPs occur near the light cylinder. They suggest that the magnetic field near the light cylinder where GPs would be generated could be stronger than that of other pulsars. But not all known pulsars with GPs have a relatively high magnetic field at the light cylinder (i.e., see Table 1 in [156]). In [157] they divided the known pulsars with GPs into two groups. One group contains pulsars with strong magnetic fields at the light cylinder, the other contains millisecond-period pulsars with weaker magnetic fields near the light cylinder of $\sim 1 - 100$ Gauss.

Regarding the location where GPs and normal pulses are generated, it is found that there is no difference in the arrival time (e.g., our study of GPs from PSR B0031-07 and B950+08). This shows that the normal pulse and the GPs may also be generated in a similar region of the magnetosphere. So the exact origin of the giant pulse is still inconclusive.

Low frequency and broadband radio observatories, such as the LWA, provide more opportunities to test the GP models based on coherent/incoherent emission at low frequency. The LWA also provides a large bandwidth capability. Recently, Kujiack et al. used the Amsterdam-ASTRON Radio Transient Facility and Analysis Centre to observe giant pulses from PSR B0950+08 [158]. Their observations were carried out in an all-sky imaging mode at 58.3 and 61.8 MHz, with a 1.5 MHz bandwidth and 1 second integration time. The typical fluence (units of Jy s) for their detected giant pulses is about 10 times larger than our results at frequency 42 and 74 MHz with bandwidth of 16 MHz, while the normal-pulse average fluence is similar to that for our observations. One of the possible reasons is that some or all GPs from PSR B0950+08 at low frequency are narrow band (note that the bandwidth of our observations is roughly 10 times larger than in reference [158]). In reference [158] they argue that the GP fluence discrepancy is unlikely to be the result of magnification during interstellar propagation but is the intrinsic emission pattern. It will be very interesting to re-observe the known pulsars with GPs and study the narrow band properties below 100 MHz using the LWA.

As we reported on our observation at GPs from PSR B0950+08 [2] (and this thesis) and other pulsars summarized by [158], GPs are sometimes not simultaneously detected in the different bands. The LWA already shows the capability to do long-term and large bandwidth observation below 100 MHz at two frequencies simultaneously. It will be very helpful to investigate the emission mechanism of GPs from pulsars with a survey of the spectral properties of GPs using the LWA.

We already know there are similarities between GPs and FRBs, such as the stability of

the linear polarization angles in radiation from FRB 121102 and GPs from the Crab pulsar above ~ 4 GHz. Furthermore, no circular polarization has been observed from FRB 121102 while most GPs of the Crab pulsar above ~ 4 GHz also show no circular polarization [145]. But these similarities alone are not sufficient to conclude that the same mechanism is at work.

There are theoretical studies suggesting that FRBs are extremely bright GPs from pulsars [140, 159, 160]. The source FRB 180916.J0158+65 may hold the key to understanding this class of objects. We are currently attempting to detect this repeating source, using the LWA. If we are successful this will be the lowest frequency at which this source has been detected. Nevertheless, the discovery rate of FRBs is speeding up and more statistics on their properties will help to distinguish their origin and emission mechanism.

One of the applications of FRBs is to probe the quantity of intergalactic baryons. From the cosmic microwave background radiation, it is inferred that the universe is made up of ~ 5 percent baryonic matter, and more than three-quarters of this matter is difficult to detect [161]. It is expected to perhaps be in what is known as the warm-hot intergalactic medium (WHIM). Probing the WHIM has been a challenge as it is hard to detect [161]. FRBs may provide an alternative tool, allowing us to find all of the missing baryons by the probing intergalactic dispersion (using the dispersion measure DM as discussed in previous chapters). The DM measures the electron column density along the line of sight and given a distance one can infer the average number density of electrons in the intergalactic medium, and thus the density of baryons, assuming an ionized medium [161]. Although these authors assumed the portion of electron column density lying in the host galaxy and Milky way to determine the amount of intergalactic electron density from six lines of sight, we can expect this uncertainty will be smaller as more FRBs are detected and used in such work, and especially after we have a better understanding of FRB progenitors and their environments.

There had been several models proposed to explain the environments or mechanism of the FRBs (e.g., see a catalog by [162]). A recent review paper [163] discussed the similar scientific progress made in understanding gamma-ray bursts (GRBs) and FRBs, such as occurred after the first discovery when it was wondered if GRBs (and FRBs) are astrophysical or due to human interference, and the two classifications of different types, such as long or short GRBs or soft gamma-ray repeaters vs. single-burst FRBs or repeating FRBs with/without an apparent period. And multiple types of sources are possible for FRBs, just like for GRBs.

After the discovery of the FRB 200428 [80] and its possible source of the magnetar SGR 1935+2154, [164] conducted optical and infrared imaging of the repeating FRB 20180916B using the Hubble Space Telescope and the 10.4-m Gran Telescopio Canarias. They found a bright, but compact nebula which they suggest is the birth site of the FRB-producing object. Yet the location of the FRB emission is not from the location of nebula. Furthermore, the distance between the nebula and FRB emission location is larger than the distance a magnetar could remain active while traveling at a typical speed. Thus, they conclude, a

source other than a magnetar might have to be considered for this FRB.

There are other observatories like LWA which observe at low frequencies, e.g., the Low Frequency Array (LOFAR), in Europe, and the Murchison Widefield Array (MWA), in Australia. LOFAR [165] detected the fast radio burst repeater FRB 180916.J0158+65 down to 110 MHz and that is the lowest frequency FRB detection to date. There is a bit of a competition going on to see who can detect this repeater at the lowest frequency. And, of course, that information will be important in constraining the spectrum of this source, and burst mechanisms. The Canadian Hydrogen Intensity Mapping Experiment/FRB (CHIME) [62] is a powerful, relatively new tool for FRB detection and study. Its large field of view and good sensitivity have made it a productive FRB detector. CHIME has been expanding the number of detections of FRBs more than any other observatory. We hope to expand our work into lower frequencies than observed by CHIME. As of April 2021, CHIME has reported detecting 18 FRB repeaters at frequencies above 400 MHz, their lowest frequency of observations (<https://www.chime-frb.ca/repeaters>). But only two of those sources have any periodicity. Follow-up observations by LOFAR [165] resulted in the detection of bursts from one of FRB repeaters, as mentioned above. We are continuing LWA observations of repeating FRBs in the hope of detecting and understanding the behavior of these interesting sources at still lower frequencies.

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Appendix A

Code for Searching for Transient Radio Pulses

I developed the pipeline and Python code used to conduct searches for radio transients using LWA. Some of the code depends on the LSL library [86] to handle the raw data. To use some of the code, which does parallel computation, you need to set up an environment depending on which parallel-processing machine is used. Other parts can be run on a single machine. Sub-functions which calculate the dispersion time lag and the output format in `dv.py`, were designed by Sean Cutchin (not published elsewhere, shared by Sean Cutchin). The use of a smoothing method by Savitzky&Golay, was implemented by other authors as noted in `dv.py`. All the code written for this work, and displayed in this Appendix, utilizes the Python programming language.

Please find the last version on <http://github.com/ilikeit813>

Pipeline:

01. Use `waterfall.py` to produce coarse spectrogram
02. Use `chkwaterfall.py` to check if there are un-continue files.
03. If there are broken frames, that can't be FFTed, use `interpolate` to insert the necessary files.
04. Use `eyexam.py` to do a final check if there are any missing files. If there are still missing files, create an average spectrogram from 2 nearby spectrograms using `interpolate.py` and insert it.
05. Use `waterfallcombine.py` to combine the individual `numpy` files into a `waterfall.npy`

06. Use `watchwaterfall.py` to view the spectrogram (`waterfall.npy`).
07. Examine the spectrogram (`bandpasscheck.py`) to find a region in frequency that is RFI quiet, determining the low frequency (`fcl`), high frequency (`fch`) of that region.
08. Use `ft.py` to produce a spectrogram again with a new frequency range you favor (`fcl`, `fch`).
09. Check the file continuity again using `chkspectrogram.py`, `eyexam.py`
10. If there are broken frames, that can't be FFTed, use `interpolate.py` to insert the files.
11. Use `dv.py` (set `pol = 1` or `2` for low or high tuning in `dv.py`) to dedisperse spectrogram and generate pulse candidates list.
12. After generating the candidate list (a text file), use `awk` and `gnuplot` to examine the file.

`eyexam.py`

```
'''
Use this code to see if there are missing files.
'''

windownumber = 2
nodes = 2
pps = 6
nChunks = 1000
nFramesAvg = 4*windownumber

fn = sorted(glob.glob('05*.npy'))
j = numpy.zeros((len(fn)))
x = numpy.arange(j[-1]/nChunkSNRFramesAvg)*nChunks*nFramesAvg
offset = numpy.setdiff1d(x, j)
print 'missing_', offset.shape, 'files'
```

`waterfallcombine.py`

```
def Decimate(ts, ndown=2):
    #return a decimated array shape = x, y, z, ...) with shape = x/
    ndown, y, z, ....
    if ndown==1:
        return ts
```

```

    ncols = len(ts)
    n_rep = ncols / ndown
    ts_ds = np.array([ts[i::ndown][0:n_rep] for i in range(ndown)]).mean(0)
    return ts_ds

fn = sorted(glob.glob('waterfall05*.npy'))
sp = np.zeros((len(fn), np.load(fn[0]).shape[0], np.load(fn[0]).shape[1]))
for i in range(len(fn)):
    sp[i, :, :] = np.load(fn[i])

np.save('waterfall', Decimate(sp, sp.shape[0]/4000))

```

watchwaterfall.py

```

def RFI(sp, std):
    sp[:, np.where( np.abs(sp[:, :].mean(0)-np.median(sp[:, :].mean(0)) ) >
        std/np.sqrt(sp.shape[0]) ) ] = np.median(sp)
    sp[ np.where( np.abs(sp[:, :].mean(1)-np.median(sp[:, :].mean(1)) ) > std/
        np.sqrt(sp.shape[1]) ) , :] = np.median(sp)
    return sp

def snr(a):
    return (a-a.mean() )/a.std()

sp = np.load('waterfall.npy')
#bandpass
bp = 0.*sp[0, :, :]
#baseline
bl = 0.*sp[:, :, 0]
bp[:, :] = np.median(sp, 0)
bp[0, :] = savitzky_golay(bp[0, :], 151, 2)
bp[1, :] = savitzky_golay(bp[1, :], 111, 2)
#correct the bandpass
for tuning in (0,1):
    sp[:, tuning, :] = sp[:, tuning, :] - bp[tuning, :]
bl[:, :] = np.median(sp, 2)
bl[:, 0] = savitzky_golay(bl[:, 0], 151, 2)
bl[:, 1] = savitzky_golay(bl[:, 1], 151, 2)
#correct the baseline
for tuning in (0,1):

```

```

    sp[:,tuning,:] = (sp[:,tuning,:].T - bl[:,tuning].T).T

for tuning in (0,1):
    sp[:,tuning,:] = RFI(sp[:,tuning:],5.*sp[:,tuning,:].std())

for tuning in (0,1):
    sp[:,tuning,:] = snr(sp[:,tuning,:])

for tuning in (0,1):
    sp[:,tuning,:][ np.where( ( abs(sp[:,tuning,:]) > 3.*sp[:,tuning,:].std
        ()) )] = sp[:,tuning,:].mean()

'''
plt.imshow(sp[:,0,:].T, cmap='Greys_r', origin = 'low', aspect = 'auto')
plt.suptitle('Spectrogram_Low_Tuning', fontsize = 30)
plt.xlabel('Time_(14_sec)',fontdict={'fontsize':16})
plt.ylabel('Frequency_(4.7_kHz)',fontdict={'fontsize':14})
plt.colorbar().set_label('std',size=18)
#plt.show()
plt.savefig('Low')
'''
plt.clf()

plt.imshow(sp[:,1,:].T, cmap='Greys_r', origin = 'low', aspect = 'auto')
plt.suptitle('Spectrogram_High_Tuning', fontsize = 30)
plt.xlabel('Time_(14_sec)',fontdict={'fontsize':16})
plt.ylabel('Frequency_(4.7_kHz)',fontdict={'fontsize':14})
plt.colorbar().set_label('std',size=18)
#plt.show()
plt.savefig('High')

```

bandpasscheck.py

```

sp = np.load('waterfall.npy')
plt.plot(sp[:,0,:].mean(0))
plt.suptitle('Bandpass_Low_Tuning', fontsize = 30)
plt.ylabel('Intensity',fontdict={'fontsize':16})
plt.xlabel('Frequency',fontdict={'fontsize':14})
plt.show()
plt.plot(sp[:,1,:].mean(0))
plt.suptitle('Bandpass_High_Tuning', fontsize = 30)

```

```
plt.ylabel('Intensity',fontdict={'fontsize':16})
plt.xlabel('Frequency',fontdict={'fontsize':14})
plt.show()
```

ft.py

```
def main(args):
    nodes = 4 #total blades used
    pps = 6 #process per blade

    windownumber = 4 # The length of FFT = windownumber * 4096

    #Low tuning frequency range
    Lfcl = 1700 * windownumber
    Lfch = 2100 * windownumber
    #High tuning frequency range
    Hfcl = 670 * windownumber
    Hfch = 1070 * windownumber

    totalrank = nodes*pps
    comm = MPI.COMM_WORLD
    rank = comm.Get_rank()
    t0 = time.time()
    nChunks = 3000 #the temporal shape of a file.
    LFFT = 4096 * windownumber #Length of the FFT. 4096 is the size of a
        frame readed. The mini quantized window lenght is 4096
    nFramesAvg = 1*4* windownumber # the intergration time under LFFT, 4
        = beampols = 2X + 2Y (high and low tunes)

    #for offset_i in range(4306, 4309):# one offset = nChunks*
        nFramesAvg skipped
    for offset_i in range(0, 1000 ): # one offset = nChunks*nFramesAvg*
        worker_rank skipped
        offset_i = 1.*totalrank*offset_i + rank
        offset = nChunks*nFramesAvg*offset_i
        # Build the DRX file
        try:
            fh = open(getopt.getopt(args,':')[1][0], "rb")
            nFramesFile = os.path.getsize(getopt.getopt(args,':')[1][0]) / drx.FrameSize #drx.FrameSize = 4128
        except:
            print getopt.getopt(args,':')[1][0],'_not_found'
```

```

        sys.exit(1)
    try:
        junkFrame = drx.readFrame(fh)
        try:
            srate = junkFrame.getSampleRate()
            pass
        except ZeroDivisionError:
            print 'zero_division_error'
            break
    except errors.syncError:
        print 'assuming the srate is 19.6 MHz'
        fh.seek(-4*drx.FrameSize, 1)
    # Sanity check
    if nFrames > (nFramesFile - offset):
        raise RuntimeError("Requested integration time +
            offset is greater than file length")
    masterSpectra = numpy.zeros((nChunks, 2, Lfch-Lfcl))
    # Save the results to the various master arrays
    outname = "%s_%i_fft_offset_%.9i_frames" % (getopt.getopt(
        args,':')[1][0], beam,offset)
    numpy.save(outname, masterSpectra)
if __name__ == "__main__":
    main(sys.argv[1:])

```

chkspectrogram.py

```

def main(args):

    windownumber = 2
    nodes = 1
    pps = 6
    nChunks = 1000 #the temporal shape of a file.

    #Low tuning frequency range
    Lfcl = 360 * windownumber
    Lfch = 3700 * windownumber
    #High tuning frequency range
    Hfcl = 360 * windownumber
    Hfch = 3700 * windownumber

    LFFT = 4096 * windownumber #Length of the FFT. 4096 is the size of a
        frame readed.

```

```

nFramesAvg = 1*4*windownumber # the intergration time under LFFT, 4
    = beampols = 2X + 2Y (high and low tunes)
totalrank = nodes*pps
comm = MPI.COMM_WORLD
rank = comm.Get_rank()
t0 = time.time()

fn = sorted(glob.glob('05*.npy'))
for i in range(len(fn)):
    j[i] = fn[i][30:39]

#x = total perfect offset
x = numpy.arange(j[-1]/nChunkSNRFramesAvg)*nChunks*nFramesAvg
# k = the different between perfect and real
k = numpy.setdiff1d(x, j)

for m in xrange(len(k)/totalrank):
    offset = k[m*totalrank + rank]
    # Build the DRX file
    try:
        fh = open(getopt.getopt(args,':')[1][0], "rb")
        nFramesFile = os.path.getsize(getopt.getopt(args,':')[1][0]) / drx.FrameSize #drx.FrameSize = 4128
    except:
        print getopt.getopt(args,':')[1][0],'_not_found'
        sys.exit(1)
    try:
        junkFrame = drx.readFrame(fh)
        try:
            srate = junkFrame.getSampleRate()
            pass
        except ZeroDivisionError:
            print 'zero_division_error'
            break
    except errors.syncError:
        print 'assuming the srate is 19.6_MHz'
    masterSpectra = numpy.zeros((nChunks, 2, Lfch-Lfcl))
    masterSpectra[i,0,:] = ((numpy.fft.fftshift(numpy.abs(numpy.fft.fft2(
        (data[:2,:]))[:,1:]))[:,Lfcl:Lfch])**2.).mean(0)/LFFT/2.
    masterSpectra[i,1,:] = ((numpy.fft.fftshift(numpy.abs(numpy.
        fft.fft2(data[2:,:]))[:,1:]))[:,Hfcl:Hfch])**2.).mean(0)/
        LFFT/2.

```

```

        # Save the results to the various master arrays
        outname = "%s_%i_fft_offset_%i_frames" % (getopt.getopt(args,':')
            [1][0], beam,offset)
        numpy.save(outname, masterSpectra)
if __name__ == "__main__":
    main(sys.argv[1:])

```

dv.py

```

def DMs(DMstart, DMend, dDM):
    """
    By Sean Cutchin
    Calculate the number of DMs searched between DMstart and DMend, with
    spacing dDM * DM.
    Required:
    DMstart - Starting Dispersion Measure in pc cm-3
    DMend - Ending Dispersion Measure in pc cm-3
    dDM - DM spacing in pc cm-3
    """

    #NDMs = np.log10(float(DMend)/float(DMstart))/np.log10(1.0+dDM)
    NDMs = (DMend-DMstart)/dDM

    return int(np.round(NDMs))

def delay2(freq, dm):
    _D = 4.148808e3
    tDelay = dm*_D*((1/freq)**2 - (1/freq.max())**2)
    return tDelay

def Threshold(ts, thresh, clip=3, niter=1):
    """
    By Sean Cutchin
    Wrapper to scipy threshold a given time series using Scipy's threshold
    function (in
    scipy.stats.stats). First it calculates the mean and rms of the given
    time series. It then
    makes the time series in terms of SNR. If a given SNR value is less
    than the threshold, it is
    set to "-1". Returns a SNR array with values less than thresh = -1, all

```

```

        other values = SNR.
Also returns the mean and rms of the timeseries.
Required:
ts - input time series.
Options:
thresh - Time series signal-to-noise ratio threshold. default = 5.
clip - Clipping SNR threshold for values to leave out of a mean/rms
        calculation. default = 3.
niter - Number of iterations in mean/rms calculation. default = 1.
Usage:
>>sn, mean, rms = Threshold(ts, *options*)
"""
# Calculate, robustly, the mean and rms of the time series. Any values
# greater than 3sigma are left
# out of the calculation. This keeps the mean and rms free from
# sturation due to large deviations.

mean = np.mean(ts)
std = np.std(ts)
#print mean,std

if niter > 0:
    for i in range(niter):
        ones = np.where((ts-mean)/std < clip)[0] # only keep the values
            less than 3sigma
        mean = np.mean(ts[ones])
        std = np.std(ts[ones])
    SNR = (ts-mean)/std
    SNR[SNR<thresh]=-1
    #SNR = st.threshold((ts-mean)/std, threshmin=thresh, newval=-1)

return SNR, mean, std

def Decimate_ts(ts, ndown=2):
    """
    By Sean Cutchin
    Takes a 1-D timeseries and decimates it by a factore of ndown, default
    = 2.
    Code adapted from analysis.binarray module:
        http://www.astro.ucla.edu/~ianc/python/_modules/analysis.html#
        binarray
    from Ian's Python Code (http://www.astro.ucla.edu/~ianc/python/index.

```

```
html)
```

Optimized for time series' with length = multiple of 2. Will handle others, though.

Required:

ts - input time series

Options:

*ndown - Factor by which to decimate time series. Default = 2.
if ndown = 1, returns ts*

```
"""
```

```
if ndown==1:
    return ts
```

```
ncols = len(ts)
n_rep = ncols / ndown
ts_ds = np.array([ts[i::ndown][0:n_rep] for i in range(ndown)]).mean(0)

return ts_ds
```

```
class OutputSource():
```

```
'''
```

By Sean Cutchin

```
'''
```

```
pulse = None # Pulse Number
SNR = None # SNR of pulse
DM = None # DM (pc/cm3) of pulse
time = None # Time at which pulse occurred
dtau = None # Temporal resolution of time series
dnu = None # Spectral resolution
nu = None # Central Observing Frequency
mean = None # Mean in the time series
rms = None # RMS in the time series
```

```
formatter = "{0.pulse:07d}{}{}{}{0.SNR:10.6f}{}{}{}{}{0.DM:10.4f}{}{}{}{}{0.
    time:10.6f}{}_+"\
    "{}{}{}{}{0.dtau:10.6f}{}{}{}{}{0.dnu:.4f}{}{}{}{}{0.nu:.4f}{}{}{}{}{0.
        mean:.5f}{}_+"\
    "{}{}{}{}{0.rms:0.5f}{}_n_"
```

```

    def __str__(self):
        return self.formatter.format(self)

def snr(x):return (x-x.mean())/x.std()

def bpf(x, windows = 40):
    bp = savitzky_golay(x, windows, 1)
    x2 = x / bp
    mask = np.where(snr(x2)>1)[0]
    mask2= np.zeros(x.shape[0])
    mask2[mask] = 1.
    y = np.ma.array(x, mask = mask2)
    bp = savitzky_golay(y, windows, 1)
    fit = np.ma.polyfit(np.arange(len(y)), y, 4)
    p = np.poly1d(fit)(np.arange(len(y)))[mask]
    bp = x
    bp[mask] = np.poly1d(fit)(np.arange(len(y)))[mask]
    bp = savitzky_golay(bp, windows, 2)
    return bp

def fold(t, period, T0=0):
    time = np.arange(len(t))
    epoch = np.floor( 1.*(time - T0)/period )
    phase = 1.*(time - T0)/period - epoch
    foldt = t[np.argsort(phase)]
    return Decimate_ts(foldt, 1.*len(t)/period )

def RFImask(spr):#sp has shape[:,:]
    x = np.where(abs(spr.mean(1))>np.sort(spr.mean(1))[spr.shape[0]/2]+np.
        sort(spr.mean(1))[spr.shape[0]/2]-np.sort(spr.mean(1))[1])
    y = np.where(abs(spr.mean(0))>np.sort(spr.mean(0))[spr.shape[1]/2]+np.
        sort(spr.mean(0))[spr.shape[1]/2]-np.sort(spr.mean(0))[1])
    return [x[0], y[0]]

def massagesp(spectrometer, windows_x=43, windows_y=100):
    bp = bpf(spectrometer.mean(0), windows_x)
    spectrometer /= bp
    bl = bpf(spectrometer.mean(1), windows_y)
    spectrometer = (spectrometer.T - bl).T
    mask = np.array ( RFImask(spectrometer) )

```

```

mask2 = np.zeros((spectrometer.shape))
mask2[mask[0],:] = 1.
mask2[:,mask[1]] = 1.
temp_spec = np.ma.array(spectrometer, mask = mask2 )
mean = temp_spec.mean()
spectrometer[mask[0],:] = mean
spectrometer[:,mask[1]] = mean
spectrometer -= mean
return spectrometer

if __name__ == '__main__':
    fcl = 360/4
    fch = 3700/4
    comm = MPI.COMM_WORLD
    rank = comm.Get_rank()
    fpp = 264/12 #spectrogram per processer you want, limited mainly by 64
        GB memory per node (32GB Hokieone)
    nodes = 2 #the number of node requensted in sh
    pps = 6 #processer per node requensted in sh
    numberOfFiles=fpp*nodes*pps #totalnumberofspec = 6895.

    maxpw = 600 #Maximum pulse width to search in seconds. default = 1 s.
    thresh= 5.0 #SNR cut off

    fn = sorted(glob.glob('05*.npy'))
    tInt = np.load('tInt.npy')

    pol = 1 # 0 = lower tunning, 1 = higher tunning.

    DMstart = 0 #1.0 #initial DM trial
    DMend = 5000 #90.0 #finial DM trial
    npws = int(np.round(np.log2(maxpw/tInt)))+1 # +1 Due to in range(y) it
        goes to y-1 only

    spect=np.load(fn[0],mmap_mode='r')[:,:,fcl:fch]
    spectarray = np.zeros((fpp,spect.shape[0],spect.shape[2])) # X and Y are
        merged already after bandpass

    #cobimed spectrogram and remove background
    for i in range(fpp):
        print '1',(np.load(fn[rank*fpp+i])[:,pol,fcl:fch]).shape
        print '2',massagesp( np.load(fn[rank*fpp+i])[:,pol,fcl:fch] ).shape

```

```

spectarray[i,:,:] = messagesp( np.load(fn[rank*fpp+i])[:,pol,fcl:fch
    ], 10, 50 )

np.save('spectarray%.2i' % rank, spectarray)
#sys.exit()

if pol < 4:
    if pol==0:
        freq=np.load('freq1.npy')[fcl:fch]
    else:
        freq=np.load('freq2.npy')[fcl:fch]
    freq /= 10**6
    cent_freq = np.median(freq)
    BW = freq.max()-freq.min()
    DM = DMstart

    txtsize=np.zeros((npws,2),dtype=np.int32) #fileno = txtsize[ranki
        ,0], pulse number = txtsize[ranki,1],ranki is the decimated
        order of 2
    txtsize[:,0]=1 #fileno star from 1

    DMtrials = DMstart # 0
    if rank == 0:
        while DM < DMend:
            #dDM = disper.dDMi(DMtrial = 1.*DM, nuCentralMHz = 1.*
            cent_freq, channelMHz = freq[1]-freq[0], BMHz = freq[-1]-
            freq[0], SSratio = 0.8, temporal_resol = 1.*tInt)
            #print dDM
            if DM < 1000:
                dDM = 0.1
            elif DM >= 1000:
                dDM = 1.
            DM += dDM
            DMtrials = np.append(DMtrials,DM)

    DMtrials = comm.bcast(DMtrials,root =0)

    for DM in DMtrials:
        #print 'rank = ',rank, ' DM trial = ',DM
        tb=np.round((delay2(freq,DM)/tInt)).astype(np.int32)

```

```

ts=np.zeros((tb.max()+numberOfFiles*np.load(fn[0],mmap_mode='r').
    shape[0]))
for freqbin in range(len(freq)):
    for i in range(fpp):
        ts[tb.max()-tb[freqbin] + (rank*fpp+i)*spect.shape[0] :tb.
            max()-tb[freqbin] + (rank*fpp+i+1)*spect.shape[0] ] +=
            spectarray[i,:,freqbin]

tstotal=ts*0#initiate a 4 hour blank time series
comm.Allreduce(ts,tstotal,op=MPI.SUM)#merge the 4 hour
    timeseries from all processor
tstotal = tstotal[tb.max():len(tstotal)-tb.max() ]#cut the
    dispersed time lag

'''
# save the time series around the Pulsar's DM
if rank == 0:
    if np.abs(DM - 10.922) <= dDM:
        print 'DM=',DM
        np.save('ts_pol%.1i_DMx100_%.6i' % (pol,DM*100),tstotal)
sys.exit()
'''

#####search for signal with decimated timeseries
if rank<npws:#timeseries is ready for signal search
    ranki=rank
    filename = "ppc_SNR_pol_%.1i_td_%.2i_no_%.05i.txt" % (pol,
        ranki,txtsize[ranki,0])
    outfile = open(filename,'a')
    ndown = 2**ranki #decimate the time series
    sn,mean,rms = Threshold(Decimate_ts(tstotal,ndown),thresh,
        niter=0)
    ones = np.where(sn!=-1)[0]
    for one in ones:# Now record all pulses above threshold
        pulse = OutputSource()
        txtsize[ranki,1] += 1
        pulse.pulse = txtsize[ranki,1]
        pulse.SNR = sn[one]
        pulse.DM = DM
        pulse.time = one*tInt*ndown
        pulse.dtau = tInt*ndown

```

```
pulse.dnu = freq[1]-freq[0]
pulse.nu = cent_freq
pulse.mean = mean
pulse.rms = rms
outfile.write(pulse.formatter.format(pulse)[: -1])
if txtsize[ranki,1] >200000*txtsize[ranki,0]:
    outfile.close()
    txtsize[ranki,0]+=1
    filename = "ppc_SNR_pol_%.1i_td_%.2i_no_%.05d.txt" % (
        pol,ranki,txtsize[ranki,0])
    outfile = open(filename,'a')
```

Appendix B

Code for Analysis of Interstellar Scattering using a CLEAN-based Method

I developed the following Python code, based on a description in reference [116], to calculate the scattering time constant for archived pulsar pulse-profiles using a CLEAN algorithm.

```
def pbfts(x,tau):#thin screen
    return 1./tau*np.exp(-x/tau)

def pbfm(x,tau): #average median
    if x[0] == 0:
        x[0] += tau*10**-20
    return ((np.pi**5.*tau**3.)/(16.*x**5.))*0.5*np.exp(-((np.pi)**2.*tau)
        /(4.*x))

def step(x,mu):
    return np.append(x[np.where(x<=mu)]*0.,x[np.where(x>mu)]*0.+1)

def conv(x,f,g):
    return (np.convolve(f,g)*(x[1]-x[0]))[:len(x)]

def baseline(ytemp):
    y = 1.*ytemp
    win=50./100
    y = smooth(y,int(len(y)*win))
    baseline = y[0:4].mean() + y[-5:-1].mean()
```

```

    return baseline/2

pbf1 = pbfm
pbf='PBF2'

Gama = 0.05

a = open('period')
periodict={}
filename = []

for line in a:
    key, value = line.split()
    periodict[key]=value
    filename=np.append(filename,key)

fDM = open('DM')
dmdict={}

for line in fDM:
    key, value = line.split()
    dmdict[key]=value

for ii in range(len(filename)):
    psr = filename[ii][0:8]
    period= float(periodict[filename[ii]])
    textX1=0.7*0.3*period
    textX2=0.0
    xlim1=0
    xlim2=256
    #fn = sorted(glob.glob('%.8s*summ*' % filename[ii]))
    fn = sorted(glob.glob('%.8s*' % filename[ii]))
    #temphigh=5
    for ifn in range(len(fn)):
        freq = int(float(fn[ifn][9:14]))
        if freq > 90: continue
        else:
            a = np.loadtxt(fn[ifn])
            a[:,0]*= period/len(a[:,0])
            x = a[:,0]# in second
            tempresol=4096/(19.6*10**6)

```

```

        channelwidth = 19.6/4096
y = a[:,1]

if x[-1]-x[0]<period*0.9 or np.where(y==y.max())[0]<len(x)/4.-4 or
    np.where(y==y.max())[0]>len(x)*3./4:
    print fn[ifn][:8],int(float(fn[ifn][9:14])), 'skipped'
    continue
#continue

y-=baseline(y)
wl, wr = width(y) # profile width for real
yoff = 1.*np.delete(y,np.arange(wl,wr)) # off pulse for real
yp = y*1.

textX1=0.7*0.3*period
Mu=x[1]-x[0]
mert1=[]
mert2=[]
mert3=[]
mert4=[]
tau =[]

temp_jjj1 =0
temp_jjj2 =0

dt = x[1]-x[0]
for jjj in np.arange(dt*0.4, (wr-wl)*dt, dt*0.2): # tau = j
    j = jjj # initial tau

    y=yp*1.
    temp_y=y*0.
    cc = [[],[ ]]
    intrinsic=0

    iteri=0
    while y.std() > yoff.std() or y.mean() > yoff.mean() or y.std() >
        yoff.std():
        #calculate t0
        temp_t0=0
        temp = conv(x, pbf1(x,j), gauss(x, x[np.where(y[wl:wr]==y[wl:
            wr].max())[0].mean()+wl-temp_t0], Mu, y[wl:wr].max()))
        while np.where(temp==temp.max())[0][0] > np.where(y[wl:wr]==y

```

```

[wl:wr].max())[0][0]+wl:
temp_t0+=1
#if np.where(y==y.max())[0].mean()-temp_t0<0:break
temp = conv(x, pbf1(x,j), gauss(x, x[np.where(y[wl:wr]==y[
    wl:wr].max())[0].mean()+wl-temp_t0], Mu, y[wl:wr].max
    ()))
t0=temp_t0

temp /= temp.sum()/gauss(x, x[np.where(y[wl:wr]==y[wl:wr].max
    ())[0].mean()+wl-temp_t0], Mu, y[wl:wr].max()).sum()

if temp.max() == 0: break

y -= Gama*(y.max()/temp.max()).max()*temp
temp_y += Gama*(y.max()/temp.max()).max()*temp

#print np.where(y[wl:wr]==y[wl:wr].max())[0].mean(),wl,
    temp_t0

intrinsic +=Gama*(y.max()/temp.max()).max()*gauss(x, x[np.
    where(y[wl:wr]==y[wl:wr].max())[0].mean()+wl-temp_t0], Mu,
    y[wl:wr].max()/(temp.sum()/gauss(x, x[np.where(y[wl:wr
    ]==y[wl:wr].max())[0].mean()+wl-temp_t0], Mu, y[wl:wr].max
    ()).sum())

cc=np.hstack(( cc, [ [np.where(y[wl:wr]==y[wl:wr].max())[0].
    mean()+wl-temp_t0], [y[wl:wr].max()] ] ))

iteri+=1

if y[wl:wr].std()<yoff.std()*1:
    #print jjj, 'y[wl:wr].std()<yoff.std()'
    temp_jjj1+=1
    break
if y.mean() < yoff.mean():
    #print jjj, 'y.mean() < yoff.mean()'
    temp_jjj2+=1
    break
if temp_jjj2==2*temp_jjj1:
    break

tbar = (cc[0]*cc[1]).sum()/cc[1].sum()

```

```

#print 'tbar',tbar,'x',x[tbar]
ttt3 = ( ( (cc[0]-tbar)**3 )*cc[1] ).sum() / cc[1].sum()
ttt2 = ( ( (cc[0]-tbar)**2 )*cc[1] ).sum() / cc[1].sum()

mert1=np.append(mert1, len(np.where(np.abs(y-yoff.mean())<=0.5*
    yoff.std())[0])*1.0/len(y))
mert2=np.append(mert2, y.std()/yoff.std()) # the tau was the
    mini of mert2, the error is ?
if ttt2==0:mert3=np.append(mert3,0)
else:mert3=np.append(mert3, np.abs((ttt3/ttt2**1.5)))
mert4=np.append(mert4, (y[np.where(y<0.5*yoff.std())]**2).sum()/
    len(y)/yoff.std()**2)
tau = np.append(tau,j)

plt.subplot(5, 1, 1)
plt.ylabel(r'$N_{<3\sigma}/N_{tot}$')
plt.plot(tau,mert1,'ko')
plt.subplot(5, 1, 2)
plt.ylabel(r'$\sigma_{clean}/\sigma_{off}$')
plt.plot(tau*0+tau[np.where(mert2==mert2.min())[0].mean()],mert2,'ko')
plt.plot(tau,mert2,'ko')
plt.subplot(5, 1, 3)
plt.ylabel(r'$\Gamma$')
plt.plot(tau,mert3,'ko')
plt.subplot(5, 1, 4)
plt.ylabel(r'fr')
plt.plot(tau,mert4,'ko')
plt.subplot(5, 1, 5)
plt.ylabel(r'fc')
plt.plot(tau*0+tau[np.where( (mert3+mert4) == np.nanmin(mert3+mert4)
    )[0].mean()],mert3+mert4,'ko')
plt.plot(tau,mert3+mert4,'ko')
plt.savefig('clean%smertit%.8s_%.5iMHz' % (pbf,filename[ii][0:8],int(
    float(fn[ifn][9:14])))

j = tau[np.where(mert2==mert2.min())[0].mean()] # initial tau

y=yp*1.
temp_y=y*0.
cc = [],[]

```

```

intrinsic=0

while y.std() > yoff.std() or y.mean() > yoff.mean() or y.std() >
    yoff.std():
    #for i in range(2000):

        #calculate t0
        temp_t0=0
        temp = conv(x, pbf1(x,j), gauss(x, x[np.where(y[w1:wr]==y[w1:wr].
            max())[0].mean()+w1-temp_t0], Mu, y[w1:wr].max()))
        while np.where(temp==temp.max())[0][0]>np.where(y[w1:wr]==y[w1:wr
            ].max())[0][0]+w1:
            temp_t0+=1
            #if np.where(y==y.max())[0].mean()-temp_t0<0:break
            temp = conv(x, pbf1(x,j), gauss(x, x[np.where(y[w1:wr]==y[w1:
                wr].max())[0].mean()+w1-temp_t0], Mu, y[w1:wr].max()))
        t0=temp_t0
        temp/=temp.sum()/gauss(x, x[np.where(y[w1:wr]==y[w1:wr].max())
            [0].mean()+w1-temp_t0], Mu, y[w1:wr].max()).sum()

        if temp.max() ==0:
            print psr, freq, pbf1,'tau_sig<□', j*1000, '+/-', dt
                *0.2*1000, 'ms',',□tau/dt',j/dt, ',□Mu', Mu*1000,'ms'
            break

        y -= Gama*(y.max()/temp.max()).max()*temp
        temp_y += Gama*(y.max()/temp.max()).max()*temp
        intrinsic +=Gama*(y.max()/temp.max()).max()*gauss(x, x[np.where(
            y[w1:wr]==y[w1:wr].max())[0].mean()+w1-temp_t0], Mu, y[w1:wr].
            max()/(temp.sum()/gauss(x, x[np.where(y[w1:wr]==y[w1:wr].max
            ()) [0].mean()+w1-temp_t0], Mu, y[w1:wr].max()).sum())

        cc=np.hstack(( cc, [ [np.where(y[w1:wr]==y[w1:wr].max())[0].mean
            ()+w1-temp_t0], [y[w1:wr].max()] ] ))
        if y[w1:wr].std(<yoff.std()*1:
            temp_jjj1+=1
            break
        if y.mean() < yoff.mean():
            temp_jjj2+=1
            break
plt.clf()

```

```

plt.subplot(2, 1, 1)
plt.xlim(x.min()*1000,x.max()*1000)
plt.title(r'%s, %iMHz, %\tau=$%.2f\ms'%(psr , freq ,j*1000))
plt.ylabel(r'Intensity_($\sigma$)')
plt.plot(x*1000,yp/yoff.std())#+yp.max()*1.2)

plt.subplot(2, 1, 2)
plt.xlabel('Time_(ms)')
plt.ylabel(r'Intensity_($\sigma$)')
plt.plot(x*1000,intrinsic/yoff.std())
plt.plot(x*1000,pbf1(x,j)/pbf1(x,j).max()*intrinsic.max()/yoff.std
())
plt.plot(x*1000,y/yoff.std(), '--')
plt.xlim(x.min()*1000,x.max()*1000)

if temp.max()>0:
    print psr, freq, pbf1,'tau_sig', j*1000, '+/-', dt*0.2*1000, 'ms'
    ,',\tau/dt',j/dt, ',\mu', Mu*1000,'ms'
plt.savefig('cleanpbf1%.8s_%.5iMHz_tau_sig' %(psr,freq))
plt.clf()

```

Appendix C

Observation Scheduler

The LSL [86] provides a GUI version of Observation Scheduler for users to organize observing plans. Below is a screen shot of the GUI.

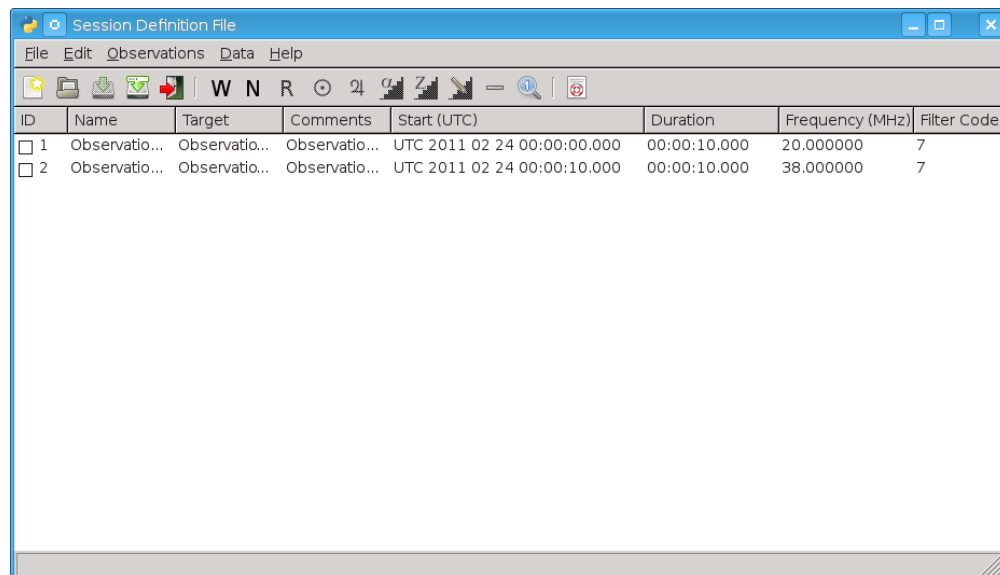


Figure C.1: The screenshot of scheduler for a observation request.

The user can output the observing plans from the GUI of Observation Scheduler and the schedule can be saved as a text file that can be uploaded to the LSL server for validation. Below is a example of the text file.

```
PI_ID 1
PI_NAME Tsai, Jr-Wei
```

```
PROJECT_ID XXXXXXXX
PROJECT_TITLE Project Title
PROJECT_REMPI Project REMPI
PROJECT_REMPO Project REMPO

SESSION_ID 1
SESSION_TITLE test #1
SESSION_REMPI Detect green little man
SESSION_REMPO Session REMPO

OBS_ID 1
OBS_TITLE Observation 1 Title
OBS_TARGET Observation 1 Target
OBS_REMPI Observation 1 REMPI
OBS_REMPO Observation 1 REMPO
OBS_START_MJD 55616
OBS_START_MPM 0
OBS_START UTC 2025 02 31 00:00:00.000000
OBS_DUR 10000
OBS_DUR+ 00:00:10.000
OBS_MODE TRK_RADEC
OBS_RA 5.6
OBS_DEC 22.0
OBS_B SIMPLE
OBS_FREQ1 438261968
OBS_FREQ1+ 19.999999955 MHz
OBS_FREQ2 1928352663
OBS_FREQ2+ 87.999999977 MHz
OBS_BW 7
OBS_BW+ 19.600 MHz

OBS_ID 2
OBS_TITLE Observation 2 Title
OBS_TARGET Observation 1 Target
OBS_REMPI Observation 1 REMPI
OBS_REMPO Detect green little man
OBS_START_MJD 55616
OBS_START_MPM 10000
OBS_START UTC 2025 02 31 00:00:10.000000
OBS_DUR 10000
OBS_DUR+ 00:00:10.000
OBS_MODE TRK_RADEC
```

OBS_RA 5.6
OBS_DEC 22.0
OBS_B SIMPLE
OBS_FREQ1 832697741
OBS_FREQ1+ 37.999999997 MHz
OBS_FREQ2 1621569285
OBS_FREQ2+ 73.999999990 MHz
OBS_BW 7
OBS_BW+ 19.600 MHz