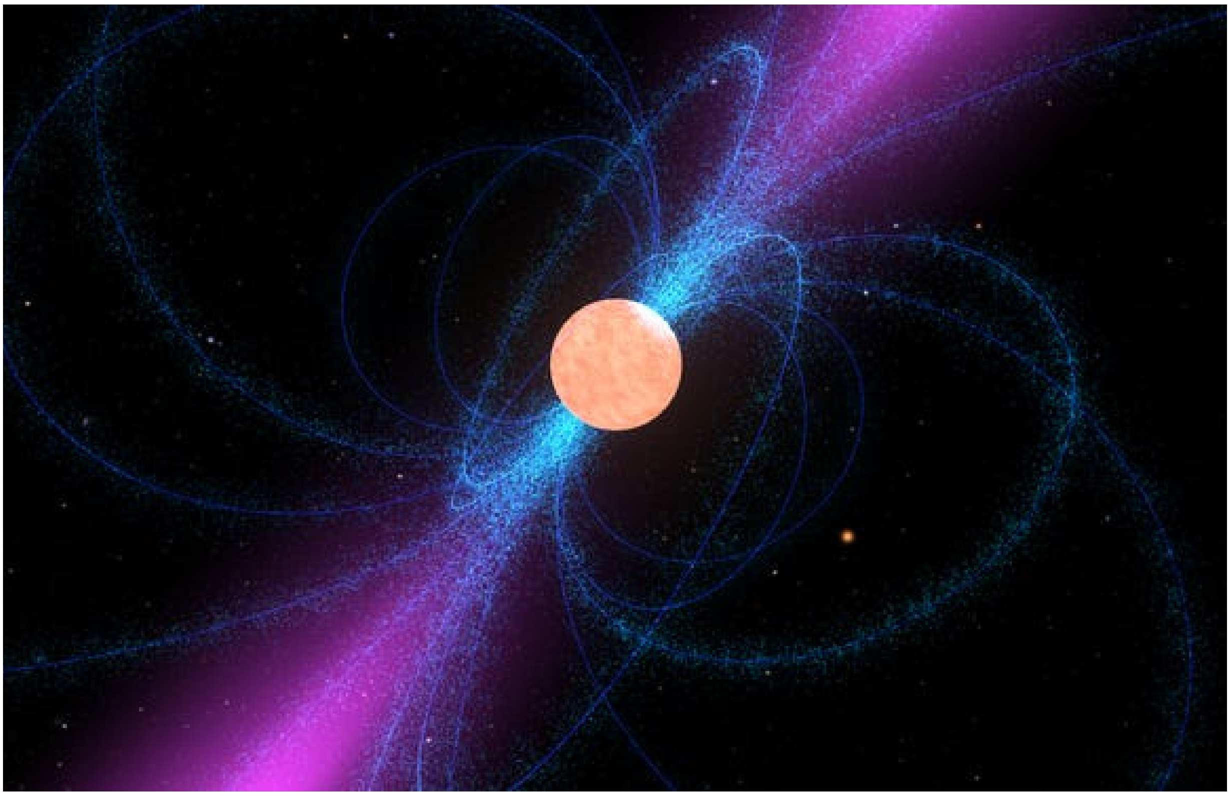
IDENTIFYING A PULSAR USING VOLTAGE DATA FROM THE OOTY RADIO TELESCOPE



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Contents

1. Introduction

Pulsars are highly magnetized and rotating neutron stars. Pulsars radiate two steady, narrow beams of light in opposite directions. Although the light from the beam is steady, pulsars appear to flicker because they also spin. The time interval between consecutive pulses is called the pulsar's period. Periods of one second are quite common although pulsars have been discovered with periods from a few milliseconds up to eight seconds.
Vela is the brightest pulsar in the sky and spins 11.195 times per second. It has the third-brightest optical component of all known pulsars (V = 23.6 mag) which pulses twice for every single radio pulse. The Vela pulsar is the brightest persistent object in the high-energy gamma-ray sky. It is the only pulsar visible in both optical and X-ray range.

Fig.: X-ray Image of the Vela Pulsar as captured by the Chandra X-ray Telescope.

The data provided for this experiment is voltage time series obtained from the observations of the Vela Pulsar using the **Ooty Radio Telescope**. The Ooty Radio Telescope consists of a cylindrical paraboloid reflecting surface which is 530 m long and 30 m wide, placed on a slope of 11.2 degrees in the north-south direction in Muthorai village near Ooty. The antenna beam can be steered in the north-south direction by electronic phasing of the 1056 dipoles placed along the focal line of the reflector. The reflecting surface is made up of 1100 thin stainless-steel wires, each 530 m long. It is supported by 24 parabolic frames separated by 23 m from each other.

This data analysis includes:

1. Signal Statistics
2. Time and Frequency Domain Properties
3. Discovering the Pulsar

Programming Language used: Python

2. Description of the Data

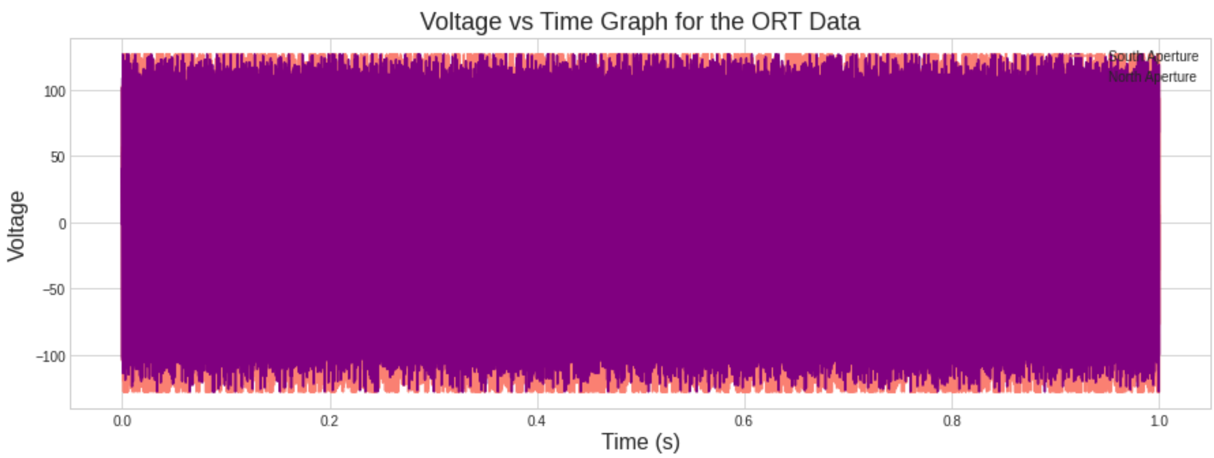
- Voltage time series from the Ooty Radio Telescope (ORT) — North and South apertures.
- The data is raw and has not been calibrated or processed.
- As raw voltages, the data are is arbitrary units.
- The observation frequency is 326.5±8.25 MHz which has been down-converted to the base band. The voltages hence occupy the 0–16.5 MHz band.
- The data is sampled at the Nyquist rate, i.e., two real valued voltage measurements in a period corresponding to the maximum variability time-scale (maximum frequency).
- The length of the data is about 1 second.
- The data are presented in a header-less (numeric data only without any descriptive text), ASCII format file.

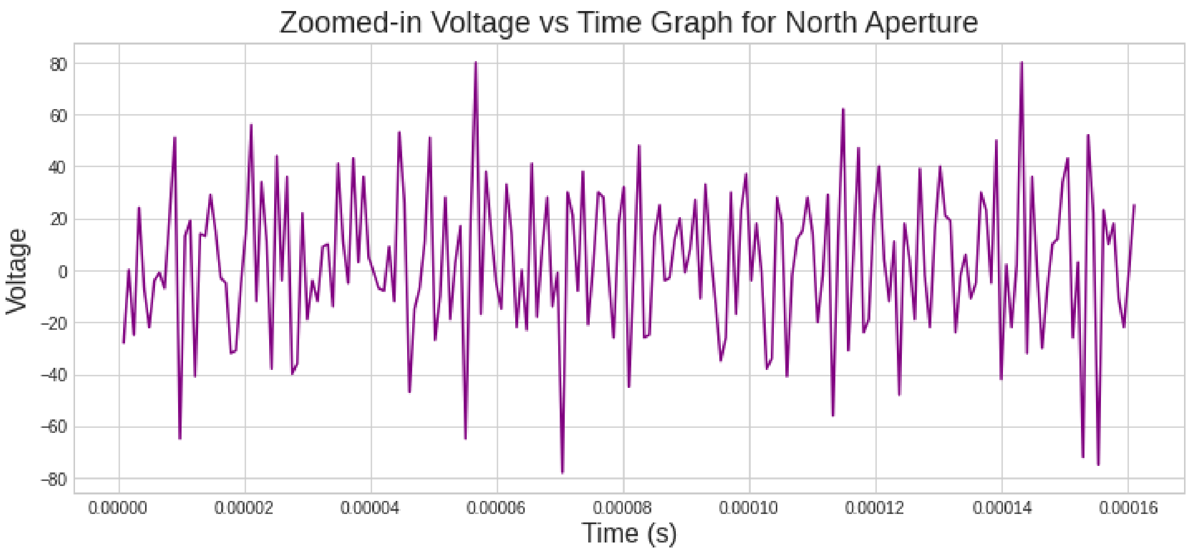
3. Signal Statistics

3.1. Voltage Signal Characteristics

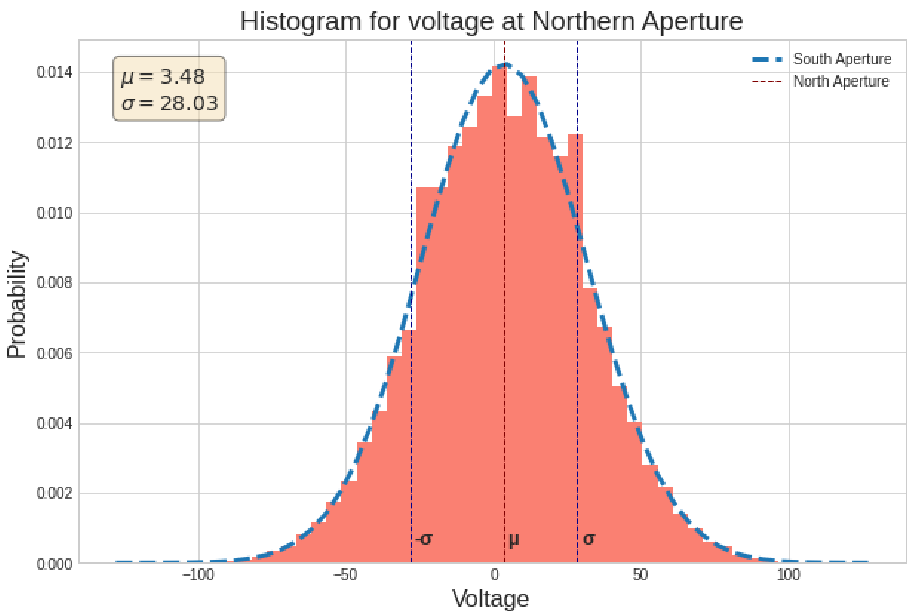
Investigating the statistical properties of the signal received at the telescope, we expect the voltage signal to have a Gaussian distribution with some mean and standard deviation. To observe the characteristics of the voltage signal received at the telescope, the time-series of the voltage received at the northern and southern feeds of the telescope were plotted. The zoomed-in graph helps us to observe the fluctuations in voltage.

Voltage Time-series:





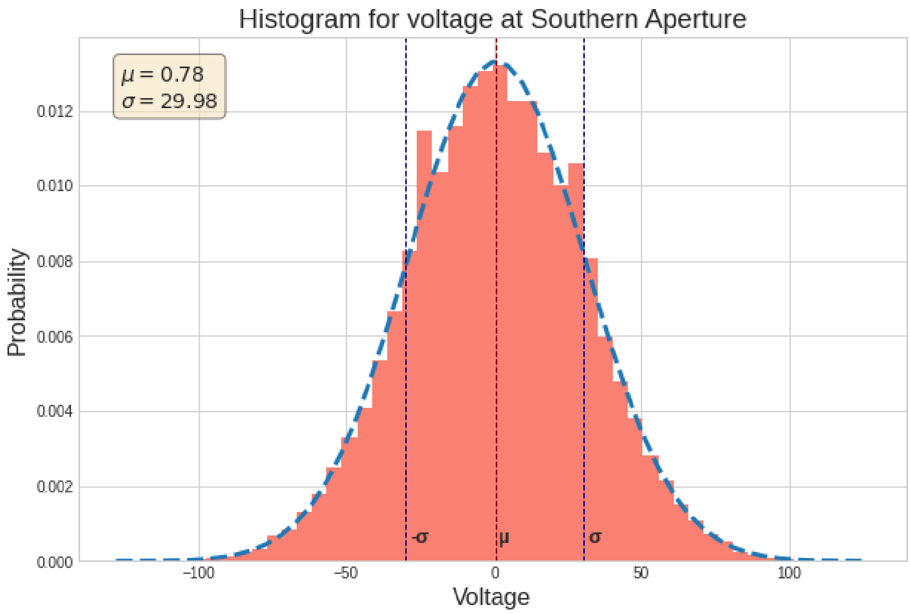
In order to investigate the statistical properties of the signal, the histograms for the voltage received at the northern and southern feeds were plotted. It is now evident that the system has a characteristic Gaussian shape.



For North Aperture,

μ = 3.482

σ = 28.03



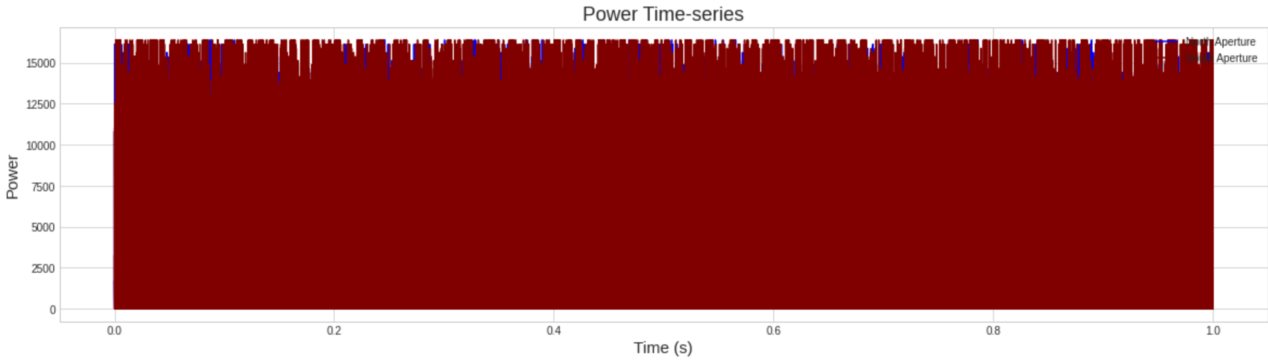
For South Aperture,

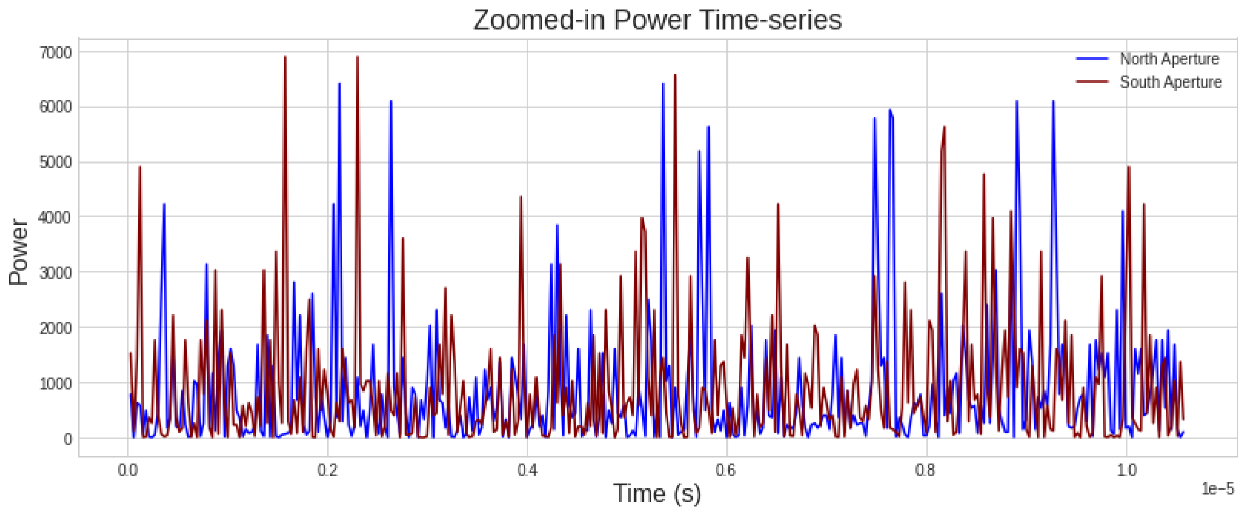
μ = 0.78

σ = 29.98

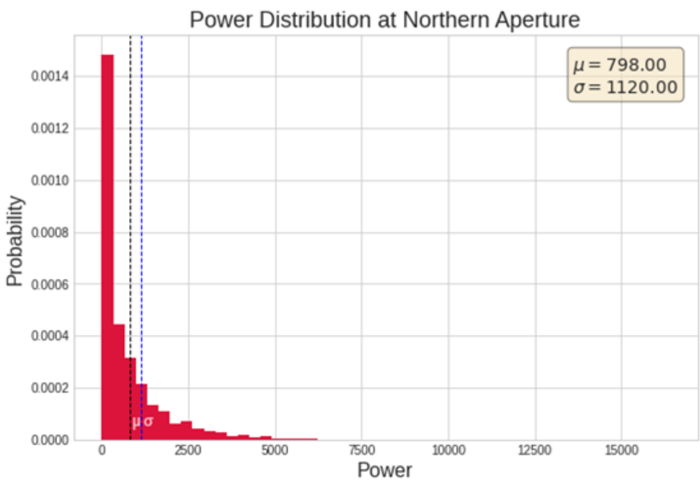
3.2. Power Signal Characteristics

The next step is to study the power signal characteristics. The power is obtained by squaring the voltages. The time-series of the power (square of voltage signal) at the northern and southern feeds of the telescope were plotted. The zoomed-in graph helps us to observe the fluctuations.





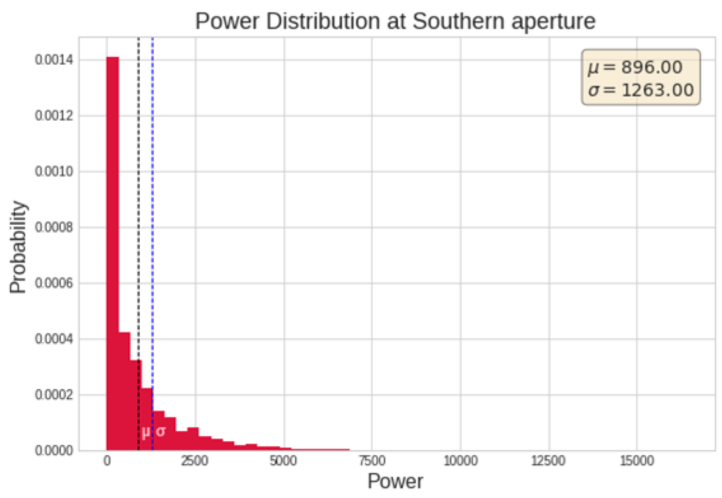
The signal is expected to show an exponentially decaying distribution, which is evident from the plotted histograms.



For North Aperture,

μ = 798

σ= 1120



For South Aperture,

μ = 896

σ = 1263

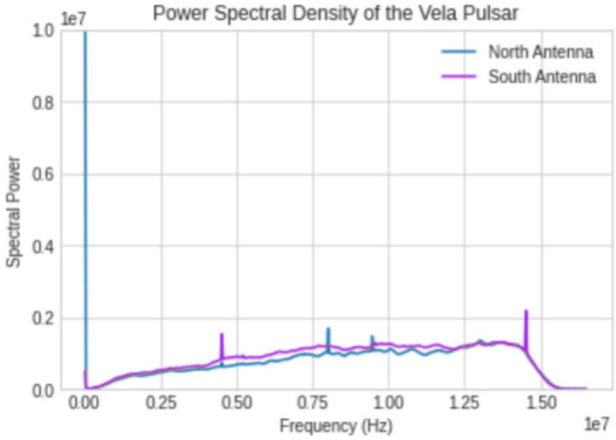
4. Frequency Domain Properties

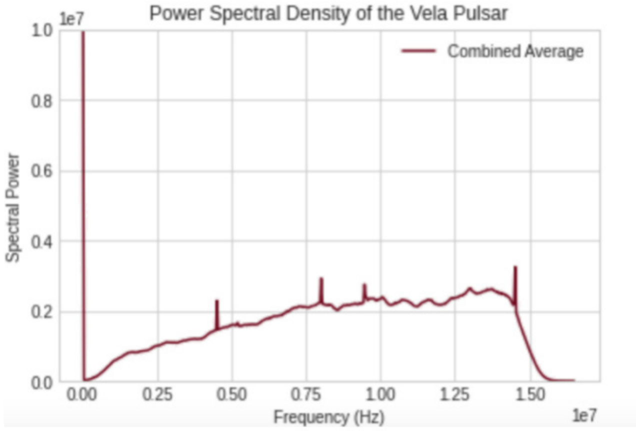
Now it is required to obtain contribution of various frequencies that produce the voltage time-series — using a **Fast Fourier Transform** (FFT).
A Fourier transform consists of the contributions from the constituent frequency which can be squared to give the power distribution. Sequences of power spectra can be combined and added to reduce the statistical uncertainties.
First, we want to obtain the spectral composition of the time series. In order to find the spectral information, we select a small part of the time-series, take the Fourier series to convert it to the spectrum in that time range.
The spectral information is obtained at the cost of time resolution (since FFT of voltage time samples gives the spectrum). For time-resolution 'dt', **an N–point FFT will output the amplitude and phase of N/2 frequencies** that contains information equivalent to the time-series
The data can now be transformed to a time series of time bin-size 'N×dt' but with a N/2 -bins spectrum in each time bin.
The power spectral distribution is obtained by squaring the Fourier spectrum.

- Number of Frequency Bins= 512
- Time Resolution of Voltage Sampling= 30.3 nanoseconds
- Lowest Frequency probed= 32.23 kHz
- Number of voltage samples to obtain FFT= 953
- Time Resolution of spectral series= 28.88 microsecond

4.1. Average Power Spectral Density for the Voltage Signal

We would now like to analyze the signal in the frequency domain. It has been told that the observations have been carried out with a bandwidth of 16.5 MHz. Using the Fast Fourier Transform (FFT) with 512 frequency channels (a sufficient frequency resolution of ≈ 32.23 kHz; power of 2 increases the speed of the FFT), we find the average power spectrum of the voltage signal by averaging the power spectrum obtained from all 953-point (time samples) FFTs. The spectra for the northern and southern half are given below.





It is easy to see that the DC channel power is much larger in the northern signal, than the southern signal which is consistent with the fact that the norther signal voltage mean is much larger than the southern signal mean, which is closer to zero. We can clearly see that the power spectrum smoothly tapers off to zero at both the edges of the band, indicating that aliasing is very minimal for these receivers. The sharp peaks in the spectra may be signatures of local Radio Frequency Interference (RFI).

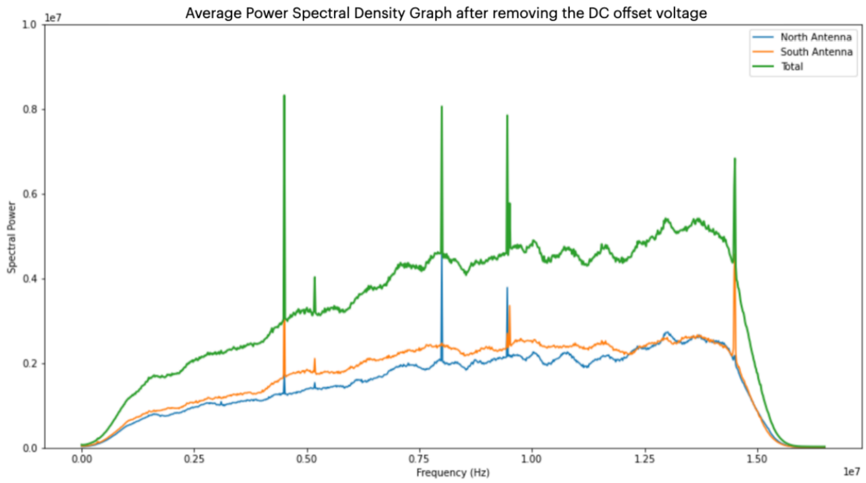
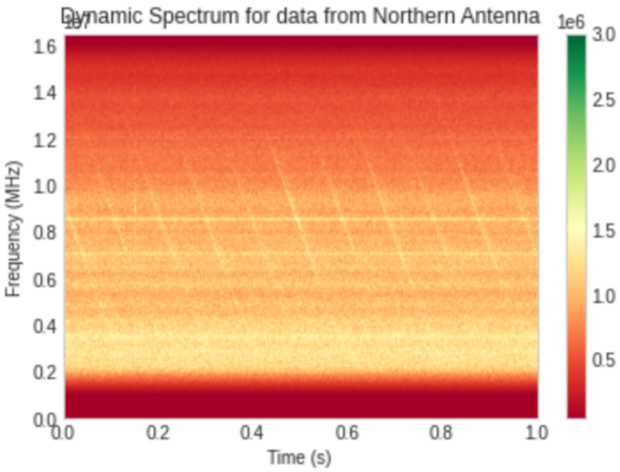
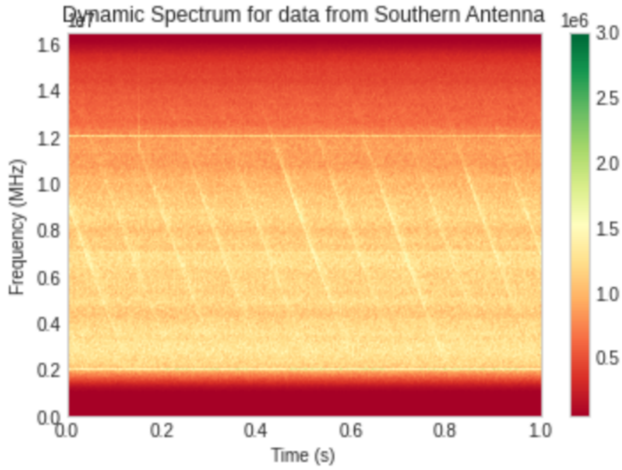


Fig.: Average Power Spectral Density Curve after removing the DC Offset of receiver.

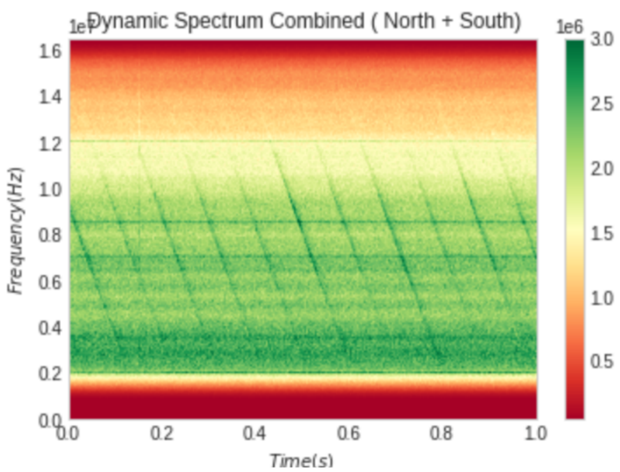
4.2. Dynamic Spectrum

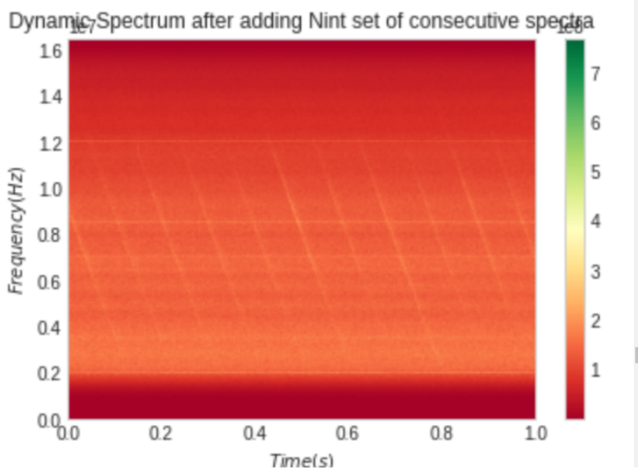
We now try to detect the first signs of the pulsar signal by looking at the dynamic spectrum of the signal, i.e., the power in the signal as a function of time and frequency. As a trial, we examine ≈ 1 s of the data to detect a pulsed signal, if present. The dynamic spectrum is shown below, where the y-axis is frequency in MHz, x-axis is time in ms and the color code indicates the signal power for a particular frequency and time sample. To improve the Signal to Noise Ratio (SNR) of the signal, the power from the two halves of the array have been added (Incoherent addition). A pulsed signal appears earliest at the high frequencies, and gradually appears later at lower frequencies. This frequency dependent delay is a characteristic sign of a signal dispersed in the interstellar medium. The observed delays can be used to estimate the Dispersion Measure (DM) along the line of sight to the pulsar.





Further, we can also obtain the dynamic spectra combining all the data and extend this idea to obtain the Dynamic Spectra for a set of 32(Nint) data points.





5. Pulsar Discovery

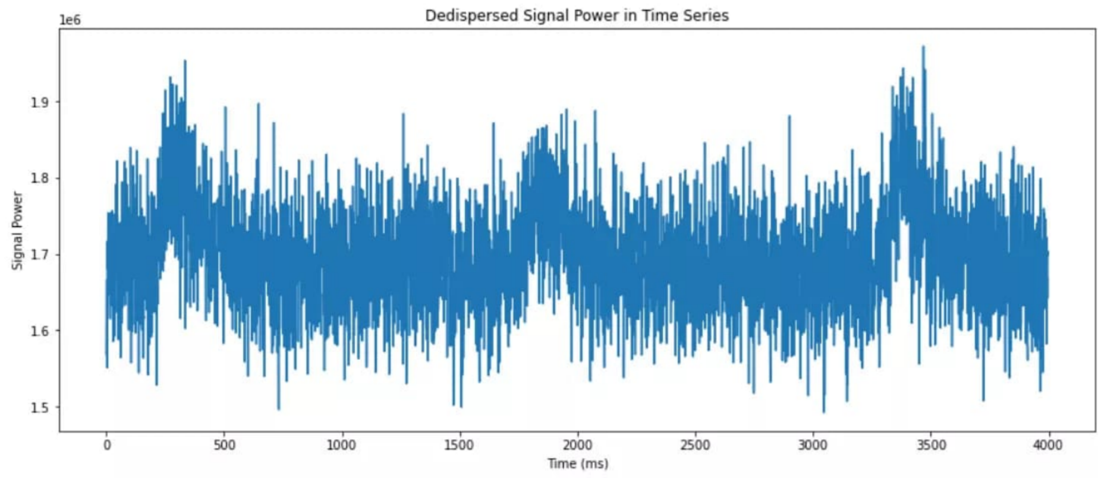
5.1. The Interstellar Medium (ISM)

The propagation of pulsar signals through the tenuous plasma of the ISM produces **dispersion of the pulses**. This is because the speed of propagation through a plasma varies with the frequency of the wave. Low frequency waves travel progressively slowly, with a cut-off in propagation at the plasma frequency. At high frequencies, the velocity reaches the velocity of light asymptotically.
Interstellar dispersion degrades the effective time resolution of pulsar data due to smearing, and this effect becomes **worse with decreasing frequency** of observation.
Thus it is important to reduce the effect of interstellar dispersion in pulsar data. This is called **dedispersion**.

The **DM (Dispersion Measure)** is defined as the integrated column density of free electrons along the line of sight, and has units pc cm−3 . The DM is proportional to the distance between the Earth and the pulsar. Assuming that the electron density number is constant, we use the DM value to calculate the distance of the pulsar from Earth.
From the crude analysis of the dynamic spectrum, we have DM= 64.31pc/cc.

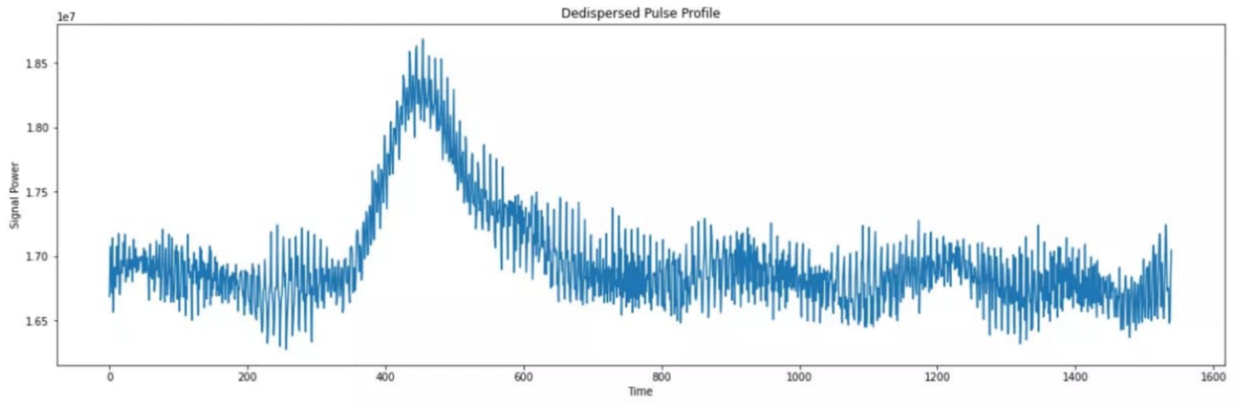
5.2. Shifting the Time Delay

We can now de-disperse this signal by correcting for the frequency dependent delays using our knowledge of the DM. Going back to our original 512 channel resolution (to minimize intra-channel smearing), we correct for the frequency dependent term by applying the required time delays to the frequency channels. The De-dispersed Power-Time series is:



5.3. Time Folding

With a number of high SNR single pulses available, we are now in a position to estimate the periodicity of the signal, i.e., the rotation period of the pulsar. We require the arrival times of the individual pulses to fit a period solution, and hence, we go back to an earlier technique of fitting Gaussian curves to individual pulses, to estimate the arrival times. Finally, based on the period estimated, we can fold the entire time series with the pulsar period to obtain an average profile for the pulsar. This is shown below-



The Time Folding has been done at Pulsar period of **92ms**. The plot clearly shows the presence of a pulsar.

6. Conclusion

- DM ≈ 64.31pc/cc as obtained from the Dynamic Spectrum.
- Pulsar Distance ≈ 2.143 kpc, But the actual distance of the pulsar is 294 pc. This error has occurred because of the presence of Gum Nebula.
- Pulsar period obtained is 92 ms while the actual period is 83.33 ms.

Since the method of determining DM is crude, some amount of error is observed in the Pulsar Period and Pulsar Distance. This implies the requirement of sophistication in the method used, for example taking averages over more sets.

7. References

- http://rac.ncra.tifr.res.in/ort.html
- Essential Radio Astronomy by James J. Condon and Scott M. Ransom
- https : //ui.adsabs.harvard.edu/abs/2018JApA...39...51J/abstract
- https : //link.springer.com/article/10.1007/s12036 – 018 – 9549 – y
- https://www.edx.org/course/the-radio-sky-ii-observational-radio-astronomy