Vela Pulsar (PSR B0833-45) analysis from The Ooty Telescope Data

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1. Introduction

Pulsar stands for 'Pulsating Radio Source' discovered in the 1960s. Pulsars are highly magnetized and rotating neutron stars, emitting electromagnetic radiation from their magnetic poles. These are weak radio sources in terms of their signal intensity that reaches us; the radiation from pulsars can only be observed when its poles are in the line of sight with the observer after each rotation; this is responsible for its pulsed appearance and hence the name Pulsar.

We have been given a sample of the voltage signal of the Vela Pulsar (PSR B0833-45) obtained from The Ooty Radio Telescope as ASCII data. Throughout this analysis, we will investigate the Vela Pulsar's time and frequency domain characteristics and find its Rotation Period and distance.

2. Signal Statistics

We would first like to analyze the given data and its distribution. The data provided was an ASCII file consisting of voltages in North and South arrays; the data is worth 1 second as was observed at 16.5 MHz bandwidth centered at 326.5 MHz. There are 30,720,000 values in both arrays, which immediately tells that each value is separated by an interval of approximately 1/33 microseconds.

We expect the data to have gaussian distribution, which is verified visually by plotting 50,000 random data points. We estimate the Mean and Standard Deviation of both arrays for scaling and normalization of the data; since no calibration data was provided, we will not use any specific units.

$$\mu_{north} = 3.48 \qquad \sigma_{north} = 28.04$$

$$\mu_{south} = 0.73 \qquad \sigma_{south} = 29.85$$

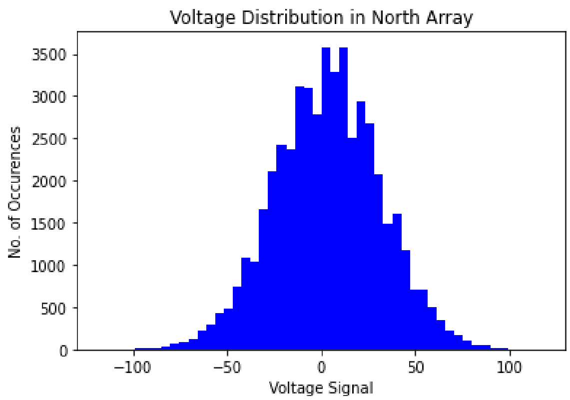


Figure 1: Voltage Distribution in North Array

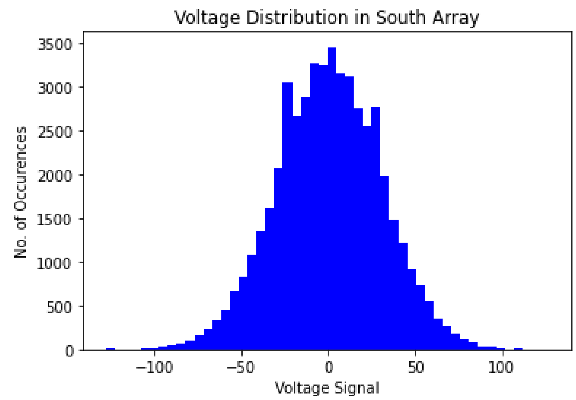


Figure 2: Voltage Distribution in South Array

3. Discovering the Pulsar

We now analyze the data in the frequency domain; for this, we took both the North and the South array and divided all the data into sets of 512, giving us 60000 data sets. Using the Fast Fourier Transform (FFT) with 256 frequency channels (with a frequency resolution of 125kHz), we find the average power spectrum by averaging the modulus square of all the 512 point data sets after performing the FFT.

In both the power spectrum, we observe some sharp peaks, and these may be due to Local Radio Frequency Interference (RFI); also, the 0 frequency channel has a much larger power than the nearby channels due to DC offset in voltages, this also explains the non-zero mean in the data despite having gaussian distribution.

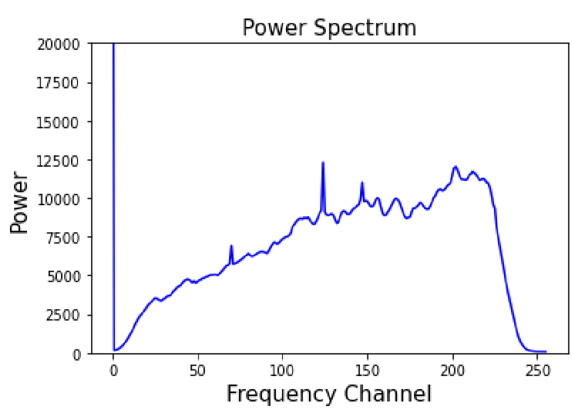


Figure 3: Power Spectrum for North Array

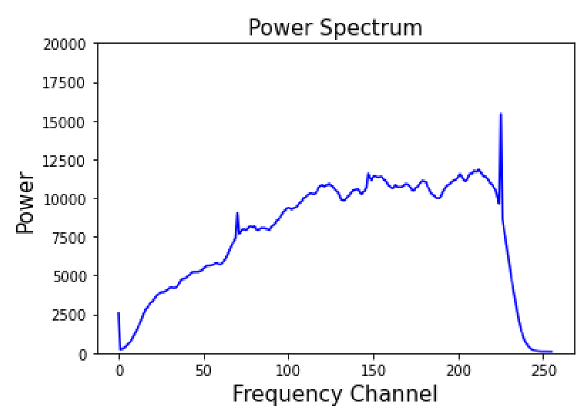
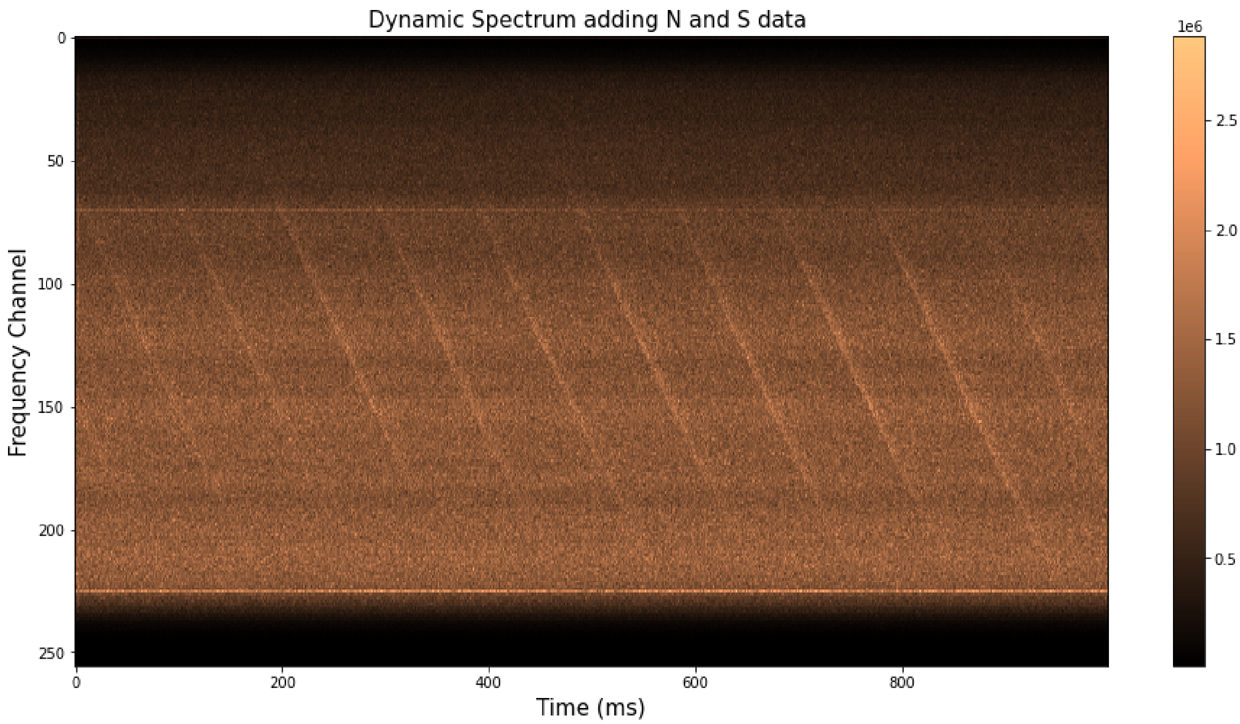


Figure 4: Power Spectrum for South Array

We now detect the existence of pulses by looking at the Dynamic Spectrum of the signal. Dynamic Spectrum (DS) is the power of a signal as a function of time and frequency, and the Dynamic Spectrum is obtained by plotting all 256 channels array as an image. The y-axis

represents the frequency as the channels numbered from 0 to 255, where the 127th frequency channel represents the central frequency of observation. As all frequency channels are equally spaced, their frequency can be calculated by adding/subtracting a particular frequency of the bandwidth.
The X-axis indicates the time, and the color code indicates the signal power.

Figure 3: Dynamic Spectrum obtained by adding N and S data for increasing SNR



Clearly the pulses are visible in the plot as tilted lines, because of the delay in observations due to the Interstellar Medium (ISM). The pulses are detected first in the higher frequencies and subsequently in the lower frequencies. However, we will not use this plot to estimate the period of the pulsar because individual frequency channels have a low Signal to Noise Ratio (SNR); we will try to correct the delay from all channels to sync them with a selected frequency channel.

4. Estimating the DM and Period of Rotation

We will select a strong pulse in the Dynamic Spectrum and estimate the time at which this pulse is detected in 4 different frequencies to obtain the Dispersion Measure (DM). The powers from both arrays were added to further increase the SNR value.
The time of arrival of each pulse is calculated by fitting the Gaussian curve to that single pulse, the time of arrival is given by the mean of the gaussian.

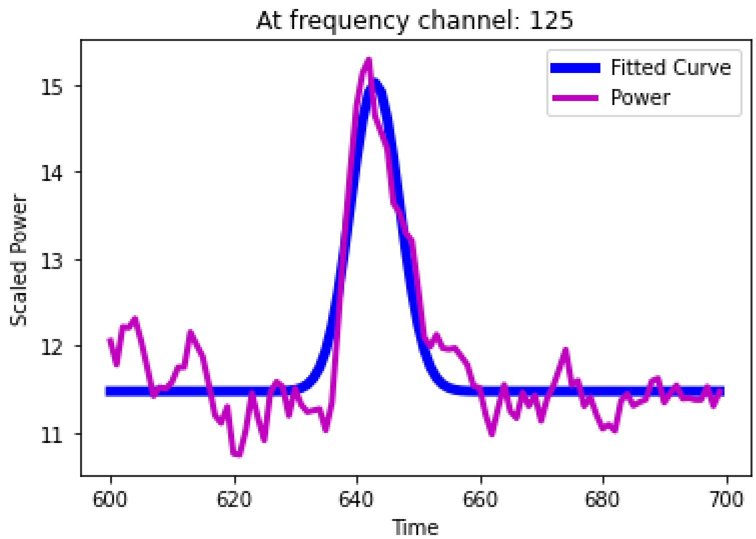


Figure 3: Fitting the Gaussian for 125th frequency channel. The time is obtiained by x value of peak which is the mean of Gaussian. Similarly arrival times of at 3 another frequencies were also calculated.

S.No.	Frequency Channel	Observation Frequency (MHz)	Arrival Time (ms)	Uncertainty (ms)
1	125	326.69	643.01	0.26
2	143	325.53	662.94	0.31
3	153	324.89	674.07	0.19
4	163	324.24	682.53	0.12

Table 1: Time of arrival of a particular pulse at 4 different frequencies

The pulse arrival time (t), frequency (f), and Dispersion Measure (DM) are related as

$$t = t_{\infty} + 4.149 \times 10^{3} \times DM \times f^{-2}$$

Given that time is measured in seconds, frequency in MHz, and Dispersion Medium in pc/cc. Where t_{∞} is the pulse arrival time at infinite frequency. We can estimate the DM by plotting t vs f^{-2} curve. It is expected that this curve will be linear, and its slope will be 41490*DM.

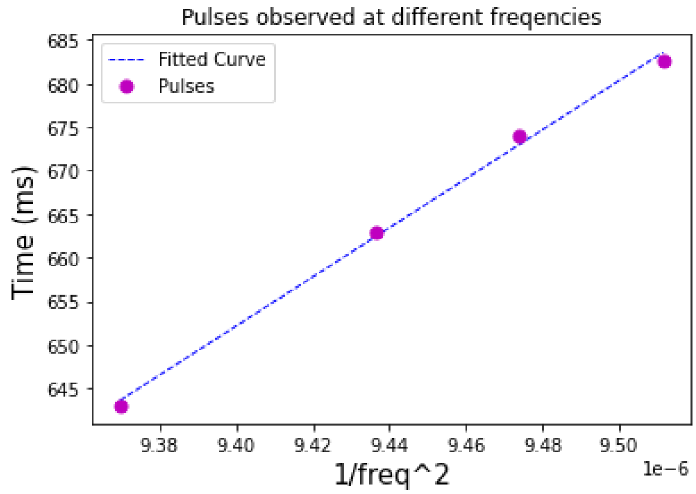


Figure 5: Linear fit for arrival time vs inverse square of frequency

The slope of the fitted line was found to be $(2.81 \pm 0.14) \times 10^5\ s\ MHz^{-2}$, therefore the DM is estimated as 67.94 ± 2.77 pc/cc. The distance to pulsar is given by

$$L = \frac{DM}{n_e}$$

Where n_e is the mean electron density in the intergalactic medium, assuming n_e to be 0.3/cc, the distance comes out to be 2.24 ± 9.23 Kpc.

We can now use our DM in correcting the delay, using the above relationship between time and Dispersion Measure we can get rid of t_∞ variable by writing the delay as

$$delay = 4.149 \times 10^3 \times DM \times \left(f_1^{-2} - f_2^{-2}\right)$$

Where f_1 and f_2 are the two frequency channels used in calculating the delay, we adjust the time domain position of all lower frequency channels and align them to the highest frequency channel, and finally add the signal intensity in all the channels and we obtain the dedispersed signal intensity.

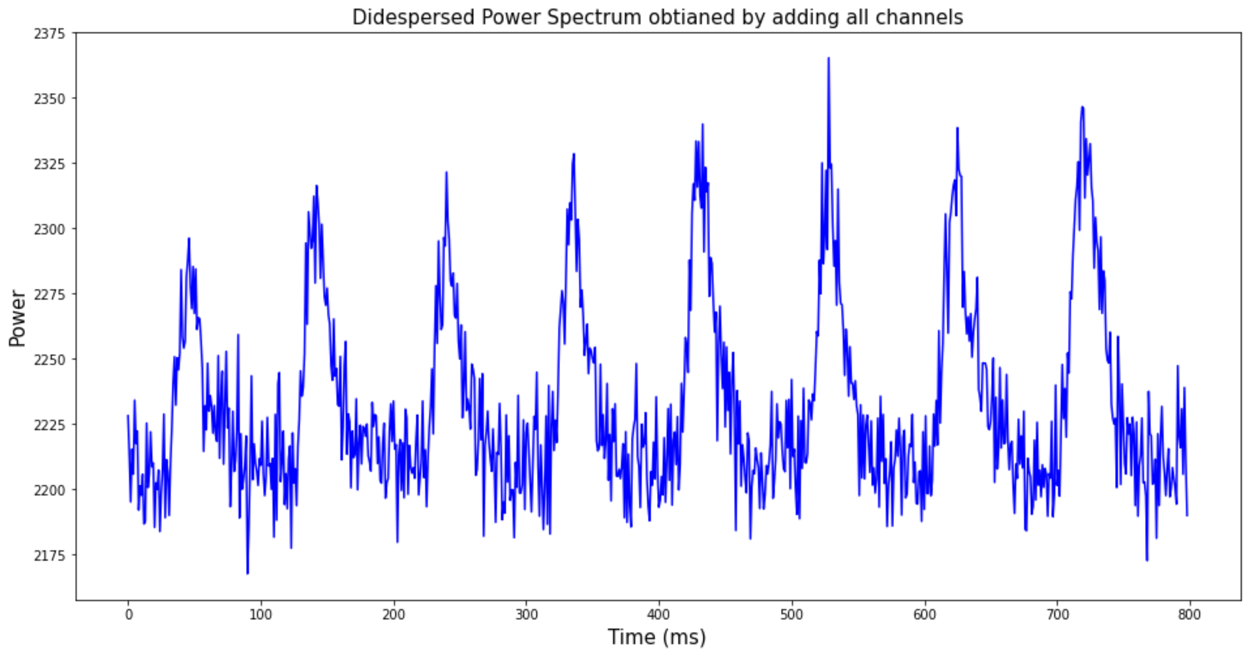


Figure 6: Didespersed Power Spectrum obtained after correcting delay from all frequency channels.

We have successfully increased the SNR value, and the pulses are clearly visible above background noise. Note that we have lost the last two pulses because time delays could not be applied to channels where the pulse did not arrive at the lower edge of the band before the end of the observation.
We are now in a position to estimate the periodicity in the time series, i.e., the rotation period of the pulsar. We will again fit individual pulses in didespersed Power Spectrum to the Gaussian function to determine the arrival times. An example of the curve fit is shown in fig.7, and the arrival times of all the pulses present in dedispersed time-series are shown in the table. Using linear fit on the pulsar arrival times, we estimate the pulsar period to be P = 96.42 ± 0.14ms.

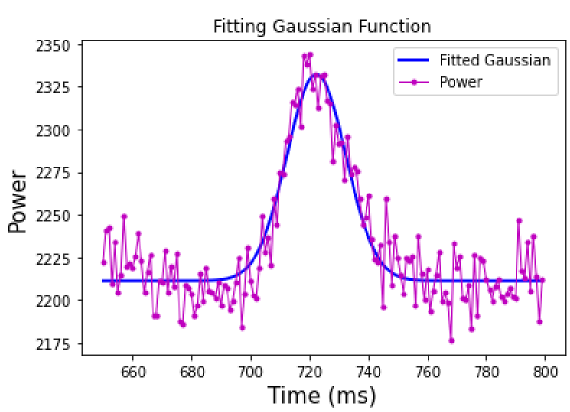


Figure 7: A dedispersed single pulse with a Gaussian fit.

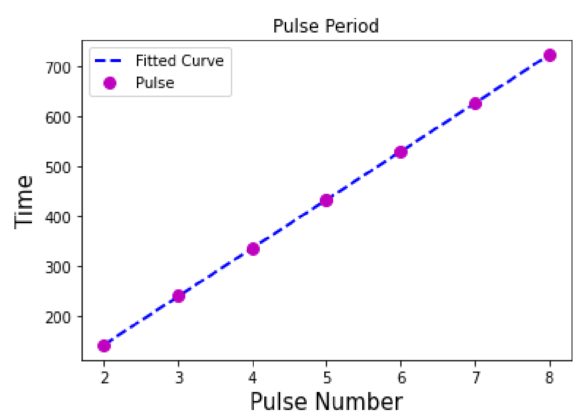


Figure 8: A linear fit to the pulse arrival times to estimate the rotation period

Pulse Number	Time of Arrival (ms)	Uncertainty (ms)
1	142.89	0.51
2	241.19	0.55
3	335.97	0.49
4	432.36	0.43
5	529.17	0.46
6	625.30	0.54
7	722.34	0.42

Table 2: Pulse arrival times for the given data set

5. Conclusion

After this long effort we have successfully managed to find the Dispersion Measure and Period of rotation of pulsar, we also plotted the average pulsar profile by folding all the pulses on the pulse period, and found that this fits well with the gaussian function.
We managed to obtain these parameters from a small data set (~1s) and with fair accuracy. Indeed, longer observations would help to significantly reduce the error bars.
The DM and distance were estimated to be 67.94 ± 2.77pc/cc and 2.24 ± 0.1 Kpc, the estimated rotation period 96.42 ± 0.14ms, whereas the actual period was 89.33ms. We managed to obtain these parameters from a small data set (~1s) and with fair accuracy.
Indeed, longer observations would help to significantly reduce the error bars

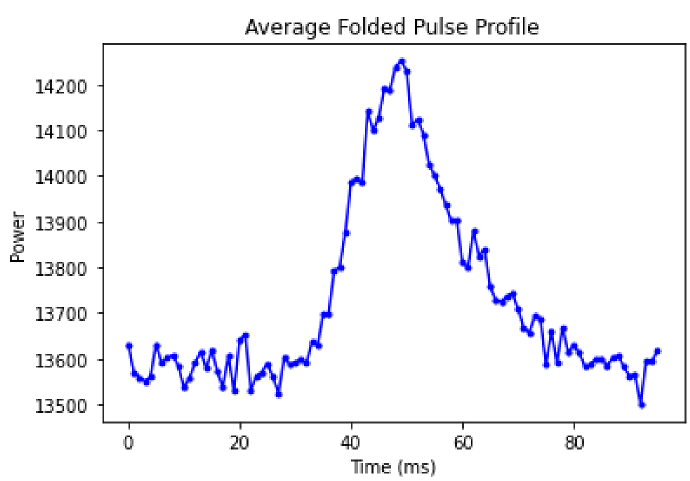


Figure 9: The average profile of the pulsar, folded with the estimated pulsar period