Detecting a pulsar in Ooty Radio Telescope voltage data

Group 3, Radio Astronomy Winter School 2021

Abstract

A pulsar is a neutron star emitting radio waves along the magnetic axes and can be detected on the earth as periodic pulses as its emission cone sweeps past through the observer. We are given the raw data for one such pulsar - PSR B0833-45, also known as the Vela pulsar, observed from Ooty Radio Telescope. Based on the resolution required to identify the pulses, we can manipulate the data to give the dynamic spectrum and fold the pulsar as per the estimated time period to find the integrated pulse profile. We can also estimate the dispersion measure for the pulsar by calculating the delay in the pulse at different frequencies.

Introduction

The radio telescope collects and measures the electrical signal proportional to the electric field incident on the antenna. The voltage recorded is a combination of the system noise and the astronomical signal. Hence it is necessary to understand the statistical properties of the data. According to the central limit theorem, the sum of independent random variables described by distinct or similar probability density functions (distributions with formally defined mean and standard deviation) will tend towards a Gaussian. Therefore, the voltages from system noise and the observed signal both follow Gaussian statistics.

Power is proportional to the square of the voltages, which follows the exponential distribution with distribution mean equal to the standard deviation.

The signal properties can also be examined in the frequency domain at fine spectral resolution. For these we calculate the fourier transform of the data. We first divide the data in certain bins, (usually of size 2^n, because an N-point FFT works considerably faster if the number of data points (N) is a power of 2) and fourier transform each bin. This results in the complex values in each frequency channel. We can find the modulus of these values and obtain the power spectrum. Dynamic spectra require optimally selected frequency channels and time bins to best highlight the source's spectral and time variability. The optimization is between the spectral-/time-resolution and the signal to noise. An optimally constructed dynamic spectrum for a pulsar signal should show a smooth dispersion curve across the frequency band and repeating pulsed signal distributed over multiple bins.

Dispersion measure (DM) is a measure of the dispersion of a signal, i.e., the phenomenon of the duration of a short signal growing longer as it travels. Electromagnetic radiation is slowed by the material it is passing through, generally, the longer the wavelength, the more it is slowed, so the shorter wavelengths of the signal are received earlier than longer wavelengths that were sent at the same time, and dispersion measure is a measure of to what degree additional wavelength results in a delayed signal [3]. In order to obtain the pulse profile, we need to de-disperse our data, that is to undo the dispersion delays introduced by the interstellar medium.

The dispersion measure is given by

$$\mathrm{DM} = \frac{t_2 - t_1}{K(\nu_2^2 - \nu_1^2)} \tag{1}$$

Where, DM - dispersion measure.
ν1 and ν2 - earlier and later frequencies received.
t1 and t2 - earlier and later reception times.
kDM - dispersion constant: 4.149 GHz2 pc-1 cm3 ms (for time difference in ms)

The de-dispersed dynamic spectrum will have repeating and aligned pulses. The periodicity reflects the pulsar period, roughly estimated from the separation between pulses in the dynamic spectrum.

Section I describes the data given. Section II contains the procedure followed during the analysis of the given data to obtain the integrated pulse profile including the graphs obtained during each step. Section III contains discussion and interpretation of of graphs including calculations to obtain DM. The results are summarized in the section IV

I. Data

We are provided with the data file containing 2 columns of integer values separated by a space, corresponding to the voltage readings from North (column 1) and South (Column 2) apertures at Ooty Radio Telescope (each column contains 30720000 values). The recorded voltage amplitudes are in arbitrary units. The radio frequency (RF) range 326.5 ± 8.25 MHz is down-converted to the base 0 − 16.5 MHz band. sampling time resolution equals 30.30 ns and data spans approximately 1 second.

II. Data Analysis steps and Graphs

1. Examining voltage time series and power time series

We plot the voltages for North and South aperture against time to visualize the voltage-time series. (Fig. 1) The voltages are also plotted on a histogram to understand their distribution. A Gaussian curve can be fitted on this data as shown in Fig.2. The mean and standard deviation are calculated for the data and hence the probability distribution function is obtained.

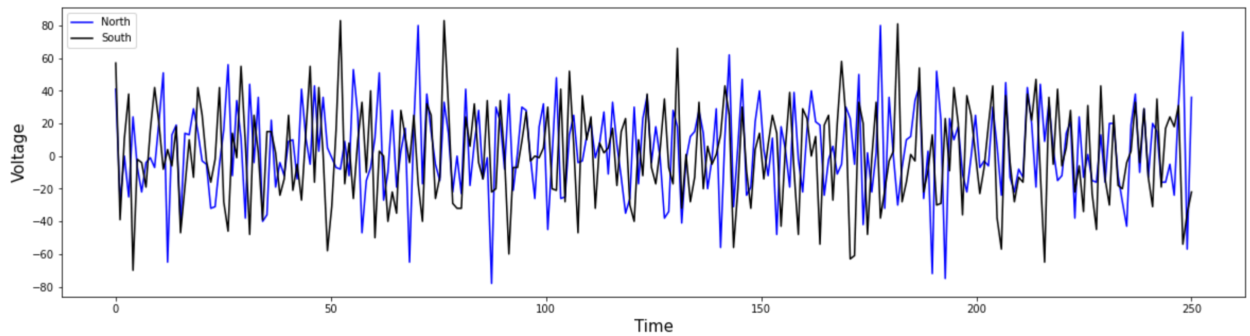
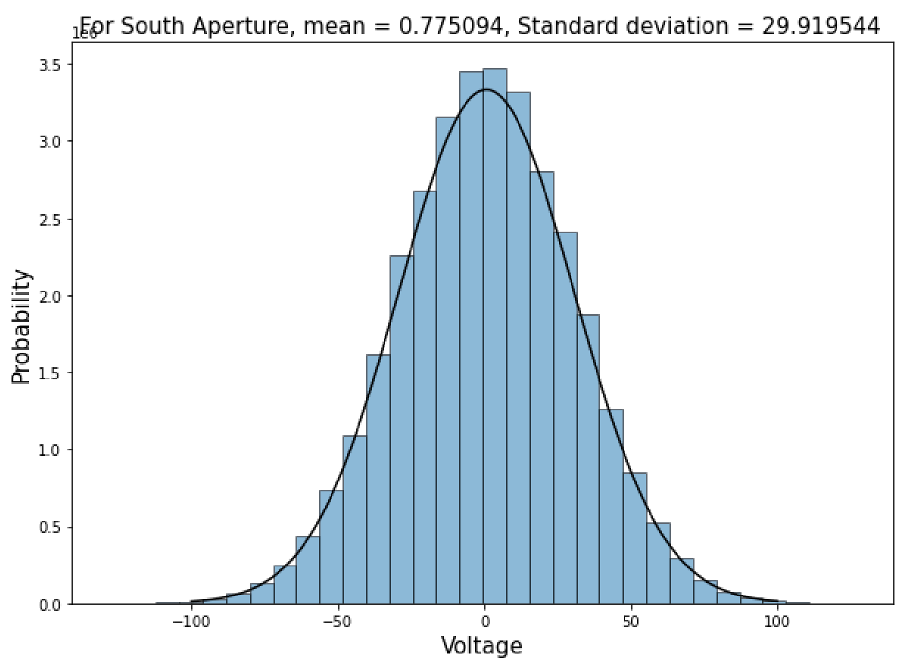


Fig. 1: Voltage vs time plotted for first 250 values in the data file to visualize the voltage-time series. Blue shows voltage record by north whereas, black shows that by the south aperture.



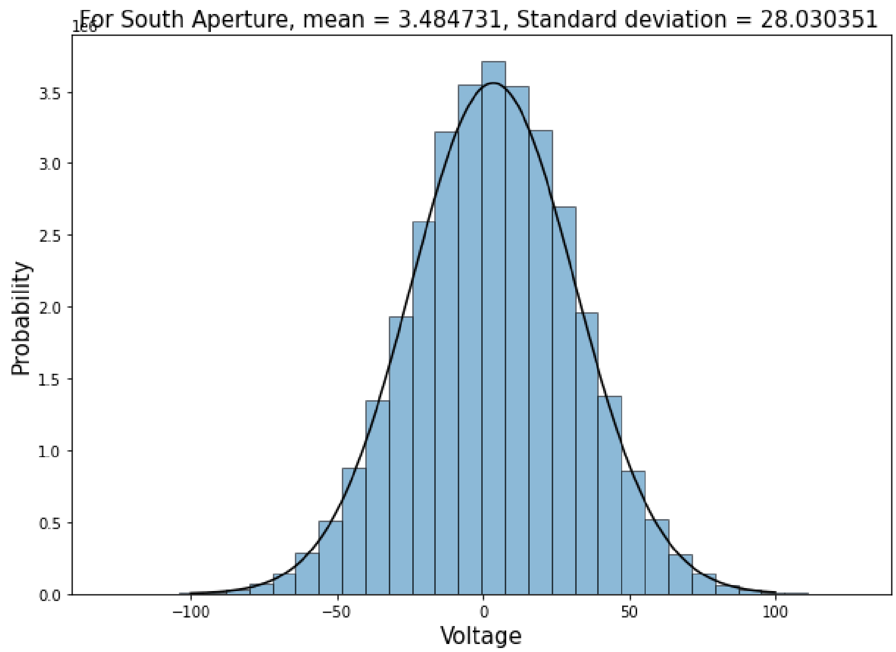


Fig. 2: histograms showing the distribution of voltages for both the apertures. The distribution is fitted with a Gaussian with parameters as indicated in the title.

To find the power, we simply square the voltages. Fig. 3 visualize the power-time series for the given data. The power data can be fitted using the chi-squared function, by calculating the mean and standard deviation of the powers obtained. (Fig.4)

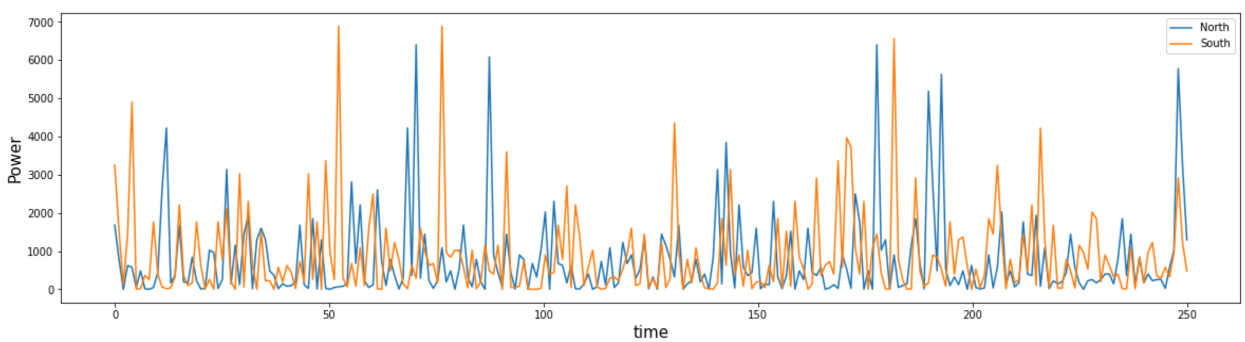


Fig. 3: Plot visualizing power-time series for the first 250 values in the data file.

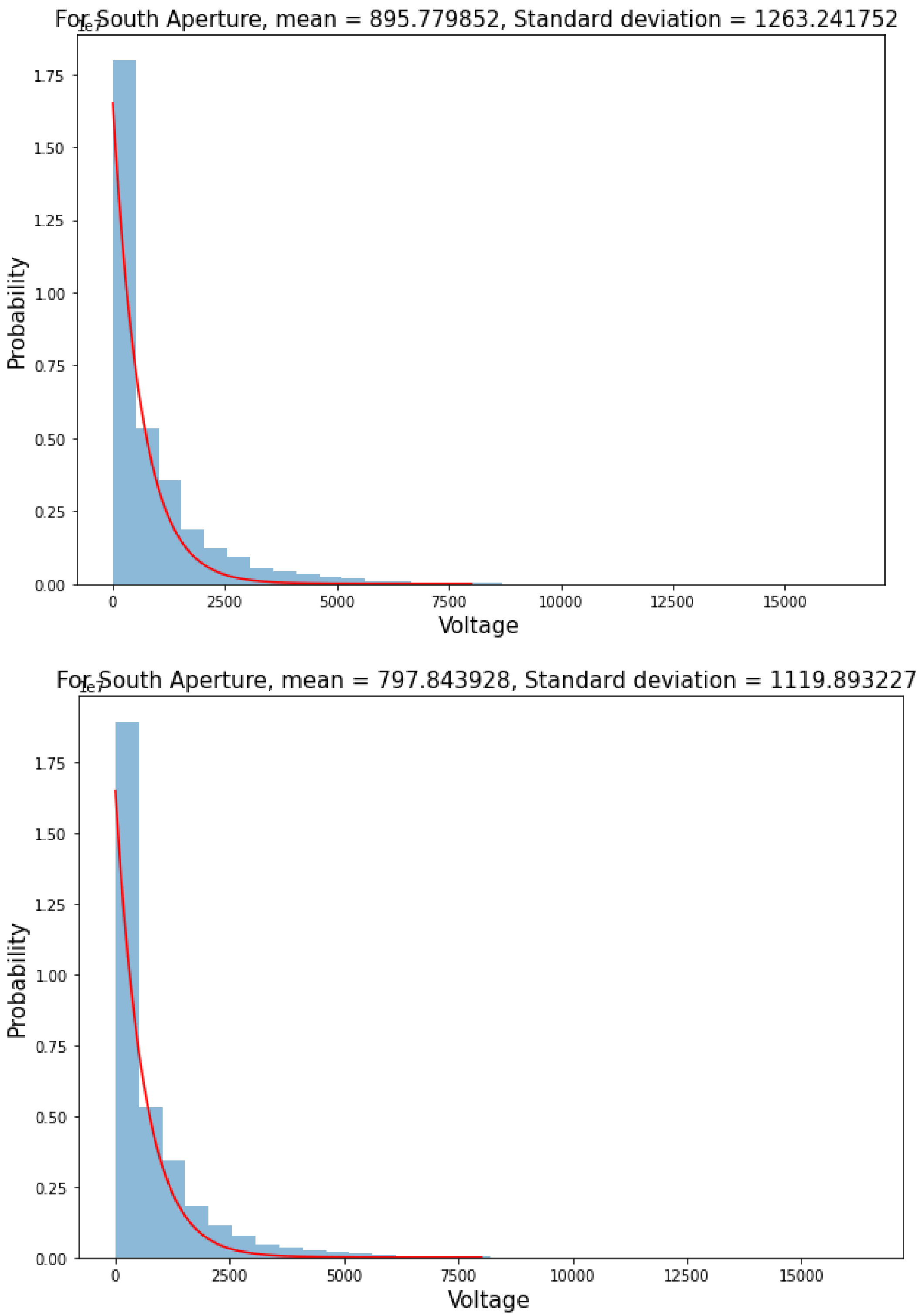


Fig. 4: DIstribution of power shown in the histogram, which is fitted by the chi-squared distribution function

2. Power spectrum and Dynamic Spectrum

To obtain the power spectrum, we need to find the Fourier transform of the given voltages, thereby transforming them to the frequency domain. To do this, we break our data into bins of size 512. The total size of data is 30720000. Hence we get 60000 such bins each of size 512. We perform the Fourier transform for each of these bins and take only positive values of the Fourier transformed data. This results in 60000 power spectrums for 256 frequency channels. For each of these 60000 power spectra, the power vs frequency plots are obtained and one for each of the apertures is shown in Fig. 5.

Further, the power spectrum was averaged over 60000 spectra to obtain an averaged power spectrum for both the apertures. The averaged power vs frequency plot for each of the apertures is shown in Fig. 6. The original power spectrum obtained by directly plotting the average values wrt time were flipped. Hench, we inverted the matrix to flip it and this flipped matrix was used for further data analysis.

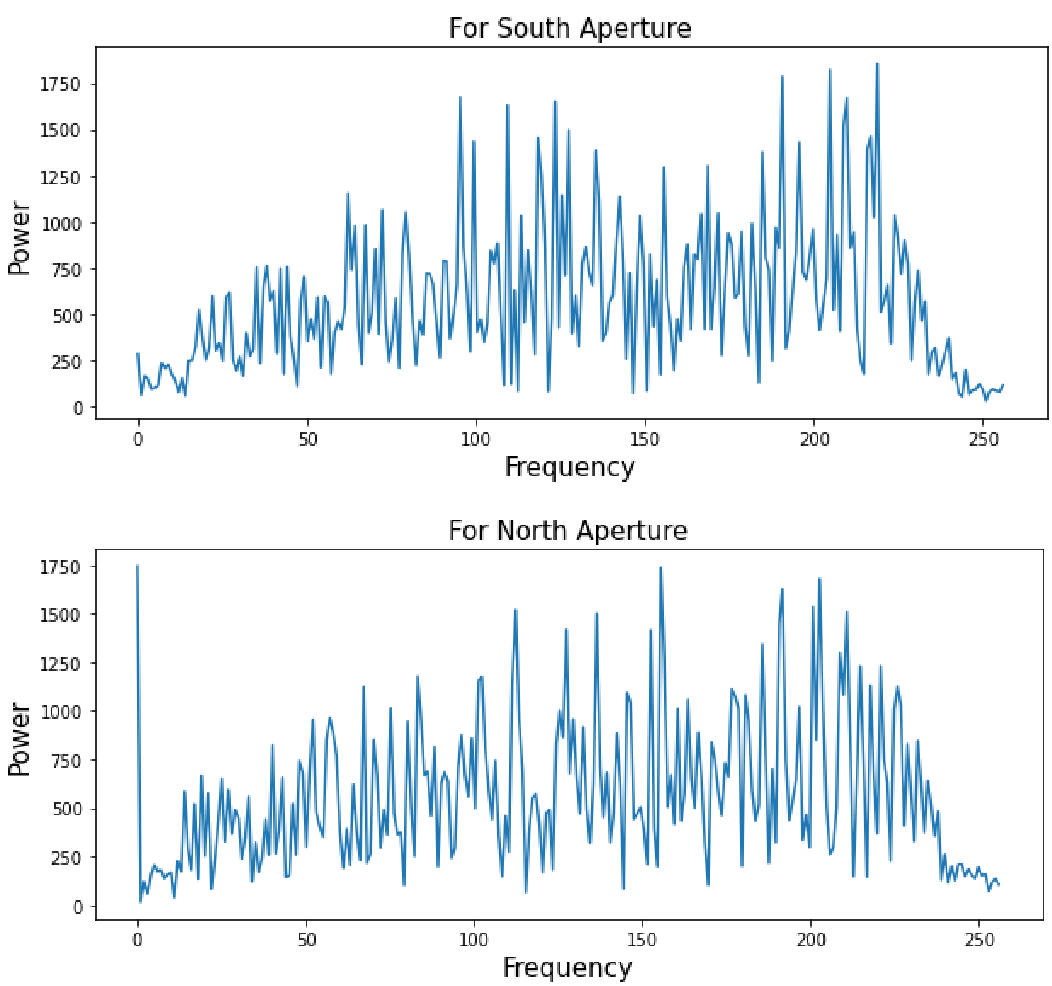


Fig. 5: Power spectrum for one of the frequency bins for north and south apertures.

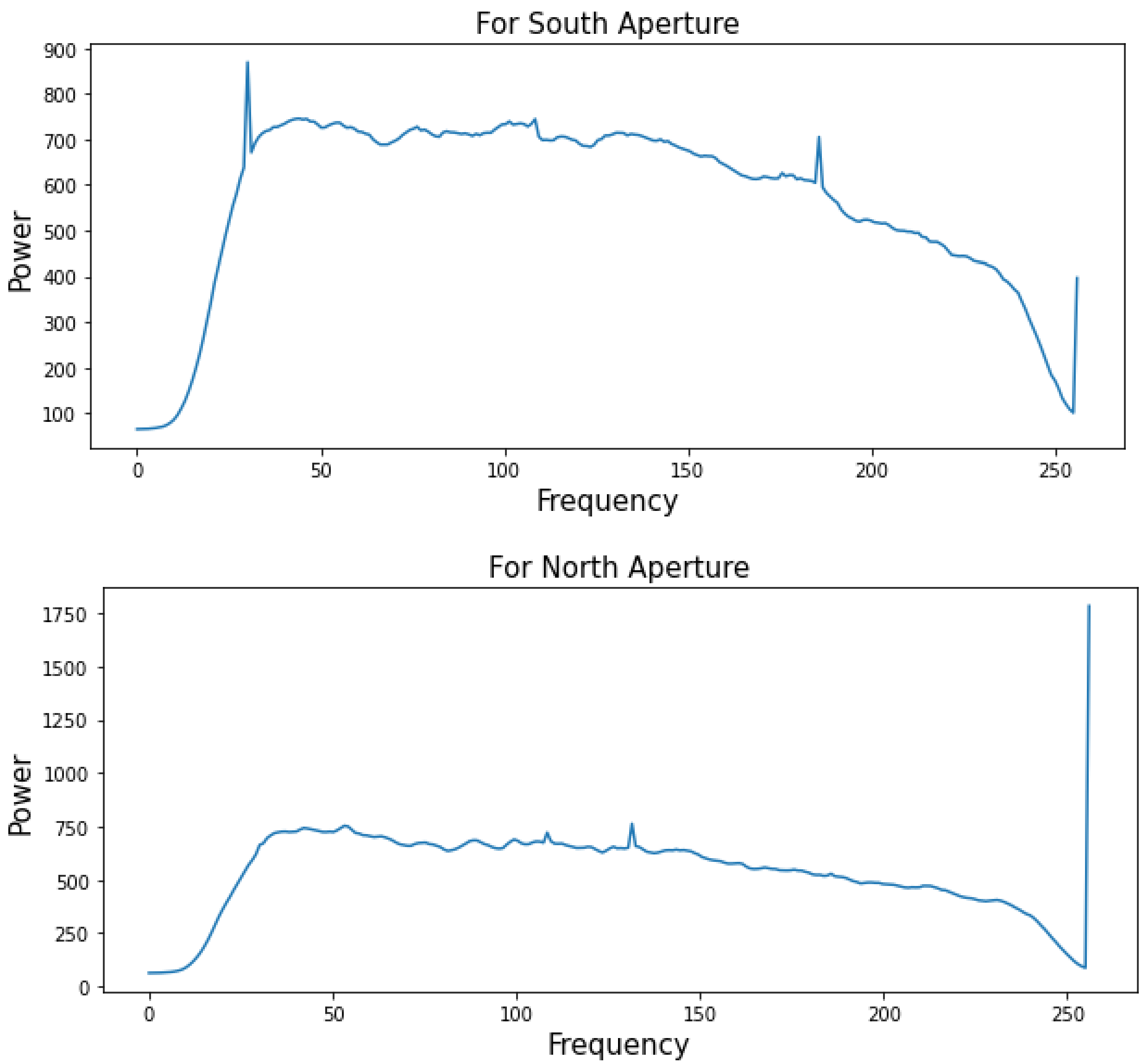


Fig. 6: Average power spectrum for both the apertures.

The dynamic spectrum of the data can be obtained by averaging out certain bins in order to give the desired time resolution. Here we average over 60 bins to get the time resolution of 1ms. This results in 1000 averaged spectra, which are stacked in a 2-d array. We can plot frequency vs time for this 2-d array and indicate the intensity at each point by a color map. Fig. 7 shows the dynamic spectrum for both the apertures.

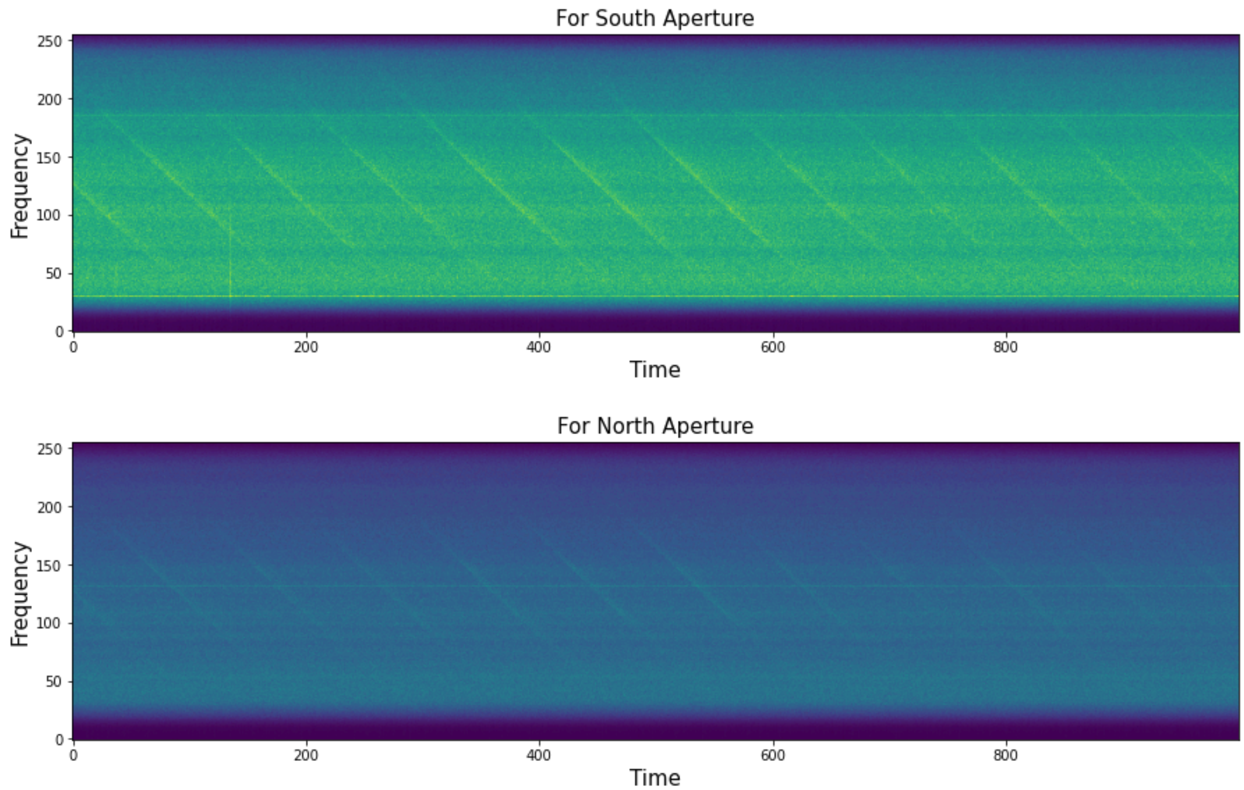
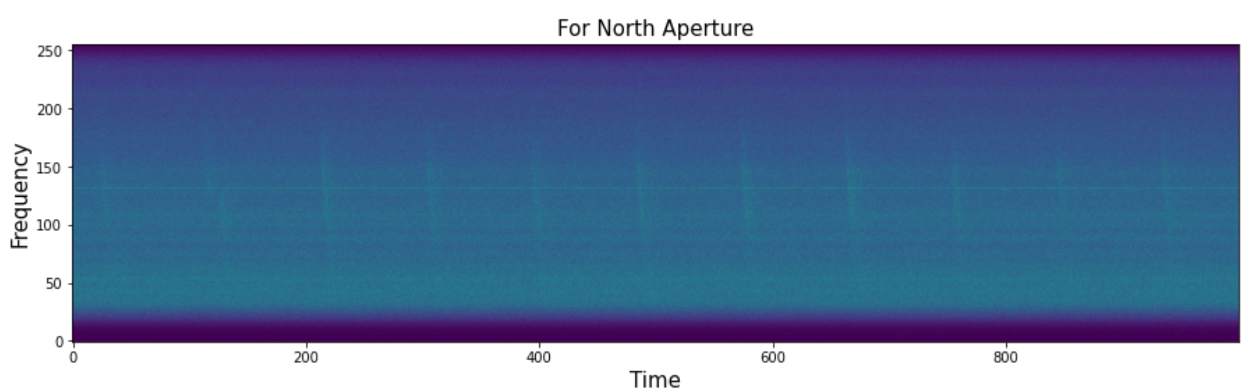


Fig. 7: Dynamic spectrum obtained for each of the apertures.

3. De-dispersion and phase folding

We first estimate the value of the dispersion measure (DM) by accounting for the delay in the frequencies of the pulse (slanted lines) seen in the dynamic spectrum. Using this estimated DM value we can find the relative time offset due to dispersion at all the frequency channels and thus correct the DM for the entire data and again plot the dynamic spectrum. (Fig. 8)



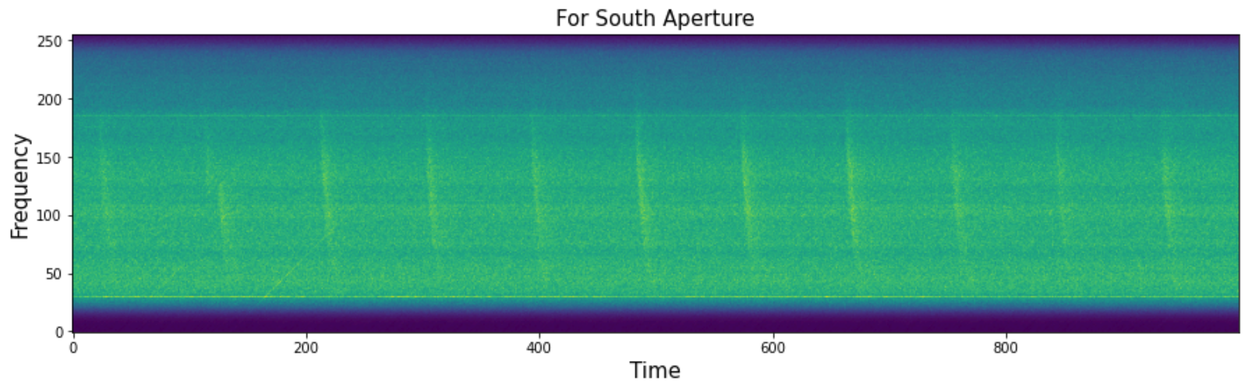


Fig. 8: De-dispersed dynamic spectrum for both apertures.

Once the dynamic spectrum is de-dispersed, it is collapsed onto the frequency axis to obtain pulses which can be studied to obtain other parameters like the period of the pulsar. (Fig. 9)
We also fold the de-dispersed dynamic spectrum over the time axis with the pulsar period estimated above and plot the integrated pulse profile (Fig. 10).

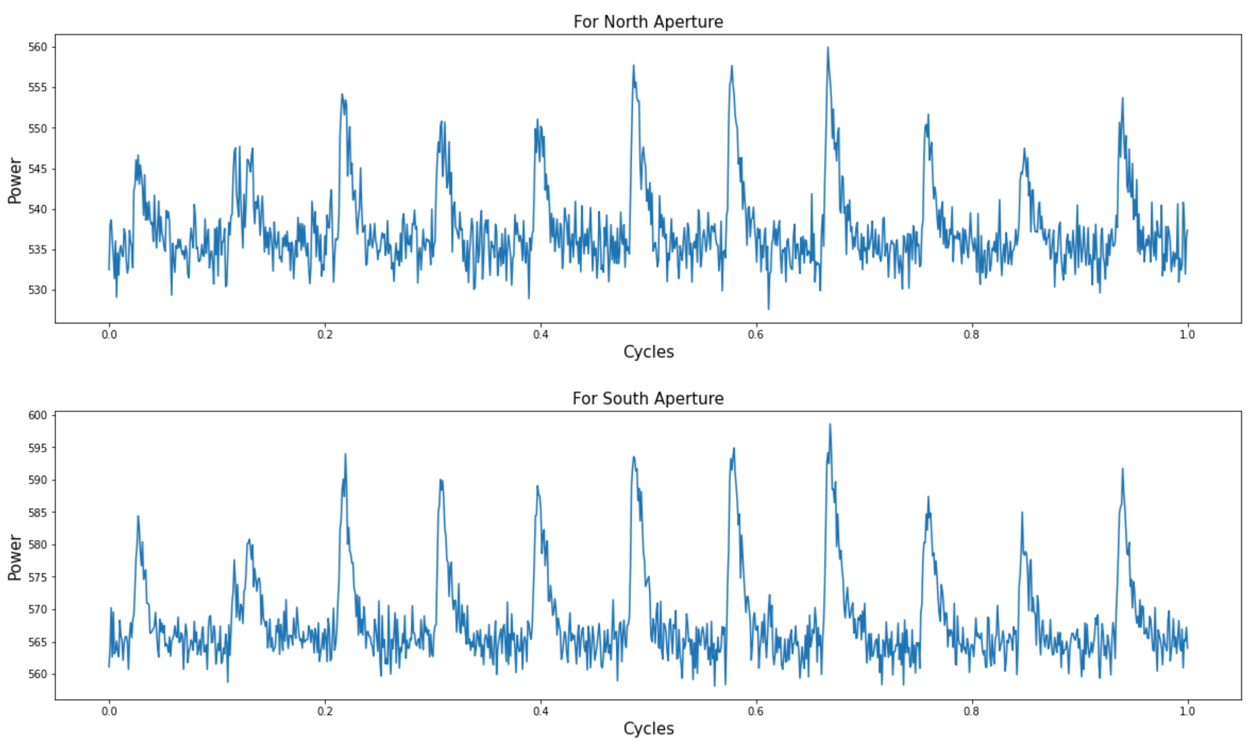


Fig. 9: Power vs time plots for the power averaged over the frequency bins.

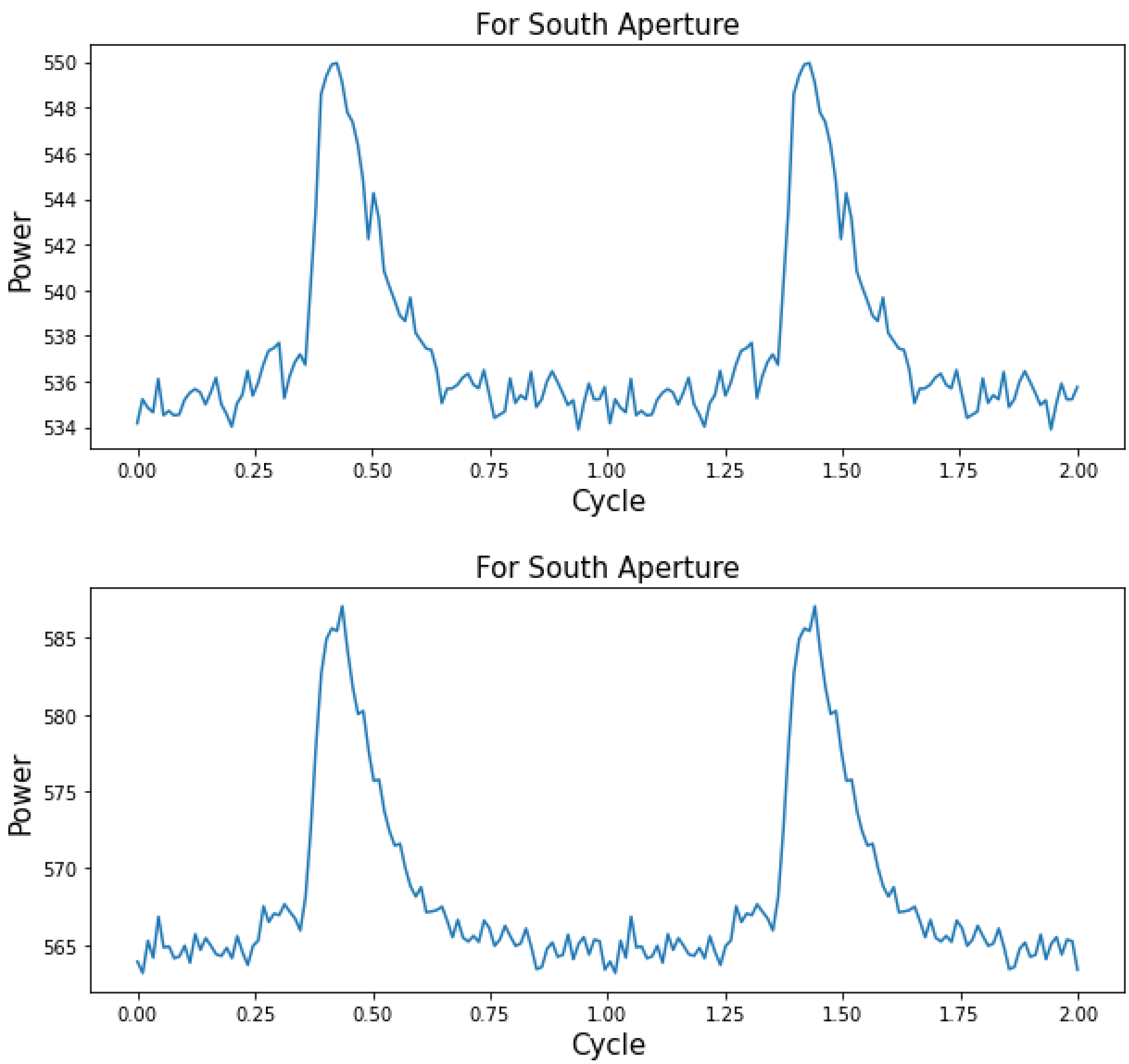


Fig. 10: Integrated pulse profile of the Vela pulsar obtained from the analysis of the data from both the apertures.

III. Discussion and Interpretation of the Graph

We obtained the dynamic spectrum for the given data as shown in Fig. 7. We can see 11 slanted streaks across the frequency band, indicating the presence of pulsar signal in the data.

For correcting the dispersion delay, we take 2 frequencies on the same streak (dispersed pulse) and find the time delay between these frequencies. Using the equation (1) we can estimate the Dispersion Measure (DM) for the pulsar.

We obtained DM = 69 $pc^{-1} cm^{3}$

Using this estimated DM value we can correct for the dispersion delay in each frequency channel. Hence we get a de-dispersed dynamic spectrum shown in Fig. 8. In this we see 11 straight lines corresponding to the pulses. Any breaks in the vertical lines are a result of wrong correction applied in that frequency bin. In our analysis we use the numpy.roll() function to correct the dispersion delays, which actually shifts the frequency bins at the end towards the start of the matrix and hence the break seen in the first 2 lines in Fig. 8 can be accounted for the same reason.

Once we collapse this spectrum on frequency axis, we see 11 peaks on the power vs time plot (Fig. 9). We can thus have a rough estimate of the time period of the pulsar.

The obtained time period of pulsar = 89 ms

Thus we fold the data around the period of the pulsar to get an integrated pulse profile. Fig. 10 shows the Integrated pulse profile plotted twice one after the other for better visualization.

IV. Result

The calculated value of DM = 69 $pc\ cm^{-3}$

Time period of the pulsar = 89 ms

Our results roughly match those obtained in the previous studies:

DM = 67.771 $pc\ cm^{-3}$

Time period = 89.32 ms

(Values from the ATNF Pulsar Catalogue [4])

V. Reference

1. Detecting a pulsar in Ooty Radio Telescope voltage data, Prakash Arumugasamy

2. Time Frequency Analysis of RF data of the Vela Pulsar received at the Ooty Radio Telescope, Pradyoth H Shandilya

3. http://astro.vaporia.com/start/dispersionmeasure.html

4. https://www.atnf.csiro.au/research/pulsar/psrcat/

VI. Contributions of group members

The python code for analysing the given data file and the report including calculations are done by Shreya Umesh Prabhu.