Detecting a pulsar in Ooty Radio Telescope voltage data

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Keywords:- Radio astronomy | Time series analysis | Radio pulsars | Magnetospheric radio emissions

Level of difficulty: 5

1. Prerequisites

To gain maximum benefit from this activity, we recommend knowledge of the following aspects of radio astronomy and pulsars:

1. A qualitative understanding of how a radio antenna works and how observing in the radio is different from observing in the optical.
2. Basic understanding of radio receiver elements such as low noise amplifiers, mixers, filters, and integrators and their effect on electrical signals.
3. Basic probability theory and statistics, including knowledge of the Gaussian distribution and the central limit theorem; basics of Fourier transforms.
4. Observational aspects of pulsar radio emission, including its coherent nature, pulsar rotation, stability, and spin-down, and the effect of interstellar dispersion.
5. Experience with file handling, data manipulation, and plotting using any programming language appropriate for data analysis.

Alternatively, we suggest that you explore and read up on these topics as you attempt the activity.

Although one can find plenty of online resources and books covering the prerequisites listed above, here are a few standard references on these topics.

- Low Frequency Radio Astronomy a.k.a. GMRT Blue Book
- J. J. Condon, SM Ransom, Essential Radio Astronomy (2016). [Online version]
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2. Aims and Objectives

The main aim of this activity is to provide hands-on experience in analyzing the rawest form of data received by a radio telescope and understanding/interpreting such signals. The data are voltage time series containing signal proportional to electric field component of the incident electromagnetic radiation received by a radio telescope, including that of astronomical origin. The activity provides simple yet non-trivial voltage data from the observations of the well-known Vela pulsar using the Ooty Radio Telescope (ORT). We will start with background reading and summarizing how radiation from an astronomical source like the Vela pulsar is recorded as voltages in a radio telescope. With this knowledge of the origin and properties of the processed antenna signal, we begin by visualizing the voltage time series and verifying whether the voltages and the power follow the expected distributions. After characterizing the distributions, we will obtain a dynamic spectrum to look for visible evidence of the pulsar signal. We will use the intrinsic pulsating nature of the pulsar signal and the dispersing effect of the Inter-Stellar Medium (ISM) to understand the observed dynamic spectrum. We will recover the Vela pulsar's integrated pulse profile and constrain the relevant pulsar parameters using de-dispersion and folding of the pulse profiles.

In summary, the plan is to accomplish the following objectives:

1. Understand how the radiation received by an antenna and the receiver elements together produce the recorded voltages?
2. Obtain the probability density distribution for voltages and power. Estimate the parameters of the distributions.
3. Obtain the integrated power spectrum and create a dynamic spectrum – intensity as a function of time and frequency.
4. Identify the pulsar signal in the dynamic spectrum and estimate the pulsar's dispersion measure and period.
5. Use de-dispersion and phase folding to recover the pulsar's integrated pulse profile.

Prompt 1: Write an introduction providing background information on the topics covered in this experiment. Finding the answers to the following questions may help you write a good introduction:

1. How are radio waves converted to electrical current in an antenna?
2. What are the various steps involved in a radio receiver that converts electrical signal and noise from the feed to the final recorded voltages?
3. Briefly describe the telescope used for obtaining the data used in this activity.
4. Describe the nature of pulsar's radio emission, the emission region, and the spectral/temporal properties of the observed signal.
5. How are radio signals affected by the ISM? How is the effect of ISM dispersion quantified?

3. Methods

Description of the data: The data contains raw voltage time series from the Ooty Radio telescope (ORT) — North and South apertures. Raw voltages are recorded at the receiver end and are not calibrated or further processed by any software processing pipeline. 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. The data sampled at the Nyquist rate (See Nyquist-Shannon sampling theorem*) contains two real-valued voltage measurements in a period corresponding to the maximum variability timescale (equal to the inverse of the frequency bandwidth). Hence, the sampling time resolution

$$\delta t = \left(\frac{1}{2 \times 16.5\,\text{MHz}}\right) \approx 30.30\,\text{nanoseconds} \qquad [1]$$

The data spans approximately 1 second.

Description of the data files: There are four separate data files with identical observation parameters. The data files are header-less (numerical data only without any descriptive text or observation parameters) in ASCII format. The files contain two columns of integer values separated by a space, corresponding to voltages from the north (in column 1) and south (in column 2) apertures.
Download any one of the following files from the repository at http://hdl.handle.net/11007/4565 for analysis:

- Data file 1: ch00_B0833-45_20150612_191438_011_1.txt
- Data file 2: ch00_B0833-45_20150612_191438_011_2.txt
- Data file 3: ch00_B0833-45_20150612_191438_011_3.txt
- Data file 4: ch00_B0833-45_20150612_191438_011_4.txt

Examining the properties of the voltage data: First, we will examine the statistical distribution of the voltage data. The purpose of a radiometer is to measure the electrical signal proportional to the electric field incident on an antenna. The voltage in the receiver is a combination of predominantly the system noise and signal due to the astronomical source of interest. Hence, understanding the statistical properties of the noise is essential to estimate the receiver's sensitivity and identify source contribution over the system noise. The receiver noise is a combination of noise introduced by various electronic/electrical components that are also amplified along with the signal to produce the final receiver voltages. The signal received from astronomical sources is an incoherent sum of many coherently/incoherently emitting regions within the source region. 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† (1). Therefore, the voltages from system noise and the observed signal both follow Gaussian statistics.

The associated power is proportional to the modulus square of the voltages ($P \propto |V|^2$). If only the real part of the voltage is sampled, the Nyquist sampling rate will be $2\Delta\nu$, which is twice the bandwidth $\Delta\nu$. In such a case, the power P follows a distribution of the form $\sim e^{-P}/\sqrt{P}$ (See Appendix B.6 in 2). The distribution mean (mean power $\langle P \rangle$) then equals to the variance of the voltages and the standard deviation (Root-Mean-Squared deviation in power) is equal to $\sqrt{2}$ times the mean power. On averaging the Nyquist-sampled power over some time, τ, the noise power fluctuations (σ_n) reduce by a factor $1/\sqrt{N}$, where $N = 2\Delta\nu\,\tau$ is the number of samples averaged, and thus $\sigma_n = \sqrt{2}\langle P \rangle/\sqrt{(2\Delta\nu\,\tau)} = \langle P \rangle/\sqrt{(\Delta\nu\,\tau)}$

Alternatively, and in general, V is complex, where the real and imaginary parts both follow Gaussian statistics and the Nyquist rate then is equal to $\Delta\nu$. Such is the case even when we consider real-valued data (say, over M samples) that is Fourier analyzed to obtain complex voltage contributions across $M/2$ independent spectral channels. Here, the power P follows an exponential distribution of the form $\sim e^{(-P/\langle P \rangle)}$. The distribution mean

* https://en.wikipedia.org/wiki/Nyquist–Shannon_sampling_theorem
† https://gregorygundersen.com/blog/2019/02/01/clt/

then equals to the sum of the variance of the real and imaginary voltage components, and the standard deviation equals to the mean power. Again, on averaging the Nyquist-sampled power over some time τ, σ_n reduce by a factor $1/\sqrt{N}$, but here $N = \Delta\nu\,\tau$ is the number of samples averaged, and thus $\sigma_n = \langle P\rangle/\sqrt{(\Delta\nu\tau)}$ The power $\langle P\rangle$ to be used in the estimation of the RMS noise fluctuation σ_n refers to the total system noise power P_{sys}.

These properties of the distribution of noise power are central to the radiometer equation. The radiometer equation quantifies a telescope's sensitivity by comparing source power against the system noise fluctuations to give the Signal to Noise Ratio (SNR). For source power P_{src} and system noise power P_{sys}, the SNR can be estimated from the following ideal radiometer equation:

$$\frac{S}{N} = \frac{P_{\text{src}}}{P_{\text{sys}}}\sqrt{\Delta\nu\,\tau} \qquad [2]$$

In practice, the expression needs modifications to account for gain fluctuations, and the ideal estimates can deviate from observed sensitivity due to radio frequency interference.

We will look at voltage and power distributions in our data and characterize the noise. We can simulate power distribution from complex voltage measurements by treating successive pairs of real voltages as components of complex voltages. The power time series is obtained by pair-wise addition of squared voltages within a time-intervals equal to inverse bandwidth (Nyquist rate). The power distribution will now follow an exponential function with distribution mean equal to the standard deviation.

Obtaining the power spectrum and the dynamic spectrum The signal properties can also be examined in the frequency domain at fine spectral resolution, and in fact a path essential for (a) enabling proper processing of dispersed pulses, (b) accounting for non-uniformity, if any, in the receiver gain over the observed frequency range, and (c) identifying and excising spectral regions affected by radio frequency interference. The amplitude and phase of the frequency components constituting the observed voltage time series are decoded via Fourier transforms. The output in terms of complex voltage in each of the narrow spectral channels is modulus-squared to obtain the power spectrum. The power estimate in any spectral channel seen from the raw individual spectra varies significantly and randomly about the mean intensity, following an exponential distribution (for which the standard deviation is equal to the mean value that we are after). However, a suitably integrated spectrum obtained by combining consecutive spectra can reduce the noise fluctuations.

Modern receivers employ either digital devices for performing real-time (online) Fourier transforms, power estimation and integration, to directly produce and record the power spectrum, or record the raw voltage data directly to enable flexible off-line processing in software. Our data are the latter type, that is time sequences of raw voltage, and we will use Fourier transforms in software processing to obtain the power spectrum. A time series of power spectra, or the so-called dynamic spectrum, shows the variation of the spectrum with time. Variable sources can benefit from a simultaneous examination of both spectral and time information. Such observations require high time-resolution recording (i.e., short time integration) and the observation span to be larger than the variability timescale to capture the source variability information.

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. For pulsar signals, interstellar dispersion can produce significant relative delays within the frequency band, and choosing a large number of frequency channels can better correct these delays. Similarly, a large number of time bins can better capture the narrow profile shapes. However, data distributed over many spectral and time bins can reduce the signal to noise to below detection limits. The best contrast (SNR) is obtained when time resolution is comparable to the pulse width. However, one may require higher resolution to study the details within the pulse, by correspondingly sacrificing SNR. The apparent pulse width itself is a combination of the intrinsic pulse width and the (uncompensated) dispersion smearing within a narrow spectral channel. Thus the best time resolution with a given setup and dispersion is achieved (3)[‡] when the dispersion smearing within the narrow spectral channel equals the time-width, which is inverse of bandwidth of the channel (this latter being the

[‡] "A report on the front-end of the pulsar instrumentation for GMRT": .doc, .ps

unavoidable intrinsic limit to time resolution). 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. The dynamic spectrum is also helpful in identifying and removing narrow-band intermittent radio frequency interference (RFI), allowing fine-grained control over improving the SNR.

De-dispersion and phase folding Our goal is to detect the pulsar and obtain its pulse profile. The dynamic spectral data must be de-dispersed and folded with the pulsar period to obtain a high SNR pulse profile. De-dispersion attempts to undo the dispersion delays introduced by the interstellar medium under the assumptions (i) that the pulses across frequencies are emitted simultaneously at the source and (ii) the dispersion relation corresponds to that of a cold ionized medium. You may research and determine the limits of validity for these assumptions. In cold ionozed medium, a signal at frequency ν, is delayed by

$$\Delta t \approx 4.149 \times 10^3 \left(\frac{\text{DM}}{\text{pc cm}^{-3}}\right) \left(\frac{\nu}{\text{MHz}}\right)^{-2} \text{ seconds} \qquad [3]$$

relative to a non-dispersed (infinite-frequency) signal emitted at the same time from the source. In the above expression, DM is the 'dispersion measure' defined as the column density of electrons, which is equal to the integral of the electron density over the line-of-sight distance to the source. The pulse delay measured between a pair of frequencies from the dynamic spectrum can be used to invert Equation 3 and estimate the pulsar's dispersion measure. Then the DM estimate is used to calculate the delays for each frequency channel relative to an arbitrary reference frequency within the band (chosen to be the center frequency or the highest frequency). Finally, all the time series are offset in time by appropriate amounts, compensating for the relative dispersion delays to align the pulses across frequencies.

The de-dispersed dynamic spectrum will have repeating, aligned pulses. The periodicity reflects the pulsar period, roughly estimated from the separation between pulses in the dynamic spectrum. A more accurate period can be measured from the peak to peak pulse separation in a de-dispersed, frequency integrated time series obtained by integrating (co-adding) the de-dispersed dynamic spectrum along the frequency axis. Folding is the process of aligning and combining the pulses repeating in time to produce a single integrated pulse profile. It involves selecting a zero phase reference (usually arbitrary) and assigning phase to the time series data using the period estimate. A time series t_i having a periodicity P will be assigned phases $\phi_i =$ fractional part$(t_i - t_0)/P$, where the zero phase reference t_0 may be chosen as the first time sample for simplicity. Note that if t_0 is later than the first time sample, then the phase will be $\phi_i = 1 -$ fractional part$\{(t_i - t_0)/P\}$ for times preceding t_0. An integrated pulsar pulse profile with 'N' bins in the $0-1$ phase range, i.e., across one period, can now be obtained by adding the intensity contributions from these phase-assigned pulses to the integrated profile phase bins.

4. Procedure

Perform the following tasks to achieve the goals of this activity.

Task 1 – Plot and visualize the voltage time series from the two antennas. Include $1-2$ plots in the report with appropriately chosen time ranges to best show the voltage variability. See Figure 1 for some schematic plots[§].
You may use any programming language or software for plotting. Choose the first voltage sample as zero time reference or zero time reference plus the sampling interval and assign a time coordinate to the X-axis. The Y-axis voltages can remain in arbitrary units.

Task 2 – Plot the voltage amplitude distribution for the two antennas and calculate the mean and standard deviation of the probability density function (PDF).
Obtain the distribution of the observed voltage data by plotting a histogram. Calculate the mean and standard deviation of the north and south antennae voltage samples using the standard formulae. Use

[§] Ensure that your plots have proper axes ticks, labels, and units.

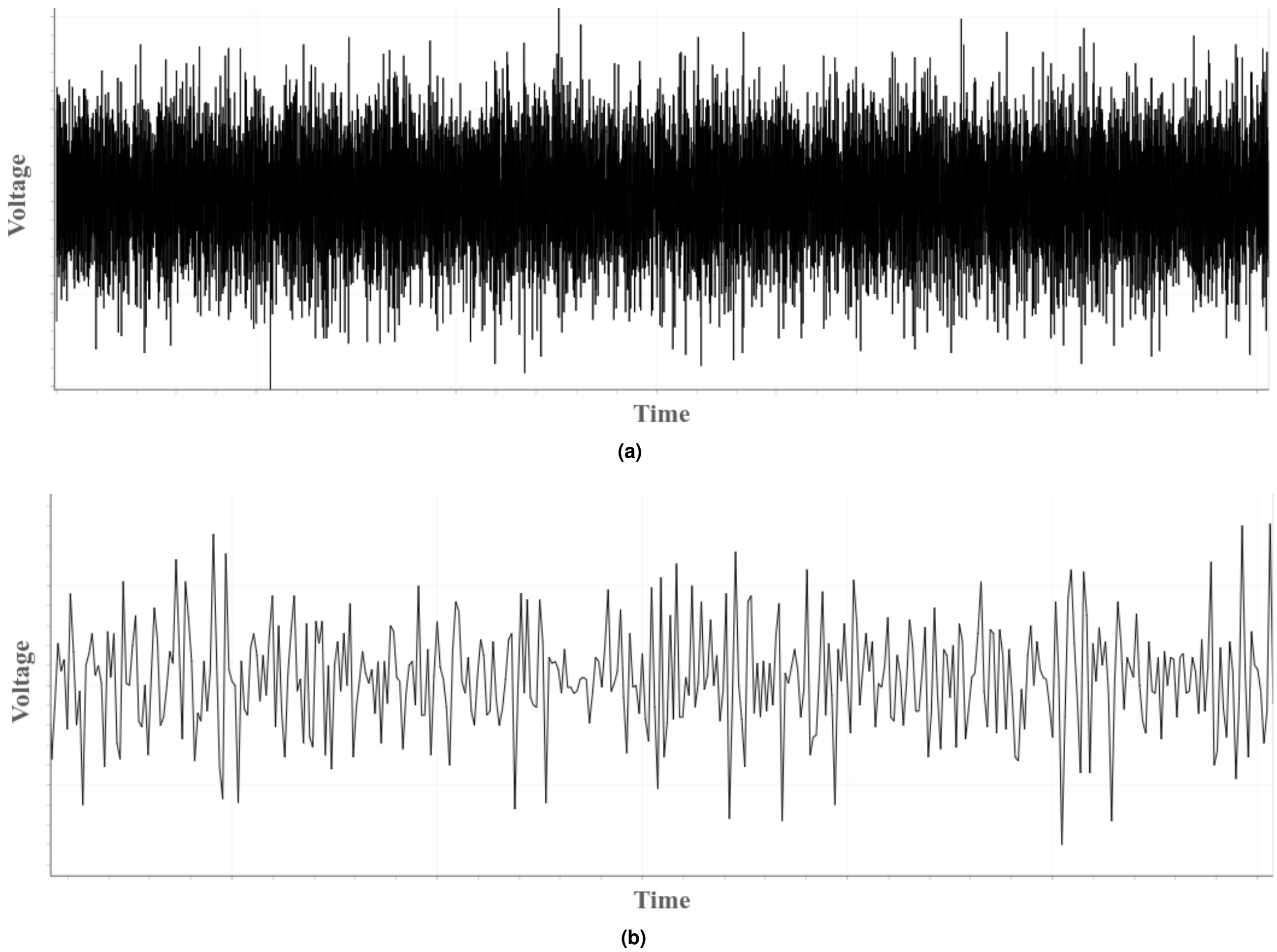


Figure 1. (a) A schematic plot of a voltage time series over an extended time span. (b) A zoomed-in section of the voltage time series showing the fluctuations.

the calculated mean and standard deviation to plot a Gaussian probability density function curve over the histogram. The PDF curve may require appropriate scaling to match the histogram. Mention the formulae used to obtain the distribution parameters, provide the estimated values, and mark those in the plots. See schematic plot in Figure 2.

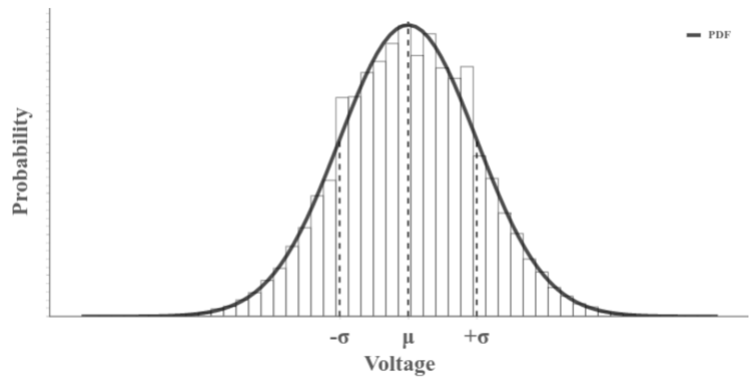


Figure 2. A schematic diagram showing histogram of voltages from a radio receiver with the Gaussian probability density function overlaid. The distribution mean and standard deviation are also marked.

Task 3 – Obtain the (uncalibrated) power from the voltages. Plot the power time series and the power distribution and estimate the parameters characterizing the probability density function.
Calculate the electrical power by squaring the voltages and adding successive pairs together. Obtain the distribution of the power by plotting a histogram. Calculate the mean and standard deviation of the north and south antennae voltage samples using the standard formulae. Determine the functional form of the distribution followed by the power. Use the calculated mean and standard deviation to plot a probability density function curve over the histogram. The PDF curve might require appropriate scaling to match the histogram. Mention the formulae used to obtain the distribution parameters, provide the estimated values, and mark those in the plots. See schematic plots in Figure 3.

Task 4 – Power spectrum: Use discrete Fast Fourier Transform (FFT) to determine the power distribution across the various frequencies in the signal bandwidth.
We will use Fourier transform to analyze the spectral content (amplitude distribution over the constituent frequencies) of the time-varying voltage signal.

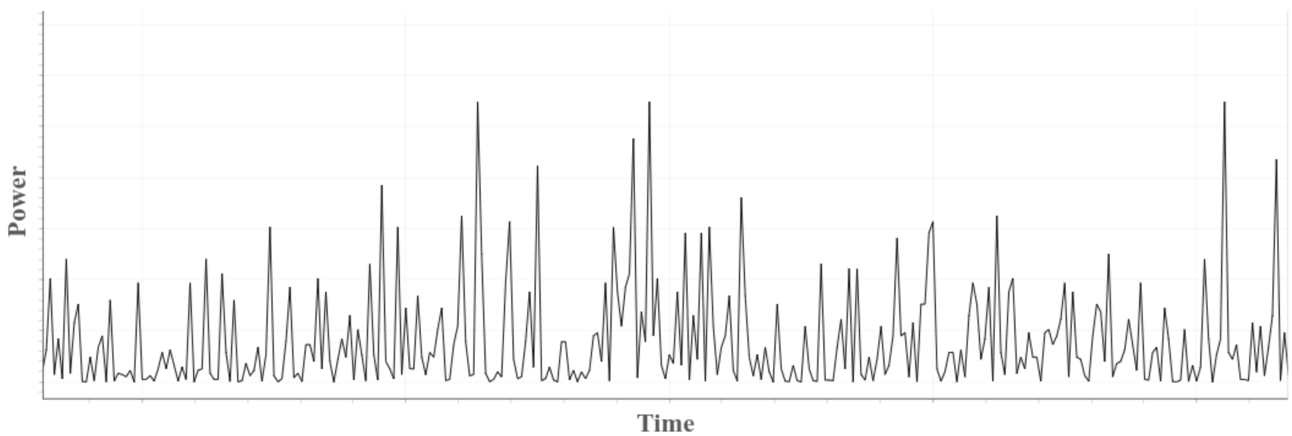
Step i – Choose an appropriate number of bins (N_f) for dividing the signal's total bandwidth of 16.5 MHz. An N-point FFT works considerably faster if the number of data points (N) is a power of 2 (E.g., 2^3, 2^4, ..., 64, 128, 256, 512, and so on.). Remember that there is a trade-off between frequency resolution and SNR in each bin.

Step ii – Fourier transforms convert N complex-valued or 2N real-valued voltages to N frequency amplitude-phase pairs[¶]. Since our data are real-valued, $N = 2 \times N_f$ voltage samples are required to produce a spectrum with a frequency resolution of $16.5/N_f$ MHz.

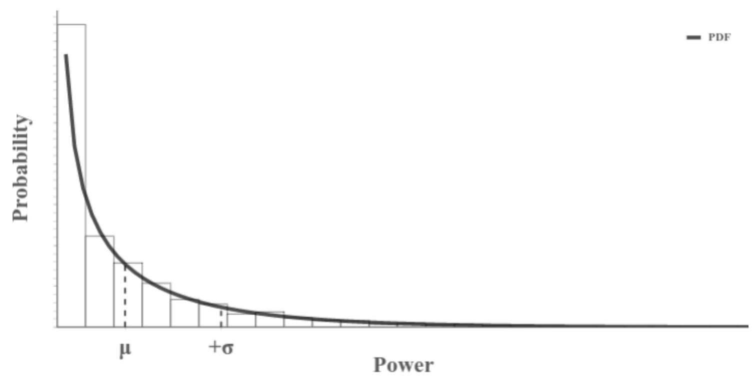
Step iii – Each spectrum now corresponds to a time span $T_{\text{fft}} = 2 \times N_f \times dt$, where, dt is the sampling time interval. The size of this spectral time bin must be smaller than the variability time scale of interest (E.g., expected period of the pulsar). Calculate the number of spectra available in the 1-second data.

Step iv – Modulus-square the Fourier transform output, which is complex in general, to obtain the power spectrum. An average power spectrum is obtained by averaging these power spectra. Plot the averaged power spectrum over the observed radio frequency range (See schematic in Figure 4).

[¶]N-point FFT gives N Fourier components. If the array to be FT-ed is real, the transform is Hermitian symmetric, rendering redundant information over one half, where N/2 complex contribution on one side are complex conjugates of the other half. If the array to be FT-ed is complex, the transform, in general, has no redundancy, and all N bins in the Fourier domain will be defining the spectrum.



(a)



(b)

Figure 3. (a) A schematic diagram showing the power time series. (b) Histogram of power values from a radio receiver with the probability density function overlaid. The distribution mean and standard deviation are also marked.

List the following parameters:

- Total bandwidth of signal, $df =$
- Time-resolution of voltage sampling, $dt =$
- Chosen number of frequency bins, $N_f =$
- Number of voltage samples to obtain FFT, $N_{\mathsf{FFT}} =$
- Number of spectra obtained through the $N_{\mathsf{FFT}}-$point FFT, $N_S =$
- Time-resolution of the spectral series, $dt_S =$

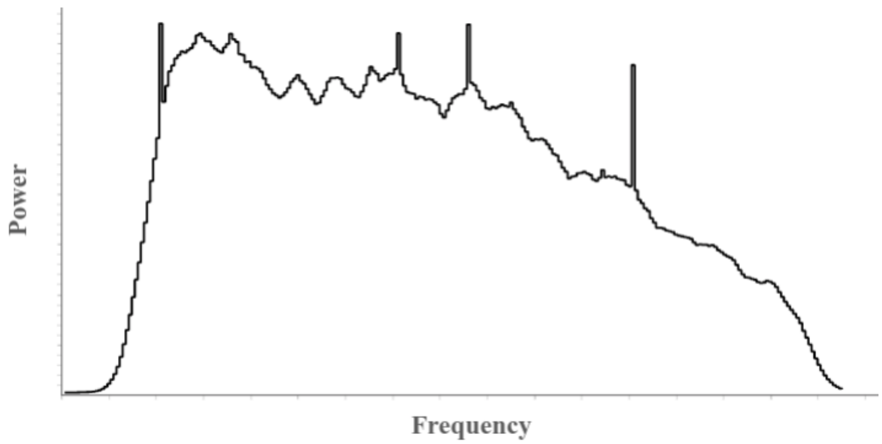


Figure 4. A schematic diagram showing the averaged power spectrum.

Important note:- The recorded spectra may get flipped in a few cases depending on how the signal is processed in the receiver. It may be easy to identify such a flip if the gains at different frequencies are known. In our case, we can use the properties of the pulsar signal to identify any spectral flip. The dispersed signal from the pulsar should be visible in the dynamic spectrum produced in the next step. If the spectrum is flipped, the dispersion pattern will be reversed, with the pulses at higher frequencies appearing delayed relative to those at lower frequencies. In such cases, the power spectra and the dynamic spectrum must be flipped along the frequency axis.

Task 5 – Construct a time-series of power spectra which is referred to as the dynamic spectrum.
The dynamic spectrum shows time variability of the power spectrum (See schematic plot in Figure 5). Use a 'heat-map' plot to show the color-coded power values over a two-dimensional grid of time (N_S bins of size dt_S) versus frequency (N_f bins over the RF range). Typically, the time is plotted along the X-axis and frequency along the Y-axis for such a plot. At this stage, if the number of spectra is large, sets of consecutive spectra can be co-added, provided the size of the combined time interval is still smaller than the time scale of interest. Combining spectral bins improves the SNR at the expense of time-resolution but only up to an integration time equal to the pulse width. For instance, if our time scale of interest, say the expected period of the pulsar is close to 100 milliseconds, and the original spectral bin is 10s of microseconds, then 100s of spectra added together will result in a time-resolution of 1 millisecond which is a 100 times lower than the pulsar period.

Task 6 – Identify the pulsar signal through its dispersion pattern and periodicity and estimate rough period and dispersion measure from the dynamic spectrum plot.
The pulsar signal will be distinctly identifiable as periodically repeating, dispersed narrow streaks against the background noise for a range of appropriate time and frequency resolutions. In addition, there might be vertical or horizontal streaks of enhanced intensity manifesting RFI that is short-duration but broadband or

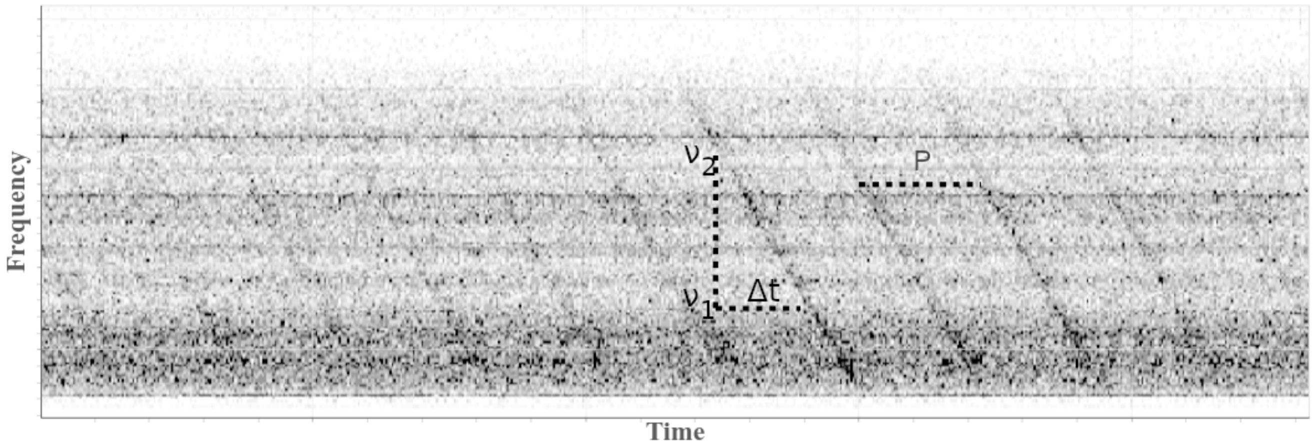


Figure 5. A schematic dynamic spectrum with pulsar signal showing how to roughly measure DM and period.

persistent but narrow-band, respectively. The RFI is often traceable to artificial sources of electromagnetic radiation, including some electrical systems. As introduced earlier, the dispersion of an astronomical signal will introduce frequency-dependent delays during propagation through the interstellar medium. Identify a pair of frequencies and crudely measure the approximate relative delay between the signals at these two frequencies from the dynamic spectrum. From the pair of frequencies and the signal delay, roughly estimate the dispersion measure for the pulsar. To determine the rough period, measure the separation between streaks along any single frequency bin of the dynamic spectrum.

Task 7 – De-disperse the dynamic spectrum, integrate the contribution across frequency to get a de-dispersed time sequence, and then fold the time-series with the pulsar period to obtain a folded pulse profile.
The dispersive effect on the pulsar signal can be corrected using the pulsar's dispersion measure. The correction aims to make the 'curved streaks' (pulsar signal) straight and vertical in the dynamic spectrum.

Pick a central frequency bin for reference (zero delay). Using the rough dispersion measure estimated above, estimate the relative time offset due to dispersion at all other frequency bins. Suppose we view the dynamic spectra as rows of different time series. In that case, the time-series above and below the central frequency needs to be delayed and advanced using the relative time-offsets estimated above to align simultaneously emitted broadband signals along a single time bin.

One can collapse (spectrally average) the de-dispersed dynamic spectrum along the frequency axis to obtain the series of pulsar pulses useful for single pulse studies. Alternatively, the de-dispersed dynamic spectrum is folded over the time axis with the pulsar period to obtain integrated pulse profiles for various frequency bins. We will spectrally average the de-dispersed dynamic spectrum to obtain the series of single pulses and then fold it with the approximate pulsar period determined above. A schematic for the integrated pulsar pulse profile is shown in Figure 6. The profile over the rotational phase $0-1$ is repeated over the $1-2$ phase range for clarity. A stable, characteristic pulse profile of a pulsar requires the addition of typically 1000s of individual pulses. Hence, an integrated pulse profile obtained with a small number of pulses may have significant deviations from the characteristic pulse profile of the pulsar. Nevertheless, if the individual pulses do not vary significantly, they can provide reliable DM and period measurements.

Prompt 2: State your results, including the issues you faced in the analyses and tasks you could not complete. Discuss the implications of those results in the context of radio observations and astrophysical source properties. The following pointers could help you write this section.

1. What are your thoughts on the voltage data you visualized and worked on regarding what it represents?

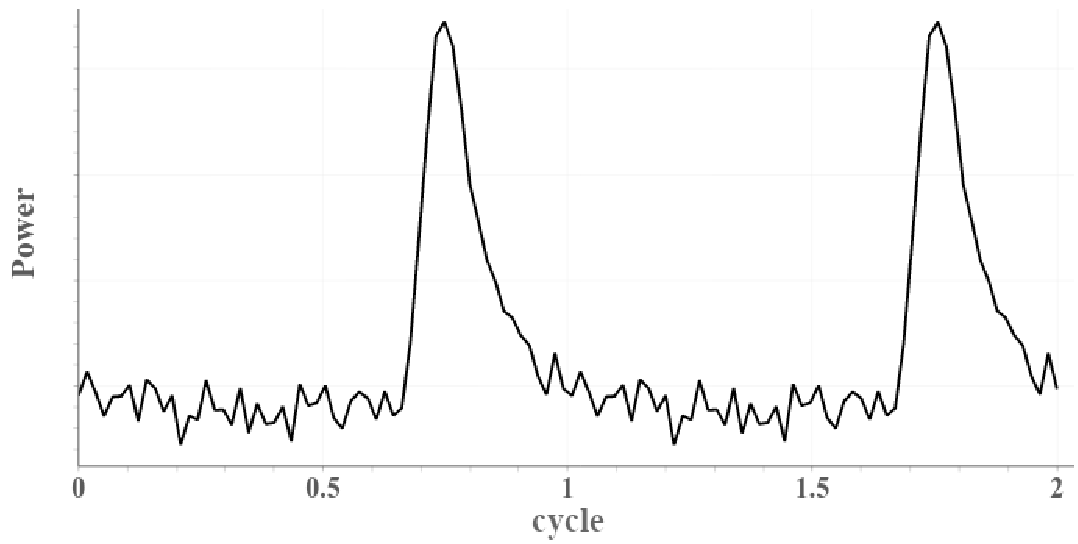


Figure 6. A schematic of the integrated pulse profile for the Vela pulsar. The pulse over a rotational period is repeated for clarity.

2. List the parameters estimated from the voltage and power distributions and draw inferences about the noise characteristics, including how they follow/deviate from the expected behavior.
3. Describe the averaged power spectrum and its main features.
4. Describe the features observed in the dynamic spectrum, any source signals, or radio frequency interference that you observe. Relate these to what you know about the source signal and RFI.
5. How did you estimate the pulsar's dispersion measure and period? Include the formula used and the process details.
6. What are some of the noticeable features in the pulsar's integrated pulse profile? Identify the source of power in on-pulse and off-pulse regions. How does the integrated profile confirms/contradict what you know about pulsar's radio emission?
7. Compare your results with already known properties of the pulsar.

5. Future work

The worksheet is designed to help beginners take the first few crucial steps in understanding and working with radio data. It does not attempt to exhaust all the analysis possibilities with the data. We encourage the discerning learner to follow their lines of inquiry beyond this point, a few of which are outlined here:

- How would you improve the accuracy of the DM and period values? How would you assign uncertainties?
- Is the integrated profile symmetric? If not, research the reason for the observed asymmetry. How can one model this phenomenon, and are any corrections to the pulse profile feasible?

Acknowledgments

The data sets used for this experiment are time sequences of raw voltage, each of 1 second duration, drawn from a much longer observation in the direction of the Vela pulsar made with the Ooty Radio Telescope (4) using a Miniaturised Portable Dual-Channel Receiver (5)[‖] developed at the Raman Research Institute (RRI), Bangalore. This particular observation over a few tens of minutes was made during the 2015 edition of the CHERA: Camp for Hands-on Experience in Radio Astronomy, conducted jointly by RRI and the Radio Astronomy Centre (NCRA/TIFR) at Ooty. The concept of the experiment, the basic tasks, the data, and the overall execution of the experimental activity were already developed in 2015, and has since being extensively used; first time as a part of assignments for graduate students, and more routinely as one of the instructive hands-on activities in data analysis at RRI for students interested in the radio astronomy and pulsars, in general, and in the SWAN project, in particular. The Teaching Learning Centre of IUCAA introduced this as one of the experimental activities during the Radio Astronomy Winter School (first time during RAWS 2020) organized jointly by TLC-IUCAA and NCRA.

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