Pulsar Detection System using Radio Telescope

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Abstract**:** ***Radio astronomers and researchers have detected numerous neutron stars in our galaxy, and they also predicted the existence of many more neutron stars in space. Pulsars are very peculiar, yet almost inscrutable celestial objects. This is an object which is impelling radiation into space closest to the speed of light. Neutron stars are the most interesting galactic bodies to mankind. The objective of this research work is to develop the intelligent system to detect the Pulsar. The fascinating properties of pulsar i.e. high density, a small diameter, strong gravity, and strong magnetic field are the main motivation behind the research work. Pulsars are distant objects with peculiar properties and the extreme nature, which enabled to draw the attention of Astronomers. The detection of Pulsar is a very tedious job. The radiations coming from pulsar are detected by the proposed system which consists of an antenna, filters, amplifiers, and receiver. The signal capture through the antenna is processed to extract the signal of importance buried in noise. The fast-folding algorithm (FFA) and Fast Fourier transform (FFT) techniques are proposed to detect the pulse signal from raw signal collected by antenna. The antenna design is also discussed in detail.***

Keywords**: Pulsar detection, antenna design, software radio, PSD.**

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I. INTRODUCTION

Solar system, galaxies, neutron stars, black holes, nebulae and all the elements which comprise universe, have been a topic of great interest in the research world of astronomy for many years. Their exploration is going on since then. Among them Neutron Stars rather special case of Neutron Stars i. e. Pulsars have been eye-catching in the field of radio astronomy to both professionals and amateurs.

This research work primarily focuses on the successful detection of a pulsar. The aim is to design a pulsar detection system at an affordable cost.

The proposed system consists of a high gain antenna, amplifiers, filter, and a receiver. The project is based on the basics of antenna theory which will be used while designing the antenna. RF electronics play an important role while calculating performance parameters of the system such as Noise Figure (NF), sensitivity and SNR. Signal processing is the heart of this project and it plays a crucial role in the detection of pulsar because the power of the signal is very low.

II. BACKGROUND

Hydrogen fuses at the core of stars to produce helium and tremendous amounts of energy is released in the process. A delicate balance of pressure and gravity sustains the star. After the hydrogen is exhausted, the internal pressure reduces and allows gravity to compress the star. This process continues until atomic forces balance out the gravitational forces. Such stars are called white dwarfs. If the gravitational force is greater than the atomic forces, then nuclear forces may be able to sustain the gravitational collapse. In such cases the only subatomic particles that are left are neutrons. Hence such stars are called neutron stars. A further gravitational collapse will lead to the formation of a black hole.

The neutron star has an extremely strong gravitational and magnetic field reaching up to 10^{15} gauss. [1] They are compact objects with a diameter of about 10 Km and a mass of about 1.35 MSN. The rotation period of the pulsar can reach milliseconds, which is highly predictable. These properties make pulsar an important object for studying interstellar medium, gravitational waves, etc.

Walter Baade and Fritz Zwicky predicted the existence of pulsars in 1934. They were not detected until 1967 by Jocelyn Bell Burnell and Antony Hewish (1965 Nobel Award). They observed periodic pulses in their radio telescope array which could be explained only by a compact object like a neutron star. In 1974, Joseph Taylor and Russell Hulse were awarded the Nobel Prize in physics for their discovery of gravitational waves using radio observation of a binary pulsar.

After the first successful detection, radio waves emanating from the Milky Way Galaxy. Karl Jansky becomes one of the founding figures of **Antenna theory and Radio Astronomy.**

The parabolic reflector antennas are analogous to the parabolic reflectors which are made using mirrors in an optical system. According to the study of John D. Kraus another type of reflector, [2] which from a practical and effective system consist of two conducting sheets which are connected at certain angle to form a corner and the attachment should be electrically conductive, this system is termed as Corner Reflector Antenna. This antenna is particularly suitable for high frequencies (HF) where dimensions are feasible to build. There is another type of Corner Reflector i.e. 3D Corner reflector antenna. According to the study of Dragouslav Dobričić (YU1AW) structure of a 3D Corner reflector antenna concentrates electromagnetic energy in a relatively narrow beam, whose direction is the same as that of the main diagonal of the cube. Under angle 45 degrees between beams and all reflector surfaces.

A. Noise

As the power of the received signal is very low, the signal would be drowned in the noise. In this signal the noise contributing sources include thermal radiations from earth and sky, cosmic background noise, and random thermal processes in the receiving system. The figure of merit for noise produced by an antenna is often called antenna temperature. It is not the physical temperature rather it's the measure of noise being produced by the antenna. The antenna temperature of our receiving system is to be less.

The signal traveling in between the source and earth, travels through the interstellar medium. This interstellar medium is non-homogeneous throughout its journey. There are some points where the signal encounters some ionized gases or tenuous plasma. This non-homogeneity over some distance leads to some effects on the pulsar radio signal. The pulse delay is given as follows:

$$t_d = K.(DM) . \left[\frac{1}{f_1^2} - \frac{1}{f_2^2}\right] \quad (1)$$

Where, DM = Dispersion Measure of Pulsar at observing frequency

f_1= lower frequency components

f_2= higher frequency components

K= 4.149 x 10^6

B. Dispersion of pulses

As we know the speed of propagation through free space is dependent on the frequency of the wave, so ISM accounted above, at some places due to plasma, low-frequency waves travel slowly conversely, high-frequency components travel faster even they reach almost speed of light. the difference between two travel times of two frequency 'f_L' and 'f_H' is given by the formula. [3]

$$t_d = K.(DM) . \left[\frac{1}{f_L^2} - \frac{1}{f_H^2}\right] \quad (2)$$

Interstellar dispersion degrades the time resolution of the pulsar signal, as well as broadens the pulse giving it an exponentially decaying tail. This effect of dispersion is dependent on the bandwidth of the receiver as well. In our case PSR B0329+54 for bandwidth of 2Mhz, the dispersion measure is around 26.76 pc cm^{-3}, but if the bandwidth of the receiver is 1400Mhz then there is no dispersion seen. Thus while doing the pulsar detection one should carefully handle the situation of dispersion for the proper reconstruction of the pulse. the process of elimination of dispersion is known as De-dispersion

Scintillation is an effect caused by the scattering of the radiation caused by the random fluctuations in electron density in interstellar plasma. A detailed study of scintillation effects can be useful to know the valuable information of interstellar plasmatic medium; we can locate the medium as well as know its extent in terms of mean electron density

III. SYSTEM DETAILS

A. Project Specifications

- ***Pulsar***

Future prospects in pulsar observations are directed towards the direct detection of gravitational waves. Two major worldwide collaborations, which India is a part of, are the Laser-Interferometer Gravitational-Wave Observatory (LIGO) and the Pulsar Timing Array (PTA). LIGO detected a merger signal from binary pulsars in 2019, which was then observed by several observatories in various bands of the electromagnetic spectrum. This discovery led to the confirmation of the formation of heavy elements like gold, platinum, etc, in these kinds of events. The PTA will be used to observe several pulsars and extract the gravitational wave signal from these observations.

- ***Frequency:***

We have selected is 408MHz frequency for observation. The ratio of pulsar signal strength and galactic background noise is optimum for detection at 408 MHz and the Pulsar which we are focusing i.e. PSR B0329+54 is brighter at this frequency. Based on the availability of the precise components and SNR of the system we have finalized our frequency to 408 MHz and constructed an antenna and signal processing system considering this frequency.

- ***Estimated SNR for the system:***

The Pulsar which we have selected for the observations is **PSR B0329+54**, as this Pulsar is more suitable for observations in our location.

S_{av}= Average Flux of source= 1.5Jy

A_{eff}= Effective aperture= 0.6 m^2

K= Boltzmann Constant= 1.38*10^{-23} J/K

T_{sys}= System temperature= 200K

P=Pulse period= 0.714sec

W=Width of pulse= 6.6 * 10^{-3} sec

B=Bandwidth=2*10^6 Hz

τ_s=Integration time=7200sec

N_p=Number of Polarizations =1

$$SNR_{Avg} = \frac{S_{av} A_{eff}}{k T_{sys}} \frac{P}{W} \sqrt{B \tau_s} \sqrt{N_P} \qquad (3)$$

SNR$_{(best\ case)}$=10.2 dB

SNR$_{(worst\ case)}$= 8.7 dB

Note:

i) *The values used in the above calculation are all approximate or some of them are assumed to be the worst case.*

ii) *The above results are calculated using the Pulsar Radiometer equation calculator from the **Neutron Star group.***

B. Block diagram

- ***Radio Telescope***

The radio telescope will consist of an antenna, amplifiers, filters, and a receiver as shown in figure 1. These are discussed in the following sections. The system is designed to detect the strongest pulsars known to us, namely, B0833-45 (5000 mJy at 400 MHz), B0329+54 (1500 mJy at 400 MHz), and B1749-28 (1100 mJy at 400 MHz).

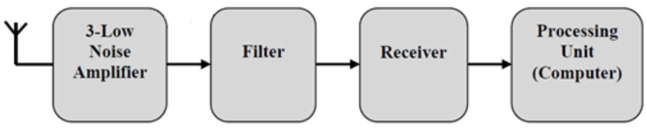

Fig. 1. Block Diagram of System

- ***Antenna***

The antenna gain required for the detection is about 15 to 20 dBi. The antenna should have low sidelobe power as it may cover the noise produced from the ground and the Antenna should follow impedance matching parameter. Yagi-Uda Antenna, Corner reflector Antenna, and Helical antenna were explored for their characteristics and feasibility of construction. Yagi-Uda antenna is having maximum directivity but the sidelobe power is quite higher which can decrease SNR. As well as the helical antenna has a higher value of impedance. Considering side lobe power and impedance, Corner Reflector antenna is chosen. The antenna is optimized for the best possible gain, reflection coefficient, and sidelobe level. The simulation results are given in following section.

- ***Receiver***

The ratio of pulsar signal strength and galactic background noise is optimum for detection at **408MHz**. This allows a better signal-to-noise ratio (SNR) for the system. Hence, the frequency of observation is chosen to be 408MHz. The receiver that we are implementing for data acquisition is a Software Defined Radio (SDR) receiver. RTL SDR receivers are best suited for the experiment considering the cost, accessibility, open-source codes, and support. They offer frequency tuning, gain adjustment, and frequency correction, which is ideal for pulsar detection. The RTL-SDR receivers can be used to acquire and sample RF signals transmitted in this frequency range [4].

- ***Low Noise Amplifiers and Filter***

The most significant electronic noise contribution comes from the first amplifier in the receiver chain. Hence, we need to use a Low Noise Amplifier (LNA) as the first stage. The amplifier should have a low value of noise figure. The value of the gain of the LNA should be high enough to get a decent value of SNR. The filter should have a high rejection property and removes the Harmonics of the signal.

IV. SYSTEM DESIGN

The design of the antenna was done on Altair Cad-feko software which is the best tool for the simulation of the RF components and various antennae. The design of the antenna was done on Altair Cad-feko software which is the best tool for the simulation of the RF components and various antennae.

For the optimization of technical parameters of the antenna, cadfeko has its very own user-friendly environment, which allows a proper design. The software also has an effective optimizing tool, which runs some no of iterations to give the best possible or optimized value for that particular parameter for which the optimizer was applied by the user. Corner reflector antenna was selected based on Ease of making and availability of the components while designing the antenna, mainly three parameters were focused gain, reflection coefficient, and impedance. The minimum value of the gain required for the faithful detection of pulsar signal was 15-20 dBs. An optimizer was used to get the best possible value of the gain. Corner Reflector Antenna Construction is shown in figure 2.

The gain of the antenna is a function of the reflector size so, the greater the size, the greater the gain. But after a certain amount of side of the square-shaped reflector, the gain of the antenna starts settling to a constant value. The distance of monopole from the origin and its height plays an important role to optimize the reflection coefficient and impedance of the antenna, therefore the distance of the monopole and its height was adjusted properly to get the required value of reflection coefficient and impedance.[5][6][7] Simulated Result of Corner Reflector Antenna are given in table 1. 3D Radiation Pattern of Corner Reflector Antenna is given in figure 3 and Optimized Antenna Result are given in table 2

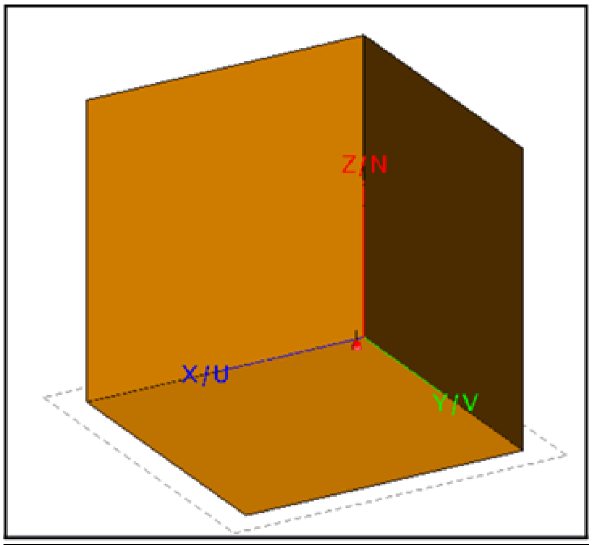

Fig. 2. Corner reflector antenna construction

TABLE I. SIMULATED RESULT OF CORNER REFLECTOR ANTENNA

Parameter	Simulated Result
Directivity (in dBi)	15.5 dBi
Impedance	52.6 ohm
Beamwidth	24.42 Degree
First Null Beamwidth	50.0 degree
First sidel3obe level	4.82 dB

TABLE II. OPTIMIZED ANTENNA RESULT

Parameter	Optimum value
Length of Reflectors	2m
Position of Monopole	(0.242m,0.242m)
Height of Monopole	0.1635m
Guage of Copper wire for Monopole	10 (3.251mm)

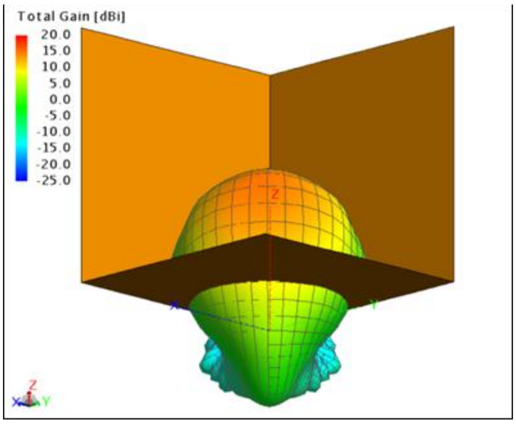

Fig. 3. *3D Radiation Pattern of Corner Reflector Antenna*

For the construction, we have prepared a frame of CNC Square tube of dimension 2m x 2m x 2m for support and an Aluminum sheet of 0.5mm thick is used for the reflector as shown in Figure 4. The aluminum sheet is riveted with an iron frame. The three faces of the Corner reflector are perpendicular to each other with a monopole placed at the bottom face. We need to take care that there should be proper conductivity between the three faces of the Antenna. Also, a rotation mechanism to direct the main lobe of an antenna in the direction of the source. [8] The Layout is given below in Fig 4.

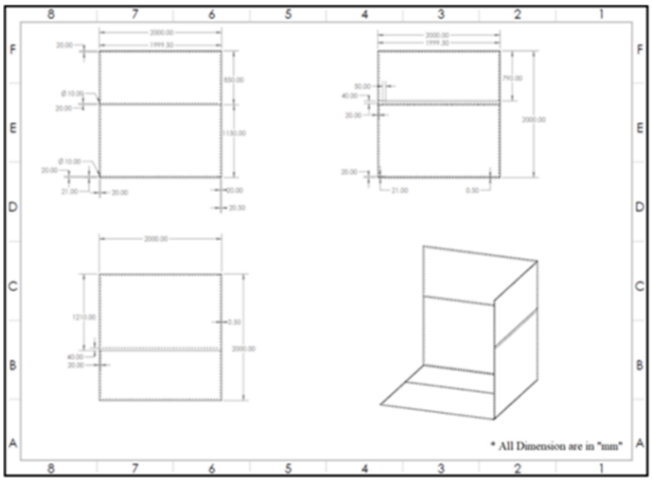

Fig. 4. Layout

V. SITE SURVEY

We have performed a survey to check the background noise effect. We have surveyed two locations they are (a) Ashoka Universal School, which is located outskirts of Nashik (b) K.K Wagh College of Engineering, Nashik. As the frequency of Observation is 408 MHz so, there should be minimum Noise interference. Therefore, based on the following results

Captured on RTL SDR Scanner Software we have decided to go with the location of observation to be K.K Wagh Institute of Engineering Education and Research, Nashik

The antenna response in between 400MHz to 500MHz without filter and with filter was taken and results obtained are given in Figure 5 and 6 respectively.

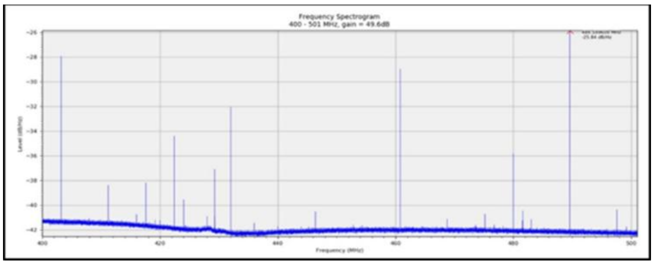

Fig. 5. *Antenna response in between 400MHz to 500MHz (without filter)*

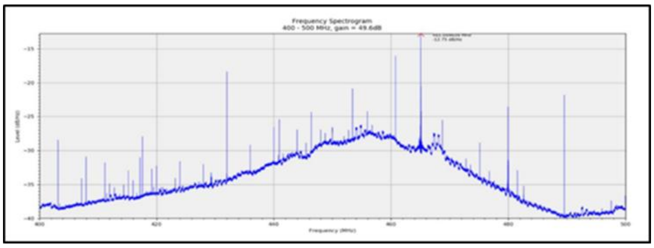

Fig. 6. *Antenna response in between 400MHz to 500MHz (with filter)*

VI. DATA PROCESSING

The Ooty radio telescope is a well-known radio telescope situated at a famous hill station of India called Ooty. This telescope is mounted on a downhill slope of **11°**. This antenna is an array of 1056 dipoles along the focal line of the reflector. The length of the telescope is 500m long and 30m wide. The telescope is having Cylindrical Paraboloid Reflecting surfaces. The telescope is operated at **326.5MHz** having about 15MHz of usable bandwidth. The large size of the antenna makes it a highly sensitive radio telescope in the world.

The raw data used for signal processing has been taken from the Ooty radio telescope. This data corresponds to the vela pulsar having the following properties:

Pulse width = 0.089328 sec.

Brightness = 5000mJy.

Time period = 2.1m sec.

Dispertion measure = 67.73 pc/cm^3

Voltage noise estimation:The first 10,000 samples are read to get the voltage noise estimate [9]. We know that sampling frequency plays an important role in signal processing.

A bandlimited continuous-time signal can be sampled and can be perfectly reconstructed from its samples if the waveform is sampled over twice as fast as its highest frequency component.

$$f_s >= 2f_{max} \quad (4)$$

Where, f_s = sampling frequency

f_{max}=maximum frequency component of i/p signal

No information is lost if sampling is done according to the above theorem. the sampling frequency is decided using the Nyquist theorem.

As a standard procedure, it is assumed that the pulse will be lying somewhere in **the "-3σ to 3σ"** part of the histogram the rest of the part of the histogram can be considered as noise. The table III shows the probability of signal content in the given range of σ.

TABLE III. PROBABILITY OF SIGNAL CONTENT

Range	Probability of signal content (in %)
-σ to σ	68.2
-2σ to 2σ	95.4
-3σ to 3σ	99.7

Power spectral density (PSD): Power spectral density is the frequency response of a signal. PSD is used to find the average power distribution as a function of frequency. The PSD has been plotted and shown in the Figure 7.

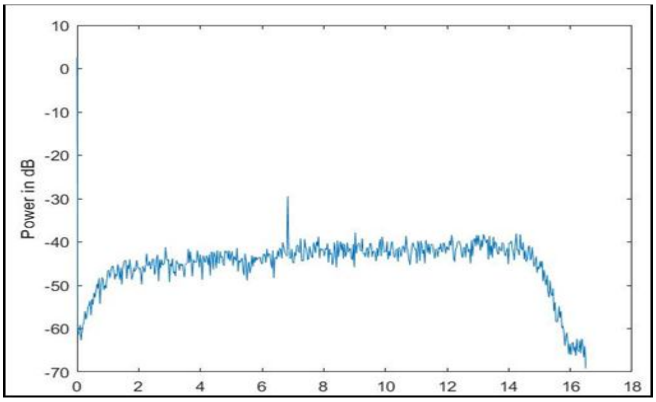

Fig. 7. *Power spectral density*

Ideally, the signal from the source should reach Earth at a time, but due to some non-homogeneity in the Interstellar Medium (ISM), the above-said statement does not hold. In the ISM, a signal from the source encounters some obstruction. The low-frequency signal travels slowly and, the high-frequency component reaches almost the speed of light. This phenomenon is known as ***Dispersion***. The reasons for this phenomenon are some patches of tenuous plasma in which there exists unionized electron density. [10] The speed of propagation through plasma is a function of frequency. Therefore the delay of travel times in both the frequencies can be calculated using the formula:

$$t_d = K \cdot (DM) \cdot \left[\frac{1}{f_1^2} - \frac{1}{f_2^2}\right] \quad (5)$$

Where, DM= Dispersion Measure.

K = Constant=4.149 x 10^6

t_d = dispersion delay(in msec)

f_1,f_2 are in MHz.

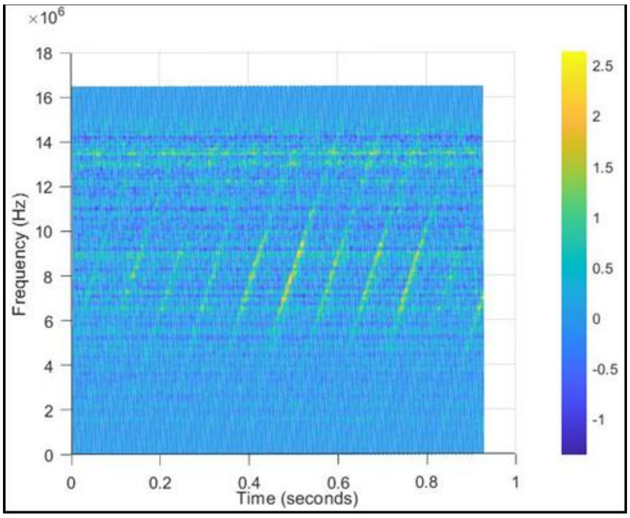

Fig. 8. *Waterfall diagram showing dispersion effect*

Typically for the path of 1 Parsec, the 1-DM reaches a value of 30pc/cm approximately.

As a result of dispersion, it degrades the signal-to-noise ratio heavily as well as affects the time resolution of pulsar data due to dispersion smearing. The effect of dispersion gets even worse at low frequency. Due to dispersion, we observe the broadening in pulsar means there exists an exponentially decreasing tail to the pulsar signal, which is a sign of degradation of SNR.

The spectrogram clearly shows the pulsar data is affected by dispersion.

A spectrogram is a visual way of representing power spectral density overtime at various frequencies. In which one axis is for time, another axis is for frequency and the color grading is used to represent the power of spectral components.

In the Figure 8, it is visible that as we increase in time, the pulse coming slowly. The amount of dispersion is measured in a measure called “Dispersion measure”.

Now to increase SNR, in a Dispersion affected the signal, a counteraction is taken against, which is known as De-dispersion.

Each Pulsar has its dispersion measure. Similarly, Vela pulsar’s dispersion measure is 67.73 pc $cm^{-}3$, de-dispersion is a process in which the pulses are circularly shifted by an appropriate value of t_d so that it will be added to get the maximum SNR possible.

There are mainly two techniques of de-dispersion named Coherent De-desperation and Incoherent De-Desperation.

In Incoherent De-desperation the total observing bandwidth is broken down into channels, then through each channel, the pulsar is observed and simultaneously detected. In each channel the smearing effect would be less as compared to the whole bandwidth, the detected signal is delayed with the appropriate value of delay, then combined (added) all channels into one channel to obtain a final signal.

Incoherent De-dispersion, the total observation bandwidth is used and the De-dispersion is done, the result of de-dispersion is shown in Figure 9.The observed signal goes through the detector.

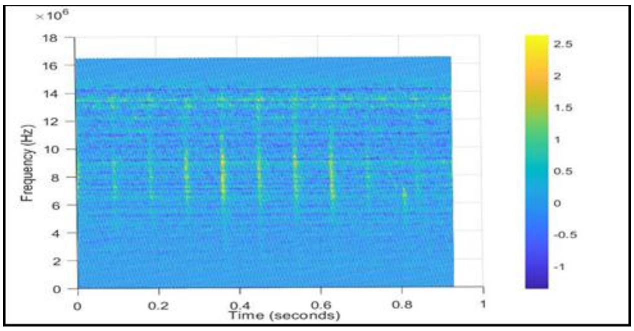

Fig. 9. *Waterfall diagram after de-dispersion*

VII. RESULT

The final and most important step in pulsar signal processing is folding. This step is used to significantly pull out the pulses from the processed data or increasing SNR by averaging out the noise.

The data first is divided into times bins, then appropriate amount of samples are accommodated then the number of a sample are added to the next or consecutive time bin, similarly, this process is carried out until the last time bin, again the next sample is added in the first time in this process is repeated until we reach the end of the data [11][12].

In this process, the noise average down, and the pulsar signal emerges out..!! as shown in Figure 12. For HPBW refer Figure 10 and for Reflection Coefficient and Impedance refer Figure 11. The optimized antenna construction parameters and technical parameters are given in table 3.

TABLE IV. PROBABILITY OF SIGNAL CONTENT

Optimized parameters	**Parameter**	**Values**
Construction	Length of Reflector	2x2 m
	Position of active element	x=0.242m, y=0.242m
	Height of active element	0.1635 m
	The gauge of wire used for active element	10 (Dia 3.251mm)
Technical	Gain	15.22 dB
	Reflection coefficient	-19.3dB
	HPBW	35.8194˚
	impedance	52.7 Ω

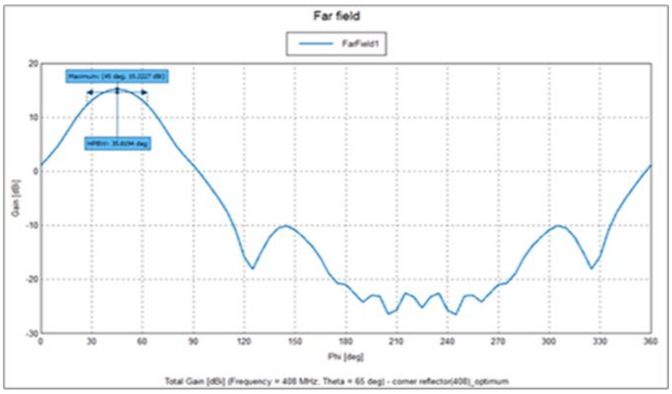

Fig. 10. *Half power beam width (HPBW)*

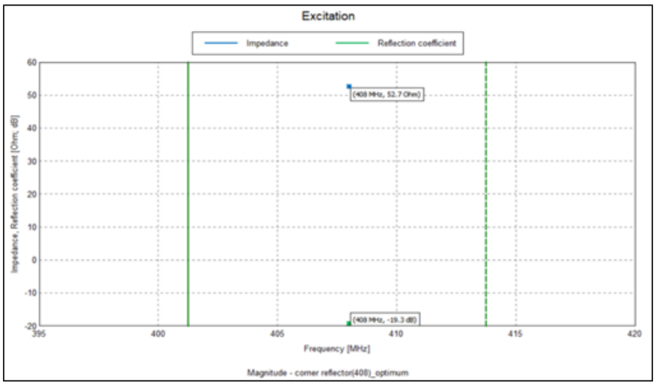

Fig. 11. *Reflection coefficient and impedamce*

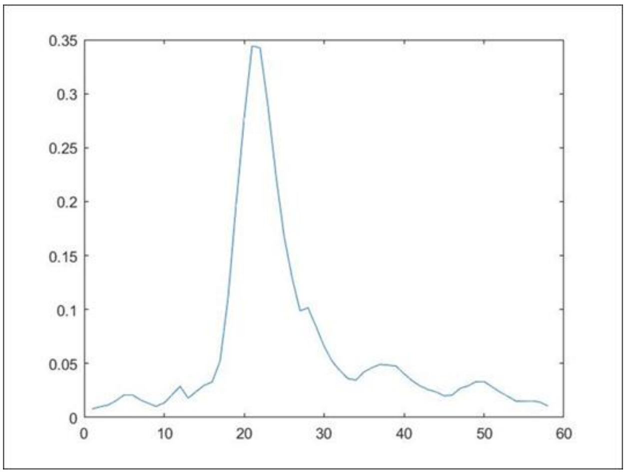

Fig. 12. *Final PULSE*

VIII. Applications

i) **Pulsar MAPS:** Around 45 years ago NASA has sent a probe in space named "voyager 1".This was the first manmade spacecraft to leave the solar system. Along with some testing instruments for study, the spacecraft also carried a special encrypted message. The message is for some intelligent extraterrestrial life, commonly known as Aliens. The message is for some intelligent extraterrestrial life commonly known as 'aliens' the message is famously known as 'golden record'. On this message, the creator of that message used 14 pulsars to create a map with our sun at the Centre. Each pulsar is connected to the sun by a solid line. The length of the lines represents the distance between the pulsar and the sun. Along with each pulsar line, vertical and horizontal dashes represent a binary number that can be converted into decimals. So assuming that those "Intelligent beings" can successfully decode the message and can locate us [13]

ii) Pulsars are good timekeepers Their accuracy of timekeeping is greater than the atomic clocks.

iii) Pulsar Positioning System: Pulsar can be used to make a galactic scaled navigation system which will be useful for navigation in the solar system as well as in deep space expeditions. Even the research is going on for making a pulsar positioning system (PPS) just like we have Global Positioning System (GPS) here on earth.[14]

IX. Conclusion

Designing the complete receiving system, where every element contributing some of the other noise power, requires a meticulous judgment of every component like LNA, Filter, receiver, antenna.

The SNR of the system needs to be reasonably high. In radio astronomy, the signal power level is commonly quite low, of the order of 10^{-15} W to 10^{-20} W. Therefore, the high sensitivity of the system is an obvious requirement. A corner reflector antenna was chosen among the three surveyed antennae. As a requirement, we wanted its gain to be high, because of this its size was also quite big.

Signal processing is the "heart" of this project. while doing the De-dispersion the dispersion delay was found to be (-7.507×10^{-5}) sec at 326.5MHz.while the dispersion measure for vela pulsar is 67.73 PC/cm^3

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