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Tracking and analysis of solar radio waves using a low-cost Radio Telescope in urban areas

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Abstract. Radio telescopes are specialized instruments to detect radio-waves between 30MHz-300GHz from different astronomical sources. It has ability to capture radio signals from satellites effectively during high light pollution and cloudy weather. In Kolkata, light pollution being significant, radio telescopes offer an alternative to optical telescopes for signal tracking from different radio sources. Although radio telescopes are typically expensive devices, here the main objective is to develop a low-cost, user-friendly model by using dish antenna, connecting cables, low-cost satellite meter (SF720) and spectrum analyser (OWON Model XSA 1036TG) for training students in the area. Sun being a source of radio waves and its proximity to Earth helps in capturing the solar radio waves easily. Here, the signal capture is done from the Sun primarily. The signal analysis is done through two methods: by varying the inclination angles of the radio telescope and by measuring the signals at different hours of day at a fixed angle of 90^0. The results showed that signal strength improved as inclination angle changed from 0^0 to 90^0. In second case, the peak intensity was obtained around 2:00PM when Sun is overhead. This radio telescope is able to capture radio signals of frequency up to 3GHz.

1 Introduction

Radio telescopes (RT) enable us to explore the universe by detecting naturally occurring radio waves emitted by stars, galaxies, black holes, and other celestial entities. Additionally, we can utilize these specialized telescopes to transmit and reflect radio signals off planetary bodies within our solar system, allowing for further study. Operating at the longest wavelengths of light, ranging from 1 millimetre to over 30 metres, radio telescopes provide unique insights into the cosmos. They offer valuable insights into the structure and

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composition of celestial entities. For instance, they can uncover the distribution of hydrogen gas within galaxies and detect the presence of magnetic fields in the vast expanse of space.

The basic blocks of a Radio Telescope consist of Antenna, Receiver and signal processing unit. Antenna is basically a large parabolic dish which collect and concentrate radio waves onto a receiver. The diameter of the dish is critical, as it determines the telescope's sensitivity to detect faint signals emanating from distant celestial objects. The radio waves gathered by the dish are converted into electrical signals by the receiver systems, which are extraordinarily sensitive and capable of detecting extremely faint signals. Advanced electronics and software meticulously process the received signals, employing techniques such as filtering, amplification, and analysis to extract valuable insights, reveal patterns, and define characteristics. Radio Telescope is used in various fields like Astronomical research, Space weather studies and Mapping the Universe etc.

A radio telescope is very expensive device because it demands exceptional engineering precision to capture elusive radio signals from the vastness of space. However, in this work, the main objective is to develop a low-cost, user-friendly device at the level of an educational institute of higher learning for the benefit of the students. Commonly available materials are used to achieve this, including dish antennas, connecting cables, a low-cost satellite meter (SF-720), and a spectrum analyzer (OWON XSA 1036-TG), chosen for their reliability and performance. The Sun, being a prominent source of radio waves and proximal to Earth, facilitates the easy capture of solar radio waves. By triangulating the positions of other satellites with the Sun as the origin, their signals can be effectively captured. In this setup, the primary focus is on capturing signals from the Sun, it being nearest to the Earth. Signal analysis is conducted through two methods: varying the inclination angles of the radio telescope and measuring signals at different times of day at a fixed angle of 90°. However, the obtained signals were noisy, so that Butterworth Low pass filter can be applied using MATLAB to eliminate noise for further study and analysis.

The novelty of this work is that this setup is highly beneficial for tracking signals from Sun and other satellites even in times of excessive light pollution. Development of such a low-cost radio telescope using commonly available materials has been attempted for the first time in the eastern region of India. Its design focused on simplicity, affordability and effectiveness. The performance of the developed radio telescope has been found to be comparable with the “Lovell Telescope”, located at Jodrell Bank Observatory in Cheshire, England. It offers a unique opportunity for students to gain practical knowledge and understanding of signal capture and satellite tracking, making complex concepts more accessible and engaging providing hands-on experience in capturing signals from the Sun and tracking various satellites.

The rest of the article has been organized as follows: Section 2 of the article focuses on the related work of radio telescope in literature, Section 3 deals with the motivation of this work where an overview of the developed model, the mathematical expressions and the procedure for collection of data has all been covered. Section 4 presents the results and analysis related to the collected data while Section 5 concludes the work and provides the scopes of future work.

2 Related Work

Several initiatives have focused on creating low-cost radio telescopes. In an earlier work, a project was attempted that utilized commercially available television dish antennas, specifically the SUN DIRECT HD STC 11-04 model, which operates within the frequency range of 10.7 GHz to 18 GHz [1]. The inherent parabolic curvature of these dishes provides superior performance in capturing and focusing radio frequency signals emitted by high-frequency sources, serving as the primary consideration in selecting this particular model [1]. A parabolic reflector (or dish) was used in most of the RT, generally to collect and focus the incoming radio waves. The radio waves can be detected at the focus of the dish or reflected back through the middle of the dish and then directed towards the focus of the dish [2]. Achieving high angular resolution was challenging due to the practical limitations of handling large antennas and their high manufacturing costs. As a result, radio astronomy observations have shifted towards shorter wavelengths [2]. The radio telescope configuration comprises a 1.20m diameter parabolic dish antenna, supplemented by a Low Noise Block (LNB), satellite finder, and receiver. While exhibiting limitations in terms of orientation sensitivity and accuracy, the system demonstrates capability in detecting solar radiation and blackbody radiation. Notably, manual orientation enables directed observation of radio sources, with signal acquisition and recording facilitated by the integrated satellite finder [3]. Commercial dish TV antennas was employed parabolic geometry to receive radio frequency (RF) signals from communication satellites. Leveraging advancements in TV technology, these antennas and their corresponding front-end receiver systems have undergone significant improvements. Operating within the Ku-band frequency spectrum (10.7-11.7 GHz), they provided exceptional signal-to-noise ratio (SNR) performance. Importantly, the Sun is known to emit intense radio frequency energy within this frequency range [4]. The radio emission characteristics of solar flares exhibit distinct differences between metre/decimetre wavelengths and centimetre/millimetre wavelengths. This disparity stems from the dominant radiation mechanisms: incoherent gyro synchrotron radiation at shorter wavelengths and coherent plasma radiation at longer wavelengths. Specifically, the 1-3 GHz frequency range represented a transitional regime, bridging the two emission mechanisms [5]. Radio astronomy is deeply connected to advancements in physics, electrical and mechanical engineering, mathematics, and computer technology. Physics played a crucial role in understanding celestial radio emissions and absorptions, including blackbody radiation, synchrotron radiation, molecular rotation bands, and electron spin. Electrical and mechanical engineering are evident in the design of radiometers and massive radio antenna structures [6].

The beam width (Bw) of a telescope can be calculated using the formula: $Bw = 1.2\lambda/D$ (in radians), where λ represents the observing wavelength and D is the diameter of the telescope [7]. If the diameter D is greater than λ, the half power beam width (HPBW) formula will be derived as $1.2\lambda/D$ [8]. The Butterworth filter was invented by British engineer Stephen Butterworth. This filter type is characterized by its constant gain and maximally flat amplitude response within the passband, with attenuation levels of -3 dB and -20 dB [9]. The rate at which the amplitude decreases were tied to the filter order, N. As N increases, the passband becomes flatter, the transition band narrows, and the amplitude drop-off in the stopband accelerates. Additionally, the difference between the actual frequency response and the ideal low-pass filter characteristics diminishes [10]. The Butterworth filter struck an optimal balance between attenuation and phase response. Notably, it features no ripple in either the passband or stopband, earning it the designation 'maximally flat filter.' However, this flatness comes at the cost of a relatively broad transition region between the passband and stopband, with moderate transient characteristics [11]. The concept of radio astronomy using satellite dishes was born when it was discovered that solar radiation interferes with TV signals. This occurs when the Sun aligns with geostationary satellites in the sky, affecting antenna reception. Subsequent experiments pointing antennas at the Sun revealed strong signal strengths, leading to system optimization for solar observations [12].

In summary, an examination of the literature highlights the absence of low-cost radio telescope solutions in urban areas of the eastern region of India. The pervasive light pollution in these regions severely hinders astronomical observations with optical telescopes. Consequently, the development of a cost-effective radio telescope designed to mitigate the effects of light pollution and adverse weather conditions is essential for advancing astronomical research in the eastern part of India.

3 Methodology

3.1 Motivation

There are several limitations of Optical telescope that can be mitigated using radio telescopes. Firstly, optical telescopes are specifically designed to detect visible light and are incapable of detecting other forms of electromagnetic radiation, including infrared, ultraviolet, X-rays, and radio waves. Secondly, the presence of artificial lighting in urban and suburban areas can significantly interfere with the observations made by optical telescopes. Light pollution poses a major obstacle to observe faint celestial objects, as it degrades the quality of observations and renders them less effective and most important is the optical telescopes require ideal weather conditions, specifically clear skies, to produce accurate and reliable observations. Adverse weather conditions, including cloud cover and high humidity, can obstruct the telescope's line of sight, compromising the quality of the data collected. Radio telescope provide solutions of these limitations because radio telescopes are designed to detect radio waves, which have a much longer wavelength than visible light, allowing them to study celestial objects. The radio telescopes are designed to detect radio waves, which are not affected by the presence of artificial light sources, making them ideal for use in urban areas where light pollution would hinder optical telescope observations. Radio telescopes can operate seamlessly in diverse weather conditions, including cloudy skies and heavy rainfall, owing to the fact that radio waves can effortlessly penetrate through clouds and precipitation, ensuring uninterrupted observation and data collection. But the main problem is radio telescope is very expensive. This has been the main motivation to develop a low-cost radio telescope which is as well student friendly. The block diagram discussed hereafter helps to understand the development of the model for the university purpose.

3.2 Block Diagram of the system

The easily available components are used here to develop radio telescope like dish antenna, connecting cables, low-cost satellite meter (SF-720) and spectrum analyzer (OWON Model: XSA 1036-TG) [13].

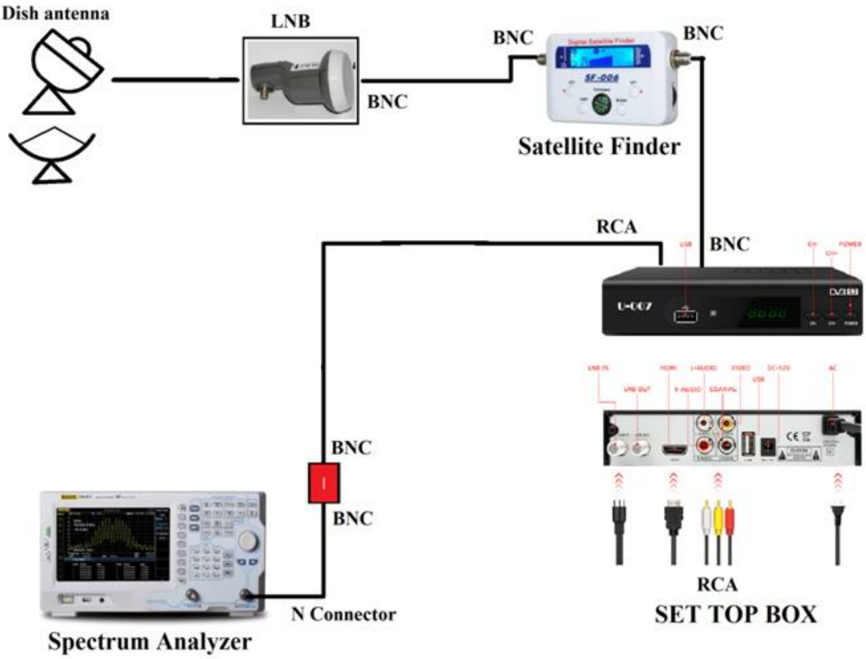

Fig. 1. Block Diagram of radio telescope setup.

The block diagram for the setup has been shown in Fig. (1). In the proposed design TATA Sky dish antenna [14] was used as parabolic reflector antenna. The radio signals are received by using this parabolic reflector antenna operating in the Ku band (12-18 GHz). The signal is then passed through a Low Noise Block amplifier (LNB) connected in the antenna itself with the feed section. The LNB (Low Noise Block) acts as a low noise amplifier that amplifies the incoming signal without amplifying the noise. BNC (Bayonet Neill–Concelman) connectors are the sections for the coaxial cables. The signal is passed through a digital satellite finder that helps to recognize the signal strength and accordingly the antenna orientation is changed to receive maximum signal strength. For example, during the reception of signals from Sun the antenna is pointed towards it and the elevation of the antenna is adjusted following the satellite finder. The LNB also eliminates the unwanted frequencies and down-converts the radio signals to the intermediate frequency (IF). This down conversion is essential to make the signal compatible with the other signal processing equipment. In the case of KU-band, the LNB frequency typically falls within the range of 10.7 to 12.75 GHz. The radio signals might be converted to the frequency range of 950-1950 MHz. The satellite finder is also used to verify whether the LNB is receiving any radio wave or not. The signal strength might also be estimated using certain satellite finders. The down converted signals in the range of 950-1950 MHz contains the information in the radio waves coming from Sun, other planets or any source of radio waves. The output signal from the set top box is in the form of audio as well as video signal and appropriate signal amongst them is fed to the Spectrum Analyzer. Here for the proposed radio telescope a OWON Model: XSA 1036-TG spectrum analyzer was used and the frequency range is 9 KHz to 3.6 GHz. The Spectrum is studied in detail and the frequency components between the down conversion range and even beyond 1.9 GHz is analyzed.

3.3 Data Collection Methods

Data was collected in two different ways for analysis of the performance of the radio telescope. During the first method, the signal spectrum is received at different inclination angle of the radio antenna at a fixed time of a particular day. In the other method, the spectrum is received at different times for a particular angle. Multiple peaks were observed in the received signal. However, considering the proximity to the Sun, the highest peak is attributed to the Sun's signal. But the received signal was very noisy because of interference of other signals. So the 2nd order Butterworth Low pass filter was used to eliminate the noise from the received signal. The Butterworth filter is renowned for its maximally flat frequency response within the passband, ensuring minimal amplitude distortion across the desired frequency range. This characteristic makes it an ideal choice for applications requiring precise signal preservation, maintaining the original signal shape with exceptional fidelity.

3.4 Mathematical Representation

Butterworth low pass filter has been found to be an effective filter to find out the best signal. The transfer function of 2nd order Butterworth Low pass filter as described by equations (1) and (2) has been considered here as found in [9]-

$$H(s)=\frac{1}{(s+\frac{1}{\sqrt{2}}-j\frac{1}{\sqrt{2}})(s+\frac{1}{\sqrt{2}}+j\frac{1}{\sqrt{2}})} \tag{1}$$

$$H(s)=\frac{1}{s^2+\sqrt{2}\times s+1}=\frac{1}{s^2+1.414s+1}=\frac{1}{1+1.414s+s^2} \tag{2}$$

Where ‘s’ represents poles.

The Butterworth filter can be easily designed in the analog domain using Laplace Transform and then converted to the digital domain using Z Transform. The process involves calculating the transfer function of the analog Butterworth filter, typically in the s-domain, and then applying either Impulse Invariance or Bilinear Transformation to obtain the digital filter response [9].

The beam width of a radio telescope is important because it determines the resolution of the telescope and the strength of the signal it receives. The beam width (or angular resolution) of radio telescope can be expressed mathematically as in Equation (3):

$$\theta=\frac{k\lambda}{D} \tag{3}$$

Where,

θ is the bean width in radian

k is a constant, typically between 1 and 1.22 depending on the design of the telescope. For parabolic reflector antenna value of k is 1.22

λ is the wavelength of the observed radio signal

D is the diameter of the telescope's aperture (the dish).

Based on the above methodologies and proposed mathematical formulations, the observed signal strength and the achieved results have been analyzed.

4 Results and Discussion

The results have been obtained in respect to the different methodologies adopted to collect the data. The first set of experimentation focused on varying the inclination angles of the dish antenna at a fixed time of the day around 12.30 PM when the SUN is overhead and the maximum signal is received.

4.1 Method 1: Collection of Data at Various Inclination Angles of Radio Telescope at 12.30PM on 19th April 2024.

4.1.1 Data Collected at 12.30PM during heat wave at inclination angle of 0^0

Fig. 2a. Radio telescope at angle of inclination 0^0

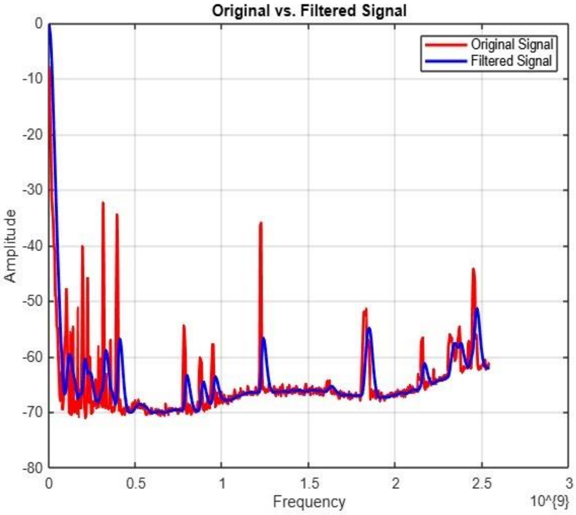

Fig. 2b. Received signal at angle of inclination 0^0

For angle of inclination of 0^0 as shown in Fig-2a. the maximum signal strength was achieved to be -53.8465 dBm as shown in Fig- 2b. The several peaks were received in the original signal because of interference of other signals but using a MATLAB programming the maximum peak value was calculated out of several peaks and as per the proximity of Sun the highest maxima was attributed to the Sun's signal.

4.1.2 Data Collected at 12.30PM at inclination angle of 20^0

Fig. 3a. Radio telescope at angle of inclination 20^0

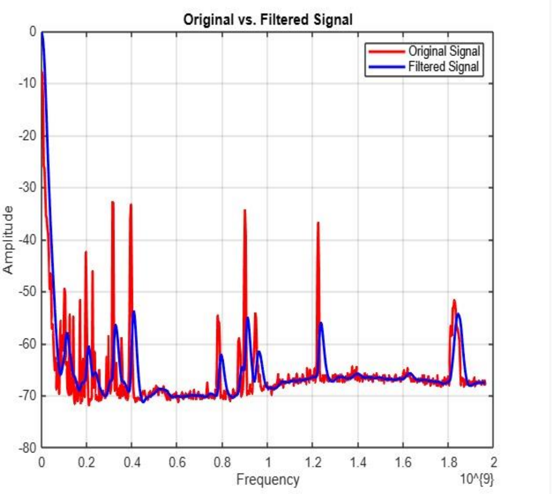

Fig. 3b. Received signal at angle of inclination 20^0

For angle of inclination of 20^0 as shown in Fig-3a, the maximum signal strength obtained was **-51.4225 dBm** was obtained as shown in Fig- 3b. The Butter Worth filter is designed to have flat frequency response in passband which means no ripples and distortions present in frequency are allowed to pass through it. This flatness ensures the desired signal was not altered.

4.1.3 Data Collected at 12.30PM during heat wave at inclination angle of 50^0

Fig. 4a. Radio telescope at angle of inclination 50^0

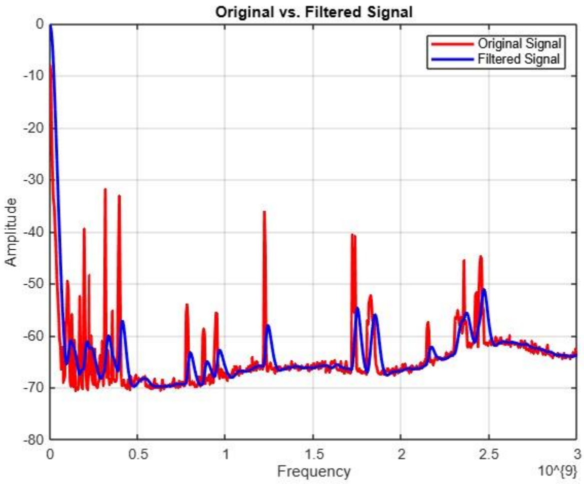

Fig. 4b. Received signal at angle of inclination 50^0

For this angle of inclination as shown in Fig-4a., the Maximum Signal Power: -51.1659 dBm was obtained as shown in Fig- 4b.

4.1.4 Data Collected at 12.30PM during heat wave at inclination angle of 90^0

Fig. 5a. Radio telescope at angle of inclination 90^0

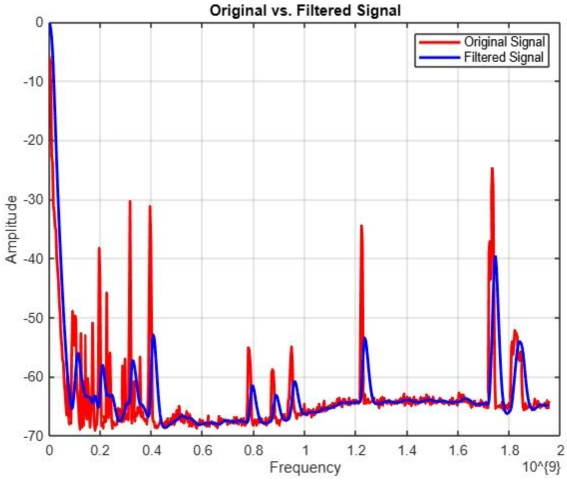

Fig. 5b. Received signal at angle of inclination 90^0

For this angle of inclination as shown in Fig-5a., the Maximum Signal Power: -39.7187 dBm was obtained as shown in Fig- 5b.

Table 1. Angle of Inclination Vs Maximum Power for fixed time.

Angle in degree	Maximum Power in dBm
0^0	-53.8465
20^0	-51.4225
50^0	-51.1659
90^0	-39.7187

The maximum signal power at various angles of inclination of radio telescope was experimented between 0^0 to 90^0 of inclination of the radio telescope. Utilizing some sample data of maximum amplitude data collected across a range of inclination angles, an Angle-Amplitude characteristic curve was generated. Fig-6, reveal a direct correlation between the angle of inclination of the radio telescope and the amplitude of the Sun's signal. As the inclination angle increases, the telescope's alignment with the Sun improves, leading to an enhancement in signal reception. It is seen that when the angle of inclination is above 750, the best signal strength is achieved.

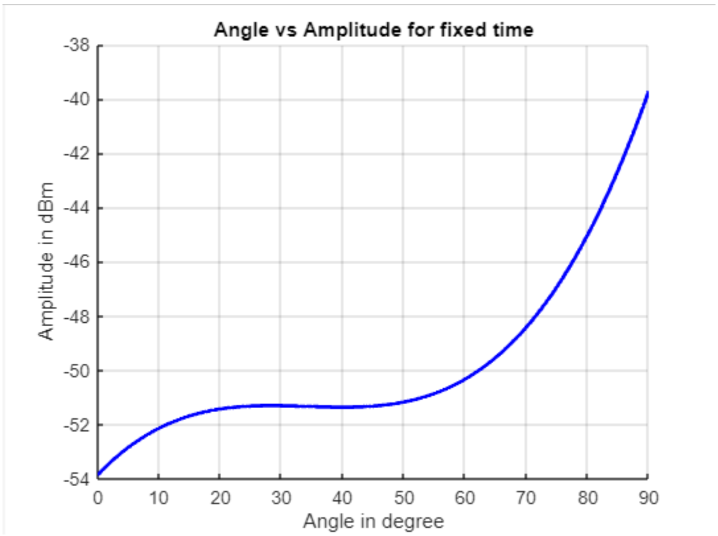

Fig. 6. Angle of inclination vs Amplitude graph

4.2 Method 2: Data Collected at different times of a day for inclination angle of 90^0

Data was collected for various times of a particular day keeping a fixed angle of inclination of 90^0. As it was seen from the earlier experimentation, the best signal from Sun was received by the radio telescope at an angle of inclination of 90^0, thereby the radio telescope's inclination was fixed at this particular angle.

4.2.1 Data Collected at 10.30AM on 25th June, 2024 at inclination angle of 90^0

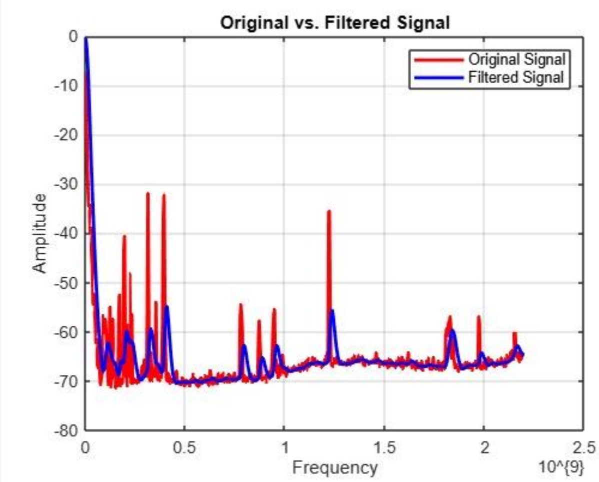

Fig. 7. Spectrum received at 10:30 AM

As seen from Fig- 7, the Maximum signal power obtained at around 10.30AM was -54.8759 dBm. The signal strength is relatively poor compared to the signal strength at around 2PM since at this time the Sun is at a position in between the zenith and the horizon. The inclined radio telescope is still not able to receive the strongest signal at this position.

4.2.2 Data Collected at 2.00PM on 25th June, 2024 at inclination angle of 90^0

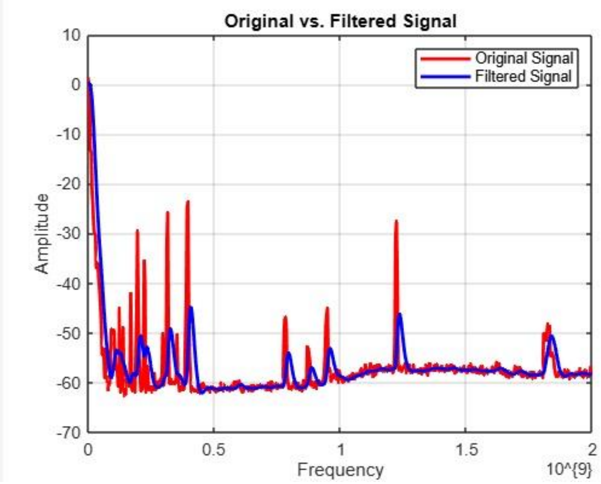

Fig- 8. Spectrum received at 2:00 PM

The Sun being overhead at 2PM and the corresponding signal spectrum received at this instant has been depicted in Fig- 8 when the maximum power obtained was -44.8606 dBm.

4.2.3 Data Collected at 5.00PM on 25th June, 2024 at inclination angle of 90^0

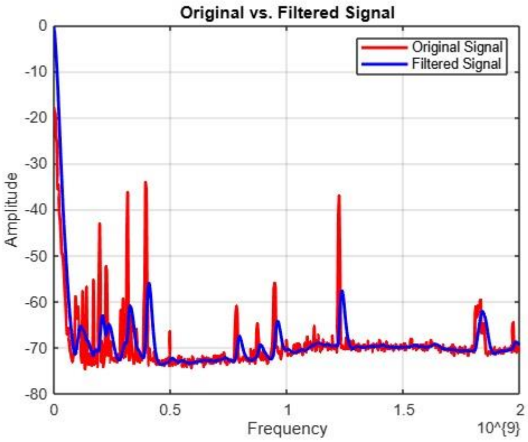

Fig- 9. Spectrum received at 5:00 PM

As seen from the spectrum received at 5PM, it is seen that the maximum signal strength achieved was -55.9263 dBm. As the Sun is about to set at this time and not in an overhead position, thereby the signal strength considerably reduces at this time of the day.

In case of Fig-7,8,9, all most similar pattern was obtained throughout the day but the maximum power was received at 2:00 PM.

Table 2. Time Vs Maximum Power for fixed angle

Time	**Maximum power in dBm**
10:30 AM	-54.8759
2:00 PM	-44.8606
5:00 PM	-55.9263

Based on the maximum amplitudes obtained at various times of a day for a particular angle of inclination 90^0, a Time vs. Amplitude graph was plotted as shown in Fig- 10.

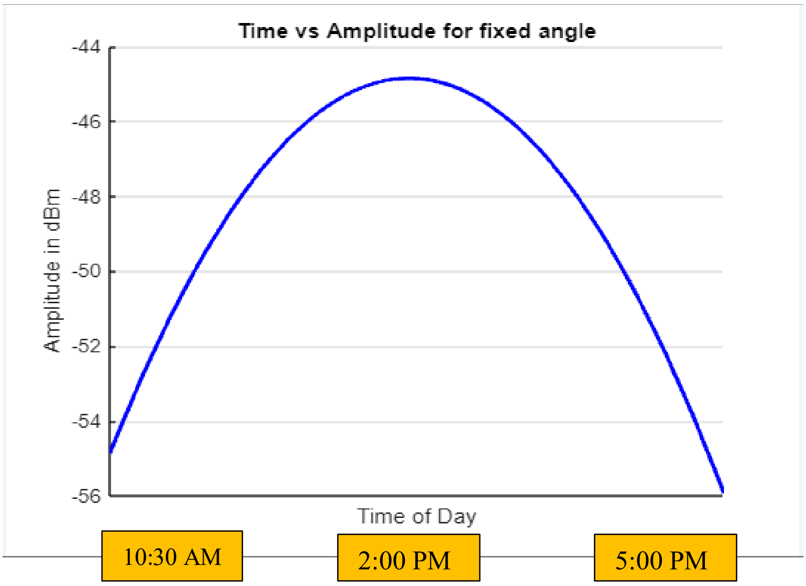

Fig- 10. Time vs Amplitude graph

As the time progresses during the day, the intensity of the Sun increases until afternoon, after which it decreases. At 2:00 PM the Sun was exactly at the zenith position and at this position a best alignment was made between the parabolic reflector antenna and the Sun so that at this position radio telescope gathered more radio waves that's why at 2:00 PM maximum power was obtained. After that as the Sun's position shifted from zenith towards the horizon the reception of radio wave decreases gradually so that the power also decreases. This phenomenon is clearly illustrated in the Time vs. Amplitude graph.

4.3 Beam Width calculation and operating frequency

4.3.1 Calculation of beam width of radio telescope

From Fig-6 representing the Angle vs Amplitude characteristics curve, it's showing that at 900 the amplitude of Sun is maximum. So, considering the corresponding frequency at that particular inclination, the wavelength is found to be:

$$\lambda = \frac{c}{f} = \frac{(3 \times 10^{10})}{(2 \times 10^{9})} = 10\ cm$$

The diameter D of dish antenna is 90 cm.
Therefore, as the D>> λ

Beam Width (BW)= 1.22 λ/ D= 0.135 radian

A narrower beam width corresponds to a higher angular resolution. With a beam width of 0.135 radians (about 7.7 degrees), the telescope can resolve sources that are separated by this angle. This beam width determines the telescope's field of view. A beam width of 0.135 radians indicates a relatively broad field of view compared to optical telescopes. This broad field of view enables the telescope to observe larger regions of the sky at once along with several geostationary satellites as well making it useful for surveying large areas or studying extended structures.

4.3.2 Calculation of beam width of radio telescope

The low-cost radio telescope model set up in the University campus in Newtown, Kolkata, India is the first of its kind. Setting up of a budget friendly radio telescope with the commonly available materials is itself an achievement which would also provide the students an option to practice hands on experimentation with radio telescope. It is observed from the spectrums received that the developed radio telescope can receive signals up to 3GHz. A similar kind of radio telescope that can sense signals between 0-2 GHz is the Lovell Telescope, that is located in Jodrell Bank Observatory in Cheshire, England. The operating range of this developed telescope is near to the Lovell Radio telescope; however, the small size of the antenna and the beam width does not allow this telescope a broader field like the Lovell Telescope.

5 Conclusion & Future Scope

A low-cost radio telescope was successfully established. The signal from Sun was efficiently detected by this telescope and it was perfectly determined from the two graphical representations - Time vs. Amplitude and Angle of Inclination vs. Amplitude - revealed distinct characteristics of the Sun's radiation pattern. This radio telescope can track signals across a frequency range up to 3 GHz. In urban environments, severe light pollution limits optical astronomy. Radio telescopes, however, can effectively detect and study numerous radio sources in the sky, unaffected by optical interference. Noise in the signal is caused by interference from other signals, which can be effectively removed using a Butterworth low-pass filter implemented in MATLAB. This device is extremely user-friendly, making it easy for students to comprehend and operate the radio telescope.

Future enhancements will automate the radio telescope, enabling satellite tracking capabilities. Additionally, various filters will be tested to determine the most effective noise-reducing filter for this application. Reconstruction of various celestial images can be possible by using an array structure of more than one radio telescopes because it provides better resolution. Design of different antenna for comparative analysis and selection of best radio telescope module can also be attempted in the future.

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