Observation of the Galactic plane using 21-cm Radio Telescope and Observation of Radiation Pattern of various types of radio antenna

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Abstract: There are two important stages to this experiment in the field of radio astronomy. The first phase include scanning for 21-cm radio signals in the galactic plane within the constellations Cygnus, Sagittarius, Aquila, Scorpio, and Scutum. Despite difficulties in reducing interference from the earth When taking atmospheric conditions into consideration, the analysis offers insightful information about the distribution and the interstellar medium's neutral hydrogen dynamics. The subsequent stage delves into the directional properties of various radio antennas through their radiation patterns. The use of calibration techniques improved precision. This section emphasizes the significance of parameters for antenna design in communication system optimization. Collectively, these studies contribute to a thorough comprehension of radio astronomy by obliginggating theoretical ideas with real-world communication technology applications.

I. OBJECTIVES

1. Observations of the HI line emission from the radio sources using horn antenna.

3. Setup the motorized Scientech 2261A antenna trainer and plot radiation pattern of simple dipole, folded dipole, phase array and yagiuda multi element antennas.

II. THEORY

A. Introduction

In this experiment we are trying to understand the velocity distribution of the milky galaxy using radio telescope, further we also tried to understand how different types of antenna behave using polar plots. Here in this theory section we will give a brief overview how the antenna's work and theory behind the 21 cm HI line emission.

B. Antenna Theory

Antenna theory is a branch of electrical engineering and physics that deals with the design, analysis, and application of antennas, which are devices that transmit or receive electromagnetic waves. Antennas play a crucial role in various communication systems, including radio and television broadcasting, wireless communication, radar, satellite communication, and more. Here are some fundamental concepts in antenna theory:

1. **Antenna Basics:**
   - An antenna is a transducer that converts electrical signals into electromagnetic waves (transmitting antenna) or vice versa (receiving antenna).
   - Antennas are characterized by their radiation pattern, impedance, bandwidth, gain, and efficiency.
2. **Radiation Patterns:**
   - The radiation pattern of an antenna describes how the radiated power is distributed in space.
   - Patterns can be omnidirectional (equal in all directions) or directional (focused in a specific direction).
3. **Types of Antennas:**
   - **Dipole Antenna:** Simplest form, consists of two conductors.
   - **Monopole Antenna:** A single conductor over a ground plane.
   - **Patch Antenna:** Used in wireless communication, often in planar structures.
   - **Yagi-Uda Antenna:** Directional array of dipole elements.
   - **Parabolic Reflector Antenna:** Uses a parabolic reflector to focus the radio waves.

- **Horn Antenna:** Shaped like a horn, used for microwave frequencies.

4. **Antenna Parameters:**
   - **Gain:** The ability of an antenna to direct its radiated power in a specific direction.
   - **Directivity:** A measure of how well an antenna focuses its radiation in a specific direction.
   - **Efficiency:** Ratio of power radiated to the input power.
5. **Antenna Impedance Matching:**
   - For efficient power transfer, the impedance of the antenna should match the impedance of the transmission line and the transmitter or receiver.
   - Matching networks, such as baluns and impedance transformers, are used to achieve impedance matching.
6. **Bandwidth:**
   - The frequency range over which an antenna operates effectively without significant degradation in performance.
7. **Polarization:**
   - The orientation of the electric field vector in the electromagnetic wave radiated by the antenna.
   - Common polarizations include linear (horizontal or vertical) and circular.
8. **Near-Field and Far-Field Regions:**
   - The near-field region is close to the antenna and contains reactive fields.
   - The far-field region is where the radiated energy becomes predominantly electromagnetic waves.
9. **Antenna Arrays:**
   - Multiple antennas arranged in a specific configuration to achieve desired properties, such as increased gain or beam steering.
10. **Antenna Measurements:**
    - Techniques and instruments for measuring antenna characteristics, including anechoic chambers and network analyzers.

Antenna theory is a broad and interdisciplinary field that combines principles from electromagnetics, RF engineering, and signal processing. It is essential for the design and optimization of communication systems in various applications.

C. Horn Antenna's

Horn antennas are a type of microwave antenna known for their wide bandwidth, high gain, and directional radiation pattern. They are commonly used in various applications, including radar systems, satellite communication, and terrestrial point-to-point communication. Here's a brief overview of horn antennas:

1. **Wave Propagation:**
   - Horn antennas are designed to support the propagation of electromagnetic waves, typically in the microwave frequency range.
   - The flared shape helps in gradually transitioning the electromagnetic waves from the transmission line (or from free space) to the open space of the horn.
2. **Waveguide Mode:**
   - Horn antennas often use a waveguide structure, where the electromagnetic waves propagate in a waveguide mode.
   - The waveguide allows the efficient transfer of energy between the transmission line and the open space of the horn.
3. **Mode Transition:**
   - The flared shape of the horn facilitates the transition between the confined mode of the waveguide to the open space, enabling efficient radiation.
4. **Directivity:**
   - Horn antennas exhibit high directivity, meaning they focus the electromagnetic energy in a specific direction.
   - The flare of the horn contributes to the directivity by controlling the radiation pattern.

Mathematical Formulations:

1. **Flare Angle (θ):**
   - The flare angle is an important parameter that determines the shape of the horn.
   - It is the angle between the sidewalls of the horn and is often denoted by θ.
2. **Horn Antenna Gain:**
   - The gain of a horn antenna (G) is a measure of its directivity. It is the ratio of radiation intensity in a specific direction to the average radiation intensity.
   - The gain can be calculated using the following formula:
     $$G = \frac{4\pi A_e}{\lambda^2}$$
     where A_e is the effective aperture and λ is the wavelength.
3. **Effective Aperture (A_e):**
   - The effective aperture is related to the physical aperture size (A) and the directivity (D) of the antenna:
     $$A_e = \frac{D\lambda^2}{4\pi}$$
4. **VSWR (Voltage Standing Wave Ratio):**
   - VSWR is a measure of how well the antenna is impedance-matched to the transmission line.
   - It is defined as the ratio of the maximum voltage to the minimum voltage along the transmission line:
     $$\text{VSWR} = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$
     where Γ is the reflection coefficient.
5. **Reflection Coefficient (Γ):**
   - The reflection coefficient is related to the impedance matching of the antenna.
   - For a matched antenna (Z_0 is the characteristic impedance of the transmission line), $\Gamma = 0$, and there is no reflection:
     $$\Gamma = \frac{Z - Z_0}{Z + Z_0}$$

These mathematical formulations provide a quantitative understanding of the performance characteristics of horn antennas. The specific details may vary depending on the design and geometry of the horn, and more advanced formulations can be derived for specific horn antenna configurations.

D. 21-cm Radio Astronomy

Radio astronomy at the 21-centimeter wavelength (21 cm) is a branch of observational astronomy that involves studying celestial objects and phenomena using radio waves with a wavelength of approximately 21 centimeters. The 21-cm line corresponds to the hyperfine transition of neutral hydrogen atoms, and it is a crucial tool for investigating the structure and dynamics of the interstellar medium in galaxies.

Hyperfine Transition of Hydrogen:

1. **Spin-Flip Transition:**
   - The 21-cm line corresponds to the transition between two hyperfine levels of the ground state of neutral hydrogen ($^1_0$H).
   - The transition involves a spin-flip of the electron and proton in the hydrogen atom.
2. **Wavelength:**
   - The rest wavelength of the 21-cm line is approximately 21.10611405413 centimeters. Redshift due to the relative motion of the source and observer shifts this wavelength.

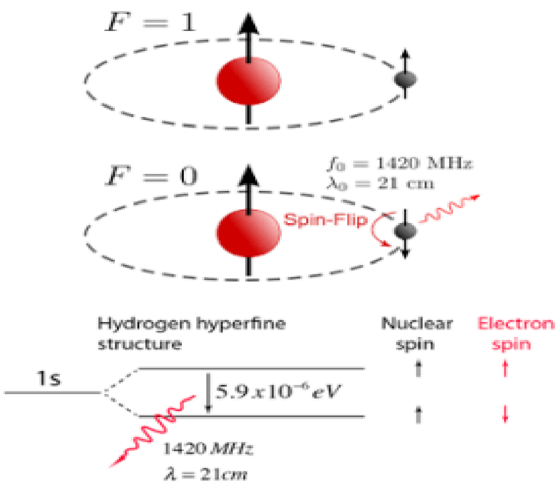


FIG. 1. H-line spin orientation

Applications in Astronomy:

1. **Interstellar Medium (ISM) Studies:**
   - 21-cm observations are used to study the distribution and properties of neutral hydrogen gas in the interstellar medium of galaxies.
   - This allows astronomers to map the structure and dynamics of spiral arms, molecular clouds, and other features within galaxies.
2. **Cosmic Microwave Background (CMB):**
   - The 21-cm line has implications for the study of the cosmic microwave background radiation, providing information about the early universe.
3. **Dark Matter Studies:**
   - The distribution of neutral hydrogen can be influenced by the gravitational effects of dark matter. 21-cm observations contribute to our understanding of the large-scale distribution of dark matter.
4. **Galactic Dynamics:**
   - Radio observations at 21 cm help in studying the rotation curves of galaxies, providing insights into the distribution of mass and the existence of dark matter in galaxies.

Radio Telescopes:

1. **Single-Dish Telescopes:**
   - Large single-dish radio telescopes, such as the Arecibo Observatory, have been used for 21-cm observations. These telescopes are well-suited for mapping large areas of the sky.
2. **Interferometers:**
   - Radio interferometers, such as the Very Large Array (VLA), consist of multiple antennas working together to simulate a large aperture. Interferometers are used to achieve high angular resolution in 21-cm observations.

Radio telesope using horn antenna

Designing a radio telescope using a horn antenna involves considerations of the antenna's characteristics, beam patterns, and overall system performance.

1. **System Temperature (T_{sys}):**
   - The system temperature represents the equivalent noise temperature of the entire receiving system. It is a critical parameter for determining the overall sensitivity of the radio telescope.

     $T_{\text{sys}} = T_{\text{ant}} + T_{\text{feed}} + T_{\text{receiver}}$

     where T_{ant} is the physical temperature of the antenna, T_{feed} is the noise temperature of the feed system, and T_{receiver} is the noise temperature of the receiver.
2. **Sensitivity (S):**
   - Sensitivity is a measure of how well the telescope can detect weak signals. It is often expressed as the system temperature normalized by the antenna gain:

$$S = \frac{T_{\text{sys}}}{G}$$

3. **Point Source Sensitivity ($S_{\mathbf{ps}}$):**
   - Point source sensitivity is a measure of the telescope's ability to detect a point source. It is given by:

   $$S_{\text{ps}} = \frac{T_{\text{sys}}}{G\sqrt{\Delta f \cdot \tau}}$$

   where Δf is the frequency bandwidth and τ is the integration time.

4. **Beamwidth ($\theta_{\mathbf{HPBW}}$):**
   - The half-power beamwidth (HPBW) is an important parameter that defines the angular width of the main lobe of the antenna's radiation pattern.

These formulations provide a simplified view of the key parameters involved in the design and performance assessment of a horn antenna-based radio telescope. The actual design process would require detailed knowledge of antenna theory, electromagnetic simulations, and consideration of practical engineering constraints.

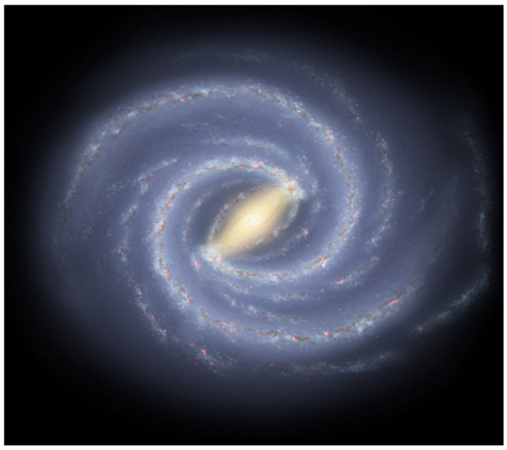
21-cm radio astronomy continues to be an important tool for understanding the universe's large-scale structure and evolutionary history, and ongoing and future projects aim to push the observational limits in this wavelength range.

E. Software Guide- GNU Radio

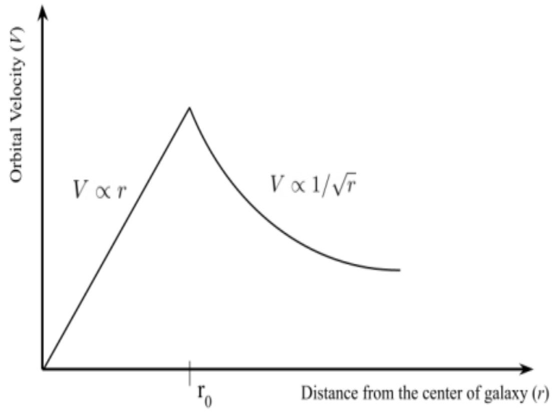
A popular open-source software toolkit is GNU Radio utilized in the development of systems for software-defined radio (SDR). It offers an adaptable and user-friendly platform for radio communication system design and implementation through software-based processing. Users of GNU Radio can create, model, and implement a range of applications of radio signal processing, from basic from complicated communication protocols and signal processing tasks to signal modulation and demodulation.
Through the use of software and a graphical user interface, users can connect and configure signal processing blocks to create a flowgraph that visually displays the intended radio system. Because it supports multiple hardware platforms, it can be used with a wide variety of radio frequency (RF) devices. GNU Radio is a potent and adaptable tool for researching and experimenting with radio frequency technologies. It is widely used in telecom, wireless communication, and signal processing research. GNU Radio is an open-source project that fosters community participation and cooperation, making it a dynamic and ever-evolving platform for software-defined radio development.

F. Galaxy rotation curve

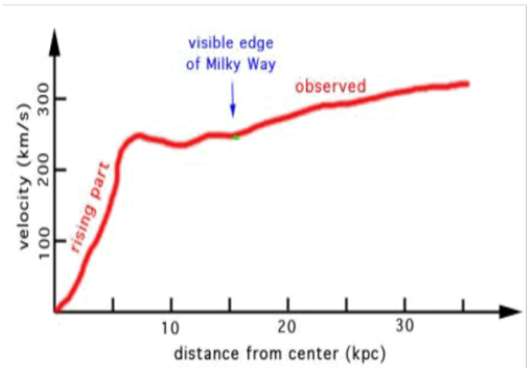
Coming to the concerned topic of the galaxy rotation curve, consider our own Milky Way Galaxy. Most of the stars in the Milky Way are concentrated near its center and as we move outwards the density of visible mass decreases. An artistic concept of how the milky way should look is shown in figure.



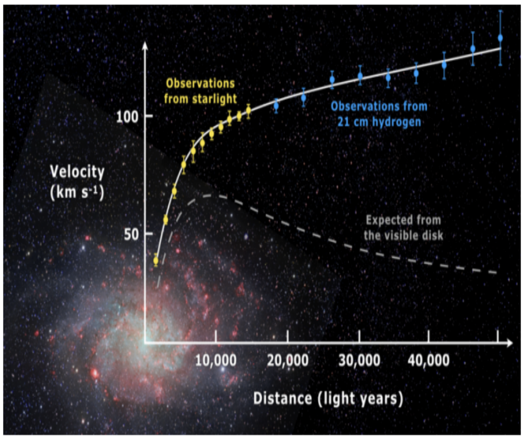
The higher intensity near the center is related to the higher mass and higher density. As we are moving outwards, the intensity is gradually decreasing, which also says the density of visible mass is decreasing. So, starting from the center up to a certain distance the galaxy can be considered equivalent to a disk, and beyond that, we can expect that as we get further from the center the stars would revolve around the center of the galaxy more slowly in the same way that the planets orbit relatively slowly as we get further from the Star. Thus the rotation curve of a galaxy should be like the graph shown in the figure.



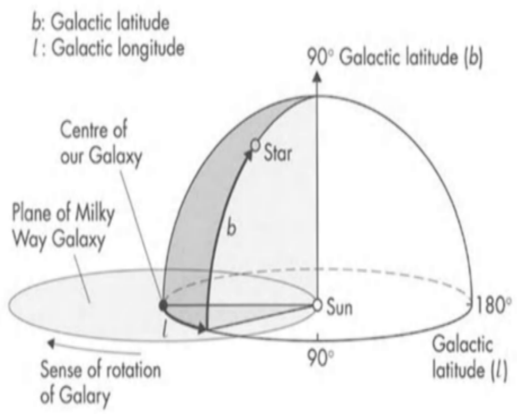
A lot of research has been conducted in the past using data from multiple surveys to plot the milky way rotation curve. But, unlike our expectations, the observation of the galaxy rotation curve looks quite different. Initially, the velocity is increasing up to a distance as expected, but beyond that, it doesn't decrease and remains almost constant till large distances.



A flattened curve essentially means there is a large amount of unseen material, more widely spread than the stars and gas. These unseen materials are termed "dark matter". Thus, similar to the near center region of the galaxy, the surroundingmass, felt by stars even at large distances increases due to the presence of this dark matter. They essentially trap the fast-moving stars and maintain a high average velocity of stars. So, theories involving the existence of dark matter are the main postulated solutions to account for the variance.



Galactic Coordinate System: The latitude and longitude lines of the earth are well-known. The galactic coordinate system also has similar latitude and longitude lines. For the galactic coordinate system the galactic plane of our Milky Way galaxy is set to be the zero degrees latitude line, and the direction, towards the center of our galaxy, is used to define the zero degrees longitude line. The latitudinal angle and longitudinal angles are termed the galactic latitude and the galactic longitude.



Tangent Point method The tangent point method is a technique used in astronomy to estimate the rotation curve of a spiral galaxy. The rotation curve represents the distribution of mass within the galaxy as a function of radial distance from its center. This method relies on observing the motion of neutral hydrogen gas in the galaxy.

The tangent point method is a powerful tool for studying the mass distribution in galaxies, revealing the presence of dark matter. The method assumes that the neutral hydrogen gas is a good tracer of the overall mass distribution, and the observed rotation curves often indicate the existence of unseen mass (dark matter) in the outer regions of galaxies. We use the matical formulation as: In this method, our ultimate goal is to plot the rotational speed (V_R) as a function of the distance (R) from the galactic center, we can get,

$$R = R_0 \sin l$$

Here $R_0 = 8.5\,\text{kpc}$. Also, the radial velocity in the circular orbit is given by[25],

$$V_r = W \sin l$$

Where,

$$W = [\theta \left(\frac{R_0}{R}\right) - \theta_0]$$

The observed frequency, f_{observed}, in terms of redshift z is given by:

$$f_{\text{observed}} = f_{\text{emitted}} \cdot (1 + z)$$

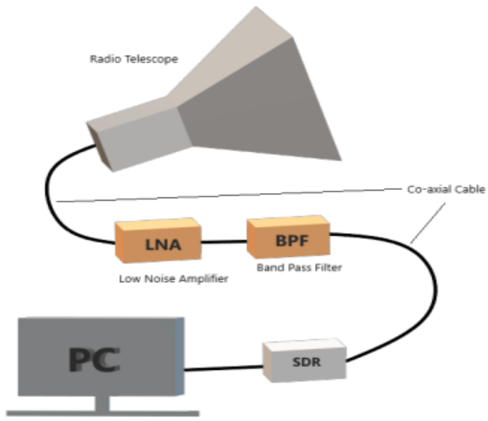
The velocity θ in terms of redshift z is given by:

$$\theta \;= z \cdot c$$

Here R and θ are radii and circular velocity at some point on the Galaxy. The tangential velocity along a line of sight is basically the circular velocity for that longitude. θ_0 is the circular velocity of the sun ($= 220\,\text{km/s}$)[25]. So, for observation along a particular longitude (l), we can get individual R and V_r.

III. EXPERIMENTAL SET-UP

To set up the system, solder the power supply wires to the low-noise amplifiers (LNAs), ensuring careful handling to prevent damage from electrostatic discharge. It is advisable to ground yourself to provide electrostatic protection while working with LNAs. Connect the two LNAs, followed by the filter, using appropriate connectors. Further, link the assembly to the antenna and attach a long (10 m) RG58 coaxial cable to the filter, connecting the other end to the receiver. Finally, plug the receiver into a computer or laptop, and connect the LNA power cables to a battery, turning it on to initiate the system.



Low Noise amplifier : Low Noise Amplifiers (LNAs) are a crucial component in the front-end of many communication and sensor systems. They play a vital role in amplifying weak signals while introducing minimal additional noise. LNAs are commonly used in radio frequency (RF), microwave, and millimeter-wave applications.LNAs are designed to have a low noise figure, which quantifies how much the amplifier contributes to the overall noise of the system. Lower noise figures indicate better performance in preserving the signal-to-noise ratio.

While providing low noise is essential, LNAs also aim to offer sufficient gain to overcome signal losses in subsequent stages of the system.LNAs are designed for specific frequency bands based on the application requirements. Different technologies and designs are used for RF, microwave, and millimeter-wave frequencies.

Band Pass Filters : A Bandpass Filter is an electronic device or circuit that allows signals within a certain frequency range, known as the passband, to pass through while attenuating or rejecting frequencies outside of this range. Bandpass filters find applications in various communication systems, audio processing, and signal conditioning.The passband is the range of frequencies that the filter allows to pass through with minimal attenuation.

RTL-SDR : RTL-SDR (Software-Defined Radio using a Realtek RTL2832U and Rafael Micro R820T/820T2) refers to a popular and affordable software-defined radio (SDR) hardware platform that utilizes a Realtek RTL2832U chipset for receiving and demodulating signals over a broad frequency range. This platform gained popularity due to its low cost and widespread availability, making it accessible to hobbyists, radio enthusiasts, and professionals interested in exploring the capabilities of software-defined radio.The core component responsible for USB interfacing, data transfer, and basic signal processing.

The RTL-SDR covers a wide frequency range, typically from around 24 MHz to 1.7 GHz, making it suitable for various radio frequency (RF) applications.The RTL-SDR platform offers an affordable entry point into the world of software-defined radio, providing a versatile and accessible tool for various RF exploration and reception applications.

GNU-Radio : GNU Radio is an open-source software toolkit that provides signal processing blocks to implement software-defined radios (SDRs) and signal processing systems. It allows users to design and implement radio communication systems on general-purpose computers using readily available, low-cost external RF hardware.In this experiment we have used the GNU-Radio software to retrieve and analyse the data.

IV. OBSERVATION

Radiation Pattern : A number of type of antennas were observed for the radiation patterns. Occasionally, fine-tuning the antenna match is necessary to optimize the transmission and reception of radiation for various antennas, ensuring maximum forward power. For low-gain antennas, adjusting the distance between the Transmitting mast and Receiving mast may be necessary to achieve adequate signal levels at the RF Detector. If low readings persist for low-gain antennas, set the Directional Coupler's DPM reading to 50 Micro Amp and then adjust the RF detector's level to display three-quarters of the main unit's reading. This process enhances the overall performance and signal reception for different antenna configurations.

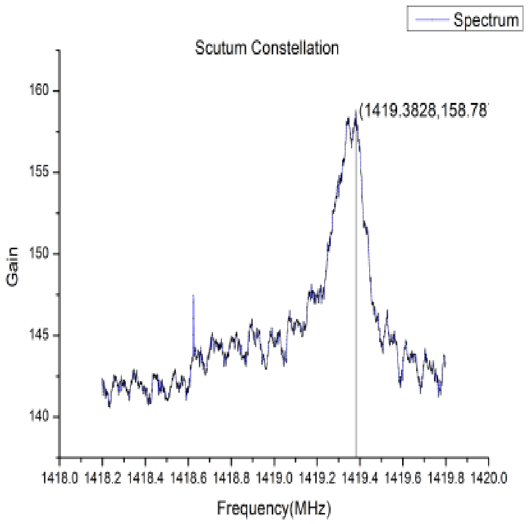
V. RESULTS AND ANALYSIS

A. 21 cm HI line signals

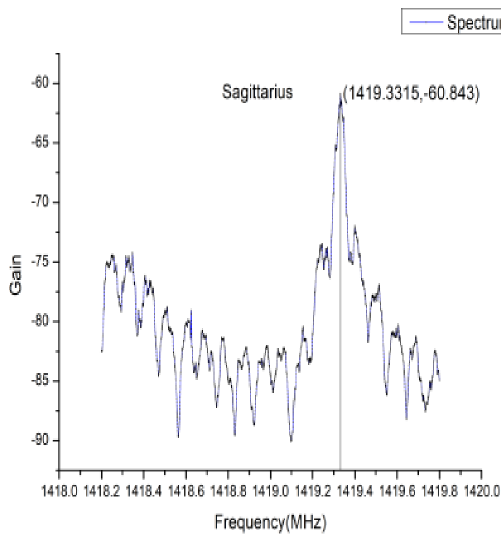
Due to the horn setup's instability and a considerable wind disturbance, it was not possible to direct the telescope precisely, therefore we pointed it toward a few constellations on the galactic plane. The data that has been noticed is as shown below. Signal gain values vary because of various calibration periods, climates, and various days of observation. There is a five-minute integration time.

1) Scutum Constellation, Observed

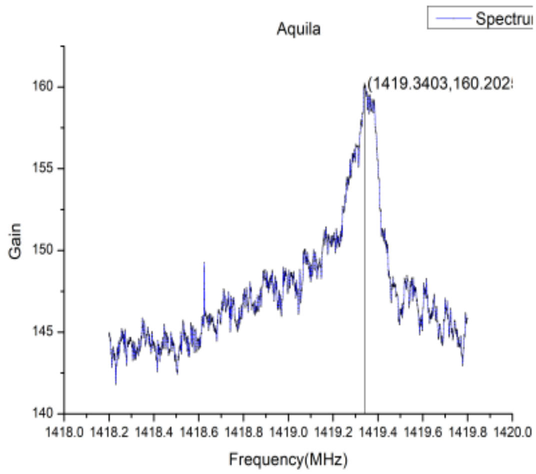
Peak at Frequency = 1419.3828 MHz



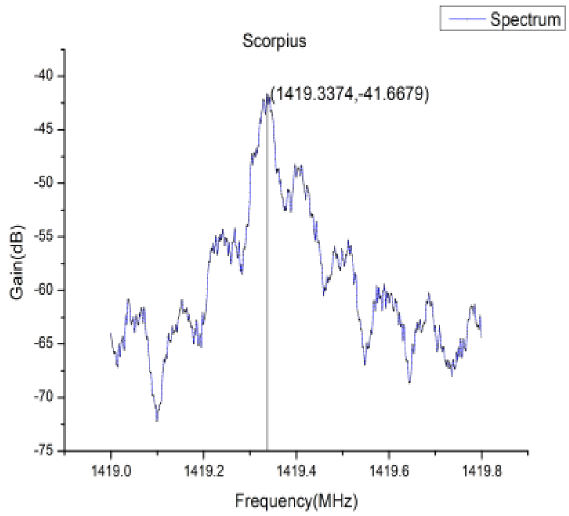
2) Sagittarius Constellation, Observed Peak at Frequency = 1419.3315 MHz



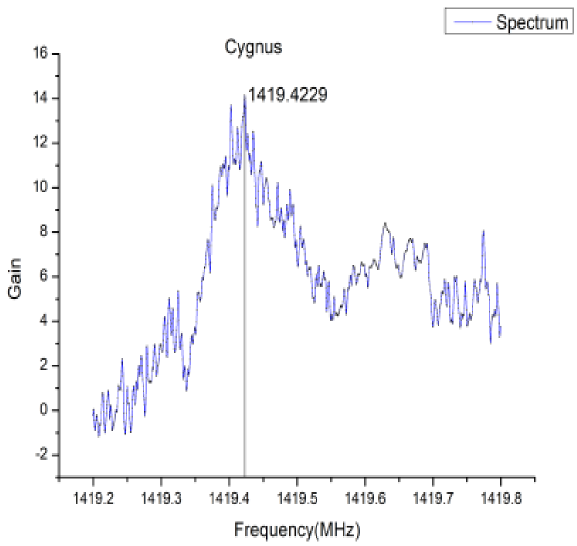
3) Aquila Constellation, Observed Peak at Frequency = 1419.3403 MHz



4) Scorpius Constellation, Observed Peak at Frequency = 1419.3374 MHz

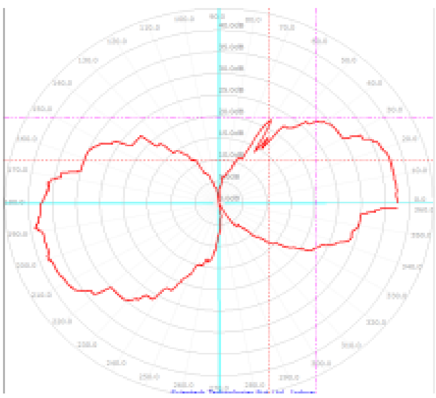


5) Cygnus Constellation, Observed Peak at Frequency = 1419.4229 MHz

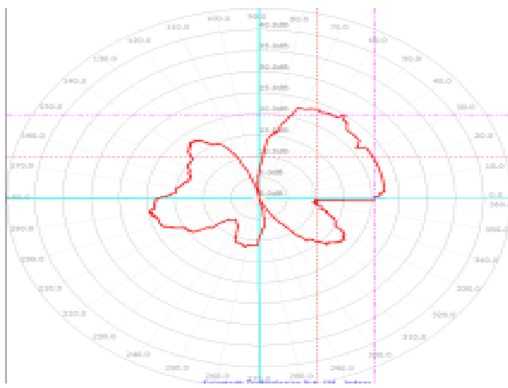


B. Radiation Pattern

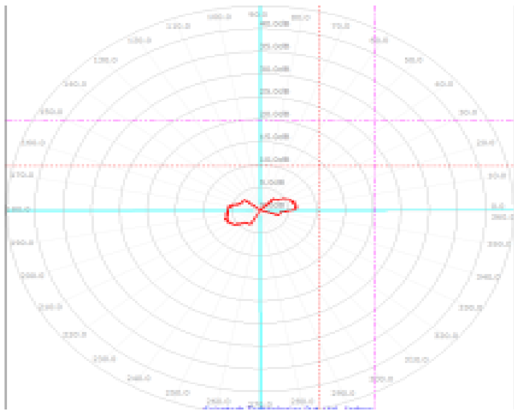
The observed radiation patterns are attached below (The angles are in θ degree and gain in dB):
1. Simple Dipole $\lambda/2$



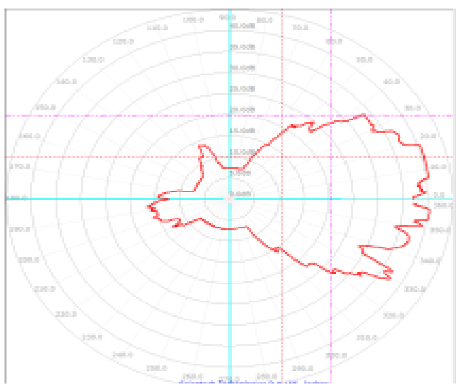
2. Simple Dipole $3\lambda/2$



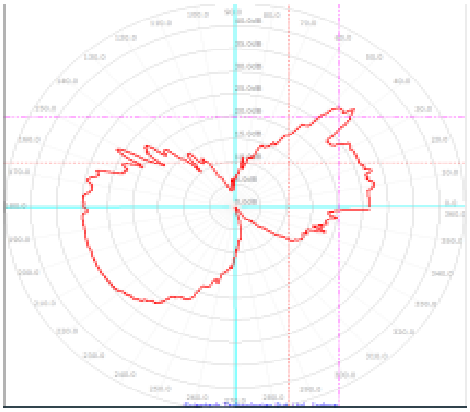
3. Simple Dipole $\lambda/4$



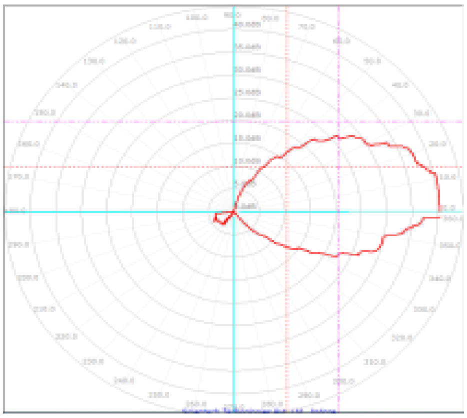
4. Phase Array $\lambda/2$



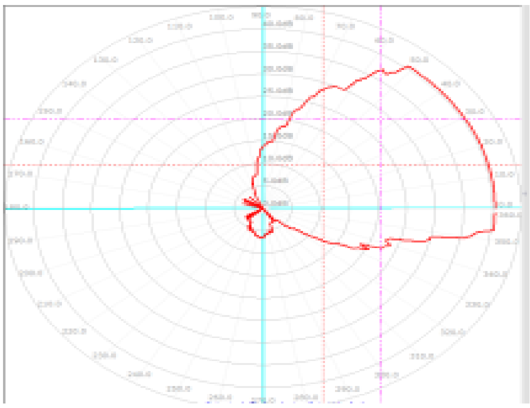
5. Phase Array $\lambda/4$



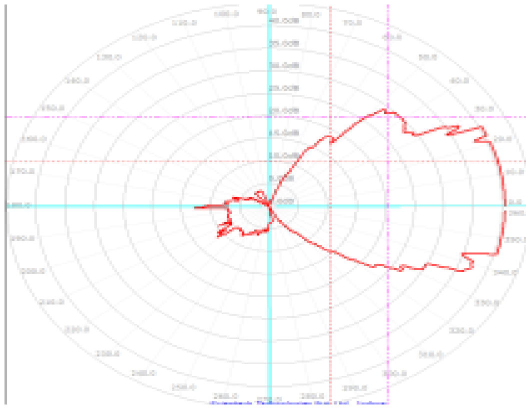
6. YagiUda 5 Element Folded Dipole



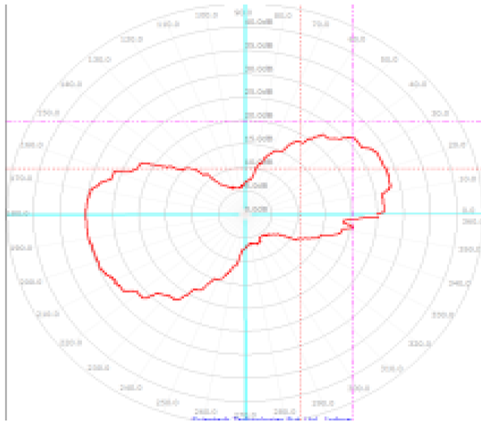
7. YagiUda 5 Element Simple Dipole



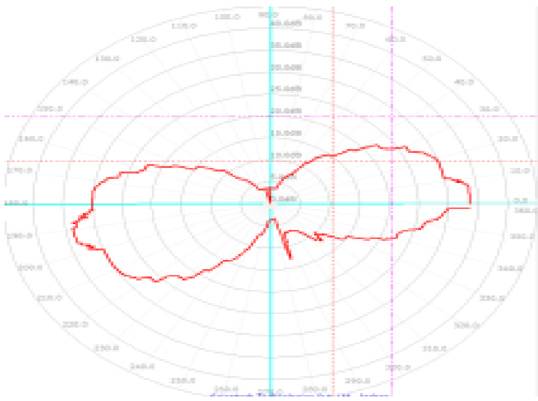
8. YagiUda 3 Element Folded



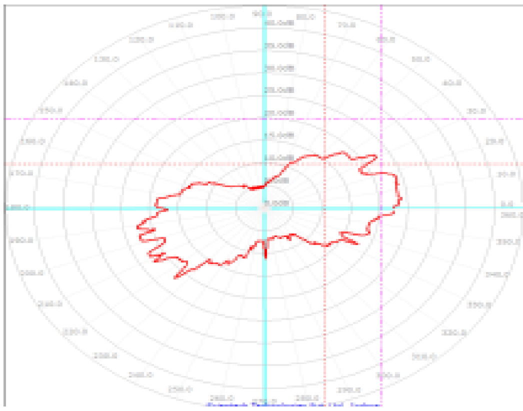
9. YagiUda 7 Element Simple Dipole



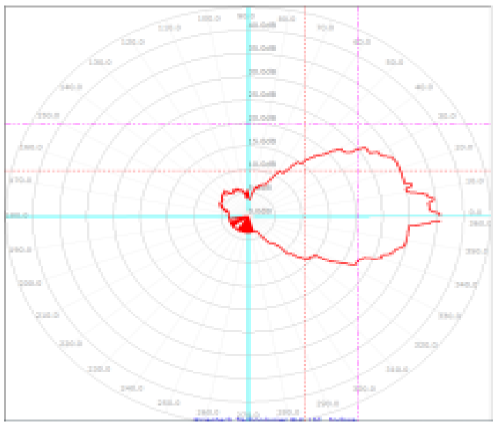
10. Combined Co-linear Array



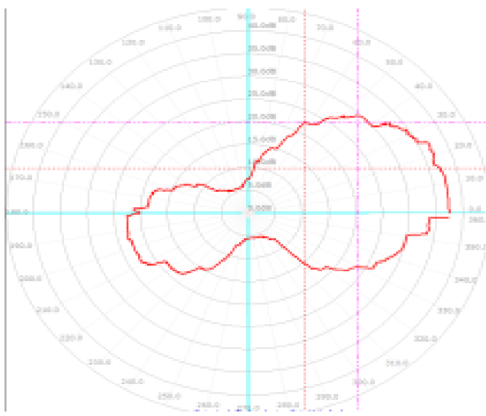
11. Hertz Antenna



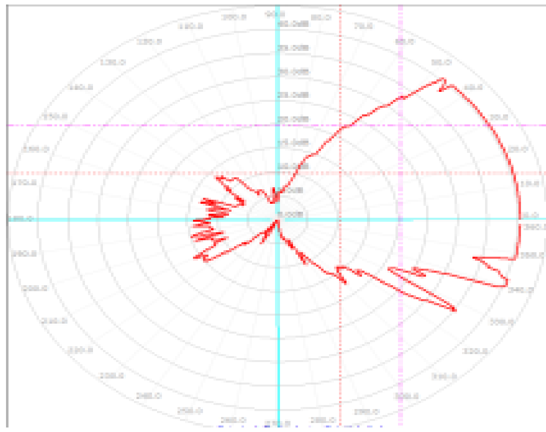
12. Log-Periodic Antenna



13. Loop Antenna



14. Zeppelin Antenna



VI. CONCLUSION

Observation of 21-cm Radio Signals in Galactic Constellations : Some sources of error were found during the experiment's initial phase, which involved observing 21-cm radio emissions inside particular constellations in the galactic plane. Potential interference from terrestrial radio transmissions posed a serious problem since it may introduce noise and compromise the precision of our observations.

Furthermore, changes in the atmosphere, like as shifts in humidity and temperature, may have an impact on signal strength. Our efforts to reduce the impact of these ambient variables on our data, including thorough calibration and signal processing, were not entirely successful. Furthermore, it was difficult to precisely identify the features of the recorded 21-cm signals due to the sensitivity of our equipment and the intrinsic complexity of the interstellar medium.

Analysis of Radiation Patterns in Different Radio Antenna : We ran into a few sources of inaccuracy in the second portion of the experiment, which examined the radiation patterns of several radio antennas. Variations in the electromagnetic environment, poor connectors, and cable losses all had an impact on the accuracy of our measurements.

Although calibration techniques were put in place to reduce these mistakes, some degree of uncertainty remained. In addition, there were small variations in the observed radiation patterns due to the actual use of antenna configurations and the mechanical stability of the rotating systems.Not withstanding these difficulties, an attempt was made to measure and talk about how these errors might affect the reliability and validity of our findings. In general, identifying and resolving these error sources offers a thorough grasp of the constraints related to our experimental design and data interpretition.

VII. FUTURE PROSPECTS

1. After we got the signals if possible we can try to map the rotation curve using the observation data we got of 21 cm Hydrogen emission lines signals from the radio sources using horn antenna, and thus verify the theoretical model with our observations.

2. We can collect more data to get precise measurements of the velocity as well as other parameters like temperatures, etc.

VIII. PECAUTIONS

1. Use the radio telescope gentle and make the joinings more precise.

2. Avoid movements of the antennas to reduce noise and errors.

IX. REFERENCES

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