ASTROLAB

An Accessible Galactic Neutral Hydrogen Measurement Using a Kitchen *Karahi* extending the antenna design proposed in [L.W.H. Fung, A.W.K. Lau, *et al.* https://arxiv.org/abs/2309.15163]

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ABSTRACT

Recent advancements in radio observation have empowered astronomers to overcome obstacles presented by light pollution in urban areas. This current study delves into the utilization of *karahi* based antennas as a novel approach to observing celestial phenomena, with a specific focus on the emission of galactic neutral hydrogen. By capitalizing on radio waves' exceptional ability to penetrate urban noise, in conjunction with advanced digital signal processing techniques and Software-Defined Radios (SDRs), precise measurements of galactic emissions can be attained. The paper provides comprehensive insights into the design, construction, and optimization of *karahi* antenna, elucidating engineering considerations and addressing practical challenges encountered throughout the project. Through a combination of simulation studies and field observations, the study showcases the potential of *karahi* antenna in radio astronomy applications, thereby offering a promising avenue for facilitating accessible astronomical research and promoting public engagement efforts. The basic idea derives from [https://arxiv.org/abs/2309.15163].

Keywords: Astronomy, Radio Observation, *karahi* Antennas, Galactic Neutral Hydrogen, Light Pollution, Software-Defined Radios, Digital Signal Processing, Urban Astronomy, Radio Astronomy

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1 Introduction

Engaging the public with astronomy, particularly in urban areas plagued by intense light pollution, has long been a challenge. However, recent strides in radio observation technology offer promising solutions. One such innovation involves the use of *karahi* antennas to measure galactic neutral hydrogen, a critical element in understanding our galaxy's structure and dynamics. This strategy is extensively discussed in[1,2], where significant advancements were achieved in this field. *Karahi* is a traditional cooking utensil widely used in the Indian subcontinent. It is a thick, circular, and deep pot made from cast iron, stainless steel, or copper, designed for deep frying and slow cooking.

The idea of employing *karahi* antennas for astronomical observation arose from recognizing radio waves' ability to penetrate urban noise and atmospheric disturbances. Unlike optical wavelengths, radio waves are less affected by light pollution, making them ideal for celestial observations even in noisy urban settings. Through the application of digital signal processing techniques and affordable hardware like Software-Defined Radios (SDRs), astronomers can capture and analyze radio emissions from space with remarkable precision.

Traditionally associated with culinary usage in the kitchen, the *karahi*-based antenna provides an inventive alternative to conventional parabolic dish antennas. Its concave shape resembles a parabola, offering a cost-effective means of capturing and focusing radio signals. By combining a dipole antenna with the *karahi* reflector, researchers can enhance signal reception and sensitivity, especially in narrow band observations targeting the 21 cm emission line of neutral hydrogen. The origin of the 21 cm line in physics stems from the hyperfine structure of neutral hydrogen atoms. This phenomenon involves transitions between the spin orientations of the electron and proton, emitting radiation at a distinct wavelength of approximately 21 centimeters. This characteristic wavelength facilitates the study of galactic dynamics and cosmology by astronomers[3,4].

This project draws inspiration from past endeavors in amateur radio astronomy and builds upon principles outlined in publications such as "Digital Signal Processing in Radio Astronomy" (DSPiRA) or SDRSharp. DSPiRA is a code which is written in GNU Radio for radio telescopes. Integration of GNU Radio or SDRSharp software and hardware components like the HackRF One SDR empowers researchers to implement sophisticated signal processing algorithms and conduct precise measurements of galactic neutral hydrogen emissions[2,5]. The block diagram of Figure 1 describes the setup of radio telescope.

In this paper, we delve into the design, construction, and optimization of *karahi* antennas for measuring galactic neutral hydrogen emissions. We explore engineering considerations including antenna geometry, impedance matching, and signal processing techniques, highlighting practical challenges and innovative solutions encountered during the project. Additionally, we present simulation results and experimental data from field observations, demonstrating the feasibility and effectiveness of *karahi* antennas.

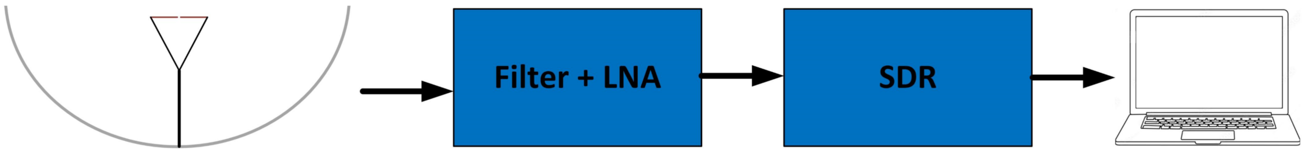

Figure 1. A block diagram of the radio telescope describing a dipole antenna which is coupled in a *karahi* reflector, a filter with LNA to improve SNR before processed by the SDR and a software (GNU Radio) for extracting meaningful information about galactic neutral hydrogen. Here LNA = low-noise amplifier and SDR = software-defined radio.

1.1 Historical Background

In earlier research, Rubin conducted studies on the speeds at which stars within the Milky Way were moving away, revealing velocities that exceeded what could be accounted for solely by gravitational interactions among the stars. This finding has commonly been interpreted as evidence supporting the existence of dark matter[6].

The structure of the Milky Way remains a subject of significant scientific interest today. Serving as the galaxy that houses Earth, it provides a valuable platform for studying galaxy formation. The ability to identify individual stars within the Milky Way allows for precise dating of star formation events within the context of the galaxy[7–9].

The motion of neutral hydrogen within the galactic plane is one primary focus of the current project, as it encompasses the distribution of particles' phase space, encompassing stars and gas particles. This movement is influenced by diverse mechanisms of galaxy formation and the structure of the dark matter halo, thereby impacting their velocity distribution. Hence, studying the motion of stars within the galaxy offers valuable insights into the nature and characteristics of dark matter[10,11].

Theoretically, with notable improvements in the system's noise figure, it could be utilized to investigate extragalactic 21 cm emission, requiring a narrow beam to minimize interference from the galactic foreground. Given that hydrogen makes up approximately 70% of the universe, accurately mapping its distribution holds promise for significant cosmological insights. Extragalactic 21 cm tomography is currently a standard technique for studying matter distribution on large scales (approximately 100 Mpc), with numerous research-class radio experiments focusing on early universe 21 cm emission. Moreover, there are ongoing efforts to enhance designs for 21 cm detection[12,13].

The spatial distribution of 21 cm emission provides valuable indications about the distribution of cold gas, as it closely correlates with the distribution of dark matter. Research into the sudden absence of 21 cm emission from the early universe is actively pursued, attributed to cosmic reionization, during which most neutral hydrogen became ionized due to the emergence of the first generation of stars[14,15].

1.2 Educational Versatility: Tailoring Learning Opportunities with the *Karahi* Antenna

The *karahi* system offers valuable opportunities for educational use across a wide spectrum, from elementary school to undergraduate levels. For students with basic mathematical skills, the focus can be on utilizing the *karahi* system to observe and gather real-time data. Complex data analysis can be simplified to allow students to concentrate on understanding astronomical implications.

On the other hand, students with a stronger background in mathematics and engineering can delve into both the hardware and software aspects of the telescope. This project not only involves astronomy but also serves as a practical application for digital signal processing and radio-frequency electronics. Understanding concepts like Fourier transform is essential for processing the data collected by the radio telescope accurately. Additionally, knowledge of engineering principles in radio-frequency, such as impedance-matching, shielding, and signal balancing, plays a crucial role in optimizing the system's sensitivity and ensuring successful detection of the hydrogen signal.

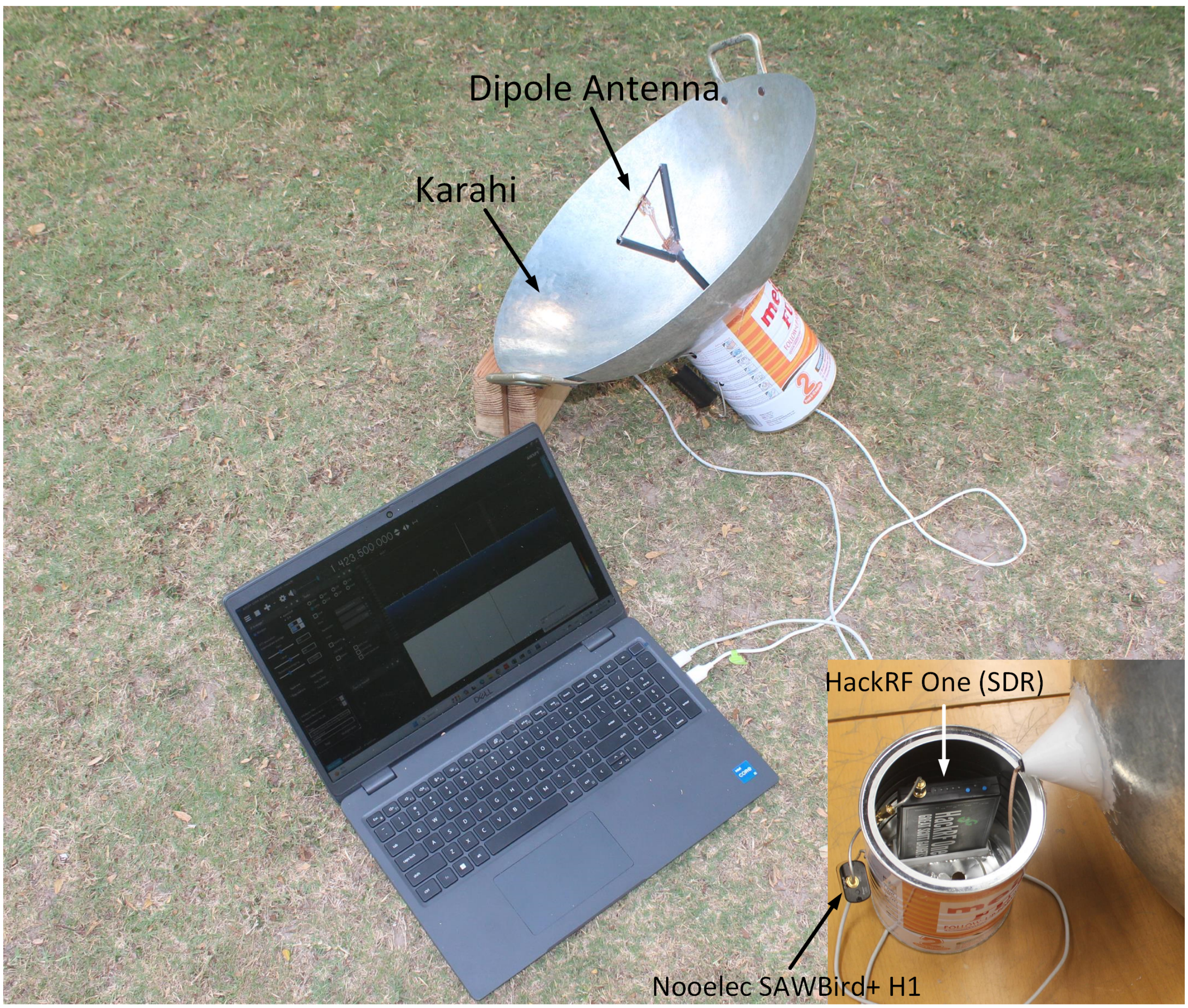

Figure 2. The Galactic dish (GD) system containing the *karahi*, dipole antenna, pre-amplifier and a HackRF One for signal processing.

Recent advancements in software-defined radio (SDR) technology have democratized radio observation, making it accessible to the general public. SDR serves as an integrated instrument that can convert radio signals into a data stream readable via standard USB output to a computer. The cost of SDR varies from as low as $40 to a few hundred dollars for hobbyists, and even a budget-friendly $40 SDR can effectively measure the diffuse emission from the Milky Way.

Inspired by this accessibility, we build upon a cost-effective design for a radio telescope tailored for educational purposes. This radio telescope is specifically designed for observations at 1.42 GHz, the emission frequency of the 21 cm forbidden transition from neutral hydrogen. While the telescope's gain profile is optimized at 1.42 GHz, it can also capture neighboring wavelengths despite a slight drop in sensitivity. We deliberately selected easily accessible materials for constructing the telescope. Aside from electronic components readily available for online purchase, another hardware component can even be found in a typical kitchen. The primary reflector of the telescope is a *karahi*, commonly used for stir-frying. Coupled with a dipole antenna made of copper wire optimized for 21 cm observations, the *karahi* serves as an efficient reflector. To shield the readout electronics from noise, we encase them in a metallic cookie box. We've named this system a "Galactic Dish" (GD). Figure 2 depicts the complete GD system.

Previous amateur radio telescope designs targeting 21 cm emission often utilized commercial satellite dishes as antennas. However, these dishes are typically customized for WIFI or satellite transmission frequencies and are not optimized for 21 cm hydrogen line detection. Additionally, their relatively higher focal ratios are suboptimal for weak radio astronomy sources. While other projects have explored horn antenna designs optimized for 21 cm detection, these antennas are also larger in size compared to *karahi* antennas to achieve similar gain characteristics. Most of these projects were conducted in radio quiet areas, rendering extra noise shielding unnecessary. In contrast, the GD project aims to address these issues. We provide detailed documentation of the antenna design and underlying engineering considerations, with a focus on noise mitigation. Additionally, we outline the data analysis pipeline and the dark frame calibration procedure necessary for improving signal-to-noise ratio (SNR) in noisy environments[16–19].

2 Hardware Setup

Here we discuss each component of the Figure 2 in detail.

2.1 *Karahi* Antenna Design

In our pursuit of educational initiatives, our objective is to develop a 21-cm line antenna that fulfills specific criteria: simplicity, lightweight construction, and cost-effectiveness. We aim to keep the price below a hundred US dollars, ensure a weight of less than 5 kg for easy single-person deployment, and design it without the need for extensive machining. Moreover, durability is paramount for conducting multiple experiments, and the antenna should be self-standing without requiring external support.

Traditionally, hobbyists constructing small-scale 21-cm radio antennas have favored the horn and waveguide design, often utilizing thick aluminum boards or cardboard combined with aluminum foil[2, 17–19]. However, challenges such as the high cost of obtaining large aluminum boards, especially in regions like

Pakistan, and the lack of durability in cardboard-aluminum combinations in humid climates have prompted us to explore alternative designs. Inspired by modern radio observatories' preference for parabolic dish reflectors, particularly the deep dish reflector design observed in projects like CHORD, we seek to adapt kitchenware for potential use as a radio reflector[20]. Despite the unsuitability of most kitchen utensils due to their flat bottoms, we discovered that commercial *karahis*,also known as *karahis*, closely resemble small dish reflectors in geometry. These *karahis*, crafted from iron sheets and featuring a large, deep, round bottom, meet our requirements for lightweight construction and suitable reflectivity. Consequently, we obtained a 431.8 mm *karahi* from a local outlet for approximately $15 to conduct tests, with further discussions on finalizing the antenna design centered around determining its geometry and focal point. The dimensions of the *karahi* and inserted dipole antenna on the *karahi* are shown in Figure 3.

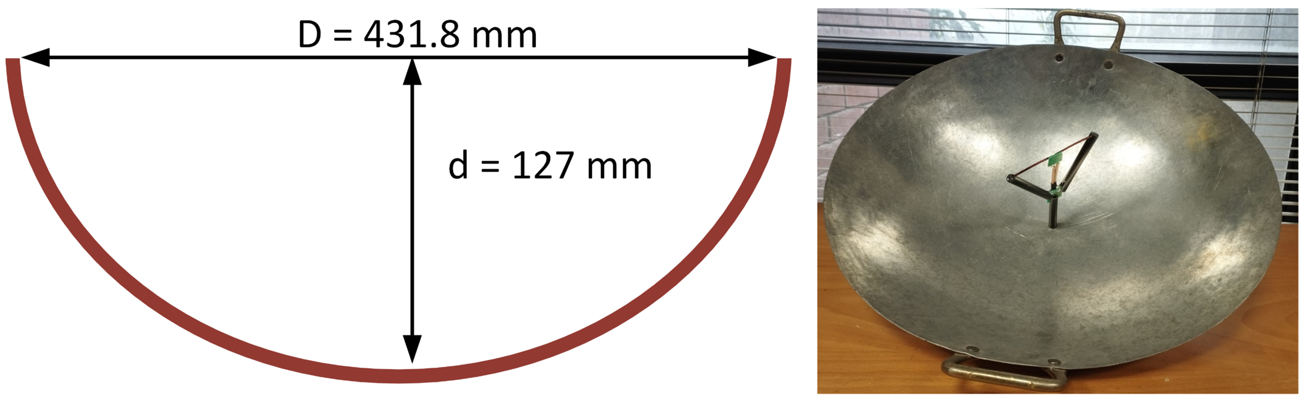

Figure 3. On the left, we depict the dimensions of the *karahi*. To the right, the dipole antenna is inserted in the *karahi* by measuring the center of the *karahi*.

2.2 Focal Point Determination

We describe the process of determining the focal point crucial for optimizing the signal strength of a 21 cm line antenna. We begin by examining how the geometric properties of the reflecting surface influence the calculation of the focal point, particularly focusing on parametric shapes such as spherical and parabolic surfaces. Given the dimensions of our antenna, with a measured diameter of 431.8 mm and a depth of 127 mm, we undertake the calculations for parabolic configurations to estimate their respective focal lengths. The focal length for a parabolic surface is calculated by $h_f = \frac{r^2}{4\times d}$, where r is the radius and d is the depth of the *karahi*. The predicted focal point, calculated is $h_f = 91.8$ mm, reflects adjustments made to accommodate variations in dielectric properties. However, the focal point according to the simulation $h_f{}^*$ is 143 mm. These adjustments are aligned with the construction parameters outlined in Table 1, ensuring coherence between theoretical estimations and practical implementations of the antenna system.

2.3 Crafting the Dipole Antenna

To effectively capture electromagnetic waves and convert them into electric current, it's crucial to position the antenna element at the focal point of the *karahi* reflector. One commonly used antenna type for

Reflector Diameter	431.8 mm
Reflector Depth	127 mm
Dipole antenna total length	105.5 mm
Focal length h_f	91.8 mm
Adjusted length of antenna	97.5 mm
Adjusted focal length $h_f{}^*$	143 mm
Directivity	10.97 dBi
Impedance	$(51.23 - 0.16j)\Omega$

Table 1. Specifications of the GD. The upper section lists measured quantities, while the lower section (below the horizontal line) contains derived values obtained from simulation. The adjusted focal length refers to the optimal focal length following adjustment for impedance matching and differs from the geometrical focal length.

this purpose is the dipole antenna, valued for its simplicity and widespread applicability, offering an omnidirectional radiation pattern that efficiently illuminates the deep *karahi*[21]. Given the dipole antenna's insensitivity to the axial direction, the illumination across the *karahi* tends to be around 70%. The term "illuminates" here refers to the process of directing electromagnetic waves towards the reflector in a way that maximizes their coverage and effectiveness in capturing or reflecting signals. By using a dipole antenna with its omnidirectional radiation pattern, the waves are efficiently spread across the reflector's surface, ensuring good coverage and efficient signal capture or reflection.

Our dipole antenna is constructed using robust 2 mm copper wires, ensuring structural integrity and resistance to bending. Ideally, each arm of the dipole antenna should measure $\lambda/4$, approximately 53 mm, with a negligible gap between them to achieve an overall length of $\lambda/2$. The wavelength λ can be calculated by $c = f\lambda$. The schematic in Figure 4 describes the dipole antenna design. However, practical considerations, such as soldering requirements and the need to prevent short circuits, necessitate slight adjustments to the arm length. Fine-tuning of the arm length is also undertaken to optimize sensitivity and ensure impedance matching with the *karahi* reflector. The finalized design parameters are outlined in Table 1. Naturally, a free-standing dipole antenna in air exhibits an impedance of $(73+43j)\Omega$. By coupling the dipole antenna with our *karahi* reflector, we aim to align the overall antenna impedance with the input impedance of the readout system, approximately $(50+0j)\Omega$. The detail about antenna construction can be seen in A.

2.4 Simulating the Galactic Dish

The geometry of both the antenna and the *karahi* were optimized after conducting simulation using the MATLAB antenna toolbox. These simulations were performed by assuming the *karahi* as a parabolic in shape. The simulation process and Matlab code is given in B. The radius of the *karahi* is set to 215.9 mm. The impedance profile resulting from the simulations is presented in Figure 5 a).

To attain optimal impedance matching, we adjusted the length of the dipole antenna to 97.5 mm, slightly shorter than the theoretical value of $\lambda/2 = 105.5$ cm. This adjustment ensured a matched

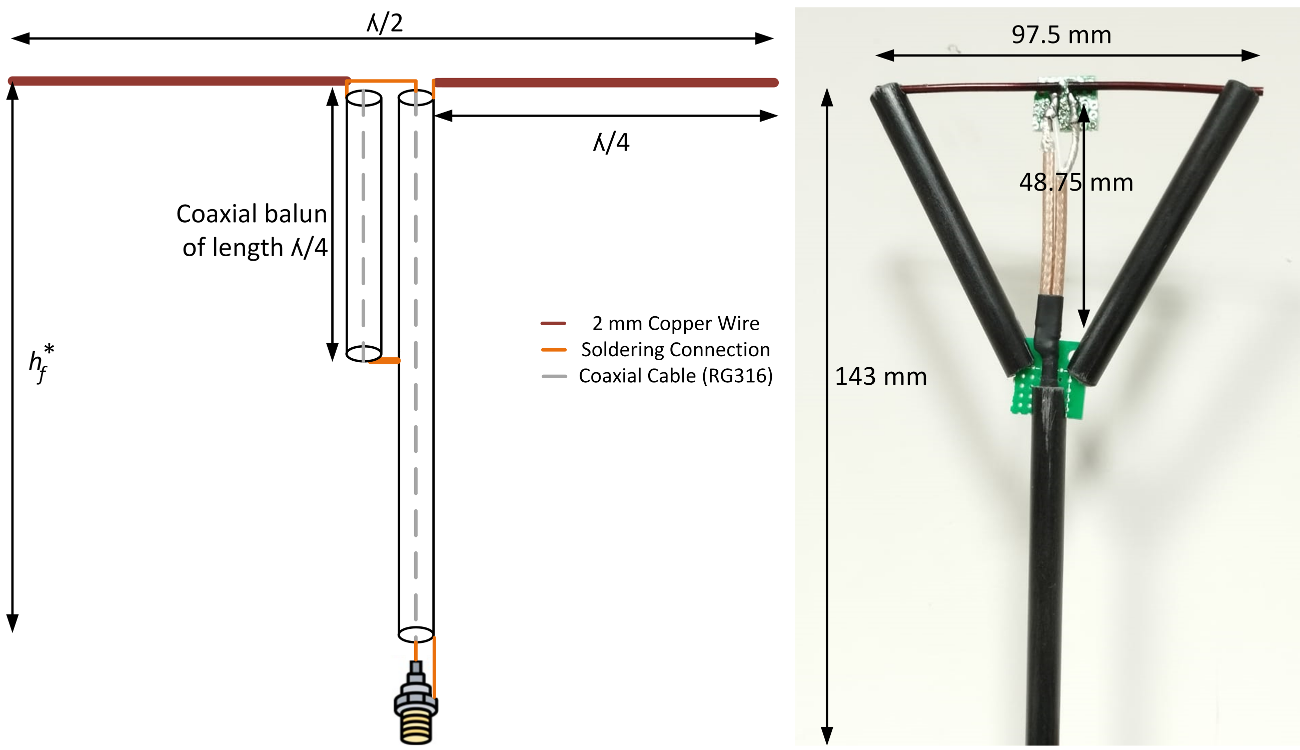

Figure 4. On the left, the schematic of the dipole antenna is depicted. To the right, we can see the mechanical arrangement of the dipole antenna, featuring a black diagonal structure providing mechanical support to prevent deformation of the copper wire dipole. A coaxial balun measuring 53 mm in length is visible. Moreover, the adjusted focal length and antenna length are also depicted for reference.

impedance of $(50+0j)\Omega$ at a focal length of 143 mm. Further reduction in the focal length could enhance impedance matching to $(51.23-0.16j)\Omega$, reducing return loss, although this would come at the expense of decreased directivity due to a smaller illumination area. Figure 5 b) illustrates the directivity, indicating that our antenna design can achieve a directivity of 10.45 dBi under ideal conditions. The finalized specifications for the antenna are summarized in Table 1.

3 The Radio Hardware

3.1 Achieving Signal Symmetry

The natural symmetry of a dipole antenna, where both arms carry the same signal strength, contrasts with most reading systems that rely on asymmetrical setups with a wire connected to ground. When you connect a symmetrical antenna to such an asymmetrical system, you risk losing signal and encountering accuracy issues because of ground reflections. To address this problem, we introduced a folded quarter-wave balun design, depicted in the right panel of Figure 4. This design enables a smooth conversion of impedance from a balanced 50 Ω signal to an unbalanced 50 Ω signal using two parallel coaxial cables, resulting in minimal signal loss and a compact setup.

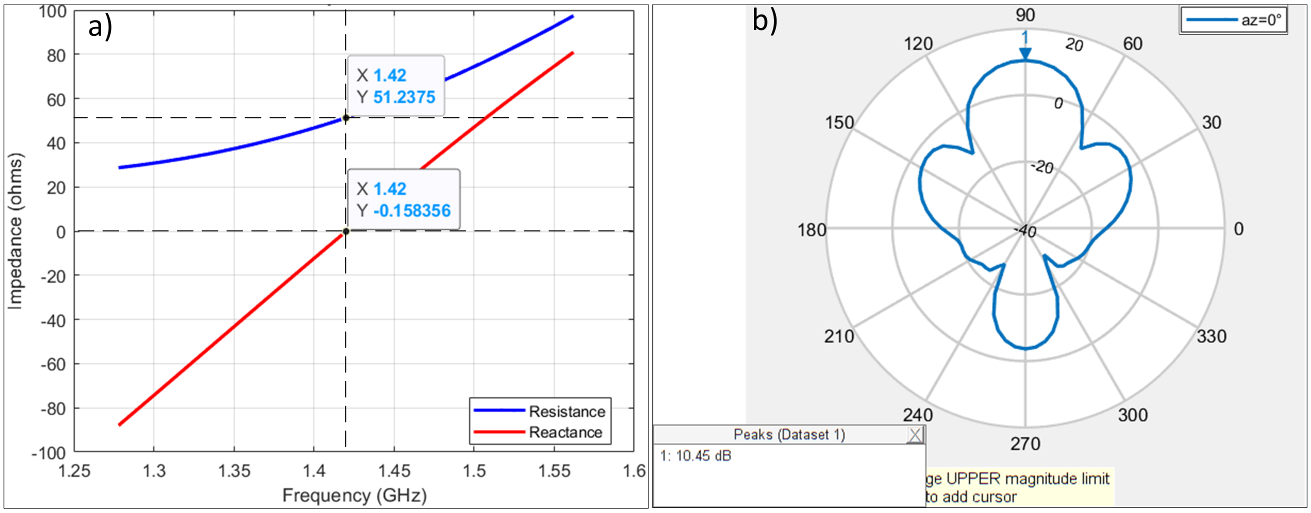

Figure 5. a) Simulated impedance of the reflector-antenna system, from 1.25 GHz to 1.6 GHz, b) the projected directivity profile along the section that cut the plane of highest directivity gain.

3.2 Pre-amplifier

Upon capturing the incoming radio wave, the dipole antenna channels the signal along the transmission line, a path covering a short distance equivalent to the adjusted focal length of the *karahi*. To minimize cable loss, our initial amplification stage is positioned immediately behind the *karahi*. Utilizing the Nooelec SAWBird+ H1, this first-stage amplification system implements a surface acoustic wave filter. This filter effectively isolates the signal at the frequency of 1408 MHz, shielding it from unwanted noise that may interfere within the readout system. Following filtration, the signal enters the amplification module, yielding a gain of 42 dB at 1420 MHz with bandwidth of 65 MHz, specifically tailored for the 21 cm emission[22]. A flow diagram of the amplifier is shown in Figure 6 a). Operating within a voltage range of $3-5$ V, aligning with the USB-driven power supply standard, the amplifier is powered through a dedicated bias-T design, see Figure 6 b). A bias tee is a device that lets you send both a radio signal and a DC power signal down the same wire. This configuration ensures the DC power shares the same interface with the RF output, enabling the LNA to draw power indirectly from the computer's USB interface via the software-defined radio, a setup meticulously designed to prevent any potential signal contamination stemming from minor fluctuations in the DC power supply.

3.3 The Software Defined Radio (SDR) Device

Following the initial amplification stage, the signal proceeds to the SDR device. The HackRF One, created by Great Scott Gadgets, is a versatile Software Defined Radio peripheral capable of transmitting or receiving radio signals across a wide frequency range from 1 MHz to 6 GHz[23]. It serves as a valuable tool for testing and developing modern and future radio technologies, offering an open-source hardware platform that can be utilized as a USB peripheral or programmed for standalone operation. Key features of the HackRF One include its operating frequency spanning from 1 MHz to 6 GHz, half-duplex transceiver

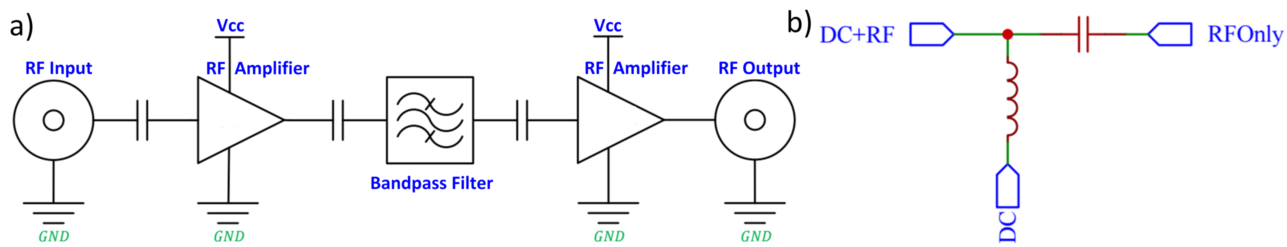

Figure 6. The schematic layout depicts the internal configuration of the Nooelec SAWBird+ H1 amplifier, providing insight into its electronic components and connections[22]. b) The bias-T design refers to a circuit topology used to introduce a DC bias into a coaxial transmission line while allowing RF signals to pass through unaffected. This design is commonly employed in RF systems to power active components such as amplifiers or LNAs (Low Noise Amplifiers) through the same coaxial cable used for signal transmission.

functionality, support for up to 20 MHz sampling rate, and compatibility with various software such as GNU Radio and SDR. It provides software-configurable RX and TX gain, along with baseband filter, and allows for software-controlled antenna port power. The device is powered via Hi-Speed USB 2.0 and comes with convenient programming buttons and internal pin headers for expansion.

4 The Radio Software

GNU Radio and SDRSharp are powerful tools in the realm of software-defined radio (SDR) technology. GNU Radio is an open-source toolkit that provides signal processing blocks to implement software radios. It offers a wide range of functionalities for creating radio systems and experimenting with various modulation techniques. With GNU Radio, users can design custom signal processing flows using a graphical interface or by coding in Python[24].

On the other hand, SDRSharp is a popular software application specifically designed for use with SDR hardware. It provides a user-friendly interface for tuning into radio frequencies, visualizing spectrum data, and demodulating signals. SDRSharp supports a wide range of SDR devices and offers features such as frequency scanning, signal recording, and audio playback[25].

Both GNU Radio and SDRSharp are widely used by radio enthusiasts, amateur astronomers, and researchers for exploring radio frequencies, including the 21 cm line emission of neutral hydrogen in the galaxy[26]. They provide essential tools for capturing, processing, and analyzing radio signals, making them indispensable in the field of radio astronomy and SDR experimentation. To detect the hydrogen line, it's essential to utilize software that can integrate or average numerous Fast Fourier Transform (FFT) samples over time. This averaging process helps mitigate the quantization noise inherent in software-defined radios (SDRs), thereby enhancing the visibility of the faint hydrogen line peak. Given the relatively slow movement of the galaxy across the sky, it's feasible to conduct averaging for intervals of 5 to 10 minutes at a stretch, ensuring sufficient data accumulation for accurate detection.

In this project we'll use SDRSharp, as we found it to be more user friendly and possesses built in

GUI that accelerates the process to measure galactic neutral hydrogen. So our main focus will be on it. The installation of GNU Radio and the required DSPiRA GNU Radio code for measuring hydrogen can be seen in C. We'll also incorporate a freely available astronomy program called Stellarium to track the movement of the Milky Way's galactic plane across the sky. The idea is to orient the GD in the direction of the desired stellar constellation in the Milky Way.

4.1 Setting up Stellarium and Aligning the Dish

1. Begin by downloading Stellarium from its official website[27]. Download the Windows version using the prominent button located at the top of the page if you are using windows.

2. Upon launching Stellarium, you may notice that stars are not visible if the program simulates daylight conditions. To remedy this, press the 'a' key to disable atmospheric effects. Figure 7 depicts the user interface of the Stellarium software, showcasing its intuitive design and comprehensive features for exploring the cosmos.

Figure 7. The user interface of Stellarium software, highlighting its intuitive design and comprehensive features for exploring the cosmos.

3. Navigate to the options menu by pressing the `F4` key. Here, consider adjusting the brightness of the Milky Way to enhance its visibility. Increasing it to 6.0 is recommended for optimal viewing.

4. Within the markings tab of the options menu, activate the Azimuthal grid feature. This grid provides a useful marker for identifying Zenith, the point directly overhead.

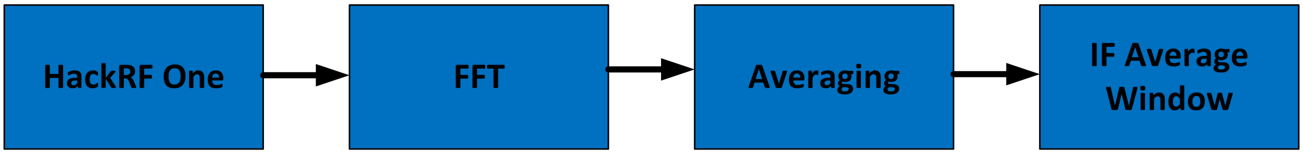

Figure 8. Flow diagram depicting the operational sequence of SDRSharp with the HackRF One device, illustrating signal acquisition, FFT processing, averaging, and display in the IF average window.

5. Verify the accuracy of the location displayed in the bottom left corner of the screen. If necessary, correct it by pressing `F6` and entering the correct coordinates.

6. Use the mouse controls to zoom out until the entire sky is visible on the screen. Adjust the camera's orientation to face Zenith for a comprehensive view of the celestial sphere.

7. Stellarium typically opens in full-screen mode. To switch to windowed mode, simply press F11 for a more convenient viewing experience.

8. Explore the cosmos by clicking on objects within or beyond the Milky Way. Stellarium provides detailed information, including Galactic coordinates, upon selecting an object. Right-click to remove the displayed information text and continue your exploration.

9. Use Stellarium's search function or manually navigate the sky to locate your target constellation or object. You can search for specific objects, constellations, or even specific coordinates.

10. Once you've identified your target in Stellarium, determine its direction in the sky. You can use compass directions (north, south, east, west) or altitude and azimuth coordinates.

11. Adjust the position of your dish antenna to point it in the same direction as your target in Stellarium. Use a compass or inclinometer to find the correct azimuth and elevation angles.

4.2 Setting Up SDRSharp with the "IF Average Plugin"

The flow diagram in Figure 8 illustrates the operational sequence of SDRSharp with the HackRF One device. Initially, the signal is acquired by the HackRF One. Subsequently, the signal undergoes Fast Fourier Transform (FFT) processing, which converts it from the time domain to the frequency domain. Following FFT processing, the signal enters the averaging stage, where multiple samples are combined to reduce noise and enhance signal clarity. Finally, the processed signal is displayed in the IF average window, providing a visual representation of the FFT output.

1. Setting Up SDRSharp with IF Average Plugin:

    - Begin by downloading the latest version of SDR (v1920 or newer) from its website[28].

- To read more about the hackRF One SDR which we are using in this project, you can download its complete documentation from[29].

2. Obtain the IF Average Plugin:

   - Access Daniel's GitHub repository to download the latest version of the IF average plugin.
   - On the GitHub page[30], locate the Green "Code" button and select "Download Zip" to acquire the plugin files.
   - After downloading, extract the contents of the ZIP file.

3. Copy Plugin Files:

   - Navigate to the extracted folder and locate the "SDR_AVE_new-master Release" directory.
   - Copy the following files from this directory into your SDR plugins folder:
     - `MonoGame.Framework.dll`
     - `SDRSharp.Average.dll`
     - `SharpDX.DXGI.dll`
     - `SharpDX.Direct3D11.dll`
     - `SharpDX.dll`
   - Next, locate the `ft2.xnb` file in the main"SDR_AVE_new-master" folder and copy it into the main SDR directory.

By following these steps, you can successfully set up SDRSharp with the IF Average Plugin, enhancing your SDR capabilities for effective signal processing and analysis.

4.3 Configuring SDRSharp and Preparing for Hydrogen Line Detection

1. Set Up of SDRSharp HackRF One:

   - Select the devices option from the `Menu` button and then select "HackRF One" from the devices. The `Menu` button is on the top left corner window of Figure 9.
   - Tune to the frequency of 1420 MHz by using up/down and left/right arrows to ensure this particular frequency is centered on the screen. The value of the centre frequency is depicted in the top center window as shown in Figure 9.

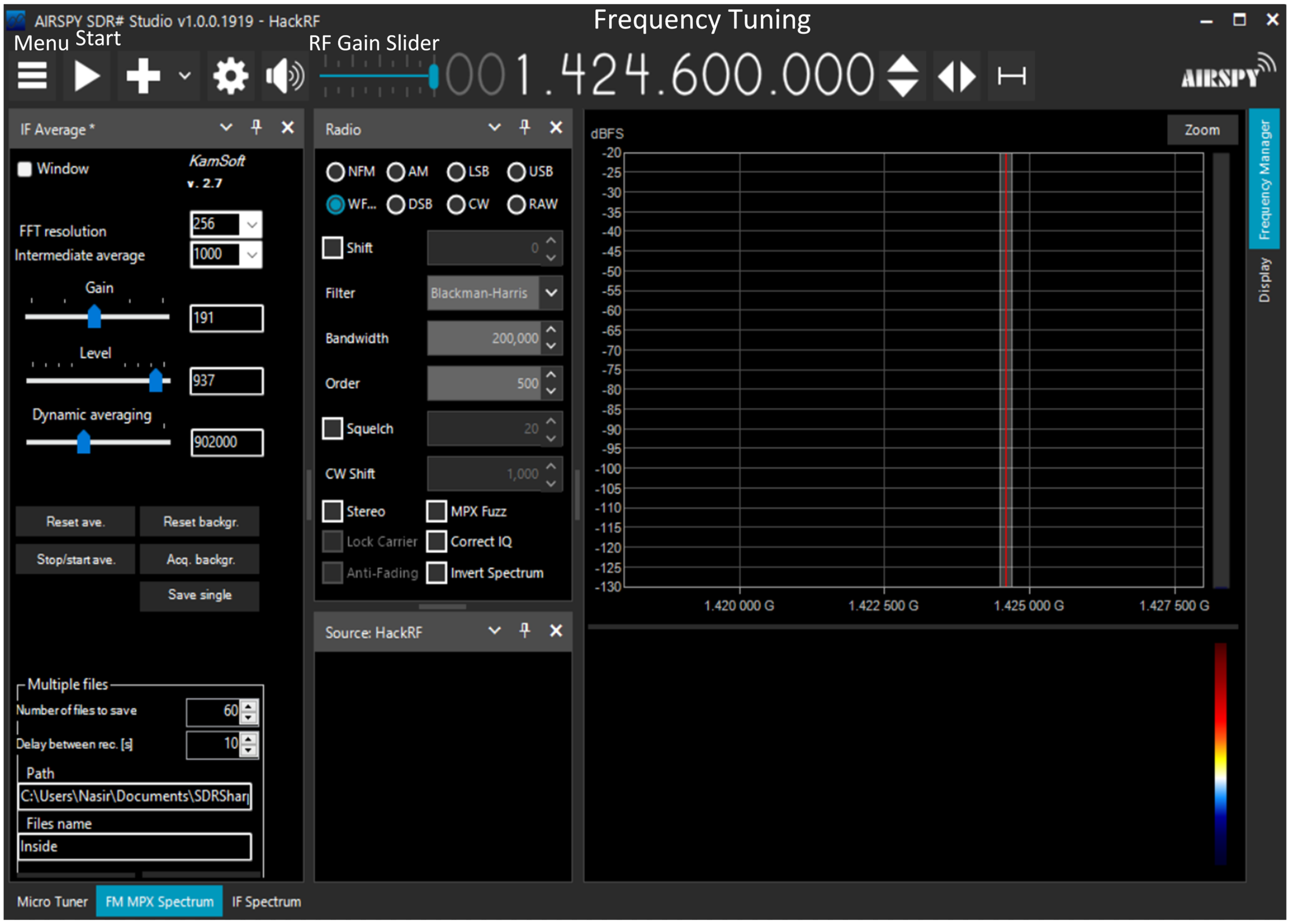

Figure 9. This figure illustrates the setup process for receiving and averaging the hydrogen line FFT using HackRF One SDR. The steps include setting up HackRF One, enabling the IF Average plugin, configuring plugin settings, performing hardware calibration, conducting a background scan, and confirming background correction. These procedures are essential for accurate detection and analysis of the hydrogen line signal.

- Shift the offset (red line in main graph window of SDR Sharp) away from 1420 MHz e.g. towards 1423 MHz.

2. Enable and Configure the IF Average Plugin:

   - Click on the `Menu` and navigate to Plugins → IF Average. Adjust this window to your desired position by dragging.
   - Adjust the following settings for optimal performance, resulting in a 10 minute averaging time (though shorter times may also suffice). See the left corner of the Figure 9:
   - The IF Average plugin in SDRSharp provides various parameters to configure and optimize the signal processing. Below are detailed explanations of the key parameters:

- **FFT Resolution:** The FFT (Fast Fourier Transform) resolution specifies the number of points used in the FFT computation. A resolution of 1024 means that the FFT will be computed using 1024 points.
- **Intermediate Average:** The intermediate average parameter defines the number of FFT frames that are averaged together to smooth out short-term variations and reduce noise.
- **Gain*:** The gain parameter controls the amplification level applied to the signal. A gain value of approximately 230 indicates a high level of amplification, which is useful for boosting weak signals to a detectable level.
- **Level*:** The level parameter adjusts the baseline or reference level for the signal display. Setting the level to 950 calibrates the display to ensure that the signal strength is represented accurately. This adjustment is important for correctly interpreting the amplitude of the received signals. (the Gain and Level slides are essentially used to adjust the graph in the IF Average Window)
- **Dynamic Averaging:** Dynamic averaging is a process that continuously averages the signal over a specified number of samples to smooth out variations and enhance signal stability. With a value of 902000, the plugin performs extensive averaging, which significantly reduces noise and fluctuations, providing a clearer and more consistent signal representation.

These parameters collectively enhance the performance and accuracy of the IF Average plugin, allowing for precise signal analysis and interpretation in SDRSharp.

**Note:* the Gain and Level slides are essentially used to adjust the graph in the IF Average Window.

3. Hardware Calibration Setup:

   - Provide power to the pre-amplifier through its MicroUSB port, and connect the Galactic Dish to the PC via USB for the entirety of the observation.
   - For calibration, connect the pre-amplifier to a 50 Ω terminator. If a 50 Ω terminator is unavailable, leave the pre-amplifier input disconnected.
   - Press the `Start` button to acquire data.
   - Check the “Window" checkbox and promptly press the “Acq. Background" button to initiate a reference background scan.
   - This background scan serves to remove the undesirable curved shape caused by the HackRF One SDR and LNA filters. The initial scan typically takes 10 minutes.

- Once the background scan completes, the message "Corrected background!" will appear in yellow text in the top left corner of the FFT average window.
- Reconnect the pre-amplifier input after the background correction process is finished, allowing for accurate signal reception and analysis.

4. Data File Saving:

   - At the bottom of the “IF Average Window," there is an option to save data from the spectrum. You can enter the number of files you want to save and the delay between consecutive file saves. This allows you to set the duration of your scan. For example, if you set the number of files to 60 and the delay to 1 second, a total of 60 files will be saved, each with a 1-second interval.
   - Input the file path where the data will be saved, along with the desired file name, then initiate multiple saves by clicking the appropriate button. For every observation, manually define the file saving path before initiating multiple saves saving in order to prevent software crashes.

5 Observations

5.1 Site Selection

The experiment is set to take place at the ground of LUMS University in Lahore, Pakistan, chosen for its practicality and accessibility (see Figure 2). While Lahore itself is a bustling metropolis, the relatively tranquil university grounds offer pockets of tranquility away from the city’s hustle and bustle, minimizing potential disruptions to the experiment. Users can find similar silent spots close to their areas of work or residence.

5.2 Survey Methodology

The best time to measure galactic neutral hydrogen emissions is during the night when the sky is clear and free from atmospheric disturbances. Additionally, selecting periods when the target region of the sky is overhead or away from the Sun’s direction can help reduce interference from solar radiation. After performing calibration, reconnect the antenna, we directed the antenna towards the Arcturus constellation to commence data collection. This direction of the constellation can be found out from Stellarium. Additionally, we initiated the averaging process by clicking the Stop/Start Avg button on the IF Average block.

5.3 Recession Velocity

In astronomy, recession velocity refers to the speed at which an astronomical object, such as a galaxy or a celestial body, is moving away from an observer. The recession velocity is crucial because it provides valuable information about the motion of the galactic neutral hydrogen gas relative to Earth. By measuring the recession velocity of the neutral hydrogen emission line, astronomers can infer the relative velocity of the gas clouds within the Milky Way. This velocity data helps scientists understand the dynamics and structure of the galaxy, including its rotation and the distribution of matter. The recession velocity can be calculated by the formula $v = c\left(\frac{1}{f_{\text{observed}}} - \frac{1}{f_{\text{rest}}}\right)$ where v is the recession velocity, c is the speed of light (3.08×10^8 m/s), $f_{observed}$ is the observed frequency, f_{rest} is the rest frequency of the 21 cm line (1420.40575×10^6 Hz).

5.4 Signal Processing

After acquiring the signal of galactic neutral hydrogen using the *karahi* antenna and the IF Average plugin in SDRSharp, the data undergoes a comprehensive processing workflow to ensure accurate analysis. The recorded signal, saved in a text file, is first uploaded and inspected to verify its integrity. Two methods are utilized for spike detection: the Savitzky-Golay (SG) filter method and the derivative method. However, for the primary analysis, the derivative method is emphasized. This method identifies significant changes in the signal's first derivative, effectively detecting and removing transient noise spikes[31].

After spike removal, baseline correction is performed to eliminate any systematic drifts, providing a cleaner representation of the signal. The user defines a region of interest (ROI) by selecting a specific frequency range, within which the highest peak frequency is identified. This peak frequency is then used to calculate the recession velocity of the hydrogen source.

The processed signal, including the identified peaks and calculated velocities, is visualized in a comprehensive plot. The main plot displays the original signal alongside the cleaned signal (the cleansed plot only appears when there is a meaningful signal). Additionally, an inset plot focuses on the ROI, allowing for a detailed examination of significant features within the selected frequency range. This approach ensures a thorough and accurate analysis of the galactic neutral hydrogen signal. A Python script suitable for use in Google Colab is provided on PhysLab drive[32].

5.5 Results

In our observational study, we focused on two distinct celestial regions: Virgo and Arcturus, with the goal of investigating the spectral characteristics of galactic neutral hydrogen emission within these areas. Following background correction and antenna reconnection, the Galactic Dish was positioned towards the Arcturus constellation. Over time, a discernible signal broad peak starts emerging next to the narrow baseline peak, as illustrated in Figure 10.

To find the exact frequency of the galactic neutral hydrogen signal, the data is saved by selecting the “multiple saves" option in the window. Here, multiple files can be saved after a specified number of scans by entering the time in seconds. It means that the next file will be saved after that time. The next saved file represents the average of all the previous scans, starting from the initial one. After saving the file, it can be opened in MATLAB or Python for further analysis. In our case, Python was used, revealing a recorded frequency peak at 1420.81 MHz, accompanied by a recession velocity of approximately -87 km/s. To

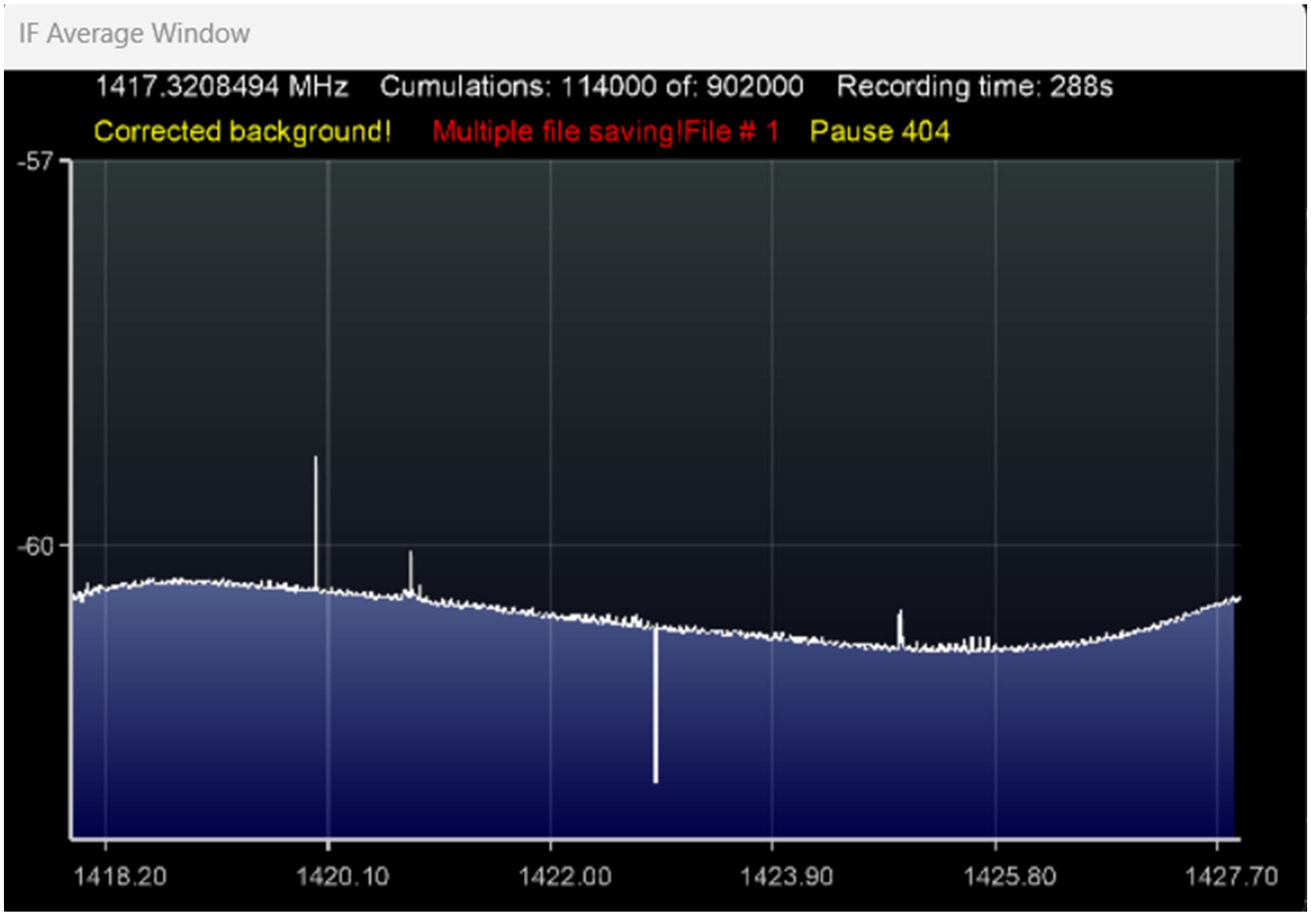

Figure 10. Spectral analysis of galactic neutral hydrogen (HI) emission observed towards the Arcturus constellation. The spectrum reveals a broad peak characteristic of HI emission, accompanied by a narrow peak that likely represents baseline noise or a digital artifact.

plot the data and measure the recession velocity, the code is already discussed in 5.4. The peak for the desired frequency is depicted in Figure 11. To zoom the the plot, An inset plot in the Figure 11 is also plotted with a frequency range spanning from 1419 MHz to 1422.5 MHz. This narrowed range allows for a detailed examination of the galactic neutral hydrogen signal, aiding in the accurate analysis of its spectral characteristics.

In the second experiment, the Galactic Dish is directed towards the Virgo constellation, following the same background correction process as in the first experiment. A discernible peak similar to that observed in the Arcturus experiment emerges for the Virgo constellation. Data is saved using the same method as before and processed in Python. The recorded frequency peak slightly differs at 1420.82 MHz, with a comparable recession velocity of approximately -89 km/s, as depicted in Figure 12. This observation contributes additional data points for comparative analysis, providing insights into potential spatial and velocity variations in galactic neutral hydrogen emission between the Arcturus and Virgo regions.

Discrepancies in observed frequencies between the Arcturus and Virgo experiments may stem from various factors, including spatial variations in gas density, differential Doppler shifts due to varying gas

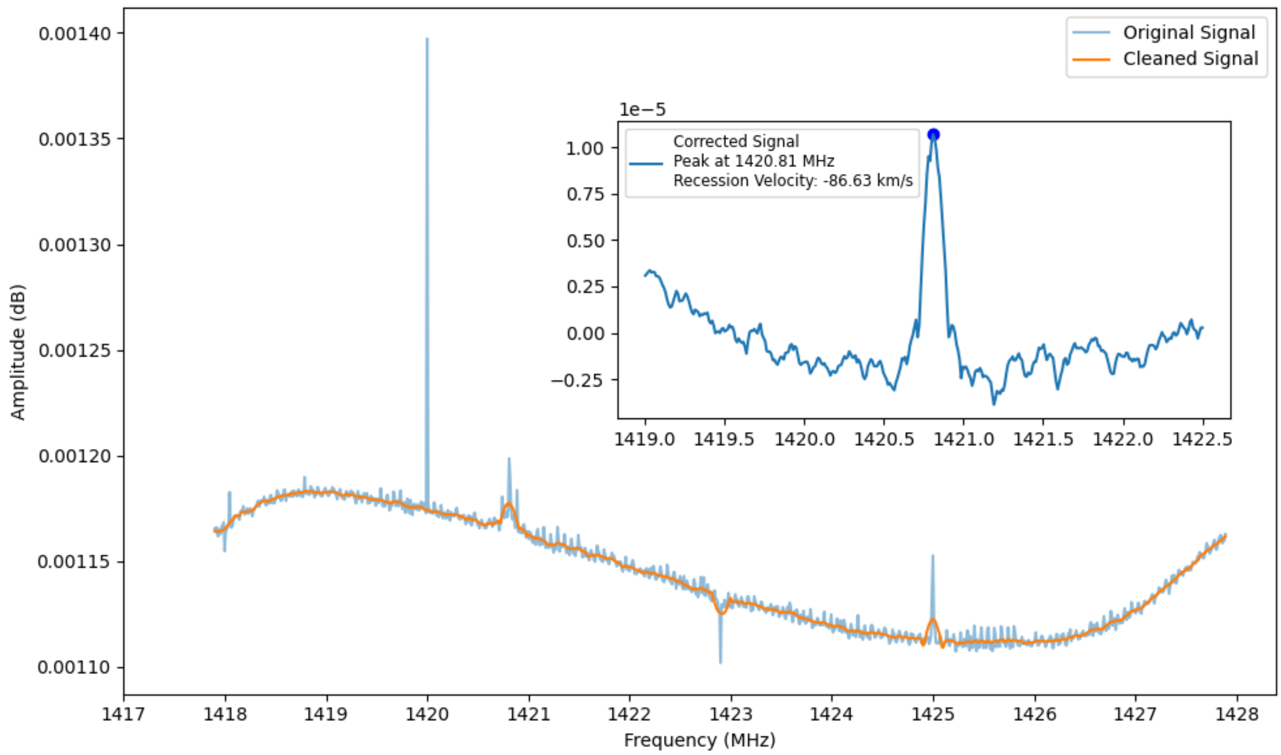

Figure 11. Spectral analysis of results for galactic neutral hydrogen emission towards the Arcturus Constellation. The H1 peak is observed at a frequency of 1420.81 MHz, with an estimated recessional speed of -87 km/s.

cloud velocities, and instrumental idiosyncrasies. To discern and interpret these nuances effectively, a comprehensive comparative analysis is warranted. Leveraging existing astronomical datasets alongside theoretical frameworks will be instrumental in elucidating the distinct characteristics of neutral hydrogen gas distribution within the targeted Arcturus and Virgo regions.

6 Summary and Conclusion

In this comprehensive discussion, we navigated the complexities of observing galactic neutral hydrogen emission through radio astronomy methodologies. Our journey began with the meticulous selection of an ideal observation site, emphasizing the grounds of LUMS University in Lahore, Pakistan, for its favorable environmental conditions and minimal electromagnetic interference.

Subsequently, we outlined the step-by-step setup process for software-defined radios (SDRs), focusing on the installation of essential software plugins like SDR and the IF Average Plugin. With our equipment configured, we directed our observations towards two distinct celestial regions: the Arcturus and Virgo constellations.

Through careful tuning and data analysis, we successfully identified frequency peaks at 1420.81 MHz for Arcturus and 1420.82 MHz for Virgo, accompanied by recession velocities of approximately -87 km/s

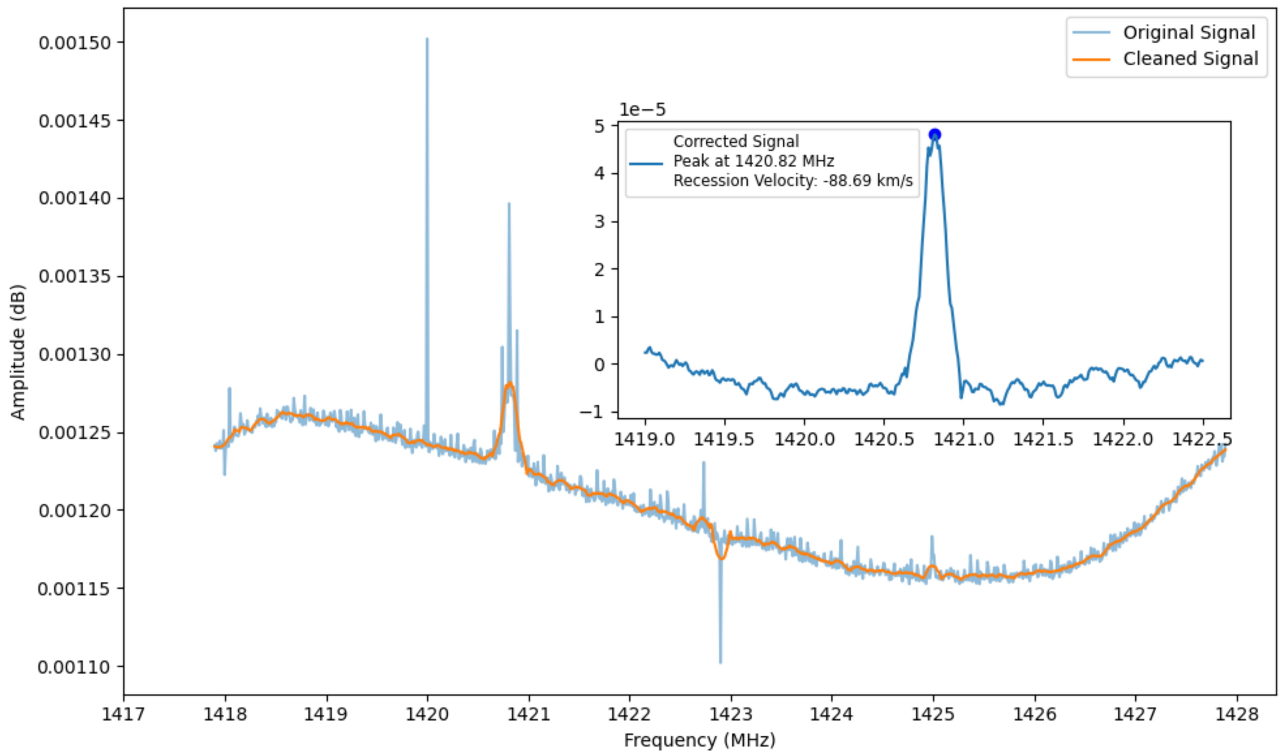

Figure 12. Spectral analysis of galactic neutral hydrogen emission toward the Virgo Constellation reveals an observed peak frequency of 1420.82 MHz and a corresponding recession velocity of approximately −89 km/s.

and −89 km/s, respectively. To ensure data accuracy, we implemented background correction procedures and real-time monitoring using graphical user interfaces (GUIs), mitigating potential disturbances such as light pollution and atmospheric conditions.

In conclusion, our interdisciplinary approach to radio astronomy yielded valuable insights into galactic neutral hydrogen emission. By combining theoretical knowledge with practical experimentation, we contributed to the broader understanding of astrophysical phenomena and highlighted the pivotal role of radio astronomy in unveiling the mysteries of the cosmos.

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A Antenna Construction

The antenna specifications are detailed in the corresponding section. The two copper patches each of length $\lambda/4 = 53$ mm were soldered onto a piece of vero board, along with the coaxial balun and signal wires. Plastic rods, hollowed internally for wire passage, provide support to the antenna. The length of the coaxial balun is 53 mm. The schematic for the connections is depicted in Figure 4. Following wire soldering, the plastic rods are inserted into the vero board and secured in place using silicone. The length of the signal wire should be enough so that it can pass through the the supporting rods and the conical support structure behind the *karahi* and can connect to the LNA input. After passing through the conical structure, a SMA male connector is soldered so that the antenna connection can be made easily with the LNA.

B Matlab code for Dipole Antenna

To effectively utilize the MATLAB code, it's important to have the Antenna Toolbox installed on your system. The code encompasses various parameter specifications for configuring both the *karahi* and the dipole antenna. For the dipole antenna, it involves determining the precise length and diameter of the copper wire to be used. Additionally, specifying the radius of the *karahi* and its focal length is crucial. The focal length can be fine-tuned to meet specific requirements and optimize performance. Adjusting this parameter enables achieving the desired outcomes in terms of antenna behavior and characteristics.

```
% Create a dipole antenna backed with reflectorParabolic
% Generated by MATLAB(R) 23.2 and Antenna Toolbox 23.2.
% Generated on: 14-May-2024 18:12:40

%% Antenna Properties

antennaObject = design(reflectorParabolic('Exciter', dipole), 1420*1
    e6);
antennaObject.Exciter.Length = 0.0975; % Length of the dipole antenna
antennaObject.Exciter.Width = 0.002; % Width of the copper wire
antennaObject.Radius = 0.2159; % Radius of the karahi
antennaObject.FocalLength = 0.143; % Focal length,
% Focal length can be adjusted to acquire the desired results
% Show
figure;
show(antennaObject)

%% Antenna Analysis
```

```
% Define plot frequency
plotFrequency = 1420*1e6;
% Define frequency range
freqRange = (1278:14.2:1562)*1e6;
% Reference Impedance
refImpedance = 50;
% Impedance
figure;
impedance(antennaObject, freqRange)

% Pattern
%figure;
%pattern(antennaObject, plotFrequency)

% Elevation
figure;
patternElevation(antennaObject, plotFrequency,0,'Elevation',0:5:360)
```

C GNU Radio

GNU Radio is a versatile and free software toolkit designed for developing radio software projects. It offers a wide range of signal processing blocks that enable the implementation of software-defined radio (SDR) systems. GNURadio can operate with external RF hardware for practical applications or simulate radio environments without hardware. It is extensively utilized in hobbyist, academic, and commercial settings to support wireless communications research and real-world radio systems. Licensed under the GNU General Public License (GPL) version 3 or later, GNURadio combines Python for high-level interfaces with C++ for low-level hardware interactions, ensuring both user-friendly operation and efficient handling of large datasets. A key feature is the GNU Radio Companion (GRC), a graphical tool facilitating the design and construction of radio components. GRC offers a visual interface where users can select and connect signal sources, processors, and sinks, akin to systems like LabView. Additionally, GRC includes blocks for creating GUI interfaces to visualize data and control SDR software. Users can create custom blocks using Python, enhancing GNURadio's flexibility and functionality. While GNURadio's extensive capabilities may require a learning curve, it provides a comprehensive toolkit for various radio projects, offering immense potential for exploration and innovation.

C.1 Installation of GNU Radio

GNU Radio is readily installable on Linux systems. Although it's possible to use it on other operating systems with some challenges, Linux is strongly recommended for optimal performance. For windows systems, first install the virtual machine and then install Ubuntu 20.04 Linux distribution on this machine. The Ubuntu setup can be downloaded from Microsoft store.

The installation process primarily involves operating from the terminal and utilizing the 'apt install' command. First, we install necessary dependencies:

```
sudo apt install git
sudo apt install cmake
sudo apt install python-apt liborc-0.4-dev
```

Next, we proceed with installing the GNU Radio application, along with the OsmoSDR drivers for SDR hardware and for Airspy:

```
sudo apt install gnuradio gr-osmosdr limesuite airspy python3-h5py
    python3-ephem
```

C.2 HackRF One working with GNU Radio

Once this installation completes, the latest version of GNU Radio (currently version 3.8) should be installed. HackRF One drivers can be installed using the following commands:

```
sudo apt-get update
sudo apt-get install hackrf
```

To verify recognition of HackRF One hardware by the PC, connect HackRF One to a USB socket and execute the following command:

```
lsusb
```

This command will list the USB devices connected to the PC. Go through all the devices and find the HackRF One device. To find the specifications of the HackRF One board connected to PC, simply write the following code line.

```
hackrf_info
```

To launch the GNU Radio application, simply type the following command in the terminal:

```
gnuradio-companion
```

The installation guide of GNU radio with DSPiRA flow graph can be read from the link[33]. To receive signal from HackRF using GNU Radio, use Osmocom Source block. To measure galactic neutral hydrogen, an open source GNU Radio program is available on the github[34]. The process to clone this git directly is also given there. To run this code manually, click on the green `Code` tab and download the zip file from there. After downloading the zip file, follow the following steps:

- Unzip the folder and go to the examples folder and then go to the DSPIRA folder.

- In DSPIRA folder, `spectrometer_w_cal.grc` is the main code file. Run GNU radio and open this particular file by following the above path.
- Connect the HackRF One to the PC using a USB cable, and execute the code by clicking on the `Play` button.
- As the code executes, a GUI display appears, as illustrated in Figure 13.

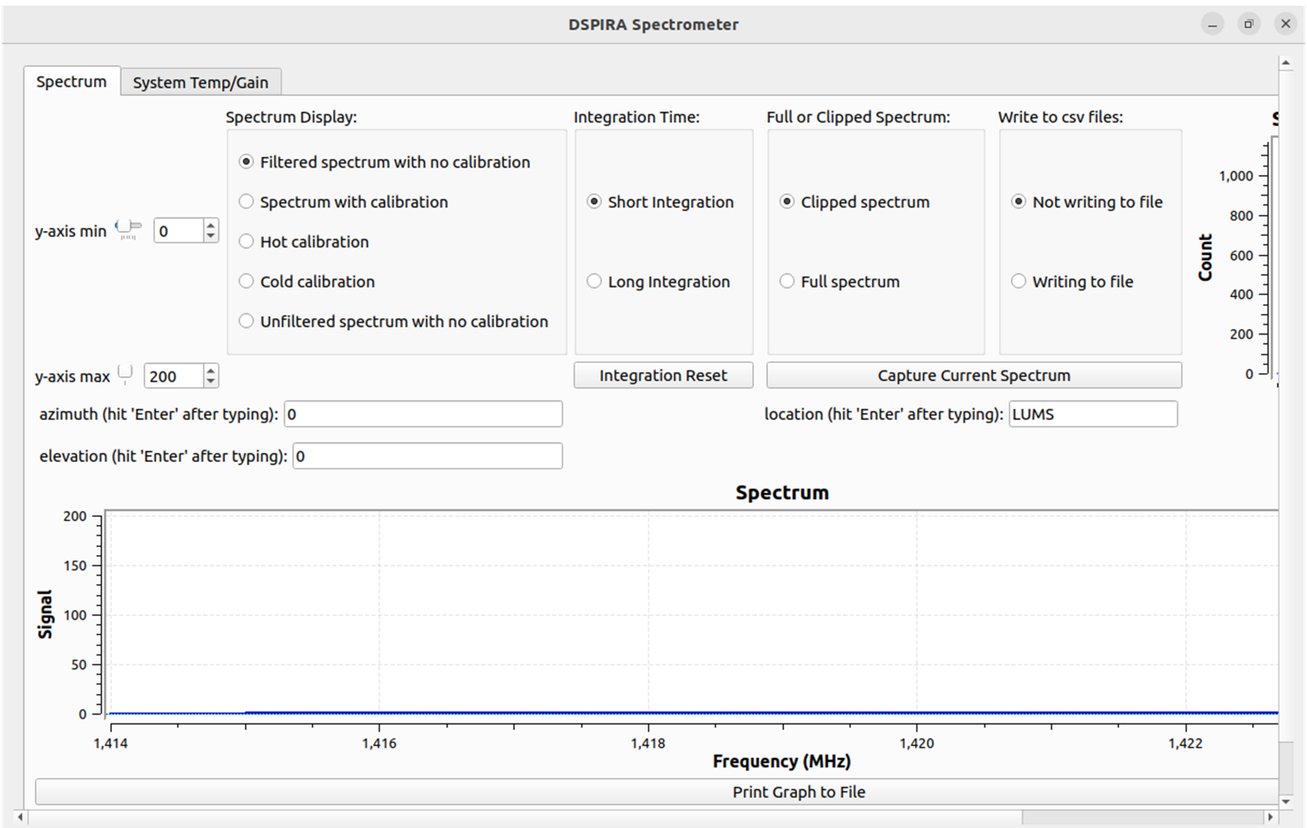

Figure 13. GUI of DSPiRA code for measuring the galactic neutral hydrogen.

We can perform various spectral analyses, including calibrated and uncalibrated measurements, as well as apply digital filters already included in the code. Both short and long integrations can be executed. Additionally, the spectrum can be saved as a .csv file, which will be written after the specified integration time. To configure the spectrometer for optimal performance with the HackRF One, several variables must be set according to the specific environment and desired outcomes. Below are the key variables and their descriptions:

- `rectfile`: This variable defines the path where the recorded data file will be saved. It is essential to set this path correctly to ensure data is stored appropriately.
- `prefix`: This variable specifies the path for saving CSV files. Proper configuration of this path is necessary for accurate data logging.

- `integration_time1`: This sets the short integration time, which is the period over which the signal is averaged to reduce noise. The default value is 0.4 seconds.
- `integration_time2`: This determines the long integration time, useful for more detailed analysis by averaging the signal over a longer period. The default value is 10 seconds.
- `samp_rate`: The sample rate, which dictates how frequently samples of the signal are taken. The HackRF One supports sample rates upto 20 MHz, and it should be set 2.4 MHz for this experiment.
- `freq`: The central frequency around which the spectrum analysis is performed. The default frequency is set to 1.419 GHz, which is typical for observing neutral hydrogen emissions.
- `vec_length`: The length of the samples vector, defining how many samples are processed at a time. The default value is 4096 samples.

By carefully configuring these variables, users can tailor the spectrometer's performance with the HackRF One to meet specific research needs and environmental conditions, ensuring precise and reliable data collection.