Observation and Analysis of the Hydrogen 21-cm Line using a Small Radio Telescope

Lisa Friederich
The University of Alabama in Huntsville
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Knowing that Hydrogen is the most abundant gas in the universe, I used the UAH small radio telescope to observe the Hydrogen 21-cm line spectrum across the galactic plane. Concentrating on three points, I created plots to display the recorded data, focusing on the intensity of the points as a function of frequency. To do this, I learned about the construction and operation of the small radio telescope as well as methods of data analysis, including the use of Microsoft Excel and the concept of linear regression.

Introduction

The goals and methods of radio astronomy are to study the characteristics of an object emitting at radio wavelengths and testing a hypothesis with experiments and observations. This is possible through the use of special telescopes, called radio telescopes, which measure the emission of sources in the radio spectrum. To be in the radio spectrum, emissions must have wavelengths of .001-30 meters. Viewing sources in this spectrum allows for the discovery of such objects as pulsars and quasars, which would otherwise remain undetected.

Many heavenly bodies emit electromagnetic radiation that astronomers may study both day and night, but the more distant bodies require nighttime viewing. Unlike normal optical viewing, which involves observing omissions within the visual spectrum, radio astronomy measures emissions in the unseen radio spectrum. Like optical astronomy, radio astronomy has its own special equipment in the form of radio telescopes. In order to detect such faint detections with good clarity, radio telescopes must be fairly large in comparison with their optical counterparts. Using a parabolic shape for the dish, these telescopes gather the incoming emissions in the dish and reflect them to their perspective receivers. Dishes as large as 100 meters wide help create some of the clearest readings, especially of the more distant sources. Many new advances in technology, however, allow for the option of smaller antenna designs that still maintain good quality of readings. This information travels to a computer where radio astronomers may save and interpret the data for a variety of uses.

Without the necessity of large dishes and with the multitude of books available on the subject, many amateur radio astronomers can participate in radio astronomy for minimal cost. Some amateurs construct their own satellites using recycled satellite television components, while others rely on programs, such as the Massachusetts Institute of Technology (MIT) Haystack Observatory, who offer the necessary parts to build a small radio telescope in a convenient kit. Using this kit, the radio astronomers at the University of Alabama in Huntsville created the small radio telescope, which I used in order to conduct my research of the Hydrogen 21-cm line as seen along the equatorial plane of the Milky Way galaxy.

To analyze the data from my research, I used Microsoft Excel. Using this program, the data is easily read into the computer and translated into an easy to read graph. Furthermore, to eliminate the background noise within the data, I used the process of linear regression.

Theory

Radio Astronomy

When a typical observer looks up at the sky, what they see is in the visible spectrum. This consists of a narrow range of wavelengths, from 400 to 700 nanometers. While this spectrum is the most commonly viewed by observers, it is the radio spectrum below the visible spectrum that is the most accessible. As in any other branch of Astronomy, the goals and methods of radio astronomy are to study the characteristics of an object emitting at radio wavelengths and testing a hypothesis with experiments and observations [2]. For radio waves, the wavelength falls within the range of 0.001 - 30 meters, translating into a frequency range below 300 GHz.

Similar to the visible spectrum divisions by wavelength in the form of color, the radio spectrum consists of divisions by wavelength. The most common category contains the classical radio wavelengths. These wavelengths generally measure around 14.6 meters, therefore residing at top of the length range, and include AM/FM and television emissions. The next category, called microwaves, consists of wavelengths between 1cm and 30 meters. Waves in this range include communications, microwave ovens, and most importantly for the SRT, the radio emission from neutral atomic hydrogen. Discovered in 1951, the hydrogen emission line occurs at a wavelength of 21 cm [1]. Another category contains millimeter waves, whose wavelengths range from 1 mm to 10 mm. The rotational spectra of molecules occur in this wavelength range. The last category contains the sub-millimeter waves. With wavelengths below 1mm, this wavelength range overlaps with the far-infrared portion of the electromagnetic spectrum.

Radio Telescopes

With these waves in the non-visible spectrum, astronomers use specific telescopes to measure them: radio telescopes. Radio telescopes differ greatly from optical telescopes in that they are much larger. The reason for this is that the angular resolution (or the angular area of the sky from which the telescope can collect emission) of a telescope is proportional to the wavelength divided by its diameter, i.e. the wider the aperture of a telescope the faster it can collect light and the fainter objects it can observe [1]. Therefore, in order for a radio telescope to detect the same angular resolution as an optical telescope, the radio telescope must be much larger. Furthermore, the larger the area of the reflecting surface, the greater the sensitivity of the telescope or the ability to detect weak emission.

The four basic elements of a radio telescope are the reflector, the subreflector, the feed and transmission line, and the receiver. The reflector collects power from astronomical sources, the subreflector directs the radiation to the feed at the center of the reflector, behind which is the receiver system that amplifies the radio signal and selects the appropriate frequency range to properly detect the signal [2].

While radio astronomy dates back to 1894, with Sir Oliver Lodge, radio telescopes similar to the classic bowl-shaped antennas of today began to appear in the 1930's [1]. Astronomers such as

Grote Reber, who in 1937 created the first actual radio telescope in his back yard, and G.C. Southworth, who took the first radio readings of the sun, were among the leaders in radio astronomy [3, 1]. With their research in place, future radio astronomers gained the chance to make incredible discoveries. Two such astronomers, Arno Penzias and Robert Wilson, used radio telescopes to detect the cosmic background radiation now used as evidence of the big bang [2]. Therefore, radio astronomy holds importance not only within its field, but across other scientific genres as well, thereby impacting numerous people.

The Hydrogen 21-cm Line

The Hydrogen 21-cm line of radiation is the emission of radio energy from atomic Hydrogen throughout the galaxy when the atom transitions from its first excited state to its ground state. This transition arises due to the spin-spin interaction between the electron and the proton, since the parallel spin has a higher energy than the anti-parallel spin. The emitted photon has a rest wavelength of 21.1 cm and frequency of 1420.4 MHz. At this frequency, radiation from Hydrogen is able to penetrate the dust clouds, when their visible light cannot. In addition to this ability, our location within the galaxy allows for clear view of nearly all points along the galactic plane, which is an excellent source of emission of the 21-cm line.

Basic Setup of the UAH Small Radio Telescope

The following section depicts the physical construction of the small radio telescope at the University of Alabama in Huntsville, as provided by the Massachusetts Institute of Technology Haystack Observatory website.
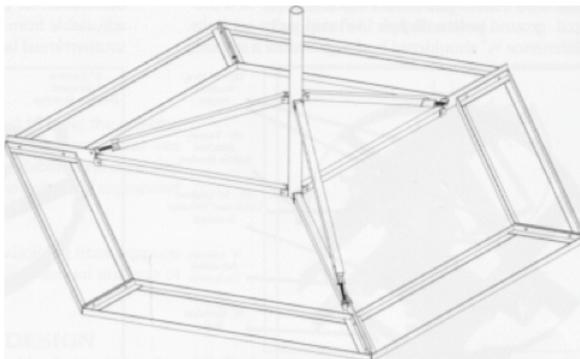
Construction

Mount

Figure 1 NPRM [4]

In order to construct a small radio telescope (SRT), it is important to choose a proper location as well as decide on a permanent or temporary mount. Since the UAH SRT sits on the roof of the Optics building, the chosen foundation is a temporary mount called a non-penetrating roof mount (NPRM). Being a temporary mount, there are no supports within the ground (or in this case, roof) itself. To keep the telescope stable, concrete blocks must be placed along the edges. Their weight serves to hold the telescope in place in any inclement weather.

Reflector

The purpose of the reflector is to focus the emissions from the source so that it may be received and translated into data. The reflective surface and parabolic shape of the dish help in this focusing process. Incoming emissions bounce off the surface of the antenna to the feed horn, the cylindrical container held above the center of the dish, which directs them back through the center of the antenna to the receiver.

3

Receiver

Between the mount and the antenna sits the receiver, whose purpose is to collect the incoming data. Upon retrieval of the data newly focused by the dish and feed horn, the receiver transmits the data by wires to the amplifier connected to the computer.

Assembly

Constructing the mount and antenna dish separately, following instructions provided by the MIT Haystack Observatory, use a mounting ring to place the finished antenna on the NPRM, and bolt the dish into place to finish construction of the SRT.

Focusing

Before using the newly constructed SRT, adjustments to the focal point of the dish are necessary in order to maximize the antenna's efficiency.
Measure from the bottom of the dish to the base of the Quad Feed Support to find the focal point.

Note: This should be the same value as calculated using the dish's diameter, D, and depth, x, in the following formula: $f = D_2/16x$. For a 10-ft diameter dish, such as the UAH SRT,

Figure 2 UAH SRT

the focal point should be 47.6 inches.

For any difference in measurement, adjust the feed supports (the metal bars connecting the dish to the feed horn) accordingly.

Operating the UAH SRT

Before conducting the basic operation of the SRT, connect the cables to their corresponding locations on the amplifier box connected to the computer. Before using the telescope, turn on the amplifier, then the computer.

Using the Software

As a small radio telescope, the UAH SRT is capable of spectral line (1420 MHz hydrogen) and continuum observations using source tracking, 25-point maps and drift-scans. The SRT is an all sky telescope, covering from horizon to zenith, and a near 360 degree azimuth. The software required for operation of the SRT is a Java-based program with compatibility for most operating systems. One main file in this program is a file labeled srt.cat. This file contains items such as the user source list, the telescope station latitude and longitude, and telescope azimuth and elevation limits.

After downloading the required software onto a computer, following basic downloading

procedures, use the control screen for telescope operation.

Across the top of the SRT Control Panel is the 15-button command toolbar.

Figure 3 Command Toolbar

As the label implies, the clear button will clear the control console display of accumulated data. This function is useful if the user is accumulating multiple spectra from different sources or galactic coordinates.

Enabling the atten (attenuation) button adds or removes a 10dB attenuation to the receiver with successive left-button mouse clicks. The atten will illuminate red while the 10dB attenuation is active. To read the attenuation value, see the area just above the center of the message board area to the right of the power/temperature information.

Clicking Help opens a window titled srthelp that contains a 6-button taskbar. The six choices in the taskbar contain usage information for each section.

Clicking on the Stow button will return the telescope to the "normal" stow position in the eastern-most, low-elevation position. The travel zone is established by the AZLIMIT and ELLIMIT commands in the srt.cat file. While this is the telescope's programmed stow position, the builder of the UAH SRT, Laci Gambill, suggests moving the telescope to point to zenith before force quitting the program. This position has the least amount of dish area subjected to wind, therefore reducing the probability of structural damage.

The track button enables the antenna to move to and follow a selected source found from clicking on the map, selecting from the source list, or after typing the source information on the command entry text box.

The Azel button allows the user to enter a fixed azimuth/elevation position in the command entry text box, as long as the position is within telescope limits.

Npoint initiates a 25-point scan of the selected source. The map is 1/2 beam-width spaced and displays a false-color, Gaussian plot to the left of the accumulated spectrum plot.

The bmsw button initiates a continuous "off/on/off " beamswitched comparison observation of the selected source at the frequency settings entered with "freq". Left-clicking on the bmsw button after starting the scan aborts the operation. All results appear in the red accumulated spectrum window.

Freq sets the center frequency and observing mode. After clicking on the freq button, enter the desired settings in the command entry window at the bottom of the screen in the following format: "frequency mode".

The offset button enables the user to enter any azimuth/elevation pair desired. For readings of the exact desired location entered, use an offset of 0,0.

A left mouse click on Drift will offset the SRT in Right Ascension and allows the selected source to drift through the 7-degree beam of the telescope.

Pressing record begins data collection. Clicking once enables the user to name the data file, while clicking twice designates a default name. When recording, the record button turns green. Click once more to end recording.

Rcmdfl initiates reading of the default command file (srt.cmd) and begins data recording. The current line number and text being read appears on the message board above the text entry box.

Cal starts an automatic calibration sequence during which a noise source, located at the apex of

the antenna surface, is enabled for approximately 1 second. The system then takes a data sample without the noise source enabled; this allows for the proper system noise temperature reading (Tsys).

The Vane button starts an automatic calibration sequence during which the receiver is blocked by an ambient temperature vane calibrator. This also outputs the system temperature.

In addition to this Command Toolbar, there is an information sidebar on the right of the screen containing such information as antenna coordinates, time, center frequency, and system temperature. The center of the screen is the Sky Map: a map that shows full sky coverage in azimuth and elevation. The axes contain tick marks for every 10 degrees. The points that automatically appear on the sky map are the sources located in the srt.cat file, and include the galactic equator, the Sun and Moon, and various constellations, galaxies, and nebulas.

Taking a Reading
To choose a source for data readings, the user can click on one of the mapped sources, or use the Azel button to enter coordinates. Prior to taking a reading, calibrate the telescope by entering a coordinate location of clear sky horizontal to the desired source (at a distance at least seven degrees from the source) and click Cal.

Once calibrated, click on the desired source. This will direct the telescope to the proper location. Click record to begin a reading (see above for details of record button).

Note: For a good reading, let the telescope collect data for a minimum of ten minutes.

Click record again to end data collection.
To see the data, open the folder with the designated name or time label from the reading.
Save the data for future use.
Click on the red graph (accumulated data) to pull up a larger graph.
Press print screen to save a screen shot (if desired).
To gather another set of data, repeat the above steps.

Data Analysis

Importing and Reading Data into Microsoft Excel
While there are several available programs to import and read the data gathered by the SRT, for my research I chose to use Microsoft Excel for its ease and availability. The following steps outline the procedure required for importing the data gathered from a reading by the SRT using this software.

Create a blank spreadsheet.
Click File, then Open. Find the saved data and double click the file to open it.

Note: Before importing it, it is important to set the delimitations of the data in order to read it correctly. Tabs, spaces, and colons delimit the data of the SRT.

Click the box next to Tab, Space, and Other, typing : in the blank to read the colons.

On the next screen, click Finish, then OK (this should open a spreadsheet of the data with each number in its own block).
Label each column according to the format of the data, as seen below.

Example line of data: 2010:154:16:00:12 312.0 26.8   0.0   0.0 1419.79 0.00781250   4 156 448.8 …
Year:Day:Hour:Min:Sec Azimuth Elevation OffsetX OffsetY Frequency Increment Mode #Bins RawData

Upon completing the labels, save the excel graph for future use.

This completes the importing data process.

Creating Plots to Present the Given Data
To create a plot of the data now saved as an Excel file, use the following steps.

Open the Excel file previously saved after importing.

Note: When studying the chart, notice that the last two columns of data say vslr and a number. These numbers are not actual data points, therefore ignore them when calculating the average of the raw data.

Average
To calculate the average of a row, follow these steps.

Click an empty box to the right of the first row and begin typing "=AVERAGE".
Click the option for the AVERAGE function when it appears.
Highlight the raw data points in the first row; the number of data points in this section is the number of bins.
After highlighting the data, close the parentheses and press enter.
Click the box with the first row average and drag the box to the last row of data.
Press 'ctrl-d' to fill-down the column with the averages of the rows.

Note: These row averages are the points for the y-axis of the graph (graphs may also be made using a single row). Choices for x-axis points are averaging the columns in the same manner as above (except pressing 'ctrl-r' to fill-right), using the time column, or calculating the corresponding frequencies. Since graphs commonly contain the averages (or a row) as a function of frequency, the next steps outline how to calculate these frequencies.

Frequency
Click on a blank cell below the data
Enter the value of the frequency shown in the first row of the frequency column.
In the adjacent cell, type =(position of previous cell)+(value of increment).

Note: For the position of the previous cell, look at the column and row labels for that cell (example J2). The value of the increment is a constant value and appears in the column to the right of the frequency column.

Press enter and move to the next cell.

Using the same fill right technique as with the averages, click the newly created cell, drag right for the same number of cells as there are averages, and press 'ctrl-r'.

This creates the frequency range corresponding to the averages of the rows.
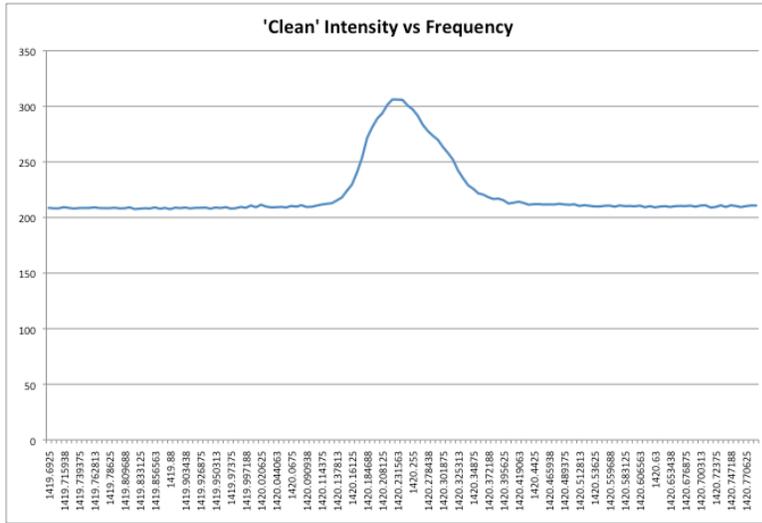

Figure 4 Sample Graph (excluding erroneous raw data)

Plot
The following steps outline how to create a plot of the averages with respect to the frequencies. Highlight the column with the averages of the rows and click the Chart icon located in the toolbar (if icon is not present, click Insert, Chart).
Click Line to make a line chart, and Next to proceed to the next screen.

Note: This screen is the Series part of the window. The y-values are set to the averages and the x-values are unset.

Click the icon next to the blank space labeled "Category (X) axis labels" to pull up the saved data.
Highlight the row containing the incremented frequencies (a dotted line appears around the highlighted data)
Again, click the icon to the right of the blank space (now containing the locations of the highlighted data) to return to the Series screen.
Click Next and name the graph and the axis accordingly, if desired.

As observed in the sample graph above, the white space below the plot is the noise interference. To eliminate this from the graph, use the process of linear regression.

Linear Regression
In order to eliminate the white space caused by interference, calculate the value of the horizontal portion of the graph. To do this, use the following steps.

Copy the cells containing the data points corresponding to the horizontal portion of the plot into one row.
Using the same Plot procedure as above, create a line plot of this row of data.
Click Chart -> Add Trendline: Options, with equation.

On the graph, a linear line with the corresponding equation will appear. Record the value of the y-intercept.

Note: On the sample graph, the equation for the trendline is y = -0.0014x + 210.4. Therefore the slope of the horizontal sections of the graph is -0.0014 with a y-intercept of 210.24.

Back on the original Excel data sheet, subtract the y-intercept value from all data points in the complete plot (corresponding to sample plot above) and create a new graph.

Note: On the sample graph, the y-intercept is 210.24, therefore subtract this value from the row of values to create the final graph seen below.

After saving this final graph, the process is complete; close the program.

Figure 5 Sample Final Graph

Results

The following are some results from my research of Hydrogen emission along the galactic plane. After collecting readings of all galactic points, I chose to focus on three points: G20, G30, and G120. Using the data from these points, I used the data analysis procedure above to create the final graphs seen below.
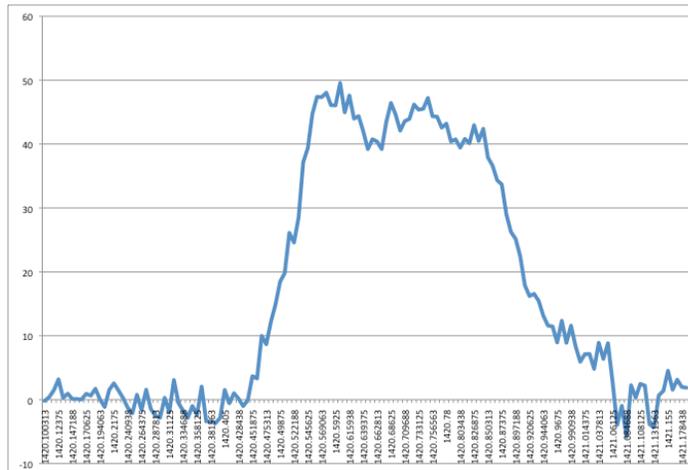

Figure 6 G20 Final Graph
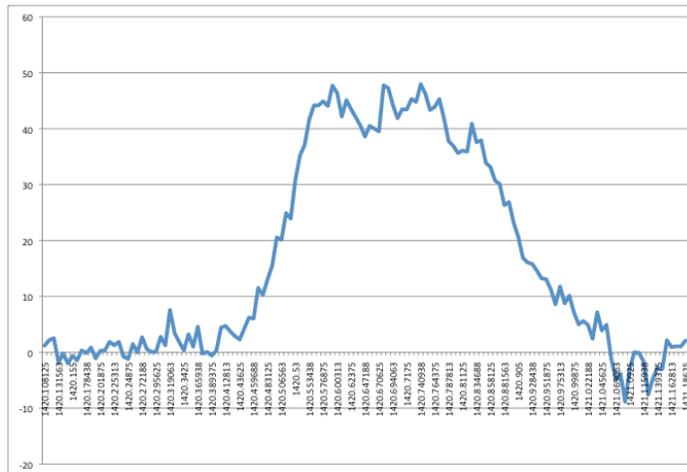**Linear regression: y = 0.0021x + 217.32**

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Figure 7 G30 Final Graph
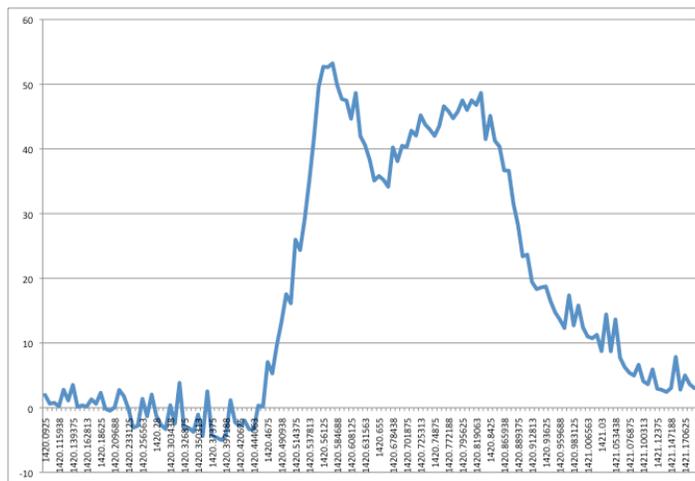**Linear regression: y = -0.04x + 218.42**

Figure 8 G120 Final Graph
Linear regression: y = -0.0837x + 219.17

As seen in G20 and G30, the single peak of the graph represents the maximum temperature emitted from the source. For G120, the two peaks represent emissions from two sides of the galaxy. As with other sources viewed at multiple locations in the galaxy, the emissions are shifted. Sources traveling away from the Earth, creating a redshift, have a graph with a peak shifted to a lower frequency. For sources traveling toward Earth, undergoing a blueshift, the peak of the graph shifts to a higher frequency. Therefore, for sources such as G120 with two peaks, the two emissions located at different points are moving toward and away from the Earth, thereby causing two shifts in frequency.

Conclusions

For my research, I learned about the construction and operation of the UAH small radio telescope. Using this telescope, I observed the Hydrogen 21-cm line across the galactic plane. My various readings gave data for each galactic point, from which I made plots of the emissions. Choosing the three clearest plots, I furthered the data analysis process by using linear regression to remove the value of the background (system) temperature, thereby finalizing the graphs. Despite the presence of interference, conducting research in radio astronomy through the use of a small radio telescope is a useful tool for observing and recording the temperature intensities of emission sources as a function of their frequencies.

References

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