Exercises Using the SRT

Note: The data analysis instructions in these labs use the SRT_Plotter package, which is written for data obtained with the Haystack SRT using the digital receiver. Data files using the dongle receiver can be converted to the format readable by SRT_Plotter with the python program *SRT_File_Converter.py*. To convert dongle data (on a computer with python), copy the SRT_File_Converter.py file to your data file folder, and in a command terminal type: SRT_File_Converter.py *filename* (without the .rad).
This will create a new file called your filename_SRTPlot.rad, which can then be read into SRT_Plotter.

1. Measuring the System Temperature, Pointing Correction, and Beam Pattern

Since you can't actually see the sky that a radio telescope is pointed at, knowledge that the radio telescope correctly points to the location in the sky that it was instructed to is crucial for any observation with the telescope. Additionally, one of the first characteristics of a radio telescope that one needs to know is its system temperature, which is a measure of the amount of noise that will appear in a measurement and which the signal from the source (measured as antenna temperature) needs to stand out from to be detected. A third important parameter that will also be determined in this lab, is the beam width, which is another way of describing the resolution of the telescope. .

Follow the procedure listed below. This will both help you become familiar with the operation of our telescope as well as make the measurements needed for this lab.

For your report for this lab, imagine that you are merely writing a document for yourself and future users of the telescope to refer to. Do not write it like a scientific report, but rather like a report for the telescope manual. So, you do not need to write an abstract. The introduction should be very short, merely stating the purpose of the report. List all results in a clear, well-organized table right at the beginning, and then follow the table with a discussion of how you made the measurements. Finally, put in a discussion in which you analyze the results; e.g., how reliable do you think the measurements are?

Procedure:
1. Turn on the radio telescope computer
2. Turn on the radio telescope control box
3. Click on the SRT icon in the lower left:
    An MSDOS window will open--do nothing and wait a minute or so.
    Then, the SRT window will open.
    Wait until the screen no longer says "slewing" (a few seconds)
4. Click on "record" (on top bar) and in the "text window" at the bottom type in a data file name.
    Make sure that it says "recording *yourdatafile*.rad" in the lower right, at the bottom of the "information side bar".
5. Set the frequency adjustments by clicking on "Freq"and in the text bar at bottom, enter:

1420 1
(meaning, L.O.=1420 MHz, operating in mode 1)
6. Click on "Sun" in the display window. You should see a yellow cursor appear at the position of the Sun and the red cursor to the lower left corner should start moving (slowly) toward the Sun. When the red cursor reaches the Sun, the yellow cursor will disappear.
7. Click on "Offset" and type in "0 15" in the text box at the bottom (this will move the telescope 15 degrees North of the Sun).
8. Calibrate the signal: Click on "Cal" and wait until a value for Tsys to the right appears. Record the value of Tsys. Click on "Cal" two more times, record each value of Tsys and calculate the average of the three. **Record the average Tsys value for your report and for future information**. When done set "Offset" back to "0 0."
9. Determine the pointing of the telescope:
   Click on "NPOINT" and wait about 5-minutes. (The telescope will now measure the antenna temperature at 25 different positions in a 5x5 array.)
   When the NPOINT is done, you'll see a false-color plot displayed at the top of the screen.
   Near the bottom of the information side bar, under "Scan Results", you should now see:
   the calculated "Offset" based on the NPOINT data,
   the maximum T_{ant},
   and the width of the apparent image will be listed.
   Write these pointing corrections down.
   The computer will automatically set the pointing to the peak position.
   After you move to another source, though, this offset is lost.
10. Repeat step 9 to get a second measurement of this *very important determination*.
    Average your two sets of *Offset values* values, *send me an e-mail reporting these numbers,* and save these numbers where you can find them to use in future labs.
11. **Measure the beamwidth** of the telescope more explicitly by doing the following:
    Click on Offset, and enter "-20 0".
    Let data be recorded for about 30 seconds, then
    Move to an Offset of -19 0, then to -18 0.
    Continue all the way to an offset of +20 0.
    Then do the same range of offsets in Elevation (offsets from 0 –20 to 0 +20).
12. Click on "Record" to stop the recording of data.
13. Click on "Stow" to return the telescope to its initial, and storage, position.
14. Exit the program.
15. Install your flash drive and copy your data file from C:\SRTvsrt.
17. Shutdown the computer.
18. Turn off the ground control box.

Analysis of Data:
1. On a data analysis computer (classroom computer or your own) open SRT_Plotter. Click on "Open file" and "browse" to find your data file.
2. Click "Plot Beam," opt to "plot vs. azimuth," and then select only the data blocks corresponding to observations of the Sun with offset in azimuth (the first set of data, if you followed the procedure above). You'll then see a plot of your data.
3. To save the plot as a JPEG file, move the mouse to the plot screen and right click.

4. Note the full-width-at-half-maximum (FWHM) of the beam pattern. This is the beam width of the SRT in degrees of azimuth.
5. Now, to convert the angle in azimuth to angles of arc, you need to multiply the azimuth angles by cos(elevation). Consider that when the telescope is pointed straight up, for example, movement in azimuth merely rotates the antenna about its central axis and so moves the telescope 0° in the sky. When it's pointed at the horizon, then movement of 360° in azimuth does actually correspond to 360° of arc. To find the elevation setting of the telescope during these scans, use Notepad to open the raw data file (the datafile.rad file written during the observation) and read the third column of numbers for the rows used in the azimuth beam scans. Measure and write down the azimuthal beamwidth in real degrees. (Improvement for future: the ability to read elevation and azimuth angles and to convert azimuth to real angles by multiplying by cos(elevation) will be added to SRT_Plotter.)
6. Convert your primary beam width to radians and compare with that given by
$$\text{FWHM} = 1.15\ \lambda/D$$
where D is the diameter of the reflector and λ is the wavelength of the radiation. The diameter of the SRT is 2 m and $\lambda = c/\nu$, where ν is the frequency as determined by the L.O. setting you typed in when you clicked on "freq" (see step 4 of the observation instructions.)
7. Click "Plot Beam" again and this time opt for "plot vs. elevation" and select the appropriate data blocks. Save this graph, measure the FWHM in this direction.
8. For the discussion of your report, consider the following questions:
   (a) What is the pointing correction (Azimuth and Elevation)?
   (b) The angular size of the Sun, as seen at radio wavelengths, is between 0.5 and 1 degree. How does this compare to the FWHM of the telescope beam? If it is comparable or larger, than the measured beam is larger than the true beam, and if the Sun is much smaller, than this is a good measure of the beam.
   (c) How do the beamwidths compare with $1.02\ \lambda/D$ if D = 2.1 meters? or with $1.15\ \lambda/D$?
   (d) What is the "effective diameter" of the telescope?
   (e) How does that compare with the 2.1 meters, which is the physical diameter of the telescope? Why might they be different?
   (f) Are the beamwidths the same in both directions, within reasonable uncertainties?
   (g) How accurate is the pointing of the telescope, in comparison to the beam width? Were the calculated pointing offsets smaller than 1/10th of the beam width?

2. Determining the DPFU and aperture efficiency of the SRT

Another important characteristic of a telescope that one needs to know in planning observations is the sensitivity of the telescope. This can be described in several ways. The amount of radiation detected is a fraction of that which enters the antenna aperture. The **aperture efficiency** is the ratio of the **effective aperture area** to the geometric area (πR^2) of the reflector. Knowing the effective aperture can be used to convert the measured antenna temperature to the flux density of the radiation entering the telescope. This concept is sometimes described as the degrees-per-flux-unit (or **DPFU**), i.e. the number of degrees K in antenna temperature that results for every Jy of flux density from an astronomical source).

The sensitivity of a telescope is crucially important for planning observations when you have an idea of the flux density of the source and know the system temperature (measured in lab 1). In this lab, you will measure the antenna temperature when observing a source of known flux density, and hence directly measure the DPFU and calculate the effective area. The known source that you will use is the Crab nebula, whose flux density at 1420 MHz is 875 Jy.

The procedure in this lab will also familiarize you with how to carefully measure the antenna temperature. The receiver noise plus signal from the background is measured, interpolated in two-dimensions, and subtracted to yield the antenna temperature of only the source of interest. This method is called **switching**. In any single-dish observation in which the flux density of a source is desired, switching must be performed.

You will also learn in this lab about writing and using a command file. Command files are helpful and useful for a number of reasons. Once familiar with the allowed commands, you are less likely to make mistakes in the observation by writing and carefully examining a command file in advance of the observation. As you may have unfortunately discovered in lab 1, mouse clicks and inputs from the keyboard during a long observation are prone to mistakes. Secondly, command files enable one to obtain an observation at a telescope without having to travel to the telescope, as is generally desired when granted time on a national facility far from one's home.

Switching Observation of Crab Nebula:
To determine the antenna temperature due to only the source of interest, a single-dish observation should always include observations of positions aimed away from the source (called the "off" source scans) as well as the position "on" source, and the average of the "off" source scans are subtracted from the average of the "on" source scans. There should be off source positions symmetric about the source.

Because of temporal variations in the gain of a telescope, the on source and off source scans need to switch on a time scale fast enough that the gain fluctuations do not alter the on-off calculations. With the SRT, we should switch on a time scale of order 10 seconds.

The Crab Nebula is in the plane of the Milky Way Galaxy which, itself, emits significant radio wavelength emission. Therefore, we will need to be sure that, in addition to the noise of the receiver, the background of the galactic plane is also subtracted off in our switching observation.

This is accomplished by using off positions that contain the same amount of galactic plane emission. The Galactic coordinates of the Crab Nebula are 184.6º -5.8º; the first number is the galactic longitude and indicates how far, in degrees, along the galactic plane, it is from the Galactic center and the second number is its galactic latitude and indicates its distance in degrees above the galactic plane (the negative indicating the Crab is below the plane)). For our switching observations, then, we want off positions with Galactic coordinates of 177 -5.8 and 192 -5.8. To ensure we get these positions, instead of using offsets in azimuth and elevation, we can define positions using "galactic coordinates", using the command "galactic".

Time to Make the Observation:
As always with observational astronomy, you need to take care in choosing the time to make your observation, which depends on the location of your source and the calendar date. In general, you need to know the rise, set, and transit times of the target source. For this observation, your target source is the Crab Nebula. The Crab Nebula is not bright enough to get a reasonable NPOINT results, so for this lab you should use the pointing corrections you measured in Lab 1.

Command File Guidelines:

The filename should have suffix .cmd

Each command must start with a colon (":") followed by a blank space.

A line starting with an asterisk ("*") is a comment, which is recorded in the data file but does not instruct the telescope to do anything.

Some commands that can be used are:

> freq *ffff m*– sets the central frequency and mode number (for this lab, use mode 1)
>
> noisecal – perform a Tsys cal using the noise diode
>
> record *filename*
>
> mode n (perform NPOINT)
>
> Crab (go to the Crab)
>
> azel *aa ee* (azimuth and eleation to move to)
>
> offset *aa ee*
>
> radec *hh:mm:ss dd:mm:ss* (RA and Dec to move to)
>
> galactic *ll.l bb.b* (galactic longitude and latitude, in degrees, to move to)
>
> A colon followed immediately by a number with no space (e.g. ":30") instructs the computer to collect data for this period of time.
>
> roff (stop recording)
>
> stow

Here is a simple example of a command file.
* Probing beam of Sun in elevation
* Lab 1, Joe Smith and Betty Jones

: record lab1smithjones
: Sun
: offset 0 10
: noisecal
: offset 0 0
* Do NPOINT
: mode n
* Measure beam in elevation, in steps of 2 degrees, with 30 second integrations
: offset 0 -10
:30
: offset 0 -8
:30
: offset 0 -6
:30
: offset 0 -4
:30
: offset 0 -2
:30
: offset 0 0
:30
: roff
: stow

Procedure:
Well in advance of your observation, prepare a command file to accomplish the following procedure. Email your command file to your instructor, for examination, at least two days in advance of the observation. Write a command file to perform the following.
1. Record your data into a file whose name includes observers' names
2. Sets the frequency to 1419 and mode 1
3. Slews to the Crab Nebula,
4. Moves to an offset of +10 degrees in elev, measures the Tsys, and then returns to 0 offset.
5. Sets an offset equal to the pointing correction from lab 1.
6. Performs a switching observation using off positions one beam width to either side of the Crab and parallel to the Galactic plane (i.e., same b as Crab but with l that shifts by 7.5° in each direction).
7. Contains a total of 100 scans to create a total of 20 minutes of data. (Copy the four lines for one full switching cycle and paste 25 times.) However, taking into account the slewing time between positions, of about 18 seconds, this will take a total of about 35 minutes of telescope time (and your time).
8. Stops the recording
9. Returns to stow.

At the time of the observation:
1. Turn on the computer and ground controller box and click on the SRT icon.
2. Click on "Rcmdfl" and type in the name of your command file. Make sure that you get confirmation in the lower part of the SRT display of this filename. Watch the screen, taking

note of the appearances of yellow crosses and the "cmd" positions, to ensure that the program is doing what you expect it to.

3. When it reaches the end of the file, the telescope should have returned to stow. If so, click on "exit", turn off the ground controller, copy the recorded data file to your flashdrive, and shut down the computer.

Analysis of Data:

1. Open SRT_Plotter, click "Open File" and "browse" to find the data file you just created.
2. Note that in the plot the measured antenna temperatures in the channels at the very ends are very low and that the antenna temp takes about 8 channels to get up to the proper value. Click "Delete End Channels." This will bring up a window in which you get to select which data blocks you want to delete. Then, you might as well as choose "select all" to delete the end channels from all scans. And then use the mouse and the left button to select an area containing the points in the end channels on the left and another area for the channels on the right. The selected data points will turn to red diamonds. When you've got all the end channels selected, click on "Delete Selected End Channels"
3. Now click "Average Blocks of Data" and select all the data blocks that correspond to observations with the telescope pointed directly at Crab. Then click "Select". This will create a new data block at the end of the list, which is the average of your selected data blocks. This new data block, therefore, should be the average of all your **on source** scans of Crab.
4. Now average all the data blocks of the calibrated observations when the telescope is pointed away from Crab. This new data block is your average of all the **off source** Crab observations.
5. Select the average Crab on-source data block, which you created in step 3. Click on "Average Over Frequency." A number then appears underneath the list of data blocks. This is your final measure of the power (in kelvins) when observing the Crab.
6. Select the off-source data block and click on "Average Over Frequency".
7. Subtract your answer in step 6 from that in step 5. By doing this, you have subtracted the signal from the background and all other radiators in your system. Your final answer is:
$$T_A(\text{source}) = T_P(\text{on-source}) - T_P(\text{off-source}).$$
8. Now divide your measured antenna temperature by the known flux density of Crab (875 Jy) and **write this value in your report as the telescope's DPFU**.
9. Calculate the effective aperture of the telescope by using Equation 4.31 from the textbook. Write this value in your report as the telescope's effective aperture.
10. Calculate the aperture efficiency by dividing the effective aperture by the geometrical area of the dish, i.e. πR^2, where R = 1 m. **Write your inferred value of the aperture efficiency in your report.**

Write your report for this lab the same as for lab #1 (i.e. no abstract--just give the results and explain how you got them, followed by any discussion).

3. Measuring the Surface Temperature of the Moon

Now that we've calibrated and characterized our telescope, let's use it for a simple observation. In particular, let's measure the surface temperature of the Moon. Since the Moon is opaque and has a temperature above 0 K it will emit a Rayleigh-Jeans radio spectrum. So, its brightness temperature is a good measure of its surface temperature. Chapter 3 discusses the relation between brightness temperature and antenna temperature.

There is, however, one potential complicating factor, and that is that the surface of the sunny side of the Moon is probably hotter than the dark side, which would make the data analysis complicated. So, it would be better to make a measurement of just the dark side (when it is a New Moon) or just the full side (when it is a Full Moon). The Full Moon side will be hotter and easier to measure, and you can tell whether the telescope is at least pointed in the right direction, while the New Moon will be near the Sun, which can confuse the measurement (if the Sun is within a beam width or two), so we will make this measurement with a Full Moon.

Even the full moon is not bright enough for an NPOINT, so, as in Lab 2, you should use the pointing corrections determined in Lab 1.

Time of Observation:
The Moon moves significantly each night, and so the times that it is high enough in the sky changes from night to night. First, use the following web page:
http://aa.usno.navy.mil/data/index.php
to determine the date and time of full moon (note that the chart you get will be for Universal Time, which is 5 hours ahead of Eastern Standard Time and 4 hours ahead of Eastern Daylight Savings Time) and decide on an observing date that is within 2 days of the full moon. Then use the same webpage (scroll down to find "Altitude and Azimuth of the … Moon During One Day") to obtain a chart of the altitude and azimuth of the Moon for many times throughout your observation day (this chart will be for your local time). For our SRT, we need the Moon to have an azimuth between 90° and 270°. Pick a 1.5 hour period (to be safe) to make your observation.

Procedure:
Write a command file to perform the following steps
1. Record the data into a specific filename.
2. Set the frequency to 1420 MHz, mode 1.
3. Use "offset" to input the pointing corrections established in lab 1.
4. Slew to the "Moon."
5. Go to an offset with an additional $+10^{\circ}$ in elevation, measure the Tsys, and return to the offset in step 3.
6. Perform a switching observations using "offset" to define off positions at least one beam width to above and below the Moon. (Since azimuth angles equal smaller angles of arc at larger elevations, it takes longer to move one beamwidth away in azimuth than in elevation. So, switching only in elevation allow for slightly faster switching.) Remember to include the pointing corrections in all your offsets.

7. Make a total of 300 scans to create 20 minutes of data. However, taking into account the slewing time between positions, of about 18 seconds, this will take a total of about 100 minutes of telescope time (and your time).
8. Slew to "stow"
9. Stop the recording.
Carefully examine your command file and then send to your instructor.

At observation time:
1. Turn on the radio telescope, computer, and control box, and click on the SRT icon.
2. Copy your command file into the C:/SRTvsrt folder.
3. Run your command file by clicking "rcmdfl" and inputting your command file name
4. When done, exit the program, copy your data file to flashdrive, shutdown the computer, and turn off the radio control.

Analysis of Data:
1. Open SRT_Plotter, Click "Open File" and find the data file you just created.
2. As in Lab 2, delete the bad end channels from all blocks of data. (Click "Delete End Channels," choose "select all," use the mouse and the left button to select the bad end channels on the left and right, and click "Delete Selected End Channels.").
3. Click "Average Blocks of Data" and select all the data blocks of the On-Moon scans and click "Select."
4. Average all the data blocks of the off-source scans.
5. Select the average on-source data block, click on "Average Over Frequency," and read and record the final power (in Kelvin) of the Moon scans (that appears underneath the list of data blocks).
6. Select the average off-source data block, click on "Average Over Frequency," and read and record the final off source power (K).
7. Subtract your answer in step 6 from that in step 5 to get the antenna temperature of the Full Moon.
8. Convert to brightness temperature using
$$T_B = T_{ant} \, (\Omega_{beam} / \Omega_{source}),$$
   where $\Omega_{source} = \pi/4 \, (\theta_{moon})^2$ and $\theta_{moon} = 1/2°$ (remember to convert to radians),
   and $\Omega_{beam} = \lambda^2/A_{eff}$ and A_{eff} was calculated in Lab 2.
9. What is your measured surface temperature of the surface of the lit side of the Moon? Is this reasonable?

4. Submitting Proposal and Measuring the Flux Density of a Source

Pick one of the following sources, explore the literature to learn about this source and, in particular, find a report of a measurement of its flux density at or near 1420 MHz. You may start your reading with a popular science article, or even Wikipedia. If the source is extragalactic, you may be able to find references to 1420 MHz flux density measurement on the NASA Extragalactic Database. Using all the previously determined parameters of the SRT (specifically, the Tsys and DPFU or A_{eff}, from labs 1 and 2), to calculate how much time will be needed to measure the flux density of this source with a SNR of at least 5. Remember to include the time needed to obtain the 'off-source' scans and to allow time for slewing between positions.

Sources: 3C273; M87; Cygnus A; Cassiopeia A

Write a short (one page) proposal to ask for time on the SRT to make this observation. Your proposal should include:
a) a short introduction which explains why this source is of interest to study;
b) a "Technical Justification" section which shows your calculation that this source is likely to be detected in the amount of time your requested;
c) the range of LST (local sidereal times) that you can observe your source. (Remember that LST is discussed in Chapter 1.);
d) a References section listing the articles or sources that contain the information you mentioned (and don't forget to cite the reference in the text at the places you state these facts (in your introduction and technical justification sections).)

Submit the proposal to your instructor by email and check your email regularly to see if you have been granted time.

If and when your proposal is accepted and you are assigned time on the SRT, perform the observation using the methods you learned in previous labs.

At the end of your data analysis, remember to convert your measured antenna temperature to a flux density using
$$F\nu = T_{ant} \times DPFU$$
Also, be sure to calculate the uncertainty in your measured flux density.

Write a short lab report with a Title, Abstract, Introduction, Observations, Results, and Conclusions sections. The entire report should only be about 2 pages.

5. The 21-cm Line and the Galactic Rotation Curve

Neutral Hydrogen atoms have an emission line at a frequency of 1420.4 MHz, or a wavelength 21 cm. This emission line has proven to be an extremely useful probe for mapping the interstellar medium of the Milky Way Galaxy (or of any galaxy, for that matter). The interstellar gas of the Milky Way Galaxy is ~90% Hydrogen, by number of atoms, and most of the interstellar gas is relatively cold (~100K) so the Hydrogen atoms are mostly in the ground state. The 21-cm line is due to a spin flip of the electron in Hydrogen atoms in the ground state orbital. This transition is **forbidden** and so the photons are not easily absorbed by another Hydrogen atom. Additionally, at a wavelength of 21 cm, these photons are also not absorbed by interstellar dust, which blocks our view at optical wavelengths. Because there are so many Hydrogen atoms in the Galaxy, the strength of the total emission along any line of sight in the plane of the Galaxy is significant. And, because this radiation is not absorbed easily, we can detect the emission from Hydrogen atoms far across the galaxy.

One exceptionally clever application of the 21-cm line observations, which you will do in this lab, yields a determination of the **rotation curve** of the Milky Way (the rotation speed vs. distance from the center), which, in turn, leads to a measure of the mass of the Milky Way Galaxy. The results, even as performed with our simple 2-meter telescope, are enlightening.

Timing of Observations:
If doing this lab in the Fall, the galactic plane is up in the late afternoon.

Observing Procedure:
Write a command file to perform the following steps

1. Move the telescope to Galactic 10 0 (i.e. at Galactic longitude 10°, or 10° away from the center of the Galaxy, and latitude 0°, which is in the Galactic plane) and perform a switching observation with offsets one beamwidth to either side of the Galactic plane (Galactic 10 8 and Galactic 10 -8) for a total of 60 scans.

2. Move the telescope to Galactic 20 0 and perform switching with offsets at Galactic 20 7 and Galactic 20 -7 for 60 scans.

3. Do similar switching observations for positions every 10 degrees in Galactic longitude up to Galactic 80 0.

At the time of the observation:
1. Turn on the computer and ground controller box and click on the SRT icon.

2. Click "record" and input a data file name.

3. Set the frequency to 1420 MHz, mode 4 (this has 3 times the bandwidth as mode 1).

4. Move to a blank area of the sky and click "cal". Examine the Tsys value. If unreasonable, do "cal" again.

5. Input the established pointing offsets (from Lab 1).

6. Click on "Rcmdfl" and type in the name of your command file. Make sure that you get confirmation in the lower part of the SRT display of this filename. Watch the screen, taking note of the appearances of yellow crosses and the "cmd" positions, to ensure that the program is doing what you expect it to.

7. When done remember to: stop recording data, click on "Stow", and *after* the telescope has reached 'stow' to close the program. Transfer your data file to your flashdrive, shut off the computer, and turnoff the controller box.

Data Reduction:
1. Open SRT_Plotter, Click "Open file" and browse to find your data file.

2. Click "Delete End Channels," choose "Select All," and use the mouse and the left button to select an area containing the data in the end channels on the left and on the right. Click on "Delete Selected End Channels".

3. Click "Average Blocks of Data" to average all the scans of Galactic 10 0. Also average all the data of the off-source scans to either side of Galactic 10 0.

4. Repeat step 4 for each Galactic longitude.

5. Click "Subtract Background." For data block "A" click on the average of the "Galactic 10 0" data and for data block "B" click on the average of off-source data block at this longitude.

6. Repeat step 5 for each Galactic longitude.

7. Select the first "SUB" block. This should then show the final data block for Galactic longitude 10º.

8. In the pull-down menu that says "Plot Channels" select "Plot Velocities."

9. Note the flat-baseline and the range of the emission (with antenna temps greater than the baseline). Identify the highest-velocity point of the range of the emission. You can move your cursor to that point and read velocity (the x-coordinate). Record this value in your data table along with the Galactic longitude

10. Right click in the graph window to save a jpeg file of the plot.

11. Repeat steps 7-10 for the other Galactic longitudes.

Analysis:
Consider the range of frequencies in your spectra and why there is such a range. The large range results because of the Doppler effect and a large range of recessional velocities of the gas along the line of sight. Note that the emission goes to frequencies well below the natural frequency of the 21-cm line (1420.406 MHz), but not to much higher frequencies. This means that the range of velocities includes large redshifts (or positive recessional velocities) and only small blue shifts (negative recessional velocities). The reason for this is that you pointed the telescope where there was gas whose orbit about the center of the galaxy gave it a velocity relative to the Sun that was recessional. In the figure below, the line of sight through the Galaxy when looking at some non-zero galactic longitude is delineated.
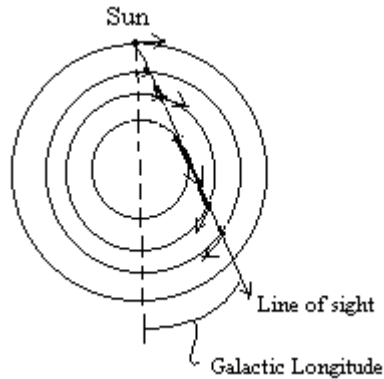
Figure B.4.1. Depiction of an observation through the plane of the Galaxy at Galactic longitude less than 90°.

The gas in the plane of the Galaxy follows circular orbits. So, at each point along the line of sight the gas has a component of velocity that is along the line of sight and is directed away from the Sun. The Sun also has a component along the line of sight, but all points interior to the Sun have a larger fraction of their orbital velocity along the line of sight than does the Sun. So, all the gas at Galactic radii closer than the Sun's should appear redshifted.

The first thing to do, then, is convert your minimum frequency of emission to a velocity. By the Doppler shift, this corresponds to a maximum recessional velocity, and so we can write this as

$$V_{max} = \frac{|\Delta v|}{v} c = \frac{1420.406\,\text{MHz} - v_{min}}{v_{min}} 3x10^5 \text{ km/s} .$$

However, this is the maximum recessional velocity relative to us, here on Earth. And, during your observation, because of the Earth's orbit and rotation, you were moving relative to the Sun. Additionally, the Sun has an extra component of velocity in addition to its orbital velocity, and to correctly we need to calculate the Galaxy's rotational velocities we need to compare only to the Sun's orbital velocity (see Figure B.4.1). Fortunately, you have already recorded the difference in the component of your velocity along the line of sight during the observation from the Sun's orbital velocity component in that direction – this was the VLSR numbers you were instructed to write down (this stands for velocity relative to the local standard of rest). So, now, for each of your Galactic longitudes, subtract the VLSR for that pointing direction from the V_{max} you just calculated for that direction. Let's call this $V_{max,LSR}$.

$$V_{max,LSR} = V_{max} - VLSR .$$

Now note that the gas along the line of sight that is closest to the Galactic center has a motion that is entirely along the line of sight. This gas, then, is responsible for the largest redshifted velocities in the emission. The distance of this gas from the center is easy to determine, using simple geometry. The line of sight at this point is tangent to the circular orbit of this gas, and so the line from the galactic center to this gas is perpendicular to the line of sight.
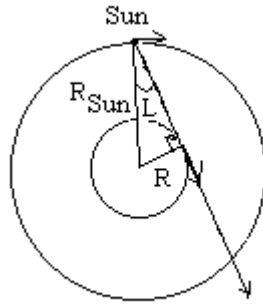
Figure B.4.2. The largest redshifted emission correspond to gas at the position along the line of sight closest to the Galactic center.

We therefore have a right triangle, with the Galactic longitude, L, being the angle opposite the line representing the distance of this gas from the center. If R_{Sun} is the distance of the Sun from the Galactic Center, then,

$$\sin L = R(gas)/R_{Sun},$$

or **$R(gas) = R_{Sun}\, \sin L$** B.4.1

The distance of the Sun from the Galactic Center is believed to be **8.0 kpc**.

So, the $V_{max,LSR}$ for each L is its orbital velocity minus the component of the Sun's orbital velocity along the line of sight, which, as shown in Figure B.4.3., equals V(Sun)sinL.

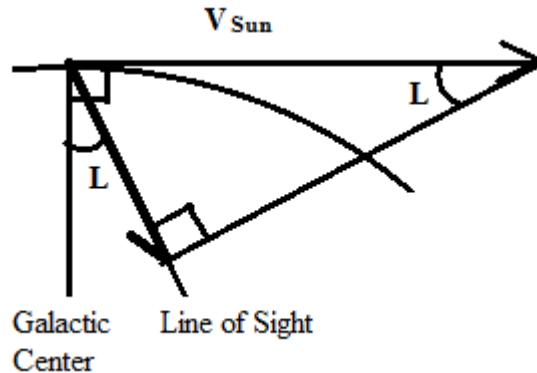**Figure B.4.3.**: The component of the Sun's orbital velocity along the line of sight, defined by Galactic longitude L, is given by $v_{Sun}\sin L$.

So, if $V_{max,LSR}$ is the maximum observed redshift velocity in the 21-cm emission along the line of sight for Galactic longitude L, then

$$V_{max,LSR} = V(gas) - V(Sun)\sin L,$$

and so the orbital velocity of the gas is:

$V(gas) = V_{max,LSR} + V(Sun)\sin L$ 4.2

By other means, we believe that the Sun's orbital velocity in the Galaxy is **220 km/s**. By using the trigonometry above and substituting in the Sun's velocity, you can calculate the galactocentric distance of the gas moving at that speed.

In sum then, for the spectrum at each position (from longitude = 10° to 80°), do the following calculations:

1. Determine the V_{max} in the emission line (you want the high velocity *edge* of the emission);
2. Subtract off the VLSR.
3. Calculate the orbital velocity of this gas (using equation B.4.2)
4. Calculate the galactocentric distance of this gas (using equation B.4.1),
5. And, plot rotational velocity vs. galactocentric distance.

Lab Report:

Write a standard formal lab report, which includes Title page (containing also the date, your name and partner(s) name(s)), Abstract, Introduction, Observations, Results, Discussion, and Conclusions. In the Introduction discuss the 21-cm emission line and the presence of cold Hydrogen in the interstellar medium of the Galactic disk. Also give an equation using Newton's Universal Law of Gravity to determine the mass of a larger body when you know the speed and radius of a much smaller body in orbit about the larger.

Questions to consider for the Discussion Section.

1. Is the velocity vs. radius relation Keplerian (meaning that $v^2 \propto 1/r$)? Keplerian velocity curves result when all the mass is at the center (as in the Solar System). If your data suggests that the Galaxy rotation curve is not Keplerian, go to #2

2. Use Newton's Universal Law of Gravity to calculate the amount of galactic mass inside each of your measured galactocentric radii. Describe, roughly, the relation between M(enclosed) vs. R (especially for the larger radii)? How does this compare with the distribution of star light, which drops with R as an exponential?

3. Try to fit function to the M vs. R curve. (You may want to try plotting logM vs. logR, fitting a straight line and finding the slope. The slope of the log-log plot is the power of R in the equation for M.)