Astronomy 465 – Fall 2024
Lab # 1: Measuring the Telescope Beamwidth with the Sun

Reports due: Sep 27 2024

Note: Due to the nature of astronomy observations, source visibility, and telescope availability, students will be required to use the lab space and the UW telescopes beyond the expected class hours so that they can collect relevant observations.

Motivation: The *antenna pattern* or *beam pattern* of a radio telescope describes its response to EM radiation as a function of direction. This pattern will be the same whether the telescope is being used to transmit or detect radio waves. If θ and ϕ are polar coordinates describing the location of a source relative to the telescope's axis (i.e., the direction in which the telescope is pointing), then we can define the *normalized beam pattern* $P_{\rm n}(\theta, \phi)$ to have a value of unity at $(\theta, \phi) = (0, 0)$. Radio telescopes with perfect circular symmetry have beam patterns that do not depend on ϕ. In this case, we define the *beam width* as $2 \times \theta_{1/2}$, where $\theta_{1/2}$ is the angle at which

$$P_{\rm n}(\theta_{1/2}, \phi) = 0.5 \tag{1}$$

We refer to $2 \times \theta_{1/2}$ as the *full width at half-maximum* (FWHM) of the beam pattern, or simply as the *half-power beamwidth* (HPBW). Note that in addition to the *main lobe* of the beam pattern, within which the HPBW is measured, we can also have *sidelobes*– directions far from the telescope's axis in which there is still a nonzero response. If a strong source happens to fall in a sidelobe when you are trying to detect a weak source in the main lobe, you may be in trouble!

The theoretical beam pattern expected for a uniformly illuminated circular aperture with the width of your antenna dish:

$$P(\theta) = \left(\frac{2J_1(x)}{x}\right)^2, \tag{2}$$

where $x = \pi \sin\theta/(\lambda/D)$ and θ is the angular offset from the center of the beam in radians (D is the diameter of the SRT antenna). Here $J_1(x)$ is the spherical Bessel function of the first kind with order 1.

To measure a telescope's HPBW, we need to drive the telescope in very short steps across a bright radio source. Although certain radio-bright sources (e.g., Cygnus X-1) and geosynchronous satellites can be used for this exercise, in the case of the SRT, our best strategy is to use the Sun.

References: These chapters provide theoretical background.
Marr, Snell & Kurtz, "Fundamentals of radio astronomy", Chapter 4.2.
Condon & Ransom, "Essential radio astronomy", Chapters 3.2.4 and 3.2.5

Preparation:

Become familiar with the basics of the SRT interface by using the "UW-Madison SRT Manual", and the old Haystack's "Small Radio Telescope Operator's Manual." The manuals have examples of simple scripts and commands for pointing, frequency setting, data files etc etc.
Check the off-line version of the SRT software to familiarize yourself with the graphical interface. To access: go to any iMac except OBSERVERS, click on the SRT icon (bottom of the screen), select "Simulate Anntena Motion" and "Simulate Signal" options and "Run Program".

Write a command file to measure the radio signal at 16 points spaced by 3 degree, starting at $-24°$ offset from the Sun and going to $+24°$ offset. The procedure should open a file with a unique name (using something like snez_sun_20sep23.rad will allow you to identify your file easily), store your results in that file, and close it when the measurements are done. You can choose to scan EITHER along the Azimuth or Elevation axis. You can select a central frequency in the range 1420.0 MHz to 1440 MHz, integrate for 10 seconds (this will result in $\sim$ 10 spectra) at each pointing using the observing mode 1 (this mode is for continuum observations and has 64 frequency channels). With about ten samples at each point, you can improve your precision in measuring the signal-to-noise ratio, and you can get a decent estimate of the uncertainty in the result.

Once you have your script ready test run it in the Simulator. Please see Sections 3 and 4 of the UW-SRT Manual for instructions.

Connect to one of the SRTs:
Use the Microsoft Remote Desktop. Click on "dome" or "pbo92". Passwords: "srt", "srt". After finishing, stow the SRT and Exit from the interface. Then go back to the Microsoft Remote Desktop and disconnect.

Observing:

1. Transfer your command file to one of the OBSERVER computers. Best to e-mail the file to yourself and then open a mail program on the OBSERVER and download the file. The observing file needs to be in the directory called SRTvsrt (you will see other observing files there). Please make sure the file has an executable extension. Click on the file name and make sure it is listed as a Windows Command Script[1].

2. Run your command file and copy (e-mail) the data file to your computer[2].

3. As there are 25 students this semester, you may have to obtain observations at a time outside of lecture/lab periods.

[1]For troubleshooting see the UW SRT Manual.
[2]For troubleshooting on running the SRT please see the UW SRT Manual.

Analysis:

1. The SRT data files are simple text files but have a specific format. We will use Python for data analysis. The class Canvas web site has basic pointers on how to start using Python.

2. See section below about the data file format. Check the file first using Word or Unix to familiarize yourself with the data format. Then read the file in Python. You will need to extract pointing (angular) offsets where you observed, and for each position calculate the integrated intensity of radio emission for each of the observed positions. For example, you will most likely end up having about 10 samples of the integrated intensity for each offset position. Save the average value of the integrated intensity and the standard deviation as separate variables.

3. Be careful with counting individual scans, use your .rad file as a guide. For each measurement (spectrum) calculate the integrated intensity of the continuum spectrum. For each offset position, calculate the average of your measurements from multiple scans and the uncertainty (standard deviation) in the average.

4. Plot the average values (with error bars) for your elevation/azimuth scan. You should have the angular offset from the center of Sun on your x-axis, this information can be read from the .rad data file.

5. Estimate the half-power beam width (HPBW). A complication with the azimuth scan is that each change of 1 degree in azimuth is really only (1 deg) cos (elevation) on the sky. Correct your azimuth HPBW for this effect to get the true beamwidth in that direction. How does the HPBW compare with we expect for the SRTs? Is the peak of the beam pattern centered at $(0, 0)$? If not, then the telescope has a pointing error.

6. Overplot on your plot the beam pattern expected for a uniformly illuminated circular aperture with the width of your antenna dish:

$$P(\theta) = \left(\frac{2J_1(x)}{x}\right)^2, \tag{3}$$

   where $x = \pi \sin\theta/(\lambda/D)$ and θ is the angular offset from the center of the beam in radians (D is the diameter of the SRT antenna). Here $J_1(x)$ is the spherical Bessel function of the first kind with order 1. Scale $P(\theta)$ by a constant and then add another constant so that the theoretical beam pattern has the same peak value and value at large offsets as your real profile. Comment on any difference in shape between the theoretical and observed beam pattern.

7. Prepare an individual lab report presenting your results and conclusions. Your writeup and conclusions should be your own, not the results of a group effort. Please use LaTeX (and Overleaf) to do this. Please see the last section on what to include in the report.

Data format and how to read .rad file in Python:

The SRT data files have extension .rad and have a well-defined format. These are essentially text files, to see what's in the file you can use Microsoft Word or simple Unix commands. Data files look like:

```
* STATION LAT= 43.07 DEG LONGW= 89.67
2005:148:10:55:41 92.0 5.0 0.0 0.0 1419.75 0.00781250 1 64 4.7 5.9 10.5 20.1 40.1 70.
```

Each line of a data file contains a spectrum, and various information about the telescope pointing and frequency setting. Commands executed by the telescope are shown with * in the first column (these are lines read from your observing script). If the file already exists, the data are appended to it. This can look messy and may happen if something unusual happens during observing. By looking at the list of commands in the .rad file you will be able to understand what exactly happened and select good data.

The fields used for each data line (which contains a spectrum) are always the same:

```
Field 0 - time (yyyy:ddd:hh:mm:ss)\\
Field 1 - azimuth(deg)\\
Field 2 - elevation(deg)\\
Field 3 - azimuth offset(deg)\\
Field 4 - elevation offset(deg)\\
Field 5 - first frequency bin (in MHz)\\
Field 6 - digital frequency separation (in MHz) = freq. channel width\\
Field 7 - digital spectrometer mode \\
Field 8 - number of frequency channels \\
Field 9 { data value (in calibrated temperature units) at first frequency channel \\
field 10 { data value at second frequency channel \\
Etc etc
```

You can read .rad file in Python in many different ways, I like using functions "open" and "readline" . Here is an example of what can be used to read spectra from a .rad file. As the .rad file contains lines that start with *, first we ignore those lines. For each line of data from the file, we need to split the line into individual data points. Then take the last 64 data points from each line as your spectrum, and save all spectra into a 2D array. I also find Az values and save those as a 1D array (az1).

```
import matplotlib.pyplot as plt
import numpy as np

spectra = []
frequency = []
velocity = []
counter = 0
az = []
```

```
az1=[]

file="cross_sun_1sep23.rad"
infile=open(file)

for line in infile.readlines():
    if ('*' not in line[0]):
        print(line)
        line_list = line.strip().split()
        str_spec = line_list[-64:]
        az = float(line_list[3])
        print(az)
        specific_spec = []
        for item in str_spec:
            specific_spec.append(float(item))
        plt.plot(specific_spec)
        plt.ylabel('Brightness Temperature(K)')
        plt.xlabel('Bin number')
        plt.show()
    #plt.savefig('spectra.png')
        spectra.append(specific_spec)
        az1.append(float(az))
infile.close()
```

Note: the number of channels (64 in this case) will depend on the exact spectrometer mode used. Only mode 4 has 156 frequency channels, while all other modes have 64.

What to include in your lab report:

Please include the following sections: Introduction (why are we doing this), Observations, Data analysis, Conclusions. Under Observations please include and explain your observational setup and the observing script. Under Data Analysis, please include your Az/El scans across the sun, estimates of the FWHM beam width, and your Python code. Provide a summary of the analysis steps you took, explain how you calculated error bars. Under Conclusions, please explain how your results compare with the theoretical beam shape, comment on any complications/problems during the experiment, pointing offsets that you noticed, and any suggestions on how to improve the experiment in the future. The Canvas page has tex style files and a sample paper tex file that you can copy to Overleaf and use as a template for your report.

Common issues that can result in losing points: figure axes not well labeled, missing error bars, missing analysis steps, missing or super brief introduction.