Investigating Radio Interferometry

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ABSTRACT

This paper covers the basics of radio interferometry. We use the interferometer on the roof of Campbell Hall to take data from the Sun, Moon, and the Orion Nebula (our chosen point-source). I then analyzed this data by plotting the power spectrums of the Sun, Moon, and Orion, calculating the range of expected fringe frequencies for Orion, and using least squares fitting on the data to measure the east-west and north-south baselines of the interferometer, and using the modulating function to find the diameter of the Sun and Moon. I found the value of the range of expected fringe frequencies for Orion to be 0.050005406 Hz. Using 1D least-squares fitting, I found the value of the east-west baseline of the interferometer B_{ew} to be 17.029076 m and the value of Q_{ew} to be 565.125. Running another fit using 2D least squares fitting, I found Q_{ns}=10.000, Q_{ew}=412.500, B_{ns}=0.000 m, and B_{ew}=12.375 m. I could not accurately find the diameter of the Sun or Moon.

Contents

1. Introduction

In this lab, we learned about radio interferometry and how the interferometer on the roof of Campbell Hall works. The interferometer we used is a multiplying interferometer with a baseline of about 20 m that operates at about 12 GHz. The interferometer consists of two telescopes, each with about 1 m diameter dishes, and multiplication of the signals from the two telescopes (E_1 and E_2) using a mixer produces an output of interference fringes. Figure 1 shows a block diagram of the mixer used for our interferometer. The fringe properties such as frequency, amplitude, and phase are then used to derive point-source declination, interferometer baseline lengths, and the diameter of the Sun and Moon using least-squares fitting.

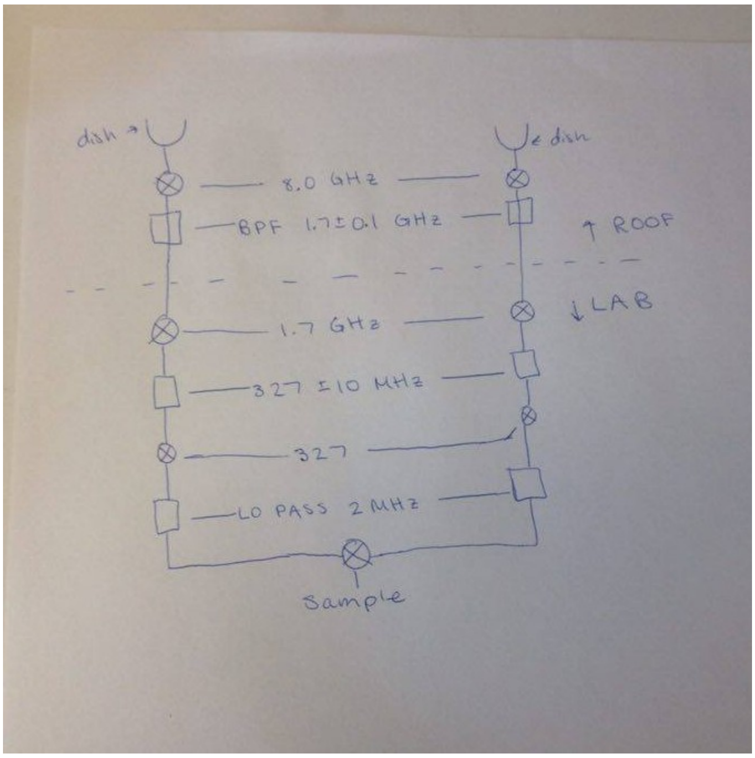

Fig. 1.— A diagram of the mixer used in the interferometer on the roof of Campbell Hall.

The Sun and Moon are considered extended sources, which means that their fringe amplitudes change with time, based on their brightness distribution. For the Orion Nebula, our point source, the fringe amplitude does not change with time. Orion is an HII region, which means that hot stars have produced warm ionized gas and electrons flying past protons produce free-free radiation. Free-free radiation is also emitted by the Sun. When measuring the Moon at radio wavelengths, we are not actually measuring the light reflected off the Moon's surface but rather blackbody radiation emitted from it's surface, heated by sunlight.

2. Data Collection and Analysis

This section details the data we collected from the point-source, Sun, and Moon, and how we used Fourier transforms and least-squares fitting to analyze the data and derive values for the east-west and north-south baselines of the interferometer and diameter of the Sun and Moon.

2.1. Testing the Interferometer- A Short Sun Observation

In order to confirm that the system was working and to practice using the interferometer and the observing software, we first took an hour long test observation of the Sun, and plotted the power spectrum of the data to confirm that we saw fringes. We used the IDL function `follow` to keep the interferometer pointed at the Sun, and we simultaneously ran the IDL function `startchart1` to collect the data from the interferometer output. Once we confirmed that we saw the fringe in the resulting data, we moved on to our point-source observation. Figure 2 shows a plot of the data collected from the interferometer and a plot of the power spectrum for the data, showing the fringe.

2.2. Point-Source Observation- The Orion Nebula

Our chosen point source was the Orion Nebula, located at r.a. $12^h30^m49.423s$, dec $-05°23'28''$, and $S_{Jy} \sim 340$. To get the data for the Orion Nebula, we first plugged the r.a. and dec into the IDL function `precess` to precess the coordinates to the current equinox. Next, we calculated when the source would be up in the sky so we knew when to start and stop our observation. We then programmed the resulting precessed coordinates into the `follow` command and started recording horizon to horizon data when our source was up. Figure 3 shows a plot of the data collected from the interferometer and a plot of the power spectrum for the data, showing the fringe.

Next, I wrote a program called `fringefreq` to calculate the range of expected fringe frequencies using Equation 1:

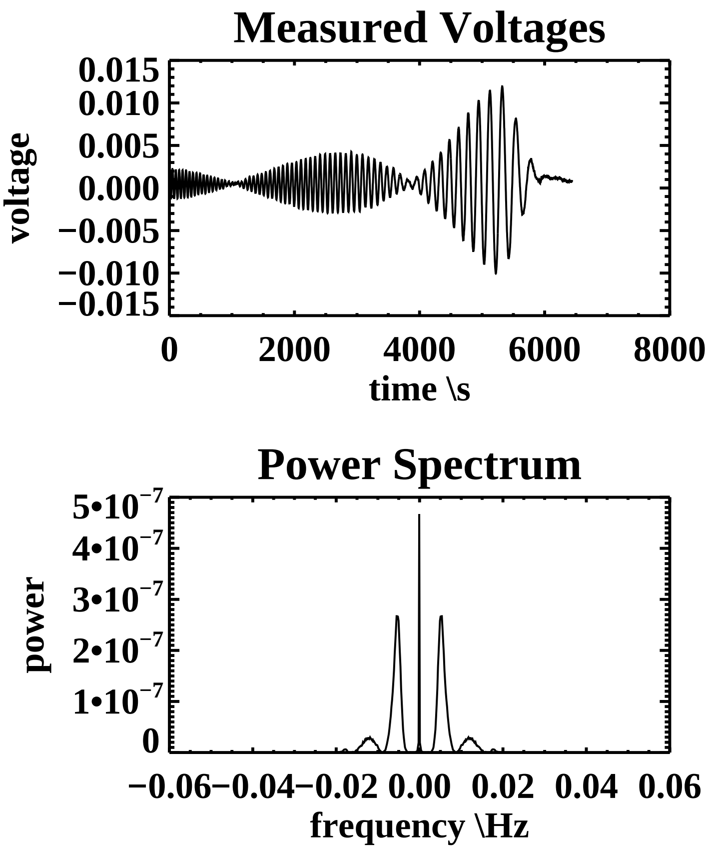

Fig. 2.— The top graph shows the measured voltages vs time for a one-hour long observation of the Sun and the bottom graph shows the power spectrum of the Sun data.

$$f_f = \left[\frac{B_{ew}}{\lambda}\cos\delta\right]\cos h_{s,0} - \left[\frac{B_{ns}}{\lambda}\sin L\cos\delta\right]\sin h_{s,0} \tag{1}$$

The output of `fringefreq` is the range of local fringe frequencies in cycles per second, which I found to be 0.050005406 Hz. This value is consistent with what I saw in the power spectrum graph.

The next step was to use the 'brute-force' least-squares fitting method to derive values for B_{ew} and B_{ns}. To do this, I first ran a 1D least squares fit of the data to derive values for B_{ew} and Q_{ew} by assuming that B_{ns}=0. Q_{ns} and Q_{ew} are related to B_{ns} and B_{ew} through the equations $Q_{ew} = \left[\frac{B_{ew}}{\lambda}\cos\delta\right]$ and $Q_{ns} = \left[\frac{B_{ns}}{\lambda}\sin L\cos\delta\right]$. The first step in computing the least squares fit was to create a guess value for Q_{ew}, which I set to 550. I then changed the

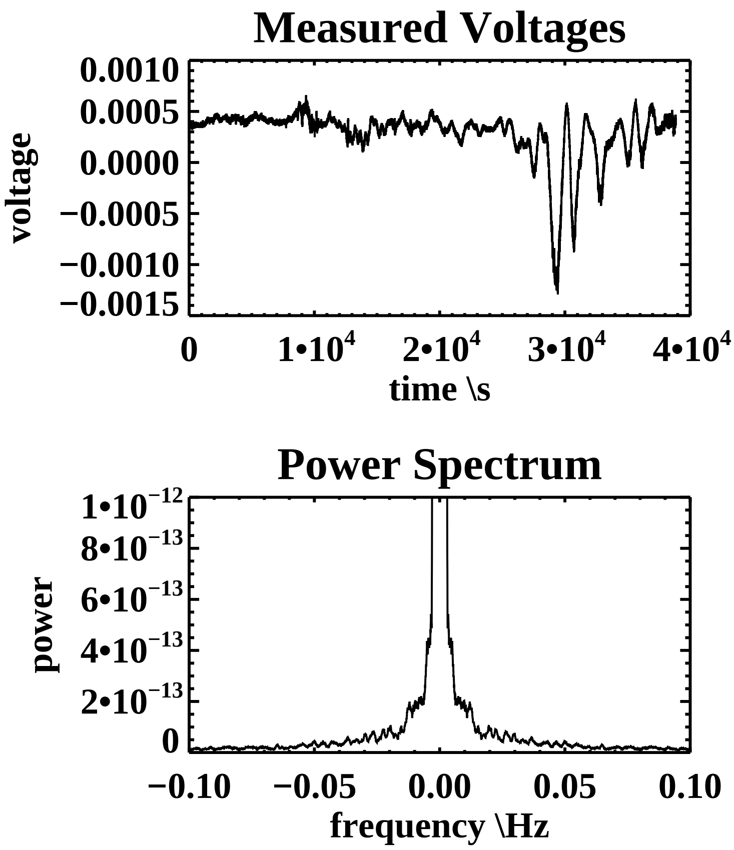

Fig. 3.— The top graph shows the measured voltages vs time for the horizon-to-horizon observation of the Orion Nebula and the bottom graph shows the power spectrum of the Orion data.

guess value of Q_{ew} several times and created a matrix of the sum of squares of the residuals, which I then plotted against Q_{ew}. The plot is shown in the top graph of Figure 4. I used the least-squares procedure to calculate the minimum value of Q_{ew}, which was 565.125. From this, I calculated the minimum value of B_{ew} to be 17.029076 m. Both of these calculated values are somewhat close to their actual values, suggesting that the fitting process works but our data might be a little skewed, resulting in a slightly different fitted baseline measurement than the true value.

Next, I used 2D brute force fitting to find the best values for Q_{ew} and Q_{ns} by creating a 2D array for S and plotting it against the guessed values for Q_{ew} and Q_{ns}. I wrote the program `twodfit` to compute the 2D brute-force least squares fit and return values for Q_{ns}, Q_{ew}, B_{ns}, and B_{ew}, along with a contour plot of the values of S^2. The darkest area of

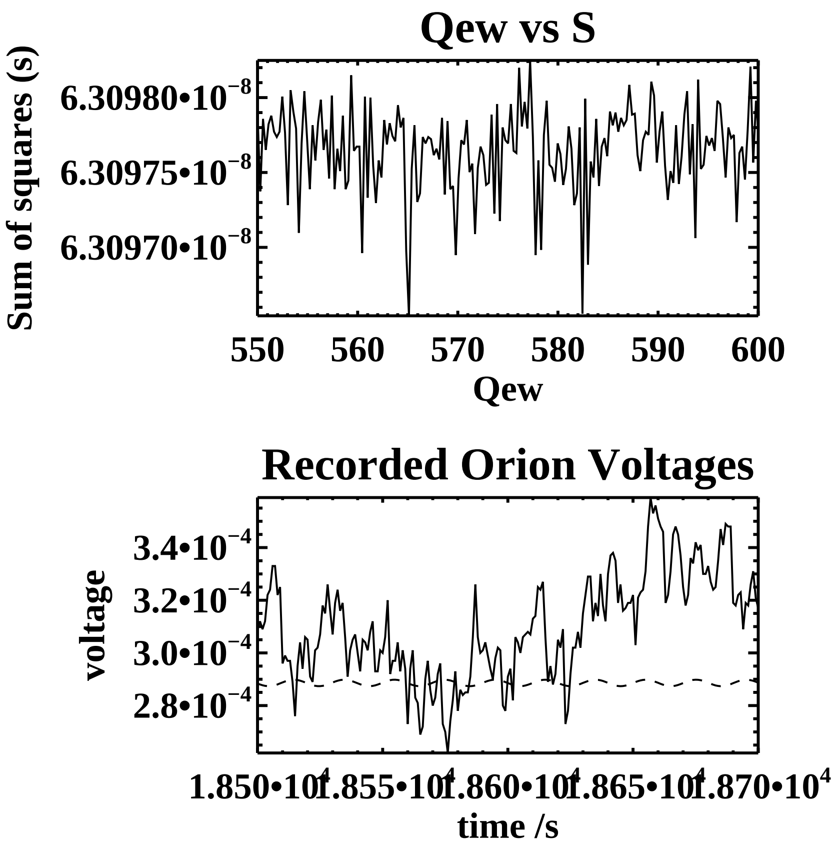

Fig. 4.— The top graph shows the calculated Q_{ew} vs S values from the least squares fit of the horizon-to-horizon observation of the Orion data. The minimum of the graph is the best value of Q_{ew}. The bottom graph shows the voltage vs time graph for a small piece of the Orion data, overplotted with a dashed line showing the predicted values (ybar).

the contour plot shows where the global minimum value of S^2 is. The program returned the least-squares fitted values of Q_{ns}=10.000, Q_{ew}=412.500, B_{ns}=0.000, and B_{ew}=12.375. Again, this data is not very accurate, and suggests either an error in the data we collected or in the analysis. Figure 5 shows the contour plot of the sum of squares for the two dimensional fitting, which should show the minimum of the 2D least-squares fitting.

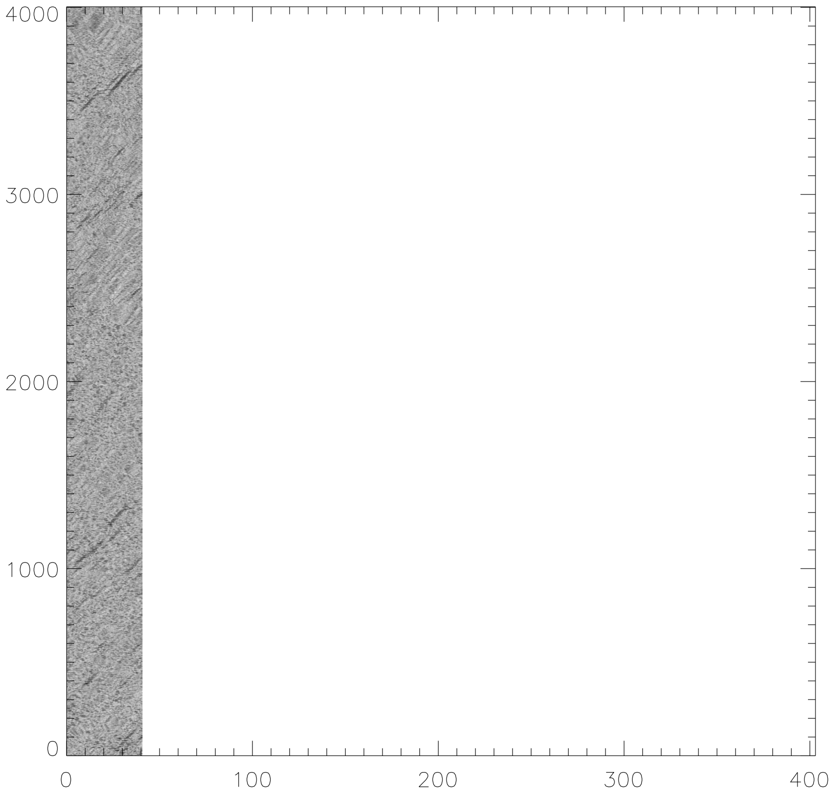

Fig. 5.— This contour plot shows the calculated Q_{ew} and Q_{ns} vs S values from the 2D least squares fit of the horizon-to-horizon observation of the Orion data. The darkest part of the graph is the minimum of the sum of squares matrix, and gives the best-fit values of Q_{ew} and Q_{ns}.

2.3. Horizon-to Horizon Sun and Moon Observations

After analyzing the point source data and becoming familiar with the least-squares fitting process, we took one horizon-to-horizon observation each of the Moon and Sun. We then analyzed this data to find the diameter of the Sun and Moon. For these calculations, we modeled the interferometer as an east-west interferometer, with B_{ns}=0. Since the Sun and Moon never get far from $\delta = 0°$, our data essentially consists of a 1D sampling of the source with a range of baseline lengths. When looking at the Sun and Moon data, we must integrate the 2D fringes along vertical strips to get the 1D brightness distribution. We do this using a “modulating function”, which is the Fourier transform of the source intensity distribution on the sky. The zero points of the Fourier transform of the horizon-to-horizon intensity distribution for the Sun and Moon data should give the diameter for each one, respectively. Figure 6 shows the plot of the Fourier transform of the Sun and Moon horizon-to-horizon data, used to get the diameter. This gives us the locations of zero crossings for the observed modulating function, $MF_{observed}$. We then compare this to the zero crossings of the theoretical modulating function, MF_{theory}:

$$MF_{theory} \approx \delta h \sum_{n=-N}^{n=+N} \left[1 - \left(\frac{n}{N}\right)^2\right]^{1/2} \cos\left(\frac{2\pi f_f R n}{N}\right) \tag{2}$$

Comparing the zero crossings of MF_{theory} and $MF_{observed}$ should give us the radius, R, of the Sun and Moon. However, it seems that our Sun and Moon data might not have been very accurate, because the zero crossings of their $MF_{observed}$ (as seen in Figure 6) do not appear to correspond to what we would expect from MF_{theory}.

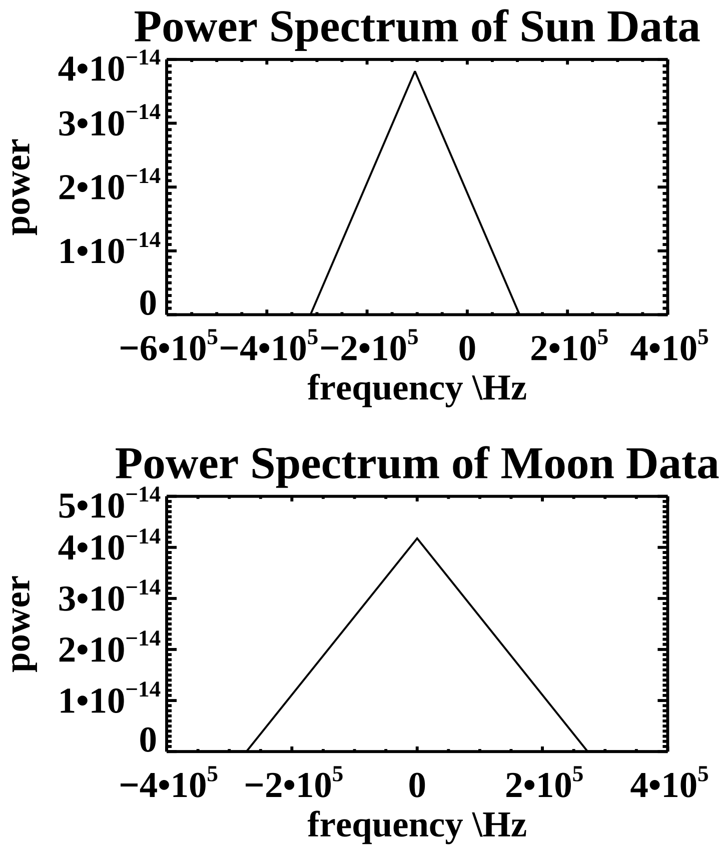

Fig. 6.— Plot of $MF_{observed}$ for the Sun and Moon. $MF_{observed}$ is a calculated by doing a Fourier transform of the source intensity distribution.

3. Analysis Software

Our observations of the Orion Nebula and the Sun and Moon were completed by the group consisting of Megan Allen, Morgan Welch, Spencer Abrams, and Elisha Jhoti. The software used to analyze the data and perform the least-squares fitting was written by me. The following programs were written and used to analyze the data for this lab, and can be found in `home/meganallen/astro121/lab3` in the `/week1` and `/week2` folders, respectively:

1. `data_ft`: Program that uses information from the data files from the interferometer to plot both the measured voltages vs time and the power spectrum. Can be set to plot voltages and power spectrum either individually or simultaneously, and can be set to plot data from the initial sun test, or the horizon-to-horizon observations of Orion, the Moon, and the Sun.
2. `fringefreq`: Program that calculates the maximum, minimum, and range of expected fringe frequencies for the Orion data.
3. `lsfit`: Program to calculate the 1D least squares fit for the point-source data. Returns a plot of Q_{ew} vs S and a plot of the measured voltages overplotted with the predicted values. Also prints the minimum Q_{ew} and the minimum B_{ew} values.
4. `twodfit`: Program to calculate the 2D least squares fit for the point-source data. Returns a contour plot of the values of S^2. Also prints the minimum Q_{ew}, Q_{ns}, B_{ns}, and B_{ew} values. Note: takes a long time to run.
5. `sunmoondiameter`: Program that calculates and plots the fft of the source intensity distribution of the Sun and Moon (modulating function).

4. Conclusion

In conclusion, this lab covered a lot of material in radio interferometry including using the interferometer on the roof of Campbell Hall and understanding the mixing process that it undergoes, obtaining data from point sources and extended sources using the interferometer, least-squares fitting the data to derive values for the interferometer baseline, and using modulating functions to solve for the diameter of the Sun and Moon. Using the interferometer to collect data and plotting the output helped me to investigate the fringes of point-source and extended source data, and the amplitudes and phases of those fringes. Fourier transforming the observed fringes revealed information about the fringe frequencies and allowed me to calculate the diameter of the Sun and Moon. Obtaining horizon-to-horizon spectra of the

Sun, Moon, and Orion Nebula allowed me to use least-squares fitting on the data to derive the projected baseline lengths of the interferometer.

While our observations ran smoothly for the most part, we did have some hiccups that most likely affected the data and subsequently the analysis. When observing the Orion Nebula, our data started to look very strange during the last third of our data taking time. During this time, we noticed that the interferometer was pointed in the direction of the Campanile and San Francisco, so we assume that the crazy looking data may be from interference from either of those objects. Also, when recording our horizon-to-horizon Sun data, we started the interferometer earlier than sunrise (about 3 am) and accidentally set the observing script to run for too short of a time and had to restart it, so we have a large portion at the beginning of the data that contains no relevant information and a portion near the end where the data cuts out for about an hour. This most definitely negatively affected the computational analysis of the Sun data, which may be why it was hard to derive the correct diameter.