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The Invisible Sun: Building a Radio Interferometer Telescope

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The Invisible Sun: Building a Radio Interferometer Telescope

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by
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When we think of astronomy, we often associate the word implicitly with observing astronomical bodies with our own eyes, or from a signal collected in the visible light range. However, there is more information we can collect from these bodies when observing them using other kinds of light, unseen to the naked eye. Radio astronomy is an important tool in an astronomer’s toolkit, and can help us image hidden parts of the universe. Recently, radio astronomy was used to directly image a black hole in the center of a nearby galaxy for the first time!

This project aims to further explore the ways in which radio interferometry can broaden and enhance our understanding of distant astronomical bodies, approaching it both physically and conceptually. Specifically, I worked on the design and construction of a radio telescope here at Bard, that will be able to detect radio waves coming from the Sun. Concurrently, I worked to understand the theoretical implications of radio interferometry and how the signal would be processed and used to determine the diameter of the Sun.
Dedication

Dedicated to those who persevere.
Acknowledgments

I would like to thank my advisor, Antonios Kontos, and my machine shop mentor, Richard Murphy, for helping me realize this project, for giving me guidance along the way.

I would like to thank my mother for encouraging me throughout my education, especially when I needed it the most.

I would like to thank my friends for supporting me through this achievement.
1

Introduction

1.1 Background of the Project

When starting this project, I began by reading *Two Topics in Astrophysics: Exoplanetary Gravitational Microlensing and Radio Interferometry* [1], to familiarize myself with the work that had already been done on the telescope and the direction it now needed to take. The original Senior Project was split into two very different topics, as noted by the subtitle, and while my own Senior Project will focus exclusively on the second topic, radio interferometry, I found it necessary to review the project as a whole in order to fully grasp the origin of this project and the beginning steps previously taken to build the telescope.

The design for the telescope was drawn from an academic paper titled *A Michelson-type radio interferometer for university education* [2], as published in the American Journal of Physics. The paper lays out method by which universities could build their own fairly cheap Michelson-type radio interferometer, as the authors believe “the future of radio astronomy relies strongly on interferometers” (249) [2]. They developed a design that could be used in the classroom, both to build the telescope and then subsequently using it to gather data and make measurements. The paper end goal was to be able to measure the diameter of the Sun with this homemade radio interferometer. As this measurement
is one that is already determined, we can compare our measurement to the actual one and thus assess the accuracy or inaccuracy of the telescope.

This project consists of two different aspects of building a radio interferometer telescope: the mathematical side through signal processing and the physical construction of the telescope. This project uses *A Michelson-type radio interferometer for university education* [2] as the inspiration for the design of the radio interferometer, which means that much of the design as described in this project is taken from the description of Koda et. al.’s design.

The general design of both the telescope built for this project and the one built for the Koda et. al. paper is as follows: we have four aluminum covered flat mirrors at the sides of the telescope; these then redirect the signal to the satellite dish and feed horn. Then these signals are mixed together during the detection. The satellite and feed horn used in the Koda et. al. paper operate at a frequency of $\nu \sim 11$ GHz ($\lambda \sim 2.7$ cm). Two mirrors are also attached to a typical 16 ft ladder, enabling them to move back and forth, thereby allowing us to change the distance between the mirrors. The altitude and azimuthal directions of the interferometer are each controlled by a motor and gear set up enabling us to point the telescope at the desired location in the sky. Throughout the paper, the design and set up of the telescope is further described as it relates to the additions and modifications to the existing structure, specifically in Chapter 4. To more fully and fundamentally understand the telescope as it was at the beginning of the project, and to read a detailed parts list, please read Chapter 3 of [1].

1.2 Radiation of the Sun

From Figure 1.2.1, we can see that the source for our observations is the Sun, as proposed by Koda et. al. in their paper. This is a useful source to use, as we already know significant information about the Sun and so can compare the diameter we find using the interferometer to the standard diameter of the Sun.
Figure 1.2.1. A schematic of how a radio interferometer collects signal from the Sun. In our set up, 1 and 2 would be the mirrors attached to the ladder, separated by some distance B, the baseline length. L is the path length difference of the light traveling to the mirrors [11].

Like all astronomical bodies, the Sun has an electromagnetic spectrum containing waves of all kind, peaking in the visible spectrum, as seen in Figure 1.2.2. This makes sense, given that the Sun is our light source and we have thus adapted to be able to see light in its range. However, despite the Sun’s peak being in the visible spectrum and its rather low intensity in the radio spectrum, radio waves from the Sun are still easily detectable by a small telescope. Generally, one of the challenges of optical astronomical observation is that what we see can be affected in its travel from the Sun to the observer. However, we do not encounter this same problem with radio astronomy, as radio waves can pass through space dust with little alteration to the signal, thus we are still able to detect these radio waves even at their lower intensity.
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Figure 1.2.2. In this graph, we see the electromagnetic spectrum of the Sun. The x-axis shows the wavelength and the y-axis shows the intensity of the radiation. As we can see, the Sun’s radiation peaks in the visible range and is quite low in the radio wave range [12].

We can also theoretically calculate the diameter of the Sun using an empirical understanding of how far the Sun is from the earth. Simplifying our set up, we think of the earth as a point and the Sun as a body with some diameter $S$. The telescope will help us determine the angular diameter of the sun. We can then use the known distance, $d = 149.6 \times 10^9$ meters, to find the diameter of the sun, $S$, using the formula $S = \theta d$.

Figure 1.2.3. Using the equation for arc length, $S = \theta d$, we can come up with a pretty good approximation for the diameter of the Sun.
In the following chapters, I will discuss the further steps taken to work towards completing the radio interferometer telescope. Chapter 2 will explain the theoretical and background information necessary to understand radio interferometry. Chapter 3 will discuss the signal processing aspect of this project, using the equations provided in the Koda et al. [2] to simulate the plots and signal that would be received by the radio interferometer to determine the diameter of the Sun. Chapter 4 will go delve more deeply into understanding the telescope at Bard as a whole, including more information on its at the beginning of the project, as well as where it is now. Chapter 5 will discuss the main accomplishments of this project: the design and implementation of the stepper motor mounts and the motors themselves. In this chapter, I will detail the specific choices and steps taken to create an initial design, the function of the pieces and the alterations that we made as the project progressed. The conclusion will focus on the next steps needed to complete the radio interferometer telescope, both the plans made during this project that were not executed as well as the subsequent general next steps required to properly operate the telescope and then collect and process the signals observed.
2

Basic Principles of Radio Interferometry

Figure 2.0.1 shows the design of the radio telescope depicted in Koda et. al. [2], which was followed in designing the telescope described in this project. This design does not look like what you would expect it to, as it is a radio interferometer rather than a visual optical telescope that is usually associated with the word “telescope.” Thus, as shown in the figure above, there are flat mirrors that collect the light from the source selected, in this case the Sun. These mirrors are angled to direct the data to the satellite dish. The satellite dish is then curved such that the data directed to it gets sent to the feed horn, which is connected to a spectrum analyzer that then analyzes the signal collected.

Figure 2.0.1. A rough schematic of the telescope as designed by Koda et. al [2].
This type of radio interferometer is called an “adding interferometer,” as when in use, it adds the signals together. Before we can go further in depth to understand this design, we must also be sure to understand the basic concepts upon which the basis of this design is built. Thus we must be sure we can answer the question: what is an interferometer, and, more specifically, what is an adding interferometer? By definition, an interferometer is “an instrument in which the interference of two beams of light is employed to make precise measurements” [7]. There are many different types of interferometers, however in this design Koda et. al. use a Michelson type interferometer. Figure 2.0.2 below demonstrates the basic layout of this type of interferometer.

Figure 2.0.2. Basic layout of a Michelson Interferometer, where the light source originates from the laser on the left and follows the path as directed by the arrows. [7]

In this figure we see how the interferometer depends on the interference of a light source, where the beam is split by a beam splitter and the two beams travel to the data collector differently, whether it be due to a path length difference or a change in medium with a different index of refraction, such that when the two beams recombine at the beam splitter and travel to the end point of the set up the two beams are no longer moving in the same
way. This creates an interference pattern which we can then use to extract information and data about the light source, path and the material the signal traveled through [4].

Using what we now know about the Michelson interferometer, we can apply that knowledge to our understanding of any adding interferometer such as the one used in this radio interferometer set up. In radio astronomy, an adding interferometer, also known as a simple interferometer [10], combines the data collected by multiple radio antennas that are focused on the same source. This is done because in combining multiple measurements, we can effectively gather data with better resolution than data collected using only one radio antenna. Combining these two ideas, we can consider the design for the interferometer and see that each mirror placed along the ladder collects light and sends it to the dish. Thus, we can apply what we know about Michelson interferometers to extract information from the signals being collected due to the difference in path length and we can raise the resolution of the data from our multi-mirror set up.

This increase in resolution quality is an important motivator for using radio interferometers; it enables us to more easily collect better data with higher resolution than what could be collected using just one telescope. This is due to the resolution of the data we are collecting. We can look at the formula for angular resolution and see that $\theta = 1.22\lambda/D$. We can take $D$ to be the distance between two mirrors and notice that as the angular resolution is inversely proportionate to the distance between the mirrors, the further apart they are the better the angular resolution is [3]. So instead of building one extremely large telescope, we can build multiple smaller “telescopes” with mirrors that all point to one source, simulating the data collection of one large telescope, while still maintaining or even increasing the angular resolution of the collected data, as shown in Figure 2.0.3.
2. BASIC PRINCIPLES OF RADIO INTERFEROMETRY

Figure 2.0.3. Two smaller radio interferometer telescopes can simulate the data collection capabilities of a larger telescope.

With a basic conceptual understanding of radio interferometry, we can now delve further into the math of how this works. As mentioned above, an important part of how radio interferometry works is the distance between the two (or more) mirrors. To simplify, we can first think of an example where two mirrors are length $B$, also know as the baseline length, apart. The signals collected by these mirrors are mixed together; in Koda et. al.’s design the different signals are collected by the four flat mirrors and then mixed together as they are sent to the satellite dish and feed horn. Due to the separation between the mirrors, there is a time difference $\tau$ between the two, as one mirror will be minutely closer to the source and therefore receive the signal before the second mirror.

In Figure 2.0.4, we see how the signal travels to the mirrors. Using $\theta$, the direction of the telescope, and $\theta_0$, the direction of the observed object in the sky, both from some arbitrary origin, we can construct an equation for $\tau$

$$\tau = \frac{B \sin(\theta - \theta_0)}{c} \approx \frac{B(\theta - \theta_0)}{c}$$

(2.0.1)
where \( c \) is the speed of light and we use the small angle approximation to say \( \sin(\theta - \theta_0) = \theta - \theta_0 \). Depending the relative angle between the telescope and the source, \( \theta \), we get different times delays, \( \tau \). If a source has some finite dimension, then the signal will be the result of the superposition of multiple point sources with different \( \tau \)'s; this is what we use to gather information about the size of the source.
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Expected Signal from the Sun

We can now calculate the energy and power of the signal as collected by the telescope. In the following derivations and equations, I will focus only on the electric waves present in the radio signal. Although radio signals are comprised of electromagnetic waves, we can simplify this set up and focus only on the electric waves of the signal without sacrificing much accuracy or generality. Using Figure 2.0.4 as a reference, we can say that the electric field at position 1 is

\[ E_1(t) = E(\theta_0) \cos(2\pi \nu t). \]  

Equation 3.0.1

The electric field detected at position 2 is quite similar to Equation 3.0.1, however we must take into account the time delay \( \tau \) that occurs. Thus, the electric field at position 2 is

\[ E_2(t) = E(\theta_0) \cos(2\pi \nu (t - \tau)). \]  

Equation 3.0.2

Since this is an adding interferometer, to find the total electric field we simply add the two electric fields at each position together

\[ E_{\text{tot}}(t) = E(\theta_0) \cos(2\pi \nu t) + E(\theta_0) \cos(2\pi \nu (t - \tau)). \]  

Equation 3.0.3
Now that we have the equation for the total electric field of the interferometer, we can use this to find the power detected. To simplify the equation we can say $2\pi \nu = \omega$.

$$P(\theta) = \langle E_{\text{tot}}^2(\theta) \rangle = \langle E(\theta_0)^2(\cos(\omega t) + \cos(\omega(t-\tau)))^2 \rangle. \quad (3.0.4)$$

We can note that the power is not just equal to the total electric field squared, but more specifically equal to the time average of the total electric field squared. Now plugging in for what we found for $E_{\text{tot}}$ in Equation 3.0.3, we find that the power is

$$P(\theta) = E(\theta_0)^2(\langle \cos^2(\omega t) \rangle + 2\langle \cos(\omega t) \cos(\omega(t-\tau)) \rangle + \langle \cos^2(\omega(t-\tau)) \rangle). \quad (3.0.5)$$

In looking at the equation we have for power, we can recall that the time average of any $\cos^2$ term simplifies to $1/2$, thus we can rewrite the equation as

$$P(\theta) = E(\theta_0)^2(1/2 + 1/2 + \langle \cos(\omega t - \omega(t-\tau)) + \cos(\omega t + \omega(t-\tau)) \rangle) \quad (3.0.6)$$

Simplifying what we found above, we can write the following:

$$P(\theta) = E(\theta_0)^2(1 + \langle \cos(\omega \tau) + \cos(\omega \tau + \omega(t-\tau)) \rangle). \quad (3.0.7)$$

From this we can look at the two $\cos$ terms and see that the first term has only a $\tau$ dependence, whereas the second $\cos$ term has only a $t$ dependence. We can see this as the $\tau$ dependence of this term is canceled out, thus we are left with only a $t$ dependence within the cosine: $\cos(\omega \tau + \omega t - \omega \tau)$. Because of this, the time average of the second cosine term is equal to zero. We can not do the same for $\cos(\omega \tau)$, as it does have a $\tau$ dependence. We can, however, say that the time average of that term is simply equal to the term itself. Thus, we can once more rewrite the equation for power as

$$P(\theta) = E(\theta_0)^2(1 + \cos(\omega \tau)) \quad (3.0.8)$$

From this equation for power, we can refer back to Equation 2.0.1 and substitute in what we found for $\tau$, as well as plug in our longer expression for $\omega$

$$P(\theta) = E(\theta_0)^2(1 + \cos(2\pi \nu B(\theta - \theta_0)/c)) \quad (3.0.9)$$
We can simplify this equation by noting that $\lambda = c/\nu$, thus

$$P(\theta) = E(\theta_0)^2(1 + \cos(2\pi \frac{B(\theta - \theta_0)}{\lambda})) \quad (3.0.10)$$

To further simplify this equation for power, we can introduce a new variable $B_\lambda \equiv \frac{B}{\lambda}$ as the normalized baseline length and substitute that into our equation

$$P(\theta) = E(\theta_0)^2(1 + \cos(2\pi B_\lambda(\theta - \theta_0))) \quad (3.0.11)$$

This equation for power can be generalized for objects with volume, also know as an extended body, by integrating Equation 3.0.11 with respect to $\theta$

$$P(\theta) = \int \varepsilon(\theta_0)d\theta_0(1 + \cos(2\pi B_\lambda(\theta - \theta_0))) \quad (3.0.12)$$

From this, we can model more accurate plots for larger bodies, such as the Sun. Note that in this equation $\varepsilon(\theta_0)$ has replaced $E(\theta_0)$, representing an intensity/energy density distribution of the observed object. At this point, we would like to express the above equation in terms of a more commonly used parameter: the visibility, $V_0(B_\lambda)$.

$$P(\theta) = \int \varepsilon(\theta_0)d\theta_0 + \int \varepsilon(\theta_0)\cos(2\pi B_\lambda[\theta - \theta_0])d\theta_0 \quad (3.0.13)$$

$$\equiv S_0 [1 + V(\theta, B_\lambda)] \quad (3.0.14)$$

in which

$$S_0 \equiv \int \varepsilon(\theta_0)d\theta_0 \quad (3.0.15)$$

and

$$V(\theta, B_\lambda) \equiv \frac{1}{S_0} \int \varepsilon(\theta_0)\cos[2\pi B_\lambda(\theta - \theta_0)]d\theta_0 \quad (3.0.16)$$

which, using trig identities, can be simplified to the form

$$V(\theta, B_\lambda) \equiv V_0(B_\lambda)\cos[2\pi B_\lambda(\theta - \Delta \theta)]. \quad (3.0.17)$$

We can then define the normalized visibility $|V_0(B_\lambda)|$ as

$$|V_0(B_\lambda)| = \left|\frac{1}{S_0} \int \varepsilon(\theta_0)e^{-i2\pi B_\lambda \theta_0}d\theta_0\right| \quad (3.0.18)$$
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For a point source, the distribution function \( \varepsilon(\theta_0) \) is a delta function,

\[
\varepsilon(\theta_0) = \varepsilon_0 \delta(\theta_0).
\] (3.0.19)

From this we can easily calculate the visibility to be \( V_0(B_\lambda) = 1 \). This leads to the following equation for the power of a point source.

\[
P(\theta) = \varepsilon_0 [1 + \cos(2\pi B_\lambda \theta)]
\] (3.0.20)

For an extended source such as the sun, the distribution function can be approximated by

\[
\varepsilon(\theta_0) = \begin{cases} 
1, & \text{if } |\theta_0| < \frac{\Delta \theta_{\text{sun}}}{2} \\
0, & \text{otherwise}.
\end{cases}
\] (3.0.21)

With that, we can now rewrite the equation for power.

\[
P(\theta) = S_0 [1 + V_0(B_\lambda)\cos[2\pi B_\lambda (\theta - \Delta \theta)]]
\] (3.0.22)

\[
P(\theta) = \int_{-\frac{\Delta \theta_{\text{sun}}}{2}}^{\frac{\Delta \theta_{\text{sun}}}{2}} \varepsilon_0 d\theta_0 (1 + \frac{1}{2} \int_{-\frac{\Delta \theta_{\text{sun}}}{2}}^{\frac{\Delta \theta_{\text{sun}}}{2}} \varepsilon(\theta_0) e^{-i2\pi B_\lambda \theta_0} d\theta_0 |\cos[2\pi B_\lambda (\theta - \Delta \theta)]|) (3.0.23)
\]

\[
P(\theta) = \Delta \theta_{\text{sun}} [1 + \frac{1}{\Delta \theta_{\text{sun}}} \int_{-\frac{\Delta \theta_{\text{sun}}}{2}}^{\frac{\Delta \theta_{\text{sun}}}{2}} \varepsilon(\theta_0) e^{-i2\pi B_\lambda \theta_0} d\theta_0 |\cos[2\pi B_\lambda (\theta)]|] (3.0.24)
\]

\[
P(\theta) = \Delta \theta_{\text{sun}} [1 + \frac{1}{\Delta \theta_{\text{sun}}} \int_{-\frac{\Delta \theta_{\text{sun}}}{2}}^{\frac{\Delta \theta_{\text{sun}}}{2}} i e^{-i2\pi B_\lambda \frac{1}{\Delta \theta_{\text{sun}}}} \frac{1}{2\pi B_\lambda} - \frac{1}{2\pi B_\lambda} |\cos(2\pi B_\lambda \theta)|] (3.0.25)
\]

\[
P(\theta) = \Delta \theta_{\text{sun}} [1 + \frac{1}{\Delta \theta_{\text{sun}}} \int_{-\frac{\Delta \theta_{\text{sun}}}{2}}^{\frac{\Delta \theta_{\text{sun}}}{2}} i (-2i \sin[2\pi B_\lambda \frac{\Delta \theta_{\text{sun}}}{2}]) |\cos(2\pi B_\lambda \theta)|] (3.0.26)
\]

\[
P(\theta) = \Delta \theta_{\text{sun}} [1 + \frac{\sin(\pi B_\lambda \Delta \theta_{\text{sun}})}{\pi B_\lambda \Delta \theta_{\text{sun}}} |\cos(2\pi B_\lambda \theta)|] (3.0.27)
\]

With this final equation, we have a function for power dependent on only the angle \( \theta \), in terms of values and variables we know. Taking the diameter of the sun, \( \Delta \theta_{\text{sun}} \), to be \( \Delta \theta_{\text{sun}} = 0.5^\circ \), the baseline \( B = 16 \text{ ft} \) (the distance between the mirrors) and the wavelength of the radio signal at 10\text{GHz} to be \( \lambda = 0.03 \text{ meters} \), we can calculate the expected power as a function of \( \theta \) coming from the sun.
Figure 3.0.1. The amplitude of power graphed as a function of $\theta$. The blue line represents the power of the Sun and the yellow line represents the power of a point source.

Figure 3.0.1 is a plot of both the power of the Sun, an extended source, and the power of a point source, to see the contrast in the amplitudes. The blue line represents the power of the Sun and the yellow line represents the power of a point source. From this figure we can see that amplitude of the signal is dependent on the size of the source. This is due to the fact that as we scan across an extended source, such as the Sun, our angle $\theta$ constantly changes, shifting the minimum and maximum of the cosine wave horizontally. Thus, there is no distinct maximum and minimum but rather a spread, which causes the amplitude of power to get smaller.

The plot shown above does not take into consideration that the telescope’s response is limited to a very small forward angle. The actual power vs. $\theta$ is modified according to this response as shown in Figure 3.0.2, taken from Koda et. al. [2]
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Figure 3.0.2. In this figure we can see the amplitude of the power as the telescope scans across the Sun.

We can see from the plot in Figure 3.0.2 that at the peak of the wave packet there is a $P_{\text{max}}$ and a $P_{\text{min}}$ give by

$$P_{\text{max}} = S_0[1 + V_0(B\lambda)] \quad (3.0.28)$$

and

$$P_{\text{min}} = S_0[1 - V_0(B\lambda)] \quad (3.0.29)$$

Using our equation for the normalized visibility (3.0.18) we can now write an equation for the amplitude of the visibility in terms of $P_{\text{max}}$ and a $P_{\text{min}}$, dependent on our baseline length, $B\lambda$.

$$|V_0(B\lambda)| = \frac{P_{\text{max}} - P_{\text{min}}}{P_{\text{max}} + P_{\text{min}}} \quad (3.0.30)$$

which we have calculated to be

$$|V_0(B\lambda)| = \frac{\sin(\pi B\lambda \Delta \theta_{\text{sun}})}{\pi B\lambda \Delta \theta_{\text{sun}}} \quad (3.0.31)$$

By measuring $P_{\text{max}}$ and $P_{\text{min}}$ with our telescope we can find $V_0$, which we can use to determine $\Delta \theta_{\text{sun}}$! Given the distance from the Earth to the Sun and the result from Equation 3.0.31, we get the diameter of the Sun using the equation $S = \Delta \theta_{\text{sun}} d$. 
Before delving further into understanding what was accomplished on the construction of the radio interferometer during this project, we must first understand the project’s origin, including the condition of the telescope at the start, and the background necessary to continue work on this already-initiated project. By the end of the original project, *Two Topics in Astrophysics: Exoplanetary Gravitational Microlensing and Radio Interferometry* [1], most of the construction on the body of the radio interferometer was completed.
Figure 4.0.1. In this figure we can see the telescope in its current form. [1] is the lower portion of the top part of the telescope. This is connected to [3], the upper portion of the top part, with a hinge to facilitate the altitudinal adjustments of the satellite dish. [2] is the base of the telescope, a five sided box with a drawer built into it, as seen by [7]. Under the top of the base [7] is the bottom motor and mount, connected to a square bolt to rotate the dish azimuthally. [6] is the top motor, mount and motor driver, positioned to drive the rod to lift the dish altitudinally. [4] is the satellite dish, where the signal is directed off of the mirrors on the ladder. The signal is then directed to the feed horn [5] which reads the signal and is then sent to the electronics of the telescope.
Following the image of the telescope as seen in Figure 4.0.1, we see that the base of the radio interferometer is a five-sided box, with the bottom left open. This base also includes a drawer, which was designed such that various pieces or parts of the telescope could be stored there as well to be able to store delicate technical instruments away from the elements. On the top of this base is a circular groove cut out to fit the ball bearings needed to rotate the satellite. Attached to the side of the base is a crank handle which will be used to operate the wheel set up. Atop the base and the bearing balls positioned in the grooves is the top part of the radio interferometer, which consists of two pieces of plywood held together by a large hinge.

Figure 4.0.2. In this figure, we have a closer view of the top of the base [1]. The altitudinal motor [2] can be seen connected to the rod which raises the satellite dish. [3] shows the mount for the dish itself, and [4] is a closer view of the rod that lifts the dish. We can also see that the motor mount [2] is attached to [1] with a small hinge, to accommodate the slight tilt of the motor as a whole as the dish rises.
The lower portion of this top part is very similar to that of the top of the bottom part of the radio interferometer, as it also has a circular groove for the ball bearings to slide into, thus making the rotation of the top part of the radio interferometer much easier, limiting the amount of friction in the set up. The upper portion of the top part is connected to the lower portion of the top part using a very strong hinge, as this bend will be under immense strain while in use. This upper portion then has a metal holder for the satellite dish which we will use to collect the data. The upper portion will then raise and lower, assisted by the hinge and the metal rod that will go through the upper portion down to the lower portion, which will be connected to a stepper motor. The bottom part of the radio interferometer will also have a stepper motor attached to it – its job will be to rotate the the top part and satellite along the plane of the bearing balls.

Figure 4.0.3. This figure shows the bottom of the base and inside the drawer area of the base. [1] shows the square bolt used to rotate the dish azimuthally. [2] is the motor driver (though the motor is not presently shown in these images). [3] is the switch box to control the motors, further explained in Chapter 5. [4] is the top motor, mount and motor driver. [5] is the rod used to lift the dish to change the altitude.
These figures and explanations provide us with a better understanding of the radio interferometer as a whole, including both the parts completed before as well as during this project. Now, we can expand specifically on the pieces completed during this second part of the construction of the telescope.
The main accomplishment of this project is the design and implementation of the motor mounts and stepper motors, as well as working on the mechanical and technical aspects needed to transform the radio interferometer from a wooden structure to an actual piece of equipment. The stepper motors will control the movements of the radio interferometer in a stepping motion, meaning we will be able to very precisely adjust and specify where we want the radio interferometer to move to while collecting data. While the paper I am referring to specified only using a simple A/C motor to control the altitudinal and azimuthal movement of the interferometer, I’ve instead chosen to use stepper motors. This is because stepper motors have a unique motion in that each rotation of the motor is divided into distinct “steps,” with each step representing a specific degree amount. Thus, we are able to execute the azimuthal and altitudinal movement much more precisely which allows us to collect better data and get more accurate results [6]. The motor chosen to perform this task is the 23YPG210D-LW8-R47 Stepper Motor with Planetary Gearboxes from Anaheim Automation [9]. For this motor, 23YPG210D-LW8 denotes the series of motor and R47 denotes the gearbox ratio. This specific motor was chosen due to its torque output capabilities: the maximum torque for this motor is 6250 oz-in, or approximately 44 newton-meters. We can note that the motor chosen is not just a stepper motor but
a stepper motor with a planetary gearbox. This gearbox attaches to the motor and is specifically used in astronomical projects, as the gearbox reduces the speed of the motor to increase the torque output of the motor. In our current set up, we have the motors connected to a pulse generator with a switch box to manually control the motors’ motion. The pulse generator is set to put out around 1000 Hz, 1000 pulses per second. However, depending on the speed you wish to run the motors at, this can be changed. The switch box controls the size of the step that the motor takes, ranging from a full step to an eighth step, with one step being equal to one degree. Once the stepper motor type had been chosen, the way in which it attached to the telescope needed to be designed. In designing the stepper motors mounts, one must first determine the proper position of the motors and the dimensions necessary for them to both fit in the places they need to go, as well as consider how to properly secure the stepper motors. The lower motor, shown in Figure 5.0.1 to drive the azimuthal movement of the satellite dish, is positioned under the top of the box. This motor then has a small gear attached to its face, held in place with a set screw; this gear then turns as the stepper motor is directed to move in incremental steps. The gear attached to the motor is fitted to mesh properly with another gear. This second gear is attached to a square bolt, which has been turned down such that that gear can fit and be secured with another set screw. The square bolt is driven through the top of the telescope base, and as the motors and gears rotate, the base of the telescope also rotates, sitting on bearing balls in the groove to assist with easier rotation. The upper motor, shown in Figure 5.0.2 is attached to the top of the box, which also has two gears, one connected to the motor itself and the other connected to another rod. In this set up, however, instead of the rod only connecting to the gear, the rod also rests inside a bearing block. This bearing block holds the rod in place so that when the stepper motor turns the gear and the rod, the rod is fed up – or down, depending on the direction of the rotation – through an aluminum block with a threaded hole in the middle of it. This
block is connected to the top of the telescope, specifically the piece of wood that hold the satellite, which lifts the satellite altitudinally.

Starting from conceptual designs and ideas, designing the motor mounts was approached by first understanding the needs of the mounts, as described in the previous paragraph, and then roughly sketching a design out and measuring the appropriate dimensions needed so that the mounts would fit the motors. Each mount is composed of 2 pieces of quarter inch aluminum. One piece of the mount was designed to hold the motor, with a circular indent milled out to fit with the face of the motor. The second piece of the mount was designed to attach to the telescope, which a small groove milled out so the other piece of the mount would slide into it and be held in place. These motor mounts were then designed in Autodesk Fusion 360, where the 3D STEP files provided by Anaheim Automation were used to accurately build the motor mount designs around the motor. The designs for the motor and the mounts are show in Figures 5.0.1 and Figure 5.0.2.
Figure 5.0.1. The Autodesk Fusion 360 design for the bottom motor and mount, controlling the azimuthal direction of the telescope. [1] is the one of the pieces of the motor mount, which connects to the underside of the base of the telescope. This piece has a hole drilled out in the middle of it so that the square bolt (which goes through both the bottom of the top piece and the top of the base to rotate the dish azimuthally) can go through and connect to the gear [3]. [2] is the second piece of the mount, which connects to the motor [4] and [1]. [5] are the wires that attach to a motor driver, as shown in Figure 5.0.3.
Figure 5.0.2. The Autodesk Fusion 360 design for the top motor and mount, controlling the altitudinal direction of the telescope. [1] is one of the pieces of the motor mount, which connects to the actual face of the motor, as seen in the four holes in each corner of the piece. The opposite side of the first piece, facing the motor, has an indentation to mold to the face of the motor. [2] is one of the gears used to translate the stepper motion to a rotational motion to change the altitude of the satellite dish. Not pictured in this design is a rod that will sit in the bearing block [3], with another gear positioned so that it meshes with the gear attached to the motor. These gears rotate the rod, which is threaded through the top part of the telescope to lift the dish. [4] is the second piece of the motor mount, attached to the top of the base. [5] is the motor itself and [6] are the wires that attach to the motor driver, as shown in Figure 5.0.3.
Figure 5.0.3. This is the motor driver, which connects to the wires leading off the motors. This is used to connect the motors to a power source through a switch box, shown in Figure 5.0.4.

(a) Pictured here is the top of the switch box. As one can see on the labels, each switch controls various things depending on the combination of each switch, seen to operate the stepper motors. The top row of switches control the microstep resolution of the stepper motors; with the switch in the upward position, the switch is active. The middle switch controls whether or not the motor is on, with up being on and down being off. The bottom switch controls the direction the motor turns.

(b) Pictured here is the microstep resolution truth table. We can read this and see that depending on the combination of each switch, the motor will turn with varying steps.

Figure 5.0.4. The switch box made to operate the stepper motors.
After creating the designs for the motor mounts, the Fusion files were then processed and uploaded to the computer system of the CNC Mill machine used to create the motor mounts. This transfer from Autodesk Fusion 360 to the mill machine is a key step, as it is critically important to make sure that the code created by AutoDesk 360 for the mill machine is correct; alignment is crucial in the communication between the AutoDesk 360 program and the code for the mill machine, and must be done precisely. Once the motor mounts and the motors are all attached and connected to each other, they are then placed and situated on the telescope. Throughout this process, it became clear that this telescope and the pieces and techniques used to make it are prototypes. While this project follows an academic paper written about making this type of telescope, there are no step-by-step instructions; most of what is built for this telescope has been designed for this specific telescope and project. There is always room for improvement in any designed object as it is built, and often along the way during this project alterations made to the initial design. Thus, these iterated designs as shown can act as guidelines and inspiration for future designs.
The goal of this project was to continue the work on the radio interferometer telescope that was begun for the Senior Project Two Topics in Astrophysics: Exoplanetary Gravitational Microlensing and Radio Interferometry [1], and to acquire a deeper understanding of radio interferometry. Coming from a background of mostly theoretical education, the goal was to utilize this project as a way to push the boundaries of my education and engage in physical work, while still focusing on the topic of astrophysics, which has intrigued me throughout my education.

Much was accomplished during this project, but there are still things that need to be done to get the radio interferometer to a place where it can be used to collect signals. The key step yet to be completed is the fully implementation of the motors and motor mounts. In this project, the initial designs of the motor mounts were completed, produced and altered slightly so that they could be connected to the telescope and tested. During these testings, it was discovered that the original motors purchased and designed for did not sufficient torque to move the telescope. The altitudinal motor was only just barely capable of moving the dish, but only at an extremely low step rate. The azimuthal motor was unable to rotate the dish. Upon discovering this, I ordered a bigger motor and adapted the original motor mount design, though unfortunately I then did not have enough time
to reinstall the new motor or the new mounts. However, those motor mount pieces are completed and are ready to be installed.

As the motors were unable to be fully installed at the end of this project, no signal from the Sun was able to be collected. However, once it became clear that the motors would not be installed with enough time to collect data before the end of the project, I planned to collect a simulated signal using a 10GHz generator. Unfortunately, I was unable to gather any data from that for reasons that are not quite known at this time. There are two different places in the data collection process that could have caused this. First, the generator might not have been producing signal, which could not be tested as we do not have a spectrum analyzer that could detect in that range. Alternatively, the feed horn might not be working; this we also could not test, as we do not have another source that produces signal in its detectable range. However, despite not being able to collect a simulated signal, I was still able to plot the expected signal using previously determined data to model what the signal would produce.

Another step that can next be taken is the implementation of a superior method of transporting the telescope. Currently, the base of the telescope simply rests on a wooden frame with wheels. This design is quite rudimentary, though effective, but can be modified so that the telescope can be more easily moved, as well as increase the precision with which we can collect the data. We can increase this precision by utilizing the crank that is already installed on the telescope and build a set up in which the entire telescope could be raised above the ground for transportation, but also lowered to rest completely on the ground to reduce or eliminate any movement from the wheels during the signal collecting process. While what is currently implemented works well for the time being, this is just one example of how the telescope design can be improved to produce a more advanced telescope.

A further alteration that could improve the telescope design would be the materials used to build it. While wood is a relatively easy material to work with, it is susceptible
to its environment. When installing the motors, one of the issues noted was the fact that
the piece of wood holding the dish was beginning to curve and warp. This warping then
cause the edges of the piece to catch on the base of the telescope such that the dish could
not seamlessly rotate on the bearing balls. This problem was attempted to be resolved
by putting metal braces along the edges of the piece, which can be seen in Figure 4.0.1,
however this problem would be completely eliminated through the replacement of the
wooden piece with an identical piece made out of aluminum.

Ultimately, much was accomplished during this Senior Project, and it is ready to be
taken to the next level to complete the final steps necessary to be able to use the radio
interferometer to collect signal from the Sun and determine the diameter of the Sun.
6. CONCLUSION


