

On Performing Interferometry on the Sun utilizing a Yagi-Uda Array and an SRT at MIT Haystack Observatory

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ABSTRACT

Interferometry is now at the cutting edge of radio astronomy. Utilizing more than one antenna, the system can create large apertures allowing for greater resolution of objects than ever before. However, due to the complexity and cost of maintaining correlating supercomputers, large dishes, and vast quantities of personnel, these experiments are usually out of the reach of students during undergraduate years. Our goal is to bridge the gap between full scale observations with equipment like large telescopes and what is available for educational purposes. To this end we took the first step by attempting basic interferometry utilizing a Yagi-Uda Antenna and an SRT in order to begin work towards the ultimate goal of VLBI experiments run with SRTs.

I. INTRODUCTION AND ASTROPHYSICAL MOTIVATION

Our experiment consists of a simple adding interferometer designed around a Yagi-Uda Array and an SRT. The purpose of this design is to experiment with the feasibility of simple interferometry on objects such as the Sun utilizing inexpensive components and cookbook software allowing students to more readily participate in radio astronomy without access to large facilities. The setup for this experiment consists mostly of components readily available at stores that supply DBS devices and assumes availability of an SRT.

II. THE YAGI-UDA ARRAY

Between 1926 and 1929, Shintaro Uda, an assistant professor at Tohoku University, experimented with a new kind of antenna array, leading to his papers entitled, “On the Wireless Beam of Short Electric Waves” His work was primarily done with a single parasitic reflector, a single parasitic director, a reflector, and up to 30 directors on the array.

In 1926, Hidetsugu Yagi, a professor of electrical engineering at Tohoku University collaborated with Uda on a paper presented to the Imperial Academy entitled “Projector of the Sharpest Beam of Electric Waves”. After this, funding was given to Yagi to continue working on

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the array, and after several tours of the Pacific and United States, the antenna array became known as a Yagi. However, in recent years, credit has been given to Uda and all of the work he contributed to the creation of the antenna, thus becoming the “Yagi-Uda Array”.

The Yagi-Uda antenna is from the family of devices with a fairly high gain array where most of the elements are fed parasitically from one or more driven elements. Consequently, the antenna is relatively inexpensive due to the feed network being fairly simple. The upswing, however, is that dimensional adjustments may be essential to proper function. Phase, in parasitic elements, the controlling factor of the array, is modified by adjusting the element length and spacing. Consequently the antenna has a fairly high gain considering its electrical size.

The Yagi-Uda employed in this experiment has the following properties:

1421 MHz (Hydrogen Line) Loop Yagi, Model 2145LY from Olde Antenna Lab:
<http://www.setileague.org/hardware/oldeant.htm>

Frequency Range:	1.40 – 1.44 GHz
Number of Elements:	45
Boom Length:	132 inches (335.3 cm)
Boom Diameter:	0.75 inches (1.91 cm)
Mast Diameter:	1.5 inch maximum (3.81 cm)
Weight:	3 pounds
Connector:	Type N female
Gain:	Approximately 20.0 dBi
3 dB Beamwidth (E Plane):	Approximately 16 degrees
F/B Ratio:	>20 dB
Maximum Power:	400 W. Average
Stacking Distance:	22 inches vertical 24 inches horizontal

III. SRT

The small radio telescope or SRT was designed and tested at the Haystack facility in Westford, MA. The SRT is capable of performing continuum and spectral line observations in the L-Band (1.42 GHz). Because the SRT is inexpensive, it is an ideal tool for high school,

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undergraduate, or amateur introductions to radio astronomy. Beyond this it is an excellent tool because it combines both the principles of microwave and digital architecture. Students using the SRT will have the opportunity to learn astronomy, digital signal processing, software development, and data processing.

The SRT comes with a motorized Az-El mount permitting the user to execute total power measurements and contour mapping. The software required to control the SRT was written and developed by Dr. Alan Rogers of the Haystack facility and is readily available in open source from <http://web.haystack.mit.edu/SRT/srtsoftware.html> . The software is written in Java and is easily expandable by someone proficient with Java for customization to the site and constraints of the user.

The SRT digital receiver has the following properties:

L.O. Frequency Range:	1.370 – 1.800 GHz
L.O. Tuning Steps:	40 kHz
L.O. Settle Time:	<5 ms
Rejection of LSB Image:	>20 dB
Bandwidth/Resolution Modes:	1200/8 kHz
(Also supported through firmware update ver 1.0):	500/8 kHz
	250/4 kHz
	125/4 kHz
I.F. Center:	800 kHz
6 dB I.F. Range:	0.5 – 3 MHz
Preamp Frequency Range:	1.400 – 1.440 GHz
Typical System Temperature:	150K
Typical L.O. Leakage out of Preamp:	-105 dBm
Preamp Input for dB compression	
From Out of Band Signals:	-24 dBm
Preamp Input for Intermodulation Interference:	-30 dBm
Control:	RS-232 2400 baud

The SRT antenna has the following properties:

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Manufacturer:	Kaul-Tronics Inc.
Model Number:	(S-7.5)
Diameter:	90" (2.3 m)
F/D Ratio:	0.375
Focal Length:	33.75" (85.7 cm)
Gain @ 4.2 GHz:	38.1 dBi
Gain @ 1.4 GHz:	
Weight with Mount:	160 lbs
Beam Width:	7.0 degrees (L-Band)

IV. SETUP AND CALIBRATION

Instrumentation setup for the Yagi/SRT interferometry experiment is critical. Components needed are:

In Line Amplifiers (1 per 75-125 feet [depending on cable loss]): 50-2050 MHz, +15dB

2 Pre Amps: Calibrated for 1420 MHz

Several Hundred Feet of Coaxial Cable: 75 Ohm double shielded cable works best

2 5 Volt DC Power Injectors

2 5 Volt DC Power Supplies (can work with one, 2 for redundancy checking [fixed power supplies are preferable to variable power supplies so that no accidental change in voltage may impact data or short the system])

Attenuators (as needed per setup)

Several feet of wire

Solder

Soldering Iron

Adaptors (In our experiment we needed 1 Female/Female N-type to SMA, 1 Male/Male SMA to SMA, and several Male/Male and Female/Female F-type to F-type adaptors)

1 DC Block

1 Magic Tee (75 Ohm diplexer)

Switches

Receiver

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Bandpass Filter (Optional)

PC with SRT software (software at: <http://web.haystack.mit.edu/SRT/srtsoftware.html>)

Tripod for mounting the Yagi (see below for procedure)

SRT

Yagi

Below is a diagram of our setup. Users will need to modify the number of in line amplifiers to their own needs and distance.

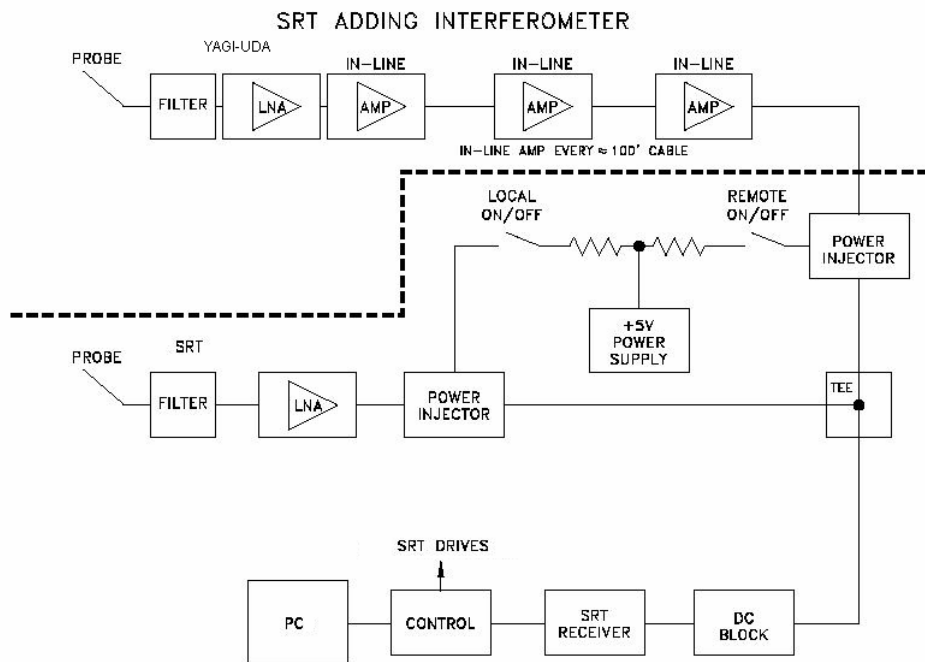


Figure 1.) SRT/Yagi Adding Interferometer Block Diagram

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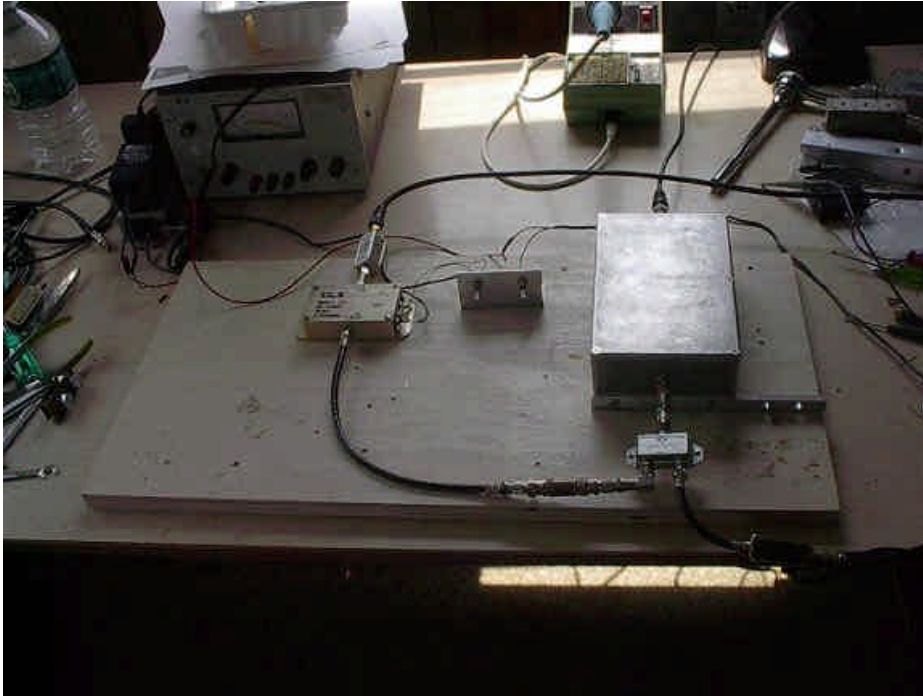


Figure 2.) SRT/Yagi Adding Interferometer Breadboard. Here the 2 DC power blocks are in the upper left hand corner. On the top is the line coming from the Yagi, connected to the in line amplifier, hitting the first DC power injector, connected to the left switch. It's output goes through an attenuator and into the magic tee. From the bottom right is the SRT input going into the second DC power injector, which runs directly into the magic tee. From the tee the system goes into the receiver, which is sent to the PC software for analysis.



Figure 3.) Picture of Yagi on sun

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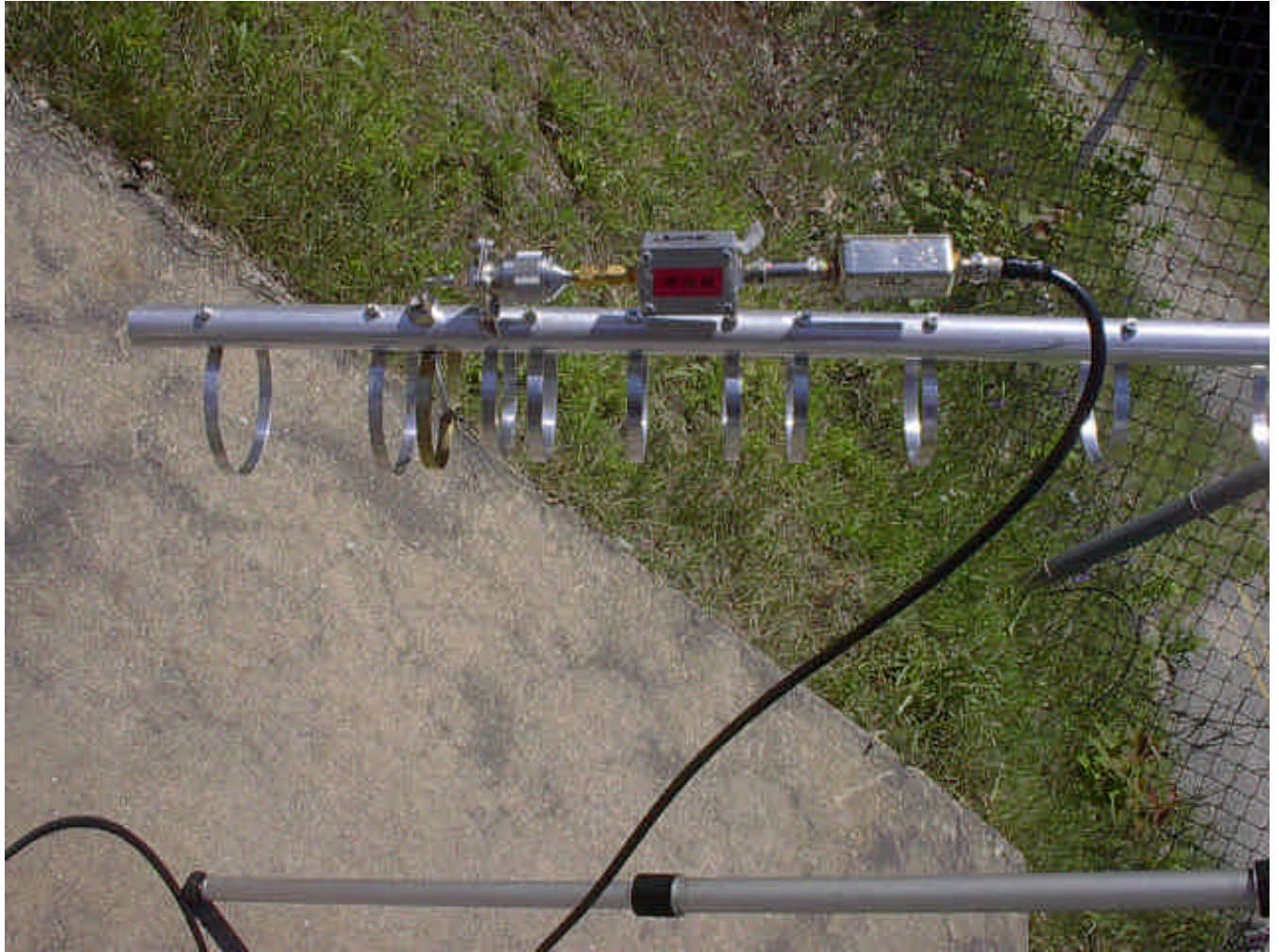


Figure 4.) Picture of Yagi amplifier chain (preamp into in line amplifier)

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Figure 5.) Yagi mounting configuration to standard camera tripod. The mount was made by taking a piece of steel and threading a hole into the center for the camera screw to attach to. Then identical holes to the ones that come with the Yagi were placed into it to join the mount to the L piece to the Yagi for a strong and easy attachment.

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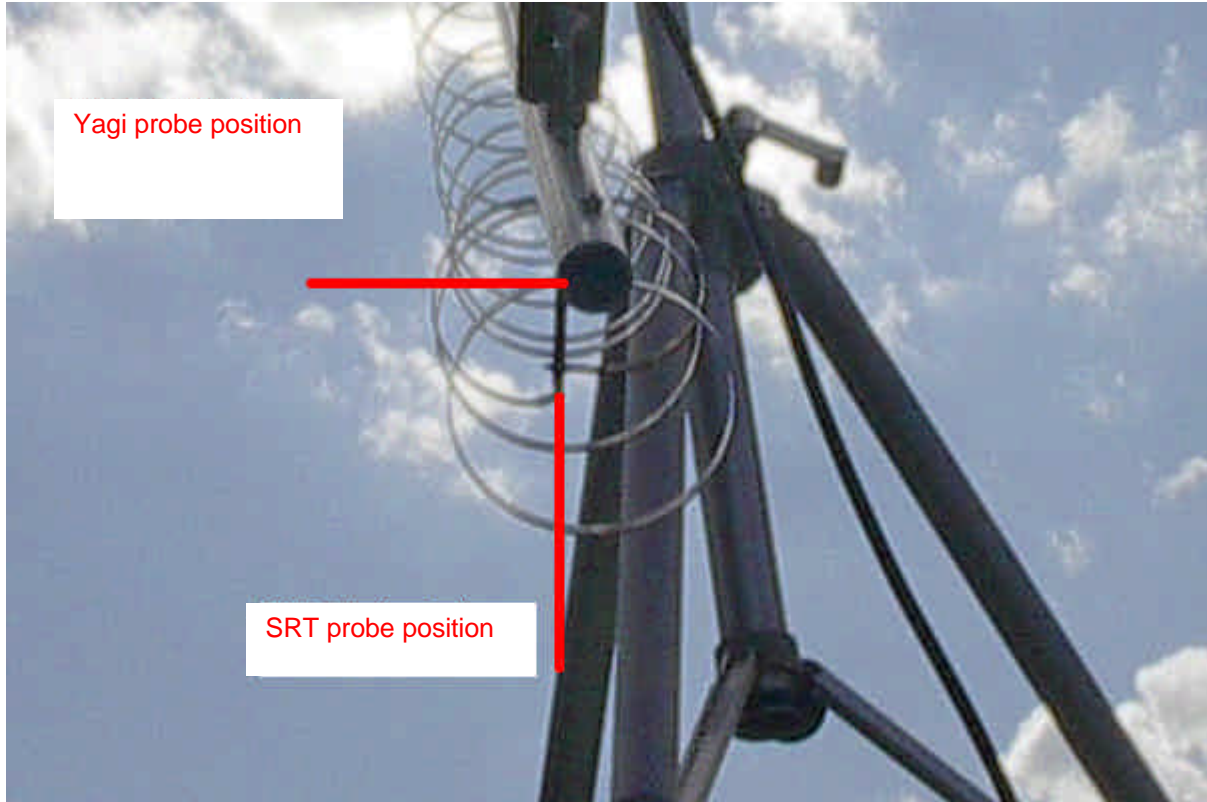


Figure 6.) Make sure in your setup that the Yagi's probe position, seen above, is perpendicular to the SRT's probe position, drawn in above.

IV. CALIBRATION

Once the setup phase is complete it is time to calibrate and test the system. The first, and most obvious, test before running the experiment is to make sure that both the Yagi and the SRT are receiving counts from the Sun. In our experiment, pointing of the Yagi was done in a crude yet low cost manner. Since there was no motor on the tripod utilized for the mount, one person must stay by the Yagi in order to keep it pointed at the sun. To point at the sun, one would watch the shadow formed by the rings of the Yagi form the most accurate circle possible from the shadows at the base. For future experiments it may be prudent to add an az-el mount to the schematic. Take note of the counts as well as system temperatures in order to later check if they are getting the gain that they should be receiving. This can be calculated from:

$$G = \frac{4\pi h A_{eff}}{l^2} \quad (1)$$

and

$$\frac{(counts_on_sun - counts_off_sun)}{counts_off_sun} \quad (2)$$

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If both antennas are functioning nominally, place them in their respective positions and point both at the sun. At this time, read the counts that both are receiving from on and off the sun. When all four data sets are acquired, attenuate or amplify the system such that the signals received by the antennas on the sun are as close in counts as possible. Our signals were approximately 100 counts off from one another at all times. The amount of play allowed between the signals is based upon the amount of counts you are receiving.

V. TAKING DATA

With the antennas both now receiving approximately the same signals, you are ready to begin taking data. When you are ready, turn both switches on (activating both antennas) and begin recording to your .rad file. The experiment is best run, in our configuration, with two people, one to monitor the computer input and troubleshoot potential problems in the system and another to point the Yagi. Data should be taken throughout the day, pausing for the points when the azimuth limits on the SRT are reached. Be sure to keep your tracking with the Yagi as smooth as possible, for it is the weak link in the setup.

VI. RAW DATA

Now that you have several hours of data, you must reduce it. The program of choice for us was Microsoft Excel, though it can very easily be done in any other spreadsheet program. The first steps in getting all of your data to import is to open Excel, go to the Data bar, and click “Import External Data” then choose “Import Data”. From here you will be given a window to choose what file to import the data from. Choose “All Files” and then click on your .rad file. After this, click “Next” at the bottom of the new window. Here, click once before and after each “:” on the time stamp within the file. This is done so that when you create your spreadsheet you can access each portion of the time (hours, minutes, seconds) separately. Click “Finish”. The data from the .rad file should be in your spreadsheet. From here, peruse down the rows weeding out any errors that were transmitted with the signal. These will usually have something to do with a failure to read out or communicate with the receiver. Once these data points have been flagged, create a new column using the following format: $=(hr)+((min)/60+(sec)/3600)$ This will give you in decimal hours the time of the experiment. You can further modify this equation to give you the time in decimal days if you so wish. Now it is time to look at the signal data. It can be noted early on, that the signal which you picked up should be spread out across 64 frequencies. All data obtained isn't actually useful, so

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what we must do is flag some of the data on the tail ends of the spectrum. This can be done easily by eye, looking from frequency 1 up until it reaches a point where the numbers become somewhat consistent. From here, use the numbers that remain close to each other until they drop back down again. In short, utilize the plateau area seen in Figure 6. With the extraneous data flagged, create a new column using the formula: =AVERAGE((first column point: final column point) . This will average your counts across the spectrum.

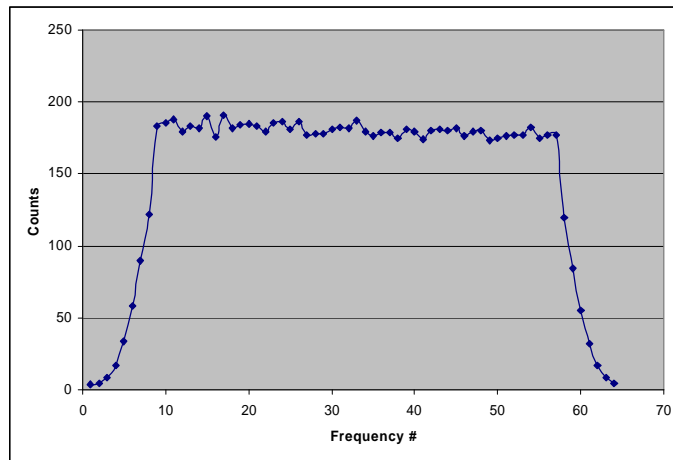


Figure 7.) Counts from frequency distribution

Now that we have our decimal hours column and averaged counts column, we will use them to graph our data. To do this, click on the graphing icon within the toolbar, choose the “XY (Scatter)” chart type, then choose the chart sub type as “Scatter with data points connected by smooth lines”. Click “Next”, and then click the “Series” tab from the window. Remove all current data series, and then click “add”. Add the column for counts to the Y axis, and the column of decimal hours to the X axis. With this completed, label your graph and set it to a chart of its own. You now have reduced your data as seen in Figure 7.

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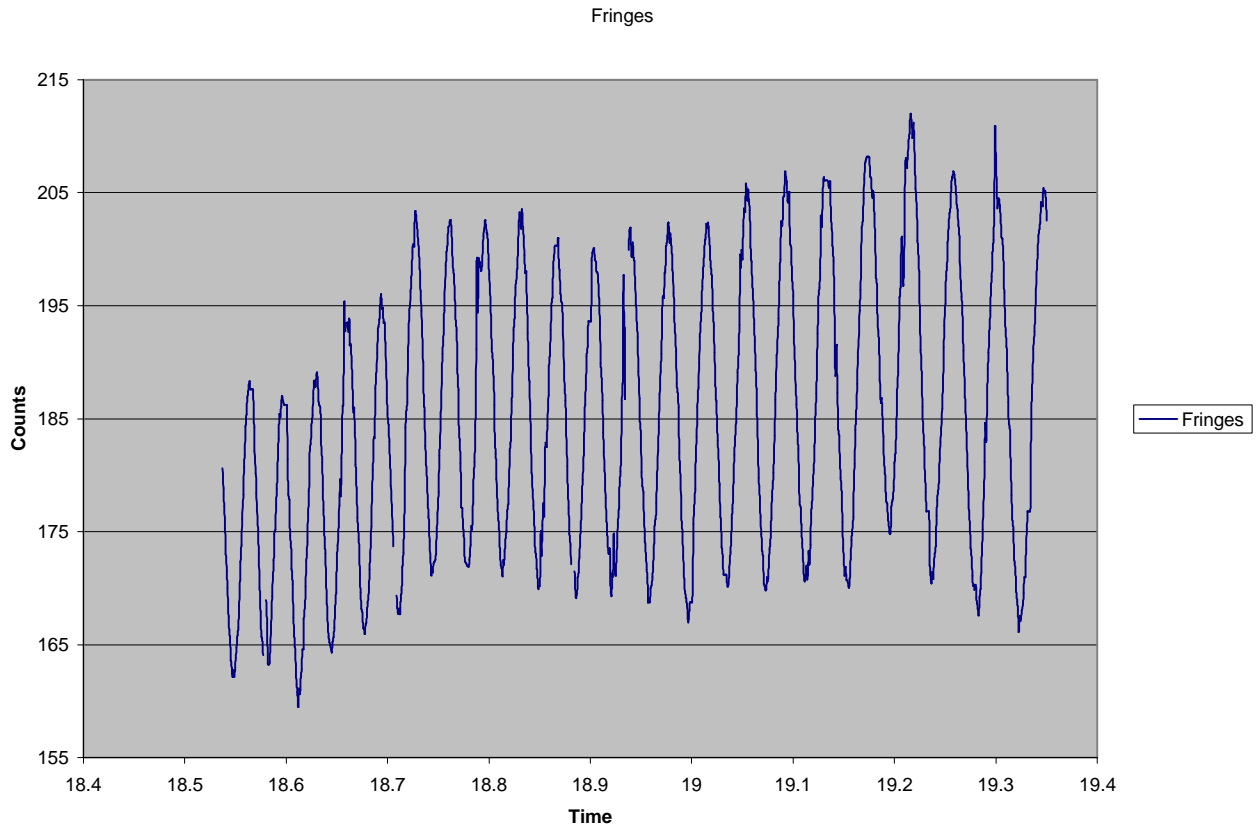


Figure 8.) Graph of counts vs time

With your graph created, you can check the results by using your knowledge of on and off sun temperatures with the Yagi-Uda and the SRT by comparing the maximum and minimum counts with the formula below.

$$\frac{\left[(T_{son} - T_{soff})^{\frac{1}{2}} \pm (T_{yon} - T_{yoff})^{\frac{1}{2}} \right]^2}{(T_{son} + T_{yon})} \quad (3)$$

VII. DATA ANALYSIS

With the data chart now in hand one can check if the gathered data is accurate to what would be expected by two antenna positioned as such looking at the Sun. To do this, we will make use of the C program "IPlot.c". IPlot.c will generate a data file that can be converted into a graph similar to the one we just completed in Excel using similar techniques.

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IPlot.c will require data taken from the positions of both antennas. The approach we chose was to use a handheld GPS device to get the approximate positions (Latitude, Longitude, and height above sea level) and then convert these into units useable by IPlot.c. The conversion was performed utilizing the following quick algorithm:

A0	Longitude 1
B0	Latitude - $p/2$
AP	Longitude 1
BP	Latitude 1
A1	Longitude 2
B1	Latitude 2

$$SB0 = \sin(B0) \quad (4)$$

$$CB0 = \cos(B0) \quad (5)$$

$$SBO = \sin(BP) \quad (6)$$

$$CBP = \cos(BP) \quad (7)$$

$$SB1 = \sin(B1) \quad (8)$$

$$CB1 = \cos(B1) \quad (9)$$

$$SB2 = SBP * SB1 + CBP * CB1 * \cos(AP - A1) \quad (10)$$

$$CB2 = (1 - SB2 * SB2)^{\frac{1}{2}} \quad (11)$$

$$B2 = \tan^{-1} \left[\frac{SB2}{CB2} \right] \quad (12)$$

$$SAA = \sin(AP - A1) \left[\frac{CB1}{CB2} \right] \quad (13)$$

$$CAA = \frac{(SB1 - SB2 * SBP)}{(CB2 * CBP)} \quad (14)$$

$$CBB = \frac{SB0}{CBP} \quad (15)$$

$$SBB = \sin(AP - A0) * CB0 \quad (16)$$

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$$A2 = \tan^{-1} \left[\frac{SAA * CBB - CAA * SBB}{CAA * CBB + SAA * SBB} \right] \quad (17)$$

The angular separation is $\frac{p}{2} - B2$. Multiply the sphere's (earth's) radius times the angular separation to get the great-circle distance. Multiply the sphere's (earth's) diameter times the sine of half the angular separation to get the straight-line distance. The initial heading (azimuth) from point 1 toward point 2 is $A2 + p$. Factoring in for the elevation difference can be done by adding the height vector to the length vector and getting the length of the hypotenuse of said triangle.

With data in hand, begin IPlot.c and input the year, day, UT hour start, UT hour end, baseline length, azimuth angle, elevation, phase offset, and wavelength observed. Output your results to a file readable by whichever plotting tool you wish to use and plot it against your observed data. The GPS data you received for the locations of each telescope will be slightly off, so you will need to adjust the theoretical points to line up the graphs. To do this observe how changing each parameter will affect your plots and use this empirical data to make the fit. Later versions of this experiment will come with a program to automate this process, but for now the researcher will have to be patient and do the work manually.

The following plots show our results for two different data sets:

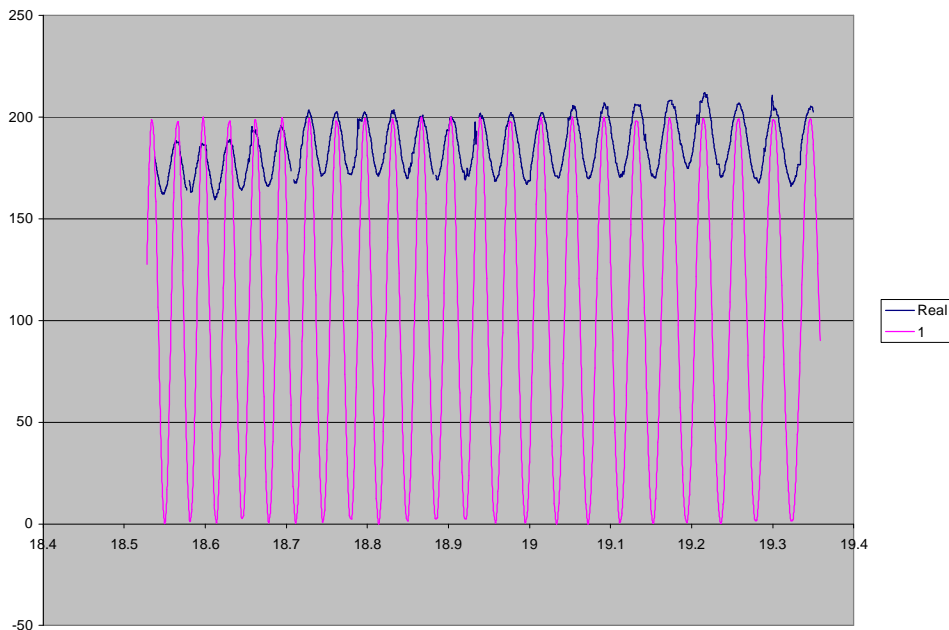


Figure 9.) Theory vs Data plot

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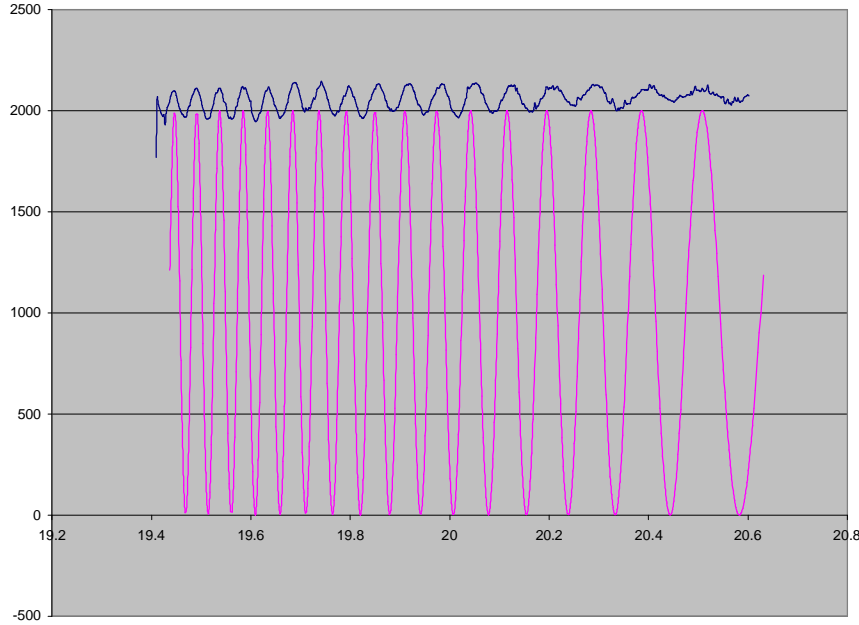


Figure 10.) Theory vs Data plot

The first plot shows fringes from the middle of the day at a relatively uninteresting point in the fringes. The second plot however shows the fringes as the sun approaches the baseline, causing the fringes to lengthen out. Many problems are observed in the second plot including pointing issues, alignment issues, and dead zone issues. These will be touched upon in the next section.

VIII. TROUBLESHOOTING AND ERROR POINTS

Throughout the experimental setup of this experiment, many issues were encountered, analyzed, and neutralized. This section will hopefully steer you away from any potential problems you may have in the course of the experiment.

- 1.) RFI Interference: This is probably the most common and most difficult problem to encounter and resolve. During our setup, a wireless connection was picked up by our preamp, modified to fit into the signal, and wreaked havoc up on Yagi counts. The Yagi has large lobes and is prone to picking up signals of just about anything that is near it. The process of discovering what is interfering with the signal is a slow game of turning everything around the system off and then turning them back on, one by one, until your signal spikes again and you have your culprit.

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- 2.) Weather and Components: Never underestimate the power of nature. Make sure that a sealant is used to make all of your components water tight and perhaps even place plastic around extra sensitive parts. In the midst of RFI interference with our experiment our preamp failed and caused us much torment in tracking down the problem.
- 3.) Polarization: The polarization on the SRT is parallel to the probe sticking out of the back of the unit. The polarization of the Yagi is perpendicular to the spike projecting from the receiving ring at the end of the array. If your polarizations are not parallel then you will achieve cross polarization and will most likely see nothing but “noise” from the sun.
- 4.) Pointing Issues: Pointing of the Yagi by hand is a difficult proposition at best. Because it is operated by hand, you can expect to incur certain degrees of human error. This error will change with the position of the sun throughout the day. At noon the Yagi needs little steering as its position with respect to the Yagi changes slowly. However, as the sun is rising or setting its position changes more rapidly and causes the operator to create more error by moving the Yagi in shorter intervals. This can be seen in figure 8 at the end as the fringes become progressively more sporadic and less clean. This is fixable by mounting your Yagi on a mount, preferably one identical to the SRT mount for reasons in the next troubleshooting section.
- 5.) Axes: The alignment of the axes is important to this experiment. Because the axes of the Yagi don't line up, and nor do those of the SRT, as the day progresses the point where information is being gathered is changing as the antennas move, causing the baseline to actually change in size and orientation. This will make aligning theory and data throughout a day to be tricky. Allow for a degree of movement in the theory when calculating the graphs throughout the day. In the current mounting configuration, the Yagi has the potential to sweep out nearly 2 extra meters in baseline length and depending on position any number of other variations of elevation, azimuth, and baseline length.
- 6.) Dead Zone Issues: Every SRT mount has two dead zones, approximately 2 degrees each where the antenna cannot observe. It is wise to plan ahead for these events. A simple test to see when it will happen on any given day is to modify your CPU clock settings and see how the graph will change on your screen. These limits can be seen in figure 8 at the end. More data would have been gathered, but the antenna couldn't go past this point, and afterwards, the sun had set and observations were not possible. With proper planning for this experiment, the dead zones should pose no significant issue.

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