N²I²: The New Mexico Tech and NRAO Instructional Interferometer

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ABSTRACT

We present preliminary observations of radio sources with the N²I² adding meridian interferometer. The interferometer is a joint project between the NRAO and New Mexico Tech to enhance the observational capabilities available at Etscorn Observatory. The interferometer will be shared for public outreach and the training of teachers, and students. The long range plan will include 4 antennas with non-redundant baselines on an east/west baseline. The observations presented in this paper represent phase one of this project: the first two antennas.

Subject headings: Interferometry: amateur

1.   Introduction

The National Radio Astronomy Association (NRAO) and the New Mexico Tech Physics department have been interested in building an instructional interferometer for several years. The goal of this project is to extend and enhance the observational capabilities at Etscorn Observatory. Both institutions will use the interferometer on a shared basis. The interferometer will be used by several NMT physics classes, by the Astronomy club, and by a Master of Science Teaching course to be offered jointly by the NRAO (Robyn Harrison) and Tech (Lisa Young). The interferometer will also be used by other NRAO-sponsored groups, such as the summer students, synthesis imaging workshops, and teachers' Chautauqua.

There have already been several attempts to develop a radio telescope at New Mexico Tech. A couple of years ago some old military radar equipment capable of observing in C band (5 GHz) was made available in the Tech bone yard. Experiments with this equipment showed

that it was not sensitive enough to perform astronomical observations. The development was then continued by two Physics graduate students, James Anderson and Darell Osgood (2001). They used a donated 1.4 GHz Ultra Cyber Hydrogen line radio receiver from Radio Astronomy Supplies, and a 16ft dish borrowed from Langmuir Labs. The 16ft dish did not have a mount or motor drive system and had to be pointed by hand. This made the detection of sources smaller than the sun very difficult, and in the end the project was only successful in detecting the sun. Although, they were only successful in detecting the sun, a very detailed site analysis was done using the Ultra Cyber. A significant amount of radio interference was found to originate in the direction of the Energetic Materials Research Facility northwest of Etscorn observatory. This type of interference may be a problem for single dish observations, but not for the interferometer.

In order to give teachers and students an opportunity to participate directly in the mechanics of observations and in the mathematical calculations, we have built the simplest interferometer possible. The N^2I^2 is an adding radio interferometer. The signals from two telescopes are added together and then detected. We will be using the same receiver equipment donated by Radio Astronomy Supplies, along with two 10ft CASSI radio dishes. The basic hardware, layout, and operation of the interferometer are described in the following paragraphs. The telescopes are capable of tracking a celestial source, but, for simplicity will be pointed at the desired declination on the meridian and allow the source to drift through the telescope beam via the rotation of the Earth. The long range plan includes a total of 4 antennas with non-redundant spacings on an east-west baseline. The first two antennas have been constructed, and became operational on April 19th, 2003. Successful observations have been made of the sun as well as several other smaller radio sources. The results of these observations are presented in the following pages of this report.

2. The Adding Meridian Radio Interferometer

To begin this analysis we imagine a pair of identical radio telescopes with circular apertures, pointed at the meridian at the declination of a point source that is near transit. We have chosen to place the telescopes on an east-west baseline of length b, and we assume that the source is monochromatic. The beam of each telescope has the power pattern of the Bessel-function. This forms the antenna power pattern or envelope, in which interference fringes are produced.

Let both telescopes have identical preamplifiers at the foci, and both amplifiers are connected to the receiver by cables of equal length. We can use figure 1 to determine the response of the interferometer. The source that we want to observe is in the direction of the

unit vector $\hat{s}$ that is changing with time as the Earth rotates. We assume the source to be at infinity so that the incoming waves are planar. The wavefronts will arrive at the telescopes at different times due to the path length difference between the two telescopes, $\triangle l_p$. The path length difference is given by:

$$\triangle L_p = |b| \cos \theta \tag{1}$$

The difference in arrival time or geometric delay is then:

$$\tau_g = \frac{\triangle L_p}{c} = \frac{b \cos \theta}{c} \tag{2}$$

where c is the speed of light. In figure 1 we take the location of the telescope on the right to be the phase reference point. Therefore the signal received at telescope 1 and 2 are:

$$A_1 = A_0 e^{i(k \cdot x - \omega t)} \tag{3}$$

and

$$A_2 = A_0 e^{i(k \cdot x - \omega(t - \tau_g))} \tag{4}$$

The signals are carried down the cables, added, and then arrive at the receiver. The output of the receiver is then:

$$A_{\text{tot}} = A_1 + A_2 = A_0 e^{i(k \cdot x - \omega t)(1 + exp(i\omega\tau_g))} \tag{5}$$

The intensity is given by:

$$I = A_{\text{tot}} A_{\text{tot}}^{\star} = 2A_0^2(1 + \cos(\omega\tau_g)) \tag{6}$$

Note that the receiver output and intensity change with time because the geometric delay changes with time as the Earth rotates. We also note that this result is analogous to the Michelson stellar interferometer with a familiar phase factor, but the fringes produced with an adding meridian interferometer are temporal rather than spatial.

2.1.   Measuring the Fringe Periods

The easiest model to use is that of the square source of uniform brightness with its top and base aligned with lines of constant declination. Thus, as the source drifts through the beam, only the hour angle changes. Therefore, we must integrate the intensity over hour angle. We get:

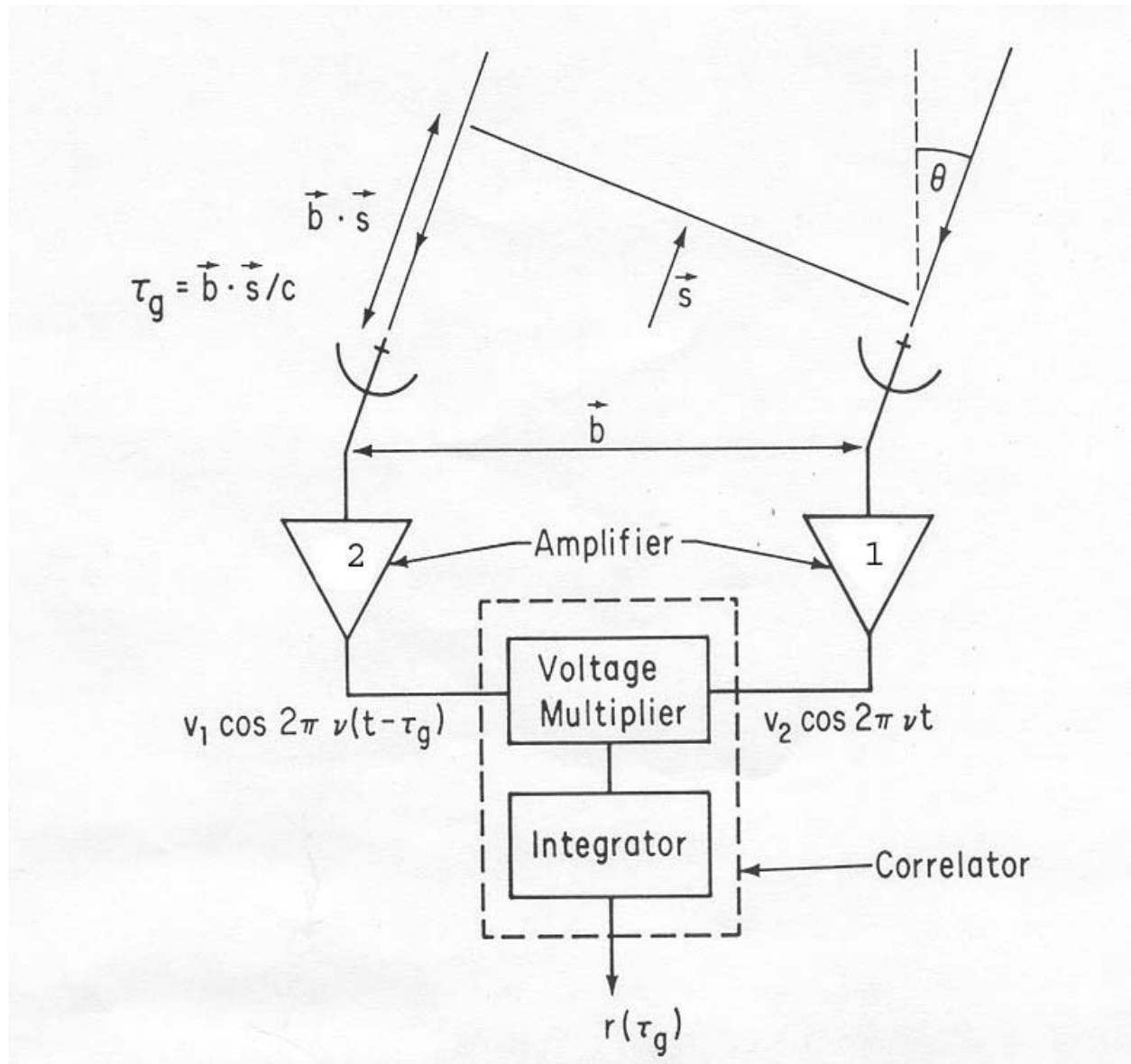$$I = 2I_0\alpha^2[1 + sinc(\frac{\pi\nu\alpha b}{c}) \cos(\frac{2\pi\nu bH}{c})] \tag{7}$$

Fig. 1.— Reproduced from Thompson (1989) in *Synthesis Imaging in Radio Astronomy*. This diagram shows a pair of antennas connected to a combiner through amplifiers. This figure also provides an illustration of the geometric delay τ_g.

where α is the source diameter, and H is the hour angle of the slowly moving center of the source of angular size α. The first term in this expression represents the total brightness observed through the two telescopes. The second term has two parts. The sinc function describes the size of the source and the cosine term describes the fringes. The expression for intensity tells us that the fringe frequency remains constant, but the amplitude of the fringes is decreased by the sinc function except where the sinc function is a maximum (Ryle et al. 1952). This is what gives us the envelope pattern.

Radio sources are generally not square. However, we use this approximation for simplicity in order to predict the fringe frequency. To do this we use the following mathematical description.

We begin by choosing the right antenna to be at the origin of a coordinate system. Relative to this, we define the position of the other telescope with a vector using a coordinate system in which $\hat{x}$ is pointed to the intersection of the celestial equator and the local meridian. $\hat{y}$ is pointed toward the intersection of the eastern horizon and the celestial equator. $\hat{z}$ is pointed toward the north celestial pole. For an east-west baseline the baseline vector, $\hat{b}$, is entirely in the y-direction. If we allow the source to be in the $\hat{s}$ direction then:

$$\hat{s} = (\cos\delta\cos H, -\cos\delta\sin H, \sin\delta) \tag{8}$$

Since H is small for observations near the meridian, and $b \cdot \hat{s} = -b_y cos\delta\ sinH$, then the equation for the intensity becomes:

$$I = 2I_o\alpha^2(1 + sinc(\frac{\pi\nu\alpha b}{c})\cos(\frac{2\pi\nu b_y H\cos\delta}{c})) \tag{9}$$

Recall that it is the cosine term that contains all the information about the fringes. If we re-write the argument of the cosine term to include explicitly the rotation of the Earth and time we get:

$$\cos(\frac{2\pi\nu b_y H\cos\delta}{c}) = \cos(\frac{2\pi\nu b_y\omega_e t\cos\delta}{\lambda}) \tag{10}$$

where ω_e is approximately 7.29×10^{-5} radians s^{-1}. The cosine term is equal to one when t=0, and again when:

$$\frac{2\pi\nu\ b_y\omega_e t\cos\delta}{\lambda} = 2\pi \tag{11}$$

Solving for the fringe period we get:

$$t = \frac{\lambda}{b_y\omega_e\cos\delta} \tag{12}$$

Take $\lambda = 0.20$ meters, $b_y = 24$ meters, and $\delta = 45^o$. Then t$\sim$162 seconds. This type of calculation will be done for actual sources and compared to their observed fringe period.

3. Interferometer Design

The design of the interferometer is modeled after the Small Radio Telescope interferometer at MIT Haystack Observatory. It consists of two 10ft radio dishes purchased from CASSI, and the 1.4GHz (L band) Ultra Cyber Hydrogen line radio receiver (fig. 9) and cylindrical feed horns (fig. 8) from Radio Astronomy Supplies. The dishes are spaced 24 meters apart (see fig. 5). High quality LMR-400 coax cable is used to carry the signal from the telescopes to a combiner that adds the signals. Two L band line amplifiers (fig. 7) are placed along the length of the cable to compensate for signal losses in the cable. To keep the signals in phase, the cables need to have the same length. The cable lengths were measured using the time domain reflectometer (TDR) at the NRAO (see figures 3 and 4). Both cables are the same length, 76.07 meters, with an accuracy of ±5mm. The LNAs were also phase matched using the TDR, and are the same length within 3.5mm. The signal is then put through a filter to filter out any transient signals within this bandwidth. The signal is then down converted and sent to the receiver back end (fig. 6). A block diagram of the telescope can be found in figure 2. The CASSI mounts are fully-steerable tracking mounts. A site map is included on the last page of this report.

3.1. Telescope Capabilities

The telescopes are manufactured by Kaul Electronics Inc. They are 3.05 meters in diameter, and have a focal length of 115.9cm. The beam width of the dish is given by λ /b$\backsim$0.2m/3.05m = 0.065 radians or 5 degrees.

3.2. Observable Sources and Baseline Layout

Some of the sources observed routinely with amateur radio telescopes include Cassiopeia A, Cygnus A, Taurus A, Virgo A, the Orion Complex, and the Sun. A survey of other amateur and small telescope web sites, e.g., `wavelab.homestead.com`, suggests that up to twenty sources are regularly detected by small interferometers.

Consider a circular object with uniform brightness. We can approximate the one-dimensional visibility as a sinc function. This is the Michelson visibility and is given by:

$$v(x) = \frac{2 sin x}{x} \tag{13}$$

where
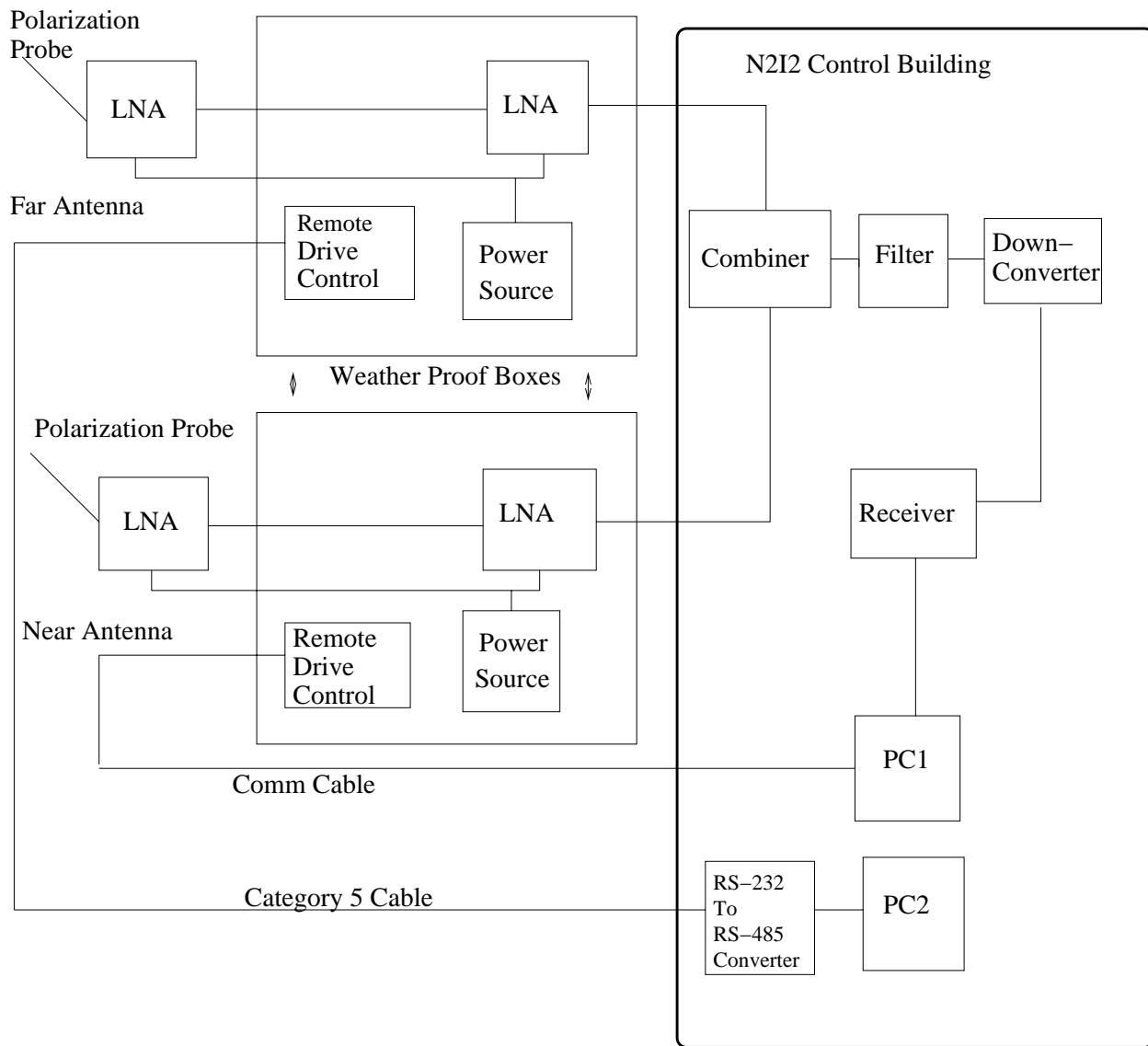
$$x = \frac{\pi \phi_o b}{\lambda} \tag{14}$$

Polarization
Probe

LNA

LNA

Far Antenna

Remote
Drive
Control

Power
Source

N2I2 Control Building

Combiner

Filter

Down–
Converter

Weather Proof Boxes

Polarization Probe

LNA

LNA

Receiver

Near Antenna

Remote
Drive
Control

Power
Source

PC1

Comm Cable

RS–232
To
RS–485
Converter

PC2

Category 5 Cable

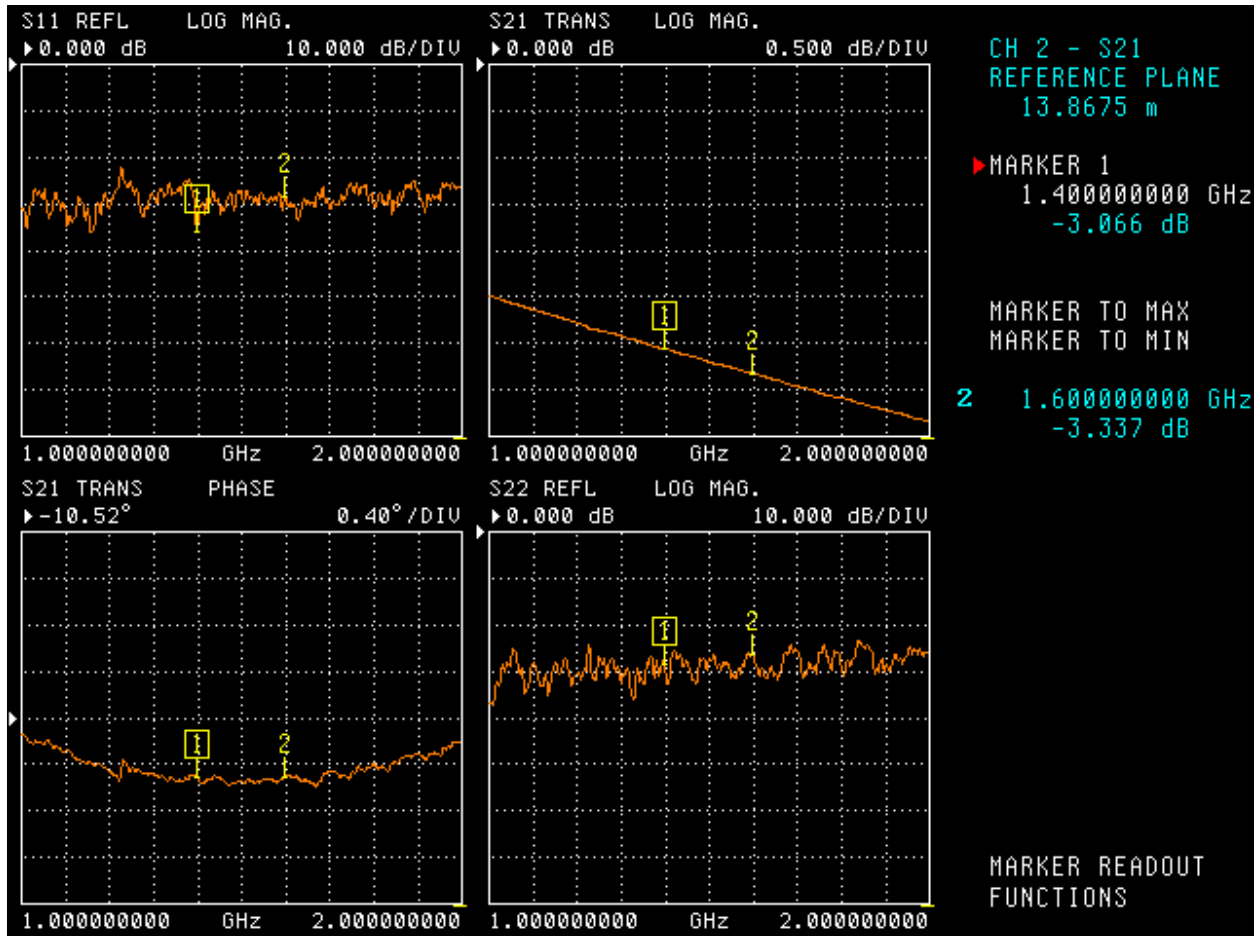Fig. 2.— Block diagram for the N^2I^2.

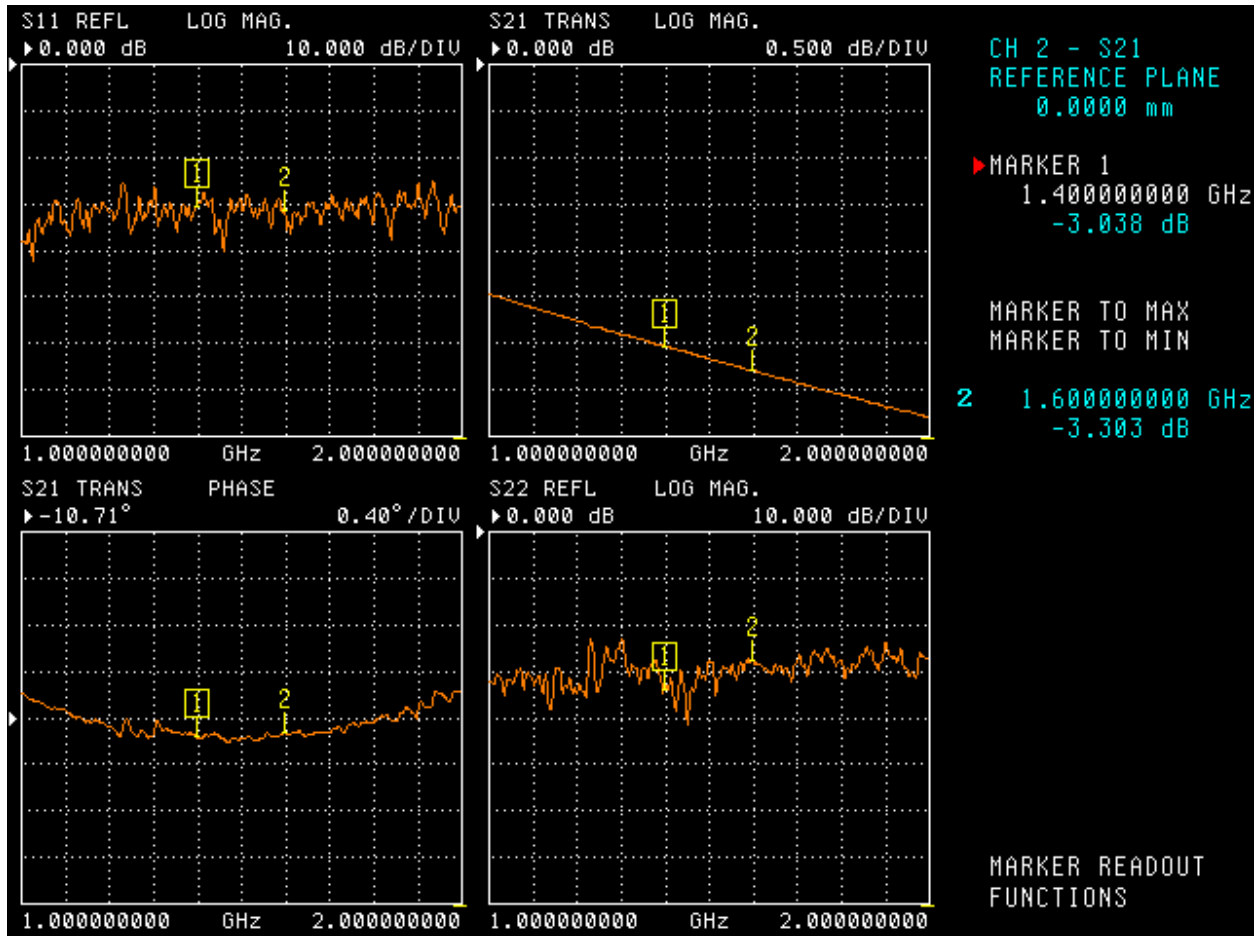Fig. 3.— TDR output for the cable to the far antenna.

Fig. 4.— TDR output fot the cable to the near antenna.

Fig. 5.— The two ten foot radio dishes spaced 24 meters apart.

Fig. 6.— Inside the N2I2 building. Shown are the computers that take the data and point the telescopes.

Fig. 7.— Inside the weather proof boxes attached to the telescope bases.

Fig. 8.— Feed horn, support, and line amplifier. The feed horn was designed based on the feed support of the 16ft dish. The horn can be moved back and forth through the middle of the support. This allows the telescope to be focused.
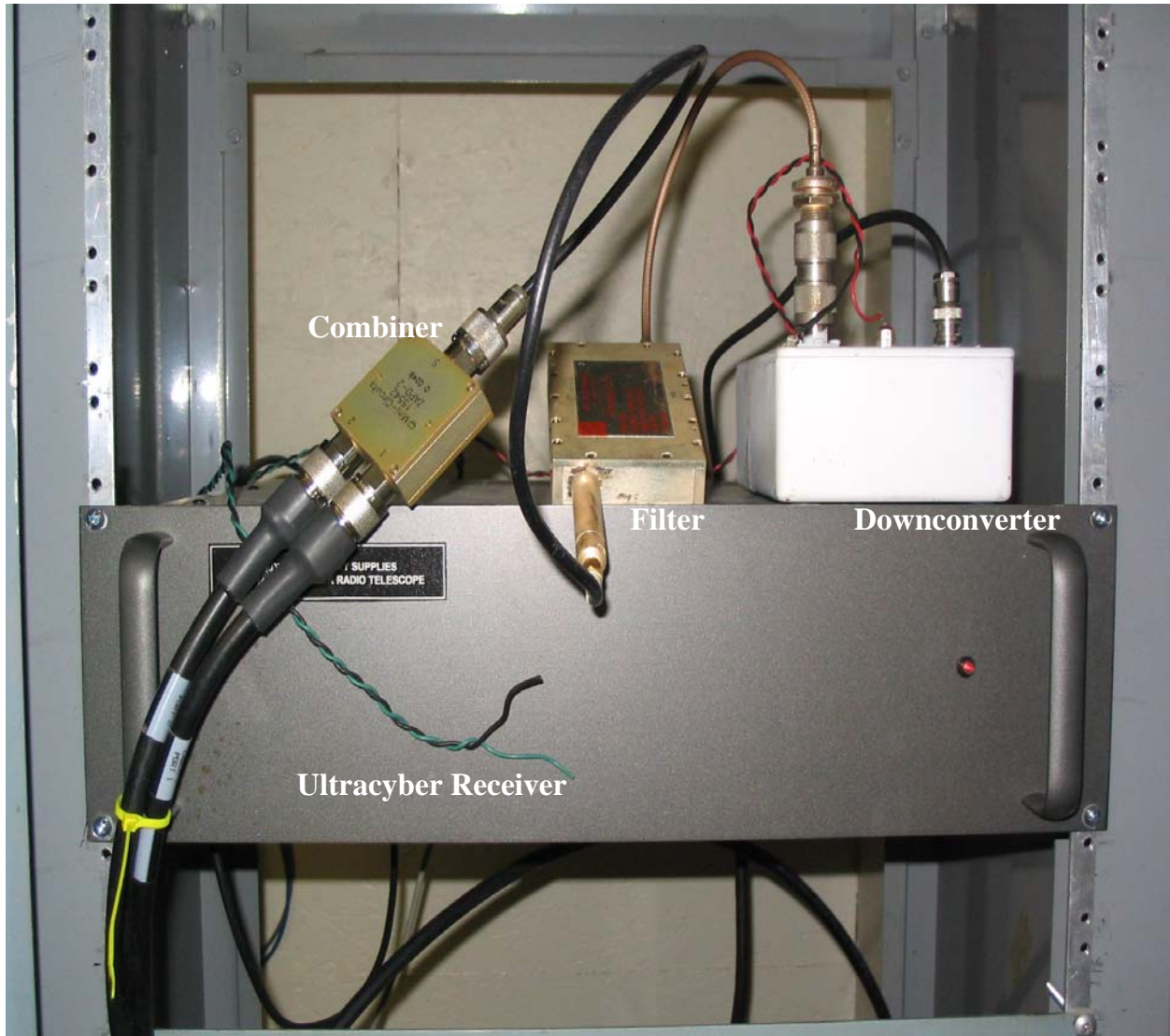
Fig. 9.— The Ultra Cyber backed.

where ϕ_o is the angular extent of the source, b is the baseline, and λ is the wavelength. The first null in the visibility occurs when $x = \pi$ or $b = \lambda/\phi$. The Sun has $\phi = 30$ arcminutes, so for a wavelength equal to 20cm we need a baseline of 24 meters. This is why we chose a baseline of this magnitude. Cassiopeia A is 6 arcminutes across, so the first null occurs at $b = 120$ meters. Cygnus A, at 2 arcminutes by 1 arcminute, requires baselines of 360 meters, and 720 meters, respectively. This is probably too long, and requires long cables and many additional line amplifiers, so these baselines are impractical. We find that baselines of 150 meters will allow us to make visibilty fitting and initial size and shape estimates. Of course initially we only have one baseline. One baseline cannot give us any spactial information about the source unless it is resolved.

3.3. SRT Software

The telescopes are controlled via two computers located in the N^2I^2 control building. The SRT control software is a JAVA based program designed to be portable to most computer operating platforms. The main telescope control is an interactive window (see figure 11) with which the user can enable the telescope functions either by a simple mouse click or a combination of mouse clicks and text entry. The SRT control software also controls the SRT receiver. However, since we are using the Ultra Cyber receiver instead of the SRT receiver, the SRT software can only be used to point the telescopes. All information concerning the user source list, the station longitude and latitude, and telescope azimuth and elevation limits is contained inside the srt.cat file. The user can add sources to the list as well as adjust the azimuth and elevation limits as needed. See figure 10 for a sample srt.cat file for Etscorn observatory. Therefore, we can point the telescope by clicking on the icon representing the source in the control window or the source's altitude and azimuth can be entered via the manual text input at the bottom of the control window. A simple RS-232 comm cable is used to transmit the pointing commands to the nearest telescope. The farthest telescope uses a RS-232 to RS-485 converter, and category 5 cable to transmit the pointing commands. The Haystack interferometer uses a wireless modem to transmit the pointing commands to their far telescope. We thought that this was a bit impractical, and decided to go with the RS-485 converter.
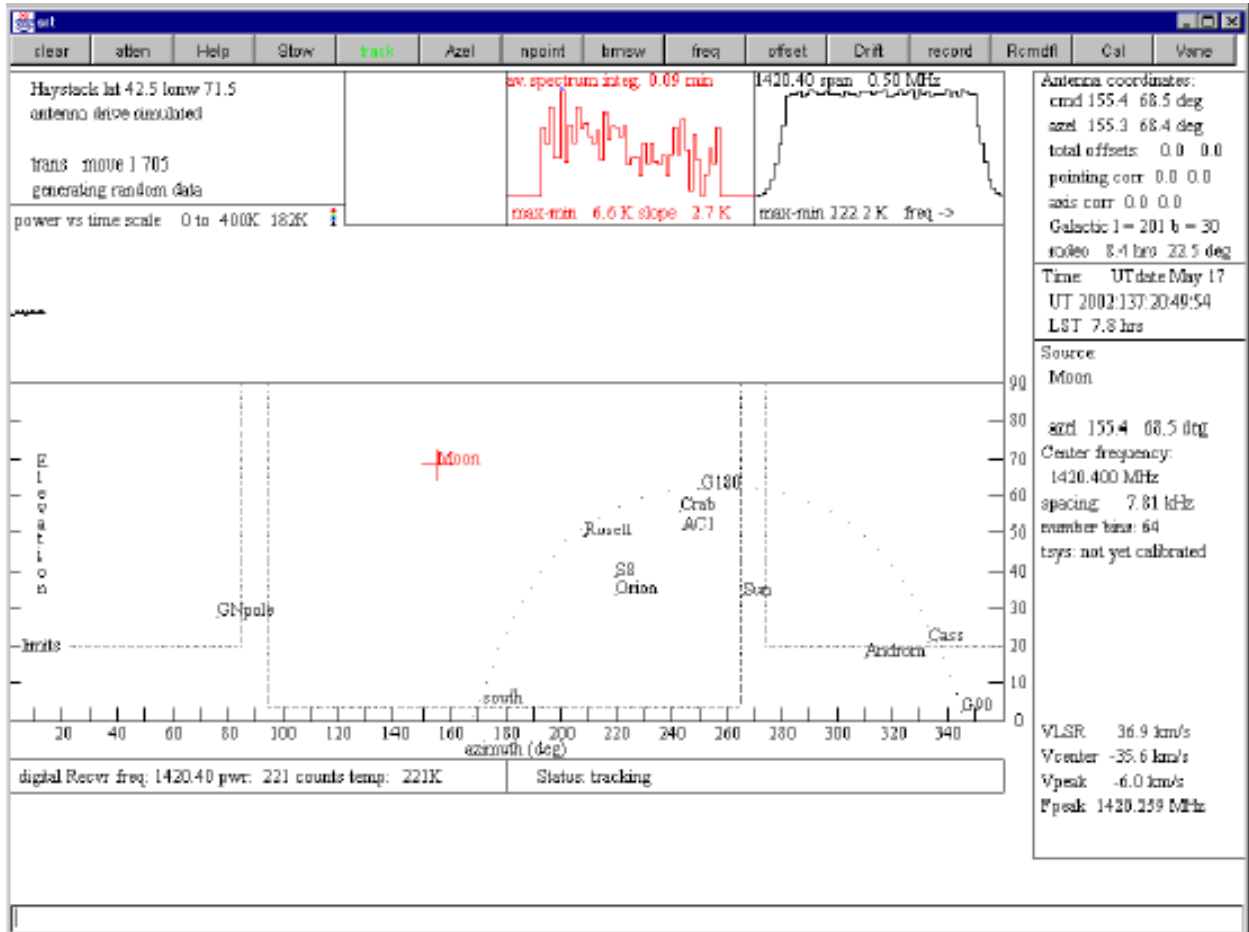
3.4. Pointing

Before we can start pointing at radio sources pointing corrections must be made. There are two methods to do this:

```
* sample srt.cat file
* first word is key word
* STATION: latitude longitude west in degrees
* SAT: satellite ID then longitude west
* SOU: source ra, dec, name, epoch
STATION 34.0 106.9 Etscorn Observatory
* source coords epoch 1950 unless specified
SOU 05 31 30  21 58 00 Crab
SOU 05 32 48  -5 27 00 Orion
SOU 05 42 00  -1 00 00 S8
SOU 23 21 12  58 44 00 Cass
SOU 00 00 00  00 00 00 Sun
SOU 17 42 54 -28 50 00 SgrA
SOU 06 29 12  04 57 00 Rosett
SOU 18 17 30 -16 18 00 M17
SOU 20 27 00  41 00 00 CygEMN
SOU 00 00 00  00 00 00 Moon
SOU 21 12 00  48 00 00 G90
SOU 05 40 00  29 00 00 G180
SOU 12 48 00  28 00 00 GNpole
SOU 00 39 00  40 30 00 Androm
SOU 05 14 12  18 44 00 AC1
GALACTIC 10 1 RC_CLOUD
AZLIMITS 95.0 265.0 /* mid az range is south */
ELLIMITS 4.0 160.0  /* elevation limit south - north */
COMM 1           /* COM 1 */
CALCONS 1.0        /* gain correction constant to put power in units of K
*/
BEAMWIDTH 7.0      /* 3 dB antenna beamwidth in degrees  - used to set
offsets for scans */
MANCAL 1          /* 0 or absence indicates automated cal vane */
NOISECAL 200.0    /* initial value for noise diode calibration */
*DIGITAL          /* enable for digital receiver only  */
TOLERANCE 5       /* optional max error in counts */
*COUNTPERSTEP 50   /* optional stepped antenna motion */
*RECORDFORM TAB VLSR /* optional tabs between fields and VLSR in
output */
*ELBACKLASH 3.0    /* optional correction for elevation backlash */
```

Fig. 10.— The srt.cat file contains all source coordiantes, and site latitude and longitude.

(Figure-1, SRT Console)

Fig. 11.— The SRT control Software.

1. The first method involves telling the SRT software to point at the Sun, and then using the Sun's shadow to orient the telescope. The telescope keeps track of where it is relative to elevation and azimuth limits that are set in the software. The telescope starts out in the stow position defined by these limits. The only limit one needs to change is the elevation limit. Once the telescope has been told to point at the sun, the azimuth correction can be made simply by loosening the elevation drive and rotating the dish until the Sun's shadow is aligned with the center of the dish. Once this is done, the lower elevation limit is changed inside the srt.cat file. A positive increase in the elevation limit will move the shadow upwards on the dish. It takes a bit of trial and error to get the shadow centered.

2. A more accurate method is to use the above method first and then use the offset option in the SRT software along with the receiver software or a power meter to find the power peak of the sun.

The pointing accuracy of the SRT telescope is approximately one degree. The pointing accuracy is adversely affected during windy conditions. It has been my experience that the telescope should not be operated in winds greater than 20mph. Not only will this affect the pointing, but high winds can damage the dish. During windy conditions the telescopes are kept in an upright position approximately 90 degrees from the lower elevation limit.

4. Receiver Capabilities

The Ultra Cyber system is a high quality, low cost, research grade radio system. The front end has dual conversion, image rejection greater than 50dB, low frequency drift, a low noise amplifier (.35-.37 dB NF @28 dB gain), and a cylindrical feedhorn. A feed horn support is available, but we opted to build our own. The backend consists of the receiver, power supply, and a 12-bit A/D converter. The receiver is controlled by Windows based software developed by Dr. John Barnard.

4.1. Receiver Software

One of the greatest things about the Ultra Cyber is that there are no adjustable controls to fool around with. The operator may adjust gain, offset and integration time from the computer console. The software also has options to begin a timed scan, save each scan, and
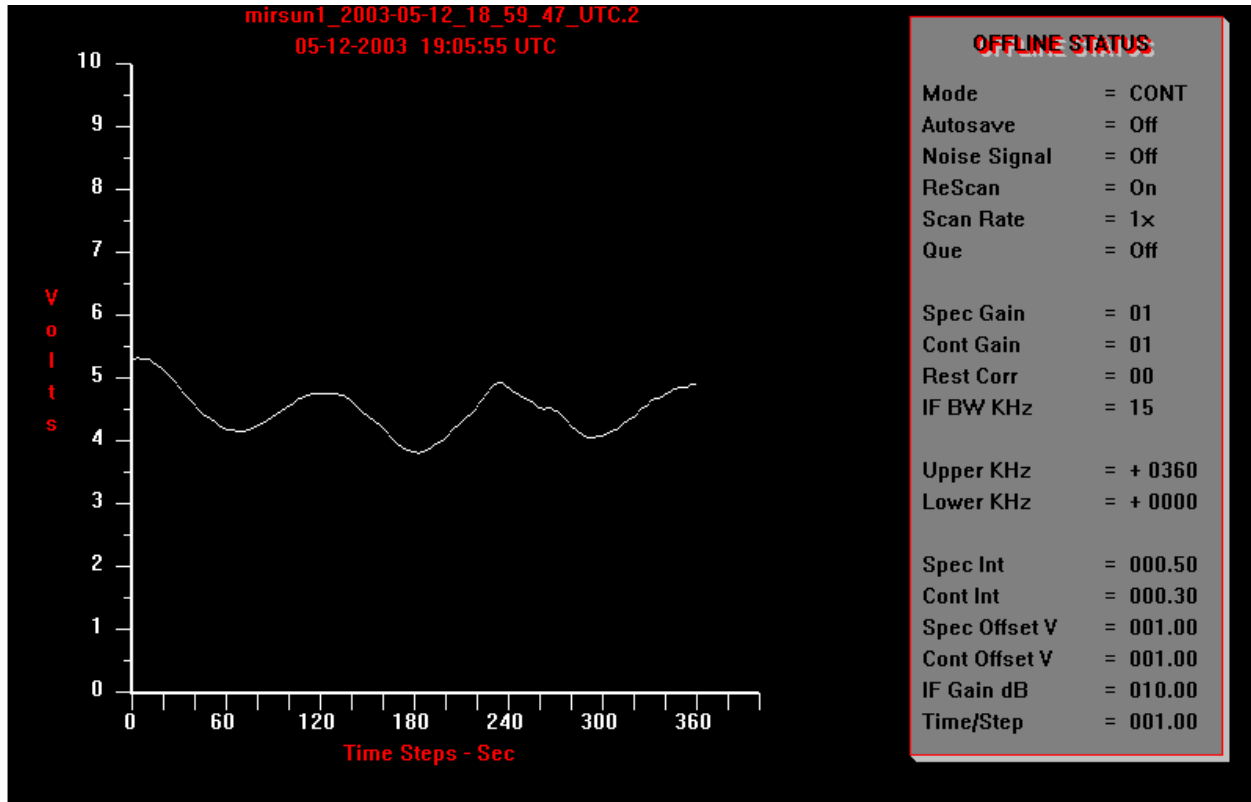
Fig. 12.— The Ultracyber control software.

then export the data to an Excel spreadsheet. However, the software is a bit sensitive to changes during a scan. Changing just about anything during a scan will abort the scan, and delete the data. It is a good idea to make all necessary adjustments before the scan has started, and be sure to have the scan autosave option turned on. If this option is not selected the software will scan over previously taken data. The software interface is depicted in figure 12.

5.   Sensitivity

The system temperature of this receiver and telescope system is around 150K. This produces an rms noise in a single 10 second scan with a two element interferometer of 5.5 Janskys. This is consistent with the experience of Chris Dapples of Red Lodge, Montana who operates a small interferometer similar to the one that we have built. He reports a system sensitivity of 6 Janskys in a single 10-second integration.

6.   Experiments and Observations

There are several modes that the telescope can be used in. These include:

1. Single dish mode: In this mode we can track an object and measure its Voltage(power) versus time or allow the object to drift through the beam of the telescope.

2. Tracking interferometer mode: In this mode we track the source with both telescopes pointing on source. This mode introduces a new technical problem. The finite bandwidth results in the modulation of the fringes by a sinc function that depends on the bandwidth. This problem can be solved by adding a compensating delay in one of the cables. This would keep the observations at the top of the sinc function envelope. The N^2I^2 does not have this capability, and will not be used in this way. The first light observations (cover page) were actually made in this mode.

3. Meridian Interferometer mode: In this mode we determine the altitude and azimuth of the meridian crossing point of a source and move the telescope to these coordinates. We then turn off the tracking and allow the source to drift through the beam.

First light observations of the sun were obtained in tracking interferometer mode on April 19th 2003. I then made some preliminary observations in each mode type. The details of

these observations can be found in table 1.

6.1. Single Dish Observations

I made some single dish observations of the sun on May 15th (see fig.14). I found the meridian crossing point of the sun on this day and pointed the far telescope to this location. I then turned the tracking off and let the sun pass through the beam. This was an experiment to try and determine the pointing accuracy of each dish. The sun was supposed to transit at 1:04 p.m. However, my results show that the voltage peak occurred at 12:54 p.m. Therefore, the pointing must be off by at least three degrees. I also did the same analysis for the near telescope and came up with the same three-degree error in the pointing. I have also attempted to make single dish drift scans of Cass A, and Cygnus A, but was not able to detect anything at the gain setting used. I intend to repeat these observations in the near future.

6.2. Meridian Drift Scans

I only managed to get one of these scans for the Sun (see fig 15). The peak in these observations correspond to the meridian crossing time within one degree. From this data we find the fringe period of the sun to be ∽120s. The Sun moves 15 degrees in one hour. If we convert the fringe period to hours, and multiply this with the angular velocity of the Sun we get that the Sun is 0.5 degrees or 30 arcminutes. This is the known angular diameter of the Sun! I also made a miridian drift scan of Virgo A (see fig 16), and from this data calculated a fringe period of 117 seconds.

6.3. Drift Scans

I observed Cass A, Taurus A, and Cygnus A in drift scan mode (see figs. 13 and 14). These scans were not made at the meridian. Recall that the fringe period is given by:

$$T_{\text{fringe}} = \frac{\lambda}{b_y \omega_E \cos(\delta)} \tag{15}$$

Where in our case λ =0.20 meters, b_y =24 meters, and δ is the declination of the object observed. The fringe periods calculated from my observations can be found in table 2. The error for Cass A, and Taurus A are 1 percent and 1.6 percent, respectively. The error for Cygnus A is quite a bit higher, at 38 percent. I am not sure of the reason for this. All

Table 1.   Observation Details.

Source	Scan Date	Scan Type	Time on Source (min)	Integration Time (s)	Gain (V)	Voltage Offset
Sun	5/12/03	Meridian	60	10	1	1.04
Sun	5/15/03	S Drift	38	10	1	1.04
Sun	6/5/03	I Track	18	10	1	1.04
Crab	5/13/03	I Drift	25	10	5	0.1
Cass A	5/14/03	I Drift	20	10	5	0.1
Cygnus A	5/15/03	I Drift	20	10	5	0.1
Virgo A	7/25/03	I Drift	12	10	20	0.25
Sag A	7/25/03	I Drift	12	10	5	0.15

Table 2.   Drift Scan Details

Source	Type	RA (hms)	DEC (dms)	T_{Theo} (s)	T_{Exp} (s)	error
Taurus A	SN Remnant	$05^h34^m32^s$	$22^o00^m52^s$	123.3	125	1.6
Cass A	SN Remnant	$23^h23^m24^s$	$58^o48^m54^s$	220.7	218.8	1.0
Cygnus A	Seyfert Gal	$19^h29^m58^s$	$40^o44^m02^s$	150	245	38
Virgo A	AGN	$12^h30^m49^s$	$12^d23^m28.04^s$	117	118	1

Note. — Coordinates are for epoch J2000. Fringe period calculated using square source approximation for simplicity. This approximation is only good for point source like objects.

four of the sources are unresolved due to the fact that we have only one 24 meter baseline. However, the fringe period should remain constant. We have also used the square source approximation here. An extended source like Cygnus A has its fringes modulated by a sinc function. Observations of point sources of known brightness can help. This essentially normalizes the sinc function to one. I will have to observe Cygnus A again to see if I get the same fringe period.

7.   Future Work

There are four major things that I would like to do in the future:

1. *Pointing Corrections*:

   There is an option in the pointing software that one can select that corrects for elevation backlash. Ironically enough this is a three degree correction. If this does not correct the pointing error, then I would like to try the offset method described in section 3.4. This is a far more accurate method, but far more tedious, and I hope that it will not be necessary.

2. *More meridian scans*:

   I would definitely like to make more meridian crossing observations of as many sources as possible. This would give me a better idea of how accurate the experimental fringe period is. Also, repeated observation of one source over the course of a couple of days may help to uncover any atmospheric effects on the fringe period.

3. *Calibration*:

   I would like to observe calibration sources of known brightness. This would give me some idea of the amplitude of the fringes in terms of volts, and allow us to convert the brightness to Janskys.

4. *System Temperature*:

   It would be nice to determine the system temperature for each telescope, and compare it to Chris Dapple's interferometer.

7.1. Phase 2

I look forward to working on the next phase of this project which will be the addition of two more telescopes. The source diameter of unresolved sources can be determined by observing with a variety of baselines. We would start out with the short baseline and then move to the large baselines successively. This can be tedious work. Since the meridian interferometer points at the meridian, we can only observe one baseline per day. Four telescopes gives us n(n-1)/2 or 6 baselines. Thus, one source would require six days of observing. The visibility can be plotted as a function of baseline. Then a sinc function can be fitted to this curve and the source size determined from the zero point of the sinc function.

Acknowledgments

REFERENCES

Westphal, D. 2001, Interferometry in Radio Astronomy: An Introduction, pg 45-58

G.B. Taylor,C.L. Carilli, and R.A. Perley, 1998, Astronomical Society of the Pacific Conference Series,v180,11,36

Ryle, M., 1952, Proceedings of The Royal Society A,211,351

Crab Nebula: Drift Scan
19:56:24 UTC
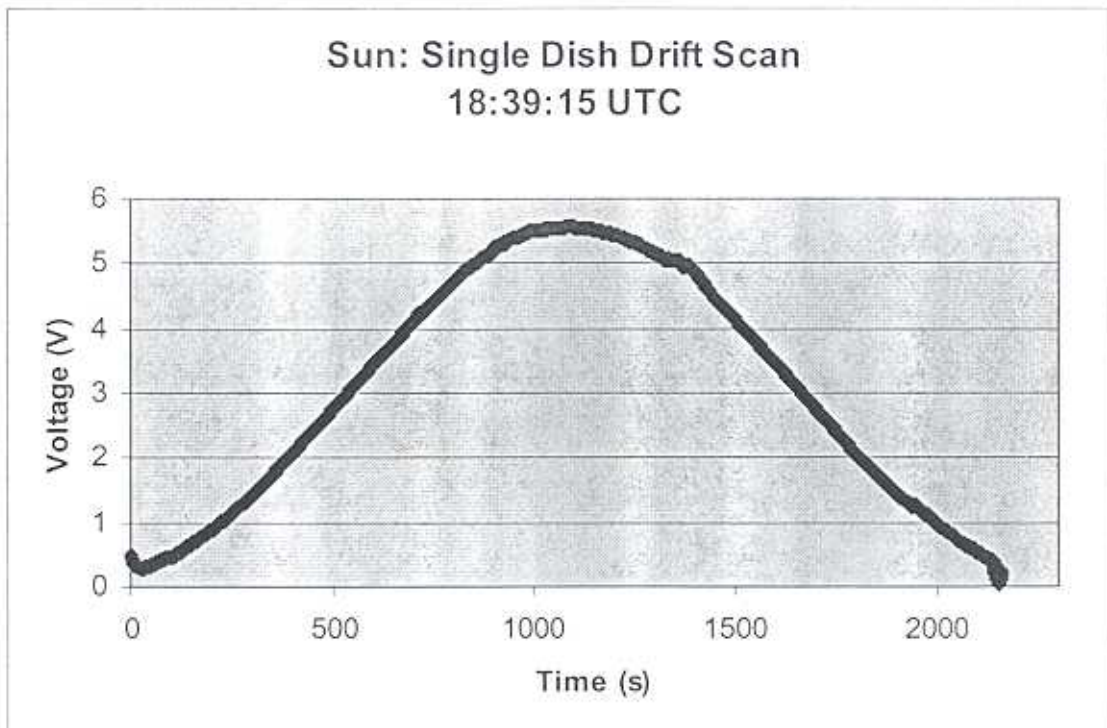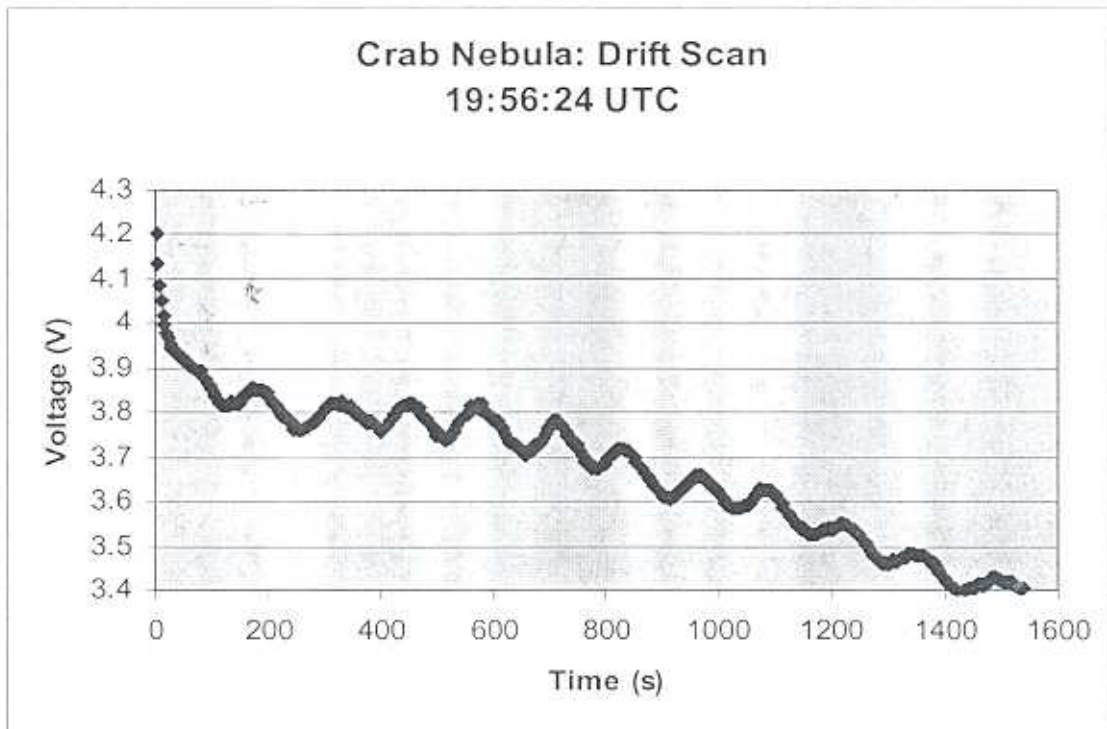

Sun: Single Dish Drift Scan
18:39:15 UTC

Fig 14. Top: A drift scan in interferometer mode of the Crab Nebula (Taurus A) observed on May 12, 2003. Bottom: A single dish drift scan of the sun observed on May 14, 2003.