Internal Report 1 3/6/2016

Comparison of Two Electromagnetic Horn Antennas

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1. Equipment

A. Antennas

The first antenna built at this observatory was a welded aluminum sided horn antenna of dimensions equal to those of the “horn of plenty” designed by Paul Shuck of the SETI institute; 50 inches in length with an aperture of 27 inches by 36 inches and backend 3.25 inches by 6.25 inches. The main difference is while the “horn of plenty” locates the feed probe, “quarter wave monopole”, within the horn itself, our horn antenna uses a rectangular waveguide of dimensions 3.25 inches by 6.25 inches by 8 inches long bolted to the back end of the horn. The brass quarter wave monopole probe is soldered to an N type connector and located approximately 2 inches from the rear of the waveguide which is constructed of welded brass.

The second horn antenna is built of dimension 51 inches long with an aperture of 28 inches by 36 inches and backend dimensions equal to those of the aluminum antenna. It also is bolted to a waveguide of dimensions equal to those the wave guide of the aluminum antenna. This waveguide is constructed of soldered galvanized steel sheet metal with the brass probe 2 inches long soldered to an N type connector and centered approximately 2 inches from the rear wall of the waveguide. The primary difference in the two antennas is the second antenna has sides of 0.25 inch galvanized steel wire mesh. The motivation for constructing the wire mesh antenna was to compare the characteristics of the aluminum antenna (our gold standard) to one of the wire mesh for the reason that we plan to ultimately do radio astronomy with much larger antennas. Because wire mesh would be much lighter weight, provide much less wind loading and would be less costly, it was an obvious choice for the sides of the test antenna. We have some preference for the horn design over the parabolic dish because of lower side lobes in the case of the horn.

A photograph of the aluminum and wire mesh antennas is shown where the two are both mounted on the same cradle. The azimuth is fixed at 216.5 +/- 1degree and the elevation is variable between -13 and + 52 degrees.

B. Electronics

Electronics used included a 1420 HPLNA, a band pass frequency filter (1420 MHz), both designed by Thomas Henderson, a Spectra-Cyber receiver designed by Carl Lyster and obtained from RAS, located in Texas, an intermediate frequency (IF) down-converter designed by Carl Lyster, a software defined receiver (NET SDR) from RF Space of Atlanta, Georgia and a Dell laptop computer with an i5 CPU.

The HPLNA is connected directly to the probe, followed by the band pass frequency filter which sends the signal through 100 feet of LMR400 50 Ohm cable to the IF down converter which converts 1420MHz to 10MHz. The 10MHz signal is the input to the NET SDR which performs the FFT ANALYSIS and measures the continuum power. A Dell laptop computer with an i5 CPU controls the Net SDR and logs the data. For scans from which numerical data was used the FFT average = 1 with no smoothing. The number of FFT samples used per block was 2,097,152 and the sample rate was $1.25*10^6$ samples/second giving a resolution bandwidth (RBW) of 0.596 Hz. Alternatively, in some continuum measurements, the Spectra-Cyber was used in place of the IF down-converter and NET SDR.

2. Measurements

A. Vertical Beam Width

Vertical beam width measurements were performed at 11 elevations centered approximately on the expected elevation of the Sun as determined from Radio Eyes software from Sky Publishing. Radio Eyes computes the location in elevation and azimuth of the solar pass as a function of a time (UTC).

We performed the vertical measurements of solar power at the time the Sun is expected to be centered in the antenna beam width. Data was collected at each of the eleven elevations for approximately 15 seconds. Each beam width measurement could be performed in an approximately 5 minutes which include starting at 11 degrees, going to 40 degrees, and returning to 11 degrees so that each elevation angle was measured twice during which the Sun moves 1.2 degrees.(1 degree per 4 minutes). [Both Tabular and plotted data for the two antennas are shown below. The measured full width at half maximum (FWHM) in the vertical plane for the wire and the aluminum antennas were 14 and 16 degrees respectively.

Table 1	Aluminum		
Angle	Total Power	Background	Net
11	9.93	9.825	0.105
14	8.88	8.7	0.18
17.5	9.23	7.73	1.5
19.4	10.5	7.17	3.33
23.2	13.2	6.56	6.64
25	14.6	6.265	8.335
27	15.5	6.045	9.455
30.5	14.9	5.37	9.53
33.5	13.2	5.185	8.015
37	9.74	5.03	4.71
42.1	6.69	4.9	1.79

Figure 2

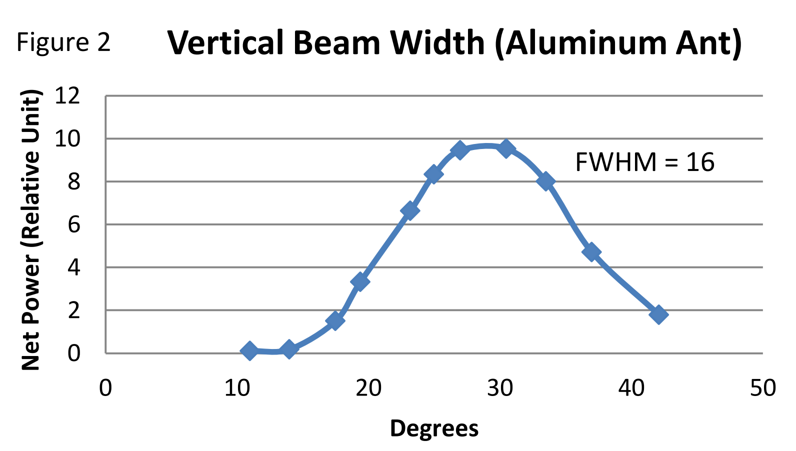
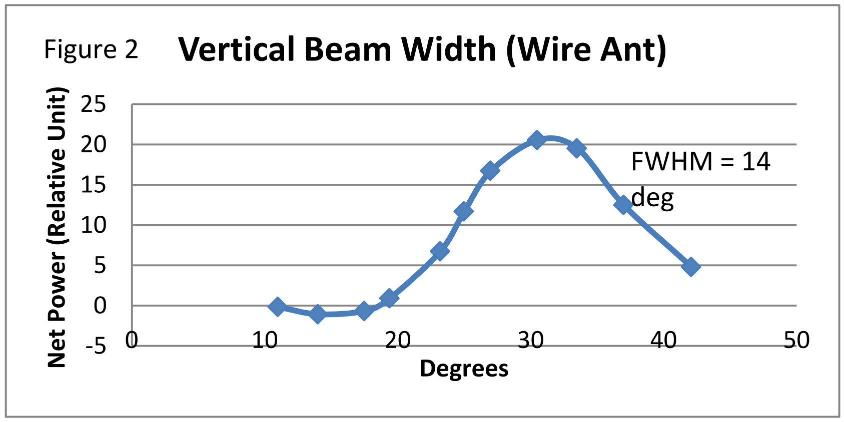


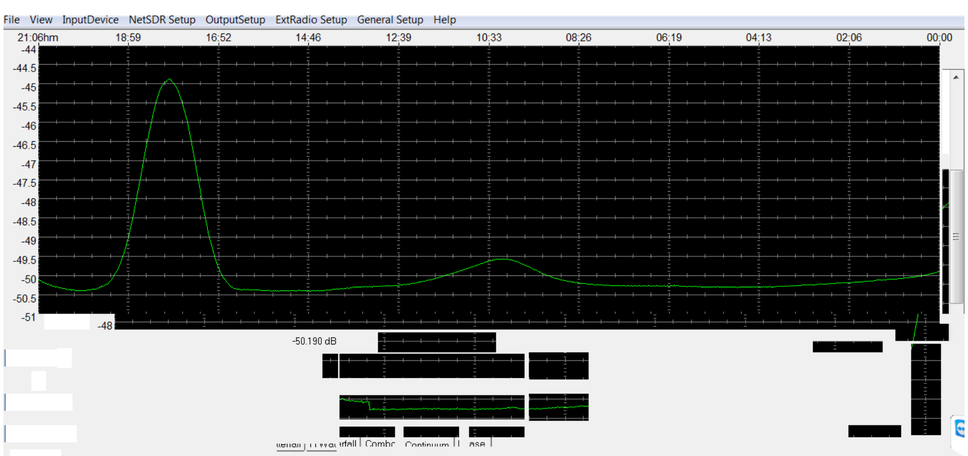
Table 2	Wire		
Angle	Total Power	Background	Net
11	33.81	33.96	-0.15
14	28.26	29.32	-1.06
17.5	25.34	26	-0.66
19.4	25.34	24.42	0.92
23.2	29.7	22.96	6.74
25	33.99	22.3	11.69
27	38.51	21.8	16.71
30.5	41.53	20.99	20.54
33.5	39.74	20.22	19.52
37	32.34	19.85	12.49
42.1	24.39	19.58	4.81



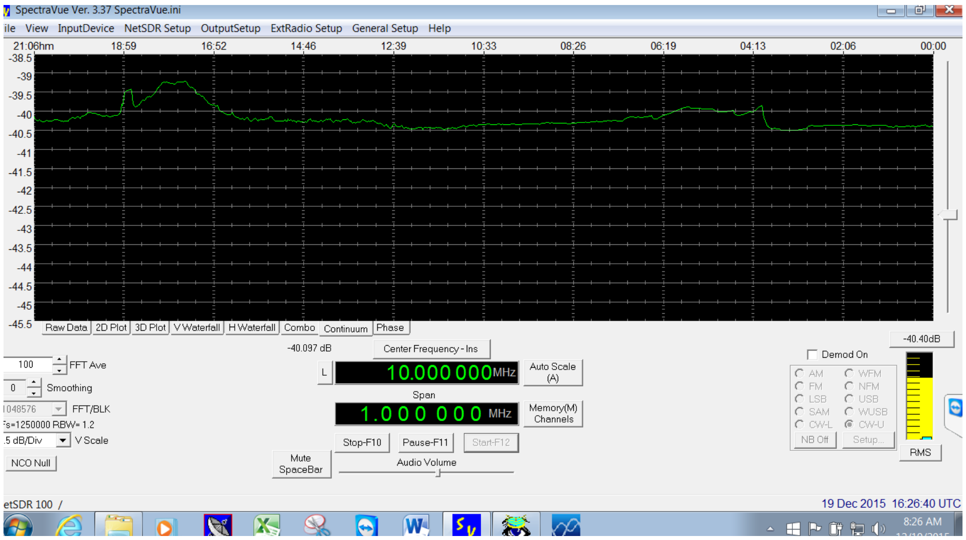
B. Horizontal Beam Width

The horizontal beam FWHM for each antenna was measured in a solar transit scan. A typical scan for each antenna is shown here. The measured results were 17 (+/-1) degrees and 18 (+/-1) degrees for the wire and aluminum antennas.

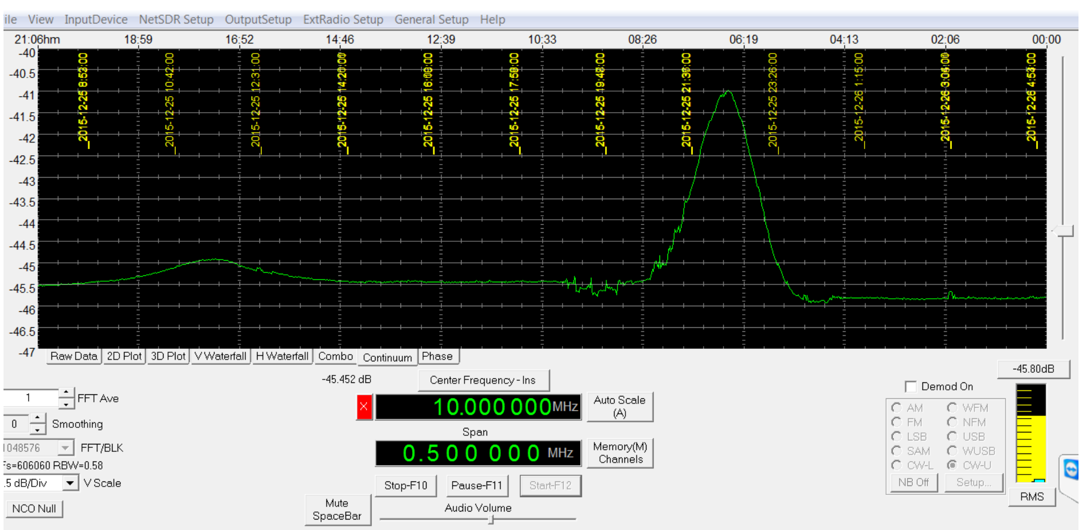
The screen image that follows is a typical transit scan of the Sun with the Aluminum antenna.



Wire antenna transit scan during light rain follows:



Wire antenna transit scan of Sun on sunny day follows:



C. Efficiencies

The efficiencies were measured using the Sun as our standard of flux density(S)

$$\text{Efficiency} = E = \frac{2kT_{a,Sun}}{A_g S}$$

which is derived in the Appendix.

Where k = Boltzmann's constant = $1.38 \times 10^{-23} JK^{-1}$

$T_{a,\,Sun}$= solar Antenna temperature in Kelvin

A_g = Geometric antenna aperture area in meter^2 = 0.63 m^2 for the aluminum and 0.65 m^2 for wire antenna respectively.

S = solar flux density in $Wm^{-2}Hz^{-1}$

Solar flux density is measured at Palehau, Hawaii with values found daily at www.swpc.noaa.gov/ftpdir/lists/radio/rad.txt

The antenna temperature of the Sun ($T_{a,\,Sun}$) = (Solar Power) (TC)

Where Solar power = (the peak solar power obtained from the dB measurement – sky background power from the dB measurement).

TC = Temperature Calibration constant of the telescope in Kelvin/Power Unit and defined as follows:

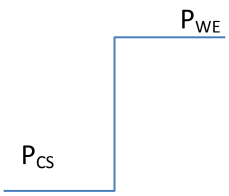
TC = (Temperature of warm earth - Temperature of cold sky)/ (Power received by the antenna from Warm Earth – power received by antenna from Cold Sky). T_{WE} and T_{CS} are taken to be 290K and 10K respectively.

Measuring the Antenna Temperature ($T_{a,Sun}$) of the Sun

All input values contained in the above efficiency equation are readily available except $T_{a,Sun}$ which we measure. In the following we describe a method (Method 1) to compute $T_{a,\,Sun}$. This requires calibrating the power scale using the temperature of warm Earth (WE) and the temperature of cold sky (CS) followed by performing a transit scan of the Sun whose flux density has been measured for that day.

Method 1 (Difference Method)

The first step in method 1 is to calibrate the power scale using the temperature of warm Earth (WE) and cold sky (CS) whose temperatures are taken to be 290K and 10K respectively.



We know the measured power is proportional to absolute temperature (Kelvin):

$P = T/C$ where C is a constant with value to the determined.

It follows that $C(P_{WE} - P_{CS}) = T_{WE} - T_{CS}$

Because our equipment measures power in dB, we convert dB to power units using the equation from the definition of dB:

$P = 10^{P(dB)/10}$

Solving for the calibration constant(C) we have

$$C = (T_{WE} - T_{CS})/(P_{WE} - P_{CS}) = (T_{WE} - T_{CS})/(10^{\frac{P_{WE}(dB)}{10}} - 10^{\frac{P_{CS}(dB)}{10}}) \qquad \text{Equation(2)}$$

Application to the aluminum antenna:

The figure displays the measured values of power in dB resulting from a WE/CS calibration:

$P_{WE} = -32.71$ dB $\qquad P_{we} = 10^{-32.71/10} = 5.36 \times 10^{-4}$ pu

$P_{CS} = -41.72$ dB $\qquad P_{CS} = 10^{-41.72/10} = 6.73 \times 10^{-5}$ pu

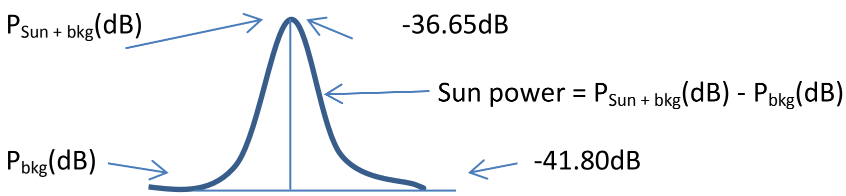
Where pu is an arbitrary power unit.

The calibration constant is computed using equation (2) above,

$$C = \frac{(290 - 10)\text{K}}{4.69\text{x}10^{-4}\text{pu}} = 5.97 \times 10^{5} \text{Kpu}^{-1}$$

Now proceed to the solar scan:

The figure includes the peak and background power values in dB



Peak power = $P_{Sun + bkg} = 10^{-36.65/10} = 2.16 \text{x} 10^{-4}$pu

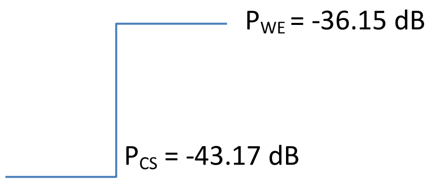
Background power = $P_{bkg} = 10^{-41.80/10} = 6.61 \text{x} 10^{-5}$pu

Power due to the Sun = the difference = $P_{Sun + bkg} - P_{bkg} = 1.50 \text{ x } 10^{-4}$ pu and is the measure of $T_{a, Sun}$.

Thus the antenna temperature of the Sun = $T_{a, Sun} = C(1.50 \text{ x } 10^{-4} \text{ pu}) = 5.97 \text{ x } 10^{5} \text{ Kpu}^{-1} \text{ x} 1.50 \text{ x } 10^{-4}$ pu = 90K.

Application to the wire mesh antenna

The analysis follows that of the aluminum antenna with only different numbers. First is determined the calibration constant using the WE/CS technique:

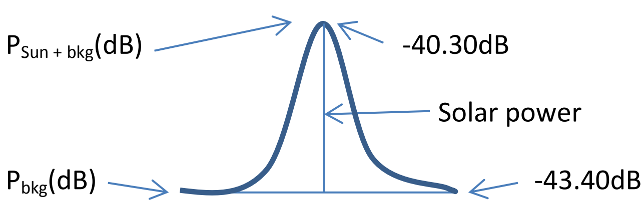


$P_{WE} = 10^{-36.15/10} = 2.43 \text{ x } 10^{-4}$ pu

$P_{CS} = 10^{-43.17/10} = 4.82 \text{ x } 10^{-5}$ pu

Substituting the above values the calibration constant C = $\frac{(290 - 10)\text{K}}{1.95\text{x}10^{-4}\text{pu}}$ = $1.44 \text{ x } 10^{6} \text{Kpu}^{-1}$

The wire mesh antenna solar transit data are on the figure:



$P_{Sun + bkg} = 10^{-40.30/10} = 9.33 \text{x} 10^{-5}$pu

$P_{bkg} = 10^{-43.40/10} = 4.57 \text{x} 10^{-5}$pu

The power due to the Sun is the difference between the two = $4.76 * 10^{-5}$ pu

Finally $T_{a, Sun} = 4.76 \text{ x } 10^{-5} \text{ pu} * 1.44 \text{ x } 10^{6} \text{ Kpu}^{-1} = 68.3$K

Compute the Efficiencies of the two Antennas using equation (1) and reported Solar Flux Densities

Al Antenna

$E_{Al} = \frac{2 \times 1.38 \times 10^{-23} \times 90K}{0.63m^2 \times 77 \times 10^{-22}} = 0.52$ Solar flux density was reported to be 77SFU

Wire Mesh Antenna

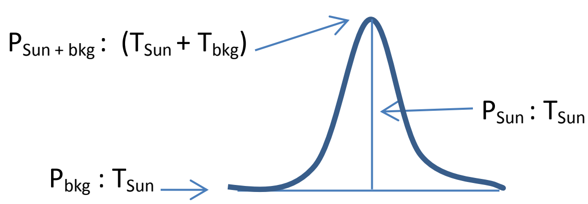
$E_{Wire} = \frac{2 \times 1.38 \times 10^{-23} \times 68.3K}{0.65m^2 \times 69 * 10^{-22}} = 0.42$ Solar flux density was reported to be 69SFU

Our antennas measure power of one polarization only. Here we have assumed the flux density (S) reported in the NOAA web site to be the vertical polarization component only.

If in equation (1), the solar flux density includes both polarizations, it must be reduced by a factor of 2. If this were the case the values of E for both antennas would be doubled.

Method 2 for Computing $T_{a,\ Sun}$

Consider the diagram of a solar transit scan:



$$\frac{P_{Sun+bkg}}{P_{bkg}} = \frac{T_{Sun} + T_{bkg}}{T_{bkg}} = \frac{T_{Sun}}{T_{bkg}} + 1 = \frac{10^{P_{Sun+bkg}/10}}{10^{P_{bkg}/10}} = 10^{[(Psun + bkg)(dB) - Pbkg(dB)]/10}$$

Finally $T_{Sun} = T_{bkg}[10^{[(Psun,\ bkg)(dB) - Pbkg(dB)]/10} - 1]$ equation(3)

Note that if there were no T_{bkg} added to $T_{s,}$ the "-1" value vanishes as would be the case for a WE, CS calibration measurement. Also note that the above equation makes good sense since one is simply subtracting T_{bkg} from the total $T(T_{bkg} + T_{Sun} - T_{bkg})$ and multiplying T_{bkg} by the factor $10^{(Psun,\ bkg(dB) - Pbkg(dB))/10}$ to obtain T_{Sun}

Although we seem able to justify all steps to equation (3) above, using it on the Aluminum wire mesh antennas does not yield result congruent with Method 1, to wit:

Aluminum Antenna:

Peak Power (dB) – Background Power (dB) = [$P_{Sun+bkg}$(dB) – P_{bkg}(dB)] = 5.12 dB

Or T_{Sun} = $T_{bkg}(10^{-5.15/10} - 1)$ = $T_{bkg}[3.27 - 1] = 2.27\ T_{bkg}$

Wire Antenna:

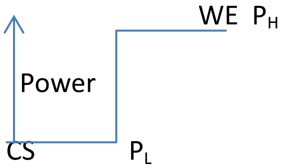
T_{Sun} = $T_{bkg}(10^{3.10/10} - 1) = 1.04\ T_{bkg}$

The measured power for cold sky on the wire antenna is approximately 0.4dB less than the power of background on the solar scan. This is a 10% effect. The measured power for cold sky on the aluminum antenna is approximately 0.6dB less than the power of background on the solar scan. This is an 11% effect.

Measure the Receiver Temperature (T_{rec})

This method is similar to that given in “Development of Small Radio Telescopes” by Johnson and Rogers

From the WE/CS measurement we can compute the T_{rec} as follows:



Where P_H and P_L are the measured power values resulting from pointing the antenna toward warm Earth and cold sky respectively.

Here we define the ratio Y as is customary: $Y = P_H/P_L$ and substitute the temperature equivalents:

$$Y = \frac{T_{WE}+T_{rec}+T_{spover}}{T_{rec}+T_{spover}+T_{CS}} \qquad \text{Equation (4)}$$

Rearranging we obtain:

$$T_{rec} = T_{WE}/(Y - 1) - T_{spover} - T_{CS}(Y/((Y-1)) \qquad \text{Equation (5)}$$

Where T_{rec} = Receiver temperature

T_{WE} = Warm Earth temperature = 290K

T_{spover} = Spill over temperature (taken to the be 0 for our horn antennas)

T_{CS} = Cold sky temperature = 10K

Apply equation (5) to the two temperatures:

<u>Aluminum Antenna</u>

Y_{Al} = 7.96 obtained from

P_{WE}(dB) = -32.71 => 5.36xx10^{-4} pu

P_{CS}(dB) = -41.72 => 6.37x10^{-5} pu

$T_{rec, Al}$ = 290K/(7.96 -1) – 10x(7.96/(7.96 -1)) = <u>30.2K</u>

<u>Wire Antenna</u>

Y_{Al} = 5.04 obtained from

P_{WE} (dB) = -36.15 => 2.43x10^{-4}

P_{CS} (dB) = -43.17 => 4.82x10^{-5}

$T_{rec, wire}$ = 290K/(5.04 -1) – 10*(5.04/(5.04 -1)) = <u>59.3K</u>

Note: a more traditional method for T_{rec} measurement uses a calibrated noise source as follows:

See for example "Electronics noise calibrator for the SRT" by R. Montez, Jr

$$\frac{P_{ON}}{P_{OFF}} = Y_{ON,OFF} = \frac{T_{noisecal}+T_{rec}+T_{spover}+T_{CS}}{T_{rec}+T_{spover}+T_{CS}} \qquad \text{Equation (6)}$$

Where P_{ON} is the measured power resulting from pointing the antenna toward cold sky with the noise calibrator on and P_{OFF} = power of cold sky with calibrator off.

$T_{noisecal}$ = Temperature of noise calibrator

T_{spover} = Temperature contributed by spill over

T_{rec} = Temperature contributed by receiver

Solving equation (6) above for T_{rec}:

$$T_{rec} = T_{noisecal}/(Y_{ON,OFF} - 1) - T_{spover} - T_{CS} \qquad \text{Equation (7)}$$

System Temperature

We take $T_{SYS} = T_{rec} + T_{sky} + T_{spover}$.

Substituting this expression for T_{SYS} into Equation (5) results, after a few obvious algebraic steps, in the more convenient expression for T_{SYS} in which T_{spover} cancels in the process:

$$T_{SYS} = (T_{WE} - T_{CS})/(Y-1) \qquad \text{Equation (8)}$$

T_{SYS} for the Al antenna telescope is therefore 40K and T_{SYS} for the wire antenna telescope is 70K .

In the above derivation of Equation (8) the route we took went through T_{rec} . A more straightforward route to Equation (8) from Equation (4) is possible by recognizing earlier in the derivation that $T_{SYS} = T_{rec} + T_{sky} + T_{spover}$.

Sensitivity using the Aluminum Antenna

Sensitivity or rms noise temperature of the radio telescope is defined here as the minimum temperature (T_{min}) measureable by a radio telescope (Radio Astronomy by J. Kraus):

$T_{min} = T_{SYS}/(BPxtau)^{1/2} = T_{rms}$ where BP is the bandwidth of the bandpass filter in the IF section of the IF downconverter (predetection bandwidth)and tau is the time constant of the integrator (postdetection integration time).

In addition, because $SA_{eff} = 2kT$, the minimum detectable flux density is $S_{min} = 2kT_{sys}/A_{eff}(BPxtau)^{1/2}$.

Setting $T_{SYS} = 40K$, $A_{eff} = 0.5x0.63m^2$, BP = 1MHz and tau = 1sec, T_{min} for the Al antenna telescope is

$40x10^{-3}K$ and $S_{min} = 350$ Jy (Janskys)

Acknowledgments: We appreciate discussions on the subject of electronics with Carl Lyster.

Appendix to Internal Report 1

Equation (1) is obtained starting with the Planck Law for blackbody radiation:

$$B = (2hv^3/c^2)/(\exp(hv/kT-1)) \qquad \text{equation (1a)}$$

Where B = brightness = specific intensity in $Wm^{-2}Hz^{-1}sr^{-1}$

h = Planck's constant = $6.63x10^{-34}Js$

v = frequency in Hz

k = Boltzmann's constant = $1.38x10^{-23}JK^{-1}$

T = temperature in Kelvin

c = speed of light = $3x10^8ms^{-1}$

We simplify equation (1a) by taking into account the fact that in the L band region (1GHz and above) $h\nu << kT$.

In this case $e^{h\nu/kT}-1$ can be approximated using a Taylor series expansion as $kT/h\nu$. This is the Rayleigh-Jeans approximation:

$$B = 2kT\nu^2/c^2 = 2kT/\lambda^2 \qquad \text{equation (2a)}$$

Since $\lambda\nu = c$

For a radio frequency source of temperature T_S and solid angle Ω_S the source flux density (S) in the Rayleigh-Jeans limit is obtained by integrating over the source solid angle:

$$S_S = \frac{2k}{\lambda^2}\int_{\Omega_S} T(\theta,\varphi)\,d\Omega \qquad \text{equation (3a)}$$

Which gives

$$S_S = 2kT_S\,\Omega_S/\lambda^2 \qquad \text{equation (4a)}$$

if the temperature is assumed to be constant over Ω_S.

Substituting $T_A\Omega_A = T_S\Omega_S$, we have

$$S_S = 2kT_A\Omega_A/\lambda^2 \qquad \text{equation (5a)}$$

where T_A is the measured antenna temperature of the source and Ω_A is the antenna solid angle.

After setting $\Omega_A = \lambda^2/A_{eff}$ and $A_{eff} = EA_g$ equation (5a) becomes

$$S_S = 2kT_A/EA_g$$

Where A_{eff} = the effective area of the antenna aperture,

A_g = geometric area of the antenna and

E = antenna efficiency

Finally

$$\mathbf{E = 2kT_A/A_gS_S} \qquad \text{equation (6a)}$$