Microwave Pickup on the Crawford Hill 7-meter Telescope

Jeff McMahon
Project Advisor: Suzanne Staggs

January 29, 2002

Abstract

This note describes work done to determine if the Crawford Hill 7-m telescope is usable in the CapMAP project, and effort to detect the polarization of the cosmic microwave background radiation (CMB). The main thrust of this work is an effort to detect any position dependent offsets around the north celestial pole where CapMAP will observe. For these measurements I built and tested a total power receiver, mounted it on the Crawford Hill telescope, and made several measurements. Preliminary results show that position dependent offsets are less than $\pm .5$ K.

1 The Crawford Hill 7-Meter Telescope

The Crawford Hill 7-meter telescope located at Bell labs in Holmdel, New Jersey is being considered for use in the CapMAP project. This antenna is a 7-meter offset Cassegrain reflector antenna. Since it is an off-axis design the support structure does not block and contaminate the beam. The rms surface error is 100 μm, which is less than 1/20-th of a wavelength at 90 GHz. This means the telescope will image properly at 90GHz. The beam width of this telescope at 90 GHz is $.02^{\circ}$ when fully illuminated. The optimal beam size for measurements of CMB polarization is somewhat less than the scale at which the angular power spectrum CMB polarization peaks, at about $.1^{\circ}$. The beam size of this telescope can be increased by under illuminating the dish. Under-illumination of the dish offers the additional benefit that signals diffracting around the edges of the mirror couple less strongly into the detector. This information suggests that this telescope might be suitable for use in the CapMAP project.

To make the final decision about using this dish, it is necessary to know the level of offsets. In the PIQU experiment the use of ground shields reduced the level of polarized offsets to less than 100 μK. Unfortunately the larger size of the Crawford hill dish and support structure makes the construction of a ground screen a much more involved and prohibitively expensive endeavor. If the offsets from this telescope are too large when the dish is under-illuminated, this telescope might be unusable.

To measure the level of these offsets, a total power receiver was built, and mounted on the Crawford Hill 7-M telescope in conjunction with a new tertiary re-imaging mirror to obtain the desired under-illumination of the dish. The remainder of this paper describes this equipment, some preliminary measurements, and other work that is currently in progress.

2 Total Power Receiver

A receiver was designed for this project to be able to detect the noise from the atmosphere at 90 GHz, and be sensitive to variations in this signal. The sky temperature at 90GHz is known to be approximately 50K[1]. The power from the sky signal is $k * T * bandwidth$, where k is the Boltzman constant and T is the temperature. Thus the power from the sky in a 15.6GHz band is expected to be $1.35 * 10^{-8}$mW. The available detector has a sensitivity of 1mV/μW. Consequently the system requires a gain factor of 10^5. This gain would not be possible at this frequency if it were not for the recent development of MMIC[1] amplifiers which are currently being built for the Planck satellite. The measurements described in this paper represent the first astronomical measurements made with these amplifiers.

The final configuration of the receiver can be seen in Figure 1. This receiver was placed in a specially designed nitrogen canister to prevent the MMIC amplifiers from adsorbing water which can cause them to fail.

To assess the overall performance of this receiver several tests are performed. These include a (1) measurement of the noise temperature, (2) a measurement of the system bandwidth, and (3) a measurement of the 1/f knee. The results of these measurements are used to determine the sensitivity of this system.

[1] Monolithic Microwave Integrated Circuit

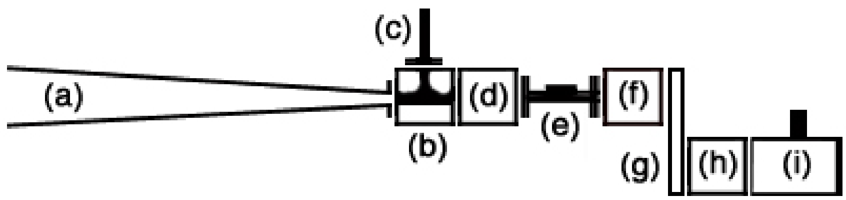

Figure 1: **The Total Power Receiver:** The sky signal enters the corrugated feed horn (a) from the left. The feed horn has a beam full width half max $8.5°$. The signal from the horn is then fed in to the ortho-mode transducer (omt). The omt splits slits the incoming signal into two linear polarizations. One polarization is fed into a termination (c) where it is absorbed. The other polarization is fed into the first MMIC amplifier (d) where it is amplified by a factor of 500. The signal then continues through a 10dB attenuator (e) where it is attenuated by a factor of 10. This attenuator is included to ensure the detector operats in the linear regime. The attenuated signal then passes into the second MMIC (f) where it is again amplified by a factor of 500. Any reflections from the front of the second MMIC are attenuated by the 10dB attenuator. The amplified signal from the second MMIC is then passed through a band defining filter (g). This filter has a pass band from 82 to 106 GHz. The signal then passes through an isolator (h) into a linear detector diode (i). The isolator is included to prevent reflections from the front of the detector diode from propagating backwards into the system and inducing oscillations. This signal from the detector diode is a DC Voltage that depends linearly on the power incident on the detector. This system has a measured bandwidth of 15.6GHz, a noise temperature of 450K, and a 1/f knee at 800Hz.

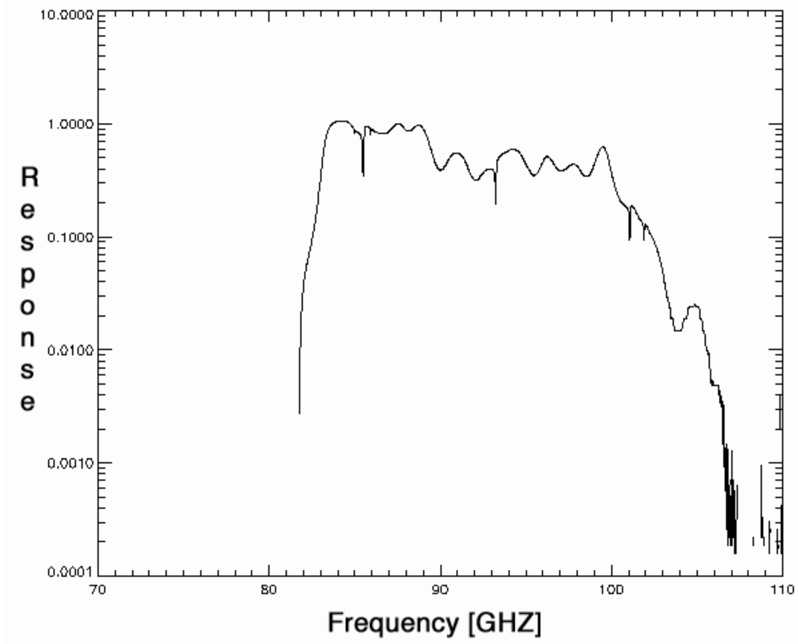

Figure 2: **Detector Response:** The bandwidth determined from this measurement is 15.6 GHz

The noise temperature (T_{noise}) of a detector is defined as the temperature corresponding to the noise that would be measured with the receiver pointed at a 0K source. The noise temperature is measured by a two load test. The receiver output is measured with the receiver pointed at sources of two known temperatures. The receiver output at these two known points is then fit to a straight line; the slope corresponds to the system gain, and the intercept is $-T_{noise}$.

In practice one of these loads is 77K, the temperature of liquid nitrogen, and the other load point is 295K, room temperature. This radiometer has a 445 ± 5K noise temperature outside of the nitrogen can. The uncertainty is due to long term fluctuations, most likely due to mechanical changes in the radiometer that occur when it is moved. With the radiometer inside the nitrogen can the noise temperature is 490 ± 5K. The higher noise temperature is due to the 30K noise contribution of the .022" polypropylene window the radiometer looks through to receive signals from the outside.

The band-width is defined as the following ratio of integrals over the response function:

$$BW = \frac{(\int_0^\infty R(\nu)d\nu)^2}{(\int_0^\infty R^2(\nu)d\nu)} \tag{1}$$

Here R is the response function, which measures the radiometer output as a function of the frequency ν. To determine the bandwidth it is necessary to measure the Response function of the detector R. The response was measured using an HP sweeper, which is a device that outputs a constant power signal into a narrow band with a variable central frequency. To make the measurement the horn, and OMT of the detector were removed, and the signal was fed directly into the first MMIC amplifier (part (c) in Figure 1). The signal from the sweeper was far too large to be sent directly into the detector, so a 30dB coupler was used in conjunction with three 10dB attenuators to reduce the power of the sweeper signal by a combined factor of 10^6. Once this system was set up, the central frequency of the sweeper was varied from 82 to 110 GHz, and the radiometer output was recorded with a 12-bit national instruments card controlled by Lab view. One hundred scans through this band were recorded, and divided up into bins .1GHz wide. The resetting data are shown in Figure 2. The plotted response function has been normalized to have its maximum value be 1.

The results of this measurement show that the radiometer has no gross problems such as oscillations, or major component failure. The slightly elevated plateau in the response function between 83 and 88 GHz is known to be due to the frequency dependent gain in the MMIC amplifiers. The bumps are due to the standing waves in the injector system. The sharp dips are frequency markers in the sweeper used to calibrate the frequency of the plot. Using this measured response function and equation 1, the bandwidth is found to be 15.6GHz.

Using the measured bandwidth, and the system noise temperature it is possible to estimate the sensitivity of the system. The maximum sensitivity is given by

$$Sensitivity = T_{sys}/\sqrt{BW} \tag{2}$$

where $T_{sys} = T_{noise} + T_{source}$. Thus for this system which has a receiver temperature of 450° K and 15.6 GHz bandwidth, the maximum sensitivity is 3.6 $mK/\sqrt{Hz}$ This is the sensitivity of the system when its noise is dominated by thermal noise. Unfortunately thermal noise is not the only type of noise in the system. The receiver also suffers from $1/f$ noise, that is, long term drifts in the gain of the system which give a power spectrum that scales as f^{-1}. To account for this additional source of noise the sensitivity equation (equation 2) must be modified through the addition of a term proportional to the gain fluctuations $\delta g/g$. The more complete sensitivity equation is

$$Sensitivity = T_{sys} * \sqrt{\frac{1}{BW} + (\frac{\delta g}{g})^2 * t_{int}}. \tag{3}$$

The term $\delta g/g$ is frequency dependent, and t_{int} is the integration time. Since the detector sensitivity and amplifier gain are stable over short time scales, $1/f$ noise is dominant at low frequencies. The frequency where the receiver noise switches from being $1/f$ dominated to being thermal noise dominated is known as the $1/f$ knee. Knowledge of the knee frequency gives all the information necessary to determine the sensitivity of the receiver at a given frequency.

The frequency of the $1/f$ knee is measured by using a 295° K source as the input of the receiver, and feeding the output into a low frequency spectrum analyzer calibrated to Kelvin per root-Hertz. The result of this measurement is shown in Figure 3. The knee frequency was determined by fitting a power law to the low and high frequency data separately. The low frequency data were found to fall as $f^{-.5}$ as expected for $1/f$ noise since the data were measured in units proportional to the square-root of fluctuation power. The high frequency data were found to scale as $f^{-.02}$ which is very close to the expected f^0 frequency dependence. By taking the intersection of these two curves, the knee frequency was found to be 800Hz.

For measurements at frequencies f below f_{knee} the sensitivity is given by

$$Sensitivity(f) \simeq \sqrt{(f_{knee}/f)} * \frac{T_{sys}}{\sqrt{BW}}. \tag{4}$$

For the measurements that will be described below, the measurement period is about 2 seconds, and T_{sys} is approximately 600° K. Thus the expected sensitivity is about 200 mK/$\sqrt{Hz}$. In

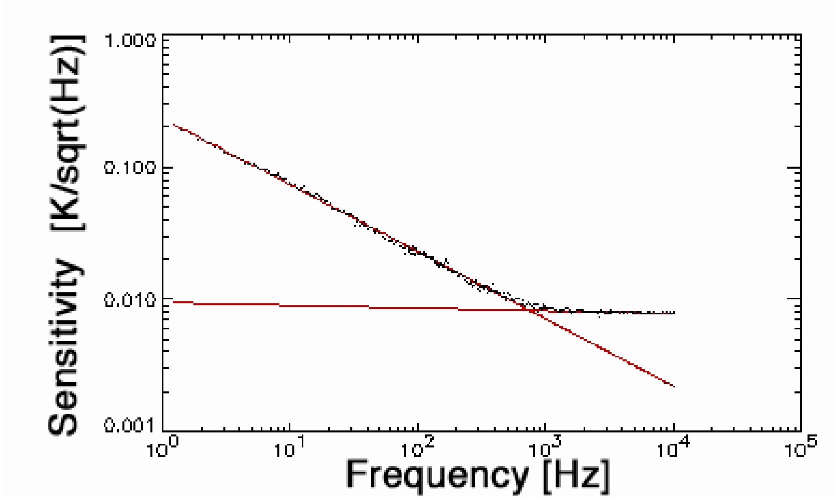

Figure 3: **Noise Power Spectrum** Power spectrum taken while pointing the radiometer at a 300 K source giving a system temperature of about 750 K. Changing the system temperature shifts the vertical level of the curve, but does not affect its shape. The low frequency noise which has a 1/f structure in power can be attributed to detector drifts. The flat noise at higher frequencies is thermal Noise. The transition between these types on noise, the "$1/f$-knee," occurs at a frequency of 800Hz.

practice this estimate is somewhat low since the atmosphere is not a thermal source, and it s fluctuations fall more steeply with frequency.

3 Data Acquisition System

The signal emerging from the radiometer is only about 10mV which is inconveniently small. Thus the signal is fed through a preamplifier with a gain of 100 located inside of the dewar. A battery powered DC-offset is then subtracted from the signal. This offset is included to shift the signal so that its variations are centered around zero. The signal is next fed into a SRS preamplifier with a variable gain and a variable filter. This serves two purposes. First it amplifies the signal to fill the range between -2.5V and 2.5V used by the analog to digital converter. The SRS unit also filters the data to prevent aliasing of high frequency noise into the recorded data. Typically the gain was set to 30 and the filter was chosen to be a 12 pole low pass with a cutoff frequency of 100Hz. The output of this amplifier was then passed into a National Instruments 12 bit A to D converter controlled by Lab View. Typically the data were acquired at 250 samples per second on a $\pm$2.5V channel.

For the measurements that are described below, it is necessary to measure the output of the receiver as a function of the telescope position. This is done as follows. The receiver signal is recorded as a function of time, and at the same time the telescope position is recorded as a function of time. Later in the analysis and the two data sets are recombined to obtain the radiometer signal as a function of position. The clocks are synchronized to $\pm.5$s. Since the period of telescope motions was approximately 5s this introduces only slight errors. In the more recent measurements the clocks are synchronized to .1s using timing from GPS receivers.

4 Configuration at the Crawford Hill Telescope

The horn used in the warm radiometer above produces a beam 8.5 degrees wide. This beam would over illuminate the secondary on the Crawford hill telescope, and thus could not be used with out modification in the test setup. To make the test setup more similar to what will be used in the CapMAP project, a tertiary re-imaging mirror is introduced between the radiometer and the secondary mirror. The tertiary was designed to illuminate the edges of the secondary mirror at -58db relative to the center, and the edges of the primary at -35db relative to the center. The size of the mirror was chosen so that its edges are illuminated at -38db. The beam size using the tertiary mirror in the system is calculated to be $.05^\circ$. This beam size is nearly optimal for detecting the polarization of the CMB.

The mirror and receiver are held in place on the telescope by a set of specially designed mounts. These mounts allow the position of the Mirror to be moved in translation and rotation, and allow the receiver to be moved translationaly in three dimensions and rotationally in 1. These degrees of freedom are necessary for aligning the system. The alignment process is done using a two-sided laser with its beam along the optical axis of the telescope. Measurements that are described below suggest that the system is reasonably well aligned, although an encoder malfunction has hampered efforts to determine this precisely.

5 Measurements

Several measurements have been made using this system. These measurements can be divided into two broad categories. The first category is measurements to characterize the beam, and the second is measurements of telescope offsets. A measurement in the first category is an observations of the moon which suggests the telescope is aligned within $.1^\circ$ in azimuth and elevation. Measurements in the second category include sky tip measurements which show that pickup is less than .7K down to elevation angles about 60° from zenith, and several azimuth scans which bound the structure of ground pickup present around the North Celestial Pole at 500mK rms. The later results are not sufficient to determine if this telescope is usable. When the encoder is fixed these will be repeated with better sensitivity. If the results are good, these measurements will be repeated with the PIQU receiver which is sensitive to polarization.

Observing the Moon Observations of the moon are made as follows. The telescope tracks the center of the moon. Then a variable pointing offset is applied causing the telescope to scan a rectangular grid around the moon. The elevation offset begins at -.5 then the telescope scans in azimuth from $-.5^\circ$ to $.5^\circ$ and back to $-.5^\circ$. The elevation offset is then incremented by $.05^\circ$. This process continues until it has covered a square 1° on each side.

The raw data from one such run is shown in Figure 4. This data is also plotted as a function of position in Figure 5. This data shows the pointing is aligned to an accuracy of approximately .1 degrees in elevation and in azimuth. This is estimated by computing the centroid of the map. The centroid was found to lie at azi=$.08^\circ$, and ele=$.11^\circ$ This method would be reasonably accurate if the intensity profile of the moon was a flat disk. This is not the case. Structure is clearly present in the map shown in Figure 5. The computed centroid is shifted toward the hot-spot at positive values of azimuth and elevation. This serves as a rough estimate of the

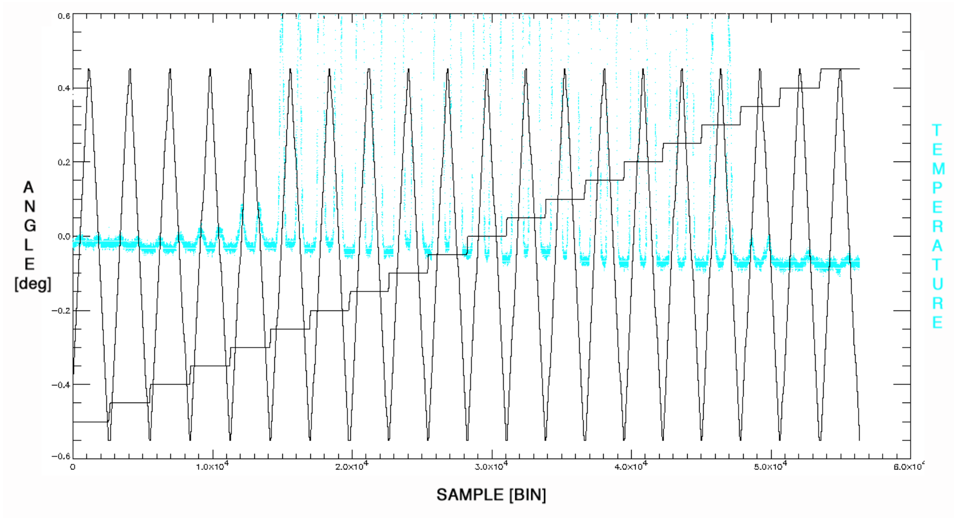

Figure 4: **Raw moon data:**The step like waveform is the elevation position. The triangular waveform is the azimuthally position. Both coordinates are measured relative to the center of the moon. The blue curve is V_{out} from the radiometer. This signal is proportional to the radiated power from the moon. The maximum temperature of the moon that is measured in this data set is $245°$ K

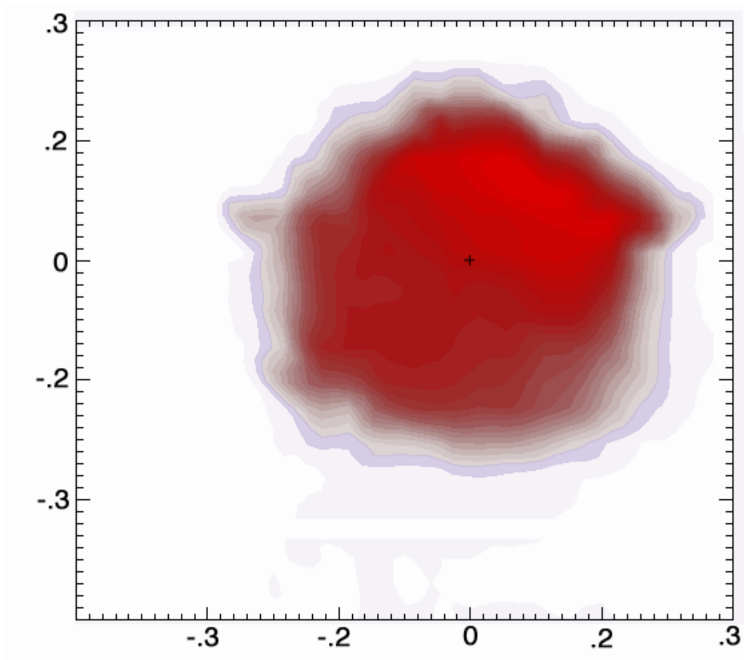

Figure 5: **Moon Map:** A map of the moon showing the pointing and the beam are approximately correct. The pointing is not terrible since the point 0-0 lies near the center of the moon.

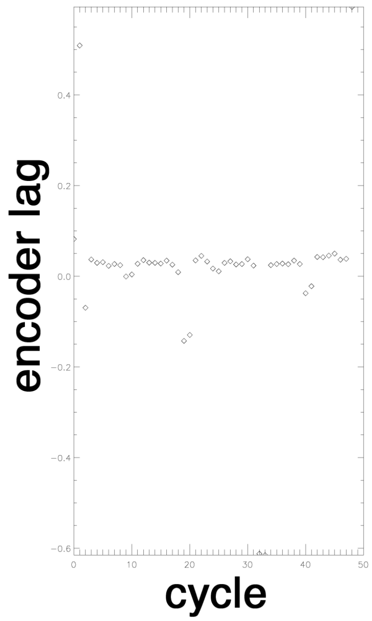

Figure 6: **Encoder Drift and Slips:** This plot reveals problems with the azimuth encoder. The data from which this plot is generated was obtained by scanning the telescope back and forth across the moon. The signal from the radiometer is periodic and has the same period as the scan. The encoder signal is also be periodic and should have this same period. The difference between these two periods is plotted in this Figure, and is very clearly non-zero. This shows that the encoder position drifts behind the physical telescope position during a scan. The points that are significantly below zero correspond to encoder jumps where the encoder is catching up for the lost angle. These jumps are about $.1^\circ$ in magnitude.

pointing and shows that the pointing is roughly correct.

Surprisingly there is also a time dependent pointing error due to a problem with the encoder. This is illustrated in Figure 6. The azimuth encoder angle lags behind the physical telescope position and then jumps to catch up. The scale of these jumps is approximately $.1^\circ$ degrees. This introduces pointing uncertainties which make it difficult to detect week signals by averaging multiple scans in spatial bins.

Sky Tips The angular dependence on the power radiated from the atmosphere is very simple and can be derived using two assumptions. The first is the flat atmosphere approximation, or the assumption that the top of the atmosphere is flat. The validity of this approximation depends on the scale hight of microwave emission being much smaller than the radius of the earth. The scale height of microwave emission is almost the same as the scale height of water which is approximately 2km[2], much less than 6400km, the radius of the earth. This justifies the first approximation. The second approximation is treating the atmosphere as optically thin. Optically thin means that photons propagating through the atmosphere have a low scattering probability. This can be verified by looking at emissions. The temperature of the atmosphere is approximately 270K. emissions near zenith are on the order of 35K. This means that about 1 in 8 photons is adsorbed. This is small enough that the approximation works.

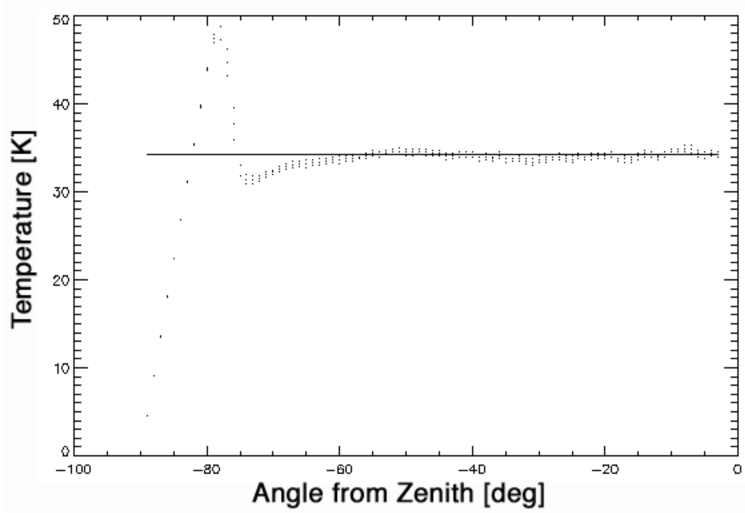

Figure 7: **Elevation Tip:** The data has been multiplied by a factor of $\cos\Theta$ so deviations from equation 5 will be visible as deviations from a straight horizontal line. The horizontal line at $T_{atm} = 34.3$ K is the best fit. Equation 5 describes the data well for angles between 0 and 60 degrees. The disagreement beyond $60°$ is probably due to the failure of the assumption that the atmosphere is opticaly thin. At $60°$ the adsorption coefficient of the atmosphere is approximately $1/3$.

With these two approximations, the angular dependence of radiated power can now be calculated by treating each volume of atmosphere as thermal microwave source at temperature T_{atm}. Since we are assuming the atmosphere to be optically thin, the total radiation adsorbed depends linearly on the distance through the atmosphere. Simple geometry shows

$$T(\Theta) = \frac{T_{atm}}{\cos\Theta} \tag{5}$$

where Θ is the angle as measured from zenith;

Deviations from this dependence can be used to search for noise pickup. In this measurement, the azimuth position of the telescope was fixed in the direction of the North Celestial Pole, and the telescope scanned from $90°$ to $3°$ in elevation as measured from zenith. The data were then binned into $1°$ wide bins. The resulting data are shown in Figure 7. The data are multiplied by a factor of $\cos\Theta$ so that deviations from equation 5 are visible as deviations from a straight horizontal line. The coefficient T_{atm} of equation 5 is measured to be 34.3K from this data set. Figure 7 shows noise pickup is less than .7K to an angle of $60°$ from zenith.

The dip between $60°$ and $75°$ is due to the breakdown of the assumption that the atmosphere is optically thin. At 60 degrees the measured power from the atmosphere is about 90K, about 1/3 of the physical temperature of the atmosphere. The ratio of the radiated power to the physical temperature is an estimate for the adsorption coefficient. The measured power dips because radiation is now adsorbed by the atmosphere. The spike below $75°$ is due to a tree entering the beam.

Azimuth Scans The observing strategy that will be used for the CapMAP experiment will require the telescope to scan back and forth across a $1°$ wide disk centered on the north celestial

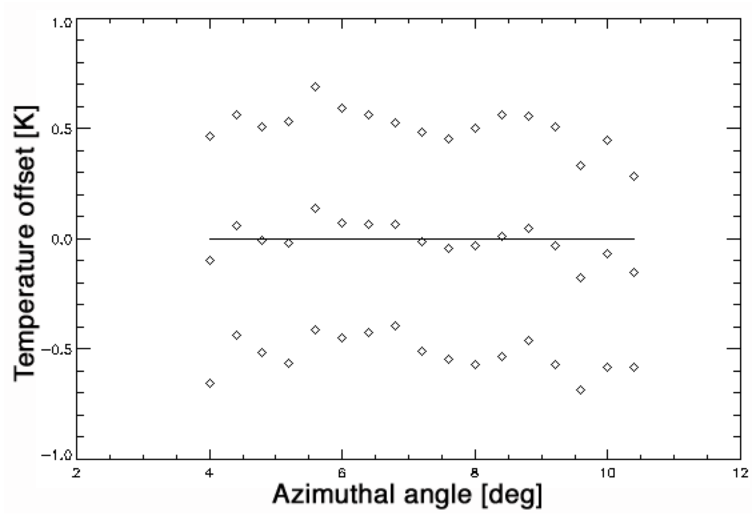

Figure 8: **Azimuth Scans:** This measurement shows that the levels of pickup for scans in azimuth near the North Celestial Pole are consistent with zero pickup.

sphere. If large offsets are detected during such a scan, the telescope will not be usable. To bound these offsets, the telescope pointed toward the North Celestial Pole and scanned back and forth in azimuth by $6.2°$ 16 times. For each scan an offset was removed. The data was then divided in to .2° bins and averaged. The resulting data is shown in Figure 8. The data in each of these bins shows that the measurement is consistent with no pickup within error bars of .5K.

6 Work to be done

Two measurements remain to be done after the azimuth encoder is repaired. First the telescopes response to a point source needs to be measured. This will verify our understanding of the configuration of the optics of the telescope and the illumination of the dishes. This is important since it will verify that these measurements are made in a configuration similar to what will be used for CapMAP. The second test that remains to be done is a repeat of the azimuth scan test that was described above, but with more scans and more sensitivity. A data set with 1600 scans will reduce the error bars on each point to about 50 mK. This can be completed in several hours since the telescope can complete a single scan in several seconds. If no structure is detected to this at this level the measurement will be repeated using the PIQU receiver that is sensitive to Polarization. This will be the critical test. If the polarized offsets are found to be less than 100 μK, then the Crawford Hill telescope will be used for CapMAP.

References

[1] M. M. Hedman,D. Barkats,J. O. Gundersen,S. T. Staggs,B. Weinstein, Phys. Rev. Lett. **vol** (2001) pp [astro-ph/0010592]

[2] E. Grossman, ”AT - atmospheric Transmission Software User’s Manuel”, v-1.5, airhead software 1989