Measurement of the Cosmic Microwave Background Radiation at 19 GHz

1 Introduction

Measurements of the Cosmic Microwave Background (CMB) radiation dominate modern experimental cosmology: there is no greater source of information about the early universe, and no other single discovery has had a greater impact on the theories of the formation of the cosmos. Observation of the CMB confirmed the Big Bang model of the origin of our universe and gave us a look into the distant past, long before the formation of the very first stars and galaxies. In this lab, we seek to recreate this founding pillar of modern physics.

The experiment consists of a temperature measurement of the CMB, which is actually "light" left over from the Big Bang. A radiometer is used to measure the intensity of the sky signal at 19 GHz from the roof of the physics building. A specially designed horn antenna allows you to observe microwave noise from isolated patches of sky, without interference from the relatively hot (and high noise) ground. The radiometer amplifies the power from the horn by a factor of a billion. You will calibrate the radiometer to reduce systematic effects: a cryogenically cooled reference load is periodically measured to catch changes in the gain of the amplifier circuit over time.

2 Overview

2.1 History

The first observation of the CMB occurred at the Crawford Hill NJ location of Bell Labs in 1965. Arno Penzias and Robert Wilson, intending to do research in radio astronomy at 21 cm wavelength using a special horn antenna designed for satellite communications, noticed a background noise signal in all of their radiometric measurements. Discoveries in science often result from new enabling technologies; in this case there were two. The first was the ultra low off-axis response of their horn antenna, originally designed to avoid strong off-axis interference from other sources. Without this clean beam from their re-purposed special horn antenna, the Bell Labs team would probably not have been able to isolate the small extra sky noise because it would have been buried the far larger noise from the ground emission in a standard microwave antenna.

The other new technology that Penzias and Wilson had to invent in order to reliably distinguish their sky noise from their radiometer system noise was the fast switching cold load. This built on previous cold load measurements by Robert Dicke during WW II. [You will also be calibrating your CMB radiometer by frequent comparison to cold and warm loads].

There is a lesson here: discovering the unexpected often occurs when the scientist doggedly pursues a small error or inconsistency in her or his measurements. Indeed, a previous team at Bell Labs had noticed a small inconsistency in their microwave receiver noise – but chose to ignore it. Figure 1 shows the horn antenna at Bell Labs which was used to discover the CMB.

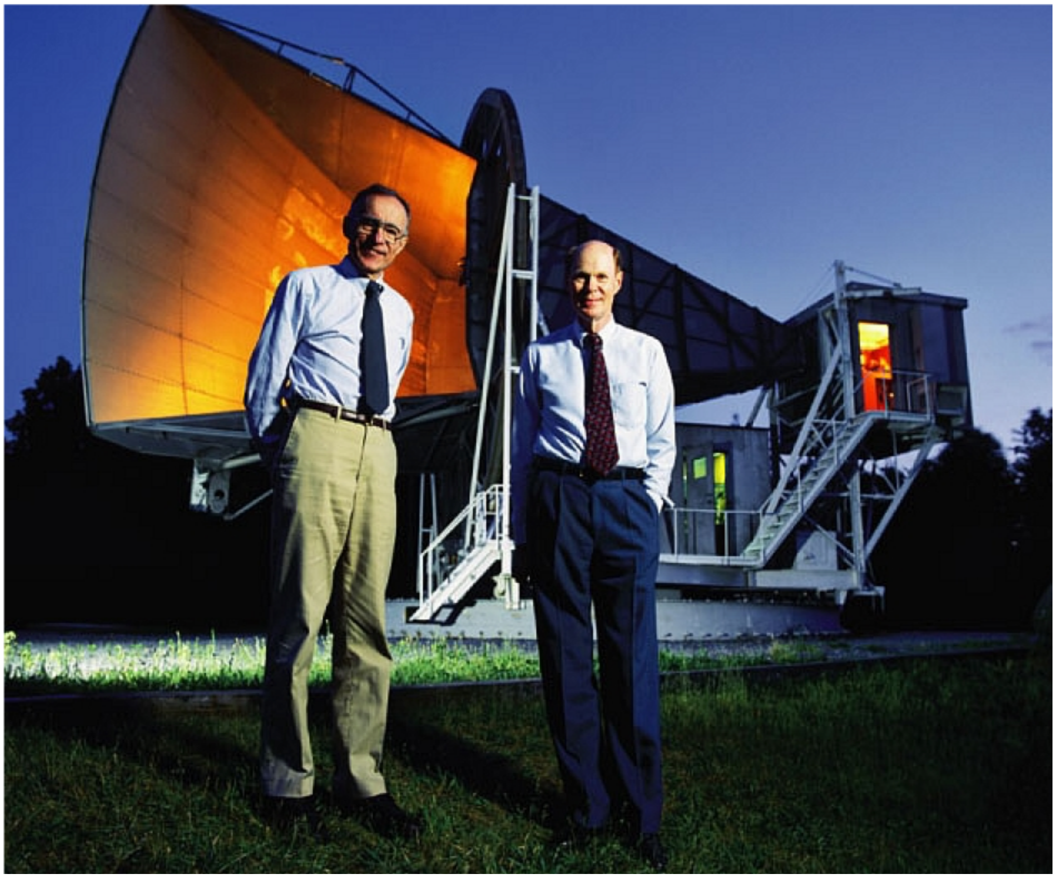


Figure 1: The Bell Labs horn antenna. Arno Penzias and Bob Wilson stand in front of the horn antenna which they used in their discovery of the 2.725 K CMB radiation. It had been designed a decade earlier by Art Crawford for a Bell Labs – NASA satellite communications project that required high rejection of off-axis response. This 18 ton, 50 foot long horn with 20x20 foot aperture is large because of the low frequency it was designed to cover (2.4 GHz) with a narrow beam.

After searching for over a year for radiation leakage and loss in joints and the antenna horn, accounting for back-lobe response from the ground, factoring out atmospheric noise, and calculating antenna temperature contributions from ohmic losses, they concluded that the residual noise signal must be from space. Radiation from astronomical bodies was quickly discounted; as they wrote in the original publication, "This excess temperature is, within the limits of our observation, isotropic, unpolarized, and free from seasonal variations"[1].

The characteristic temperature of their inexplicable noise was 3.5 ± 1 K. At the same time that this mysterious noise signal was baffling the Bell Labs scientists, Robert Dicke, Jim Peebles, P. G. Roll, and David Wilkinson were preparing a search for a background radiation in space a mere 37 miles away in Princeton. The two groups met, and two papers were immediately published back to back in the Astrophysical Journal – one by Penzias and Wilson explaining their cosmic noise detection (see [1]), and one by Dicke et al. offering a cosmological interpretation (see [2]) as the microwave signal remaining from the Big Bang.

In its early, high-density phases, the universe would be opaque to radiation; because photons are quickly scattered by high-energy electrons, the radiation field would exhibit a perfect blackbody spectrum. Even before further measurements were made on this new cosmic noise, physicists were already anticipating the confirmation that the signal was a blackbody spectrum, "as expected for the cooled fireball from the big bang" (Peebles [3]).

The original measurement by Penzias and Wilson at a wavelength of 7 cm (4.3 GHz) was quickly complemented in the subsequent year by measurements at 3 cm (10 GHz) by Roll and Wilkinson at Princeton and another at 20.7 cm (1.45 GHz) by Howell and Shakeshaft. These measurements together began to experimentally show the blackbody nature of the spectrum. General acceptance soon followed of its interpretation in inflation cosmology as the CMB radiation left over from the primeval universe.

The redshifts of observed galaxies and astronomical bodies suggested that the universe was expanding, but the Big Bang model could not be confirmed until the discovery of the CMB. From 1989-1993 a microwave spectrometer aboard the COBE CMB satellite measured the CMB spectrum to unprecedented precision. It is the most perfect blackbody ever observed [5]. The impact on cosmological theory is huge; any theory intending to explain the beginnings and history of the universe must offer an explanation for the presence of the CMB. Our understanding will improve as measurements of the CMB grow more numerous (CMB S-4 is the next big project), when combined with other next-generation optical and IR surveys.

2.2 Physics

2.2.1 The Oldest Light in the Universe

In our best current model, early in its history the universe consisted of a hot plasma that was opaque to radiation [3]. The temperatures were so high that matter and radiation interacted heavily. Once the temperature of the universe dipped below a point such that these interactions were no longer occurring at a rate faster than expansion, and the fireball cooled so that electrons and protons could recombine into neutral hydrogen, the decoupling of matter and radiation took place.

At that point (about 300,000 years after the Big Bang), the universe suddenly became transparent—that is, a photon could travel through the universe without interacting with matter. In fact, after decoupling, the mean free path of the photons became so great that they reach us today mostly undisturbed from their original emission at the time of decoupling. These photons are the oldest light in the universe and provide us with a snapshot of the universe at the time of their emission, before the development of the first galaxies and stars.

But why should this radiation exhibit a blackbody spectrum? In the early, primeval plasma, there were three main processes through which the matter and radiation could interact: Compton scattering, double Compton scattering, and thermal bremsstrahlung [4]. Compton scattering is the scattering of a photon from an electron:

$$\gamma + e^- \rightarrow \gamma + e^-.$$

Double Compton scattering is a similar process whereby a photon is created or destroyed:

$$e^- + \gamma \leftrightarrow e^- + \gamma + \gamma.$$

Finally, thermal bremsstrahlung refers to the process where charges are accelerated (or decelerated) in the field of an ion, leading them to radiate photons. Note that the number of photons is conserved in Compton scattering, while the other two processes can create or destroy photons. The combined effect of these three processes was to bring about a thermal equilibrium between particles and radiation.

The photons that existed at the time of photon decoupling (at a temperature ~ 3,000 K) 300,000 years after the Big Bang (corresponding to a redshift of 1100) have been propagating ever since. Their wavelengths have grown as a result of the expansion of space by a factor of 1100, meaning that their energies have decreased by that factor. The present-day distribution of CMB energies is extremely well described by a blackbody spectrum of temperature 2.725 K.

2.3 Absolute Temperature Measurements

The CMB provides of wealth of information for theories of the cosmos; tapping into that information requires measurements of the radiation. What we have are photons, moving in all directions, in all sections of the sky. The photons carry with them a frequency (wavelength) and a brightness, or intensity.

The intensity of light from a blackbody emitter is defined by Planck's Law,

$$\mathrm{I}(\nu) = \frac{2h\nu^3}{c^2} \frac{1}{\exp(\mathrm{h}\nu/\mathrm{kT})-1} \tag{1}$$

where h is Planck's constant, ν is the frequency, c is the speed of light, and k is Boltzmann's constant. The spectrum of a blackbody emitter (intensity I as a function of frequency ν, as shown in figure 2) is dependent *solely* on the temperature T of the radiating body. For a perfect blackbody, a single measurement is therefore enough to calculate the entire spectrum. In this experiment, you will measure the intensity at 19 GHz. At lower frequencies, interference from galactic synchrotron emission becomes more appreciable, while at higher frequencies atmospheric absorption plus non-thermal emission grows.

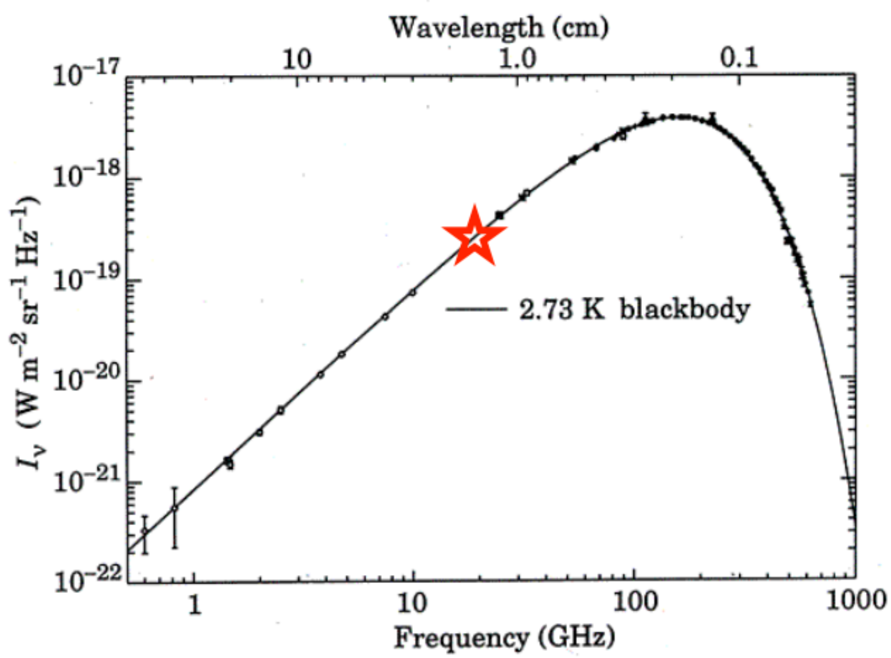


Figure 2: Spectrum of a 2.725 K blackbody emitter. Your observation of the CMB in this experiment will be made over a 500 MHz band at 19 GHz, as indicated.

Planck's Law can be further simplified by taking the Rayleigh-Jeans limit of $kT \gg h\nu$. Here, the exponent of the exponential function approaches zero, and we can make a first order approximation,

$$\exp(h\nu/kT) \simeq 1 + \frac{h\nu}{kT} \tag{2}$$

This reduces Planck's Law to the linear relation

$$\mathrm{I}_\nu(\mathrm{T}) = \frac{2kT\nu^2}{c^2} \tag{3}$$

The Rayleigh-Jeans limit begins to break down when the frequency (in GHz) approaches 20 times the temperature (in Kelvin). This experiment, in which a 2.725K blackbody signal is measured at 19 GHz, lies within the region of validity of this approximation.

A temperature measurement of the CMB, then, merely requires an accurate measurement of intensity and an application of Equation 3. However, an accurate absolute intensity measurement is beyond the capability of the equipment used in this experiment. It would require amplifying the weak CMB signal to measurable levels while keeping precise track of the overall system gain. Instead, we will exploit the *linear* relation between temperature and intensity—i.e., we will measure the intensity of blackbody radiation at known temperatures and calculate a new relation—post amplification—between temperature and intensity. This method holds as long as all measurements are subject to the same amplification, or gain *G*. Because you need to measure to a small fraction of the total system temperature, gain stability (variations with time and ambient temperature) is an issue. This is addressed through frequent gain calibration by pointing the horn antenna at a reference load. The following sections explain the process in detail.

3 Experimental Setup

3.1 Overall Setup

You will measure the intensity of incident radiation using a horn antenna (Sec 3.2), a microwave low noise amplifier, a heterodyne down-converter, and a chain of amplifiers (Sec. 3.3) followed by a square-law detector and an integrating voltmeter.

The section of sky measured is controlled by tilting the horn from the vertical (zenith) down to some angle such that the horn diffraction sidelobes do not intercept the hot ground. You should take measurements at the zenith and at various angles in order to factor out atmospheric noise (see Sec. 4.4). The horn has a narrow beam, and sidelobe interference is minimized. A short 19 GHz circular waveguide channels the EM radiation from the horn throat to a sensitive microwave radiometer.

As we can see from the vertical scale in figure 2, the small CMB signal needs amplification and as wide a bandwidth at 19 GHz as possible (units in Figure 2 are per Hz bandwidth). At the same time, we do not want the process of amplification to contribute its own inevitable noise which then competes with the very CMB noise you are trying to detect. The radiometer begins with a low noise 19 GHz pre-amplifier whose output is down-converted to 1.2 GHz via a mixer fed by a 21.2 GHz "local oscillator," followed by an amplifier at 1.2 GHz. All noise signals in a 500 MHz piece of the spectrum at 19 GHz are translated to the lower frequency of 1200 MHz where signal processing is easier. This combination is enclosed in an aluminum case called the Low Noise Block (LNB). The LNB output is fed into a band-pass filter which passes RF in the range 1000-1500 MHz, and then is fed to a post amplifier and square-law detector (whose output voltage is proportional the input RF power), and finally to an integrating voltmeter which is calibratable in watts. The entire system is called a radiometer. Below we describe these elements in more detail. In Sec. 4 we describe the observing and data acquisition sequence.

3.2 Horn antenna

The 19 GHz radiation from the sky is captured by a special directional horn antenna, where the electromagnetic waves generate an oscillating potential in the antenna, giving rise to a weak RF signal. The intensity of the incident waves determines the voltage across the antenna, and thus the RF signal. The intensity of the radiation is what you will measure. The 19 GHz horn which you will use in this experiment is shown in Figure 3.

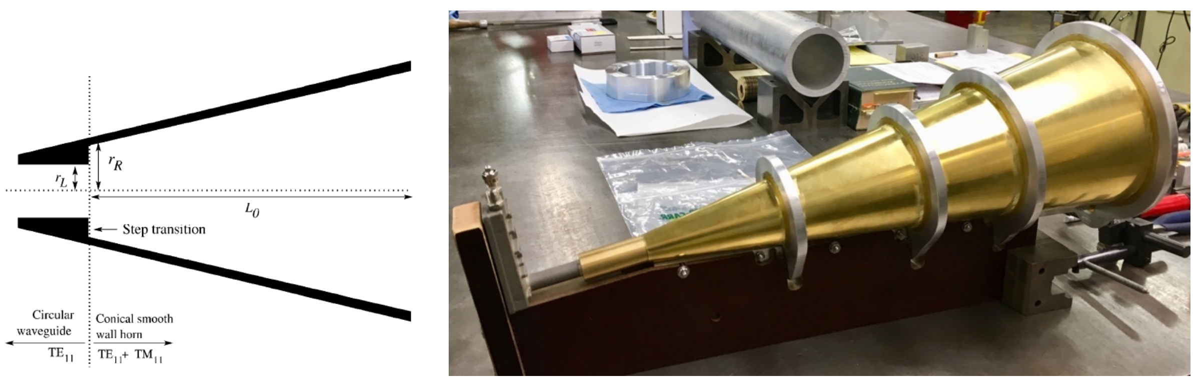


Figure 3: Potter horn antenna**.** Radiation from the sky is received by a specially designed horn, which has a narrow beam so that you can selectively observe various sections of the sky. This enables distinguishing the CMB from the atmosphere and the surroundings. The horn achieves its narrow beam by exciting other modes in the throat section (*left*) which cancel sensitivity at large angles (side lobes), creating a narrow beam shown in figure 4.

Normal horn antennas are directional, but have some off-axis response due to diffraction at their input aperture. The Potter horn antenna is special because it has ultra-low sidelobes, allowing radiation from selected areas of the sky to be isolated from emission from the ground. It also enables the independent detection of the thermal radiation from the Earth's atmosphere, by taking data at various zenith angles. The Potter horn design, shown in Figure 3 achieves its low sidelobe response by a clever discontinuity in the throat section, which launches additional EM modes which can be made to nearly cancel off-axis response at the aperture of the horn. This remarkable directional selectivity is shown in Figure 4.

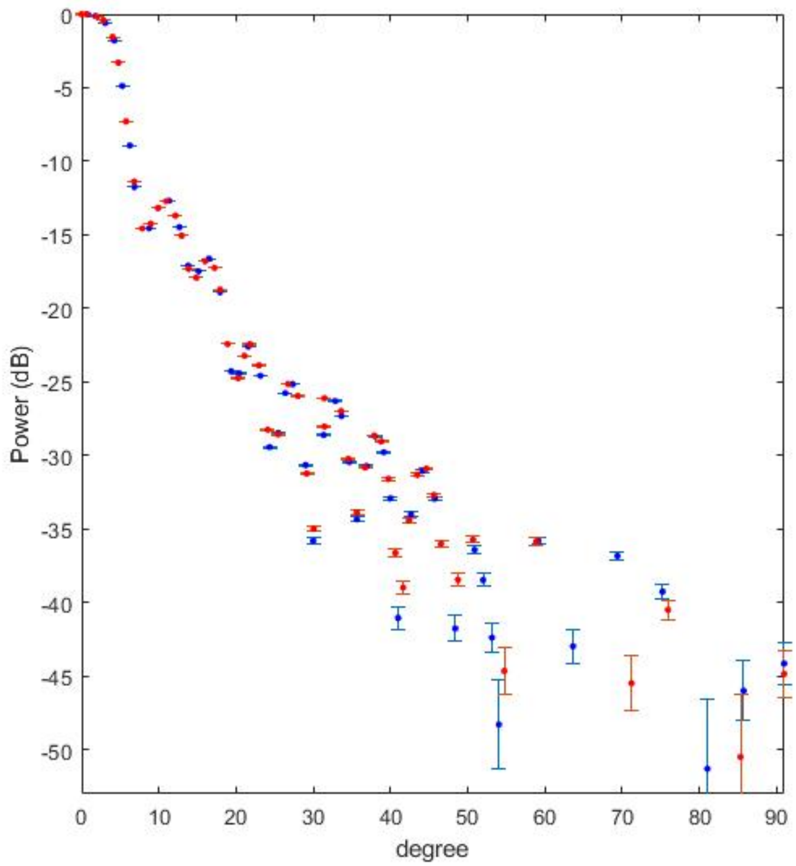


Figure 4: Beam pattern of the horn antenna**.** Radiation from the sky is received by a specially designed horn, which has a narrow beam so that you can selectively observe various sections of the sky. This enables distinguishing the CMB from the atmosphere and the surroundings. The horn achieves its narrow beam by exciting other modes in the throat section which cancel sensitivity at large off-axis angles (side lobes), creating a directional narrow beam. You will measure this beam pattern in your experiment.

A block diagram of the radiometer is shown in Figure 5. The total gain of the LNB is 50-60 dB[1]; the square-law detector plus LF amplifier plus integrator comprise the HP power sensor and power meter, with a gain of about 40 dB. However, the IF bandpass filter and mixer have some insertion loss. So the total gain is about 90 dB, a factor of a billion!

[1]The decibel or "dB" is commonly used to express signal gain on a log scale. If an amplifier has a gain of one "Bell" (as in Alexander Graham Bell) or 10 dB, its power gain is a factor of ten. Two Bells (20 dB) is a factor of 100 and so on. Since for a fixed resistance, power goes like the square of voltage, a 10 dB power gain represents a factor of square root of 10 voltage gain. To summarize the power gain of a system is $10^{\#dB/10}$ and the voltage gain is $10^{\#dB/20}$

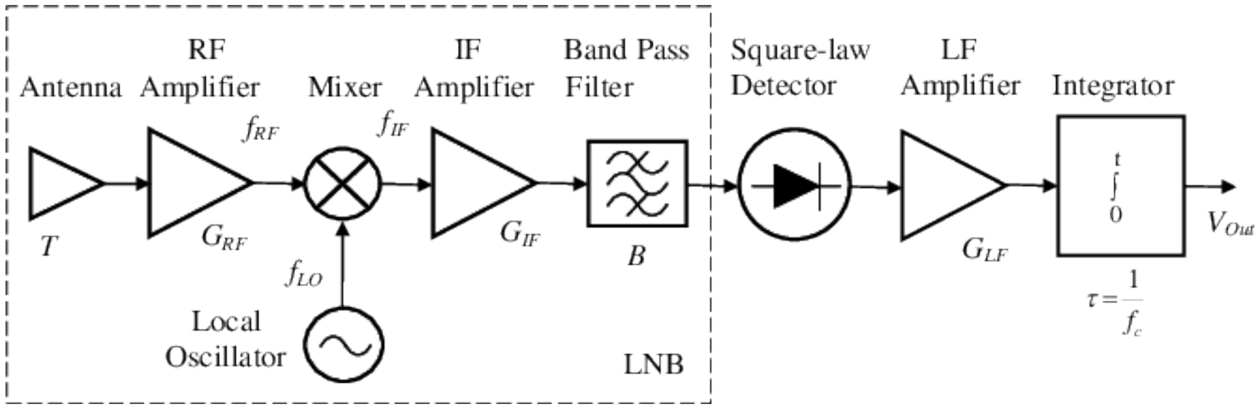


Figure 5: Block diagram of the microwave radiometer. Electromagnetic radiation is captured by the horn antenna, which feeds a low noise RF amplifier in the LNB. This 19 GHz signal is down-converted to a "IF" band 1000-1500 MHz and amplified. The bandpass filter allows only the 500 MHz wide band signal of interest to pass through. The IF signal feeds a detector diode, which converts it into a readable DC signal, before passing through a low-frequency amplifier and integrating voltmeter. This voltage is then displayed as an equivalent microwave power in watts after calibration.

The gain of the microwave receiver shown in Figure 5 can fall anywhere in the range 80-90 dB; it is temperature sensitive and changes with time. For example, tests have shown that the gain can change by 30% when going from room temperature (20 C°) to outside night temperatures. By comparison, 30% of the radiometer sky temperature is ~20K or 200 times the precision you may want to reach. It is thus important to allow the system to come into thermal equilibrium with its environment before making measurements, and to carefully monitor the LNB temperature (as well as frequent warm/cold load calibrations).

To deal with smaller changes in the gain during the ~15 minute sky dip runs, we make use of the cryo-cooled reference load. The goal is to cool the load to approximately the same temperature as the antenna temperature of the signal under measurement. After each sky dip run, we calibrate using the reference loads to see if the gain has changed. The validity of the data is dependent upon the knowledge that the gain is stable through a single short run of calibrated power measurements at various zenith angles. The stability of the temperature of the reference load is of clear importance. (See section 3.3.)

After the IF amplifier a 500 MHz part of the noise spectrum is defined by a band pass filter, and then the signal is fed to a "square-law" detector. There a radio-frequency detector diode converts the AC IF signal into a DC signal. This DC signal then can be read out on a voltmeter. The result is proportional to the square of the RF voltage and hence the power of the noise signal at 19 GHz integrated over the 500 MHz IF bandwidth. This detected noise power fluctuates naturally because it is a gaussian random noise. Thus we need to integrate for some time. But the integration time must be less than timescales of any systematics. One second integration is sufficient. Figures 6 and 7 show these components of the radiometer.

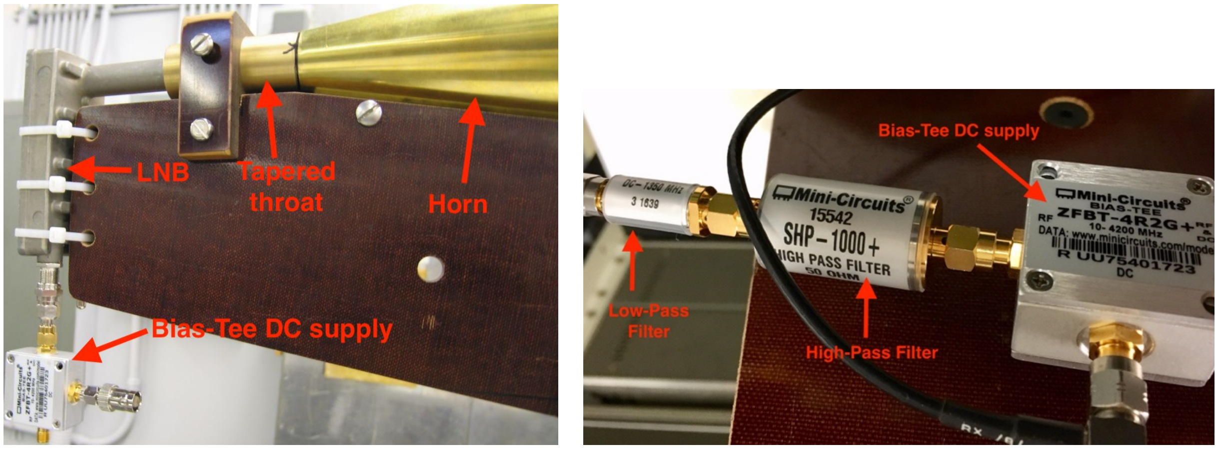


Figure 6: Radiometer electronics. On the *left* is shown the LNB mounted on the horn support. The Bias-Tee powers the LNB by routing a DC voltage through its output. Also shown is the special tapered throat and horn arrangement. On the *right* is shown the IF output of the LNB feeding (after the Bias-Tee) a 1000-1500 MHz band-pass filter composed of a 1000 MHz high-pass filter in series with a 1500 MHz low-pass filter.

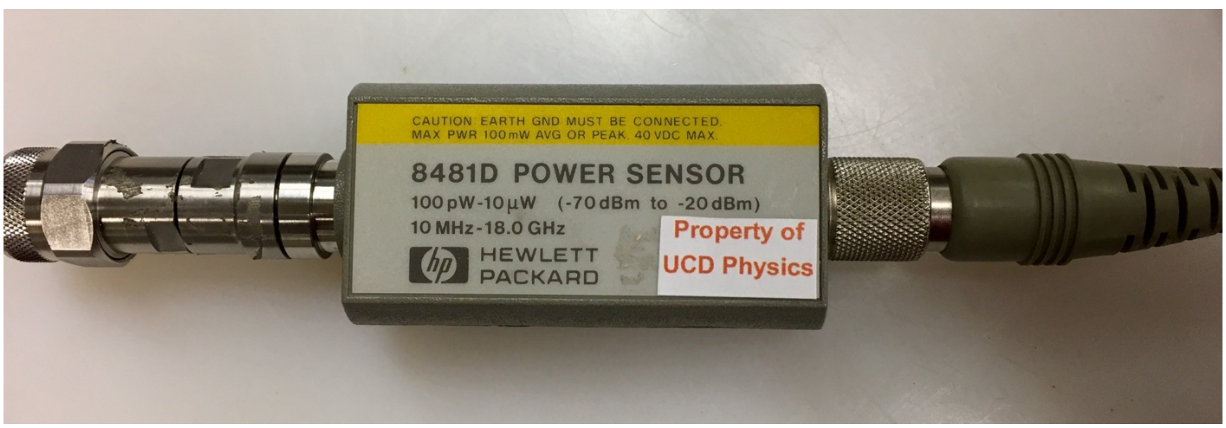


Figure 7: Square-law detector for CMB intensity measurements. This diode HP 8481D power sensor converts the 1000-1500 MHz IF AC noise spectrum into a positive definite signal whose output rms DC voltage level is amplified and displayed on a HP power meter. This sensor when used with an HP EPM power meter is quite sensitive (power gain ~ 50 dB) covering a power range of 100 picowatt to 10 microwatts. The HP 8481D measurement noise floor is about 45 picowatt per second integration, decreasing like sqrt integration time. For this radiometer used with the 19 GHz Potter horn, typical power readings are 450 nanowatts at zenith, 620 nanowatts for liquid nitrogen cold load, and 1.21 microwatts for room temperature warm load.

In order for the voltage readout to have meaning, the radiometer must be calibrated. The intensity of a blackbody signal at a given frequency will vary linearly with the temperature of the radiating body (as explained in section 2.3). By taking measurements of blackbody emitters at two different temperatures, a linear formula can be derived to calculate the temperature of any blackbody emitter from the radiometer output. Here, we use a blackbody held at ~77 K by slowly-boiling liquid nitrogen, and a blackbody at ambient temperature (about 280-290 K).

3.3 Reference Load

In this experiment we use two reference calibration loads, one at ambient temperature and the other at ~77 K. This enables frequent radiometer gain calibrations (see section 4.3). Figure 8 shows the horn pointed at the transparent Styrofoam box containing an Eccosorb microwave absorber panel immersed in liquid nitrogen. A room temperature Eccosorb panel is alternately placed in front of the horn. To avoid off-axis side lobes of the horn intercepting the hot roof and ground, you may wish to place an aluminum sheet under the box to reflect up to the cold sky.

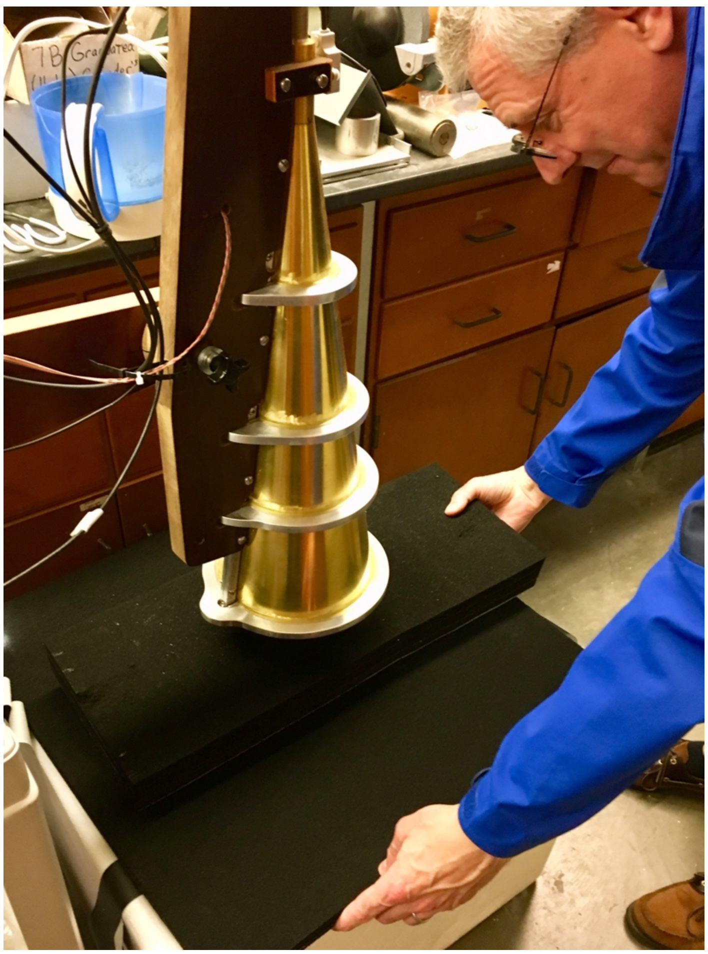


Figure 8: Cold and warm loads for calibration. The 19 GHz horn is shown pointing at the cold microwave absorber load immersed in liquid nitrogen inside the white styrofoam box, and the room temperature Eccosorb load is being placed in the beam. Calibrated diode thermal sensors in the edges of the loads report accurate load temperatures to the data acquisition system and are displayed on the Lakeshore meter.

4 Experimental Procedure

Measurements are best taken from the roof of the Physics Department, since this provides a clear view of the northern sky and helps to minimize noise from the ground and nearby structures. You will have to wait for clear weather for CMB data acquisition. Low humidity helps minimize the atmosphere thermal noise.

As in the PreLab, you will measure the horn beam pattern – this may be done in any weather, except rain. You can actually do this AFTER you make CMB measurements if you need to take advantage of clear weather early in the quarter.

4.1 Horn antenna pattern measurements

To reliably measure the radiometer horn beam pattern, you will need a distant intense point source of RF in your radiometer's 19 GHz passband. We can provide you with an identical horn connected to a 19 GHz transmitter on a cart. This may be positioned on the balcony outside Roessler lab and pointed up towards your radiometer on the physics roof. Here are the steps you can take to measure your horn beam pattern:

1. Switch radiometer power sensor to the less sensitive HP 8481A (range to 100 milliwatts). Make sure you *calibrate and zero* it (read "Power meter" under Useful Links).

2. Power up the 19 GHz oscillator transmitter down on the Roessler balcony, and verify that its output power is 10 mW or less.

3. Precisely point the transmitter horn up at the receiver horn on top of the physics roof. Remember, the beam is quite narrow.

4. With the receiving radiometer on a 100 mW scale (low sensitivity, high power) at the *edge* of the physics roof, carefully rotate the cart and dip the horn down so that it points directly at the transmitter. Position the radiometer as close to the south wall as possible, with the cart touching the wall. Vary the transmitter pointing to maximize received power.

5. Adjust radiometer horn pointing for maximum signal on the power meter. This may take some patience. Lock the cart wheels. Then repeat this maximizing routine.

6. You can now take received power readings at a number of horn angles from 0 relative to the transmitter to 90 degrees relative to the transmitter by tilting the radiometer horn up at various angles. Take enough data so you can make a plot like Figure 4.

4.2 CMB Measurements

The entire radiometer can be moved onto the physics department roof. *BE PREPARED TO TAKE ADVANTAGE OF CLEAR WEATHER – EVEN ON NON-CLASS DAYS.*

Deploy the CMB experiment cart from the penthouse out onto the physics dept. roof near the north edge. Run power cable from just outside the penthouse doors. Turn on power supplies and the HP microwave power meter. Make sure you *calibrate and zero it* (read "Power meter" under Useful Links). Point horn vertically, measure sky, and then place the warm ambient temperature Eccosorb load over the horn. Verify that you see the expected change in microwave power. Transfer liquid nitrogen into the white freezer chest until it covers the blue Eccosorb by at least 1 inch. Immediately place the white cover on the chest so that only nitrogen vapor is inside (not water fog!).

Check system stability by placing the ambient temperature Eccosorb over the horn and monitoring microwave power level, load temperature, and LNB temperature. You may need to correct your data for gain changes due to the temperature sensitivity of the LNB gain. In fact, you can *measure the change in gain of the LNB as it is warming up by pointing the horn at the warm load and recording power and warm load temperature*. Then be sure that the cold load temperature has stabilized and the amplifier chain has been running long enough to arrive at a stable gain (a few hours or more with power on).

4.3 Calibration and Temperature Conversion

Calibrate the radiometer before each round of sky dip measurements by taking readings from a cold blackbody (submerged in liquid nitrogen) and a blackbody at ambient air temperature. A material called Eccosorb is used as the blackbody emitter. From Eq. 3 and two measurements of radiometer output with the horn pointing at two blackbody loads of different known temperatures, one can deduce a relationship between the measured temperature, the system gain, and the reading of the power meter in some convenient unit such as microwatts *P*obs (see Figure 9 below).

$$P_{obs} \sim kT\nu^2/c^2 \tag{4}$$

$$P_{obs} = GT_{meas} \tag{5}$$

where *G* represents the overall gain of the system in the chosen units of power. Using the cold and warm load measurements, the value of *G* can be deduced. We can describe noise power in units of brightness temperature. Since the noise power per unit bandwidth generated by a resistor of temperature T is $P_\nu = kT$ in the low-frequency limit, we can define the *noise temperature* of any noise-like source in terms of its power per unit bandwidth. In general, the brightness temperature of radiation depends on the wavelength. However, for black bodies the brightness temperature is independent of wavelength. In fact, the brightness temperature of the radiation coming from a black body is just the physical temperature of the that source.

However the LNB is not noise free (that would violate the 2nd law of thermodynamics). The receiver has some noise which results in additional extra noise power Prec measured on the radiometer output. Referred to the receiver input, this receiver noise is equivalent to some noise temperature Trec. So that

$$P_{\text{obs}} = GT_{\text{obs}} + P_{\text{rec}} = G(T_{\text{obs}} + T_{\text{rec}}) \tag{6}$$

Then by pointing the horn at a ~77K blackbody (cold load) with measured power Pcold, and then placing the warm blackbody load (warm load) in front of the horn with measured power Pwarm, and knowing the two cold and warm load temperatures, we have two equations in two unknowns (G and Trec) and can solve for them. Armed with G and the receiver noise temperature Trec, we can observe the "antenna temperature" Tobs of anything the horn is pointing at by measuring the corresponding power meter output Pobs:

$$T_{\text{obs}} = \frac{P_{\text{obs}}}{G} - T_{\text{rec}} \tag{7}$$

You should estimate the noise temperature of your microwave receiver. With temperature sensor measurements Tc = cold load, Tw = warm load, derive the relation

$$T_{\text{rec}} = \frac{T_{\text{w}}P_{\text{c}} - T_{\text{c}}P_{\text{w}}}{P_{\text{w}} - P_{\text{c}}} \tag{8}$$

and show that your Trec agrees with the LNB noise specifications [you must convert from the quoted noise figure to effective noise temperature using the plot "LNB noise" and the noise figure specification in the file "19 GHz Receiver LNB"].

You might wonder about radiation incident on the Eccosorb being reflected. The "egg carton" shape of the blue Eccosorb forces the incoming radiation to reflect multiple times, damping the incident signal until it is negligible. Hence the Eccosorb absorbs incoming radiation and only emits its own thermal radiation.

Figure 9: Agilent E4418B EPM power meter and HP 8481D power sensor, displaying RF power from the LNB receiver in microwatts. Be sure to set it up with 4 significant figures and Watts displayed. For this measurement the horn was pointed at a 300K blackbody load. Your data consists of these power readings. Write them, all relevant temperatures, and the horn pointing relative to zenith in your lab book for each pointing of the horn. As a backup record of your observations, the power meter also outputs a continuous digital RF power record to a file on the lap top, along with the horn angle, and temperature probes, as described below. The sensitive HP 8481D power sensor has been moved up to the output of the LNB, removing cable loss. Before taking measurements, make sure you *calibrate and zero the power meter* (read "Power meter" under Useful Links).

4.4 Atmospheric Noise

Finally, one must remove atmospheric noise from the data. Because the height of the atmosphere is relatively small compared to the radius of the earth, the atmosphere can be treated as a flat layer, as shown in Fig. 10.

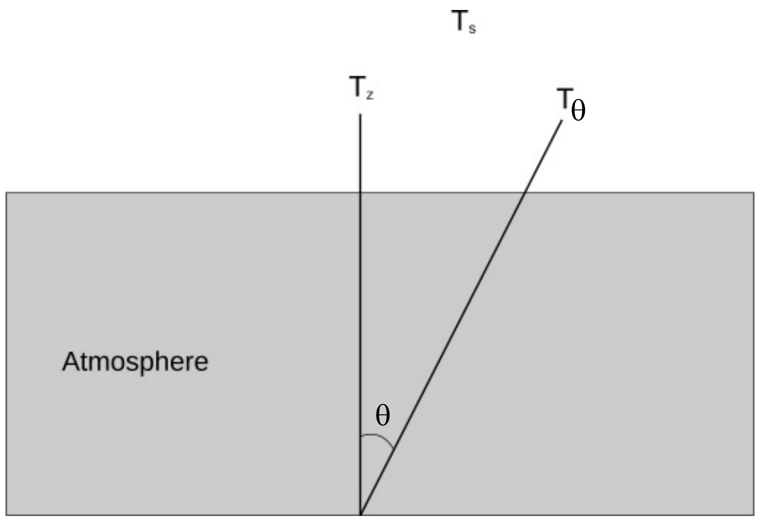


Figure 10: Calculating atmospheric noise. The intensity measured at an angle θ(T_θ) will be higher than the intensity measured at the zenith (T_z) due to more atmospheric emission microwave noise. Assuming the magnitude of atmospheric noise is a direct function of distance the signal travels through the atmosphere, we can calculate it using a measurement at the zenith and one at an arbitrary angle θ to find the sky temperature T_S.

Consider two paths through the atmosphere, one at the zenith ($\theta = 0$) and one at an angle θ. Without atmospheric noise, both would be measuring a sky signal temperature of T_s. Let T_A denote atmospheric noise contribution to the zenith measurement; assuming a linear noise-to-distance relation, the atmospheric noise for a beam at angle θ is then just $T_A \sec\theta$. The two measured intensities T_z and T_θ can be expressed as sky temperature plus atmospheric noise:

$$T_z = T_s + T_A \quad \text{and} \quad T_\theta = T_s + T_A \sec\theta \qquad (9)$$

which we can plot and fit a linear model to, as described below.

In the pre-lab you calculated the power in watts delivered by the LNB originating from the horn and the CMB backbody [Figure 2], as if you were in space. Of course, as discussed above we are at the bottom of Earth's atmosphere. So it is worthwhile to make a plot of the total spectrum including all foregrounds including the atmosphere and diffuse microwave radiation from our Galaxy. Since we are ultimately interested in measuring temperature rather than watts, we plot these various contributions to the antenna temperature in Figure 11. The CMB spectrum has a different shape than in the intensity plot in Figure 2 because temperature is proportional to intensity divided by the square of the frequency (equation 3).

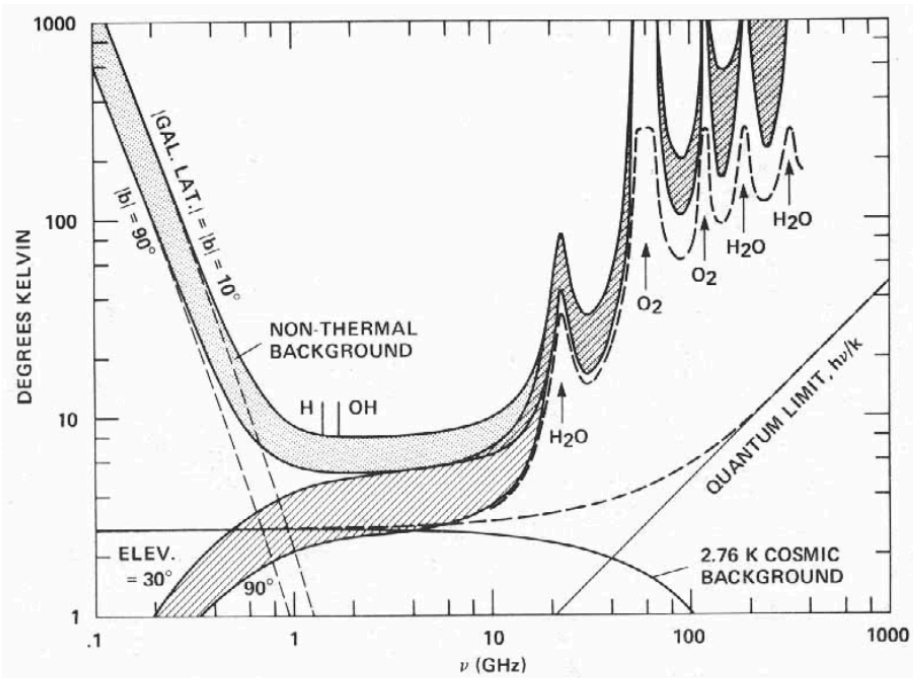


Figure 11: The total antenna temperature vs frequency arising from various sources.

At low frequencies the synchrotron radiation from electrons spiraling in the magnetic field of our Galaxy dominates (non-thermal background). In the 1-20 GHz region the atmosphere dominates over the CMB, but only by a factor of 3 or so. At higher frequencies we encounter atmospheric emission lines from water and oxygen. Of course this neglects the noise temperature of our radiometer itself, which is dominated by the first amplifier at 19 GHz. So this system noise temperature should be added (eqn 6). *In your report, you should estimate this system noise temperature.*

You might ask “why operate at 19 GHz when the atmosphere background temperature at 2-10 GHz is a factor of 2-3 lower?” There are several reasons. First, we want to avoid the size and expense of the 2 GHz horn shown in Figure 1 (size is proportional to wavelength). Second, it is much easier to build a low sidelobe horn at 19 GHz than at 10 GHz. Third, there is a low noise LNB built for Irish satellite TV reception that is available at reasonable cost. And fourth, we need to avoid RF interference. In the US there is no interference in that 19 GHz band from geo-synchronous satellites – especially in the northern sky.

Due to uncontrolled radiometer gain variations, in practice it is better to make multiple sky dip runs; repeated series of measurements at multiple zenith angles 0-70 degrees or so, each with its own cold/warm load calibrations. Then plot each calibrated run separately as T_θ vs $\sec\theta$. The best fit Y intercept is then your estimate for $T_S = T_{CMB}$. The variance between your runs enables an estimate of your statistical plus systematic error. This way it is possible to catch an erroneous run. An example of this kind of plot is shown in Figure 12. The atmosphere effective temperature is less than its physical temperature at altitude because the atmosphere is mostly transparent at 19 GHz.

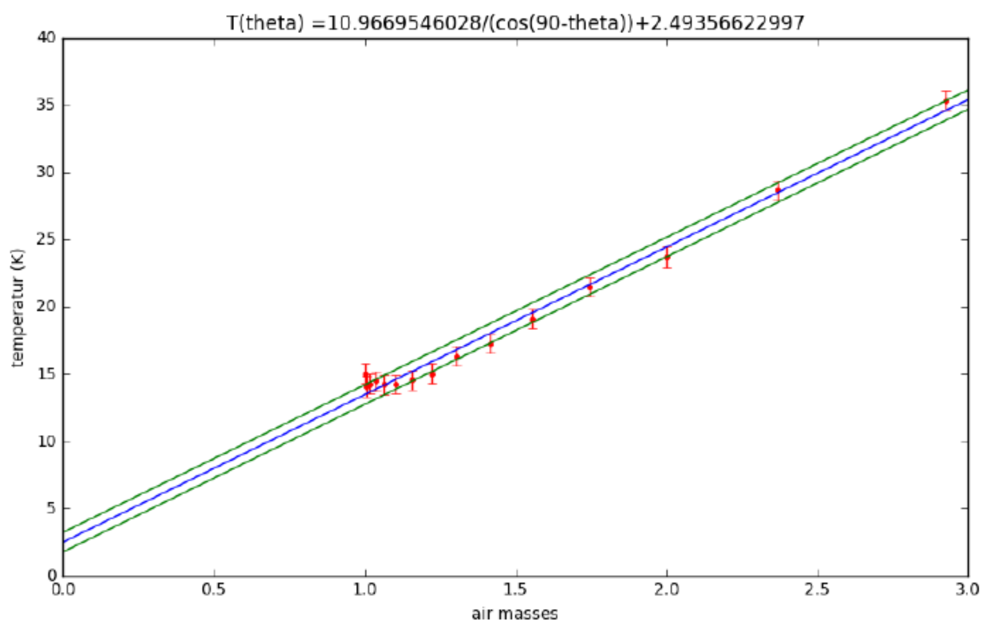


Figure 12: Estimating CMB noise temperature. This is an example of a student’s plot of data (eqn 7) obtained for a single run of measurements of temperature vs airmass. You may wish to choose a different zenith angle sampling scheme. Chi-sq fit extrapolated to zero airmass gives the estimated CMB temperature & error.

4.5 Data acquisition

It is necessary to acquire simultaneous data on radiometer measured power, temperature of critical components affecting gain, antenna tilt angle, and time. YOUR LAB BOOK IS THE PRIMARY DATA RECORD. Make 7 columns: time, horn angle relative to zenith, temperatures of the LNB and blackbody loads, microwave power, and its estimated random error (fluctuations during the ~20 sec spent at each angle. The automated data acquisition system is for BACKUP only. The analog to digital system is comprised of two separate systems and a central computer to collect the data. Temperature data are collected using the Lakeshore Cryotronics Model 218 temperature monitor. All other analog data including microwave power and angle are digitized using a *LabJack* U3-HV board (red case).

The Lakeshore thermometer system communicates using the RS-232 serial bus, which we read using USB via a serial-to-USB converter. The *LabJack* communicates directly via a second USB connection. Because they are different systems, each sensor is read sequentially and there is a small time delay between each sensor sample. This delay can be as long as 100ms. Fortunately, the temperature value time constants are more than an order of magnitude larger, so we do not expect that this will affect the accuracy of the measurements. However, you should not attempt to read out faster than one measurement each 5 seconds or the data will not be correctly aligned.

The horn tilt angle, the radiometer power meter output, and temperatures of the LNB and horn are acquired by pressing a key on the sampling computer after starting the program as described below. For data acquisition we will use the *LabJack* U3-HV. This USB connected data acquisition (DAQ) device has 16 flexible input/output channels that can be configured as either digital or analog, along with two 10-bit analog outputs, up to two counters, and up to two timers.

You will begin by starting the data collection program on the provided computer. The program is written in Python, so you will execute the command:

```
python /usr/local/share/cmb/begin_data.py /home/student/path_to_output_data.txt
```

This will start the data collection program. If everything is correctly attached, the program will say the following:

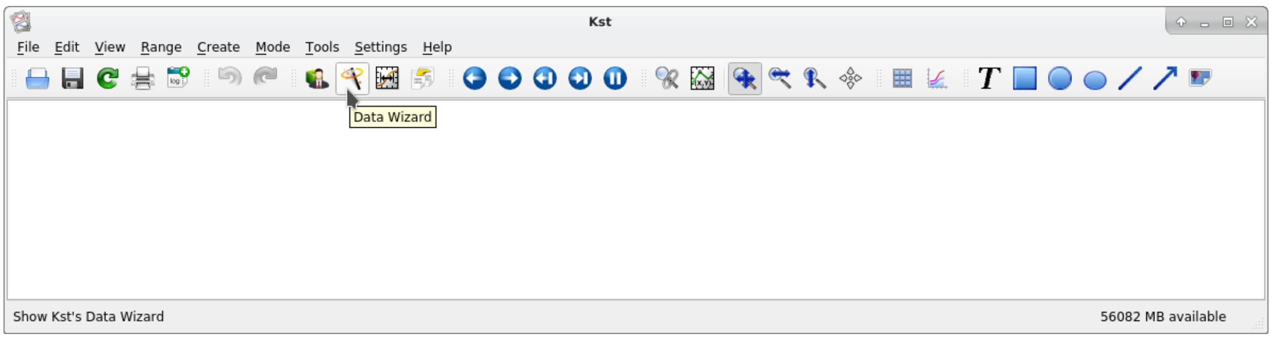
> Connecting to *LabJack* system…
> Success.
> Connecting to *Lakeshore* system…
> Success.
> Press any key to begin logging data…

If you see a failure message at either step of connecting to the system, disconnect the cables, power cycle the Lakeshore or *LabJack* and try again.

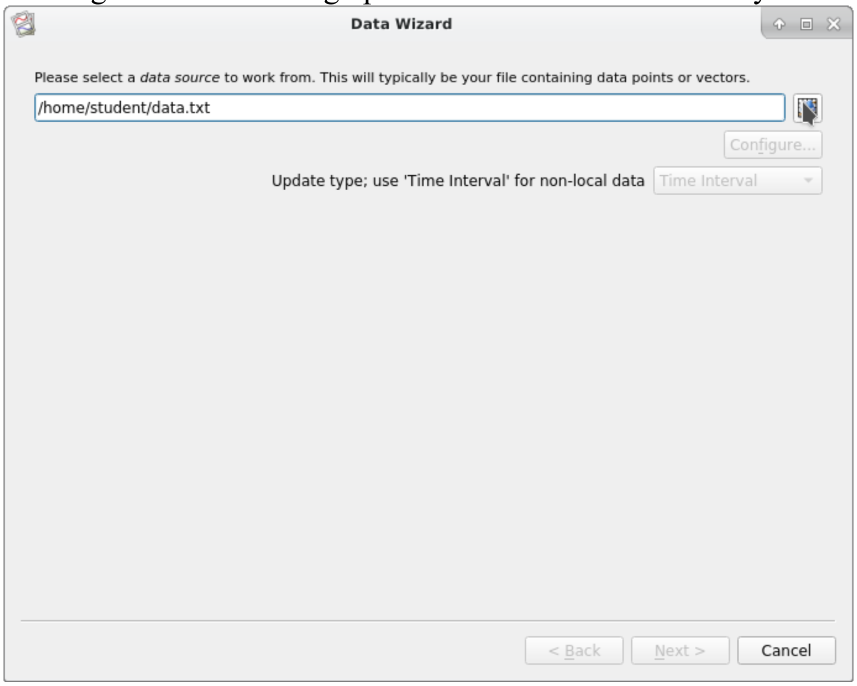
When you are finished collecting data, you can press "Ctrl-C" to stop the data collection program.

The data will then be available in a comma-separated file with a single header row at the top to denote which column corresponds to which data source. The typical columns will be "Time", "Angle", "Power", "Temp1", "Temp2", etc…

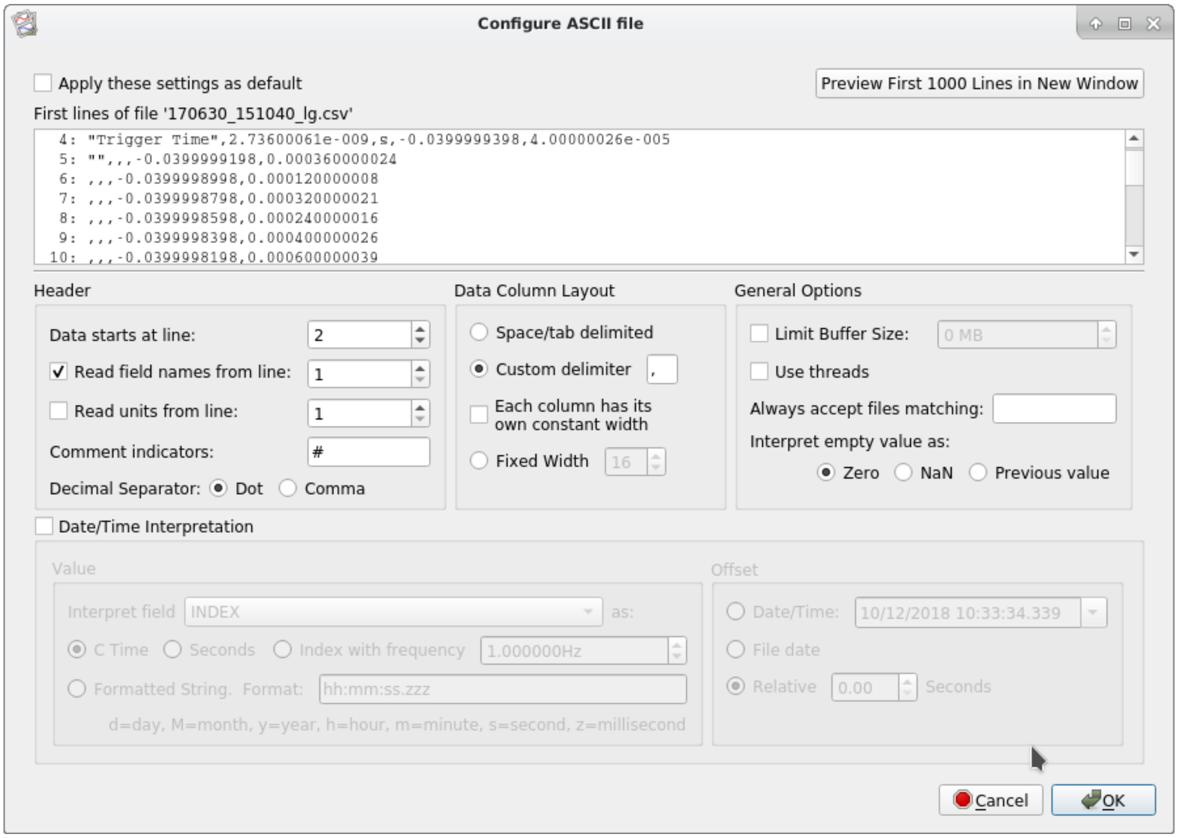
To observe the data in real time, we will utilize the open source *KST2* program. You can start this program from the application menu. Once you have it started, you can select the data file by going to the "Data Wizard" icon on the menu bar as shown below



Clicking here should bring up the selection window where you can choose your data file



After inputting the correct file name, you should click on the “Configure” button to setup the file configuration



The important elements to select here are that the

“Data starts at line: 2”

“Read field names from line: 1”

and, in the Data Column Layout, choose a “Custom delimiter” and set it to a comma.

After you have configured this setup, you can click OK and “Next” in the wizard window to choose your input data for plotting. These data are made available as a file on the attached computer.

<u>Read the guide “*Taking Data*.”</u>

5 Sources of Error

Statistical (random noise) errors and systematic errors propagate differently and the process of investigating them differs. Consider the following sources of error in determining your overall statistical and systematic uncertainty:

1. The variance in *repeated* measurements, both of the sky and the calibration blackbodies.

2. Radiation from the ground. At dip angles larger than 70 deg from the zenith the horn antenna side lobe begins to "see" the relatively hot ground and surrounding buildings. You can perform experiments to measure this and then correct for it.

3. Other radio sources in the sky (avoid satellites). Radiation from equipment (feed horn, waveguides, etc.) contributing to the antenna temperature.

4. Uncalibrated or undetected gain variations in any component of the radiometer. Measure anything that might drift with time (LNB temp is one of several). Using Eqn 7 derive a relation for the gain G as function of observed powers and cold & warm load temperatures.

5. Additional sources of systematic error you discover by doing experiments on your experiment.

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