Observation of the Cosmic Microwave Background Radiation at 10 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 theory 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 a founding pillar of modern physics.

The experiment consists of a temperature measurement of the CMB, which is “light” left over from the Big Bang. A radiometer is used to measure the intensity of the sky signal at 10 GHz from the roof of Jadwin Hall. The radiometer is calibrated to reduce systematic effects, and the signal from a cryogenically cooled reference load is periodically measured to catch changes in the gain of the amplifier circuit over time.

2 Background

2.1 History

The first observation of the CMB occurred at the Crawford Hill location of Bell Labs in 1965. Arno Penzias and Robert Wilson, intending to do research in radio astronomy and satellite communications, noticed a background signal in all of their radiometric measurements. After searching for radiation leakage and loss in joints and the antenna horn, accounting for backlobe response from the ground, factoring out atmospheric noise, and calculating temperature contributions from ohmic losses, the pair concluded that the 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 this mysterious signal was baffling the pair at Bell Labs, 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 side by side in The Astrophysical Journal – one by Penzias and Wilson explaining their cosmic noise (see [1]), and one by Dicke et al. offering a cosmological interpretation (see [2]): this is the 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 [4]. These measurements together began to experimentally show the blackbody nature of the spectrum. General acceptance soon followed of its interpretation in inflationary 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 theory of the Big Bang could not be fully cemented until the discovery of the CMB. 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. As measurements of the CMB grow more numerous and our understanding of it increases, cosmological theory can be fine-tuned to account for the data observed in present day.

2.2 Physics

2.2.1 The Oldest Light in the Universe

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, the decoupling of matter and radiation took place. At that point, 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 in present day (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 [5]. 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 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 have been propagating ever since. Their wavelengths have grown as a result of the expansion of space, meaning that their energies have decreased. The current-day distribution of 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,

\[ I_{\nu}(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1}, \]

(1)
where $h$ is Planck’s constant, $c$ is the speed of light, and $k$ is Boltzmann’s constant. The spectrum of a blackbody emitter (intensity $I$ as a function of frequency $\nu$, as shown in Fig. 1) 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 to measure the intensity at 10 GHz. At lower frequencies, interference from galactic emission becomes more appreciable, while at higher frequencies atmospheric absorption grows.

![Spectrum of a 2.725 K Blackbody Emitter](image)

**Figure 1:** Spectrum of a 2.725 K blackbody emitter. The observation of this experiment is made at 10 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,

$$e^{\frac{h\nu}{kT}} \approx 1 + \frac{h\nu}{kT}. \quad (2)$$

This reduces Planck’s Law to the linear relation

$$I_\nu(T) = \frac{2kT\nu^2}{c^2}. \quad (3)$$
The Rayleigh-Jeans limit begins to break down when the frequency (in GHz) approaches 20 times the temperature (in Kelvin) [6]. This experiment, in which a 2.725K blackbody signal is measured at 10 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 Eq. 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. The method holds as long as all measurements used are subject to the same amplification (a concern addressed through the use of our reference load). Sections 3 and 4.3 explain the process in detail.

3 Experimental Setup

3.1 Overall Setup

You will measure the intensity of incident radiation using a chain of amplifiers (Sec. 3.2) followed by a square-law detector and a voltmeter. A mechanical waveguide switch directs either the radiation from a feed horn or from a temperature-regulated, cryogenically cooled reference load (Sec. 3.3) to an antenna leading into the amplifier circuit.

The section of sky measured is controlled via a metal reflecting screen. You should take measurements at the zenith and at arbitrary angles in order to factor out atmospheric noise (see Sec. 4.4). The corrugated-metal feed horn has a very narrow beam path, meaning that sidelobe interference is minimized. 10 GHz waveguides are used to channel the electromagnetic radiation from the feed horn and reference load to the waveguide switch, and from the waveguide switch to the antenna at the head of the amplifier circuit.

3.2 Amplifier Circuit

The waveguides terminate in a simple receiver antenna, where the electromagnetic waves generate an oscillating potential in the antenna, giving rise to a weak AC signal. The intensity of the incident waves determines the voltage across the antenna, and thus the
Figure 2: **Major components.** Radiation from the sky is reflected into a corrugated feed horn; the reflecting screen controls what section of sky is viewed. Radiation is channeled using X-band waveguides. A mechanical waveguide switch sends either the incident sky signal or the signal from a cryogenically cooled reference load (Fig. 4) through to a readout chain of radio-frequency amplifiers (Fig. 3).

amplitude of the AC signal. The intensity of the radiation is what you will measure.

The signal first passes through an isolator, a device which only allows the signal to pass from the input terminal to the output. Signals at the input terminal are carried to the output terminal; signals at the output terminal are carried to the load terminal, where they are dissipated as heat in a dummy load. The isolators are used in the circuit to prevent reflected electronic noise from bouncing back and contaminating the signal. A bandpass filter is used to ensure that electronic noise at other frequencies is filtered out.

The first amplifier is an Miteq AMF-4F-08001200-09-10P, with a gain of 33 dB\(^1\); the second amplifier is an Avantek AMT-12432, with gain 17–21 dB; and the third amplifier is

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\(^1\)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 \(\sqrt{10}\) voltage gain. To summarize the power gain of a system is \(10^{\#\text{dB}/10}\) and the voltage gain is \(10^{\#\text{dB}/20}\).
Figure 3: **Amplifier circuit, of gain 77–91 dB.** Electromagnetic radiation from the waveguide switch (see Fig. 2) is carried to the antenna, where the oscillating potential creates an AC signal. The signal is carried through three amplifiers, coupled with two isolators to prevent back noise from reaching the previous component. The bandpass filter allows only the signal of interest, at 10 GHz, to pass through. The AC signal passes through a radio-frequency detector diode, which converts it into a readable DC signal, before passing through a resistor. The combined gain of the circuit is 77–91 dB. The output of the circuit was further amplified using a preamplifier before being read out.

an Avantek AMT-12713, with gain 30–35 dB. The total gain of the circuit is thus 77–91 dB (a total power gain of $5 \times 10^7$ to $1.3 \times 10^9$). The gain of the amplifier circuit can fall anywhere in that range; it is highly temperature sensitive and changes with time. For example, tests have shown that the gain can change by an order of magnitude when going from room temperature (20°C) to outside winter temperatures. It is thus important to allow the system to come into thermal equilibrium with its environment before making measurements.

To deal with smaller changes in the gain, 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. As data is read, we switch regularly between the sky signal and the reference load 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 round of calibrated measurements. The stability of the temperature of the reference load is of clear importance. (The treatment of the reference load is explained in section 3.3.)

After amplification, the signal is fed to a “square-law” detector. There a radio-frequency detector diode converts the AC signal into a DC signal. This DC signal passes through a
resistor, and 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 signal. In conducting the experiment, a preamplifier was also used after the amplification circuit to provide an addition $10 \times$ gain. The preamplifier was configured to act as a low-pass filter with a 1 Hz cutoff; this stabilized small, quick oscillations in the voltage measurement caused by small variations in the amplifier circuit.

In order for the voltage read out 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 voltage. Here, we use a blackbody held at 77 K by slowly-boiling liquid nitrogen, and a blackbody at ambient temperature (278 K at the time of the experiment). When the signal off of the reference load is observed to change, the radiometer must be re-calibrated.

### 3.3 Reference Load

The ideal reference load would have a blackbody emitter whose temperature is: i) close to the temperature of the blackbody being measured (the CMB); and ii) stable over time. Minimizing the difference between the reference load temperature and the CMB ensures that the gain in that region of the intensity spectrum is stable; consistent temperature of the reference load ensures that a round of measurements can be taken without the need to recalibrated the radiometer. We achieve both goals by cryogenically cooling the load.

The cryorefrigerator used is a Gifford-McMahon refrigerator recycled from the Millimeter INTerferometer project (MINT), (see [7]). Its design features the addition of a third cooling stage to a standard two-stage CTI 1020 CP cold head. The coldhead compressor is driven by a 3-phase, air-cooled CTI 8200 helium compressor, operating at 208 V and 60 Hz. The third stage is capable of reaching approximately 4.1 K ([7]).

The reference load consists of an iron-loaded epoxy absorber thermally sunk inside of a 2.8 kg copper waveguide block. The load is suspended from the cold head of the cryorefrigerator using custom machined copper parts, using highly conductive oxygen-free copper to allow for maximum thermal conductance and cooling of the cold load. Copper ropes are used in the connection to allow for flexibility and contraction as the cryostat undergoes cooling.

The signal from the cold load is channeled using thin-walled stainless steel X-band waveguides out of the body of the cryostat. The radiation shields for the first and second stages
Figure 4: **Cryogenic components.** The compressor cools the first and second stage plates, and the cold head. A vacuum is maintained inside the dewar to prevent conductance and convection between stages. Mounted on the cold plates are two aluminum radiation shields to prevent radiation from warmer outer stages from causing excess load on inner stages. The reference load (a blackbody emitter) is suspended with copper from the cold head. The radiation emitted from the reference load is carried through thin-walled stainless steel waveguides out of the cryostat to the waveguide switch (see figure 2). To help mitigate warming of the reference load caused by thermal conduction down the waveguides from the outside of the dewar, copper thermal connections to the cold plates are used as heat sinks for two of the waveguide joints. The first stage radiation shield is made of thicker aluminum (providing better thermal conductivity) in order to function as part of the thermal connection from waveguide to plate. The waveguides are hard-soldered to a brass fitting that holds the vacuum seal against the lid; a clear kevlar window holds the vacuum seal within the waveguides. A large, air-cooled driving compressor powers the cryogenic compressor using high-purity helium.
have been machined to allow the waveguide to pass through. The waveguide is attached to
the vacuum lid of the dewar by a custom-built flexible brass vacuum fitting hard-soldered
onto the waveguide. This allows for the passage of the waveguide out of the dewar without
breaking the vacuum seal.

Thin-walled stainless steel waveguides were chosen to minimize thermal conductance from
the environment into the cold load. Stainless steel features a lower thermal conductivity than
alternative waveguide materials, and the thinness of the walls contributes to the thermal
resistance. To mitigate heat flowing in, copper heat sinks were attached to the waveguide,
connecting two of its joints to the first and second stages of the cryorefrigerator. This allowed
for heat to be piped off to the higher temperature cooling stages where the cooling power of
the cryorefrigerator is much higher.

Even with the thermal connections to the waveguide, the efficiency of the inner cooling
stage was severely hampered by the influx of heat; cooling power for the 3rd stage is ap-
proximately 50 mW at its coldest. Heat conducted down the waveguide, as well as radiation
carried through the body of the waveguide, makes it difficult to get the cold load much below
20 K.

The internal temperatures of the dewar are read out using calibrated Lakeshore silicon
diodes (accurate to ± 0.2 K). There are three functioning diodes used in the radiometer:
one on the cold load itself, for reference as measurements are taken, and one on each of the
waveguide heat sink connections, to monitor cooling and heat flow within the waveguides.

An alternative to using the Gifford-McMahon cryostat (or other methods of cryocooling)
would be the simpler method of submerging the cold load in liquid helium, requiring a less
complicated setup. However, the use of a temperature-regulated cryocooler provides for a
robust and reliable experiment. The compressor is powerful and consistent, and can run for
extended periods of time with no operator intervention. The refrigerator used is consistent
down to a few milliKelvin on the timescale of several minutes. Moreover, the cost of liquid
helium would become substantial for extended data-taking periods.

4 Experimental Procedure

Measurements are best taken from the roof of Jadwin\textsuperscript{2}, since this provides a clear view of
the sky and helps to minimize noise from the ground and nearby structures. If weather

\textsuperscript{2}Access to the roof requires a key that you can obtain only after submitting a signed statement that you
understand and agree to comply with the rules associated with the roof ares.
conditions are particularly unpleasant, you may prefer to perform some of the initial steps with the radiometer inside.

4.1 Cool Down

If the apparatus has not be used for some time and the compressor has been switched off, you will need to spend a day or so cooling it down. The steps below should be followed. Depending on the state of the system, some may be skipped (or at least may go very quickly). If you are unsure of any of the steps, contact an instructor, since doing things incorrectly could damage the apparatus. If you are starting with a warm system, make sure that you will be able to attend to the apparatus three hours after you begin the steps below (you don’t need to be there the whole time, but you shouldn’t start the process and leave for the day with the vacuum valve open).

1. Verify that the vacuum pump is connected to the vacuum port on the cold load chamber. The valve at the vacuum port of the chamber should initially be closed.

2. Switch the pump on and wait a short while until the line between the radiometer and the pump is evacuated.

3. Open the valve between the apparatus and the pump to begin pumping down the cold-load’s chamber. The reading on the vacuum gauge should drop steadily until the apparatus reaches 10 mTorr or so. If the chamber has been allowed to come up to atmospheric pressure, this could take several hours.

4. Once the vacuum has stabilized at a low value (< 10 mTorr), verify that the lines from the compressor are connected to the chamber (if they aren’t properly connected, or if you aren’t sure, contact an instructor) switch on the compressor.

5. Read and record the voltages on three temperature sensors once every several minutes. Use the chart that has been provided to convert the voltage readings to temperatures. Initially you should see the first stage temperature drop the fastest. After some time, the rate of temperature decrease on the first stage will slow and the second and third stages will catch up and go to even colder temperatures.

6. Once the innards of the radiometer get cold enough, they will begin to trap residual gas molecules and the vacuum will drop to a lower value. **When this happens, be sure to close the vacuum valve. If it’s left open, you will start to cryo-pump oil from the mechanical vacuum pump. This is not a good idea!** Make sure
that the value is closed before you leave for the day. The cool down will most likely take over night.

7. Switch on the amplifier chain during the overnight cool-down period, so that the gain has a chance to come stabilize.

8. When you return the next day, take some additional temperature readings separated by half an hour or so. The temperature of the third stage should have stabilized around 20K.

4.2 Measurements

Be sure that the temperature in the cold load 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 measurements by taking readings from a 77 K blackbody (submerged in liquid nitrogen) and a blackbody at ambient air temperature. A material called Ecosorb is used as the blackbody emitter. From Eq. 3 one can deduce a relationship between the temperature and the voltage reading coming from the amplifier/detector chain—i.e.,

\[ V_{\text{out}} = GI_\nu(T) = G\frac{2kT\nu^2}{c^2} \equiv \alpha T \]  

where \( G \) represents the overall electronic gain of the system. Using the measurements at \( T = 77 \text{K} \) and ambient temperature, the value of \( \alpha \) can be deduced.

A third (and most important) calibration point is obtained from the cold load. Determination of the sky temperature is done by comparing the reading from the cold load to the reading of the sky and using the value of \( \alpha \) determined above to infer the sky temperature—i.e.,

\[ T_{\text{sky}} = T_{\text{load}} - \frac{(V_{\text{load}} - V_{\text{sky}})}{\alpha} \]
4.4 Atmospheric Noise

Finally, one must remove atmospheric noise from the data. Because the width of the atmosphere is relatively small compared to the radius of the earth, the atmospheric can be treated as a flat layer, as shown in Fig. 5.

Figure 5: Calculating atmospheric noise. The intensity measured at an angle $\theta$ ($T_\theta$) will be higher than the intensity measured at the zenith ($T_z$) because it experiences more atmospheric 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 $\theta$ to find the sky temperature $T_s$.

Consider two paths through the atmosphere, one at the zenith ($\theta = 0$) and one at an angle $\theta$. 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 noises-to-distance relation, the atmospheric noise for a beam at angle $\theta$ is then just $T_A \sec \theta$. The two measured intensities $T_z$ and $T_\theta$ can be expressed as sky temperature plus atmospheric noise:

$$T_z = T_s + T_A \quad \text{and} \quad T_\theta = T_s + T_A \sec \theta,$$

which we can solve for the true sky temperature

$$T_s = \frac{T_\theta - T_z \sec \theta}{1 - \sec \theta}.$$
5 Sources of Error

Consider the following sources of error in determining your overall systematic uncertainty.

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

2. Radiation from the ground can be mitigated by using a ground screen behind the radiometer reflecting screen. Any radiation diffracting across the edge of the reflecting screen into the feed horn is sourced from the sky (which obviously does not contaminate the signal) as opposed to the ground.

3. Radiation from equipment (feed horn, waveguides, etc.).

References


