Columbia University E. K. A. Advanced Physics Laboratory
The Cosmic Microwave Background
Lab Manual

Alexander Leunig
Adriana Perez Rotondo
Max Abitbol (TA)
Rees McNally (TA)
Professor Morgan May

July, 2019

Abstract

In this lab you will use a radio telescope to measure the power of the radiation from the Cosmic Microwave Background (CMB). Using this data, as well as careful calibration measurements, you will be able to compute the actual temperature of the CMB. This document will walk you through the theory behind the measurements, the setup, the data collection procedure and the analysis.

1 Introduction

The cosmic microwave background (CMB) is thermal radiation originates from the last scattering surface.Some 380,000 years after the big ban during a period known as recombination, the plasma of hot electrons, protons, neutrons and photons had cooled enough for protons to capture electrons and form stable and neutral hydrogen (and helium) atoms. With this formation, the mean free path for photons increased drastically since low energy photons rarely interact with neutral atoms - the photon were not limited by Thompson scattering any more [1]. As soon as their mean free path length approached the length of the visible universe they were able to travel freely without losing any information in scattering processes. Thus, measuring the cosmic microwave background temperature helps us understand the process of recombination and leads to important predictions in Cosmology. One is the following example: The Saha equation relates the fraction of ionized hydrogen atoms to other parameters, especially redshift z and temperature T:

$$\frac{{n_e}^2}{n - n_e} = \frac{2}{\Lambda^3}\frac{g_1}{g_0}e^{-\frac{E}{k_b T}} \tag{1.1}$$

where n_e is the density of electrons during recombination, n is the density of hydrogen atoms, Λ is the de Broglie wavelength with $\Lambda = \sqrt{\frac{h^2}{2\pi m_e k_b}}$, and E is the ionization energy of hydrogen (13.6eV.)

Taking n_p as the density of protons and n_H as the density of hydrogen, we can relate the ratio $f = \frac{n_e}{n_p + n_H}$ to a temperature

$$\frac{f^2}{1-f} = \frac{1}{n_p + n_H}\frac{1}{\Lambda^3}e^{-\frac{E}{k_b T}} \tag{1.2}$$

Using $T = 2.7(1 + z)$ and $n_p + n_H = 1.6(1 + z)^3$ we can solve this equation and see that recombination for a 50% fraction of ionized hydrogen atoms occurs at roughly $4000K$ and $z = 1500$. Hence using our temperature measurement, we were able to predict the temperature at which recombination happened, as well as the redshift.

1.1 History

Although the CMB was predicted independently by several theoretical physicists as early as 1948, it was only discovered in 1965 by Arno Penzias and Robert Wilson using the Homdel Horn antenna.

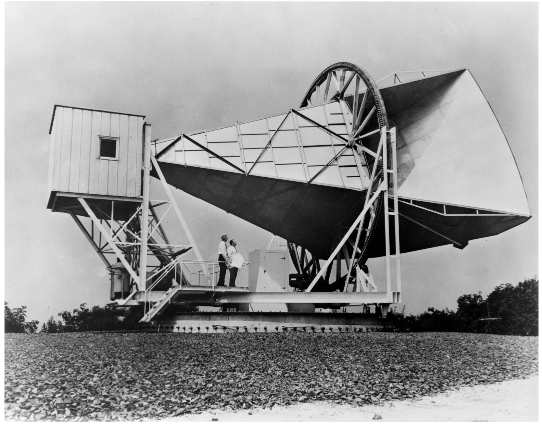


Figure 1: Holmdel Antenna, NASA

This aluminum antenna was about 15m by 10m (ca. 36m^2 aperture) originally designed to detect radio waves reflected off satellites and high altitude balloons at about 2.36 GHz – enough to catch a glimpse of the constant radio signal that comes from all directions of space: the cosmic microwave background [2]. The existence of the microwave background not only confirmed predictions and the current understanding of the universe, but also provided a window to look further back in time. Anisotropies (inhomogeneities) in the cosmic microwave background temperature across the sky can be used to measure the curvature of the universe, the baryon density, the dark matter density of the universe, the Hubble constant, age of the universe, dark energy density among others. After Penzias and Wilsons initial experiment many more have been launched, with the satellites COBE (1989), WMAP (2001) and Planck (2009) being some of the most successful ones. Figures 2-5 show the extent to which the measurements of the CMB have been refined over the last 50 years. While Penzias and Wilson could only measure a constant temperature all across the sky, Planck is able to detected temperature anisotropies in a spectrum between 30 and 857 GHz with a fluctuation of $\frac{\Delta T}{T} = 10^{-6}$ at 10 arcminutes angular resolution [3].

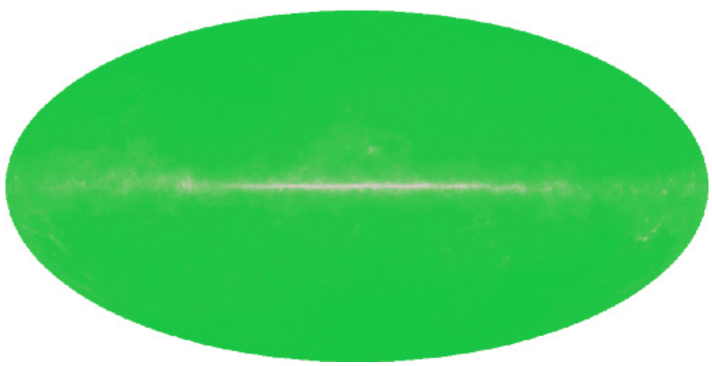


Figure 2: Constant CMB temperature accross the sky as was measured by Penzias and Wilson (and what you will measure), Cardiff University

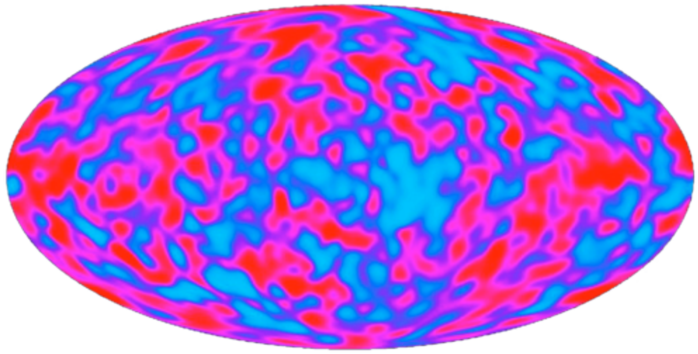


Figure 3: CMB anisotopies accross the sky as measured by COBE, NASA Goddard Space Flight Center

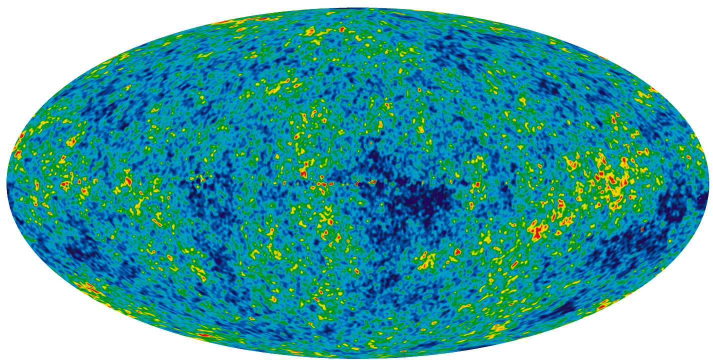


Figure 4: WMAP 1 year CMB anisotropy map, NASA Goddard Space Flight Center

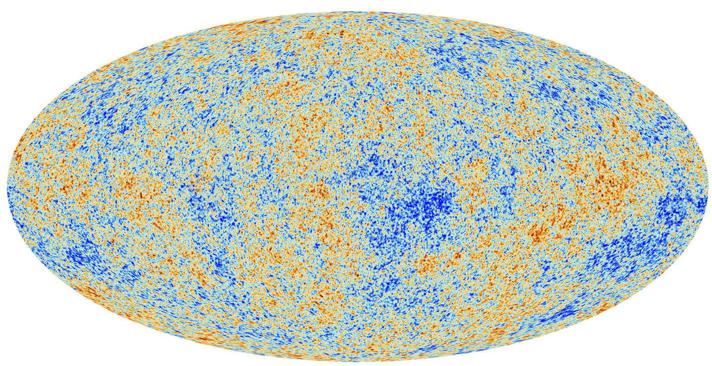
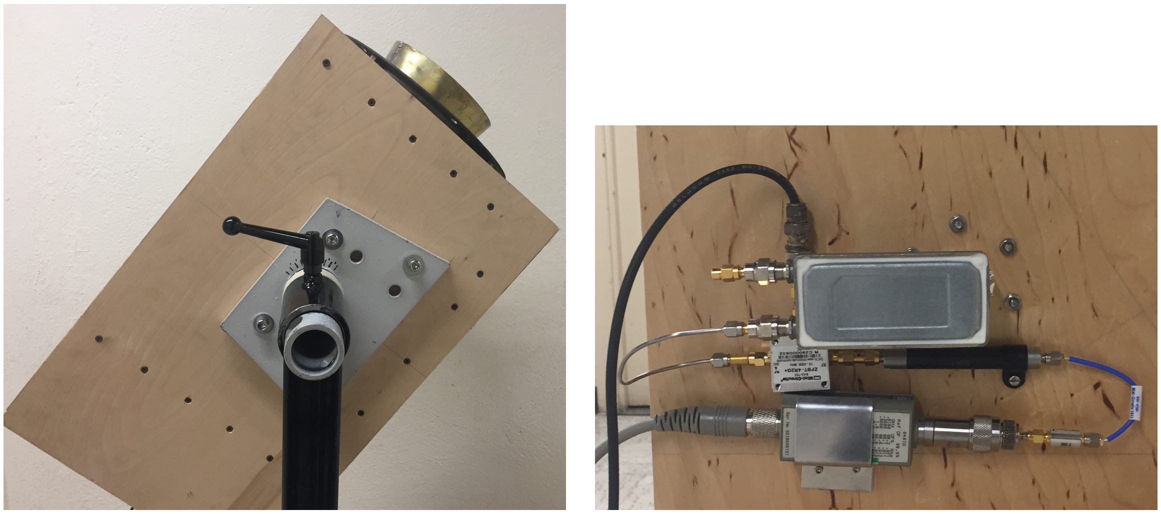


Figure 5: CMB anisotropies as measured by Planck, ESA

In this lab you won't be able to detect such anisotropies, but hopefully you will get a good estimate of the constant temperature of the CMB.

2 Experimental Setup

2.1 Radio Telescope



(a) (b)

Figure 6: Radio telescope used detect the CMB. The metal horn is encased in a wooden structure that rotates around an axis to set the direction of measurement (6a). At the end of the horn, the receiver detects the radiation and transforms the signal into a electric signal (6b).

Figure 6 shows the radio telescope we use to detect the CMB.The radio telescope has two main parts: the horn and the radiometer. A metal horn of about 15cm of diameter captures the radiation and redirects it to the radiometer found at the end of the horn. The radiometer converts the radiation around a frequency of 19GHz into an electric signal. This signal is then coupled to the power supply and goes through an attenuator to finally reach the power sensor. The voltmeter measures the power of the signal across the power sensor, then the digital voltmeter digitalizes it to be read by the computer.

The horn has two main functions: selecting and redirecting the radiation coming straight form the sky and blocking other radiations form reaching the receiver. Since the solid angle of the horn is quite small, it will only survey a small part of the sky. Radiation that does not come in perfectly parallel to the cone will be reflected by the aluminium casing and after a few reflections this radiation will be dampened; it will not affect the measurement.

Metal coating around the radiometer prevents stray radiation from entering the horn and affecting the measurement. It is still advised to stay away from the horn opening at least half a meter since body heat or cell phone radiation might affect the measurement considerably.

Figure 7: Instruments connected to the radiometer and computer to get power measurements: On the left the analog voltmeter, on the right the digital voltmeter and power supply.

The radiometer is a converted satellite receiver that outputs a voltage that is measured by the power sensor. The volt meter measures the voltage across the power sensor, which is directly related to the power measured by the radiometer. The actual voltage measurement is done by an analog voltmeter with 4 significant figures, too little for very precise measurement. In order to increase precision and to prevent note taking by hand, the analog voltmeter is connected to a digital voltmeter which can be directly connected to a laptop via USB. Figure 7 shows the power meter and voltmeters.

2.2 Calibration

As explained in section 3.2.1 in order to have reliable measurements, the radiometer needs to be calibrated. We need to measure the power output corresponding to radiation from a black body at known temperature. This requires a calibration target that is both as near to a perfect black-body as possible, and that has a very well known temperature. For this we will use Ecosorb, which is an microwave absorbing foam (and therefore a good black-body in the GHz frequency range) placed inside a foam cooler. The Ecosorb provides the black-body properties we need, and the foam cooler provides temperature isolation of the calibration target, to ensure the temperature is well known. Temperature sensors placed on the Ecosorb will be used to monitor the temperature in real time as we calibrate.

Figure 8: Calibrator placed under the horn opening to block external radiation and serve as a known temperature black body radiation source

A temperature sensor is placed under the Ecosorb to measure its temperature as accurately as possible. When the calibrator is cooled down by filling the cooler with liquid nitrogen it will emit black body radiation at a temperature. When targeted by the horn, the apparatus will only measure this radiation from the target as shown in Figure 8. In practice, we keep two calibration targets, one at liquid nitrogen temperatures and one at room temperature, each one monitored with an individual sensor. This is a critical step in the experiment, and care should be taken to ensure as accurate a calibration is made.

2.3 Physical Setup

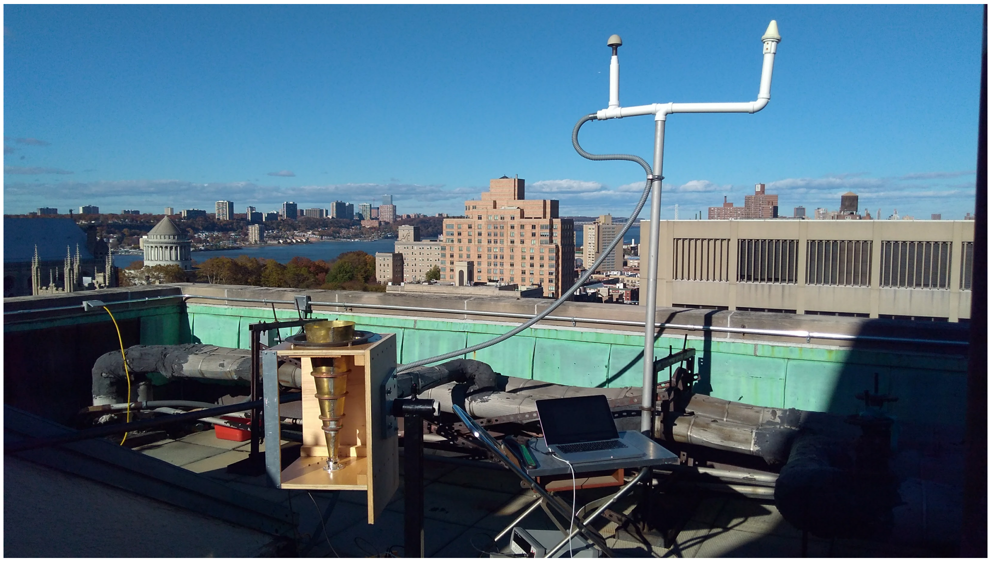


Figure 9: Instruments on the Pupin roof facing North-West for a clear view

Since glass is thermally insulating and buildings tend to produce a lot of stray radiation, the best place to make measurements of the CMB is on the roof. It guarantees an unimpeded view of the sky and minimizes interference from other buildings. You will have to carry up the equipment, since the last set of stairs does not have an elevator to go with it. A clear view on the roof is facing North-West, over the Hudson onto New Jersey (see Figure 9). Starting at about 25 degrees, sky sweeps upward should be relatively free of any interference, minding clouds and planes of course.

3 Methods

3.1 Black Body Radiation and Brightness Temperature

The spectrum of the CMB radiation has two important characteristics; it is highly isotropic (up to one part in 10^3) and it corresponds closely to the radiation of a black body. Planck's law gives a formula for the radiance of a black body as a function of its temperature and frequency. The low temperature approximation reduces to the Rayleigh-Jeans expression:

$$B(\lambda, T) = \frac{2ck_B}{\lambda^4}T \tag{3.1}$$

where λ is the wavelength, c is the speed of light in vacuum, k_B is Boltzmann constant and T is the temperature. Thus, for a fixed wavelength, the power of the radiation is proportional to the temperature of the source. Because of this relationship between radiation intensity and temperature, we can convert any measured power into a brightness temperature at the measured wavelength.

$$T_b = \frac{\lambda^2}{2k_b}I \tag{3.2}$$

where λ is the wavelength, T_b is the brightness temperature, and k_B is Boltzmann constant and I is the radiation intensity. In general, the brightness temperature of a radiation depends on the wavelength. However, for black bodies the T_b is independent of wavelength [4]. In fact, the brightness temperature T_b of the radiation coming from a black body is just the temperature of the source.

$$T_b = T \tag{3.3}$$

3.2 Observation Strategy

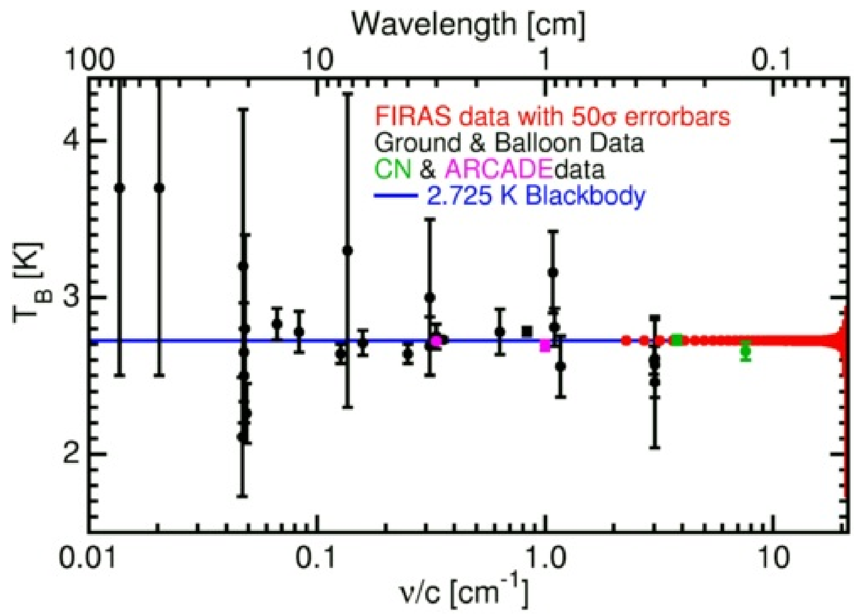


Figure 10: Measured brightness temperature T_B of the CMB at different wavelengths. $T_B = 2.725\text{K}$ is consistent with all the data within error bars [4].

The main goal of this lab is to measure the temperature T_{CMB} of the cosmic microwave background (CMB). From Equation 3.3 we know that it is enough to find the brightness temperature of the CMB. Figure 10 shows a graph of CMB brightness temperature at different wavelengths that were measured on top of Pupin. The measurements are consistent withe the brightness temperature at a black body at 2.725K.

Since the black body brightness temperature is independent of wavelength, in theory, we could measure it for any radio frequency. Because the CMB is not the only source of radiation measured from earth, some frequencies are preferable for measurements form the ground. At small frequencies ~100MHz, the synchrotron radiation from (the center of) the galaxy is large. At higher frequencies ~22GHz, the Earth's atmospheric emission dominates [5]. Hence, in order to maximize the proportion of measured radiation coming from the CMB, we choose a frequency in the middle of this window: 19GHz.

As discussed in Section 2.1 we measure the power of the 19GHz radiation that reaches the receiver. Then we can find the corresponding brightness temperature. Although these two quantities are proportional according to Equation (3.2), we must do a calibration measurement to find the exact proportionality coefficients specific to the instruments used.

Furthermore, the brightness temperature value we obtain is a combination of multiple sources of radiation. Thus, to obtain the brightness temperature corresponding solely to the CMB radiation we must identify the other sources of radiation and subtract their contribution to the total brightness temperature. It turns out that the main source of background is the Earth's atmosphere. With the "sky dip" technique one can determine the radiation from the atmosphere.

Hence there are two main steps to obtain a value for the CMB temperature:

1. Calibrate the response of the system to the brightness temperature
2. "Sky dip" test

3.2.1 Calibration

The calibration is the most delicate part of the measurement. It is essential to find the most accurate relation between the power output and the brightness temperature. According to Equation (3.1) we expect the measured power P_{obs} to increase linearly with respect to brightness temperature of the source T_{obs} the rate of increase is called the gain G:

$$P_{obs} = GT_{measured} \tag{3.4}$$

Furthermore, the receiver electronics have some intrinsic noise that produce a residual output power P_{rec} with corresponding temperature T_{rec}.

$$P_{obs} = GT_{source} + P_{rec} = G(T_{obs} + T_{rec}) \tag{3.5}$$

To find the values of G and T_{rec}, we perform power measurements for black bodies at known temperatures with the calibrator described in section 2.2. Calibrations should be done multiple times, at least once at the beginning and once at the end to detect any drifts. Each calibration consists on two or three power-temperature measurements: one with the calibrator at room temperature, one at dry ice temperature and, depending on the availability, one at liquid nitrogen temperature. Using these P and T values and equation (3.5) we find the best values for G and T_{rec} and can convert power measurements into temperature measurements:

$$T_{obs} = \frac{P_{obs}}{G} - T_{rec} \tag{3.6}$$

Note that the temperature at which the calibrator is radiating does not need to be the same temperature as the liquid nitrogen or dry ice. You will need to make very careful temperature measurements of the surface of the calibrator after it has been cooled down. Do not cool the metal temperature sensor down to nitrogen/dry ice temperature - it heats up less quickly than the calibrator itself. Furthermore you will need to look up the emission spectrum of the Eccosorb (it can be found on the Internet) to determine if the calibrator radiates as a black body, and if not what the shift in power radiated is. With this estimate you can add a temperature shift to the assumed calibrator emission temperature. That means you assume the calibrator radiates as a black body at a temperature $T_{N_2} + \Delta T$ instead of just T_{N_2}. This will allow you to arrive at a right estimate for the CMB temperature.

3.2.2 "Sky Dip" Test

Once we have the relation between the power measurement and the brightness temperature, we must find the brightness temperature of the CMB radiation reaching the earth. As explained in section 3.2, to do this we must find the brightness temperature from the atmosphere's thermal radiation and subtract it to the total value. The remaining radiation is the radiation that we would measure if there were no atmosphere: this corresponds to the CMB.

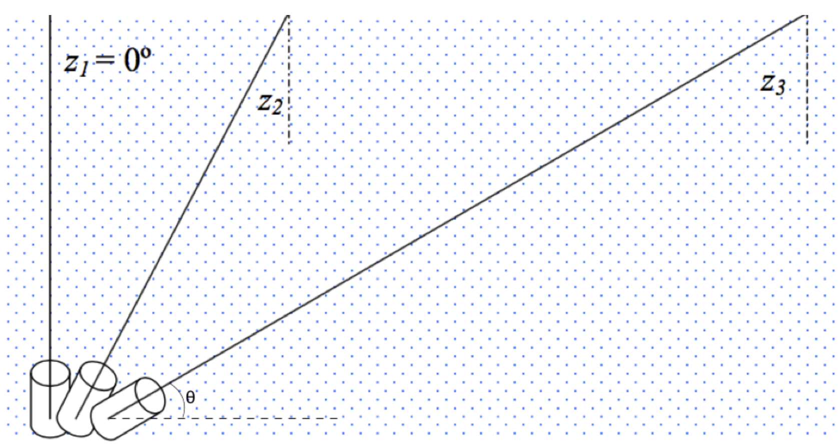


Figure 11: Schematic showing the amount of air mass traveled through by the radiation to reach the receiver for different θ angles. Note that $\theta = 90 - z$. Modified from [6]

We assume a linear attenuation of the signal through the atmosphere. Hence, we expect the temperature to increase proportionally to the amount of "air mass", the amount of atmosphere the signal travels to reach the earth. Yet, from simple trigonometry (see Figure 11), we know that the number of air masses decreases by a factor of $\frac{1}{\cos(90-\theta)} = \frac{1}{\sin(\theta)} = \mathrm{cosec}(\theta)$ where θ is the angle from the horizontal to the angle the direction at which the horn is pointing. Thus, the temperature also decreases by the same factor as θ increases:

$$T_{obs} = T_{CMB} + \frac{T_{vertical}}{\sin(\theta)} \tag{3.7}$$

,where $T_{vertical}$ is the temperature measured when $\theta = 90$, the horn is pointing upwards.

The “sky dip” technique is based on this fact. We measure multiple temperatures for different angles θ and find the best fit to equation (3.7). You should take measurements for angles between 90 and 25. If you reduce the angle too much, you might get interferences from surrounding buildings. Take at least one minute measurements for each angle and use the average power to reduce random fluctuations in the power measurements.

3.3 Data Taking

3.3.1 Power Measurements

The digital voltmeter is connected to the laptop with a USB cable. In the laptop directory `/Users/cosmology/Google Drive/Projects/radiometer` you can find a python class in `Readout.py` to communicate with the voltmeter. In the same directory, you there is also a python program called `BasicReadout.py`. To take data open the BasicReadout file in an editor, it is recommended to do it with PyCharm IDE. First specify the values of the presets (duration, path and extension, angles, calibrator boolean, temperatures and weather, units). These strings will be written in the header of the file containing the measurements. They provide information about the measurement that are important for the analysis later. Save the file and run the program `BasicReadout.py`. This will create a .txt file in the path you indicated with a name of the form ”2016-11-10_10:20:50_Readout.txt”.

The value read by the computer from the voltmeter is just a number with no units. Yet the analog and digital voltmeters changes units automatically. Hence, the values from measurements with very different signals, for example from the calibration and the sky dip, might be in different units. Therefore, it is very important to keep track of the units for each set of measurements. On the right of the power sensor display there is a light next to the unit of the measurement (see Figure 7). Before each measurement check the unit and set the “units” variable in BaicReadout.py file to this value. Later in the data analysis you will have to convert all the power measurements to the same unit.

3.3.2 Temperature Measurements

As explained in section 3.2.1 to have an accurate value of the temperature we need a good calibration and hence precise temperature values. The main source of error in the temperature measurement is the placement of the thermometer and hence the measured temperature of the calibrator. It should reflect accurately the temperature of the calibrator, mainly the eccosorb that is emitting the black body radiation to the receiver. Section 5.3 describes a good technique.

Ideally, the temperature sensors will be connected to the computer to get the exact temperatures during the calibration measurements. If this is not possible, you can record a video of the temperature and later extract the values during the analysis. In any case, you should at least write an approximate ambient temperature and calibrator temperature in the header of the power measurement file. The ambient temperature is important, as the performance of the apparatus, especially the amplifiers, varies with temperature. Remember to do two calibration measurements. One before the sky dip test and one after. This helps you detect any systematic amplitude drifts that might occur during the session.

4 Data Analysis

Plot power versus time after each measurement to detect any anomalies and repeat the measurements if so. The anomalies could be caused by movement of the cables while recording, a faulty connection, something blocking the horn or a bug in the program refer to Section 6 for more information. It is also recommended to find the calibration coefficients on the spot to check that they give sensible temperature values.Figure 12 shows example calibration measurements. For the ambient temperature power values we averaged all the measurements to reduce the random errors. However, when the calibrator is at dry ice temperature or liquid nitrogen, the temperature increases rapidly during the one minute measurement. Hence we couldn't average all the power values - instead we used the first power measurement with its corresponding temperature. A later analysis should be done to find the best fit to the sky dip measurements according to the Equation (3.7). Figure 13 shows the results from the sky dip test. We get a value of $T_{CMB} = 2.5 \pm 0.8$K.

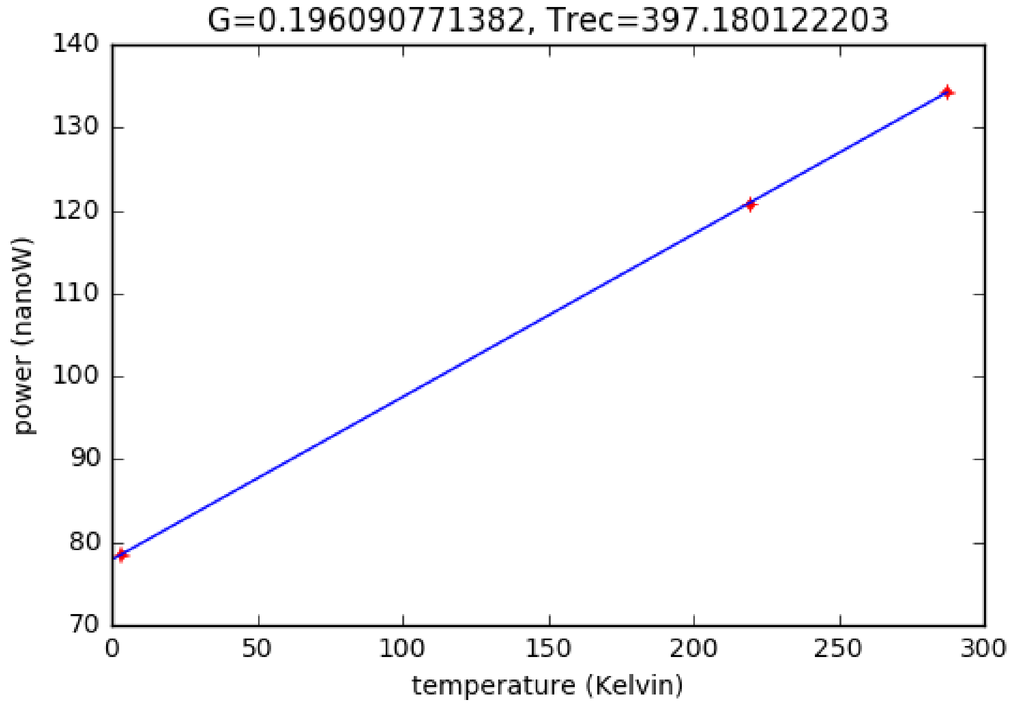


Figure 12: Plot of measured power with calibrator at liquid nitrogen, and ambient temperature and the best fit. The error bars are very small.

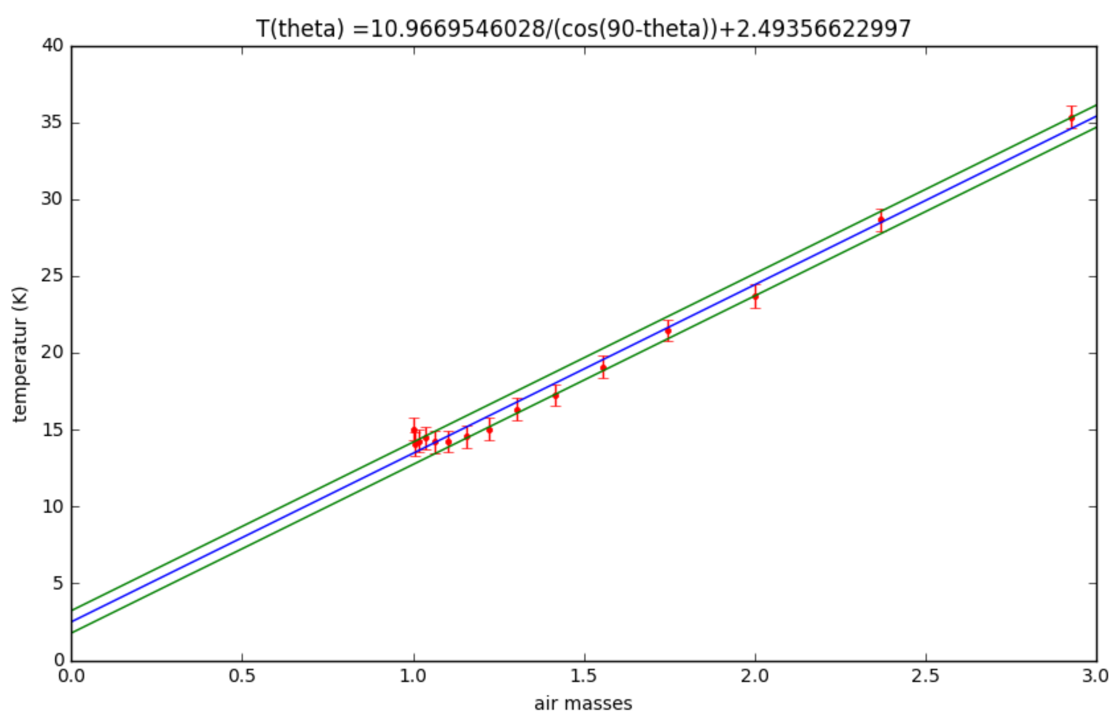


Figure 13: Plot of measured power with respect to air masses (in red). The blue line is the best fit and the green lines the high and low fits using one standard deviation.

5 Checklists

5.1 Inventory

– CMB radio telescope (Includes horn, radiometer and power sensor) ☐

– Antenna rotating stand ☐

– MacBook Pro Laptop ☐

– Analog Voltmeter (Newlett Packard 436A Power Meter) and cable ☐

– Digital Voltmeter (Agilent 34405A), cable and USB connector ☐

– Power Supply (Agilent E3620A) on 12-13V and cable ☐

– Extension cord ☐

– Mobile cart for instruments ☐

– 2 Eccosorb Calibrators ☐

– 2 Temperature sensors ☐

– Digital thermometer ☐

– Cryogloves ☐

– Liquid nitrogen container ☐

– Liquid nitrogen ☐

5.2 Setup

– Connect instruments and laptop to power supply ☐

– Connect power sensor to analog voltmeter ☐

– Connect analog voltmeter to digital voltmeter ☐

– Connect radiometer to power supply ☐

– Switch on the power supply ☐

– Switch on the voltmeters ☐

– Open `/Users/cosmology/Google Drive/Projects/radiometer/BasicReadout.py` in PyCharm IDE ☐

– Set the variables: `path`, `extension`, `temperatureOutside`, `weather` and `units` in the python file ☐

– Check measurements by placing ambient temperature Eccosorb on top of antenna and reading ca. 0.13-0.14μW on the voltmeters ☐

5.3 Calibration

Do the calibration twice, once before sky dip and once after. Do at least two measurements: the first one with the ambient temperature calibrator and the second one with the dry ice or liquid nitrogen temperature calibrator. It is important that this (and the sky dip) is done efficiently, as the exact calibration will drift over time as the temperature of the horn changes.

– Aim the horn down, pointing into the calibration target. ☐

– If the calibration target is the cold target, ensure there is minimal fog in the cooler, as this will corrupt the calibration. ☐

– Lift the target so the horn can only see the Ecosorb. ☐

– Plug in the temperature sensor for that target. ☐

– Check the units on the voltmeter display and record them. ☐

– Take 2-3 measurement of the simultaneous power and temperature. ☐

– Repeat with the other calibration target ☐

– Set the calibration targets aside, point the horn vertically, and begin the sky dip. ☐

5.4 Measurement - one sky sweep

– Rotate antenna so horn is pointing upward ☐

– Check that the horn is at 90º from the horizontal, iether with the marks on the rotation axis (see Figure 6a) or with a level app on your phone ☐

– Check the units on the voltmeter display and set the value of the variable `units` in BasicReadout.py ☐

– Set angle and duration values in BasicReadout.py ☐

– Start program to take measurements ☐

– Change antenna angle, to 85º and repeat measurements ☐

– Repeat until 20º ☐

6 Troubleshooting

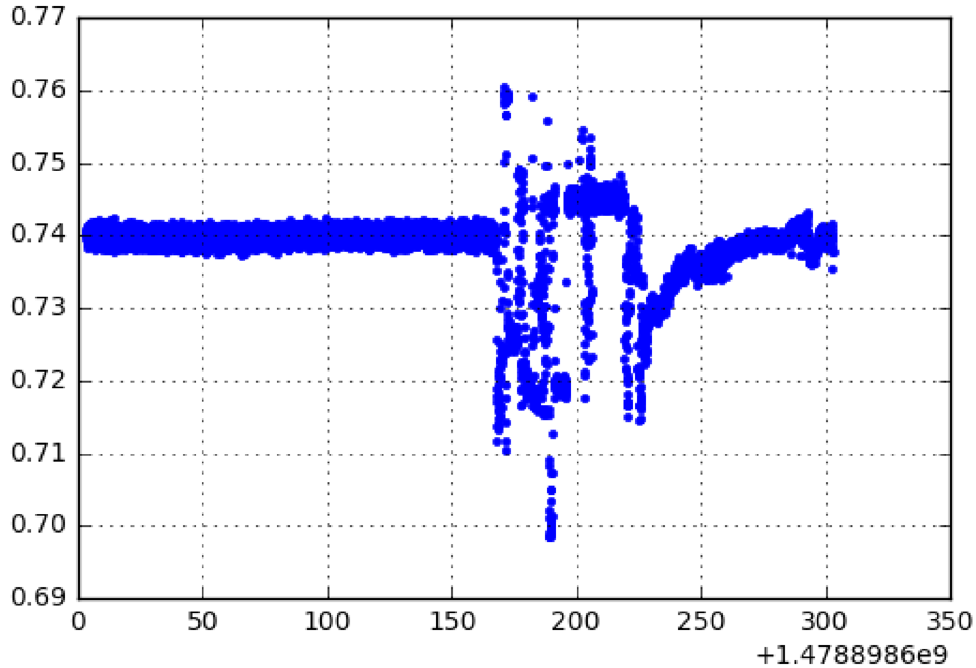


Figure 14: Plot of measured power with respect to time. The fluctuations between 170-250s are due to the movement of the connection cables

1. Random fluctuations in power measurement (large peaks):
   - Tape down any cables, movement due to wind distorts measurement. Figure 14
   - Point antenna further upward
   - Take data for longer than 1min
   - Turn power supply off and on again
2. Time drift in data
   - Turn power supply off and on again
   - Calibrate often to be able to predict temperature correctly
3. Python program does not connect with Voltmeter
   - Check USB connection
   - Check whether you have the latest PyVisa version `https://pypi.python.org/pypi/PyVISA`
   - Re-pull the python program from git if you have changed any variables
4. Analysis yields wrong CMB temperature (by a lot)
   - Quality-check your sky dip measurements:
     - Make sure there are no large scale time drifts
     - Calculate the temperature of the sky according to the measurements - is it reasonable?
   - Make sure you measured the calibrator temperature correctly, it should be above T_{N_2} or T_{dryice}
   - Adjust your uncertainty in angle measurements (it should be at or above 1 degree)

References

[1] Hale Bradt. *Astrophysics Processes: The Physics of Astronomical Phenomena*. Cambridge University Press, reprint edition edition, May 2014. ISBN 978-1-107-67724-1.

[2] Alaina G. Levine. Arno Penzias and Robert Wilson - Bell Labs, Holmdel, NJ, 2009. URL `https://www.aps.org/programs/outreach/history/historicsites/penziaswilson.cfm`.

[3] ESA Planck Mission Objectives, May 2015. URL `http://sci.esa.int/planck/30968-objectives/`.

[4] Cosmic Microwave Background. URL `http://www.astro.ucla.edu/~wright/CMB.html`.

[5] James Condon. Introduction to Radio Astronomy, 2016. URL `http://www.cv.nrao.edu/course/astr534/Introradastro.html`.

[6] Curt Nehrkorn. Measurement of the Cosmic Microwave Background Temperature at 11.2 and 12.2 GHz, May 2011.

[7] Astronomical radio source, November 2016. URL `https://en.wikipedia.org/w/index.php?title=Astronomical_radio_source&oldid=751168333`. Page Version ID: 751168333.

[8] James Condon. 3 Radio Telescopes and Radiometers. Essential Radio Astronomy, 2016. URL `http://www.cv.nrao.edu/~sransom/web/Ch3.html`.