An Amateur Instrument for the Detection of the Cosmic Microwave Background

Jack J Gelfand PhD
Baldwinsville, NY USA
Jgelfand.net

ABSTRACT

Astronomers detect the Cosmic Microwave Background (CMB) as an extra noise equivalent to a black body radiating at a temperature of 2.73 K. They do this with an instrument called a microwave radiometer. A radiometer is a radio telescope whose response is calibrated with known temperature sources. A professional apparatus utilizes the temperature of liquid helium to calibrate the temperature scale and also to cool the electronics for quiet operation. I have found that one can obtain a reasonable level of performance with inexpensive electronics operating at 10 GHz at ambient temperature and a calibration configuration using liquid nitrogen at 77K.

I. Introduction

As the universe cooled after the Big Bang, it entered a stage in which it was a uniform, ionized plasma. As the plasma cooled further, the electrons and protons recombined to form a neutral, transparent gas. When we look into the sky today we see back in time to the light left over from that transition. Because of the cosmic redshift, we now see that light shifted to microwave frequencies. This radiation, called the Cosmic Microwave Background, is the most ubiquitous electromagnetic radiation in space, and fills the entire sky in all directions.

The original homogeneous, dense plasma absorbed all light. A property of a material that completely absorbs radiation is to thermally radiate in a mathematically specified way called a black body radiator. The CMB is detected as thermal noise equivalent to a black body radiating at 2.73 K. A microwave radiometer is used to measure this radiation (Dicke 1946). A radiometer is calibrated with thermal black body radiation from a perfect absorber material at two known temperatures.

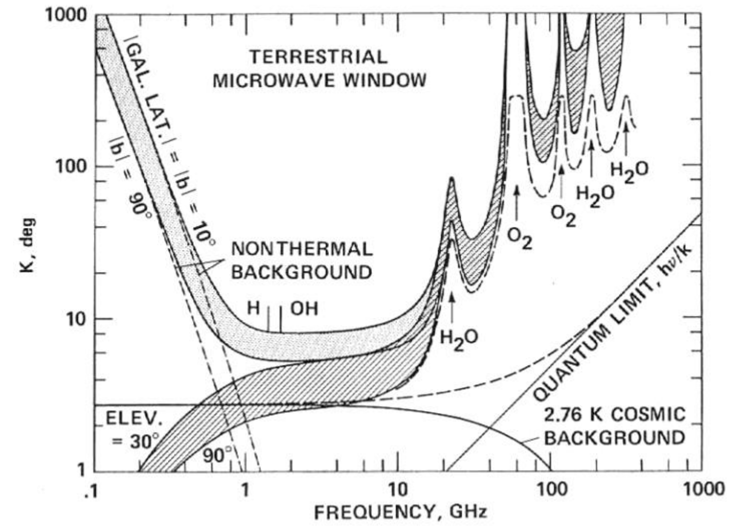
A professional apparatus utilizes a very quiet microwave amplifier to detect the tiny signal. The electronics must be cooled in liquid helium to obtain this level of performance. Furthermore the liquid helium is used to calibrate the temperature scale of the apparatus. This setup is quite expensive and complex, and outside the reach of amateur astronomers. With some simplifications, though, it is possible for an amateur to construct a similar apparatus to detect the CMB. I have found that one can achieve a reasonable level of performance with inexpensive electronics operating at room temperature and a temperature calibration using a black body radiator in liquid nitrogen at 77K. The design of my instrument, shown in the photograph below, is adapted from earth-based instruments used by George Smoot and his group to make measurements in the lower microwave region (Kogut et al. 1988, 1990). Some components are simplified while retaining the critical elements of the design. Additionally, there have been other amateur oriented systems of somewhat similar design (Koppen, 2015; Piat, 2017; Stein & Foster, 2008).

II. Design

The principal feature of the design is the use of a microwave horn antenna for reception. Horn antennas have the high degree of spatial selectivity needed to detect the weak CMB in the sky in the presence of ambient thermal noise in the local environment. A dish antenna has poorer spatial selectivity because of scattering from the structure and leakage around the edge of the dish. Another principal feature of the design is the use of a Dewar flask configured as a microwave waveguide matched to the diameter of the horn antenna. The Dewar has microwave absorber material placed at the bottom. The absorber material is covered with liquid nitrogen to serve as a cold thermal radiation source

Figure 1. The microwave radiometer system described in this paper

The frequency range of the CMB black body radiation extends from approximately 0.5 GHz to 300 GHz in the radio frequency spectrum, with a peak at 164 GHz. Oxygen and water vapor in the atmosphere absorb microwaves over most of this frequency range. That is why most measurements of the CMB are performed using satellites, high altitude balloons or telescopes at the South Pole. The atmosphere is, however, substantially transparent from 1 GHz to 10 GHz at the low end of the CMB frequency spectrum. This window is shown in Figure 2 below.



NASA

Figure 2. Diagram of the thermal emission of atmospheric gasses versus frequency in GHz. Note that additional noise present in our own galaxy from relativistic electrons creates substantial background noise below 1 GHz.

Numerous types of amateur and commercial microwave receiving equipment are available for use in the 1 – 10 GHz range. I have chosen to use components from an X-band dish satellite antenna as described below.

II.a. Antenna Size

The most important factor to consider in designing a microwave radiometer to detect the CMB is how large the antenna must be. One would think that detecting a signal from the beginning of time would require a huge dish antenna. This is not true. For a diffuse source, antenna size does not determine signal strength (Hanny et al. 2012). This can be explained as follows. We know that for a larger antenna diameter, we would typically expect to intercept more microwave flux because of the larger collection area. However, from diffraction theory we know that this larger antenna receives signals from a smaller area of the sky. The increase of the collecting area is exactly offset by the antenna receiving from a smaller sky area. This must be so, or it would violate the Second Law of Thermodynamics. Because of this fact, antenna size does not determine received signal strength. Fortunately then, an amateur can choose a receiving antenna, which satisfies other design criteria. Keep in mind, though, that the size of the antenna determines the beamwidth, which may be important for other considerations.

This antenna size design criterion is unlike that of an optical telescope in which we focus on single point sources such as a star or small galaxy. It is also different from that of a receiving antenna in a communication system, which seeks to detect a signal from a single transmitting source. In those cases a larger mirror or antenna is very beneficial to performance.

II.b. Microwave Radiometer

The measurement configuration in our experiment is that of a total power radiometer. We are operating in the region of the Raleigh-Jeans approximation to the low frequency end of the Black Body curve. In the Raleigh-Jeans region the total noise power signal, P, intercepted at the antenna is directly proportional to the temperature of the antenna (Kogut, 1990),

$$P = k\,T(\text{ant})\,B \qquad (1)$$

Where k is the Boltzmann constant, T(ant) is the temperature observed at the antenna, and B is the frequency bandwidth. In this regime, temperature measured by microwave noise power at the antenna corresponds to the actual (thermodynamic) temperature of the radiating sources. Contributions to the total ,noise temperature are additive. For example, under the conditions in the observations described here,

$$T\,(\text{antenna}) = T\,(\text{CMB}) + T\,(\text{atmosphere}) + T\,(\text{amplifier noise}) \qquad (2)$$

This fact allows us to calibrate the response of the radiometer with two calibration temperatures, 77K and ambient outdoor temperature, ~296K, and use a linear extrapolation to determine T (Sky).

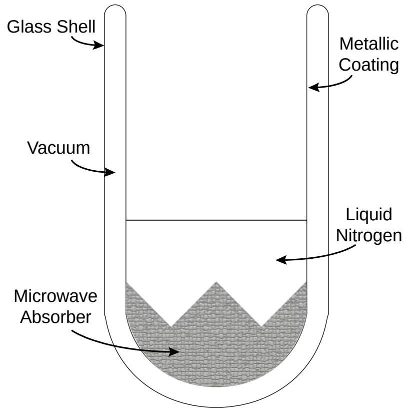


Figure 3. Cutaway view of the liquid nitrogen cold calibration source

An important component of the radiometer system is the cold temperature calibrator, or cold-load. In the cold-load, thermal emission of the liquid nitrogen cooled microwave absorbing material is coupled to the receiving antenna. This must be done in such a way as to avoid emission from water ice or fog in the microwave cavity. The microwave cavity calibrator that I use is adapted from the design of Bensadoun (1992). A cutaway view is shown in Figure 3. A Dewar flask is used as a microwave waveguide with a section of microwave absorber at the bottom. The absorber is covered with liquid nitrogen. The liquid nitrogen slowly boils at 77K to maintain the temperature. The absorber materials are typically made by mixing powdered carbon with various polymer materials. I use Laird Technologies 0.5" foam built into small pyramidal shapes on the surface to match the shape of the Dewar.

The walls of the Dewar are coated with a thin metal film when manufactured. This serves to keep out infrared radiation. In this design the metal film also serves as the walls of a microwave waveguide to confine the black body radiation from the liquid nitrogen cooled microwave absorber. Additionally, the professional design has numerous thin film windows to keep moist air from entering the cavity. The windows are necessary because in professional observations one may maintain this configuration for 24 hours or more while filled with liquid helium. I have found that slow evaporation of dry nitrogen from the bath is sufficient to provide water vapor free operation without windows for an hour, long enough for my data runs.

II.c. Microwave Receiver

The microwave receiver uses the horn antenna feed from a TV dish network receiver. I do not use the parabolic dish but use the small horn antenna feed and associated electronics. As mentioned earlier, the dish antenna configuration is more susceptible to stray noise than a horn antenna alone. The antenna feed module receives in the range of 10.7 -11.7 GHz. The module is called a Low Noise Block (LNB) and can be purchased on eBay for as little as $ 3 each. Most X-Band LNBs are of substantially the same design. They comprise a 2" diameter microwave horn antenna feeding a circuit board in a cast aluminum housing. The circuit board contains a low noise preamplifier and RF mixer circuit to shift the frequency of the receiver to the 1 - 2 GHz intermediate frequency (IF) range where it is transmitted through a cable to the TV receiver in the house. In this system the receiver is tuned to 10.75 GHz by the choice of a 1 GHz IF filter with a 50 MHz bandwidth. The total noise power in the 50 MHz bandpass is read on a Hewlett Packard HP-432A RF power meter.

There are numerous other configurations, which could be used, such as a commercial 10 GHz communications receiver. Also, the IF section could be replaced by a software defined receiver with a noise power measurement algorithm. The most important performance criterion for the detector system is linearity. As discussed earlier in this paper, the radiometer works on the linear extrapolation of the temperature calibration response. Keep in mind that most commercial and amateur equipment use an Automatic Gain Control (AGC) circuit to keep the output constant in spite of signal strength changes. This circuit must be disabled for use in this application.

II.d. Horn Antenna

The 2” horn antenna provided with the LNB is designed as a feed horn for the parabolic dish. For this application, it has a very broad beam width of 75 degrees. I have added an extension horn to the original 2” diameter horn to narrow the beam width to a 10 degree field of view. This makes it possible to point at the sky without interference from surrounding trees and buildings. A narrow beamwidth is also required by the procedure to determine atmospheric emission by measuring T(Sky) at different elevations.

Figure 4 The configuration of the extension horn antenna as it attaches to the end of the small horn on the LNB

The extension horn is shown in Figure 4. It is fabricated from .010“ sheet brass formed into a cone with a 2.0” diameter opening at the smaller end and a 6.0” opening at the larger end. The cone is 9.0” long. This is an optimum horn configuration for a 10 degree beamwidth (Aboserwal and Balanis 2013). The starting pattern is cut from sheet brass, see www.cmrp.com/cone-calculator.

II.e. Atmospheric Emission

When pointing at the CMB through the atmosphere, we also receive the glow from atmospheric gasses added to the sky temperature. The emission is principally from oxygen and water vapor. This phenomenon has been studied by astronomers (Bersanelli et al. 1995), and also extensively by the atmospheric science community (Janssen, 1993), where this emission is used to remotely sense conditions in the atmosphere. The glow corresponds to a brightness temperature at 10 GHz at sea level of approximately 5 K to 15 K, depending on the level of moisture and cloud cover. Professional astronomers have the advantage of observing from balloons or from space where this correction is negligible. It is a substantial correction, however, for amateurs who principally observe at sea level. The situation gets better at higher altitudes. At 12,000 feet the atmospheric noise is about 1 K at 10 GHz (Bersanelli et al. 1995).

In our case atmospheric noise adds linearly to the CMB.

$$T(\mathrm{Sky}) = T(\mathrm{CMB}) + T(\mathrm{Atm}) \tag{3}$$

We can separate the two components by measuring T(Sky) at the zenith and at least one additional angle. This can be done because of the geometric relationship between the power detected and the length of the path.

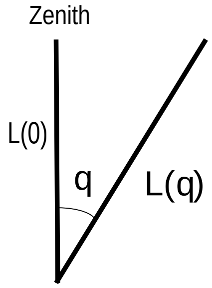


Figure 5 A diagram showing the relationship between air mass and observing angle

Figure 5 shows the path length in the atmosphere as a function of observation angle. We can see that this path length, called the air mass, is related by the factor Sec θ as shown in Equation 4 below.

$$L(\theta) = L(0)\ \mathrm{Sec}\ \theta \tag{4}$$

Where L(0) is the path length through the atmosphere at the zenith and L(θ) is the path length at the observing angle θ. In the Raleigh-Jeans approximation the observed temperature grows linearly with airmass as shown in Equation 5.

$$T(\mathrm{Atm}, \theta) = T(\mathrm{Atm}, 0)\ \mathrm{Sec}\ \theta \tag{5}$$

Where T(Atm, 0) is the atmospheric component of the observed temperature measured from the sky at the zenith, and T(Atm, θ) is the atmospheric component of the observed temperature measured from the sky at angle θ. From Eq. 3 and Eq. 5 we can derive a relation expressing the contribution to T(Sky) from T(Atm) shown in Eq. 6 below. Measurements can be made at a number of angles and combined.

$$T(\mathrm{Atm}, 0) = [T(\mathrm{Sky}, \theta) - T(\mathrm{Sky}, 0)]\ \mathrm{Cos}\ \theta \tag{6}$$

III. Method

These measurements must be performed with a completely unobstructed view of the sky. Trees and other objects thermally radiate at the ambient temperature of the environment causing substantial errors. There is no need to perform these measurements in darkness. You do need to avoid pointing the antenna toward the south where TV satellites are transmitting near the receiver bandpass.

The procedure is simple. The total microwave power emitted from the 77K cold load, an ambient temperature black body radiator and the sky must be measured in sequence. This sequence is shown in the photographs in Figure 6.

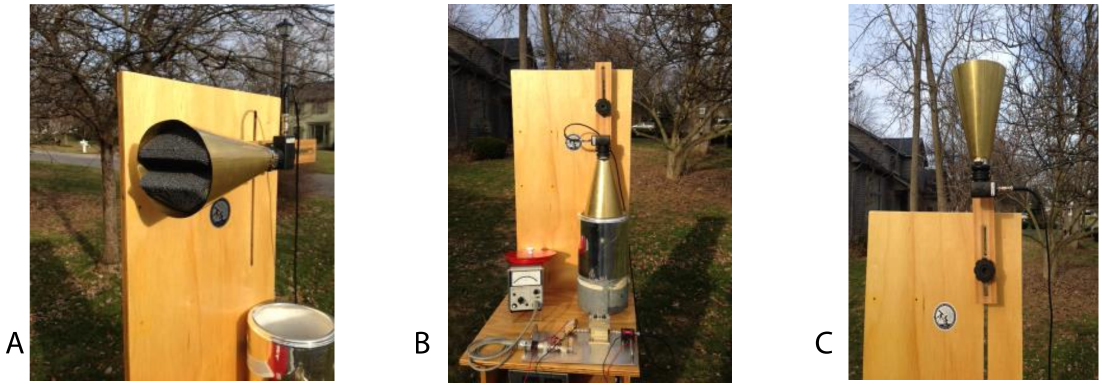


Figure 6. Sequence of antenna positions and sources for calibrating the radiometer
A. Ambient temperature absorber mounted at the end of the microwave horn
B. Horn antenna aimed into the cold load source at 77K
C. Horn antenna aimed at the zenith

The electronics in professional equipment are thermostatically controlled. I do not stabilize the temperature of my equipment. I warm up my equipment for at least one hour and try to execute the measurement quickly. I try to avoid times when the ambient temperature is changing rapidly.

The input to the Hewlett Packard power meter is reset to zero before each measurement. The stability of the 77 K power reading is a measure of the stability of the entire system as the boiling point of nitrogen is constant. I find that the total power reading is stable to 1% over the course of a one hour data run.

IV. Results

The analysis of the data and the determination of the measured CMB radiation are best understood graphically. We can construct a graph of microwave noise power versus source temperature as shown in Figure 7 below.

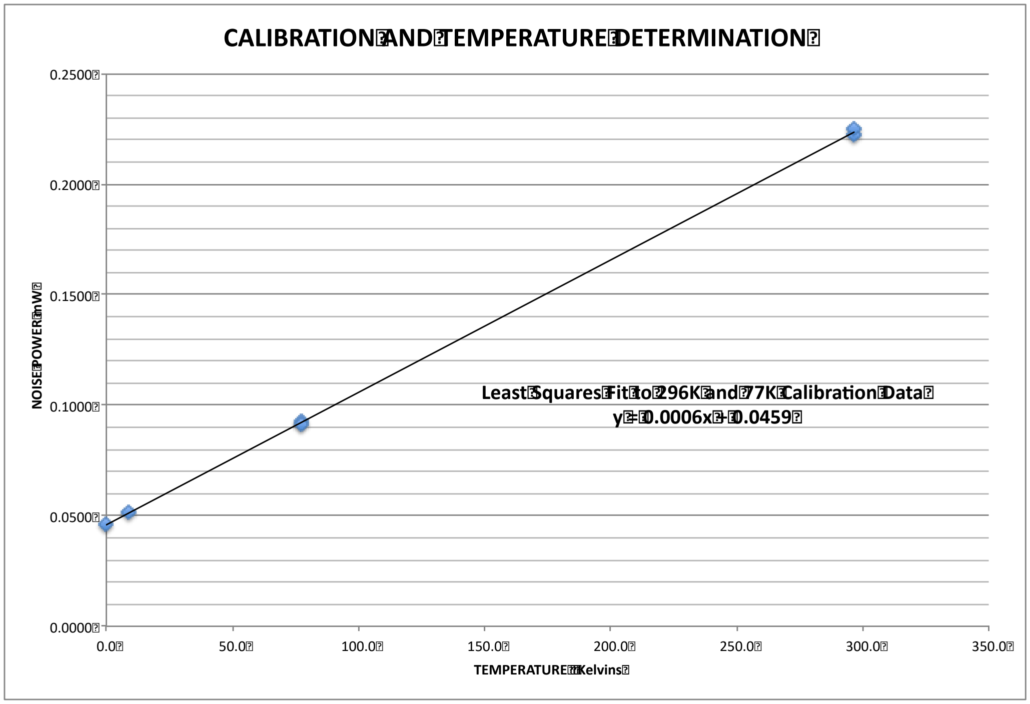


Figure 7. A graphical representation of the measurement of T(Sky) on the basis of a two-temperature calibration of a microwave radiometer.

The noise power data at ~296K (room temperature) and 77K (Liquid nitrogen temperature) are least squares fitted to a line. The value of measured sky noise power is then plotted on the calibration line. The value of the temperature of the sky is read off of the x-axis. You can clearly see the advantage of using liquid Helium for the cold temperature calibration from the graph. There is a substantial extrapolation from 77K to T(Sky).

On this run measured sky temperature was calculated from this data and found to be 8.9 K. For a clear sky the correction for the 10 GHz emission of the atmosphere was 5.0 K. The measured T(CMB) is,

$$T(CMB) = T(Sky) - T(Atm) = 8.9K - 5.0K = 3.9K \qquad (7)$$

The accepted T(CMB) = 2.73K is close to the measured temperature of 3.9K. Results vary for T(CMB) from 0K – 5K

V. Discussion

It is my hope that amateurs will try to duplicate these measurements. The procedures discussed here are not that difficult. Older, analog instruments such as the HP432A power meter are suitable for these measurements, and are moderately priced on ebay. It is also easily possible to adapt a USB dongle software defined radio (SDR) as the IF amplifier and detector, though one should check the linearity of the response.

I feel that with care it is possible to reproducibly obtain the value of the temperature of the CMB within 1K but it will require some improvements. I can see that temperature stabilization of the electronics will probably be necessary. Also, there is a problem in the configuration of the cold load. There is a change of index of refraction at the surface of the liquid nitrogen air interface, which causes standing waves of +/- 2% in power level in the cavity. I am experimenting with tilting the Dewar to cause the liquid nitrogen surface to be at an angle to the horn antenna axis. This appears to alleviate the problem but needs some further work.

VI. References

Bensadoun, et al., A Liquid-Helium-Cooled absolute reference cold load for long-wavelength radiometric calibration, Review of Scientific Instruments, 63, 4377-4389 (October 1992)

Bersanelli et al., Effects of Atmospheric Emission on Ground-Based Microwave Background Measurements, Astrophysical Journal, 448, 8-16 (July 1995)

Janssen, Atmospheric Sensing by Microwave Radiometry, Wiley (1993)

Kogut, et al., Measurement of the Temperature of the Cosmic Microwave Background at a Frequency of 7.5 GHz, Astrophysical Journal, 355, 102-113 (May 1990)

Kogut, et al., The Temperature of the Cosmic Microwave Background Radiation at a Frequency of 10 GHz, Astrophysical Journal, 325, 1-15 (Feb 1989)

Dicke, The Measurement of Thermal Radiation at Microwave Frequencies, Review of Scientific Instruments, 17, 268-275 (July 1946)

Hanany et al., CMB Telescopes and Optical Systems, preprint, to appear in Planets, Stars and Stellar Systems, Volume 1, Telescopes and Instrumentation, arXiv: 1206.2402v1 Page 9 (2014)

Koppen, How to Measure the Cosmic Microwave Background with TV Satellite Equipment (2015) Stein and Forster summary in English. portia.astrophysik.uni-kiel.de/~koeppen/CMB.pdf

Michel Piat at Paris Diderot University has been experimenting with amateur style equipment.
http://www.apc.univ-paris7.fr/~piat/Michel_Piats_site/Lexperience_PW.html

Stein and Forster, Kosmologie mit Kaninchendraht und Wasser (Cosmology with Rabbitwire and Water), Sterne und Weltraum, 84-90 (July 2008)