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SIMULTANEOUS MEASUREMENTS OF ATMOSPHERIC EMISSIONS AT 10, 33 AND 90 GHZ

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Chapter 1

Atmospheric Emission and Absorption

1.1 Introduction

The microwave spectral behavior of the atmosphere plays an important role in fields such as radio frequency communications, remote microwave sensing and radioastronomy (Crane, 1981). For example, precise measurements of the cosmic microwave background spectrum, which would yield a wealth of information about the early universe, are severely restricted not only by galactic emissions due to synchrotron radiation and thermal emissions from HII regions, but also by atmospheric emissions due to rotational transitions of molecular oxygen and water. To reduce the galactic contributions to negligible levels, one generally measures the spectrum at frequencies greater than about 2 GHz. However, although one can reduce the atmospheric emissions by using a high altitude site, the intensities are nevertheless significant, even at frequencies corresponding to atmospheric windows, and one must account for them in ones measurements. Since the atmosphere acts both as a microwave emitter and as an attenuator of the cosmic background radiation (CBR), a good understanding of the atmospheric absorption and emission is expedient to making real-time atmospheric corrections for the spectrum measurements.

Since Van Vleck's pioneering work on atmospheric absorption by oxygen (Van Vleck, 1947a) and water (Van Vleck, 1947b), much progress has been made in understanding and calculating the functional dependence of the atmosphere's opacity or emission on frequency, pressure and temperature. Recent calculations of the specific attenuation due to the absorption by diatomic oxygen have met much success in explaining observed absorption both in the laboratory and in direct measurements of the atmosphere. However, discrepancies, usually accredited to water, have been observed in the regions corresponding to the atmospheric windows (Van Vleck, 1947b; Liebe, 1980). In fact, the observed attenuation in these regions is as much as 3-5 times greater than the expected attenuation derived from calculations for water vapor. Such discrepancies have led to many proposed explanations, none of which are widely accepted, and an increased effort to make more accurate measurements in these regions.

As part of a larger experiment to measure the cosmic microwave background spectrum, frequent simultaneous measurements of the atmospheric antenna temperature were made at three fixed frequencies, namely, 10 GHz, 33 GHz and 90 GHz. We performed these measurements at two separate locations, Berkeley and White Mountain, which greatly differ in altitude and climatic conditions. As stated before, such measurements provide real-time corrections essential to the experiment. Being simultaneous, they not only helps to check the validity of atmospheric models used to make the correction, but also provides constraints on models of the microwave emission of the earth's atmosphere, especially models developed to describe the emission as a function of the precipitable water content through which one looks.

1.2 General Features of the Atmosphere

Both the constituents (oxygen, water vapor, etc.) and the physical properties of the atmosphere determine its spectral microwave behavior. Several similar models of the physical properties of the atmosphere exist, the most commonly known and used one being the 1962 U.S. Standard Atmosphere (Cole *et al.*, 1965) which represents average conditions of the atmosphere in the mid-latitudes around 45° North. One commonly divides the atmosphere into a number of layers according to the sign ($\pm$) of the vertical temperature gradient $\partial T / \partial z$. Despite the varied thermal structure of the atmosphere, except for water vapor variations, the relative composition of the atmosphere is essentially constant up to about 90 km above sea level, with diatomic nitrogen (78 percent) and diatomic oxygen (20.9 percent) being the major constituents.

Let us briefly describe the 1962 U.S. Standard Atmosphere since it is the basis of many calculations of atmospheric opacity. As one would expect from thermodynamical models of the atmosphere which treat air as an ideal gas, the density $\rho(z)$ of dry air as a function altitude varies approximately exponentially with a density scale height of $H_a = 9.5$ km and a mean sea level density of $\rho_0 = 1.225 \text{ kg m}^{-3}$, i.e.

$$\rho(z) = \rho_0 e^{-z/H_a}$$

The temperature profile of the atmosphere is modelled as being piecewise linear with respect to the geometric altitude. For altitudes less than 32 km the average temperature can be approximated as follows:

$$T(z) = \begin{cases} T_0 - az, & 0 \leq z \leq 11 \text{ km}; \\ T(11), & 11 \leq z \leq 20 \text{ km}; \\ T(11) + b(z - 20), & 20 \leq z \leq 32 \text{ km}; \end{cases}$$

where $a = 6.5 \text{ K km}^{-1}$ and $b = 1 \text{ K km}^{-1}$. Generally we only need to consider the first 30 km of the atmosphere since at an altitude of 30 km the density of dry air is only about 1.5 percent of its sea level value. The water vapor density, although sometimes greatly variable over short time intervals, also generally varies exponentially on clear days and may be expressed as

$$\rho_{wv} = \rho_{0wv} e^{-z/H_{wv}}$$

where the scale height H_{wv} is between 2 km and 2.5 km, and the average sea level value $\rho_{0wv} = 7.72 \text{ g m}^{-3}$. Using the ideal gas relation, one can determine the dry air pressure and the partial water vapor pressure from the above expressions for the respective densities.

1.3 Sources of Microwave Absorption in the Atmosphere

In general one must consider two types of interaction, absorption due to energy transitions in the atmospheric gases, and absorption and scattering due to interaction between the incident radiation and particles, such as those found in fog and clouds containing liquid water or ice. To compute the attenuation due to the latter, it generally suffices to use the Rayleigh approximation of Mie scattering, since for the frequencies with which we are concerned ($< 90 \text{ GHz}$), the wavelength of the incident radiation is much larger than the size of the drops involved (Ulaby, 1981). It must be noted that this approximation does not remain valid for rain or heavy rain clouds. For our purposes, however, we are primarily concerned with clear weather behavior, although some of our measurements were taken under foggy or cloudy conditions. We will thus neglect attenuation due to scattering processes, but nevertheless estimate their values as well as check the validity of the calculations in this respect. Complete discussions and calculations of such attenuation may be found in the references (Ulaby, 1981; Waters, 1976).

Let us consider the other type of interaction which leads to attenuation and emission, namely interaction with atmospheric gases. Transitions between energy states of a molecule may involve changes in electronic, vibrational or rotational energy, or combinations of these in accordance with the appropriate selection rules. Of these transitions, only pure rotational transitions corresponding to changes of energy on the order of 10^{-4} to 5×10^{-2} eV fall in the microwave region (Townes and Schawlow, 1955). Of the constituents in the atmosphere, only oxygen and water vapor significantly contribute to absorption and emission in the microwave region when making measurements from low altitudes. At higher altitudes (> 20 km) other molecules such as ozone, nitrous oxide and carbon monoxide play increasingly important roles in the microwave absorption spectrum of the atmosphere (Waters, 1976; Ulaby, 1981).

1.3.1 Oxygen

Lacking a permanent electric dipole moment because of its charge density symmetry, the oxygen molecule, possessing a permanent magnetic moment, magnetically interacts with incident radiation producing a family of rotation lines in the 60 GHz region and an isolated line at 118.8 GHz (Townes and Schawlow, 1955). The ground electronic state of $O_2^1\Delta_g$, characterized in spectroscopic notation as $^3\Sigma_g$, has a component $\Lambda = 0$ of total angular momentum along the inter-nuclear axis and electron spin $S=1$, resulting from the fact that two p-electrons are unpaired. Because of its $S=1$ triplet state, for a given rotational quantum number K , the total angular momentum quantum number J can assume three values, namely $K-1$, $K+1$, and K , in order of increasing energy. Magnetic spin-spin coupling as well as spin-rotation coupling produce the energy level splitting between these three states, the energy levels being degenerate with respect to M , the component of J along a fixed axis. Because the oxygen molecule does not possess any spin, symmetries principles (Pauli exclusion principle) restrict N to odd values. Transitions between these states in accordance with the magnetic dipole selection rules result in a family of transitions ranging from about 50 to 70 GHz. The states $J = N \pm 1$, having non-zero diagonal matrix elements of the magnetic dipole, also give rise to so-called 'non-resonant' absorption near zero frequency. Although magnetic dipole transitions generally have relatively small transition probabilities, the great abundance of oxygen along any given line of sight increases the strength of these absorption lines.

1.3.2 Water Vapor

In contrast, the water molecule, possessing an electric dipole moment, electrically interacts with the incident radiation to produce rotation lines at 22.2 GHz, 183.3 GHz and other frequencies in the far-infrared region (above 300 GHz) (Townes and Schawlow). The water molecule is a planar asymmetric rotor with a permanent electric dipole moment pointing along the axis of symmetry. The asymmetry lifts the energy degeneracy of the total angular momentum quantum number J . A particular energy level may be described by four quantum numbers J (total angular momentum), M (projection of J along a fixed spatial axis), K_{-1} and K_{+1} (which correspond to projections of J on other axes defined by the theory of asymmetric rotors). Symmetry considerations allow only transitions with $\Delta J = \pm 1$ and transitions between $++/-$ and $+ -/-$ where the plus-minus signs refer to the symmetry of the $K_{\pm 1}$. For the case of water, non-resonant transitions are thus not allowed.

1.4 Theory of Absorption and Emission

1.4.1 Solution of Radiative Transfer Equation

Let us now try to quantitatively understand the atmospheric emission/absorption process. The formal solution of the equation of radiative transfer is given by

$$I_\nu(s) = I_\nu(0)e^{-\tau_\nu(s,0)} + \int_0^s J(s')e^{-\tau_\nu(s,s')} \kappa_\nu(s') ds' \quad (1)$$

where $I_\nu(s)$ is the intensity of radiation at frequency ν and position s , $J_\nu(T)$ is the source function for frequency ν and temperature T , $\kappa_\nu(s')$ is the specific attenuation coefficient at frequency ν and position s' , and $\tau_\nu(s, s')$ is the optical depth between points s and s' , given by

$$\tau_\nu(s', s) = \int_{s'}^s \kappa_\nu(s'') ds'' \quad (2)$$

(Chandrasekhar, 1960). For the case of a non-scattering, non-refractive atmosphere in thermal equilibrium, the source function is given by the Planck blackbody intensity function $B_\nu(T)$, i.e.

$$J_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1} \quad (3)$$

where c is the speed of light and k is Boltzmann's constant. We may physically interpret equation (1) in a very simple manner. The first term on the right hand side represents the original signal attenuated along the path between $s' = 0$ (the top of the atmosphere) and $s' = s$, the point of observation. The second term expresses the emission $B_\nu(T) \kappa_\nu(s') ds'$ from path element ds' attenuated along the pathlength between s' and s . If we multiply each side by the factor $(c^2/2k\nu^2)$ and define an antenna temperature T_A by

$$T_A = (c^2/2k\nu^2) I_\nu(s) \quad (3)$$

we arrive at

$$T_A = T_A(0)e^{-\tau_\nu(s,0)} + \int_0^s T_{B,A}(s') e^{-\tau_\nu(s,s')} \kappa_\nu(s', s) ds'. \quad (4)$$

As we shall later see (section 3.1), the definition of the antenna temperature will prove to be experimentally useful. In our experiment, $T_A(0)$ corresponds to the CBR antenna temperature along with other small contributions from the galaxy. Of course, equation (4) represents only a formal solution to the radiative transfer equation and the real task lies in computing the specific attenuation coefficient.

1.4.2 Specific Attenuation Coefficient

The specific attenuation coefficient $(\kappa_\nu)_{lm}$ corresponding to a transition between states denoted by l and m may be expressed as

$$(\kappa_\nu)_{lm} = (4\pi\nu/c) S_{lm} (10^6 \log_{10} e) f(\nu, \nu_{lm}) \quad (5)$$

where S_{lm} is the line strength of the particular transition, ν_{lm} is the frequency (in GHz) corresponding to the energy change, and $f(\nu, \nu_{lm})$ is the line shape function describing the shape of the absorption line. The factor of $10^6 (\log_{10} e)$ is used to convert $(\kappa_\nu)_{lm}$ from cm^{-1} to units of dB km^{-1} . The line shape function expresses the effects of line broadening mechanisms on the spectral line. For

altitudes lower than about 70 km, the broadening due to collisions dominates the spectral broadening mechanisms (Waters, 1976). Both natural and Doppler (thermal) broadening are negligible at these altitudes. The standard approach for calculating the line-shape factor due to pressure broadening entails treating the collisional process as an interaction (in the impact approximation) between a harmonic oscillator (the absorber) and a perturber (Lam, 1977; Ben-Reuven, 1969). The only significant perturbers in the atmosphere are diatomic oxygen and diatomic nitrogen. Commonly used line shapes are the Van Vleck-Weisskopf line shape and the Gross or kinetic line shape, both of which have met some success in correctly describing the observed shapes of spectral lines. More detailed calculations taking into account the interference effects due to overlap have been made by several authors (Rosenkranz, 1975; Lam, 1977; Smith, 1981). In Liebe's notation (1981), the resulting line shape as calculated by Rosenkranz is

$$f_R(\nu, \nu_{lm}) = \left(\frac{\nu}{\nu_{lm}} \right) \left[\frac{\gamma - (\nu - \nu_{lm})\delta}{(\nu - \nu_{lm})^2 + \gamma^2} + \frac{\gamma - (\nu_{lm} + \nu)\delta}{(\nu_{lm} + \nu)^2 + \gamma^2} \right] \quad (6)$$

where γ is the width of the line and δ is the overlap interference coefficient. The line strength S_{lm} of a given transition depends on the transition matrix element, the density of molecules, and the populations of the initial and final energy states. The total specific attenuation coefficient resulting from all of these transitions is just the sum over all $(\kappa_\nu)_{lm}$:

$$\kappa_\nu = \sum_{l,m} (\kappa_\nu)_{lm}. \quad (7)$$

The sum is taken over all transitions of oxygen and water vapor that contribute to absorption in the microwave region.

1.5 Calculations for Water Vapor and Oxygen

As stated in the introduction, in the atmospheric window regions the observed attenuation is approximately 3–5 times larger than the one obtains from direct calculations. This problem has become known as excess water attenuation (EWA). As of yet no widely accepted theory accounting for this phenomenon exists. Because of this, most calculations of the atmospheric attenuation include an empirical term κ_{ewa} approximating the EWA as formulated by Gaut and Reifstein (1971). Designating κ_{nr} as the attenuation due to non-resonant oxygen absorption, the total specific attenuation becomes

$$\kappa_\nu = \sum_{l,m} (\kappa_\nu)_{lm} + \kappa_{nr} + \kappa_{ewa}$$

Both the line strength S_{lm} and the line shape factor depend on the pressure and temperature. We may express these dependencies for oxygen as follows:

$$\begin{aligned} S_{lm} &= a_{lm,1} p^{\theta^2} \exp[a_{lm,2}(1 - \theta)] \\ \gamma_{lm} &= a_{lm,3} (p + 1.3e)^{\theta^{0.9}} \\ \delta_{lm} &= a_{lm,4} p^{\theta^{a_{lm,5}}} \end{aligned} \quad (8)$$

where $\theta = 300/T$, T being the temperature expressed in Kelvin, p the partial dry air pressure, and e the partial water vapor pressure (Liebe, 1981). The pressures are expressed in units of kPa (1 kPa = 10 mbar). The constants $a_{lm,1}$ – $a_{lm,5}$ depend on the individual transitions and may be obtained from laboratory experiments and/or calculations. For water:

$$\begin{aligned} S_{lm} &= b_{lm,1} e^{\theta^{2.5}} \exp[b_{lm,2}(1 - \theta)] \\ \gamma_{lm} &= b_{lm,3} (4.80e + p)^{\theta^{0.63}} \end{aligned} \quad (9)$$

Since water transitions exhibit isolated line behavior (they are not clustered as is the case for oxygen) the interference coefficients δ_{lm} are all negligible for water. The constants $b_{lm,1-3}$, like the $a_{lm,1-3}$, depend on the individual transitions. Tables containing these constants, as well as expressions for the empirical and non-resonant terms, may be found in Liebe (1981).

Figures I and II show the results of calculations using relations similar to the ones shown above for the specific attenuation (Crane, 1981) and the atmospheric emission at sea level (Waters, 1976). Figure I gives one an idea of the magnitude of the empirical correction term needed to account for the observed attenuation. These figures reveal that the atmosphere's most significant effect in CBR spectrum measurements (at 10, 33 and 90 GHz) is as an emitter and self-attenuator, and not as an attenuator of the CBR. Figure II, the atmospheric windows centered around the frequencies 32 GHz, 90 GHz, 137 GHz and 245 GHz are quite noticeable. Using relations (3-9), one can also calculate the atmospheric antenna temperature from a given altitude as a function of the amount of precipitable water content W (in mm) by using average temperature and dry air pressure profiles. Using relations found in Waters for the values of the absorption coefficients and atmospheric profiles by McClatchey *et al.* (unpublished), Partridge *et al.* (1984) obtained the following results for an altitude of 3800 m:

$$\begin{aligned} 10.0 \text{ GHz: } T_{VA} &= 1.048 + 0.040W \\ 33.0 \text{ GHz: } T_{VA} &= 3.182 + 0.360W \\ 90.0 \text{ GHz: } T_{VA} &= 4.706 + 2.197W \end{aligned} \quad (10)$$

Accuracies of these calculations are estimated to be 100 mK, 150 - 200 mK, and 500 mK, respectively. More recent calculations by Danese (1984), using for the most part relations and data presented in Liebe (1981), obtained

$$\begin{aligned} 10.0 \text{ GHz: } T_{VA} &= 1.055 + 0.033W \\ 33.0 \text{ GHz: } T_{VA} &= 3.589 + 0.358W \\ 90.0 \text{ GHz: } T_{VA} &= 5.389 + 1.951W. \end{aligned} \quad (11)$$

As one can see, these calculations agree fairly well with each other except for the water contributions at 33 GHz and 90 GHz and the oxygen contribution at 90 GHz. The differences in the coefficients can be explained by the fact that the calculations by Danese include more oxygen and water lines at higher frequencies. The uncertainties in the interference coefficients and the incomplete understanding of the excess water absorption limit the accuracy of these expressions, especially at the higher frequencies.

Eliminating W from their results (relations 10-11) and expressing the temperatures as a function of one another, we obtain:

$$\begin{aligned} T_{VA,10} &= 0.111T_{VA,33} + 0.695 \\ T_{VA,10} &= 0.0182T_{VA,90} + 0.962 \\ T_{VA,33} &= 0.164T_{VA,90} + 2.41 \end{aligned} \quad (12)$$

using the results of Partridge *et al.*, and

$$\begin{aligned} T_{VA,10} &= 0.0922T_{VA,33} + 0.724 \\ T_{VA,10} &= 0.0169T_{VA,90} + 0.964 \\ T_{VA,33} &= 0.184T_{VA,90} + 2.60 \end{aligned} \quad (13)$$

using the results of Danese. By making simultaneous measurements at these frequencies of the vertical atmospheric antenna temperature and plotting these measurements against one another,

we may check the validity of these expressions, thereby checking the validity of the atmospheric emission models used.

In the above calculations, attenuation due to liquid water was neglected. For conditions encountered at White Mountain on a clear day, Danese (1984) estimates the attenuation κ_{lw} due to liquid water to be

$$\kappa_{lw} = 10^{-6} \rho^{-6} \nu^{1.90}$$

in dB km^{-1} , where ν is, as before, in GHz. This is a factor 10–100 times smaller (largest at 90 GHz) than the total calculated attenuation due to water vapor and oxygen at the frequencies with which we are concerned. The effects of scattering are also neglectable since the efficiency factor for scattering is much smaller than that of attenuation (Ulaby, 1981). Thus we are justified in neglecting contributions arising from liquid water attenuation on clear days. As we shall later see, our Berkeley data taken during foggy and cloudy weather qualitatively reveal the effects of increased emission for increasing frequency due to liquid water.

Figure I: Calculated and Measured Specific Attenuation as a Function of Frequency at a pressure of one atmosphere, 20° C temperature and 7.5 g/m³ water vapor density (from Crane, 1981). Note the magnitude of the attenuation in the window regions.

Figure II: Calculated Atmospheric and CBR Emission as a Function of Frequency (adapted from Waters, 1976). Calculations are for zenith observations from sea level and include 3 K for the intensity of the cosmic background radiation.

Chapter 2

Experimental Concepts

2.1 Radiometers and Microwave Sources

The intensity of atmospheric emission is measured at a fixed frequency by a radiometer, an instrument whose output signal is proportional to the power received by the antenna. In the Rayleigh-Jeans limit, the intensity I of radiation emitted by a black body at a temperature T is given by

$$I = 2kT\nu^2/c^2 \quad (14)$$

where k is Boltzmann's constant, ν is the frequency and c is the speed of light. One often reports intensity measurements in terms of an equivalent antenna temperature. One defines the antenna temperature T_A such that a blackbody at a temperature T_A which fills the antenna beam would emit an intensity I in the Rayleigh-Jeans limit. Thus

$$T_A = Ic^2/2k\nu^2 \quad (15)$$

From these relationships (14-15) it follows that the antenna and thermodynamic temperatures of a black body are related by

$$T_A = \frac{Tz}{(e^z - 1)} \quad (16)$$

where $z = h\nu/kT$ and h is Planck's constant. In the small frequency limit ($h\nu \ll kT$), the antenna and thermodynamic temperatures are nearly equal.

Several sources comprise the total power received by the antenna. To a good approximation, the power $T_{A,Zenith}$ received by the radiometer when directed at the zenith is given by

$$T_{A,Zenith} = T_{A,CBR} + T_{galaxy} + T_{ground} + T_{VA} \quad (17)$$

where $T_{A,CBR}$ is the antenna temperature of the CBR, T_{galaxy} is the antenna temperature of the radiation from the galaxy, T_{ground} is the antenna temperature of the terrestrial thermal radiation intercepted by the antenna sidelobes, and T_{VA} is the vertical antenna temperature of the atmosphere. Note that since the power received and the voltage output of the radiometer are linearly related, the radiometer may be calibrated in units of antenna temperature per voltage output. If care is taken to insure that the moon (measurements are taken at night) is not in the beam path of the antenna, the galactic term at 33 GHz is generally negligible (< 2 mK). The contribution from the antenna sidelobes can be measured and is generally also relatively small (< 20 mK). By far the largest signals come from the CBR (about 2.8 K) and the atmosphere (4-30 K at 33 GHz depending on altitude and weather conditions).

Figure III: The 33 GHz Radiometer. Not shown are the cart, side screens and reflectors, and electronics box. The view looks along the rails (east-west) upon which the carts are placed.

In practice, the radiometers used in this experiment have two antennas, the output being the difference of the two signals received by each horn. Then, for example, with one antenna looking at the zenith while the other is pointed at a reference load, we have the following relation

$$T_{A,Zenith} - T_{A,Load} = G(V_{Zenith} - V_{Load})$$

or

$$T_{A,Zenith} = G(V_{Zenith} - V_{Load}) + T_{A,Load} \quad (18)$$

where G is the calibration constant ($K \text{ volt}^{-1}$) and $T_{A,Load}$ is the antenna temperature of the load.

2.2 Reference Loads

One measures the calibration constant by simultaneously looking with the radiometer at two targets whose temperatures widely differ and are known to sufficient accuracy. Ideally one desires that the targets not only radiate in a blackbody-like manner but also have very stable temperatures. The gain G of the radiometer may be expressed as

$$G = dT_A / dV$$

where dT_A is the difference in antenna temperatures of the two loads pointed at and dV is the resulting signal obtained. Of course one must check to make sure that dV is indeed a linear function of dT_A for the temperature differences with which one is concerned. We checked the linearity of the gain and determined that the effects of saturation were less than 0.4 percent. The overall uncertainty of the gain (combining the saturation uncertainty with the uncertainty of the temperatures of the loads used) is less than 0.5 percent.

As cold reference loads, we used either a liquid helium- or liquid nitrogen-cooled dewar or the zenith sky. Although a convenient reference load for atmospheric measurements, the zenith sky varies too quickly and randomly for precise determinations of the system gain and of the CBR intensity. Affording a much more stable cold reference load, the dewar is cylindrical in shape (75 cm in diameter and 150 cm long) terminated on one end by a 20 cm thick slab of cone-shaped eccosorb and on the other end by two polyethylene windows which served to thermally insulate the LN or LHe from the ambient temperatures of the surroundings. The eccosorb, having a measured emissivity of greater than 0.9998 at 33 GHz (De Amici, 1984), behaves for all practical purposes as a blackbody.

The warm reference load consists of a microwave absorber maintained at ambient temperatures. The reflectivity of the absorber was measured to be less than -36.8 dB (0.02 percent at 33 GHz) (De Amici, 1984), hence also providing a very good blackbody target. The temperatures of the dewar target and the warm reference load were constantly monitored and measured to accuracies of 20 mK and 0.3 K respectively. More detailed descriptions of the reference loads may be found in previous papers (Smoot *et al.*, 1983).

2.3 Measurement of T_{VA}

One determines the thermal contributions from the atmosphere by measuring the antenna temperature of the incoming radiation at various known zenith angles. In order to understand the general procedure used to measure the atmospheric antenna temperature, let us first consider a very simple model of the atmosphere. Consider the atmosphere as a homogeneous, isotropic, perfectly transparent slab. Under these assumptions the atmospheric emission will be proportional to the

column length of air which is looked through. The signal V_{Out} ($= T_{Out}/G$), obtained when one antenna points at the zenith while the other points at an angle α from the zenith, is then

$$V_{Out} = (T(0) - T(\alpha))/G. \quad (19)$$

But from equation (17),

$$T(\theta) = T_{CBR}(\theta) + T_{galaxy}(\theta) + T_{ground}(\theta) + T_{Atm}(\theta).$$

Equation (19) becomes

$$V_{Out} G = dT_{CBR} + dT_{galaxy} + dT_{ground} + dT_{Atm}. \quad (20)$$

where $dT_i = T_i(0) - T_i(\alpha)$. Since the CBR is isotropic to a high degree (Weiss, 1980), then $dT_{CBR} = 0$, neglecting the atmospheric attenuation which, as revealed in figure 1, is very small. As previously stated, the galactic contributions at 33 GHz (but not necessarily at 10 GHz) are negligible (< 2 mK) so we may set $dT_{galaxy} = 0$. Neglecting for a moment the sidelobe contribution which is generally also relatively small, our simple model yields

$$V_{Out} G = dT_{Atm} = T_{VA} - T_{Atm}(\alpha). \quad (21)$$

(Note that $T_{VA} \equiv T_{Atm}(0)$.) Since the signal from a given angle is proportional to the column length through which the horn looks,

$$T_{Atm}(\alpha)/T_{VA} = \sec(\alpha).$$

For the vertical antenna temperature of the atmosphere we thus obtain

$$T_{VA} = \frac{GV_{Out}}{(\sec(\alpha) - 1)}. \quad (22)$$

The secant law is found to generally be accurate up to 1 percent for zenith angles less than about 70 degrees (Ulaby, 1981). To determine the atmospheric contributions with greater accuracy one must take several things into account. Because the antennas have a finite beam width (HPBW $\approx 7.5^\circ$) the calculation of T_{VA} must involve convolving the measured antenna beam pattern with the atmosphere, at the same time accounting for the curvature of the atmosphere and atmospheric self-absorption. Other corrections which we make in our calculations include system offset, sidelobe contributions, the imperfect reflectivity of the mirrors, among other things. The actual procedure used to calculate T_{VA} may be found in appendix A.

Chapter 3

The 33 GHz Radiometer

3.1 General Description and Common Features

Systematic errors determine the accuracy of our measurements of the CBR intensity and of the atmospheric emissions. The operating frequencies of the radiometers were primarily chosen to minimize two important sources of systematic errors, namely the galactic contributions and atmospheric fluctuations. As discussed in the second chapter, the frequencies of 33 and 90 GHz correspond to atmospheric windows. Figure III shows the 33 GHz radiometer. Common features of the radiometers include superheterodyne receivers operated with Dicke switching, thermal control systems, corrugated horn antennas, mirrors, carts and side screens. All three radiometers share the same power supplies, digital recording system and cold-load dewar. The function of each of these as they pertain to the 33 GHz radiometer is briefly described below. Descriptions of the 10 GHz and 90 GHz radiometers and a more detailed description of the 33 GHz radiometer may be found in previously published papers (Friedman, 1984; Witebsky, 1984; De Amici, 1984).

3.2 Receiver and Support Electronics

The receiver is mounted to a cart with bearings to allow for rotations in the north-south vertical plane. The antennas are conically shaped and corrugated in the inside to increase the directivity and to suppress the sidelobes. A Dicke switch operating at 100 Hz switches between the sources rapidly enough so that neither the system noise nor the gain can significantly change during a given period. The output of the switch is then mixed with a 32.91 GHz signal from a local oscillator. The resulting signal at the differential frequency is amplified by two intermediate frequency amplifiers having band pass widths of 500 MHz. After being rectified by the detector diode the signal is sent to a synchronous (lock-in) amplifier located in the support electronics box attached to the cart. The lock-in demodulates, amplifies and integrates the signal for two second intervals. Every two seconds the data digitizes and records the output. Thermal control systems, also located in the support electronics box, monitor and control the temperatures of the receiver and support electronics to prevent large changes in system gain. The sensitivity of the radiometer is about $80 \text{ mK Hz}^{-1/2}$.

3.3 Mirrors, pointing system and ground screens

Each mirror consists of an aluminum honeycombed core sandwiched by two flat aluminum sheets and reinforced by channels along the edges. This design has proved to be effective in prevent-

ing warps. The pointing system allows the mirrors to be set at pre-set angles to an accuracy of 2 arcminutes. The fact that the mirrors do not intercept 100 percent of the beam pattern necessitates the use of ground screens to minimize the thermal terrestrial emissions intercepted by the antenna sidelobes. With the ground screens in place, the contribution T_{ground} is reduced to less than 20 mK.

3.4 System Performance Tests

In order to check the performance of the radiometer several tests were done, some of which were periodically repeated. These tests include magnetic sensitivity tests, flip-offset tests, integration tests, gain stability tests, side lobe tests and radio frequency tests. Testing the sensitivity of the magnetic materials in the Dicke switch to the orientation of the earth's magnetic field, the magnetic sensitivity test yielded an effect well within the noise of the radiometer (about 15 mK). Similarly, the flip-offset test, designed to test the receiver's sensitivity to the manual rotations which need to be periodically performed during our measurements, also yielded a result well within the noise level. Designed to ascertain whether there are any periodic modulations in the system noise, the integration tests failed to reveal any periodic structure in the noise. The results of the gain stability tests indicate that the gain of the radiometer does not drift by more than 0.1 percent during a 17 minute period. The point-to-point fluctuations of the output of the radiometer can easily be accounted for by fluctuations in the sources pointed at, indicating that the gain is sufficiently stable. Although small, the signal intercepted by the antenna sidelobes, measured by the side lobe tests, is accounted for during the analysis of the data. Finally, the radio frequency test indicated that the amplifiers were sufficiently shielded from external man made radio sources. More detailed accounts of these tests can be found in the literature (De Amici, 1984).

Chapter 4

Observations

4.1 Berkeley

During the summer months of 1984, we measured the atmospheric emissions several times a week from the roof of building 50 at the Lawrence Berkeley Laboratories. The laboratories are located in the Berkeley hills and are at an elevation of several hundred feet above sea level. As is desirable when making studies of the atmospheric emissions, the measurements were made under a variety of weather conditions. Attempts were especially made to take data on either very dry or very humid (foggy) nights. Typical values for the ambient temperature and barometric pressure are 15–24 °C and 760 mmHg, respectively. For the most part, the measurements were done during the night though it is not absolutely essential to do so. Although the lab is equipped with all of the modern conveniences, our set-up on the roof was designed to simulate (as best as was possible) the set-up at White Mountain. The measuring sequence used is exactly the sequence used at White Mountain when the radiometer was not over the dewar (see section 4.2.2). In contrast to the procedure used in White Mountain, most of the data was read directly from voltmeters and recorded by hand. In addition to measurements of the atmospheric emissions, the previously mentioned system performance tests were also carried out for each radiometer to insure that the radiometers were ready for the more important White Mountain measurements.

4.2 White Mountain

4.2.1 Site and Conditions

Located near Bishop, California on a plateau at an elevation of 3800 meters is the University of California's high-altitude White Mountain Research Station (Nello Pace Laboratory), where we stayed during the month of August 1984 and carried out our measurements. Because of the high altitude and semi-arid climate of the site, the atmospheric intensity is greatly reduced. Typical values for the ambient temperature and barometric pressure were 2–10 °C and 490 mmHg. The typical column density of precipitable water is roughly one-fifth the minimum column density at Berkeley. Accessibility and weather conditions limit ones measurements to the summer months.

Our set-up consisted of a set of 20 meter-long rails spaced 1.9 meters apart and aligned in the east-west direction, a electronics hut located several meters south of the tracks, a supply hut, and a dewar centrally located with respect to the tracks and suspended in a hole in the ground. The rails allowed the carts to be moved with minimal effort over the dewar one at a time. With one radiometer positioned over the dewar to measured the CBR, the other radiometers could perform measurements and tests which do not require the use of a very stable cold reference load.

4.2.2 Data-Taking Routines

After setting up our equipment at the White Mountain site, we proceeded to repeat some of the tests performed in Berkeley (integration, atmospheric stability, gain stability, etc.) to make sure that the radiometers survived the rough trip. These tests also included several practice CBR measurement runs using an LN cooled dewar. Between these tests we interspersed frequent simultaneous measurements of the vertical antenna temperature of the atmosphere. When not over the dewar, we measured T_{VA} at 33 GHz using the following sequence:

Calibration of both horns

$N = 0, S = -50, -45, -40, 40, 50$

Offset

$S = 0, N = 50, 45, 40, -40, -50.$

The + (-) sign refers to zenith angles pointing to the north (south), whereas N (S) refers to the north (south) reflector. Through the use of manually operated switches, the position of each mirror is recorded along with the radiometer output. We measured each of these for approximately 32 seconds, an entire sequence lasting about 7 minutes. The essential features of a sequence in addition to measuring the intensity as a function of angle are measurements of the gain and instrumental offset. The 10 and 90 GHz radiometers followed similar sequences. When over the dewar, in order to measure the CBR as often as possible, the atmospheric emissions at 33 GHz were only measured at ± 40 and ± 50 degrees. The measuring sequence followed for the 33 GHz radiometer was:

CBR and Calibration (for each horn)

Offset

$N = 0, S = -50, -40$

$S = 0, N = 50, 40$

So that the atmospheric emissions could be correlated at different frequencies, when one radiometer was positioned over the dewar, the other radiometers made several T_{VA} measurements. The CBR runs over the dewar for each radiometer lasted approximately one hour and were repeated 3-4 times over a two night span.

Chapter 5

Data Reduction and Analysis

5.1 General Approach

Because of the variability of the weather conditions over short time intervals, the data taken in Berkeley during the summer was for the most part analyzed using the simple model discussed before which neglects attenuation, curvature, emissivity of the mirrors, etc. Similarly, the data taken at the White Mountain Research Station was first analyzed in the field in this manner. These rough calculations in 'real' time allow us to identify any problems if they should arise. Upon returning to Berkeley, the data, after being transferred from the magnetic tape to more accessible data files, were edited by hand to get the most complete use of the data and to avoid faulty records. Of the possible 32 seconds for each position, 24–28 seconds usually contain usable data. The other 4–8 seconds contain data recorded when the radiometer and/or mirrors were being positioned. In order to obtain the best possible estimates of the experimental uncertainty involved in measuring T_{VA} , we separated statistical and systematic errors as much as possible during our analysis of the data.

5.2 Calculation of Experimental Uncertainty

Because the equation used for determining T_{VA} is rather involved, the error in T_{VA} cannot be treated in the conventional fashion, i.e.

$$(dT_{VA})^2 = \sum_{i=1}^n \left[\left(\frac{\partial T_{VA}}{\partial x_i} \right) dx_i \right]^2$$

To overcome this difficulty, we calculate the change in T_{VA} when mean of each variable is replaced by the sum of the mean and the associated standard deviation. The total error squared is then just the quadrature-summation of the individual errors, i.e.

$$(dT_{VA})^2 = \sum_{i=1}^n (dT_{VA}(x_i, x_i \pm dx_i))^2 \quad (16)$$

where $dT_{VA}(\dots)$ is the change of T_{VA} when the one-sigma variations are substituted in the equations for T_{VA} . The sources of uncertainty are: the gain, the rms system noise, pointing angles, antenna beam pattern, side-lobe contributions, mirror emissivity, and atmospheric scale height. Whereas the rms system noise is statistical in nature, the other sources of error are systematic. Table 5.1 shows our best estimation of each of these errors. Let us briefly discuss each of these errors for the 33 GHz.

Source of Error	10 GHz* Radiometer	33 GHz Radiometer	90 GHz Radiometer
Gain	1.8 %	25 mK	160 mK
Atmospheric temperature	small	< 15 mK	16 mK
Atmospheric depth	small	< 10 mK	15 mK
Beam shape	small	< 50 mK	small
Sidelobes	7 mK	0-20 mK	11 mK
Pointing	10 mK	20 mK	45 mK
Mirror Emissivity	25 mK	80 mK	40 mK
Flip-offset	30 mK	none	9 mK
Total in quadrature	120 mK	90 mK	173 mK

Table 5.1: Summary of magnitudes of systematic errors for all three radiometers.

* Uncertainties quoted for the 10 GHz radiometer, except for the total uncertainty, are uncertainties in the quantities themselves (not the resulting uncertainty in T_{VA}).

5.2.1 System noise

Random thermal noise in the system, being for the most part statistical in nature as verified by integration tests, decreases as the inverted square root of the integration period for periods of up to 8 minutes. Auto-correlations and Fourier analyses of the radiometer output fail to reveal any periodic structure, indicating that we may treat the system noise as being purely statistical.

5.2.2 Gain

The systematic error resulting from the gain uncertainty has two different sources. One has to do with the uncertainty in the measurement of the gain, resulting from uncertainties in the temperatures of the calibrators, possible reflections of the power radiated by the radiometer by the targets, etc. The other uncertainty arises from an imperfect knowledge of the linearity of the radiometer's response.

5.2.3 Physical Temperature of the Atmosphere

When computing the atmospheric antenna temperature, we assume a fixed mean value of 250 K for the physical temperature of the atmosphere. Because of the variability of weather conditions, this value could be off by as much as 20 K which result in an uncertainty in our calculation of T_{VA} of about 15 mK.

5.2.4 Antenna Beam Pattern

The calculation of T_{VA} involves convolving the atmospheric intensity with the beam pattern of the antenna. The measured beam pattern is approximated by an ideal gaussian shape. Deviations of 1 percent from the actual beam pattern, the maximum deviation observed, result in an uncertainty of less than 50 mK.

5.2.5 Sidelobes and Diffraction

Contributions from effects of diffraction around the upper edges of the mirrors and from other ground contributions intercepted by the antenna sidelobes result in another systematic uncertainty. These were measured by chop tests to be less than 20–30 mK.

5.2.6 Systematic Corrections

Depending on whether or not the radiometer was over the dewar doing CBR measurements, we either measured the atmospheric intensity at four or ten angles. The atmospheric emission when measured at the four angles was found to be about 2 percent cooler than the measured intensity averaged over all angles. We attribute this to an imperfect understanding of the process of atmospheric emission or some systematic effect of the radiometer itself.

5.2.7 Pointing Angles

Although measured within an accuracy of about 1 arcminute, reflector angles have a measured repeatability of about 2 arcminutes. Since the reflector angles cannot be feasibly measured during each measurement, this uncertainty of the reflector position results in a possible systematic error of about 25 mK.

5.2.8 Mirror Emissivity

The uncertainty in the emissivity of the mirrors results in another systematic uncertainty. Differences between calculated and measured values indicate that the thermal emission from the mirrors could be as much as 60 mK higher than expected, resulting in an uncertainty of equal magnitude.

5.2.9 Atmospheric Scale Height

In our calculations we used an atmospheric model with a density scale height of 8 km. Liberalizing allowing for a 50 percent error in this value, the antenna temperature of the atmosphere would change by no more than 10 mK.

Chapter 6

Results and Interpretation

6.1 Results of White Mountain Measurements

From theoretical considerations we expect the atmospheric antenna temperatures at various frequencies to be linearly correlated. Our results strongly confirm this correlation. Plots I–III show our results for our White Mountain measurements. Plot IV shows simultaneous measurements taken at 33 and 90 GHz during good weather only. Each point on the plot corresponds to the average measured atmospheric temperature during a sequence (4–6 points). Since the number of measurements made over a sequence is small, the standard deviation of the data may not in some cases give one a good idea of the statistical error. To overcome this, statistical errors were averaged over a set of consecutive measuring sequences. The resulting averages were then summed in quadrature with the system noise fluctuations. Generally, the average statistical fluctuations of a given sequence were larger than the noise of the system. Quite noticeable in the plots, especially in the 33 vs. 90 GHz plot, are the regions corresponding to various weather conditions, i.e. clear weather (lower left), foggy weather (middle region), and cloudy weather (upper right hand corner). Typical values of the atmospheric antenna temperature during good weather ranged between about 1.02–1.47 K at 10 GHz, 3.95–7.05 K at 33 GHz, and 9.08–13.8 K at 90 GHz. These measurements are consistent with other measurements made at White Mountain about the same time of year. At frequencies of 9.4 GHz (Wilkinson, 1967) and 35 GHz (Stokes *et al.*, 1967), the vertical atmospheric antenna temperatures were measured to be 1.37 ± 0.10 K and 6.5 ± 0.2 K, respectively. Ewing *et al.* (1967) reported their measurements of T_{VA} to be 4.6 ± 0.2 K. Although the measurements by Stokes *et al.* and Wilkinson seem to be a little high as noted by Partridge *et al.* (1984), they still fall within the ranges we observed during clear weather.

The values for the slopes and intercepts are obtained from a linear best-fit procedure outlined in appendix B. Since the statistical uncertainties in the slopes and intercepts as calculated by the program only represent 'formal uncertainties,' the actual statistical uncertainty may be quite different. For example, the uncertainties quoted for plot II are much too small, as one can easily verify visually. By assuming that the statistical uncertainties of plots I and II are percentage-wise equal, we can get a reasonable estimate of the statistical uncertainty involved, especially since the 33 and 90 GHz data agree so well. The statistical uncertainties of the other plots calculated by the program seem to be reasonable.

To calculate the systematic uncertainty of these measurements we must consider two general types of errors: those which would merely shift the line without affecting its slope; and those which would change the scale (stretch or shrink) thereby changing the slope and the intercept. The first type of error (offset errors) includes uncertainties in the physical temperature of the atmosphere, atmospheric scale height, pointing angles, sidelobe contributions and mirror emissivity. The second

Plot I: T_{VA} : 10 GHz vs. 33 GHz (White Mtn. 1984).

Plot II: T_{VA} : 10 GHz vs. 90 GHz (White Mtn. 1984).

Plot III: T_{VA} : 33 GHz vs. 90 GHz (White Mtn. 1984).

Plot IV: T_{VA} : 33 GHz vs. 90 GHz (White Mtn. 1984). In contrast to the previous plot, the best fitting line is drawn through data corresponding to clear weather.

Frequency [GHz]	Offset [mK]	Scale [%]
10.0	83	6.03
33.0	121	2.30
90.0	66	1.28

Table 6.1: Offset and Scale Uncertainties

Plot	Slope	Intercept [K]	χ^2	No. Pts.
10 vs. 33 GHz	0.118 ± 0.008 ± 0.008	0.591 ± 0.085 ± 0.084	31.3	38
10 vs. 90 GHz	0.0282 ± 0.0026 ± 0.0017	0.821 ± 0.144 ± 0.083	54.9	30
33 vs. 90 GHz (good weather)	0.232 ± 0.008	1.92 ± 0.13	12.8	38
(combined)	0.237 ± 0.008 ± 0.006	1.87 ± 0.13 ± 0.12	40.2	51

Table 6.2: Results of our White Mountain measurements. The errors listed below the values represent the systematic errors.

type (scale errors) include uncertainties in the gain and beam pattern. Belonging to both of these groups is the systematic error discussed in regards to the 33 GHz radiometer (the 10 GHz radiometer has a similar problem) involving discrepancies of the atmospheric intensity as measured by different sets of angles. Table 6.1 summarizes the amplitudes of each of these errors for each radiometer.

Although the statistical errors may in some tenuous ways include the offset and scale errors mentioned above, this correlation should be relatively small. To estimate the total uncertainty we can combine the statistical and systematic errors in quadrature. This will provide us with an upper limit for the uncertainties, since in the limit as the number of measurements becomes very large, the statistical error should approach zero. Of course, we are ultimately limited by systematic errors, which give us a lower bound on our experimental uncertainties. However, because of the limited number of measurements, we must content ourselves with the above estimates. For these reasons the estimated total and systematic uncertainties are listed separately in Table 6.2 which summarizes the results from the plots. For reasons of comparison, the values for the 33 vs. 90 GHz plot are given for both the good weather data as well as the combined data.

One other possible source of error which must be considered is the effect of points representing extreme conditions tending to 'tie down' the slope. Related to this type of error is the additional attenuation that results from Mie scattering during weather conditions with fog or water clouds. If the uppermost point in plot I is removed from the plot, the slope decreases to 0.1160 which is still well within the estimated uncertainty. Similarly, if we remove the two uppermost points in plot II, the slope increases to 0.0283 which is also well within the experimental uncertainty. Plot III obviously shows no signs of extreme values being inconsistent with the other values. However, since the additional attenuation should increase with frequency (the specific attenuation goes approximately as $\nu^{1.90}$ as derived by Danese), these effects should be most noticeable in the plots II and

Value	Experimental	Calculated	
		Partridge <i>et al.</i>	Danese
$\alpha_{10,33}$	0.118 ± 0.008	0.111	0.092
$\beta_{10,33}$	0.591 ± 0.085	0.695	0.724
$\alpha_{10,90}$	0.0282 ± 0.0026	0.0182	0.0169
$\beta_{10,90}$	0.821 ± 0.144	0.962	0.964
$\alpha_{33,90}$	0.237 ± 0.008	0.164	0.184
$\beta_{33,90}$	1.87 ± 0.13	2.41	2.60

Table 6.3: Comparison of Results with Theoretical Expectations. The β 's are in units of Kelvin.

III. However, the large fluctuations of the points as well as the lack of significant amounts of bad weather data prevent us from detecting any additional attenuation due to liquid water. Although the slope of plot IV is slightly smaller than that of plot III, this could not be due to liquid water attenuation since we would expect the slope to decrease as a result of the accompanying increase of atmospheric emissions at 90 GHz. Furthermore, the slopes of plots III and IV agree with each other within experimental error. Thus the values measured under extreme conditions are very consistent with behavior observed in the lower regions of the plots, and do not pose any additional source of experimental uncertainty.

6.2 Self-Consistency and Comparison With Calculations

One test of the self-consistency of our results is the condition (by definition) on the slopes that within experimental error,

$$F_\alpha \equiv \frac{\alpha_{10,33}\alpha_{33,90}}{\alpha_{10,90}} = 1. \quad (23)$$

Our results yield the value $F_\alpha = 0.988 \pm 0.118$. Although this value is slightly low, it indicates that our values are most likely accurate. Because of the very good correlation of the 33 and 90 GHz data, this condition also suggests that the ratio of the slopes of plots I and II is fixed (and governed by the slope of plot III), although they both may be off a little due to experimental uncertainty.

Table 6.3 summarizes our results along with the values predicted from calculations by Partridge *et al.* and Danese. The slopes and intercepts are denoted by α_{ν_y, ν_x} and β_{ν_y, ν_x} respectively, where ν_y (ν_x) denotes the frequency of the y (x) axis. Although the experimental and theoretical values agree very well for the case of the two lower frequencies, the agreement for the other plots is substantially less. As expected, the inclusion of more water lines did in fact improve the ratio $\alpha_{33,90}$ of the water coefficients for 33 and 90 GHz, though the discrepancy is still somewhat large. Perhaps due to the uncertainty in the experimental values for the interference coefficients, the discrepancy between the experimental and theoretical intercepts has increased for the newer calculations.

If we denote the oxygen and water coefficients at a frequency ν by a_ν and b_ν , respectively, then the slopes and the intercepts are related to these coefficients by:

$$\begin{aligned} \alpha_{\nu_y, \nu_x} &= b_{\nu_x} / b_{\nu_y} \\ \beta_{\nu_y, \nu_x} &= a_{\nu_x} - a_{\nu_y} \alpha_{\nu_y, \nu_x}. \end{aligned} \quad (24a, b)$$

Thus the α 's serve to constrain the relative water coefficients, whereas both the α 's and the β 's constrain the oxygen contributions at the respective frequencies. Our measurements in themselves do not allow one to directly ascertain the oxygen and water contributions at each frequency. We

must have some foreknowledge of at least one a_v and one $b_{v'}$. However, by comparing the values obtained from theory and the constraints set upon them by our measurements one can get some idea of what the true values are.

The most reliable calculated coefficients are the ones for the lower frequencies not only because of their agreement with our experimental values but also because of their smaller dependence on the higher frequency water lines and the interference coefficients of the oxygen lines. Let us then consider the oxygen and water coefficients at 10 and 33 GHz. Because the oxygen contribution at 10 GHz for the most part depends only on the non-resonant term, this calculated value should be fairly accurate. It is also consistent with the minimum observed atmospheric antenna temperature at 10 GHz (about 1.02 K with a minimum uncertainty of 0.12 K). The observed ratio of the 10 and 33 GHz water coefficients agrees with the earlier calculations fairly well, despite the fact that it did not include as many water lines. The discrepancy between the newer calculations and the experimentally obtained slope may be reflected in a need to reevaluate the empirical correction in light of the inclusion of more far wing lines. It is quite possible that the empirical Gaut-Reifenstein term already accounted for some of the attenuation of the far wing frequency lines added in the newer calculations, thereby adversely affecting the newer calculations to some degree. An underestimate of the oxygen contribution in the earlier calculations would account for the discrepancy between the observed and calculated intercepts. Because both calculations yield approximately the same water coefficient at 33 GHz, it is reasonable to assume that this may be fairly accurate, especially in light of the fact that both calculations used quite different data bases. Our data would then indicate that b_{10} and b_{90} are 42 and 1510 mK mm⁻¹ water. That the value for 10 GHz agrees more with the older calculation could possibly be explained by the empirical correction term used in both calculations.

As a first estimation of the oxygen contributions at 33 and 90 GHz, we may use relation (24b), the results of plots I and II, and the a_{10} as calculated by Danese, which result in values of $a_{33} = 3.93$ K and $a_{90} = 8.30$ K with very appreciable uncertainties (several degrees). However, the correlation between 33 and 90 GHz is quite good, indicating that if we can make some reasonable guess of the oxygen contribution at one frequency, we presumably have a equally reasonable idea of the oxygen contribution at the other frequency. Uncertainties in the interference coefficients would effect both calculated values of a_{33} and a_{90} , affecting the latter more severely. Because of its greater distance from the 118.3 GHz oxygen line and far wing contributions, the calculated oxygen emission at 33 GHz is thus the more reliable of the two. An assumed $a_{33} = 3.60$ K would imply an oxygen contribution of about 7.3 K at 90 GHz. In light of the calculations by Danese and our Berkeley measurements as we shall later see, this value appears to be a little high, indicating that the oxygen emission at 33 GHz probably is not as high as 3.6 K. A more reasonable estimate of the oxygen contribution at 33 GHz would be about 3.5 K, resulting in an oxygen contribution at 90 GHz of about 6.9 K.

Fortunately, we can get some idea of the accuracy of the above estimates by comparing resulting estimates of the precipitable water content using measurements performed in 1983 with measurements taken with a solar hygrometer. However, such comparisons are complicated by the fact that the hygrometer readings necessarily were made during the day whereas the radiometer measurements were taken at night, after the radiometers, being somewhat exposed to the sun during the day, had had a chance to cool down. Plot V shows the results of such a comparison using the 90 GHz measurements. The overall consistency of the two sets of data appears to be decent, indicating that our estimates are not totally inaccurate.

To summarize, the estimated values for the water and oxygen coefficients for the conditions

Plot V: Precipitable Water Content (mm). This plot shows the precipitable water content as measured by a solar hygrometer and as calculated using relations (23) and measurements at 90 GHz (outlined by boxes), during August of 1983.

at White Mountain are:

$$\begin{aligned}T_{10} &= 1.055 + 0.042W \\T_{20} &= 3.50 + 0.359W \\T_{30} &= 6.88 + 1.51W.\end{aligned}\quad (23)$$

In principle, these expressions should be more accurate than the expression calculated by Partridge *et al.* and Danese. However, in light of the large discrepancies between our experimental results and the expected values from calculations, relations (23) are estimated to have uncertainties of about 15 percent. It must be stressed that the experimental obtained correlations between the various frequencies remain our best measure for the accuracy of future computations of the atmospheric emission.

6.3 Berkeley Measurements

Although calculations of the atmospheric emission at sea level as a function of the precipitable water content are not available, using the results of Waters for the oxygen contribution as well as the standard atmospheric model, both in light of our White Mountain results, we can obtain rough estimates of their magnitude. Plots VI–VIII show the results of our Berkeley measurements. For the 10 GHz measurements we used a slightly different technique (rotation of the mirror instead of the antenna), which in general yields atmospheric antenna temperatures about 100–200 mK higher due to reflector emission. Because the exact offset is not known, the 10 GHz values in plots VI and VII are not corrected for this effect. These plots also reveal an offset affect due to the uncertainty in polarization correction used. (Some of the measurements (for the most part good weather measurements) of the 10 GHz radiometer were performed without a polarizer. This effect was measured and found to increase the atmospheric antenna temperature by 280 mK. We made corrections for this effect; but, as our plots reveal, the corrections did not fully account for this effect, resulting in another source of uncertainty.) The fluctuations due to the variability of the atmospheric conditions, i.e. relative humidity, are more evident in these plots. Average clear night values of the atmospheric antenna temperature are 3.18 ± 0.29 K, 12.3 ± 0.3 K, and 34.4 ± 0.5 K, in order of increasing frequency. Due to effects of reflector emission discussed below, the average value at 10 GHz is more likely to be 3.03 K. Table 6.4 summarizes the results of the plots. To correct for the effects of reflector emission, 150 mK was subtracted from the intercepts of plots VI and VII. Again, both the total estimated error and the systematic error are listed. Uncertainties due to polarization and reflector emission increase the offset error in the 10 GHz measurements to about 101 mK (in contrast to 83 mK for White Mountain measurements). The best-fit lines are drawn through the points representing clear weather since there are obvious deviations resulting from attenuation and scatter by liquid water. Unfortunately, the low number of points taken during foggy or cloudy nights as well as the scatter and large errors of the ones that were taken prevent us from obtaining a quantitative result for the extra attenuation resulting from liquid water. The scatter of these points as well as their large uncertainties reflect the spatial and temporal variability of the atmospheric conditions on time scales smaller than the time it takes to perform a set of measurements (4–6 minutes).

Although the good weather data are very well linearly correlated as one can see from the plots, their small spread and number increases the experimental uncertainty, as defined and computed in the program. Most likely these measurements are more accurate than the 'formal' uncertainties reveal. The high confidence levels (low χ^2 's) reflect the large statistical fluctuations of the data and thus do not necessarily imply extremely good data bases. To check the consistency of our measurements, we may evaluate F_0 , as we did before for our White Mountain measurements. For these measurements, $F_0 = 1.08 \pm 0.09$. This value is fairly good and reflects an overall self-consistency not quite as good as that of our White Mountain measurements.

Plot VI: T_{VA} : 10 GHz vs. 33 GHz (Berkeley 1984). Note that the line is drawn through the data corresponding to clear weather. Also note the combined effects due to polarisation offset and liquid water attenuation. The 10 GHz values are not corrected for reflector emission (around 150 mK).

Plot VII: T_{VA} : 10 GHz vs. 90 GHz (Berkeley 1984). Note that the line is drawn through the data corresponding to clear weather. Also note the combined effects due to polarisation offset and liquid water attenuation. The 10 GHz values are not corrected for reflector emission (around 150 mK).

Plot VIII: T_{VA} : 33 GHz vs. 90 GHz (Berkeley 1984). Note that the line is drawn through the data corresponding to clear weather. The effects due to liquid water attenuation are clearly noticeable in the region corresponding to foggy or cloudy conditions.

Plot	Slope	Intercept [K]	χ^2	No. Pts.
10 vs. 33 GHz	0.171 ± 0.009 (± 0.008)	0.797 ± 0.144 (± 0.103)	1.47	10
10 vs. 90 GHz	0.0417 ± 0.023 (± 0.0017)	1.60 ± 0.11 (± 0.10)	3.22	16
33 vs. 90 GHz	0.263 ± 0.007 (± 0.006)	3.27 ± 0.15 (± 0.12)	6.94	17

Table 6.4: Corrected results of Berkeley measurements. The fits are to the good weather data only.

Frequency	Estimated Oxygen Emission [K]
10 GHz	2.0
33 GHz	7.0
90 GHz	9.0

Table 6.5: Calculated Oxygen Emission from Waters (Figure 1). Note that 3 K must be subtracted off to account for the cosmic background radiation.

To get an idea of the oxygen and water coefficients, we may use figure 1 from Waters. Since the calculations of Partridge *et al.* primarily used the results of Waters, we may use our White Mountain results to get an idea of how accuracy of figure 1. Table 6.5 summarizes estimates of the oxygen emission at sea level based on the calculations by Waters.

Our White Mountain measurements indicate that the calculated oxygen contribution at 10 GHz is fairly accurate. Furthermore, our White Mountain measurements also indicate that the emission at the 90 GHz is most likely under-estimated. Using a value of 6.3 K for the estimated oxygen contribution at 33 GHz and the results from the 33 vs. 90 GHz plot, we can estimate the oxygen contribution at 90 GHz to be about 11.5 K, which several degrees higher than the calculated value by Waters. We can check the consistency of these estimates by subtracting them from the average measured atmospheric antenna temperature. The ratios of these differences, the differences being the result of water vapor contributions, should agree with the measured slopes. The ratios of the differences corresponding to plots VI and VII (by construction plot VIII will agree) are 0.172 and 0.0450, which agree very well with the slopes considering the uncertainties in the slopes as well as the uncertainty in the average antenna temperatures. These ratios are very sensitive to the difference between the average good weather average atmospheric antenna temperature at 10 GHz and the estimated oxygen contribution at 10 GHz. An incorrect correction for the effects of reflector emission could easily change these ratios.

To estimate the water coefficients we may use a standard atmospheric model and estimates of the precipitable water content at 3800 m based on our White Mountain results. Our White Mountain results indicate that the mean precipitable water content is about 2.8 mm for a clear night, which is consistent with an exponentially varying water vapor density, with a sea level value of 7.72 gm^{-3} and a scale height of 2.15 km. Using these values, we can estimate the precipitable water content at Berkeley to be about 16.6 mm. Although the weather conditions at Berkeley and

Frequency	Average T_{VA} [K]	Oxygen Contribution [K]	Water Contribution [K]	Water Coefficient [K/mm water]
10 GHz	3.03 ± 0.30	2.0	1.03	0.062
33 GHz	12.3 ± 0.3	6.3	6.0	0.361
90 GHz	34.4 ± 0.5	11.5	22.9	1.40

Table 6.6: Estimates of the oxygen and water contributions at sea level assuming a water vapor scale height of 2.15 km and a mean sea level value of 7.72 gm^{-3} .

White Mountain might not have exactly the same type of behavior, this estimate gives us a rough idea of the precipitable water content. Because of Berkeley's proximity of the San Francisco Bay we would expect the precipitable water content normally to be a little higher. A scale height of 2.5 km would result in a precipitable water content of about 19.3 mm. The ratio of the estimated of the average estimated water contribution and the average estimated precipitable water content should give us a good indication of the water coefficients. Using 16.6 mm as the average precipitable water content on a clear night, we obtain 0.062, 0.361, 1.40 (in units of Kmm^{-1} water for 10, 33 and 90 GHz. Using 19 mm, we obtain 0.054, 0.316, and 1.21.

Table 6.6 summarizes estimates using 16.6 mm water as the precipitable water content. In light of the weather conditions at White Mountain this year, this value is probably fairly accurate. It must be remembered that the uncertainty involved in these estimates is relatively large and much hand waving has been done to make these estimates. These arguments, however, illustrate the considerations which must be taken into account when making such estimates. As is the case for our White Mountain measurements, the results of the Berkeley measurements best serve to constrain models of the atmospheric emission and suggest where more careful considerations must be made.

6.4 Conclusion

In general, our White Mountain results and our Berkeley results both reflect the need for an increased understanding of the microwave spectral behavior of the atmosphere. The discrepancy between the experimental and calculated values of the relative oxygen and water vapor dependencies could be the result of many things. The most obvious shortcoming of existing theories is the inability to explain the excess absorption observed in the window regions. As Lam notes (1977), the validity of the impact approximation, especially for the case of water vapor is somewhat questionable. However, the insolubility of many-body problems in quantum mechanics presently hinder calculations which do not use the impact approximation. Another more tangible cause of the discrepancy between our measurements and calculations, especially at higher frequencies, could be the uncertainty in the interference constants for the oxygen lines (Danes, 1984). Although many measurements under 100 GHz of atmospheric attenuation and emission already exist (Crane, 1981), our measurements, being simultaneous in nature, will provide very good constraints on future models of atmospheric attenuation and emission, especially in the window regions where the discrepancy is the greatest.

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Appendix A

Calculation of T_{VA}

As derived in the second chapter, as simple calculation of T_{VA} would involve an expression similar to that of equation (22). Let us now derive a more rigorous expression which we use in our actual calculations. Let us recall equation (4) of the first chapter:

$$T_A = T_A(0)e^{-\tau(\theta, \theta)} + \int_0^\theta T_{B,A}(\theta') e^{-\tau(\theta', \theta)} \kappa_\nu(\theta', \theta) d\theta'. \quad (4)$$

If we set $T_{B,A} = T_{aa}$, the antenna temperature representing the average physical temperature of the atmosphere, we may easily evaluate the integral and obtain:

$$T_A = T_A(0) e^{-\tau(\theta, \theta)} + T_{aa} (1 - e^{-\tau(\theta, \theta)}) \quad (A.1)$$

For our purposes $T_A(0) = T_{CBR}$, the antenna temperature of the cosmic background radiation. Accounting for the reflection of the mirrors but for the moment neglecting the finite beam width of the antennas, we can express the signal $T(\theta)$ intercepted from a given line of sight as:

$$T(\theta) = T_{CBR} e^{-\tau(\theta)} R(\theta) + T_{aa} (1 - e^{-\tau(\theta)}) R(\theta) + T_{RefI} (1 - R(\theta)) \quad (A.2)$$

where R is the reflectivity of the aluminum mirror, T_{RefI} the antenna temperature of the reflectors, and θ the zenith angle. Note that for a fixed value of θ , the elevation, the optical depth may be expressed as a function of angle. We can express the optical depth $\tau(\theta)$ as a function of the zenith optical depth $\tau(0)$:

$$\tau(\theta) = \tau(0) f(\theta) \quad (A.3)$$

where $f(\theta)$ accounts for the relative optical path lengths. Expressed to first order by the secant law, $f(\theta)$, when accounting for the curvature of the earth as well as its exponentially varying density and pressure, takes on the form:

$$f(\theta) = \sec(\theta) - (S/2) \sec^3(\theta) \quad (A.4)$$

where S is the ratio between the vertical scale depth of the atmosphere and the earth's radius. This correction, as one can see, is very small.

The atmosphere being very transparent at 33 GHz, i.e. $\tau(\theta) \ll 1$, we can expand the exponential in a power series:

$$e^{-\tau(\theta)} = 1 - \tau(\theta) + \tau^2(\theta)/2 - \tau^3(\theta)/6 + \dots \quad (A.5)$$

Since τ is of order 2×10^{-2} (nepers), the error introduced by neglecting terms in τ of order four and higher is small. To account for the finite beam width of the antennas, we may rewrite equation

effects are large and this interaction can mix excited states into the ground state. Using a model which considered only the mixing of these two states, Edelstein, et al. fit a series of g values for Pu^{3+} in CaF_2 , SrF_2 , and BaF_2 showing that the crystal field interaction decreased as the lattice parameter increased [14]. This same model has been applied to fit the g values for Am^{4+} in ThO_2 and CeO_2 [16]. The results are consistent with CeO_2 (the smaller lattice) having a larger crystalline field interaction at the Am^{4+} site than ThO_2 . A plot of the g values vs. the crystal field parameter is shown in Fig. 2. A more complete

Figure 2. Plot of calculated g value vs. B'_4 . The solid line describes the calculated values for $B'_6 = 0$. The dotted line describes the values for $B'_6/B'_4 = -0.2$. The arrows show where the experimental g values are located for $\text{Pu}^{3+}/\text{CaF}_2$, SrF_2 , BaF_2 . A similar plot may be drawn for $\text{Am}^{4+}/\text{CeO}_2, \text{ThO}_2$.

where

$$T_{VA} = (T_{aa} - T_{CBR}) \epsilon(\theta) [a(0) + \epsilon(\theta) (a(0)B(\theta)/(2A(\theta)) - b(0)/2) + \epsilon^2(\theta) \{B(\theta)/(2A(\theta)) (a(0)B(\theta)/(A(\theta)) - b(0)) + (c(0) - a(0)C(\theta)/(A(\theta)))\}]. \quad (A.13)$$

Here we have anticipated the meaning of the third term in equation (A.12) to be the atmospheric contribution, since all other sources of radiation have been accounted for in the first two terms. Thus equation (A.13) gives us an expression for calculating the vertical atmospheric antenna temperature. Similar routines were used to calculate T_{VA} at the other frequencies. It should be noted that the use of an actual atmospheric temperature profile instead of an average temperature does not pose any large difficulty, though the end result is very much the same (Witebsky, 1984).

Appendix B

Best linear fit routine

To calculate the best fitting line for the atmospheric plots, we employed a chi-squared minimization method. In this two-dimensional case, chi-squared takes on the form:

$$\chi^2 = \sum_{i=1}^n \left[\frac{(y_i - mx_i - b)^2}{\sigma_i^2} \right] \quad (B.1)$$

where

$$\sigma_i^2 = (\Delta y_i)^2 + (m \Delta x_i)^2.$$

The uncertainties in x_i and y_i are taken to be the random statistical uncertainties. We want to minimize chi-squared with respect to the slope m and the intercept b . Since differentiation with respect to m is very cumbersome and the solution for m cannot be expressed in close form, we prefer to differentiate with respect to b and solve for b in terms of m . We obtain:

$$b = \frac{1}{\sum_{i=1}^n \sigma_i^{-2}} \left(\sum \left[\frac{(y_i - mx_i)^2}{\sigma_i^2} \right] \right) \quad (B.2)$$

Plugging (B.2) into (B.1) and minimizing chi-squared with respect to m in a numerical fashion, we obtain the 'best fitting line,' as we have defined it.

For the one-dimensional case (when there are only uncertainties in the y coordinates of the data), the uncertainties in the best slope and intercept are given by the so-called error matrix. When the uncertainties are uncorrelated, the non-diagonal elements vanish in which case the uncertainties are given by the diagonal elements. Geometrically, in m and b space, the bounds of the ellipse $\chi^2(m, b) = \chi_{min}^2 + 1$ represent these uncertainties. For the two-dimensional case (uncertainties in both coordinates), we can estimate the uncertainties in the best slope and intercept by estimating the major and minor axes of the ellipse. To do this, we simply increase m , keeping b fixed at the value which minimized χ^2 , until χ^2 increases by one unit and repeat the process for b keeping m fixed. The absolute difference between the resulting values of m and b , and the values which minimize χ^2 then gives us some estimate of the statistical uncertainty of our values. In our case, this estimate is particularly good because of the small slopes and relatively equal uncertainties. In this case, $\sigma_i^2 = \Delta y_i^2 + (m \Delta x_i)^2$ is roughly equal to Δy_i^2 , thereby reducing the problem to the previous one-dimensional problem. This method ignores the correlation between the uncertainties, but nevertheless serves to generate good estimates of the uncertainties.

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Simultaneous Measurements of Atmospheric Emissions at 10, 33 and 90 GHz.

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Abstract

As part of a larger experiment to measure the cosmic microwave background radiation spectrum, frequent simultaneous measurements of the microwave thermal emission from the earth's atmosphere were made at three fixed frequencies, namely, 10 GHz, 33 GHz and 90 GHz. We performed these measurements at two separate locations, Berkeley and White Mountain, which greatly differed in altitude and climatic conditions. Typical values measured in Berkeley of the atmospheric antenna temperature during good weather are 3.13 ± 0.30 K, 12.3 ± 0.3 K and 34.6 ± 0.5 K, for 10, 33, and 90 GHz respectively. Corresponding values measured at White Mountain are 1.15 ± 0.1 K, 4.51 ± 0.18 K and 11.0 ± 0.2 K. Because the measurements are simultaneous in nature, correlations between the measurements taken at the various frequencies provide constraints on models of the microwave emission of the earth's atmosphere, especially models describing atmospheric emission as a function of precipitable water content.

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