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A Measurement of the Cosmic Microwave Background Temperature at 7.5 GHz

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ABSTRACT

We have measured the temperature of the Cosmic Microwave Background (CMB) radiation at a frequency of 7.5 GHz (4 cm wavelength), obtaining a brightness temperature of $T_{CMB} = 2.70 \pm 0.08$ K (68% confidence level). The measurement was made from a site near the geographical South Pole during the austral spring of 1989, and was part of an international collaboration to measure the CMB spectrum at low frequencies with a variety of radiometers from several different sites. This recent result is in agreement with our 1988 measurement at the same frequency (Kogut *et al.* 1990), which was made from a different site with significantly different systematic errors. The combined result of the 1988 and 1989 measurements is 2.64±0.06 K.

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1. Introduction

The low-frequency spectrum of the Cosmic Microwave Background (CMB) has long been expected to contain information relevant to the physical processes that occurred in the early universe (*e.g*. Danese and De Zotti 1982). Recent measurements (Mather *et al.* 1990, Gush *et al* .1991) have ruled out significant deviations from a blackbody spectrum above 30 GHz, leaving the low frequency spectrum as the most likely place for the detection of large spectral distortions.

This measurement was part of a continuing effort which began with an international collaboration in 1980. In the last decade, we and our collaborators have measured the CMB temperature at 0.60, 0.82, 1.4, 1.5, 2.5, 3.7, 3.8, 4.75, 7.5, 10, 33, and 90 GHz from sites in Italy, the United States, and Antarctica (Sironi *et al.* 1991, Smoot *et al.* 1987, and references therein). This measurement from the South Pole in 1989 employed the same 7.5 GHz radiometer used to measure the CMB temperature from the White Mountain Research Station on Mt. Barcroft, California in 1988 (Kogut, *et al.*1990). By repeating the measurement from a different site and using different techniques of data analysis, we are able to compare some of the systematic errors which have historically been a source of difficulty. Measurements with radiometers at other frequencies also increase our understanding of systematic errors, particularly those associated with atmospheric emission and with calibration. In this paper we will discuss some of these cross-checks on the systematic errors, but an in-depth discussion of this and other measurements in the larger context of the entire CMB measurement program will be left for a later paper.

2. Concept of the Measurement

The fundamental measurement concept remains unchanged, and is described in more detail elsewhere (*e.g*. De Amici et *al.* 1988, Kogut *et al.* 1990). We measured the CMB temperature with a total-power radiometer, calibrated in units of antenna temperature,

T_A, which is related to the power emitted by a blackbody completely filling the antenna aperture by the relation

$$T_A = \frac{P}{kB} = \frac{x}{e^x - 1} T , \tag{1}$$

where P is the received power, k is Boltzmann's constant, B is the bandwidth, T is the blackbody temperature, x is the dimensionless frequency

$$x = \frac{h\nu}{kT} , \tag{2}$$

h is Planck's constant, and ν is the frequency of observation (7.5 GHz).

The antenna temperature of the zenith sky, $T_{A,zen}$, is measured by comparing the signal from the sky with the signal from a cold-load calibrator (CLC) cooled with liquid helium. The antenna temperature of the CMB is then calculated by correcting for contributions from foreground sources, such as the Earth's atmosphere and emission from the Galaxy. A calibration load with antenna temperature close to $T_{A,CMB}$ is used to minimize the effects of errors in the gain calibration. The antenna temperature of the CMB is

$$T_{A,CMB} = G(S_{zen} - S_{CLC}) + T_{A,CLC} - T_{A,Atm} - T_{A,Gal} - T_{A,Gnd} - T_{A,RFI} - \Delta T_{sys} , \tag{3}$$

where G is the calibration constant of the radiometer, S_{zen} is the output voltage when the radiometer is pointed at the zenith, S_{CLC} is the output when the radiometer is pointed at the cold load calibrator, $T_{A,CLC}$ is the antenna temperature of the CLC, $T_{A,Atm}$ is the antenna temperature of the atmosphere observed at zenith, $T_{A,Gal}$ is the antenna temperature of the Galaxy at zenith, $T_{A,Gnd}$ is the antenna temperature of the ground seen through the antenna sidelobes, $T_{A,RFI}$ is the contribution from man-made radio frequency interference (RFI), and ΔT_{sys} refers to any systematic change (such as might be caused by gravitational stresses or twisting cables) in the radiometer performance when it is inverted to look at the CLC. Radiation from the Sun and the Moon were negligible from the South Pole site at this frequency, with the proviso that care was taken to measure the atmosphere (with tip scans) at times when neither the Sun or Moon was near the direction of observation.

The calibration constant of the radiometer was determined by comparing the signal from the CLC with an ambient temperature (~240 K) blackbody target. $T_{A,CLC}$ was calculated based on known and measured properties of the CLC (Bensadoun *et al.* 1992). $T_{A,Atm}$ was measured by tip scans, in which the changes in signal are correlated with the increased airmass in the beam resulting from tilting the radiometer to observe angles away from zenith. The small (0.007 K) galactic contribution was calculated by extrapolation from published measurements at lower frequencies. $T_{A,Gnd}$ was calculated from measurements of the antenna gain, and confirmed by tests which modulated the temperature of the radiation in the antenna sidelobes. The only sources of RFI in our frequency range were downward-looking radars from airplanes which occasionally (less than once per day) landed at the station, and spark noise from vehicles driven in the immediate vicinity of the radiometer. We rejected all data taken when airplanes or vehicles were within a kilometer of the observation site. ΔT_{sys} was measured by fixing stable targets (at various temperatures) to the antenna and repeatedly inverting the radiometer. Each of these contributions to the calculation of $T_{A,CMB}$ is discussed in greater detail below.

3. The Measurement

The 7.5 GHz radiometer is described in (Kogut *et al.* 1990), and remains unchanged with the exception of additional thermal insulation added for use at the South Pole. Measurements were made in December 1989 from a temporary camp 1.8 km away from Amundsen-Scott South Pole Station, in the direction of 30° W longitude. Atmospheric measurements were made from a metal platform with reflectors partly covering the adjacent ice (see Figure 1). Measurements of $G(S_{zen} - S_{CLC})$ were made from a nearby platform suspended above the CLC. The site lies on an ice field 2800 meters above sea level, has negligible water vapor (<1.4 mm precipitable water), a nearly flat horizon, and less RFI than any previous measurement site. In addition, we reduced ground emission by covering the ice immediately adjacent to the radiometer with 130 m^2 of aluminum to redirect sidelobes to the sky during atmospheric scans (Figure 1).

We made four sets of measurements of the difference between sky and CLC antenna temperature. Results of the measurements are given in Table 1, and the combined average (weighted by the inverse square of the RMS fluctuations of the individual measurements) is -0.126±0.006 K. Note that the variation of the four runs is larger than expected if all 4 sets of measurements were drawn from the same Gaussian distribution. A possible explanation of this is discussed in connection with ΔT_{sys} below. The unweighted average of the four measurements is -0.122 K with an RMS variation of 0.013 K. The value we substitute in Equation 3 is

$$G(S_{zen} - S_{CLC}) = -0.126 \pm 0.013 \text{ K}.$$

4. Calibration

The Cold Load Calibrator and the techniques used to calculate and verify its antenna temperature are described in detail in a separate paper (Bensadoun et al. 1992). It consists of a microwave absorber immersed in liquid helium (LHe), and its temperature is calculated from the boiling point of LHe, with small corrections for the radiometric properties of the surrounding Dewar. For all of the CMB observations, the ambient pressure was 522±1 Torr and the antenna temperature of the CLC was 3.685±0.018 K. There was an additional interface plate between the radiometer and the CLC, and its effects were measured at the South Pole, introducing a correction of -0.014±0.014 K. Thus the final value for the CLC antenna temperature was $T_{A,CLC} = 3.671 \pm 0.023$ K.

The calibration constant of the radiometer was determined by comparing the signal from the CLC with an ambient-temperature target, and the calibration constant was stable to better than ±1.4% over the course of the entire campaign. Non-linearity in the radiometer gain was measured by comparing the signal from the CLC, an ambient target, and an additional target immersed in liquid nitrogen, as described in (Kogut *et al.* 1990). The correction due to gain non-linearity was 0.97±0.01. Note that the effect on $T_{A,CMB}$ of a systematic error in radiometer calibration is proportional to the small (<1.2 K) difference between $T_{A,CMB}$ and $T_{A,CLC}$.

5. ΔT_{sys}

ΔT_{sys} was measured by "flip tests", in which a stable target is fixed to the radiometer, which is repeatedly inverted to simulate CMB measurements. Flip tests were performed with targets at various temperatures, ranging from 73 K (cooled with liquid nitrogen) to 303 K (electrically heated). Contributions to ΔT_{sys} which are due to changes in insertion loss or reflection should be proportional to the difference between target temperature and radiometer temperature. Contributions to ΔT_{sys} which are due to changes in gain should be proportional to target temperature plus radiometer system temperature. Electrical effects (such as might be caused by stressed cables and the like) should be independent of target temperature. The sum, ΔT_{sys}, therefore, should be linear in the target temperature. Figure 2 is a plot of ΔT_{sys} vs target temperature. Based on the linear extrapolation depicted in Figure 2, the value of ΔT_{sys} for CMB observations was $\Delta T_{sys} = -0.221 \pm 0.025$ K. We do not have a definite explanation for the day-to-day variation of $G(S_{zen} - S_{CLC})$ seen in Table 1, but it falls within the error bar for ΔT_{sys}, suggesting that variability of ΔT_{sys} is a possible explanation. The trip to the South Pole can be strenuous, and it is possible that ΔT_{sys} was caused in part by components loosened during the journey and insufficiently tightened at the South Pole. The ΔT_{sys} measurements depicted in Figure 2 were taken over the course of several weeks at the South Pole.

6. Atmospheric Emission

We measured the atmospheric antenna temperature by comparing the signal from the zenith sky ($T_{A,zen}$) to the signal when the radiometer was tipped to zenith angles of 31.1° ($T_{A,31}$) and 42.3° ($T_{A,42}$).

As discussed elsewhere (e.g. Witebsky *et al.* 1986), the antenna temperature seen by a pencil beam observing at zenith angle z is

$$T_{A,pen} = T_{kin}(1 - e^{-\tau h}) + T_{A,ext}(e^{-\tau h}), \tag{4}$$

where h is the path length through the atmosphere, defined by

$$h = \frac{1+R}{(\cos^2 z + 2R + R^2)^{1/2}} , \tag{5}$$

R is the atmospheric scale height in units of Earth radii, T_{kin} is the effective kinetic temperature of the atmosphere, τ is the effective optical depth of the atmosphere, and $T_{A,ext}$ is the emission from sources above the atmosphere (*i.e.*, the CMB, the Sun, and the Galaxy). Note that the angular dependence of the atmospheric emission simplifies to Secant(z) for $R \ll 1$ and $\tau \ll 1$.

The response of a radiometer tipped to zenith angle z is the convolution of Equation 4 with the antenna gain,

$$T_{A,z} = \int g(\theta,\phi)\, T_{A,pen}(\theta,\phi) \sin\theta \, d\theta \, d\phi , \tag{6}$$

where the dependence of the antenna gain g on zenith angle θ and azimuth ϕ takes into account the tip angle of the radiometer and $T_{A,ext}$ includes azimuthal dependence because it takes into account contributions from the Sun, the Galaxy, and the ground. Antenna gain pattern measurements were made with the ground shield in place, and the result is shown in Figure 3.

We assumed a value of $T_{A,CMB}$, numerically integrated Equation 6, adjusted τ to match the measured values of $T_{A,31} - T_{A,zen}$ and $T_{A,42} - T_{A,zen}$, and subtracted the assumed value of $T_{A,CMB}$ and the calculated values of $T_{A,Gal}$ and $T_{A,Gnd}$ to get $T_{A,Atm}$.

We then iterated to achieve a self-consistent value of $T_{A,ext}$ and hence $T_{A,CMB}$. Because τ is small (<0.01), $T_{A,31}$ - $T_{A,zen}$ and $T_{A,42}$ - $T_{A,zen}$ are nearly independent of $T_{A,CMB}$, and the iteration converged very rapidly. A 1 K change in the assumed value of $T_{A,CMB}$ would result in a change of less than 0.005 K in the calculated value of $T_{A,CMB}$, so the calculation required only a single iteration.

For purposes of the integration in Equation 6, the antenna temperature of the ground was taken to be 230 K, and the reflective aluminum ground covering was treated as a uniform 4 K blackbody. A 10 K change in the temperature of the ground would result in approximately a 0.001 K change in the estimate of $T_{A,CMB}$. Figure 4 shows the calculated contribution due to the Earth, the Sun, and the Galaxy as a function of angle, for a representative time. Because of the Earth's rotation, Solar and Galactic emission depend on the time of observation. We chose to measure the atmosphere at times when the scanning apparatus would tilt the radiometer nearly opposite to the Sun, a direction which nearly minimized Galactic corrections as well.

As a cross-check on the ground emission calculations, we performed a number of tests in which we repeatedly blocked part of the sidelobes with a large aluminum sheet, redirecting the sidelobes from the ~230 K ground to the ~4 K sky. The resultant signal difference is an indication of the ground emission seen by the radiometer during atmospheric scans. The results were in good agreement with the ground emission calculated using Equation 6 as described above. Table 2 compares the results of the measurements with the calculations. The error bars given for the calculations are systematic errors associated with the possibility of an error in the measurement of the antenna gain.

The Sun was modelled as a 0.5° diameter disk of temperature 6000 K, and contributed less than 0.005 K to most atmospheric measurements. Estimates of synchrotron and HII emission from our galaxy were based on measurements at lower frequencies (Haslam *et al.* 1982) and scaled with spectral power law indices of 2.75 and

2.1, respectively, as described in previous CMB measurement papers (e.g. De Amici *et al.* 1991). Both Solar and Galactic emission were small at the times and directions chosen for atmospheric scans (Table 3).

Because atmospheric tip scans involve tilting the radiometer, they open the possibility of a spurious signal caused by variation in the radiometer under gravitational stress. To determine the possible magnitude of this "atmospheric flip offset", we attached a stable radiometric target to the antenna, and performed tip scans in the same manner as for atmospheric measurements. The results were analyzed in the same way as the measurements of ΔT_{sys} described above, and the resulting corrections of 0.014±0.018 K and 0.006±0.012 K were applied to ΔT_{42} and ΔT_{31} (respectively), the measured signal differences between zenith and the two tip angles.

Table 3 show the results of the 10 tip scans used to determine $T_{A,Atm}$. Water vapor is the dominant source of variability in atmospheric emission at 7.5 GHz, because oxygen temperature fluctuations are partially compensated by the associated density fluctuations. Because of the negligible water vapor content at the South Pole, atmospheric emission variation at 7.5 GHz is expected to be small. Measurements at 90 GHz (which have a higher percentage contribution from water vapor) confirm that atmospheric emission varied by less than 5% over the time of observations (Figure 5). Consequently, we combine all of the atmospheric measurements by averaging them together, weighted appropriately by their error bars.

While the variation in the last columns of Tables 3a and 3b is within the stated error bars (the unweighted RMS of the measurements at 42° and 31° is 0.045 K and 0.069 K, respectively), the errors discussed above are mostly systematic in nature and the variation is greater than expected based on the statistical variation alone. As discussed in the preceding paragraph, the variability must be due to measurement error, rather than an actual variation in the atmospheric emission. One possible explanation for the additional variability is fluctuations in the atmospheric flip offset. We use the minimum total error from an individual measurement as the error on the combined final result, $T_{A,Atm} = 1.222\pm0.064$ K.

7. Other Contributions

There remain three small terms in Equation 3, $T_{A,RFI}$, $T_{A,Gal}$, and $T_{A,Gnd}$, which we have not yet discussed in detail. By spot checking with a spectrum analyzer and maintaining contact with the communications center at South Pole Station, we avoided taking data when RFI was present, so we take $T_{A,RFI}$ to be 0. $T_{A,Gal} = 0.007\pm0.004$ K and $T_{A,Gnd} = 0.022\pm0.015$ K are calculated by numerically convolving the antenna gain pattern with the source distribution.

Because the pattern of reflective ground covering is different over the CLC, $T_{A,Gnd}$ is not the same as the ground contribution to $T_{A,zen}$ discussed in Section V. We performed additional tests with the radiometer over the CLC (in the position used for CMB observations), adding and removing metal reflectors as described in Section V. The measured ground emission was 0.018±0.011 K, and we used the calculated emission of 0.022±0.015 K.

8. Conclusions

The terms in Equation 3 are summarized in Table 4. The total is $T_{A,CMB} = 2.517\pm0.075$ K. Inverting Equation 1 to convert to thermodynamic temperature, the brightness temperature of the CMB at 7.5 GHz is $T_{CMB} = 2.693\pm0.080$ K.

One of the reasons for repeating the measurement at the South Pole was to change the sources of systematic error and obtain a nearly independent measurement. The dominant source of systematic error in both years was the measurement of the atmosphere. The horizon was different in 1988 from 1989, reducing any similarity in the ground emission. Furthermore, the reflective ground covering added in 1989 was not present in 1988, and the method of estimating the ground emission, while equivalent, employed a different numerical technique. The galactic correction was different because of the change in location. The total atmospheric signal was different, and the relative contribution due to water and oxygen was different because of the differing pressure and humidity, resulting in a less variable atmosphere at the South Pole. Other changes from 1988 to 1989 include a change in the radiometer temperature, different measured ΔT_{sys}, different RFI environment, and different ambient temperature. The CLC was the same for both years, but was operated at different ambient pressures and hence different $T_{A,CLC}$. Table 5 presents an estimate of the correlation between the errors in 1988 and 1989. The result of the 1988 measurement was 2.597±0.074(±0.062) K, where the parentheses indicate the part of the error which we estimate to be uncorrelated with the 1989 result. Combining this with the 1989 result of 2.693±0.080(±0.066) K, we get T_{CMB} is 2.642±0.063 K, with a χ^2 of 1.1 for 1 degree of freedom.

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Time of Observation [UT]	$G(S_{zen} - S_{CLC})$ [K]	$RMS/(N-1)^{1/2}$ [K]	Number of Comparisons (N)
12/14/89 06:26 to 12/14/89 07:20	-0.127	0.012	17
12/14/89 21:06 to 12/14/89 21:28	-0.122	0.080	2 (Data after 21:16 rejected due to airplane radar)
12/16/89 15:13 to 12/16/89 16:05	-0.102	0.011	21
12/17/89 15:14 to 12/17/89 15:52	-0.138	0.008	17

Table 1. Measured comparisons of antenna temperature of vertical sky with antenna temperature of Cold Load Calibrator (CLC).

Radiometer Tip Angle	Measured Ground Emission	Calculated Ground Emission
Zenith	0.015±0.013 K	0.008±0.004 K
31.1°	0.008±0.015 K	0.013±0.007 K
42.3°	0.004±0.020 K	0.021±0.011 K

Table 2. Comparison of ground emission measurements with calculations based on the measured antenna gain pattern. Measurement and calculation both include the effects of the sheet metal ground covering depicted in Figure 1.

Time	ΔT_{42}	Flip Offset	$\Delta T_{gnd,42}$	$\Delta T_{gal,42}$	$\Delta T_{sun,42}$	$T_{Atm,42}$
12/14/89	0.522	0.014	0.013	0.007	0.000	1.297
05:37UT	±0.005	±0.018	±0.007	±0.004	±0.001	±0.065
						(±0.012)
12/14/89	0.508	0.014	0.013	0.009	0.000	1.256
05:57UT	±0.007	±0.018	±0.007	±0.005	±0.001	±0.066
						(±0.017)
12/14/89	0.536	0.014	0.013	0.025	0.004	1.276
07:57UT	±0.008	±0.018	±0.007	±0.013	±0.004	±0.085
						(±0.019)
12/14/89	0.494	0.014	0.013	-0.002	0.000	1.246
20:29UT	±0.005	±0.018	±0.007	±0.004	±0.001	±0.067
						(±0.013)
12/16/89	0.503	0.014	0.013	0.008	0.000	1.250
02:46UT	±0.004	±0.018	±0.007	±0.004	±0.001	±0.066
						(±0.010)
12/16/89	0.482	0.014	0.013	0.000	0.000	1.210
14:24UT	±0.008	±0.018	±0.007	±0.004	±0.001	±0.068
						(±0.020)
12/16/89	0.494	0.014	0.013	-0.001	0.000	1.245
16:47UT	±0.005	±0.018	±0.007	±0.004	±0.001	±0.066
						(±0.013)
12/17/89	0.460	0.014	0.013	0.000	0.000	1.152
14:27UT	±0.004	±0.018	±0.007	±0.004	±0.001	±0.066
						(±0.010)
12/17/89	0.473	0.014	0.013	-0.001	0.000	1.189
16:36UT	±0.003	±0.018	±0.007	±0.004	±0.001	±0.064
						(±0.008)

Table 3a. Atmospheric emission calculation. ΔT_{42} is the measured signal difference between the 42° tip angle and zenith, and $T_{Atm,42}$ is the calculated value of the atmospheric contribution to the vertical antenna temperature of the sky (see text). ΔT_{42} includes contributions due to ground emission ($\Delta T_{gnd,42}$) and Galactic emission ($\Delta T_{gal,42}$), and a "flip offset" from changes in the radiometer induced by mechanical stress. The quoted error on ΔT_{42} is statistical only and does not include systematic errors. The effect of this statistical error on $T_{Atm,42}$ is given in parentheses in the last column. The value given for $T_{Atm,42}$ is derived from the data using Equation 6 as described in the text.

Time	ΔT_{31}	Flip Offset	$\Delta T_{gnd,31}$	$\Delta T_{gal,31}$	$\Delta T_{sun,31}$	$T_{Atm,31}$
12/14/89 05:37UT	0.251 ±0.006	0.006 ±0.012	0.005 ±0.003	0.016 ±0.008	0.000 ±0.001	1.272 ±0.095 (±0.030)
12/14/89 05:57UT	0.246 ±0.006	0.006 ±0.012	0.005 ±0.003	0.017 ±0.009	0.000 ±0.001	1.238 ±0.096 (±0.030)
12/14/89 07:57UT	0.270 ±0.006	0.006 ±0.012	0.005 ±0.003	0.026 ±0.013	0.000 ±0.001	1.323 ±0.113 (±0.029)
12/14/89 20:29UT	0.210 ±0.005	0.006 ±0.012	0.005 ±0.003	0.007 ±0.004	0.000 ±0.001	1.139 ±0.087 (±0.027)
12/16/89 02:46UT	0.245 ±0.005	0.006 ±0.012	0.005 ±0.003	0.016 ±0.008	0.000 ±0.001	1.241 ±0.095 (±0.025)
12/16/89 14:24UT	0.224 ±0.011	0.006 ±0.012	0.005 ±0.003	0.000 ±0.004	0.000 ±0.001	1.212 ±0.100 (±0.060)
12/16/89 16:47UT	0.221 ±0.004	0.006 ±0.012	0.005 ±0.003	-0.001 ±0.004	0.000 ±0.001	1.200 ±0.087 (±0.022)
12/17/89 14:27UT	0.206 ±0.005	0.006 ±0.012	0.005 ±0.003	0.000 ±0.004	0.000 ±0.001	1.108 ±0.087 (±0.027)
12/17/89 16:36UT	0.212 ±0.004	0.006 ±0.012	0.005 ±0.003	-0.001 ±0.004	0.000 ±0.001	1.146 ±0.087 (±0.022)

Table 3b. Atmospheric emission calculation. ΔT_{31} is the measured signal difference between the 31° tip angle and zenith, and $T_{Atm,31}$ is the calculated value of the atmospheric contribution to the vertical antenna temperature of the sky (see text). ΔT_{31} includes contributions due to ground emission ($\Delta T_{gnd,31}$) and Galactic emission ($\Delta T_{gal,31}$), and a "flip offset" from changes in the radiometer induced by mechanical stress. The quoted error on ΔT_{31} is statistical only and does not include systematic errors. The effect of this statistical error on $T_{Atm,31}$ is given in parentheses in the last column. The value given for $T_{Atm,31}$ is derived from the data using Equation 6 as described in the text.

Source	**Effect**
$G(S_{zen} - S_{CLC})$	-0.126±0.013 K
$T_{A,CLC}$	3.671±0.023 K
$T_{A,Atm}$	-1.222±0.064 K
$T_{A,Gal}$	-0.007±0.004 K
$T_{A,Gnd}$	-0.022±0.015 K
ΔT_{sys}	0.223±0.025 K
$T_{A,CMB}$	2.517±0.075 K
T_{CMB}	**2.693±0.080 K**

Table 4. Calculation of $T_{A,CMB}$.

Source	Effect		Estimate of Correlated Error
	1988	1989	
$G(S_{zen} - S_{CLC})$	-0.146±0.012 K	-0.126±0.013 K	0.000 K
$T_{A,CLC}$	3.621±0.022 K	3.671±0.023 K	0.022 K
$T_{A,Atm}$	-1.083±0.059 K	-1.222±0.064 K	0.032 K
$T_{A,Gal}$	-0.010±0.005 K	-0.007±0.004 K	0.004 K
$T_{A,Gnd}$	-0.013±0.010 K	-0.022±0.015 K	0.007 K
ΔT_{sys}	0.052±0.028 K	0.223±0.025 K	0.020 K
$T_{A,RFI}$	0.000±0.005 K	---	0.000 K

Table 5. Estimate of correlation of errors between these results and our 1988 measurement (Kogut *et al.* 1990). The last column gives (for each source of error) an estimate of the amount of the error which should have been the same in 1988 as in 1989.

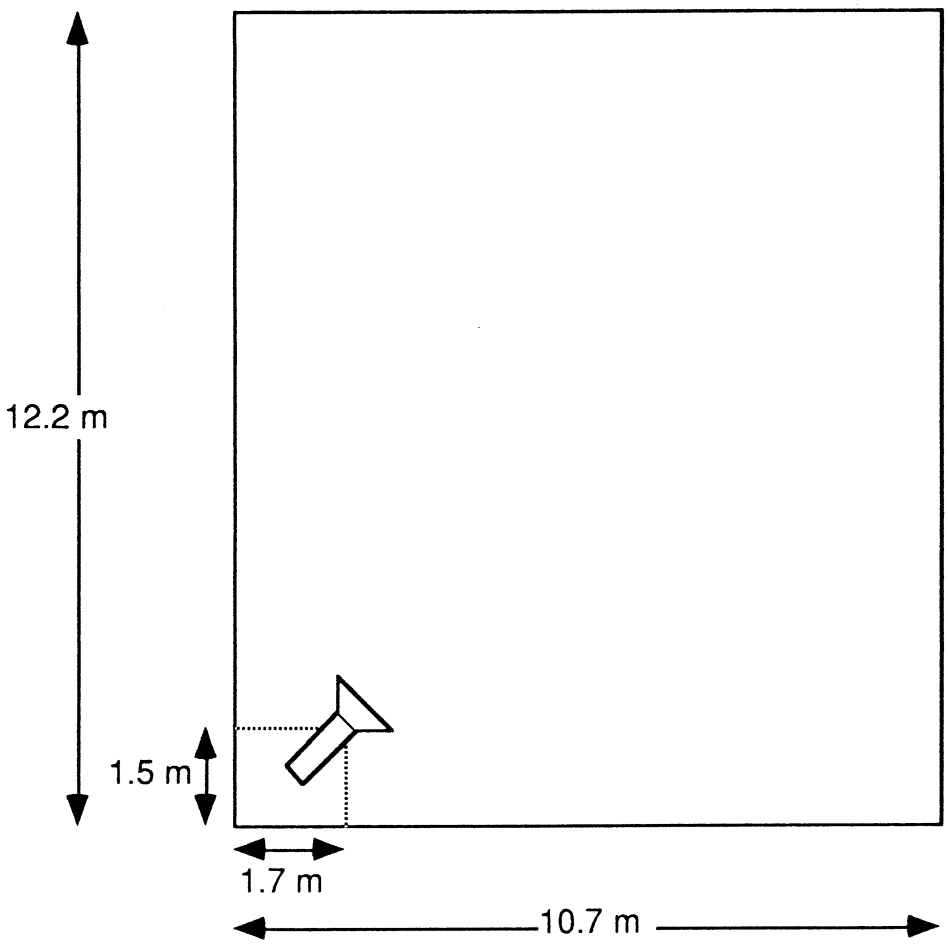


Figure 1. Sheet metal ground covering. Ice adjacent to the radiometer was covered with aluminum to redirect sidelobes to the sky. Atmospheric measurements (tip scans) were performed with the radiometer tilting towards the ground covering, as shown.

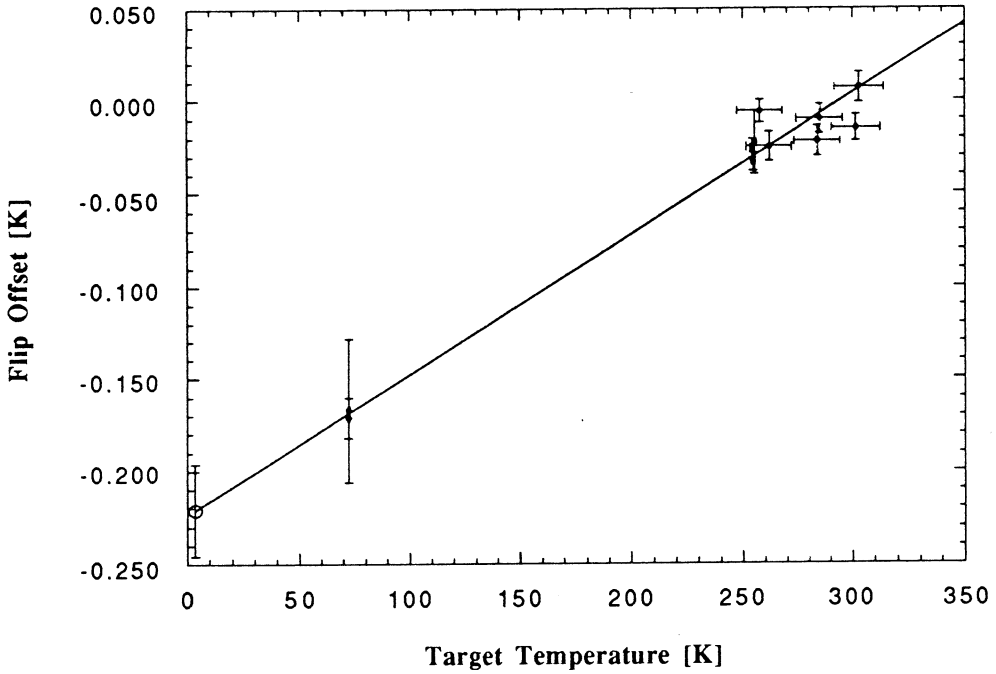


Figure 2. Vertical "flip offset" (ΔT_{sys}) vs the temperature of the target used to perform the test. The value of ΔT_{sys} which is appropriate to use for our CMB measurements corresponds to a target temperature of $T_{A,CLC}$ = 3.67 K. Filled circles represent measurements, and the open circle is the best estimate of ΔT_{sys} at 3.67 K, based on the linear extrapolation depicted, which is based on a 2-dimensional least-squares fit to the data.

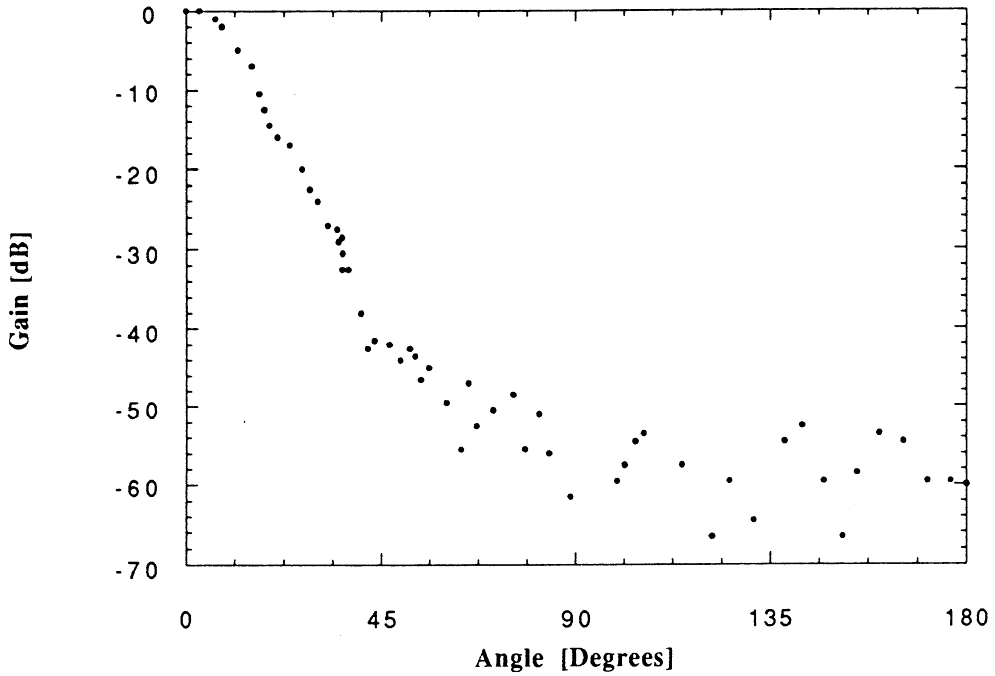


Figure 3. Measured antenna pattern of the 7.5 GHz antenna, with movable ground screen attached.

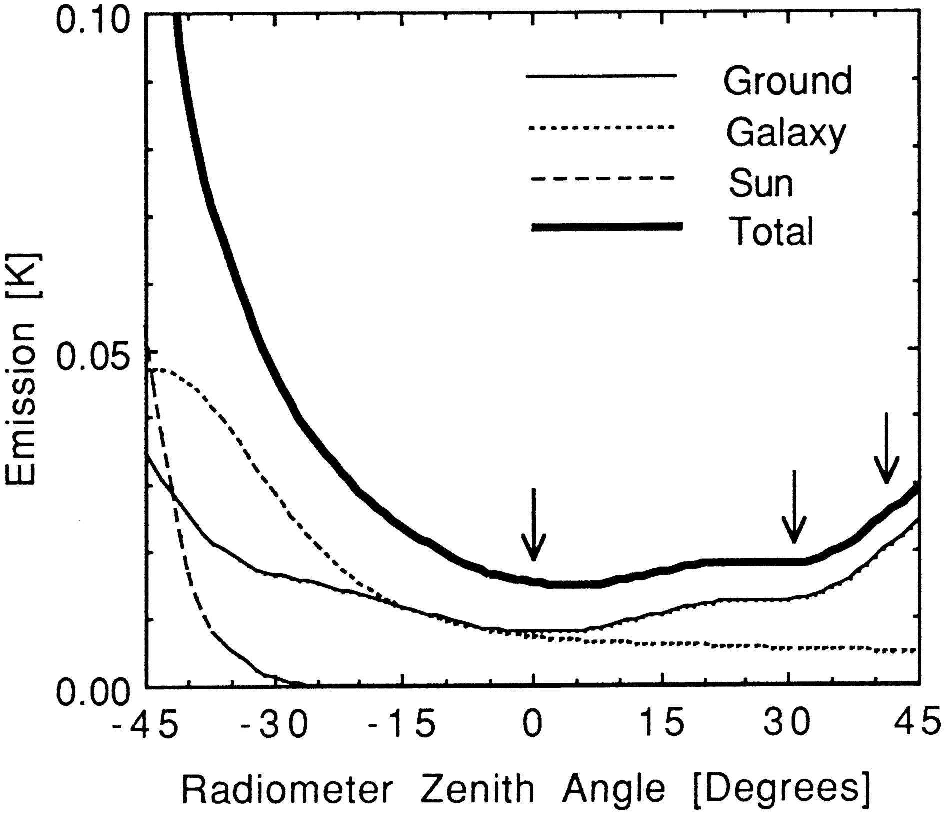


Figure 4. Calculated contributions from the ground, the Galaxy, and the Sun as a function of radiometer tip angle, with all ground shields in place and the radiometer on the stand used for atmospheric measurements. Emission from the Sun and the Galaxy is a function of position on the sky, and hence depends on the time of day (since radiometer tip direction remained fixed with respect to the rotating Earth). The time chosen for the calculation shown here corresponds to atmospheric observations with the radiometer tipping directly away from the Sun. The arrows correspond to tip angles used for atmospheric measurements.

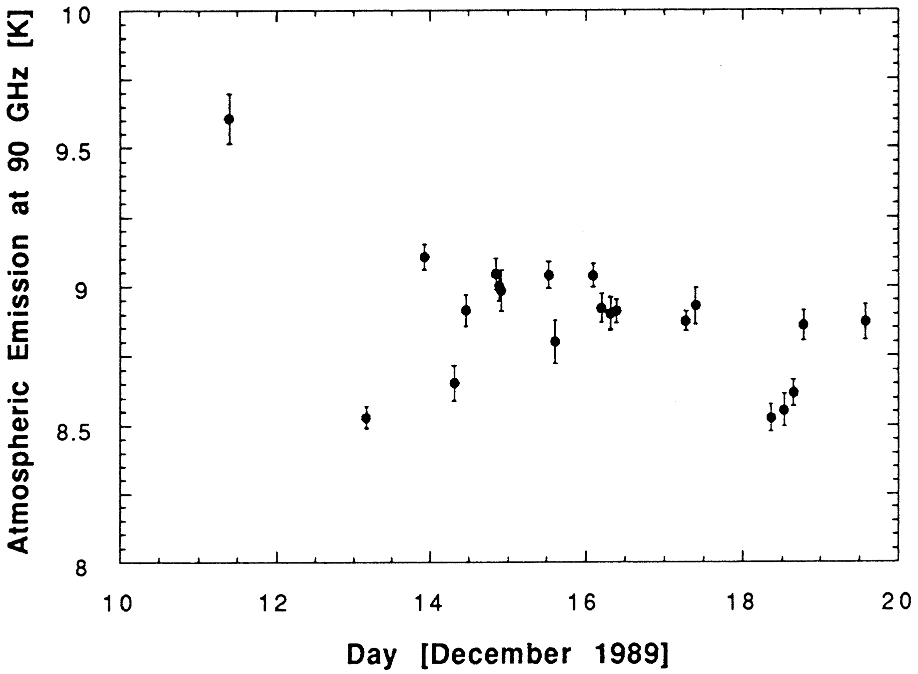
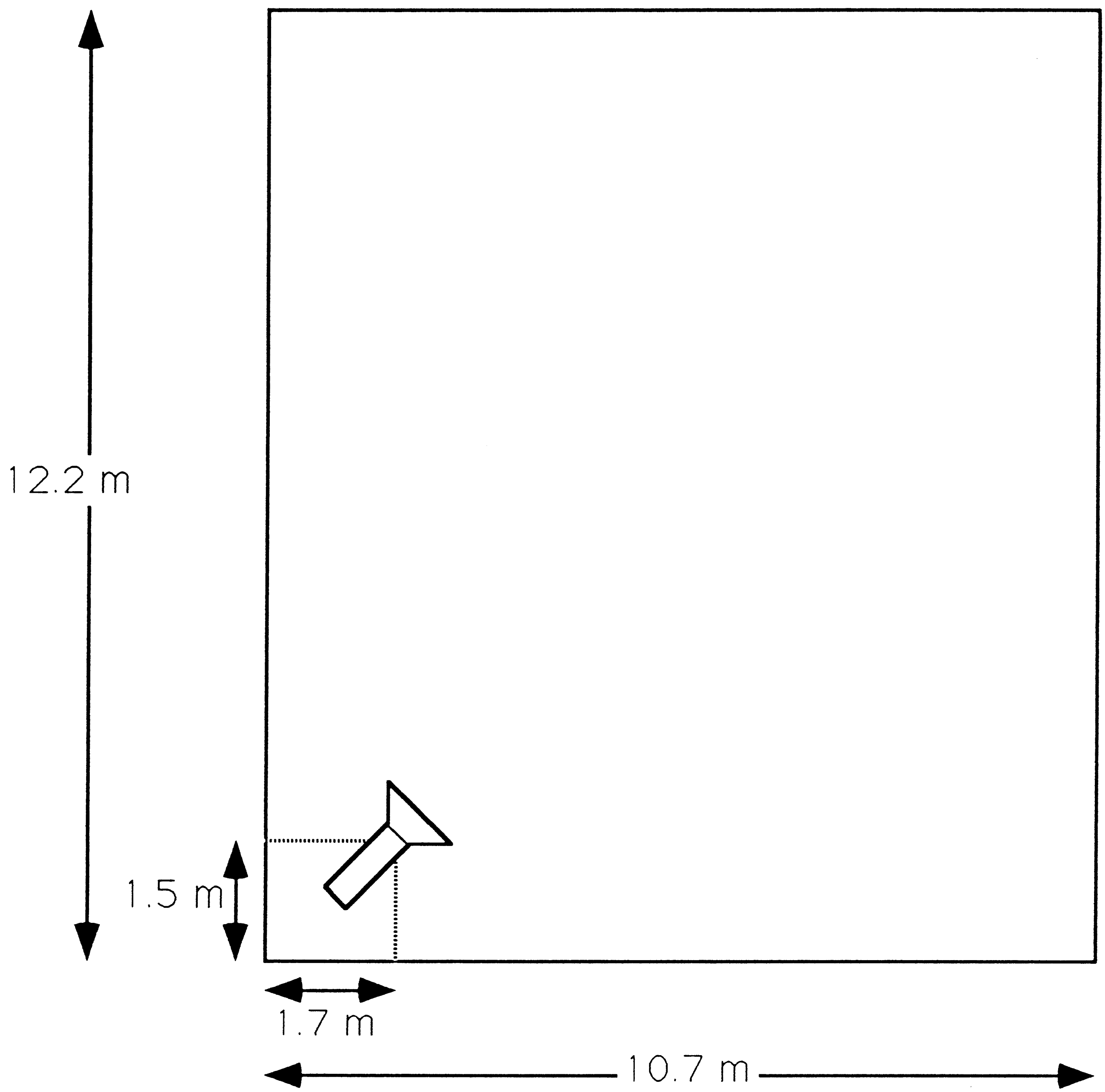
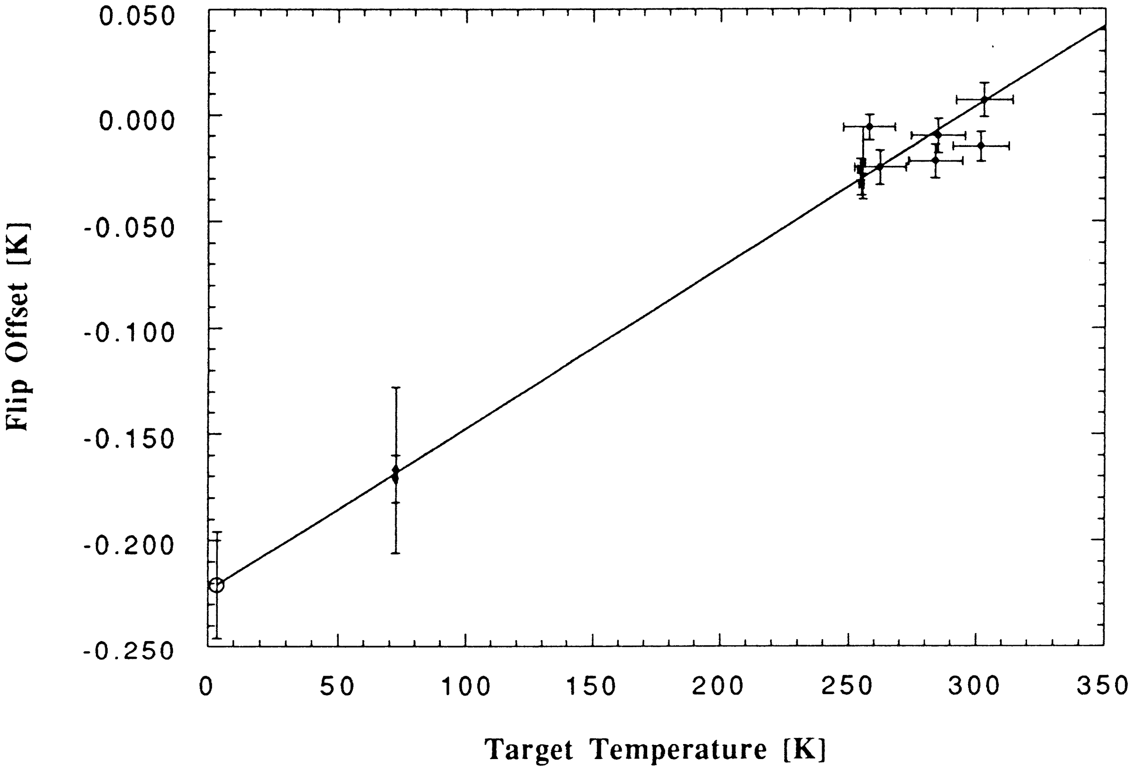
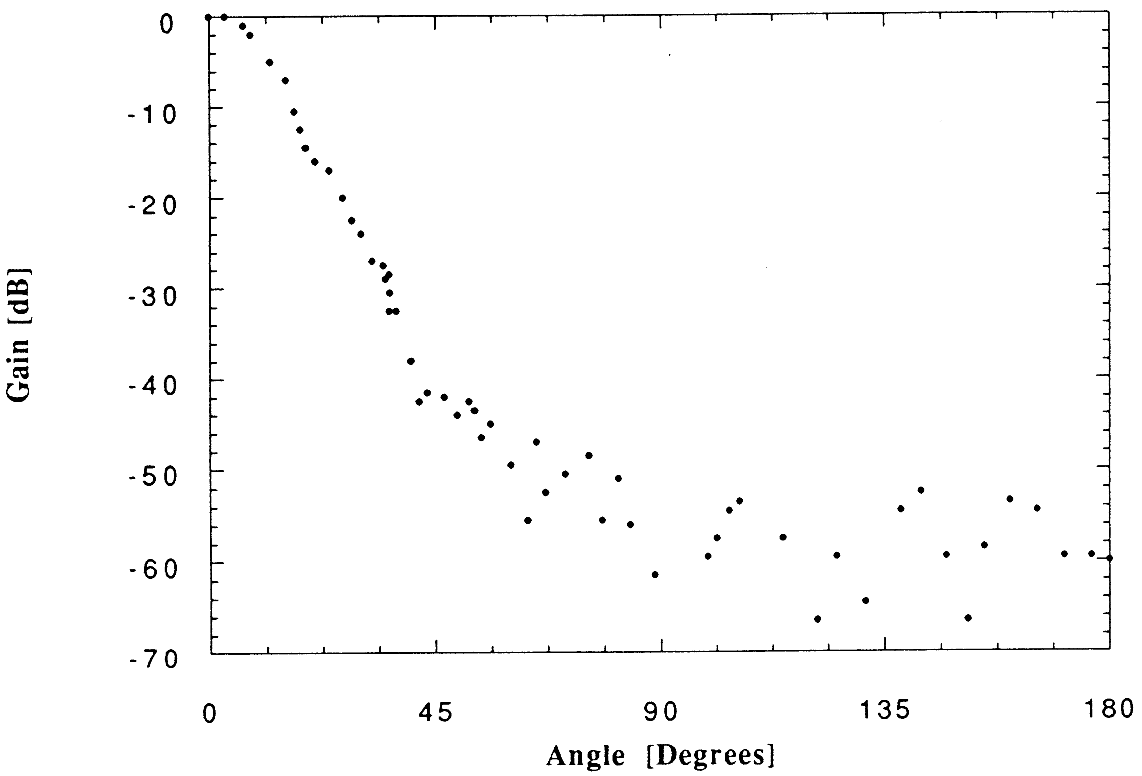


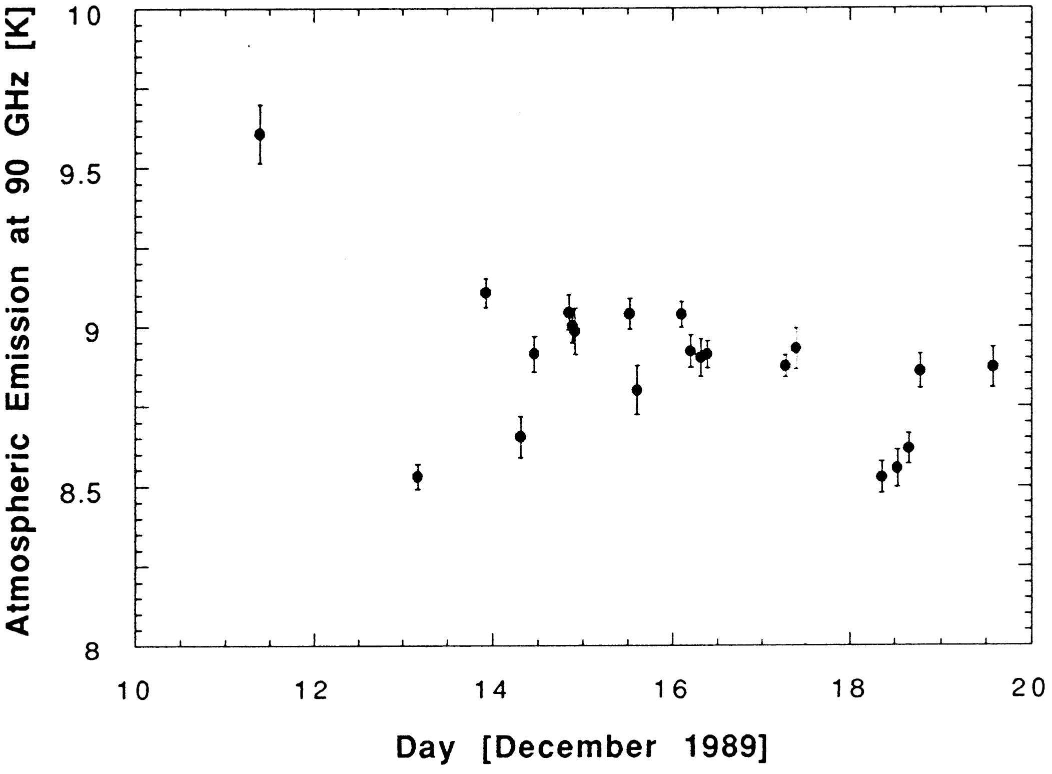
Figure 5. Atmospheric emission measurements at 90 GHz. Because of the greater importance of water vapor emission, the atmospheric emission at 90 GHz should be both larger and more variable than the emission at 7.5 GHz. These 90 GHz measurements therefore give us confidence that the atmospheric emission at 7.5 GHz was constant over the period of observation, and as a result 7.5 GHz atmospheric measurements from 4 consecutive days have been averaged together for use in the calculation of T_{CMB}.

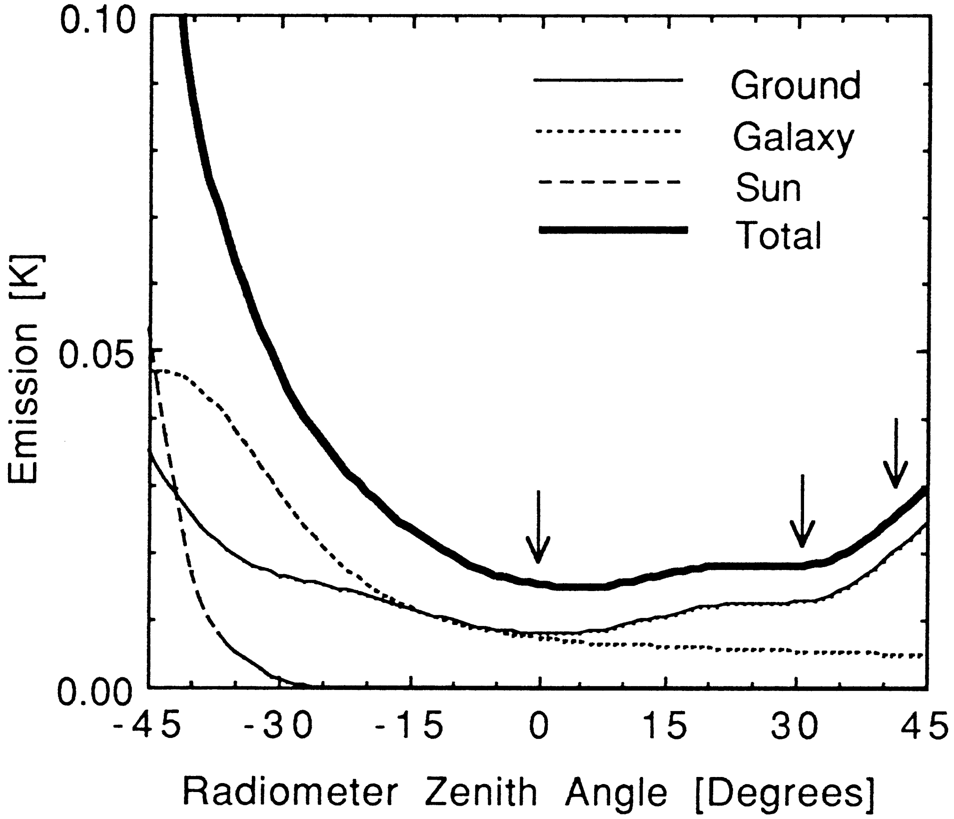

12.2 m
1.5 m
1.7 m
10.7 m



0.050
0.000
-0.050
-0.100
-0.150
-0.200
-0.250
Flip Offset [K]
0
50
100
150
200
250
300
350
Target Temperature [K]


0
-10
-20
-30
-40
-50
-60
-70
Gain [dB]
0
45
90
135
180
Angle [Degrees]


Atmospheric Emission at 90 GHz [K]
10
9.5
9
8.5
8
10
12
14
16
18
20
Day [December 1989]


0.10
0.05
0.00
Emission [K]
Ground
Galaxy
Sun
Total
-45
-30
-15
0
15
30
45
Radiometer Zenith Angle [Degrees]