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Automated measurement of the temperature of the atmosphere at 3.2 cm

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Concurrent with measurements of sky temperature reported in companion papers by De Amici *et al.*, Friedman *et al.*, Mandolesi *et al.*, and Sironi *et al.*, we made automated measurements of the temperature contributed by the Earth's atmosphere at 9.4 GHz (3.2-cm wavelength) every 8 min. Typical values for T_{ATM} in clear weather were 1.03 ± 0.03 K; the total range of recorded values was 0.89–1.24 K. These values were used to provide real-time atmospheric temperature corrections for the spectrum observations described in the companion papers, and to constrain models of the microwave emission of the atmosphere.

The aim of this work was to make frequent, automated measurements of the antenna temperature produced by thermal emission from the Earth's atmosphere at 9.4 GHz. The observations were made at the same time as the measurements of the total sky temperature (which included a contribution from both the Earth's atmosphere and the cosmic microwave background) reported in companion papers.[1,2] The contribution from the Earth's atmosphere, T_{ATM}, was found by recording the antenna temperature of radiation received from a set of different zenith angles through the atmosphere.

I. THE INSTRUMENT

The radiometer employed for these measurements was a Dicke-switched system with 1.0-GHz rf bandwidth centered at 9.4 GHz. It was kept fixed, and the radiometer components were enclosed in a thermostatically controlled box. One port of the ferrite Dicke switch was attached to a reference antenna pointed to the zenith. This was a corrugated-horn antenna with a half-power beam width of 12°; it accepted linear polarized radiation. The main antenna, a corrugated-horn antenna with half-power beam width 12.6°, was mounted horizontally. An elliptical aluminum reflector, mounted at 45° to a horizontal shaft at its center and coincident with the optical axis of the main antenna, was used to deflect radiation from a preselected set of zenith angles into the main antenna (Fig. 1). The reflector was approximately 112 cm by 79 cm. The projection of the reflector into the mouth of the main antenna was a circle which intercepted the inner $\pm14.3°$ of the beam. The inner 14.3° of the beam contained 99.6% of the power pattern, that is, all but 0.4%. We tested this figure directly by entirely covering the reflector with absorbing material (Eccosorb) and comparing the antenna temperature so obtained with the value obtained by fully covering the antenna mouth.

Note also that this arrangement of the reflector ensures that the small sidelobe and backlobe contributions to the antenna temperature of the main antenna remain fixed as it rotates.

The reflector was rotated to one of nine preset angular positions every 48 sec. The nine positions corresponded to zenith angles of 0°, ±36°, ±47°, ±54°, and ±59°. These angles were chosen to give approximately equal increments in the function $f(z)$, where $f(z)$ is the convolution of the secant of the zenith angle z (corrected for the curvature of the atmosphere) with the measured beam shape of the inner 14.3° of the main beam. The values of z could be set and read by a shaft encoder to an accuracy of ±0.5°, corresponding to an error of less than ±0.03 K in our results.

The main antenna accepted circularly polarized radiation to minimize changes in emissivity of the aluminum

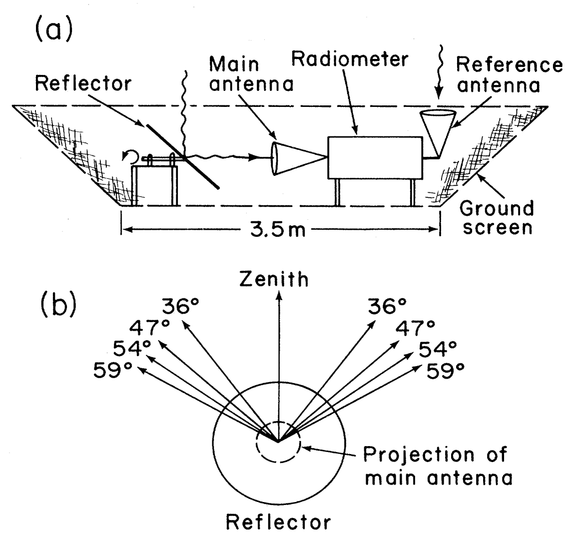

FIG. 1. Schematic of the 3.2-cm atmospheric monitor radiometer.

surface as the reflector rotated. From measurements made by heating the reflector, we determined that the largest correction required for emission from the surface of the reflector was 0.005 K. These angle-dependent corrections were made.

The great circle along which the reflected beam passed went through the zenith and cut the horizon at 65° and 245° azimuth. This orientation was chosen to reduce emission from nearby mountain peaks, especially in the west, into the sidelobes of our beam at large zenith angles. We also used 6-ft-high ground screens, constructed of window screen, to shield backlobes and sidelobes of both antennas (Fig. 1). Ground emission into the sidelobes and backlobes of the antennas was reduced by ~ 0.5 K when the screens were in place.

We expected some diffraction of the beam of the main antenna around the top edge of the screens, especially at the largest zenith angles. Comparison of measurements of the atmospheric temperature at different zenith angles showed that the diffraction contribution to the measured antenna temperature was small in the east (at $\sim 65°$ azimuth), but was substantial (~ 0.08 K at $z=59°$) toward the west because of the higher local horizon there. For this reason, we report our results in two ways: *with* corrections made for diffraction and *without* corrections, but omitting the value at the largest zenith angle, $z=59°$, in the west only. Diffraction corrections were calculated in two ways. The two methods produced results which agreed to $\lesssim 0.015$ K. First, a wave-optics calculation was made for diffraction around a straight edge. These results were combined with measurements of the local horizon to calculate the amount of ground radiation diffracted into the beam as a function of zenith angle. Second, we made an empirical determination by calculating, as a function of zenith angle, the portion of the beam striking the top 3 cm ($\sim 1\lambda$) of the screens, then assuming that a fixed fraction g of this part of the beam was diffracted onto the ground. Values of g were found empirically from our measurements at various zenith angles. In the east, $g=0.13\pm0.06$, and in the west where the horizon was higher, $g=0.30\pm0.07$. We used these values to make the diffraction corrections, which were $\lesssim 0.03$ K in $T_{\rm ATM}$.

II. OBSERVATIONAL METHOD AND RESULTS

The reflector was moved to a new position every 48 sec. While the reflector was in motion, the radiometer output was blanked. Readings from each angular position were averaged over 32 sec. and recorded. An entire cycle of readings took roughly 8 min.

The instrument was calibrated approximately once per hour by using ambient-temperature Eccosorb to cover the main and the reference antennas. Calibration values varied by a few percent over the course of a night, but could be determined to $\pm 0.5\%$. A test of the nonlinearity of the receiver gain was made by calibrating with both ambient-temperature and liquid-nitrogen-cooled Eccosorb. A $13\pm1\%$ nonlinearity in receiver gain was found and taken into account. We thus believe the calibration values are accurate to $\sim 1\%$ or 10—12 mK.

From measurements $T(z_i)$ made at a set of zenith angles z_i, the average antenna temperature of the atmosphere may be found from

$$\overline{T}_{\rm ATM}=\frac{1}{n}\sum_{i=1}^{n}\frac{T(z_i)-T(0)}{f(z_i)-f(0)} .$$

These values we refer to as the *unweighted* averages. We also took weighted averages, giving those measurements at larger zenith angles greater weight:

$$(\overline{T}_{\rm ATM})_w=\sum_i\,[T(z_i)-T(0)]\Big/\sum_i\,[f(z_i)-f(0)] .$$

In cloudless weather, at night, $\overline{T}_{\rm ATM}$ ranged from 0.89—1.23 K and was typically 1.02 ± 0.04 K. The weighted averages had a smaller range, and were typically 1.03 ± 0.03. A few sample results are displayed in Table I.

The values listed in Table I have been corrected for galactic emission at 9.4 GHz using a map which included galactic synchrotron emission[3] scaled to our frequency and thermal emission.[4] The largest correction required

TABLE I. Values of $T_{\rm ATM}$, weighted and unweighted, found at 9.4 GHz. In column 3, the errors are standard deviations of the means; the errors are similar for other columns. The 90-GHz values were provided by Witebsky (private communication).

Day	Time	Without diffraction correction $\overline{T}_{\rm ATM}$ (K)	Without diffraction correction $(\overline{T}_{\rm ATM})_w$ (K)	With diffraction correction $\overline{T}_{\rm ATM}$ (K)	With diffraction correction $(\overline{T}_{\rm ATM})_w$ (K)	90 GHz $T_{\rm ATM}$ (K)
5/7/82	$03^{\rm h}\ 31^{\rm m}$	1.048±0.020	1.073	1.039	1.059	14.6±0.9
	03 39	1.030±0.045	1.064	1.025	1.055	
5/7/82	07 23	1.012±0.016	1.027	1.001	1.012	12.3±0.3
	07 31	1.039±0.035	1.053	1.021	1.027	
6/7/82	05 24	1.027±0.020	1.047	1.018	1.032	
	05 32	0.993±0.022	1.014	0.989	1.007	
6/7/82	08 04	1.015±0.034	1.043	1.015	1.041	12.7±0.2
	08 12	1.006±0.033	1.018	1.010	1.026	
7/7/82	04 01	1.097±0.033	1.111	1.085	1.117	17.6
	04 09	1.103±0.038	1.124	1.102	1.139	21.5[a]
	04 17	1.141±0.038	1.143	1.124	1.136	23.5[a]

[a]Clouds in the southern sky caused anomalously large values of $T_{\rm ATM}$ at 90 GHz.

for any of our measurements of T_{ATM} was 0.05 K. In a subsequent paper, we hope to use the 9.4-GHz and 10-GHz measurements reported here and in Friedman *et al.*[1] to refine models of the galactic emission.

III. COMPARISON TO MODELS OF ATMOSPHERIC EMISSION

As noted in the companion papers,[1] the radiometers operating at 2.5, 4.75, 10, 33, and 90 GHz were also used to measure the atmospheric emission. Intercomparison of some simultaneous measurements are also displayed in Table I. Since the sensitivity to O_2 and H_2O contributions to T_{ATM} is different at the different frequencies employed, our joint results permit us to set constraints on models of the Earth's atmospheric emission.

For comparison purposes, we have constructed a model for the emission of the Earth's atmosphere at 3800-m altitude. It is based on a stratified atmosphere with spherical symmetry, and we consider only H_2O and O_2 emission, since other atmospheric gases contribute negligibly at our frequencies. We employ models described by McClatchey *et al.*[5] for the vertical dependence of pressure, density, temperature, and water-vapor content of the atmosphere. To calculate the absorption coefficient of water vapor, we use the results of Waters.[6] We note that $\sim\frac{2}{3}$ of the absorption far from the H_2O resonance lines is accounted for by an empirical term which Waters claims fits measured values of the absorption to 5% accuracy at frequencies below 1000 GHz. For O_2 we assume good mixing with the usual volume mixing ratio of 0.21. For the contribution to the absorption coefficient from individual O_2 transitions, we use the results of Rosenkranz,[7] and for the nonresonant terms the usual results of Van Vleck.[8] Finally, we combine these calculated absorption coefficients with the models for the vertical structure of the atmosphere to calculate antenna temperatures of the Earth's atmosphere in K as a function of the precipitable water-vapor content (in mm) above 3800 m, which we call W. Self-absorption is included in the calculations of T_{ATM}. For frequencies of 10 GHz and below we believe our models to be correct to $\lesssim 10\%$ or $\lesssim 100$ mK. At 33 GHz we estimate an accuracy of ± 150–200 mK; at 90 GHz comparison with experimental data becomes more difficult because of variability in the water-vapor content, but we estimate an accuracy of ± 0.5 K. Calculated values are

$$2.5\ \text{GHz:}\quad T_{ATM}=0.932+2.2\times10^{-3}W\ ,$$

$$4.75\ \text{GHz:}\quad T_{ATM}=0.960+8.1\times10^{-3}W\ ,$$

$$9.4\ \text{GHz:}\quad T_{ATM}=1.035+3.50\times10^{-2}W\ ,$$

$$10.0\ \text{GHz:}\quad T_{ATM}=1.048+4.04\times10^{-2}W\ ,$$

$$33.0\ \text{GHZ:}\quad T_{ATM}=3.182+3.60\times10^{-1}W\ ,$$

$$90.0\ \text{GHz:}\quad T_{ATM}=4.706+2.197W\ .$$

At 3800-m altitude, we expect $W\approx 3$ mm; hence the water-vapor contribution is important only at 33 and 90 GHz. During the day, we were able to measure W using a solar hygrometer. We obtained values of W from 1.8 to 4.9 mm with a mean of 3.4 ± 0.4 mm. In addition, since the 90-GHz measurements are very sensitive to the water-vapor content, we may use them to determine W. If $T_{ATM}=12.3\pm1.0$ K, we find $W=3$–4 mm from our model, in agreement with estimates from model atmospheres and the direct hygrometer measurements. For comparison with the observations (Ref. 2, Table II), let us take $W=3.5$ mm. The calculated values of T_{ATM} are consistent within the estimated errors with our measurements at 2.5, 9.4, and 90 GHz, and marginally so at 10 and 33 GHz. We would expect T_{ATM} measured at 10 GHz to be 30 mK higher than at 9.4 GHz; it is actually measured to be 100 mK lower. Although it is covered by the errors in the 10-GHz measurement, we plan to investigate this difference further.

Other groups have measured T_{ATM} at the same site (and at roughly the same time of year). At 32.5 GHz, Ewing, Burke, and Staelin[9] found $T_{ATM}=4.6\pm0.2$ K, in good agreement with both the models and our 33-GHz results. At 35 and 9.4 GHz, the Princeton group[10,11] report $T_{ATM}=6.5\pm0.2$ and 1.37 ± 0.10, respectively. In view of our measurements and our atmospheric model, these seem high.

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