Brightness Temperature of the Terrestrial Sky at 2.66 GHz

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1. Introduction

The zenith brightness temperature of the clear terrestrial sky in the centimeter wavelength region has been extensively investigated by many workers in the field and was first calculated by Hogg (1959) from the Van Vleck-Weisskopf line-shape theory for oxygen absorption. The experimental observations from 0.3 to 10 GHz have been reviewed by Medd and Fort (1966) and Howell and Shakeshaft (1967). Fig. 1 shows the summary of the observations to date. These results include, in addition to the references given in the review articles, the more recent measurements of Penzias and Wilson (1967) at 1.415 GHz and Khrulev *et al.* (1969) at 0.631 and 0.940 GHz. In general, the observations fall into two distinctive groups, those which give an average brightness temperature observed at the ground of ~4K and those that give a value of ~2K. Since the higher values were, for the most part, results of early observations, it is generally believed that the 4K measurements between 0.3 and 3 GHz are probably in error. Howell and Shakeshaft point out in their review article that, in fact, at least some of the high-value measurements are suspect due to either neglecting or improperly taking into account of corrections due to atmospheric refraction in the data reduction.

There is currently great interest in developing microwave remote sensors to measure the properties of the earth's surface. One of the more significant and practical measurements that can be made, in principle, from a satellite is the absolute ocean surface temperature. A study program aimed at achieving this possibility was undertaken at the North American Rockwell Corporation in the late 1960's, and prototype radiometers have been constructed and operated in airplane flight tests at 2.67 and 2.69 GHz. The details of the instrument design and preliminary test data are reported elsewhere (Hidy *et al.*, 1971). In order to evaluate the practical limitations on measurements of absolute sea surface temperature, we have undertaken, as part of our development program, to measure the atmospheric contribution to the observed brightness temperature so as to further verify the value of the zenith brightness temperature of the terrestrial sky in the region from 2.65–2.70 GHz. The method selected for this measurement was to investigate the variation of sky temperature with zenith angle over the range −75° to +75°. An estimate of the fit of these data to the expected theoretical variation yields a value of 2.2±0.3K for the zenith sky brightness temperature.

2. Experimental method and results

Observations were made using a high-resolution radiometer in the early morning and late at night during the spring of 1970 on the roof of the Science Center under conditions of cloudless skies. The time of the day during which the data were taken and the location of the experimental equipment were chosen to minimize spurious effects introduced through the side lobes of the antenna pattern. Strong microwave sources such as the sun and the galactic center were either not in view or low enough in the horizon so that the contribution to the apparent temperature of the sky was expected to be small. The southwest corner of our laboratory roof was chosen to minimize the influence of hilly terrain to the north and east of the building. The distant hills on the west side of the Science Center were less than 5° above the horizon.

The experimental set-up is shown in Fig. 2. Two antennas were used with the radiometer. The Potter horn, with half-power point beamwidth (HPBW) of 16°

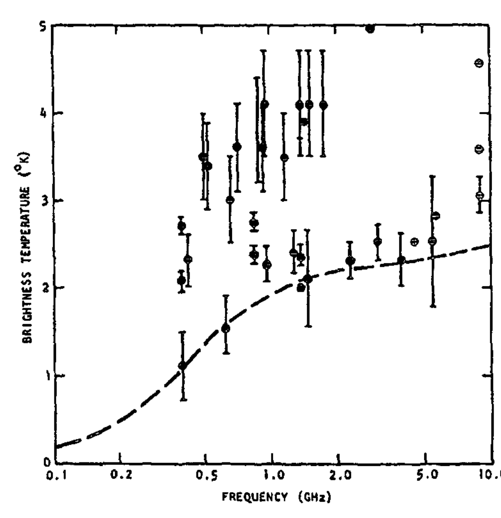

FIG. 1. Zenith brightness temperature of the earth's atmosphere due to oxygen absorption as a function of frequency.

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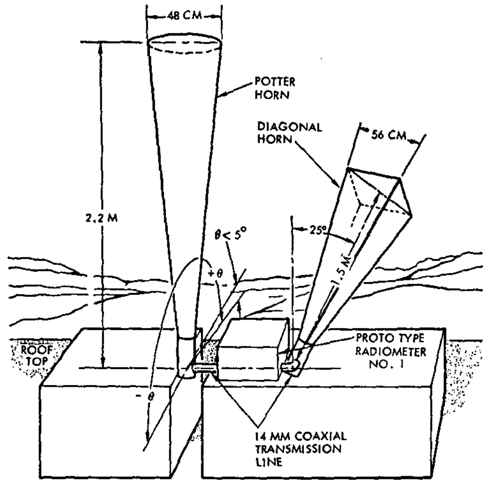

Fig. 2. Experimental apparatus used to observe the sky brightness temperature as a function of viewing angle θ.

was the rotatable antenna. A diagonal horn with HPBW of 18° was used as a reference load. The diagonal horn was pointed at an angle of about 25° from the zenith to minimize any coupling between the two antennas. It was connected to the reference arm of the radiometer. The Prototype 1 radiometer used has been described in detail by Hidy *et al.* (1969). It consists of a ferrite circulator switching between the two horns, followed by a tunnel diode amplifier, an 80-MHz filter centered at 2.66 GHz, a square law detector, and an audio amplifier with an automatic gain control system. Calibration of the radiometer was carried out before and after each set of observations using cryogenically cooled coaxial terminations (see Hidy *et al.*, 1969). All of the microwave components were interconnected with precision, rigid, 14-mm coaxial transmission lines. The radiometer was coupled in turn to the antennas through coaxial-to-waveguide transition sections.

One can identify four possible sources of error in the radiometer reading: the usual output fluctuations due to the finite measuring time, non-reproducibility of the rotary joint, and instability of the radiometer zero and of the calibration constant. The maximum temperature fluctuations ever observed for the undisturbed radiometer were 0.53K peak to peak with an rms value of less than 0.1K. The largest discrepancy between radiometer readings for a given value of $|\theta|$ was 1.0K, but the rms deviation from the mean of such readings was less than 0.2K. This is some measure of the reproducibility of the coaxial joint which had to be loosened and retightened each time the horn angle was changed. The instrument was operating to within 1K of null for $\theta=0$, and changes in the zero could be safely ignored. The calibration factor, however, can change with ambient temperature, 3% being an upper limit on the total variations in gain; this amounts to 0.12K for a signal 4K away from null (corresponding to $\theta=60°$). The various errors are uncorrelated, and adding their squares one gets a combined rms error of 0.25K for readings at $\theta=60°$. In spite of great care to avoid them, undetected systematic errors (such as in the rotary joint) may exist. We expect them to be small, but we do not have quantitative limits on them.

The results for the observed variation of antenna temperature with the rotation of the Potter horn from zenith are plotted in Fig. 3.

The measured sky temperature represents an average over the horn pattern of the actual temperature $T_B(\theta)$, which for a horizontally stratified atmosphere is given to a high degree of accuracy by

$$T_B(\theta)=\int_0^\infty \frac{dz\alpha(z)T(z)}{\cos\theta'(z)}\exp\left[-\int_0^z \frac{dz'\alpha(z')}{\cos\theta'(z')}\right]+T_c\exp\left[-\int_0^\infty \frac{dz\alpha(z)}{\cos\theta'(z)}\right], \quad (1)$$

where θ is the zenith angle, $\alpha(z)$ the atmospheric absorption coefficient at altitude z, $T(z)$ the temperature at z, and $\cos\theta'(z)$ is given to second order by

$$\cos\theta'(z)=\left[1-\frac{\sin^2\theta}{(1+z/R)^2}\right]^{\frac{1}{2}}, \quad (2)$$

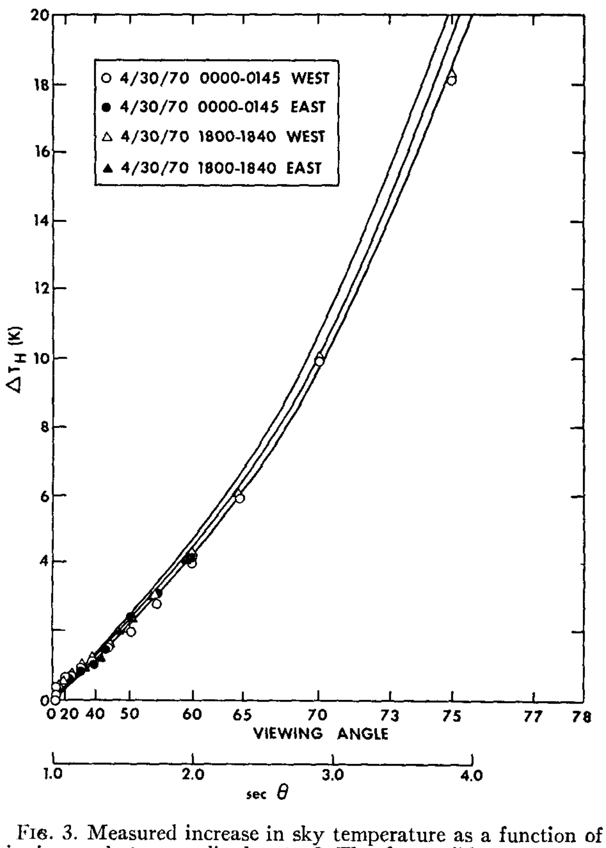

Fig. 3. Measured increase in sky temperature as a function of viewing angle θ, normalized to $\theta=0$. The three solid curves correspond to three different values for the line-broadening parameter in the Van Vleck-Weisskopf line-shape theory. See text for discussion.

where R is the radius of the earth. The extraterrestrial microwave radiation T_c incident on the atmosphere consists of a thermal cosmic background of 2.7K and galactic noise whose equivalent temperature at S band is ~0.3K.

The zenith brightness temperature of the sky (excluding extraterrestrial sources) is defined as

$$T_0=\int_0^\infty dzT(z)\alpha(z)\exp\left[-\int_0^z dz'\alpha(z')\right]. \qquad (3)$$

Assuming azimuthal symmetry for the horn pattern, the observed sky temperature can be written as

$$T_H(\theta)=\int_0^{2\pi} d\phi\int_0^\pi d\theta' T_B(\theta')G[\cos\gamma(\theta,\theta',\phi)], \qquad (4)$$

where G is the normalized antenna gain and γ is the angle between the horn axis and the direction specified by θ' and ϕ, i.e.,

$$\cos\gamma=\cos\theta\cos\theta'+\cos\phi\sin\theta\sin\theta'. \qquad (5)$$

For directions (θ',ϕ) intersecting the ground, T_B is taken to be the earth's surface temperature, 300K, since the ground emissivity at S band is very close to unity.

The atmospheric absorption coefficient $\alpha(z)$ in Eq. (1) is evaluated using the temperature and pressure profiles for the 1962 U. S. Standard Atmosphere and the Van Vleck-Weisskopf (1945, 1947) pressure-broadening theory for oxygen. The only unknown constant of the theory is the broadening parameter $\Delta\nu$ for oxygen in air, for which Kaufman (1967) obtained $\Delta\nu=(693\pm46)\times(T/300)^{0.47\pm0.39}$. To reflect the experimental uncertainty in $\Delta\nu$, $T_B(\theta)$ was calculated for three values of $\Delta\nu$ differing by $\pm10\%$ about Kaufman's nominal value. Eq. (4) was then integrated using an experimentally determined pattern for the Potter horn; the results are plotted in Fig. 3. The corresponding zenith sky temperatures obtained from (3) are 2.15, 2.39 and 2.63K for the low, middle and high values of $\Delta\nu$, respectively.

As can be seen from Fig. 3, the measured values fall, in general, slightly above the lowest curve, which corresponds to the lowest value assumed for $\Delta\nu$. We therefore adopt a value of 2.2K as the zenith sky temperature inferred from our measurements, with an uncertainty of 0.3K, which we estimate by considering the degree of agreement obtained in Fig. 3, plus a possible error of 0.1K introduced due to reasonable departure of the actual pressure and temperature profiles from the standard atmosphere. Essentially no variation in the curves of Fig. 3 is obtained for a 1K change in T_c, so no additional uncertainty occurred from this source.

Our experimental results also imply, to the extent that the Van Vleck-Weisskopf theory is strictly applicable, that the proper value for $\Delta\nu$ is bounded by $(624\pm85)(T/300)^{0.47}$ which is lower than that given by the laboratory measurements of Kaufman, but is still within the error quoted for the two determinations.

When the zenith brightness temperature T_0 is calculated from (3) as a function of frequency using $\Delta\nu=624(T/300)^{0.47}$, we obtain the dashed curve shown in Fig. 1, which agrees satisfactorily with the lower of the two sets of observed values.

3. Conclusion

The observations indicate that the zenith brightness temperature and, therefore, the opacity of the cloudless terrestrial sky, is consistent with the predictions of the Van Vleck-Weisskopf line-shape formula for oxygen absorption and with the lower of the two sets of measured values reported in the literature in the range 2–3 GHz. Our measurements give 2.2±0.3K for the zenith sky temperature at 2.66 GHz.

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