tion from the centrally-located dielectric slab. The value of k_d is approximately the same in the case of the groove guide.

Conclusion

It is shown that a deformed-wall guide with grooves in the central region of the cross section is equivalent to a parallel-wall guide with a dielectric contained in the central section. The guide has, consequently, similar properties to those of an H-guide. Theoretically, it is characterized by low attenuation which decreases with increasing frequency and by an exponentially decreasing field distribution in the direction from the center of the cross section parallel to the walls. Since the guide contains no dielectric, it is expected to have a lower attenuation than the H-guide. Besides the application for long-distance transmission and as a delay line, the simple structure makes the guide suitable for the design of millimeter wave circuitry and of circuit elements.

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Factors Affecting Earth-Satellite Millimeter Wavelength Communications*

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***Summary*—The use of millimeter wavelengths for earth-satellite transmissions is suggested by the large bandwidths and high gain with small antennas possible at these wavelengths. The factors discussed are 1) propagation path loss, 2) refraction, and 3) antenna temperature.**

The attenuation through the entire atmosphere over the millimeter spectrum is given as a function of elevation angle of the antenna beam. The attenuation and scattering loss due to water and ice particles varies over a wide range of values depending on the number of particles and their sizes.

Refraction by the atmosphere is less than one milliradian for elevation angles for which the absorption is low enough to make the transmission practical. Fluctuations due to refraction may, however, be quite severe.

Contribution to antenna temperatures from the atmosphere, the earth, the sun and moon are given for earth-based antennas and antennas in space.

Introduction

EARTH-SATELLITE millimeter wavelength applications, as the name implies, involve transmission through the earth's atmosphere. It is the purpose of this paper to discuss several of the important factors which determine the propagation characteristics of wavelengths from 1 mm to 1 cm and to present the results of recent measurements which provide further quantitative evaluations of these factors.

This paper will be concerned with 1) propagation path loss, 2) refraction, and 3) antenna temperature. These factors are pertinent to both active and passive systems, and form the framework for the choice or rejection of a millimeter wavelength for a particular application.

Propagation Path Losses

The losses experienced in propagating millimeter wavelengths through the earth's atmosphere, other than free-space losses, are caused predominantly by atmospheric gases, clouds, particles and precipitation. Longer wavelengths are attenuated by the same mechanisms but to a lesser degree because of the remoteness of the wavelengths from the resonant frequency of the gas and the smaller size of precipitation and cloud particles relative to the longer wavelengths.

The attenuation by atmospheric gases is primarily associated with oxygen and water vapor molecules and is most conveniently described by the Van Vleck-Weisskopf equation.[1] Due to the magnetic moments associated with oxygen and the electric moments associated with water vapor, there are a large number of energy transitions that produce peak values of absorption at millimeter wavelengths. Most of the energy transi-

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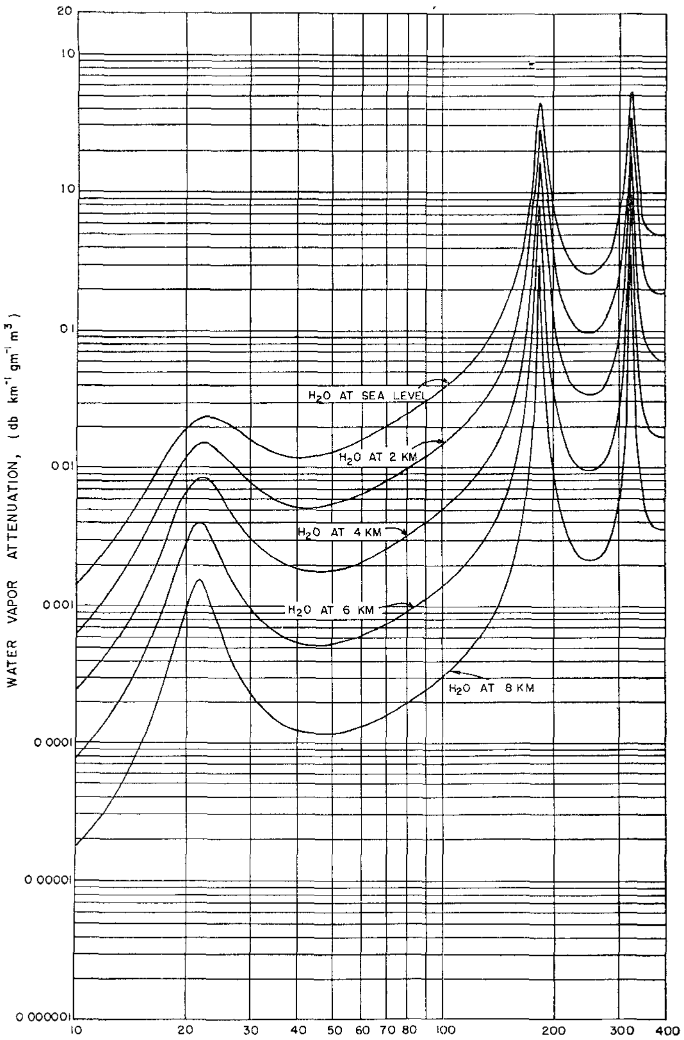

Fig. 1—Attenuation due to water vapor at five elevations.

tions, however, result in peak values of absorption at the submillimeter and infrared wavelengths.

For a single absorption line, the attenuation, α, at an angular frequency of ω associated with collision broadening is given by

$$\alpha = \frac{2\pi Ne^2}{mc}\left(\frac{\omega}{\omega_c}\right)^2 \cdot\left[\frac{1/\tau}{(\omega-\omega_0)^2+(1/\tau)^2}+\frac{1/\tau}{(\omega+\omega_0)^2+(1/\tau)^2}\right],$$

where e and m are the charge and mass of an electron, c is the velocity of electromagnetic wave, ω_0 is the center line angular frequency, N is the number of molecules per cubic centimeter, τ is the mean interval between collisions.

The contributions to the absorption from the various lines may be obtained by adding their individual attenuations. The term $(1/\tau)$ may be replaced by $\Delta\omega$, the half width of the line at its half-power point.

The number of molecules per cubic centimeter and the line width are approximately proportional to pressure,

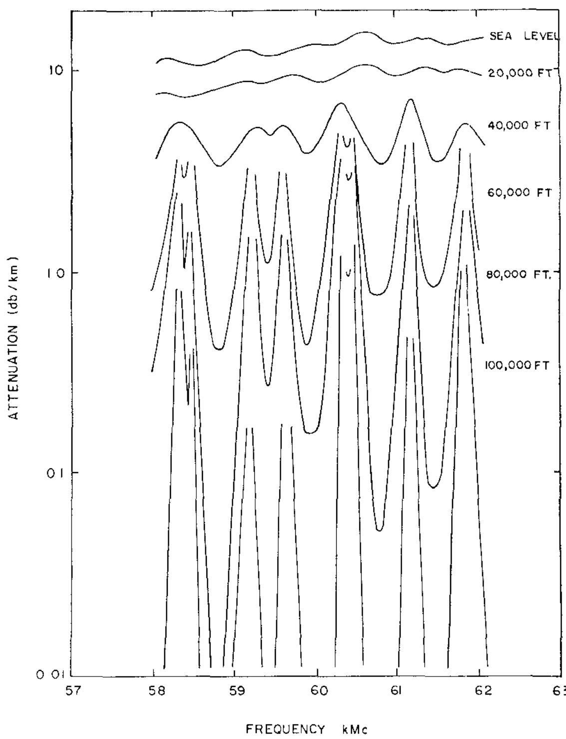

Fig. 2—Attenuation due to oxygen at six elevations.

thus allowing the extrapolation of low-altitude measurements to give an approximation of the losses in the upper atmosphere.

The attenuation through the earth's atmosphere in decibels per kilometer per gram of water vapor in a cubic meter for wavelengths between 3 cm and 0.75 mm (frequencies between 10 and 400 kMc) is shown in Fig. 1 for five elevations. These curves are based on measurements at elevations of 0.2 and 4 km at single frequencies of 35, 70, 90, 140, 170, 183 and 209 kMc and over frequency intervals between 18 and 25 kMc and between 100 and 117 kMc.[2–4] The curves are for a water vapor density of one gram per cubic meter. The actual attenuation may be obtained by multiplying by the density at the time of measurement.

The attenuation of atmospheric oxygen for the frequency range between 58 and 62 kMc for six elevations is shown in Fig. 2. These data are plotted from measurements at 75 frequencies in this range using the 500-ft absorption cell at The University of Texas to simulate the conditions at the various altitudes.

Using the data shown in Figs. 1 and 2, the attenuation through the entire earth's atmosphere can be determined by interpolating and extrapolating the values of

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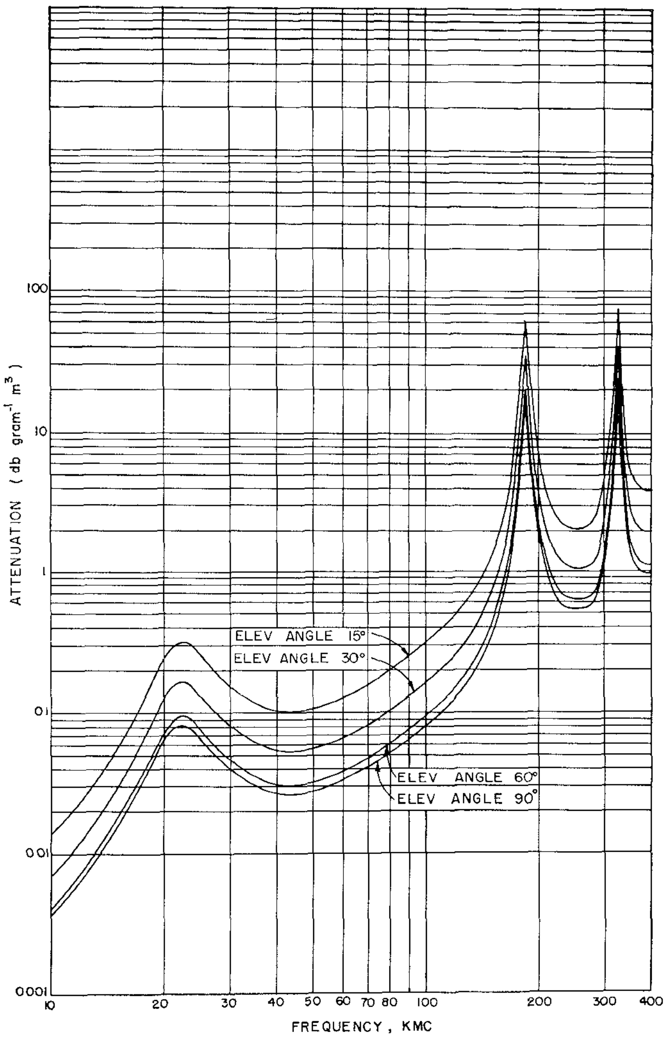

Fig. 3—Attenuation through entire atmosphere due to water vapor.

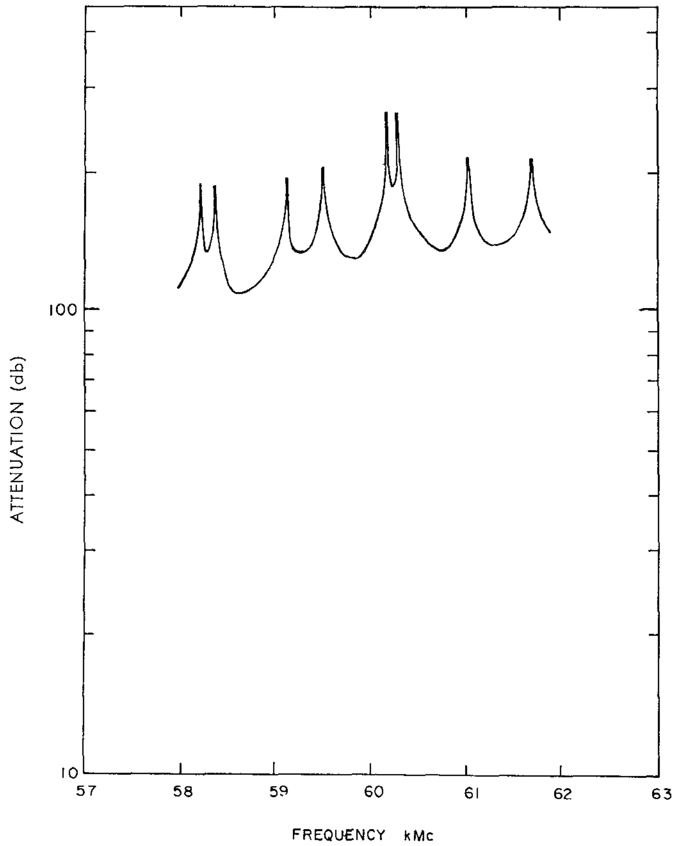

Fig. 4—Zenith attenuation due to oxygen.

attenuation to all elevations of the earth's atmosphere by use of the Van Vleck-Weisskopf equation and the commonly accepted models of height variations of molecular density, absolute pressure and temperature. The attenuation through the atmosphere due to water vapor for elevation angles of 15, 30, 60 and 90 degrees are shown in Fig. 3. This is based on a water vapor density at the surface of one gram per cubic meter and a rate of decrease with height in accordance with $e^{-0.5z}$ where z is the elevation in kilometers. The losses shown in the curves of Fig. 3 must be multiplied by the ground level water vapor concentration to obtain the total water vapor loss.

The zenith attenuation through the atmosphere due to oxygen between 0 and 100,000 feet elevation is shown in Fig. 4. This curve is obtained by summing the attenuations in Fig. 2 over the appropriate height intervals.

The attenuation, particularly at the "window" frequencies, can be measured by observing the intensity of solar radiation vs solar elevation angle. Such measurements have been made over extended periods of time at frequencies of 69, 94 and 140 kMc. The attenuation thus obtained is plotted as a function of the water vapor in a centimeter square column taken vertically, and the least mean-square lines are obtained. These are shown in Fig. 5. The water vapor distribution was obtained from radiosonde measurements and was found to agree reasonably well with the assumed standard atmosphere adjusted for ground level water vapor density. The slope of the lines gives the water vapor loss in db per gram per cm square column. The Y intercept value represents the attenuation due to other atmospheric gases—oxygen, in particular. Some of the other atmospheric gases—ozone, hydrogen sulfide, and carbon monoxide—while having large values of peak attenuation at the millimeter wavelengths produce negligible attenuation because of their low molecular densities.

Each band of wavelengths has distinctive propagating characteristics. In general, however, increasing the elevation of a ground-based terminal will decrease the opaqueness of the atmosphere because of the decreased value of water vapor density with increased elevations. It is to be noted that there are large bands of wavelengths throughout the spectrum where the vertical and near-vertical attenuation is relatively small—less than 2 db. Judicious location of earth-based terminals would make the values of attenuation loss.

Other constituents of the atmosphere that contribute to the losses are precipitation and cloud particles. Again, as in the case of atmospheric gases, these particles also cause losses at the longer wavelengths. The

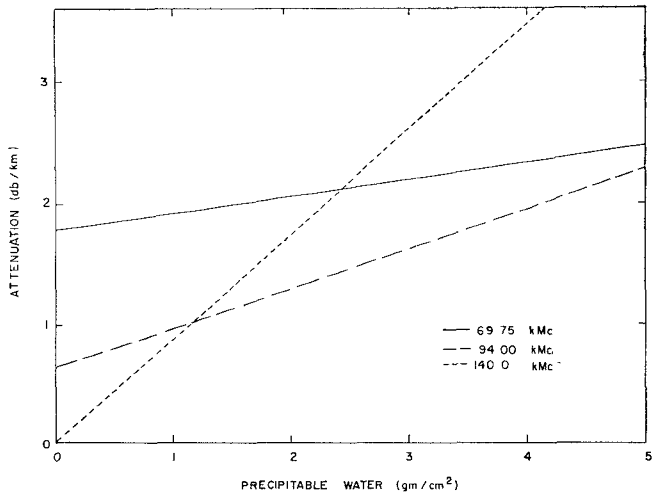

Fig. 5—Measured total attenuation through the atmosphere at frequencies of 69, 94, and 140 kMc.

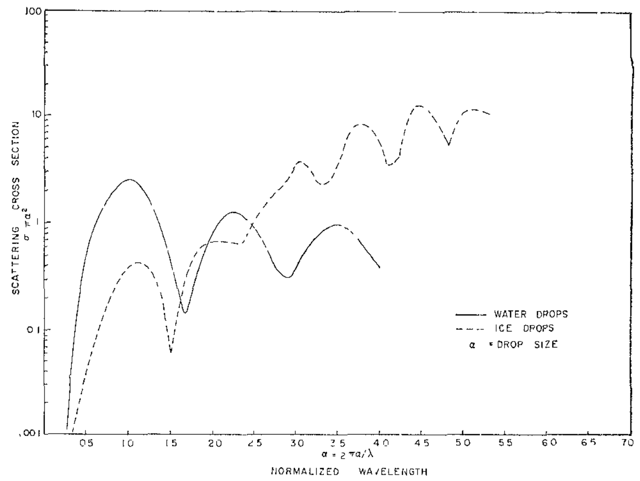

Fig. 6—Back-scattering cross section of water and ice.

increased attenuation at the millimeter wavelengths is due to the increased size of the particles relative to the wavelength. The most significant loss results from scattering of the energy by particles with diameters in excess of approximately one-tenth of a wavelength. Shown in Fig. 6 is the measured back-scattering cross section of water and ice particles at a number of wavelengths.[5] While there is a dispersion of the dielectric of these two media—water and ice—over the frequency interval of the millimeter spectrum, it is not so great that a scaling of wavelengths and particle size is not in order. In general, clouds not containing precipitation particles will cause values of attenuation less than 0.5 db. This loss is primarily due to the absorption of energy, with the fractional contributions from scattering being small because of the small cross section of the cloud particles.

The attenuation due to precipitation has a wide range of values and can be quite large—10 db per kilometer—for short propagation paths. Vertical and near-vertical propagation paths are not immune. Precipitation from clouds based at 3000 to 10,000 ft can cause losses of the order of 10 db for vertical propagation. The attenuation minima in Fig. 6 are smoothed out by the spread in rain-drop sizes in an actual shower, and as a result the attenuation increases consistently with decreasing wavelength. Curves of attenuation vs precipitation rate are presented elsewhere.[6]

Refraction

One of the characteristics of the millimeter wavelengths is the fluctuation signal strength associated with line-of-sight propagation in an inhomogeneous atmosphere. The signal strength fluctuations are caused by variations in refraction and absorption.

The correlation coefficient of 70-kMc signal fluctuations vs antenna separation over a seven-mile path was found to be approximately Gaussian with a half width of 10 ft. Signal strength fluctuations are closely correlated with refractive index fluctuations. These fluctuations will, in general, decrease with elevation since the refraction index fluctuations decrease rapidly with increased elevation above the earth's surface, with the exception of the occurrence of interfaces between differing air masses in the atmosphere.[7] A comparison of the signal strength fluctuations observed at 70 kMc over a 60-mile path between the 14,000-ft levels of Pikes Peak and Mount Evans[8] showed that the rms values were approximately proportional to frequency. High elevation angle propagation through the earth's atmosphere would not be expected to fluctuate as greatly as propagation parallel to the earth's surface.

The higher values of atmospheric attenuation at millimeter wavelengths do not significantly change the refractive index of the atmosphere from its value at longer wavelengths. A comparison of the angular refraction through the earth's atmosphere of 70-kMc wavelengths relative to optical wavelengths is shown in Fig. 7. At elevation angles greater than 15°, the average value of the angular refraction is less than 1 milliradian. Absorption through the earth's atmosphere, in general, prohibits propagation at elevation angles where the refraction is large.

Most of the measurements made of refraction and signal level fluctuations through the atmosphere have been made with relatively narrow bandwidths—less than 10 cps. One of the unanswered questions in this

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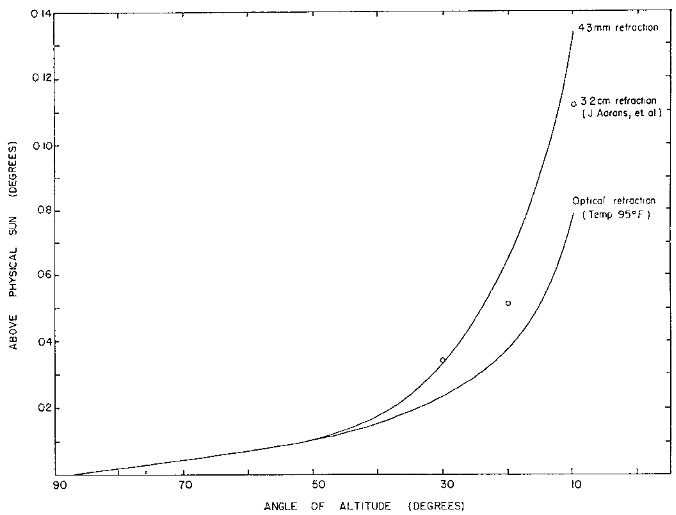

Fig. 7—Refraction through entire atmosphere.

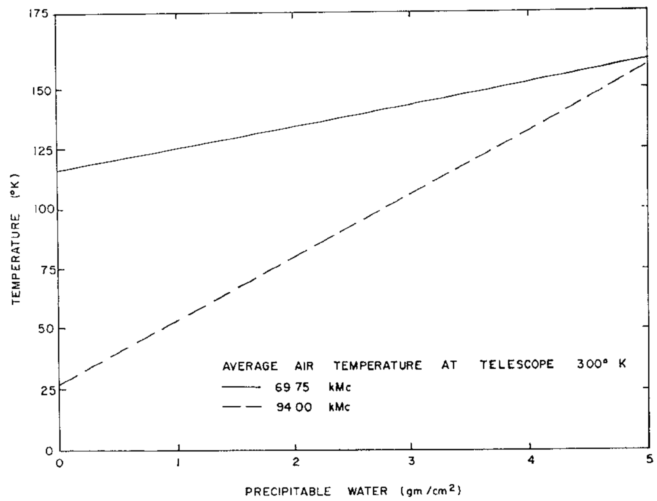

Fig. 8—Zenith antenna temperatures as a function of water vapor content.

area, therefore, is the degree of restriction of information bandwidths that can be caused by inhomogeneous atmosphere.

Antenna Temperature

The emission contributing to the antenna temperature of earth-based millimeter wavelength antennas originates primarily from the earth, the earth's atmosphere, the sun and the moon. The level of emission from the atmosphere is a function of the temperature and opactity of the atmosphereic gases within the volume viewed by the antenna. Antenna temperatures resulting from atmospheric emission will therefore be maximum where the opacity and temperature of atmospheric gases are maximum such as near the earth's surface. Antenna temperatures with vertical pointing for clear skies have been measured at 70 and 94 kMc and are shown in Fig. 8 as a function of the precipitable water in a square centimeter vertical column. Antenna temperatures will increase as the antenna pointing angle is moved from the vertical position and will approach ground level temperatures for horizontal pointing.

Antenna temperatures over the interval of the millimeter wavelengths can have a wide range of values—approximately 310°K to approximately 0°K—depending upon the temperature and opacity of the gas within the volume of the antenna beam. Measured and calculated values of temperature for an antenna pointed downward vs elevation for frequencies of 60.00 and 60.37 are shown in Fig. 9. The measurements were made by lifting a Dicke type radiometer with a 2.9 million cubic foot balloon to an elevation of approximately 100,000 ft.

Other contributions to antenna temperatures originate from the surface of the earth, from particles in the atmosphere, and from celestial sources. Emission from the earth's surface is typified by radiation from water and land surfaces. The emissivity of both surfaces varies with grazing angle, polarization, and surface roughness.

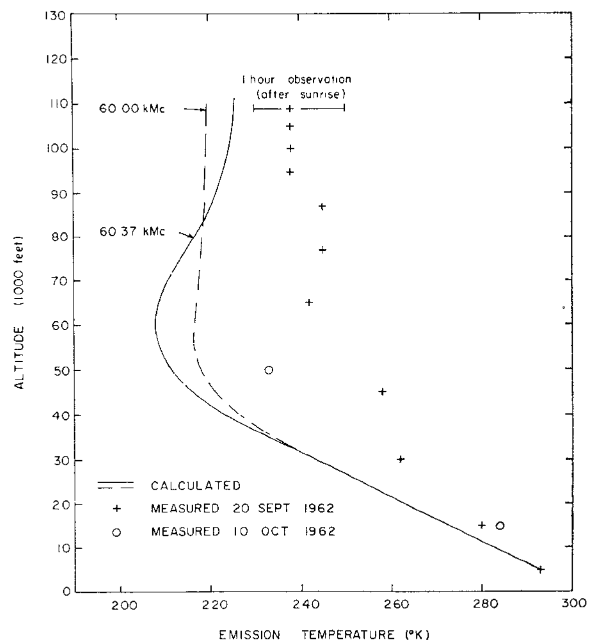

Fig. 9—Antenna temperatures as a function elevation for antenna pointed downward.

Fig. 10 shows the apparent emission temperatures of water, land, and several manufactured materials at 70 kMc.[9] Because of surface reflectivity, the emission from water surfaces and most other materials at small grazing angles is, to a large extent, a function of the emission temperature of portions of the sky reflected by the material. The emission temperature of particles in the atmosphere is a function of the absorptivity and reflectivity of particles and the temperature of the reflected volume, and therefore of the particle size and the aspect from which they are viewed. Shown in Fig. 11 is

[9] A. W. Straiton, C. W. Tolbert, and C. O. Britt, "Apparent temperatures of some terrestrial materials and the sun at 4.3 millimeter wavelengths," *J. of Appl. Phys.*, vol. 29, pp. 776–782; May, 1958.

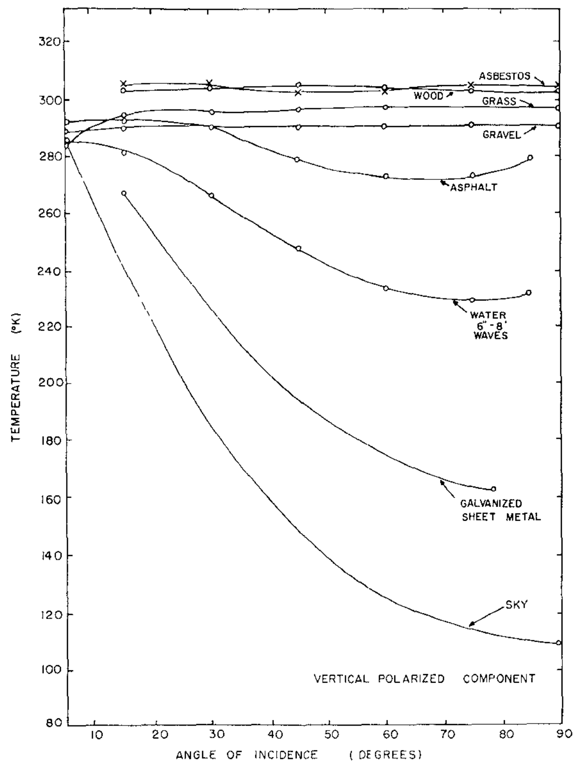

Fig. 10—Emission temperatures at 70 kMc of various surfaces.

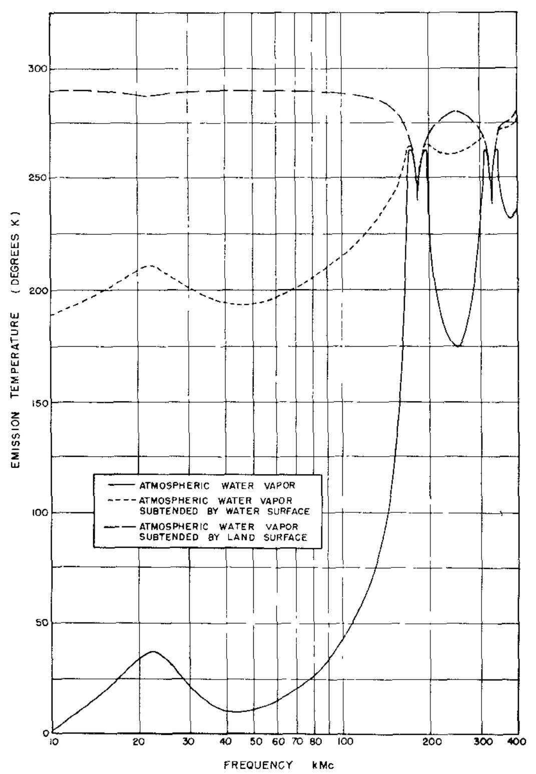

Fig. 11—Calculated emission temperatures into space from the earth and its atmosphere water vapor.

the calculated value of emission temperature into space normally from the earth's surface and from the water vapor contribution of the atmosphere. This figure is based on the ARDC 1960 standard atmosphere.

The celestial sources that contribute most significantly to millimeter wavelength antenna temperatures for antenna beamwidths greater than approximately one minute of arc are the sun and the moon.[10] These two sources, because of the angle they subtend, far exceed in brightness other sources of the celestial sphere. The average temperature of the sun and moon at the millimeter wavelengths is approximately 8000°K and 200°K, respectively. Scattered and reflected solar radiation by precipitation particles and water surfaces can contribute significantly to the apparent temperatures of these media.

In general, the temperature of antennas outside the earth's atmosphere directed toward space will have temperatures near 0°K with the exception of those solid angles subtended by the sun, the moon, and planets of the solar system. Antennas directed toward the earth will have temperatures between approximately 100°K and 300° depending upon the wavelength and the nature of the earth's surface subtending the volume viewed by the antenna.

General Considerations

The advantages of the millimeter wavelengths relative to the longer wavelengths for propagating information accrue through the use of their atmospheric absorbing characteristics, from their possibilities for providing new frequencies to relieve the presently overcrowded spectrum regions, from their information bandwidth or from improved monolobe resolution with decreasing wavelength for a fixed size antenna. Given the same power generation capability and signal-to-noise ratio obtainable at the longer wavelengths, antennas with areas inversely proportional to the wavelength must be used at the millimeter wavelengths to receive an equivalent signal level. Large size millimeter antennas—greater than approximately 10 ft—are difficult, costly, and, at present, tax fabrication techniques. Merit for the millimeter wavelengths must, therefore, be found in improved resolution or in the utilization of the spectrum expansion, bandwidth, and/or loss characteristics.

As a scientific tool for investigation, the millimeter wavelengths are unexcelled, particularly in applications where the emissions from the atmospheric gases are utilized. The increasing need for new information bandwidths makes the development and utilization of the millimeter wavelengths attractive. The development of components and techniques for generating, detecting, and manipulating these wavelengths obviously must precede their fullest utilization.

[10] C. W. Tolbert and A. W. Straiton, "Solar emission at millimeter wavelengths," *Astrophys. J.*, vol. 134, pp. 91–95; July, 1961.