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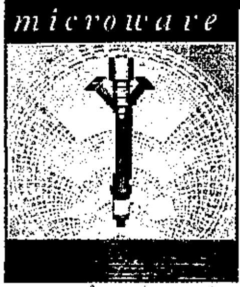

TECHNICAL SECTION

MILLIMETERS — THE NEW RADIO FRONTIER

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Introduction

One of the scarcest commodities in this country today is space in the radio spectrum. The increasing requirement for broadcasting services, public and private communications, aircraft guidance, military applications, and a thousand other uses of the radio spectrum has created a demand for available frequencies that far exceeds the supply.

This overpopulation of the radio spectrum has caused many to look toward the new frontier as an area for expansion of the useful radio spectrum. The part of the spectrum, known as extremely high frequencies (EHF), forms such a frontier. Its bounds are from one millimeter wavelength to one centimeter wavelength with corresponding frequencies of 300,000 megacycles per second and 30,000 megacycles per second. This frequency range of 270,000 megacycles is nine times that of all the other bands combined. It is no wonder, then, that millimeter radio waves are being investigated more and more frequently for their application potential.

Millimeter radio waves, however, do not present a panacea for all of the radio requirements, but they, like most frontiers, have their hardships which may be quite discouraging to the explorer. It is the purpose of this paper to describe the unique characteristics of millimeter radio waves with the hope that it will be useful in evaluating their adaptation for specific purposes.

The two features of millimeter radio waves which separate them from their longer wavelength cousins are that they are in a frequency region where they suffer absorption by atmospheric gases and that their very short wavelength makes them have many of the characteristics of light waves. A successful use of EHF will be one for which these characteristics will be an advantage or one for which they will present little disadvantage.

Absorption of radio waves by the gases in the atmosphere is almost nonexistent for wavelengths longer than a few centimeters. Furthermore, optical wavelengths are also essentially free of this loss factor. The short centimeter, the millimeter and the infrared frequencies are, however, subject to this loss which may be very minor at certain frequencies and very severe at others.

The absorption by atmospheric gases results from the fact that radio waves cause changes in rotational energy levels of the molecules. Each energy level change has a particular frequency associated with it and this frequency is directly proportional to the change in energy involved. The absorption frequencies in the millimeter domain correspond to changes between levels with nearly equal energy content. At very low pressures, the absorption is associated with a very narrow region of the spectrum around this resonant frequency. For higher pressures such as that at sea level, the absorption occurs over a wide frequency spread. This broadening of the absorption lines is due to collisions between the molecules preventing free interchange of energy between the electromagnetic wave and the individual molecules. Thus, to evaluate the extent of the absorption it is necessary not only to know how much of the absorbing gases is present but also to know the total gas pressure. A particular frequency which may be very rapidly absorbed on a short path over the ocean, may be relatively free of attenuation between mountain peaks.

The absorption of millimeter waves is due primarily to two constituents of the atmosphere. These are oxygen and water vapor. The first of these is considerably simpler to treat because its amount is practically constant for a given altitude and because the pattern of the absorbing frequencies is relatively simple.

The interaction of the oxygen molecular and electromagnetic field results from the fact that the oxygen molecule has a magnetic dipole which tries to align itself with the varying field. If the rotational frequency is nearly that of the incoming wave the energy transition will be accomplished.

The water vapor molecule on the other hand has an electrical dipole which interacts with the electric field. The general result of the interaction is the same whether the dipole characteristic is magnetic or electric.

In the lowest energy level state, the O_2 molecule may have one of three values. The transition producing the millimeter absorption are from this triplet ground state to the higher energy levels and all of these energy changes except one are very close to the frequency of 60,000 megacycles per second. The one remaining transition has approximately twice the energy and twice the corresponding frequency. Thus, one oxygen absorption peak occurs at 2.5 millimeters and the rest are grouped around 5 millimeters. At sea level pressure or higher, the absorption lines around 5 millimeters blend together to form a smooth band. At low pressures, the absorption varies erratically with frequency in this region but smooths out at frequencies removed from the resonant ones. Thus the effect of oxygen is limited to a wavelength sector around 5 millimeters and to a small sector around 2.5 millimeters. Again the frequency extent of the absorption is a function of the pressure and to a lesser amount is a function of the temperature. A small amount of continuous absorption occurs but its effect is negligible except for very long paths.

The absorption by water vapor is considerably more complicated because of the vast array of absorption lines which influence millimeter and centimeter radio wave propagation. For water vapor, one absorption line occurs near 1.35 cm and one at 1.63 mm. In addition, there are 149 energy conversions with critical wavelengths between 0.05 and 1.0 millimeters. Individually, these lines contribute little to the EHF loss, but collectively they provide a continuous loss which increases rapidly as the shorter millimeter wavelengths are approached.

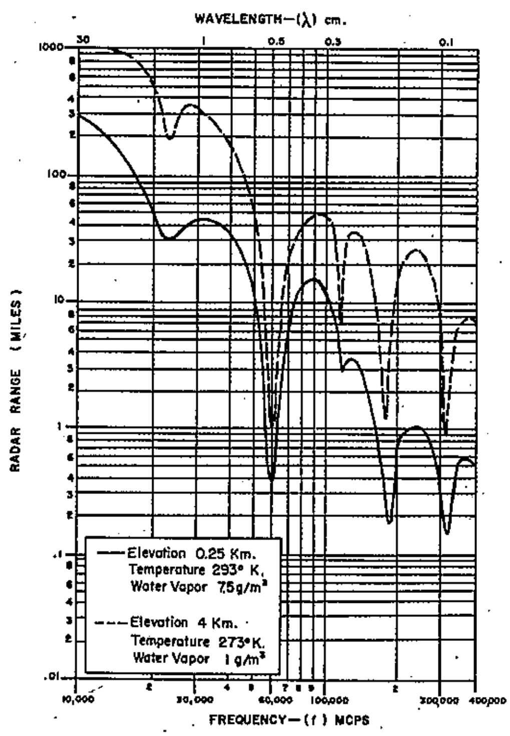
The water vapor content of the atmosphere changes greatly not only with geographical location and elevation, but also with time at a given site. In order, then, to predict the amount of absorption at a particular frequency, it is necessary to know the water vapor content, the temperature and the pressure. The problem is particularly complicated if the transmission is through a significant range of elevations since all of these factors would be variable functions of height. After the absorption has been calculated, the effective range would be a function of the radiated power.

For practical purposes, we have chosen an arbitrary definition of range based on a comparison of attenuation due to divergence and the attenuation due to absorption. The divergence of the beam causes the power density to be inversely proportional to the square of the distance from the transmitter. This means that for greater distances, the power density due to divergence will decrease very slowly. The attenuation due to absorption, in a homogeneous atmosphere, however, will be the same for all distances. This means that for a finite absorption, a distance can be found at which attenuations due to the two factors will be the same. This distance is the one which has been designated as the transmission range. For distances greater than this, absorption will be the predominant factor and for distances less than this, divergence will be the predominant factor.

Using this arbitrary definition, the range as a function of frequency has been plotted in Figure 1 for two typical conditions. The lower curve is for the water vapor content of 7.5 grams per cubic meter at sea level and the upper curve is for the water vapor content of 1 gram per cubic meter at an elevation of 12,000 feet above sea level. These water vapor concentrations would fall in the ranges usually anticipated at these two elevations. From Figure 1, it is seen that very substantial ranges would be associated with some of the longer millimeter wavelength, particularly, for the elevation of 12,000 feet.

The other unique feature of millimeter waves which will be discussed in this paper is related to the semi-optical characteristics associated with these wavelengths. The customary designations of radio band such as High Frequency, Very High Frequency, etc. are based on decade steps in frequency. On this scale, the millimeter region is closer to the optical

Figure 1 — Radar range for atmospheric absorption.



frequencies than it is to the standard A-M radio broadcasting frequencies and many of its features are similar to those of light waves.

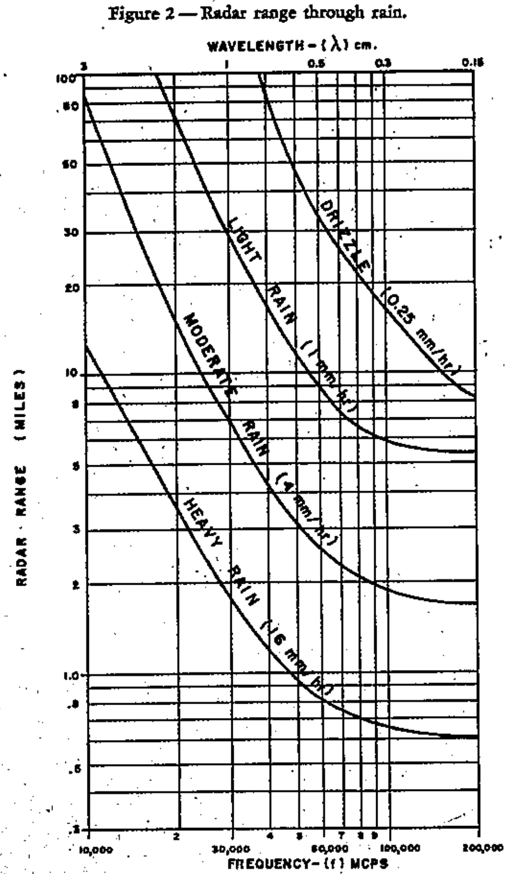
One of these features is the possibility of producing a very narrow beam with a small antenna. Thus, at a wavelength of two millimeters, a parabolic reflector one foot in diameter would produce a beam only one half of a degree between half power points whereas a fifty foot reflector would be required for a similar beam width at a wavelength of ten centimeters. This feature suggests the possible use of millimeter wavelengths for application where high directivity is desired but space limitation prevent the use of large antennas.

As in the case of light, serious propagation effects are encountered whenever precipitation occurs. For longer radio waves, the diameter of water drops is much less than the radio wavelength, but for millimeter waves, the wavelength is comparable to and sometimes smaller than the diameter of raindrops. As a result, rain causes a large amount of absorption and scattering of the incident radio waves. For wavelengths much greater than the diameter of the drops, the attenuation is inversely proportional to the square of the diameter. Very severe attenuation will result in the millimeter region from rain showers and if any proposed millimeter application is to be used in rain, the transmitted power must be adequate to penetrate the area of precipitation.

The size of water drops in a fog is so small that they present comparatively little attenuation. One application tried for millimeter waves has been that of a harbor radar for guiding vessels through fog. The high definition plus the ability to penetrate the fog has made their application a feasible one.

A range through rain can be defined as in the case of the range associated with absorption to be the distance at which the loss due to the rain is equal to the loss due to the divergence of the beam. Figure 2 shows this range as a function of frequency and rainfall rate. This presupposes that the rain is homogeneous over the path. Fortunately many rain showers are of limited areal extent so that the range in rain is not as pessimistic as would be indicated by Figure 2.

Figure 2 — Radar range through rain.



A last disadvantage associated with the shorter wavelengths is the enhanced effects of refraction. Some of the fluctuations may be accounted for by variability of the water vapor absorption of the atmosphere, but the larger part of the refraction results from the focusing and defocusing associated with dielectric blobs.

The atmospheric absorption, the attenuation and scattering by rain and the greater refractive effects are very discouraging to the millimeter system designer. On the other hand, the tremendous bandwidth potential available and the high directivity with small antennas are the encouraging features of millimeter radio waves.

These desirable features may be used effectively in short range radars. Ground mapping from aircraft is a natural since the atmospheric loss will be low from an aircraft to ground, and it is not essential that the mapping be done during rain storms.

Harbor guidance has been mentioned as a possible application for millimeter waves which would be useful under foggy conditions.

The Bell Telephone Laboratories have announced a transmission system using millimeter waves. By using a non-polar gas such as nitrogen in an oversize circular waveguide, the attenuation will be kept small. Other millimeter uses in confined systems could be readily imagined. Indoor transmission, either through pipes or in the open room, might be a desirable and feasible use of millimeter wavelengths.

The resonant characteristics of atmospheric gases might be turned to a useful purpose in space flight. The energy transition of oxygen and water vapor also produce radiation at millimeter wavelengths. A passive detector in space could use this radiation to home on the earth.

In spite of all the limitations discussed in the paper, it seems inevitable that millimeter wavelengths will have many future uses. The development of generators, which is now moving slowly, will be accelerated as particular uses are found for various frequencies in this band.