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THE REFRACTIVE INDEX OF THE ATMOSPHERE
AS A FACTOR IN TROPOSPHERIC PROPAGATION FAR BEYOND THE HORIZON

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Summary

In order to plan a tropospheric beyond-the-horizon radio link, it is at present necessary to make transmission tests to establish the median path loss and to determine the magnitude and duration of the path loss variations. Recent measurements indicate, however, that the relation existing between transmission loss and the refractive index of the atmosphere may enable estimates to be made, from climatic data alone, of the transmission characteristics of any particular path. Extreme values of transmission loss are believed to be chiefly due to exceptional variations with height of the refractive index, while the monthly median values of path loss have been found to be a function of the average surface values of the refractive index of the atmosphere on the transmission path. Curves are given showing the relation found on various paths between radio transmission loss and the refractive index of the atmosphere.

Introduction

No completely satisfactory theory has yet been advanced to explain tropospheric radio transmission far beyond the horizon, but it is known that the so-called scatter field is many orders of magnitude larger than the normal diffraction field at distances far beyond the horizon.

Path loss measurements made with UHF transmissions beyond the horizon show wide variations in received signal level occurring from hour to hour, from day to day and in some cases from month to month; in addition, the median path loss at these frequencies has been found to vary considerably with latitude. These variations in path loss are believed to be entirely due to changes occurring in the characteristics of the lower atmosphere, the most important meteorological factors being temperature and humidity which, with pressure, determine the refractive index of the atmosphere.

In general, it has been found that the atmospheric conditions at any instant are not uniform along the transmission path; and the average conditions at any particular time are, therefore, difficult to determine. However, the weather differences occurring along the path tend to average out during a period of a few weeks, so that daily meteorological measurements made at the two ends of a path, when averaged over, say, a four-week period, are likely to represent the average weather conditions along the transmission path during that month.

Measurements, made by the Bureau of Standards, Federal Telecommunication Laboratories and others, indicate that the monthly median path loss is, in general, a function of the monthly average value of surface refractivity on the transmission path; but the day-to-day variations do not, as a rule, show the same close correlation.

Although it has been shown that there is a close correlation between the long-term median path loss and the average surface value of the refractive index of the atmosphere, tropospheric radio propagation is influenced by several other meteorological factors. For example, the formation of reflecting and refracting layers[1] in the lower atmosphere may have a considerable effect on path loss, and super-refraction can reduce the path loss to less than the free-space value. In addition, atmospheric turbulence may produce scattering of radio waves in the troposphere[2].

Tropospheric radio propagation far beyond the horizon is thus a complex phenomenon influenced by several different meteorological factors; however, a recently established fact of some practical importance is that the median path loss, when averaged over a period of several weeks, is closely correlated with the average value of surface refractivity.

Refractive Index of the Atmosphere

The refractive index of the atmosphere is given by the following expression:

$$(n - 1) = \frac{79}{T}\left(P - \frac{e}{7} + \frac{4800\,e}{T}\right) 10^{-6} \quad --- (1)$$

where

- n = refractive index
- T = absolute temperature in degrees Kelvin
- P = total atmospheric pressure in millibars (1000 mb = 29.5" of mercury)
- e = partial pressure of water vapor in the atmosphere in millibars = 0.00161 PS, where S = grams of water per kilogram of air

The refractive index of the atmosphere at sea level varies between a value of about 1.000240 and 1.000400. Thus, expressed in 'N' units where $N = (n - 1)\,10^6$, the practical limits of 'N' at the surface of the earth lie between about 240 and 400. Under normal atmospheric conditions, the value of 'N' decreases with height above the surface of the earth; and it has been shown, by Strickland[3] and others[4], that this decrease is approximately logarithmic.

Figure 1 shows the change in the value of 'N' with height, the normal variations in the refractive index at the earth's surface decreasing to almost zero at a height of 30,000 feet. The ordinate on the right of this figure shows the path length in statute miles corresponding to a height 'H' of the volume defined by the intersection of the two tangent antenna beams as shown on the left-hand ordinate. Thus, for a path length of 200 miles the height of this common volume is 5000 feet. The distances shown in Figure 1 are based on an effective radius of the earth of 4/3 the true radius, and the heights of the common volumes assume that the antennas are close to sea level and are directed horizontally.

The expression for the refractive index of the atmosphere in 'N' units is of the form:

$$N = \frac{AP}{T} + \left(\frac{Be}{T^2} - \frac{De}{T} \right) \quad --- \qquad (2)$$

where $N = (n - 1)\, 10^6$, n being the refractive index, and where the values of the constants are approximately as follows:

$$A = 79,\ B = 3.8 \times 10^5,\ D = 11$$

The value of the first term of the above expression is dependent only on atmospheric pressure and temperature and is known as the "dry term," whereas the value of the second term is dependent on water-vapor pressure and atmospheric temperature and is known as the "wet term." As the temperature increases, the value of the "dry term" decreases for a given atmospheric pressure, but the value of the "wet term" increases for a given relative humidity. This is so because of the relation between saturation-vapor pressure and air temperature. If the atmospheric pressure and relative humidity remain constant, the value of the refractive index increases with increasing temperature above about -5°C; however, below this temperature, the value of the refractive index increases with a decrease of temperature.

When the air temperature is low a given change in relative humidity produces a much smaller change in the value of the refractive index than when the temperature is high. For example, at a temperature of -5°C, a change in relative humidity of from 50 per cent to 80 per cent produces a change in the surface value of 'N' of only 6 units or, say, about 2 per cent. However, at a temperature of +25°C, the same change in relative humidity results in a change in the value of 'N' of 40 units or, say, 13 per cent.

The value of the atmospheric pressure at the surface of the earth may vary, under extreme conditions, from 900 millibars to 1060 millibars (mb); however, under normal conditions, the surface pressure varies from about 990 mb to 1030 mb. The change in pressure experienced when going from cyclonic to anticyclonic conditions is thus about ±20 mb, producing a change in the value of 'N' of 12 units or, say, about 4 per cent. It is seen, therefore, that at low temperatures, say at -5°C, the normal variations in atmospheric pressure produce about twice as great a change in the value of 'N' as would a normal variation in relative humidity of from 50 per cent to 80 per cent. However, at higher temperatures, say +25°C, the reverse is the case; and a change in relative humidity of from 50 per cent to 80 per cent results in a change in the value of 'N' more than three times as great as would a normal change in atmospheric pressure of from 990 mb to 1030 mb.

Thus, in cold climates the daily variations in the values of the refractive index of the atmosphere are largely caused by variations in atmospheric pressure, whereas in temperate or warm climates the daily changes in temperature and relative humidity are likely to cause much greater changes in the value of the refractive index than do the normal changes in pressure. The seasonal change in the value of the refractive index at any particular location is almost entirely due to the seasonal change in temperature and relative humidity.

The refraction of rays passing through the atmosphere is due to the change in refractive index with height. The average conditions are represented by an atmosphere having a linear refractive index gradient below about 10,000 feet of 11.9 'N' units per thousand feet; rays passing at small elevation angles through such an atmosphere have a constant curvature. It can be shown that with this standard atmosphere the earth may be replaced by an equivalent earth with a modified radius of 4/3 the true radius, and the refracted rays may then be drawn as straight lines. In practice, however, it is found that the refractive index gradient is not, in general, linear, being greatest in the lower layers of the atmosphere; and under such nonlinear conditions, the curvature of the rays is not constant but may be determined from the refractive index distribution with altitude[4]. Considerable changes in path loss may result from variations from the normal in the vertical gradient of the refractive index; with large vertical gradients, elevated reflecting layers may be formed which, under certain conditions, greatly influence the path loss.

In considering the effect of the surface value of the refractive index of the atmosphere on radio transmission, the question arises as to what value of the refractive index should be taken when transmission paths of, say, several hundred miles in length are being considered. It has been found that the surface values of 'N' at any particular time may be quite different at points separated by such distances and that the daily variations of 'N' at the two ends of an over-the-horizon path may show little correlation. For example, Figure 2 shows the values of surface refractivity measured each day during February 1955 at points separated by about 180 miles;

the correlation coefficient in this case is only 0.60. However, if the values of 'N' at the two ends of the transmission path are averaged over a week or more, it will be found that there is a much closer correlation of the variations. Figure 3 shows the surface values of 'N' measured again at Miami and at Havana; but in this case, the average monthly values are compared showing a correlation coefficient of 0.95.

In comparing transmission loss with the surface values of the refractive index, the values of 'N' assumed for the transmission path should, therefore, be the values measured at each end of the path, and at other points on the path if possible, averaged over periods of not less than about one week and preferably over about a four-week period. Thus, the weekly or monthly median transmission loss should be compared with the median value of the surface refractive index of the transmission path for the same period.

Tropospheric Propagation Characteristics

In the case of UHF transmission far beyond the horizon at frequencies between about 400 mc and 2000 mc, the following general characteristics have been established:

1. Large variations in path loss from the monthly median lasting on the average for periods of up to, say, one hour[5, 6] but persisting in some cases for several days.
2. A day-to-day variation in median path loss.
3. A seasonal change in path loss amounting to about ±12 db is usual on paths of, say, between 100 and 200 miles in length in temperate latitudes, the path loss being greater in winter than in summer[7, 8].
4. A Gaussian distribution of hourly medians on overland paths with a standard deviation of about 8 db.
5. A decrease in the amplitude of the variations in path loss with increasing path length[9, 10, 11, 12].

In addition, there is the Rayleigh-distributed fast fading, which is not considered in this paper.

Causes of Path Loss Variations

In considering the characteristics of radio propagation beyond the horizon, the transmission path may be thought of as consisting of two separate parts, the first being the common volume at the intersection of the two antenna beams and the second the two line-of-sight paths from the antennas to the common volume. A small fraction of the transmitted energy is reflected, or scattered, to the receiving antenna by inhomogeneities within the common volume; and measurements indicate that the median loss at this common volume is a function of the angle of intersection of the two antenna beams.

The transmission loss between isotropic antennas for the line-of-sight paths is given by the expression:

$$\text{Loss in db} = 37 + 20 \log F + 20 \log d \qquad (3)$$

where 'F' is the frequency in mc and 'd' the distance in statute miles. The two line-of-sight paths are subject to atmospheric refraction and, due to the small angles of elevation of the rays, are particularly sensitive to changes in the vertical gradient of the refractive index in the lower atmosphere. An increase in the refraction of these rays decreases the angle of intersection of the antenna beams and is thus equivalent to a decrease in the effective length of the transmission path.

Large Variations in Path Loss Lasting for Short Periods

The decrease in the value of the refractive index of the atmosphere with height near the surface of the earth is 11.9 'N' units per 1000 feet for the standard atmosphere. However, under certain conditions, the gradient of 'N' with height may be above the normal value so that the curvature of the line-of-sight paths is increased; and the angular distance of the path is, therefore, decreased. Under extreme conditions, the rays may follow paths parallel to the earth's surface, or be bent downwards towards the earth, giving a path loss even lower than the free-space value. On the other hand, a decrease in the gradient of 'N' with height will result in a decrease in the refraction of the rays and an increase in the path loss. It is believed that extreme conditions of low path loss are more likely to occur on over-water than on overland paths.

Path loss measurements made by the American Telephone and Telegraph Company[6] at 800 mc on an over-the-horizon path between Florida and Cuba showed that the exceptional conditions of path loss occurred at times when either high or low values of surface refractivity existed over the transmission path. It was also found that these exceptional values of path loss were associated with unusual variations of the refractive index with height. The average gradient of the refractive index was determined during these tests from radiosonde measurements which did not, however, show the fine structure of the index gradient.

Path loss values considerably below the monthly median were frequently recorded during the Florida - Cuba tests; for example, at about 10 p.m. on May 9, 1955, the measured path loss was some 17 db less than the monthly median value. The gradient of 'N' at this time was found to be much greater than the normal value. Figure 4 shows the decrease in the value of 'N' with height as measured near the two ends of the path at the time when these low values of path loss were recorded. In this figure are also shown the gradient for the standard atmosphere and the average gradient for May at Miami. It will be seen that not only was the gradient of the refractive index very high at this time, but the surface value of 'N' was about 370 instead of the standard value of 322.

High values of path loss were, on the other hand, associated with low gradients of 'N'. For example, Figure 5 shows the decrease in the value of 'N' with height, near the two ends of the path, when the recorded transmission loss was about 25 db above the monthly median value. For comparison, the gradients for the standard atmosphere and for the February average at Miami are also shown. It will be noted that the gradient of the refractive index at Miami for the first thousand feet of altitude was considerably below normal at this time and that the surface value of 'N' at Miami was only 296 instead of the standard value of 322.

Conditions of median path loss were, however, associated with a gradient of the refractive index close to that of the standard atmosphere. For example, Figure 6 shows the gradients of 'N' near the two ends of the path measured at about 10 a.m. on February 23, 1955; the normal gradient for the standard atmosphere is also shown in this figure. At the time these measurements were made, the median path loss was about 15 db less than would be expected from transmission loss measurements made in the northeast of the United States. It will be noticed that the average gradients of 'N' were about normal at altitudes below 4000 feet, but the average surface value of 'N' was about 347 as compared with the standard value of 322.

The extreme values of path loss measured during tests between Miami and Havana were, therefore, found to be due to a combination of unusual values of surface refractive index and to exceptional gradients of this index. Under normal conditions, however, the relatively low value of transmission loss measured on this path seemed to be chiefly due to the high average value of surface refractive index, typical of the warm humid climate of that area, and not to an unusual gradient of the refractive index.

Day-to-Day Variations in Median Path Loss

Transmission loss measurements made in different parts of the world have shown daily variations in median path loss of as much as ±20 db. These variations seem to be largely dependent on the gradient, and on the surface value, of the refractive index of the atmosphere prevailing at the time along the transmission path. The daily averages of these meteorological characteristics are difficult to measure, particularly on over-water paths; and some uncertainty exists as to the relative importance of atmospheric turbulence on the daily values of path loss. However, in spite of these difficulties, measurements show some correlation between daily values of path loss and the average surface refractive index measured at the two ends of the path.

Transmission loss tests were recently conducted on a frequency of about 900 mc between sites near Buenos Aires in the Argentine and Montevideo in Uruguay. Figure 7 shows the daily average values of surface refractivity and the daily median level of the received carrier for one month. There is, in general, some degree of correlation between the daily values of the refractive index and the daily median path loss; but as has been shown, the gradient of the refractive index is also an important factor in UHF radio propagation far beyond the horizon. Daily measurements made near Buenos Aires of the variation with height of the refractive index showed that at times of poor correlation between path loss and surface refractive index the gradient of the refractive index was, in general, abnormal. Since the refractive index gradient was measured at only one end of the path, it was not possible in this case to make an estimate of the average gradient over the transmission path. More complete information on the daily average gradient would probably have indicated the reason for the poor correlation found on certain days between the path loss and the surface value of the refractive index.

The Seasonal Change in Path Loss

The value of the refractive index near the surface of the earth varies in temperate latitudes with the seasons; the value increases as the weather becomes warmer. In most tropical and arctic areas, however, the refractive index at the earth's surface changes much less from month to month than it does in the more temperate areas of the world. This relatively small change is due to the fact that in many tropical areas the temperature and relative humidity remain more or less constant throughout the year; and in arctic areas, the low average temperature results in a fairly constant, and relatively low, value of the refractive index. For example, at temperatures below 0°C, the surface value of 'N' only varies between about 290 and 320 for relative humidity changes of from 10 per cent to 90 per cent.

As an example of typical variations of the refractive index of the atmosphere, Figure 8 shows the monthly average values of the surface refractive index at San Juan in Puerto Rico, at Charleston in South Carolina, and at Goose Bay in Labrador. It will be seen from this figure that the seasonal change in the refractive index is comparatively small at San Juan and at Goose Bay, being much greater at Charleston.

Measurements made at a number of locations along the Atlantic Coast, from the tropics to the arctic, show that the maximum seasonal change in the surface refractive index, of about 60 'N' units, occurs at a latitude of about 33° north whereas the minimum seasonal change, of about 15 'N' units, occurs both in the tropics and in the arctic.

It has been shown, by Bean[13, 14], that at a frequency of about 100 mc there is a close correlation between the monthly median transmission loss and the average monthly value of refractive index at the earth's surface. The surface value of 'N' is, on the average, a measure of the gradient of 'N' with height; but it was shown during the Florida - Cuba tests that a gradient of 'N' corresponding to the normal 4/3 earth radius occurred at times when the median carrier level was some 15 db above what would be expected from path loss measurements made in the northeastern part of the United States. Thus, a high value of 'N' at the earth's surface, but a normal gradient, was in this case associated with low values of path loss.

Other measurements of path loss have also shown that there is a close correlation between the average monthly surface values of refractive index and the monthly median path loss[7, 8, 15]. For example, during 1955 transmission loss measurements were made on a frequency of 238 mc between the islands of Minorca and Sardinia in the Mediterranean. Figure 9 shows the monthly median path loss and the average monthly value of surface refractivity, which in this case showed a correlation of 0.76 between these monthly values.

Radio propagation measurements made on beyond-the-horizon paths thus show good correlation between the seasonal changes in median path loss and the seasonal changes in the average value of refractive index measured near the surface of the earth on the transmission path.

<u>A Gaussian Distribution of Hourly Medians With a Standard Deviation of About 8 db</u>

The distribution of the hourly median path loss values vary with geographic location; and as has been shown, there is a close correlation between the monthly variations in path loss and the monthly variations in the surface value of refractive index. The distribution of the monthly median path loss values is, thus, largely determined by the distribution of the values of refractive index; large seasonal changes in the value of 'N' would, thus, be expected to result in large values of standard deviation of the monthly median path loss distribution.

However, during the Florida - Cuba tests, it was found that the extreme values of path loss, which occur, in general, for a small percentage of the time, were a function, not only of the surface values of 'N', but also of the gradient, or rate of change of 'N', with height. Thus, the final distribution of the hourly median path loss values is determined for, say, 90 per cent of the time by the distribution of the surface values of 'N' and the remaining 10 per cent of the time by abnormal gradients of the refractive index occurring at heights below the common volume.

<u>The Decrease in the Amplitude of the Variations in Path Loss With Increasing Path Length</u>

It has been shown that under the same climatic conditions the long-term variations in path loss are of smaller amplitude at a distance of 300 miles than at, say, 100 miles[9, 10, 11, 12]. If the slow changes in path loss are due to changes in the refractive index, not at the surface of the earth, but at some height which increases with the path length, then it is clear from Figure 1 that there will be a smaller change in loss at, say, 300 miles than at 100 miles. The fact that the variations in path loss have been reported to be very small at distances of about 600 miles indicates that the path loss variations may be a function of the variations in refractive index, not at the surface of the earth, but at a height close to the intersection of the antenna beams. However this may be, the decrease in the amplitude of the long-term variations of path loss with distance suggest that the loss may be a function of the variations in refractive index, not at the earth's surface, but at a height proportional to about the square of the path length.

<u>Path Loss as a Function of Distance and of the Surface Value of the Refractive Index of the Atmosphere</u>

Path loss measurements indicate that there is a close correlation between path loss variations and the variations in the value of the refractive index of the atmosphere at a height close to the intersection of the antenna beams.

Measurements made between Florida and Cuba[6] showed that the median loss over a path length of 184 statute miles was about 53 db below free space. From meteorological measurements made at Miami and Havana, the average surface value of 'N' at the time of the path loss measurements was 360; and the variation in path loss was found to be 0.5 db per unit change in 'N'.

Measurements made on the 238-mile path between Dorado in Puerto Rico and Ciudad Trujillo in the Dominican Republic showed a median path loss below free space of about 65 db for an average surface value of 'N' of 364. The variation in loss in this case was about 0.4 db per unit change in the surface value of 'N'.

From these results and from measurements made in the Mediterranean, in the Argentine and elsewhere, Figure 10 has been prepared showing the median path loss as a function of distance and of the average value of the refractive index at sea level for frequencies in the neighborhood of 900 mc. This figure summarizes the results of recent path loss measurements and illustrates, in a general way, the relationship between median path loss, distance and the average value of refractive index at sea level. From this figure, estimates may be made of the monthly median path loss at 900 mc for any distance from 80 to 300 miles and for average surface values of the refractive index, expressed in 'N' units, of from 300 to 360.

Conclusion

Tropospheric propagation far beyond the horizon is entirely dependent on the atmosphere.

The monthly median path loss has been shown to be a function of the average monthly refractive index of the atmosphere on the transmission path. When the temperature and relative humidity are high, the path loss is low, and vice versa, thus giving rise to seasonal variations in loss in temperate latitudes.

The exceptional values of path loss are chiefly due to abnormal vertical gradients of the refractive index of the atmosphere on the transmission path. Extreme conditions lead to ducting or to the formation of reflecting layers resulting in low values of path loss.

Path loss measurements show that the variations in transmission loss decrease as the length of the path increases, suggesting that the variations in median path loss may be a function of the variations in the average index of refraction of the atmosphere at a height close to the intersection of the two antenna beams.

In UHF tropospheric propagation far beyond the horizon, measurements indicate that the monthly median path loss is a function of the average monthly surface value of the index of refraction and of the angular distance. This relation is of considerable practical interest since it may permit estimates to be made of the monthly median transmission loss over any path for which the average monthly surface values of the index of refraction are known.

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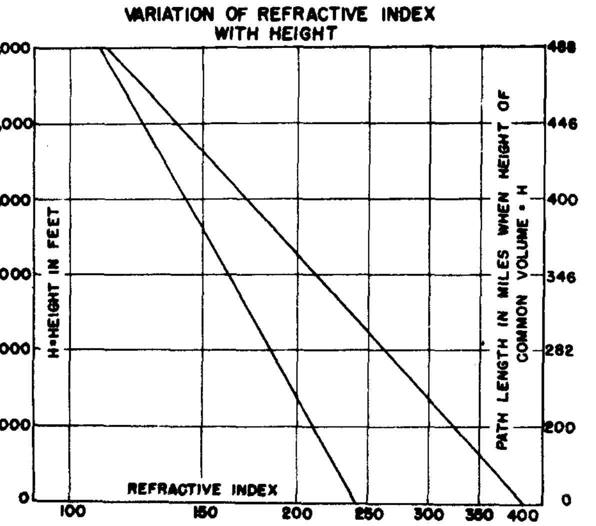

Fig. 1
Variation of refractive index with height.

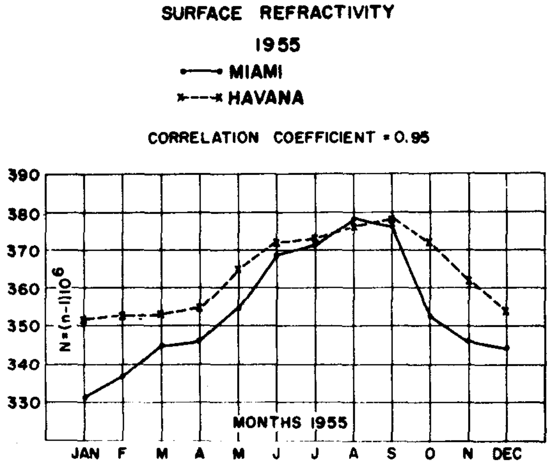

Fig. 3
Surface refractivity, 1955, Miami and Havana.

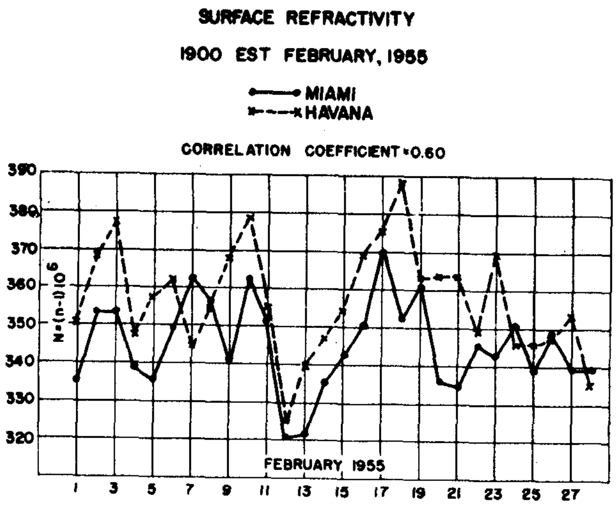

Fig. 2
Surface refractivity, 19.00 EST, February 1955, Miami and Havana.

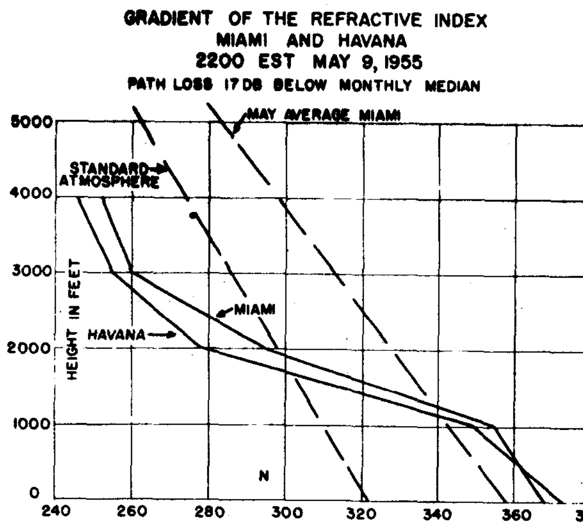

Fig. 4
Gradient of the refractive index, Miami and Havana, 22.00 EST, May 9, 1955, path loss 17 db below monthly median.

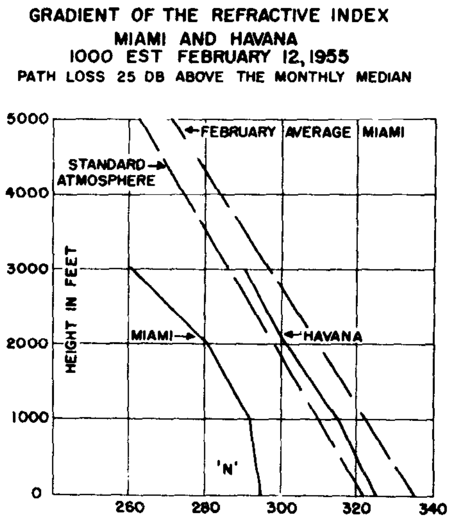

Fig. 5
Gradient of the refractive index, Miami and Havana, 10.00 EST, February 12, 1955, path loss 25 db above the monthly median.

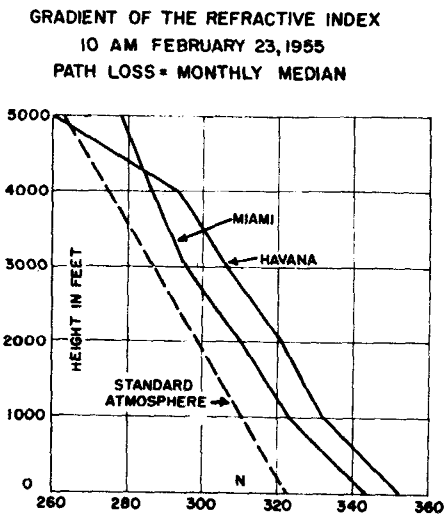

Fig. 6
Gradient of the refractive index, 10 A.M., February 23, 1955, path loss = monthly median.

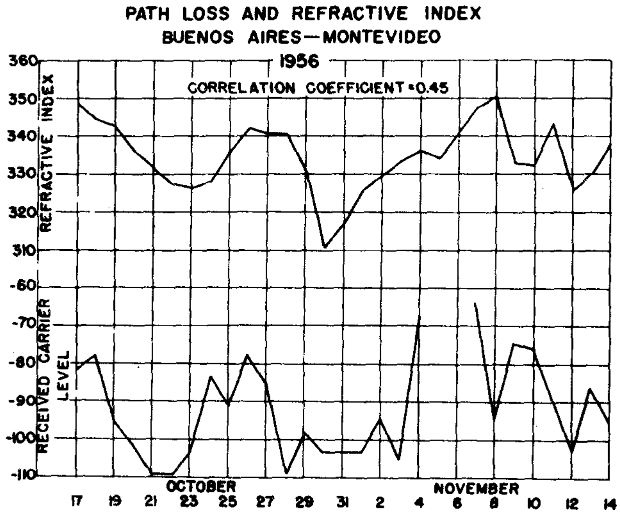

Fig. 7
Path loss and refractive index, Buenos Aires - Montevideo, 1956.

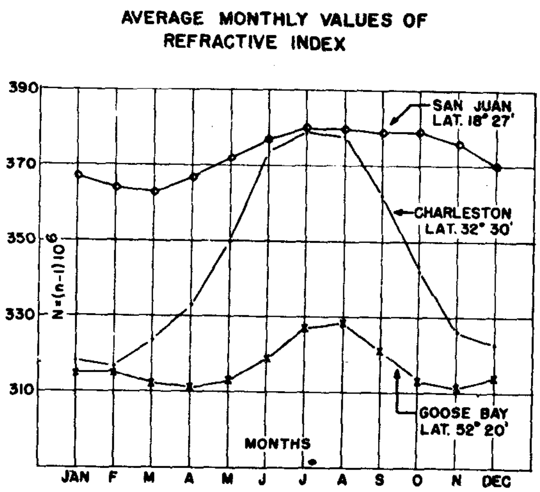

Fig. 8
Average monthly values of refractive index.

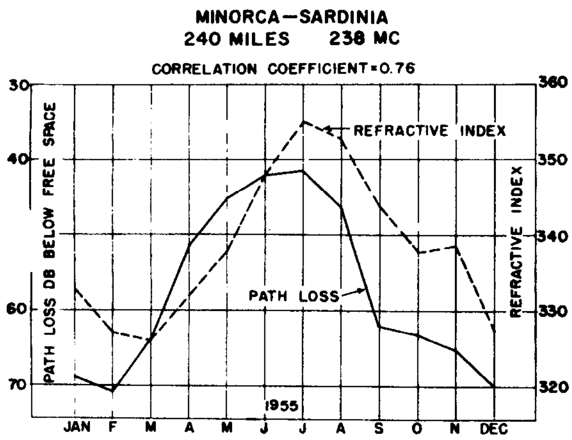

Fig. 9
Minorca - Sardinia, 240 Miles, 238 Mc.

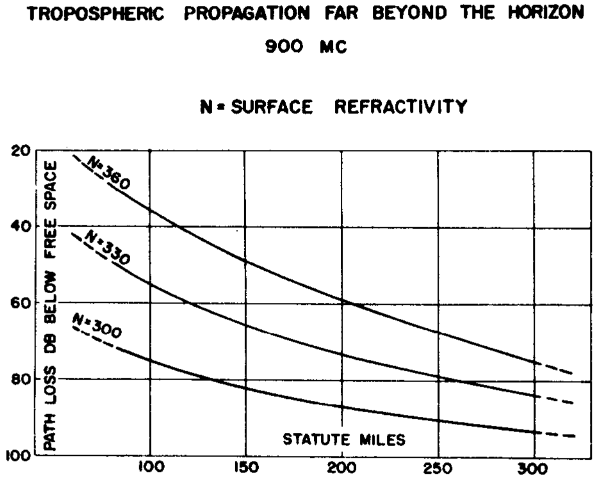

Fig. 10
Tropospheric propagation far beyond the horizon.

ATTENUATION AND FLUCTUATION OF MILLIMETER RADIO WAVES

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The University of Texas

Abstract

This paper contains a résumé of the millimeter propagation measurements conducted by the Electrical Engineering Research Laboratory of The University of Texas.

These measurements were made at wavelengths of 8.6 millimeters and 4.3 millimeters, and more recently and as yet unreported, at a wavelength of 3.35 millimeters. The 8.6 and 4.3 millimeter measurements were made at elevations of 0.25 kilometer and 4 kilometers above sea level. The path lengths ranged from 3.5 miles to 61 miles. The 3.35 millimeter measurements were made at an elevation of 0.25 kilometer over a path length of 7.5 miles.

The measured oxygen and water vapor attenuations at the three millimeter wavelengths are compared to theoretical attenuations. Spectra of scintillations are shown and several of the refraction characteristics are noted. A comparison of the propagation of the millimeter wavelengths with that of 3.2 centimeter wavelength is also made.

Introduction

For the past several years, a series of radio propagation measurements have been carried on at millimeter wavelengths by the Electrical Engineering Research Laboratory of The University of Texas. In a previous paper,[1] tests using wavelengths of 8.6 and 4.3 millimeters under several conditions of range and elevation were reported.

This paper describes two additional measurement programs and interprets them in light of the previous data. One of the recent tests was the transmission of a 4.3 millimeter wavelength signal at 4 kilometer elevation over the 61 mile path between Pikes Peak and Mount Evans in Colorado. The other recent test involved the transmission of a 3.35 millimeter wavelength signal over the seven and one-half mile path between the Main Campus and the Balcones Research Center of The University of Texas in Austin.

High Elevation Tests at 4.3 Millimeters

During August 1956, radio propagation measurements were made between Mount Evans and Pikes Peak in Colorado using a wavelength of 4.3 millimeters. The elevation of this path was approximately 4 kilometers and the path length was sixty-one miles.

Thirty-one samples of five minutes duration were taken at one and one-half hour intervals over a six day period. The free space signal level at 61 miles was established by projecting the signal received over a 2000 foot path according to the inverse square law relationship. Simultaneous transmission at a wavelength of 3.2 centimeters was made for comparison purposes.

The mean value of the signal level when no precipitation was apparent on the path was the free space value for the 3.2 centimeter signal and 24.4 db below the free space value for the 4.3 millimeter signal. During two intervals when rain was apparent on the path, the mean value of the signal levels for the millimeter waves were 48 and 32 db below the free space values while the mean values of the signal level for the centimeter signal remained essentially at the free space value.

Psychrograph readings were made on the two peaks at the time each radio measurement was made and the water vapor content determined. In addition, radiosonde data were obtained from Lowry Air Force Base in Denver and their indicated water vapor content at 4 kilometers noted. The radiosonde values were approximately 25 per cent less than the average of the values measured on the peaks. The two sets of data would appear to set the limits on the probable values of water vapor content.

The millimeter signal level was plotted in Figure 1 as a function of the water vapor content excluding the samples for which the rms values of the fluctuations exceeded 2 db. A line drawn through the plotted points to provide a least mean square error was extended to the origin to give a measure of the oxygen loss and its slope was used as a measure of the water vapor loss. The limits of the slope were established according to the limits of the water vapor content mentioned above.

The total oxygen loss was found to be 21.3 db or 0.22 db per kilometer. The water vapor loss over the whole path was between 0.76 and 1.00 db per gram of water vapor per cubic meter or between 0.0077 and 0.010 db per kilometer per gram per cubic meter of water vapor.

Propagation of 3.35 Millimeter Waves on A 7.5 Mile Path

During January and February of 1957, radio propagation measurements were made from a room in the twenty-fifth floor of the tower on The University of Texas Main Campus to the second floor of the Millimeter Laboratory building at the Balcones Research Center of The University of Texas. Each end of the path was at approximately 0.25 kilometer elevation and the path length was 7.5 miles. The transmitter used an experimental magnetron built by the Radiation Laboratory of Columbia University. This tube was mounted in a permanent magnet yoke which produced a field of 22,000 gauss across the magnetron cavities. The receiver was of the crystal video type. Calibration of the receiver and an attenuator were made over short path lengths by the use of the inverse power relationship.

Eleven three minute samples were taken over a period when a wide range of water vapor content of the atmosphere was experienced. The value of the water vapor content at the time of the radio measurements was determined from Weather Bureau data. Psychrometer readings at the two ends of the path have agreed very closely with the data obtained from the Weather Bureau.

In Figure 2 the median values of the signal levels are plotted as a function of the water vapor content and the line drawn on the least mean square deviation basis. The vertical lines through the points indicate the range between the maximum and minimum signal levels noted during the three-minute sampling periods. From the ordinate intercept of this curve, it is found that the oxygen loss is 0.07 db per kilometer and from the slope of the line it is found that the water vapor loss is 0.033 db per kilometer per gram per cubic meter.

Scintillation Characteristics of Millimeter Signals

In general, the scintillations of the millimeter radio signal are of a greater magnitude than those for longer wave lengths. In the presence of rain the levels are sharply reduced with comparatively little rapid scintillations of the signal level. The rapid changes frequently noted in the absence of precipitation are attributed to refraction and to focusing and defocusing due to inhomogeneities in the atmosphere. Several independent observations concerning the scintillation of the millimeter signals are presented in this section.

Correlation of 8.6 Millimeter Signal Scintillations with Index of Refraction Fluctuations. During one of the earlier tests at a wavelength of 8.6 millimeters over a 3.5 mile path in Austin, index-of-refraction at the transmitter was recorded on a Crain Refractometer[2] simultaneously with the radio measurements. The index-of-refraction traces had the usual characteristics of a broad frequency spectrum with the fluctuations ranging from slow drifts to rapid variations. The 8.6 millimeter signals did not have changes corresponding to the long time drifts in the index-of-refraction data, but had higher frequency fluctuations whose magnitude was approximately proportional to the higher frequency refractive index changes. The magnitudes of the fluctuations of the radio signal are greater than would be experienced if all of the water vapor in the air were removed. This would seem to indicate that the index changes are not due to changes in absorption but are due to refraction effects.

Comparison of Scintillations of 4.3 Millimeter and 3.2 Centimeter Wavelengh Signals. During the peak-to-peak tests in Colorado in 1956, simultaneous measurements were made at wavelengths of 4.3 millimeters and 3.2 centimeters. The rms values of the scintillations of the two signals in the absence of precipitation are shown in Figure 3. The line drawn on a least mean square basis showed a direct proportionality between the scintillations of the two frequencies with 5 db of millimeter wavelength scintillation for each db of centimeter wavelength scintillation.

A further relationship between the two frequencies is shown in the comparison of the spectra of the scintillations shown in Figure 4.

Similar features are noted in the lower frequencies of the two spectra with the millimeter wavelength spectra extending to higher frequencies than the 3.2 centimeter spectra.

Scintillation of 3.35 Millimeter Signals in Frontal Activity. One of the measurement periods for the 3.35 millimeter signal occurred about 9:00 A.M. on January 17, 1957, when a sharply defined polar air mass was arriving at the measurement site. This dry air was replacing humid Gulf air and considerable turbulence existed which must have contained sharp contrasts in index of refraction. During this period the 3.35 millimeter signal strength fluctuated rapidly over an 8 db range. This range could not be attributed to average changes in water vapor content as the signal rose at times to approximately the free space value.

Drop in Median 4.3 mm Signal Level During Periods of Severe Scintillation. During the 4.3 millimeter peak-to-peak tests in Colorado, periods of severe scintillation were noted. The plot of the rms values of the scintillation as a function of signal level shown in Figure 5 indicates a loss of signal associated with severe signal strength fluctuations. This is attributed to a type of radio hole situation in which nonstandard refracting layers existed at or near the path altitude. Visual observations of a significant wind shear with height and/or haze layers at these altitudes were noted. In the curve of 4.3 millimeter attenuation as a function of water vapor content shown in Figure 1, data for which the scintillation exceeded 2 db were excluded.

Attenuation Due to Rain

Theoretical curves have been presented showing the attenuation of millimeter waves in rain. These curves are based on assumed drop size distributions associated with given rainfall rates. Figure 6 shows one-way attenuation measurements made through rain superimposed on a theoretical attenuation curve based on the drop distributions proposed by Laws and Parsons.

It is to be noted here that the predicted attenuation for the millimeter wavelengths based upon the rainfall rate is in general higher than the measured attenuation for large rainfall rates.[3] This discrepancy in the case of our measurements was primarily due to a rainfall rate-drop size distribution different from that postulated by Laws and Parsons.[4]

Water-Vapor and Oxygen Absorption

8.6 Millimeter Measurements. Errors in measuring the water vapor content of the atmosphere and in measuring differences of the order of 30 decibels in signal strength mask the oxygen losses at 8.6 millimeters. Our measurements therefore do not yield a value for the attenuation of oxygen at 8.6 millimeters but only indicate that it was small in value as was predicted by Van Vleck. The water vapor losses, though small, can be measured since this computation only requires measurements of the relative signal strength over a small range. Measurement in Austin, Texas, over several paths indicated a loss of 0.010 db per kilometer per gram per cubic meter at an elevation of approximately 0.25 kilometer. Measurements over the sixty-one mile path from Pikes Peak to Mount Evans indicate a loss of approximately 0.003 db per kilometer per gram per cubic meter at an elevation of 4 kilometers.

4.3 Millimeter Measurements. From Figure 1, the oxygen and water vapor loss at 4 kilometers were found to be 0.22 db per kilometer and 0.009 db per kilometer per gram per cubic meter respectively.

Earlier measurements in Austin at 0.25 kilometer elevation gave corresponding values of 0.50 per kilometer for oxygen and 0.025 db per kilometer per gram per cubic meter for water vapor.

3.3 Millimeter Measurements. The loss per kilometer at 0.25 kilometer elevation for the 3.35 millimeter signal was given earlier as 0.07 db per kilometer of oxygen and 0.033 db per kilometer per gram per cubic meter of water vapor.

Comparison of Theoretical and Measured Loss for Oxygen. Laboratory measurement of several experimenters[5] indicated that a line breadth constant of 0.02 per centimeter should be used to determine the attenuation due to oxygen. A curve calculated on this basis by T.F. Rogers showing the attenuation due to oxygen at sea level and at an elevation of 4 kilometers is shown in Figure 7. These elevations correspond approximately to those in the tests described in this paper.

The oxygen loss calculated by Rogers at 4.3 millimeters is 0.6 db per kilometer compared to our measured value of 0.5 db per kilometer. Crawford and Hogg[6] reported good agreement with Rogers' curve in 5 to 6 millimeter region but in private correspondence have indicated a value of 0.46 db per kilometer may be applicable for 4.3 millimeters. The Rogers' calculations indicate a loss of 0.1 db per kilometer at 3.35 millimeters, whereas our measured values indicated a loss of 0.07 db per kilometer.

Comparison of Theoretical and Measured Loss for Water Vapor. The water vapor attenuation in the millimeter range is commonly discussed in terms of that due to the absorption line at 1.35 centimeters and that due to an array of lines in the infrared spectrum. Reasonably good agreement with measured data in the vicinity of the 1.35 centimeter line has been obtained by using a line breadth constant of 0.1 per centimeter.[7] Becker and Autler[8] noted that the disagreement which they found around this line could be attributed to the residue effect from the higher frequency lines.

T.F. Rogers[9] of Air Force Cambridge Research Center has calculated the attenuation in the millimeter range using the Van Vleck-Weisskopf formula for the 1.35 cm line and for the higher frequency lines which would have a significant loss contribution in this range. He used one per cent water vapor concentration at sea level and at an elevation of 4 kilometers assuming a line breadth constant of 0.1 for all of the lines.

The measurements of water vapor loss by The University of Texas were at approximately the same altitudes as used by Rogers and hence the measured data are superimposed on his curves as shown in Figure 8. A curve through the measured data at the three wavelengths for sea level conditions has been sketched to provide an estimate of the loss at other frequencies.

A similar sketch can be made for the 4 kilometer elevation but with less accuracy since the loss is known at only two wave lengths. It is noted that at near sea level the measured loss at 8.6 millimeters is 2.5 times the calculated loss while at 3.35 millimeters it has increased to 3.5 times the measured loss.

At 4 kilometers elevation, the measured loss is 1.5 to 2 times the calculated loss at 8.6 millimeters and has increased to 3 to 4 times the measured loss at 4.3 millimeters.

These relationships would seem to show that the deviation from the theory and experiment is due to the loss resulting from the lines of wave length other than 1.35 centimeters as suggested by Van Vleck.

Theissing and Caplan[10] report a ratio of approximately 3 between their measured results using a bolometer detector accepting millimeter radiation from the sun and the calculated attenuation. This is in general agreement with the measured curves rates shown in Figure 8 since their results are integrated both with respect to frequency and with respect to elevation.

References

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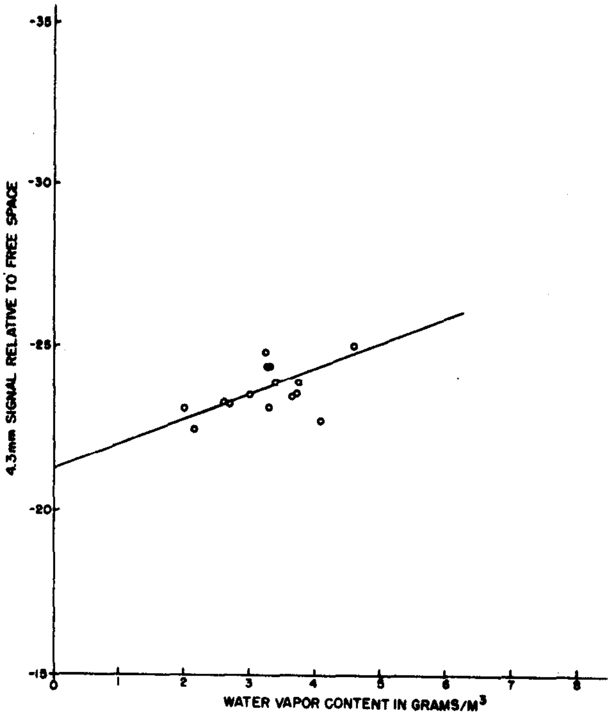

Fig. 1
Attenuation as a function of water vapor content 4.3 millimeters - 14,000 foot elevation -- 61 mile path.

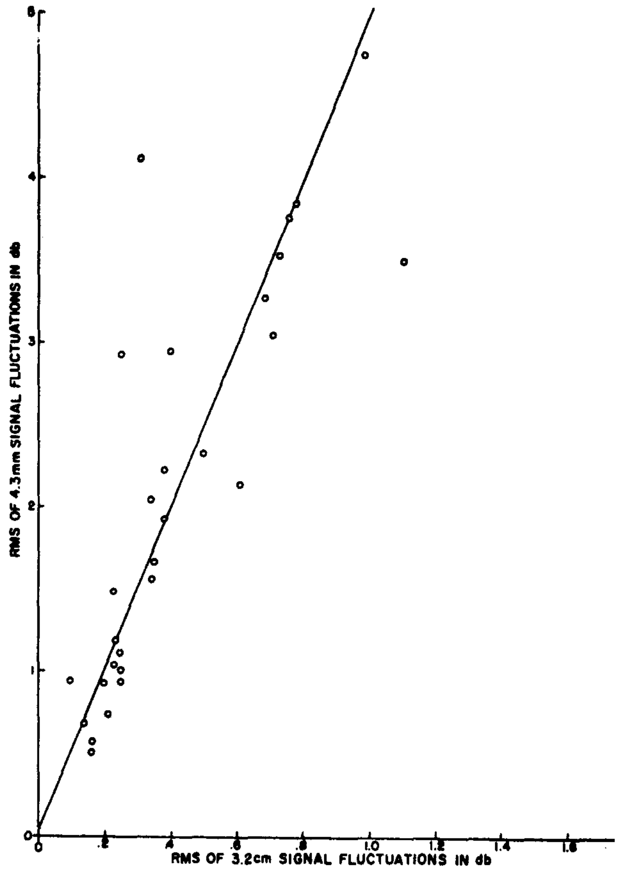

Fig. 3
Comparison of fluctuations of 3.2 cm and 4.3 mm signals.

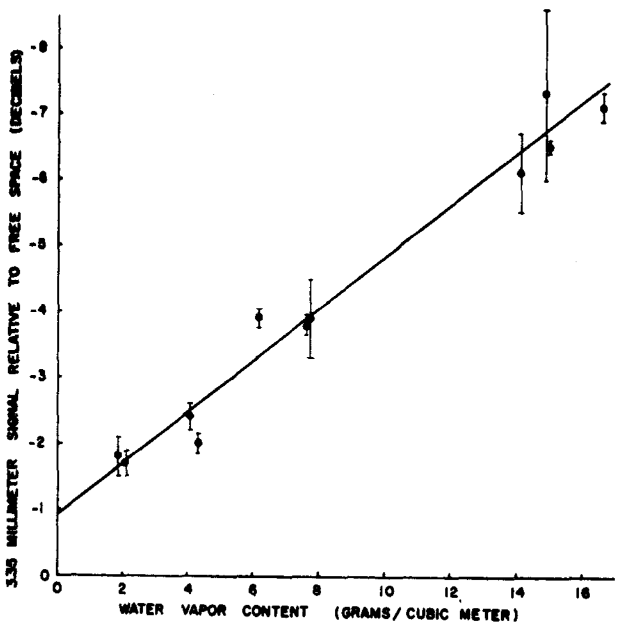

Fig. 2
Attenuation as a function of water vapor content 3.35 millimeters - 0.25 KM elevation -- 7.5 mile path.