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Atmospheric Propagation and Measurable Effects in Microwave Range Transmission

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Abstract: The main aim of this study is to find out the effect on the microwave transmission as it propagates through the atmosphere. Atmospheric variation has been shown to cause measurable effects on the propagation of microwave and millimeter-wave signals. Although these effects are not as strong as those encountered at visible wavelengths because of their variations in frequency, the contribution of the humidity structure function makes these effects significant for many applications. This paper presents the calculations and measurements of the effects of atmospheric variation on millimeter wave signals at GHz range.

Key words: Atmospheric variation, measurable effect, humidity, millmeteric wave

INTRODUCTION

During a series of measurements of millimeter wave propagation through dust and smoke by, Bohlander *et al*. (1985), then working at the georgia tech research institute, observed large intensity fluctuations of 94 and 140 GHz signals propagating through clear air. Although this observation was not surprising in light of atmospheric variation theory which predicts contributions to the index of refraction structure parameter from both the temperature structure parameter and the humidity structure parameter as well as their cross-correlation at millimeter wave frequencies. It was unexpected to the microwave and millimeter wave communities because it is not, been observed before. A report on these measurements led to support from the U.S. army research office for more detailed measurements of these phenomena including careful micro meteorological instrumentation for characterization of the structure parameters mentioned above and correlation of these observations with millimeter wave measurements. This series of experiments was carried out with the support and collaboration of the national oceanic and atmospheric administration, primarily responsible for meteorological instrumentation, by the author and colleagues at the Georgia tech research institute. The results of these measurements, which were made at a site near champagne-Urbana, Illinois, chosen for the homogeneity of its terrain, are given in several papers (Hill *et al*., 1988; Bohlander *et al*., 1985). These results will be discussed in more detail in subsequent sections. A potentially serious problem for microwave and millimeter wave radar systems in particular is that of angle-of-arrival of the signals scattered by targets caused by variation-induced wavefront distortion. for most radar scenarios, the effect is negligible, but in those cases where the wavefront must travel through great distances in the atmospheric boundary layer, for example in long range, low angle tracking applications, effect can be significant. Measurements of effect fluctuations at x-band over both one-way and two-way paths have been made by Mcmillan *et al*. (2000). These results have been compared to a theory developed by Churnside and Lataitis (1987) and his coworkers and adapted for longer wavelengths by the author. Finally this study is focused to find out the certain measurable parameters such as intensity and phase fluctuations, angle of arrival of signal, standard deviation, etc.

MILLIMETER WAVE MEASUREMENTS

For an experiment characterizing millimeter wave variation considering the propagation path length of 1.3 km. The transmitter was placed such that the propagation path would be horizontal. The receiver is taken as device comprising 5 apertures mounted on an i-beam in a semi-trailer. The spacing between these apertures was nonlinear. Each of the 5 super heterodyne receivers was pumped by a single local oscillator, distributed by an optical beam waveguide. An attempt was made to place some of the measurement frequencies on atmospheric absorption lines to determine the effects, if any, of absorption on turbulent fluctuations. These effects, if they exist, are considered minimal. Figure 1 shows intensity

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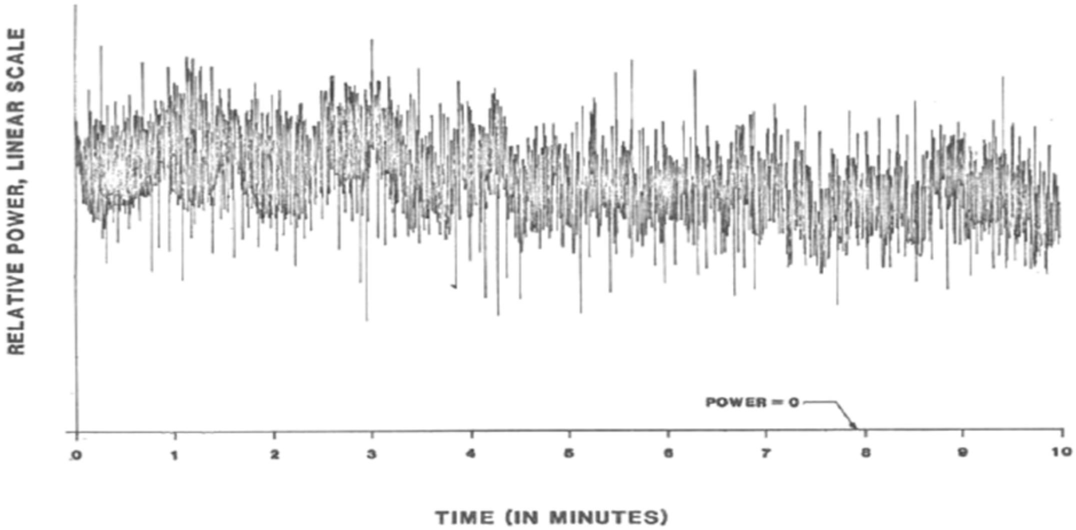


Fig. 1: Intensity fluctuations measured

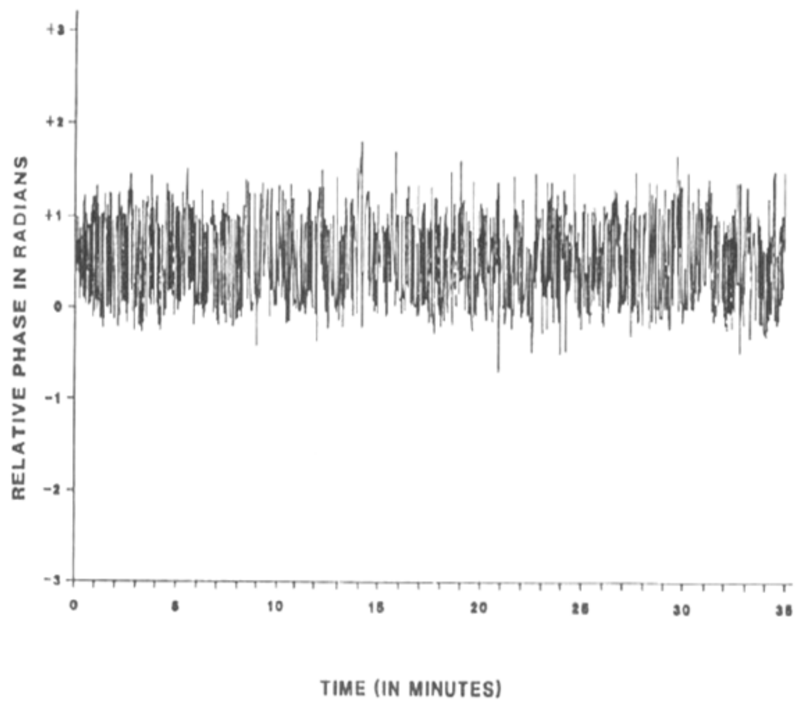


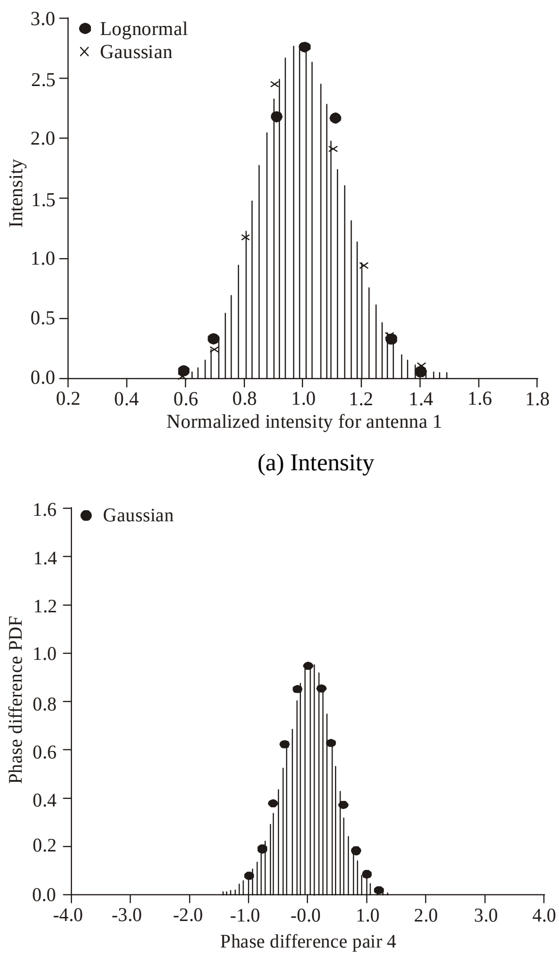
Fig. 2: Phase fluctuations corresponding in correspond to Fig. 1.

fluctuations measured at 140 GHz on a hot, humid summer day. The scale is linear and the fluctuations are about 2 db peak to peak. Figure 2 shows the corresponding phase fluctuations, also measured at 140 GHz. as shown in the figure, the phase fluctuations are about ±1 radian. In making these phase measurements, the spacing between the most widely separated antennas, about 10 m, was used, so that Fig. 2 shows the phase difference between two apertures separated by 10 m. Figure 3a shows the distribution of intensity fluctuations and Fig. 3b shows the distribution of phase fluctuations. Variation theory predicts that the distribution of intensity fluctuations will be log normal, while phase fluctuations are predicted to be normally distributed. Note that these figures are in agreement with theory, although the difference between log normal and normal in Fig. 2 is

Table 1: Measured and calculated values of cn^2.

$$C_n^2 = A_T^2 \frac{C_T^2}{\left\langle T^2 \right\rangle} + A_Q^2 \frac{C_Q^2}{\left\langle Q^2 \right\rangle} + 2 A_Q A_T \frac{C_{TQ}}{\langle T \rangle \langle Q \rangle}$$

Time	Mode	$A_T^2C_T^2/\langle T\rangle^2$	$A_Q^2C_Q^2/\langle Q\rangle^2$	$2A_TA_QC_{TQ}/\langle T\rangle\langle Q\rangle$	C_n^2 Metrological measurements	C_n^2 Propagation measurements
1130	Optical	2.1×10^{-14}	$+7.5\times10^{-16}$	$+7.3\times10^{-15}$	$= 2.9\times10^{-14}$	5.0×10^{-14}
	MMW	4.4×10^{-14}	$+7.2\times10^{-12}$	-1.1×10^{-12}	$= 6.2\times10^{-12}$	5.5×10^{-12}
1140	Optical	2.0×10^{-14}	$+6.5\times10^{-16}$	$+6.8\times10^{-15}$	$= 2.7\times10^{-14}$	4.0×10^{-14}
	MMW	4.1×10^{-14}	$+6.2\times10^{-12}$	-9.5×10^{-13}	$= 5.2\times10^{-12}$	4.3×10^{-12}
1850	Optical	1.9×10^{-14}	$+1.4\times10^{-16}$	-3.1×10^{-15}	$= 1.6\times10^{-14}$	1.9×10^{-14}
	MMW	4.5×10^{-14}	$+1.4\times10^{-12}$	$+4.7\times10^{-13}$	$= 1.9\times10^{-12}$	1.6×10^{-12}



(a) Intensity

(b) Phase difference

Fig. 3: Intensity and phase distributions measured at 173 GHz

a bit difficult to distinguish. As mentioned above, the index of refraction structure parameter for microwave and millimeter wave propagation is affected by the humidity structure parameter and the cross correlation between the temperature and humidity parameters in addition to the temperature structure parameter. This dependence is evident from the measurements made during this series of experiments. Table 1 shows the obtained measurement each of these parameters using the micrometeorological instrumentations. The largest value the variation was observed in mid-afternoon of a hot, humid day and that this value of 5.4 0^{-12} m^{-2} is almost two orders of magnitude larger than the value of 10^{-13} m^{-2} considering heavy variation in the visible wavelengths. The agreement between values measured by the micrometeorological instrumentation and by observation of actual millimeter wave turbulent fluctuations is considered good. The optical observations are indeed 2 orders of magnitude smaller than the millimeter wave under the same conditions.

MICROWAVE RADAR ANGLE-OF-ARRIVAL

The effects of atmospheric variation on radar angle errors are generally small, but in those cases where radar is required to guide a missile without a seeker (command guide), a few microradians of error may be enough to cause the missile to miss its target. In this study we compare two methods of calculating these angle-of-arrival errors and show that the geometrical optics approach derived by Churnside and Lataitis (1987), the first method, gives larger angular errors than those determined by experiment. This method is characterized by perfectly collimated and focused beams and ideal plane waves. The second method involves the adaptation of the approach described in Churnside and Lataitis (1987) to a physical optics model in which the beams have a gaussian profile. This method of calculation gives results reasonably close to experimental values. To determine the effect using both approaches and compared the results obtained to an experiment conducted using an interferometric radar capable of measuring the small angles expected for this scenario.

In reference Churnside and Lataitis (1987), the authors have derived the effect of a focused beam in the geometrical optics limit for a one-way path and have shown that their result reduces to those obtained for plane and spherical waves in the limits of infinite and zero focal lengths, respectively. They also show that the effective approaches infinity in a predictable way as range

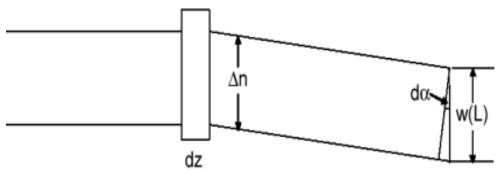


Fig. 4: A thin atmospheric layer with varying index causes beam steering

approaches the focal length of the focusing optic. They used the simple model shown in Fig. 4 as the basis of their calculations. The tilt angle dα is given by:

$$d\alpha = \Delta n(z)dz / w(L) \quad (1)$$

So that the total tilt angle over path l is:

$$\alpha = \frac{1}{w(L)}\int_0^L \Delta n(z)dz \quad (2)$$

Using this result, and assuming that there is no average gradient of refractive index, Churnside and Lataitis (1987) derive an expression for the one-way effect based on geometrical optics. Extending the arguments leading to Eq. (1) to the two-way case, we find that the tilt back at the transmitter is given by:

$$d\alpha = \frac{\Delta n_t(z) + \Delta n_r(z)}{w_{r(0)}} \quad (3)$$

where Δn_t and Δn_r are the refractive index differences across the transmitted and reflected beams, respectively, and wr(0) is the diameter of the reflected beam at the transmitter. Summing contributions along the entire path as for Eq. (2) gives a total tilt angle of:

$$\alpha = \frac{1}{w_r(0)}\int_0^L \left[\Delta n_t(z) + \Delta n_r(z)\right]dz \quad (4)$$

Just as Eq. (2) is the basis for derivation of the expressions for effect for one-way propagation, Eq. (4) is used to derive expressions for two-way propagation. The details of these derivations are given in Churnside and Lataitis (1987) and will not be repeated here. in deriving the effect for the physical optics case, we proceed exactly as for the geometrical optics case using the procedure given in Churnside and Lataitis (1987). For one-way transmission, we have shown Eq. (5) that the variance of the effect measured at the target is:

$$\sigma_t^2 = 2.92\frac{C_n^2}{w^2(L)}\int_0^L \left[w(z)\right]^{5/3}dz \quad (5)$$

where w(L) and w(z) are the beam widths measured at ranges l and z, respectively. In the physical optics (po) case, the beam has a gaussian profile and its width varies as (Yariv, 1989):

$$w(z) = 2w_0\left[1 + \left(\lambda z / \pi w_0^2\right)^2\right]^{1/2} \quad (6)$$

where λ is wavelength and w_0 is the beamwidth at the transmitter. For a reflected beam, this approach is extended to 2-way transmission using the method described in Eq. (1). The result for the effect variance back at the radar receiver is:

$$\sigma_r^2 = 2.92\frac{C_n^2}{w_r^2(0)} \int_0^L \left\{ \begin{array}{l} \left[w_t(z)\right]^{5/3} + \left[w_r(z)\right]^{5/3} \\ + \dfrac{1}{2^{2/3}}\left(\begin{array}{l} \left[w_t(z) + w_r(z)\right]^{5/3} \\ - \left[w_t(z) - w_r(z)\right]^{5/3} \end{array} \right) \end{array} \right\} dz \quad (7)$$

where wr(0) is 1/2(1/e) times the diameter of the radar antenna, wt(z) is the diameter of the transmitter beam, and wr(z) is the diameter of the reflected beam. These latter parameters are determined by substituting 1/2(1/e) times the diameter of the transmitter and the reflector, respectively. The reflector is assumed to be a circular mirror normal to the direction of propagation of the transmitter beam for these calculations. To determine the one-way effect using the physical optics approach, we must integrate Eq. (5) numerically using the beam diameter given by Eq. (6). For the two way case, we simply substitute Eq. (6) for the gaussian beam profile into the two way effect expression (7). The resulting equation must be solved numerically as must Eq. (5). To obtain the geometrical optics result we use an equation derived in (4) that is based on the geometrical optics scenario of a collimated transmitter beam illuminating a reflector with a negative focal length. We choose the focal length to be negative because most targets of interest will be convex. This result is Eq. (31) of Churnside and Lataitis (1987) and gives the variance of the effect, σ_r^2 :

$$\sigma_t^2 = 7.01 C_n^2 L D_t^{-1/3} \quad (8)$$

where L is slant range and D_i is antenna diameter. In deriving this result, we have used the approximation

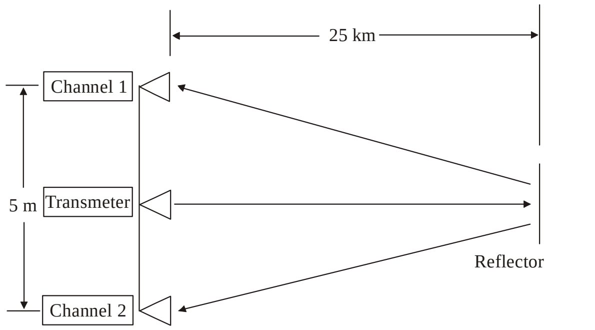


Fig. 5: Diagram of the interferometric radar used for long-range effect measurements

L>>fr, where fr is the (negative) focal length of the reflector. We do not have to know the value of the focal length because if we use this approximation, the entire bracketed term in Eq. (31) of reference Churnside and Lataitis (1987) reduces to 2.40. Measurements of effect were made on two separate occasions at a location in beach, ca. The first series of measurements was made over a path length of 25 km using a passive reflector located on a hillside such that the elevation angle was about four degrees. Results from this series of measurements are presented in this study. The second series of measurements was made in the same locality over a range of 3.5 km but with active repeaters instead of reflectors. Since these latter measurements were made with repeaters, they are considered to represent a one-way path, so that Eq. (5) is applicable. These latter measurements also gave very useful values of cn^2, which were used in the calculations presented herein, both for the one-way and the two-way paths. Figure 5 shows the experimental arrangement used for the long-range measurements and of these experiments use interferometric radars for measurements of the very small effects characteristic of microwave frequencies. For determination of cn^2, the fluctuations from a single channel were used and cn^2 was calculated from the log amplitude variance σ_χ^2 using the relation:

$$\sigma_\chi^2 = 0.31 C_n^2 k^{7/6} L^{11/6} \quad (9)$$

where k is wave number $2\pi/\lambda$.

It was first necessary to determine the values of cn^2 for the short-range experiment. Calculations of effect were then made using Eq. (8) with these values and compared to measured results. Other measurements of c_n^2 made at millimeter waves (Mcmillan *et al.*, 2001) have shown that this parameter can be as high as 5.5×10^{-12} $m^{-2/3}$ under hot, humid conditions. These parameters are much smaller in the visible and infrared range and partially explain the result that turbulent

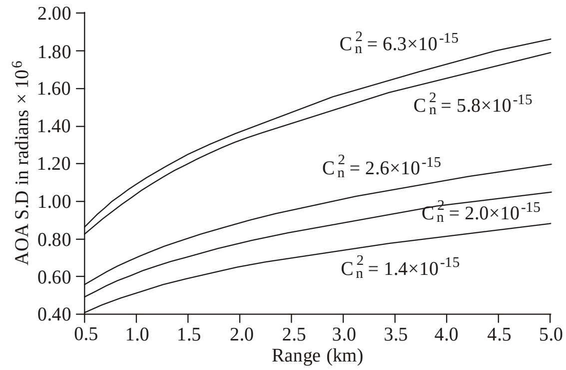


Fig. 6: Calculated effect variance as a function of range for the one-way path for the conditions described in the text

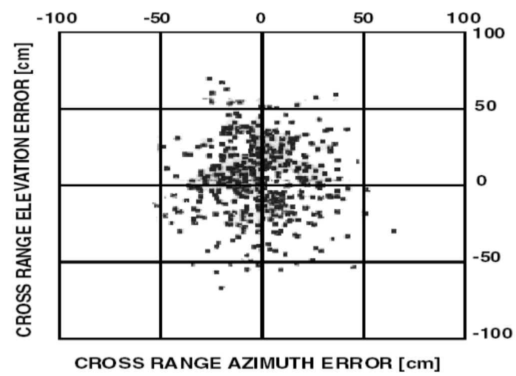


Fig. 7: With a 0.6 m transmitter and reflector over a 25 km path using an interferometric receiver with 5 m spacing. The measured standard deviation is 10 μrad

fluctuations are still observable in the microwave bands even though theory predicts that they should decrease as $f^{7/6}$ where f is frequency. We have solved Eq. (7) numerically for ranges between 500 and 5000 m, a transmitter aperture of 0.1 m, a frequency of 9.5 GHz, and values of c_n^2 varying from 1.4×10^{-13} to 6.8×10^{-13} $m^{-2/3}$, and the results are shown in Fig. 6. Table 2 summarizes these results for the 3.5 km range used in the measurements. These are the Physical Optics (po) results shown in the table. Calculation of the Geometrical optics (GO) numbers were made using the equations of reference Churnside and Lataitis (1987) and the values of cn^2 were determined using Eq. (1). This level of agreement is considered good for this type of experiment for both sets of calculations, but the results show that the po formalism gives better agreement with experiment.

We have used Eq. (7) to calculate the effect expected for the 25 km two-way path. Although simultaneous measurements of cn^2 were not made, a typical value of 3.3×10^{-13} $m^{-2/3}$ was used. The results obtained in making this calculation gave a standard deviation of 27 μ rad which should be compared to a measured value of 10 μ rad, as shown in Fig. 7. Part of this error is ascribed to a

Table 2: Results of effect measurements over a one-way, 3.5 km path

AQA SD in μrad					
C_n^2 in $m^{-2/3}$	5.8×10^{-13}	2.8×10^{-13}	1.4×10^{-13}	2.6×10^{-13}	6.3×10^{-13}
GO calculated	5.9	3.5	2.9	3.9	6.1
PO calculated	1.6	0.9	0.8	1.1	1.7
Measured	0.9	0.5	0.3	1.2	2.8

lack of knowledge of the value of Cu^2. The classical go theory of effect gives 263 μrad for this case.

CONCLUSION

we have found that the atmosphere can have measurable effects on the propagation of microwave and millimeter wave signals, although these effects may not be significant except in specialized applications. reasonable agreement between theory and experiment has been observed.

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