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TRANSMISSION LOSSES IN A FOREST FOR ANTENNAS CLOSE TO THE GROUND

by

D. Dence

(U. S. Army Electronics Command)

T. Tamir

(Polytechnic Institute of Brooklyn)

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RESEARCH AND DEVELOPMENT TECHNICAL REPORT
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D. DENCE
(U.S. ARMY ELECTRONICS COMMAND)

T. TAMIR
(POLYTECHNIC INSTITUTE OF BROOKLYN)

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ABSTRACT

During the last few years, measurements have been made to determine the electrical characteristics and the predominant mode of propagation in a forest environment. This work was essential because of the severe attenuation of radio communication signals which occur when operating in a forest medium. Theoretical investigations have shown that for distances greater than 1 km and for frequencies between 2 and 200 MHz the forest can be represented to a first approximation as a conductive slab bounded on one side by air and on the other side by the earth. Using this conductive slab as a model, the transmission losses between two elementary dipoles located close to the ground in a forest were calculated for both horizontal and vertical polarization. Those parameters which would affect the transmission losses are examined and then the sensitivity of the respective parameters is evaluated in detail. It turns out that the change in input resistance caused by the ground proximity produces a loss which may be considerably larger than the other losses. Various data are presented which show the theoretical transmission losses vs frequency for different parameters which include the height of the antenna above ground, the height of the forest, and the electrical characteristics of the ground and the forest.

ACKNOWLEDGMENTS

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I. INTRODUCTION

The present report investigates the transmission losses encountered when the transmitting and/or receiving antennas are situated very close to the ground in a forest. To the authors' knowledge, no experimental data are available which yield the transmission losses under those conditions. The present theoretical study therefore had to employ certain assumptions in order to obtain realistic approximations whose justification and limitations are stated in detail.

During the last few years, measurements have been made to determine the electrical characteristics and the predominant mode of propagation in a vegetated environment*. Theoretical investigations[1,2] have shown that, for distances greater than 1 km and for frequencies between 2 and 200 MHz, the forest can be represented to a first approximation as a conductive slab bounded on one side by air and on the other side by a ground plane, as shown in Fig. 1. These studies have shown that the predominant mode of propagation is a lateral wave. This wave may be regarded as a ray generated at the source T and is incident upon the forest-air interface at the critical angle of reflection in geometrical optics, as shown at point A in Fig. 1. The wave thereafter is refracted into the air region and proceeds along the interface while continuously leaking energy back into the forest at the critical angle of reflection. Hence the wave reaches the receiver R along the ray BR and thus the total traveled path for the lateral wave is given by TABR as shown in Fig. 1.

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*Atlantic Research Corporation and Stanford Research Institute have been making measurements in tropical jungles of Thailand. The reports published by the respective companies are too numerous to reference in the Bibliography, but were performed under contracts DA 36-039 SC-90889 and DA 36-039 AMC-00040.

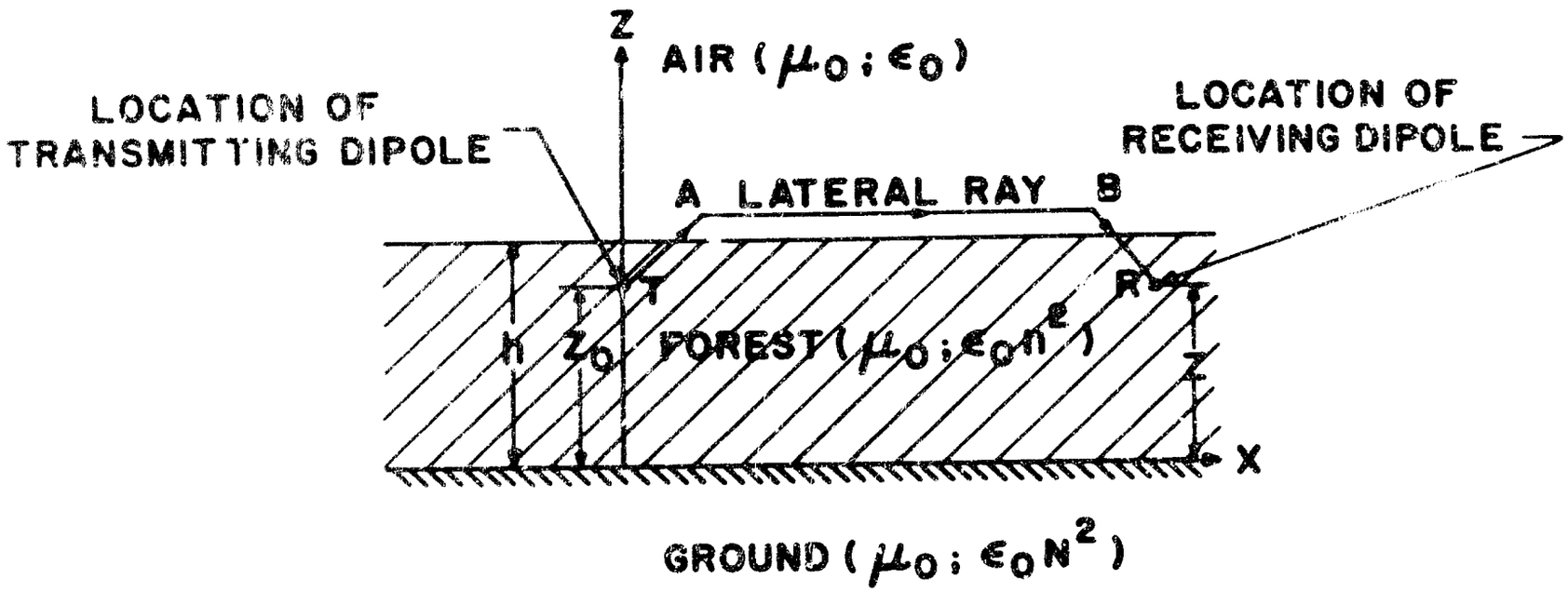

FIG. 1 BASIC SLAB MODEL GEOMETRY

The transmission loss L_o for antennas situated in the conducting slab close to the air interface (i.e. the distances TA and BR are negligible) has been calculated for the case when the ground plane is neglected.[2] As the antennas are lowered into the dissipative forest, an additional loss designated by L_s occurs due to the fact that the lateral wave has to travel an increased distance within the lossy forest medium (along the paths TA and BR in Fig. 1). As the antennas approach the ground, further transmission losses will occur because of the increasing influence of the ground.

Section II describes the additional losses in conjunction with the electrical and physical parameters of a forest environment. The attenuative loss L_s is calculated in Section III for typical heights and for various electrical parameters of a forest. The influence of the ground on the electric field for an antenna situated close to the ground forest interface and the range of validity of the derived equations are examined in Section IV.

In Section V, the change in radiation resistance for antennas close to the ground is calculated showing the sensitivity in the radiation resistance as a function of the height of the antenna above various grounds. Typical calculations of the total transmission losses are shown in Section VI with the conclusions being presented in the final section.

II. TRANSMISSION LOSSES ADDITIONAL TO THE INITIAL LOSS L_o

When the transmitting and receiving antennas are in the forest but close to the forest-air interface, the electric field produced by an elementary current element Il is closely given [2] by:

$$E_L = \frac{60\ Il}{n^2-1} \cdot \frac{e^{-jk_o \rho}}{\rho^2} \cdot e^{-jk_s s} \qquad (1)$$

where E_L refers to the maximum value (at a distance ρ) of the field component whose polarization corresponds to that of the transmitting dipole. The other quantities are defined by:

$\rho = \sqrt{X^2 + Y^2}$ = Longitudinal separation between transmitter and receiver (as shown in Fig. 1)

$n = \sqrt{\epsilon_1 - j60\ \sigma_1\ \lambda_o}$ = index of refraction of the forest

$k_o = \omega \sqrt{\epsilon_o\ \mu_o}$ = free space wave number

$k_s = k_o \sqrt{n^2 - 1}$ = forest slab wave number

$s = 2h - z_o - z$ = separation distance .

The formula for E_L disregards the presence of the ground and it is then seen that, for small s, the transmission loss depends primarily on the ρ^{-2} geometrical wave spread. For s = C, the transmission loss is given by:

$$L_o = 700 \left[|n^2 - 1|\ \mathrm{Re}\ (n) \left(\frac{\ell}{\lambda_o} \right)^2 \right]^2 \qquad (2)$$

where $L_o = \left(\frac{2}{3}\right)^2 L_{bo}$, and L_{bo} is given reference 2*. Relation 2 shows that the transmission loss is strongly dependent on the electrical properties of the forest characterized by the refractive index (n) and also by the wavelength λ_o.

As the antenna is lowered, the lateral wave remains the predominant mode but is affected quantitatively. A further loss L_s occurs because the wave traverses through additional vegetation to reach the forest-air interface. Since this vegetation is dissipative, the wave is attenuated when traversing through the vegetation, as shown by the factor $\exp(-jk_s s)$ in Eq. (1).

Since both formulas (1) and (2) neglect the presence of the ground, it is necessary to introduce further correction factors to ensure that all known transmission losses are considered. A first correction factor is obtained by replacing E_L of Eq. (1) with a modified expression which accounts for the presence of the ground. This change causes an additional transmission loss referred to as L_1. A second correction factor must be added to account for the drastic change which occurs in the antenna input resistance. As will be discussed later, it turns out that this effect produces a loss, denoted by L_r, which may be considerably larger than any of the preceding additional losses.

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*The factor $\left(\frac{2}{3}\right)^2$ is accounted for by the gain G of the two dipoles which occurs in $L_o = \left(\frac{2}{3}\right)^2 L_{bo}$.

In view of all of the losses enumerated above, the total transmission loss can be expressed as (See also Appendix)

$$L_{tot} = 10 \log \frac{P_t}{P_r} = L_o + L_i + L_s + L_r \qquad (3)$$

where P_t and P_r refer to the transmitted and received powers, respectively. Before discussing the quantitative aspects of the total transmission loss, it is advantageous to consider the electrical properties associated with a vegetated environment.

Recent measurements of the refractive index of the vegetation indicate that the relative permittivity varies from 1.01 to 1.5 and its conductivity ranges from a low of 10^{-5} mho/meter to a high of 10^{-3} mho/meter. (3) When one examines the profile of a tropical forest, (4) it appears that the effective or median height of the trees varies from 5 meters to 20 meters with isolated trees extending upwards to 40 meters. The ground constants in a tropical forest environment (5) are such that the conductivity varies from 5×10^{-4} to .5 mho/meter, whereas the relative permittivity varies from 5 to 50.

Due to the wide latitude of the various parameters mentioned above, it is impractical to obtain curves for all possible combinations of these constants. For the purpose of illustration, three cases were therefore chosen which are expected to typify often-encountered situations and are summarized in the following chart.

Forest Type			"THIN"	"AVERAGE"	"DENSE"
Tree Height	h	(meters)	5	10	20
Forest:	ϵ_1		1.03	1.1	1.3
	σ_1	(mmho/m)	.03	.1	.3
Ground:	ϵ_2		5	20	50
	σ_2	(mmho/m)	1	10	100

The smaller values in the table correspond to the case of a thinly vegetated area comprised of short trees over poorly conducting soil. The larger values correspond to thickly vegetated areas with tall trees over well-conducting earth. The medium values relate to an average situation; this case actually uses values representative of regions of Thailand where extensive measurements were conducted.[3,4,5] The three cases above are considered over the frequency range from 2 - 200 MHz and the transmission losses are calculated for the antennas located at various heights above ground.

III. EVALUATION OF THE INITIAL LOSS L_o AND THE HEIGHT LOSS L_s

Since the ground effect does not manifest itself in the terms L_o and L_s, these quantities may be found quite readily from existing formulas. The former quantity is found directly from Eq. (2) and the result is plotted for 1 km as shown in Fig. 2. Examination of Fig. 2 reveals that the smaller values of L_o occur when ϵ_1 and σ_1 are smaller and the larger value of L_o occurs when ϵ_1 and σ_1 are larger. It is worth mentioning that, for the "average" forest case, namely $\epsilon_1 = 1.1$ and $\sigma_1 = .1$ (mmho/m), L_o lies close to halfway between the other cases.

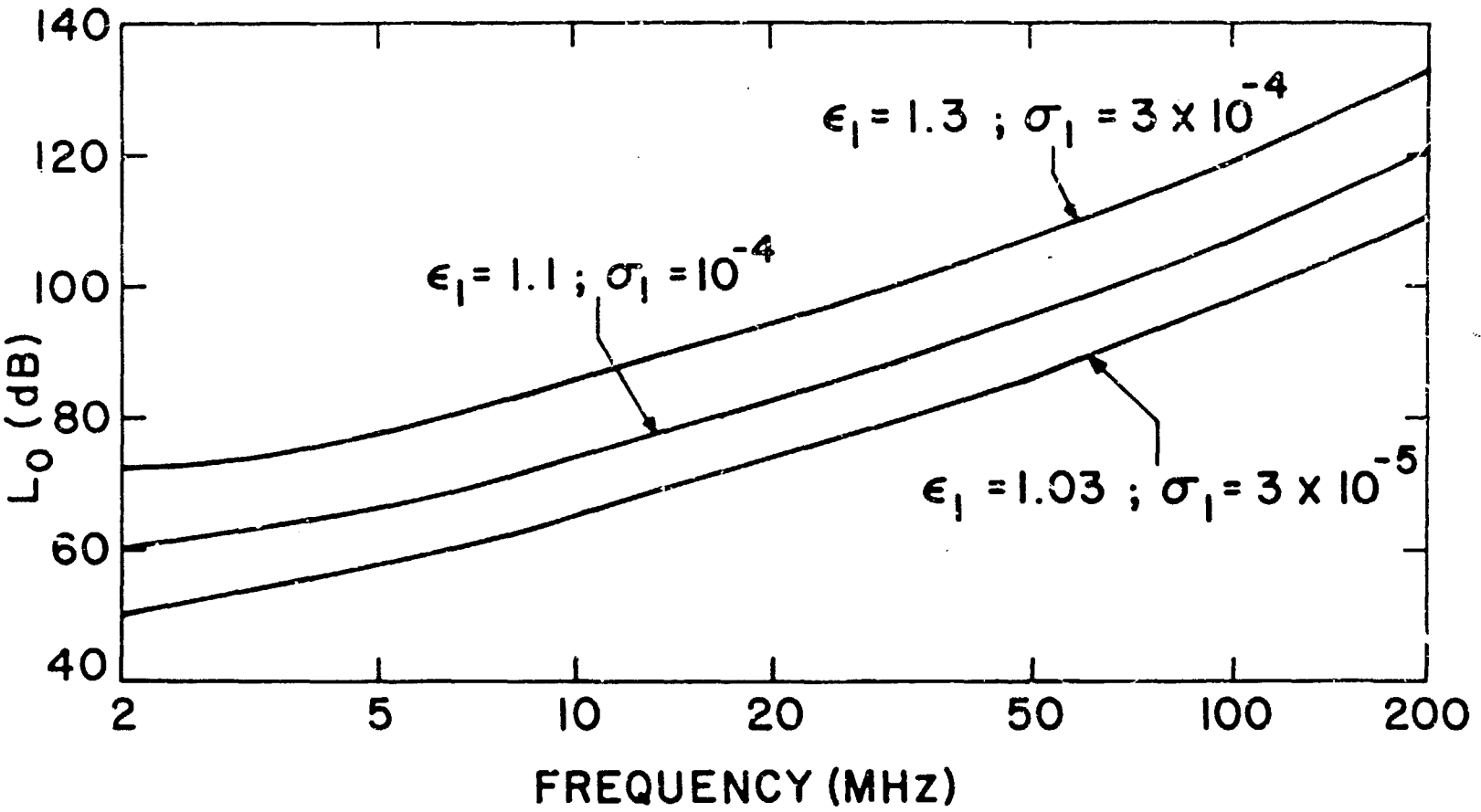


FIG. 2 TRANSMISSION LOSS L_0 (FOR $\rho = 1$ km) VS. FREQUENCY FOR VARIOUS ELECTRICAL PARAMETERS OF THE FOREST. THE LOSS L_0 OCCURS BETWEEN ANTENNAS LOCATED AT THE FOREST-AIR INTERFACE WHEN THE GROUND EFFECT IS NEGLIGIBLE.

It was previously stated that, as the antennas are lowered away from the forest-air interface, an additional loss L_s will occur due to the wave having to travel a greater distance in the dissipative medium.

Referring to Eq. (1), it is clear that

$$\frac{E_L(s)}{E_L(o)} = e^{-jk_s s} \qquad (4)$$

where the dependence of E_L on the parameter z is shown explicitly. It therefore follows that the loss incurred due to lowering the antennas to a combined depth s below the tree tops is given by:

$$L_s = 20 \log \frac{E_L(s)}{E_L(o)} = \alpha_L s \quad \text{(dB)} \qquad (5)$$

where

$$\alpha_L = 8.686 \cdot \frac{2\pi}{\lambda_o} \quad \text{Im} \sqrt{n^2 - 1}. \qquad (6)$$

Since α_L is dependent on permittivity, conductivity and frequency, it is important to know the possible variation of α_L. Its functional dependence is shown in Fig. 3 for the three representative cases. Examination of Fig. 3 reveals that, above 20 MHz, α_L is independent of frequency but is still highly dependent on the electrical parameters of the forest. It should be noted that both ϵ_1 and σ_1 are considered to be invariant with frequency in the present analysis. Because the antennas

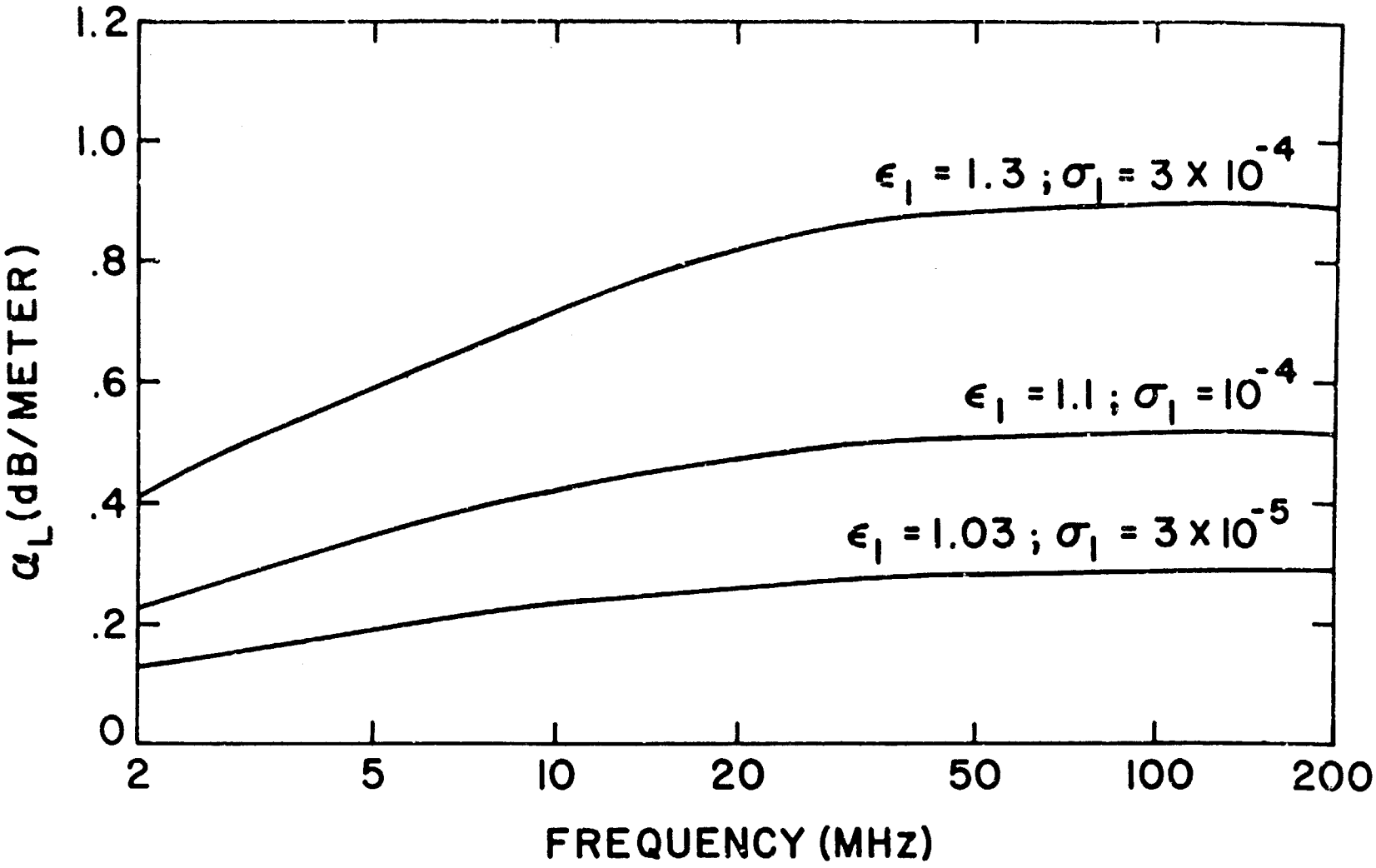


FIG. 3 ATTENUATION α_L VS. FREQUENCY FOR VARIOUS ELECTRICAL PARAMETERS OF THE FOREST. THE ATTENUATION α_L IS MEASURED IN dB PER METER OF VEGETATION ABOVE THE ANTENNAS.

are located near the ground, s in Eq. (5) can be replaced by 2h and therefore L_s is

$$L_s = 2\alpha_L h \cdot \tag{7}$$

This loss is shown in Fig. 4 and, as expected, the additional exponential loss L_s has the same behavior as α_L.

IV. EVALUATION OF THE WAVE-INTERFERENCE LOSS L_i

As discussed before, Eq. (1) does account for the attenuation L_s produced by lowering the antennas down from the tree tops. However, it does not account for the modification of the field due to the presence of the ground plane. Essentially, this means that Eq. (1) assumes that the received field is produced by the single wave path TABR of Fig. 1, which is true only if reflections from the ground plane are neglected.

To improve the above result, it is necessary to allow for the presence of all the additional lateral wave paths which may occur by reflection at the angle of critical incidence within the slab. This aspect has been previously analyzed,[10] and the various additional paths are shown in Fig. 5. To emphasize the significance of Fig. 5, it is recalled that, when both antennas are close to the forest-air interface, the lengths TA and BR are much smaller than all of the other paths (such as T c d, v w R, etc.). Hence, the additional reflected waves undergo large attenuation as they travel within the lossy slab and they may be neglected when compared to the primary ray along TABR.

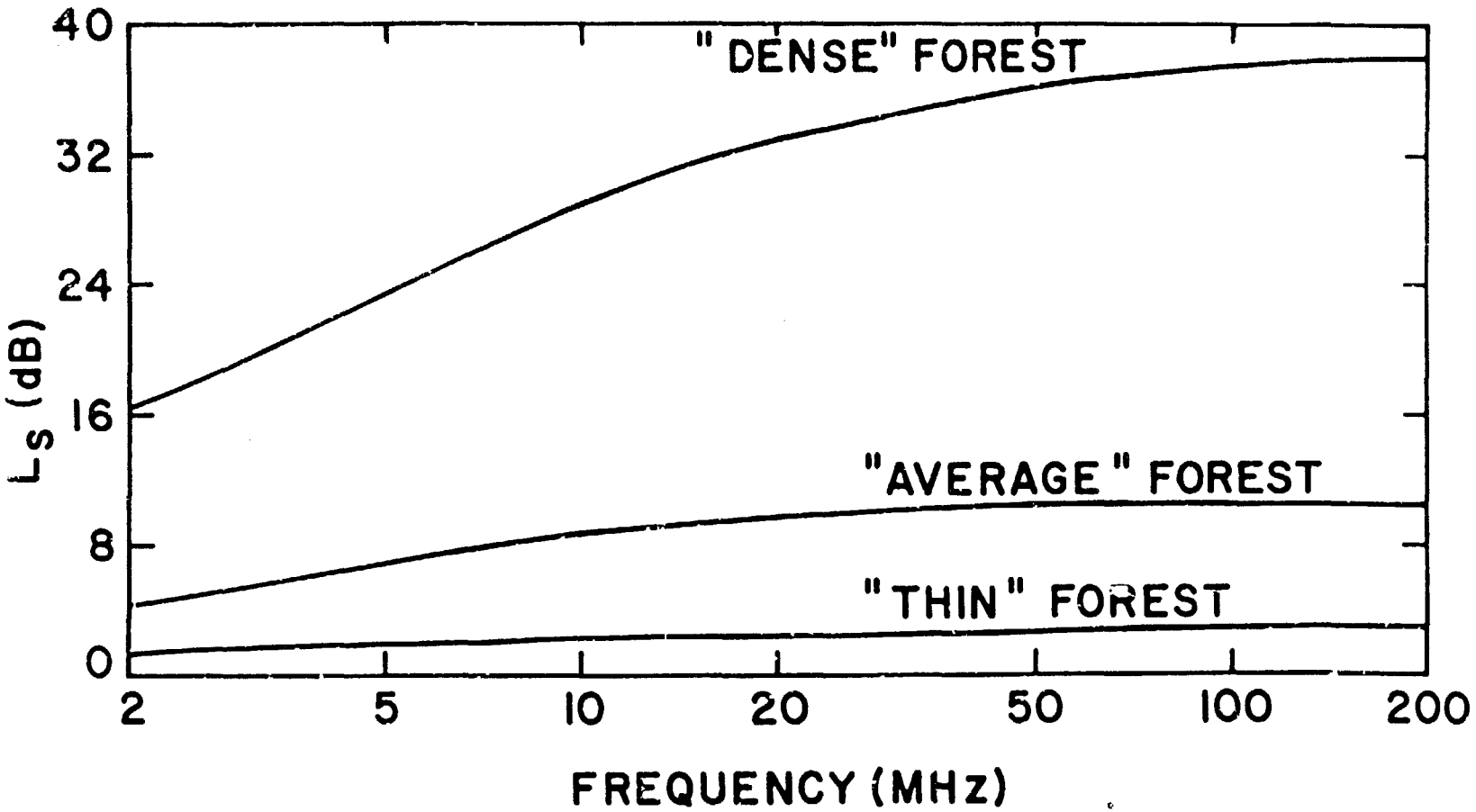
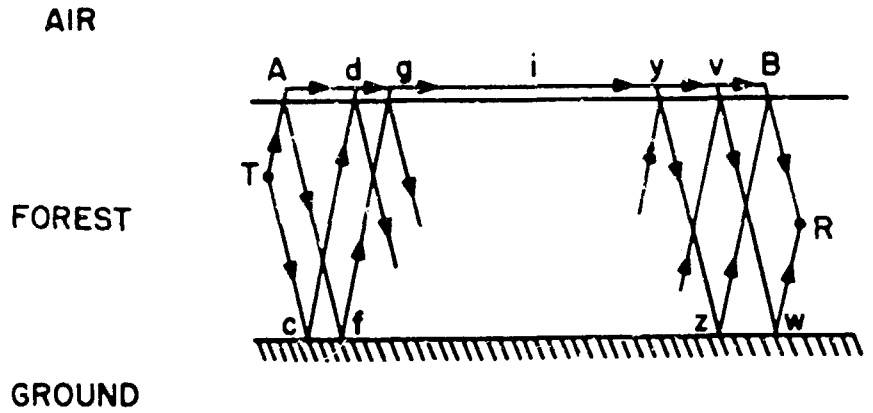


FIG. 4 TRANSMISSION LOSS L_s VS. FREQUENCY FOR VARIOUS FOREST TYPES. THE LOSS L_s IS DUE TO THE PRESENCE OF VEGETATION ABOVE THE ANTENNAS.



Primary ray	TAi	iBR
Secondary rays	Tcdi	ivwR
Tertiary rays	TAfgi	iyzBR
.	.	.
.	.	.
.	.	.

FIG. 5 LATERAL RAY COMPLEX DUE TO THE PRESENCE OF THE GROUND PLANE.

However, when the antennas are close to the ground, the paths TA and BR are closely equal to T c d and v w R and therefore one must at least account for the latter pair of wave paths. It is evident that the additional reflected waves produce an interference which may be either constructive or destructive and thus may decrease or enhance the value of the actual field E_L' as compared to E_L of Eq. (1).

The presence of the additional wave paths may be expressed[1] in the form of correction factors F (z), such that

$$E_L' = F(z) \; F(z_o) \; E_L \tag{8}$$

where E_L' refers to the corrected field, and

$$F(z) = \frac{1 + \Gamma e^{-2jk_s z}}{1 + \Gamma e^{-2jk_s h}} \tag{9}$$

where $F(z_o)$ is obtained by replacing z in F(z) by z_o. Γ is reflection coefficient which, in the case of vertical and horizontal polarizations, can be expressed as

$$\Gamma_v = \frac{N^2 \sqrt{n^2 - 1} - n^2 \sqrt{N^2 - 1}}{N^2 \sqrt{n^2 - 1} + n^2 \sqrt{N^2 - 1}} \quad \text{Vertical Polarization}$$

$$\Gamma_h = \frac{\sqrt{n^2 - 1} - \sqrt{N^2 - 1}}{\sqrt{n^2 - 1} + \sqrt{N^2 - 1}} \quad \text{Horizontal Polarization} \tag{10}$$

In order to understand the limitations of the lateral wave field given by Eq. (8), it is necessary to know the underlying approximations used in its derivation. After the electric field has been expressed in terms of an integral, the integrand is then expanded in a power series whose radius of convergence is dependent on the numerical distance defined below. As long as the pertinent values in the integrand are located near the center of the circle of convergence, the resulting lateral field can be obtained by omitting certain terms in the series expansion. To ensure that Eq. (8) represents a valid approximation to this integral, it is essential that the following inequality be satisfied[8]

$$W^2 = \frac{k_o \rho}{2|N|^2} \gg 1 \quad . \tag{11}$$

The numerical distance W will dictate the lower limit on the minimum allowable distance ρ_{min} between the transmitter and receiver. The curves displayed in Fig. 6 give values where $\frac{k_o \rho_{min}}{2|N|^2} = 1$ for various ground constants. One must bear in mind that, because various transmission losses are calculated for a wide frequency range and a large range of ground constants, the minimum range where these equations are valid is quite sensitive to the ground parameters.

The additional loss L_1 due to the modification of the field to account for the presence of the ground is given by:

$$L_1 = -20 \log \left| \frac{E'_L}{E_L} \right| = -40 \log \left| F(z_o) \right| \tag{12}$$

where $z = z_o$ was assumed.

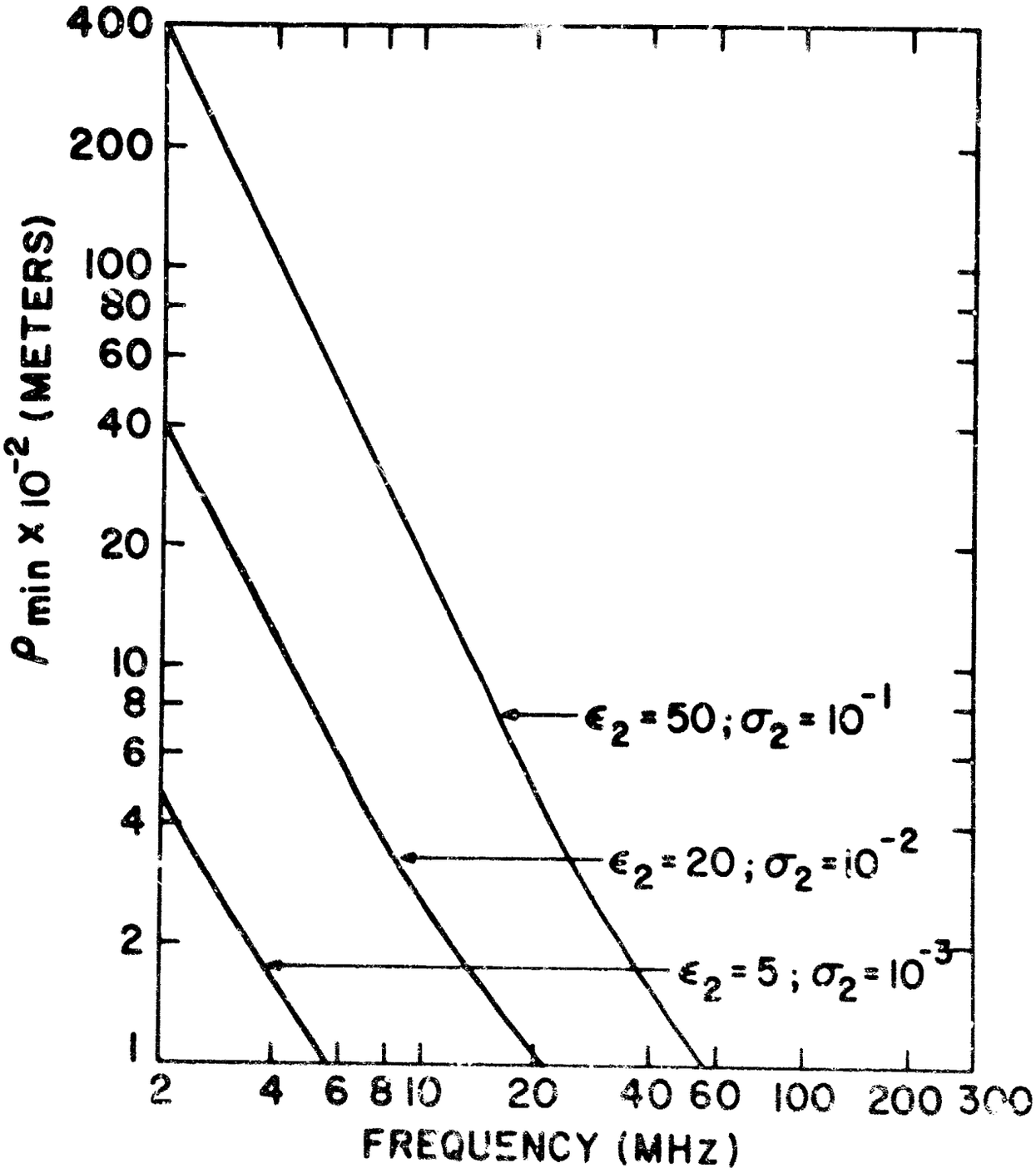


FIG. 6 NUMERICAL DISTANCE ρ_{min} VS. FREQUENCY FOR VARIOUS GROUND PARAMETERS.

The quantity L_1 for antennas situated above but close to the forest-ground interface is plotted in Fig. 7 (vertical polarization) and Fig. 8 (horizontal polarization). For vertical polarization (for the "average" and "dense" forests), L_1 actually represents a gain rather than a loss showing that the field interference is constructive. For the chosen forest and ground parameters, the electric field changes very slowly as a function of the effective height of the antenna above ground. Although the difference in the electric field for various heights (for the "thin" and "average" forests) is not plotted in Fig. 7, numerical computation reveals that the difference in the electric field for antennas situated .05 m and .2 m above ground is of the order of .5 db. Furthermore, the shift in the nulls and peaks as a result of changing the height of the antennas above ground is very small (i.e. less than 1 MHz). For horizontal polarization, L_1 actually represents a substantial loss indicating destructive field interference due to the presence of the ground. This can be explained by noting that the tangential electric field close to a perfectly conducting half space should be small (the tangential field on the boundary would of course be zero). In our particular case the earth is not a perfect conductor, but one still expects a substantial decrease in the electric field.

The oscillatory behavior of the curves in Figs. 7 and 8 is also caused by the very low impedance of the ground plane which thus effectively acts as a shorting circuit. When the antenna is placed at a distance of about $\lambda/4$ away from the ground, the effect of the short-circuit action is least, as expected from an analogy with a transmission line shorted at one end. In that case, the electric field at the antenna

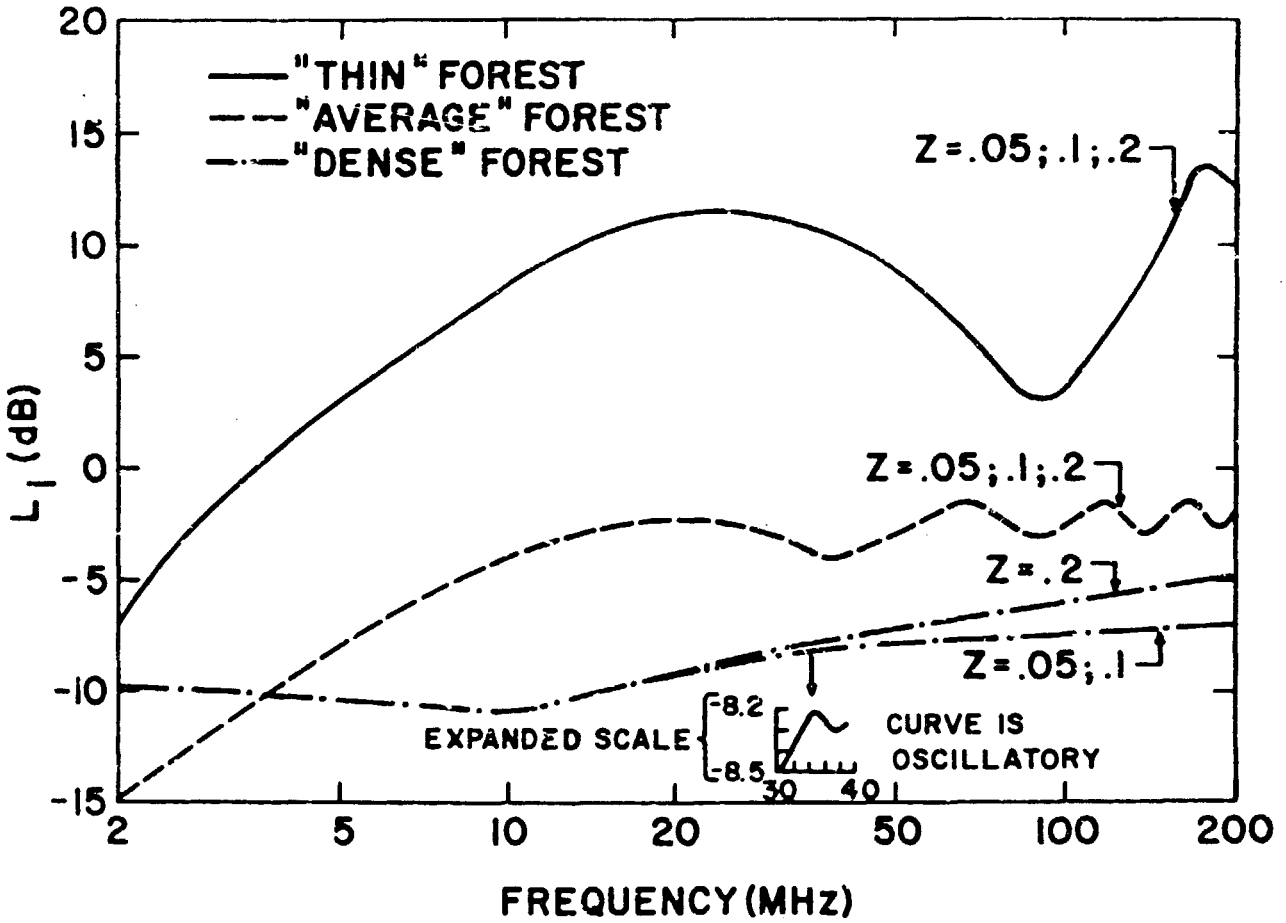


FIG. 7 TRANSMISSION LOSS L_i VS. FREQUENCY FOR VERTICAL POLARIZATION. THE LOSS L_i IS DUE TO FIELD MODIFICATIONS PRODUCED BY THE PRESENCE OF THE GROUND PLANE.

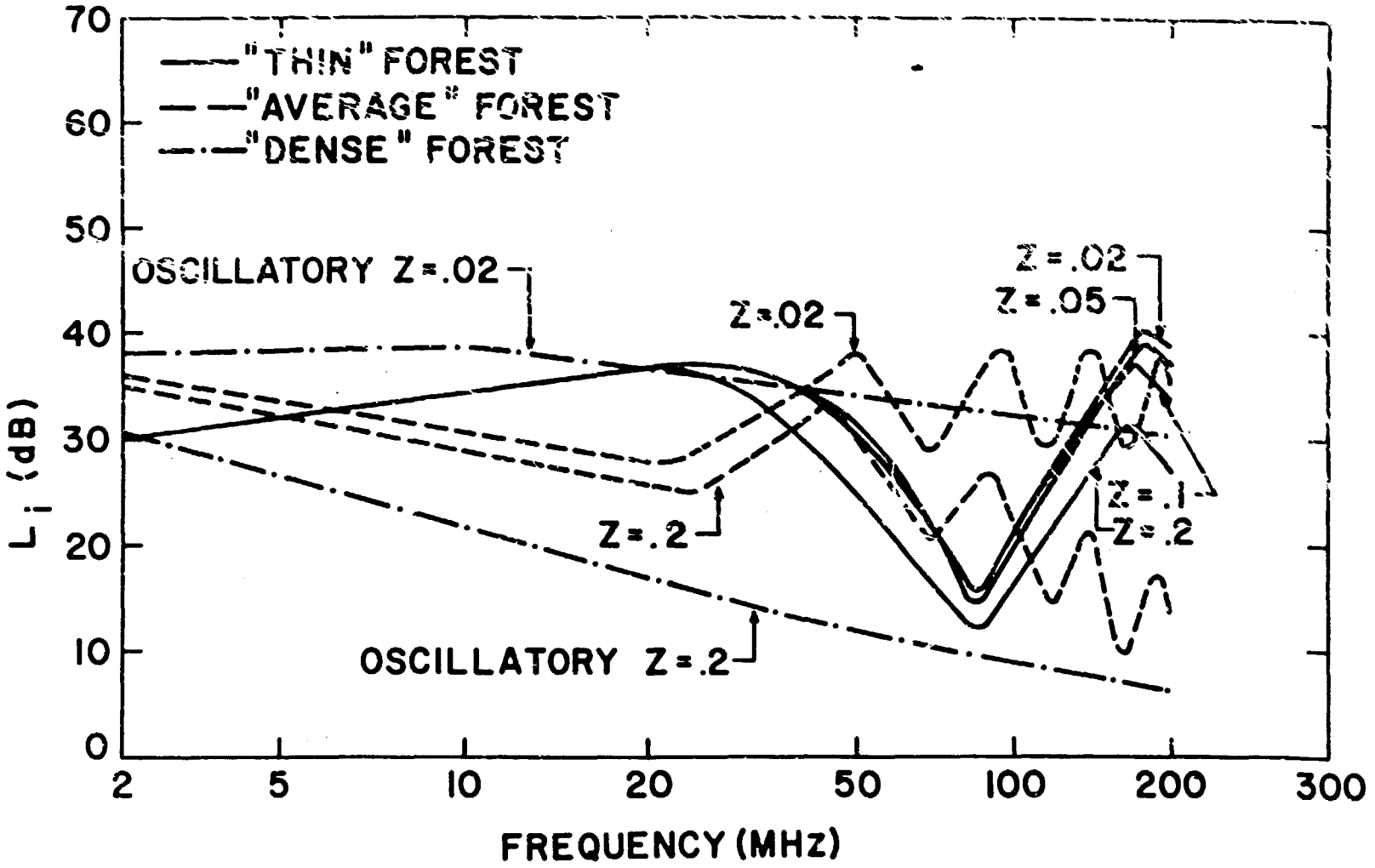


FIG. 8 TRANSMISSION LOSS L_i VS. FREQUENCY FOR HORIZONTAL POLARIZATION. THE LOSS L_i IS DUE TO FIELD MODIFICATIONS PRODUCED BY THE PRESENCE OF THE GROUND PLANE.

is at a maximum. Similarly, the electric field goes through a minimum when the antenna is $\lambda/2$ away from the ground and the short-circuit action is greatest. This general behavior is well known and an example from the literature [9] is shown in Fig. 9 to illustrate this effect. In the case discussed in this report, the antennas are fixed but the frequency varies so that the distances z and z_o vary through values of $\lambda/4$, $\lambda/2$... and thus lead to the oscillatory behavior which is evident in Figs. 7 and 8.

V. EVALUATION OF THE ANTENNA INPUT RESISTANCE LOSS L_r

The exact loss L_r due to the change in the antenna input resistance is given by (see Appendix)

$$L_r = 10 \log \frac{R(z)}{R_f} \cdot \frac{R(z_o)}{R_f} \qquad (13)$$

where $R(z)$ is the input resistance for an antenna in the forest at a height z above ground, while R_f is the input resistance for an antenna located in an infinite forest medium.

For the purposes of this report, it was assumed that the loading of the antenna was due primarily to the ground effect. Hence the change in input resistance due to the antenna being surrounded by vegetation rather than by air could be neglected. The validity of this assumption is justified since the index of refraction of the forest is close to unity, and furthermore, the index of refraction of the ground is much greater than the index of refraction of the forest. Measurements to date indicate that the vegetation does not affect the input resistance to a great degree* except by slightly changing the effective wavelength.

* Private communication by J.H. Hagn, Stanford Research Institute, Menlo Park, Calif.

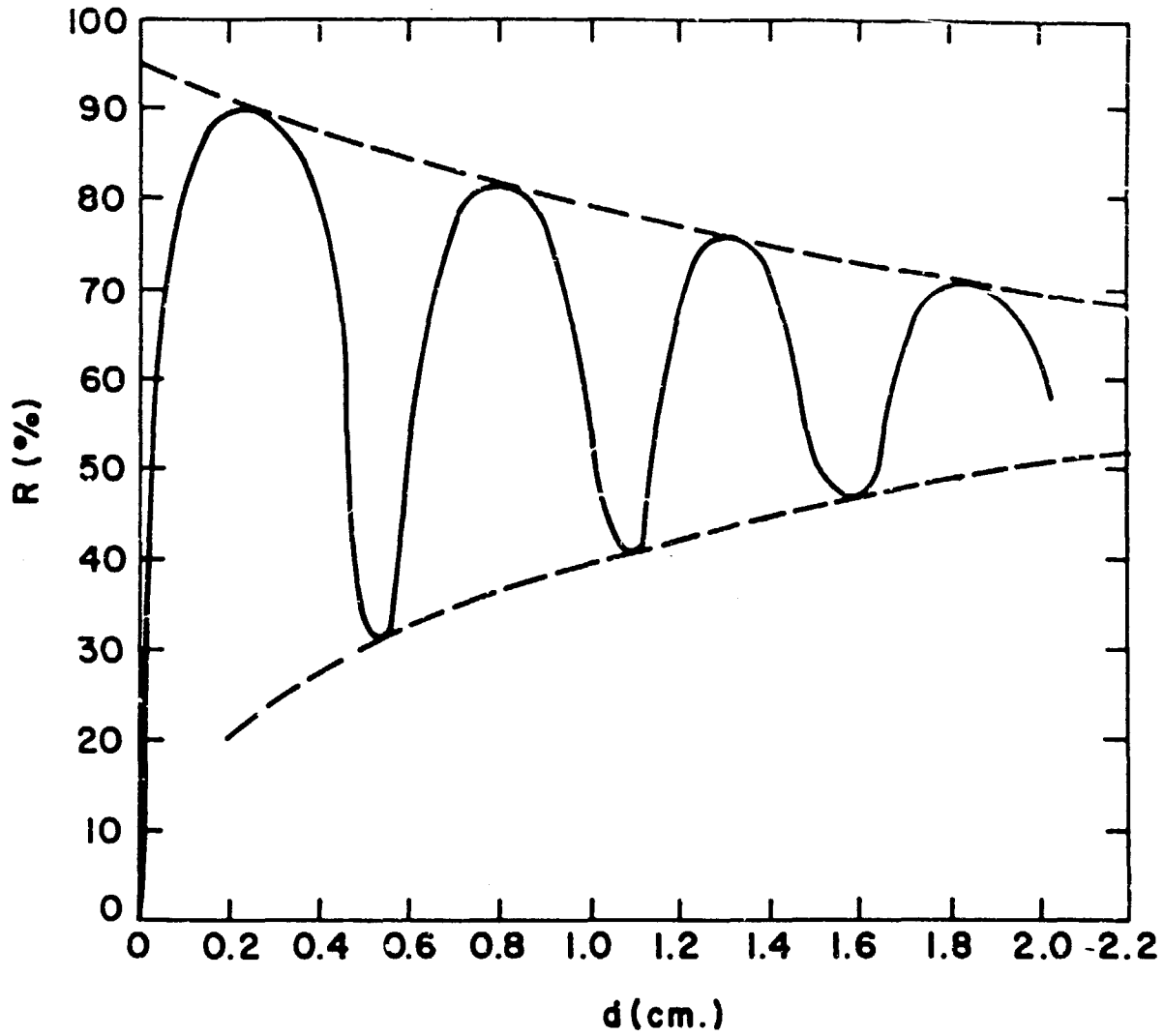


FIG. 9 REFLECTION COEFFICIENT OF A PLANE SHEET OF WATER OF THICKNESS d cm., $\lambda_0 = 9.35$ cm., $\alpha_2 = 5.95$ cm.$^{-1}$, $\beta_2 = .456$ cm.$^{-1}$ (FIG. 98, ELECTROMAGNETIC THEORY BY J. A. STRATTON).

Subject to the above assumption, the ratio $R(z)/R_f$ corresponds to that of a dipole located in air above a conducting half-space. This ratio has been calculated by Vogler and Noble [6,7] and the loss L_r may then be found, with $z = z_o$, from

$$L_r = 20 \log \frac{R(z_o)}{R_f} \qquad (14)$$

so that L_r will be twice the amount obtained from the appropriate curves which are given in reference 6.

The loss L_r due to the change in input resistance caused by the ground proximity was plotted for various ground parameters and for various heights above the earth. For values $\frac{z_o}{\lambda_o} > .1$, the loss L_r is quite small. If one assumes the antennas to be at a fixed height z_o above ground, then one observes from Figs. 10 and 11 that L_r decreases with increasing frequency. For high frequencies (i.e. $f > 50$ MHz for the particular heights in the plot), it appears that L_r is independent of the ground parameters. However, as the frequency decreases below 50 MHz, the ground constants affect L_r to a large extent. In fact, for frequencies less than 10 MHz, one might expect a 30 dB variation in L_r depending upon the ground constant. Since L_r is highly sensitive to the effective height of the antenna above the ground, this affords a degree of freedom that the design engineer can adjust such that L_r will be small.

VI. TOTAL TRANSMISSION LOSS

While an examination of the constituent losses that comprise the total transmission loss can reveal the sensitivity of the various parameters, the total transmission loss is of value in that it will

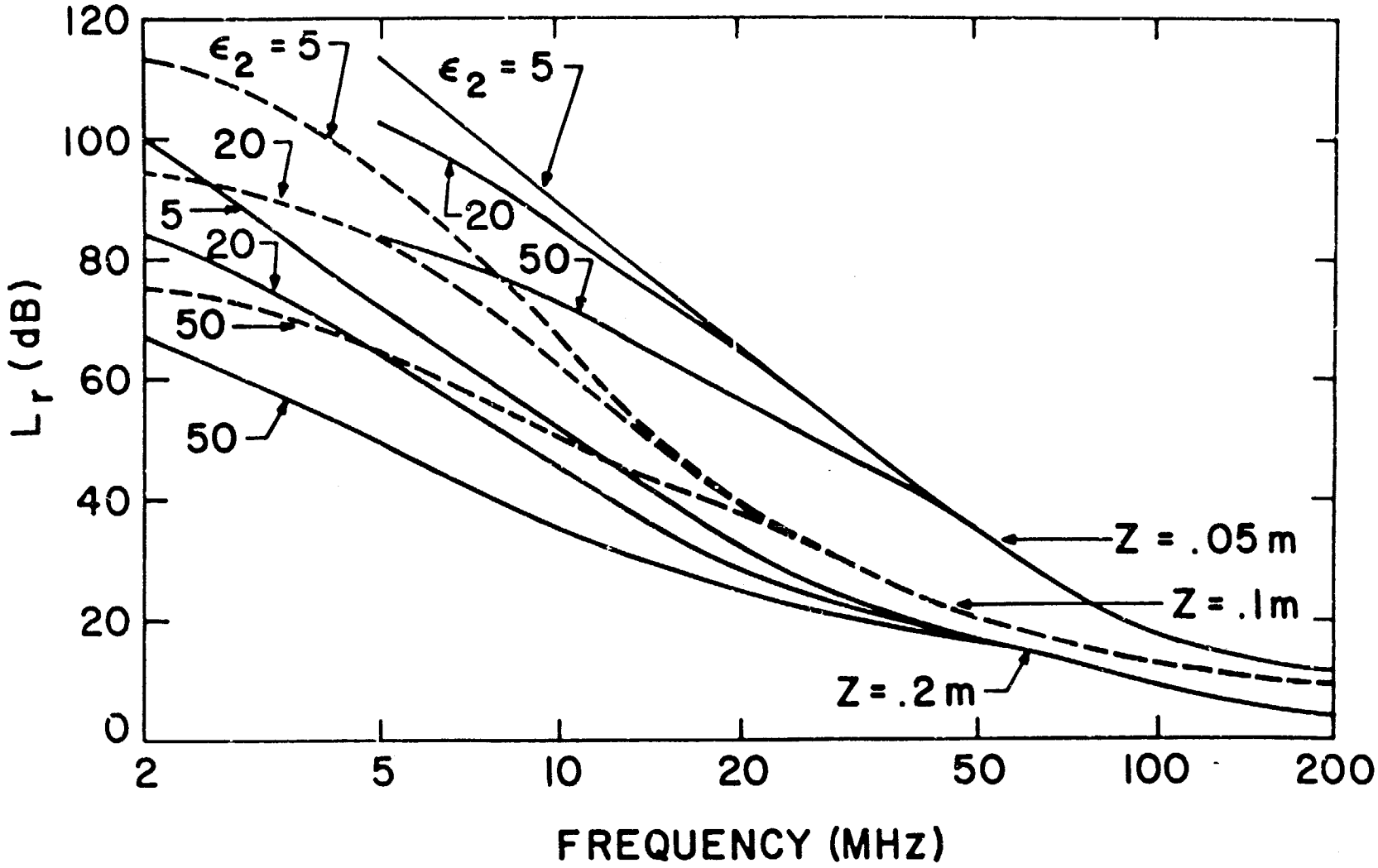


FIG. 10 TRANSMISSION LOSS L_r VS. FREQUENCY FOR VERTICAL POLARIZATION. THE LOSS L_r IS CAUSED BY THE ANTENNA INPUT RESISTANCE CHANGE PRODUCED BY THE GROUND PROXIMITY.

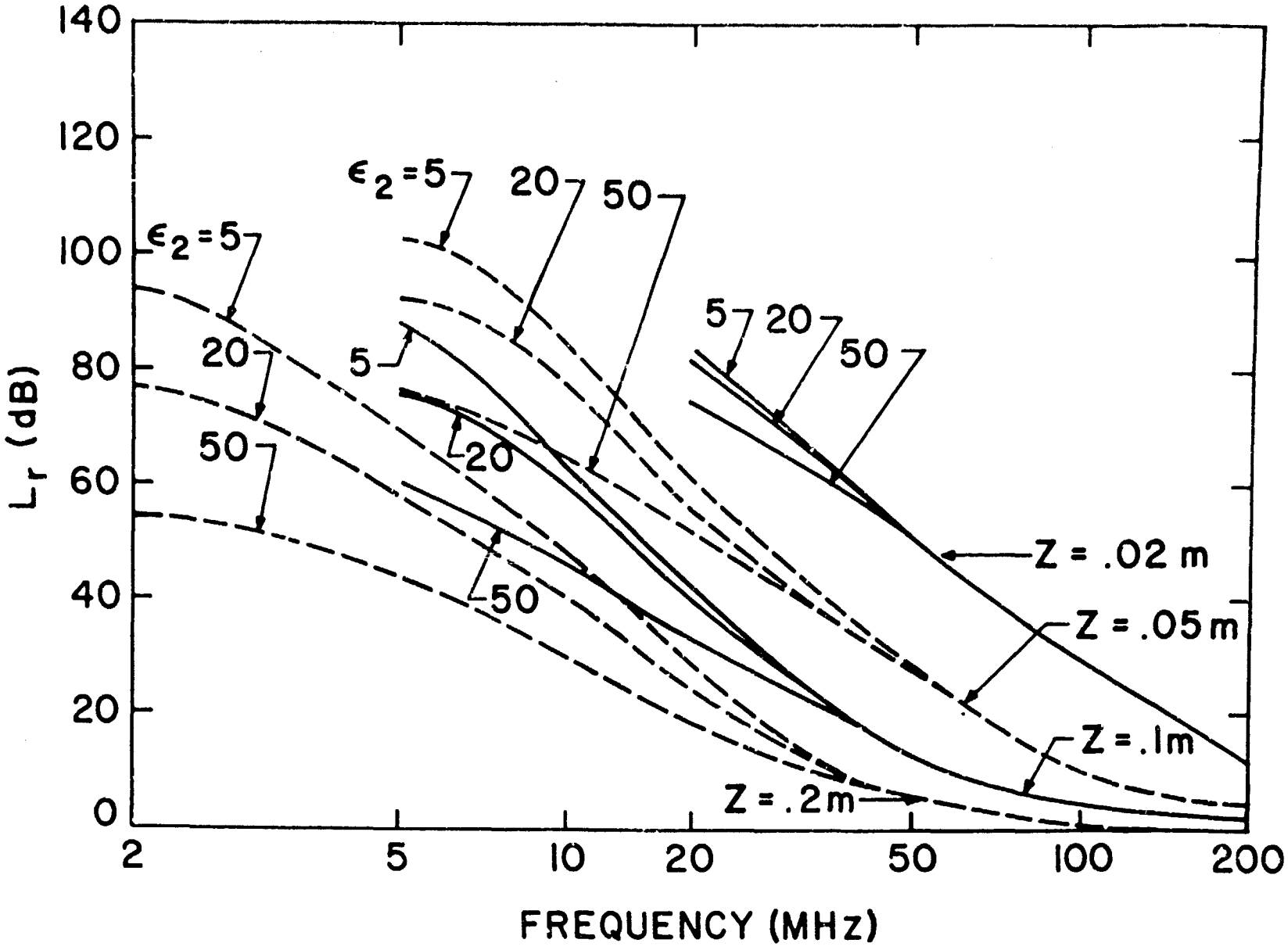


FIG. 11 TRANSMISSION LOSS L_r VS. FREQUENCY FOR HORIZONTAL POLARIZATION. THE LOSS L_r IS CAUSED BY THE ANTENNA INPUT RESISTANCE CHANGE PRODUCED BY THE GROUND PROXIMITY.

ultimately determine the power requirements for a given system. The total transmission loss will also be of value in determining the optimum operating frequency band as a function of polarization, the forest and ground parameters, and the antenna height above ground.

One of the first steps in calculating L_{tot} is to determine the minimum range ρ_{min}, explicit in Eq. (11) for which the lateral field given by Eq. (8) is valid. Since L_o is plotted in Fig. 2 for $\rho = 1$ km, it may be necessary to adjust L_o for other distances. Once this has been accomplished, the additional losses may then be added to L_o employing Eq. 3.

A typical example of L_{tot} is shown in Fig. 12 which reveals several interesting features. For the case shown, vertical polarization is preferred over horizontal polarization, with the difference in L_{tot} decreasing with increasing frequency. There seems to occur a frequency band, roughly between 20 and 50 MHz, where L_{tot} is a minimum. In the higher frequency range, there occur many local minima and maxima due to the oscillations of the lateral field. The oscillations of L_{tot} for vertical polarization are of the order of 1.5 dB and therefore were not included. For convenience, the pertinent curve in Fig. 12 was drawn through the median of these oscillations.

VII. CONCLUSIONS

The characteristic example shown in Fig. 12 reveals two interesting features which distinguish between propagation with antennas close to the ground and that with antennas close to the tree tops. The latter situation is the one shown in Fig. 2 which should be contrasted with Fig. 12. It is then observed that, whereas L_o increases strongly

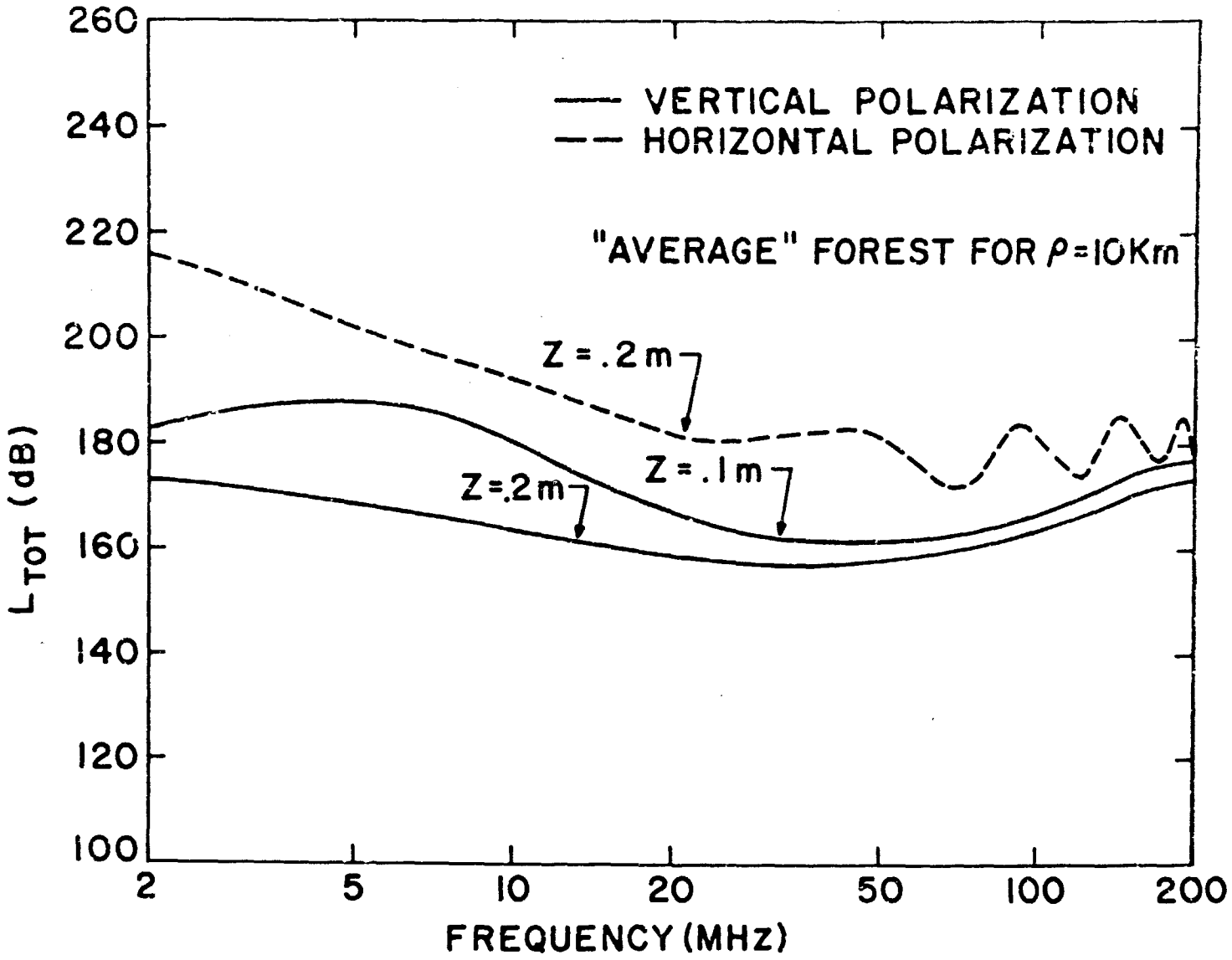


FIG. 12 TOTAL TRANSMISSION LOSSES VS. FREQUENCY AT A DISTANCE = 10 km FOR A REPRESENTATIVE FOREST.

with increasing frequency, L_{tot} for the case of the ground-based antennas in Fig. 12 does not always increase with increasing frequency. Consequently the preference for lower frequencies would not be justifiable for the ground-based antennas.

The second feature which involves the preferable polarization is not evident from Fig. 2 since those results do not distinguish between the two (vertical and horizontal) cases. However, at the frequencies considered here, the experimental results [4] show that lower losses L_{tot} occur for high antennas which are horizontally (rather than vertically) polarized. On the other hand, Fig. 12 shows that vertical polarization yields lower losses for ground-based antennas; this is not surprising in view of the strong effect of the ground plane on horizontal antennas, which are effectively shorted out by the conducting properties of the earth.

Although the example of Fig. 12 does not include all of the possible forest types, it is believed that the above characteristics are also preserved, to a smaller or greater degree, also in the "thin" and "dense" forests. The exact curves for each individual case are easily obtained by following the same procedure which yielded Fig. 12, as outlined above. It should nevertheless be remembered that the present calculations do not account for any possible anisotropy of the forest medium which could modify this result.

APPENDIX

The individual losses L_o, L_i, L_s and L_r discussed herein were assumed to be independent and therefore led to a total transmission loss L_{tot} which was obtained in Eq. (3) by a simple superposition. This follows from the definition of each loss and the validity of Eq. (3) is shown below. The transmitted power is given by:

$$P_t = |I|^2 \; R(z_o) \; , \tag{A1}$$

where I is the current of the transmitting dipole and $R(z_o)$ is its input resistance whose dependence on the height z_o is shown explicitly. The maximum received power is obtained from:

$$P_r = |E_L'(s)|^2 \; \frac{l^2}{4R(z)} \; , \tag{A2}$$

where l is the length of the receiving dipole and $R(z)$ is its input resistance. The field $E_L'(s)$ at this dipole is expressed in terms of $s = 2h - z - z_o$ to bring the s dependence in evidence. The total transmission loss is therefore given by:

$$L_{tot} = 10 \log \left| \frac{2I}{l \, E_L'(s)} \right|^2 R(z) \; R(z_o) \; , \tag{A3}$$

which may be written in the form:

$$L_{tot} = 10 \log \left| \frac{2IR_f}{l E_L(o)} \right|^2 \left| \frac{E_L(o)}{E_L(s)} \right|^2 \left| \frac{E_L(s)}{E_L'(s)} \right|^2 \frac{R(z)}{R_f} \; \frac{R(z_o)}{R_f} \tag{A4}$$

where $E_L(s)$ is the received lateral wave field in a semi-infinite

forest ($h \rightarrow \infty$); hence $E_L(o)$ is that field in the particular case where both antennas are at the forest-air interface. The quantity R_f is the input resistance of a dipole embedded in an unbounded forest medium.

An inspection of Eq. (A4) reveals that the first squared term corresponds to the transmission loss

$$L_o = 20 \log \left| \frac{2IR_f}{IE_L(o)} \right| , \tag{A5}$$

already evaluated in reference 2 (except for a constant multiplier which accounts for the antenna gains). The other terms relate to the additional losses:

$$L_s = 20 \log \left| \frac{E_L(o)}{E_L(s)} \right| , \tag{A6}$$

$$L_i = 20 \log \left| \frac{E_L(s)}{E'_L(s)} \right| , \tag{A7}$$

$$L_r = 10 \log \left| \frac{R(z)\, R(z_o)}{R_f^2} \right| . \tag{A8}$$

It therefore follows that the above relations imply the addition of the various losses (expressed in decibels) for obtaining the total loss L_{tot}, as expressed in Eq. (3).

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13. ABSTRACT

During the last few years, measurements have been made to determine the electrical characteristics and the predominant mode of propagation in a forest environment. This work was essential because of the severe attenuation of radio communication signals which occur when operating in a forest medium. Theoretical investigations have shown that for distances greater than 1 km and for frequencies between 2 and 200 MHz the forest can be represented to a first approximation as a conductive slab bounded on one side by air and on the other side by the earth. Using this conductive slab as a model, the transmission losses between two elementary dipoles located close to the ground in a forest were calculated for both horizontal and vertical polarization. Those parameters which would affect the transmission losses are examined and then the sensitivity of the respective parameters is evaluated in detail. It turns out that the change in input resistance caused by the ground proximity produces a loss which may be considerably larger than the other losses. Various data are presented which show the theoretical transmission losses vs frequency for different parameters which include the height of the antenna above ground, the height of the forest, and the electrical characteristics of the ground and the forest.

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