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Relative Attenuation of TM-TE Waves Propagating in the Earth-Ionosphere Waveguide

PAUL A. KOSSEY
EDWARD A. LEWIS

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13. ABSTRACT

Ionospheric and ground reflection coefficients for transverse magnetic (TM) and transverse electric (TE) waves are given, at a frequency of 17 kHz and over a wide range of incidence angles. Both normal and severely disturbed ionospheric conditions are considered, and the relative attenuations of the TM and TE waves upon reflection from a soil of high electrical conductivity, and from ice, are given. A method of determining modal resonance angles from computations of ionospheric and ground reflection coefficients is described, and estimates of the relative attenuation rates of the TM and TE waves propagating in the earth-ionosphere waveguide are given.

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Abstract

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1. INTRODUCTION

Very low frequency radio waves (VLF) propagate in the earth-ionosphere cavity somewha as in a waveguide whose lower boundary is effectively a good conductor, and whose upper boundary has high permeability. The transverse magnetic (TM) modes of propagation are then as symbolized in Figure 1. These modes are characterized by having maximum field strengths at the lower boundary of the waveguide, and minimum field strengths at the upper boundary. The TM modes are conventionally used for long range VLF communication purposes. Figure 1 also illustrates the transverse electric (TE) modes of propagation in which the field strengths are a maximum at the upper boundary of the waveguide and a minimum at the lower boundary. To date relatively few theoretical and experimental studies of the propagation characteristics of TE waves have been made, primarily because no suitable VLF transmitters have been available to efficiently excite the TE modes in the earth-ionosphere waveguide. Such transmitters necessarily must be at a high altitude, with their antennas oriented horizontally with respect to the earth. It now appears that the Air Force's ARC 96 trailing wire system, while designed for conventional TM modes, should excite the TE modes as well; so there is an increasing interest in the relative propagation characteristics of

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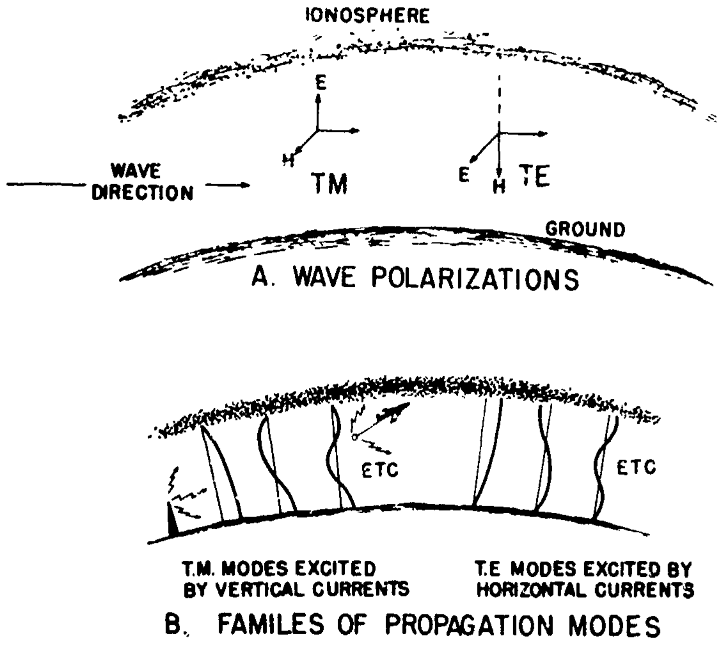

Figure 1. Characteristics of TM and TE Waves

the TE and TM modes, both under normal and severely disturbed ionospheric conditions; and, for propagation over areas of the earth with low electrical conductivities, such as in the polar regions. Of particular interest for long range VLF communication purposes is the relative attenuation of TM and TE waves as they propagate in the earth-ionosphere waveguide.

Following Watt (1967), an estimate of the attenuation rate of a wave in the earth-ionosphere waveguide can be obtained using the equation

$$\alpha_{dB/Mm} = \frac{10^3 \left[(R_g)dB + (R_i)dB\right] \cos\phi}{2\,h \sin\phi} \qquad (1)$$

where R_g and R_i are the ground and ionospheric reflection coefficients respectively, h is the height of the waveguide, and ϕ is the mode angle of propagation with respect to the vertical (the 'angle of incidence'). Because the attenuation rate is highly dependent upon the magnitudes of the ground and ionospheric reflection coefficients, it is instructive to compare these quantities for the TM and TE modes of propagation.

2. COMPARISON OF TM/TE IONOSPHERIC REFLECTION COEFFICIENTS

2.1 Normal Ionosphere

Magnitudes of the TM and TE ionospheric reflection coefficients at a frequency of 17 kHz are plotted as a function of angle of incidence in Figure 3. These curves were computed with an AFCRL plane wave computer program, using the typical daytime electron density and collision frequency profiles shown in Figure 2 to model the ionosphere. At all incidence angles, the TE reflection coefficient, $_{\perp}R_{\perp}$, is greater than the TM reflection coefficient, $_{\parallel}R_{\parallel}$. The curves also show the relative attenuation, upon reflection from the ionosphere, of the TM and TE waves. For example, at an incidence angle of 50°, the TM wave suffers 5.5 dB more attenuation upon reflection than the TE wave, while at 80° the difference is 1.5 dB.

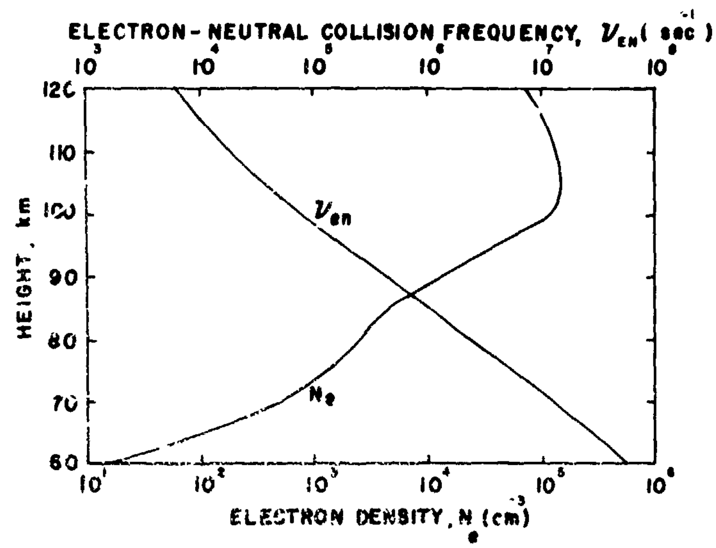

Figure 2. Model of a Normal Daytime Ionosphere

2.2 Severely Disturbed Ionosphere

The TM and TE ionospheric reflection coefficients calculated for a severely disturbed ionosphere (Figure 4) are given in Figure 5, and show that the relative attenuation of the TM and TE waves upon reflection is even greater than that calculated for the normal ionosphere. For example, at an incidence angle of 50°, the TM wave suffers 7 dB more attenuation than the TE wave (compared to 5.5 dB for the normal ionosphere), while at 80° the difference is 2 dB (compared to 1.5 dB for the normal ionosphere).

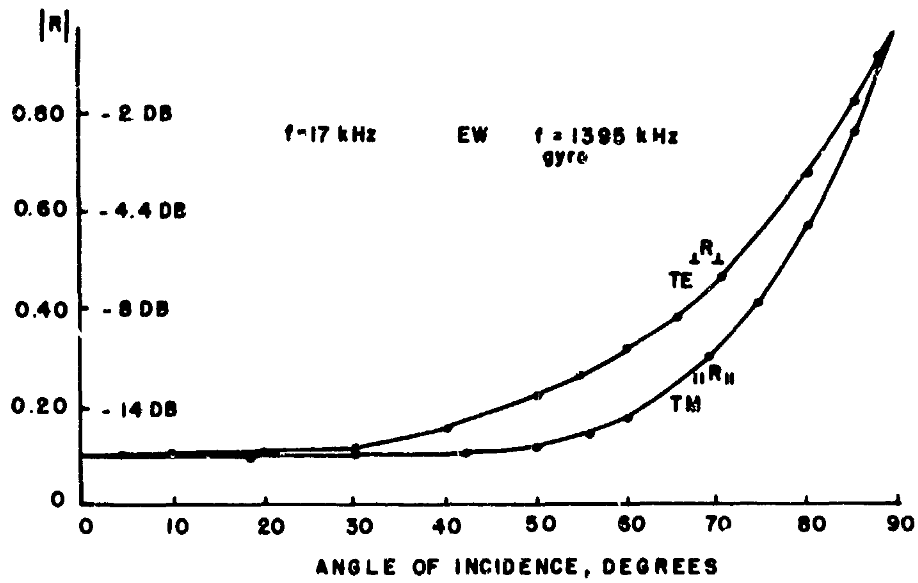

Figure 3. Ionospheric Reflection Coefficients—Normal Daytime Ionosphere

The calculations of the plane wave reflection coefficients also show that for the severely disturbed ionosphere, the reflections occur in regions of very high collision frequency, and the effects of the earth's magnetic field on the wave propagation are negligible. Under normal ionospheric conditions the reflection coefficients are dependent on the direction of propagation relative to the magnetic field; and, waves propagating to the magnetic east are less attenuated than waves propagating to the magnetic west. The calculations for the severely disturbed ionosphere show no such azimuthal characteristics.

3. COMPARISON OF TM/TE GROUND REFLECTION COEFFICIENTS

Shown in Figure 6 are the relative attenuations of the TM and TE waves upon reflection from (a) good soil, $\sigma = 10^{-2}$ mho/m, and from (b) ice, $\sigma = 2 \times 10^{-5}$ mho/m. At all angles of incidence the TM waves suffer more attenuation than the TE waves. For reflections from ice, such as would be the case for propagation over the polar regions, the relative attenuation of the TM and TE waves is

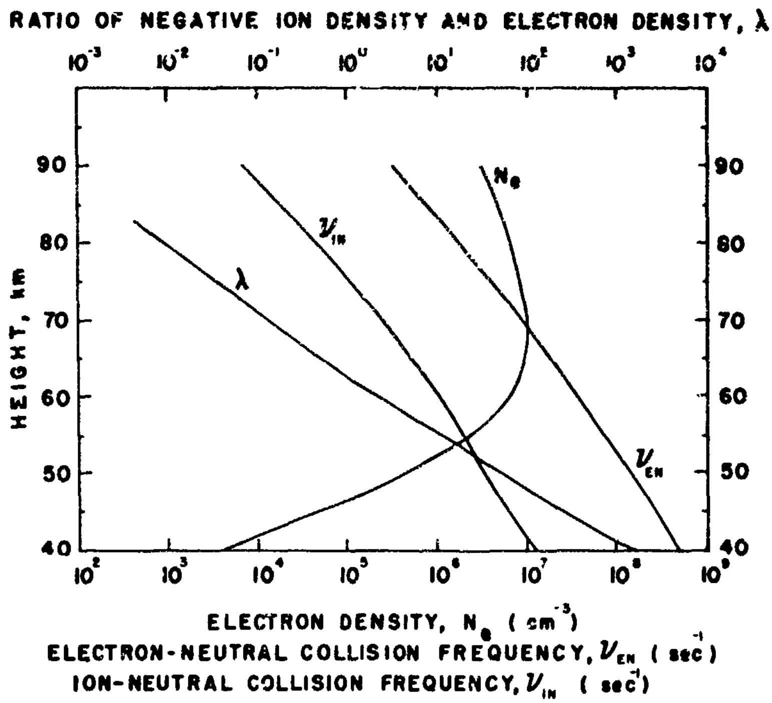

Figure 4. Model of a Severely Disturbed Daytime Ionosphere

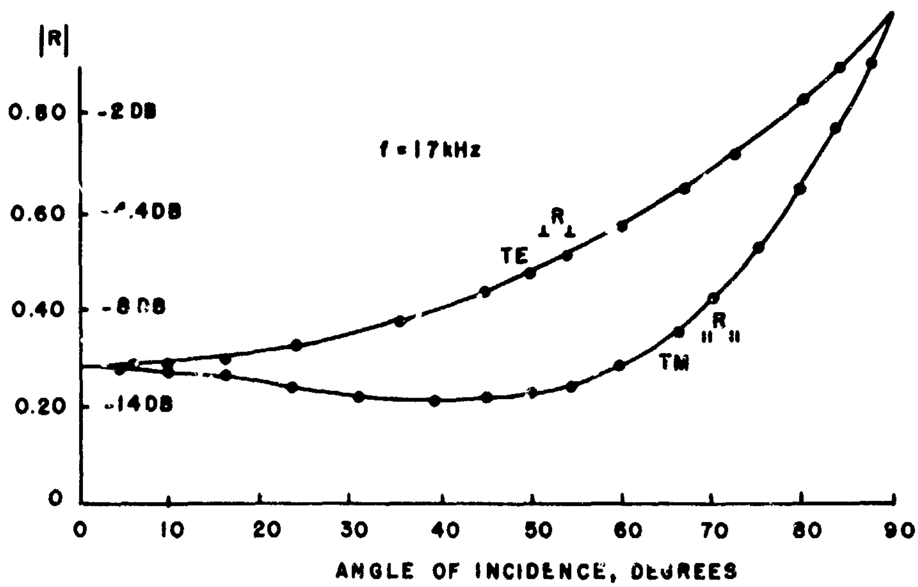

Figure 5. Ionospheric Reflection Coefficients—
Severely Disturbed Daytime Ionosphere

considerable; for example, at an incidence angle of 80° the TM wave suffers 8.5 dB more attenuation than the TE wave.

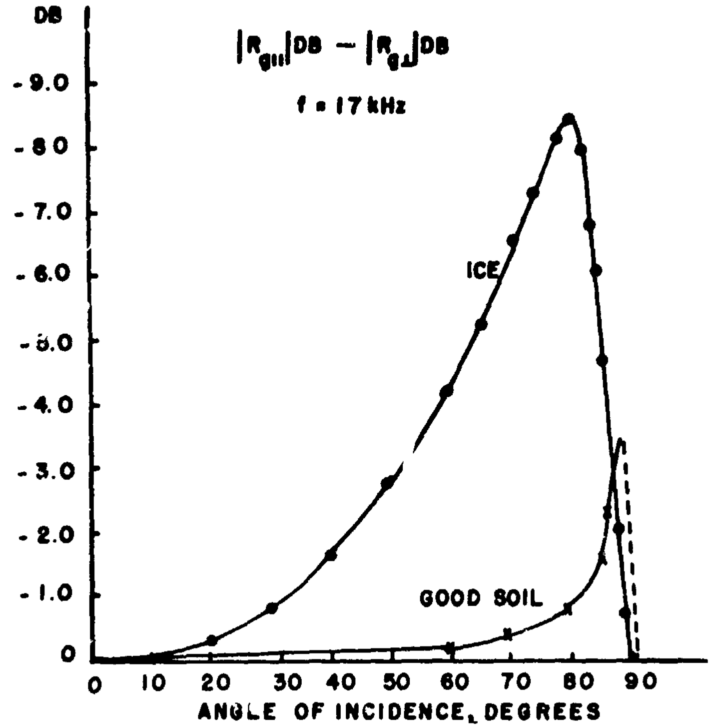

Figure 6. Relative Attenuation of TM and TE Waves Upon Reflection From the Earth

4. ESTIMATION OF THE MODAL ANGLE FROM IONOSPHERIC AND GROUND REFLECTION COEFFICIENT CALCULATIONS

In order that Eq. (1) can be used to estimate attenuation rates in the earth-ionosphere waveguide, it is necessary to determine the angle of incidence ϕ for which there is mode resonance (this angle is then called the 'mode angle'). Referring to Figure 7, the condition that must be met for mode resonance is that the upward going wave at R be coherent (in phase) with the upward going wave at 0, referred to R.

The phase of the upward going wave at 0, referred to R, is

$$\phi_1 = (2\pi/\lambda)(d_s + d) \tag{2}$$

where λ is the wavelength.

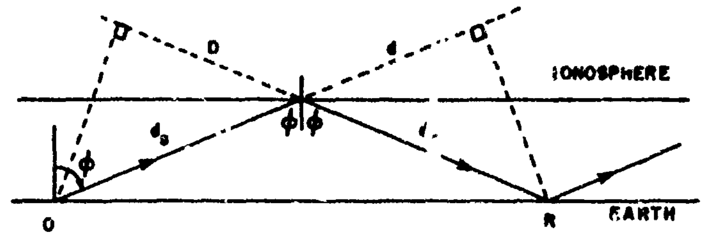

Figure 7. Geometry Used in Determining the Mode Resonance Condition

The computer program for the ionospheric reflection coefficients gives the ratio of the down-going wave and the up-going wave at 0, where it is assumed that the up-going wave has a reference phase equal to zero. Effectively then, the computer calculations give the phase of the down-going wave, referred to 0. Letting this phase be denoted as ϕ_c, the value of the phase of the down-going wave at R, before reflection from the earth, is

$$\phi_2 = \phi_c + (2\pi/\lambda)(d_s + D). \tag{3}$$

After reflection from the earth, the phase is

$$\phi_3 = \phi_c + \phi_g + (2\pi/\lambda)(d_s + D) \tag{4}$$

where ϕ_g is the phase of the ground reflection coefficient, R_g.

For mode resonance, Eqs. (4) and (2) must be equivalent, or

$$(2\pi/\lambda)(d_s + d) = (\phi_c + \phi_g) + (2\pi/\lambda)(d_s + D) \pm 2\pi N \quad (N = 0, 1, 2, \ldots). \tag{5}$$

From Figure 7, d = D, so that the mode resonance condition is

$$\phi_c + \phi_g = 2\pi M \quad (M = 0, 1, 2, \ldots). \tag{6}$$

In practice, for a specified ionosphere and ground conductivity, the solution of Eq. (6) for the modal angle of incidence ϕ, is found by the use of successive approximations, since both ϕ_c and ϕ_g depend on the incidence angle.

5. ESTIMATION OF TM AND TE ATTENUATION RATES

In view of the preceding discussions, particularly those related to Figures 3, 5 and 6, and Eq. (1), TE waves should propagate in the earth-ionosphere waveguide with less attenuation than TM waves, especially so if the propagation is over ice. In the numerical examples that follow, the estimates for attenuation rates have been calculated using Eq. (1), with the modal resonance angle ϕ determined by use of Eq. (6). The ionospheric and ground reflection coefficients have been calculated using AFCRL computer programs. For the severely disturbed ionospheric profiles, a sharply bounded ionosphere at a height of 40 km above the earth has been assumed in the attenuation calculations, since at this height and above the ionospheric parameters change appreciably, relative to height changes in the order of one wavelength at 17 kHz.

Example 1: Severely Disturbed Ionosphere (Figure 3)
Good Earth ($\sigma = 10^{-2}$ mho/m, $\epsilon/\epsilon_0 = 20$)

TM Waves		TE Waves	
ϕ	$= 83°$	ϕ	$= 78°$
$_{\parallel}R_{\parallel}$	$= 0.74$	$_{\perp}R_{\perp}$	$= 0.82$
$R_{g\parallel}$	$= 0.86$	$R_{g\perp}$	$= 0.99$
α_{TM}	$= -6$ dB/Mm	α_{TM}	$= -4.8$ dB/Mm

In this example, for propagation over good earth and severely disturbed ionospheric conditions, the TE waves suffer approximately 1.2 dB/Mm less attenuation than the TM waves.

Example 2: Severely Disturbed Ionosphere (Figure 3)
Ice ($\sigma = 2 \times 10^{-5}$ mho/m, $\epsilon/\epsilon_0 = 5$)

TM Waves		TE Waves	
ϕ	$= 80°$	ϕ	$= 78°$
$_{\parallel}R_{\parallel}$	$= 0.65$	$_{\perp}R_{\perp}$	$= 0.82$
$R_{g\parallel}$	$= 0.35$	$R_{g\perp}$	$= 0.94$
α_{TM}	$= -28.4$ dB/Mm	α_{TE}	$= -6.01$ dB/Mm

In this example, for propagation over ice, the TM waves suffer approximately 22 dB/Mm more attenuation than the TE waves.

6. SUMMARY

Transverse electric (TE) and transverse magnetic (TM) plane wave reflection coefficients were computed at 17 kHz for a horizontally stratified ionosphere, for both normal and severely disturbed conditions. In both cases the ionospheric reflection loss was less for the TE polarization at all angles of incidence.

Reflections of the TM and TE waves at the surface of the earth were also considered; again, the TE polarization was found to be reflected better, the difference being especially appreciable in the case of ice.

Attenuation rates, under severely disturbed ionospheric conditions for the first order TM and TE propagation modes, were estimated using modal angles, and assuming a sharply bounded ionosphere at a height of 40 km. For good earth, the TE mode attenuation was somewhat less than that for the TM mode; but, in the case of ice, the difference was considerable, being only about one-hundredth (1/100) that of the TM mode.

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