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EVALUATION OF WEDCOM PROPAGATION MODELS

B. Gambill

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WASHINGTON, D.C. 20305

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The current WEDCOM code gives good agreement with more detailed propagation calculations for many nuclear weapon conditions of interest. Poor agreement with detailed calculations can result when magnetic field effects are important, particularly when the ground conductivity is also low. Mode conversion may be significant for some environments. Conclusions and recommendations for model improvements are given.

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ACKNOWLEDGMENTS

The author gratefully acknowledges helpful discussions with R. Pappert of the Naval Electronics Laboratory Center. L. A. Berry, Office of Telecommunications/Institute for Telecommunication Sciences, supplied computer programs used in the comparisons. R. Rutherford of TEMPO made necessary changes in the programs supplied by Berry and performed numerous computations.

CONTENTS

LIST OF ILLUSTRATIONS

SECTION 1
INTRODUCTION

The WEDCOM computer program (Reference 1) provides a convenient method for providing estimates of VLF and LF propagation disturbances that are produced by nuclear detonations. The distinguishing feature of the program is that it combines an atmospheric chemistry model, a nuclear ionization model, and propagation models in a single program.

The design of the propagation models has been governed by an attempt to:

1. Make computations rapidly so that parametric variations in chemistry and ionization models can be evaluated economically (in terms of computer usage)
2. Achieve a balance between propagation computation accuracy and accuracy of the physical models
3. Allow a reasonable variation of inputs in terms of antenna orientation, ground conductivity, path orientation, day or night variations, etc.

The first version of WEDCOM provided calculations for propagation between two vertically polarized, ground-based antennas. The ground conductivity corresponded to sea water (5 mhos/meter) or highly conducting earth (10^{-2} mho/meter). The nuclear disturbance was produced by a single burst.

The first major modification of WEDCOM resulted in WEDCOM MB. The major additions were

1. Multiple bursts (up to 50) could be included
2. Path conductivity could be given as an input
3. Improvements were made in the analytic fit to reflection coefficients.

In response to user inquiries and in anticipation of future uses, the following changes have recently been made to WEDCOM:

1. VLF propagation calculations can now be performed for elevated vertical or horizontal antennas
2. An improved solution for VLF mode parameters when the path conductivity is very low (less than 10^{-3} mho/meter) has been included.

The validation of the code in the past has relied on the demonstration that the estimates agree with other more detailed calculations when the nuclear disturbance is intense. When the nuclear disturbance is weak, particularly for nighttime conditions when magnetic field effects are very important, the results produced by WEDCOM may be questionable.

The purpose of this report is to provide a quantitative estimate of the accuracy degradation caused by some of the approximations and omissions in WEDCOM. In particular, magnetic field effects, mode conversion, and effects of very low ground conductivity are discussed. The transition from waveguide mode theory to approximate ray theory, which is made in the program at a frequency of 30 kHz, is also evaluated.

SECTION 2

CURRENT WEDCOM MODELS

The documentation of the latest WEDCOM propagation model is being published separately and the details and equations will not be repeated here. Instead, a general description of the model is provided, followed by a discussion of approximations that are made in the models. These discussions are provided to introduce the comparative calculations that are given later.

VLF MODEL

The VLF propagation model is used for frequencies between 10 and 30 kHz. A waveguide model using impedance boundary conditions as described by Wait (Reference 2) is used. The formulation is in terms of Airy functions. Various limiting forms of the Airy functions are used to determine approximate model solutions. The approximate solutions are used as initial guesses to obtain a more precise solution using the Newton-Raphson method.

The impedance of the ionospheric boundary is determined from reflection coefficients computed assuming a nonhomogeneous but isotropic ionosphere. The ionospheric impedance is defined to be that of an equivalent homogeneous ionosphere that would produce the same reflected field in the region below the ionosphere. An approximate altitude where reflection maximizes is defined, and the ionosphere boundary is assumed to be at that altitude. Analytic fits to reflection coefficients computed using two real angles of incidence are used in an iterative solution to the mode equation.

Excitation factors and height gain functions for vertical dipoles are also as defined by Wait (Reference 2). Excitation factors and height gain functions for elevated horizontal antennas are computed using the method defined by Galejs (Reference 3).

The electric field strength is computed by

1. Obtaining the isotropic mode constant (attenuation rate and phase velocity) at various points along the propagation path.
2. Correcting the attenuation rates based on precomputed values of attenuation rates that include effects of anisotropy for quasi-TM modes. No correction factor is currently applied for quasi-TE modes.
3. Averaging the phase velocity and corrected attenuation rates along the path.
4. Computing the field strength, using the averaged attenuation rates and phase velocities and the geometric mean of excitation factors at the transmitter and receiver locations (commonly referred to as the WKB approximation).

A vector sum and an RMS sum of the field produced by the individual mo[illegible] mputed.

The most important approximations and omissions are discussed below.

Magnetic Field Effects

Anisotropy produced by the earth's magnetic field affects both the excitation and attenuation rate of the waveguide modes. Under isotropic conditions, fields are linearly polarized and modes can be labeled TM (vertical E-field or TE (horizontal E-field). When the anisotropic effects are moderate, the fields are no longer linearly polarized, but have a dominant component and can be labeled quasi-TM or quasi-TE. For moderate anisotropy, quasi-TE modes are excited by vertical antennas and quasi-TM modes are excited by horizontal antennas transmitting in the broadside direction; however, the excitation is small relative to the excitation of the dominant component. Also, for moderate anisotropy, attenuation rates for TM modes depend in a predictable way on propagation azimuth.

When the anisotropic effects are strong, modes can no longer be identified as quasi-TM or quasi-TE, and association of modes with those produced with isotropic cases is difficult.

In WEDCOM, only modes that are excited when the ionosphere is isotropic are considered. An attempt has been made to associate these isotropic modes with quasi-TM or quasi-TE modes that occur for a moderately anisotropic ionosphere, and to provide an appropriate correction factor. To determine the correction factor, excitation factors and attenuation rates were computed by L. A. Berry, Office of Telecommunications/Institute of Telecommunication Sciences, using the WEDCOM normal ionosphere (results described in Reference 4). The calculations were performed with and without the geomagnetic field. All calculations were performed for a vertical, ground-based dipole. Two values of ground conductivity were used (5 mhos/meter and 10^{-2} mho/meter). For the case including the magnetic field, the calculations were performed for various dip angles, propagation azimuths, and frequencies. Determination of the necessary correction factors from the data supplied by Berry is discussed below.

Excitation Factors

When all dip angles were considered, the magnitudes of the excitation factors varied significantly with propagation azimuth. However, by restricting interest to high dip angles (>45 degrees), well excited modes could be identified as quasi-TM modes and the variation of excitation factor magnitude with propagation azimuth was small (less than a factor of 2). Also, for the well excited modes, the anisotropic and isotropic excitation factor magnitudes were in good agreement. Therefore, no correction of the isotropic excitation factors is included in WEDCOM. The consequences of ignoring anisotropic effects for weakly excited modes are more important for ground conductivities much less than 10^{-2} mho/meter and are discussed later.

Attenuation Rate Correction Factor

Using the data supplied by Berry and restricting the range of interest to high dip angles, an analytic fit to the ratio of attenuation rate with magnetic field to attenuation rate without magnetic field was determined as a function of propagation azimuth for the first three quasi-TM modes. This ratio is the correction factor when the ionosphere is undisturbed.

When the nighttime ionosphere is weakly disturbed, but not depressed sufficiently to cause anisotropic effects to be unimportant, the correction factor is assumed to vary exponentially with reflection altitude. It is applied in full under normal nighttime conditions and decreased (or increased) toward unity exponentially with decreasing reflection altitude. The e-folding distance for the exponential variation was chosen to be 7 km, because that is approximately the e-folding distance for the electron-neutral collision frequency. It is assumed that magnetic field effects are inversely proportional to the ratio of electron-neutral collision frequency and the electron gyrofrequency.

No correction factor is included for the recently added quasi-TE modes. A brief analysis of the data computed by Berry (see Reference 4) for the quasi-TE modes for high dip angles indicates that:

1. Attenuation rates are not as sensitive to magnetic azimuth as quasi-TM modes
2. The variation with azimuth is not regular enough to allow a simple correction factor.

A mitigating argument to the crude treatment of the magnetic field is that under conditions of strong nuclear disturbance, the ionosphere is depressed sufficiently that magnetic field effects are indeed unimportant.

A discussion of the validity of the approximate treatment of magnetic field effects is given in Section 4.

Mode Conversion

Steps 3 and 4 in the field strength determination ignore mode conversion (scattering of energy from one mode into another mode) due to variation in ionospheric properties (altitude of reflection or ionospheric impedance) in the direction of propagation. Pappert has shown (Reference 5) that mode conversion at a day-night terminator is important in determining field structure if the transition distance is much less than 1000 km (distance to change the reflection altitude by about 20 km). Wait (Reference 6) has shown that mode conversion is important for changes in ionospheric reflection altitude of a few kilometers.

The importance of mode conversion for nuclear-produced disturbances depends on the weapon yield and detonation altitude. In general, low-altitude detonations produce disturbances that vary rapidly along the propagation path, and high-altitude detonations produce widespread ionization and ionospheric parameters that vary slowly with distance.

An argument with some validity is that

1. Small disturbed regions produced by low-altitude detonations produce small changes in field strength when WKB approximations are used, due to the limited extent of the disturbance along the path. The field disturbance would not be important in system analyses even if mode conversion is included.
2. The WKB approximation is nearly valid when the disturbance is widespread, resulting in a predicted disturbance that is significant; thus predictions that are significant to systems analyses are nearly correct.

Exceptions to the validity of the WKB approximation can be found, even for widespread disturbances, and one will be dicussed later.

LF MODEL

The LF model has been changed little from the original version (Reference 1). The model uses geometric-optics approximations with correction factors for diffraction effects and ionospheric convergence.

The total electric field is computed as the sum of a ground wave field and the fields of sky waves with various numbers of hops. Two field sums are provided: a vector sum and an RMS sum. The latter is provided because of uncertainty in ray path length and therefore phase when the ionosphere is irregular along the propagation path.

The LF model is applicable for vertical, ground-based antennas, and magnetic field effects are neglected entirely.

The approximate ray theory model is readily adaptable to a nonuniform ionosphere. A relatively simple iteration procedure is used to determine the ray path that connects transmitter and receiver via a nonuniform ionosphere. One difficulty is that the geometric-optics model requires that a particular reflection altitude be chosen. When the ionosphere is intensely disturbed, the reflection altitude may be poorly defined (i. e., significant reflections come from a relatively thick region). Some calculations that show where reflections maximize (Reference 7) indicate that the approximate definition of reflection altitude in WEDCOM is quite good.

Results obtained using the approximate ray theory will be compared with results obtained from more accurate computational models in Sections 3 and 4.

SECTION 3

WEDCOM EVALUATION

The evaluation has been performed in two parts. In the first part, ionosphere models have been used that result in reflection at altitudes low enough to cause magnetic field effects to be very small. With these depressed ionospheres, the new additions to WEDCOM and the approximations made in the LF ray theory model can be tested without confusing other approximations with magnetic field effects. Also, a comparison is made of the LF and VLF models at the transition frequency.

In the second part, the evaluation has been performed using the WEDCOM nighttime ionosphere model and a hypothetical nighttime ionosphere model used by Pappert (Reference 8) to evaluate the combined effects of anisotropy and low conductivity on vertical E-field excitation by horizontally polarized antennas.

The electron density profiles that have been used are shown in Figure 1. Profiles 1 and 2 were used by Pappert (Reference 8). Note that profile 1 is similar to the WEDCOM normal daytime profile, at least down to the reflecting region near 60 km. Profile 2 will result in a reflection altitude significantly higher than would result from the WEDCOM normal nighttime profile, and thus anisotropic effects can be expected to be larger. It is anticipated that the WEDCOM D-region chemistry model will be modified in the near future and at that time it may be advantageous to

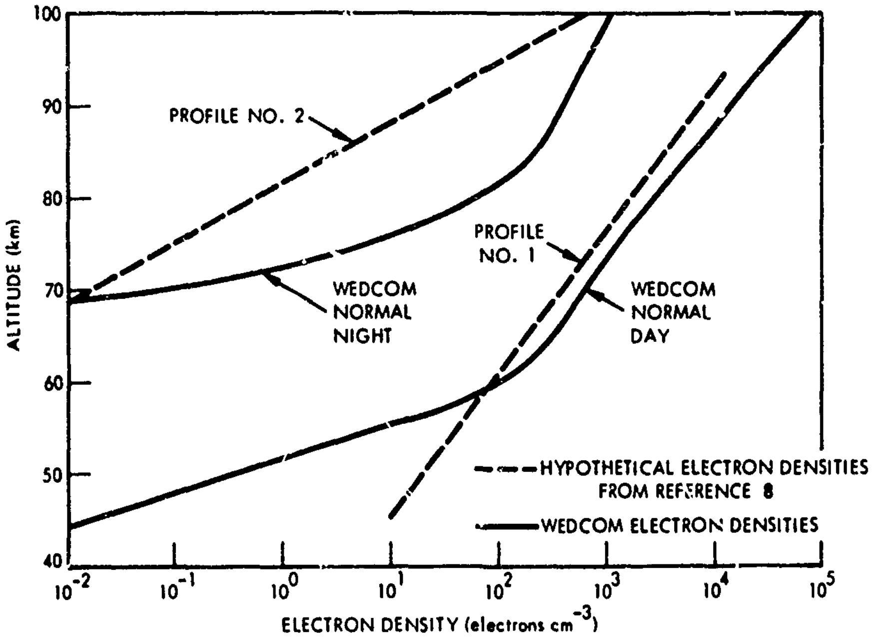

Figure 1. Electron density profiles used in evaluating WEDCOM propagation models.

modify the nighttime ionosphere so that an increase in reflection altitude results. Thus, comparisons made using profile 2 will provide useful guidelines for defining improvements or changes that potentially will be required in WEDCOM because of the modified ionosphere.

VLF PROPAGATION—ISOTROPIC CASE

The recent additions to WEDCOM include

1. Propagation from elevated horizontal antennas
2. Propagation over very-low-conductivity ground.

Pappert (Reference 8) has studied the effect of ground conductivity, ionospheric anisotropy, and antenna elevation on the excitation of vertical electric field from a horizontal electric dipole. He considered a hypothetical daytime ionosphere and a highly anisotropic ionosphere (see Figure 1). In the notation of Wait and Spies (Reference 9), the daytime ionosphere had a β of 0.3 and a reference altitude of 70 km.

The conductivity of the ground (σ) was varied between 10^{-5} and 10 mhos/meter. The relative dielectric constant of the ground (ϵ_g) was 15 for all cases, and the magnetic field strength (B_m) was 0.44 gauss.

Pappert used a frequency of 19.8 kHz, a dip angle of 50 degrees, and a propagation azimuth of 270 degrees. For profile 1, reflection occurs at an altitude near 60 km and the results show little effect of anisotropy.

Figure 2 shows attenuation rates for the first two quasi-TM modes and the first two quasi-TE modes as a function of ground conductivity. The curves are from Pappert's published results. The symbols on or near the curves are from WEDCOM. The results are in quite good agreement. The slight difference in the values for mode 3 may be due to the very simple fit used for reflection coefficients in WEDCOM or to slight effects of anisotropy.

WEDCOM results for the second quasi-TM mode (mode 3) were not obtained for conductivities less than 4×10^{-5} mho/meter. The mode solution procedures in WEDCOM do not converge at the very high attenuation rates associated with high order modes and low conductivity. The attenuation rate is assumed to be equal to its value at 4×10^{-5} mho/meter for all lower conductivities. Time-consuming iterative procedures currently must be used to find the low-conductivity solution. Because the attenuation rates are so high when the

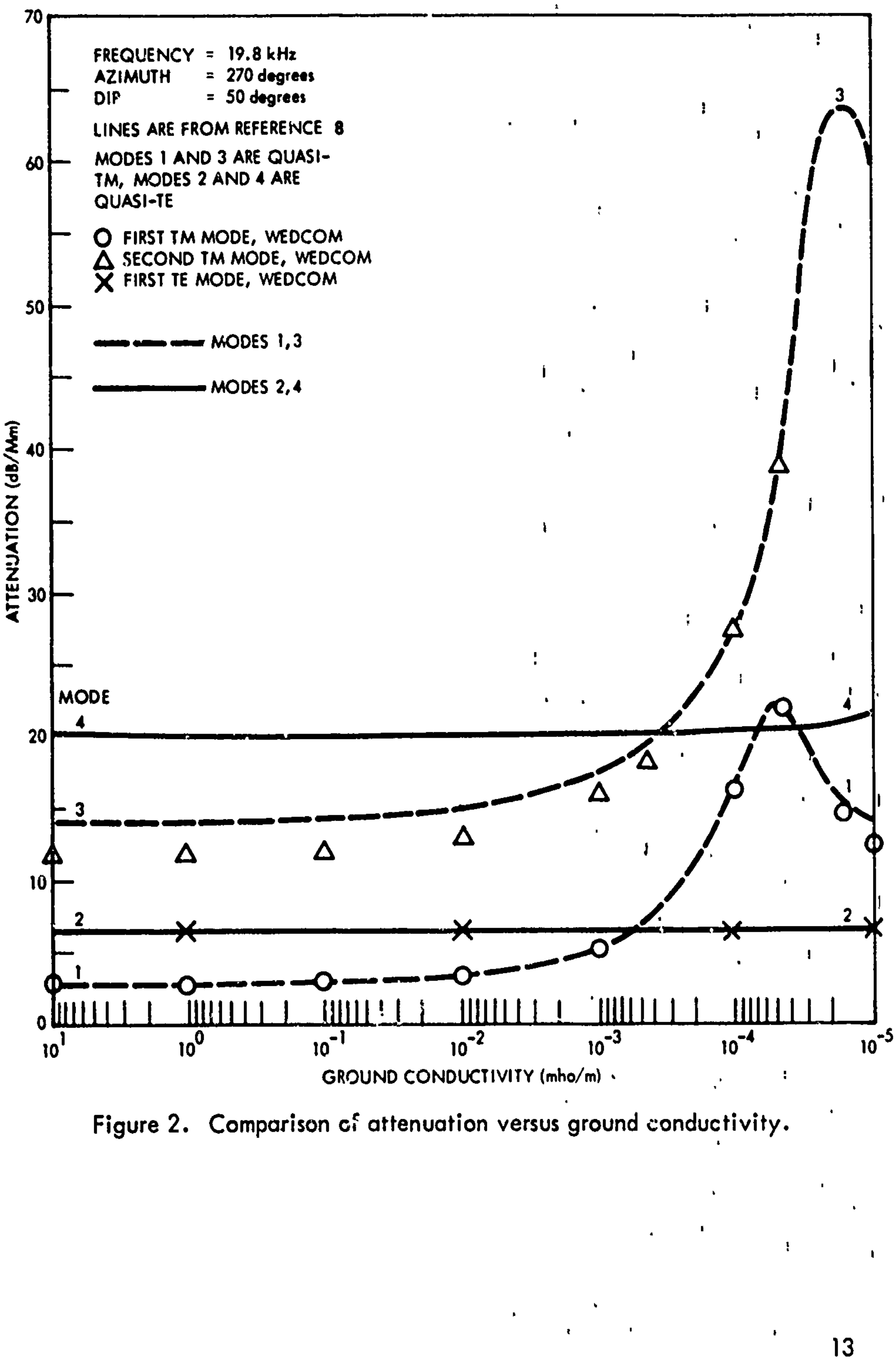

Figure 2. Comparison of attenuation versus ground conductivity.

conductivity is very low, the mode is essentially lost. These procedures are not considered necessary in WEDCOM.

Figure 3 shows excitation factors for a ground-based vertical dipole as a function of conductivity. The agreement is good for the quasi-TM modes. The excitation factor for the quasi-TE mode is a direct result of anisotropy and cannot be produced by the current WEDCOM model. Note that for this nearly isotropic case, the quasi-TE modes are weakly excited. Their omission is of little consequence for conductivites greater than about 10^{-4}. As pointed out in Reference 8, for very low conductivities the weak excitation of the quasi-TE modes tends to be balanced by the higher attenuation rates of the quasi-TM mode, and the quasi-TM and quasi-TE fields will be comparable for long paths.

Figure 4 shows the excitation of the vertical E-field versus ground conductivity for an elevated horizontal electric dipole transmitting in the direction of the dipole (end fire). Again the comparisons between WEDCOM and Pappert's result are good for the quasi-TM modes. The excitation of the quasi-TE modes is dependent directly on anisotropy, and these modes are not computed for end-on launch in the WEDCOM model. The discussion given above regarding the importance of the quasi-TE modes applies here.

The results produced by WEDCOM and those described in Reference 8 for a horizontal dipole generally agree well when anisotropic effects are weak. However, there are situations (low conductivity, long paths) where even very weak anisotropic effects become important.

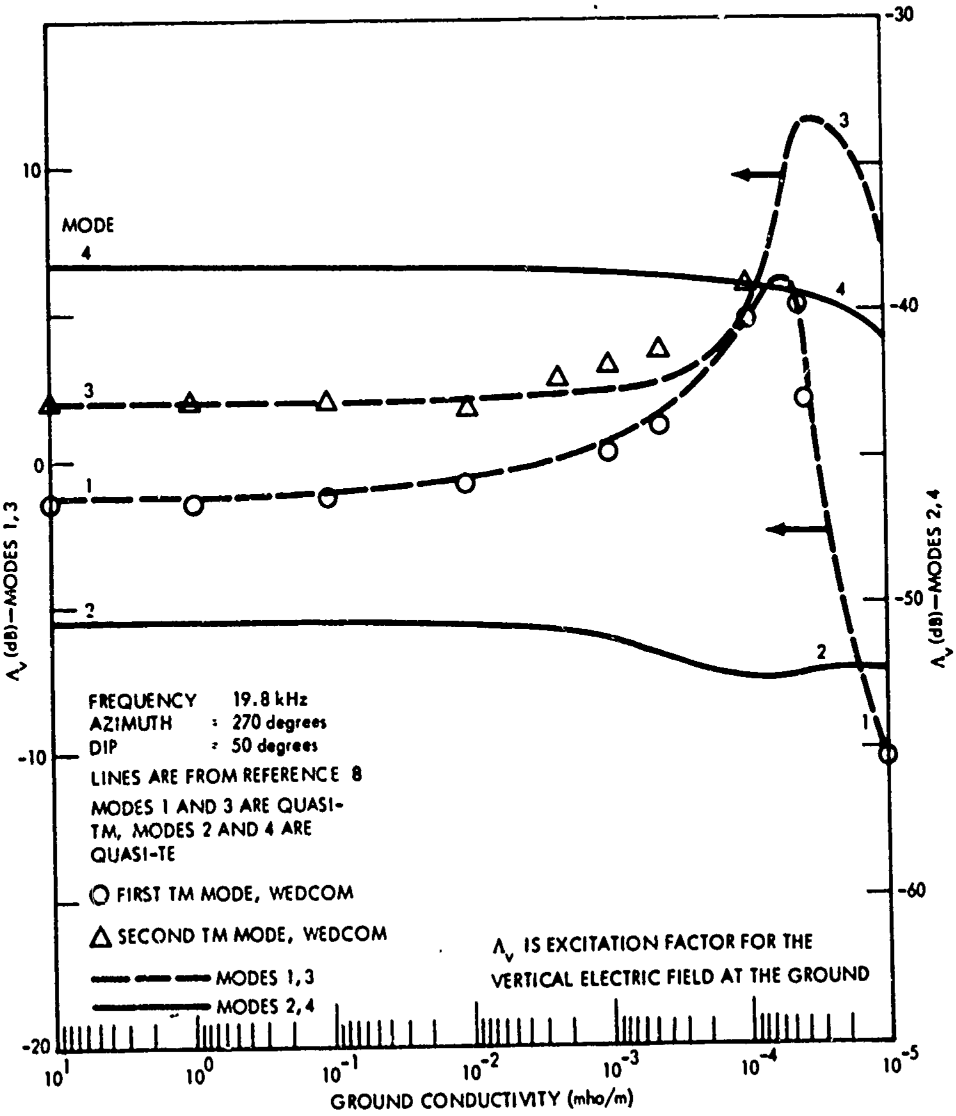

Figure 3. Comparison of the magnitude of the excitation factor Λ_v versus ground conductivity for a ground-based vertical dipole.

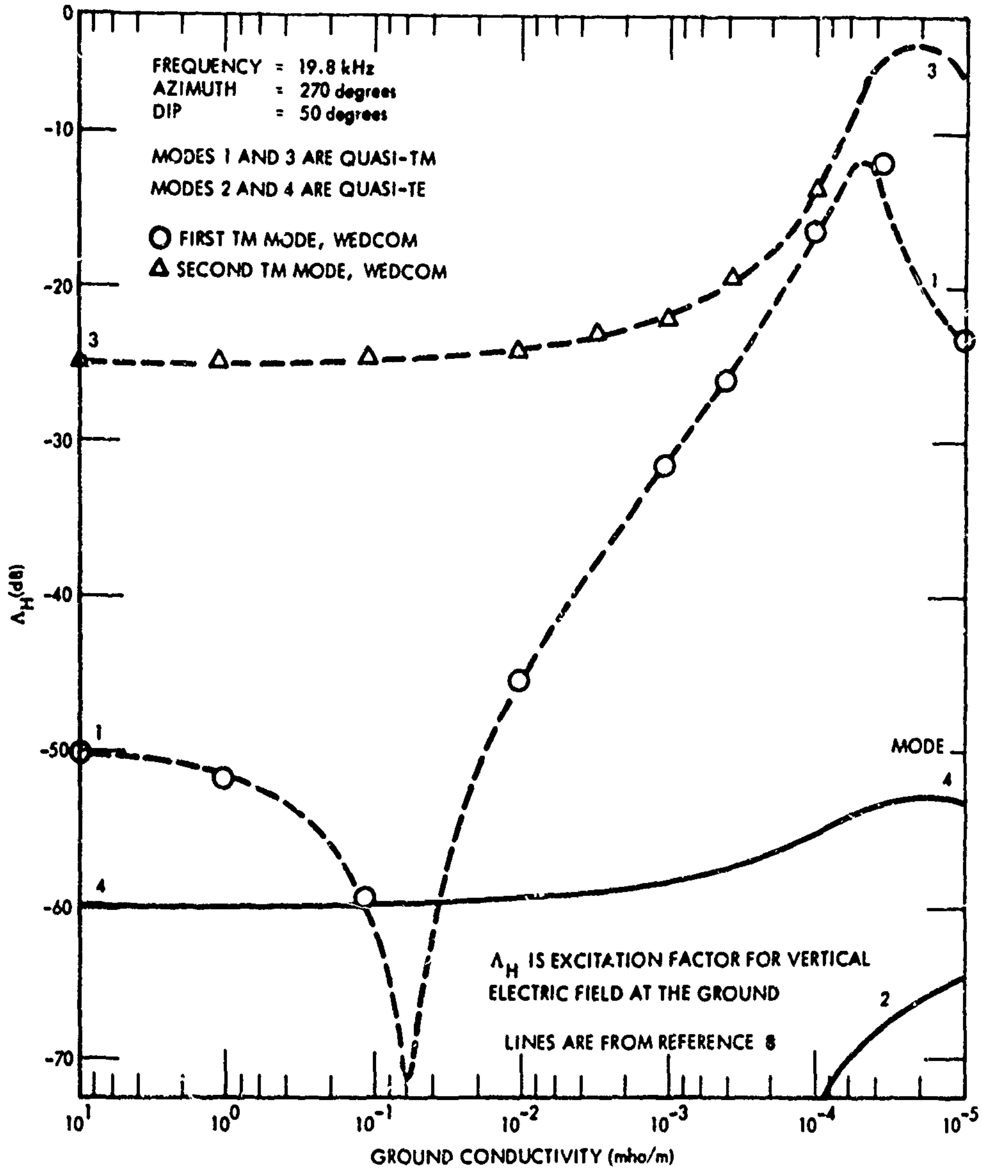

Figure 4. Comparison of the magnitude of the excitation factor Λ_H versus conductivity for a horizontal dipole at 4 km. End-on launch.

LF PROPAGATION—ISOTROPIC CASE

The results produced by the LF propagation model in WEDCOM have been compared to results obtained using a computationally accurate wavehop model supplied us by Berry of the Office of Telecommunications/Institute for Telecommunication Sciences. The wavehop program, called ANIHOP, is described in Reference 10. The program requires as input the four components of the reflection coefficient matrix that are computed by program ANIREF, taking into account the anisotropy produced by the magnetic field. ANIREF is also described in Reference 10.

Field calculations as a function of distance were obtained with ANIHOP using reflection coefficients that were calculated for propagation azimuths of -90, -60, -30, 0, 30, 60, and 90 degrees and frequencies of 40 and 100 kHz. The static magnetic field was taken to be 0.5 gauss. The electric field strength variation with azimuth was very small, as expected, because the ionosphere is nearly isotropic for the ambient daytime ionosphere. Similar calculations were made with WEDCOM except that no azimuthal dependence is obtained from WEDCOM.

Figures 5 and 6 show the results obtained using WEDCOM and ANIHOP. Figure 5 shows field strength as a function of distance, assuming a ground conductivity of 5 mhos/meter (sea water). The WEDCOM results are the RMS field sum. The ANIHOP results show the vector sum of the ground wave and wavehops. Figure 6 shows the same results except that the ground conductivity had been changed to 10^{-3} mho/meter.

The agreement between the results at 40 kHz is very good. The WEDCOM model predicts a significantly higher field than ANIHOP

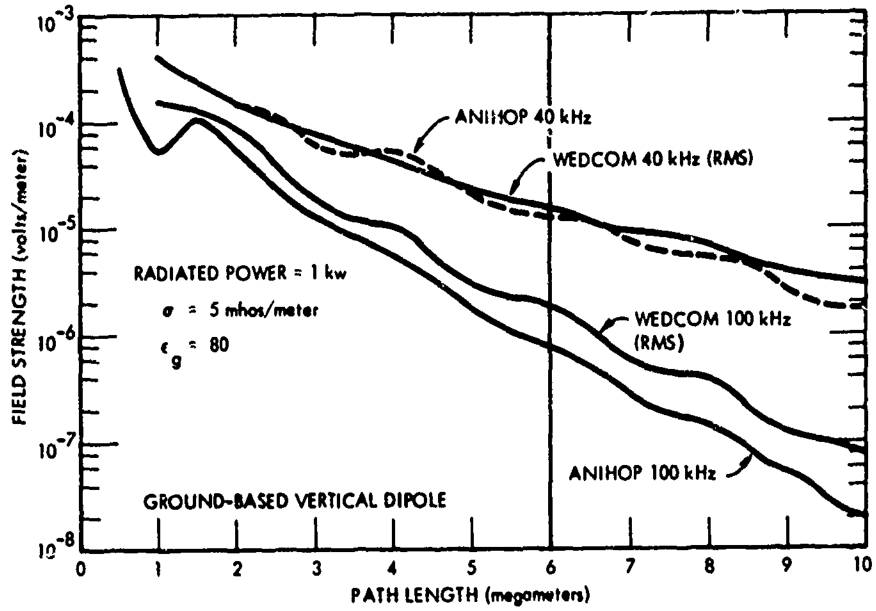

Figure 5. Comparison of WEDCOM and ANIHOP results using WEDCOM normal daytime ionosphere.

for 100 kHz. This difference has been traced to a difference in reflection coefficients, rather than to propagation model approximations. The reflection coefficients computed by WEDCOM and by ANIREF are compared as a function of angle of incidence in Figure 7. It can be seen that results are in agreement at 40 kHz, but WEDCOM predicts a value of about 2 dB higher than ANIREF for 100 kHz. This difference in reflection coefficients is sufficient to explain the difference in calculated field strength.

The reason for the difference in reflection coefficients has not been determined. It may be caused by the different numerical procedures used in calculating the reflection coefficients, or it may be a result of the weak anisotropic effects that remain while using the daytime ionosphere. Some calculations with ANIREF using a very

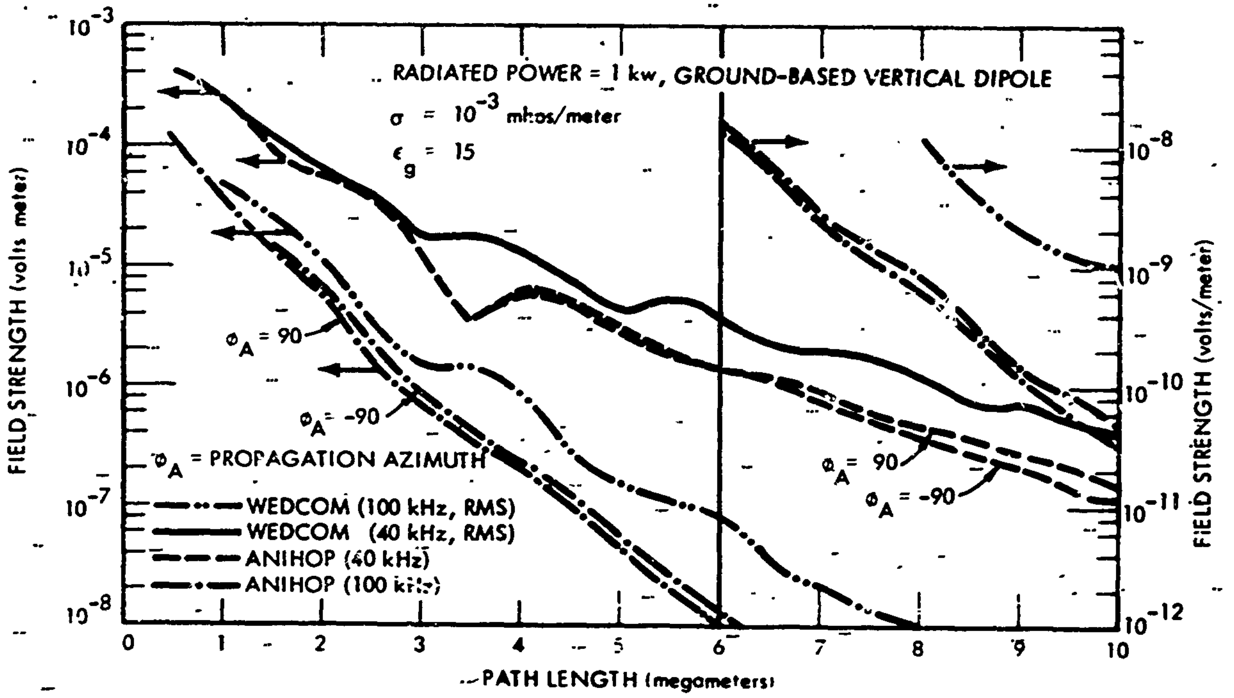

Figure 6. Comparison of WEDCOM and ANIHOP results using WEDCOM normal daytime ionosphere.

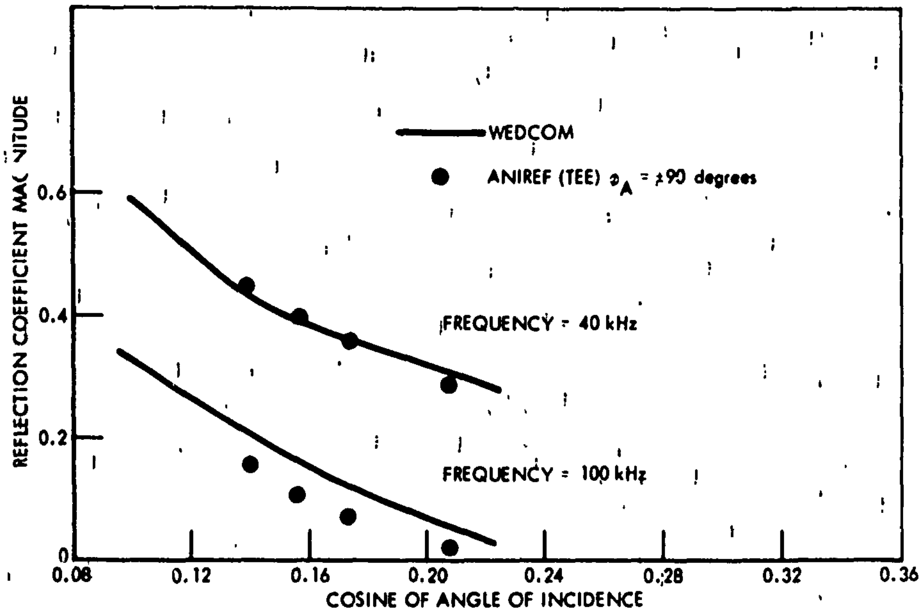

Figure 7. Comparison of WEDCOM and ANIREF reflection coefficients using WEDCOM daytime ionosphere.

low value for the static magnetic field strength indicate that the former reason is the most likely.

COMPARISON OF VLF AND LF MODELS AT THE TRANSITION FREQUENCY

Propagation calculations made in WEDCOM use waveguide mode theory for frequencies of 30 kHz or below and use approximate ray theory for frequencies above 30 kHz. An isotropic ionosphere is assumed in both methods.

The waveguide mode theory model contains fewer approximations than the ray theory model; thus it should provide a better estimate of field strength than the ray theory model when the ionosphere is uniform. On the other hand, the approximate ray theory model is more readily adaptable to calculations with a disturbed ionosphere.

Thus when the approximations in the ray theory method are valid, this method is better than mode theory for cases where the ionosphere is highly disturbed. This is mainly because mode conversion is not included in the waveguide mode model.

The comparison between the LF and VLF models in this section is for a uniform ionosphere model. Calculations were made along a propagation azimuth where the magnetic field correction factor is unity in the waveguide mode calculations. Comparisons between the two models for disturbed cases are discussed later under mode conversion.

Figure 8 shows the RMS field strength versus distance obtained at 30 kHz (VLF waveguide model) and at 30.1 kHz (LF ray theory model). Results were obtained for high (5 mhos/meter) and low (10^{-3} mho/meter) ground conductivity. The ionosphere used was the WEDCOM ambient daytime model. The agreement is very good

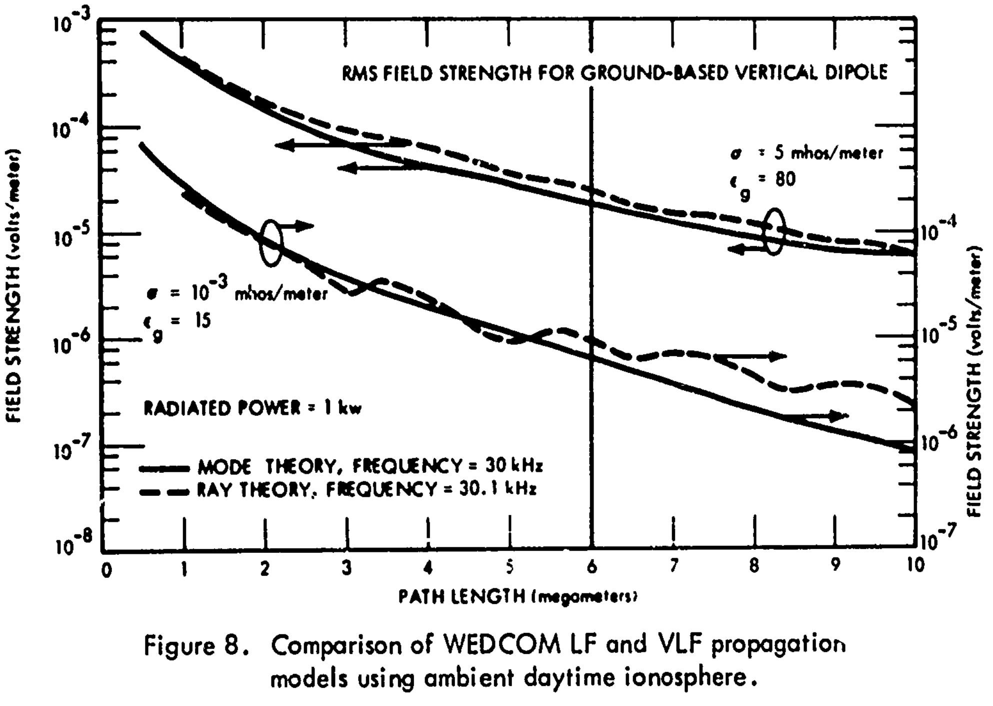

Figure 8. Comparison of WEDCOM LF and VLF propagation models using ambient daytime ionosphere.

for high conductivity and good for low conductivity out to about 6 megameters. The difference beyond 6 megameters is due either to the use of Fresnel ground reflection coefficients or to the approximation of the antenna foreground factors, both of which depend strongly on conductivity in the ray theory model.

Figure 9 shows the same comparison, except that the WEDCOM ambient nighttime model ionosphere is used. Differences between the two results for lcw conductivity are noted at 3.5 to 4 megameters.

In general, for both ionospheric conditions, the agreement is excellent considering the approximation made in the ray theory model.

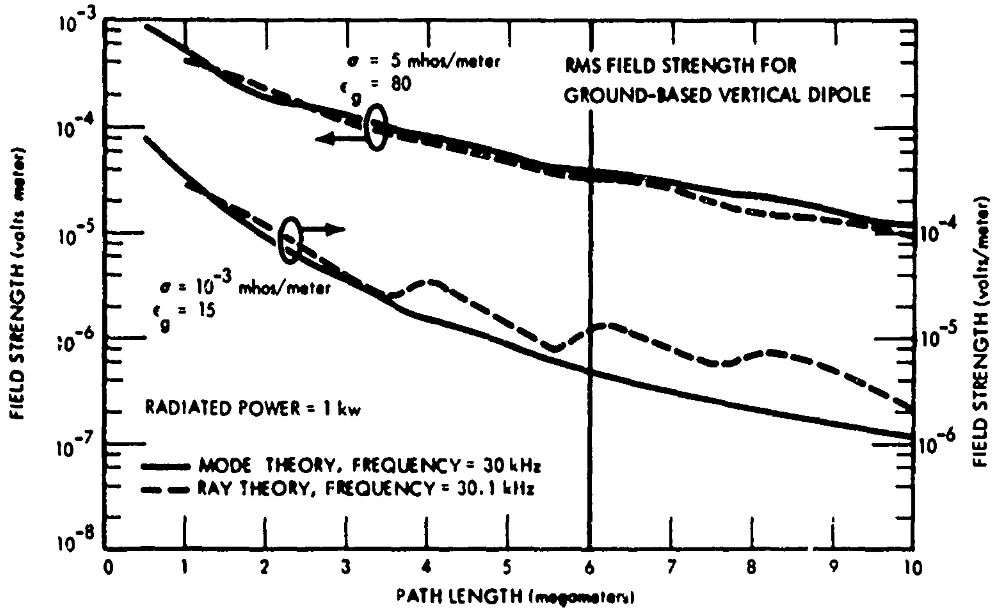

Figure 9. Comparison of WEDCOM LF and VLF propagation models using WEDCOM normal nighttime ionosphere.

SECTION 4

MAGNETIC FIELD EFFECTS

EFFECTS ON VLF PROPAGATION

The factor used to correct mode attenuation rates that are calculated assuming isotropic ionospheric conditions was described earlier. The weaknesses of the method are

1. The correction factors apply only for the particular ionosphere, dip angles, ground conductivities, and polarization for which calculations were performed
2. The altitude variation applied to the correction factors has not been established by computations at various altitudes
3. It is not always possible to establish a one-to-one correspondence between mode parameters computed using isotropic and anisotropic ionospheres (i.e., the mode numbering system may be ambiguous).

In analyzing the anisotropic mode parameter data supplied by Berry (Reference 4) that were computed using the current WEDCOM nighttime profile, some difficulty was experienced in choosing which anisotropic mode to compare with a given isotropic mode number. However, in most cases, the choice was obvious, particularly at the lower frequencies where quasi-TM modes are well excited and quasi-TE modes are poorly excited by a vertical antenna. It will be seen later that if the nighttime profile is raised a few kilometers, the anisotropic effects become stronger and establishing mode correspondence is difficult. Establishment of mode correspondence becomes even more difficult when the ground conductivity is low or when elevated horizontal antennas are used.

The weaknesses listed under items 1 and 2 above can be checked and corrected by performing a more complete set of calculations including anisotropy that also encompass a reasonable variation of the important parameters. These calculations would have to be performed each time the ambient nighttime profile is substantially changed. In performing the calculation to determine altitude variation of correction factor, consideration would have to be given to the effects of change in ionospheric gradient as well as altitude. As an example of the effect of varying ionospheric altitude, the anisotropic reflection coefficients were computed for an electron density profile described by

$$N_e(h) = 50 \exp\left(0.5\,(h - H_R)\right) \quad \text{cm}^{-3} \quad , \qquad (1)$$

where

h = altitude (km)

H_R = reference altitude (km)

$N_e(h)$ = electron density (cm^{-3}) .

The reference altitude was varied from 60 to 80 km, which caused the peak reflection altitude to vary over nearly the same range. Figure 10 shows the reflection coefficient magnitude of the four components (TEE—vertical incident, vertical reflected; TEM—vertical incident, horizontal reflected; TME—horizontal incident, vertical reflected; and TMM—horizontal incident, horizontal reflected). A frequency of 20 kHz, a dip angle of 50 degrees, a real angle of incidence (ϕ_i) of 80 degrees, and a propagation azimuth (ϕ_A) of 58 degrees

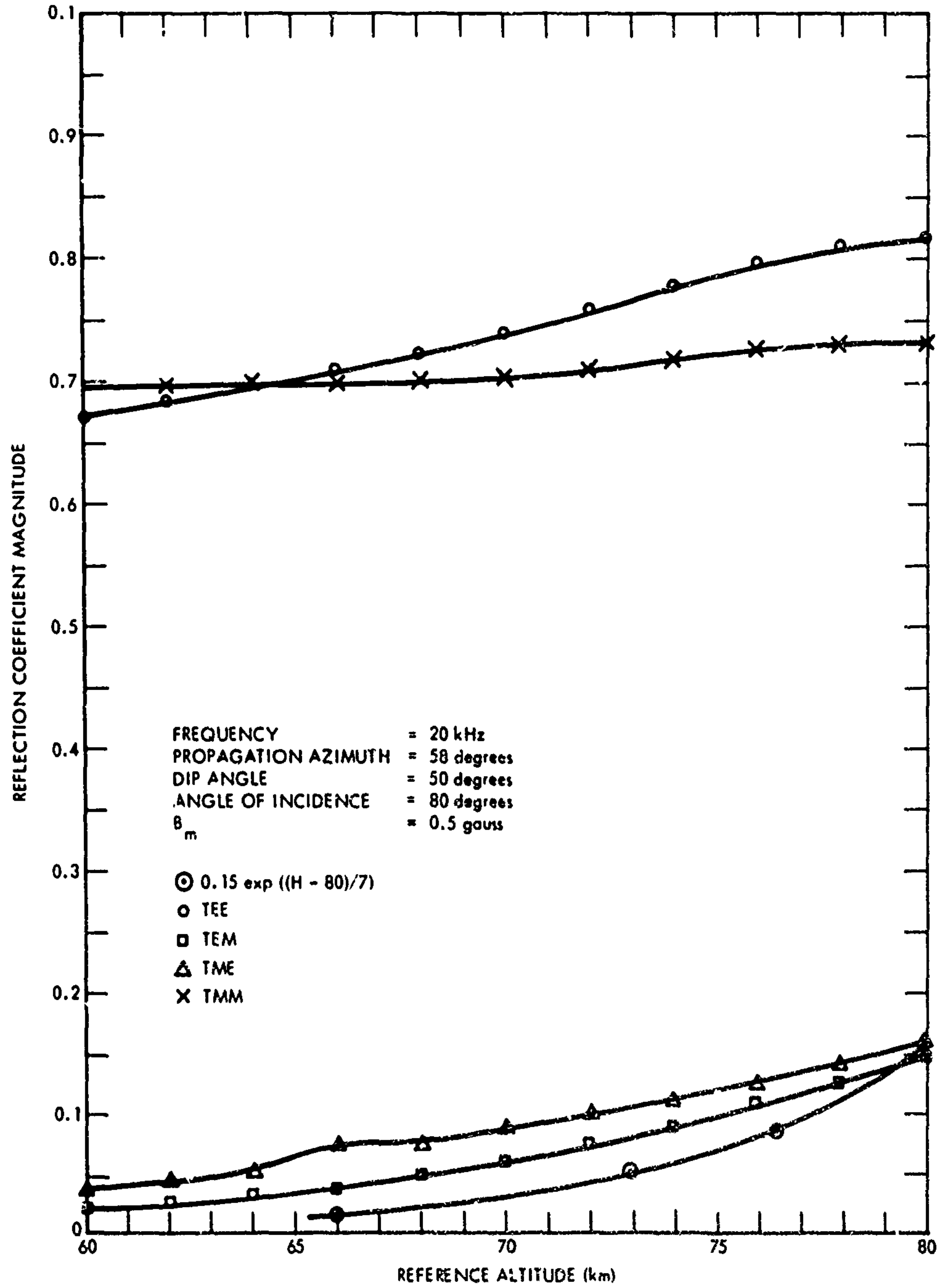

Figure 10. Reflection coefficient variation as reference altitude of electron density profile is varied.

were used. The coupling coefficients, which are a measure of anisotropy, decrease with reference altitude. A curve decreasing in magnitude with decreasing altitude with an e-folding distance of 7 km is also shown on Figure 10. Based on comparison of the TEM and TME components and the exponential curve, the decrease of the magnetic field correction factor with altitude is too rapid.

Figure 11 shows the same plot but for a propagation azimuth of 238 degrees, where coupling effects are stronger. In this case the exponential curve is a good representation of the decrease in coupling coefficients with decreasing reflection altitude.

If the ambient nighttime ionosphere is changed infrequently, the use of precomputed correction values may be appropriate. However, as the number of variables is increased, resulting in increased difficulty of establishing mode-to-mode correspondence, it may be more feasible to include anisotropy in the model explicitly. To minimize computer time, the program could revert to the isotropic model when the ionosphere is sufficiently depressed to warrant the isotropic approximation.

As an example of the difficulties in establishing mode-to-mode correspondence and to estimate the effect of failing to establish such correspondence, results obtained using the models in WEDCOM for vertical and elevated horizontal antennas are compared below to results obtained by Pappert (Reference 8) for an ionospheric profile where anisotropy is very important. The profile in the notation of Wait and Spies (Reference 9) is a $\beta = 0.5$, $H' = 90$ profile (profile number 2, Figure 1).

In Reference 8, a frequency of 19.8 kHz, a propagation azimuth of 270 degrees, and a dip angle of 50 degrees are used. It should be

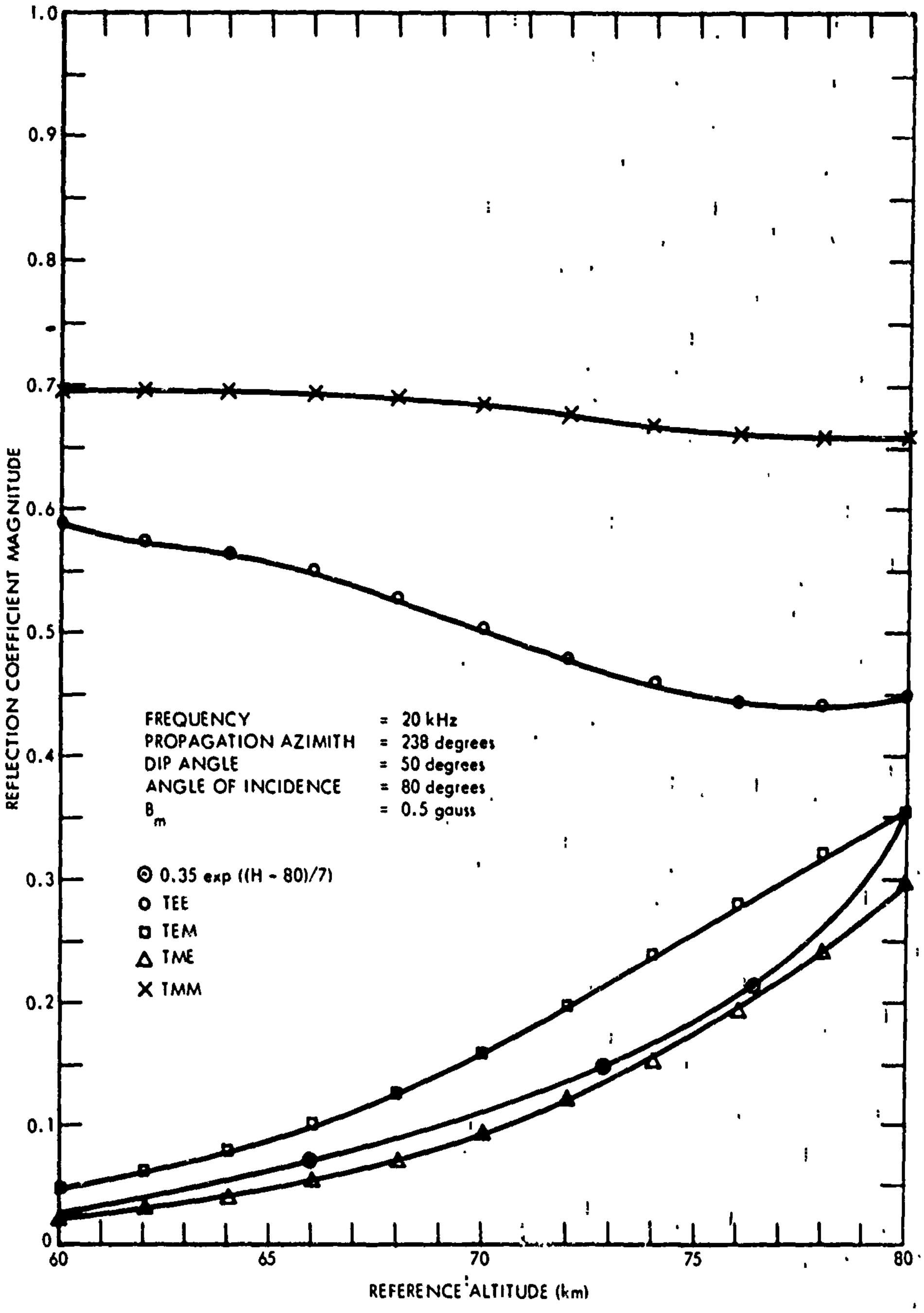

Figure 11. Reflection coefficient variation as reference altitude of electron density profile is varied.

noted that the 270-degree propagation azimuth results in near maximum coupling effects for the anisotropic case.

The WEDCOM isotropic model results were obtained using a frequency of 20 kHz. The slight change in frequency should have an inconsequential effect on the comparison. It should be noted that profile 2 results in a reflection altitude (using the WEDCOM definition) above 80 km, which is substantially higher than the altitude obtained using the current WEDCOM ambient nighttime profile.

Figure 12 shows the attenuation rates obtained (Reference 8) for the first five modes and one high-order mode. The accompanying discussion by Pappert indicated that there was strong polarization mixing in all modes, and the modes are not identified as quasi-TM or quasi-TE. Also shown on the curve are attenuation rates for the first two TM modes obtained using the WEDCOM model. Mode 1 has the same general variation with conductivity as Pappert's modes 2 and 4, and mode 2 has the same general variation with conductivity as Pappert's modes 3 and 5. However, there is no clear way of establishing correspondence between the isotropic and anisotropic modes.

Figures 13 and 14 show the comparison between excitation factors obtained by Pappert and obtained using WEDCOM models for a ground-based vertical dipole and a horizontal dipole elevated 4 km and transmitting in the end-fire direction. Again, there is no clear correspondence between isotropic and anisotropic values. Pappert also computed the excitation of the vertical E-field from a horizontal antenna transmitting in the broadside direction (not shown here). This excitation factor does not occur at all for the isotropic assumption.

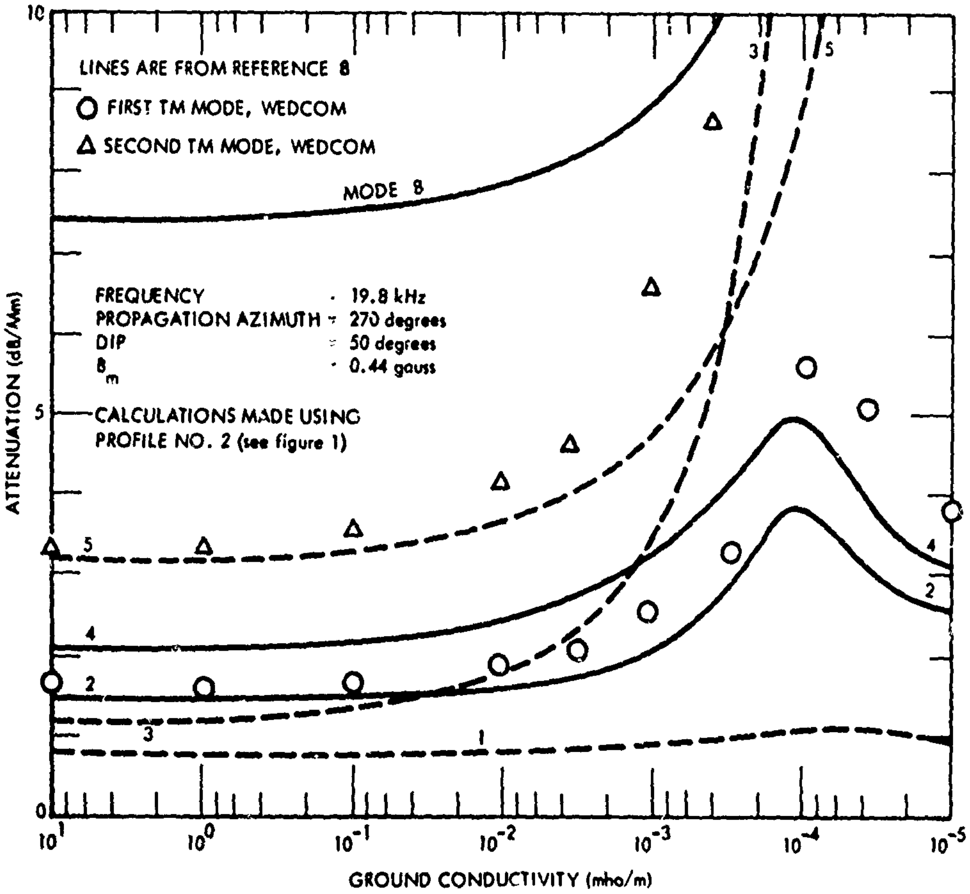

Figure 12. Comparison of attenuat versus ground conductivity.

To further examine the consequences of ignoring anisotropy and to see if a method of defining correction factors can be deduced, the relative field strength as a function of distance for the various modes was computed. Specifically, E_{db} was computed where

$$E_{db} = \Lambda + 8.7\,\alpha d \quad , \tag{2}$$

where

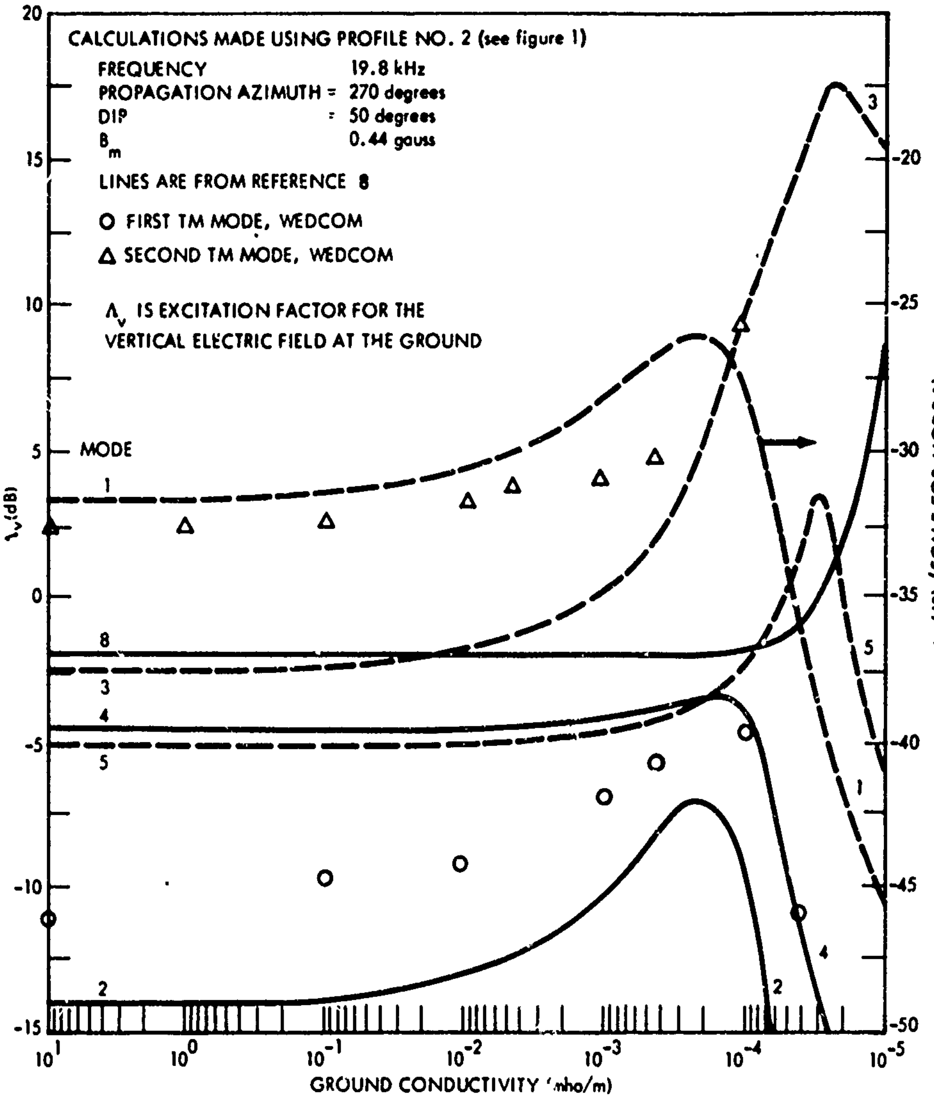

Figure 13. Comparison of the magnitude of the excitation factor Λ_v versus ground conductivity for a ground-based vertical dipole.

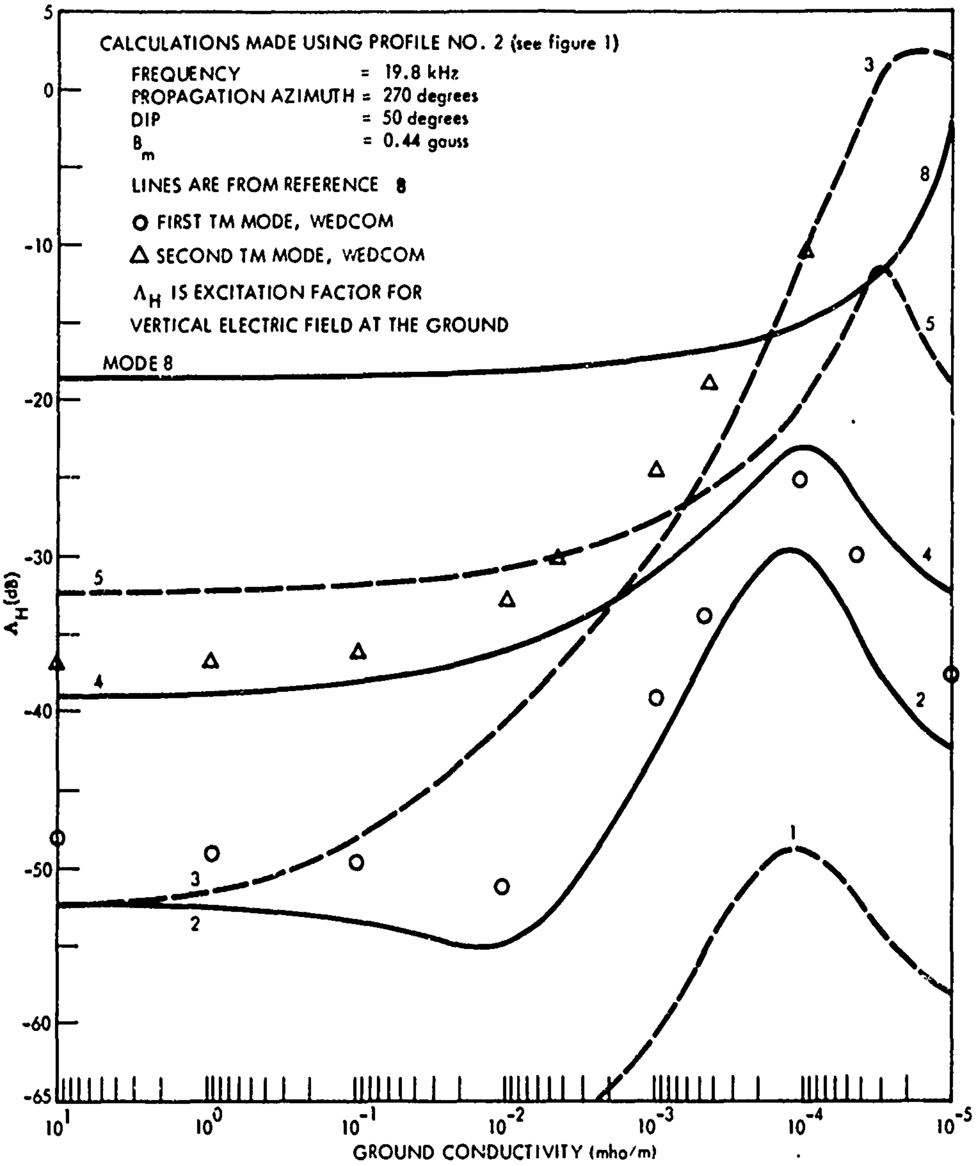

Figure 14. Comparison of the magnitude of the excitation factor Λ_H versus conductivity for a horizontal dipole at 4 km. End-on launch.

Λ = excitation factor for vertical E (dB)

α = attenuation rate (dB/Mm)

d = distance in megameters.

E_{db} is related to the actual electric field strength by a constant and the distance spreading factor. The constant and the spreading factor are the same for all modes and for either isotropic or anisotropic calculations.

For each type of excitation and two values of ground conductivity (1.0 and 10^{-4} mho/meter), E_{db} was computed at various distances for all modes defined by Pappert and the maximum value was determined. A similar calculation was performed for the first two TM modes computed using WEDCOM models.

Figure 15 shows a plot of the values of relative field strength versus distance for a ground conductivity of 1 mho/meter. The curve labeled V_A is the field excited by a vertical antenna as computed in Reference 8. The field labeled V_I is the field excited by a vertical antenna as computed by WEDCOM. (The subscripts A and I refer to anisotropic and isotropic, respectively). The numbers by the tick marks on the curves at d = 1 megameter indicate the dominant mode at short distances. The tick marks on the curves at other distances indicate where the dominant mode number changes, and the numbers indicate the new dominant mode.

Comparing the V_A and V_I curves, it can be seen that

1. A correction in both attenuation rate and excitation would be required to bring the fields into agreement
2. The change would require that the attenuation rate computed for isotropic conditions be increased, contrary to the popular notion that attenuation is increased for westerly propagation and decreased for easterly propagation as a result of anisotropy.

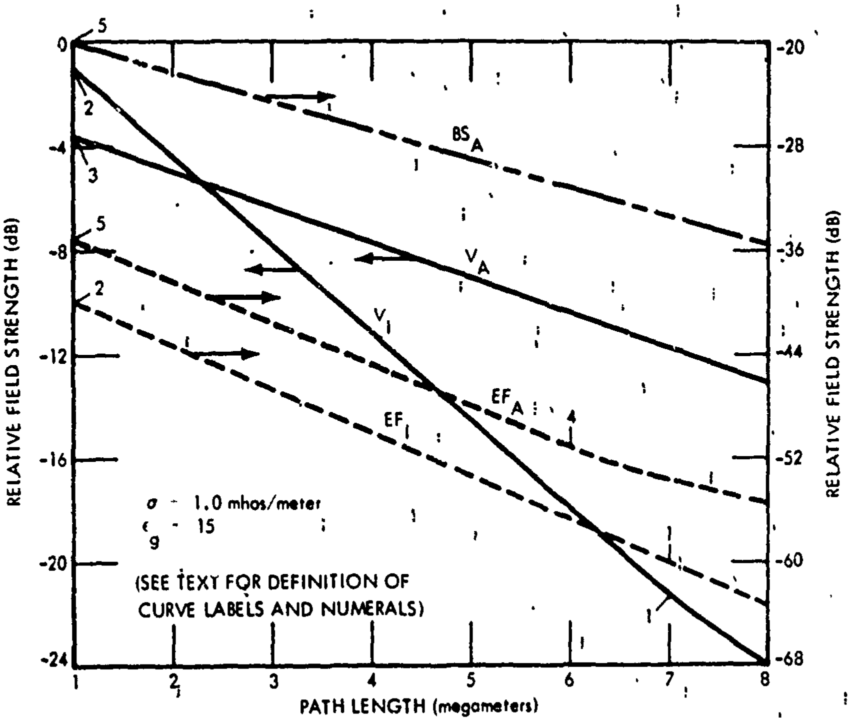

Figure 15. Comparison of dominant mode relative field strength for the vertical electric field at the ground (high conductivity).

The curves labeled EF_A and EF_I are relative vertical E-fields produced by a horizontal antenna at 4-km altitude radiating in the end-fire direction. A correction in excitation factors would bring these curves into close agreement. However, the field excited from the elevated horizontal antenna in the broadside direction (labeled BS_A) is greater than that excited in the end-fire direction, and this field is nonexistent when the ionosphere is isotropic.

It should be noted that the mode association suggested by the relative shape of the attenuation rate and excitation factors, namely isotropic mode 2 (2_I) with anisotropic mode 5 (5_A) and 1_I with 4_A, is in agreement with the dominant modes for the horizontal end-fire antenna, but not for the vertical antenna.

Figure 16 shows the same comparisons as described above but for a ground conductivity of 10^{-4} mho/meter. The fields from the vertical antenna are in better agreement out to about 5 megameters. However, the change in dominant mode with distance for the anisotropic case would result in field variations that would not occur in the isotropic case.

The fields from the horizontal end-fire antenna (EF_A and EF_I) are in good agreement out to about 4 megameters, but they change

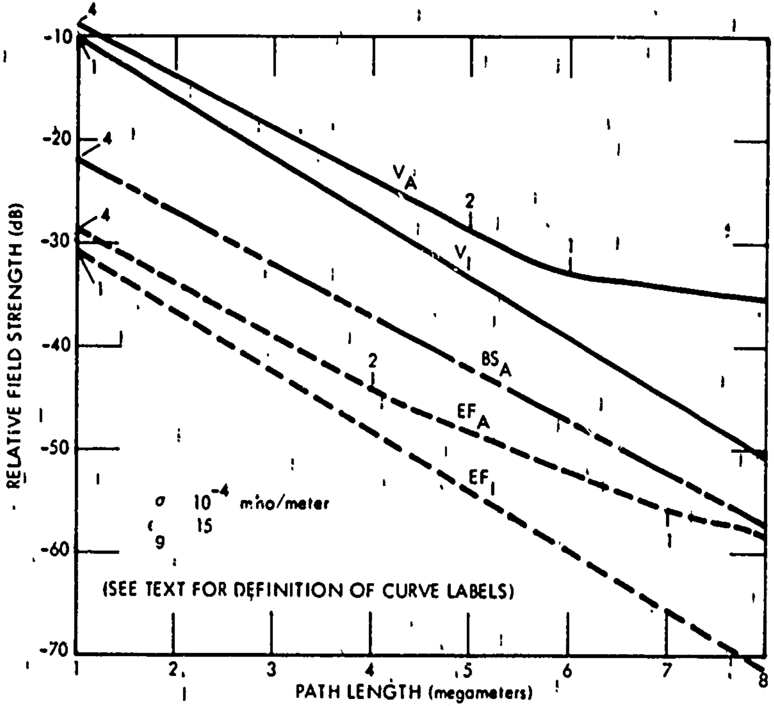

Figure 16. Comparison of dominant mode relative field strength for the vertical electric field at the ground (low conductivity).

significantly beyond that point. As before, the vertical field from the horizontal antenna in the broadside direction exceeds the field produced in the end-fire direction.

The general conclusions are that when the anisotropic effects are as strong as indicated by the examples chosen here,

1. Any correction scheme would have to include excitation factors as well as attenuation rate
2. The choice of which isotropic mode to compare with a given anisotropic mode to determine a correction factor would be extremely difficult.

Comparisons similar to the ones made here will be necessary when any revised WEDCOM ambient nighttime profile is introduced. If the difficulties of defining correction factors for other propagation azimuths are as great as indicated by this study, it will be necessary to include explicit calculations for anisotropic effects on WEDCOM.

EFFECTS ON LF PROPAGATION

The electric field strength as a function of distance computed by WEDCOM has been compared to that computed by ANIHOP (Reference 10), which includes the effects of the geomagnetic field. Computations were made with both programs for frequencies of 40 and 100 kHz, ground conductivity of 5 mhos/meter, and relative dielectric constant of 80. The ANIHOP results were obtained for propagation azimuths of -90, -60, -30, 0, 30, 60, and 90 degrees. The magnetic field strength, B_m, was 0.5 gauss.

Figure 17 shows the comparison between WEDCOM and ANIHOP computed fields for 40 kHz. The ANIHOP results are presented as an envelope that contains the results obtained for all propagation

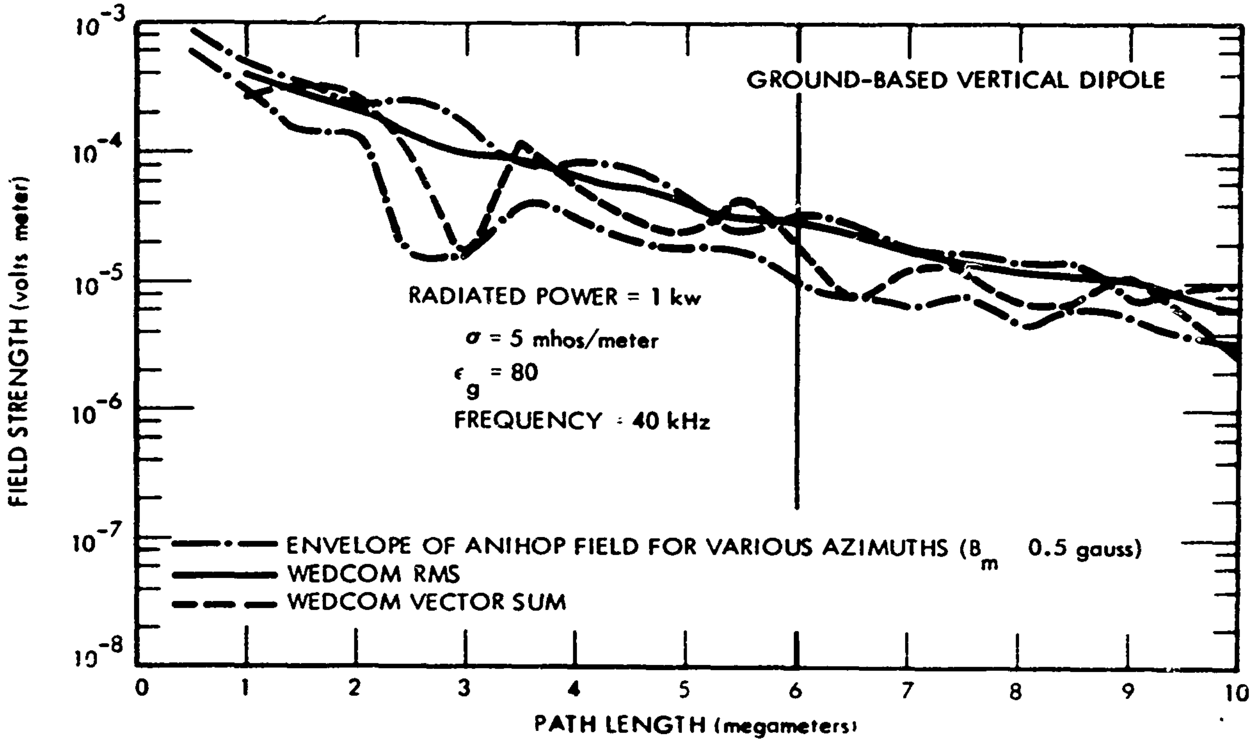

Figure 17. Comparison of WEDCOM LF model and ANIHOP using WEDCOM normal nighttime ionosphere.

azimuths. The WEDCOM RMS sum and vector sum are shown. The results compare favorably with the exception of the 2000-to-3000-km path segment. The results are generally within a factor of 2 for other path lengths. For this uniform ionosphere case, the WEDCOM vector sum is to be preferred.

Figure 18 shows the field computed with WEDCOM compared to the field computed with ANIHOP for 100 kHz. Again the envelope of the field for azimuths of -90, -60, -30, 0, 30, 60, and 90 degrees are given for ANIHOP, and both the RMS and vector field sums are shown for WEDCOM. For 100 kHz the WEDCOM fields are consistently higher than the field computed in ANIHOP.

The reason for the 100-kHz field difference is clearly shown in Figure 19, which shows the anisotropic reflection coefficient component magnitude for two propagation azimuths as a function of cosine of angle of incidence. Also shown is the isotropic reflection coefficient computed in WEDCOM. The comparison illustrates that the effect of the magnetic field in addition to making propagation a function of azimuth is to generally reduce the reflection coefficients for all azimuths.

Also shown in Figure 19 is the reflection coefficient obtained for a very low value of magnetic field strength in ANIREF. (The value used was 0.01 gauss; ANIREF will not run with a zero magnetic field). This small magnetic field reflection coefficient is significantly lower than the reflection coefficient computed in WEDCOM. (A similar comparison between ANIREF and WEDCOM was noted in Section 3 for the ambient daytime ionosphere). It is probable that this difference is due to different numerical procedures in the two reflection coefficient programs.

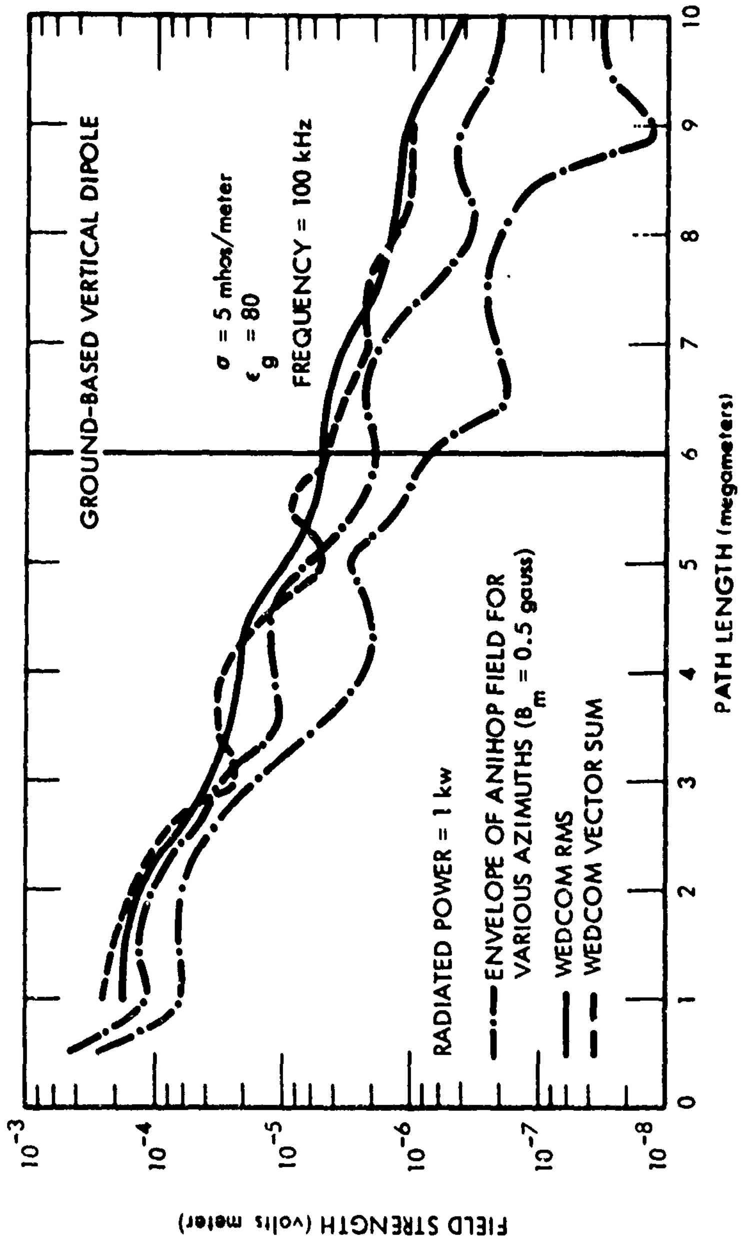

Figure 18. Comparison of WEDCOM LF model and ANIHOP using WEDCOM normal nighttime ionosphere.

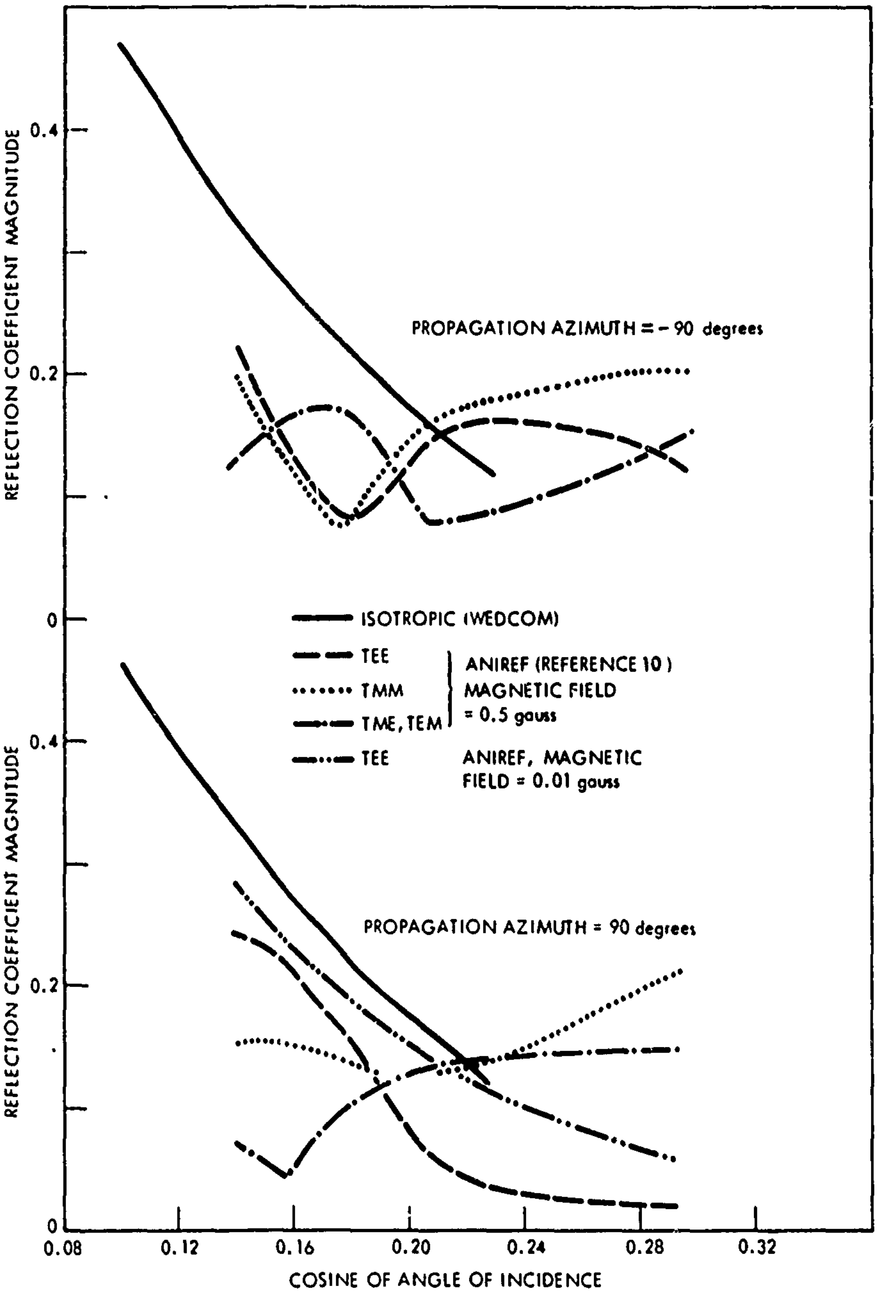

Figure 19. Comparison of isotropic and anisotropic reflection coefficients.

The conclusion to be drawn from the results shown in Figures 17, 18, and 19 is that the effects of the magnetic field can be partly accounted for, at the higher LF frequencies, by simply using a reduced value of the reflection coefficient. The magnitude of the reduction will depend on frequency and reflection height.

SECTION 5

MODE CONVERSION

The field strengths for each mode in the waveguide mode solution are obtained by using average values of attenuation rate and phase velocity over the path length, and using the geometric mean value of the excitation factors computed at the path end points. The approximation is commonly referred to as the WKB approximation.

It has always been clear that the approximation is more nearly valid for some types of nuclear detonations (high-altitude, widespread debris sources) than for other types (low-altitude, contained sources). When the ionosphere varies rapidly in the direction of propagation, energy is scattered from one mode to another mode. Formulations to compute mode conversion for certain idealized situations have been developed (References 6 and 11) and have been used to explain the propagation across the day-night terminator. Recently Pappert (Reference 5) has used mode conversion to study propagation across a day-night terminator as a function of distance required for the transition from daytime conditions to nighttime conditions. The reflection altitude was assumed to vary from nighttime (90 km) to daytime (70 km) over a distance ΔD, and ΔD was varied from 0 to 1000 km. One conclusion was that a transition distance near 1000 km (a variation of 1-km altitude per 50-km path length) was required before the WKB approximation and the calculations using mode conversion were in substantial agreement.

Mode conversion is not accounted for in WEDCOM, nor is any attempt made to recognize situations where the WKB approximation is violated.

In making comparisons between WEDCOM LF and VLF models at the transition frequency (30 kHz), and for a disturbed ionosphere, a case was identified where mode conversion effects are clearly important. This case is discussed here.

The disturbance was produced by placing 1 MT of fission debris at an altitude of 200 km directly over the midpoint of a 10-Mm path. The debris was distributed over a 315-km radius, and the computation time was 100 sec after detonation. Nighttime conditions were assumed to prevail over the entire path.

The depression produced by this disturbance is shown plotted in Figure 20. The reflection altitude, as defined in WEDCOM, is plotted as a function of distance along the path. Also shown is the depression profile that would be produced if the debris source is moved 1500 km at right angles to the propagation path. The steepness of the sides of the depression changes very little as the source is moved, although the minimum reflection altitude is significantly increased.

Also shown for reference is the nighttime-to-daytime transition analyzed by Pappert (Reference 5) where the transition distance is 1000 km. The slope of the transition region is roughly the same as that of the nuclear-produced depression, but the total altitude change is much less.

Figure 21 shows the field strength versus distance computed by the LF and VLF models in WEDCOM for frequencies of 30.1 and 30 kHz, respectively. Also shown for reference are the fields computed

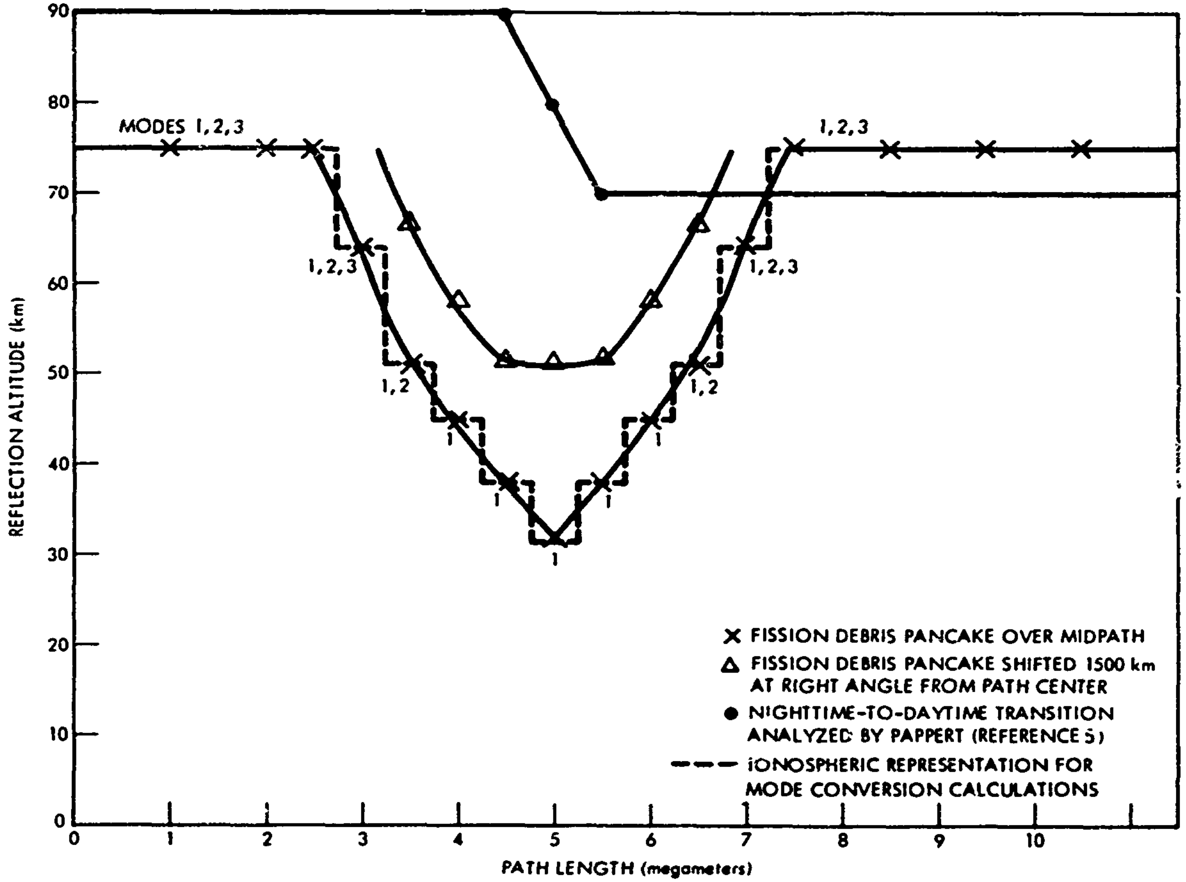

Figure 20. Reflection heights for nuclear disturbance and for nighttime-to-daytime transition.

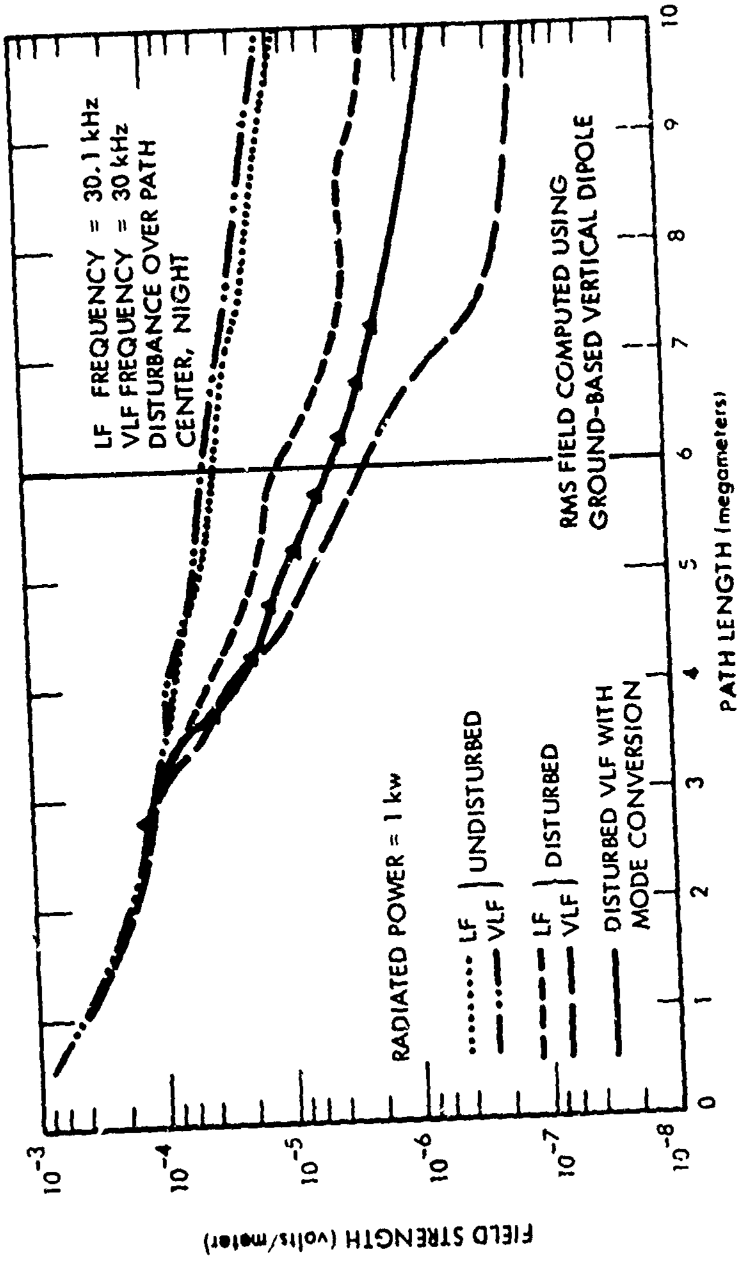

Figure 21. Comparison of WEDCOM LF and VLF models for the disturbed ionosphere profile shown in Figure 20.

by the two models for the undisturbed ionosphere. Despite the close agreement for the undisturbed case, the agreement for the disturbed case is poor. Some consideration of the mode structure for the disturbed case leads to the conclusion that mode conversion may be an important contributor to the disparity in results. Those considerations are

1. In the undisturbed case, mode 2 is the dominant mode, even to a distance of 10 Mm, due to the very weak excitation of mode 1.
2. In the disturbed case, only mode 1 can propagate any significant energy through the region that is severely depressed. Thus mode 2 is eliminated, and much of the difference between disturbed-undisturbed fields is accounted for by the difference between mode 2 and mode 1 excitation factors.

If mode conversion causes significant energy to be scattered from the dominant mode 2 into mode 1 at the beginning of the depression (taking advantage of the lower attenuation rate of mode 1 in the depressed region) and then if energy is scattered from mode 1 back to mode 2 at the end of the depression (taking advantage of the higher excitation of mode 2), the disturbed field strength may be much larger than the WKB value.

Some calculations were performed to see if inclusion of mode conversion would improve the agreement between the LF and VLF models. Mode parameters were available at 500-km intervals along the path from the WEDCOM calculation. The ionosphere was modeled by the series of steps shown in Figure 20, and mode conversion coefficients were computed using the formulation described by Wait (Reference 6). In this formulation the field along the vertical part of the steps is neglected in computing the conversion coefficients.

The calculations started with three modes incident at the beginning of the depression. However, due to numerical difficulties in calculating height gain functions and derivatives of height gain functions when the attenuation rates were large (resulting in large arguments for the Airy functions), some modes were dropped out of the calculation in the most depressed part of the ionosphere. The numbers on the steps show the modes that were assumed to propagate across the steps. Energy scattered into the higher order modes was assumed to be lost in the very depressed portion. Modes 2 and 3 were recovered by scattering from mode 1 at the receiving side of the depression, and mode 2 again became the dominant mode at the receiver.

Figure 21 also shows the field strength obtained as a function of distance for 30 kHz under the disturbed ionosphere using mode conversion. The agreement between the two models, while still not good, is substantially improved.

The case discussed here is ideal to demonstrate the importance of mode conversion, i.e., one where there is a great difference between excitation factors in the undisturbed part of the path and a great difference between attenuation rates in the disturbed part of the path. A comparison between LF and VLF models for the same disturbance but assuming the path was in daylight showed much less difference in the models, because mode 1 is well excited using the normal daytime ionosphere. However, this example indicates that there are situations where mode conversion can be very important.

Mode conversion can also occur when the propagation path crosses a land-sea boundary. Calculations performed by Wait (Reference 11) indicate that the conversion coefficients from one mode to another are very small for the transitions from sea to land with conductivity of 10^{-2} mho/meter, and they are on the order of 0.1 for the transition from sea to land with conductivity of 10^{-3}. The calculations in Reference 11 considered the first three modes and a frequency of 20 kHz. The results indicate that mode conversion effects due to a ground conductivity discontinuity are less important than for those due to changes in ionospheric height that result from nuclear disturbances.

SECTION 6

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The comparison of WEDCOM results to results produced by more rigorous models provides a basis for some general statements about the computational accuracy of WEDCOM. The accuracy is strongly dependent on the state of the ionosphere and, to a lesser extent, is dependent on ground conductivity and antenna orientation. The conclusions are categorized below by typical ionospheres:

1. Normal daytime ionosphere, or nighttime ionosphere sufficiently depressed to reduce anisotropic effects.

   VLF — The WEDCOM results generally agree well with results of more rigorous models. This statement applies when the recently added options that allow calculations to be performed for elevated horizontal antennas and for propagation over poorly conducting ground are exercised. An exception can occur for long propagation paths over very low conductivity ground ($<10^{-4}$ mho/meter).

   LF — The approximate LF propagation results agree well with the more accurate mode calculations at the transition frequency (30 kHz), and with results obtained using the more accurate formulation in ANIHOP (Reference 10) at the lower LF frequency used in the comparison (40 kHz). The agreement between WEDCOM and ANIHOP was not as good for 100 kHz as it was at the lower frequencies. The reason was identified as a small difference in reflection coefficient values, not to approximations in the propagation model.

2. Current WEDCOM normal nighttime ionosphere

VLF — For ground-based vertical antennas, the comparison was made previously and is essentially contained in Reference 4, where the derivation of the magnetic field correction factors is presented. So long as the program is used for vertically polarized antennas and for mid-latitude, good-to-high conductivity paths, the correction factors are appropriate.

The variation of the magnetic field correction factor with decrease in reflection altitude is partially substantiated by the variation of the reflection coefficient coupling terms with altitude (see Figures 10 and 11).

No results from the rigorous models were available for comparison for horizontal antennas and for very low conductivity ground.

LF — The WEDCOM and ANIHOP field strength versus distance results are in substantial agreement at 40 kHz. The envelope of the ANIHOP results (the minimum and maximum of the field strength values for various propagation azimuths) contains the WEDCOM results, and the maximum difference in field strength values was generally less than a factor of 2.

The WEDCOM and ANIHOP field strength results are significantly different at 100 kHz. A substantial improvement in WEDCOM results could be obtained by simply reducing the isotropic reflection coefficients to account for anisotropic effects.

3. Ionosphere producing strong anisotropic effects (Profile 2 of Figure 1)

   Only VLF was compared using profile 2. The reflection altitude obtained using this profile is 5 to 10 km higher than that obtained using the WEDCOM normal nighttime profile. Currently planned modifications of the WEDCOM D-region chemistry (Reference 10) may be accompanied by changes in the nighttime ionosphere model that will result in reflection altitudes between those obtained using the current nighttime profile and those obtained from profile 2. Because of this possible modification, the comparison made here indicates what modifications are necessary for WEDCOM to remain consistent with the new nighttime ionosphere model.

   The conclusions reached here are tentative, since the comparison was made for only one frequency, one dip angle, and one propagation azimuth. The tentative conclusions are

   a. Magnetic field correction factors will be difficult if not impossible to define
   b. Because of the recent options allowing propagation from horizontal antennas and over poorly conducting earth, excitation factors as well as attenuation rates would have to be corrected for anisotropic effects.

4. Disturbed profile

   The comparison between results for the LF and VLF models at 30 kHz for a severely disturbed ionosphere shows the

> potential significance of mode conversion. As described in Section 3, the choice of disturbance geometry and frequency tends to maximize conversion effects. For lower frequencies or for disturbances over path terminals, the difference in excitation of modes is less, and the effect of mode conversion would be less dramatic.

The above comments apply to a comparison made using two propagation models, both of which assume an isotropic ionosphere. Because of the wide variation of mode excitation factors and attenuation rates when anisotropic effects are large, perhaps mode conversion will be very important for all frequencies when parts of the path are in the dark portion of the earth-ionosphere waveguide or over very low conductivity ground.

RECOMMENDATIONS

The comparisons indicate that the current WEDCOM code gives good agreement with more detailed propagation calculations for many cases of interest. However, there are some cases of practical concern where the WEDCOM models are deficient and improvements could be made. The following modifications would improve predictions for these cases:

1. Add the capability to compute reflection coefficients taking into account the anisotropy of the ionosphere. This can be done by adapting the model from ANIREF (Reference 10) or the model used at the Naval Electronics Laboratory Center (NELC) (Reference 12).
2. Add the capability to compute VLF mode constants, using the reflection coefficients obtained by including anisotropic effects. Provided the modes can still be identified as quasi-TM

or quasi-TE, the method used in ANIMOD (Reference 13) will fit easily into the framework of WEDCOM. Otherwise, the procedure used by NELC (Reference 12) can be adopted.

3. Retain the modified ray theory calculations for LF, but include diffraction correction for elevated horizontal antennas. The propagation model, given reflection coefficients calculated including anisotropy, appears to be good and is readily adaptable to disturbed ionospheres.
4. With the more rigorous models included in WEDCOM, retain most of the capability for fast computations by doing the following:
    a. Organizing the program so that ionization calculations are made at relatively short increments along the propagation path, but so that the points for making propagation calculations are under program control.
    b. Perform propagation parameter calculations at some initial point on the path.
    c. From the ionization calculations and the path geometry, determine when ionosphere properties have changed sufficiently to require new propagation calculations.
    d. Use the mode solutions obtained for a previous calculation (the initial point being the first previous calculation) as inputs to obtain the solution iteratively at the next location. The procedure will help to establish mode correspondence in the transition from anisotropic to isotropic regions.
    e. When progressing from a near-normal nighttime portion of the path to a disturbed region, revert to calculation methods that assume an isotropic ionosphere. This procedure should result in performing a few anisotropic

calculations in the undisturbed portion of the waveguide and many isotropic calculations in the disturbed portion of the waveguide.

f. Include a rudimentary form of mode conversion, or flag results to indicate where mode conversion may be important. The art of computing conversion coefficients while accounting for anisotropic effects, is not developed enough for WEDCOM application. Addition of approximate mode conversion calculations in the isotropic portion of the waveguide probably would be useful.

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