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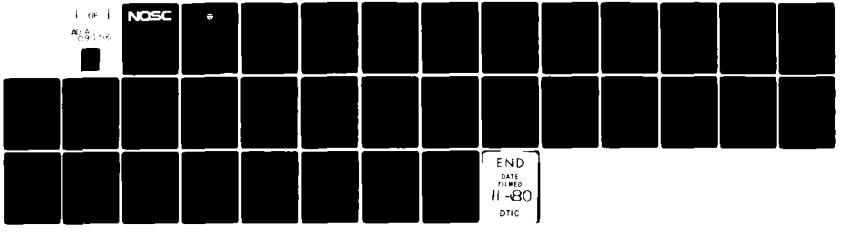

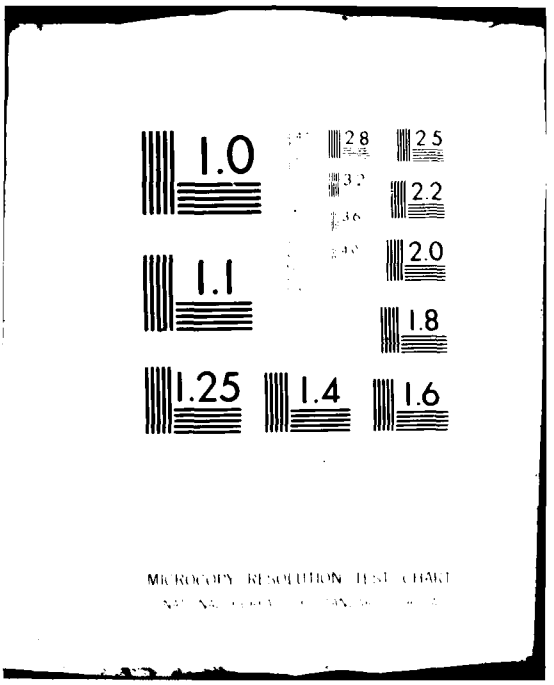
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Technical Report 561

EFFECTS OF IONOSPHERIC REFLECTION HEIGHT AND GROUND CONDUCTIVITY ON EARTH-IONOSPHERE WAVEGUIDE MODE AND GROUND-WAVE ATTENUATION RATES.

(10) W.F. Moler
R.A. Pappert

(11) June 1980

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A surviving ground-wave signal has previously been assumed to represent the minimum expected for vlf and lf systems operating in a severely disturbed environment. The authors show that for propagation over poorly conducting soil and under a depressed ionosphere, path losses may markedly exceed those predicted by the normal ground-wave attenuation rates. This is shown to be caused by the invasion of the ionosphere into the presupposed free-space region of the diffraction mode (ground-wave) "dust." Because of inherent uncertainties in the ground-wave model for some propagation conditions, the authors recommend that estimates of system performance in severe environments be based on earth-ionosphere waveguide mode computational models.

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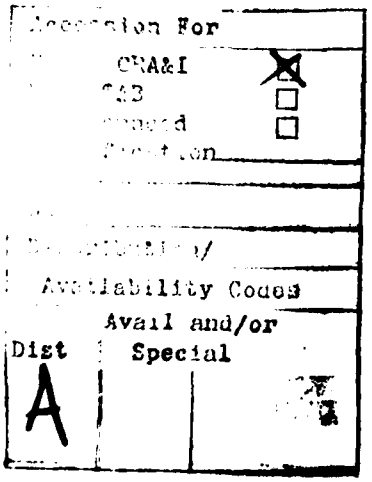
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CONTENTS

FIGURES

OBJECTIVE

Determine whether the ground-wave signal for vlf and lf radio systems represents the minimal expected field strength under severely disturbed ionospheres.

RESULTS

Path losses can markedly exceed those predicted by normal ground-wave attenuation rates for propagation under simultaneously occurring conditions of depressed ionospheres and poorly conducting ground. When these conditions apply, the safest way to evaluate the vlf and lf system performance is by use of waveguide mode theory rather than by wave-hop or ground-wave techniques.

RECOMMENDATION

Because of the possible errors and misconceptions which may arise from using the ground-wave computation for estimating lf coverage in severely disturbed environments, a complete propagation analysis of coverage should be performed by means of numerical methods based on waveguide mode theory.

1. INTRODUCTION AND BACKGROUND

Much effort has been expended during the past few years in developing survivable communications for control of the strategic forces by the NCA and CINCS under nuclear warfare conditions. Both the Navy and the Air Force have developed airborne and fixed ground-station transmitters which radiate in the vlf and lf (10^4–10^5 Hz) radio bands to provide assured one-way communications from the command authorities to the strategic forces. The reliance on long-wave systems arose because practical transmitters and powers can provide near-global (or at least very-long-range) one-way assured communications. In addition, long-wave communications were considered to be much less vulnerable to disruption by the effects of nuclear detonations in the atmosphere than long-range hf communications. Radio measurements made during the 1962 high-altitude tests in the Pacific confirmed that long-wave systems did indeed suffer less severe propagation effects than hf systems, but the effects were much more severe than had been anticipated. Subsequently, researchers were able to show that, if positive and negative ions were included in the vlf and lf propagation models, the theoretical predictions were in line with observations made during the high-altitude nuclear tests.

A working group was organized by the Defense Nuclear Agency (DNA) at the RAND Corporation in November 1963 to study the effects of nuclear environments on lf propagation. Although details of the chemistry were not well known, it became apparent to the group that nuclear perturbation of the atmosphere below the normal D-region could drastically reduce lf (and vlf) sky-wave propagation. The major conclusion of the working group was: "In any event, it appears basically sound, in order to provide invulnerability to nuclear burst-produced propagation effects, to design lf systems on the basis of the surviving ground wave signal and normally expected noise background."[1] The remarks preceding the above quotation are essentially a distillation of the introduction and background from reference 1 and serve well as background material for this report.

In part D of reference 1, Crain illustrates how one may calculate the signal amplitude reduction for a given path length and for several radio frequencies if the sky wave were completely absorbed by a severe nuclear environment. That is, the signal reduction represents the difference between signal levels in a normal quiescent environment and that produced by a ground wave only. In presenting this approach, Crain points out that it is approximate and that path losses are apt to be greater than given by the simple sky-wave–ground-wave difference in signal level; that losses increase with decreasing radio frequency and with increasing nuclear perturbation. Crain assumed "typical" earth conductivity and typically normal day and night ionospheres.

Crain's ground-wave attenuation rates were calculated for free-space conditions above a conducting earth. Johler[2] examined ground-wave propagation in a uniformly ionized atmosphere and found that if the ionization were sufficiently intense, ground-wave attenuation

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[1] Crain, C.M., An Overview Discussion of Propagation Effects of Nuclear Environments on VLF-LF Communications Systems, RAND Corporation Report to Defense Nuclear Agency, DNA 3778T, 31 August 1975.

[2] Johler, J.R., Ground Wave Propagation in a Normal and an Ionized Atmosphere, ESSA Research Laboratories Report ERL 121-ITS 85, July 1969.

would be increased. In a subsequent report, Johler[3] again examined the effects of nuclear-produced ionization on ground-wave propagation but with a more realistic ionization profile, one which had a steep gradient of ionization with altitude. He again found sizeable increases in ground-wave attenuation for large nuclear contamination. Using Johler's approach[3], it certainly would be possible to modify the path loss estimation method of Crain[1] to take into account ground-level ionization for appropriate nuclear fallout models. However, in this report we examine some other effects which increase the ground-wave attenuation of long waves. It has long been recognized that combinations of low ground conductivity and low ionospheric heights lead to very large attenuations in the earth-ionosphere waveguide. Pappert[4] analyzed the effects of ground conductivity variations on quasi-TE and quasi-TM waveguide modes excited by both vertical and horizontal dipoles. Calculations for ground conductivities ranging from 10 to 10^{-5} S/m showed that excitation factors drop rapidly with decreasing conductivity and that the dominant TM mode attenuation rates for 10^{-5} S/m ground conductivity were the order of 15–20 dB/Mm as opposed to a few dB/Mm for 10^{-3} S/m ground. The increased attenuation was much more severe in the daytime than at night. Field et al[5] demonstrated that theoretical computations of long-wave (elf/vlf/lf) path losses over ice during PCAs were consistent with experimental measurements of vlf transmissions over propagation paths crossing the Greenland ice cap. They also demonstrated that path losses measured in a scaled physical model waveguide gave qualitative substantiation of both the theory and vlf transmission measurements. Most important, they conclusively demonstrated that ionospheric depression over low conductivity ground (ice) produces path losses far in excess of those produced by the same ionospheric depression over sea water.

Westerlund et al[6] found that a depressed polar ionosphere from a proton precipitation event caused extreme attenuation of vlf waves passing over the Greenland ice cap. In a subsequent paper, Westerlund and Reder[7] demonstrated that the high attenuation of TM modes over ice is a function of ionospheric height, surface conductivity, and the dielectric constant of the ice. They also show that there is always a TM mode with eigenangles near the Brewster angle for conductivity less than about 10^{-4} S/m. They found good agreement between the theoretical models (using the NOSC waveguide program) and radio measurements.

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3. Johler, J.R. , Atmospheric Nuclear Disturbances with Respect to the Ground Wave, ESSA Research Laboratories Technical Memorandum, ERLTM-ITS 217, March 1970.
4. Pappert, R.A., Effects of Elevation and Ground Conductivity on Horizontal Dipole Excitation of the Earth-Ionosphere Waveguide, Radio Science, vol 5, pp 579–590, March 1980.
5. Field, E.C., C. Greifinger, and K. Schwartz, Transpolar Propagation of Long Radio Waves, R-683-DASA, DASA 2621, RAND Corporation, March 1971.
6. Westerlund, S., F.H. Reder, and C. Abom, Effects of Polar Cap Absorption Events on VLF Transmissions, Planetary and Space Science, 17, pp 1329–1374. 1969.
7. Westerlund, S., and F.H. Reder, VLF Radio Signals Propagating over the Greenland Ice-Sheet, Journal of Atmospheric and Terrestrial Physics, vol 35, pp 1475–1491, 1973.

In the following sections, we look more closely at the assumption that a surviving ground wave provides the minimum expected signal in a severely disturbed environment. We briefly discuss the ground-wave model and indicate weaknesses in the model for real environments. We compare diffraction mode and waveguide mode attenuation mechanisms as a function of ground conductivity, ionospheric height, and frequency. Curves showing total principal mode attenuation rates as a function of ionospheric height, radio frequency, and ground conductivity are compared with ground-wave attenuation rates to indicate the environmental conditions for which the ground wave represents a reasonable, an unreasonably low, or an unreasonably high estimate of the surviving signal in a disturbed environment.

2. THE GROUND WAVE

The contribution of ground-wave components to the total field is accounted for by both the waveguide mode and wave-hop theories of EM wave propagation in the earth-ionosphere waveguide. The mode theory includes all propagating field components within a set of self-consistent resonant modes; the ground wave is included implicitly. The wave-hop theory considers the total field at some position in the guide to be the sum of contributions arriving along rays connecting transmitter and receiver via (1) reflections off the earth and ionosphere and (2) the ground-wave field. The ground wave makes an explicit contribution and is calculated separately. It follows from the wave-hop theory that, if the ionosphere becomes so lossy that sky-wave contributions to the field are negligible, the ground-wave field would remain as the minimum expected signal. It should also follow that, under the same lossy conditions, fields calculated by using waveguide mode theory would also approach a minimum at the ground-wave signal level. That these assumptions can be incorrect, particularly under conditions of low ground conductivity, is evidenced by figure 1.

The curve in figure 1 is the locus of "reflection height" (H') and ground conductivity (σ) combinations which produce a waveguide mode attenuation rate at 20 kHz equal to the ground-wave attenuation rate for the same ground conductivity. All combinations of H' and σ below the curve produce waveguide attenuation rates greater than the ground-wave rate; all above the curve produce waveguide attenuation rates less than the ground-wave attenuation rate. The attenuation rates considered were for the principal waveguide and ground-wave modes and represent the total field attenuation rates well beyond the horizon.

The waveguide mode parameters here and throughout this report are for ionospheric profiles which are exponential in terms of the conductivity parameter ω_r where:

$$\omega_r(h) = \frac{\omega_p^2(h)}{\nu(h)} = 2.5 \times 10^5 \exp[\beta (h-H')]^{-1}, \qquad (1)$$

as given by Wait and Spies.[8] The circular plasma frequency ω_p is proportional to the square root of the electron density and ν is the electron-neutral collision frequency. The scale height β is in inverse kilometers; the altitude h and the "reflection height" H' are in kilometers. For all calculations, $\beta = 0.2515$ km $^{-1}$, taken to be representative of the weak conductivity gradients associated with the more lossy disturbed environments. The electron density profiles for several H's, along with the assumed electron collision frequency profile, are shown in figure 2.

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8 Wait, J.R., and K.P. Spies, Characteristics of the Earth-Ionosphere Waveguide for VLF Radio Waves, US Dept of Commerce, National Bureau of Standards, Technical Note 300.

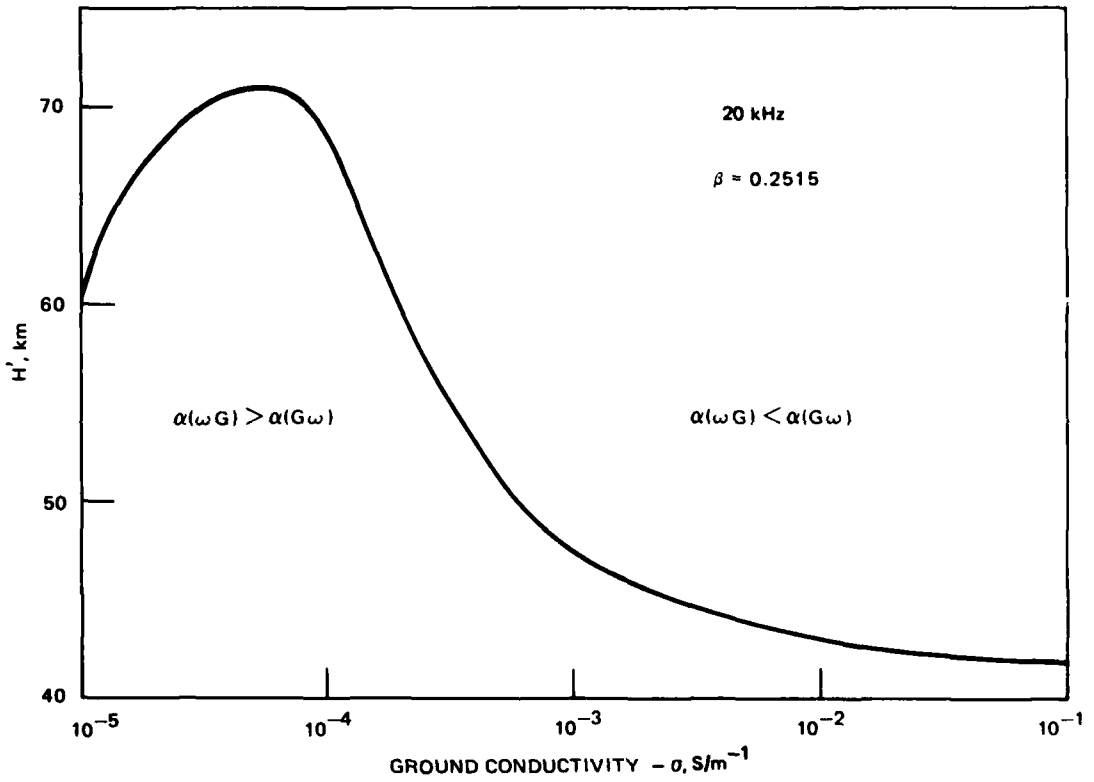

Figure 1. Locus of reflection height H′ and ground conductivity σ combinations which produce a principal TM waveguide mode attenuation rate α(WG) equal to the principal diffraction (ground-wave) attenuation rate α (GW) at 20 kHz.

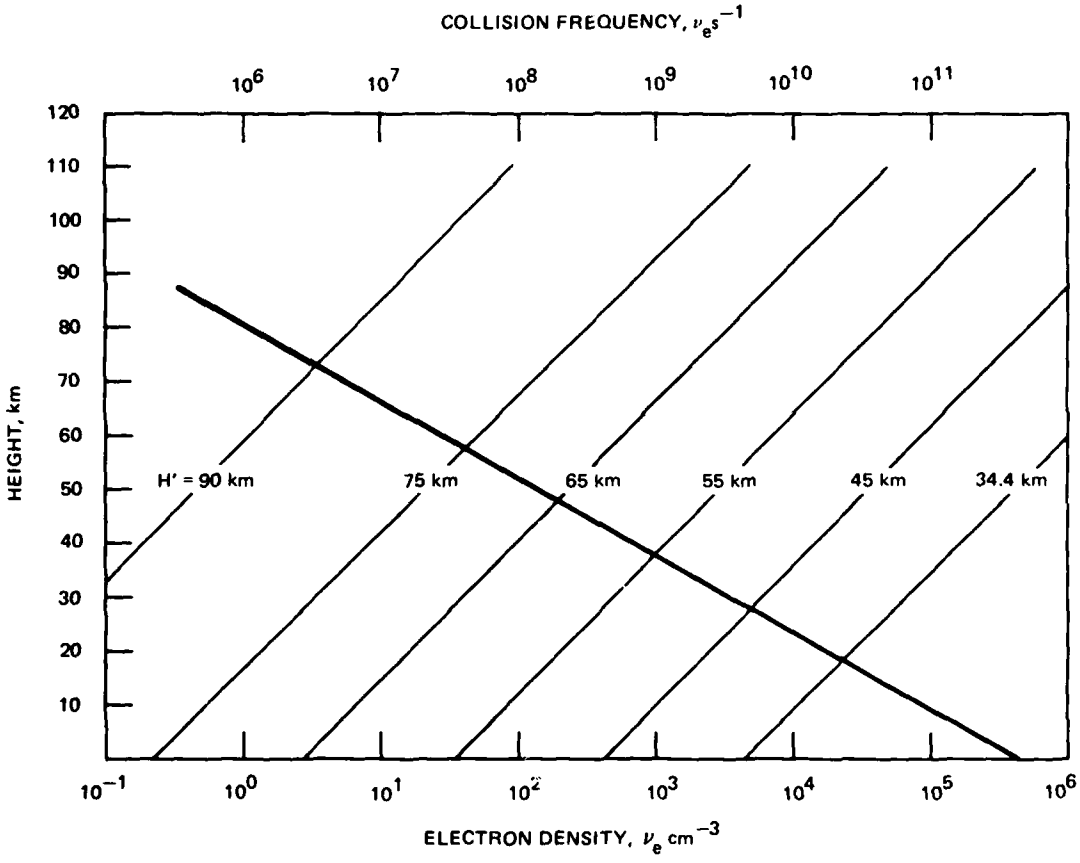

Figure 2. Electron collision frequency ν_e profile and electron density profiles consistent with ionospheric conductivity profiles given by $\omega_r(h) = 2.5 \times 10^5 \exp[\beta(h - H')]s^{-1}$ where $\beta = 0.2515$ km^{-1}.

One can better understand the discrepancy between earth-ionosphere waveguide and ground-wave computations of fields by examining the ground-wave model. For computation, the physical model of a spherical, finitely conductive earth surrounded by free space can be replaced by a planar earth of the same conductivity under a continuous refractive atmosphere. The gradient of refractive index is such that a horizontally launched ray has an upward curvature equal to the earth's curvature. The model is identical to that often used for earth-ionosphere waveguides for the free-space region below the ionosphere except that for the diffraction model the free-space region is infinite. It can be shown (Budden[9]) that, for certain complex angles of wave normals, upgoing waves are converted by an apparent reflection process into downgoing waves. At some angles of incidence, the downgoing waves are reflected from the earth and become indistinguishable from the original upgoing waves. These are, of course, the conditions for a set of self-consistent waveguide modes.

Near the ground, then, the diffraction modes consist of both upgoing and downgoing waves consistent with the modal condition. Yet at high altitudes only upgoing waves are allowed. This implies that something akin to reflection takes place at an intermediate height. The phase integral method, sometimes used as a first approximation for determining the modal solutions, involves the concept of a "complex reflection height", Z_o. Booker and Walkinshaw[10] have called the real part of Z_o the "track width". The track width or, equivalently, "duct height" gives some physical feel for the depth of free space above the ground required to satisfy the diffraction field computational model. Figure 3 shows the track width as a function of frequency for the zero, first, and second diffraction modes for a standard earth and perfectly reflecting ground.

For ground of finite conductivity, changes in earth reflectivity modify the modal conditions and consequently the track width. Figure 4 shows the track width for the zero-order mode as a function of radio frequency for ground conductivities ranging from 10^{-1} S/m to 10^{-5} S/m. The track widths for $\sigma = 10^{-1}$ S/m are nearly identical to those shown by the n = 0 curve of figure 3.

If the concept of "track width" has any real physical significance, it is clear that at frequencies below about 25 kHz, daytime ionospheres encroach on the free-space region required by the ground-wave model for other than the zero-order mode (figure 3). It is equally clear (figure 3) that for conductivities less than 10^{-3} S/m it takes but little ionospheric depression below normal to modify the refractivity of the ground-wave "duct" of the zero-order mode. The implication of these arguments is that, under conditions leading to complete loss of sky waves, the conditions assumed for the ground-wave computation are likely not satisfied. Thus the assumption that the ground-wave field represents the minimum possible signal may be incorrect for certain combinations of radio frequency, ground conductivity, and ionospheric height.

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9. Budden, K.G., The Waveguide Mode Theory of Wave Propagation, Logos Press, London, 1961.

10. Booker, H.G., and W. Walkinshaw, The Mode Theory of Tropospheric Refraction and its Relation to Wave-Guides and Diffraction, in Report: Meteorological Factors in Radio Wave Propagation, pp 80--127, London, Physical Society, 1946.

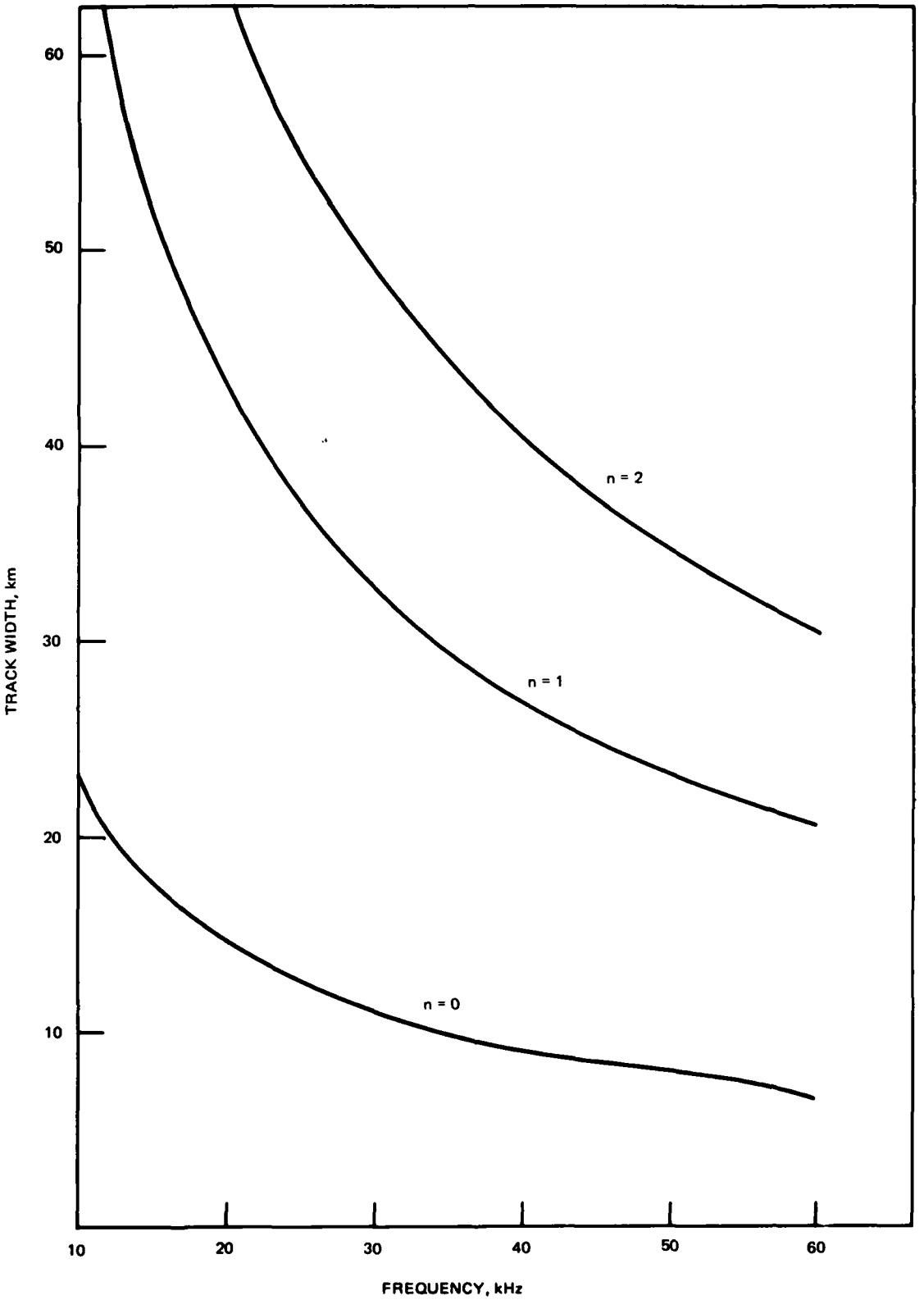

Figure 3. Track width as a function of frequency of the first three diffraction modes for propagation over a standard earth and perfectly reflecting ground.

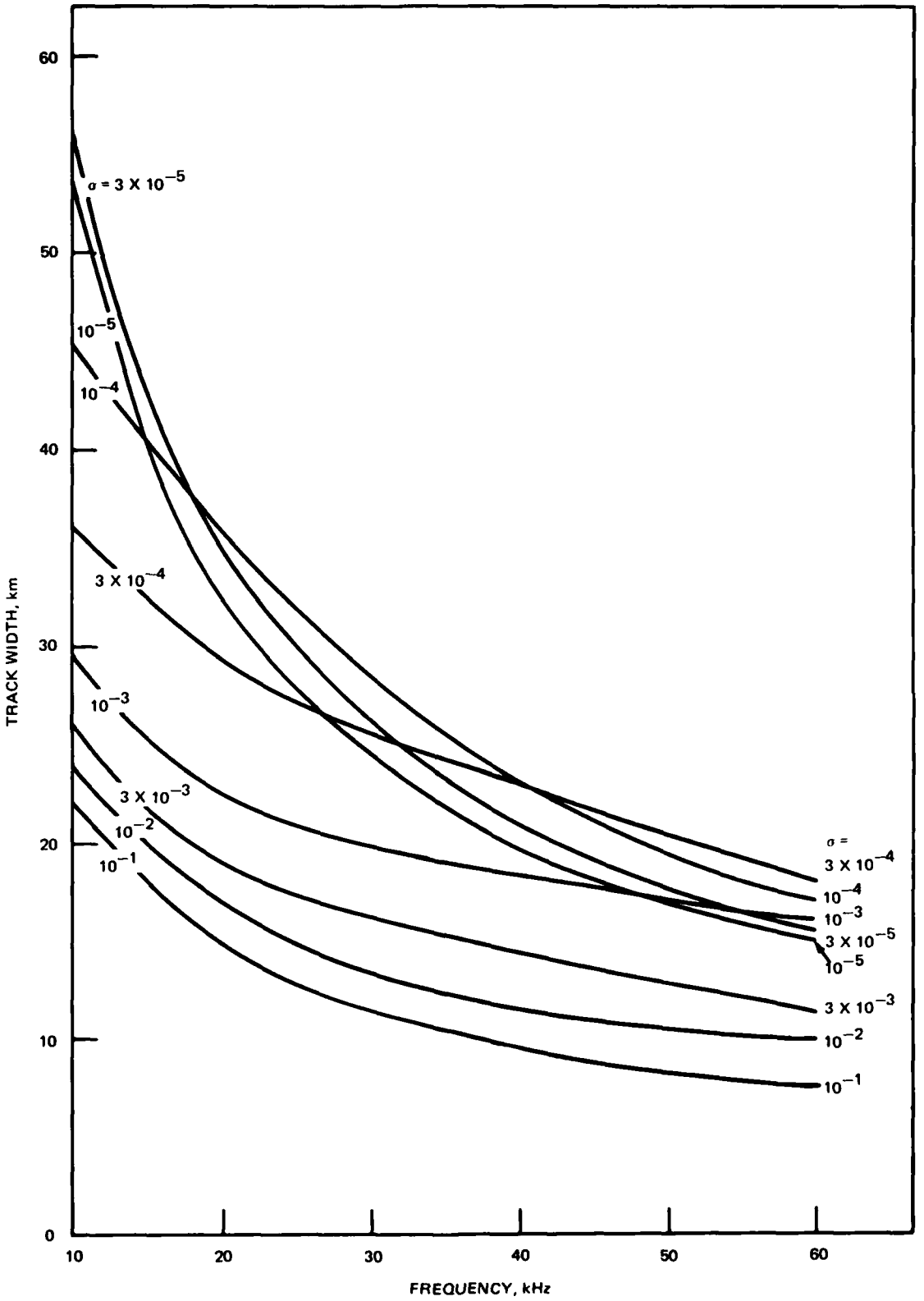

Figure 4. Track width of the zero-order diffraction mode as a function of frequency and of ground conductivity σ .

2.1 GROUND-WAVE ATTENUATION

Ground-wave fields lose energy by absorption in the earth and by leakage away into space. The total ground-wave attenuation rate can be calculated from its functional relationship with the diffraction mode eigenangle. Alternatively, it can be calculated directly from the field components at and above the earth's surface. Figures 5a–d show the attenuations due to ground absorption and to leakage, as well as their sum as a function of ground conductivity for 10-kHz, 20-kHz, 40-kHz, and 60-kHz ground waves, as calculated from the field components by taking the height of the guide equal to the track width.

The curves of attenuation due to ground absorption all show a steady increase with decreasing ground conductivity until they reach a broad maximum about some particular value of conductivity. At 20 kHz (figure 5b), attenuation by ground absorption is less than 1 dB/Mm at 10^{-1} S/m and increases to nearly 12 dB/Mm at 8×10^{-5} S/m before falling off to 9 dB/Mm at 10^{-5} S/m. At the same time, the attenuations resulting from leakage away from the earth show broad minima where the ground absorption losses maximize. In general, the leakage losses are the greater part of the total ground-wave attenuation except within a frequency-dependent band of surface conductivities. We will see later that the bulges of maximum ground absorption occur when the diffraction mode eigenangle is near the Brewster angle.

2.2 WAVEGUIDE MODE ATTENUATION

Waves propagating in the earth-ionosphere waveguide are attenuated by ohmic "heating" of the ground and of the lower ionosphere, and by leakage out of the guide along the geomagnetic field lines. Leakage losses are negligibly small during midday or when the ionosphere is overionized and depressed. Figures 6a–d show attenuation due to ground and ionospheric heating losses for the principal waveguide mode as a function of ground conductivity for several ionospheric heights (H') at 10, 20, 40, and 60 kHz, respectively. The total ground-wave attenuation rate is also included in each of the figures.

There are some striking differences in the attenuation due to ground heating between the ground-wave and waveguide modes. For both models, the attenuation from ground absorption has a broad maximum centered about those conductivities where the waveguide and diffraction mode eigenangles approach the surface complex Brewster angle. However, the waveguide modal eigenangles approach the Brewster angles at somewhat lower conductivities than do the diffraction mode eigenangles, particularly at the lower frequencies. The most important difference obviously results from the presence of an upper boundary of the waveguide. Lowering the ionosphere not only increases ionospheric absorption, but also greatly increases ground absorption. At the lower conductivities, even if the assumption were true that sky-wave absorption is identically equal to the ground-wave leakage losses, the enhanced ground losses under the depressed-ionosphere can materially exceed ground-wave surface absorption. In the next section we will, within the constraints of the model ionosphere show the conditions under which waveguide attenuation rates will exceed ground-wave attenuation rates.

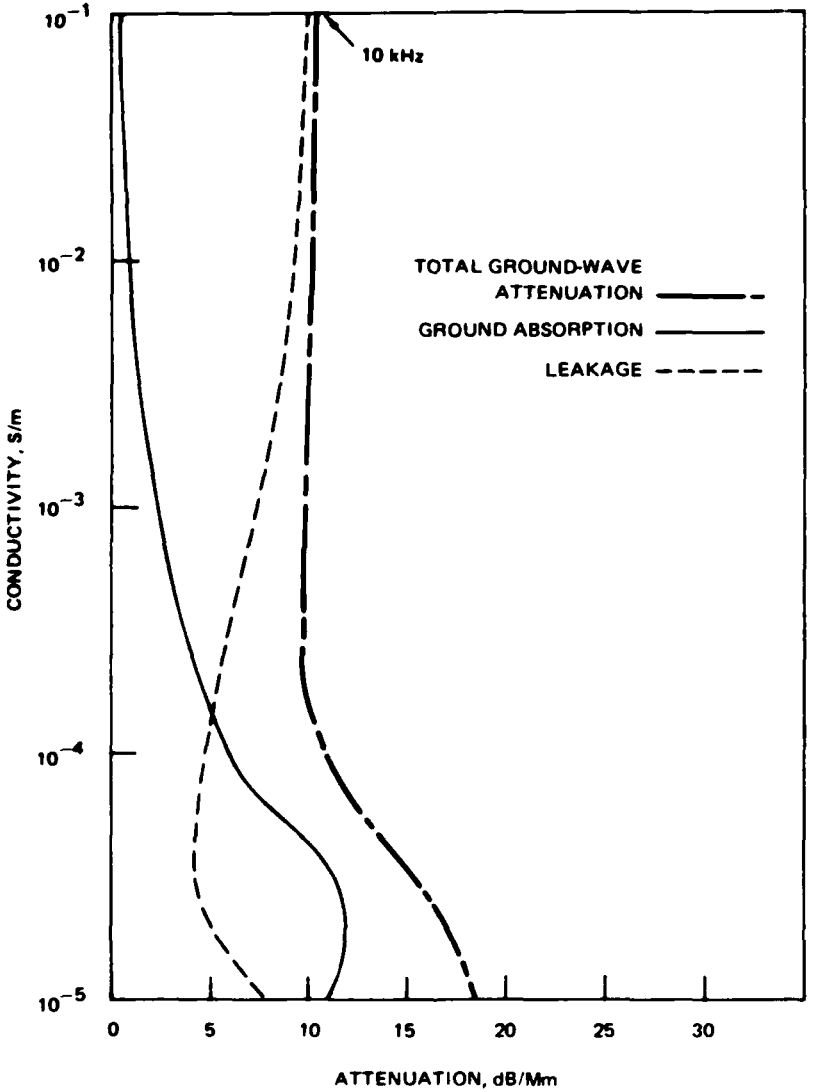

FIGURE 5a

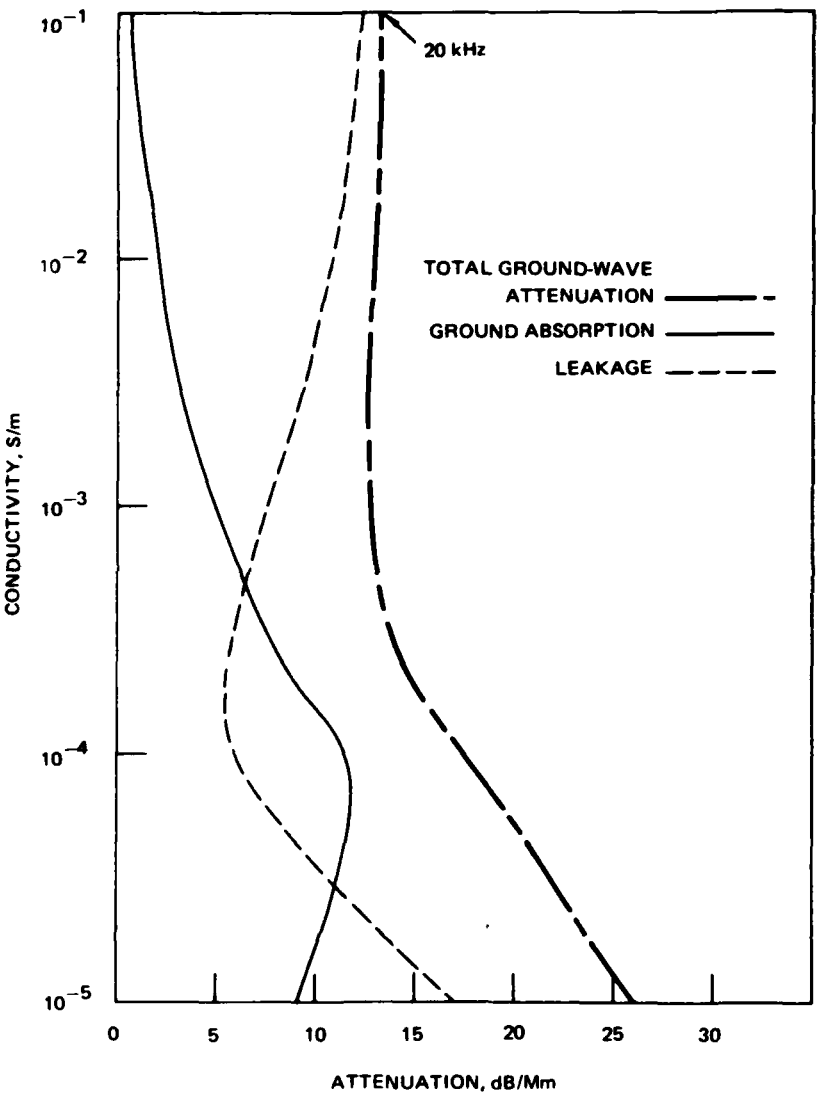

FIGURE 5b

Figure 5 a-d. Principal ground-wave mode attenuation rate as a function of ground conductivity for 10, 20, 40, and 60-kHz propagation. The solid curve is the attenuation resulting from ground absorption, the dashed curve is for attenuation resulting from leakage, and the broken curve shows the total attenuation.

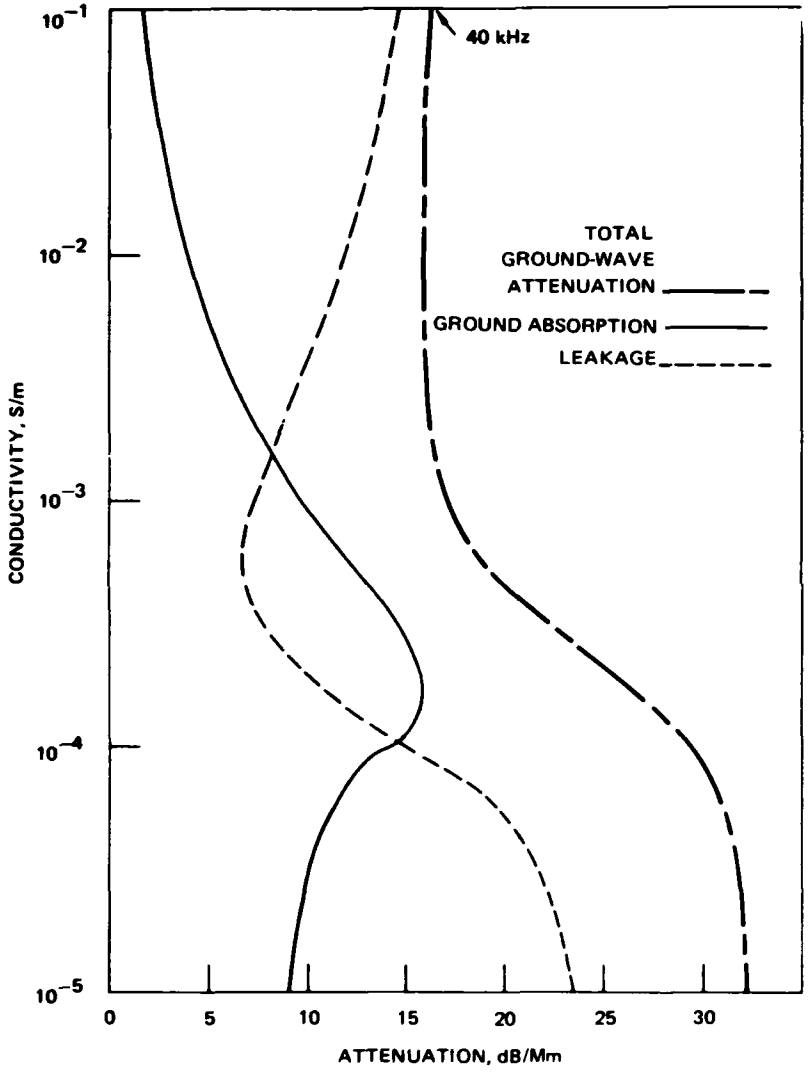

FIGURE 5c

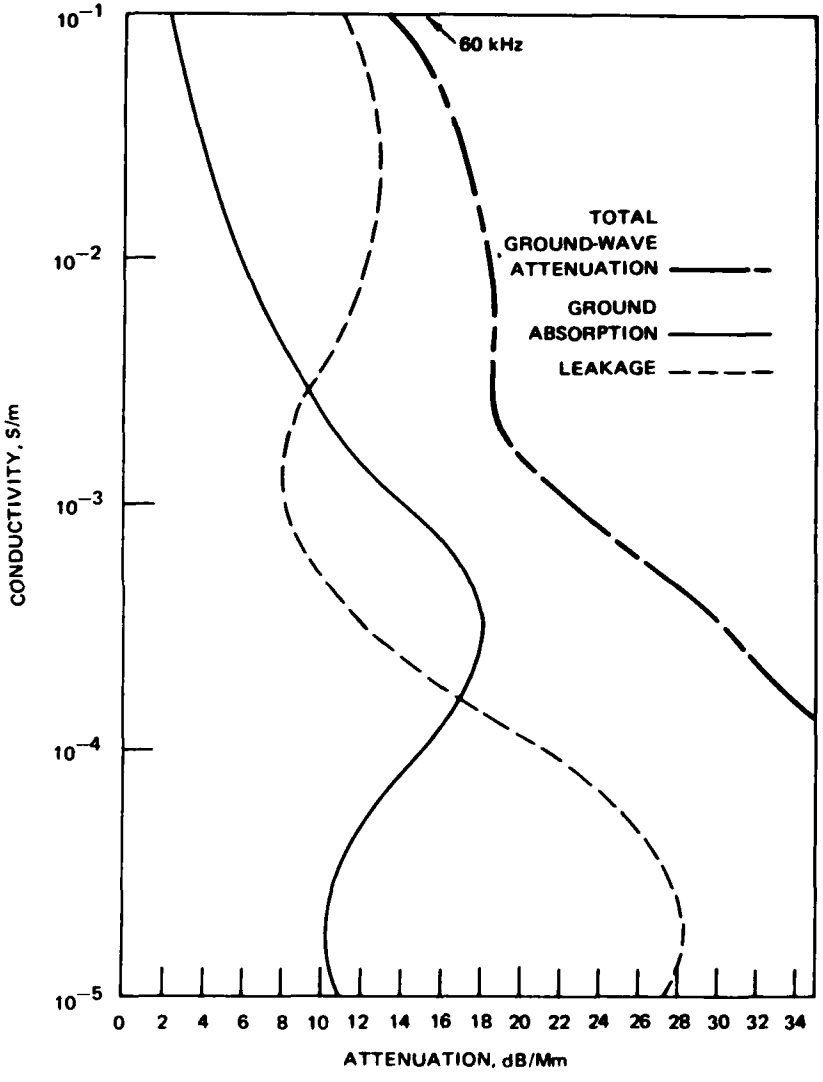

FIGURE 5d

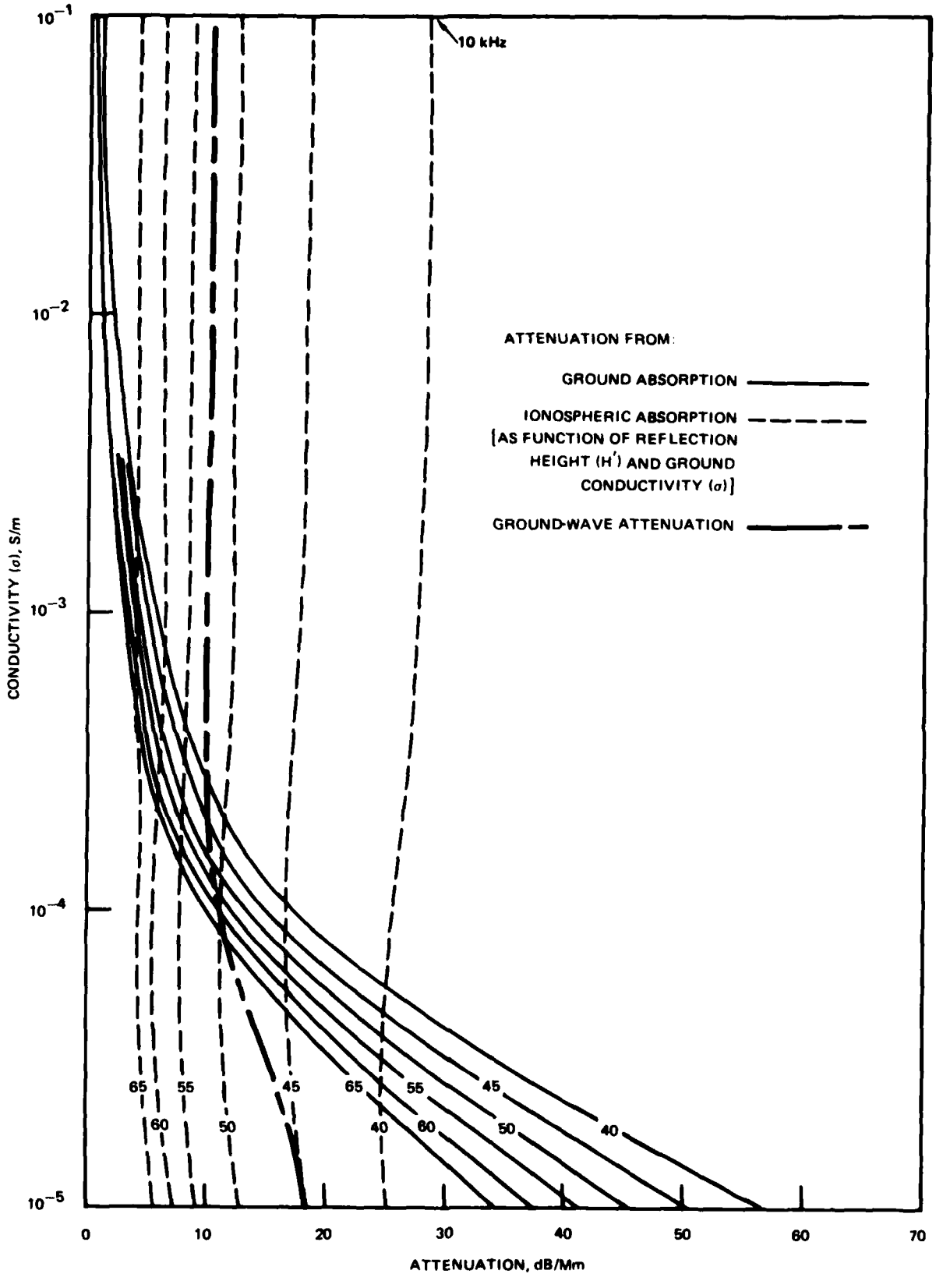

Figure 6 a-d. Attenuation rate of the principal waveguide mode resulting from ground absorption (solid curve) and resulting from ionospheric absorption (dashed curve) as a function of ground conductivity for a number of reflection heights H'. The broken curve is the ground-wave attenuation as a function of surface conductivity.

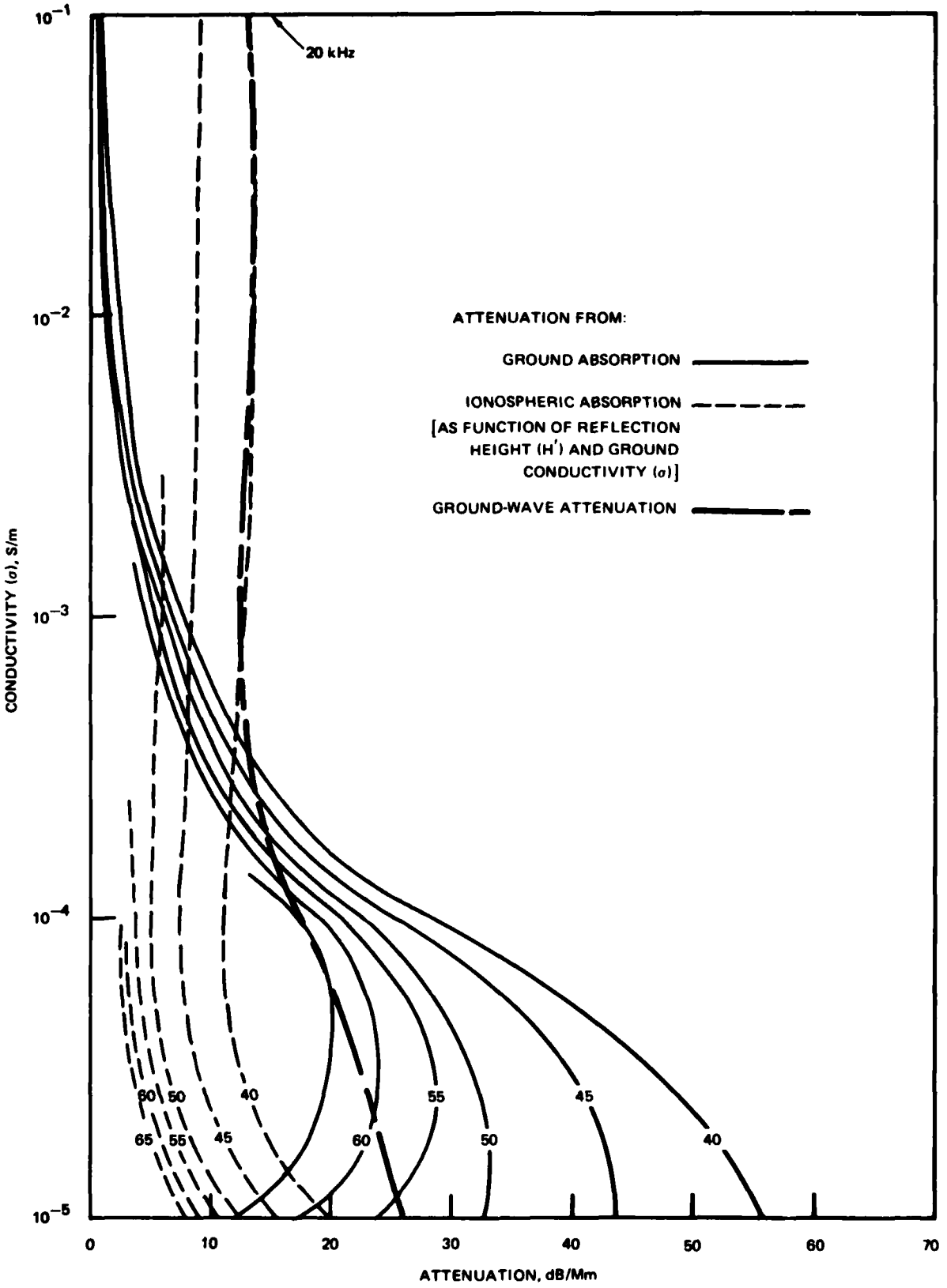
20 kHz
ATTENUATION FROM:
GROUND ABSORPTION
IONOSPHERIC ABSORPTION
[AS FUNCTION OF REFLECTION HEIGHT (H') AND GROUND CONDUCTIVITY (σ)]
GROUND-WAVE ATTENUATION
CONDUCTIVITY (σ), S/m
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0
10
20
30
40
50
60
70
ATTENUATION, dB/Mm
80
65
50
55
40
45
60
55
50
45
40

FIGURE 6b

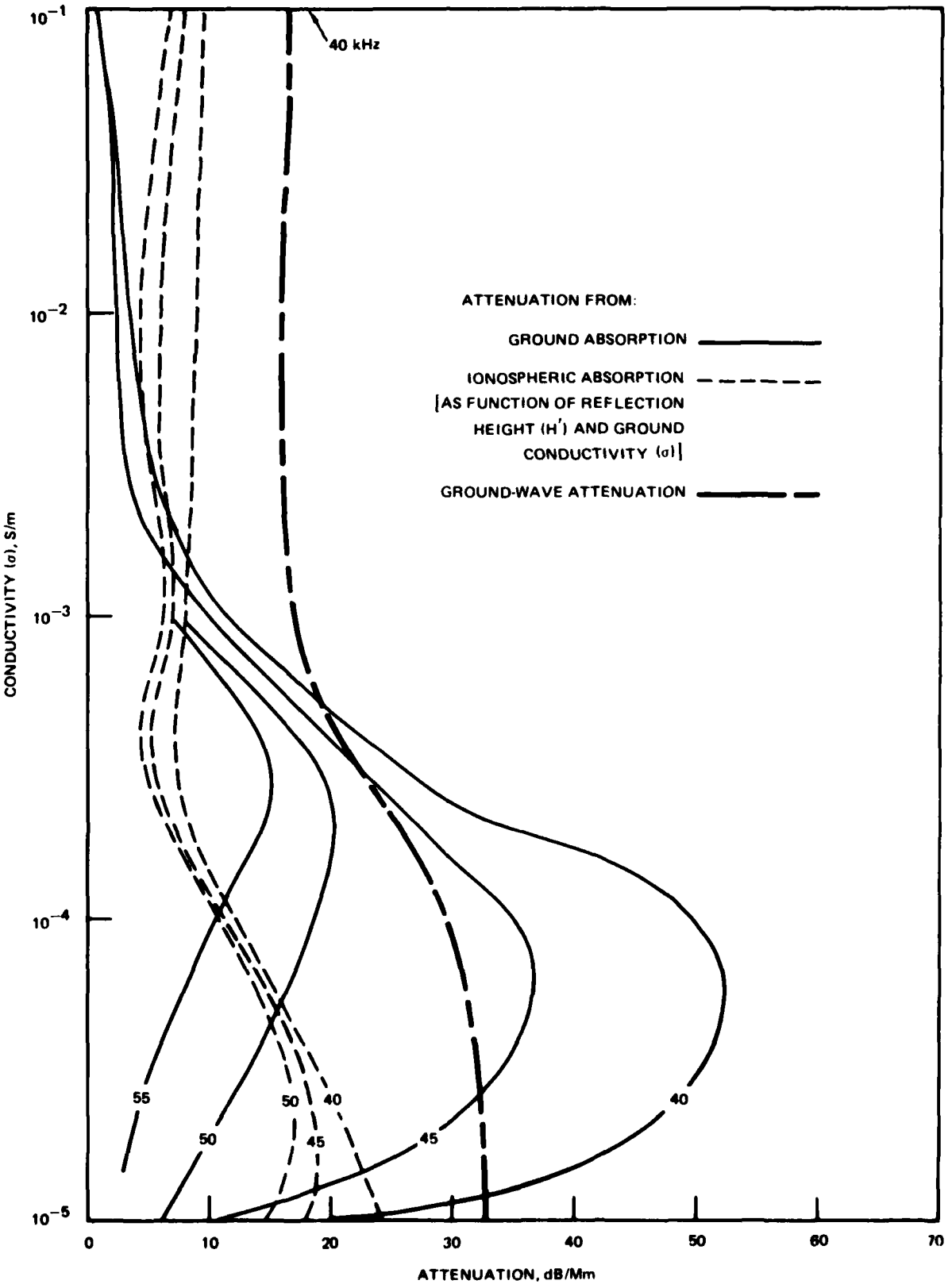
40 kHz
ATTENUATION FROM:
GROUND ABSORPTION
IONOSPHERIC ABSORPTION
[AS FUNCTION OF REFLECTION HEIGHT (H') AND GROUND CONDUCTIVITY (σ)]
GROUND-WAVE ATTENUATION
CONDUCTIVITY (σ), S/m
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
55
50
50
45
40
45
40
0
10
20
30
40
50
60
70
ATTENUATION, dB/Mm

FIGURE 6c

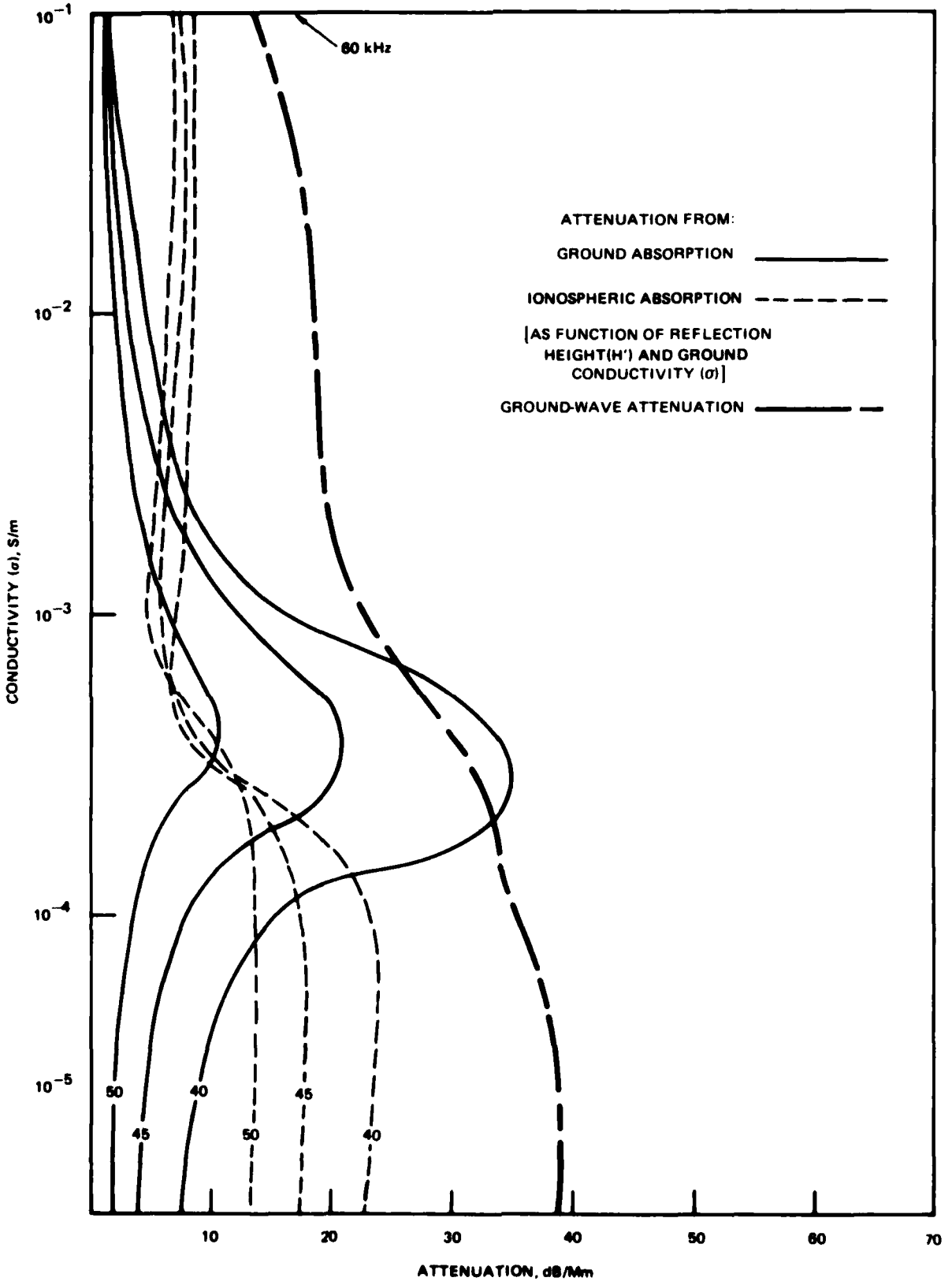
60 kHz
ATTENUATION FROM:
GROUND ABSORPTION
IONOSPHERIC ABSORPTION
[AS FUNCTION OF REFLECTION HEIGHT(H') AND GROUND CONDUCTIVITY (σ)]
GROUND-WAVE ATTENUATION
CONDUCTIVITY (σ), S/m
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
50
45
40
45
50
40
10
20
30
40
50
60
70
ATTENUATION, dB/Mm

FIGURE 6d

3. DISCUSSION OF RESULTS

3.1 COMPARISON OF WAVEGUIDE AND GROUND WAVE

Waveguide mode attenuation rates were calculated over the frequency band of 10 to 60 GHz by using the NOSC-developed "MODESRCH"[11] program. Ground-wave attenuation rates were calculated by using an adaptation of a computer program developed by Berry and Herman.[12] Both programs also were used to calculate attenuation rates for a number of ground conductivities, but the waveguide calculations were also parametric in terms of the "reflection height" for exponential ionospheric profiles. The results of the calculations are shown in figures 7a through 7g, where the curves in each figure are for a specific ground conductivity. The conductivities range from 10^{-1} S/m (figure 7a) to 10^{-5} S/m (figure 7g). The attenuation rate for a mode which is characterized by a complex eigenangle at the ground equal to the Brewster angle is given by the curve labeled θ_β.

Ionospheric anisotropy was included in the waveguide mode calculations. All results are for a dip angle of 51°, a magnetic flux density of 4.31×10^{-5} webers per square meter, and a geomagnetic azimuth of propagation of 58.5°. However, because most of the calculations are for depressed daytime ionospheres, the magnetic effects are negligible and the results are representative of isotropic ionospheres.

From figures 7a–g, it is clear that path losses under depressed ionospheres can materially exceed the theoretical ground-wave losses, particularly at the low end of the vlf-lf spectrum. However, for surface conductivities equal to or greater than about 10^{-3} S/m, the ionosphere must be extraordinarily depressed before waveguide attenuation rates exceed ground-wave rates, particularly at lf.

At conductivities below 10^{-3} S/m, the waveguide attenuation rates begin to exceed ground-wave rates for moderately depressed ionospheres. In the 3×10^{-4} to 10^{-4} S/m conductivity range, the phenomenon pointed out by Westerlund and Reder[7] becomes evident. That is, the maximum attenuation across the frequency band is closely associated with the modal eigenangles near the Brewster angle.

The data described by figures 7a–g are summarized from a different perspective in figure 8, where those combinations of reflection height H′ and surface conductivity σ, which lie above each frequency curve, produce a smaller attenuation rate for the principal TM mode than the ground wave. For combinations of H′ and σ lying below each frequency curve, the principal earth-ionosphere waveguide mode attenuation rate is greater than that of the ground wave.

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11. Morfitt, D.G., and C.H. Shellman, 'MODESRCH', an Improved Computer Program for Obtaining ELF/VLF/LF Mode Constants in an Earth-Ionosphere Waveguide, Naval Electronics Laboratory Center Interim Report No. 77T for DNA, 1 October 1976.

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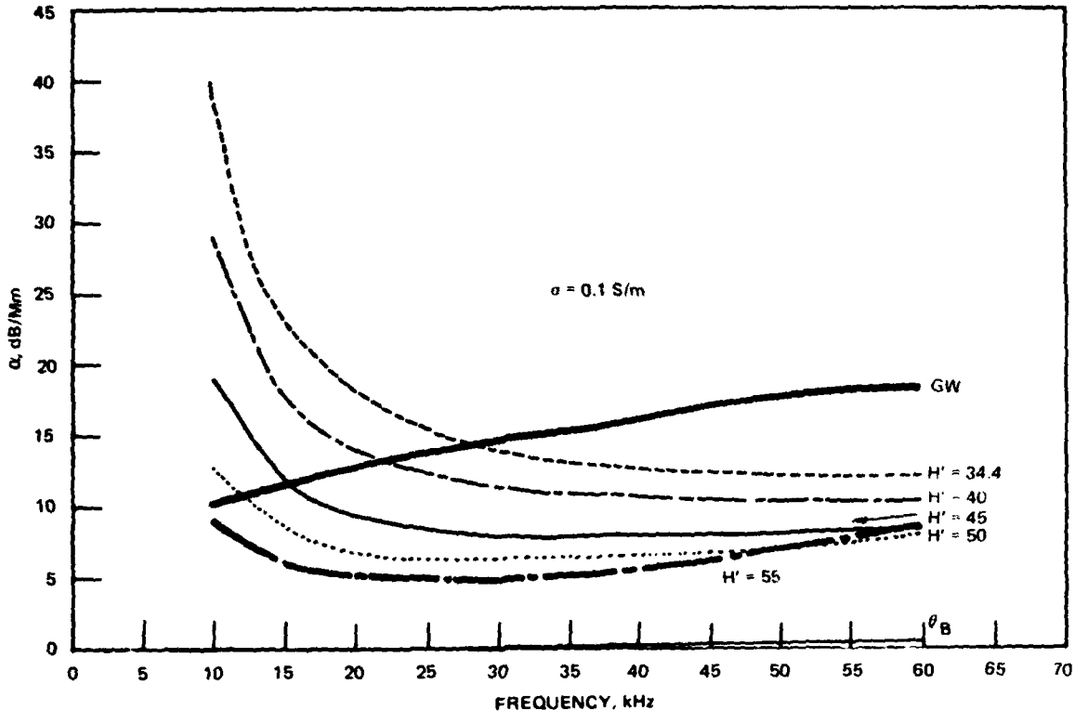

FIGURE 7a

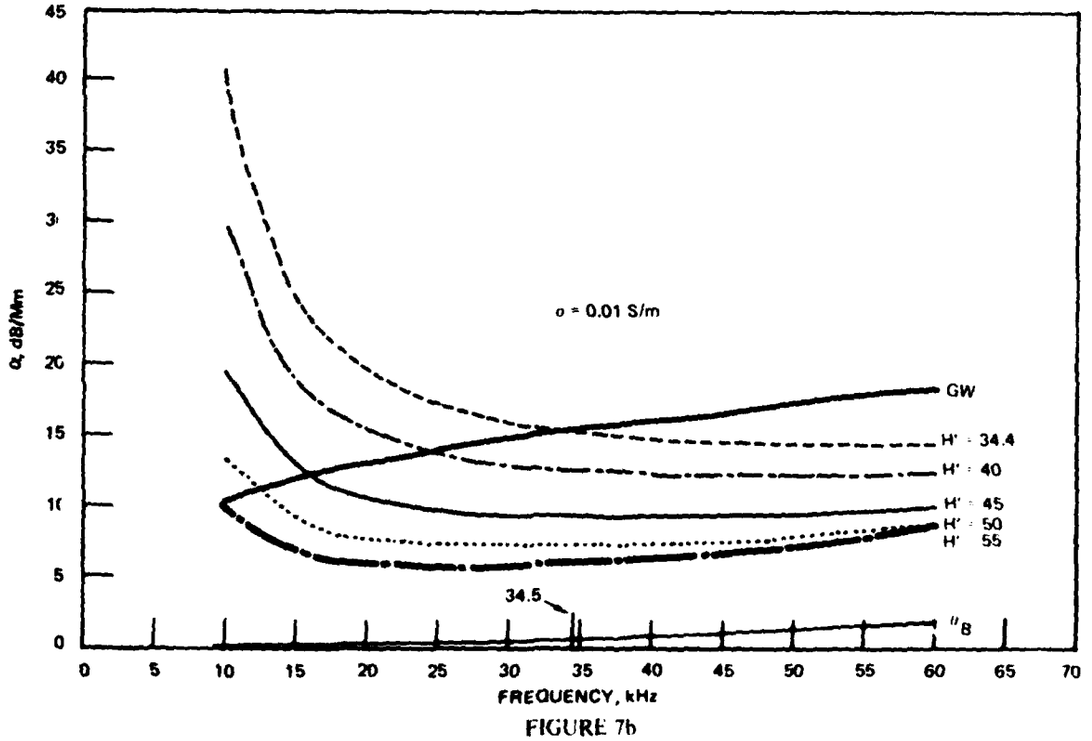

FIGURE 7b

Figure 7 a-g. Attenuation rate of the principal waveguide mode as a function of frequency for a number of reflection heights H' and for the ground conductivity σ specified on each figure. The ground-wave attenuation rate (curve GW) and the attenuation rate of a mode characterized by eigenangles equal to the complex Brewster angle (curve θ_B) are also shown for each ground conductivity.

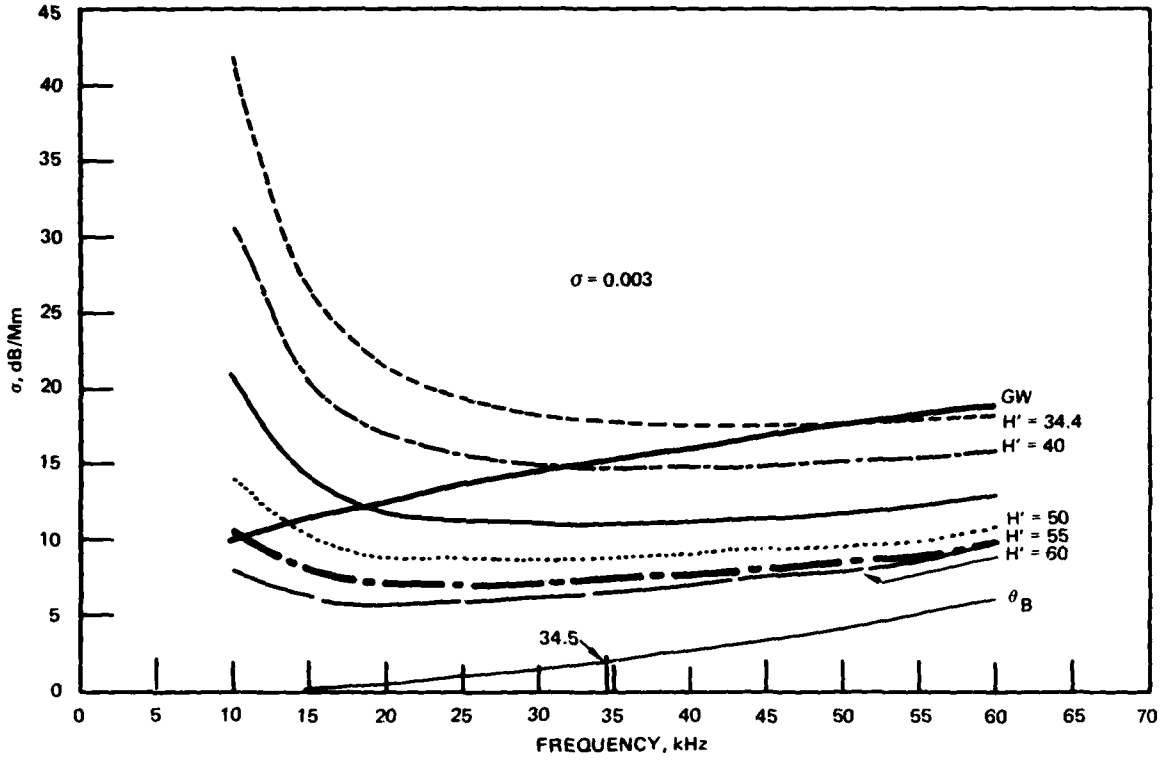

FIGURE 7c

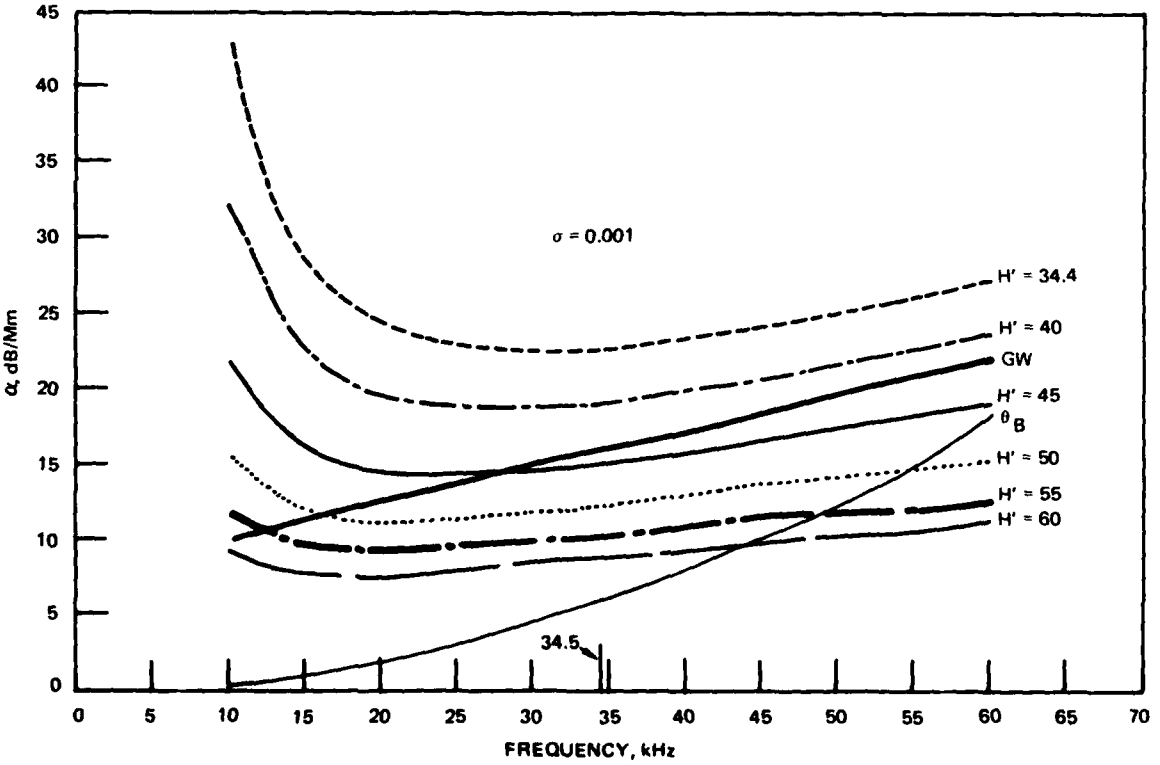

FIGURE 7d

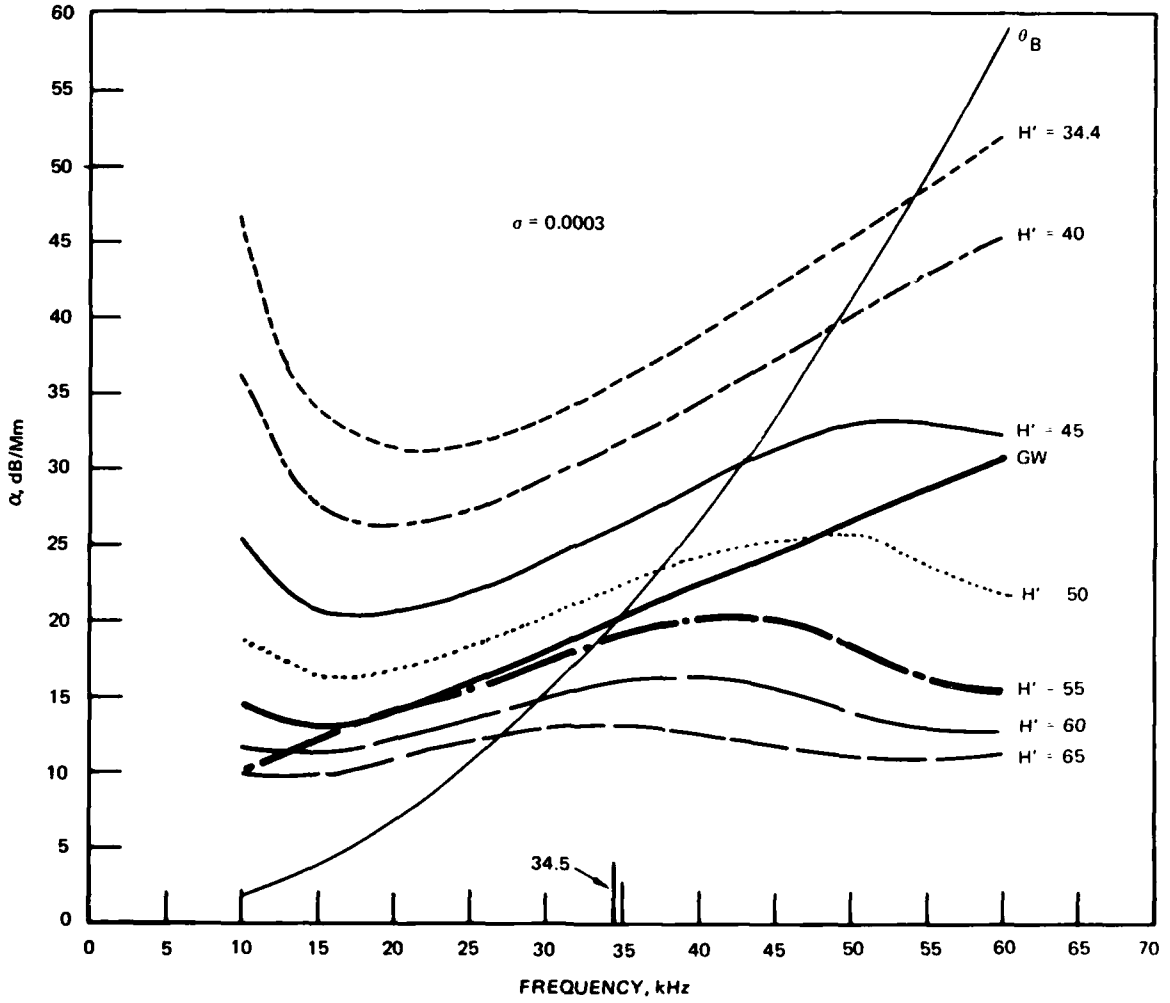
α, dB/Mm
FREQUENCY, kHz
σ = 0.0003
θB
H' = 34.4
H' = 40
H' = 45
GW
H' 50
H' = 55
H' = 60
H' = 65
34.5
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70

FIGURE 7e

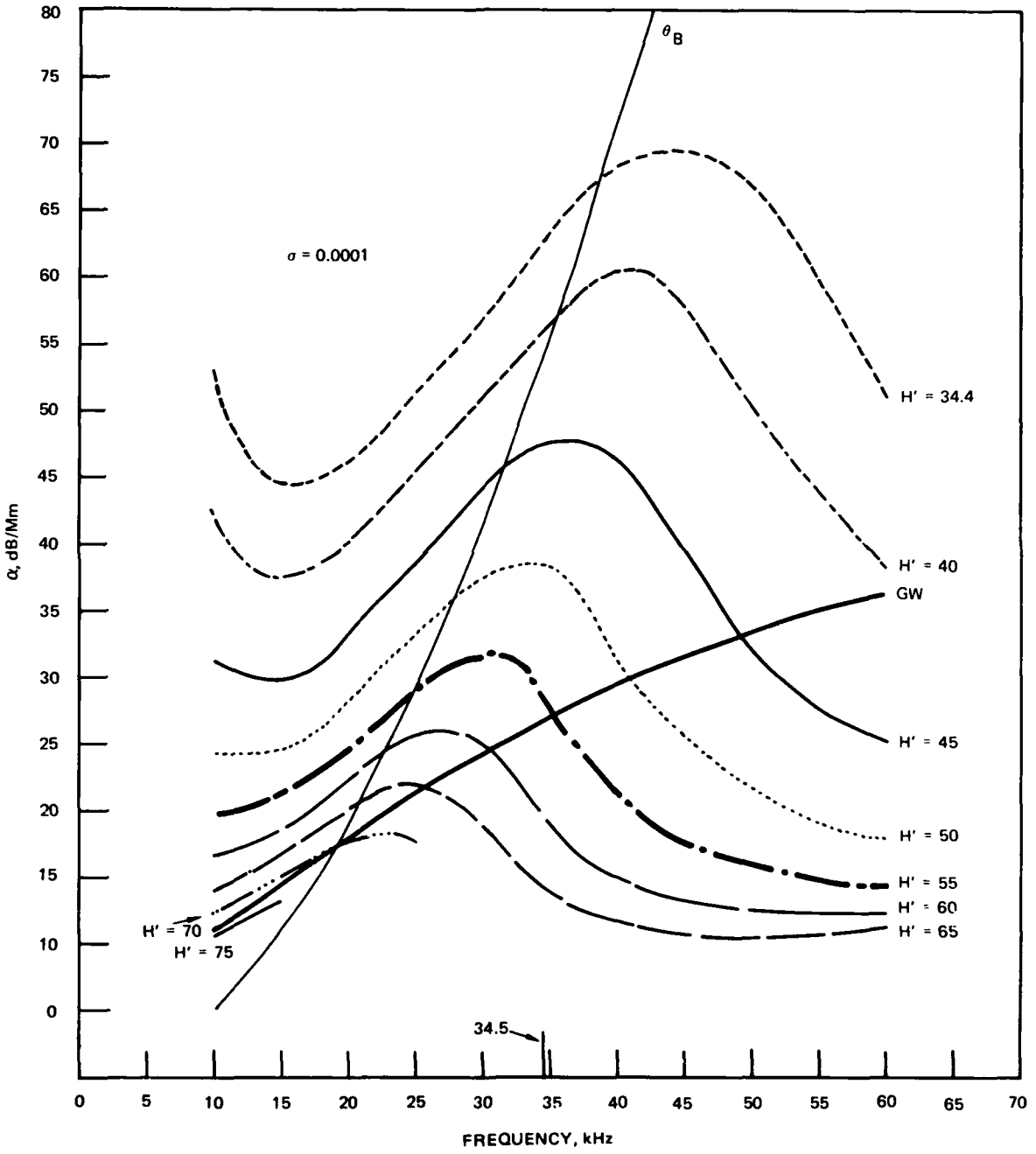
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
0
α, dB/Mm
θB
σ = 0.0001
H' = 34.4
H' = 40
GW
H' = 45
H' = 50
H' = 55
H' = 60
H' = 65
H' = 70
H' = 75
34.5
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
FREQUENCY, kHz

FIGURE 7f

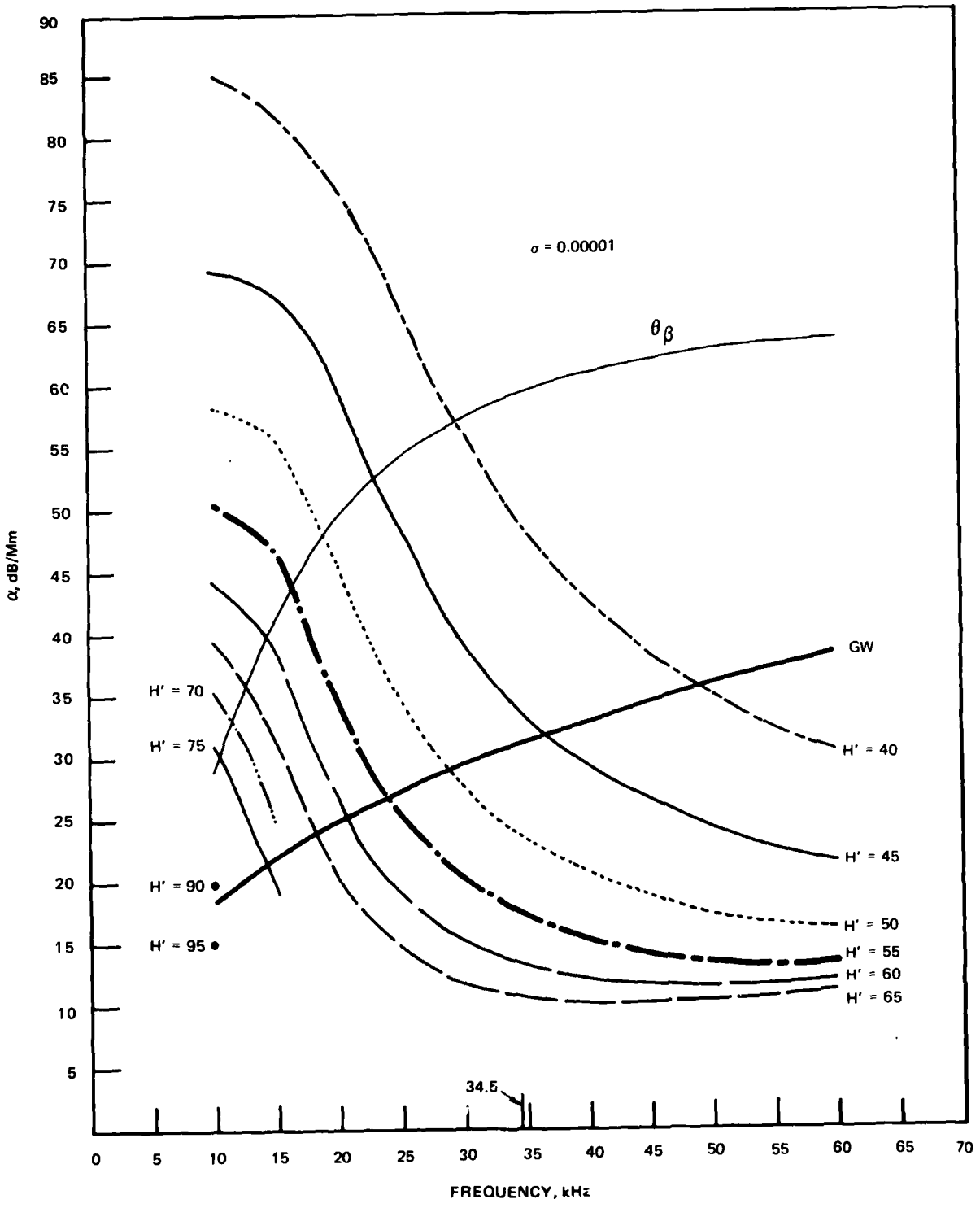
α, dB/Mm
FREQUENCY, kHz
σ = 0.00001
θβ
GW
H' = 70
H' = 75
H' = 90
H' = 95
H' = 40
H' = 45
H' = 50
H' = 55
H' = 60
H' = 65
34.5

FIGURE 7g

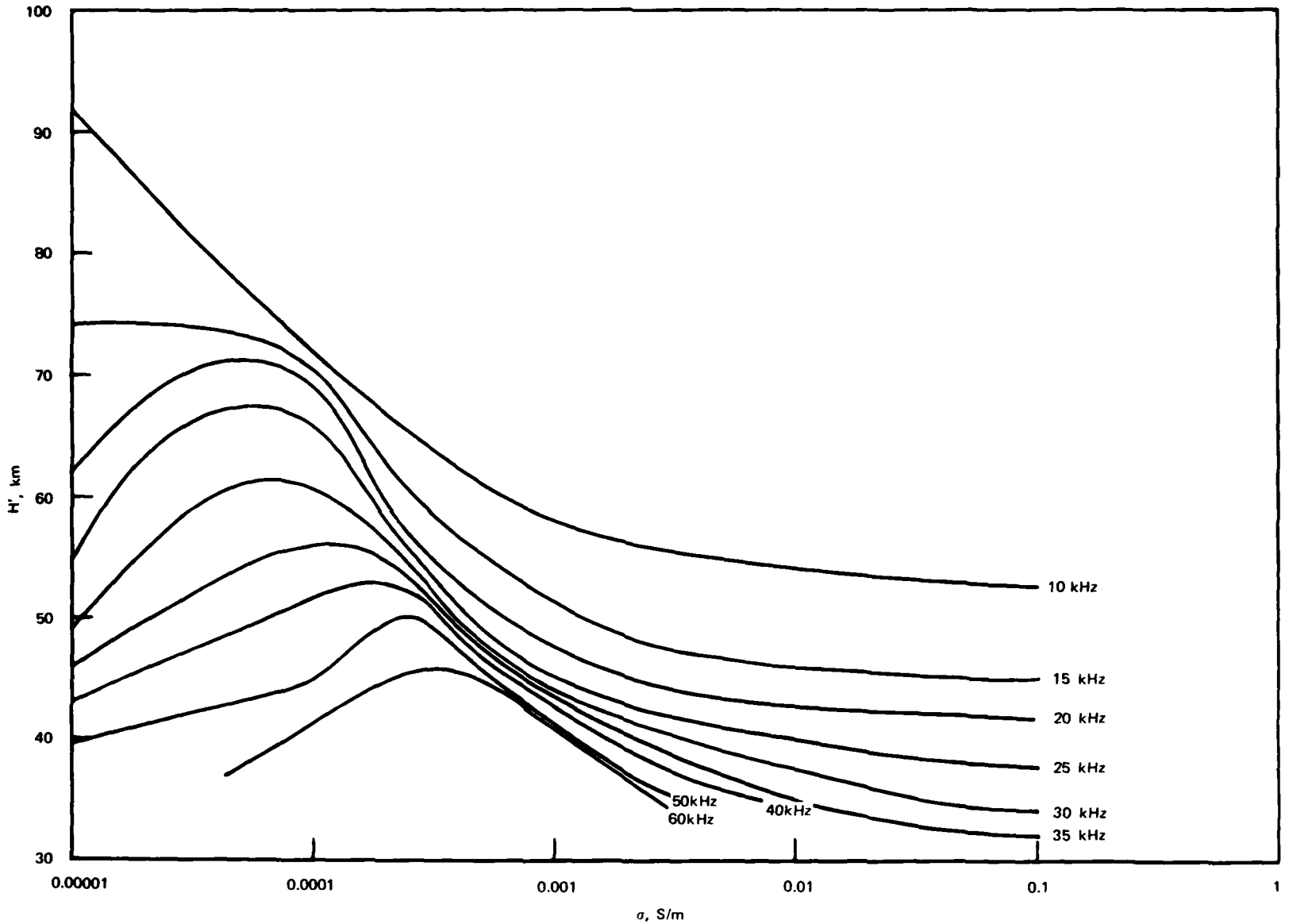

Figure 8. Combinations of reflection height H′ and surface conductivity σ which produce a principal TM waveguide mode attenuation rate equal to the ground-wave attenuation rate. For those combinations of H′ and σ lying above each of the frequency curves, the TM waveguide mode attenuation is less than the ground-wave attenuation rate for that frequency and ground conductivity. For combinations below the curve, the TM mode attenuation rate is greater than the ground-wave attenuation rate.

For the particular ionospheric conductivity gradient β used for this study and for ground conductivity σ less than about 10^{-3} S/m, ionospheric depressions typical of polar cap events or nuclear disturbances can produce path losses greater than ground-wave path losses. Although the conductivity gradient $\beta = 0.2515$ km^{-1} was selected after an examination of a number of conductivity profiles for variously disturbed ionospheres, it should be pointed out that the model becomes less appropriate for the more normal reflection heights. For example, figure 7g shows waveguide mode attenuation rates at 10 kHz for reflection heights up to 95 km. From the data, one deduces that for 10^{-5} S/m ground conductivity and reflection heights below 90 km, waveguide path losses exceed ground-wave path losses. But it is hard to imagine the circumstances which would produce a scale height $\beta = 0.2515$ km^{-1} for altitudes much greater than 70 km. Thus the results shown in figures 7 and 8 are most useful for locating possible problem areas but not their precise boundaries.

4. CONCLUSIONS AND RECOMMENDATIONS

The assumption that lf communications systems designed to operate at ground-wave signal levels will maintain connectivity in a severe nuclear environment is safe only for propagation over relatively highly conductive ground. At the lower vlf frequencies, the assumption is never safe. Lf systems designed to operate on ground-wave propagation over highly conductive ground should have a considerable system margin. For lf propagation over poorly conducting ground or fresh water ice, losses may considerably exceed ground-wave losses when the ionosphere is moderately depressed.

When the DNA working group recommended that lf systems be designed on the basis of a surviving ground wave, it was recognized that methods for calculating lf propagation and the propagation environment were inadequate. Today, although we still have questions regarding some of the air chemistry, there is little doubt that severe disturbances can be modeled with good confidence. In addition, we no longer rely on "wave-hop" methods (with the attendant inaccuracies for severely disturbed ionospheres) for calculating lf propagation parameters. Waveguide mode propagation prediction methods work well to at least 100 kHz. Because of the possible errors and misconceptions which may arise from using the ground-wave computation for estimating lf coverage in severely disturbed environments, it seems far safer to do a complete propagation analysis of coverage by means of numerical methods based on waveguide mode theory.

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