R-558-PR

November 1970

TRANSMISSION OF ELECTROMAGNETIC WAVES THROUGH NORMAL AND DISTURBED IONOSPHERES

H. G. Booker, C. M. Crain and E. C. Field

A Report prepared for

UNITED STATES AIR FORCE PROJECT RAND

Rand
SANTA MONICA, CA. 90406

This research is supported by the United States Air Force under Project Rand—Contract No. F44620-67-C-0045—Monitored by the Directorate of Operational Requirements and Development Plans, Deputy Chief of Staff, Research and Development, Hq USAF. Views or conclusions contained in this study should not be interpreted as representing the official opinion or policy of Rand or of the United States Air Force.

R-558-PR

November 1970

TRANSMISSION OF ELECTROMAGNETIC WAVES THROUGH NORMAL AND DISTURBED IONOSPHERES

H. G. Booker, C. M. Crain and E. C. Field

A Report prepared for

UNITED STATES AIR FORCE PROJECT RAND

Rand
SANTA MONICA, CA 90406

Published by The RAND Corporation

PREFACE

This report is part of Rand's continuing study of the effects of abnormally ionized atmospheres, such as those produced by nuclear bursts, on the propagation of radio waves and on military radio communication systems, present and future. As a tool useful for providing answers to many problems arising in such studies, we have developed a general computer program which could be applied over a wide range of frequencies (typically 10^{-3} to 10^{10} Hz) for any specified vertical ionization structure of the atmosphere. Both electrons and positive and negative ions are included in the program. For specified frequencies, angle of wave incidence on the ionosphere, and ionization profiles the program provides the real and imaginary components of the complex refractive index at all heights, the local wavelength of the signal, the differential absorption at all heights, and the reflection and transmission parameters for the nonpenetrating and penetrating signal components, respectively. The program provides results for either quasi-longitudinal or quasi-transverse conditions of transmission.

The program is developed from a ray-theory approach and as such has certain restrictions and accuracy limitations, in particular at the lower frequencies used. Despite such limitations the program is a very versatile tool for obtaining results which can be applied to practical assessment of many problems in radio transmission, both for earth-to-earth and earth-to-space radio links, and for ambient or arbitrarily disturbed ionospheres.

A description of the equations and models used, and a detailed discussion of the approximations and range of validity of the analysis, are given in a companion report, R-559-PR, *A Panoramic View of Ionospheric Reflection and Transmission Under Ambient and Disturbed Conditions*. Also given there are some numerical results and diagrams which are useful for purposes of interpretation and general background. The reader who desires a fairly detailed description of ionospheric transmission and reflection processes is thus referred to the companion report; however, the material herein is presented in a self-contained manner and can be read independently.

Henry G. Booker is Chairman of the Department of Applied Physics and Information Science at the University of California, San Diego and is a consultant to The Rand Corporation.

SUMMARY

This report, which is responsive to current interest in earth-satellite transmission in the LF/VLF/ELF ranges, presents selected results of an analysis of the transmission of electromagnetic waves through the atmosphere. Calculations of expected total transmission attenuation are presented on earth-to-satellite paths for an ambient and a nominally disturbed ionosphere under both day and night conditions for frequencies from 10^{-3} to 10^{10} Hz. Height profiles of attenuation are given for frequencies of 1 Hz to 100 kHz.

Results show that under ambient conditions and for quasi-longitudinal propagation, the ionosphere is relatively transparent to electromagnetic waves having frequencies lower than about 10 kHz. For certain classes of artificially or naturally disturbed ionospheres, frequencies lower than a few tens of Hz must be used if less than 30-dB transmission loss is to be suffered.

Another possible scheme for a working system would be to use several satellites configured so as to maximize the probability that at least one satellite is transmitting under undisturbed ionospheric conditions, and reliance is thus placed upon part of the propagation path being in the earth ionosphere cavity.

CONTENTS

I. INTRODUCTION

In this report we will present the results of an analysis of the transmission of electromagnetic waves through the ionosphere. The objective of the calculations is to provide estimates of the propagation losses to be expected on communication links between satellites and the ground. A wide range of frequencies, 10^{-3} to 10^{10} Hz, is considered, and normal and disturbed nighttime and daytime conditions are analyzed. The models and computational methods are summarized briefly in Section II, extensive numerical results for the total transmission loss and height dependence of ionospheric attenuation are presented in Section III, and the conclusions are given in Section IV.

A description of the equations and models used and of ionospheric transmission and reflection processes is given in Ref. 1.

II. MODEL IONOSPHERES AND COMPUTATIONAL METHODS

Calculations were made for four profiles of electron and ion density identified in Fig. 1 as ambient night (AN), ambient day (AD), disturbed night (DN), and disturbed day (DD). The first two are nominal models of the undisturbed ionosphere and are representative of models in current use. The disturbed night and disturbed day models represent either a mild nuclear environment or a very strong polar cap absorption event. The ion and electron collision frequency profiles used are essentially as given by Ginzburg,[(2)] a mass number of 29 was assumed for the ions, and the ground-level electron gyrofrequency was taken as 1.7×10^6 Hz.

The major approximation is the use of WKB methods to compute the transmission loss. This, of course, neglects the effects of gradient reflection, thereby underestimating the transmission loss on a given link. Gradient reflection should be significant only when the wavelength *in the ionosphere* is comparable with or larger than the characteristic distance over which the medium changes substantially, i.e., a few kilometers. For frequencies above, say, 1 kHz, the transmission curves to be given should provide quite reliable estimates. However, as the frequency is lowered much below 100 Hz, the curves should be taken as order-of-magnitude lower bounds on the transmission loss. Also, phenomena such as the well-known transmission resonances associated with geomagnetic micropulsation (frequency $\lesssim$ 1 Hz) cannot be predicted without recourse to full-wave solutions. Rand has, in fact, run full-wave solutions to spot check some of the results to be given presently and, even for frequencies as low as a few Hz, the agreement was found to be better than within an order of magnitude.

The calculations have been done for waves travelling vertically, (i.e., for waves having vertical propagation vectors) and for waves having propagation vectors at an angle of 80 deg with respect to the vertical at the base of the ionosphere. For the 80-deg case, the effects of glancing incidence were accounted for in a very approximate manner. The corresponding results therefore should be taken only as an indication of when incidence angle matters and of roughly how much.

The geomagnetic field was taken to be vertical, and longitudinal propagation was assumed. Strictly speaking, this limits the analysis to polar regions, although as a practical matter quasi-longitudinal (QL) propagation obtains even at temperature latitudes at the ionospheric heights at which most of the absorption occurs. At and below LF the group velocity (the ray) can be in a very different direction from the phase velocity (the wave normal). In fact, in the absence of collisional effects, the ray path tends to be more or less along the geomagnetic field line which, at mid-latitudes, is distinctly nonvertical. On the other hand, the large ionospheric refractive index at low frequencies implies that waves having real and allowable *phase* propagaton directions below the ionosphere must have a vertical or nearly vertical wave normal in all but the lowest ionosphere. Thus our QL results obtained by vertical or nearly vertical integration should apply reasonably well to many practical mid-latitude situations.[1] We have also run calculations for vertical equatorial propagation, whence the geomagnetic field is transverse to the direction of propagation. These results will not be given in detail here. We note, however, that the transmission losses for transverse propagation tend to be (at VLF/ELF) much more severe than for longitudinal propagation.

The earth's curvature has been neglected in the calculations as has the curvature of the geomagnetic field lines. The height-dependent strength of the geomagnetic field has been included, however.

III. NUMERICAL RESULTS

The computed transmission losses in decibels are plotted versus frequency in Figs. 2 to 9. Results are shown for four model ionospheres and the two propagation modes, 0 (left-hand polarized) and X (right-hand polarized). Two incidence (or emergence) angles, 0 and 80 deg, are also shown for those cases where the loss difference between the two is of any consequence. The curves show the total loss incurred between a height of 1000 km and the base of the ionosphere. However, in all cases where the losses are small enough that a mode is of practical interest, almost all of the absorption occurs below about 200 km at ELF and below about 100 km at VLF. Thus, for reasonable ELF/VLF communication links, Figs. 2 to 9 are applicable, provided the satellite is above about 200 km (for ELF) and 100 km (for VLF).

For the ambient night and day cases, the 0 mode has two pass bands. One is the hydromagnetic band below the ion gyrofrequency (i.e., below a few tens of Hz) and the other is above the critical frequency, appropriately interpreted in the case of nonvertical incidence. Thus, for frequencies between a few or a few tens of Hz and several MHz, the 0 mode does not penetrate the ionosphere. For the X mode, there is again an upper transmission band above the critical frequency, namely, above 5 to 10 MHz. However, the low-frequency transmission band extends into the whistler range, reaching about 1 MHz at night and nearly 10 kHz in the daytime. Thus, the entire ELF/VLF spectrum is readily transmitted through the normal nighttime ionosphere, as are the ELF and lower VLF bands through the normal daytime ionosphere.

As seen in Figs. 6 to 9, the transmission losses are much more severe for the disturbed conditions than for the ambient ones. For both the daytime and nighttime models, the entire frequency range between a few Hz and 10 MHz is forbidden as far as the 0 mode is concerned. The X mode fares only somewhat better, since the anomalous ionization causes the absorption in the whistler range to become prohibitively high. In order to make practical use of the lower passband, say no more than 30 dB transmission loss, one must use frequencies below a few hundred Hz in the disturbed night and below a few tens of Hz in the disturbed day. The situation is summarized in Table 1. Two possible ways of alleviating the very unfavorable propagation under disturbed conditions are evident. One is to use a sufficiently low frequency, provided such a low frequency can be effectively radiated. Another is to employ enough satellites such that at least one will be transmitting at local night or, better, under locally undisturbed conditions. The propagation path would then be vertically or obliquely under the satellite and then around the world in the earth-ionosphere cavity. These possibilities require further study.

The height dependences of the attenuation for the two modes, four model ionospheres, and frequencies in the LF/VLF/ELF/ULF band are illustrated in Figs. 10 to 19. For ambient conditions and hydromagnetic frequencies ($\lesssim$10 Hz), most of the attenuation is due to ion-neutral collisions and occurs near the altitude where the ion-neutral collision frequency is about equal to the ion gyrofrequency; i.e., around 120 km. Under disturbed conditions attenuation due to electron heating, which occurs at lower altitudes (40-90 km), is important even in the hydromagnetic band. This behavior is shown in Figs. 10 to 13. Figures 14 to 19 show some attenuation profiles in the ELF/VLF/LF bands. As indicated by Figs. 15 and 17, the O wave is evanescent at altitudes above about 150 km and is thus of little practical interest. The X wave attenuation occurs in an altitude layer a few tens of km thick centered around 75 km for the parameters used here. This attenuation is almost entirely due to ohmic heating of the electrons. The small amount of attenuation shown to occur below about 50 km for the disturbed cases in Figs. 16, 18, and 19 is due mainly to ion heating, since the conductivity is dominated by the relatively numerous ions at these low altitudes. The very severe anomalous attenuation which can be caused by ionospheric disturbances is evident from Figs. 10 to 19.

Table 1

IONOSPHERIC TRANSMISSION BANDS IN HERTZ[a]

Wave	Ambient Night		Ambient Day		Disturbed Night		Disturbed Day	
	f <	f >	f <	f >	f <	f >	f <	f >
Vertical Incidence, i = 0 deg								
Ordinary	30	4×10^6	1.4	8×10^6	3	1.4×10^7	0.5	4×10^7
Extraordinary	1.1×10^6	7×10^6	10^4	1.3×10^7	200	1.8×10^7	30	5×10^7
Glancing Incidence, i = 80 deg								
Ordinary	30	3×10^7	1.4	6×10^7	3	4×10^7	0.5	1.1×10^8
Extraordinary	5×10^5	3×10^7	5×10^3	6×10^7	200	5×10^7	10	1.3×10^8

[a]For transmission loss less than 20 to 30 dB.

IV. CONCLUSIONS

Under ambient conditions and for quasi-longitudinal propagation, the ionosphere is relatively transparent to electromagnetic waves having frequencies lower than about 10 kHz. For certain classes of artificially or naturally disturbed ionospheres, frequencies lower than a few tens of Hz must be used if less than 30-dB transmission loss is to be suffered.

Another possible scheme for a working system would be to use several satellites configured so as to maximize the probability that at least one satellite is transmitting under undisturbed ionospheric conditions, and reliance is thus placed upon part of the propagation path being in the earth ionosphere cavity. More study is needed on these aspects.

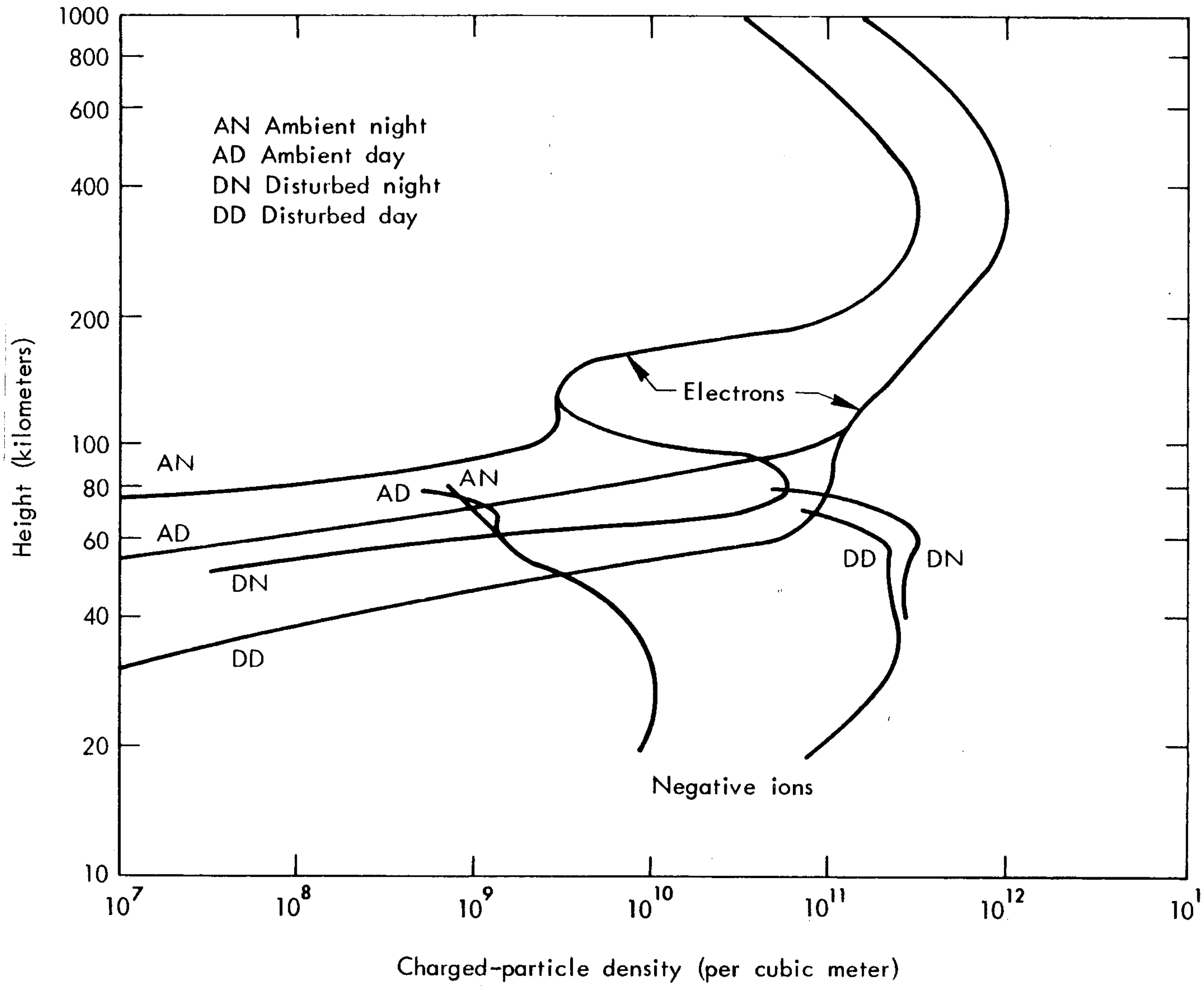

Fig. 1—Models of undisturbed and disturbed atmospheres

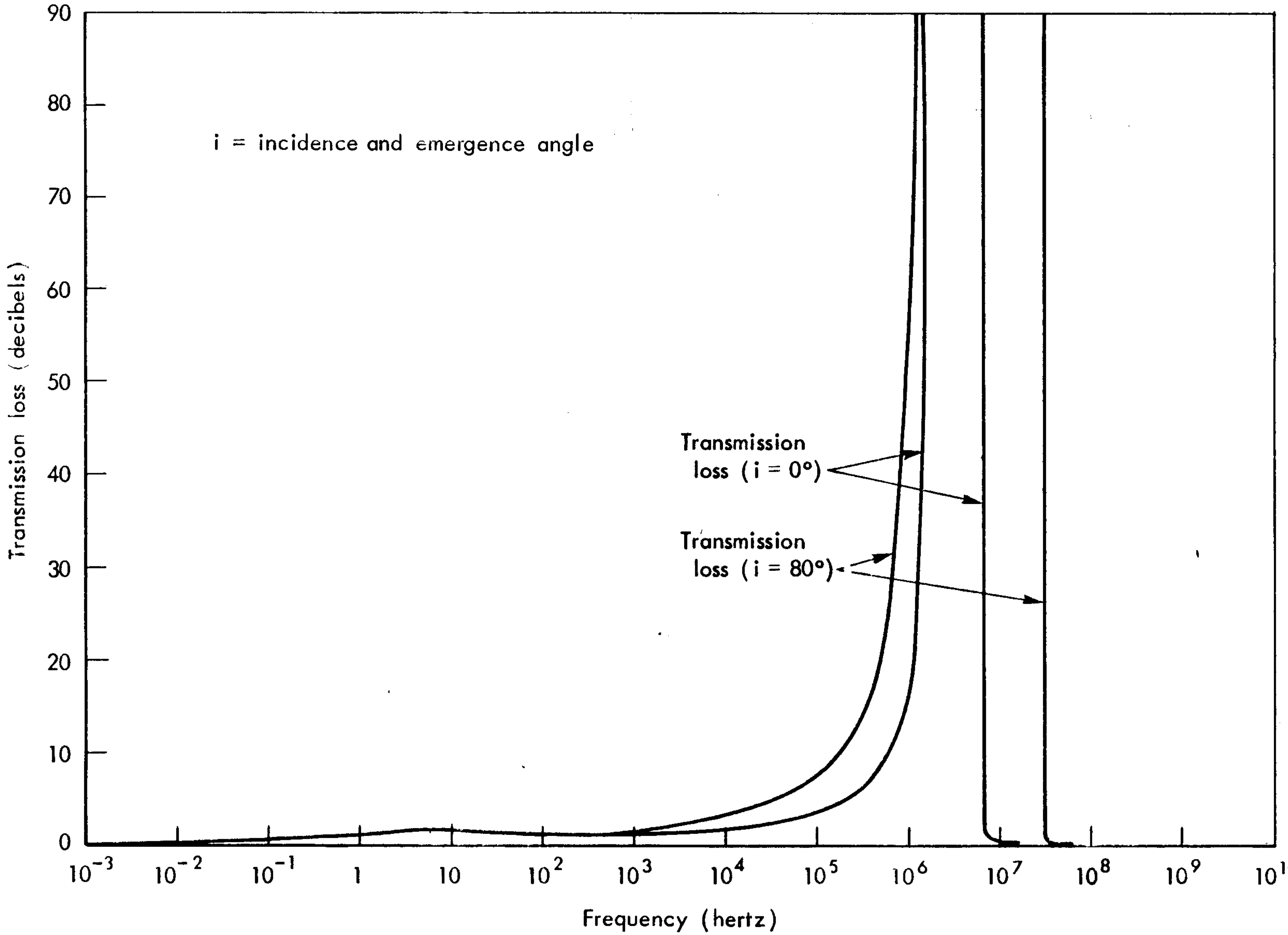

Fig. 2—Ambient night, X wave

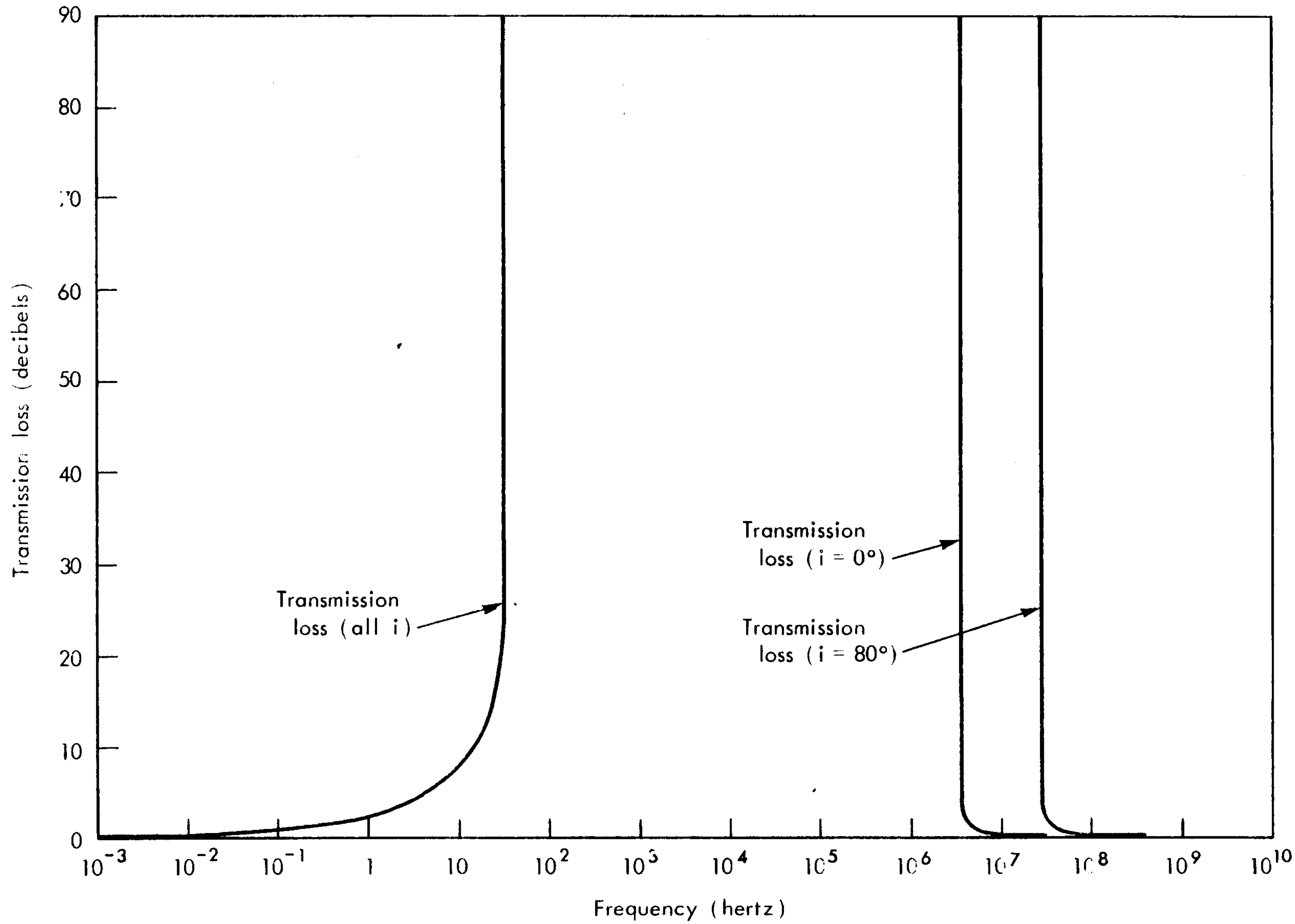

Fig. 3—Ambient night, 0 wave

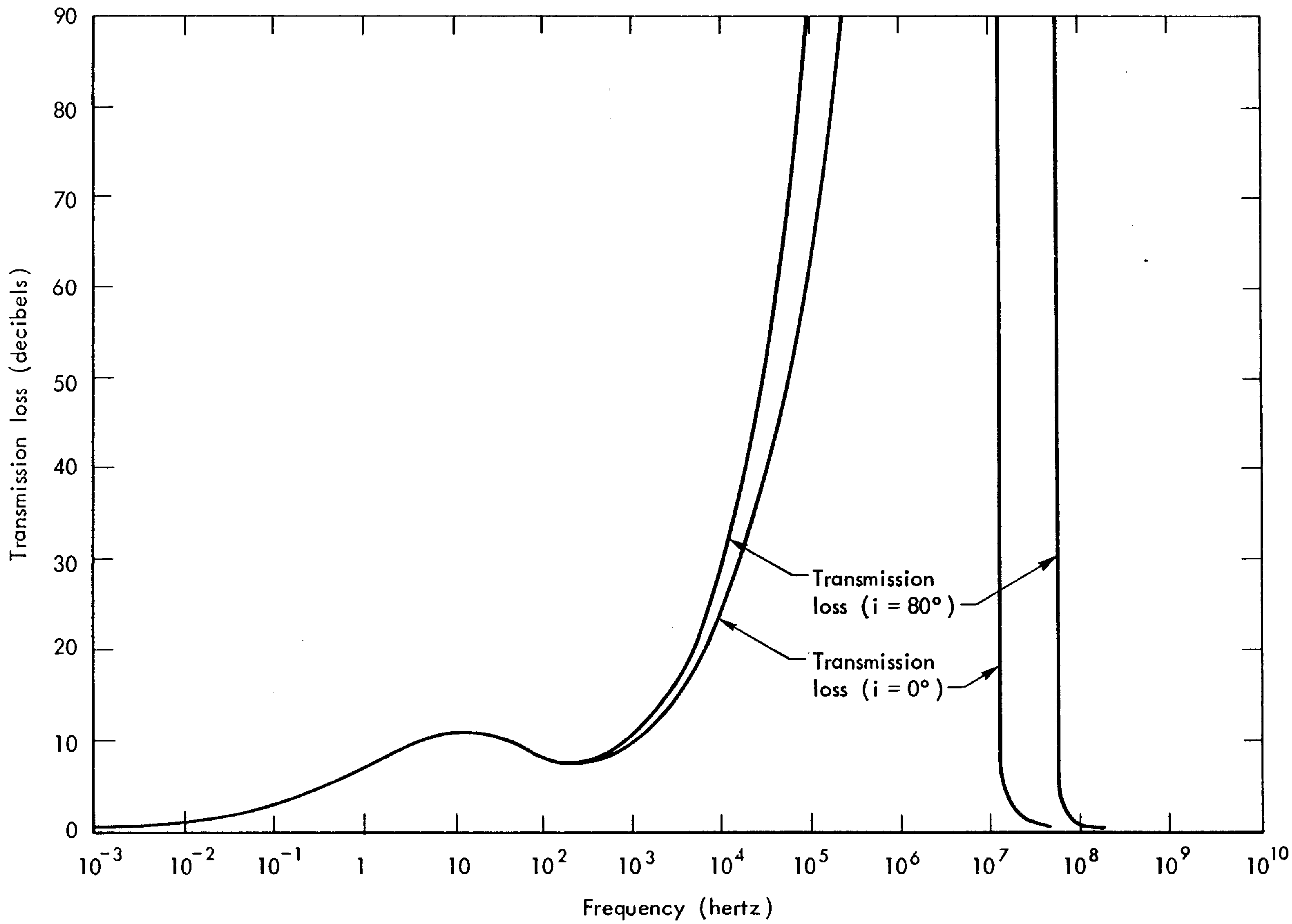

Fig. 4—Ambient day, X wave

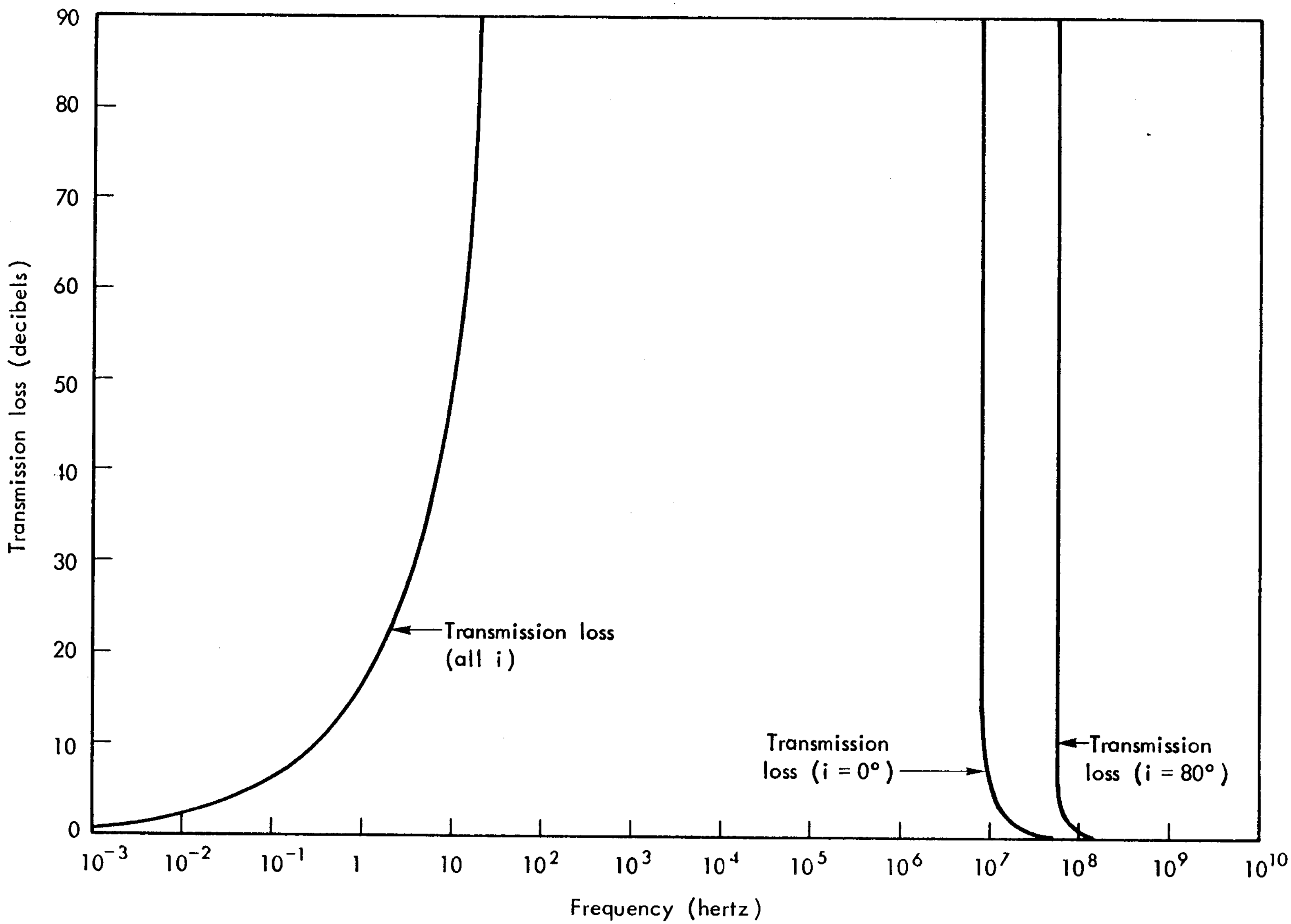

Fig. 5—Ambient day, 0 wave

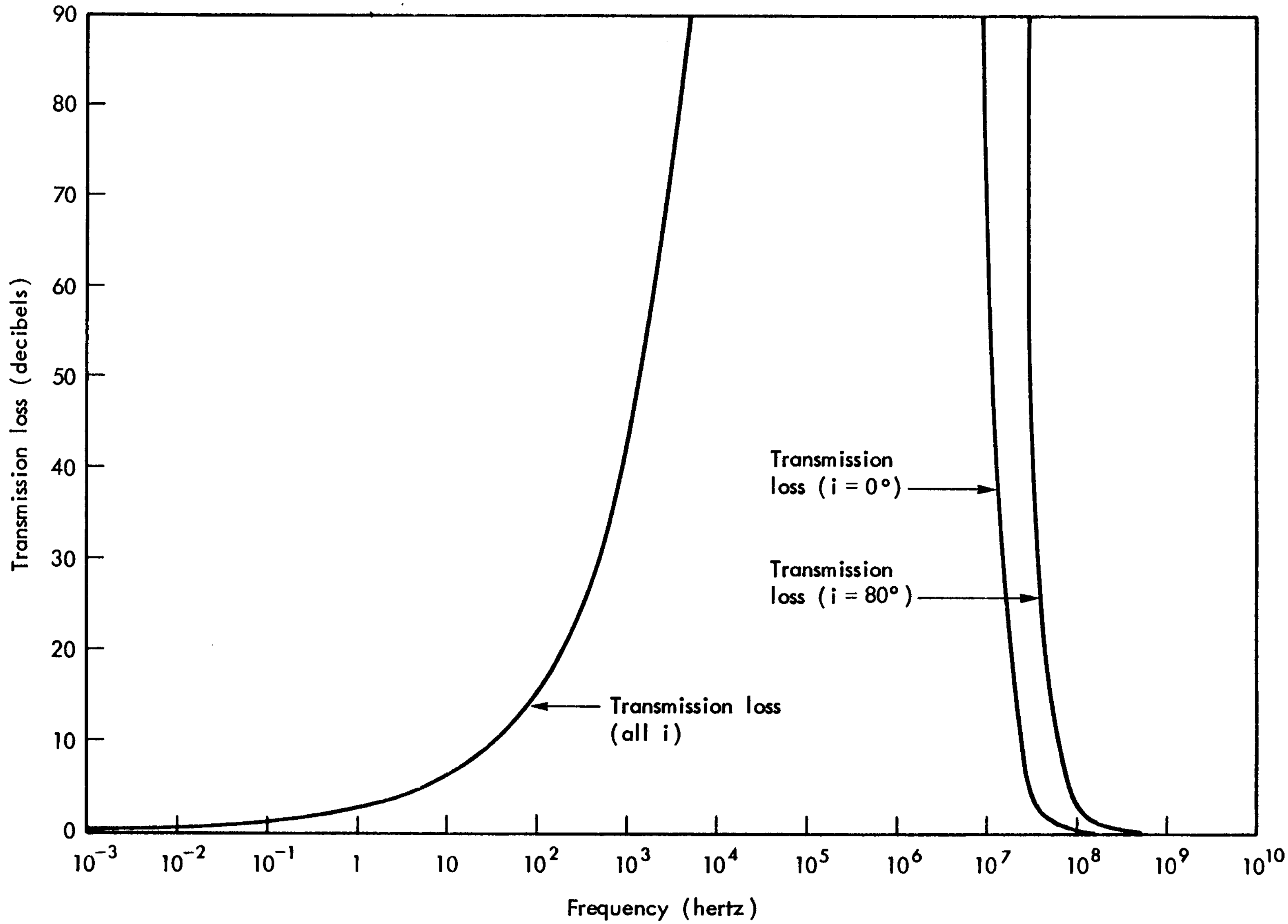

Fig. 6—Disturbed night, X wave

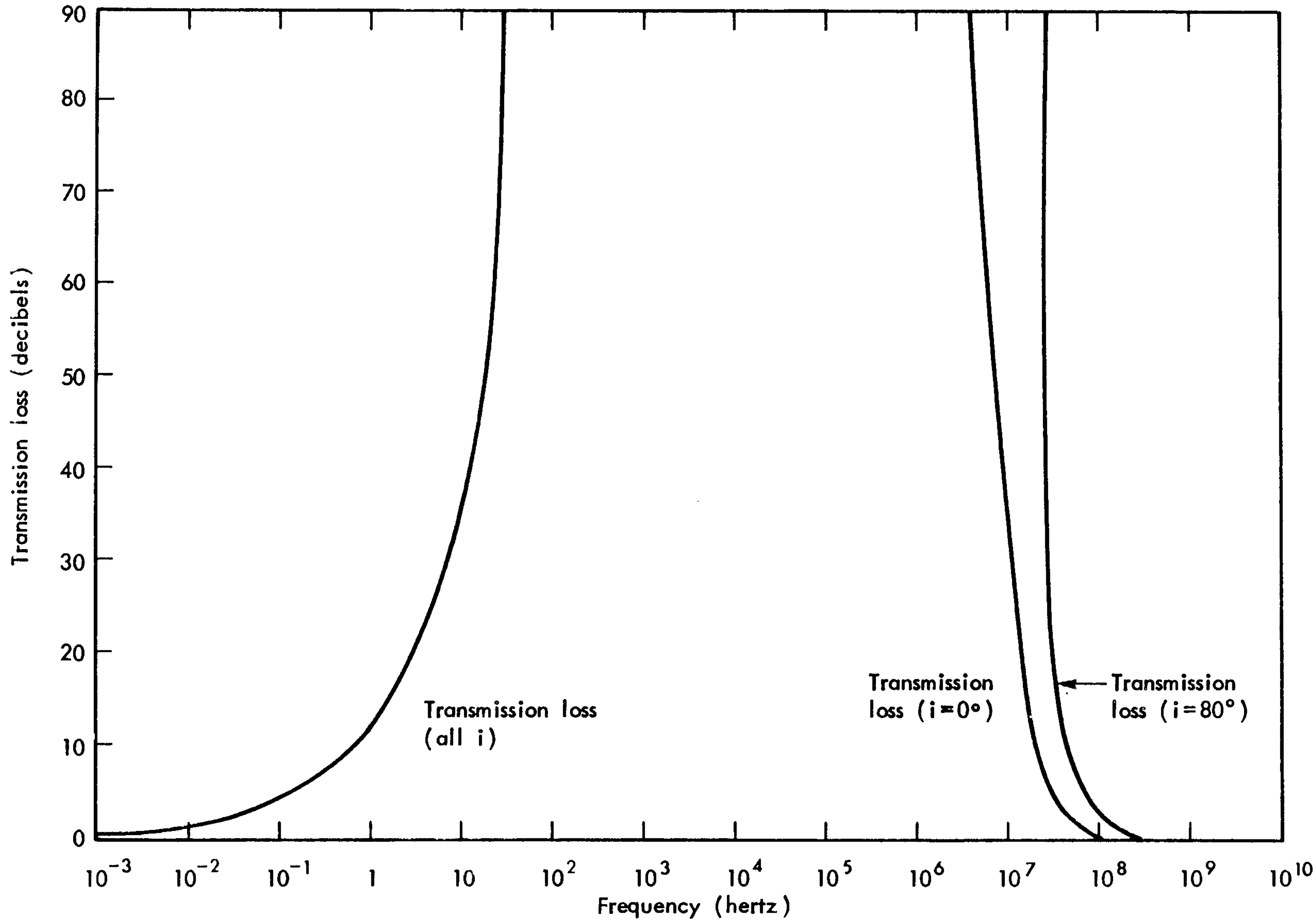

Fig. 7—Disturbed night, 0 wave

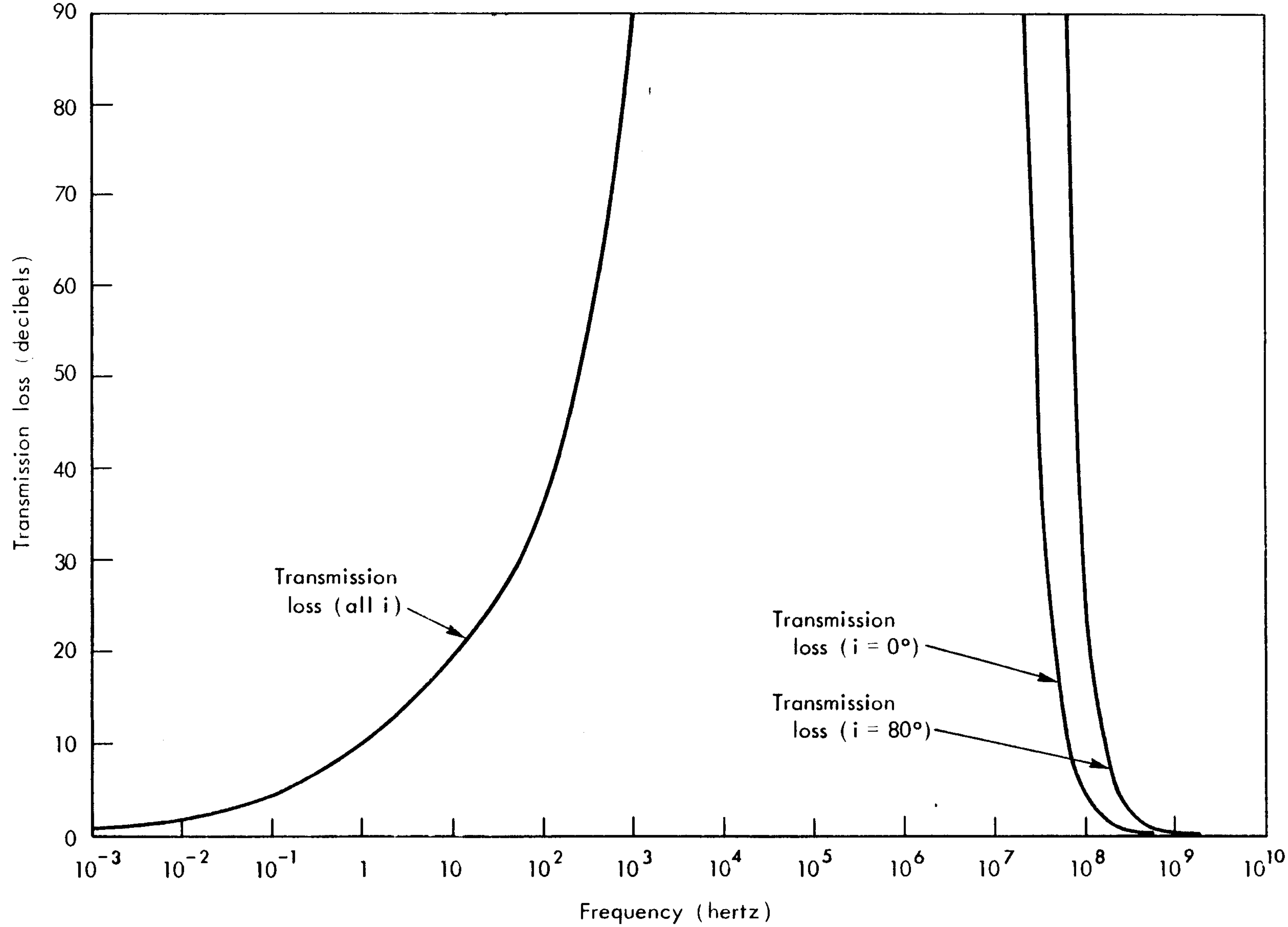

Fig. 8—Disturbed day, X wave

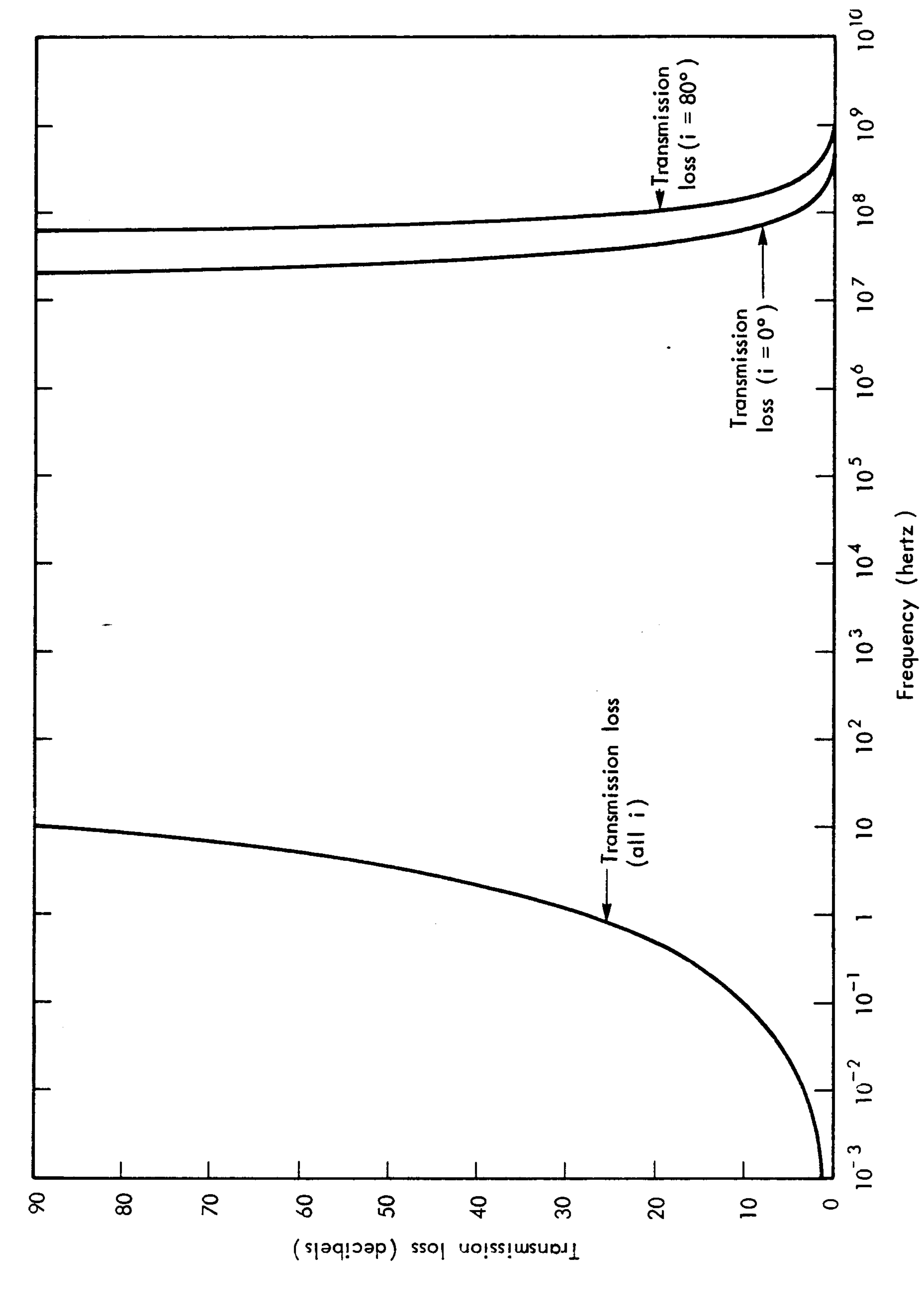

Fig. 9—Disturbed day, 0 wave

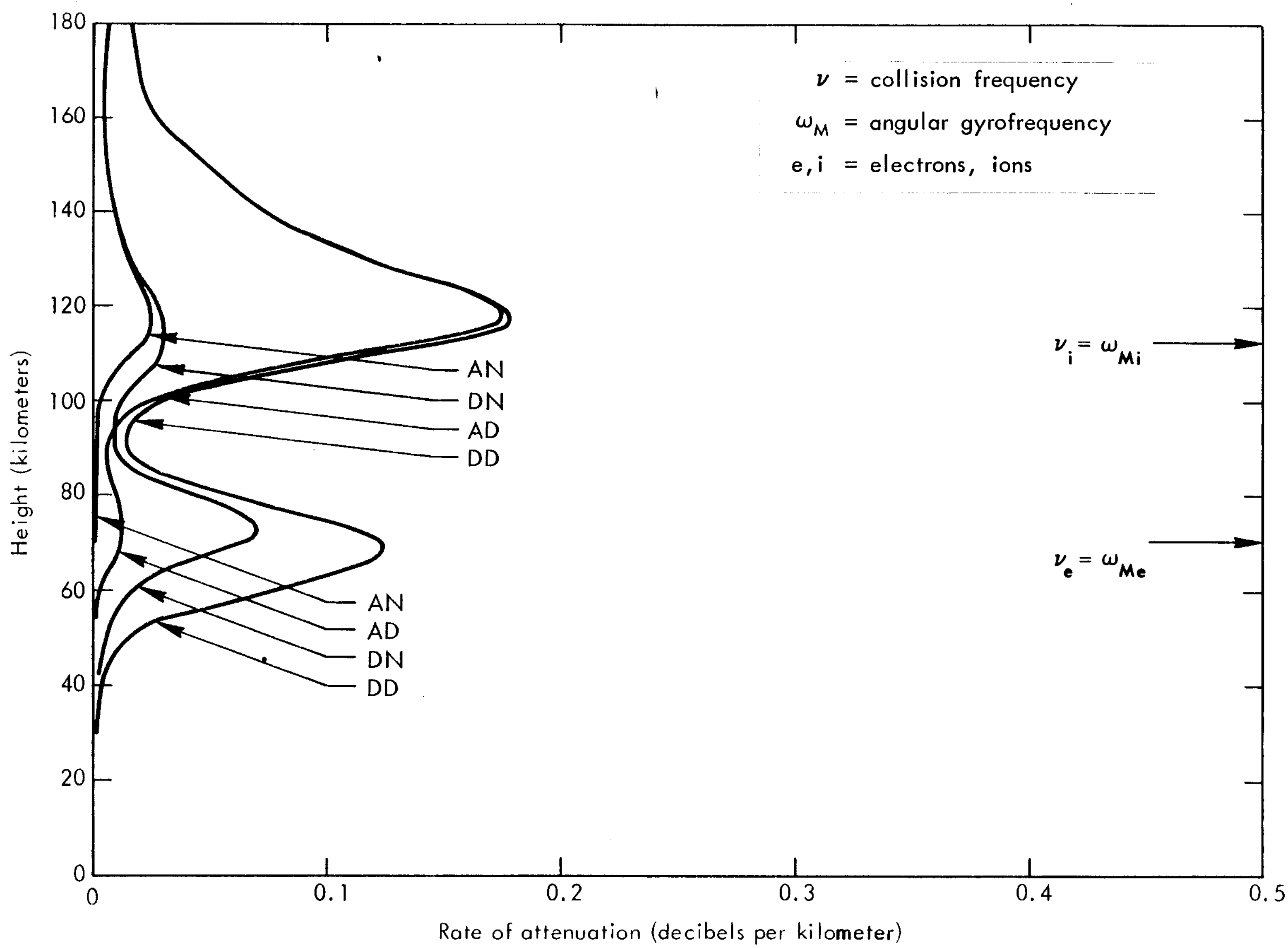

Fig. 10—X wave, frequency 1 Hz, all i

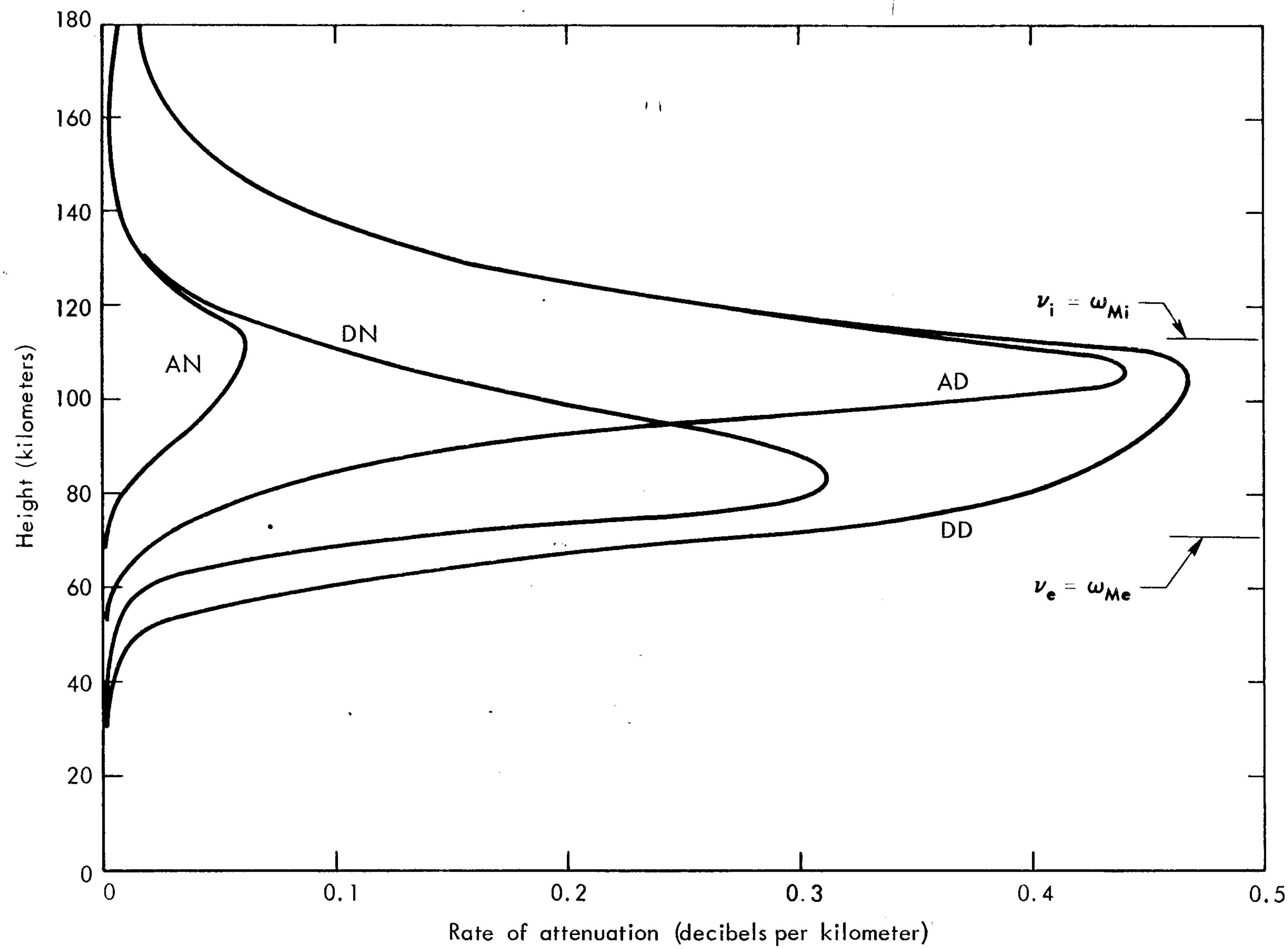

Fig. 11—0 wave, frequency 1 Hz, all i

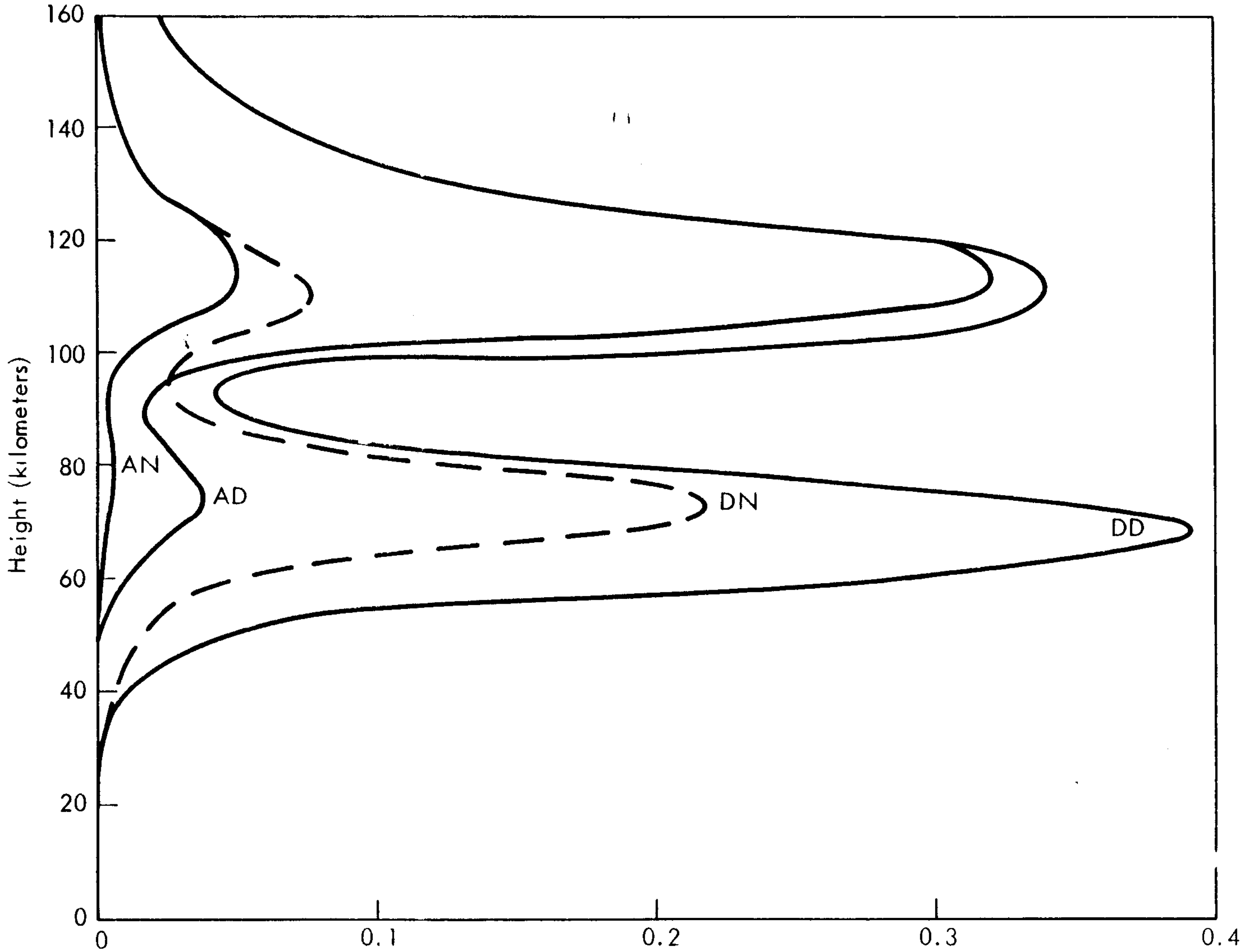

Fig. 12—X wave, frequency 10 Hz, i = 0 and 80 deg

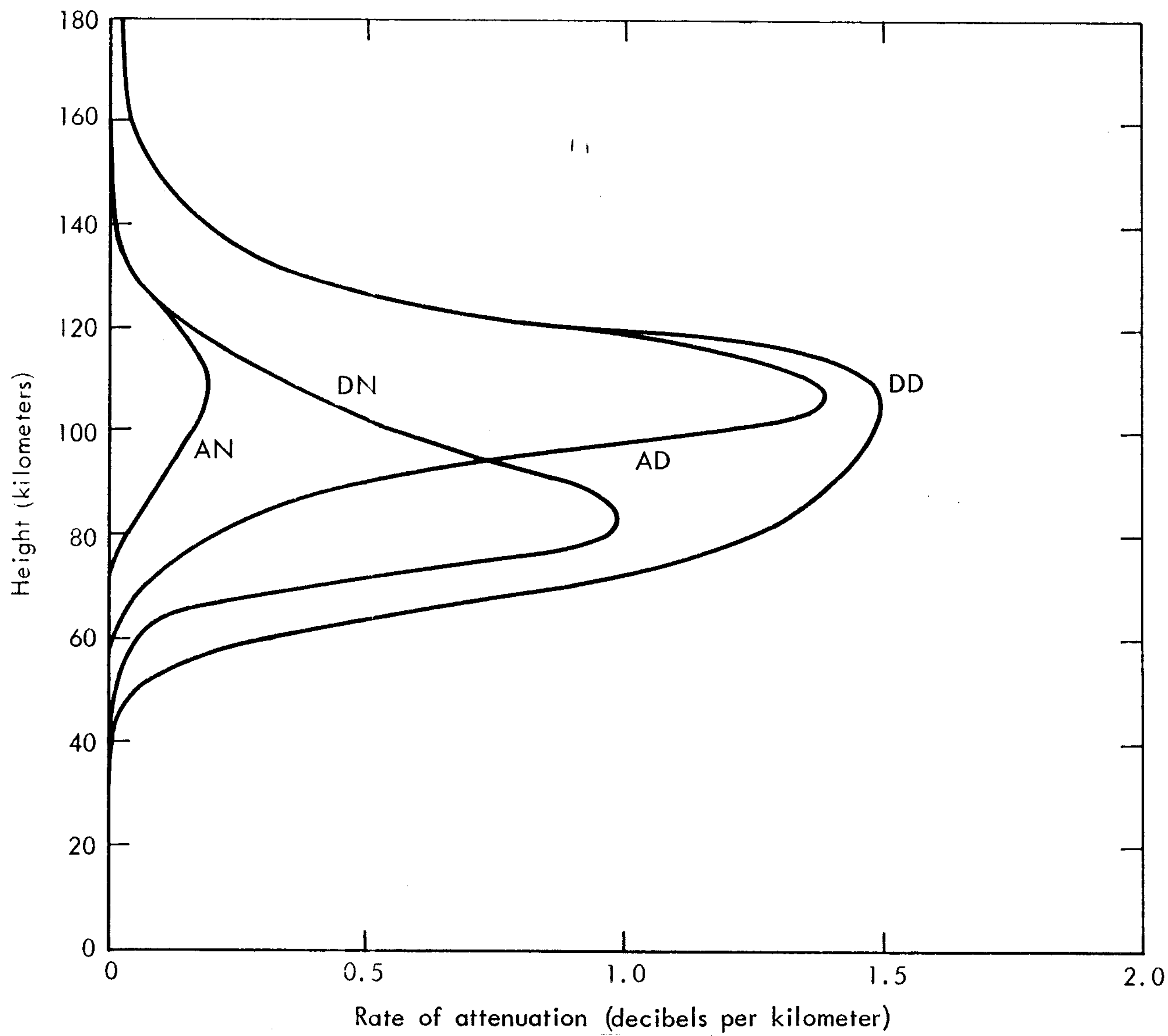

Fig. 13—0 wave, frequency 10 Hz, i = 0 and 80 deg

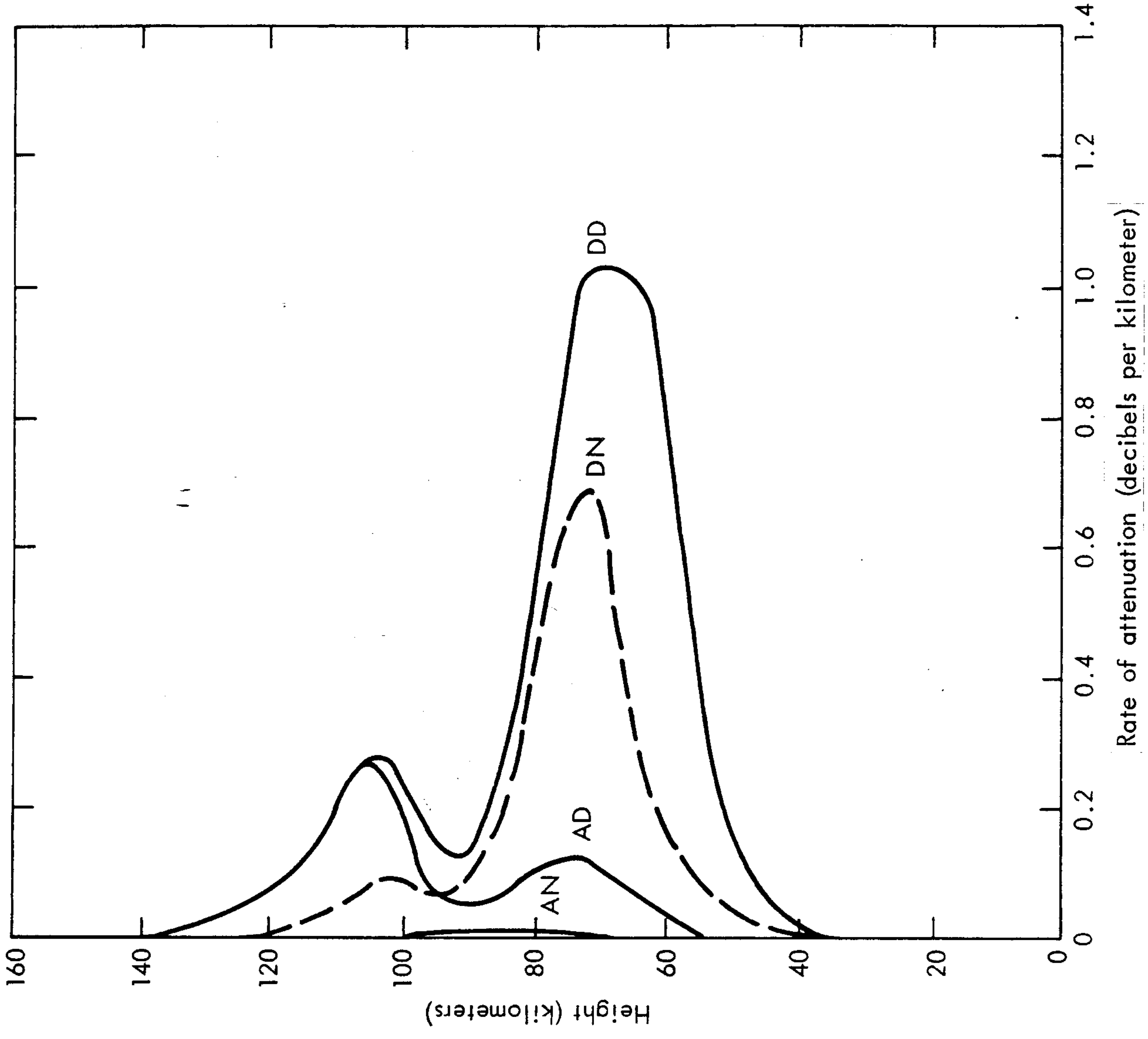

Fig. 14—X wave, frequency 100 Hz, i = 0 and 80 deg

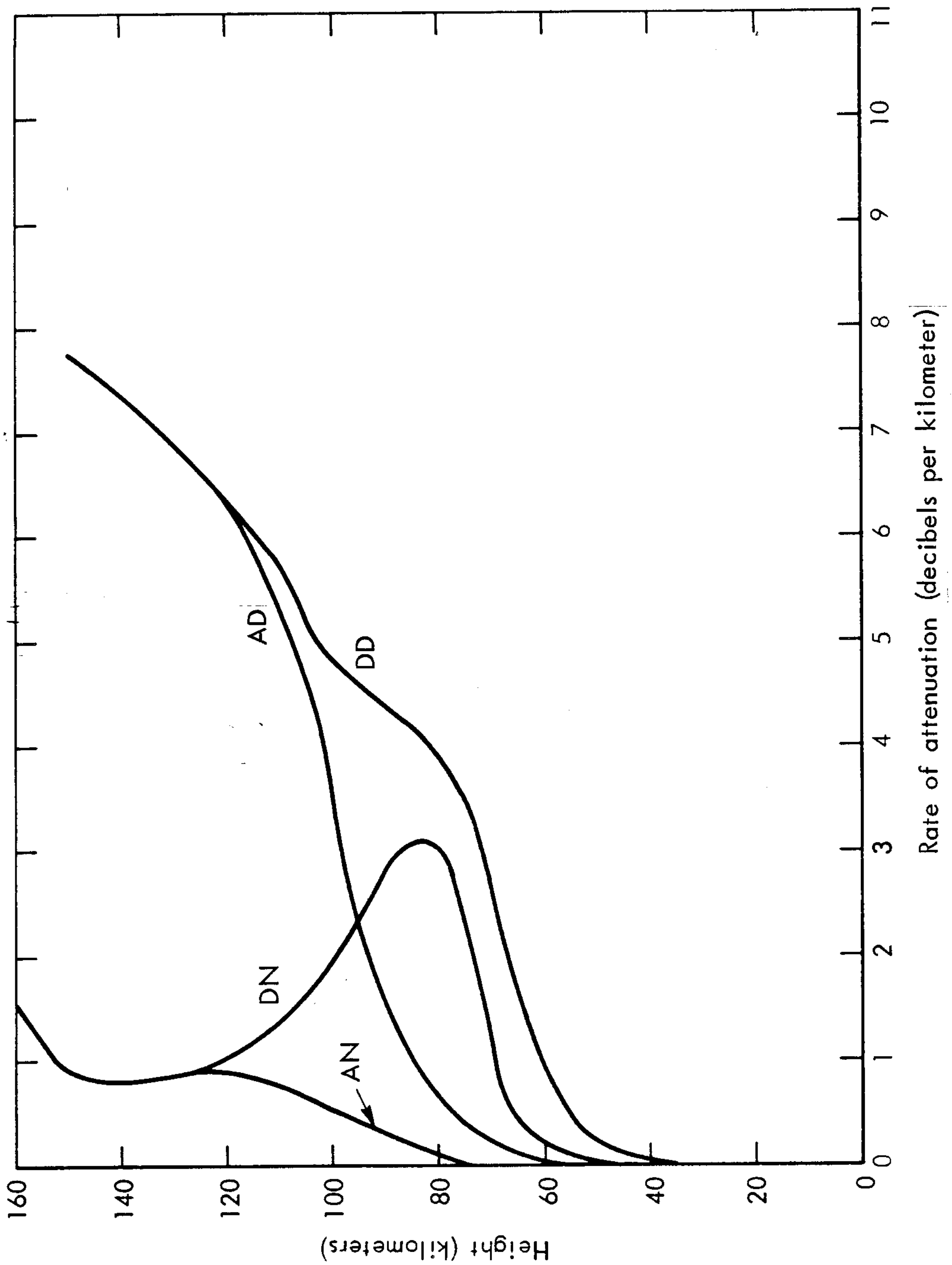

Fig. 15—0 wave, frequency 100 Hz, i = 0 and 80 deg

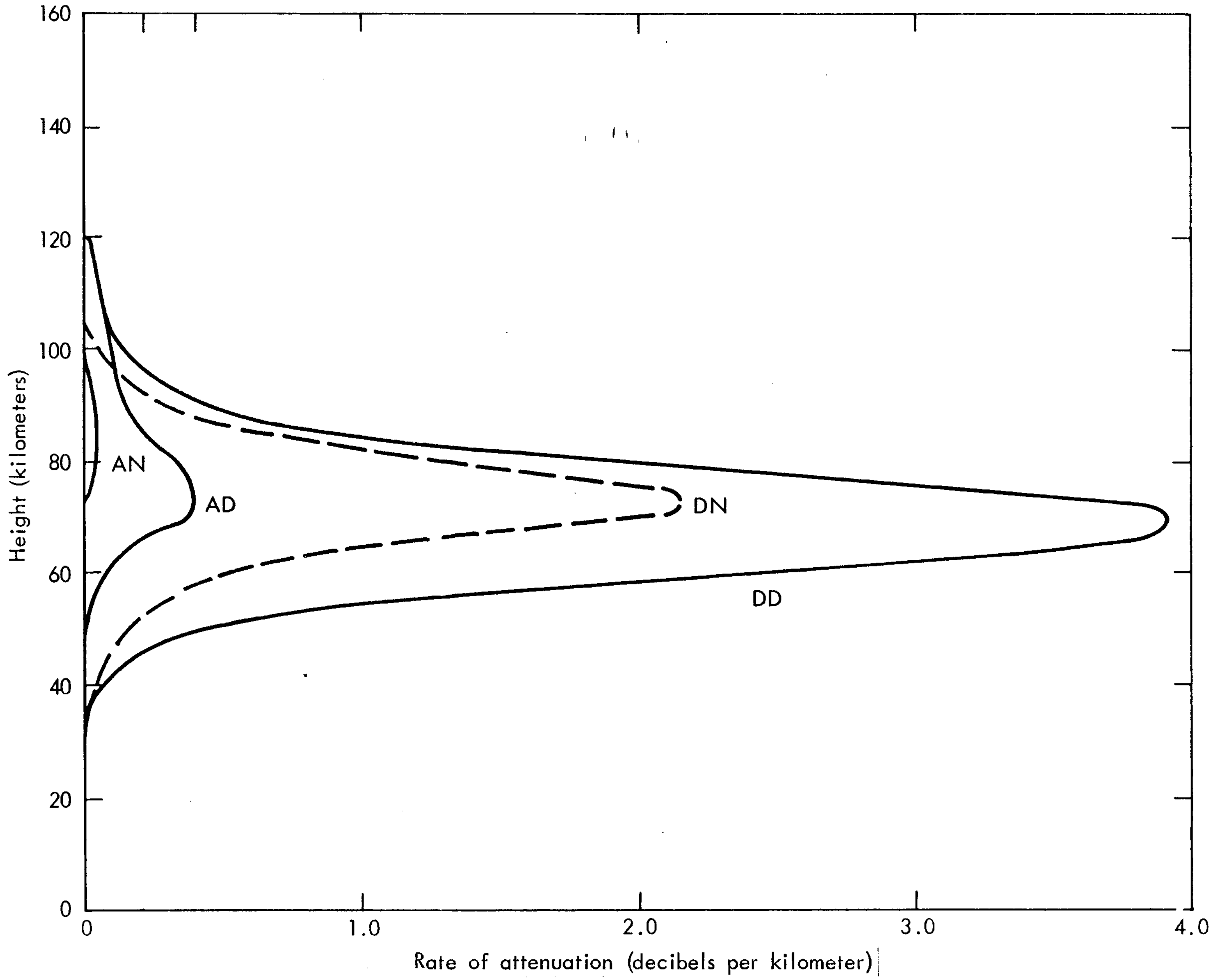

Fig. 16—X wave, frequency 1 kHz, i = 0 and 80 deg

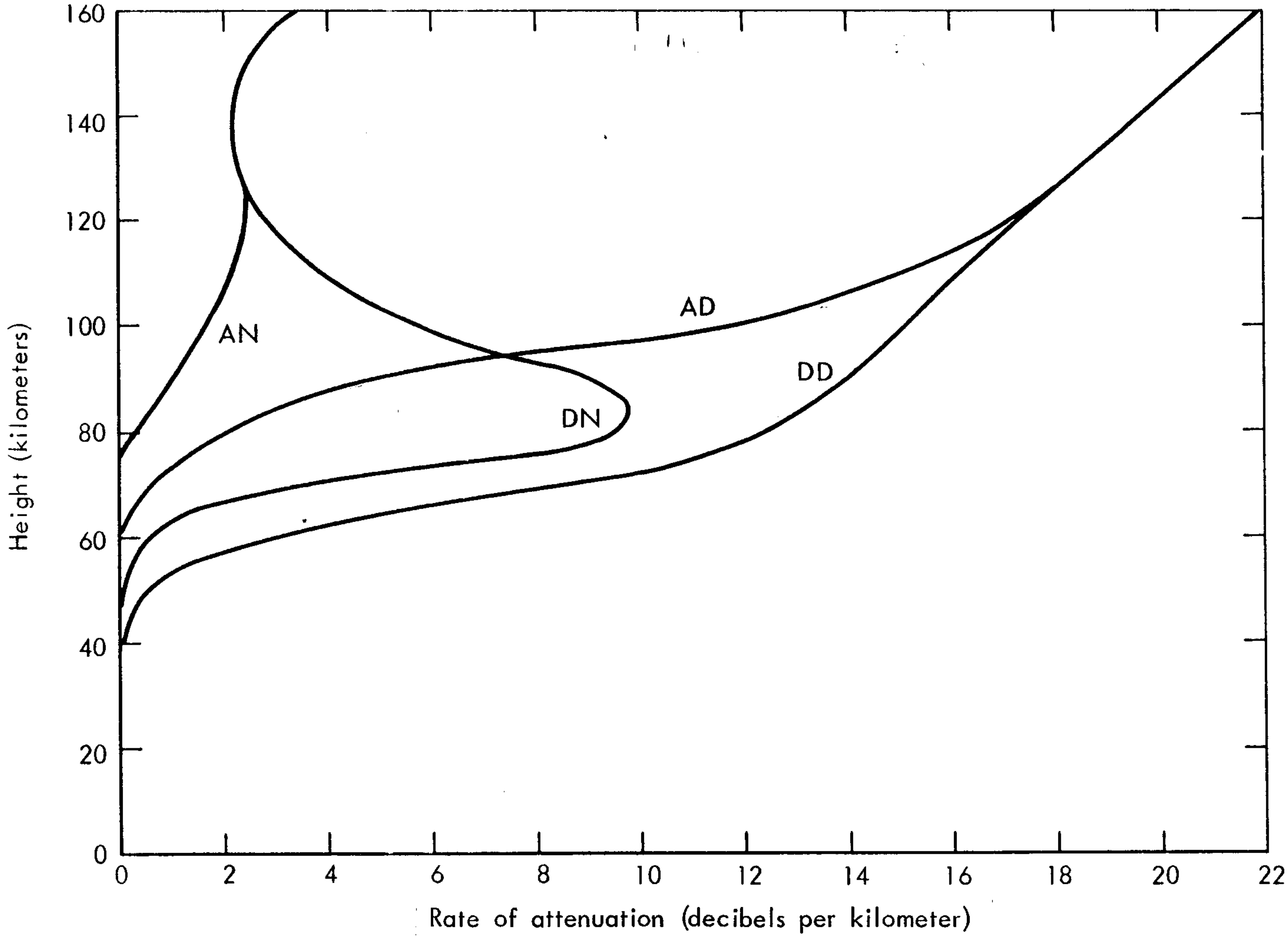

Fig. 17—0 wave, frequency 1 kHz, i = 0 and 80 deg

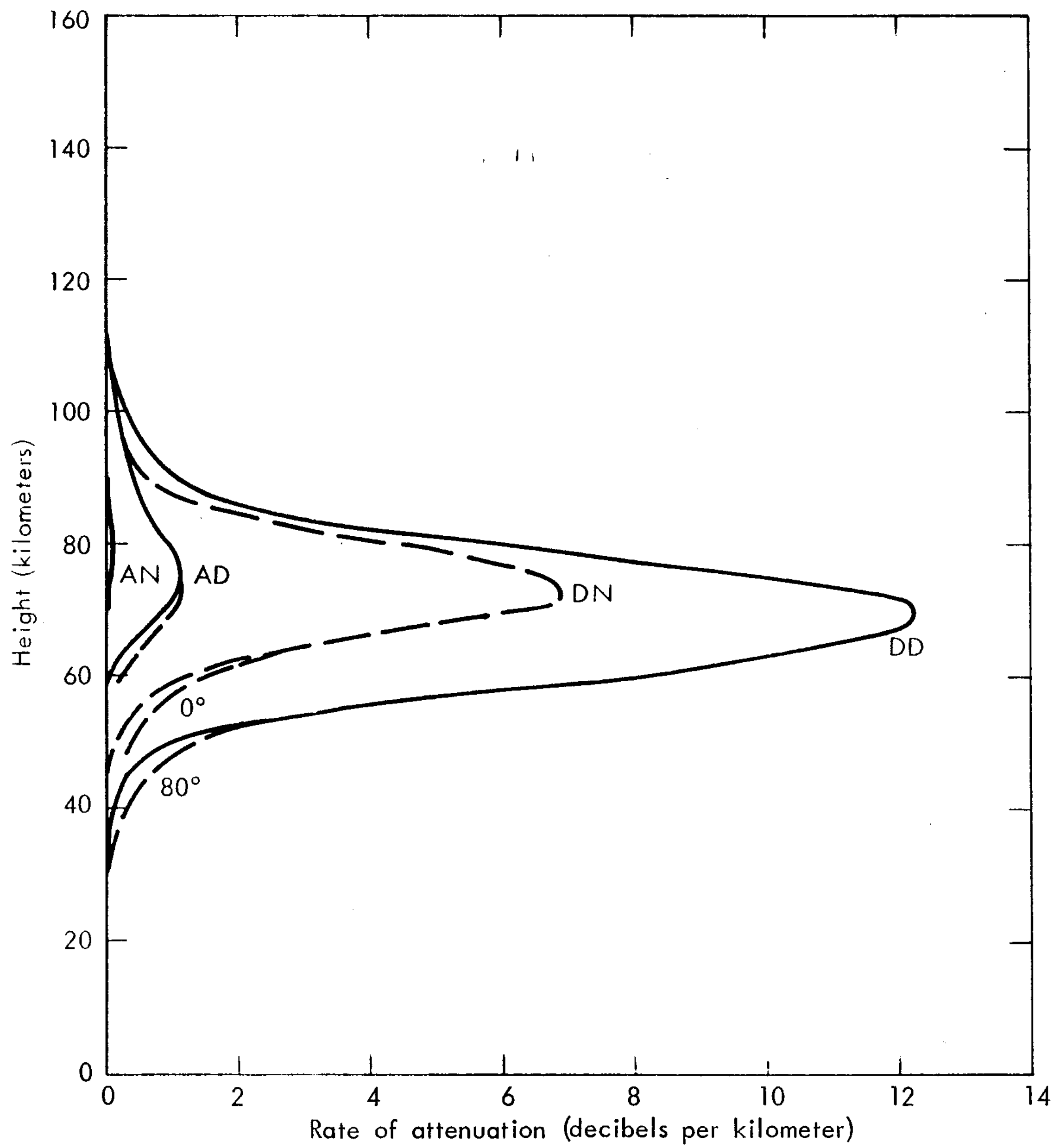

Fig. 18—X wave, frequency 10 kHz, i = 0 and 80 deg

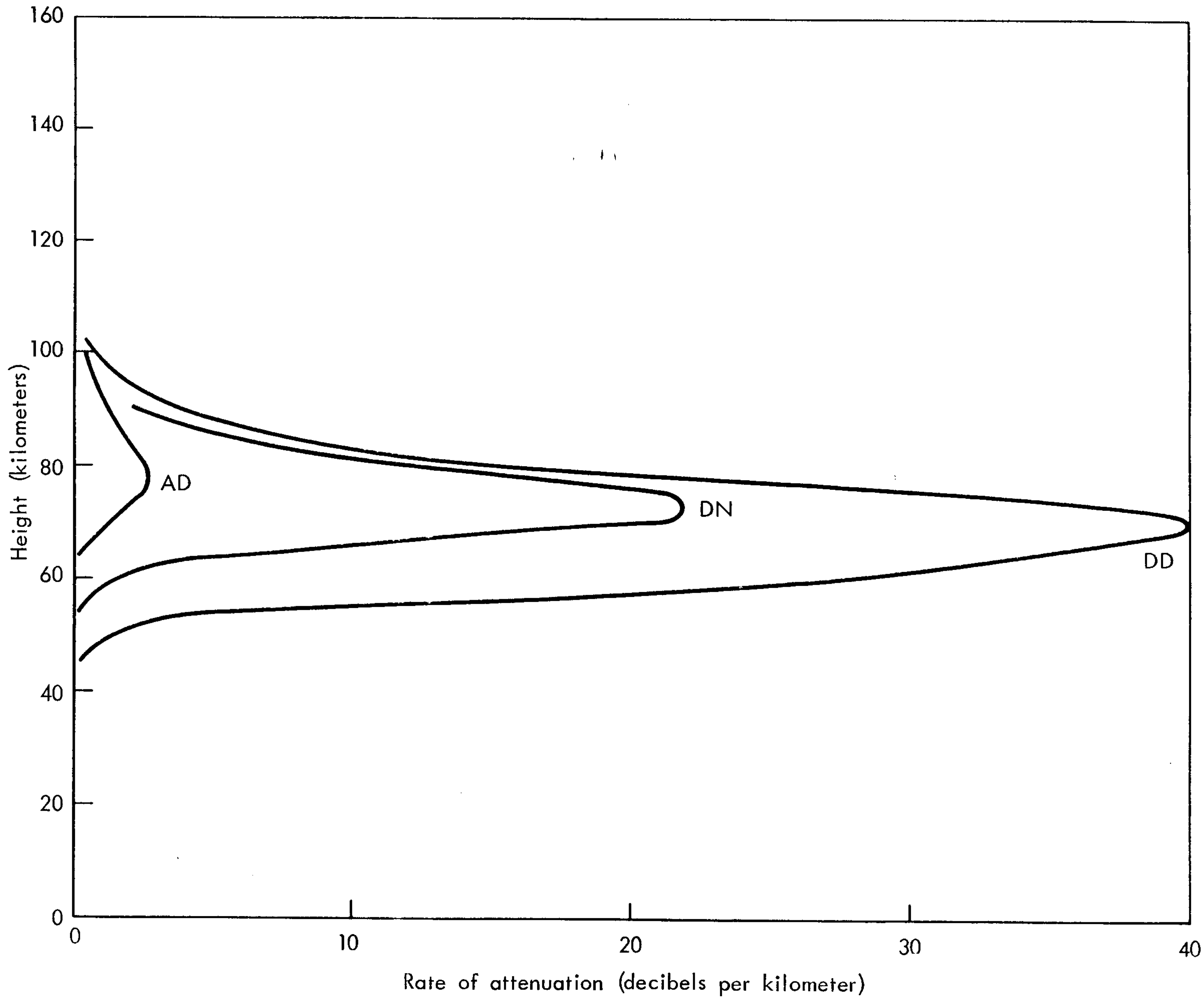

Fig. 19—X wave, frequency 100 kHz, i = 0 deg

REFERENCES

1. Booker, H. G., C. M. Crain, and E. C. Field, *A Panoramic View of Ionospheric Reflection and Transmission under Ambient and Disturbed Conditions*, The Rand Corporation, R-559-PR, November 1970.

2. Ginzburg, V. L., *Propagation of Electromagnetic Waves in Plasma*, Gorden and Breach Science Publishers, New York, 1961

COPY FOR INSIDE OF BACK COVER
R-558-PR

Rand maintains a number of special, subject bibliographies containing abstracts of Rand publications in fields of wide current interest. The following bibliographies are available upon request:

Africa • Arms Control • Civil Defense • Combinatorics
Communication Satellites • Communication Systems • Communist China
Computing Technology • Decisionmaking • East-West Trade
Education • Foreign Aid • Health-related Research • Latin America
Linguistics • Long-range Forecasting • Maintenance
Mathematical Modeling of Physiological Processes • Middle East
Policy Sciences • Pollution • Procurement and R&D Strategy
Program Budgeting • SIMSCRIPT and Its Applications • Southeast Asia
Systems Analysis • Television • Urban Problems • USSR
Water Resources • Weather Forecasting and Control

To obtain copies of these bibliographies, and to receive information on how to obtain copies of individual publications, write to: Communications Department, Rand, 1700 Main Street, Santa Monica, California 90406.