NASA TM X-56033

REVIEW OF AIRCRAFT NOISE PROPAGATION

Terrill W. Putnam

(NASA-TM-X-56033) REVIEW OF AIRCRAFT NCISE PROPAGATICN (NASA) 61 p HC $4.25 CSCL 20A

N75-32119

Unclas

G3/07 41085

September 1975

NASA Flight Research Center
Edwards, California 93523

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No
TM X-56033		

4. Title and Subtitle	5. Report Date
REVIEW OF AIRCRAFT NOISE PROPAGATION	September 1975
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Terrill W. Putnam	
	10. Work Unit No.
9. Performing Organization Name and Address	505-03-12
NASA Flight Research Center P. O. Box 273 Edwards, California 93523	11. Contract or Grant No
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, D. C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This paper reviews the current state of knowledge about the propagation of aircraft noise. The literature on the subject is surveyed and methods for predicting the most important and best understood propagation effects are presented. The available empirical data are examined and the data's general validity is assessed.

The methods used to determine the loss of acoustic energy due to uniform spherical spreading, absorption in a homogeneous atmosphere, and absorption due to ground cover are presented. A procedure for determining ground-induced absorption as a function of elevation angle between source and receiver is recommended. Other factors that affect propagation, such as refraction and scattering due to turbulence, which were found to be less important for predicting the propagation of aircraft noise, are also evaluated.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Noise propagation Aircraft noise	Unclassified - Unlimited

19. Security Classif. (of this report)	20. Security Classif (of this page)	21. No of Pages	22 Price*
Unclassified	Unclassified	58	

For sale by the National Technical Information Service, Springfield, Virginia 22151

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Terrill W. Putnam
Flight Research Center

INTRODUCTION

An unwanted byproduct of technological society is noise. As the complexity of technology has increased, the noise levels to which the general populace is subjected have risen. Because of this increase in noise, it has become desirable to control and reduce the noise from various sources.

Fundamental to the control and reduction of community noise is the ability to account for the propagation of noise into and throughout a community. Basic to this ability is an understanding of the factors governing the propagation of noise through the atmosphere near the earth's surface. An investigation of noise propagation through the atmosphere and over the ground must include the following subjects (fig. 1): uniform spherical spreading, atmospheric absorption and reflection of sound energy, ground or terrain absorption losses, losses due to the scattering of sound by atmospheric turbulence, and refraction. Other less important factors such as fog, dust, and precipitation also affect the propagation of noise. A thorough understanding of how these phenomena change the character of the noise with distance from the source is necessary before accurate estimates of noise levels in the community can be made. Also necessary if accurate predictions of the levels of sound propagated through the atmosphere near the earth's surface are to be made is an understanding of the effects of a real, nonhomogeneous atmosphere near the earth's surface on sound propagation.

This report summarizes the current state of knowledge of the factors governing the propagation of noise, with particular attention to the propagation of aircraft noise. The report is organized around each major factor that influences noise propagation. The way in which each factor affects sound propagation is defined. The pertinent literature is reviewed, and the procedures and data base used to predict the effect of each propagation factor are analyzed and evaluated. Finally, areas where research is needed to enhance the understanding of the problem are identified.

The purpose of this report is to recommend procedures for calculating the effects of the atmosphere and the terrain on the propagation of noise. The limitations of the procedures are estimated as well.

SYMBOLS

A	reference sound pressure amplitude
$A(f)$	atmospheric attenuation function
a	absorption coefficient in decibels per unit distance
a_c	classical absorption coefficient
a_{mol}	molecular absorption coefficient
a_{molmax}	maximum molecular absorption coefficient (eq. (32))
B	numerical constant defined by equation (30)
b_0,b_1,b_2,b_3	numerical constants
c	speed of sound
D	nozzle diameter
d	elementary source separation distance
d_k	distance from nozzle center to elemental source
$F(w)$	function defined by equation (15)
f	frequency
$f_{i,1}$	lower band limit of ith one-third octave band
$f_{i,2}$	upper band limit of ith one-third octave band
f_0	octave band frequency
Δf	one-third octave bandwidth
$g(f)$	mean square spectral density
h_a	absolute humidity
h_m	height of nozzle center above plane surface

h_{molmax}	absolute humidity at which maximum molecular absorption occurs (eq. (31))
h_R	height of receiver above plane
h_S	height of source above plane
I	image source
i =	$\sqrt{-1}$
J	vertical wind gradient
K	vertical temperature gradient
k	propagation constant for air
k_2	propagation constant for plane surface
L_b	band sound pressure level
ΔL_p	incremental change in sound pressure level
ΔN	sound pressure level reflection factor
n	number of elementary sources
P	atmospheric pressure
p	sound pressure
Q	complex plane wave reflection coefficient
Q′	modified complex plane wave reflection coefficient (eq. (19))
R	sound receiver, acoustic resistance
R_p	plane wave reflection coefficient
RH	relative humidity
r	radial distance
r′	reflected path length

r'_k reflected path length from kth source

r_m distance from nozzle centerline to receiver

Δr difference between direct and reflected path length

Δr_k difference between direct and reflected path lengths for kth source

Δr_m difference between direct and reflected path length with sound source at nozzle center

S sound source

T temperature

u,w dummy variables

x,y,z coordinate axes

x_s distance to shadow zone

Z acoustic impedance

Z_2 acoustic impedance of plane surface

z' ratio of reflected path length to direct path length, r'/r

z_m ratio of reflected path length to distance between nozzle centerline and receiver, r'/r_m

α absorption coefficient in nepers per unit distance

β quantity defined by equation (5)

γ elevation angle

δ phase angle

θ azimuth angle

λ sound wave length

μ quantity defined by equation (4)

ρ	air density
φ	complement of elevation angle
χ	acoustic reactance

Subscripts:

0	reference condition
i	ith one-third octave band

SPECIFICATION OF PROBLEM

No existing theory adequately describes the propagation of sound out of doors. Much of the inability to define the noise field at great distances from a sound source, such as an aircraft, precisely is due to the nonhomogeneity of the atmosphere and the terrain. Because of the inability to quantify the nonhomogeneities, certain simplifying assumptions must be made to construct propagation models that yield reasonable engineering results. The assumptions made for the analysis presented herein are as follows: sound propagates through the atmosphere above a flat earth; the source behaves as a point source; sound propagation occurs in the acoustic far field; sound pressure amplitudes are sufficiently small for linear acoustic theory to be applicable; and the sound source is considered to be stationary. The effects of motion on the source strength and directivity are beyond the scope of this report. The coordinate system used throughout this investigation is shown in figure 2.

UNIFORM SPREADING LOSSES

The most significant influence on sound level at any position is the distance between the receiver and the source. For the simple case of sound propagating in a lossless atmosphere far from any boundaries, the sound pressure at any point in the far field can be represented by the equation:

$$p = \frac{A(\theta,\varphi)}{r} \tag{1}$$

where $A(\theta,\varphi)$ is the reference pressure amplitude at unit radius and angle θ,φ from the source. Using equation (1) in the definition of sound pressure level, the change in sound pressure level, ΔL_p, due to a change in distance between source and receiver is:

$$\Delta L_p = -20 \log \left(\frac{r}{r_0}\right) \tag{2}$$

Equation (2) represents the well understood inverse square law of spherical divergence for a point source in decibel form. For each doubling of distance, the sound pressure level decreases by 6 decibels.

The use of equation (2) is recommended for determining the uniform spreading losses in the far field of a noise source.

GROUND ABSORPTION AND REFLECTION

When a sound wave propagates nearly parallel to the earth's surface, the amplitude and phase of the sound waves are greatly dependent upon the acoustical properties of the earth's surface. The surface characteristics vary from acoustically hard to acoustically soft, where an acoustically hard surface is one that acts as a perfect reflector of sound and an acoustically soft surface is one that acts as an absorber of sound. Figure 3 compares a spectrum measured over a concrete surface with a spectrum measured in a free field at a radius of 60 meters. The reinforcement and destructive interference pattern is obvious in the spectrum measured over concrete; the ground plane significantly distorts the true (free field) sound spectrum. In this section, the theoretical effects of ground impedance on sound propagation are reviewed, including the effects of finite source size and directivity. The available experimental data are reviewed, and an engineering procedure for predicting the effects of ground impedance on sound propagating near the earth's surface is recommended.

Point Source Over Hard Surface

In the geometric configuration of sound propagation (fig. 4), the sound received at a point R is the sum of the sound propagated along the direct path r and the reflected sound propagated along the path r'. The reflected sound can be considered to be coming from an image source, I. A theoretical analysis of this configuration was developed in reference 1 for the case in which there is a point source above a specular reflecting plane (where the incidence angle equals the reflection angle) and a finite bandwidth receiver. The analysis indicates that the sound pressure at R also depends on the shape of the source spectrum. The effect of spectrum shape has been studied and is reported in reference 2. It was shown that a spectrum slope that varies between 2 and -2 has no effect for purposes of analysis by one-third octave bands. Therefore, to reduce the analysis to the application of a single closed-form equation, a white noise spectrum was assumed. It was shown in reference 2 that for an actual spectrum slope between ±3, the assumption of a white noise spectrum in the development of the equations resulted in errors of less than 0.5 decibel for one-third octave band analysis. Thus, the difference between data measured in the presence of a reflecting plane and the free field data for a white noise spectrum is given by

$$\Delta N_i = 10 \log\left[1 + \left(\frac{1}{z'}\right)^2 + \frac{2}{z'} \frac{\sin\left(\mu\Delta r/\lambda_i\right)\cos\left(\beta\Delta r/\lambda_i\right)}{\mu\Delta r/\lambda_i}\right] \qquad (3)$$

where z' is r'/r, λ_i is the wavelength of the one-third octave center frequency, f_i, and

$$\mu = \frac{2\pi\Delta f}{2f_i} \tag{4}$$

$$\beta = 2\pi\sqrt{1 + \left(\frac{\Delta f}{2f_i}\right)^2} \tag{5}$$

Two important limiting cases should be noted. When $\Delta r/\lambda_i = 0$, which implies that the path length difference $\Delta r = 0$, the direct and reflected signals are added and the sound pressure level increases 6 decibels.

For the case where the source emits only a single frequency, $\mu = 0$ and $\beta = 2\pi$. Equation (3) reduces to the following equation, which shows the classic patterns of constructive and destructive interference between the direct and reflected sound.

$$\Delta N_i = 10 \log \left[1 + \left(\frac{1}{z'}\right)^2 + \frac{2}{z'} \cos \left(2\pi\Delta r/\lambda_i\right)\right] \tag{6}$$

The general validity of these equations was established by experiments like those reported in reference 3. For limiting geometries like the grazing incidence of sound, the validity of equation (6) tended to diminish, probably because the assumption of a point source over a rigid specular reflecting ground plane was no longer valid.

Point Source Over Soft Surface

Reference 2 extended the reflection model to include the reflection of sound from a partially absorbing surface. It was assumed that the reflective plane was characterized at a given incidence angle by the plane wave reflection coefficient for a normal impedance boundary. With this modification, equation (3) becomes:

$$\Delta N_i = 10 \log \left[1 + \left|\frac{Q_i}{z}\right|^2 + \frac{2\left|Q_i\right|}{z'} \frac{\sin\left(\mu\Delta r/\lambda_i\right) \cos\left(\beta\Delta r/\lambda_i + \delta_i\right)}{\mu\Delta r/\lambda_i}\right] \tag{7}$$

where δ_i is the phase angle for the ith one-third octave band and Q_i is the complex plane wave reflection coefficient as defined by the following equation:

$$Q_i = \left|Q_i\right| e^{-i\delta_i} = R_p = \frac{\left(Z_i/\rho c_0\right) \cos(\varphi) - 1}{\left(Z_i/\rho c_0\right) \cos(\varphi) + 1} \tag{8}$$

where Z_i is the normal acoustic impedance of the surface and φ is the incidence angle of the sound wave.

For the case of a point source emitting a pure tone, equation (7) reduces to the following form:

$$\Delta N_i = 10 \log \left[1 + \left| \frac{Q_i}{z'} \right|^2 + \frac{2|Q_i|}{z'} \cos \left(2\pi \Delta r / \lambda_i + \delta_i \right) \right] \tag{9}$$

The inclusion of the complex plane wave reflection coefficient in the analysis has two significant effects. First, in equation (7), the reflected wave amplitude decreases as $|Q_i|$ decreases, with the effect of decreasing the magnitude of the sound pressure oscillations caused by the interference. For a perfectly absorbing surface, $|Q_i| = 0$ and there is no interference. The second effect of the absorptive surface is to cause the interference pattern to shift to lower frequencies because of the phase shift, δ_i.

Normal impedance data from typical ground surfaces, which are required for the computation of the plane wave reflection coefficient, are extremely limited. The results of field tests made to determine the normal impedance of several ground surfaces are reported in reference 4. Shown in figure 5 are results obtained for the impedance of grass at several moisture conditions and the impedance of several mineral-covered surfaces. The resistive and reactive components are related to the normal impedance through the following equation:

$$Z_i = R + i\chi \tag{10}$$

The frequency range of the data is limited to between 200 hertz and 1000 hertz; however, that range should prove to be useful for a variety of practical applications. The resistive and reactive components of the normal impedance can be related to the magnitude and phase of the reflection coefficient by the following equations:

$$Q_i = \frac{\sqrt{\left[|Z_i/\rho c_0|^2 \cos^2 (\varphi) - 1 \right]^2 + 4\left(\chi/\rho c_0\right)^2 \cos^2 \varphi}}{\left(Z_i/\rho c_0\right)^2 \cos^2 (\varphi) + 1 + 2\left(R/\rho c_0\right) \cos \varphi} \tag{11}$$

$$\delta_i = \sin^{-1} \left\{ \frac{2\left(\chi/\rho c_0\right) \cos (\theta)}{\sqrt{\left[|Z_i/\rho c_0|^2 \cos^2 (\varphi) - 1 \right]^2 + 4\left(\chi/\rho c_0\right)^2 \cos^2 \varphi}} \right\} \tag{12}$$

Using the values shown in figure 5 for the appropriate ground surface, the magnitude and phase of the plane wave reflection coefficient can be calculated and used to calculate the reflection effects on a sound spectrum for a given geometry and ground surface. It should be noted that these equations are valid only for incidence angles less than approximately 70°. In other words, equation (7) is invalid for cases involving the grazing incidence of sound.

The application of these equations to measured noise spectra and the limitations of the equations are discussed in the proposed draft of the Society of Automotive Engineers (SAE) AIR 1327. Methods of correcting spectra measured in the presence of a ground plane to free field conditions are presented, and a method of determining the reflection characteristics of a particular ground plane is presented. Several techniques for minimizing the errors associated with acoustic measurements made in proximity of a ground plane are discussed.

Propagation at Grazing Incidence

A more sophisticated analysis must be made to account for the reflection and absorption characteristics of sound at grazing angles. An analysis of this type was performed in reference 5, based on Weyl's solution to the electromagnetic problem. This analysis was expanded in references 6 to 8 and compared with experimental results on materials of known acoustic characteristics, such as rubberized horsehair and fiber glass. In these analyses, the ground cover layer was considered to be a wave-bearing medium and it was necessary to know the layer impedance and propagation constant as a function of frequency.

Another approach to the problem was developed in reference 9, based on Sommerfeld's method. These results were extended and applied to experimental data in references 10 and 11. Again, the comparison between experiment and theory was for sound propagation over a fibrous absorbent material, since there is little reliable information on the acoustical properties of grass-covered soil for the relevant frequency range. The equations that apply to the propagation of aircraft noise at close to grazing angles are summarized in reference 12.

The ratio of the reflected wave to the incident wave is given by the following equation:

$$Q = |Q|e^{-i\delta} = R_p + \left(1 - R_p\right)F(w) \tag{13}$$

where R_p is the reflection coefficient for a layered medium expressed as follows.

$$R_p = \frac{\left(Z_i/\rho c_0\right)\cos\varphi - \sqrt{1 - \left(k/k_2\right)^2 \sin^2\varphi}}{\left(Z_i/\rho c_0\right)\cos\varphi + \sqrt{1 - \left(k/k_2\right)^2 \sin^2\varphi}} \tag{14}$$

In equation (14), k_2 is the complex propagation constant in the surface and k is the propagation constant for air. The function $F(w)$ is defined by the following equation:

$$F(w) = 1 + i2w^{1/2}e^{-w}\int_{-iw^{1/2}}^{\infty} e^{-u^2}\,du \tag{15}$$

where

$$w = \frac{i2kr}{\left|1 - R_p\right|^2 \sin^2 \varphi} \left(\frac{\rho c_0}{Z_i}\right)^2 \left[1 - \left(\frac{k}{k_2}\right)^2 \sin^2 \varphi\right] \tag{16}$$

Equation (15) can be expanded into the following series:

$$F(w) = 1 - 2we^{-w}\left(1 + \frac{w}{3(1!)} + \frac{w^2}{5(2!)} + \ldots\right) + i(\pi w)^{1/2} e^{-w} \tag{17}$$

For values of w greater than 10, equation (17) becomes

$$F(w) = -\left(\frac{1}{2w} + \frac{1 \cdot 3}{(2w)^2} + \frac{1 \cdot 3 \cdot 5}{(2w)^3} + \ldots\right) \tag{18}$$

Equations (13) to (18) are then used to determine Q so that equation (7), which includes the effect of the filter bandwidths, can be used. Again, the surface impedance and the surface propagation constant must be known to determine the reflection and absorption characteristics.

The results of the methods described in references 5 and 9 are similar (ref. 13). Furthermore, using the plane wave reflection coefficient for a layered medium as the strength of the image source gives excellent results for most practical purposes.

A limited amount of ground impedance data was obtained and is reported in reference 14. The magnitude and phase of the impedance for wet and dry grass surfaces are given as a function of frequency for incidence sound angles of 0° to 83°. There is, however, information on the propagation constant of the surface, which must be known to apply the theory.

Reference 15 compares a limited amount of data on sound propagating over asphalt and grass at grazing incidence with the predictions in reference 5. The predictions agree reasonably well with the reference 15 ground absorption losses and spectral maxima and minima for selected geometric configurations. As stated above, however, the application of these concepts requires knowledge of the complex surface impedance, which at present is limited.

Effects of Source Directivity

The directivity of the sound source must also be considered in establishing the reflection characteristics. Figure 4 shows that in the source-image system, the sound emitted from the image source has a different direction from that of the real source. It may also have a different amplitude and phase angle. If the amplitude and phase are A_d and δ_d for the direct sound wave and A_r and δ_r for the reflected wave, then the reflection coefficient Q_i must be modified as follows:

$$Q_i^{\bullet} = \frac{A_r}{A_d} Q_i \tag{19}$$

The phase angle in the cosine term of equation (7) must be changed to correspond to the differences in the phase angles of the real and image source.

Effects of Source Size

The discussion of ground attenuation and reflection has so far been restricted to the far field of a point source. Where the distance between the source and the receiver is approximately equal to the size of the source itself, the sound waves emitted from different parts of the source are reflected from different points on the surface (ref. 16). For example, jet noise is apparently generated in a large turbulent volume that extends in back of the exhaust plane (ref. 17). With large jet engines, the extended source region smears or disperses the interference dips in the frequency spectrum. Reference 2 reports that this effect is due primarily to the distribution of sources in a vertical plane. If the jet or extended source is high above the ground ($h_s > 10D$, where D is jet exit nozzle diameter), the effects of distributed sources can be neglected (ref. 2) When the jet is close to the ground, however, the source distribution causes the peaks and dips in the spectra caused by the reflected sound waves to diminish in amplitude.

For the case of jet exhaust, the jet can be considered as a vertical distribution of n elementary sources of equal strength separated from each other by a distance d such that $d/h_m = 0.1$ (ref. 2). The symbols and geometry of this problem are shown in figure 6. For an elementary source located a distance d_k from the nozzle center, the difference in path length between the direct and reflected sound waves is as follows:

$$\Delta r_k = \Delta r_m \left(1 + d_k/h_m\right) \tag{20}$$

where Δr_m is the path length difference between the direct and reflected sound waves for a source at the nozzle center. Equation (7) must then be modified to include the source distribution, as follows:

$$\Delta N_i = 10 \log \left[1 + \left|\frac{Q_i}{z_m}\right|^2 + \frac{2|Q_i|}{z_m} \sum_{k=1}^{k=n} \frac{\sin\left(\mu \Delta r_k/\lambda_i\right) \cos\left(\beta \Delta r_k/\lambda_i + \delta_i\right)}{\mu \Delta r_k/\lambda_i}\right] \quad (\text{[illegible]})$$

For a situation in which the acoustic characteristics of the ground are known and there are several identifiable sources of sound of different magnitude or spectral composition, as in the sound produced by an aircraft engine, it is recommended that the effects of ground absorption and reflection be computed and extrapolated separately for each source and then combined on an antilog basis to determine the composite effect of the ground on the radiated noise. Large-scale experiments should be conducted to justify this approach, since few substantiating data exist.

Review of Noise Absorption and Reflection Data

The foregoing analysis is aimed primarily at an understanding and prediction of ground reflection effects. At distances from the source of greater than several hundred meters, the absorption or attenuation of noise due to the ground surface becomes significant. The preceding analysis included the effects of attenuation on a propagating sound wave; however, the lack of surface impedance data limits the usefulness of the analysis.

To make a useful determination of the absorption of sound propagating over the ground, empirical methods based on large-scale experimental data must be used. Many experiments have been conducted on ground-to-ground sound propagation over the years; however, only four of the more important sets of data are reviewed here. The ground attenuation data are presented in references 18 to 22 and are discussed in chronological order. The data were obtained over a wide range of meteorological conditions as well as a variety of open terrain. It has been observed and theoretically calculated that the least attenuation occurs for the case of downwind propagation. Therefore, the downwind propagation aspects of noise are emphasized herein.

In all the data, the inverse square spreading loss and atmospheric absorption losses are removed, and although different researchers used different methods to remove the atmospheric absorption losses, the differences are not believed to be significant, especially for frequencies of less than 2000 hertz.

Figure 7 presents the excess attenuation as a function of distance from the source for several octave band frequencies (ref. 18). The maximum attenuation occurs in the 300-hertz to 600-hertz octave band, with maximum values of 14 decibels. Attenuation was significant for frequencies up to and including the 2400-hertz to 4800-hertz octave band. It can be concluded from these data that the excess attenuation is not linearly proportional to propagation distance. Similar results are reported in reference 19.

An extensive set of experiments that included tests of downwind attenuation (ref. 18) is summarized in figure 8. There is no excess attenuation out to a breaking point that is inversely proportional to the octave band center frequency of interest. At larger distances and higher frequencies, the excess attenuation increases 3 decibels per doubling of frequency or distance. These results agreed qualitively with those of reference 5; however, the results did not agree quantatively, and reference 18 failed to explain the lack of agreement. The data behaved generally consistently except for the data for the 300-hertz to 600-hertz octave band within a 30° sector of the shadow boundary (fig. 8). Substantial sound attenuation occurred in that octave band. Unfortunately, data were not acquired at lower frequencies to determine whether this anomalous behavior persisted at lower frequencies.

In references 18 and 19, a loudspeaker was used as the noise source. An aircraft jet engine was used as a noise source in the experiments reported in references 20 and 21. The noise source in these tests was not only more realistic; it was also propagated and measured on airport terrain. The excess attenuation determined in these tests is shown in figures 9 and 10 as a function of distance from the sound source. Both sets of data are for downwind propagation with normal temperature lapse rates. Figure 9 shows the data obtained at Radlett, Eng., and figure 10 shows the data taken at Hatfield, Eng.

In both sets of data, no attenuation was measured for the 63-hertz one-third octave band; in fact, an amplification was evident. At the other end of the spectrum, the 1000-hertz one-third octave band, there was a small increase in attenuation with distance. This increase was of the order of 1 to 2 decibels per doubling of distance. The attenuation curves at both test sites for frequencies between 1000 hertz and 4000 hertz exhibited less attenuation with distance than the 1000-hertz data. Unlike the data in reference 18, the data showed no tendency for attenuation to increase with increasing frequency. Most sound absorption at both test sites occurred at frequencies between 200 hertz and 400 hertz. At Radlett the peak absorption (24 decibels) occurred near a frequency of 250 hertz, whereas at Hatfield the maximum absorption was observed at frequencies between 250 hertz and 400 hertz. Theoretical investigations have shown that the frequency of peak absorption is greatly dependent on the ground impedance, so the shift in the frequency of maximum absorption is probably due to the difference in ground impedance at the two test sites.

The most recent data for the ground-to-ground propagation of aircraft noise are reported in reference 23. The data were acquired in the vicinity of the Los Angeles and Denver airports on a radial line that extended into the community from the point where the takeoff roll of regularly scheduled transport aircraft began. The more distant measurements were made in residential areas, with houses and other obstructions between the aircraft and the measurement positions. Figure 11 presents the data for downwind attenuation as a function of distance and frequency. The data indicate that the maximum absorption occurs in the 125-hertz and 250-hertz octave bands, in good agreement with the reference 21 data; however, these data also show substantial absorption for the 31.5-hertz and 63-hertz octave bands, whereas reference 21 finds no attenuation at these low frequencies. Because of apparent problems in determining absorption losses due to atmospheric attenuation, no ground absorption losses were evident for frequencies above 500 hertz. Sufficient data were taken to determine a measure of the variability of this type of data with standard deviations for octave bands of noise ranging from 6 decibels to 12 decibels for propagation distances of 1000 meters to 2000 meters.

An engineering procedure was developed in reference 22 for estimating extra ground attenuation in a downwind direction. It was assumed that the extra ground attenuation for downwind propagation was caused by the scattering of the sound by turbulence. The procedure is apparently based primarily on the data in reference 18, with attenuation increasing with both distance and frequency. The procedure specifically excludes ground absorption effects at frequencies below 1000 hertz; thus, the dominant absorption effects noted in references 20, 21, and 23 are omitted.

Summary

There are shortcomings in all the data upon which the procedures used to estimate the ground attenuation of noise are based; however, it is recommended that the data reported in reference 23 be used for estimating ground absorption. Figure 12 shows the excess attenuation reported in reference 23 as a function of frequency and distance. These data are based on measurements taken at distances up to 2100 meters from the source. Because of the lack of data and of confidence in the validity of extrapolating these data, it is recommended that the maximum attenuation values shown in figure 12 be used for estimating excess attenuation at distances greater than 2100 meters.

A procedure based on measured excess downwind attenuation is believed to be most appropriate, because for an aircraft flying into the wind, peak noise is radiated in the aft quadrants. In addition, for temperature lapse and upwind conditions, additional attenuation occurs due to the formation of acoustic shadows. Thus, the downwind estimates of the attenuation of noise give the most conservative estimate. Furthermore, reference 8 calculates the attenuation due to the ground based on estimates of the acoustic characteristics of a grass-covered surface, and there is qualitative agreement between those estimates and the reference 23 data, in that absorption occurs primarily in frequencies below 1000 hertz with the peak absorption at 250 hertz.

It should be remembered that this procedure is valid only when both the source and receiver are near the ground.

A considerable amount of research in this area will be necessary before a high level of confidence can be achieved in estimates of the attenuation of sound propagating over the ground. Some areas where research is required are as follows:

Determination of acoustic impedance as a function of angle of incidence and frequency for a number of practical surfaces, such as grass-covered soil.

Determination of the propagation constant for several practical absorbing surfaces.

Investigation of the effects of surface roughness and determination of its impact upon current theoretical models of ground absorption.

Large-scale experimentation using broadband and single-frequency sources to verify the usefulness of the theoretical models. Data for a variety of actual ground surfaces should be acquired in sufficient quantity to be of statistical significance.

Experimentation to determine the importance of accounting for the size of a noise source such as an airplane.

TRANSITION BETWEEN GROUND-TO-GROUND AND AIR-TO-GROUND ATMOSPHERIC PROPAGATION

The discussion in the preceding section is valid only for the ground-to-ground propagation of sound; that is, when both the source and the receiver are near the ground. When the source or receiver is above the earth's surface, the effect of ground absorption on the sound diminishes; however, the effects of reflection and interference remain.

Several methods have been proposed to account for the transition from ground-to-ground to air-to-ground propagation. The most widely known methods are based on measurements of aircraft noise, and three such methods are reviewed in reference 24. The transition factors, which are multipliers of the ground absorption in subjective units, are shown in figure 13 (from ref. 24) as a function of the angle between the horizontal and the line connecting the source and receiver (elevation angle). At small elevation angles, 100 percent of the ground attenuation is accounted for, whereas at higher angles, a decreasing percentage of the ground attenuation is accounted for.

To use this type of procedure, the ground attenuation must be specified in subjective units, such as A-weighted sound pressure level (dB(A)) or effective perceived noise level in decibels (EPNdB). Two models for ground attenuation that use these units are shown in figure 14. The use of the curves in figure 14 is restricted to situations in which the spectra of the noise sources are similar to aircraft noise spectra and the noise propagates over similar terrain. It would be much more desirable to use the ground attenuation data as a function of frequency with some sort of multiplicative transition factor for each frequency band. This type of data, however, is not currently available.

The civil noise exposure forecast (NEF) transition factor shown in figure 13 provides for 100-percent ground attenuation for elevation angles up to 4° 18', and for the linear interpolation of percentage of ground attenuation for angles between 4° 18' and 7° 11'. For angles greater than 7° 11', it was assumed that the ground attenuation was zero. It is believed that no particular significance can be attached to the angles 4° 18' and 7° 11' other than the fact that they were convenient for computation purposes.

The procedure developed in reference 25 takes the form $e^{-\gamma/2}$. The transition factor provides for 100 percent of ground attenuation for $\gamma = 0$ and no attenuation for elevation angles greater than 6° (fig. 13). This transition factor is a multiplier for a dB(A) measurement of ground attenuation (fig. 14(a)) for ground-to-ground propagation of aircraft noise. Actual ground attenuation is believed to be greater than indicated by this model, because the most significant attenuation occurs for frequencies less than 1000 hertz, and the dB(A) measurement deemphasizes frequencies less than 1000 hertz.

The transition factor suggested by the Society of Automotive Engineers in their draft of AIR 1114 is given by $e^{-[\tan(3\gamma)]^{1/2}}$ where γ is the elevation angle. As shown in figure 13, that factor provides for varying amounts of attenuation in terms of EPNdB up to elevation angles of 30°. The ground attenuation recommended by the Society of Automotive Engineers in terms of EPNdB for takeoff and landing operations is shown in figure 14(b) as a function of distance. Data are not presented in the report to support the use of this particular form of the transition factor.

Experimental data on this subject are meager, and the data there are provide conflicting answers. The data in reference 26 indicate that there is significant sound attenuation at elevation angles of 0° to 2°. At elevation angles above 5°, the effects of the ground attenuation of the sound was found to be negligible. More recently, unpublished ground attenuation data based on measurements of aircraft noise were obtained by the McDonnell Douglas Company and the British Aircraft Corporation. These data are shown in figure 15, but, unfortunately, the data are again in subjective units, EPNdB and perceived noise level in decibels (PNdB). The data show that ground attenuation occurs at elevation angles greater than 40°.

Because of the meager and conflicting nature of the data, the choice of procedure used to account for the transition between ground-to-ground and ground-to-air propagation must be arbitrary. Therefore, it is arbitrarily recommended that the civil NEF method be used.

It is evident that both theoretical and experimental research need to be done to develop the proper model to account for the reduction of ground attenuation with increasing elevation angle. It is imperative that the transition data be in terms of one-third octave-band sound pressure levels. Experiments to determine the dependence of the ground attenuation on elevation angle and frequency should be conducted over different types of terrain.

ATMOSPHERIC ABSORPTION LOSSES

The propagation of sound through a real atmosphere is a complex process. It is affected by temperature and temperature gradients, humidity and humidity gradients, wind and wind gradients, and the level of turbulence. The propagation of sound is further complicated by the random variation in space and time of the temperature, wind, and turbulence level.

To simplify the problem so that it was amenable to analysis, it was assumed that time-averaged values of the fluctuating quantities were used and furthermore that those values were the same in any horizontal strata of the atmosphere.

Classical Absorption in a Homogeneous, Quiescent Atmosphere

When sound is propagated in a uniformly homogeneous, quiescent atmosphere, the absorption losses can be classified in two categories: classical losses, that is, those associated with the change of acoustical energy into heat; and molecular relaxation losses—those associated with the change of acoustic energy into internal energy within the air molecules themselves. These losses are reasonably well understood and have been found to be functions of temperature, humidity, and atmospheric pressure (refs. 27 and 28). The equation for an acoustic pressure wave propagating through a homogeneous atmosphere, including the effect of atmospheric absorption, is as follows:

$$p = \frac{A(\theta,\varphi)}{r} e^{-\alpha r} \qquad (22)$$

where α is the absorption coefficient in nepers per unit distance, which depends primarily on temperature, humidity, and frequency. Converting equation (22) to decibels and examining the change in sound pressure level at two different distances from the source, the following equation is obtained:

$$\Delta L_p = -20 \log \frac{r}{r_0} - (20 \log e)\alpha\left(r - r_0\right) \qquad (23)$$

$$\Delta L_p = -20 \log \frac{r}{r_0} - a\left(r - r_0\right) \qquad (24)$$

where a is the absorption coefficient in decibels per unit distance and is considered to be the sum of the classical and molecular or relaxation absorption, or

$$a = a_c + a_{mol} \qquad (25)$$

Classical absorption is well understood and does not contribute much to the total absorption for normal atmospheric conditions except at high frequencies. Classical absorption, as defined here, is due to viscosity, the conduction of heat, the diffusion of oxygen and nitrogen molecules among each other, and molecular absorption losses for the rotational relaxation of oxygen and nitrogen molecules. The rotational relaxation losses were lumped together with the viscosity, heat conduction, and diffusion losses because they vary in the same manner with temperature and frequency in the audio frequency range (refs. 29 and 30). Equations relating absorption to the thermodynamic and gas dynamic properties of air for each of these mechanisms are given in references 27 to 30. Using the best experimental data available, reference 31 developed the following expression for classical absorption losses in decibels per hundred meters as a function of temperature, pressure, and frequency:

$$a_c = 1.58 \times 10^{-13} \left[\frac{1.365T}{T + 107}\right] \frac{f^2}{P} \qquad (26)$$

Temperature is in Kelvin, frequency is in hertz, and static pressure, P, is in pascals. Equation (26) can be suitably nondimensionalized using the following technique:

$$a_c\lambda = \frac{a_c c_0}{f} = 5.42 \times 10^{-11} \left[\frac{0.7972(T)^{3/2}}{T + 107}\right] \frac{f}{P} \qquad (27)$$

The reference speed of sound was taken to be 343.37 meters per second at 20° C.

Molecular Absorption in a Homogeneous, Quiescent Atmosphere

The absorption of sound due to molecular collisions is not as well understood as the classical absorption process, although a preliminary theoretical basis for the process was established by Kneser in 1933 (ref. 32). This theory established the dependence of the primary molecular absorption for oxygen molecules on temperature and humidity. The theory required the experimental determination of the relaxation frequency for the oxygen molecules, and for a number of years experimental techniques and apparatus were not good enough to determine the molecular absorption coefficient accurately. The theory is summarized and early experimental results are evaluated in reference 27.

An extremely careful experiment was conducted in 1963 by Harris to measure the molecular absorption of sound in air as a function of humidity at a constant temperature and pressure (ref. 33). On the basis of these measurements, the theory described in reference 32, and experimental values of absorption based on aircraft flyover noise measurements, the Society of Automotive Engineers issued ARP 866 (ref. 34) for determining atmospheric absorption as a function of temperature and humidity. The method described in this report is widely used for determining both the classical and molecular absorption of sound in air.

After the publication of ARP 866 and the subsequent comparison of predicted results with measurements of attenuation determined from aircraft noise measurements, several authors concluded that reference 34 was in error (refs. 23 and 35). However, it appears that some of the flight measurements were taken with instrumentation that lacked sufficient dynamic range to determine the attenuation coefficients accurately. Recent careful experiments (refs. 36 to 39) conducted under a range of temperature and humidity conditions (fig. 16) indicated that, on the average, the atmospheric absorption values predicted by using the procedure defined in ARP 866 (ref. 34) agreed reasonably well with the measured attenuation values. Figure 17 shows a comparison from reference 37 of the attenuation predicted by the ARP 866 procedure with the attenuation measured for frequencies from 50 hertz to 10 000 hertz. Agreement is good except for the two highest one-third octave bands, where the system noise floor apparently intrudes and the number of samples decreased because of inadequate dynamic range in the recording instrumentation.

The most recent comparison of absorption coefficients computed from aircraft noise measurements with values computed using the procedure given in ARP 866 is reported in reference 40. The measured absorption values are compared with predicted values using the actual meteorological conditions. The predictions were made by using the method given in ARP 866, that given in reference 41, and that given in an earlier version of the method proposed by Sutherland (ref. 31). Reference 40 concludes that ARP 866 overestimates the attenuation at frequencies from 1000 hertz to 4000 hertz and underestimates the attenuation at frequencies above 4000 hertz. Most of the test results substantiated the laboratory measurements of molecular attenuation made by Harris (ref. 41). Sutherland's method tended to overestimate the attenuation values, and the difference between the measured and calculated values increased as frequency increased.

The theoretical investigations reported in reference 28 considered air to be a four-gas mixture and applied energy transfer rates to the binary collisions to calculate the sound absorption. The results are in good agreement with the experimental data for 20° C. The method of calculating atmospheric acoustic absorption coefficients suggested in reference 31 is based on the theory in reference 28. The theory given in reference 28 is based on sound physical principles, and additional evidence supporting the theory for a range of temperature and humidity needs to be developed.

Molecular Attenuation Versus Altitude

One laboratory experiment designed to measure the molecular absorption of sound in air at reduced atmospheric pressures was conducted in 1968 (ref. 42). The data in reference 42 showed that the peak molecular absorption shifted to lower humidities at reduced pressures. Using these data, reference 43 pointed out that at elevations between 762 meters and 2438 meters above sea level, the molecular absorption of sound at 4000 hertz would be reduced by approximately 0.3 decibel per 100 meters. The method described in reference 31 appears to include the effects of altitude on atmospheric absorption, whereas the method in ARP 866 does not. Additional studies and experiments are needed to determine whether altitude variations must be considered in the calculation of absorption coefficients.

Meteorological Parameters Along Propagation Path

References 36 to 40 showed that the variation in temperature and humidity along the entire noise propagation path is important and must be taken into account when the attenuation coefficients are calculated. An example of the impact of the measured meteorological parameters along the propagation path on the calculated attenuation coefficients is shown in figure 18 (ref. 40). Also shown are the attenuation values calculated by using the meterological data measured 10 meters above the ground and those calculated by using the mean meteorological data along the propagation path. The measured values of attenuation agree closely with the values predicted by using the mean meteorological data along the flight path. Using the ground-based meteorological measurements resulted in errors of up to 6 decibels per 100 meters of propagation distance.

Spectral Shape and Distance Considerations

Most of the theoretical computations and laboratory experiments dealing with atmospheric absorption were made for discrete frequencies. However, in most practical applications, absorption must be computed for a band of sound frequencies. As was pointed out in reference 34, the computation of absorption of sound for a single frequency with subsequent application to a band of frequencies can lead to erroneous results, since the actual absorption of sound across a band of frequencies depends on the shape of the sound spectrum.

A theoretical analysis of the effect of using a finite bandwidth to calculate values of atmospheric absorption was made by Francis J. Montegani at the NASA Lewis

Research Center. He derived the following expression for the attenuation of sound in the ith band propagating over a distance r.

$$a_i = 10 \log \left[\int_{f_{i,1}}^{f_{i,2}} g(f) df \right] - 10 \log \left[\int_{f_{i,1}}^{f_{i,2}} g(f) 10^{\frac{-A(f)r}{10}} df \right] \quad (28)$$

The upper and lower frequencies of the ith band are given by $f_{i,1}$ and $f_{i,2}$, respectively, and g(f) is the mean square spectral density of the acoustic signal. The atmospheric attenuation function, A(f), is continuous and depends on temperature, pressure, and humidity. The existence of the power spectral density and the attenuation function under the integral sign in equation (28) confirms the fact that the band attenuation is a function of the spectral shape. The propagation distance, r, appears in the integral of equation (28), which shows that the attenuation per unit distance is not independent of distance.

Montegani's analysis indicates that substantial errors in absorption coefficients can occur when spectral shape and propagation distance are not properly accounted for, especially at higher frequencies and larger distances. A quantitative description of the atmospheric absorption function, A(f), like that given in reference 31, should be developed and experimentally verified over a range of temperatures and humidities. A rigorous method for computing atmospheric absorption for a band of frequencies, including the effects of spectral shape, is also needed.

Recommended Molecular Absorption Procedure

This review of the data and procedures that are available for predicting the molecular absorption of sound indicated that the procedure given in ARP 866 gave absorption coefficients with the least error. The atmospheric absorption coefficients are presented in ARP 866 for octave and one-third octave bands of noise in graphical form for selected values of relative humidity. A revision of ARP 866 (ref. 44) replaces the original curves with mathematical equations more suitable for machine computation. The equations and procedure given in reference 44 are recommended for calculating molecular absorption. The equations and procedure are as described below.

First, absolute humidity is calculated, in grams per cubic meter, from the relative humidity and temperature by using the following equation:

$$H_a = 10^{[\log (RH) - B]} \quad (29)$$

where B is given by:

$$B = b_0 + b_1 T + b_2 T^2 + b_3 T^3 \quad (30)$$

Temperature, T, is in degrees centigrade, and the coefficients are as follows:

$b_0 = 1.328924$

$b_1 = -3.179768 \times 10^{-2}$, per deg

$b_2 = 2.173716 \times 10^{-4}$, per deg^2

$b_3 = -1.7496 \times 10^{-6}$, per deg^3

The second step is to compute the absolute humidity in grams per cubic meter at which maximum molecular absorption occurs as a function of frequency by using the following equation:

$$h_{molmax} = \left(\frac{f}{1010}\right)^{1/2} \tag{31}$$

where f is the frequency in hertz.

Third, the maximum molecular absorption coefficient is computed as a function of frequency and air temperature, as follows:

$$a_{molmax} = 10^{\left[\log (f) + 8.42994 \times 10^{-3} T - 2.755624\right]} \tag{32}$$

The ratio of the molecular absorption coefficient to the maximum molecular absorption coefficient is then related to the ratio of absolute humidity to absolute humidity where maximum molecular absorption occurs. In symbolic notation, this may be expressed as follows:

$$\frac{a_{mol}}{a_{molmax}} \propto \frac{h_a}{h_{molmax}} \tag{33}$$

The following table expresses this relationship. Intermediate values can be determined by using a quadratic interpolation technique.

$\frac{h_a}{h_{molmax}}$	$\frac{a_{mol}}{a_{molmax}}$	$\frac{h_a}{h_{molmax}}$	$\frac{a_{mol}}{a_{molmax}}$	$\frac{h_a}{h_{molmax}}$	$\frac{a_{mol}}{a_{molmax}}$
0	0	1.30	0.840	4.15	0.260
0.25	0.315	1.50	0.750	4.45	0.245
0.50	0.700	1.70	0.670	4.80	0.230
0.60	0.840	2.00	0.570	5.25	0.220
0.70	0.930	2.30	0.495	5.70	0.210
0.80	0.975	2.50	0.450	6.05	0.205
0.90	0.996	2.80	0.400	6.50	0.200
1.00	1.000	3.00	0.370	7.00	0.200
1.10	0.970	3.30	0.330	10.00	0.200
1.20	0.900	3.60	0.300		

The fourth step is to calculate the molecular absorption coefficient. The ratio $\frac{h_a}{h_{molmax}}$ is calculated for a given frequency, temperature, and relative humidity by using equations (29) to (31). The corresponding value for $\frac{a_{mol}}{a_{molmax}}$ is determined from the table. The quantity a_{molmax} is calculated by using equation (32) for the desired frequency and temperature. Then the molecular absorption coefficient is calculated by using the following equation:

$$a_{mol} = a_{molmax}\left(\frac{a_{mol}}{a_{molmax}}\right) \tag{34}$$

The total absorption coefficient is calculated by using equation (25).

To calculate the absorption for one-third octave bands of noise with the previous equations, the geometric center frequency should be used for frequencies up to and including 4000 hertz. For one-third octave bands above 4000 hertz, the lower limiting frequency for each band should be used.

Summary

There are limits to the application of these procedures to the calculation of atmospheric absorption. When long propagation distances are involved, careful consideration must be given to the shape of the source spectrum, the distance of the actual propagation path, and the actual atmospheric conditions along the path. The procedures described herein are for a homogeneous, quiescent atmosphere without gradients. The application of these procedures to other atmospheric conditions could result in serious errors.

Although the atmospheric absorption of sound has been a subject of investigation for 40 years, considerable research is still to be done. Areas where further research would be particularly valuable include the following:

Expansion of the absorption coefficient data base over wider ranges of temperature, pressure, and humidity, so that the more recent theoretical models of absorption can be verified.

Extension of experimental data to frequencies of 100 000 hertz to enhance the usefulness of scale model acoustic data.

Development of rigorous methods for computing atmospheric absorption for frequency bands of sound propagating over long distances.

EFFECTS OF TURBULENCE ON SOUND

An acoustic wave propagating through the atmosphere can be significantly altered by nonhomogeneities in atmospheric density, temperature, and wind velocity. These fluctuations are loosely called turbulence. One of the major effects of turbulence in the atmosphere is to cause amplitude and phase fluctuations in the sound waves passing through the air. These fluctuations in the amplitude and phase of the sound waves can cause substantial fluctuations in the time-averaged root-mean-square (rms) sound pressure level for certain conditions. In the case of a sou source emitting sound into a turbulent atmosphere over a plane boundary, for ple, the sound received at a point is the sum of the direct and the reflected sou waves. Fluctuations in their relative phases can cause major changes in the so pressure level, especially at the minimum point in the interference zone. At the minimum point in a quiescent atmosphere, the sound pressure level is at zero, but turbulence causes sound to be scattered into the minimum region, making the sound pressure level nonzero.

A second major effect of atmospheric turbulence is to scatter the sound away from the observer, which changes the directivity pattern and causes a net attenuation at the observer's position. Thus, a highly directional sound field tends to become more omnidirectional as distance from the source increases. The primary effect to be assessed is the magnitude of the attenuation due to the turbulence. It should be emphasized that the concept of attenuation due to scattering is valid only in the region of maximum intensity in a directional noise field. The acoustic energy that is scattered out of regions of high intensity is scattered into regions of lower intensity, producing an increase in the average rms level or a negative attenuation. This is a consequence of the conservation of energy.

Theoretical Considerations

Early theoretical estimates of sound attenuation due to turbulence, such as that given in reference 45, were based on the assumption that the size of the turbulence eddy was much larger than that of the sound wavelength of interest. Because of this assumption it was concluded that the scatter attenuation was proportional to the square of the frequency. However, the experimental evidence does not support this conclusion. The earlier theories are summarized in reference 46.

When the turbulence eddies are the same size as the wavelengths of the incident sound, the turbulence energy spectrum must be taken into consideration. Reference 47 suggested that the attenuation due to scattering depended on the sound frequency to the one-third power. Using the Kolmogorov turbulence spectrum, reference 48 showed that scattered acoustic power varied as $f^{1/3}$ and that the scattered acoustic power was a function of fluctuations in wind velocity and temperature. A similar formulation of turbulence-induced attenuation is given in reference 46.

Reference 49 presents the results of using the reference 48 formulation to calculate attenuation coefficients as a function of frequency for a typical summer New Mexico morning. The resulting attenuation coefficients for classical absorption, radiative absorption, molecular absorption, and scattering due to turbulence are shown in figure 19. The calculations show that for frequencies greater than approximately 400 hertz, molecular attenuation is dominant up to a frequency of 100 000 hertz. Below 400 hertz, radiative absorption equals or exceeds attenuation due to turbulence. Thus, it appears that over the audiofrequency range, attenuation due to turbulence is small in comparison with attenuation due to other absorption mechanisms.

Experimental Results

Experimental results that show the effects of turbulence on sound propagation are rather meager. Reference 50 compares its experimental results with a theory developed for a sound field above a plane reflecting boundary and found good agreement. The primary effect of the turbulence in the experimental data was to smear out the interference minimums as previously discussed.

It was reported in reference 51 that there was no attenuation of sound due to turbulence for the propagation of aircraft noise in a nearly vertical direction for a range of turbulence classified from light to heavy. There was some evidence that the peak-to-peak fluctuation of sound pressure level increased with increasing turbulence, but no quantitative relationship was established. References 20, 52, and 53 also report no attenuation due to turbulence. An examination of the extensive aircraft flyover noise data reported in reference 40 also show no consistent attenuation in addition to that caused by classical and molecular attenuation.

A series of attenuation measurements performed over a distance of 1036 meters for a variety of windspeeds is reported in reference 54. After spherical divergence and atmospheric absorption were removed from the data, some excess attenuation was left, which was attributed to scattering by turbulence. For windspeeds up to 8.7 knots and for frequencies between 500 hertz and 6000 hertz, the scatter attenuation per 100 meters derived from the test data was approximately $3.3 \times 10^{-5}(f - 1000) + 1$ where f is the sound frequency in hertz. The attenuation due to scattering is therefore probably no more than 0.7 decibel per 100 meters, which is within the accuracy of the measurements.

An analysis of selected data available in the literature was made in reference 46, which concluded that in general the attenuation due to turbulence was significant. The frequency dependence of the attenuation of sound propagating through the atmosphere was found to vary as the one-third power, $f^{1/3}$.

Thus, estimates of the effect of atmospheric turbulence upon sound propagation in the literature conflict. No data base now exists that can be relied upon to provide reasonable estimates of sound attenuation due to scattering by turbulence. Since the attenuation due to scattering is believed to be small in comparison to the attenuation due to other dissipative mechanisms, it is recommended that at this time the effect of atmospheric turbulence be neglected in calculating the attenuation of sound propagating through the atmosphere.

However, some careful experimental work should be done to determine the importance of turbulence in comparison with other attenuation mechanisms. It must be determined which turbulence characteristics correlate with sound attenuation. It must also be determined which turbulence parameters can realistically be measured. Obviously, a sound wave propagating through a turbulent medium undergoes multiple scatterings. A theoretical model is needed that includes the effects of multiple scattering.

ATMOSPHERIC REFRACTION OF SOUND

The velocity of sound propagation in the atmosphere varies as the square root of the absolute air temperature. Wind velocity adds or subtracts from the sound velocity, depending on whether the propagation is upwind or downwind. In a normal adiabatic atmosphere, temperature decreases with increasing height above the ground, and the decreasing vertical sound speed profile causes the sound to bend upward. Since the wind almost always increases with increasing height above the ground, the sound speed profile decreases for upwind propagation and again causes the sound to bend upward, reinforcing the temperature effect. For downwind propagation, the sound speed profile increases with increasing height above the ground and the sound bends toward the ground, opposite to the direction of the temperature-induced curvature. In this case, the net curvature of the sound path depends on the relative magnitude of the wind and temperature gradients. In an arbitrary sound velocity profile, different sound ray paths passing through different layers of the atmosphere have different radii of curvature. This can result in the convergence or divergence of the sound at a particular receiving point, or the focusing or defocusing of the sound. Figure 20, adapted from reference 55, shows the possible sound ray paths for arbitrary sound velocity profiles.

Shadow Zones

One of the most important effects of refraction in the presence of the ground plane is the creation of shadow zones. As shown in figure 21, the sound ray paths originating at the source and propagating upwind through a medium with a temperature or wind gradient are bent upwards. Geometric ray theory predicts that no sound penetrates the zone behind the limiting sound ray. The limiting ray is that ray that touches the ground at a distance x_s from the sound source which is at a height h_s above the ground. The distance to the beginning of the shadow zone can be calculated from the following equation from reference 55:

$$x_s = \sqrt{\frac{2c_0}{J \cos \theta - 1.086K}} \left(\sqrt{h_R} + \sqrt{h_s} \right) \tag{40}$$

where J is the vertical wind gradient and K is the vertical temperature gradient. A slightly different version of this equation is given in ref[illegible] 56 along with estimates of the temperature and wind gradients for d[illegible]l covers and time of year.

Although geometric theory predicts that no acoustic energy is propagated in the shadow zone, sound has been measured in shadow zones. As a consequence, it has been theorized that the acoustic energy propagated into the shadow results from the scattering and diffraction of the sound. A tentative method for calculating the sound pressure in the shadow zone has been developed (ref. 57). The method is semiempirical, and its general validity has not been substantiated for aircraft noise-related problems.

Ray Acoustics

To describe the effects of the refraction of sound traveling through the atmosphere, geometric ray theory is quite useful. The use of ray theory is limited, however, in that the relative change in amplitude, direction cosines, and sound speed per unit wavelength must be less than unity. For best results, the gradient values of wind and temperature must be averaged over a wavelength in the vertical direction. Acoustic ray theory has existed for many years, but its application to a real atmosphere became practical only after the advent of the high-speed digital computer. Then acoustic ray tracing techniques were developed that predicted the noise intensity far from a Saturn rocket launch (refs. 58 and 59). Preliminary comparisons of the measured noise level with the noise level predicted by using ray theory for static firings of a Saturn 1 rocket are given in reference 60. At distances up to approximately 16 kilometers, the predicted and measured noise levels agreed within 7 decibels. It was determined that the sound speed profile had to be known accurately to make it possible to predict the sound levels accurately.

The ray theory applicable to a moving sound source like an aircraft has been developed (refs. 59 and 61). However, no detailed analysis for a particular aircraft profile has been made. There are no comparisons between predicted and measured aircraft noise levels either. In short, there is insufficient documentation to justify a requirement for, or general application of, acoustic ray tracing methods in the computation of aircraft noise contours.

Focusing

Under certain atmospheric conditions, sound can be focused as shown in figure 20(c). This effect causes an increase in sound level at some distance over that which would normally be expected. Such a noise spectrum would contain acoustic energy predominantly below 1000 hertz, since higher frequency sound is absorbed by the atmosphere. The most reasonable way to calculate the increase in the sound level would be to use empirical methods; however, neither the frequency with which this effect occurs nor its importance in the aircraft noise picture is clear.

Temperature Inversions

The propagation of aircraft noise is also affected by temperature inversions. This problem was investigated by using ray tracing techniques for an aircraft flyover in reference 62. They found that for noise propagating from the airplane to the receiver at elevation angles greater than 30°, the temperature inversion had a negligible effect on the noise.

Recommendations

It is recommended that the effects of wind and temperature gradients on the propagation of noise be neglected in the calculation of aircraft noise signatures. These gradients can increase the noise level because of focusing; however, under the predominant meteorological conditions in this country, this does not occur. The formation of shadow zones and the increase in acoustic path lengths due to these gradients only serve to increase the attenuation of the sound. Thus, a calculation of propagation losses that neglects the refraction effects gives the most conservative estimate.

Before the effects of refraction are included in the computation of sound propagation, several questions need to be addressed. They include the following:

What is required in the measurement of meteorological parameters to insure that the desired accuracy for the predicted sound levels is achieved?

Below what elevation angle between the source and receiver does it become important to consider refraction effects?

What formulation of the ray tracing equations is best for computing aircraft noise contours?

After these questions are answered, outdoor tests will be necessary to confirm the predicted refraction effects with the necessary acoustic and meteorological measurements.

MISCELLANEOUS EFFECTS

There are other factors that influence the propagation of sound in the atmosphere. These factors are believed to be of secondary importance in predicting aircraft noise contours, so no method is recommended for computing their effects on the propagation of noise, and no areas for further research are suggested.

There is a popular belief that fog, rain, and snow cause significant sound attenuation. However, the limited data and analyses available for these conditions indicate the attenuation to be less than 0.3 decibel per 100 meters (refs. 27, 47, 53, and 46). The small amount of attenuation is partly due to the fact that these weather conditions are often stable, especially fog, in which there is little wind and the temperature gradients are at a minimum. These conditions enhance the propagation of sound, because the formation of shadow zones is minimized.

Reference 49 makes an analytical estimate of the sound attenuation due to dust in the air, and concludes that over most of the frequency range, attenuation due to dust is masked by other attenuating mechanisms.

Another factor that affects noise propagation is the shielding afforded by buildings and other structures. The effects of this shielding are quite localized, and the noise levels in the shielded areas can be estimated by using diffraction theory (ref. 27) or other semiempirical method. Such detailed analysis is not warranted for the calculation of aircraft noise contours; however, it would seem necessary to know the attenuation coefficients for sound propagation through an urban environment. Reference 53 states that the attenuation from an elevated source can be predicted in terms of an urbanization factor; however, no data or estimates of this factor are given. If attenuation over or through an urban environment can be characterized in such a manner, substantiating data should be developed.

CONCLUSIONS

A review of the current state of knowledge about the propagation of aircraft noise was conducted. The following conclusions and recommendations are based on this review.

(1) The uniform spreading loss is well understood and can be accounted for at any point in the far field.

(2) There is a strong theoretical base for predicting the effects of ground absorption and reflection for the ground-to-ground propagation of noise. The use of these theoretical models is recommended whenever the acoustic characteristics of the ground surface and the distribution of the sound sources are known. When they are not, estimates of ground absorption should be based on the experimental data presented herein.

(3) For elevation angles up to 4° 18', it is recommended that 100 percent of the estimate of ground attenuation be used. For angles between 4° 18' and 7° 11', a linear interpolation between ground and air attenuation should be used. For elevation angles greater than 7° 11', ground attenuation should be taken to be zero.

(4) It was found that the absorption of sound in a quiet, homogeneous segment of the atmosphere was predicted quite well by using the procedure given in the Society of Automotive Engineers' document ARP 866. To account for atmospheric absorption accurately, temperature and humidity along the sound path must be known.

(5) There is no consistent data base on which predictions of sound attenuation due to turbulence can be based, since some data show no attenuation due to turbulence and other data show small attenuation that increases with increasing frequency. For this reason, it is recommended that turbulence effects be neglected in the computation of noise contours.

(6) The effects of wind and temperature gradients on the propagation of sound are well understood qualitatively; however, the degree of detail in the meteorological measurements necessary to obtain quantitative acoustic results is not known.

Since the estimates of noise level that result when these effects are neglected is usually conservative, it is recommended that the effects of wind and temperature gradients be omitted in the calculation of aircraft noise contours.

Many other factors affect the propagation of noise, but in most instances the experimental data upon which an accurate predictive scheme must be based do not exist. However, these miscellaneous propagation factors are believed to be of secondary importance in the calculation of aircraft noise contours.

Flight Research Center
National Aeronautics and Space Administration
Edwards, California 23523
June 27, 1975

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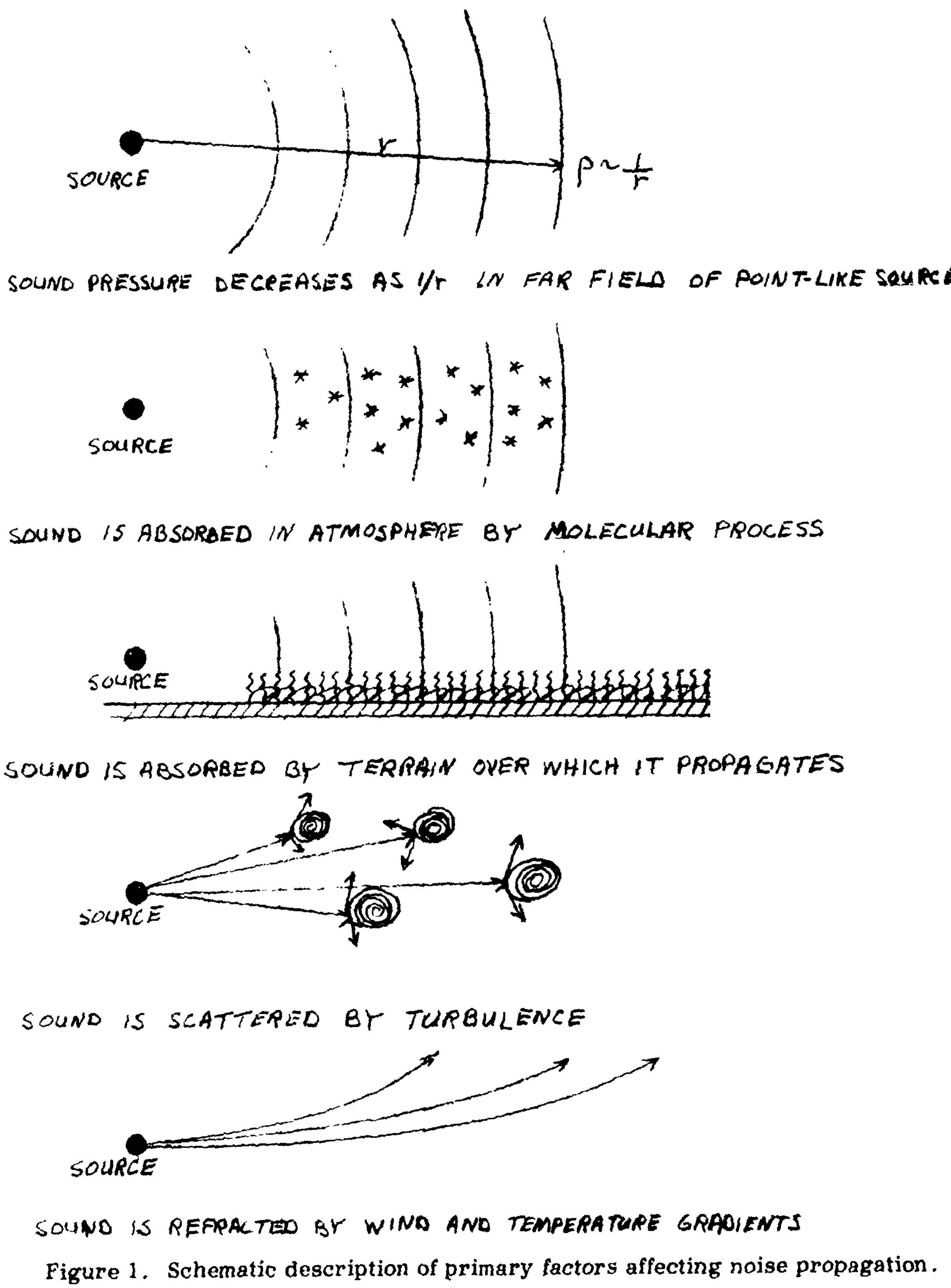


Figure 1. Schematic description of primary factors affecting noise propagation.

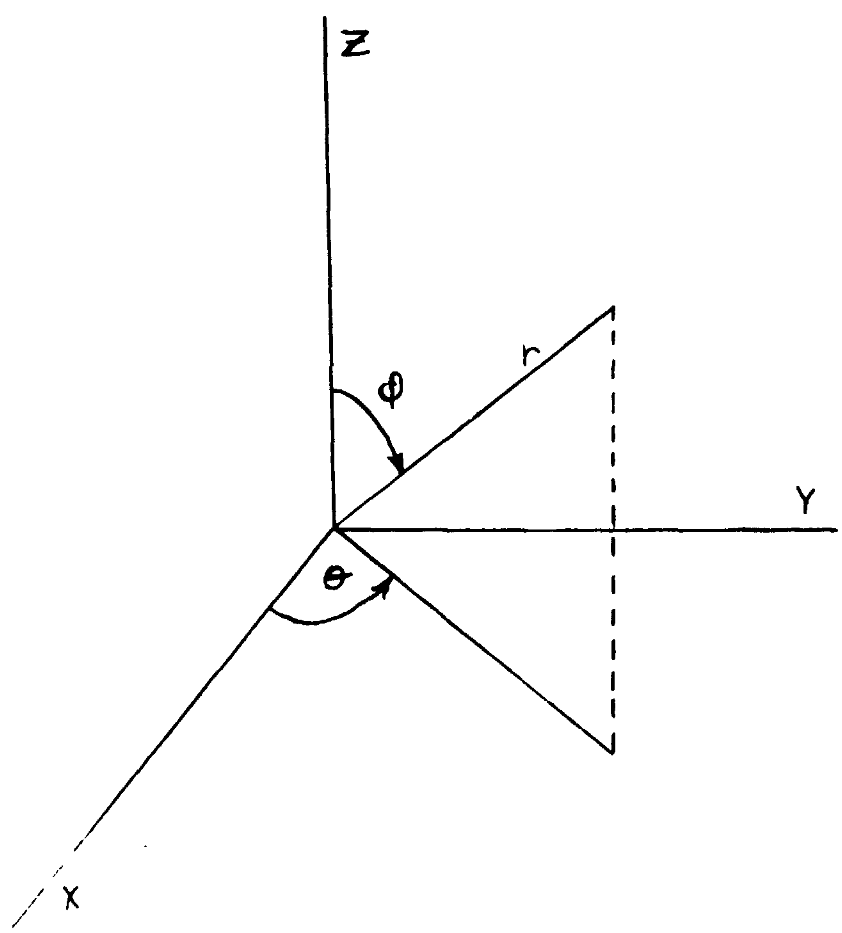


Figure 2. Coordinate s stem.

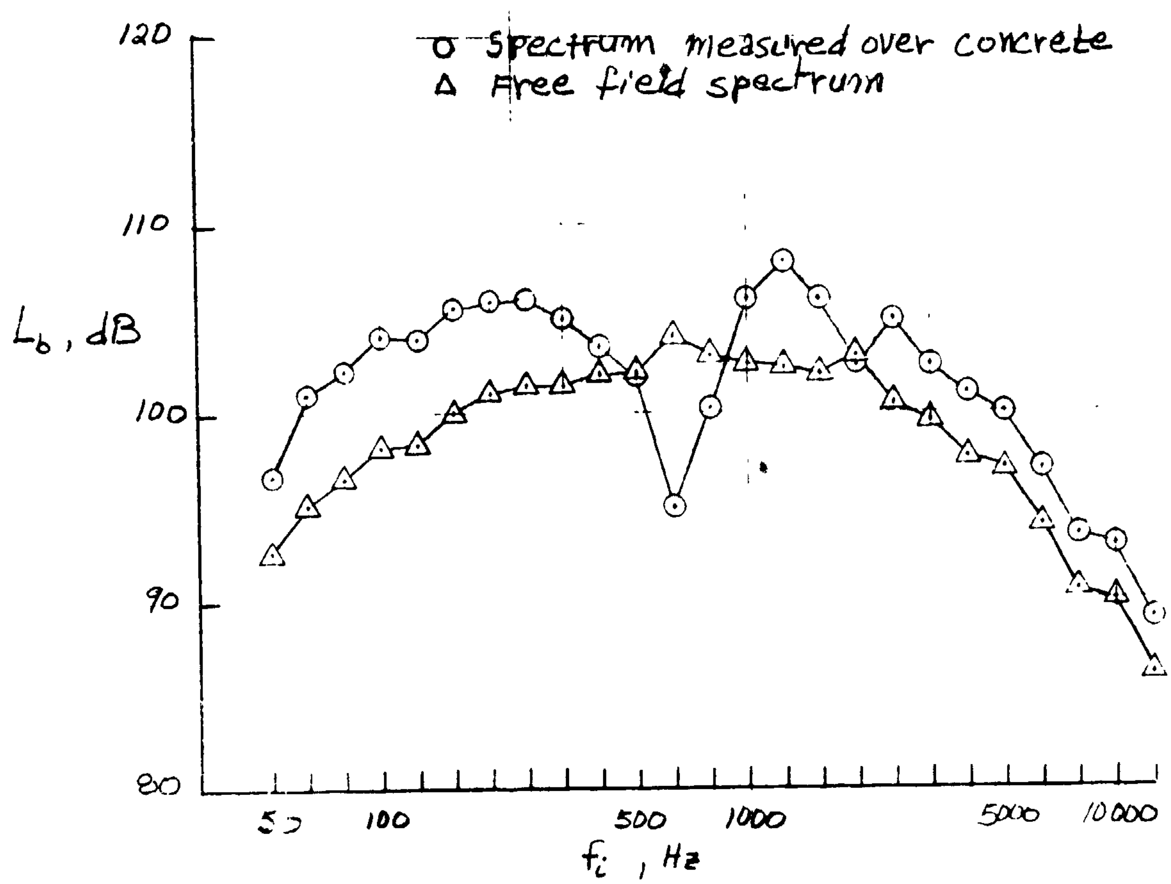


Figure 3. Comparison of free field spectrum with spectrum measured over concrete surface.

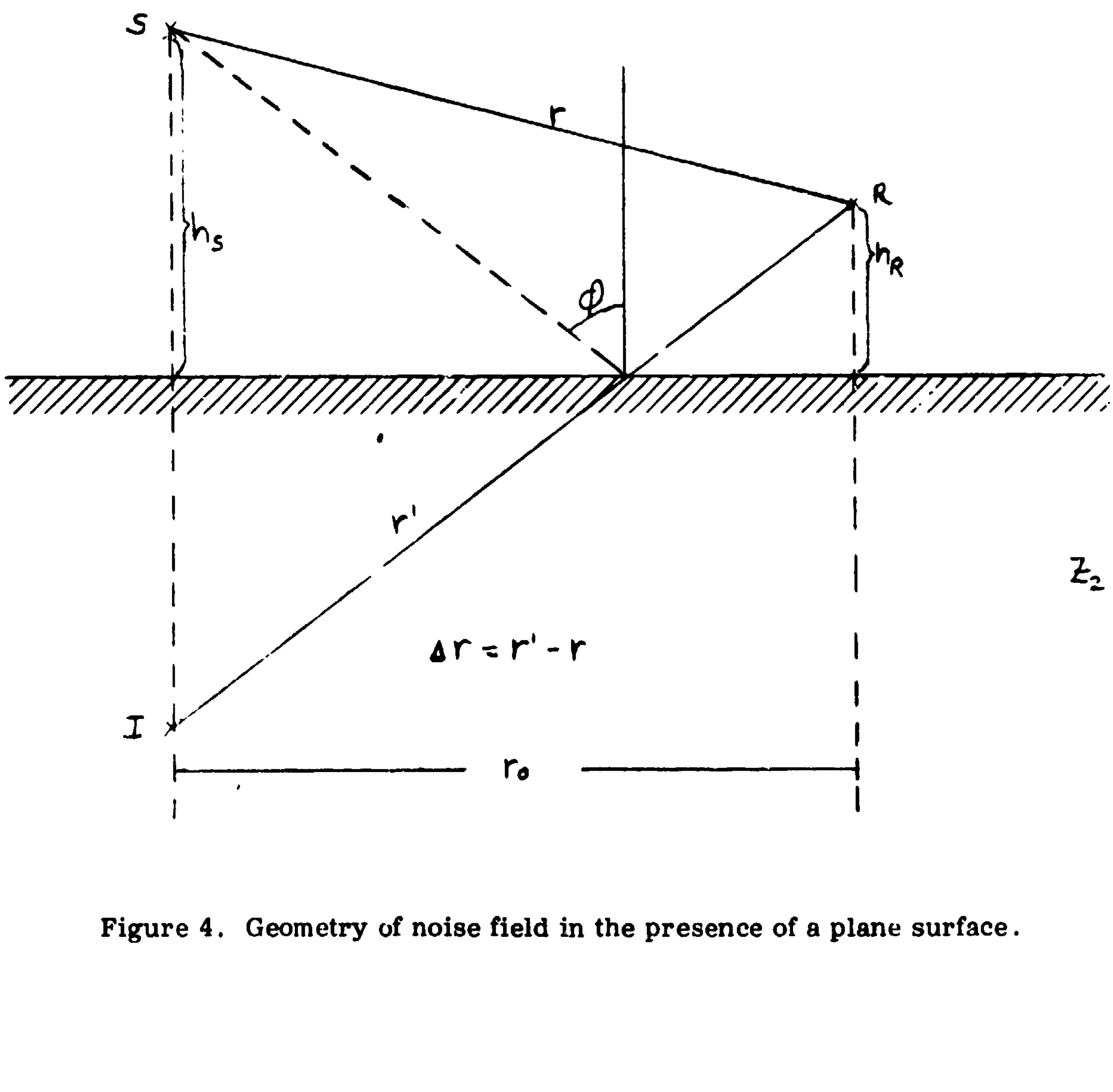
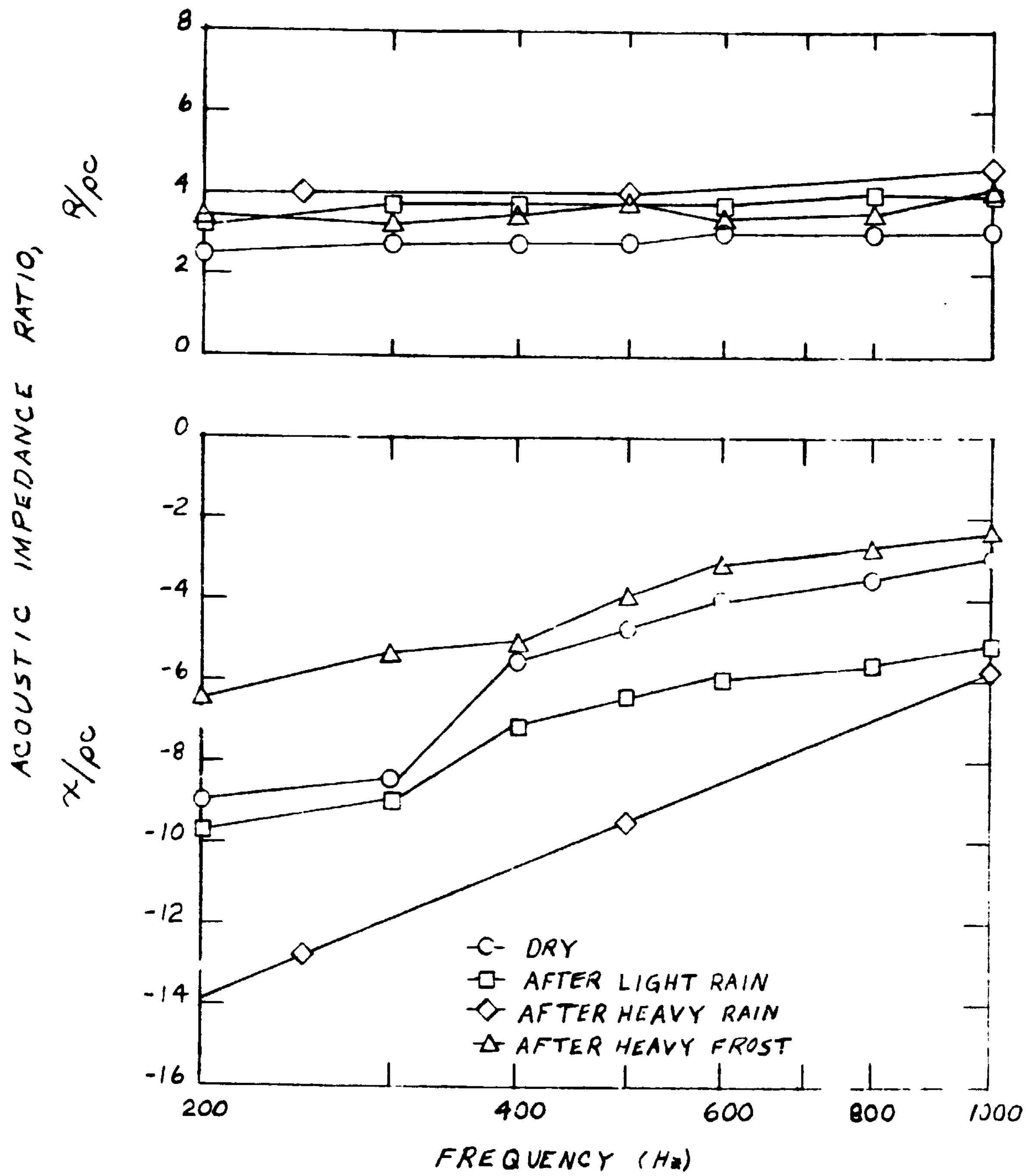
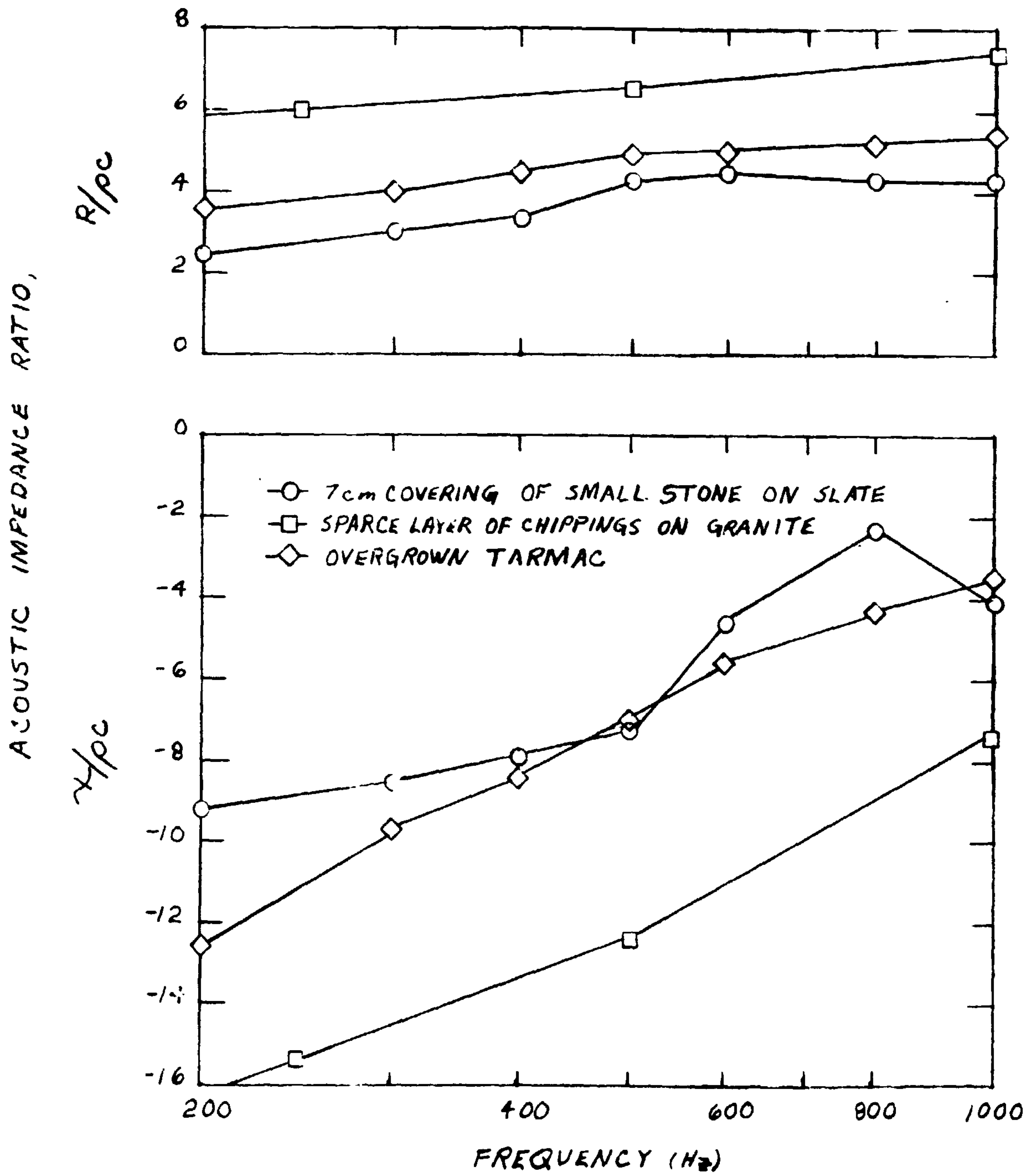


Figure 4. Geometry of noise field in the presence of a plane surface.



(a) Grass covered areas.

Figure 5. Specific acoustic impedance ratio measured for several ground surfaces.



(b) Mineral covered areas.

Figure 5. Concluded.

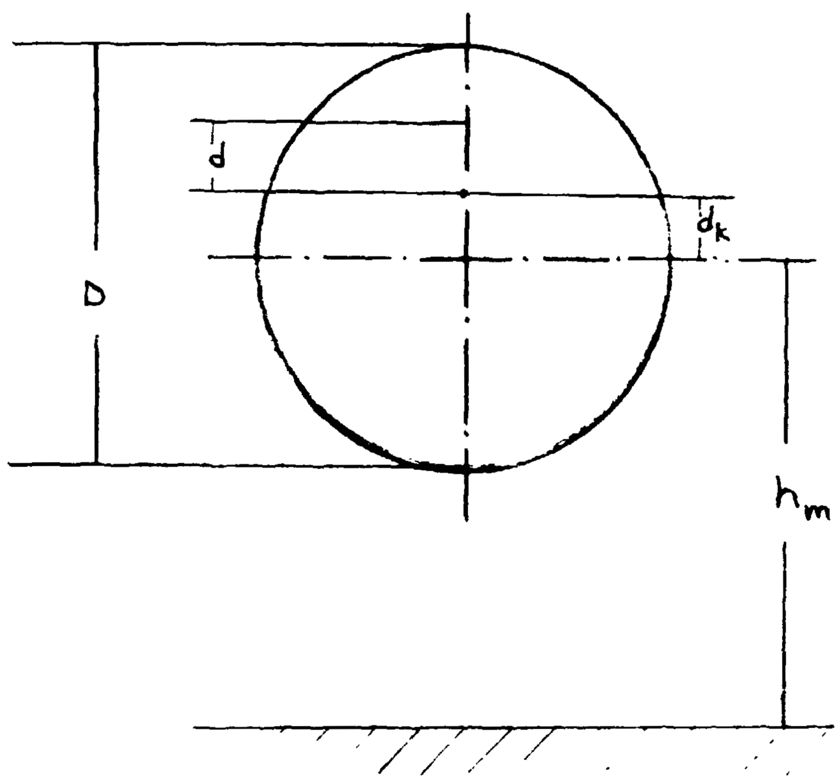


Figure 6. Jet exhaust nozzle with respect to the ground plane.

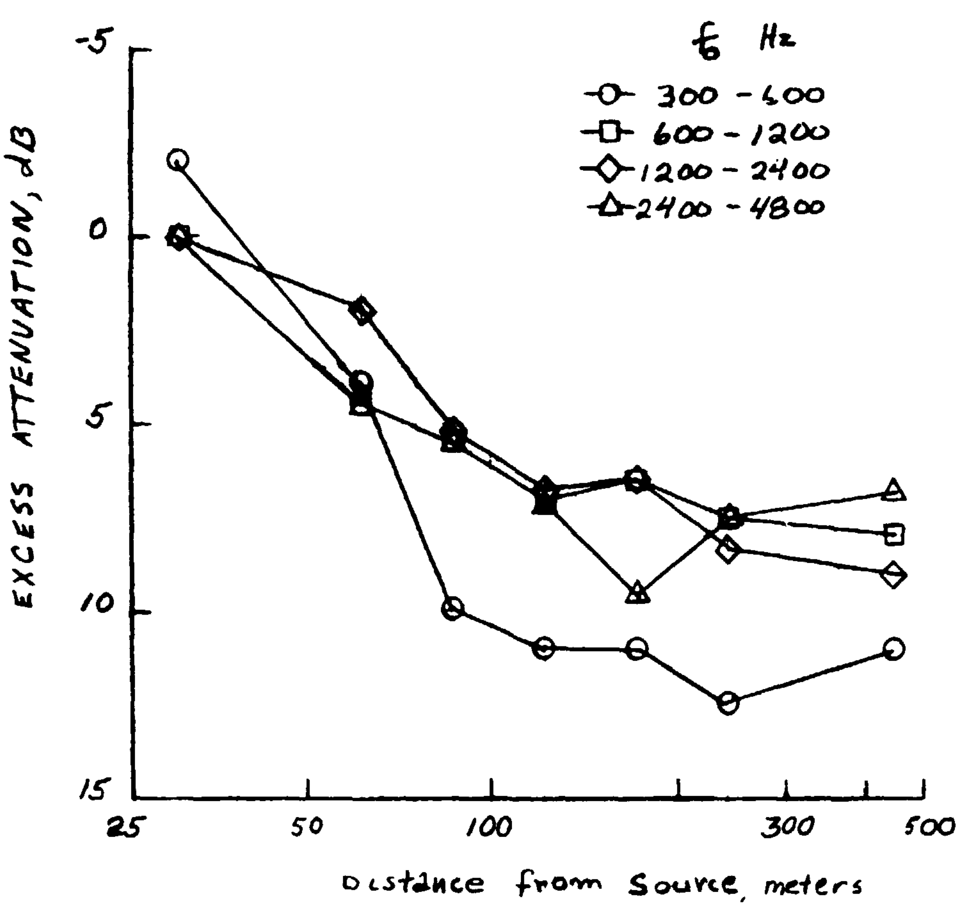


Figure 7. Downwind attenuation as a function of distance (ref. 18).

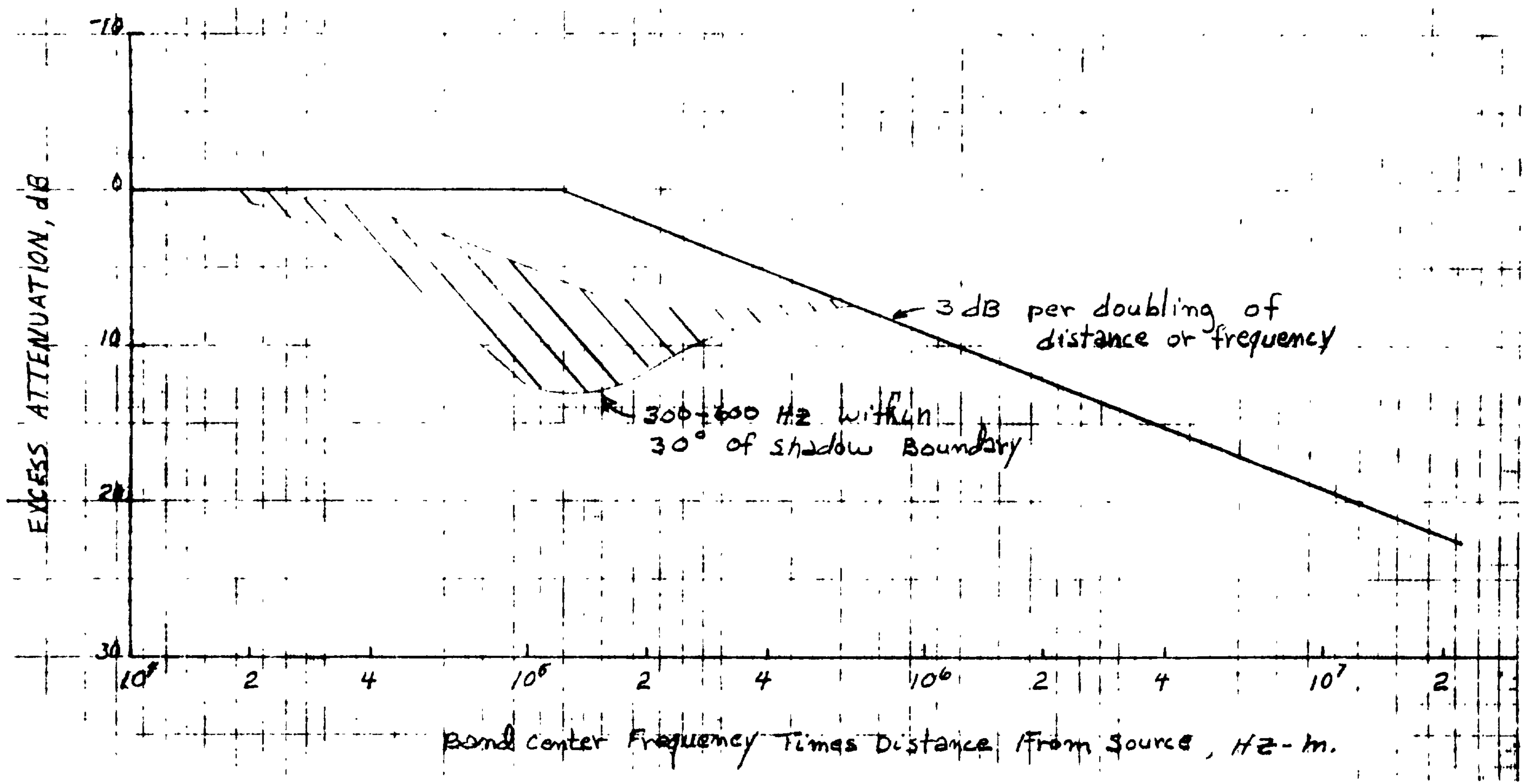


Figure 8. Downwind attenuation (from ref. 18).

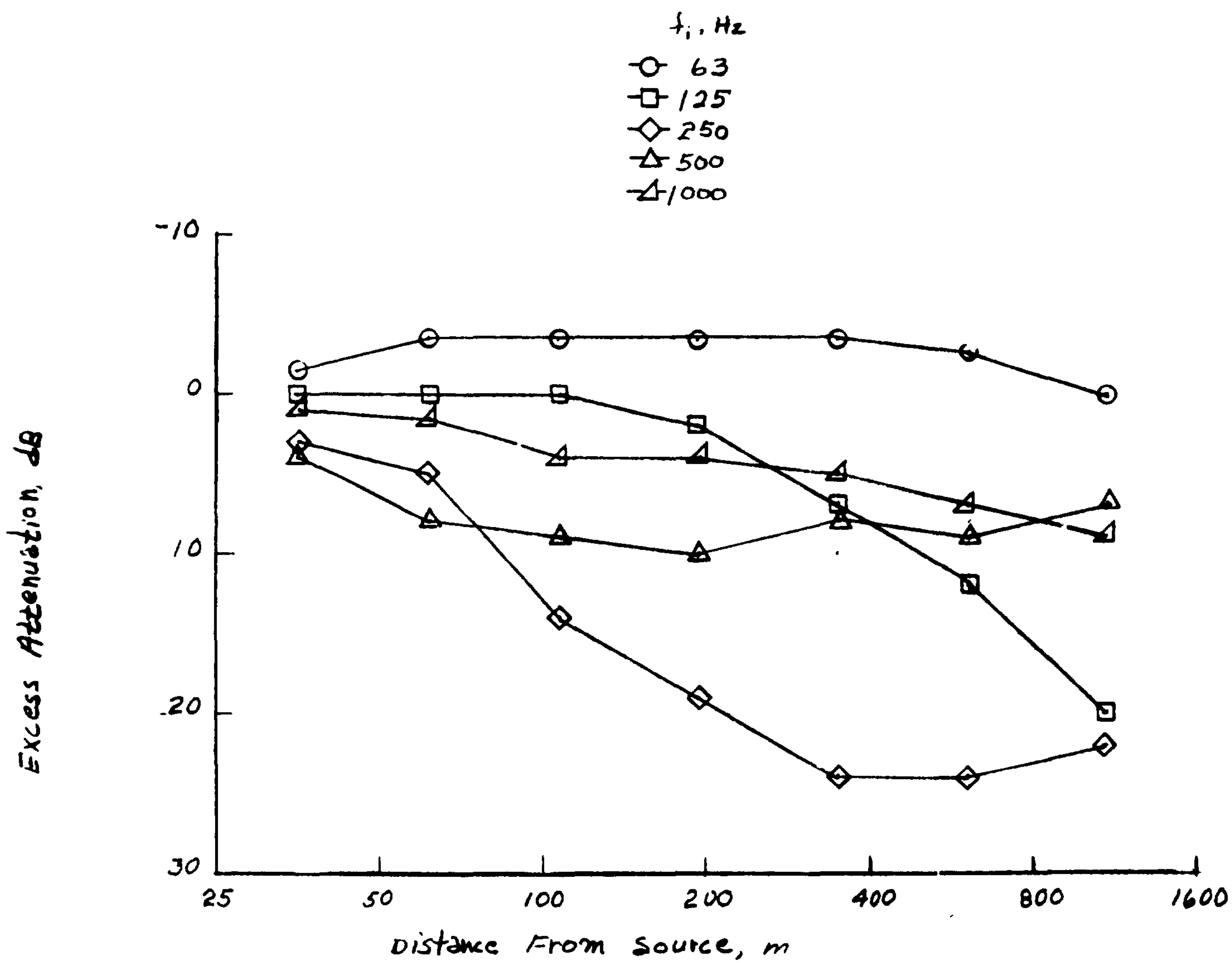


Figure 9. Downwind attenuation as a function of distance (ref. 20). Wind = 8.9 knots; Radlett, Eng.

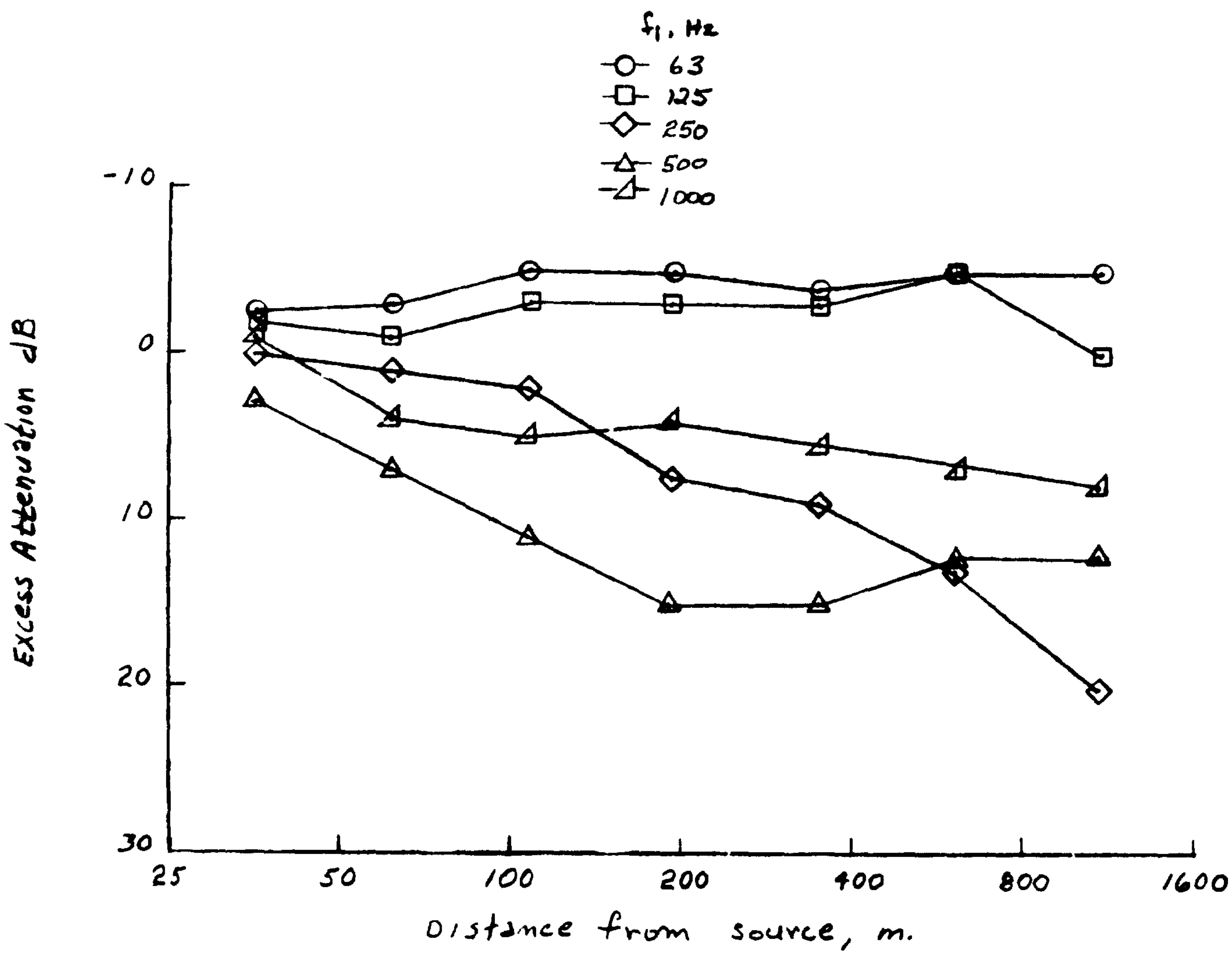


Figure 10. Downwind attenuation as a function of distance (ref. 20). Wind = 8.9 knots; Hatfield, Eng.

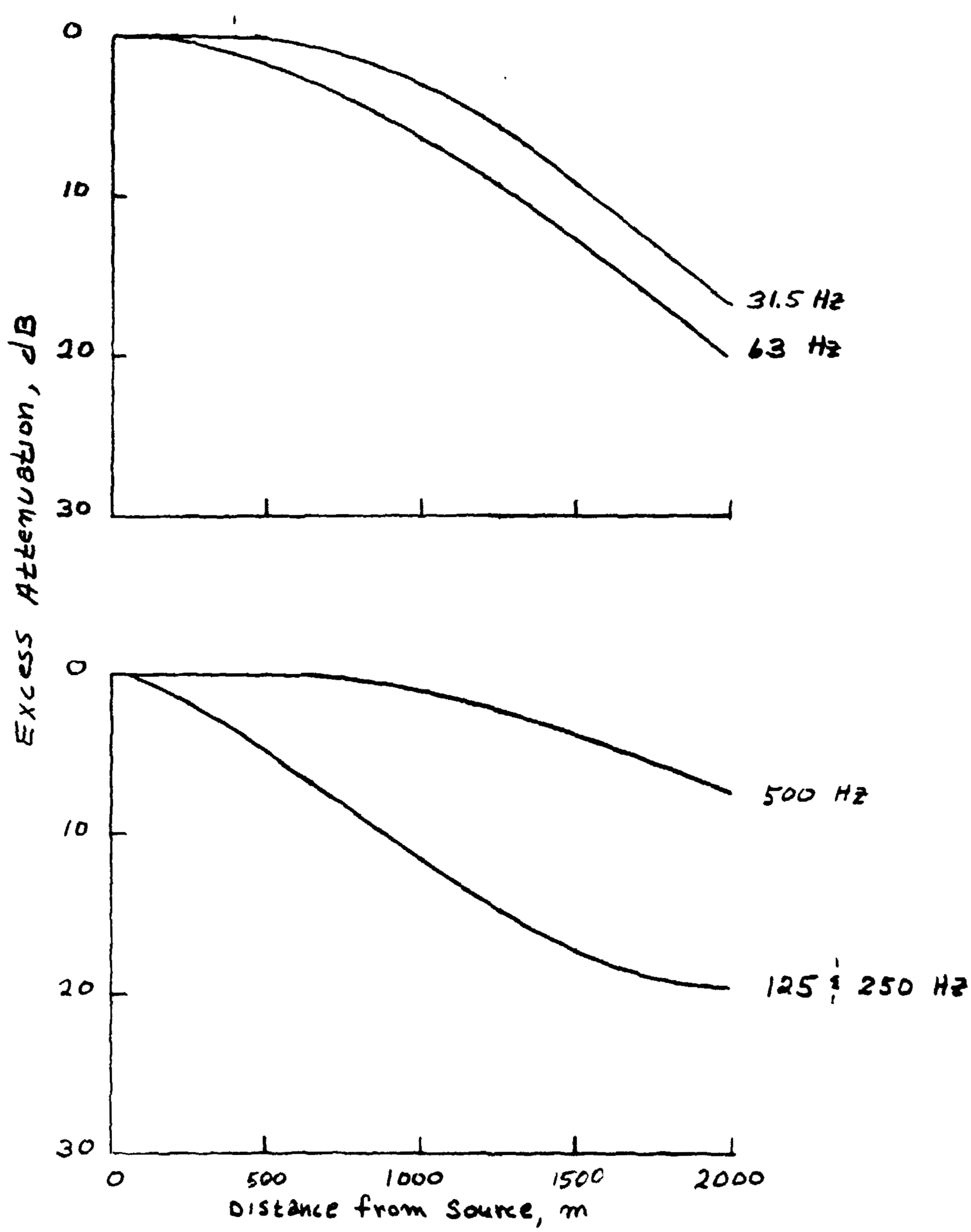


Figure 11. Downwind attenuation as a function of distance (adapted from ref. 23).

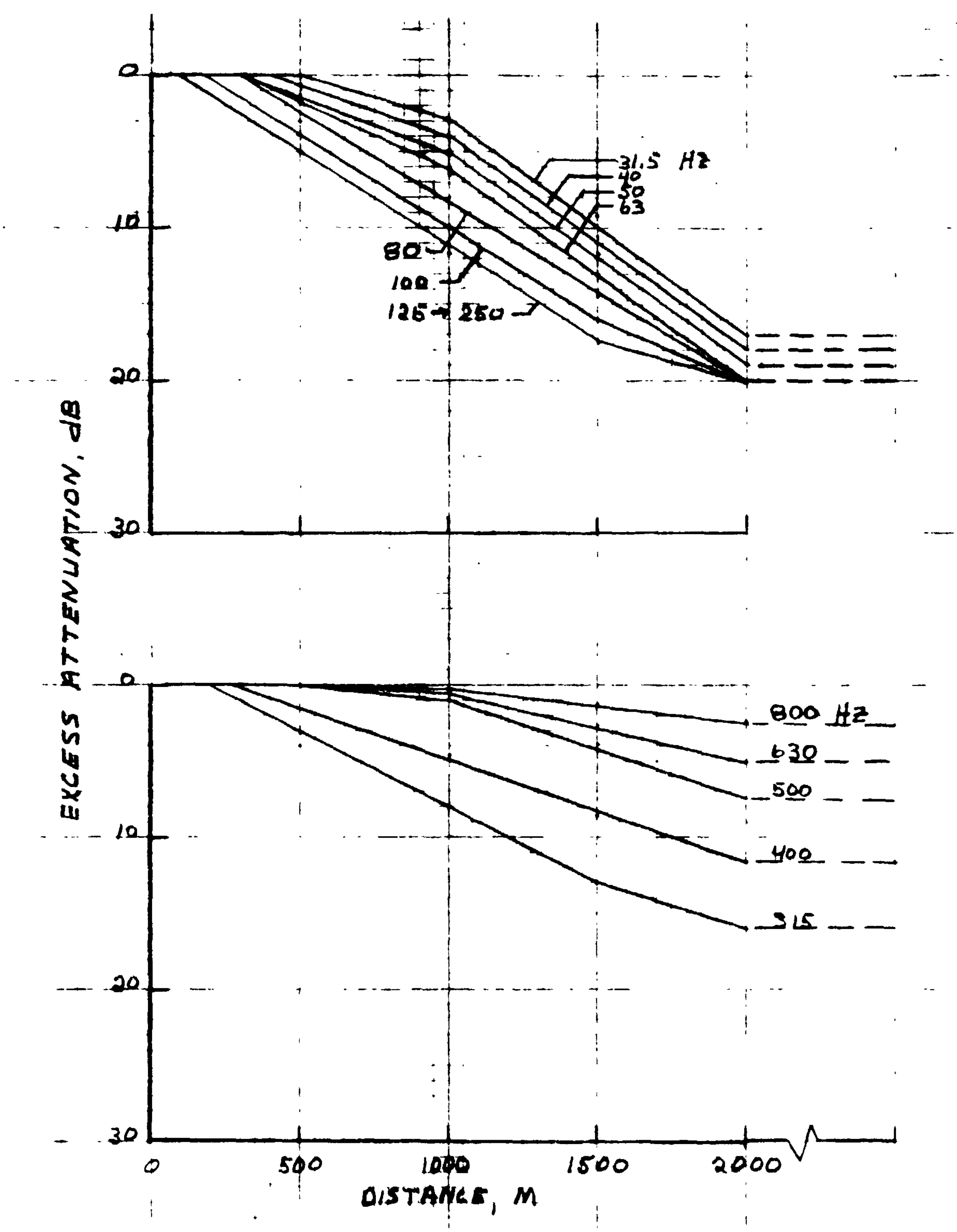


Figure 12. Downwind attenuation as a function of distance and frequency.

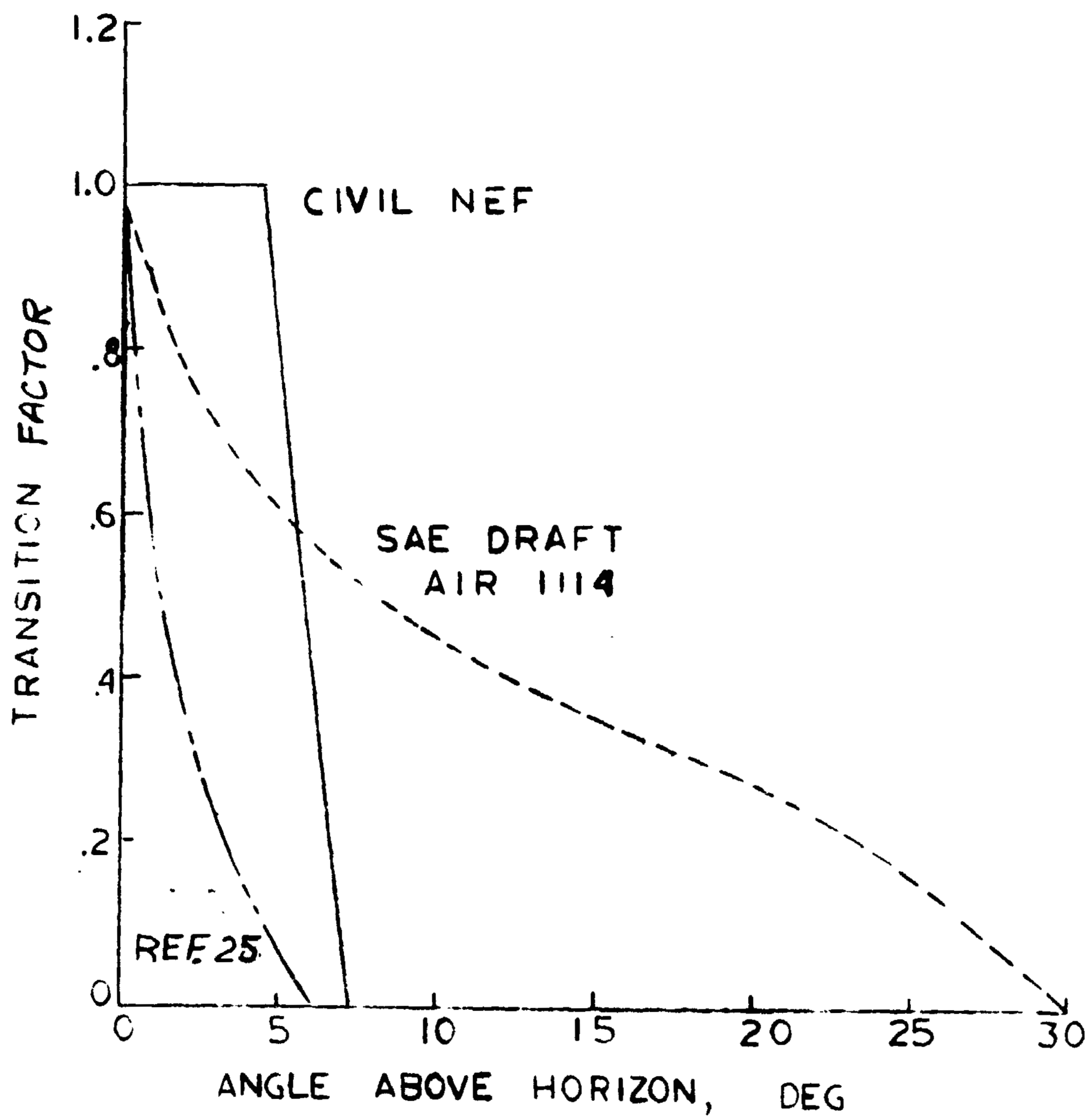
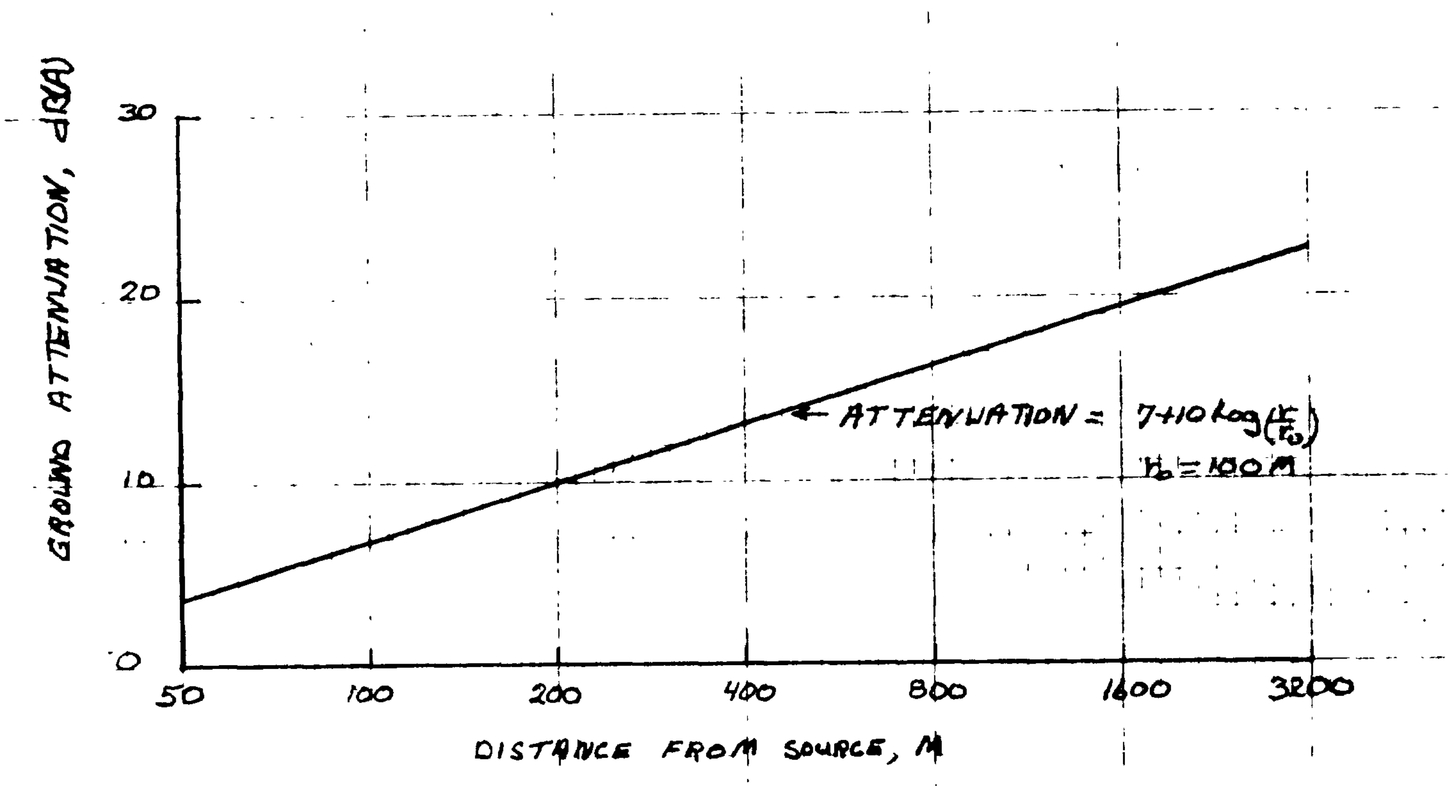
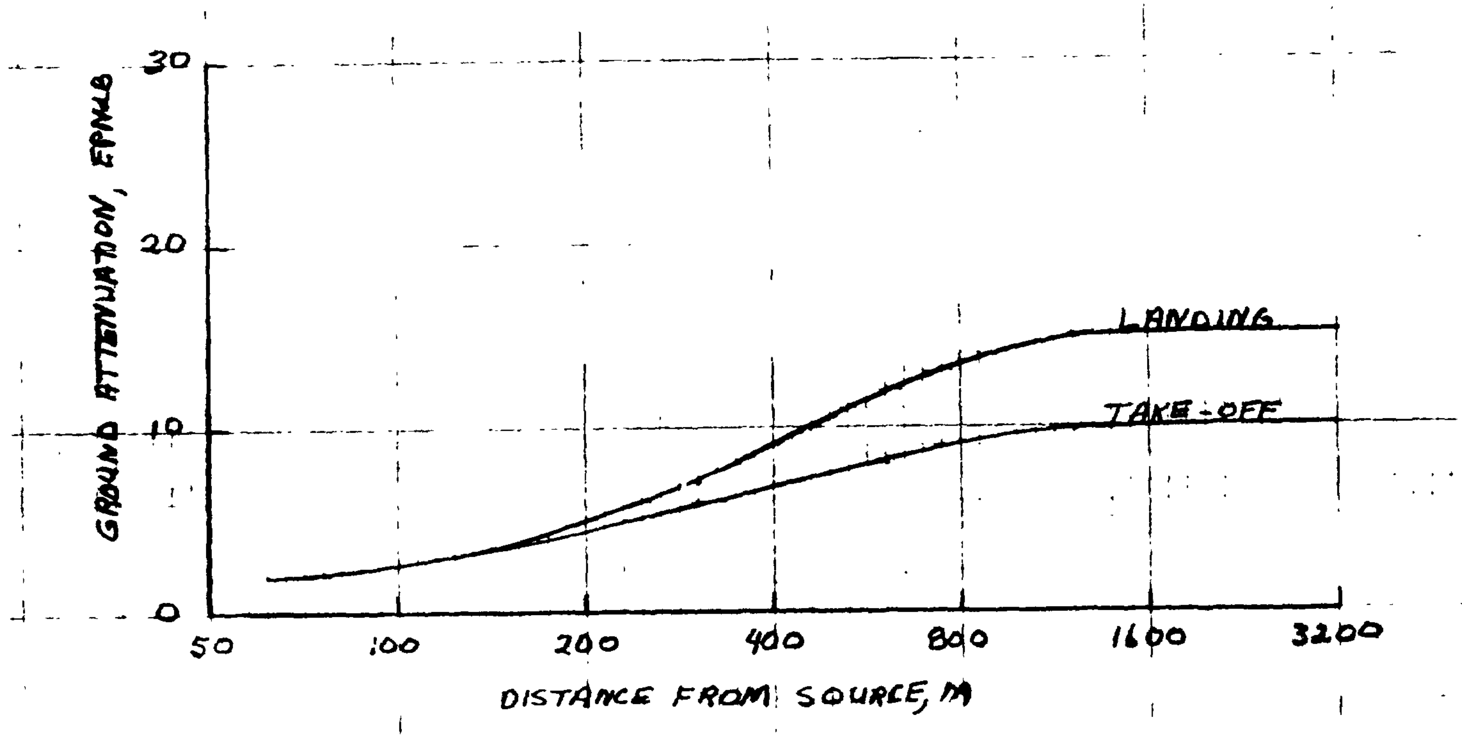


Figure 13. Transition from ground-to-ground to air-to-ground attenuation (from ref. 24).



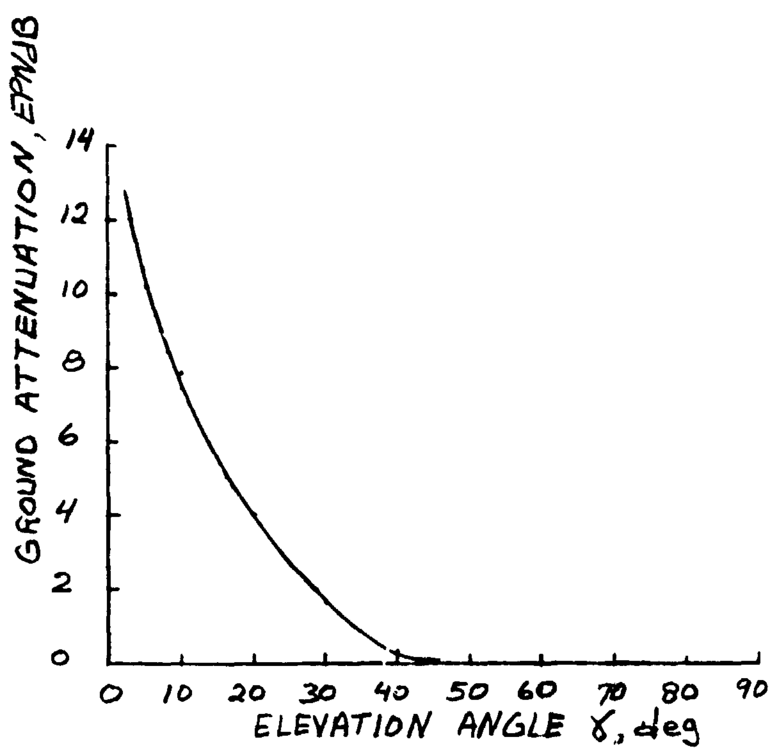
(a) Data derived from measurements at takeoff and landing thrust (from ref. 25).

Figure 14. Ground attenuation for ground-to-ground propagation of aircraft noise.

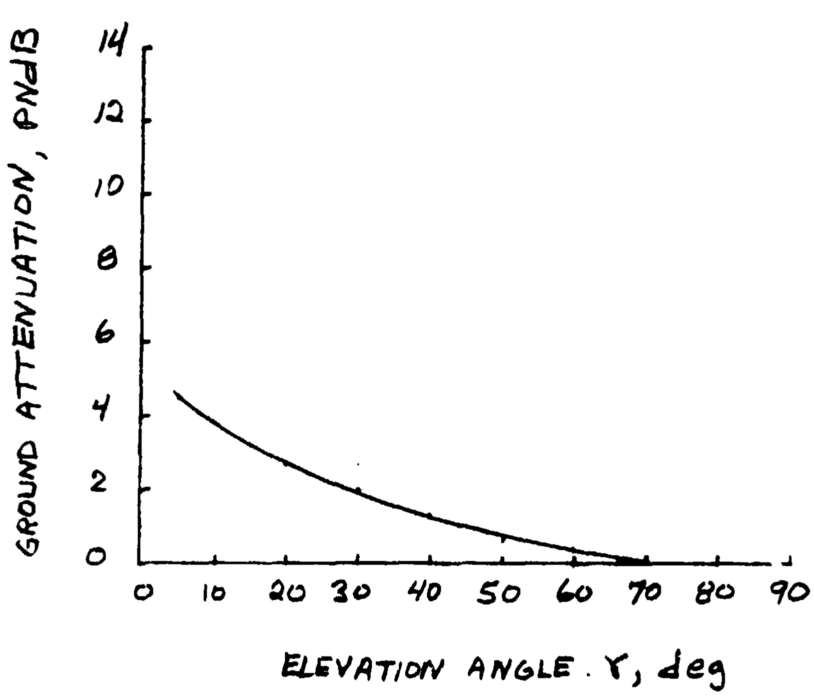


(b) Empirical data based on variety of jet transport noise measurements (from draft of AIR 1114).

Figure 14. Concluded.



(a) McDonnell-Douglas ground attenuation data.



(b) British Aircraft Corporation ground attenuation data.

Figure 15. Ground attenuation of aircraft noise as a function of elevation angle between airplane and microphone.

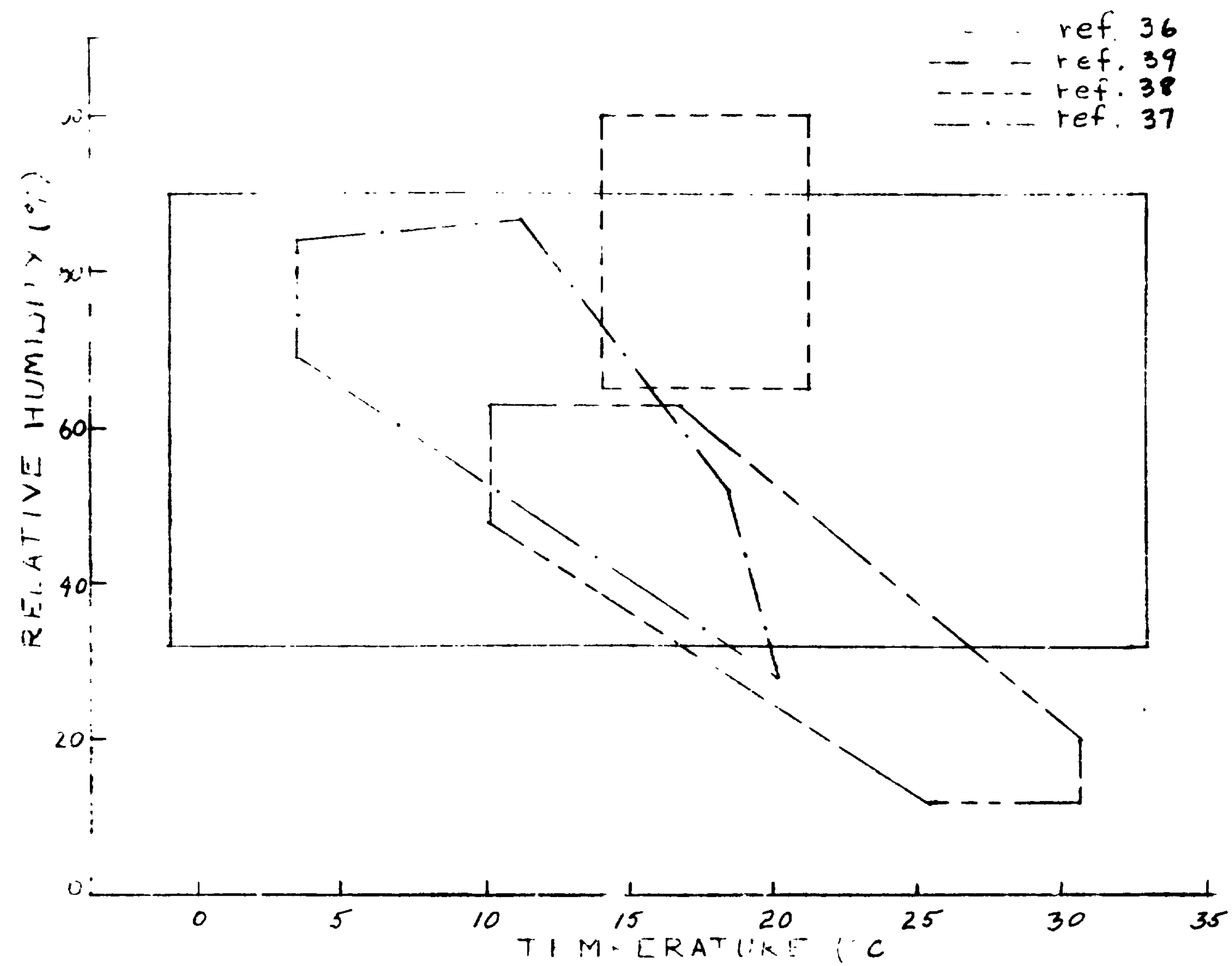


Figure 16. Range of surface climatic conditions during determination of atmospheric absorption coefficients

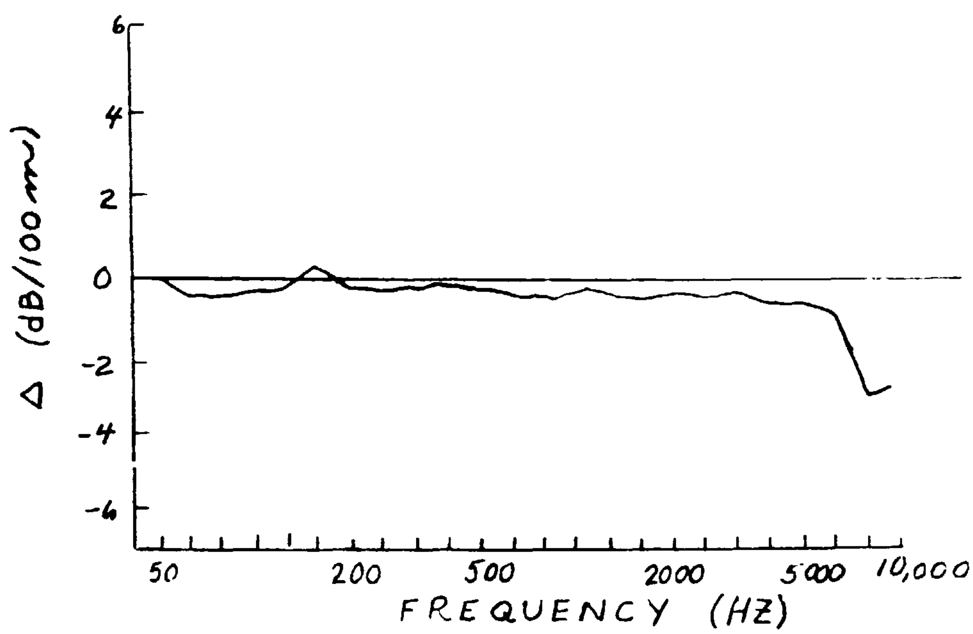


Figure 17. Difference between measured and reference 34 atmospheric absorption coefficients.

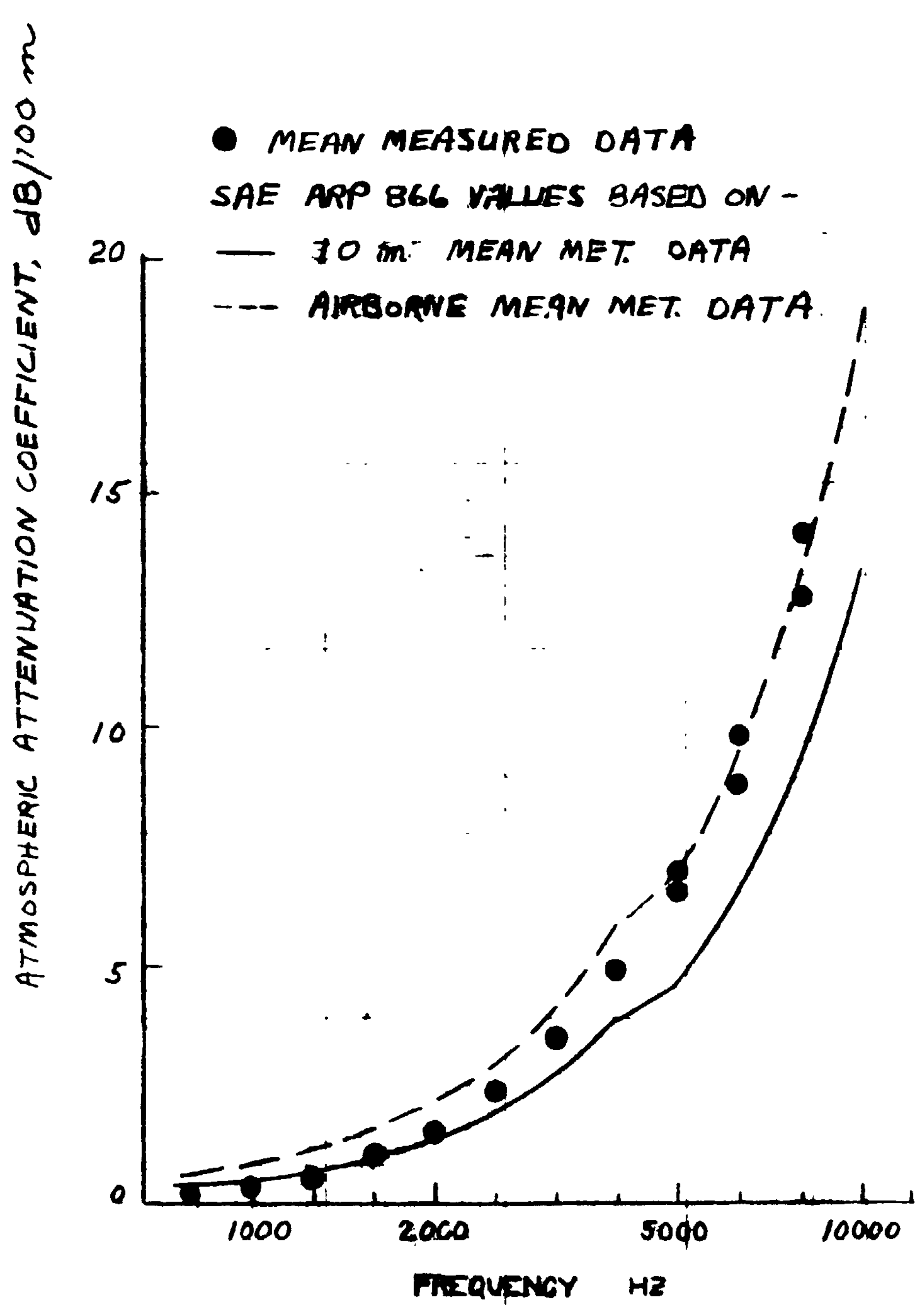


Figure 18. Comparison of measured attenuation coefficients with values predicted by using ARP 866 with meteorological conditions 10 meters above ground and along the propagation path.

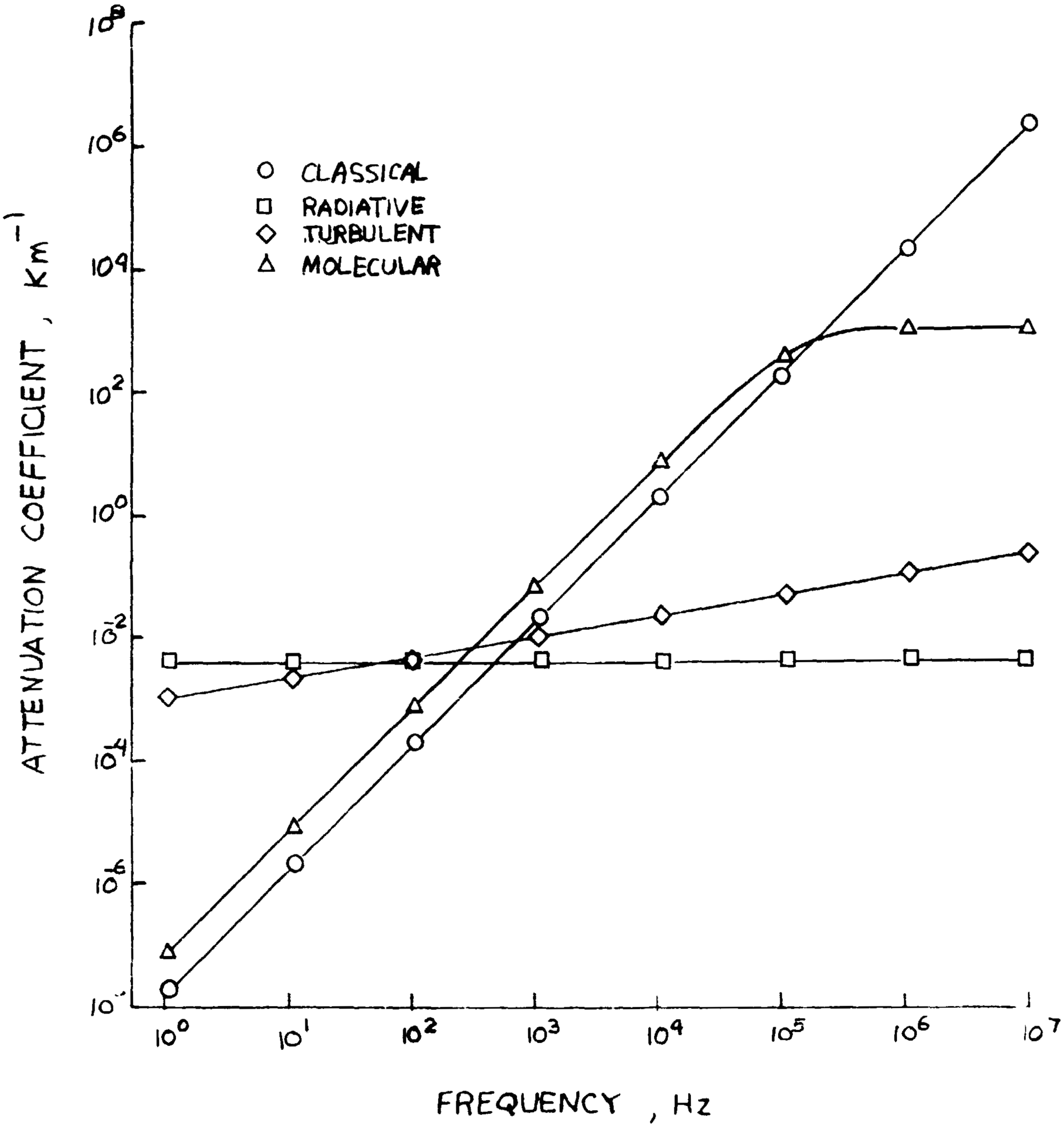


Figure 19. Frequency dependence of attenuation due to classical, radiative, and molecular absorption and scattering due to turbulence (from ref. 49).

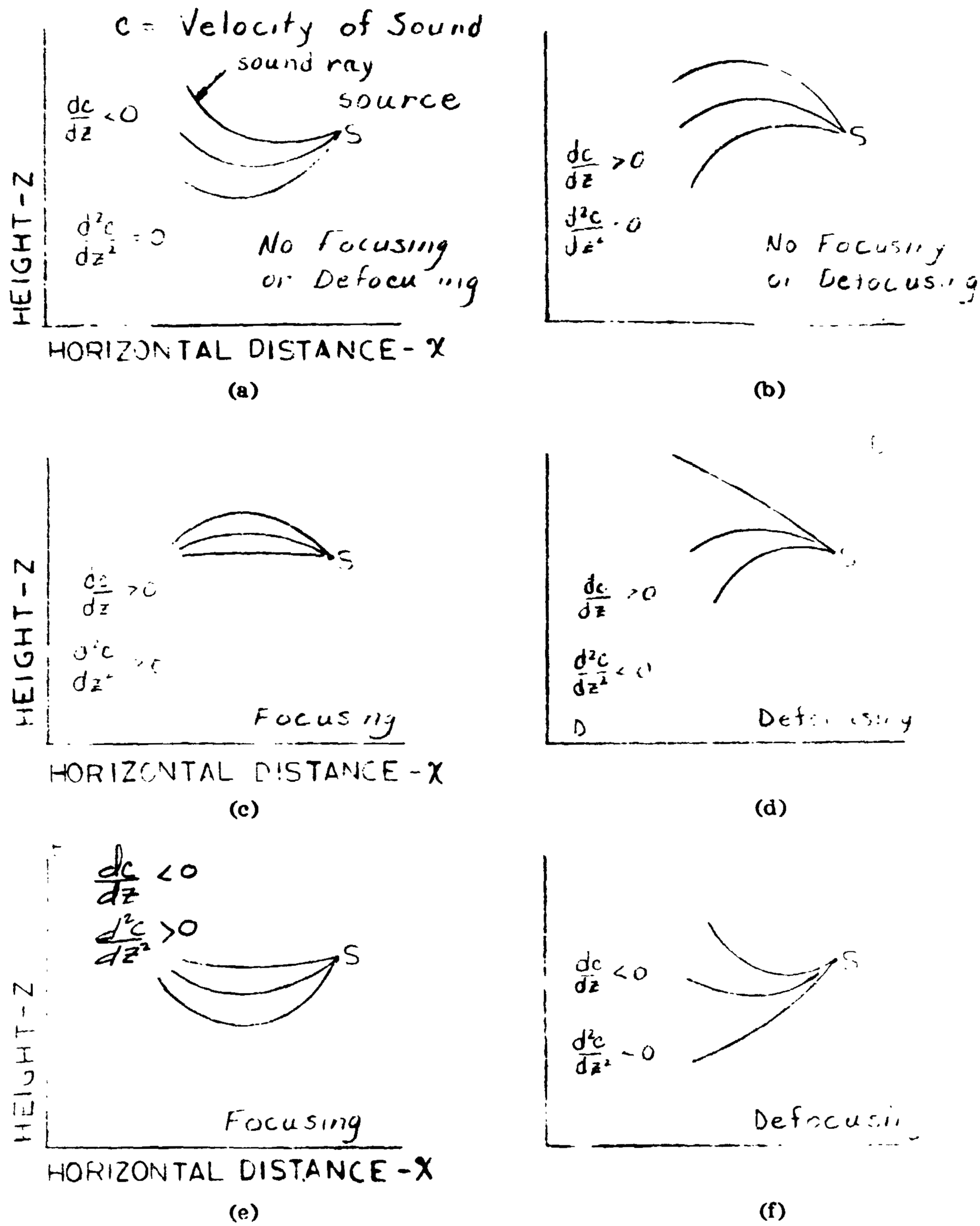


Figure 20. Effects of atmospheric refraction.

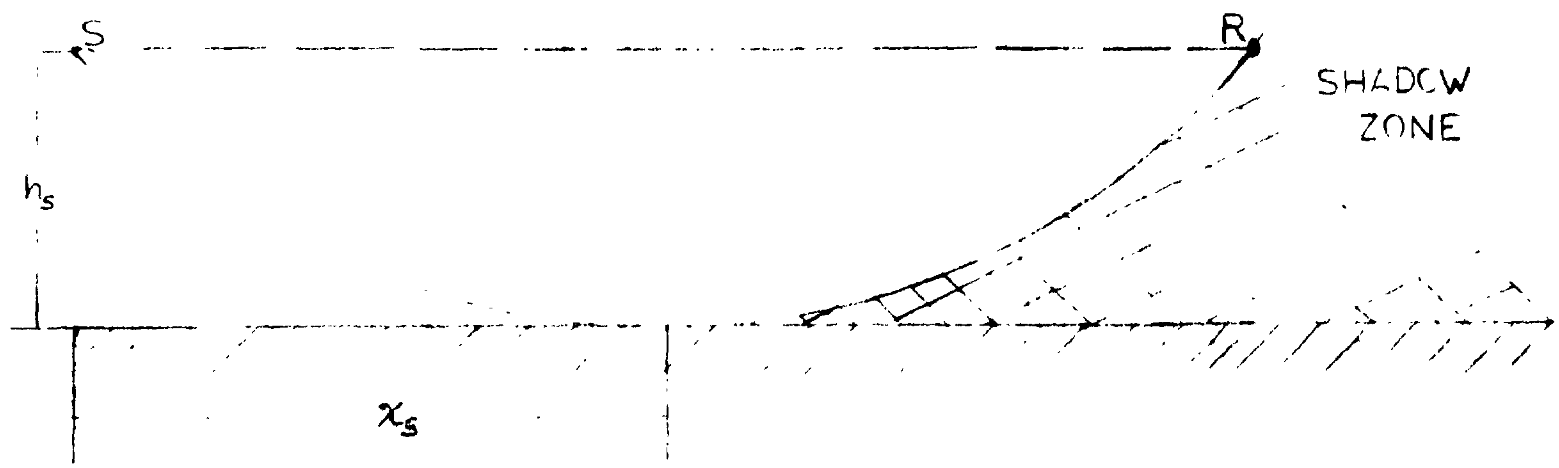


Figure 21. Shadow zone formation due to temperature or wind gradients.