Noise Pollution
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CHAPTER 2
*Review of Noise Propagation in the Atmosphere**

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ABSTRACT

A general review is presented of most areas of sound-propagation outdoors that are of interest for the control of community noise. These areas are geometrical spreading, atmospheric absorption, ground effect, (near horizontal propagation in a homogenous atmosphere close to flat ground), refraction, the effect of atmospheric turbulance, and the effect of topography (elevation, hillsides, foliage, etc.). The current state of knowledge in each area is presented and suggestions made concerning research activities, applications of existing research, and practical problems which arise in the prediction of noise levels.

2.1 INTRODUCTION

The study of sound propagation in the atmosphere has a long and intriguing history. Between 1850 and 1950 there were a number of isolated investigations of good quality in response to specific needs of the times, such as fog signaling, the location of artillery pieces, etc. (see Wescott and Kushner (1965) for an annotated bibliography of work done prior to 1965). When the noise from jet aircraft and the testing of rockets became a social problem in the 1950's, there was a resurgence of research activity, adapting existing knowledge from other fields of physics to the problem of noise propagation, and several excellent reviews of sound propagation in the atmosphere appeared at this time (Ingard, 1953; Ingard, 1955; Nyborg and Mintzer, 1955; Rudnick, 1957). The field then returned to its previous state of sporadic isolated activity, although at a substantially higher level. In recent years increased concern over noise has led once again to advances in the understanding of outdoor propagation by the

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application of knowledge from other fields of physics, which this time has been gained since the 1950's.

This review is an attempt to document the advances for most areas of sound propagation in the atmosphere which are relevant to the control of community noise. It was undertaken at the request of the Coordinating Committee on Environmental Acoustics of the Acoustical Society of America, and is part of the output of the working group on outdoor propagation (see also Lyon, 1974; Kurze, 1974). The review aims to summarize the current state of knowledge in each area and to suggest research activities, applications of existing research, and practical problems which arise in the prediction of noise levels. Because the field is so diffuse, each subject area is treated separately, accompanied by most of the suggestions of relevant to the particular area. To add perspective, however, problems in predicting noise levels are discussed generally at the end (Section 2.6) with recommendations for reserch.

The first two areas covered in the review are geometrical spreading (Section 2.2.1) and atmospheric absorption (Section 2.2.2). Together, these are the dominant mechanisms determining sound levels in air-to-ground sound propagation. Near-horizontal propagation in a homogeneous atmosphere close to flat ground (the ground effect) is then treated in Section 2.3 and the effect of surface meteorology in Section 2.4. The latter includes the effects of refraction and atmospheric turbulence. The role of topography — elevation, hillsides, foliage, obstructions, etc. — is then discussed briefly in Section 2.5.

There is much useful material in the earlier reviews of a general nature (Ingard, 1953; Ingard, 1955; Nyborg and Mintzer, 1955; Rudnick, 1957) which has been excluded here for brevity. Furthermore, specifically excluded are multipath propagation in cities, and noise reduction by barriers, which have been the subjects of recent reviews (Lyon, 1974; Kurze, 1974).

2.2 PROPAGATION AWAY FROM BOUNDARIES (AIR TO GROUND)

2.2.1 Geometrical Spreading

The geometrical spreading of sound from a coherent source is normally well covered in textbooks — an attenuation of 6 dB per doubling of distance for spherical expansion from a point source, 3 dB per doubling of distance for cylindrical expansion from an infinite line source, and parallel loss-free propagation from an infinite area source. For sources of finite size there is a nearfield where the above is approximately true and a farfield where the expansion is spherical. In community noise, however, incoherent sources are often more important and the treatment of geometrical spreading from incoherent sources has been extended in recent years to cope with multivehicle problems, particularly road traffic and railway noise.

The description above of the spreading from coherent sources remains true for sources which are incoherent, but the size of the nearfield is much more restricted, and the propagation much less directional (compare as an illustration, the light from a light bulb to that from a laser). Treatments of the incoherent acoustic line source which are useful for highway or railway design are given in Rathe (1969) and Kurze (1971).

The background noise in a city may be modelled as an incoherent area source (Shaw and Olson, 1972; Tatge, 1972; Sutherland, 1975). The effect of city boundaries — streets, barriers, and open areas — in channeling or attenuating this propagation is reviewed elsewhere (Rathe, 1969; Kurze, 1971; Shaw and Olson, 1975). A point of relevance to noise control is that the geometric spreading of different percentiles of noise from an (isolated) incoherent line source varies with the percentile (Thiessen, 1973). There is a considerable conceptual and economic benefit in specifying noise criteria for the design of roadways in such a way that the spreading loss can be accounted for in a simple manner, such as a loss of 6 dB/doubling of distance for the maximum level of individual vehicles (i.e., levels close to L_1, the level exceeded only 1% of the time), or a loss of 3 dB/doubling of distance for the equivalent continuous sound level (L_{eq})

2.2.2 Atmospheric Absorption

Present knowledge of the rate at which acoustic energy is absorbed during propagation through the atmosphere comes from three sources — direct measurements in the field, measurements of air absorption in the laboratory, and general knowledge of the mechanisms. The current state of the latter two may be examined using Figure 2.1. In this figure (Piercy, 1972), the frequency dependence of the absorption in a distance of one wavelength is shown for four different values of relative humidity (RH). The measurements are from four different investigations (Pohlman, 1961; Evans and Bazley, 1956; Harris, 1966; Harris and Tempest, 1964), and the first point to note is the close similarity between the measurements by the different investigators. The second is the agreement for each value of relative humidity between the measurements and the top curve T, which is the theoretical curve representing the sum of the contributions from the different mechanisms of absorption (identified by the curves marked C, O and N).

Line C gives the classical absorption caused by the transport processes of classical physics (shear viscosity, thermal conductivity, mass diffusion, and thermal diffusion), together with the absorption caused by rotational relaxation of the molecules in air. Curves O and N represent the contributions from the vibrational relaxation of oxygen and nitrogen molecules, respectively. The fit of curve T to the measurements shown in the figure has been achieved by the adjustment of two constants in the theory, but the basic theory (Evans *et*

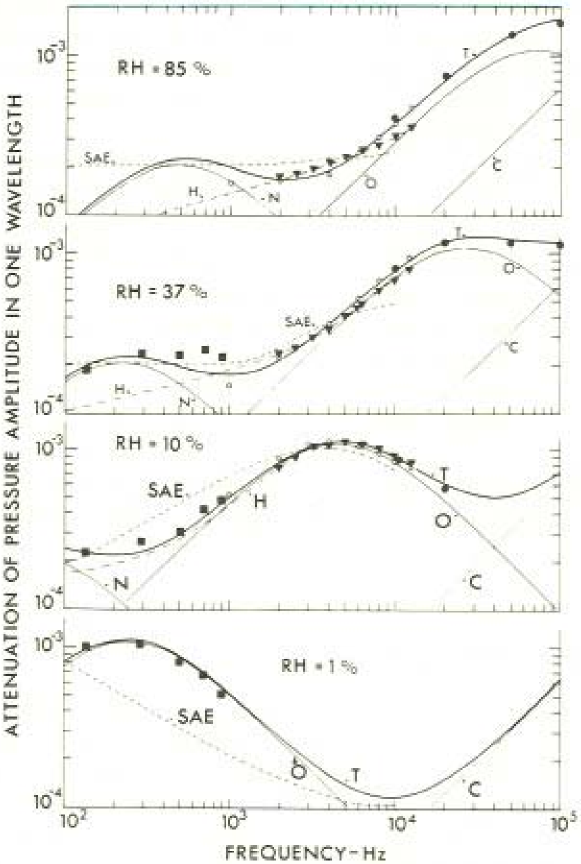

Figure 2.1 The absorption of sound in a distance of one wave-length for four values of relative humidity RH, a temperature of 20 °C, and a pressure of 1 atm (Piercy, 1972). Line C gives the classical and rotational absorption, curves O and N the contributions from the vibrational relaxations of oxygen and nitrogen, respectively, and curve T is the sum of these three contributions. Experimental points ● are from Pohlman, (1961), ○ from Evans and Bazley (1956), ▼ from Harris (1966), and ■ from Harris and Tempast 1964. The absorption predicted by SAE Committee (1964) is curve SAE, by Harris (1966) is curve H, and by Sutherland *et al.* (1974) is curve T

al., 1972) is now sufficiently firm to achieve a fit with an accuracy of approximately 25% without using any adjustment.

It is useful to compare the different methods available for predicting atmospheric absorption with the measurements shown in Figure 2.1. Kneser first developed a theory based only on contributions C and O. While predictions with his original method (Kneser, 1940) are substantially different from curve C and O shown in the figure, a later version by Evans and Bazley (1956) gives positions for these curves which are close to those in the figure. Evans and Bazley's method provides, therefore, a fairly good approximation to experimental data for higher frequencies. At the higher humidities represented by the top two sets of measurements in Figure 2.1, however, the vibrational relaxation of nitrogen (Piercy, 1969) (curve N) is the principal mechanism of absorption for the range of frequencies below about 1–2 kHz which are of major importance for community noise: both the Kneser, and Evans and Bazley methods therefore grossly underpredict the absorption in this low-frequency range.

Two similar methods of calculating atmospheric absorption were proposed before the role of the nitrogen relaxation was understood, that of Committee A21 of the Society of Automotive Engineers (1964) and Harris (1966), both of which produced a decided improvement in the low-frequency range, and these two essentially empirical methods have seen widespread use. Curves marked H and SAE in Figure 2.1 show the predictions of the method of Harris, and the SAE Committee, respectively. Major difficulties using these empirical methods for predicting absorption appear mainly for abnormal measurement conditions, due to extrapolation with an incorrect dependence on the variables, as shown in the figure, for example, for low frequencies or dry air.

It is now possible to generate curve T in Figure 2.1 using simple algorithms with a firm theoretical base, which can be handled easily, for example, by a programmable hand calculator. A new (draft) standard method for calculating atmospheric absorption has recently been proposed on such a basis (Sutherland *et al.*, 1974). The predictions of this new method have been compared with a large assembly of both laboratory and field data from the literature (Sutherland, 1975). The comparison of over 850 laboratory measurements with predictions shows that near 20 °C the predicted values agree within about 5%, with the average of the measurements throughout the audio frequency range and over a wide range of humidity. Although laboratory data at other temperatures are limited, the prediction model is estimated to be reliable within ± 10% from 0 to 40 °C. The field data included analyses of more than 750 measurements of aircraft flyover noise over wide ranges of frequency, temperature, and humidity from a number of different investigators. Although the scatter in the field results was much larger than that in the laboratory measurements, because the weather cannot be controlled, the agreement between predicted and measured absorption was good on the average, as shown in Figure 2.2.

The absorption predicted by the new method, in the practical units of dB/100 m for a pressure of 1 atm, a temperature of 20 °C, and a relative humidity of 70%, is shown in Figure 2.3. Note that the attenuation by

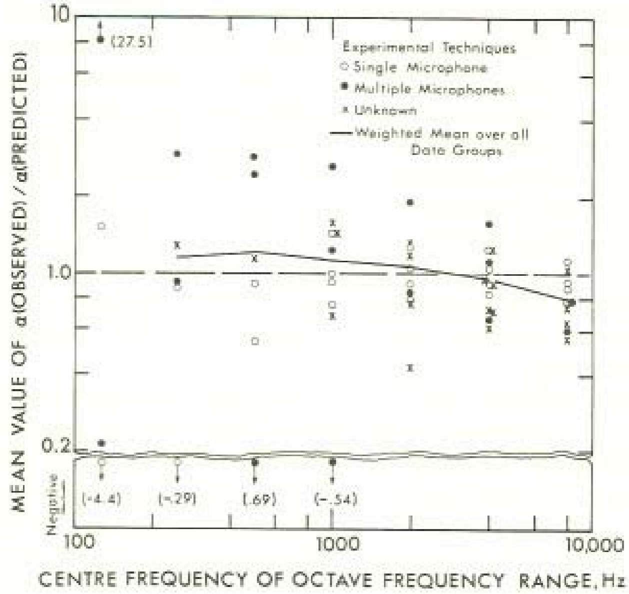

Figure 2.2 Ratio of air-to-ground (aircraft sound propagation) measurements of air absorption loss coefficients to predicted values as a function of frequency (Sutherland (1975). Predicted values were based on weather conditions on the ground, or when data were available on average weather conditions along the propagation path

absorption is constant for a given difference in propagation path lengths unlike geometrical spreading, where it is constant for a given ratio of propagation path lengths. Thus atmospheric absorption tends to become more important with increasing distance between the source and receiver. Note also from Figure 2.3 that the total absorption increases sharply with increasing frequency.

With the new proposed method of predicting atmospheric absorption, the lag between current practice and knowledge has been largely eliminated. Recently, also, this method has been confirmed by extensive measurements at high frequencies (Shields and Bass, 1976; Bazley, 1976) (4–100 kHz), and a few measurements at, in effect, very low frequencies (Lee and Sutherland, 1976) (down to 4 Hz). Nevertheless, there is still need for more data at low frequencies over a substantial range of temperature, and at low humidities. Continuing support is also needed for fundamental work on the mechanisms of air absorption. The measurements would provide needed understanding of the temperature dependence of the relaxation frequency of nitrogen, and lead in due course to the calculation of atmospheric absorption directly from fundamental knowledge (Evans *et al.*, 1972) with enhanced accuracy.

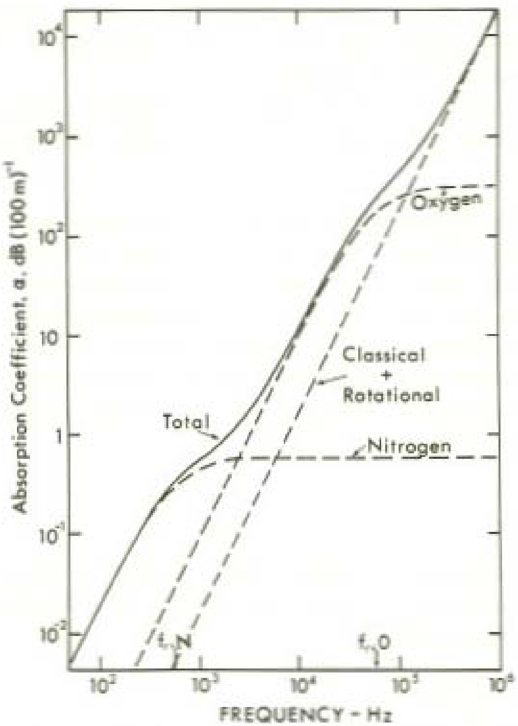

Figure 2.3 Predicted atmospheric absorption in dB/100 m for a pressure of 1 atm, temperature of 20 °C and relative humidity of 70% (Sutherland *et al.*, 1964)

It should be noted that many of the best measurements of outdoor propagation have appeared in the literature in corrected form, with the attenuation calculated for atmospheric absorption removed. The correction for absorption should now be recalculated using the new method, before the original interpretation of these measurements is accepted. In particular, the failure to recognize earlier the contribution from the nitrogen relaxation has led to a number of difficulties some of which will appear in later sections.

2.3 PROPAGATION NEAR THE GROUND

The theory of sound propagation near or along the ground has been treated analytically in the literature, with at least three levels of complexity for the ground surface:

(a) The ground is treated as a locally reacting surface, and waves within the ground are not considered.

(b) The ground is treated as an isotropic fluid medium capable of transmitting dilatational waves in any direction as the result of an impinging wave on the surface.
(c) The ground is treated as an elastic solid medium capable of transmitting both dilational and shear waves resulting from an impinging wave on the surface.

While theoretical models are available in the literature for the latter two (Mackenzie, 1960; Officer, 1958) and other more sophisticated models (Pao and Evans, 1971), there is very little evidence available as yet to show that propagation of sound over the ground is not adequately predicted by the use of the first, much simpler, 'locally reacting' model for the ground surface. Therefore, this is the only model which will be treated in detail in this review. One exception to this general applicability of a 'locally reacting' model will be covered only briefly.

2.3.1 Plane Waves

The amplitude reflection coefficient R_p for a plane wave of sound incident obliquely on a plane locally reacting surface may be conveniently represented by the formula (Morse, 1958)

$$R_p = \frac{\sin \psi - Z_1/Z_2}{\sin \psi - Z_1/Z_2}$$

where ψ is the grazing angle (Figure 2.4), $Z_1 = \rho c$ is the characteristic impedance of air, and Z_2 is the acoustic impedance of the surface (i.e., the ratio of pressure to the normal component of velocity at a point on the surface). In order to include the change of phase as well as amplitude on reflection, complex notation is used for both R_p and Z_2. The characteristics of a particular locally reacting surface may then be represented completely by a complex impedance, $Z_2 = R_2 + jX_2$, which may be dependent on the frequency but not on the grazing angle.

For a perfectly reflecting hard surface, the phase change on reflection is zero, R_p, is 1, and Z_2 must be infinite. In practice, however, Z_2 may be very large, but must always remain finite. For normal incidence in this case $\sin \psi = 1$, and R_p is effectively 1. It is always possible, however, to choose ψ sufficiently small to make the term $\sin \psi$ in Equation (1) small compared to the fixed parameter Z_1/Z_2, and hence make R_p effectively -1. This value signifies a phase change of 180° on reflection and a cancellation of incident and reflected waves at grazing incidence, even though their path lengths are equal. Plane waves at grazing incidence over a plane surface with a finite acoustic impedance thus represent a forbidden mode of propagation.

The rest of Section 2.3 is a description of the implications of this statement for the propagation of noise over the ground, where values of the grazing angle less than 5° have primary importance. The cancellation for small ψ will be shown to represent, in practice, a shadow zone whose acoustical depth is related to the value of the ground impedance.

2.3.2 Spherical Waves, Direct and Reflected

The propagation of spherical waves from a point source near a reflecting plane is an intricate and rambling subject, both mathematically and conceptually. In electromagnetics it has a long history, well chronicled by Baños (1966), from its start by Sommerfield (1926) in 1909 to its present state, as reviewed by Wait (1970). In acoustics there is also a substantial history, from Rudnick (1947) to Wenzel (1974) and Donato (1976), which is chiefly one of adoption of the ideas and solutions from electromagnetic theory. The portion of this history most relevant to the propagation of noise over the ground has recently been surveyed by Embleton *et al.* (1976). The treatment here will follow the latter study, to which the reader is referred for details.

A. Shadow Zone — Source or Receiver on the Ground

Consider, again, the basic configuration shown in Figure 2.4. There is a point source S and receiver R situated above a plane boundary with acoustic

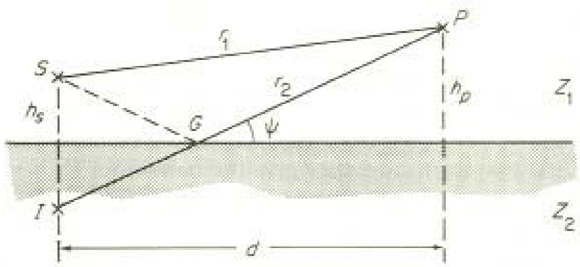

Figure 2.4 Reflection of sound from flat ground with impedance Z_2

impedance Z_2. The pressure amplitude p at point R may be represented as follows (Lawhead and Rudnick, 1951; Ingard, 1951):

$$p/p_0 = (1/r_1)\exp(-ikr_1) + (R_p/r_2)\exp(-ikr_2) + (1 - R_p)(F/r_2)\exp(-ikr_2) \tag{2}$$

Parameter p_0 is the amplitude of the pressure at unit distance from point source S in the absence of the ground surface. Equation (2) is one form of what is often referred to as the Wey–Van der Pol solution.

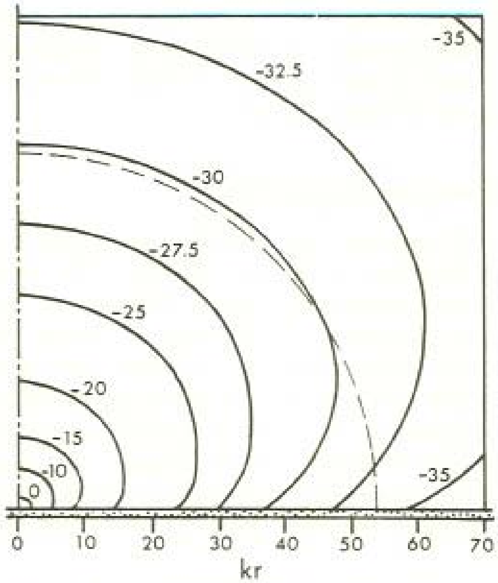

Figure 2.5 Pressure distribution around a point source located on a plane with impedance ratio $Z_2/Z_1 = 10$ (Ingard, 1951). The dashed line gives, for comparison, spherical expansion over a rigid plane

The first term on the right of Equation (2) expresses, in complex notation, the contribution from the wave proceeding directly from S to R. It is only necessary to recognize that the distance r_1 in the denominator is an expression of the inverse square law. The second term is the familiar one for the reflected wave, which appears at point R to have come a distance r_2 from the image source I. The first two terms together give the behaviour shown in Figure 2.5, which is essentially as described in the previous section for plane waves, since R_p is the plane wave reflection coefficient given by Equation (1). [The significance of the third term in Equation (2), and in particular the amplitude factor F, which gives the behaviour of ground and surface waves, will be described later in Section 2.3.4.] Propagation upwards in Figure 2.5, away from the point source on the surface [large ψ in Equation (1)], is spherical expansion: compare, for example, the 30-dB contour to the dashed circle in the figure. Along the surface, however, a shadow zone forms gradually as the sound propagates outward. In this region ($\sin \psi \ll Z_1/Z_2$), Equation (1) and the first two terms in Equation (2) indicate an attenuation A_e in excess of that from inverse square law and atmospheric absorption (and called hereafter just excess attenuation) given by Embleton *et al.* (1971)

$$A_e = 20 \log_{10}[2 \sin \psi (Z_2/Z_1)], \text{dB} \tag{3}$$

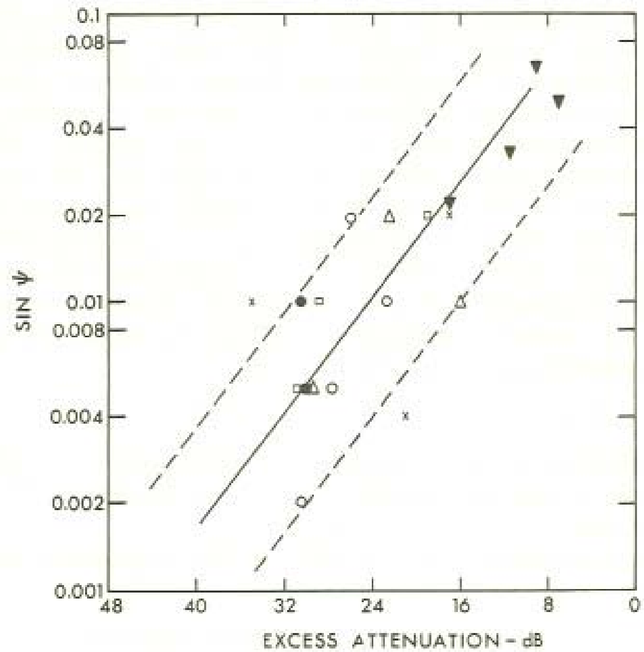

Figure 2.6 Measured excess attenuation for a point source on the surface ($h_s = 0$) of a flat grassy site and the receiver at various heights ($0 \leqslant h_r \leqslant 5$ m) and distance ($d = 5$ m for ▼, 15 m for X, 30 m for ○, 60 m for △, 120 m for □, and 240 m for ●) for a frequency of 3 kHz. There was a brisk crosswind to eliminate the gradients of wind and temperature which cause refraction. The measurements are compared to the attenuation predicted (solid line) via Equation (3) from the value of the ground impedance determined from measurements at short range. The dashed lines encompass 90% of the measured values (Embleton *et al.*, 1976)

A comparison of this prediction with measured levels at distances out to 240 m for one well-chosen example is shown in Figure 2.6. Note that the excess attenuation in the shadow zone is dependent only on ψ and the magnitude of the ratio Z_2/Z_1, and reaches values of ~ 30 dB. It is the result of cancellation between direct and reflected waves in the immediate vicinity of the souce, produced by the phase change of nearly 180° upon reflection, as described previously for plane waves.

B. Effect of Path-length Differences-Source and Receiver both above a Hard Ground

When both the source and receiver are above the ground there is a phase change caused by the difference in length between propagation paths r_1 and r_2

in Figure 2.4, in addition to the phase change on reflection described in the previous section. To show the effects of the former, free from the latter, consider propagation in the configuration of Figure 2.4 above a hard, smooth surface, whose reflection coefficient R_p is effectively 1. Spectra of excess attenuation measured (Piercy *et al.*, 1976) for two specific configurations relevant to standard vehicle tests are shown in Figure 2.7. The major dips in the spectra (of ~ 20 dB) are the result of cancellation between direct and reflected rays for path-length differences (PLD's) of an odd number of half wavelengths. The interference between direct and reflected sound over the rest of the spectra is approximately coherent addition. (Note that the minor dips and peaks are caused by turbulence, and will be considered later.) An elementary geometric calculation shows

$$\mathrm{PLD} \approx 2h_s h_r / d \tag{4}$$

for small values of ψ. Note therefore that the frequency $f_{\min}$ of the first minimum will increase with increasing d, as shown in Figure 2.7, and also decreasing h_s and h_r.

Spectra such as those shown in Figure 2.7 for propagation over a hard

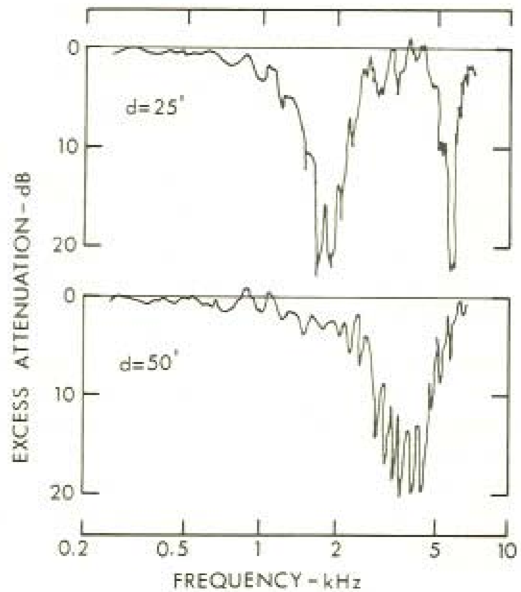

Figure 2.7 Measured excess attenuation for propagation from a point source over asphalt, h_s = 0.3 m, h_r = 1.2 m. The excess attenuation is relative to that for the point source placed on a perfectly hard surface (Piercy *et al.*, 1976)

surface may be divided into two regions: $f < \sim \frac{1}{2}f_{min}$ where the transmission characteristic is reasonably uniform, and $f > \frac{1}{2}f_{min}$ where it alternately shows the effects of constructive and destructive interference. The former is highly desirable for testing noise sources (see Section 2.6.1) and the importance of both regions for outdoor propagation in general will be discussed later in Section 2.3.5.

2.3.3 Ground Impedance

Measurements of the acoustic impedance of the surface of the ground are scarce: only for mown grass, as found on airports and around public highways and buildings, is a substantial amount of data available (Embleton *et al.*, 1976; Dickinson and Doak, 1970; Jonasson, 1972). The most detailed information on the impedance of mown grass (Embleton *et al.*, 1976) is shown in Figure 2.8. It was obtained from measurements either with a vertical impedance tube, or from interference phenomena, at oblique angle of incidence, similar to those described in the previous section. The values of impedance shown in Figure 2.8 confirm the grassy surface to have the acoustic properties of a locally reacting porous medium, which are well understood from the study of acoustic building materials. The impedance is determined by the presence of a thin porous layer on the surface that must have holes small enough to offer substantial resistance to the flow of air. Thus the impedance of short grass as in a lawn is not changed appreciably by mowing, as the main resistance to flow appears to be either in the turf itself or, more likely, in the soil near the surface kept loose by the roots. Different stretches of institutional or mowed airport grass are found to have similar values of impedance, and this impedance was not very sensitive to weather (Dickinson and Doak, 1970). It is important to note that the reactive component corresponds to a stiffness and not to a mass.

There is little information about the acoustic impedance of other ground surfaces. A stubble field (Jonasson, 1972), or the ground under a pine plantation (Aylor, 1972) both appear to have an impedance similar to that of grass, presumably because of the roots loosening the soil. Snow (Parkin and Scholes, 1965) and ground recently loosened by discing (Aylor, 1972) appear to have a much lower impedance at low frequencies. The impedance of asphalt (Parkin and Scholes, 1965), although much higher than grass, is by no means infinite.

2.3.4 Ground and Surface Waves — Source and Receiver Both on the Ground

The third term in the Weyl–Van der Pol solution of the wave equation for spherical waves (Equation (2)] arises mathematically from the need to match the boundary conditions, in particular the variation of the curvature of the wavefronts with distance along the boundary. Parameter F in this term

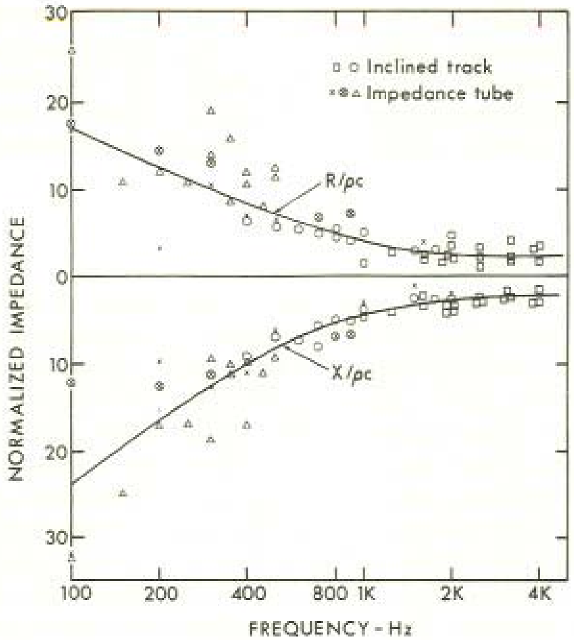

Figure 2.8 Real component R_2 and imaginary component X_2 of the acoustic impedance of grass-covered flat ground (different areas of two different sites) obtained from measurements either with an impedance tube or of interference at oblique incidence (Embleton *et al.*, 1976). (Note that the imaginary component corresponds to a stiffness reactance)

represents a complicated mathematical function (Rudnick, 1947; Lawhead and Rudnick, 1951) of a variable w called the numerical distance. This function is plotted (Wait; 1970) versus w in Figure 2.9 for various values of the phase angle $\phi = \tan^{-1}(X_2/R_2)$ of the surface impedance Z_2. The numerical distance is given by the expression (Embleton *et al.*, 1976)

$$w = (\tfrac{1}{2}ikr_1)(\sin\psi + Z_1/Z_2)^2 \tag{5}$$

where $k = 2\pi/\lambda$ is the propagation constant in air, and the other variables are defined in Sections 2.3.1 and 2.3.2. It is useful to consider the numerical distance w to represent the propagation distance r, scaled for a given value of frequency f, and grazing angle ψ, by the impedance Z_2, according to Equation (5).

The physical interpretation of the third term in Equation (2) is more elusive than that of the first and second terms which are the direct and reflected waves discussed in Section 2.3.2. The physical interpretation is most clear for both

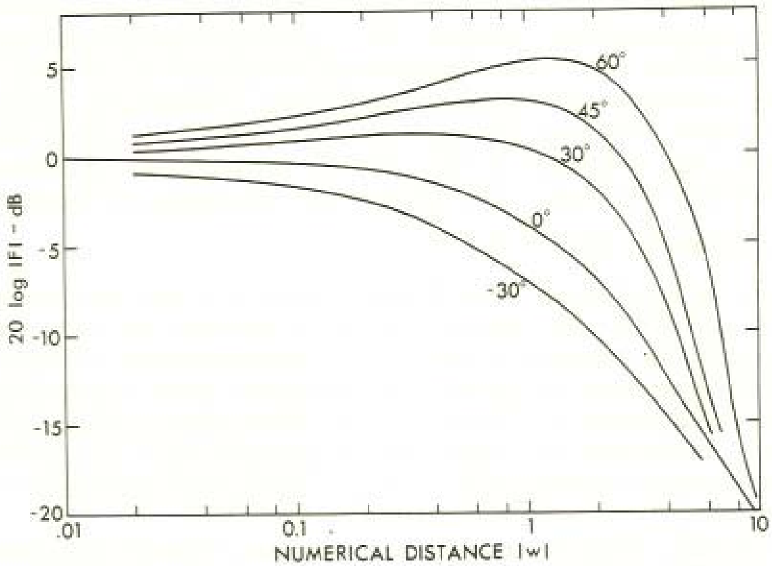

Figure 2.9 Amplitude factor $F(w)$ of the ground sand surface waves vs numerical distance w for various values of the phase angle ϕ of the surface impedance (Wait, 1970)

source and receiver on the boundary ($h_s = h_r = 0$ in Figure 2.4, and $\psi = 0$) and the boundary resistive ($\phi = 0$), because of the direct analogy to the propagation of electromagnetic waves above the earth (for which the Weyl–Van der Pol solution was originally derived). Under these conditions the direct and reflected waves cancel completely to form a shadow zone, as described earlier in Section 2.3.1 and 2.3.2A. This shadow zone is penetrated by the ground wave which is represented by the third term in Equation (2) for $\phi = 0$. The amplitude of this ground wave is indicated by the curve for $\phi = 0$ in Figure 2.9. Althought the ground wave is important for radio communications, carrying the electromagnetic energy from the antenna of the local AM station to one's radio, its exact physical nature is still obscure (Baños, 1966). The dependence on the variables, however, is well defined. The curve for $\phi = 0$ in Figure 2.9 indicates that at short distances ($w \ll 1$) the ground wave suffers no excess attenuation compared to propagation over an infinitely hard surface, but for longer distances ($w \gg 1$) exhibits a loss of 6 dB per doubling of distance in addition to that provided by the inverse square law.

The data in Figure 2.8 indicate, however, that the phase angle ϕ for the acoustic impedance of a grassy surface varies between approximately 45 and 60° over the audible range of frequencies. (By the sign convention used in this paper, a positive imaginary term for impedance corresponds to a stiffness reactance.) The amplitude of the function F for this range of ϕ in Figure 2.9

differs from that for $\phi = 0$ (and hence differs also from the values used for radio wave propagation in the atmosphere) by the presence of a substantial increase in the vicinity of $w = 1$. This increase in the function F we now know to be mainly the contribution of a surface wave (Wenzel, 1974; Donato, 1976) in the air: this wave is coupled to the ground surface owing to the latter's stiffness reactance but propagates in the air, with an amplitude that decreases exponentially with height z above the boundary according to the formula

$$p = p_b \exp[-X_2^2(R_2^2 + X_2^2)^{-1}kz] \tag{6}$$

where p_b is the amplitude at the boundary. For $w \ll 1$, e.g., for d small, the contribution of the surface wave in Figure 2.9 is relatively smaller than that of the ground wave because the surface-wave amplitude decreases at only 3 dB per doubling of distance (cylindrical expansion from a point source) compared to 6 dB for the ground wave. For $w \gg 1$ the amplitude of the surface wave again becomes smaller than the ground wave because of its attenuation by viscous losses in the pores of the boundary, which is exponential with distance r along the boundary.

In summary, theory indicates that the propagation of sound energy between a point source and receiver which are both placed on a grassy surface ($h_s = h_r = 0$) is by a ground wave, as in electromagnetic propagation, augmented by a surface wave. The scale of the distances and heights of these waves is given in Table 2.1 for a grassy surface whose impedance is that shown in Figure 2.8. Some of the properties of these waves have been verified directly by measurements over grass (Donato, 1976; Embleton *et al.*, 1976) at short distances, where disturbing phenomena such as turbulence and refraction are absent, and by model experiments indoors (Lawhead and Rudnick, 1951; Ivanov-Shits and Rozhim, 1960). The relevance of ground and surface waves to long range propagation when both source and receiver are above the ground will be discussed in the following section.

Table 2.1. The propagation distance d_w for numerical distance =1, and height z_{sw} for the amplitude of the surface wave to decrease by $1/e$ from its value at the boundary, calculated by Equation (5) and (6), respectively, from the impedances shown in Figure 3.8 for mown grass

f(Hz)	d_w(m)	z_{sw}(m)
50	4,000	58
100	1,500	23
200	270	7.3
500	24	0.9
1,000	3.6	0.5
2,000	1	0.15

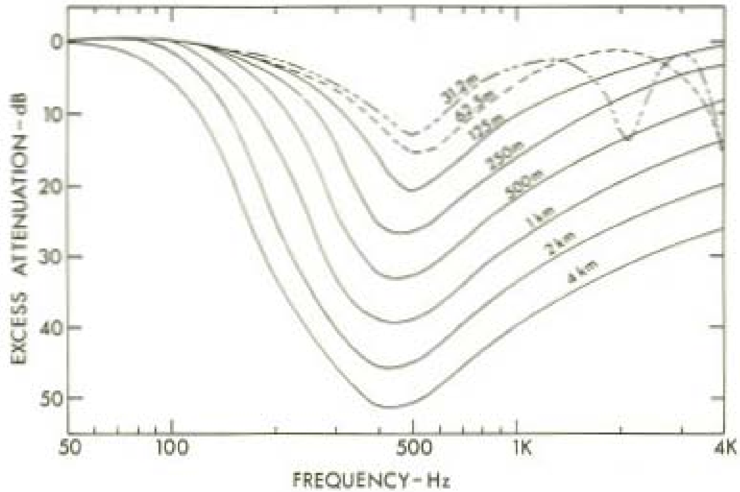

Figure 2.10 Excess attenuation calculated for propagation from a point source over mown grass for h_s = 1.8 m, h_r = 1.5 m, and the distances of propagation d indicated. The attenuation is calculated for values of impedance given in Figure 2.8. The excess attenuation is relative to that for the point source placed on a perfectly hard surface (Piercy *et al.*, 1976)

2.3.5 All Phenomena Together — Source and Receiver both above the Ground

All the phenomena described previously in Sections 2.3.1–2.3.4 must be considered when both point source and receiver are above the ground. The curves shown in Figure 2.10, for propagation in the configuration of Figure 2.4 with h_s = 1.8 m, h_r = 1.5 m, and various values of d, have been calculated (Piercy *et al.*, 1976) using the theory of Donato (Donato, 1976) with values of impedance taken from the curves for mown grass in Figure 2.8. The individual contributions to these curves from direct D, reflected R, ground G, and surface S waves are illustrated (Piercy *et al.*, 1976) for three of these distances in Figure 2.11, together with measurements of the propagation of jet noise for the same values of h_s and h_r and comparable d (110 and 615 m) under neutral atmospheric conditions at an airport (Parkin and Scholes, 1965). (These measurements will be described in greater detail in Section 2.4.2B.)

Consider first the curves for a distance of 31.2 m in Figure 2.11.Here the grazing angle ψ is sufficiently large for D and R waves alone [first two terms in Equation (2)] to be a good approximation to the complete solution. Note that the latter includes contributions from D, R and G waves only, because the angle ψ is too large for an S wave to be significant. For frequencies greater than about 1 kHz there is a series of maxima and minima caused by path length differences (PLD's) between direct and reflected waves, that is an interference

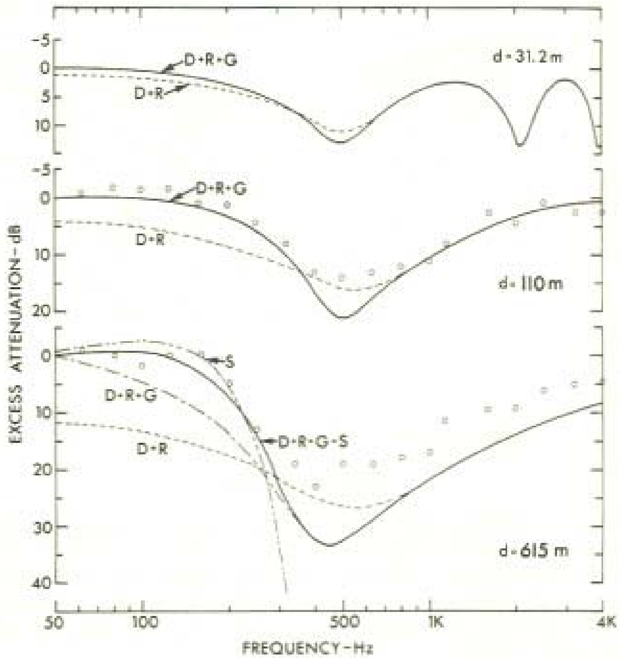

Figure 2.11 Excess attenuation for propagation from a point source over mown grass, $h_s = 1.8$ m, $h_r = 1.5$ m. The calculated curves show the contributions from the various waves—direct D, reflected R, ground G, and surface S. The points are measurements of jet noise from Parkin and Scholes (1965) at comparable distances. The excess attenuation is relative to that for a point source placed on a perfectly hard surface (Piercy *et al.*, 1976)

pattern similar to that described in Section 2.3.2 for a hard surface (see Figure 2.7). Unlike the pattern for a hard surface, however, the minima are for PLD's which are approximately even multiples of $\frac{1}{2}\lambda$, indicating that the surface is effectively soft for this configuration and frequency range. As the frequency decreases, however, the ground impedance increases (see Figure 2.8) causing the surface to give a response which is effectively hard for low frequencies ($f < \sim 150$ Hz) as in Figure 2.7. Unlike the response of the hard surface shown in Figure 2.7, however, there is a broad minimum between these two ranges centred at about 500 Hz, which is characteristic of the propagation for short distances over soft ground. It is the result of cancellation between direct and reflected waves caused primarily by the phase change on reflection. The dip shown in Figure 2.11 for a distance of 31.2 m, therefore (for source and receiver now both raised above the surface), is the remains of the shadow zone described previously in Section 2.3.2, for the source (or receiver) on the ground. It has caused major problems for the testing of noise sources such as snowmobiles at short ranges, because the cancellation and hence the noise, is dependent on the impedance of the surface of the particular site (Piercy and Embleton, 1974).

Because the curvature of the wave-front from a point source decreases with increasing distance, the behaviour for long ranges must be asymptotic to that described in Section 2.3.1 for plane waves. The curves in Figure 2.10 indicate that the dip broadens and deepens with increasing distance until most of the audible frequency range is included in the shadow zone in accordance with this principle. Comparison of the curves in Figure 2.11 for a distance of 125 m with those for 31.2 m shows how this broadening comes about. The interference pattern, which occurs at high frequencies for $d = 31.2$ m, has, for $d = 110$ m moved upward in frequency beyond 4 kHz, by virtue of the d^{-1} term in Equation (4), leaving only the rising slope to the first maximum in Figure 2.11. At the low-frequency end, the increasing cancellation between D and R waves produced by decreasing ψ [as in Equation (1)] has revealed a substantial contribution from the ground wave. The measurements are in reasonable agreement with theoretical prediction for 125 m, using impedances obtained from a different site.

Consider now the curves for 615 m in Figure 2.11. The broadening of the shadow zone to higher frequencies evident in the curves for 125 m has continued with increasing distance. There has also been a broadening to the lower frequencies, which leaves most of the energy in the frequency range 50–200 Hz in the surface wave, and the latter fact remains true for longer distances. The measurements for 615 m at low frequencies closely follow theory, showing a small enhancement (negative excess attenuation) due to the surface wave (Wenzel, 1974). There is, however, a tendency at the high frequencies for the measured excess attenuation to be consistently less than predicted.

The reason for the high-frequency discrepancy probably has to do with the use of coherent acoustic theory for the predicted curves. Turbulence in the atmosphere is known to reduce coherence between different propagation paths. While it would be premature to attempt to predict the size of this effect from existing knowledge, to be realistic one must expect significant departures from the curves shown in Figure 2.10 due to turbulence (see Section 2.4.2) particularly at higher frequencies, longer distances, and when the excess attenuation due to interference between direct and reflected waves would otherwise become large (greater than ~ 20 dB, see Section 2.4.3).

In practice, for broadband noise sources, such as a jet engine, and for distances greater than about 1 km, the high frequencies will be attenuated sufficiently by atmospheric absorption, as shown in Figure 2.3, and the midfrequencies will be attenuated by the ground shadow, as shown in Figure 2.10, so that the main contribution to the measured A-weighted sound level will come from the surface wave at frequencies below 200 Hz, as illustrated in Figure 2.11. It is likely also that the background roar from distant traffic, is transmitted mainly via this surface wave. It is interesting to note that the attenuation of the surface wave is mainly by the viscous flow of air in the pores of the ground.

2.3.6 Summary

In the preceding Sections 2.3.1–2.3.5, the present understanding of the near-horizontal propagation of sound in an acoustically homogeneous atmosphere close to flat ground has been outlined. The primary effect is a shadow zone caused by the finite acoustic impedance of the ground surface. This shadow zone is penetrated at low frequencies by the ground and surface waves. For both source and receiver above the boundary, the shadow zone is also penetrated at high frequencies by constructive interference between direct and ground-reflected waves. Sound levels can be calculated with reasonable precision using known theory within the constraints imposed by the present knowledge of the ground impedance and the use of coherent wave theory. The effect of inhomogeneity of the atmosphere produced by surface meteorology, as well as surface topography, will be discussed in Sections 2.4 and 2.5.

2.3.7 Prediction Schemes

It appears from the analysis in Section 2.3.5, that the modern theory of the propagation of sound from a point source has good potential for predicting the excess attenuation of noise produced by the ground surface within the constraints reviewed in Section 2.3.6 above. There are two equivalent formulations, by Wenzel (1974) and Donato, (1976), with the latter more suitable for computation. The theory and the mechanisms of propagation are complicated but the solutions are programmable, so that this method appears worthy of development.

A useful but less general approach has been suggested by Delany and Bazley (1970, 1971). They adapted the limited exact mathematical solution of Wisse (1929) for electromagnetic propagation to the propagation of sound. This solution is equivalent to taking only the first two terms in Equation (2). The simplified method of Delany and Bazley has the additional constraint, therefore, to regions where the contributions from the ground and surface waves may be neglected. It appears from the discussion in Sections 2.3.4 and 2.3.5 (and Figure 2.11) that this simplified scheme should not be used for low frequencies at small grazing angles. It should, however, be useful for evaluating the noise from aircraft in flight, the purpose for which it was designed, because here two of the other major constraints (weather and topography) are often not a problem.

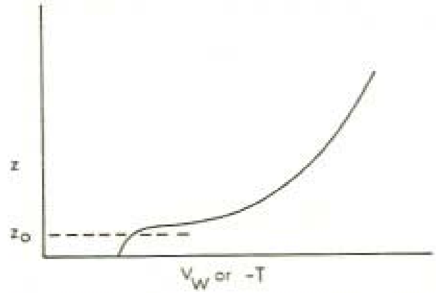

Figure 2.12 Variation of wind velocity and temperature in the vicinity of a flat ground surface ($z < \sim 10$m)

2.4 EFFECT OF SURFACE METEOROLOGY

2.4.1 Relevant Meteorological Phenomena

The variation of the average speed of the wind V_w with height z in the vicinity of the ground for a large flat open area is approximately as shown in Figure 2.12 (Wiener and Keast, 1957; Lumley and Panofsky, 1964; Sutton, 1953). For heights greater than z_0, V_w may be represented by the formula

$$V_w = K_v \log (z/z_0) \tag{7}$$

Parameter z_0 is determined by the roughness of the surface, and is often very approximately the height of a consistent obstacle, such as grass or corn. The region of logarithmic variation shown by Equation (7) is caused by the viscous drag of the surface and is known as the viscous boundary layer. The constant K_v is determined by the roughness of the surface, and the wind velocity above this boundary layer, which is usually not greater than $\sim$ 10 m thick, the height at which wind is normally measured at an airport. In practice it is often necessary to consider deviation from the velocity profile given by Equation (7) caused by the buoyancy introduced by the temperature profile.

In the vicinity of the ground, the variation in average temperature T with height for a large flat area may be represented during the daytime by the analogous expression

$$T = T_0 - K_t \log (z/z_0) \tag{8}$$

where T_0 is the temperature for $z < z_0$. The thermal boundary layer given in Equation (8), which normally has a thickness and value of z_0 similar to that of the viscous layer, is caused by the heating of the surface by the sun. It normally coincides with a condition known to meteorologists as lapse from measurements well above the boundary layer, an example of which is given (Munn, 1966) in Figure 2.13. Shown also in Figure 2.13 is an example of an inversion

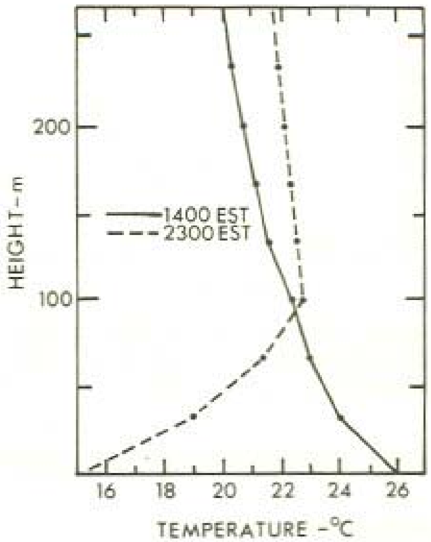

Figure 2.13 Variation of temperature aloft—examples of lapse (afternoon) and inversion (evening) conditions from Munn (1966)

caused by the cooling of the surface of the ground through radiation to the night sky. The term 'neutral' will be used later in the discussion to signify a third meteorological condition, where the dependence of temperature with height is small: This condition may arise typically under heavy clouds.

2.4.2 Refraction

A. Basic Forms

Forms of refraction produced by different meteorological conditions are shown in Figure 2.14. While the effects of wind and temperature gradients appear similar in the figure, the following differences should be noted. Because temperature is a scalar quantity the refraction of sound produced by lapse or inversion conditions is the same in all horizontal (compass) directions. Wind, however, produces refraction nonuniform in direction according to the vector component in the direction of propagation. Thus the refraction produced by the wind is zero when the sound propagates directly crosswind, and increases progressively as the direction of propagation deviates from this condition.

The major acoustic effect in refraction upwards as shown in Figure 2.14(b) is the production of a refractive shadow zone, shown crosshatched in the figure, where, according to the ray picture (geometric accoustics) no sound may enter. Refraction downwards, as shown in Figure 2.14(a) tends in practice to

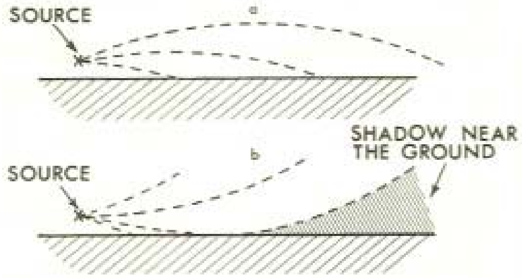

Figure 2.14 (a) Refraction downward—inversion or downwind propagation; (b) Refraction upwards—lapse or upwind propagation

enhance the sound level, by mechanisms which will be discussed in the next section.

B. Refraction Effects for Distances Less than 1500 m

The work of (Ingard (1955), Parkin and Scholes (1965), Wiener and Keast (1957,1959), Delany (1969), Parkin and Scholes (1964), Scholes and Parkin (1967), Scholes *et al.*, (1971), Dean (1961), Baron (1954), Goydke *et al.*, (1968), Franken and Bishop (1967)) may be fitted together to provide a consistent picture of the effect of refraction on the propagation of sound over distances up to 1.5 km using the meteorological and refraction phenomena described in the two previous sections and the propagation phenomena described in Section 2.3. These phenomena will be described with the help of the detailed measurements of Parkin and Scholes (Parkin and Scholes, 1965) shown in Figure 2.15 for the propagation of jet noise over mown grass on a reasonably level airport.

Measured spectra of attenuation in excess of that caused by spherical spreading and atmospheric absorption are shown in Figure 2.15 for two different distances and a number of different meteorological conditions. The source height is 1.8 m and the receiver height 1.5 m. The curves each represent the average of a number of measurements on different days. The dotted, dashed, and solid curves for each distance are designated +5, 0 and −5 to indicate the vector component of wind velocity in the direction of propagation in metres per second. For these three curves the temperature conditions are classed as neutral, as described in Section 2.4.1. Curve 0 for each distance therefore indicates the attenuation produced by the ground effect, as described in Section 2.3.5, and in fact is composed of straight lines joining the experimental points in Figure 2.11. Curve −5 (in Figure 2.15) indicates the additional attenuation produced by a wind shadow zone, and curve +5 the enhancement during downwind propagation.

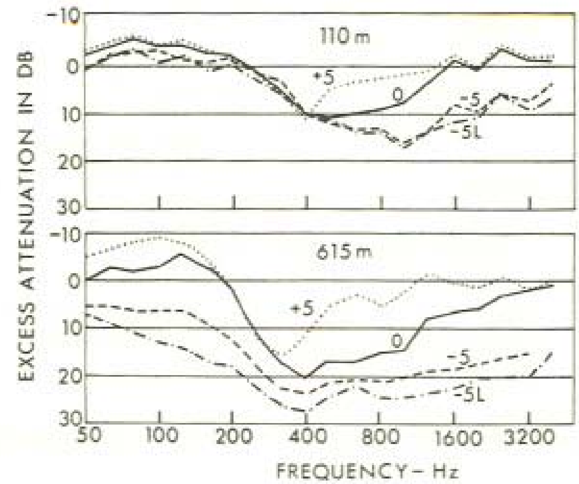

Figure 2.15 Observed attenuation of aircraft noise in a ground-to-ground configuration under a variety of weather conditions (Parkin and Scholes, 1965). Calculated losses from atmospheric absorption and spherical spreading have been subtracted from the attenuation measured in ⅓-octave bands for distances of 110 m and 615 m. These numbers on the curves indicate the vector component of the wind velocity in the direction of propagation in m/sec. All curves are for neutral conditions of temperature except for those marked *L*, which are for lapse

Parkin and Scholes resolve their measurements into two further categories according to the gradient of temperature — either lapse or inversion. The result is generally to change the labels on their curves for all distances by one step (exceptions will be discussed later). Thus their lapse +5 curve is close to the neutral zero curve in Figure 2.15, and the lapse zero curve is equivalent to the neutral −5 curve. The lapse −5 curve, which is the bottom curve ($-5L$) in the figure, represents one of the exceptions. Inversion conditions could only be attained for light winds, and their inversion zero curve is very close to the neutral +5 curve in the figure.

The first conclusion to note, therefore, from the measurements of Parkin and Scholes is that refraction due to vertical gradients of wind and temperature in practice produces equivalent acoustic effects; these are additive, moreover, within the limits imposed by a saturation phenomenon to be described presently. To understand the physical nature of these effects it is useful to divide the frequency range for the spectra shown in Figue 2.15 into three parts: a small central region from about 200–500 Hz where the effect of refraction is smallest, and separate regions for frequencies above and below this central region.

(*a*) *High-frequency region* ($f > 500$ *Hz*). In this region the measurements show a strong tendency towards two extreme values for the excess attenuation, approximately 0 dB in conditions of downward refraction (inversion or downwind propagation) and −20 dB in conditions producing upward refraction (lapse or upwind propagation), seemingly independent of frequency or distance (when the latter is sufficiently large). This pattern is reasonably clear in the measurements for a distance of 615 m shown in Figure 2.15, and obvious in the measurements for a frequency of 1.2 kHz over a range of distances shown in Figure 2.16.

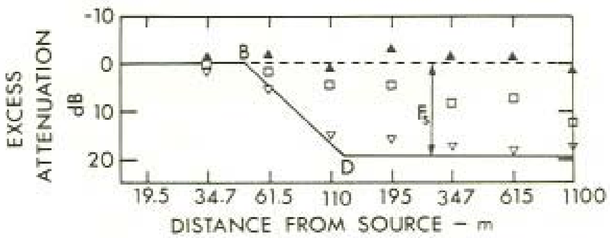

Figure 2.16 Excess attenuation measured for aircraft noise in the 1.2-kHz ⅓-octave band for the ground-to-ground configuration (Parkin and Scholes 1965). The vector component of the wind velocity in the direction of propagation for ▲ is +5 m/sec, □ is 0 m/sec, and ▽ is −5 m/sec. The temperature profile is neutral. F_s is the shielding factor, *B* is the shadow boundary

The pattern for conditions of upward refraction is idealized by the solid lines shown in Figure 2.16. There is effectively no excess attenuation in propagation out to the shadow boundary B in the figure, which is typically 50 m away from the source. The excess attenuation then increases rapidly to position D, but then stays independent of further increases in distance. In effect the signal well within the shadow zone follows the inverse square law but it also reduced in level by a fixed attenuation given by the shielding factor F_s in Figure 2.16.

It should be noted that the pattern of behaviour described above is independent of the magnitude of excess ground attenuation. Thus the measurements for a distance of 615 m in Figure 2.15 indicate at a frequency of 3–4 kHz, where the ground effect is small, there is effectively no enhancement of the signal during downwind propagation, and for a frequency of ~600 Hz, where the ground effect is large, the increase in attenuation in upwind propagation indicated by the −5 curve is small. Furthermore, the $-5L$ curve indicates that the additional refraction produced here by adding a temperature gradient is also small. This effect has been described previously as a saturation.

To explain these saturation characteristics, the following mechanism has been proposed for the solid line in Figure 2.16 (upward refraction). The behaviour well within the shadow zone is as if the signal were from a flanking path. The refractive shadow boundary is known to make a small angle, typically $< 5°$, with respect to the ground (see Section 2.5.1), and it has been widely suggested (Ingard, 1955; Shaw and Olson, 1972; Parkin and Scholes, 1965; Delany, 1969) that the flanking signal is energy scattered down across this boundary by atmospheric turbulence, as indicated by the dashed arrows in Figure 2.17. However, this model for the mechanism of the shielding factor remains untested by experiment or quantitative analysis.

Figure 2.17 A mechanism for the shielding factor, F, in Figure 2.16. The dashed lines represent the continuous scattering of energy down from the sky wave, which propagates without excess attenuation from source S

The method by which the excess attenuation becomes 0 dB for downward refraction, as given by the dashed line in Figure 2.16, is also not clear. The only *a priori* likely way is by destruction of the ground effect. The curvature in the ray path increases the grazing angle ψ in Figure 2.4, hence reduces the cancellation which causes the ground effect (Embleton *et al.*, 1976)

(*b*) *Low-frequency region* ($f < 200$ *Hz*). The curves for $d = 110$ m in Figure 2.15 indicate that the effects of refraction are much smaller for low frequencies than for high: the physical reason is that the scale of the strong gradients in wind and temperature which occur close to the ground (see Figure 2.12 and Section 2.4.1) become small compared to the wavelength of sound at the lower frequencies (Ingard, 1955; Delany, 1969; Dean, 1961). Refraction still occurs for the low frequencies but at much larger distances. The curves marked -5 and $-5L$ for $d = 615$ m in Figure 2.15, for example, indicate that at this distance the shadow zone is still only partially formed, i.e., the excess attenuation falls part way along line BD in Figure 2.16, similar to the curves for -5 and $-5L$ at high frequencies and a distance of 110 m in Figure 2.15.

The +5 curve for a distance of 615 m in Figure 2.15 indicates that during downwind propagation or in an inversion only low-frequency signals are enhanced well above that expected by inverse square law. A likely mechanism for this enhancement is provided by the unique mode of propagation at these frequencies, as described in Section 2.3.5. The surface wave may be attributed to the porosity of the ground retarding the velocity of propagation in the atmospheric layer immediately above the surface. This retardation is enhanced by the vertical gradient of wind velocity during propagation downwind, or the vertical gradient of temperature during an inversion.

(*c*) *Central frequency region* ($f = 350 \pm 150$ *Hz*). A study of curves similar to those in Figure 2.15 for other sites (Parkin and Scholes, 1964; Scholes *et al.*, 1971) and geometrical configurations (Scholes *et al.*, 1971) (h_s, h_r, d) shows the position of this limited region, where the effects of refraction are small, to be in the vicinity of the frequency of maximum ground attenuation, which is somewhere in the range 200–500 Hz. The -5 and $-5L$ curves in Figure 2.15 for a distance of 615 m indicate that the small effect of upward refraction in this region is the result of saturation in the shadow zone, as described above for high frequencies.

The persistence of the ground shadow indicated by the coincidence of curves 0 and $+5$ for a distance of 615 m is remarkable, however, and almost certainly reflects the unusual mechanism of propagation described in Sections 2.3.4 and 2.3.5. Thus, the sharp increase in excess attenuation with frequency between 200 and 300 Hz at a distance of 615 m was shown to be caused by the absorption of energy in the surface wave by the viscous flow of air in the pores of the ground. The coincidence of the $+5$ curve with the zero curve in Figure 2.15, therefore, signifies that this loss cannot be replaced by refraction.

C. *Prediction Schemes*

Wiener and Keast (1959) have provided an empirical prediction scheme for the effects of refraction by wind and temperature which is applicable to the high-frequency region described above. In this scheme the distance to the shadow boundary B in Figure 2.16 is calculated assuming linear vertical gradients of wind and temperature. Delany (1969) has improved this scheme by calculating the distance for the logarithmic profiles in the boundary layer indicated by Equation (7) and (8). Kriebel (1972) has also provided an interesting analysis of the propagation in the boundary layer.

It should be noted, however, that measurements in the low-frequency region described above show the excess attenuation to depend on the surface impedance, which is outside the scope of Wiener and Keast's method.

It should also be noted that for propagation over distances much greater than 1.5 km, different factors become important. There are scattered measurements (Ingerslev and Svane, 1968; Dneprovskaya *et al.*, 1963) which indicate a much higher attenuation in the shadow zones than predicted by Wiener and Keast. In downward refracting conditions the relevant portion of the vertical profiles of wind and temperature become higher than the logarithmic boundary layer given by Equation (7) and (8). Inversions then become more important (see Figure 2.13) and a theoretical analysis of the excess attenuation during propagation in inversions is available (Embleton *et al.*, 1976).

Empirical models have also been developed (Polly and Tedrick, 1975) to explain systematic trends observed during a very large number of measurements of low-frequency sound propagation over flat wooded terrain at distances up to 8 km. The average observed excess attenuation was primarily determined by the sign and magnitude of the vertical gradient in the speed of sound, and secondly by the wind speed.

2.4.3 Turbulence

Large eddies are formed in the atmosphere by instabilities in the thermal and viscous boundary layers at the surface of the ground, described in Section 2.4.1. Further instability causes these eddies to break down progressively into smaller and smaller sizes until the energy is finally dissipated by viscosity in eddies approximately 1 mm in size. A statistical distribution of eddies, which we call turbulence, is therefore present in the atmosphere at all times (Lumley and Panofsky, 1964; Tatarski, 1971). The intensity of the turbulence, however, is strongly dependent on meteorological conditions (and also height above the ground), being high, for example, on a windy summer afternoon, and low under nocturnal inversions.

The effect of atmosphere turbulence on wave propagation has been studied extensively during the last twenty years (Tatarski, 1971) most notably on the propagation of light and microwaves, but also of sound (Tatarski, 1971; Mandics, 1971). For sound, the condition most studied is near-vertical propagation, well away from the surface of the ground, to permit the 'acoustical sounding' of meteorological conditions (Little, 1969). There are a small number of investigations of near-horizontal propagation of sound close to the ground (Ingard and Maling, 1963; Embleton *et al.*, 1974) which are of direct relevance to noise problems, but for most questions concerning the effect of turbulence on noise propagation it is necessary to fall back on knowledge accumulated in these related areas.

It is known that atmospheric turbulence produces fluctuations in the amplitude and phase of a pure tone during propagation which increase with increasing distance until a point is reached where the phase fluctuations have a standard deviation comparable to 90°. At this point the signal effectively becomes uncorrelated with the source and the amplitude fluctuations are limited to a standard deviation (Embleton *et al.*, 1974) of ~6 dB. The distance to this point for horizontal propagation of sound near the ground on a summer day is very approximately 700 λ, for frequencies in the range 500–5,000 Hz (Embleton *et al.*, 1974). An effect of this magnitude brings into question the common use of coherent acoustic theory for predicting noise propagation in a number of critical regions, some of which have already been mentioned (Sections 2.3.5 and 2.4.2)

Perhaps the condition most sensitive to atmospheric turbulence is interference phenomena: the sharp spikes clearly visible in the minima of the interference patterns shown in Figure 2.7, for example, are caused by fluctuations in the phase difference between direct and reflected waves, and the effective depth of the minima is determined by the fluctuations (Ingard and Maling, 1963). While a good start has been made on the theory of interference in a turbulent medium (Ingard and Maling, 1963), much more work will be needed on partially coherent propagation before a satisfactory method is achieved for predicting the ground effect at the longer ranges and higher frequencies shown in Figure 2.10.

Another role of atmospheric turbulence which is important for the prediction of noise levels, is in determining the saturation effect in shadow zones, as described in terms of a shielding factor in Sections 2.4.2. The role is, in fact, even more general than described there: it should be expanded to include the acoustic shadow provided by walls (Kurze, 1971, 1974), buildings (Lyon, 1974), the ground effect (Shaw and Olson, 1972), etc. We are very limited at present in our ability to predict levels in shadow zones because of an almost complete lack of understanding of the basic phenomena which determine the shielding factor.

A less profound aspect of atmospheric turbulence, but still a nuisance, is the need to cope with amplitude fluctuations in specifying noise levels (Embleton and Piercy, 1975) from relatively distant sources such as aircraft. One recent experimental study of sound propagation to the ground from a 152 m tower indicated the potential significance of the Richardson's number on the magnitude of these fluctuations (Kasper *et al.*, 1975).

There is one role of atmospheric turbulence which used to be considered important (Ingard, 1953) in predicting noise levels, but now is generally believed to be minor (Deloach, 1975) — that is the direct attenuation of sound by turbulence. If the sound is in a highly directed beam, as for example a vertical atmospheric sounder (Little, 1969) then turbulence attenuates the beam by scattering energy out of it (a phenomena converse to the filling of the narrow shadow zone by scattered energy described in Section 2.4.2). This attenuation can now be calculated with reasonable certainty (Brown and Clifford, 1976). In practice, however, the propagation of noise is usually much closer to spherical expansion from a point source. Because the scattering from turbulence is elastic, and mostly forward through a small scattering angle, the attenuation presented to a spherically expanding acoustic field is negligible. The attenuation of sound due to scattering from a moderately directional source, such as a jet or rocket engine, must lie between these two extremes, but has never been evaluated thoroughly. It is generally believed to be negligible (Sutherland, 1975; Parkin and Scholes, 1965; Wiener and Keast, 1959; Delany,

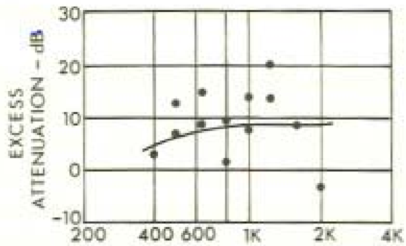

Figure 2.18 Excess attenuation derived from hilltop to hilltop transmission measurements over a distance of about 3 km. The points are measurements which were corrected for inverse square law and molecular absorption using the method of Evans and Bazley (1956) by the original investigators (Wiener and Keast, 1959). The curve is molecular absorption from the nitrogen relaxation, calculated by the method of Sutherland *et al.* (1974), which was neglected in the method of Evans and Bazley (1956)

1969) for most applications. However, where very low frequencies are of importance, for example, in the case of rocket noise, the attenuation by scattering may be significant (Sutherland, 1971) compared to the very low attenuation produced by atmospheric absorption.

2.5 EFFECT OF TOPOGRAPHY

The acoustic phenomena considered previously in Sections 2.3 and 2.4 have all been described for a particular topography, primarily large flat areas covered with short grass, such as an airport, with a receiver placed approximately ear height for a human being standing on the ground. In practice, noise levels need to be predicted for different heights above the ground, for hillsides, for various types of foliage, houses, walls, etc. The data available for such sites is generally much less extensive than for flat ground, and present knowledge is therefore more sketchy. The aim of this section, however, is to outline briefly what is known about the effects of topography. Propagation in city streets, and the attenuation due to barriers will be specifically excluded because these subjects have been covered in recent reviews (Lyon, 1974; Kurze, 1974) which this article is designed to accompany.

2.5.1 Elevation

As an extreme case, consider the propagation from hilltop to hilltop with most of the propagation path several hundreds or thousands of feet above the valley floor. Several sites of this nature have been investigated (Weiner and Keast, 1959; Delasso, 1953), and the measured attenuation is in reasonable agreement with that predicated by inverse square law and atmospheric absorption, when the latter includes the vibrational relaxation of nitrogen (see, for example, Figure 2.18 and the discussion on this point in Section 2.2.2). This attenuation is found to be independent of wind and temperature except in so far as the latter enters into the calculation of absorption.

Studies of noise from low-flying aircraft — effectively sources at low glancing angles ψ (Figure 2.4) — over flat ground are informative (Benson *et al.*, 1958, 1960, 1961). They indicate, for example, that refraction by wind gradients is negligible for $\psi > 5°$ out to a distance of about 6,000 m. There is currently a controversy, however, over a prediction of aircraft noise levels for small ψ, and this problem would probably be well served by an assembly of existing data from many investigators and a fit to the principles out-lined in Section 2.3.

Calculations for the effect of elevation produced by a shallow hillside ($\psi <$ 1°) bordering an airport (Embleton *et al.*, 1976; Piercy and Embleton, 1974) have indicated a significant reduction of the ground shadow for aircraft on the ground. There were no supporting measurements but the results correlated well with subjective observations (the structure of complaints).

2.5.2 Foliage

The effect of stands of trees, corn, reeds, etc. have been documented in several studies (Aylor, 1972; Wiener and Keast, 1957; Eyring, 1946; Embleton, 1963; Aylor, 1972; Dobbins *et al.*, 1966). Apparently the main effect at low frequencies is to enhance the ground effect (Aylor, 1972), the roots making the ground more porous, as described in Section 2.3.3. At high frequencies, where the dimensions of leaves become comparable with the wavelength, there is also a significant attenuation caused by scattering (Embleton, 1963; Aylor, 1972). A formula for the latter effect has been developed (Aylor, 1972). The propagation in a vegetative layer over the ground has also been investigated theoretically (Pao and Evans, 1971), but there were no measurements by which to judge the significance of this theory.

In a forest, the vertical gradients of wind and temperature are small (Munn, 1956), the foliage making z_0 in Equations (7) and (8) approximately the height of the trees. Presumably, therefore, the effects of refraction are small also.

2.5.3 Obstructions (Walls, Houses, Bushes, etc.)

The effect of refraction on the propagation of sound in city streets (Wiener *et al.*, 1965) as within forests, is small, and for the same reason: the obstruction to the flow of air is sufficient to raise the viscous and thermal boundary layers to the vicinity of the tops of the obstacles (buildings) (see Section 2.4.1). The attenuation of sound by the ground effect in the city (Lyon, 1974) is also much smaller than in the country (Parkin and Scholes, 1965), partly because of the paved ground, but more importantly because obstacles to the propagation of sound produce an interference pattern much different from the simple interference between direct and ground reflected waves described in Section 2.3. These effects have been studied both for cities (Lyon, 1974; Wiener *et al*, 1965) and open flat land, (Parkin and Scholes, 1965; Wiener and Keast, 1959) with results that are very different. There has been very little work, however, on intermediate sites such as suburbs. Questions such as how many obstacles are needed to destroy the effect of the ground, or refraction, as measured for flat land, cannot be answered at present. As a result the prediction of the propagation of noise from airports, freeways, etc., out into the suburbs is based largely on empirical methods not well founded on either analytical models or extensive experimental data.

2.6 PROPAGATION PROBLEMS SPECIFIC TO COMMUNITY NOISE

2.6.1 Testing and Certification of Sources

A. Vehicles and Other Ground Based Sources

There are several propagation problems in the testing of ground based noise sources such as road vehicles, lawn mowers, snowmobiles, etc. (Bettis and Saxton, 1973; Piercy and Embleton, 1974). The noise is usually measured with a microphone 1.2 m above the ground at a distance of 7–16 m with the propagation path over the surface on which the machine is designed to operate. If the surface is porous, for example, grass or snow, then there can be a problem of variability as a result of the incipient ground shadow described in Section 2.3.5. The solution here is a compromise between measurement configurations, a surface of predictable impedance, and relevance to the use of the machine. If the source is stationary, most of the relevant scientific knowledge (Embleton *et al*., 1976; Piercy and Embleton, 1974) is available, with the exception of good data on the impedance of relevant surfaces. A convenient method of measuring the impedance of surfaces over a range of grazing angle (ψ in Figure 2.4) and frequency is badly needed.

If the surface is hard, there are problems of repeatability for sources with large-amplitude pure-tone components when the transmission path introduces interference maxima and minima at similar frequencies. This phenomenon is reasonably well documented (Bettis and Saxton, 1973; Piercy and Embleton, 1974) (see also Section 2.3.2). Variability due to atmospheric turbulence has also been recorded (Piercy *et al*., 1976; Hemdal *et al*., 1974).

There is also an unresolved problem of variability for moving sources such as vehicles (Piercy *et al.*, 1976). There is a systematic variation in A-weighted pass-by levels with ambient temperature (Piercy *et al.*, 1976; La Breche, 1974) of −1 dB/10 °C, and a run-to-run variation of approximately 1 dB, both of which appear to be associated with the movement of the vehicle. The most obvious mechanism here is refraction by the movement of air in the wake of the moving vehicle (La Breche, 1974).

B. Aircraft

The new method for calculating atmospheric absorption (Sutherland *et al.*, 1974; Sutherland, 1975) described in Section 2.2.2 should bring the physics of the propagation from overhead aircraft under reasonable control. However, the factors which influence sideline propagation are much less well understood. A substantial amount of work has been done on the acoustic effects of the ground plane during ground tests of jet engines, for which a recent review is available (SAE, 1976).

2.6.2 Prediction of Environmental Impact

The basic physics underlying the propagation of noise at long range close to the ground described in Sections 2.2–2.5 is obviously intricate, and current knowledge of it patchy. As a result it is usually not possible in practice to predict noise levels with reasonable reliability at sites distant (hundreds or thousands of metres) from a strong source near the ground using basic knowledge alone. It is possible for a specific site, however, to take a completely empirical approach, measuring the noise from a source at positions of interest under various weather conditions, and predicting, for example, the levels to be expected at these positions from a highway or airport proposed for this site with tolerable precision (Ingerslev and Svane, 1968; Piercy and Embleton, 1974. After several of these individual investigations, it is tempting to generalize the empirical results for average levels and apply them to other sites. This procedure has been popular in recent years, through the development and use of empirical design guides for highways and airports. These prediction methods generally ignore conditions of topography and weather which are known to have a strong influence on sound propagation, as described in Sections 2.2–2.5. Such design guides may be expected to provide reasonable predictions on the average, but for a specific site their unaided use may well result in serious error. Consider, for example, the problems in the prediction of noise from airports reported by Piercy and Embleton (1974) and Dickinson (1976) and also the considerable difference between empirical rules for predicting noise levels from highways based on different (but large) sets of data reported by King and Oliver (1975, Hajek (1975), and Plotkin and

Kunicki (1976). In a field which is physically complex and only partly understood, such as outdoor sound propagation, there is still a decided need for human judgement based on specialist's knowledge of the current state of the art.

2.6.3 Recommendations

It is recommended, in the light of the analysis in the preceding section, as well as the history of research outlined in the introduction, that long-term support be developed at a modest level for the field of outdoor sound propagation. The aim should be to obtain the depth of understanding required to gradually improve the basic knowledge in this complex field. Attainment of the necessary depth of understanding is not compatible with short-term research studies.

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2.7 REFERENCES

Aylor, D. (1972). "Noise reduction by barriers on the ground." *J. Acoust. Soc. Am.*, **51**, 201–209.

Aylor, D. (1972). Sound transmission through vegetation in relation to leaf area density, leaf width, and breadth of canopy, *J. Acoust. Soc. Am.* **51**, 411–414.

Banos, A. (1966). *Dipole Radiation in the Presence of a Conducting Half-Space*, Pergamon, New York.

Baron, P. (1954). Propagation du son dans l'atmosphère et audibilité des signaux avertisseurs dans le bruit ambient, *Ann. Telecomm.* **9**, 258–270.

Bazley, E. N. (1976). Sound absorption in air at frequencies up to 100 kHz, *NPL (Great Britain) Report AC74*.

Benson, R. W. *et al.*, (1958), (1960), (1961). Sound propagation near the earth's surface as influenced by weather conditions, *WADC Tech. Rep.* 57–353, Pt. I, Pt. II, Pt. III.

Bettis, R. A. and Saxton, M. Z. (1973). Effect of test-site topography on vehicle noise measurements, *J. Acoust. Soc. Am.*, **54**, 332(A).

Brown, E. H. and Clifford, S. F. (1976). On the attenuation of sound by turbulence, *J. Acoust. Soc. Am.*, **60**, 788–794.

Dean, E. A. (1961). The wavelength limits of atmospheric ray acoustics, *Proc. Symp. Acoust. Propag. Texas*, 7 (AD–408716).

Delany, M. E. (1969). Range prediction for siren sources, *NPL Aero Special Report 033*.

Delany, M. E. and Bazley, E. N. (1970). Monopole radiation in the presence of an absorbing plane, *J. Sound Vib.*, **13**, 269–279.

Delany, M. E. and Bazley, E. N. (1971). A note on the effect of ground absorption in the measurement of aircraft noise, *J. Sound Vib.*, **16**, 315–322.

Deloach, R. (1975). An opposite view, *NASA Tech. Note* D7823.

Delsasso, L. P. (1953). The Attenuation of Sound in the Atmosphere, USAF contract W-28–099-ac-228 (AD89256).

Dickinson, P. J. (1976). Temperature inversion effects on aircraft noise propagation, *J. Sound Vib.* **47**, 438–443.

Dickinson, P. J. and Doak, P. E. (1970). Measurements of the normal acoustic impedance of ground surfaces, *J. Sound Vib.*, **13**, 309–322.

Dneprovskaya, I. A., Joffe, V. K. and Levitas, F. I. (1963). *Sov. Phys.-Acoust.*, **8**, 235–239.

Dobbins, D. A. *et al.*, (1966). Jungle acoustics I: Transmission and audibility of sounds in the jungle, U.S. Army Tropic *Test Center Report 7* (AD 647 804).

Donato, R. J. (1976) Propagation of a spherical wave near a plane boundary with complex impedance, *J. Acoust. Soc. Am.*, **60**, 34–39.

Embleton, T. F. W. (1963). Sound propagation in homogenous deciduous and evergreen woods, *J. Acoust. Soc. Am.*, **35**, 1119–1125.

Embleton, T. F. W., Olson, N., Piercy, J. E. and Rollin, D. (1974). Fluctuations in the propagation of sound near the ground. *J. Acoust. Soc. Am.*, **55**, 485(A).

Embleton, T. F. W. and Piercy, J. E. (1975). Relation between steady and normally distributed sound levels, *J. Acoust. Soc. Am.*, **58** S108 (A).

Embleton, T. F. W., Piercy, J. E. and Olson, N. (1976). Outdoor propagation over ground of finite impedance, *J. Accoust. Soc. Am.*, **59**, 267–277.

Embleton, T. F. W., Thiessen, G. J. and Piercy, J. E. (1976). Propagation in an inversion and reflection at the ground, *J. Acoust. Soc. Am.*, **59**, 278–282.

Evans, E. J. and Bazley, E. N. (1956). The absorption of sound in air at audio frequencies, *Acustica*, **6**, 238–244.

Evans, L. B., Bass, H. E. and Sutherland, L. C. (1972). Atmospheric absorption of sound: theoretical predictions, *J. Acoust. Soc. Am.*, **51**, 1565–1575.

Eyring, C. F. (1946). Jungle acoustics, *J. Acoust. Soc. Am.*, **18**, 257–270.

Franken, P. A. and Bishop, D. E. (1967). The propagation of sound from airport ground operations, *NASA Report CR767*.

Goydke, H., Kallenbach, W. and Schroeder, J. J. (1968). Untersuchungen zur Schallausbreitung von Sirenensignalen, *Acustica*, **20**, 276–288.

Hajek, J. J. (1975). Ontario highway noise prediction method, Ministry of Transport (Ont.) *Report RR197*.

Harris, C. M. and Tempest, W. (1964). Absorption of sound in air below 1,000 cps, *J. Acoust. Soc. Am.*, **36**, 2390–2394.

Harris, C. M. (1966). Absorption of sound in air versus humidity and temperature, *J. Acoust. Soc. Am.*, **40**, 148–162.

Hemdal, J. F. *et al.*, (1974). *A Study of Repeatability at Motor Vehicle Noise Measurement Sites*, Environmental Res. Inst., University of Michigan.

Ingard, K. U. (1951). On the reflection of a spherical wave from an infinite plane, *J. Acoust. Soc. Am.*, **23**, 329–335.

Ingard, K. U. (1953). Review on the influence of meteorological conditions on sound propagation. *J. Acoust. Soc. Am.*, **25**, 405–411.

Ingard, K. U. (1955). The physics of outdoor sound, in *Proceedings of the Fourth Annual Noise Abatement Symposium*, Publisher, City, 11–25.

Ingard, K. U. and Maling, G. C. (1963). On the effect of atmospheric turbulence on sound propagation over the ground, *J. Acoust. Soc. Am.*, **35**, 1056–1058.

Ingerslev, F. and Svane, C. (1968). *Proc. 6th Int. Cong. Acoust.* F93–96.

Ivanov-Shits, K. M. and Rozhim, F. V. (1960). Investigation of surface waves in air, *Sov. Phys.-Acoust.*, **5**, 510–512.

Jonasson, H. G. (1972). Sound reduction by barriers on the ground, *J. Sound Vib.*, **22**, 113–126.

Kasper, P. K., Pappa, R. S., Keefe, L. R. and Sutherland, L. C. (1975). A study of air-to-ground sound propagation using an instrumented meteorological tower, *NASA Report CR-2617*.

King, F. D. and Oliver, C. C. (1975). Effects of wind and temperature gradients on the propagation of highway traffic noise, *J. Acoust. Soc. Am.*, **57**, S32(A).

Kneser, H. O. (1940). A nomogram for finding the sound absorption coefficient in air, *Ak. Zeit*, **5**, 256–257.

Kriebel, A. P. (1972). Refraction and attenuation of sound by wind and temperature profiles over a ground plane, *J. Acoust. Soc. Am.*, **51**, 19–23.

Kurze, U. J. (1971). Sound propagation outdoors, in Beranek, L. L. (ed.) *Noise and Vibration Control*, McGraw-Hill, New York, 164–193.

Kurze, U. J. (1974). Noise reduction by barriers, *J. Acoust. Soc. Am.*, **55**, 504–518.

LaBreche, R. M. (1974). *Variation in Measured Automobile Passby Noise due to Operator and Environmental Factors*, G. M. Proving Ground Engl. Publ. 4587.

Lawhead, R. B. and Rudnick, I. (1951). Acoustic wave propagation along a constant normal impedance boundary, *J. Acoust. Soc. Am.*, **23**, 546–549.

Lee, M. C. and Sutherland, L. C. (1976) Laboratory measurements of atmospheric absorption in air, *J. Acoust. Soc. Am.*, **60**, S31(A).

Little, C. G. (1969). Acoustic methods for the remote probing of the lower atmosphere, *Proc. IEEE 57*, 571–578.

Lumley, J. L. and Panofsky, H. A. (1964). *The Structure of Atmospheric Turbulence*, Wiley, New York.

Lyon, R. H. (1974). Role of multiple reflections and reverberations in urban noise propagation, *J. Acoust. Soc. Am.*, **55**, 493–503.

Mackenzie, K. V. (1960). Reflection of sound from coastal bottoms, *J. Acoust. Soc. Am.*, **32**, 221–231.

Mandics, P. A. (1971). Line-of-sight acoustical probing of atmospheric turbulence, *Tech. Rep. 4502–1* Radio Science Lab., Stanford University, 92.

Morse, P. M. (1958). For a good discussion of locally reacting surfaces, *Vibration and Sound*, McGraw-Hill, New York.

Munn, R. E. (1966). *Descriptive Micrometeorology* Academic, New York.

Nyborg, W. L. and Mintzer, D. (1955). Review of sound propagation in the lower atmosphere, *WADC Technical Report 54–602*.

Officer, C. B. (1958). *Introduction to the Theory of Sound Transmission with Application to the Ocean*, McGraw-Hill, New York.

Pao, S. P. and Evans, L. B. (1971). Sound attenuation over simulated ground cover, *J. Acoust. Soc. Am.*, **49**, 1069–1075.

Parkin, P. H. and Scholes, W. E. (1964). The horizontal propagation of sound from a jet engine close to the ground at Radlett, *J. Acoust. Vib.*, **1**, 1–13.

Parkin, P. H. and Scholes, W. E. (1965). The horizontal propagation of sound from a jet engine close to the ground at Hatfield, *J. Sound Vib.*, **2**, 353–374.

Piercy, J. E. (1969). Role of the vibrational relaxation of nitrogen in the absorption of sound in air, *J. Acoust. Soc. Am.*, **46**, 602–604.

Piercy, J. E. (1972). The absorption of sound in the atmosphere, *J. Acoust. Soc. Am.*, **52**, 1310(A).

Piercy, J. E., Embleton, T. F. W. and Olson, N. (1976). Mechanisms causing variability in the noise testing of light motor vehicles, *National Research Council of Canada Report APS 560*.

Piercy J. E. and Embleton, T. F. W. (1974). Effect of ground on near-horizontal sound propagation, *Trans. Soc. Auto. Eng., Sec. I*, **83**, 928–932.

Piercy, J. E., Donato, R. J. and Embleton, T. F. W. (1976). Near-horizontal propagation of sound over grassland. *J. Acoust. Soc. Am.*, **60**, S2(A).

Piercy, J. E. and Embleton, T. F. W. (1974) Effect of weather and topography on the propagation of noise — Vancouver Airport, *NRC (Canada) Report APS 526*.

Pohlman, W. (1961). Die Schallabsorption von Luft verschiedener Feuchtigkeit zwischen 10 and 100 kHz, *Proceedings of the Third International Congress on Acoustics, Stuttgart*, by Cremer, I. L. (ed.) Elsevier, Amsterdam, 532–535.

Plotkin, K. S. and Kunicki, R. (1976). Comparison of highway noise prediction models, *Wyle Research Report WR76–25*.

Polly, R. C. and Tedrick, R. N. (1965). Measured acoustic propagation parameters in the Mississippi test operations area, *NASA MSFC, TMX-1132*.

Rathe, E. J. (1969). Note on two common problems of sound propagation, *J. Sound Vib.*, **10**, 472–479.

Rudnick, I. (1947). Propagation of an acoustic wave along a boundary, *J. Acoust. Soc. Am.*, **19**, 348–356.

Rudnick, I. (1957). Propagation of sound in air, in Harris, C. M. (ed.) *Handbook of Noise Control*, McGraw-Hill, New York, 3–1 to 3–17.

SAE Committee A-21 (1964). Standard Values of Atmospheric Absorption as a Function of Temperature and Humidity for Use in Evaluating Aircraft Flyover Noise, Society of Automotive Engineers, ARP866.

Society of Automotive Engineers (1976). Acoustic effects produced by a reflecting plane, *Aerospace Information Report AIR* 1327.

Scholes, W. E., Salvidge, A. C. and Sargent, J. W. (1971). Field Performance of a noise barrier, *J. Sound Vib.*, **16**, 627–642.

Scholes, W. E. and Parkin, P. H. (1967). The effect of small changes in source height on the propagation of sound over grassland, *J. Sound Vib.*, **6**, 424–442.

Shaw, E. A. G. and Olson, N. (1972). Theory of steady-state urban noise for an ideal homogenous city, *J. Acoust. Soc. Am.*, **51**, 1781–1793.

Shields, F. D. and Bass, H. E. (1976). A study of atmospheric absorption of high frequency noise and application to fractional Octave bands, *NASA Report CR 2760*.

Sommerfeld, A. N. (1909). Propagation of waves in wireless telegraphy, *Ann. Phys. (Paris)*, **28**, 665; **81**, 1135–1153.

Sutherland, L. C. (1971). Scattering Attenuation of Sound in the Lower Atmosphere, *J. Acoust. Soc. Am.*, **49**, 129(A).

Sutherland, L. C., Piercy, J. E., Bass, H. E. and Evans, L. B. (1974). Method for Calculating the Absorption of Sound by the Atmosphere, *J. Acoust. Soc. Am.*, **56**, S1(A). This method is now ANSI standard 51.26–1978. The theoretical and experimental background is due to be published in the series *Physical Acoustics*, vol. XVII, Mason, W. P. (ed.), Academic, New York (1984).

Sutherland, L. C. (1975). Ambient noise level above plane with continuous distribution of random sources, *J. Acoust. Soc. Am.*, **57**, 1540–1542.

Sutherland, L. C. (1975). Review of experimental data in support of a proposed new method for computing atmospheric absorption loss, *DOT Report TST-75–87*.

Sutton, O. G. (1953). *Micrometeorology* McGraw-Hill, New York.

Tatarski, V. I. (1971). *The effects of the Turbulent Atmosphere on Wave Propagation*, Keter, Jerusalem.

Tatge, R. B. (1972). Noise radiation by plane arrays of incoherent sources, *J. Acoust. Soc. Am.*, **52**, 732–736.

Thiessen, G. J. (1973). Community noise-surface transportation, *J. Acoust. Soc. Am.*, **53**, 303(A).

Wait, J. R. (1970). *Electromagnetic Waves in Stratified Media* Pergamon, New York, Chap. 2.

Wenzel, A. R. (1974). Propagation of waves along an impedance boundary, *J. Acoust. Soc. Am.*, **55**, 956–963.

Wescott, J. W. and Kushner, S. S. (1965). Propagation of sound in air — A bibliography with abstracts, *Report of Geophysics Lab.*, University of Michigan (AD 465 678).

Wiener, F. M. and Keast, D. N. (1957). *Bolt, Beranek and Newman Final Report 466*, (AD-136319).

Wiener, F. M. and Keast, D. N. (1959). Experimental study of the propagation of sound over ground, *J. Acoust. Soc. Am.*, **31**, 724–733.

Wiener, F. M., Malme, C. I. and Gogos, C. M. (1965). Sound propagation in urban areas. *J. Acoust. Soc. Am.*, **37**, 738–747.

Wisse, H. (1929). Asymptotic Dipole Radiation Formulas, *Bell System Tech. J.*, **8**, 662.