REVIEW OF SOUND PROPAGATION IN THE ATMOSPHERE*

J.E. Piercy and T.F.W. Embleton
Division of Physics, National Research Council
Ottawa, Ontario, Canada K1A 0R6

SUMMARY

Advances in our understanding of the mechanisms of outdoor sound propagation during the last five years which are relevant to community noise problems are discussed, and an attempt made to fit them into a consistent overall picture. One aspect is studies of ground impedance and the relevance of modelling the ground plane by a semi-infinite porous medium. Another is the contribution of theoretical papers on propagation from a point source through a homogeneous atmosphere over a plane of finite impedance. A third is the effect of atmospheric inhomogeneity - most notably scattering by turbulence and refraction by the thin (~10cm) thermal boundary layer close to the ground. The attenuation of barriers will also be discussed including the application of modern theory to diffraction over the top, interference effects produced by reflection from the ground, and scattering down into the diffractive shadow zone by turbulence.

SOMMAIRE

On présente une synthèse des connaissances acquises durant les cinq dernières années sur les mécanismes de propagation qui sont pertinents au bruit urbain. Premièrement on discute les travaux sur l'impédance du sol et en particulier la validité du modèle qui considère celui-ci comme milieu poreux. Ensuite on résume les études théoriques sur la propagation du son d'une source ponctuelle dans une atmosphère homogène au-dessus d'un dioptre plan. Troisièmement on considère l'effet d'une atmosphère inhomogène; notamment la diffusion par la turbulence et la réfraction par un mince (~ 10 cm) gradient thermique près du sol. On traite en plus l'efficacité des écrans sonores en considérant les théories modernes de diffraction, les effets d'interférences dus aux réflections au sol et la diffusion dans l'ombrage acoustique de l'écran par la turbulence.

It is proposed to review briefly recent advances in the understanding of outdoor sound propagation which are relevant to community noise problems. Only advances since the review[1] which appeared in JASA in June 1977 will be considered.

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I. GROUND IMPEDANCE

Figure 1 shows measurements[2] of the real and imaginary parts R and X of the acoustic impedance of grass-covered soil outside our laboratory. The measurements were laboriously carried out over one summer using two different techniques, as shown, for various grazing angles in the range 20° to 90°. We drew the solid curves as an approximate fit to our data, and found within experimental scatter there was no dependence on angle, meaning that the surface could be regarded as locally reacting.

Ian Chessell[3] then fitted this data by Delany and Bazley's[4] simplified equations for the characteristic impedance of a fibrous material. In these equations there is only one adjustable parameter, the flow resistivity σ, and he obtained the dashed curves for a value of 300 C.G.S. units which fit the data remarkably well, - as well in fact as our empirical curves. Thus a semi-infinite porous medium is a good model for the sound reflective properties of this grassy surface.

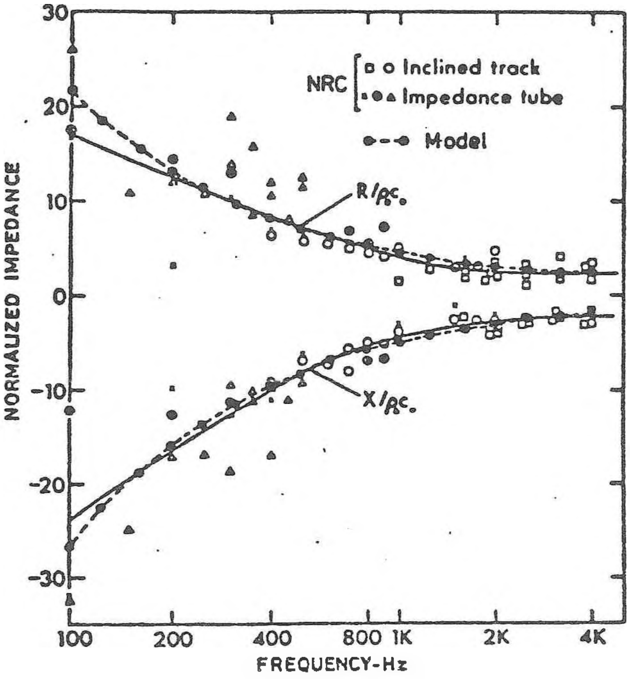

Fig. 1

Since then the measured impedances for a number of ground surfaces have appeared which show similar agreement with Chessell's model. Figure 2 shows the acoustical measurements of Bolen and Bass[5], and theoretical curves from the model for two values of the flow resistivity σ. The best fit to their acoustic data is the dashed curve for σ = 40 C.G.S. units. They also measured the flow resistivity of the soil by an non-acoustical technique and obtained σ = 60 C.G.S.

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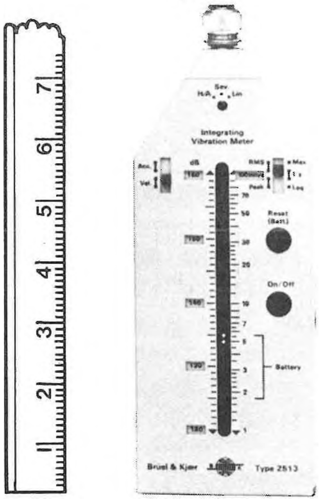

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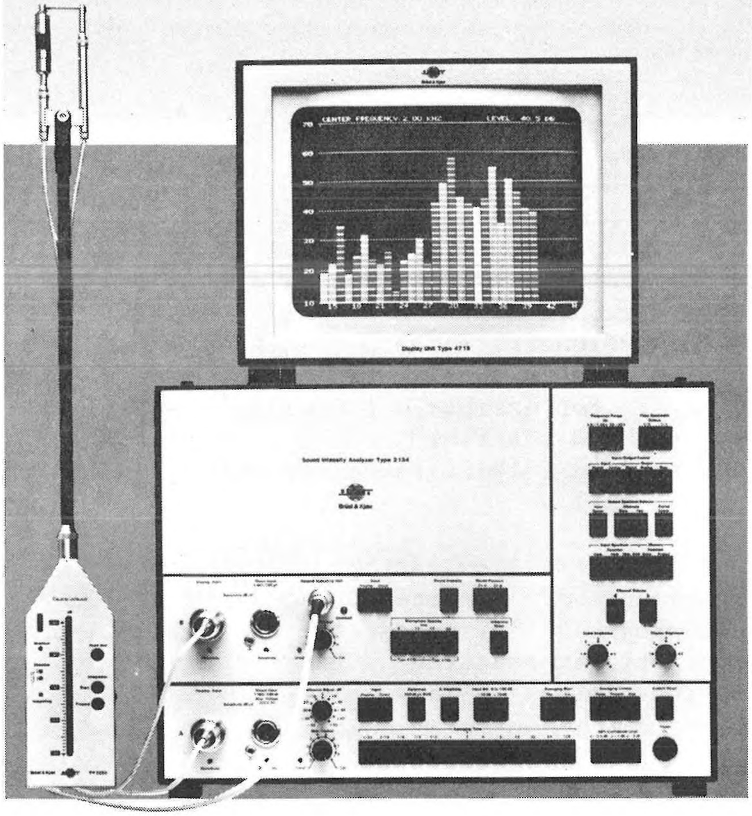

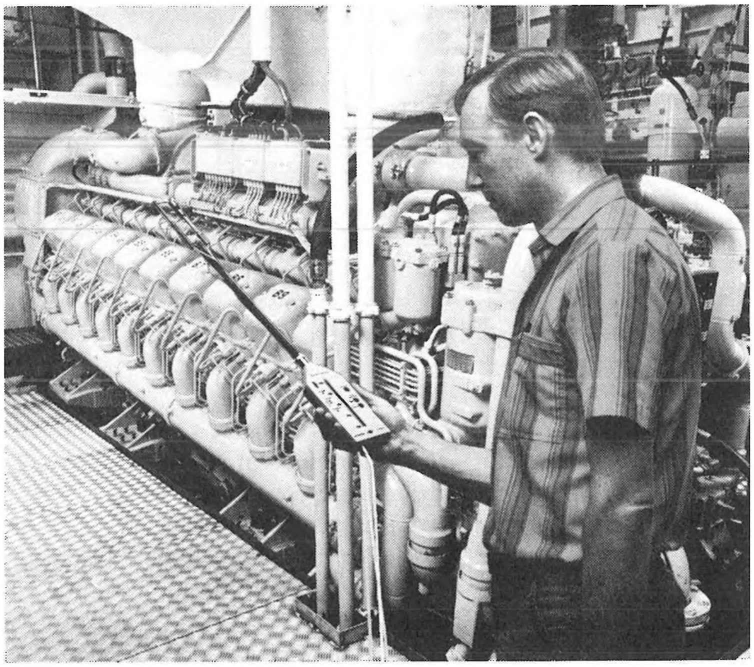

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units. The solid curve therefore represents an independent prediction. We take the closeness of predicted and experimental curves to be further verification of the model.

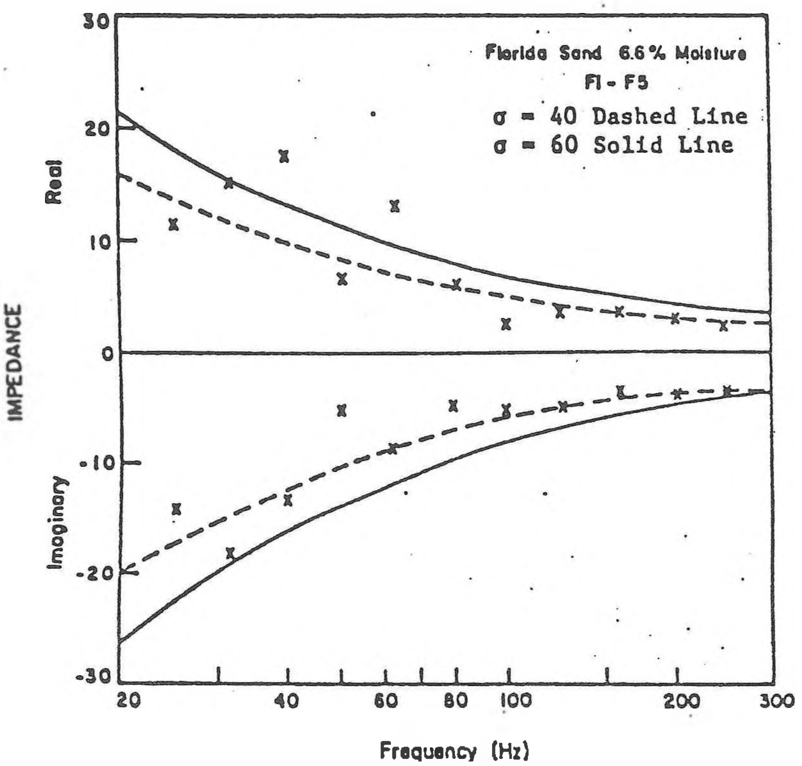

Fig. 2

A factor which needs understanding is the effect of pore size. For the impedance to go up at low frequencies, as shown here, the pore size needs to be smaller than the thickness of the acoustic boundary layer (which is in turn proportional to $f^{-\frac{1}{2}}$ and has a value of 0.1 mm at 300 Hz). Thus the wave in the pores at low frequencies is a viscous wave, which is a very slow and very highly damped wave. It is for this reason that a porous layer of soil at the surface, whose thickness may be small compared to the free space acoustic wavelength, may in practice be modelled by a porous medium of infinite thickness. There has been some work on the limits to this model: for example a 1 inch layer of new snow, where the pore size is large and the flow resistivity hence very low, has been found[6] to need a layer representation.

Nevertheless there are now values of effective flow resistivity available[7] from acoustic reflectivity measurements for a number of common surfaces outdoors, some of which are shown in Fig. 3, and the one parameter model of Chessell is a suitable fit in practice, given the low state of present knowledge and the rough needs of many practical applications.

Fig. 3: Flow resistivities of various ground surfaces. Values give best fit between measured sound spectrum and that predicted by a one-parameter model.

Description of Surface	Flow Resistivity in rayls (CGS units)
Dry snow, new fallen 7.5 cm on a 40 cm base	15 to 30
Sugar snow	25 to 50
In forest, pine or hemlock	20 to 80
Grass: rough pasture, airport, public buildings, etc.	150 to 300
Roadside dirt, ill-defined, small rocks up to 4"	300 to 800
Sandy silt, hard packed by vehicles	800 to 2500
"Clean" limestone chips, thick layer (1/2 to 1 inch mesh)	1500 to 4000
Old dirt roadway, fine stones (1/4" mesh) interstices filled	2000 to 4000
Earth, exposed and rain-packed	4000 to 8000
Quarry dust, fine, very hard-packed by vehicles	5000 to 20,000
Asphalt, sealed by dust and use	> 20,000

II. PROPAGATION OVER A PLANE WITH FINITE IMPEDANCE

Figure 4 shows the attenuation in excess of that from molecular absorption and spherical spreading from a point source to a receiver 600 m away, both approx. 2 m above a grass-covered ground surface having an impedance shown by the measurements in Figure 1. The different curves give the contributions calculated for the different wave components by Donato[1]. The lower dashed curve gives the contribution D from direct and R from reflected waves as known classically, say by Rayleigh. Contribution G from the ground wave was introduced to acoustics by Rudnick[8], and Ingard[9] and their colleagues about 1950 from radio wave propagation. Contribution S from the surface wave was introduced by Wentzel[10] in 1974 also from electromagnetic propagation. The points are measurements by Parkin and Scholes[11] of the propagation of jet noise across an airport. Note that all of these wave components are needed to get agreement within 10 dB for frequencies less than 300 Hz, and for f > 300 Hz an additional phenomenon is needed which will be discussed later. A number of different methods of calculation have been proposed recently by people such as Thomasson[12], Donato[13], Soroka[14], Filippi[15] and their various colleagues for propagation close to the ground from a point source. To assess these methods we recommend two recent critical reviews, by Attenborough[16], and Filippi[17] and their colleagues.

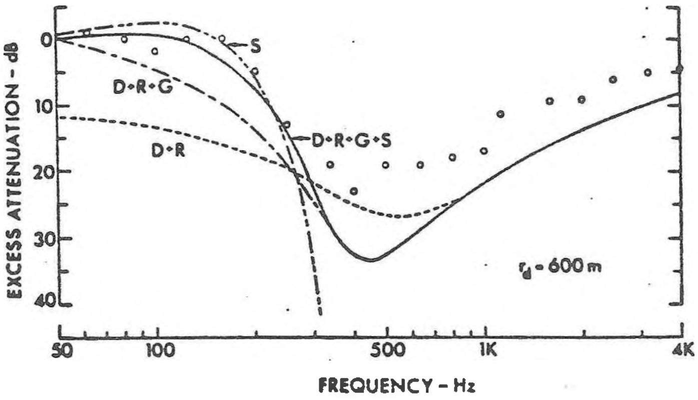

Fig. 4

III. REFRACTION

It has been known for some time that for distances greater than about 100 m over very flat open terrain, such as a large airport, the effect of curved ray paths (refraction) needs to be considered[18]. The principal effects are shown in Fig. 5. For propagation downwind, or under temperature inversions the refraction is downward, as shown at "a". The effects is usually to reduce attenuation due to the ground effect. For propagation upwind, or under temperature lapse conditions, the sound refracts upwards, as shown at "b" in the figure.

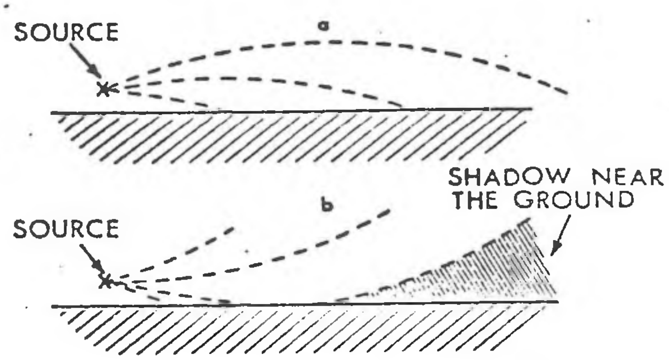

Fig. 5

The main effect here is the creation of shadow zones as shown also in Fig. 5. In both cases there exists a gradient of sound velocity in the atmosphere which extends well up from the ground (10 m or more).

One is often interested in the propagation of noise over less open terrain, such as near a highway, in a built up area, or around a small airport. Figure 6 shows typical profiles[7] of temperature that we find close to the ground for these sites, on the left for a sunny summer afternoon where there is a constant wind velocity (here ~ 6 m/sec), and on the right for comparison on a calm cool evening. The error bars give a rough indication of the variation in temperature with time. Note the existence of a thermal boundary layer during the daytime which is confined in thickness to about 30 cm by the wind. Above this layer the gradient virtually disappears due presumably to mixing by air flow around obstacles such as trees. To find whether the steep gradient close to the ground, which is responsible for optical mirages, could influence noise measurements on vehicle test sites an acoustical point source was placed right on the surface of a flat asphalt roadway.

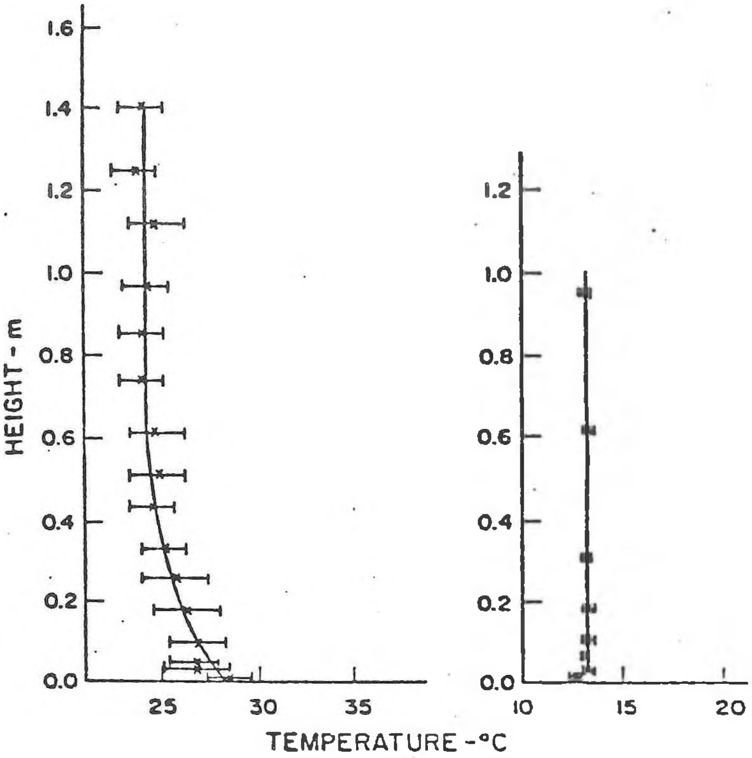

Fig. 6

The dashed lines in Fig.7 show measurements[7] of sound level at a distance of 15 m and a height of 1.0 m for propagation both upwind (the O's) and downwind (the X's) and the solid lines the same for a microphone on the ground. Note that at a height of 1.0 m there is no significant excess attenuation of sound due to the thermal boundary layer, but at ground level there is a well formed shadow zone even when propagating downwind - and that at a range of only 15 m which is common for vehicle tests.

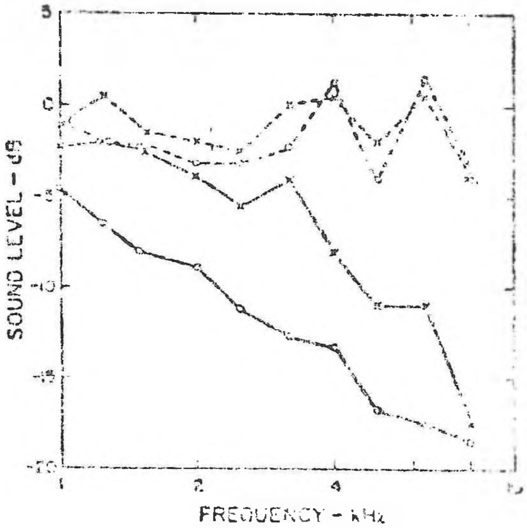

Fig. 7

The effects of refraction are probably the most difficult to quantify in noise prediction schemes at present, particularly those due to thermal gradients, as shown recently by the measurements of René Foss[19].

IV. TURBULENCE

The inhomogeneity of the atmosphere during the daytime is normally much larger than is generally appreciated. Figure 8 shows typical records of wind velocity and temperature 1 m above a flat

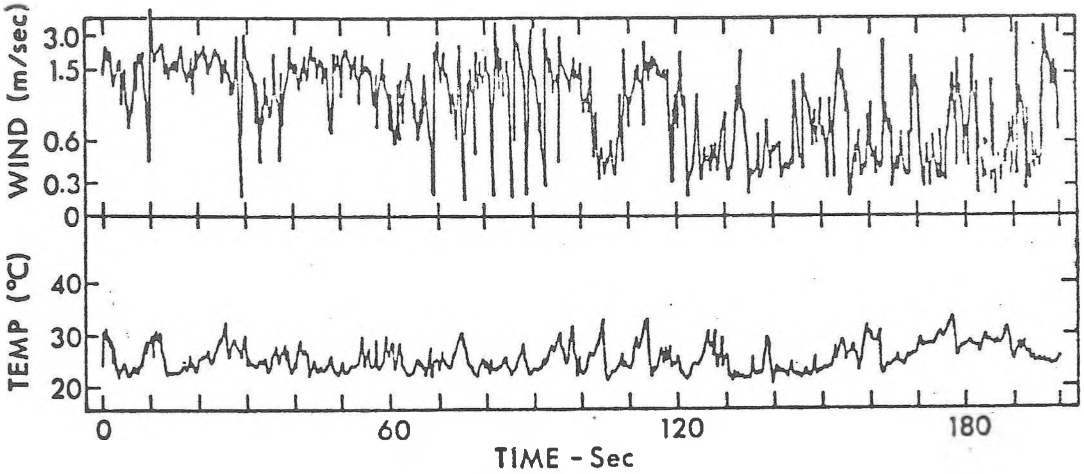

Fig. 8

ground surface on a sunny day. Note from the bottom record that fluctuations in temperature of 5°C which last several seconds are common and 10°C not uncommon. These are bubbles of hot air plucked by the wind from the thermal boundary layer at the ground shown previously. From the top record we can also see that there is really no such thing as a "steady wind", the standard deviation in velocity being commonly 1/3 of the average. The local sound velocity therefore also fluctuates rapidly. Recent work on the propagation of sound in a fluctuating atmosphere, mainly in the area of remote sensing[20], enables us to evaluate the consequences for noise propagation.

Measurements by Daigle[21] are shown in Fig. 9 for the sound propagation between a point source and microphone placed 50 m apart, each of them 1.2 m above a plane asphalt surface on a sunny afternoon. The measurements are 2 minute averages $\left(L_{eq}(2\ \text{min})\right)$. The dashed curve is the interference pattern between direct and reflected waves calculated by coherent acoustical theory. The solid curve was calculated using the theory of propagation in a turbulent atmosphere, which required simultaneous measurements of the fluctuations of temperature and wind velocity. The incoherence introduced by normal daytime turbulence can clearly destroy interference phenomena, at least for high acoustic frequencies.

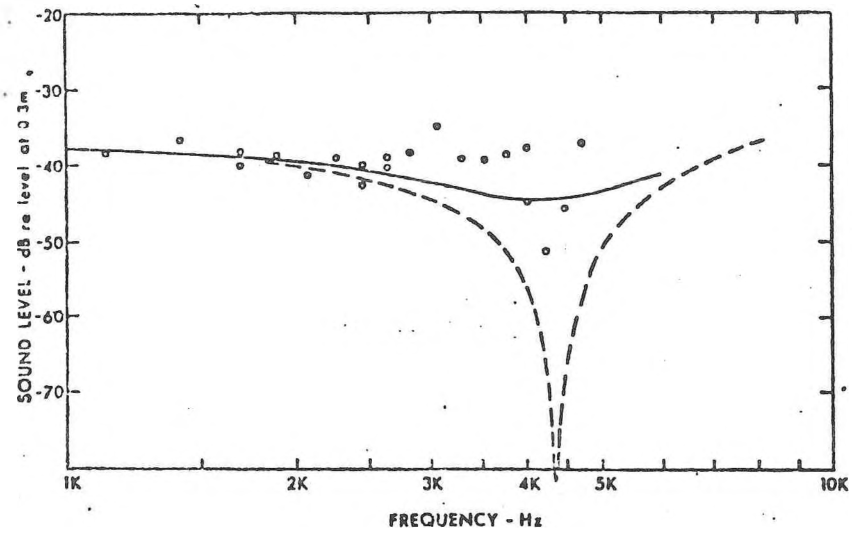

Fig. 9

Probably the most important interference phenomenon in noise propagation is the excess attenuation for frequencies of several hundred Hertz which is usually called the ground effect[1], but is really the zero frequency interference fringe for propagation over an acoustically soft boundary. Figure 10 shows measurements by Parkin and Scholes[11] of the ground effect for various distances of propagation of jet noise across an airport. The dashed curves were calculated using coherent acoustical theory as described earlier. The solid curves, which were calculated by Daigle[22], include the effect of typical daytime fluctuations of atmospheric temperature and wind velocity. The difference between the solid and dashed curves indicates that the incoherence produced by atmospheric turbulence reduces but does not eliminate the ground effect for horizontal ranges of hundreds of meters.

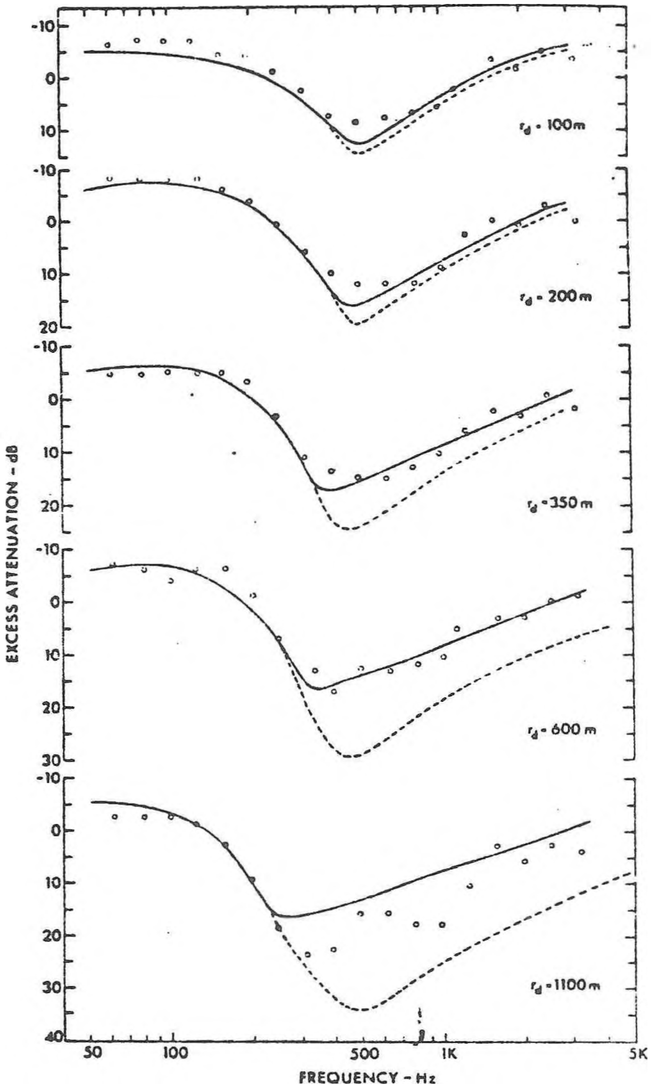

Fig. 10

Another role for atmospheric turbulence in noise propagation is the scattering of sound energy down into shadow zones[1]. Shown in Fig. 11 are a set of carefully controlled measurements of the sound level behind an experimental noise barrier again by Daigle[23] and his colleagues. The barrier was a long thin screen 2.5 m high, a point source of sound was 10 m in front of it and the microphone 30 m behind

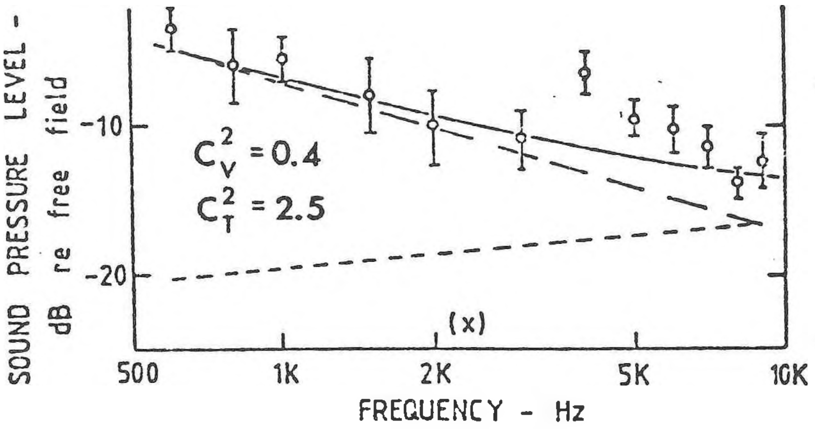

Fig. 11

it. The circles with error bars show the measured levels. The dashed line sloping down to the right gives the expected level due to diffraction over the top of the barrier. The dotted line near the bottom gives the level of scattered energy calculated from simultaneous measurements of the strength of atmospheric turbulence shown also on the figure. The sum of the two calculated contributions is the solid curve, and it agrees well with the measurements. The indication here is that typical daytime turbulence will probably reduce the attenuation by highway barriers only at very high frequencies in situations for which they are often designed - namely to protect the first one or two rows of housing by a diffracted angle (and hence also a minimum scattering angle) of 20° or more. Here only single scattering is important. For larger distances from the barrier, and hence smaller angles, multiple scattering becomes important, which makes the effect probably much larger, but also much more difficult to calculate. This case has not yet been examined.

V. BARRIERS

Although highway barriers have become much more widely used recently, they are still designed using Kirchhoff-Fresnel diffraction theory from the last century for an ideal screen via the curves of Maekawa[24] and Kurze and Anderson[25]. Recent measurements, however, show this theory to be a poor approximation at close range, even for the ideal case.[26-27] Fortunately there has also been work on more precise diffraction theory by Jebsen et al[28], and Hayek et al[29-30].

The dashed line for diffraction in Fig. 11 is only straight because the point source and microphone were both placed at the hard asphalt ground surface to avoid interference effects.

In practice we usually have a situation such as that shown at the top of Fig. 12, where there are complicated interference effects due to refraction from the ground surface, as well as diffraction over the top of the barrier. Shown below are calculations of the insertion loss I and attenuation A for this case by Isei[31] and colleagues for 1,

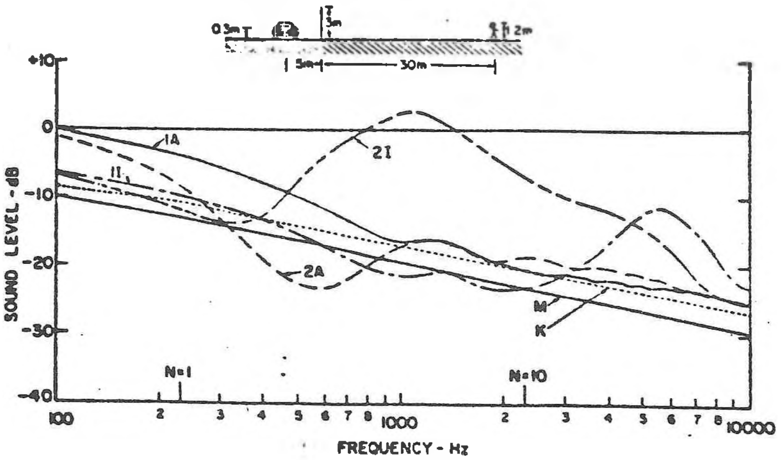

Fig. 12

a hard ground surface, and 2, a grassy surface. These predictions are obviously far from lines M of Maekawa and K by Kurze and Anderson which do not consider interference effects. Practical aspects of this matter are reported by Lawther et al[32].

Finally we must emphasize that the phenomena of outdoor propagation usually do not appear well separated, as described here, but together. They have been carefully separated here only for purposes of description. How to cope with them altogether for various uses, has been described by Soom[33], Marsh[34] and Miller[35].

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REPORT OF THE FIFTH TECHNICAL MEETING
OF THE C.A.A. TORONTO CHAPTER
SEPTEMBER 21, 1981 - 7:00 P.M.
AUDITORIUM OF ONTARIO HYDRO, 700 UNIVERSITY AVENUE, TORONTO

CHAIRPERSON: CHRIS A. KRAJEWSKI

TOPIC: IMPULSE NOISE

FIRST SPEAKER: ALBERTO BEHAR

As an introduction, the speaker gave a short historical overview of impulsive sound perception and the effect of this type of noise on hearing (references were made to the use of gunpowder and to the industrial revolution in Europe). A comparison between steady and impulsive noise and a summary of the existing and proposed descriptors followed the introduction. The complex nature of the impulsive sound signal was emphasized; peak value, time duration, rate at which impulses occur and spectral characteristics. In his presentation, the speaker also talked about the assessment of impulsive noise and the potential for hearing damage resulting from exposure to impulsive noise.

A review of Ontario Ministry of Labour evaluation criteria and difficulties in characterization of various types of impulsive noise concluded his talk. Excellent slides supported his oral explanation.