SOUND PROPAGATION OUTDOORS

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Introduction

In problems of sound propagation outdoors it is usually assumed that the ground is infinitely hard, and that sound from a point source spreads in the space above the ground according to the inverse square law. At large distances molecular absorption plays a significant role. Because sound levels at ranges greater than a few hundred feet are often 10 or 15 dB less than expected, from the mechanisms so far mentioned, sound levels are often reduced empirically by this amount in prediction schemes and attributed to a "terrain effect", or some such name. Meteorological effects, caused by gradients of wind or temperature are more difficult to allow for, and are often ignored. These gradients and related instabilities also result in turbulence, which causes fluctuations in the sound levels that are quite significant, depending on sound frequency, even a few hundred feet from the source.

There is much relevant material in the technical literature that has not yet been applied to the practical problems of outdoor sound propagation; but which can be very significant for such things as the standard testing of motor vehicles or snowmobiles at ranges of 25 or 50 feet, and at longer ranges are important for the prediction of airport or highway noise at distances of a mile or two. Precise mathematical theory of wave propagation in near-horizontal directions over a surface of finite impedance goes back to Sommerfeld in 1909 and was extensively developed by about 1940 at least for electromagnetic waves. The theory was put into acoustical form about 1950 by both Ingard and Rudnick, and the latter also confirmed the main features experimentally in the laboratory. In the last twenty years there have been several experimental studies outdoors, whose principal strength has been the careful reporting of results rather than the discussion of mechanisms. The reasons most of this is not yet applied are twofold: firstly the scarcity of measurements of ground impedance particularly for the near-grazing angles of incidence that are of practical importance; and secondly the complexity caused by several phenomena that usually coexist, although sometimes one or another can predominate.

This paper briefly summarizes some of this un-applied experimental knowledge, with a view to replacing parts of the present widely used empirical prediction methods by more quantitative schemes.

Basic Theory

The equation in Fig. 1 represents the elements of the Weyl-van der Pol solution. The first term is the direct field from the source.

It embodies only the inverse square law. The second is the familiar term for a reflected wave. Its magnitude is directly determined by the plane wave reflection coefficient R_p which is dependent on the grazing angle ϕ and the impedance ratio β. When source and receiver height are small or distance is large, sin ϕ eventually becomes small compared with any β ($\beta > o$), the value of R_p approaches minus one for all impedance ratios, r_1 and r_2 become nearly equal and the first two terms cancel. This produces a shadow zone because the value of ground impedance is not infinite, and the sound field inside the shadow zone is determined mainly by the third term of the equation. This we shall call the ground wave, following the terminology of electromagnetic-wave propagation - it is how one hears the local AM radio station and we shall show that it determines how low-frequency sound propagates outdoors in most situations of practical importance.

Ground Wave

Figure 2 shows eight spectra at a progression of distances from 2 to 50 feet. Source and receiver are both on the ground. At low frequencies the signal level decreases at the rate of 6 dB per doubling of distance — as expected from the inverse square law. At high frequencies it starts at 6 dB per doubling of distance at very short range, but beyond a few feet changes to 12 dB per doubling distance. A rough calculation will show that what happens for electromagnetic waves at frequencies of a megahertz and distances of miles, will be similar for acoustic waves of a kilohertz and distances of several feet.

The spectrum is that of the ground wave, and it can be regarded as a transmission filter between source and receiver. Taking each curve in turn, in Fig. 2, and reading off the frequency at which this filter is 3 dB down from its low-frequency value, one obtains the result shown in Fig. 3. The values at distances less than 100 feet are from measurements at N.R.C. and those beyond 100 feet are from Parkin and Scholes in Britain for neutral wind and neutral or temperature lapse conditions. There is a fair degree of agreement between the measurements. The distance at which the ground wave is 3 dB down, for any given frequency, depends on the magnitude of the ground impedance and so can be used to estimate this impedance.

This procedure produces the results shown as the shaded area in Fig. 4. It gives the magnitude of the ground impedance as a function of frequency. These results are for a grass-covered surface, and Fig. 4 also shows the degree of agreement achieved between this and other techniques. To compare the results at essentially grazing incidence with those from the impedance tube (at normal incidence) and the inclined track (generally a grazing angle of 15 to 21^0) the surface has been assumed to be locally reacting.

Ground Wave plus Direct and Reflected Waves

So far the results discussed have been for both source and receiver on the ground. Being a grass-covered surface the impedance is low enough that one then measures essentially a ground wave isolated from other effects. Figure 5 indicates that as the receiver is raised from the ground to a height of 4 feet, at a range of 50 feet, the high frequency part of the spectrum is progressively recovered. Below about 500 Hz the signal comes via the ground wave, and this is the same for each receiver height. About 500 Hz the ground wave is sharply cut-off and the signal is recovered because with increasing receiver height there is no longer perfect cancellation between the direct and reflected rays, since the reflection coefficient is no longer -1. Note though that the two paths are still equal, and there are no path-length interference effects. This comes next.

Direct and Reflected Waves

Figure 6 shows the effects of interference due to a path length difference between the direct and reflected waves. The receiver is 4 feet above the surface, 50 feet from the source and the interference pattern changes with changing height of the source. These measurements were made over asphalt, and Fig. 6 illustrates the effect of path length interference in fairly pure form because the surface impedance is too high for there to be much of a ground wave. The dotted curves are theoretical predictions, and the solid curves are experimental results. The zero of sound level is the value expected from inverse square law at this range of 50 feet.

Figure 6 is relevant to the measurement of motor vehicle noise using the standard SAE test procedure because the latter uses the same surface and microphone position. The sound of the vehicle has to pass through this transmission filter between vehicle and microphone. The shape of the transmission filter depends on the source height as shown, and also on horizontal distance, not shown. As a vehicle drives by, the interference pattern moves down from very high frequencies, looks like this at the point of closest approach, and then goes back to high frequencies (as if the frequency scale is written on a piece of elastic rubber). Obviously this process is not going to aid the reliability of vehicle noise measurements and the extrapolation of noise levels to other distances.

Figure 7 summarizes many of the ideas so far illustrated. In the top graph, the transmission filters for grass and asphalt are compared for the same source and receiver heights, 1 and 4 feet respectively and 50 feet apart. The minimum at about 3 kHz over asphalt represents a half-wavelength path length difference and a hard surface having essentially zero phase change on reflection. Over grass (the solid curve) the geometry is the same, so the path length difference between direct and reflected waves is still half-a-wavelength. But the transmission filter now has a maximum at this frequency. The difference between grass and asphalt shows that for these source and receiver heights, and separations, the grass surface provides at 180^0 phase change on reflection. This phase change is responsible for the decreasing signal below 2 kHz for grass, and the dip that has its minimum near 800 Hz. This loss of signal would persist to zero frequency except that below 800 Hz the signal exists because of the ground wave. That this is so can be verified by comparing with the middle graph of Fig. 7; this shows the ground wave free of other effects.

This broad minimum in the spectrum of outdoor sounds in the region of 500 to 1000 Hz has been observed over plowed ground, vegitation, air-fields, etc., by many workers but its explanation until now has been a bit of a mystery. An interesting feature is that it doesn't change frequency significantly for different horizontal ranges, although all the minima at higher frequencies due to path length differences do change. These effects are shown in the bottom graph of Fig. 7 by comparing results for ranges of 15 and 50 feet over grass.

Shadow Region Due to Ground Impedance

In Fig. 5 for a source on the ground, at high frequencies where the ground wave was strongly attenuated the signal level increased progressively as the receiving microphone was raised. Other results indicate that at still higher microphone locations the high frequencies are completely recovered, and the spectrum then is identical with that measured very close to the source.

The relevant geometrical parameter is the sine of the grazing angle of incidence for the reflected wave. One can look upon the vertical coordinate in Fig. 8 as the height of the receiver for a source on the ground; the horizontal coordinate indicates in decibels how the sound field near the surface is reduced because the impedance of the surface is finite - under good measuring conditions the reduction can be as much as 40 dB.

The results in Fig. 8 show a considerable scatter because the horizontal ranges are now greater than in earlier figures. This leads to the next topic, which is fluctuations in measured sound levels caused by atmospheric turbulence.

Fluctuations

Near the ground there are vertical gradients of temperature and horizontal wind. Instabilities are very common and so the air is usually an uneven propagation medium, composed of turbulent eddies having a broad spectrum of sizes. As these are convected by the wind through the sound field between source and receiver, so the sound level at the receiver fluctuates.

There is now an extensive theory of propagation in turbulence to help calculate the effects of these eddies, and it has been verified by a small number of acoustic experiments. Two major questions need to be answered, however, before this theory can be applied to most practical noise problems. The first has to do with assumption in the theory. The propagation paths are usually close enough to the ground for a number of assumptions to be very questionable, for example that the turbulence is isotropic, and that the largest eddies are greater than the wavelength.

The second question concern the phenomenon of saturation, which is best illustrated by some optic measurements.

Measurements of the propagation of light in the turbulent atmosphere are much more plentiful than those of sound, see Fig. 9. Measurements of the standard deviation of the light intensity σ_X are plotted here on the vertical scale versus σ_1, the value calculated from theory for equivalent meteorological conditions, on the horizontal scale. For $2\sigma_1$ less than 1 the values on each scale roughly correspond, indicating the theory is correct. For $2\sigma_1$ greater than about 3, however, the measured values $2\sigma_X$ saturate at a value of about 1.4, independent of σ_1. Thus if you follow a light ray in the atmosphere, be it from a star or a laser, the fluctuations in intensity caused by turbulence (traditionally called twinkling!) at first increase in a predictable manner, but then saturate.

Returning now to sound, Fig. 10 summarizes experimental results at NRC in a form that can be compared with other peoples' work. One of the principal predictions of theory, that has been confirmed experimentally, is that the fluctuations of sound level have an approximately gaussian distribution after propagation through a turbulent medium. The σ that is plotted on both ordinate and abscissa is the standard deviation of the gaussian distribution of sound level, and the numbers are decibels. The solid line on the left is the unsaturated fluctuation theory for isotropic turbulence of Tatarski - it is also the theory used to obtain the calculated values of $2\sigma_{DB}$ for all the plotted experimental results, where sound measurements at low frequencies are used as a "probe" to compute according to Tatarski what the fluctuations should be for higher frequencies. The horizontal dashed line copies from Fig. 9 the experimental results from optics in the saturated region. The only theories in the saturated region are by Brownlee, shown dotted, and within the last year by Wenzel (not shown) that lies close to the dashed line. There is definite evidence from these measurements that saturation occurs in the acoustic case and at the level predicted by theory.

Figure 11 summarizes results for six days picked at random during the three summer months in Ottawa. On these six occasions the wind speed was quite low, up to about 6 mph but with gusts sometimes to 10 or 12 mph. Propagation directions covered all possibilities - up, down and cross winds. Temperature gradients near the ground at the time of measurements was always neutral of lapse, never inversion. Going down the table we have increasing horizontal range from 50 to 1000 feet, across the table is frequency from 150 to 5000 Hz. An X in the table indicates that the fluctuation of sound level of a particular frequency at a particular distance was not satured, and a 0 indicates that the corresponding fluctuation was saturated. No entry means no measurement, and several entries means that the measurements were repeated on several different days. At low frequencies or shorter distances the fluctuations are not saturated, at high frequencies and larger distances the fluctuations are always saturated. There is a transition region between these extremes where the fluctuations can be either saturated or not, depending on the weather conditions. We found that the non-saturated X's towards the lower right hand corner of the table were associated with low wind speeds, and were independent of its direction.

Penetration of the Shadow Region During an Inversion

We saw earlier that the impedance of ground was finite, and was quite small for a grass-covered, see Fig. 4. This resulted in a shadow region near the ground that under neutral atmospheric conditions could have sound levels as much as 40 dB below what was expected, see Fig. 8. This plus the inverse square law and molecular absorption is often sufficient to make even intense sources like aircraft on the ground, highways and locomotive whistles inaudible at ranges of a mile or two, during most of the daytime hours. However the ground-impedance shadow region can be penetrated by a variety of propagation mechanisms under appropriate conditions. One example of this, where we have made some progress towards a quantitative analysis, is during propagation in a temperature inversion. Inversions occur many nights and early mornings in most parts of the world.

In an inversion sound rays follow paths between source S and receiver R that are curved and concave downwards, Fig. 12 a. If the inversion is uniform, these are arcs of circles. In addition to the direct ray, here labelled path 1, and the first reflected ray called path 2, there are other multiply-reflected rays called path 3, and so on. These form an infinite series when source and receiver are both on the ground.

This picture is more complicated when the source and receiver are not on the ground. However we can still think of sound following the same rays provided the simple source S is replaced by a composite source, see Fig. 12b. This is valid provided the source is not too far above the ground. The composite source consists of the simple source S, its image I, and the impedance of the surface which determines the amplitude and phase of the reflected waves. One change is that the series of ray paths is no longer infinite, but terminates after a relatively small number of terms - how many terms depends on the source and receiver heights compared with the height of the ray path. The strength of the composite source is different for the different ray paths 1, 2, 3 etc., because ϕ is different for each path. (ϕ enters into both the ground reflection coefficient and the path length difference $2h_S \sin\phi$).

As a brief digression, the amplitude and phase lag of the plane-wave reflection coefficient for an average grass-covered surface are shown in Fig. 13 for several small values of the grazing angle that are appropriate for propagation in an inversion to a range of the order of a mile or two.

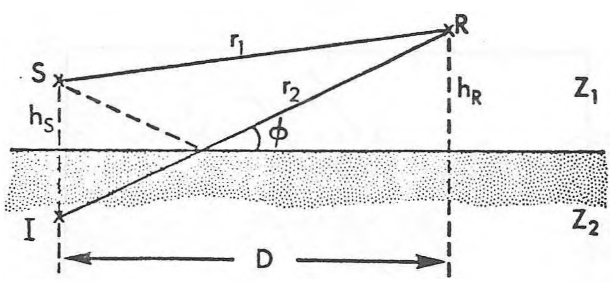
Normally at these ranges, in a neutral atmosphere, the excess attenuation beyond inverse square law and molecular absorption would be about 30 or 40 decibels. Using the theory outlined by Fig. 12, the excess attenuation for path 1 under conditions of temperature inversion are as shown in Fig. 14

for three different strengths of inversion. Between 100 and 1000 Hz the excess attenuation is between 0 and 10 decibels. The maximum correction to these curves when one adds the contribution from all other paths 2, 3, etc., is only 2.2 dB for an infinite series of paths and a reflection coefficient of unity: more typically, summing only the first 6 or 7 paths and using the reflection coefficient for a grass-covered surface for the appropriate and changing angle of incidence, given by Fig. 13, the correction is only 0.5 dB. This theory for inversions is consistent with general experience that one hears distant sources louder during an inversion, and with measurement that their sound levels rise approximately to the value calculated by inverse square law and molecular absorption alone.

Conclusion

To sum up, it is suggested that simple but accurate predictions of sound levels and spectra can be made by assuming that an excess attenuation due to finite ground impedance exists when either the source or (by reciprocity) the receiver is near the ground. Its vertical extent and magnitude increases with horizontal range and depends on the value of the impedance. This shadow region is then always penetrated by a ground wave at low frequencies, the upper-frequency limit being determined by horizontal range and ground impedance. At higher frequencies any one of several specific mechanisms can provide penetration of this shadow region: three discussed in this paper were (a) changing reflection coefficient with angle as either the source or receiver were raised above the ground, (b) path length interference when both source and receiver were above the ground, and (c) the propagation of sound under meteorological conditions of temperature inversion.

Figures



Pressure at receiver R is given by

$$\frac{p}{p_o} = \frac{e^{-ikr_1}}{r_1} + \frac{R_p e^{-ikr_2}}{r_2} + (1-R_p)F\,\frac{e^{-ikr_2}}{r_2}$$

where reflection coefficient $R_p = \frac{\sin\phi-\beta}{\sin\phi+\beta}$

and impedance ratio $\beta = Z_1/Z_2$.

R_p and β are complex and depend on angle ϕ and frequency.

Fig. 1

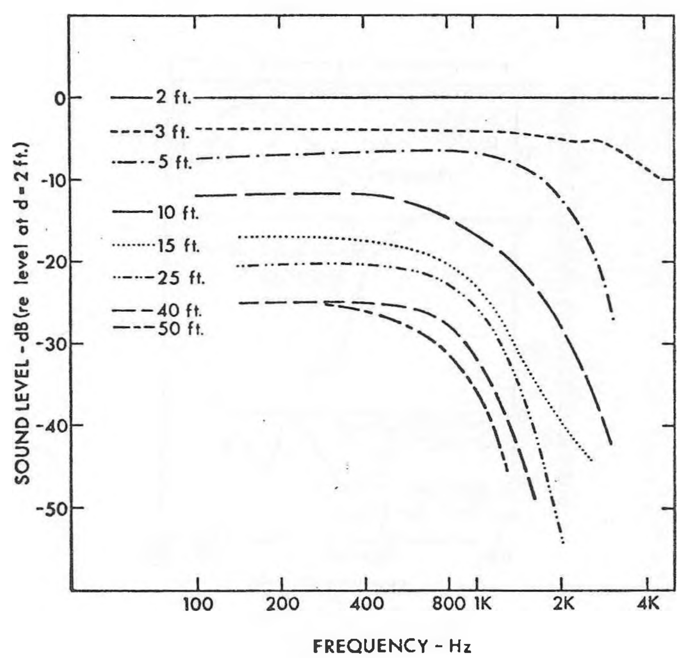


Fig. 2

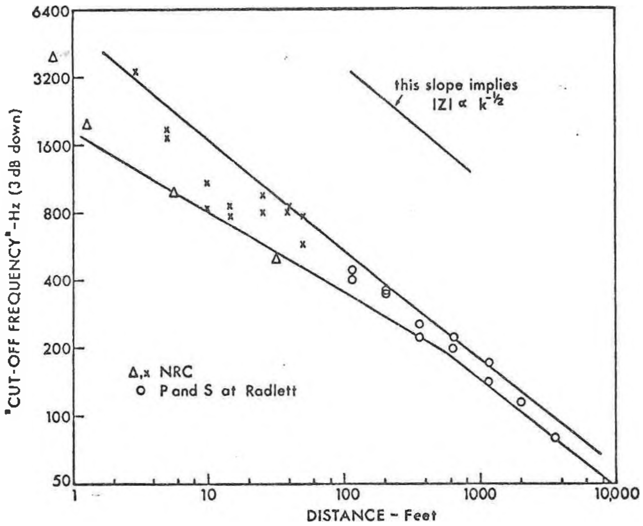
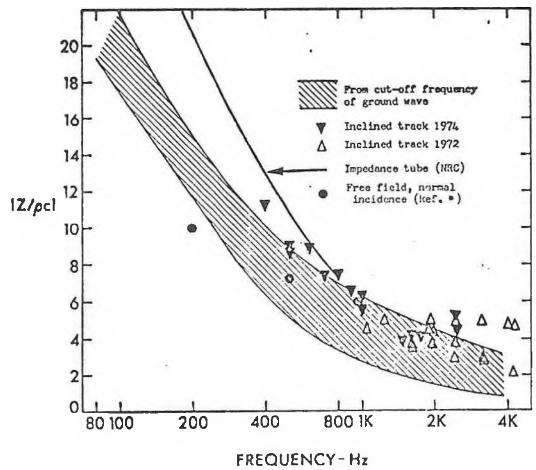


Fig. 3



*Dickinson and Doak, J. Sound Vib., 13, 309-22 (1970)

Fig. 4

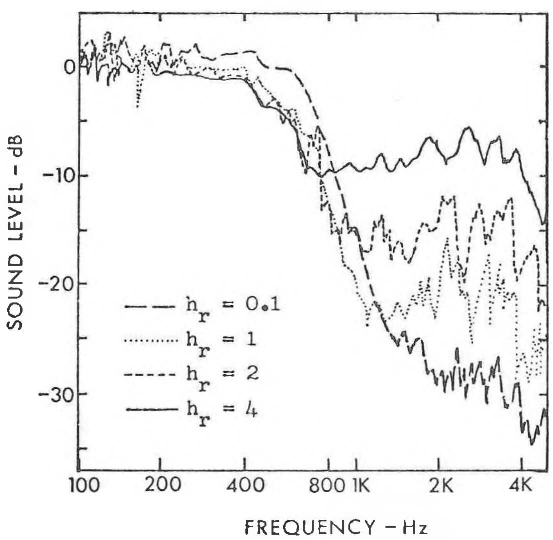


Fig. 5

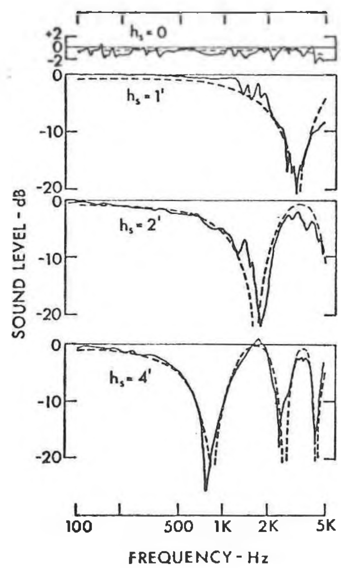


Fig. 6

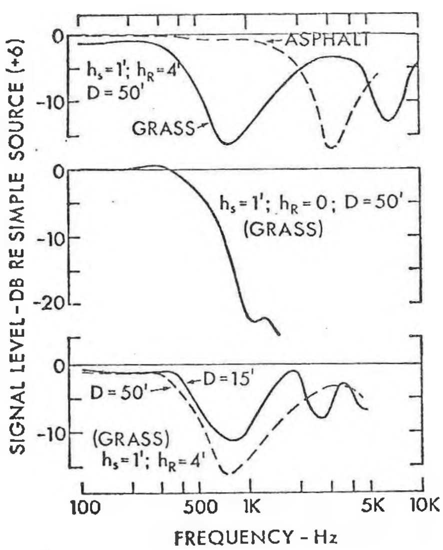


Fig. 7

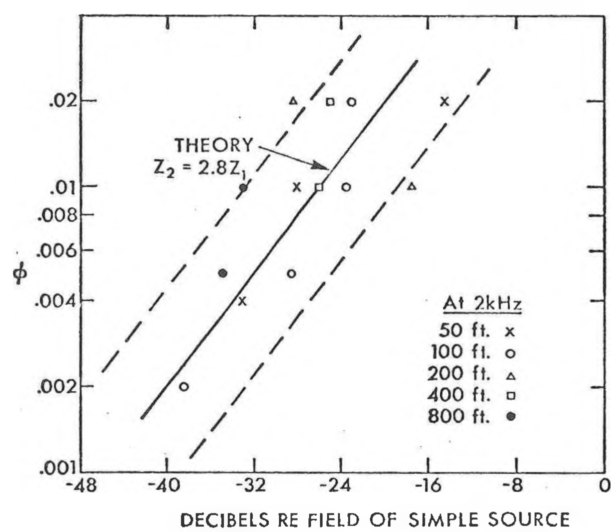


Fig. 8

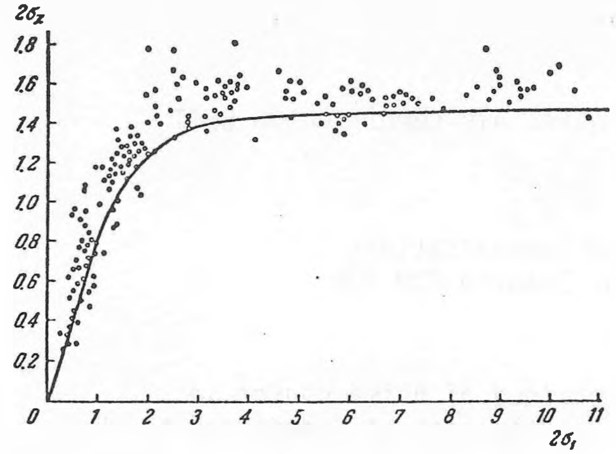


FIGURE 60. Comparison of the experimentally obtained values of the mean square of the log intensity fluctuation ($2\sigma_\chi$) with the corresponding quantity in the first approximation of the method of smooth perturbations ($2\sigma_1$).

(From V.I. Tatarskii, "Effects of the Turbulent Atmosphere on Wave Propogation" Keter Press, Jerusalem, 1971)

Fig. 9

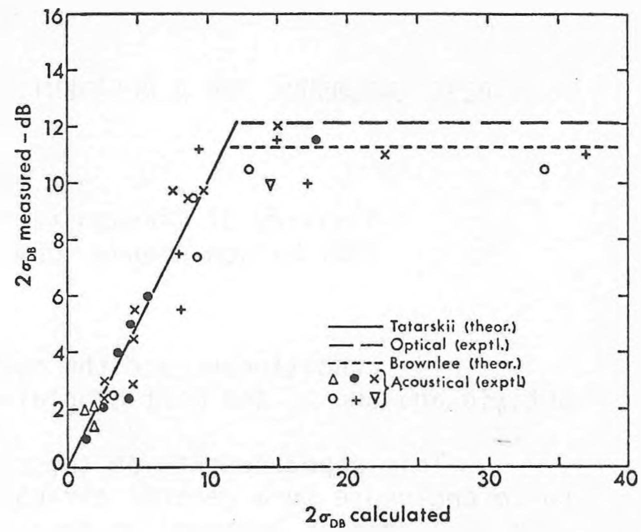


Fig. 10

Measurements on Rockcliffe Airport, Six Summer Days

H_S = 1 ft, H_r = 4 ft

Wind speed varies from < 2 to 6 mph - cross, down and upwind.

Temperature varies 16 to 31 °C.

Temperature gradient varies from neutral to 0.7 °C/m. (lapse).

Humidity moderate to saturated.

Distance (ft) \ Freq. (Hz)	150	300	600	1250	2500	4000	5000
50	XXX	XXXX	XXXXX	XXXXX	XXX	XXX	XX
100	XX	XXX	XXX	XXX	XXX	X	XX
150		XX	XXX	XXO		XXO	
200		XX	XX	XX	XX	O	X
250		XX	O	X		O	
400	XX	XXXX	XXXX	XXXO	XOO	OO	OO
500		XX	XO	OO		OO	
600			X	X	O		O
1000		X	X	X	O		O

X = non-saturated, O = saturated.

Fig. 11

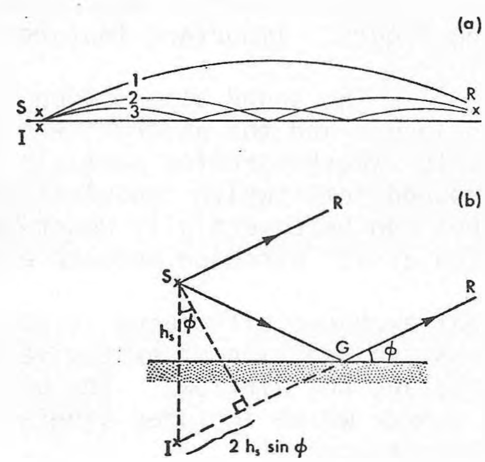


Fig. 12

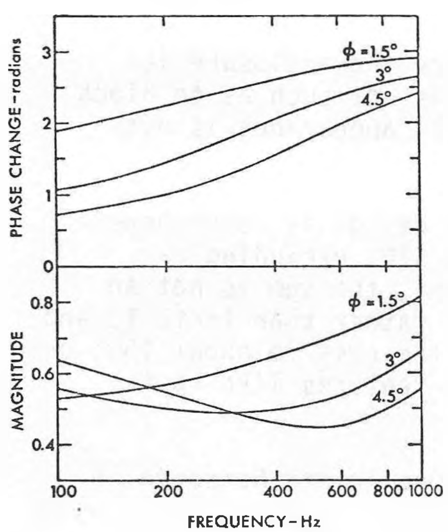


Fig. 13

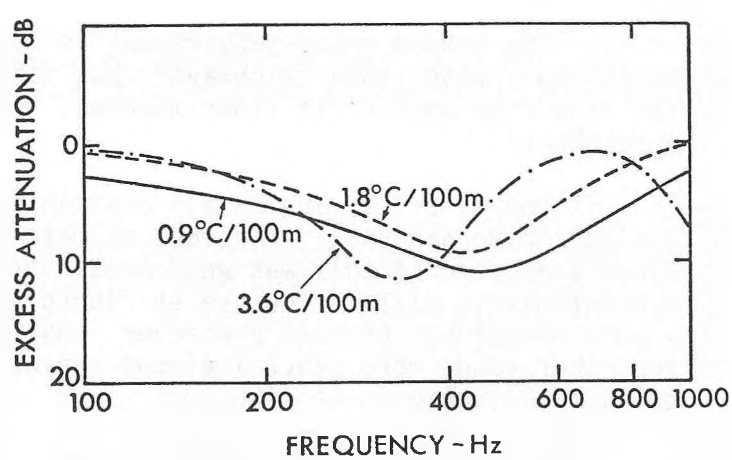


Fig. 14