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REVIEW OF OUTDOOR SOUND PROPAGATION -- THE SOUND FIELD, MICROMETEOROLOGY AND TOPOGRAPHY

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INTRODUCTION

One might think that sound propagation outdoors was a very simple problem -- sound from a point source spreading in a hemispherical space above a more or less flat ground -- but reality is far more interesting. The ground may not be flat, all grounds have finite acoustical impedance though some may be hard like concrete or soft like snow, and the atmosphere near the ground is horizontally stratified and is almost always turbulent. Many have contributed to this field over the years and a review can only touch on a few of the highlights.

Measurements of sound propagation outdoors go back at least to the 17th century The Rev. Dereham was the minister at a church in Upminster. He fired a pistol from his church tower and, with a fellow minister in another church about 5 miles away, measured the difference in time between the arrival of the flash of light and the sound.

In 1728 the speed of sound was measured under the auspices of the Academy in Paris — the value obtained then is within 0.5% of the currently accepted value, and that was 2.5 centuries ago. In the 1860's there was interest in fog signalling for ships. Tyndall in Britain borrowed a steam-driven horn from Joseph Henry -- the first curator of the Smithsonian Institution in the United States -- and set up his experiment on South Foreland, near Dover. There was considerable discussion with Stokes as to whether the signal was absorbed or scattered by water vapour or fog particles.

During the First World War the interest had shifted to the location of artillery; this is still a matter of interest to the military but today we have smaller and better microphones and do a lot of signal processing. In the 1930's the loss of brilliance of music in concert halls was too much to be explained by the absorption of surfaces. Knudsen noted that the magnitude of this effect was also observable outdoors and depended on the dryness of the air, so he undertook experiments to substantiate this. Meanwhile Kneser produced quantitative theory of absorption by molecular processes, and thus our knowledge of the oxygen-water vapour relaxation was born.

Since the 1960's noise produced by many forms of new and widely used technology, like jet aircraft, powered lawnmowers, and a great increase in motor vehicles has become an important political and social problem. In passing one should note that noise in society is not yet of any real concern in the Third World, although the serious possibility of a noise curfew at a few major airports is beginning to arise.

This past history indicates the range of possible applications of increasing knowledge and that what we have learnt has come from solving specific problems in several very different areas.

REVIEW OF OUTDOOR SOUND PROPAGATION

GEOMETRICAL SPREADING AND MOLECULAR ABSORPTION

These two mechanisms are always present. Simply stated, sound pressure levels or intensity levels decrease with increasing distance from the source as the available sound energy spreads over a wavefront of ever-increasing area. Depending on the measure used, and the type of sound source, this decrease is basically either 3 or 6 decibels per doubling of distance.

As sound waves propagate through air some of the ordered vibratory motion of the air molecules is converted into internal modes of vibration of the oxygen and nitrogen molecules. Above about 1 kHz the predominant mechanism of molecular absorption of acoustic energy is the oxygen-water vapour relaxation see Fig. 1. The effect amounts to many decibels per kilometre above about 1 kHz, (the actual frequency depending mainly on relative humidity) and is negligible below that frequency. At frequencies in the range of 100 to 1000 Hz there is a lesser absorption of 1 to 3 dB per km due to the nitrogen-water vapour relaxation.

REFLECTION AT A FLAT GROUND SURFACE

When both source and receiver are relatively near the ground, compared to their distance apart, the direct and ground-reflected sound fields are of comparable magnitude. Their interference at any point depends both on the difference in path length to the receiver and on the phase change on reflection at the ground. There are often significant phase changes on reflection, because the acoustical impedance of the ground surface is complex and often within 10 or 20 times the characteristic impedance ρc for sound waves in air. We now know that all ground surfaces are porous, or if not themselves porous behave as if they are porous, due to the thermal and viscous boundary layer on the surface. Apart from studying the complex impedance of various ground surfaces, these simple facts introduce us to the range of phenomena that have been the object of many studies during the past 25 years. To match boundary conditions, the sound field must include so-called ground waves if the impedance is finite and if there is any curvature in the wavefronts. Furthermore, porosity causes the resulting complex impedance to be "capacitative" rather than "inductive", and in most circumstances this leads to trapped surface waves travelling in the air just above the ground. Yet another effect of porosity is to cause the acoustic-to-seismic transfer of energy to be roughly three orders of magnitude greater than one would predict simply from the specific impedance ratio for air and ground.

The Legacy from before 1940

Let us look now at the major steps leading to our present understanding of the properties of ground surfaces and how they relate to sound fields in air. In 1909, 80 years ago, A.N. Sommerfeld [1] published a paper entitled "Propagation of waves in wireless telegraphy" in which he dealt with the boundary problem of radiation from an electromagnetic dipole above a flat ground. He divided the theoretical solution into two parts. One was the contribution from geometrical ray theory, and the other was the necessary correction to this that was required by wave theory. Both items are necessary in order to satisfy Maxwell's equations, and later on for us to satisfy the wave equation in acoustics. The electromagnetic literature grew rapidly, but it was not until 1935 that Norton found a sign error in Sommerfeld's earlier work. This was significant because it allowed for the existence of a trapped surface wave, locked to the ground surface and propagating as a cylindrical wave in the air. Norton's finding partly helped to explain some unusually large values of field strength found earlier by Rolf. It was also in 1935 that Weyl, van der Pol and others were developing theories for the electromagnetic field near a surface that could be dissipative. What we are left with from electromagnetic field theory of the 1930's, apart from the well known Weyl-van der Pol equation, is the idea that the field has three components:

i) the direct field,

ii) the reflected field which includes an appropriate Fresnel term to account for wave effects, the component we often call a ground wave, and

iii) a surface wave, that exists only under certain circumstances.

In 1947 Rudnick [2] adapted the earlier electromagnetic work to acoustic waves reflected at the plane boundary between two media, when the second medium was either non-absorbing or had a porous-type imaginary impedance. In 1951 Ingard [3] produced theory for the field of a point source near a plane boundary of finite admittance. Also in 1951, Lawhead and Rudnick [4] reported measurements of sound propagation above a locally reacting surface made from a close-packed array of vertically oriented drinking straws.

Acoustical Measurements

During the late 1950's there were several early systematic studies of sound propagation outdoors. Some related directly to ground effects, others included meteorological and other phenomena as well. Two that should be mentioned were both reported in 1959: "Experimental study of the propagation of sound over ground" by Wiener and Keast [5], and "Ground reflection of jet noise" by Howes [6]. The Wiener and Keast work produced a large body of measurements, including such non-ground effects as propagation between two mountain peaks about 2 miles apart.

In 1964 Parkin and Scholes [7] reported two extensive sets of carefully conducted and well documented field measurements on the horizontal propagation of sound over grass-covered airfields from a jet engine close to the ground. Their source was 1.8m above the ground, the receiver 1.5m, and at distances ranging from 35 to 1100m. They classified results according to wind direction and vertical gradients of temperature. In more recent years we at NRC in Ottawa have often used Parkin and Scholes as a benchmark against which to test our theories or experimental results. One early example relating to ground impedance is interesting, from about 15 years ago.

Figure 3 shows a small sample of Parkin and Scholes' results. The horizontal range is 615m. Focus your attention on the solid line labelled "0". The broad dip of reduced sound pressure levels in the frequency range from 200 to about 1000 Hz is due to the finite impedance of the grass-covered ground. The strong signal below 200 Hz is due to the acoustic ground wave in air. Note the cut-off frequency of this ground wave, here about 200 Hz. Plotting cut-off frequency vs. distance, Fig. 4 shows consistency between our own results from 20cm to 20m and those of Parkin and Scholes from 35m to 1100m - a range of distances covering almost 4 decades. The slope of this curve implies that the magnitude of the ground impedance is inversely proportional to the square root of frequency. The position of the curve gives a value for the magnitude of the ground impedance, here about 4 or 5 times ρc for air at 1000 Hz and consistent with other results I shall show later.

Some other early work is that of Tillotson [8] who measured the attenuation of sound over snow-covered fields. He found that the characteristic impedance of fresh snow at 800 Hz was 1.83 times ρc for air and was accompanied by a small capacitative reactance.

1970 marked the onset of considerable increase in activity related to the measurement of ground impedance. People realized that the fact that it was finite, and often not many times greater than the characteristic impedance of sound in air, significantly affected sound levels during propagation outdoors. Evidence included sound barriers that were usually not as effective as predicted, and urban noise levels that were lower than predicted from geometrical spreading and molecular absorption alone.

In 1970 Dickinson and Doak [9] measured the impedance of a grass-covered surface using an impedance tube with a sharp edge pushed into the ground, Fig. 5.

Accurate measurement of ground impedance has proved to be remarkably difficult. Techniques that work well at high frequencies become inaccurate at low frequencies, or vice-versa; some techniques become inaccurate at large impedances or long wavelengths. Real-life environmental problems frustrate attempts to make adequately precise measurements. To illustrate the kinds of problems one can run into I want to quote from Dickinson and Doak's paper in the Journal of Sound and Vibration:

"Condensation quickly formed on the inside of the tube and sound pressures fluctuated throughout its length so that no standing wave could be plotted. After a few days, earth worm casts proliferated inside the tube, although few if any appeared outside, and the soil level inside had risen several millimetres. As a large amount of work was needed to screw the tube into the ground in the first place, this latter phenomenon could not be attributed to a subsidence of the tube itself. It became obvious that the tube severely altered the micro-climatic conditions around the plant, thus perhaps altering the plants' respiration and physical characteristics."

So they developed another technique based on measuring the pressure profile along a line perpendicular to the surface below a loudspeaker suspended several meters above the surface. The microstructure of the ground remained undisturbed and the sound field was unconfined. Selecting one typical example of their results, they found both the real and imaginary parts of the specific normal impedance ratio for a grass surface to be about four at 1 kHz.

Also in 1970 both Oncley [10] in the U.S. and Delany and Bazley [11] in Britain noted the so-called ground absorption dip at frequencies in the 200 to 600 Hz range for jet engine noise propagating over grass. This agreed with Parkin and Scholes. It was clear that the dip was related to phase changes during reflection at the ground surface, and further progress depended on better understanding of the complex impedance of the ground. It was observed statistically that increased moisture content and freezing in winter lowered the frequency of the ground-absorption dip.

Later Embleton, Piercy and Olson [12] measured the interference between the direct and reflected sound fields of a point source by moving a microphone along an inclined path. This defines a constant angle of reflection and is the three-dimensional analog of the one-dimensional impedance tube. One measures the pressure amplitude as a function of position and calculates the complex value of the ground impedance through the reflection coefficient at that particular angle of incidence. This method allowed measurements at oblique angles of incidence more appropriate to sound sources near the ground but measurements were restricted to frequencies greater than about 400 Hz because the distance between interference minima becomes very large at near-grazing angles of incidence.

In 1983 Zuckerwar [13] used a cavity, with one side of the cavity open and capable of being pushed into the ground surface, to obtain a direct pressure-vs-velocity, and hence impedance, measurement. A motor-driven mechanical source provides a known volume velocity and a microphone measures the resulting pressure. This technique is restricted to frequencies below about 300 Hz both by the capabilities of the sound source and by the requirement that the sound wavelength be large compared with the dimensions of the cavity. More recently Daigle and Stinson [14] have used a two-microphone technique to measure pressure, phase and phase difference along a vertical line in the spherically spreading interference field below a source suspended several meters above the ground. Measurements in air have been made down to 30 Hz over grass-covered ground, and show some of the ground resonances for grass-covered surfaces that have been measured seismically and are predicted theoretically by Sabatier [15] and by Attenborough [16].

Measured values of the real and imaginary parts of the complex impedance of grass as a function of frequency are shown by the dashed curves in Fig. 6. Remember these are measured in different places, on different soils and different moisture contents. General features are i) the real and imaginary parts are roughly equal, ii) both decrease with increasing frequency, and iii) above about 300 Hz, both are less than about 10 times the characteristic impedance of air.

Theoretical Models

Also on Fig. 6 are several solid curves, again in pairs, one for the real and one for the imaginary part of the impedance. These are derived from some of the one-to four-parameter models that have been developed to describe ground surfaces.

In 1970 Delany and Bazley [17] developed expressions for the real and imaginary parts of characteristic impedance and of propagation constant for fibrous absorbent materials. These expressions were simple power-law functions of a single parameter, namely flow resistance divided by frequency. Chessell [18] showed that Delany and Bazley's theory for fibrous materials also provided a description of the Embleton, Piercy and Olson results for grass-covered surfaces at all frequencies, horizontal ranges, and source and receiver heights. He ascribed an effective flow resistivity to these surfaces of about 200 to 300 c.g.s. rayls (200 000 to 300 000 MKS units). Chessell also matched the field measurements of Parkin and Scholes using a flow resistivity of 150 rayls. Chessell's work provided a great simplification to our picture of surface impedances as a function of frequency.

The one-parameter model in terms of flow resistivity predicts too large a value for both components of ground impedance below about 300 Hz. Also, the one-parameter model requires a value of flow resistivity approximately one half the directly measured value of flow resistivity.

Donato [19] considered the incidence and reflection of spherical waves on a plane surface whose surface impedance was derived from an exponentially increasing or decreasing flow resistivity with depth. In 1977 Thomasson [20], published what was essentially a many-parameter model in terms of material parameters, and an extensive set of field measurements with which there was excellent agreement.

In the early 1980's Attenborough [21] adapted theories on flow in porous materials into several forms that were useful to acoustics. This theory predicts the curves labelled "A" on the slide. Basically it is a four-parameter theory for which the parameters are flow resistivity, porosity, grain shape factor and pore shape factor. These parameters can be readily understood and one or two of them can be measured directly or calculated simply. For example the effective flow resistivity mentioned earlier, as the parameter in the one-parameter model of Chessell, and Delany and Bazley, is the flow resistivity that one could measure in a flow-resistance apparatus multiplied by the porosity.

In 1980 Bass [22] and his coworkers investigated the surprisingly large signals from airborne sounds using buried geophones. Geophones respond to movement of the ground matrix and the large acoustic-to-seismic transfer function cannot be explained by modelling the ground as a simple homogeneous material having the surface-impedance values actually measured. The currently accepted model has been developed within the past 5 years by Sabatier [23], Attenborough [24] and their colleagues. It assumes that the ground is an air filled, porous elastic solid. The model is derived from earlier work by Biot [25]. In very simple terms, the air-filled pores couple very readily with the sound field above the ground and support a slow wave. The solid matrix has much larger elastic constants and so supports a fast wave. Viscous and thermal effects couple these wave types so that they interact.

At low frequencies these wave types are separate and can interfere, have their own wave speeds, attenuation rates and other features. This produces so-called seismic resonances that are generally in the frequency range of about 50 to

200 Hz. These resonances are clearly observable using geophones buried in the ground. As mentioned earlier, these resonances have also been observed by Daigle and Stinson as fine structure in the surface impedance of grass-covered ground and its effects on the airborne sound field.

NEAR-SURFACE MICROMETEOROLOGY

Refraction

Vertical gradients of wind speed and temperature are usually strong within the first metre of the ground and less so at greater altitudes. It is convenient to think of a horizontally layered atmosphere. When the sound speed increases with height, the sound field curves downwards, as in a temperature inversion (common at night) or during sound propagation downwind. When the sound speed decreases with height the field curves upwards, as in a temperature lapse (a common daytime condition) or during propagation upwind. In this latter case geometrical ray theory suggests that there is a sound shadow beyond a certain distance. Sound levels are reduced in such shadow regions but some sound does penetrate by diffraction especially at low frequencies.

During downward refraction the grazing angle of incidence of the field at the ground surface is increased compared with the situation in an atmosphere of constant sound speed. This reduces the phase changes on reflection and reduces the destructive interference caused by the finite and relatively small values of ground impedance. Sound levels at a distance then increase; that is why the sound of a distant source such as an aircraft on the ground or a train usually sound louder at night than during the daytime. (In the daytime the more common presence of a sound shadow enhances the sound reduction caused by finite ground impedance.) There is also the possibility of multiple sound paths reflected at the ground [26] in addition to the direct field. This leads to sets of reflected paths, each set having different angles of reflection and reflection coefficients, see Fig. 7. This model has been investigated and theoretically can lead to an increase in sound pressure level, compared to a neutral atmosphere, of about 1.5 dB for typical grass surfaces.

These are simple theories that assume constant vertical gradients of sound speed over large areas of open, flat terrain. In practice gradients of wind speed and temperature, and hence sound speed, vary significantly with height and other phenomena such as focussing can occur. This allows much greater increases to occur sometimes at some locations; however focussing on one place is accompanied by defocussing and reduced sound levels in another. In urban areas the presence of buildings changes the wind distribution and creates turbulence behind buildings, uneven temperature distributions occur due to shading of solar radiation, and the concept of a horizontally stratified atmosphere ceases to exist. It is better to assume that, on average, the atmosphere is isotropic at least to the height of the buildings and that sound propagation is dominated by reflection and scattering from the building facades and the ground. In forested areas, beneath the canopy of the foliage, there is very little air motion due to wind and also little selective heating of the ground by radiation, so here also the atmosphere is isotropic; Price [27] has shown that sound propagation is dominated by scattering from tree trunks and foliage and by the low acoustical impedance of the ground.

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Diffraction

Sound propagation involves waves whose wavelengths are often comparable with other linear dimensions involved, for example the heights of source, receiver, a barrier or other scatterer. Furthermore phase relationships are coherent at least over distances of a few metres, even in a turbulent atmosphere, and so adjacent parts of the sound field can mutually affect each other. Processes of diffraction allow sound waves to penetrate across the sharp shadow boundaries predicted by ray theory to an extent that is more pronounced at low frequencies than at high. Thus noise-reducing barriers are more effective at high frequencies, and tree trunks and other small obstacles scatter more sound energy at high frequencies than at low frequencies. Reflection can be regarded as the extreme case of diffraction, for example the side of a building reflects sounds of high frequency whereas low frequency sound can often diffract around the ends of the building or over the roof.

Upward refraction is caused by an atmosphere in which the sound speed decreases with increasing height. Sound therefore travels fastest if it travels through the layer of air that is closest to the ground (the hottest layer). This is the path by which the sound can reach a distant receiver that is relatively close to the ground, including locations deep within the shadow zone. This process involving a "creeping wave" has been studied recently by Pierce [28]; the sound propagates in a wave near the ground, sound energy is continually shed upwards, and that which is shed at the appropriate point travels along a path predicted by the sound speed structure of the atmosphere to reach the receiver location of interest. This path is shown schematically in Fig. 8(e). The strength of the creeping wave, the rate at which it sheds energy, the paths followed, and hence the sound level at any height and distance within the shadow zone can all be predicted.

In recent years so-called fast field programs, FFP, have been adapted from work in underwater sound. When the sound field is known, for example near the source, over some surface, or at a grid of points, the FFP uses fast algorithms to construct the field over related surfaces progressing in sequence further away from the source [29,30]. In this way the whole sound field can be mapped. The FFP can allow for any arbitrary sound speed structure of the atmosphere and any acoustic impedance of the ground surface.

Turbulence

In describing interference, refraction and diffraction of sound waves near the ground it has been assumed implicitly that the sound speed is either the same throughout the field, or if it varies in layers to produce refraction and diffraction then at least it is constant with time. However, the atmosphere is almost always turbulent. Wind-generated turbulence arises as the moving air passes obstacles and temperature-generated turbulence is caused as some patches of ground (and the air layer immediately above them) become either hotter or colder than others; the hot air then rises to be replaced by an inflow of cold air that is sinking elsewhere. This is the "source region" of large-scale turbulence; its shape, size and occurrence are usually unpredictable. The turbulent flows are unstable and break down into a larger number of smaller eddies, which in turn break down into still more smaller eddies. This cascade process continues, producing a statistically predictable and stable spectrum of eddy sizes, called a Kolmogarov spectrum. Ultimately the turbulent energy is converted into heat as the smallest eddies of the order of a millimetre in diameter dissipate through viscous processes [31,32].

The effect of turbulence on acoustic wave propagation is significant because the size of turbulent eddies is similar to the wavelength of sounds in the frequency range of usual interest. One can consider turbulence as random variations of an otherwise homogeneous propagation medium, which degrade the predictable phase relationships in the sound field. Alternatively one can consider turbulence as a changing random array of scattering vortices. The phase and amplitude of sound waves vary, both with time and with location, and must be described by mean values and standard deviations. In turn, the standard deviations can be related theoretically to the strength and scales of the spectrum of turbulence [33]. As a sound wave propagates through a turbulent medium one would expect the fluctuations to increase with increasing distance. Figure 9 shows the results [32] of such measurements on various occasions, many different distances (up to about 200 m), at various frequencies between about 500 and 5000 Hz; and show that the phase fluctuations (open circles) increase without limit and the measured values agree with those predicted. The measured values of amplitude fluctuation (solid circles) however are usually smaller than those calculated for the particular circumstances of distance, frequency, and strength of turbulence, and furthermore appear to saturate at a certain limit.

The practical effect of turbulence is to degrade the wave propagation phenomena that depend on exact or constant phase relationships in a sound field. This is particularly noticeable experimentally in shadow regions, or near interference minima. The sound pressure levels, in regions of otherwise reduced sound levels, are increased in a turbulent medium compared to the values predicted for a steady medium (see later in Fig. 11).

NON-FLAT TERRAIN

It is difficult to study effects of shape of ground surface (topography) on sound fields under the carefully controlled conditions that are necessary to understand the processes involved. A few measurements have been made at specific sites but in general this work has not been extrapolated to other locations because limits on the validity of extrapolation have not yet been delineated in useful form. However there is a close analogy between a flat ground and curved ray paths in an inhomogeneous atmosphere, and a curved ground surface above which there is an acoustically neutral atmosphere.

Figure 8 describes the analogy; Fig. 8(a) is the basic diagram for a flat ground and neutral atmosphere, there is one ray path designating a single reflection at the ground surface. Figure 8(b) considers the change in this basic concept when either source or receiver is above a rising hillside, but still in a neutral atmosphere. In general there are now 3 ground-reflected rays of different path lengths, and they have reflection points that are close to the source or receiver. For example, when the receiver is on a hillside 100 m high and 5 km from a source that is about 1 m above the ground, two of the reflection points are 50 to 100 m from the source. This implies that, in the rising-hillside case, the most significant areas of the ground are those relatively near the source and receiver, and that most of the intervening ground may not have much influence on the sound propagation.

Figure 8(c) is the analogy to Fig. 8(b). Both the ray paths and the ground shape are "bent downwards" compared with Fig. 8(b). The formerly straight ray paths become concave downwards and the ground, formerly concave upwards, becomes flat; this is appropriate for sound propagation either downwind or in a temperature inversion. In both Figs. 8(b) and (c) the grazing angle of reflection is larger than in Fig. 8(a) as shown by the dashed lines in Fig. 8(c). Calculations and a few observations for a hillside 50 to 100 m high at ranges of 4 to 6 km agree reasonably well, both show increases in the A-weighted sound level of a jet engine of 10 to 14 dB.

Figure 8(d) shows the opposite case of a falling hillside, as when source and receiver are separated by the brow of a hill. The receiver is now in a shadow region behind a topographical barrier and direct sound from the source cannot reach it. At this point we must drop the simple-minded picture of ray paths and remember that we are dealing with wave propagation and that sound waves have finite wavelengths. There is a principle of least time that states that some sound energy reaches the receiver via the path that takes the minimum time from source to receiver. This is the so-called "creeping wave" of diffraction or scattering theory that was described earlier. For the configurations shown in both Figs. 8(d) and 1(e) this sound energy will travel via the creeping wave above the ground surface and at some point be shed upwards to reach the receiver.

Some carefully controlled measurements carried out over a curved surface in a large building in which the atmosphere was homogeneous and non-turbulent are shown [34], in Fig. 10. The three configurations a, b and c are shown by the small sketch and are respectively above, on, and below the geometric shadow boundary.

The dashed curved in Fig. 10(a) is calculated by assuming a direct and reflected wave, but accounting for reflection from a rigid curved surface: the curve shows the effect of interference due to path-length difference. The short portion of solid curve is calculated from a residual series solution for the creeping wave. The calculation is only carried to ten terms and therefore ceases to converge beyond about 1000 Hz. The results in (b) were measured on the limiting ray and the solid curve is creeping wave theory. A systematic discrepancy between theory and experiment is observed in all the results in the vicinity of the shadow boundary. The theoretical calculation has converged at all frequencies and, therefore, adding more terms does not improve the agreement. The discrepancy is still observed below the shadow boundary in 9(c). Deeper within the shadow, however, the theory agrees with all the measurements to within 0.5 dB, and in most cases this agreement is obtained with only one term in the theory.

The results just discussed were for ideal atmospheric conditions, and a rigid hard surface indoors. Outdoors one expects the same theory to apply for similar configurations, but with values for finite ground impedance. Figure 11 shows experimental results (points) for two receiver heights in the shadow region behind a small grass-covered hill of almost perfect cylindrical shape - the two sets of points (open and solid) are respectively for two different curvatures of the hill. The dashed curves are predicted for the case of a perfectly hard ground, and the solid curves are the prediction for ground having the typical impedance of a grass-covered surface. There is a discrepancy above about 1 kHz between the theory and measurements in the lower set of results that was not found indoors. The higher frequencies deep within the shadow are normally where the best agreement is expected and observed indoors. Therefore the origin of the discrepancy at the higher frequencies differs from the one observed close to the shadow boundary in the case of the indoor measurements. It is usually speculated that energy scattered by atmospheric turbulence is contributing to enhance the levels here (as noted earlier in the section on turbulence).

A FINAL COMMENT

Barriers

One topic not mentioned either under diffraction of sound fields or under topography is the effect of barriers to reduce the level of sound. The performance of thin barriers imperious to sound can be calculated using any one of several theories of diffraction for thin screens, and the presence of the ground on either side of the barrier should be taken into account. In general terms, the presence of the ground reduces the effectiveness of the barrier in reducing sound, compared with the predicted diffraction loss for the direct path only. Furthermore, in practice one usually does not measure more than about 15 dB of loss however much more is predicted. The above discussion of theoretical predictions, measurements over grass-covered earth berms outdoors and the general agreement between the two, at least down to insertion losses of about 40 dB at high frequencies, indicates that more noise reduction can be achieved with earth berms than with thin barriers, see Fig. 11.

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REVIEW OF OUTDOOR SOUND PROPAGATION

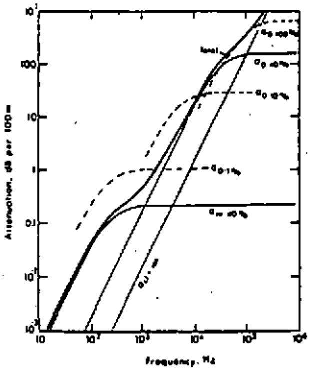


Fig. 1 The attenuation caused by molecular absorption: (----) due to oxygen relaxation at relative humidities of 1, 10 and 100%; (——) due to oxygen and nitrogen relaxations at 40% relative humidity respectively, and for absorption due to thermal, viscous and rotational processes. The thick curve shows the total absorption at 40% relative humidity and 20°C.

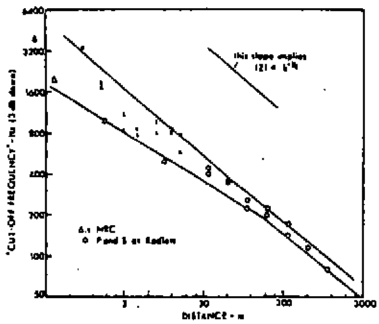
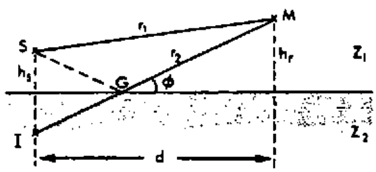


Fig. 4 Cut-off frequency of the ground wave vs distance from the source.



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

Fig. 2 Schematic diagram for interference when source and receiver, S and M, are near the ground.

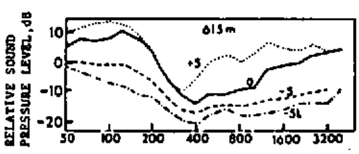


Fig. 3 Typical results for relative sound pressure level spectra [from Ref. 7] at 615m range: +5, 0, -5 and -5L represent downwind (5m/s), zero vector wind, upwind, and upwind plus temperature lapse respectively.

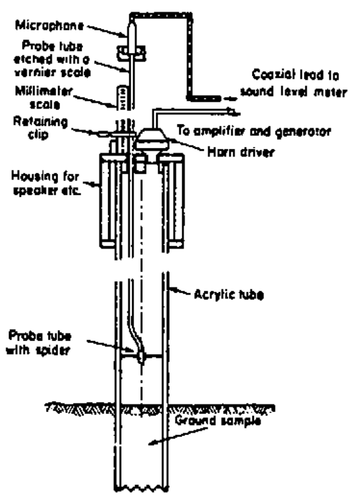


Fig. 5 Schematic diagram of early measurement of acoustic impedance of ground [from Ref. 9].

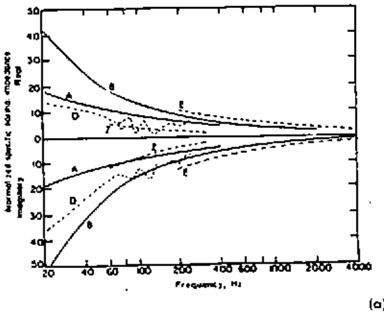


Fig. 6 Real and imaginary parts of normalized specific normal impedance of various grass-covered surfaces: (----) experimental results from Embleton et al., Daigle and Stinson, and Zuckerwar; (——) predictions from theories by Chessell and by Attenborough.

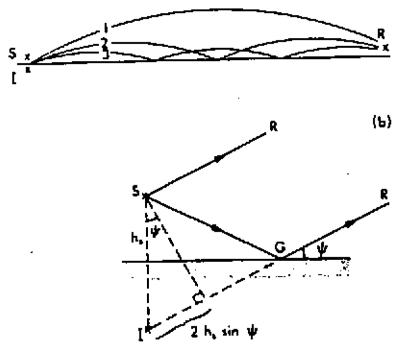


Fig. 7 (a) The multiple ray paths, 1, 2, 3 etc from source to receiver possible during temperature inversions or downwind; (b) the constituents of a source S and its image I that form a composite field associated with one of the ray paths of part (a). The angle ψ is different for each path.

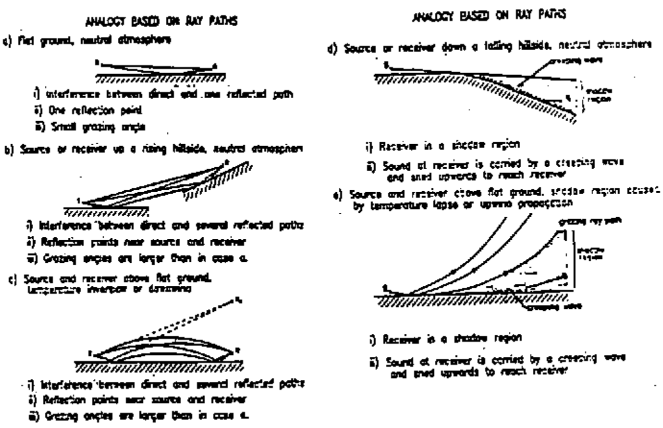


Fig. 8 An analogy based on ray paths: (a) flat ground and an acoustically neutral atmosphere (constant sound speed and straight ray paths); (b) rising hillside and neutral atmosphere; (c) flat ground and downward refraction (analogous to b); (d) falling hillside and neutral atmosphere; (e) flat ground and upward refraction (analogous to d). Both (d) and (e) have shadow regions that can be penetrated by creeping waves.

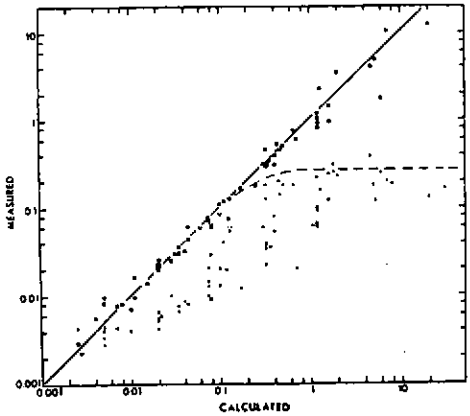


Fig. 9 The measured mean-square log-amplitude (solid points) and phase fluctuations (open points, values are rad²) vs their calculated values obtained through simultaneously measured meteorological variables related to turbulence. Phase fluctuations increase without limit, log-amplitude fluctuations clearly saturate.

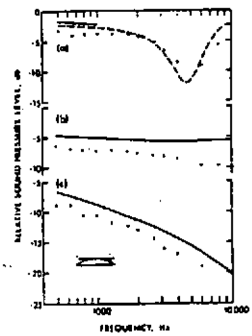


Fig. 10 Relative sound pressure level spectra for propagation over a rigid, acoustically hard cylindrical surface of radius 5m. Source-to-receiver distance is about 4m: (a)(b) and (c) are respectively for the receiver above, on, and below the geometrical shadow boundary. (•) experimental values, (——) creeping wave theory, and (----) simple interference between the direct and reflected waves, using the reflection coefficient for a curved surface.

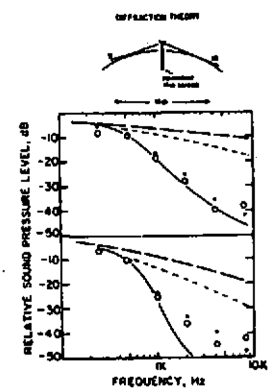


Fig. 11 Results measured outdoors over two cylindrical grass-covered surfaces. (——) creeping wave theory using impedance values for grass surfaces, (----) creeping wave theory assuming an acoustically hard surface, and (— —) diffraction at an equivalent thin screen.