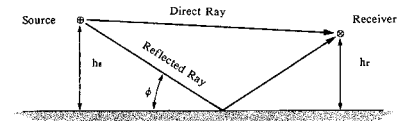


## 10. OUTDOOR SOUND PROPAGATION



### 10.1 Introduction

- Have you ever wondered why distant thunder sounds like a low rumble, while close thunder sounds more like a crackling explosion?
- Have you ever wondered why you can sometimes at night, hear distant sounds (like a train) that you cannot hear during the day?

These are but two interesting examples of outdoor sound propagation. Up to this point in this course, you have dealt with short range, time invariant propagation in a uniform medium. However, the outdoor environment is anything but uniform. Changing meteorological conditions can easily cause fluctuations in sound levels by 10-20 dB over time periods of minutes. The longer the transmission path, the larger are the fluctuations in levels. Outdoor sound propagation is affected by many mechanisms, including:

- a) Source geometry and type (point, line, coherent, incoherent)
- b) Meteorological conditions (wind and temperature variations, atmospheric turbulence)
- c) Atmospheric absorption of sound
- d) Terrain type and contour (ground absorption of sound, reflections)
- e) Obstructions (buildings, barriers, vegetation, etc)

In this lesson, these basic mechanisms will be explained and quantified. After completion of this lesson, the reader should be able to explain why thunder sounds different at a distance, or the train can be heard under some conditions and not others. Basic tools and techniques are provided to predict sound propagation over long ranges outdoors.

The successful outdoor noise consultant needs five things:

- 1) Measurement equipment (octave band sound level meter, perhaps a long term monitor)
- 2) Noise control techniques (such as barriers, damping materials, enclosures, mufflers and silencers)
- 3) A goal – what is a “good” level (from regulations, resident opinions, etc.)
- 4) A good understanding of the physical mechanisms and a basic prediction model (the subject of this unit)
- 5) Rain gear

## 10.2 Review of Hemispherical Sound Propagation

You should recall from Section 5, for a point source in a loss-less medium with no reflections, that the sound intensity is related to power and range by:

$$I = \frac{p^2(r)}{\rho c} = \frac{W}{4\pi r^2} \quad \text{Equation 1}$$

where:  $I$  = acoustic intensity (watts/m<sup>2</sup>)  
 $p(r)$  = sound pressure at radial distance  $r$  (N/m<sup>2</sup>)  
 $r$  = distance from the source in meters  
 $W$  = sound power (watts)  
 $\rho c$  = acoustic impedance (rayls)

In terms of sound levels, this translates to:

$$L_p = L_w - 20 \log r - 10 \log \left[ \frac{W_{ref} \rho c}{P_{ref}^2 4\pi} \right] \quad \text{Equation 2}$$

where:  $L_w$  = sound power level (dB re 10<sup>-12</sup> watts)  
 $L_p$  = sound pressure level (dB re 2x10<sup>-5</sup> N/m<sup>2</sup>)

for  $\rho c = 400$  mks rayls, the last term on the right becomes 11 dB.  
 (10.83 dB for  $\rho c = 415$  rayls)

$$L_p = L_w - 20 \log r - 11 \quad (\text{dB}) \quad \text{Equation 3}$$

Another useful form of this equation, comparing sound pressure levels at two different ranges, is:

$$L_{p_1} - L_{p_2} = 20 \log \frac{r_2}{r_1} \quad (\text{dB}) \quad \text{Equation 4}$$

Using this equation, you can easily show the often quoted result that sound levels decay by 6 dB per doubling of distance from a point source.

If the source is directional, an additional term, the Directivity Index DI, is needed to account for the uneven distribution of the sound intensity as a function of direction. The Directivity Index is the difference between the actual sound pressure, and the sound pressure from a non-directional point source with the same total acoustic power. It can be determined experimentally, or calculated for a limited number of analytical cases, such as a piston in a baffle (a decent approximation of a loudspeaker), a piston in the end of a long tube (engine exhaust). Reference: Acoustics, L. Beranek, McGraw-Hill, 1954.

$DI = \text{Directivity Index (dB)} = 10 \log_{10} Q$

$$Q = \text{Directivity Factor} = \frac{I_{\theta}}{I_{mean}} = \frac{P_{\theta}^2}{P_s^2}$$

where :  $P_{\theta}$  = rms sound pressure at angle  $\theta$  for the directional source

$P_s$  = rms sound pressure of a non - directional point source radiating the same total power

For an omni-directional source radiating into free space,  $DI = 0$  dB. If that same source is situated directly on a perfectly reflecting surface (hemispherical radiation),  $DI = 3$  dB.

Our general purpose propagation equation without reflection is then:

$$Lp = Lw - 20 \log r - 11 + DI \quad (\text{dB}) \quad \text{Equation 5}$$

### 10.3 Propagation in a Real Atmosphere – Excess Attenuation Model

In a real atmosphere, the sound propagation deviates from spherical due to a number of factors, including absorption of sound in air, non-uniformity of the propagation medium due to meteorological conditions (refraction and turbulence), and interaction with an absorbing ground and solid obstacles (such as barriers). We will now extend Equation 5 to account for atmospheric absorption and all other effects by introducing the concept of **Excess Attenuation**, defined as:

**Excess Attenuation,  $A_E$**  - the total attenuation in addition to that due to spherical divergence and atmospheric absorption

$$Lp = Lw - 20 \log r - 11 + DI - A_{abs} - A_E \quad (\text{dB}) \quad \text{Equation 6}$$

where :  $A_{abs}$  = atmospheric absorption, see section 2.2.1 (dB)

$r$  = distance from source to receiver (meters)

$A_E$  = excess attenuation (dB)

The total excess attenuation  $A_E$  (dB) is a combination of all effects:

$$A_E = A_{weather} + A_{ground} + A_{turbulence} + A_{barrier} + A_{vegetation} + \text{any other effects...} \quad \text{Equation 7}$$

These terms will be quantified in subsequent sections.

### 10.3.1 Atmospheric Absorption - $A_{abs}$

Sound energy is dissipated in air by two major mechanisms:

- Viscous losses due to friction between air molecules which results in heat generation (called “classical absorption”)
- Relaxational processes – sound energy is momentarily absorbed in the air molecules and causes the molecules to vibrate and rotate. These molecules can then re-radiate sound at a later instant (like small echo chambers) which can partially interfere with the incoming sound.

These mechanisms have been extensively studied, empirically quantified, and codified into an international standard for calculation: ANSI Standard S1-26:1995, or ISO 9613-1:1996.

For a standard pressure of one atmosphere, the absorption coefficient  $\alpha$  (in dB/100m) can be calculated as a function of frequency  $f$  (Hz), temperature  $T$  (degrees Kelvin) and molar concentration of water vapor  $h$  (%) by:

$$\alpha = 869 \times f^2 \left\{ 1.84 \times 10^{-11} \left( \frac{T}{T_0} \right)^{1/2} + \left( \frac{T}{T_0} \right)^{-5/2} \left[ 0.01275 \frac{e^{-2239.1/T}}{F_{r,O} + f^2 / F_{r,O}} + 0.1068 \frac{e^{-3352/T}}{F_{r,N} + f^2 / F_{r,N}} \right] \right\} \quad \text{Equation 8}$$

$$F_{r,O} = 24 + 4.04 \times 10^4 h \frac{0.02 + h}{0.391 + h} \quad \text{Oxygen relaxation frequency (Hz) Equation 9}$$

$$F_{r,N} = \left( \frac{T}{T_0} \right)^{-1/2} \left( 9 + 280h e^{\left\{ -4.17 \left( \frac{T}{T_0} \right)^{-1/3} - 1 \right\}} \right) \quad \text{Nitrogen relaxation frequency (Hz) Equation 10}$$

$$T_0 = 293.15 \text{ }^\circ\text{K} \text{ (20}^\circ\text{ C)}$$

To calculate the actual attenuation due to atmospheric absorption  $A_{abs}$  (dB) for a given propagation range for use in Equation 6:

$$A_{abs} = \alpha r / 100 \text{ (dB)} \quad \text{Equation 11}$$

where:  $\alpha$  = absorption coefficient (dB/100m) from Eq. 5

$r$  = range (meters)

A plot of the absorption coefficient for air at 20 degrees C and 70% relative humidity is shown in Figure 1 (ref. ANSI standard S1.26). The predominant mechanism of absorption (the classical and rotational relaxation) is proportional to the square of frequency. The vibration relaxation effect depends on the relaxation frequencies of the gas constituents (O and N) and is highly dependent on the relative humidity. Figure 2 shows the relation of humidity. It is interesting to note that absorption generally decreases with increasing humidity. The exception is totally dry air, which has the least absorption.

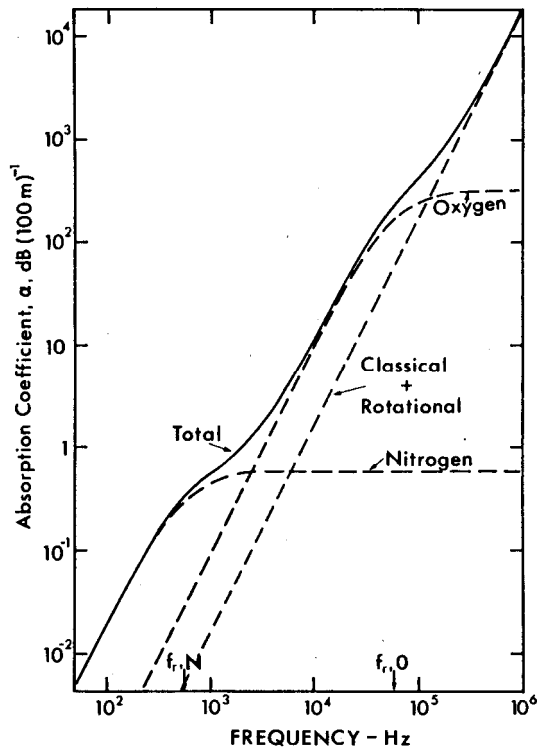


Figure 1. Predicted atmospheric absorption in dB/100m for a pressure of 1 atm, temperature of 20C and relative humidity of 70%

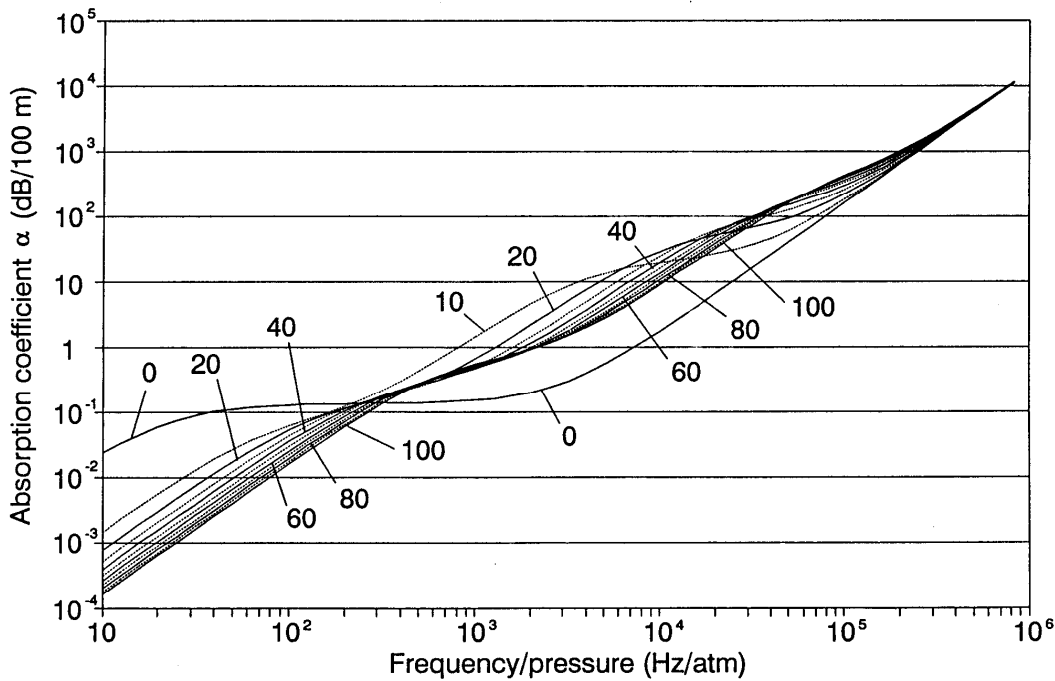


FIG. 2. Sound absorption coefficient in air (dB/100 m) versus frequency/pressure ratio for various percent relative humidities at 20 °C.

Figure 2. Sound absorption coefficient in air (dB/100) versus frequency for various relative humidities at 20°C.

**Homework:** implement a computer program, or spreadsheet to calculate the absorption coefficient. Check your program with the following values:

Frequency (Hz)	T (°C)	Relative Humidity (%)	Absorption $\alpha$ (dB/100m)
1000	20	70	0.54
10000	20	70	10.96
10000	20	10	22.05

### 10.3.2 Meteorological Conditions - $A_{weather}$

#### Effects of Wind

Over open ground, substantial vertical wind velocity gradients commonly exist due to friction between the moving air and the ground. Wind speed profiles are strongly dependent on the time of day, weather conditions and the nature of the surface. The wind speed, in the absence of turbulence, typically varies logarithmically up to a height of 30 to 100 meters, then negligibly thereafter. As a result of this velocity gradient (and the resulting change in sound velocity which it causes), a sound wave propagating in the direction of the wind will be bent downward. In the upwind direction the sound speed decreases with altitude, sound waves are directed upward, away from the ground, forming a “shadow zone” into which no direct sound penetrates (Figure 3). This process is called refraction, whereby the path of sound waves curves in the direction of the lower sound velocity. The radius of curvature of the sound path is inversely proportional to the velocity gradient. Sound always refracts toward the lower sound speed.

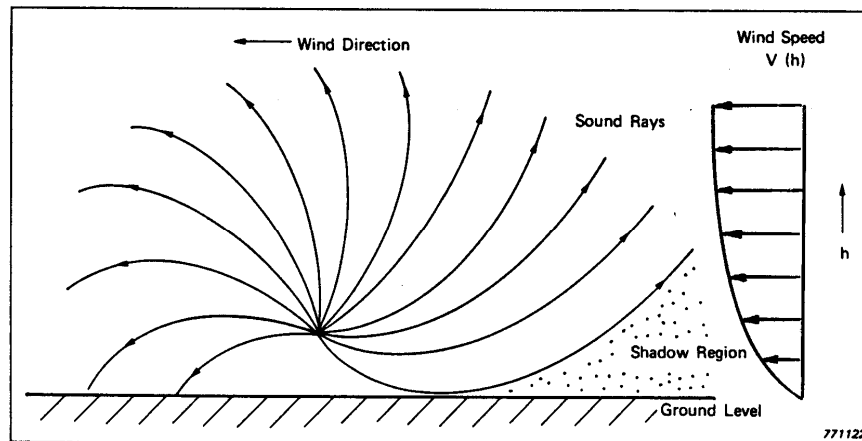


Figure 3. Refractive effects caused by wind

#### Temperature Effects

A similar refractive effect results from vertical temperature gradients. The speed of sound in air is proportional to the square root of absolute temperature by the relation:

$$c = 20.05\sqrt{T + e/p} \quad (\text{meters/second}) \quad \text{Equation 12}$$

where:  $T$  = absolute temperature °K

$e$  = partial pressure of water vapor (psi)

$p$  = barometric pressure (psia)

The minor dependence on humidity is usually neglected since large humidity gradients are not a common event in the atmosphere.

In the presence of a temperature gradient, the effect is to refract sound waves in the direction of lower sound velocity (in this case, the lower temperature). Typical temperature profiles are shown in Figure 4. A common atmospheric occurrence is a negative temperature gradient (temperature decreases with altitude). This is typical of a sunny afternoon, when significant solar insolation causes high surface temperatures and significant heat transfer from the ground to the adjacent air. This event is also known in meteorological terms as a superadiabatic or positive lapse. In this situation, sound waves will be bent upward in all directions from the source, forming a circular shadow zone. The reverse situation often occurs at night, when a positive gradient is common. This is caused by the rapid cooling of air at the surface as heat is now absorbed by the ground. This is called an inversion or negative lapse and the sound waves are bent downward. This phenomena explains why sound sometimes travels much better at night, because it is focused along the ground instead of radiating upward.

For completeness of meteorological terminology, a neutral (or statically stable) atmosphere is defined as one in which the temperature decreases at the dry adiabatic rate ( $-0.98^{\circ}\text{C}/100$  meters). In a neutral atmosphere, buoyant effects are balanced by gravity and there is no upward or downward convection. It should be noted that this is not the same as a non-refractive medium. In order to attain straight sound paths (no refraction), the atmosphere must have a constant temperature (isothermal). Temperature gradients greater than  $-9.8^{\circ}\text{C}/100\text{m}$  are called positive lapse or superadiabatic, while gradients less than this value are called negative lapse or inversion.

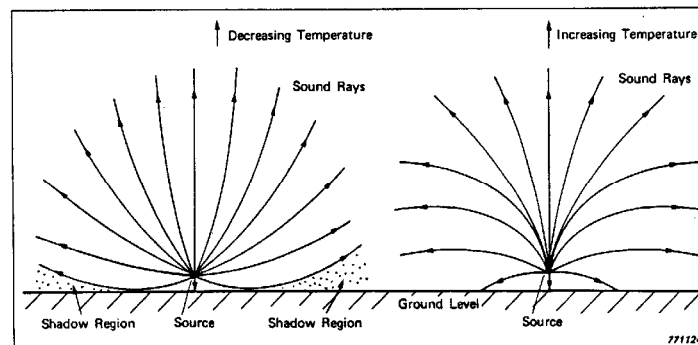


Figure 4. Refraction of sound with temperature gradients a) on left, normal lapse rate (decreasing temperature with altitude) b) on right, inverted lapse rate (temperature increases with altitude)

Determining excess attenuation due to refractive effects is not an easy task. Complex models that allow the user to specify the sound speed as a function of altitude are needed, such as ray tracing. Refractive effects can cause both increases and decreases in sound levels compared to a uniform medium. One common approach is to calculate the sound level assuming no refraction, on the assumption that this probably represents a good prediction of the equivalent, or time averaged sound level that would be observed.

It is extremely important to understand refraction in order to make reliable sound measurements. An unscrupulous consultant can take advantage of refraction to make measurements which are

the most favorable to whatever side he or she is representing. If you want the observed levels to be low, measure on a hot sunny afternoon, or upwind from the source. If you want levels that are more representative of the equivalent sound level, measure when the refractive effects are at a minimum – on a calm, overcast day or evening.

### 10.3.3 Ground Interaction - $A_{ground}$

The surface over which sound propagates can seldom be considered perfectly rigid or totally reflective (with the possible exceptions of open water, ice, or concrete). Typical soil surfaces with or without vegetation tend to absorb energy from incident acoustic waves. Accurate prediction of ground effects requires knowledge of the absorptive and reflective properties (the acoustic impedance) of the surface.

The ground surface itself also provides a significant path for transmission of acoustic energy, particularly at low grazing angles and low frequencies. Incident acoustic energy is transformed into vibrational energy and is transmitted along the surface layer. This vibration disturbance can propagate for long distances, before dissipating or re-radiating as sound. At long distances, the transmission of low frequency sound can be dominated by this surface wave mechanism.

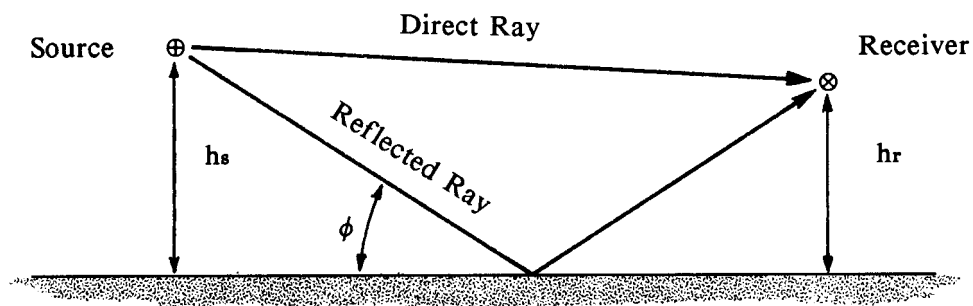


Figure 5 Geometry for reflection of sound from level ground with finite impedance

The behavior of sound propagation over ground of finite impedance is derived from analogy to electromagnetic wave theory. The geometry for this situation is illustrated in Figure 5. When airborne sound is incident on a locally reacting fluid, the transmitted wave is refracted at right angles into the surface. The reflected portion of the wave leaves the surface at the angle of incidence, with its amplitude and phase modified by the impedance of the surface. The reflected wave propagates to the receiver, along with direct wave from the source. Depending on their relative phases and amplitudes, they may constructively add or destructively interfere. In the limit, for both source and receiver near the ground and perfect reflection and no atmospheric turbulence (coherent addition), the sound level at the receiver will be increased by 6 dB (an excess attenuation of  $-6\text{dB}$ ). Effectively, the receiver sees two sources, the actual source, and a reflected or “image” source and the sound pressure is doubled.

Using the electromagnetic wave theory, the governing equation for the pressure amplitude  $p$  at the receiver, assuming a uniform medium (no refraction), over level ground is: [ref 3]



$$\frac{p}{p_0} = \frac{1}{r_d} e^{-ikr_d} + \frac{R_p}{r_r} e^{-ikr_r} + (1 - R_p) \frac{F}{r_r} e^{-ikr_r} \quad \text{Equation 13}$$

where:  $R_p$  = plane wave reflection coefficient

$$R_p = \frac{\sin \phi - Z_{air} / Z_{ground}}{\sin \phi + Z_{air} / Z_{ground}}$$

$Z_{air}$  = characteristic impedance of air ( $\rho c$ ) = 415 N - sec/m<sup>3</sup> at 20°C

$Z_{ground}$  = complex impedance of ground, N - sec/m<sup>3</sup>, for a locally reacting surface, assuming Delany and Bazley single parameter model (ref 4), where  $\sigma$  is the flow resistivity of the surface in units of cgs rayls (dyne - sec/m<sup>3</sup>):

$$\text{real component} = 1 + 9.08 \left( \frac{f}{\sigma} \right)^{-0.75} \quad \text{imaginary component} = 11.9 \left( \frac{f}{\sigma} \right)^{-0.73}$$

$f$  = frequency (Hz)

$r_d$  = path length for direct wave

$r_r$  = path length for reflected wave

$\phi$  = angle of incidence and reflection

$k$  = wavenumber =  $2\pi f/c$

$p_0$  = sound pressure at one meter from the source in the absence of ground

$p$  = sound pressure at the receiver

$F$  = ground and surface wave amplitude factor (see ref. 3 for calculation procedure)

The first term in equation 13 is the direct wave, the second term describes a reflected wave, after its amplitude and phase have been modified by the plane wave reflection coefficient. The third term accounts for the difference between the reflection of a plane wave, and that of the actual case of a spherical wave. In the terminology of electromagnetic wave propagation, this last term is called the ground and surface wave.

This equation (Eq.13) provides an effective method to predict the excess attenuation due to ground absorption if the surface impedance is known as a function of frequency. Measurements of the impedance of various surfaces have been made and curve-fitting techniques applied to the experimental results. While more complex models have been proposed, it has been found that it is sufficient to use a single parameter, the flow resistivity of the surface, to describe the absorptive properties of a surface. The flow resistivity model is only valid for surfaces of constant porosity. Some typical values for different surfaces are shown in Table 1 [ref. 3].

Table 1. Flow resistivity values  $\sigma$  for various ground surfaces

Description of Surface	Flow Resistivity (cgs rays)
Dry, new fallen snow	15-30
Sugar snow	25-50
In forest, pine or hemlock	20-80
Grass, rough pasture	150-300
Roadside dirt, ill-defined, small rocks up to 10 cm diameter	300-800
Sandy silt, hard packed	800-2500
Clean limestone chips, thick layer (12-25mm mesh)	1500-4000
Earth, exposed and rain-packed	4000-8000
Quarry dust, fine, very hard packed by vehicles	5000-20000
Asphalt, sealed by dust and use	>20000

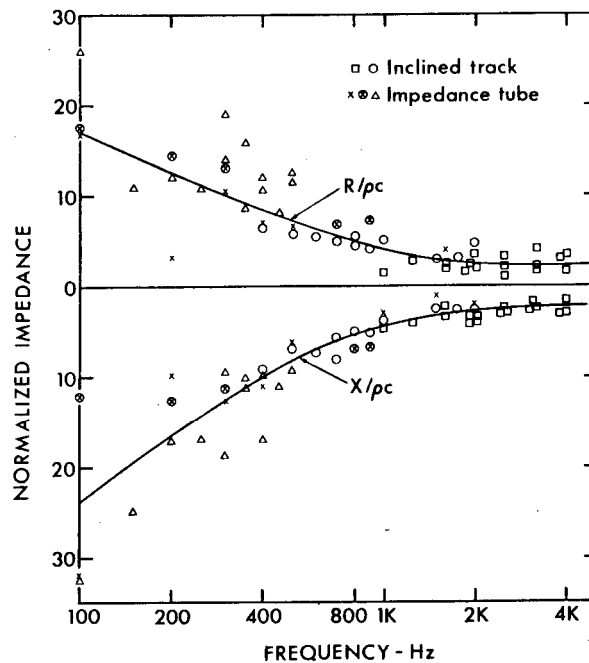


FIG. 8. Real component  $R_2$  and imaginary component  $X_2$  of the acoustic impedance of grass-covered flat ground (different areas of two different sites) obtained from measurements either with an impedance tube or of interference at oblique incidence (Ref. 38). (Note that the imaginary component corresponds to a stiffness reactance.)

Figure 6. Complex ground impedance for grass covered flat ground (ref 3)

### 10.3.4 Atmospheric Turbulence - $A_{turbulence}$

In the derivation of Equation 13, coherent addition of the direct and reflected wave is assumed. However in the real atmosphere, random fluctuations of wind and temperature cause fluctuations in amplitude and phase. This may translate into measured sound pressure fluctuations of 10 dB or more over a period of minutes. This effect was analytically modeled by Chessel [ref 5]. Daigle [ref 6] modified Equation 13 to account for the variance of sound amplitude due to turbulence to predict the statistical mean value of sound pressure and achieved good agreement with experimental data. Experimental measurements [ref 7] have resulted in estimated values for

the turbulence parameter (the mean square fluctuation of the index of refraction  $\langle \mu^2 \rangle$ ) as shown in Table 2.

Table 2. Relation between weather conditions and the turbulence parameter  $\langle \mu^2 \rangle$

Weather Condition	Turbulence Parameter $\langle \mu^2 \rangle$
Sunny, light wind (< 2 m/s)	$5 \times 10^{-6}$
Sunny, moderate wind (2-4 m/s)	9 to $10 \times 10^{-6}$
Sunny, strong wind (> 4 m/s)	15 to $25 \times 10^{-6}$
Overcast, light wind (< 2 m/s)	$3 \times 10^{-6}$
Overcast, moderate wind (2-4 m/s)	8 to $9 \times 10^{-6}$
Overcast, strong wind (> 4 m/s)	15 to $25 \times 10^{-6}$

Numerical results for the combined excess attenuation due to ground absorption and atmospheric turbulence using Daigle's model, are shown in Figures 7-8 for various ranges and surface types. A DOS Fortran program which implements Daigle's model and which generated the data for these plots is provided for your use. These plots reveal the general trends of ground absorption over grass-covered surfaces – a pronounced increase in attenuation at frequencies in the 200 to 600 Hz region. More reflective (higher impedance) surfaces result in less attenuation. Increased turbulence results in lower time-averaged attenuation. Figure 9 shows a comparison of Daigle's turbulence model to experimental data and to coherent theory (no turbulence)

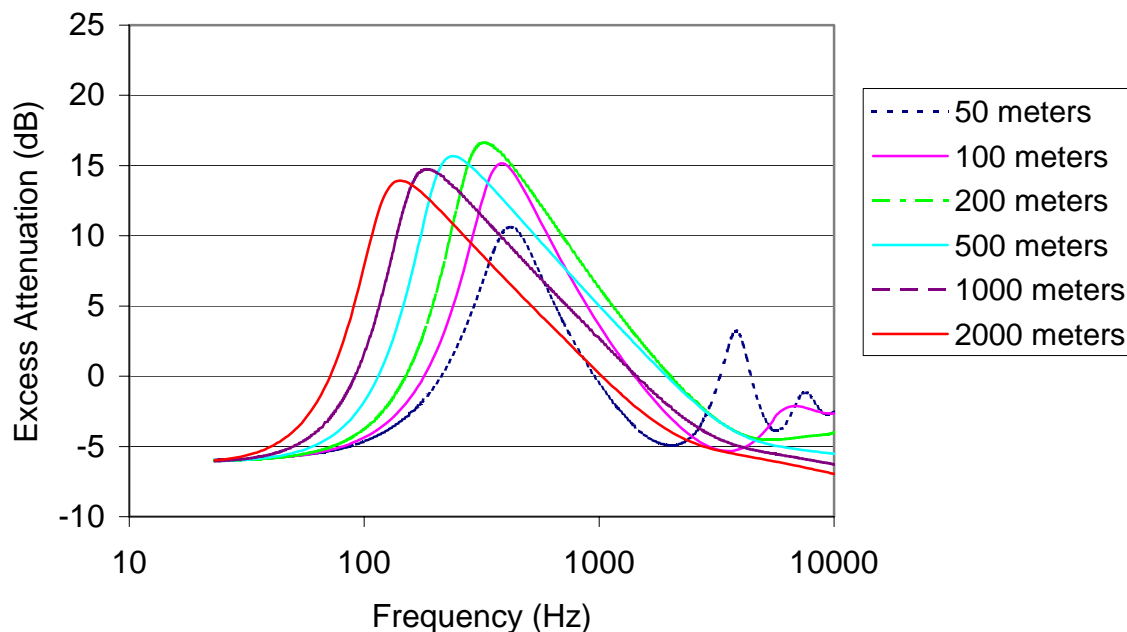


Figure 7. Effect of range on ground absorption for grass (source and receiver height=1.5m,  $\sigma = 150$  cgs rays,  $\langle \mu^2 \rangle = 3E-6$ )

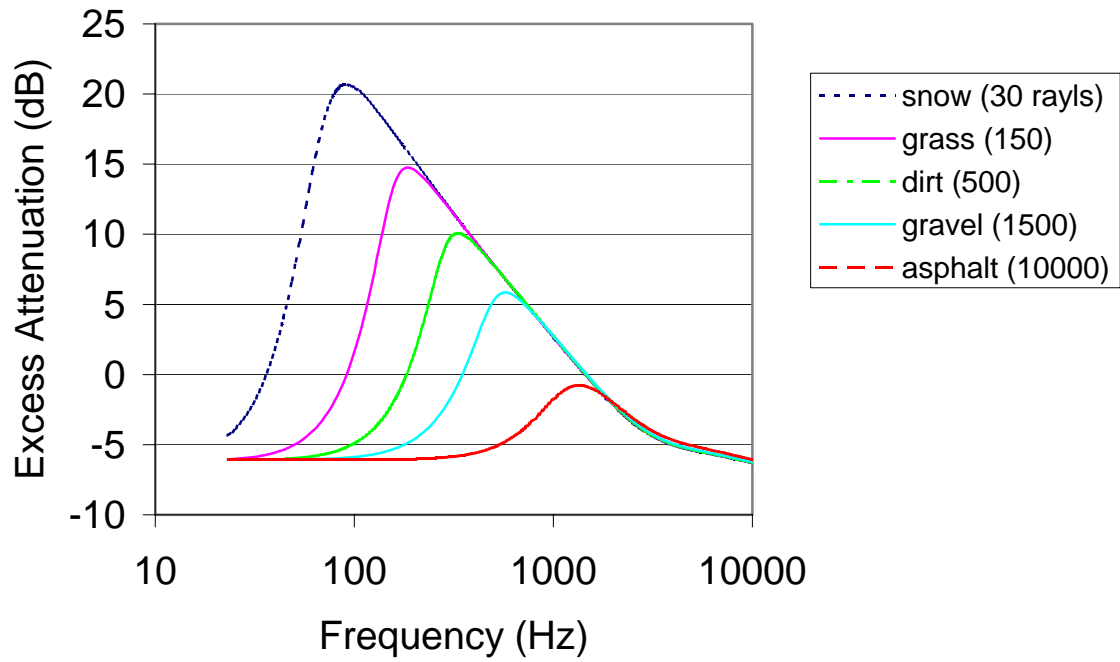


Figure 8. Effect of surface composition on ground absorption for range of 1 km (source and receiver height=1.5m,  $\langle \mu^2 \rangle = 3E-6$ )

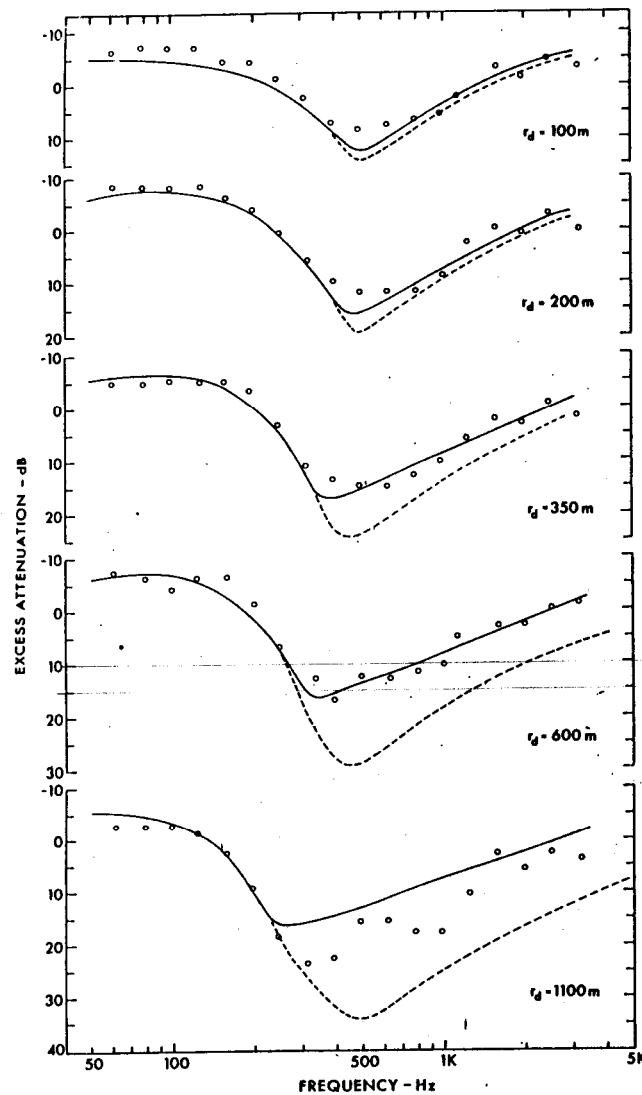


FIG. 7. Comparison of measured sound levels (points) with values predicted from the theory ( $h_s = 1.8$  m,  $h_r = 1.5$  m,  $\sigma = 300$  cgs units). —  $\langle \mu^2 \rangle = 2 \times 10^{-6}$ ,  $\rho_a = \rho_0 = 0.80$ , --- coherent acoustics theory ( $\langle \mu^2 \rangle = 0$ ).

Figure 9. Comparison of measured sound levels with prediction (ref 6)

**Homework:** Equation 13 calculates the sound pressure at the receiver for propagation over an absorptive ground. Derive an expression for the excess attenuation due to ground absorption.

### 10.3.5 Vegetation - $A_{vegetation}$

Vegetation and foliage provides a small amount of attenuation, but only if it is sufficiently dense to fully block the view along the propagation path. The attenuation may be due to vegetation close to the source, close to the receiver, or both. Approximate values for the excess attenuation from dense foliage are listed in Table 3.

Table 3. Attenuation of an octave band noise due to propagating a distance  $d_f$  through dense foliage [ref ISO 9613-2:1996]

Propagation distance - $d_f$ (meters)	Octave Center Frequency - Hz							
	63	125	250	500	1000	2000	4000	8000
$10 \leq d_f \leq 20$	Attenuation, dB 0	0	1	1	1	1	2	3
$20 \leq d_f \leq 200$	Attenuation, dB/m 0.02	0.03	0.04	0.05	0.06	0.08	0.09	0.12
$d_f \geq 200$	Attenuation, dB 4	6	8	10	12	16	18	24

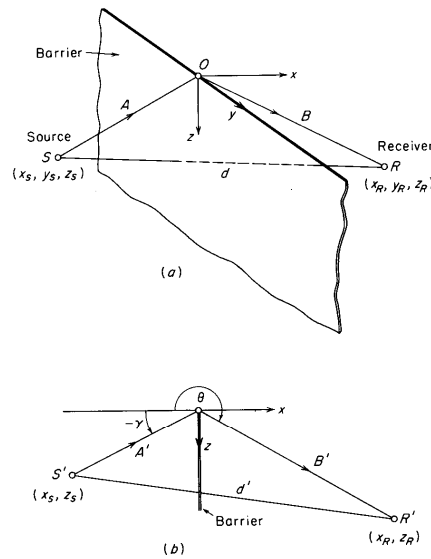
Alternate approximations for excess attenuation due to vegetation [ref 1] are:

$$\text{For shrubbery or tall thick grass: } A_{shrubs} = (0.18 \log f - 0.31)r$$

$$\text{For forests: } A_{forest} = 0.01 f^{1/3} r$$

### 10.3.6 Obstructions and Barriers - $A_{barrier}$

When the line of sight between a source and receiver is obstructed by a rigid, non-porous wall or building, appreciable noise reductions can occur. Sound waves must diffract around the obstacle in order to reach the receiver. This phenomena is used to great advantage in the attenuation of highway noise by barriers in congested urban areas.



**Fig. 7.7** Geometry of sound-propagation path over a barrier: (a) perspective view and (b) projection plane perpendicular to the barrier. The source and receiver are S and R, respectively. The coordinate system is shown in (a) and the source coordinates are  $x_s, y_s, z_s$  and the receiver coordinates are  $x_R, y_R, z_R$ . The shortest path that the sound can travel over the barrier between source and receiver is distance  $A + B$ . The angle  $(\gamma + \theta)$  gives, on the projection plane, the direction of the refracted wave relative to that of the incident wave. Ground reflections are neglected, which is permissible if the source and receiver are very near to a completely reflective ground. For other heights of source and receiver over partially absorptive ground, sound can travel to the receiver along three additional paths, with one or two reflections where phase shifts may occur, causing interference effects.

Figure 9. Geometry of sound propagation over a barrier [ref 3]

An observer in the vicinity of a rigid, infinitely long barrier (Figure 9), for sound from a point source, will experience an excess attenuation [ref 3] of:

$$A_{\text{barrier}} = 20 \log \frac{\sqrt{2\pi N}}{\tanh \sqrt{2\pi N}} + 5 \text{ (dB)} \quad \text{for } N \geq -0.2 \quad \text{Equation 14}$$

$$= 0 \quad \text{otherwise}$$

$$N = \pm \frac{2}{\lambda} (A + B - d) \quad \text{Equation 15}$$

This equation is based on optical diffraction theory and was developed by Z. Maekawa [ref 8]. The dimensionless quantity  $N$  is called the Fresnel number and is a measure of how far below the line of sight (relative to a wavelength) the receiver lies. A negative sign for  $N$  indicates that the receiver can see the source, while a positive sign denotes that the receiver is in the shadow zone. Equation 14 is plotted as a function of Fresnel number in Figure 10 along with experimental measurements [ref 1]. More complex models are needed to account for line sources, finite length and absorptive barriers. However the general trends which can be observed from this simple case still hold true, namely that barriers are most effective at high frequencies. The barrier should be as tall as possible. The effectiveness of a barrier depends on how far below the line of sight the receiver lies.

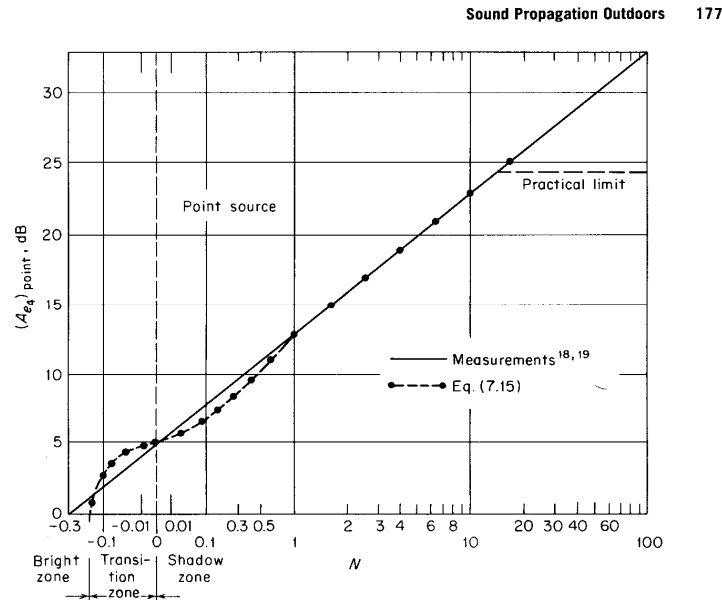


Figure 10. Excess attenuation for a point source by an infinite rigid barrier [from ref 1]

**Homework:** Show that the excess attenuation for a three-sided barrier is:

$$A_{\text{barrier, total}} = -10 \log \left[ \sum_{i=1}^3 10^{A_i/10} \right]$$

where  $A_i$  = excess attenuation for each sound path  
(around each side of barrier) by equation 14

### 10.3.7 Non-point sources

These equations assume single point sources. The noise impact of multiple point sources that are widely spaced can be treated by calculating their individual noise levels and adding the result logarithmically. Groups of closely spaced point sources can be approximated as a single point source if:

- the sources have approximately the same strength and height about the ground;
- the same propagation conditions exist from the sources to the point of reception;
- the distance from the single equivalent point source to the receiver exceeds twice the largest dimension of the sources
- the receiver is located at least one wavelength away from the single equivalent point source

A common approach to extended or line noise sources, such as road or rail traffic, or long runs of piping, is to break the source down into multiple, incoherent point sources.



## 10.4 Estimation of Source Strength

Equation 6 requires the user to specify the strength of the source (sound power level  $L_w$ ). If the source is a commercial piece of equipment, this information can sometimes be obtained from the manufacturer, but this is the exception. Most often, you must estimate the source strength from field data. The most common technique is to measure the SPL at a known distance near to the source, and use Equation 6 to estimate the sound power level. If multiple sources are present, all other sources are turned off, or the measurement should be made so close to the source in question so that its contribution is dominant. This value of SPL and the known range is then used in Equation 6 and  $L_w$  is then calculated. This value of  $L_w$  is the effective strength of the source and is used in subsequent applications of Equation 6 to determine the SPL at other ranges.

The actual measurement locations selected to represent source strength should be chosen with the receiver location in mind. Because of the complications of directivity, the noise modeler cannot assume that a single measurement of SPL can quantify a source in all directions. The assumption of a uniform point source is valid however as long as the measurement of source strength is along the line from the source to the receiver, regardless of directivity. The measurement should therefore be taken along this line whenever feasible, but near field effects and multi-source influences are probably equally important considerations. In order to approximate a general source of finite size with a point source characterized by a measured SPL at a distance from the source, the measurement position should be:

- (a) at least one wavelength of the frequency of interest  $f$  (Hz) from the nearest surface of the source  $d \geq \lambda = 343/f$  (meters)
- (b) at a distance from the nearest surface of the source at least twice the largest dimension  $h_{max}$  of the source  $d \geq 2h_{max}$

For example, if the effective noise source is the vibrating wall of a building that is 5 meters wide and 3 meters tall, measurements should be taken at least 10 meters from the edge of the building to satisfy (b) and at least 11 meters from the building to satisfy (a) if the lowest frequency of interest is 31 Hz. If a group of closely spaced sources or buildings is to be lumped together into one composite source, the major source dimension becomes the total width of the composite source. The distance from the receiver to the source is measured from the geometric center of the group.

## 10.5 Applicability of Excess Attenuation Model

The calculation procedure described in Section 2.2 is relatively simple to apply and provides data that is useful for site planning purposes. It can provide an estimate of statistical mean values of sound levels. It can be used to estimate whether a planned installation will be in compliance with local noise ordinances. It can be used as a design tool to assess the effectiveness of site changes, barriers, or changes to source strength (for instance, adding a muffler to an engine). Its validity is restricted by the underlying assumptions – point sources, uniform and level terrain, a uniform atmosphere (no temperature or wind gradients).

## 10.6 Other Propagation Models

### 10.6.1 FHWA Traffic Noise Model (TNM)

A specific tool used to predict noise impact from highways is the FHWA TNM (Federal Highway Administration Transportation Noise Model version 1.0) which is available from the University of Florida McTrans Center (<http://www-t2.ce.ufl.edu/mctrans/featured/trafficNoise/>). Included in this model are many of the outdoor noise propagation effects previously discussed, including atmospheric absorption, divergence, intervening ground (berms and hills), noise barriers, buildings and heavy vegetation. The effects of atmospheric turbulence are not included. The Traffic Noise Model predicts A-weighted hourly equivalent sound pressure levels ( $L_{EQ}$ ) and day-night levels ( $L_{DN}$ ). Sound level contours and the reductions in noise by absorption and barriers are estimated. The basic equation for the TNM is:

$$L_{Aeq1h} = EL_i + A_{traff(i)} + A_D + A_S$$

where:

$L_{Aeq1h}$  = A-weighted equivalent hourly sound pressure level

$EL_i$  = Source level for the  $i$ th type of vehicle integrated over a passby at 50 ft.

$A_{traff(i)}$  = Factor that accounts for the number of vehicles and their speeds

$A_D$  = Correction for spreading loss and length of roadway (the effective length of the source)

$A_S$  = Attenuation due to shielding and ground effects

### 10.6.2 Other Models

Similar calculation procedures, based on excess attenuation models can be found in the ISO standard 9613-2:1996, and the commercial program, SOUNDPLAN. More complex models exist which allow the calculation of sound propagation over non-level terrain with any user-specified atmospheric conditions. Such models are extremely useful for analyzing the propagation under specific meteorological conditions. The problem is that they yield results for only those specific conditions and give little indication of statistical mean values of sound levels. The user must provide substantially more information. This information can be difficult to generate, such as complete profiles of wind and temperature. These detailed models include Ray Tracing [ref 10], the Fast Field Program (FFP)[ref 11], and other models based on direct solution of the wave equation.

## 10.7 Outdoor Noise Standards and Regulations

**ISO 1996-1:1982** Acoustics – Description and measurement of environmental noise – Part 1: Basic quantities and procedures

**ISO 1996-2:1987** Acoustics – Description and measurement of environmental noise – Part 2: Acquisition of data pertinent to land use

**ISO 9613-1:1996** Acoustics- attenuation of sound during propagation outdoors- Part 1: Calculation of the absorption of sound by the atmosphere

- ISO 9613-2:1996** Acoustics- attenuation of sound during propagation outdoors- Part 2:  
General method of calculation
- ANSI S1-26-1995** Method for the calculation of the absorption of sound by the atmosphere
- ANSI S12.18-1994** Procedures for outdoor measurement of sound pressure level

## 10.8 References

- 1 L. Beranek; Noise and Vibration Control, McGraw-Hill, 1971
- 2 H. Panofsky and J. Dutton, *Atmospheric turbulence: models and methods for engineering applications*, Wiley Interscience, NY, 1984.
- 3 J.E. Piercy, T. Embleton and L. Sutherland, *Review of noise propagation in the atmosphere*, JASA 61(6), June 1977, pp 1403-1418.
- 4 M. Delaney and E. Bazley, *Acoustical properties of fibrous absorbent materials*, Applied Acoustics, Vol 3, 1970, pp 105-116.
- 5 C.I. Chessel, *Noise propagation along an impedance boundary*, JASA 62(4), 1977, pp 825-834.
- 6 G. A. Daigle, *Effects of atmospheric turbulence on the interference of sound waves above a finite impedance boundary*, JASA 65(1), Jan. 1979, pp 45-49.
- 7 M. Johnson, R. Raspet and M. Bobak; *A turbulence model for sound propagation from an elevated source above level ground*, JASA 81(3), March 1987, pp 638-646.
- 8 Z. Maekawa, *Noise reduction by screens*, Applied Acoustics, Vol 1, 1968, pp 157-173.
- 9 T. F. Embleton, *Tutorial on sound propagation outdoors*, JASA 100(1), July 1996, pp 31-48.
- 10 J. Lamancusa and P. Daroux, *Ray tracing in a moving medium with two-dimensional sound-speed variation and application to sound propagation over terrain discontinuities*, JASA 93(4), April 1993, pp 1716-1726
- 11 R. Raspet, S. Lee, et al., *A fast field program for sound propagation in a layered atmosphere above an impedance ground*, J. Acoust. Soc. Am. 77(2), Feb 1985, pp. 345-352.