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OVERVIEW OF OUTDOOR SOUND PROPAGATION

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ABSTRACT

The basic causes of attenuation of sound outdoors are reviewed. Their magnitude is defined by appropriate analytical expressions or illustrated by examples of calculated or measured values for sound propagation losses. In addition to basic spreading losses, well defined losses occur due to absorption in air. The other mechanisms for attenuation, absorption and reflection at a porous ground, refraction by a non- uniform atmosphere and diffraction or scattering by atmospheric turbulence are also reviewed. Refraction is usually the dominant cause of excess attenuation since it can cause increases or decreases in sound level from downward or upward refraction at long ranges by as much as 10-15 dB relative to spreading and atmospheric absorption losses. Scattering by turbulence can limit refraction losses below values predicted from ray paths. Analytical models are available for most of these effects.

1 - INTRODUCTION

This paper will attempt to provide a short overview of outdoor sound propagation by summarizing the various mechanisms which influence outdoor sound propagation. The subject has fascinated many scientists and engineers since at least the late 17th century and continues to challenge a dedicated group of specialists in acoustics today. The overview will draw on some of the previous reviews in the literature on sound propagation [1-3] and will rely on these reviews for citations of the extensive literature.

Elements of outdoor sound propagation. As sound propagates outdoors, it is attenuated or modified by: 1) geometrical spreading, 2) atmospheric absorption, 3) interaction by reflection or absorption by the ground or ground cover and 4) refraction and/or diffraction by a non-uniform atmosphere and by obstacles. The total attenuation, At for sound propagation, is the sum of three nominally independent terms: As, the attenuation due to geometric spreading, Aa, the attenuation due to atmospheric absorption and Ae, the Excess Attenuation due to all other effects including attenuation Ag by the ground in a homogeneous atmosphere, refraction Ar by a non-homogeneous atmosphere, attenuation Ad by diffraction and reflection by a barrier and scattering or diffraction by turbulence. The individual elements of the "excess attenuation" term, Ae may not all be present nor will they necessarily act independently.

2 - SPREADING LOSSES

A general expression for the spreading loss, As in decibels, between any two positions at distances r_1, r_2 from an acoustic source can be given by:

$$A_s = 20g\lg\left(\frac{r_2}{r_1}\right) \quad (1)$$

where r_2, r_1 are the distances between the source and the two positions, r_1 and r_2.

The "constant" $g = 0$ (i.e. $-$ no spreading loss) for plane wave propagation such as near a large source at distances much smaller than a characteristic source dimension; $= 1/2$ for cylindrical spreading from an extended or infinite line source such as a stream of traffic and $= 1$ for spherical wave propagation from a point source or at distances from a large source which are much larger than characteristic source dimensions. The latter two conditions correspond to the commonly specified condition of 3 dB and 6 dB loss (respectively) per doubling of distance from the source.

Finite arrays of stationary, incoherent sources are commonly utilized to model community noise levels from large sources such as highways, industrial plants or broad distributions of ambient noise sources. The spreading losses for these cases can be conveniently evaluated using appropriate arrays of such incoherent sources in the form of finite line or planar (circular or rectangular) sources [3]. Figure 1 illustrates general trends in spreading losses from such arrays of incoherent sources in a linear or planar array. If the sources are coherent (i.e. a rigid piston radiating sound), the near field in such cases will be much more complex. Prediction models also describe the spreading loss horizontally and vertically for an infinite array of incoherent sources representing distributed urban noise sources (Ref. 5,6 in Ref. [3]).

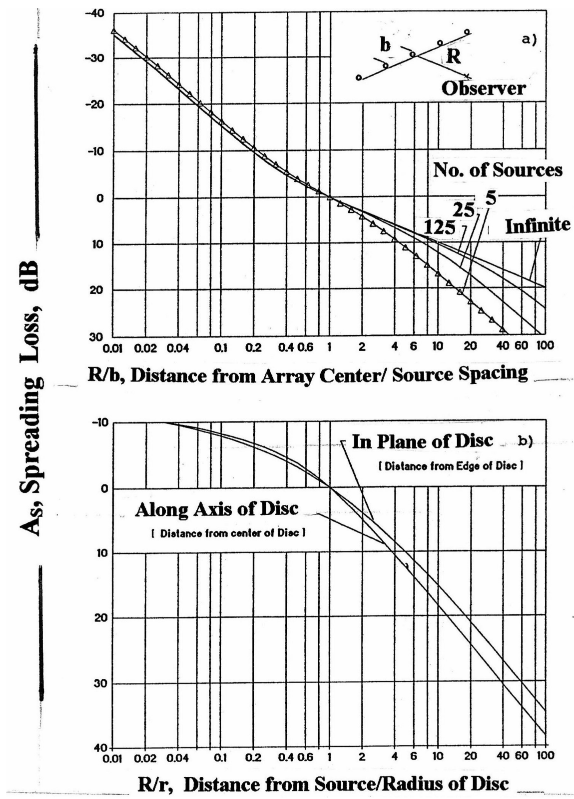


Figure 1: Spreading losses for: a) linear arrays and b) planar disc array (Ref. 4 in Ref. [1]).

3 - ATTENUATION BY ATMOSPHERIC ABSORPTION

A source of true energy loss in a sound field that is not present in spreading losses occurs as a result of atmospheric absorption caused by: 1) classical (thermal heat conduction and shear viscosity) losses and 2) molecular relaxation losses associated with an exchange between molecular translational and molecular rotational or vibration energy. The latter occurs in nitrogen and oxygen in air and each is associated with a temperature, humidity and pressure-dependent relaxation frequency. These loss components also vary with temperature, atmospheric pressure and, most importantly, with the frequency of the sound wave. The strong theoretical foundation for atmospheric absorption has evolved from the early work in the 1930's to the current thorough understanding of the mechanisms allowing development of National (ANSI S1.26-1995) and International (ISO 9613-1) standards for the calculation of atmospheric absorption. The general behavior of this loss as function of frequency is illustrated schematically in Fig. 2. At long propagation distances and for high frequencies, atmospheric absorption is usually much greater than spreading losses. Recent improvements in the ANSI/ISO model treat atmospheric absorption at altitudes above the stratosphere where the inverse pressure-dependence of classical and rotational relaxation losses cause these components to greatly exceed molecular relaxation losses [4]. For atmospheric attenuation of broad-band noise sources, the effective attenuation coefficient, for a given band-center frequency, slowly decreases with range as higher frequency energy in the band is attenuated. (See Annex E in ANSI S1.26.1999). Some atmospheric attenuation also occurs in fog, in dust in the air and, at frequencies below about 10 Hz, from absorption due to electromagnetic radiation of moist air molecules [3]. This absorption is generally not large compared to classical absorption and rotational and molecular vibration absorption (See Ref. 13,14 in Ref. [3]).

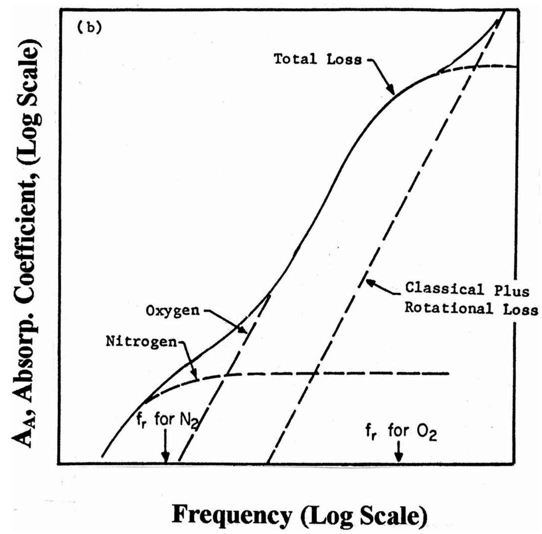


Figure 2: Components of atmospheric attenuation coefficient in dB/unit distance versus frequency (see ANSI S1.26-1995 or ISO 9613-1, 1993 for tables/equations).

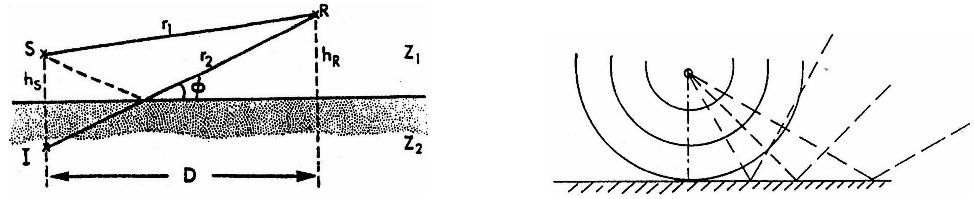
4 - ATTENUATION OVER THE GROUND

Sound propagation close to the ground is modified substantially by interaction with the ground surface. Theoretical models for evaluating this complex interaction have evolved rapidly in the last 20. years (Ref. [1] and [3] provide history and details of the literature.) The key parameter in evaluating sound propagation over the ground is the impedance of the ground surface. In the simplest ground impedance model; the ground is treated as normally reacting – the ground impedance does not depend on the angle of incidence of the impinging sound wave. One common empirical model for this ground impedance, consistent with theory for the acoustic impedance of porous media, was developed by Delany and Bazley from experimental data on porous materials [1–3]. They showed that the complex acoustic impedance could be given in terms of just one parameter – the ratio of frequency, *f*, in Hz, to the flow resistivity, of the ground surface.

Other models have been developed for defining ground impedance more accurately in terms of two or four parameters. – The former accounting for the presence of finite layers of an absorbing surface, such as grass sod, over a hard backing. The four parameter model can include details of the microstructure, e.g. – pore shape – of porous ground surfaces (see Ref [3] for further references for these more sophisticated ground impedance models).

If the incident wave is a plane wave, the well known plane wave reflection equation can be employed to define the resulting sound field over the ground [3]. This utilizes the basic feature (See Fig. 3a) for reflection of plane waves that the reflection angle, is equal, and opposite, to the incidence angle. However, the incident wave front is usually actually spherical and, as indicated in Fig. 3b, the incidence angle varies along the impinging wavefront. This matching of the complicated boundary condition of a spherical wave front impinging on a plane impedance boundary is a primary source of the complexity in the analysis of sound propagation over ground. An example of this is shown in Fig. 4 by the variation, with frequency, in the four components of the sound field from a point source near the ground – the direct wave (D), the reflected wave (R), the ground wave (G) required to match the curved wave front to the flat ground and the surface wave (S) which can exist when the imaginary part of the ground impedance exceeds the real part (See Ref. [1] or [3] for more details)

For sound attenuation through foliage and trees, ground attenuation is enhanced at low frequencies because the roots make the ground more porous [1], [3]. At high frequencies, with leaf dimensions comparable to the wavelengths there is also a significant attenuation caused by scattering [1], [3]. Experimentally-measured values for the excess attenuation through forests vary substantially – often defined only in an empirical form. A similar situation applies for attenuation through built-up urban areas (see Ref. 88 in ref. [1], Ref. 46 in Ref. [3]).



(a): The source (S), image (I) and direct (r_1) and reflected (r_2) paths.

(b): The ground incidence angle for spherical waves.

Figure 3: Geometry of sound propagation over ground.

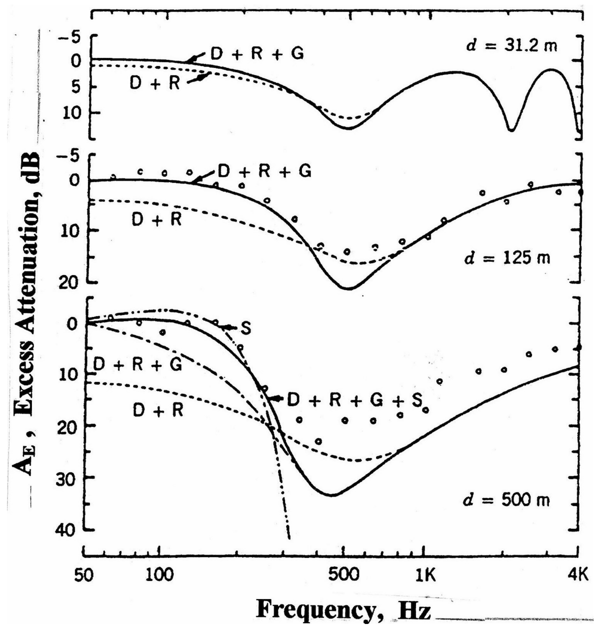


Figure 4: Excess ground attenuation, re: level over a rigid plane measured over several distances compared to theoretical prediction showing contribution by direct (D), reflected (R), ground (G) and surface (S) wave components [1].

5 - REFRACTION IN OUTDOOR SOUND PROPAGATION

For most weather conditions, both temperature and wind vary with height above the ground so that the effective velocity of sound also varies with height. This causes the sound waves to be refracted or bent as they propagate along curved paths such as illustrated in Fig. 5 for various types of sound speed profiles [3]. Ray paths for the idealized case of a linear vertical sound speed profile are arcs of circles with a radius, $R = c_o/(k\cos\theta)$ where c_o is the initial speed of sound on the ground, k is the vertical gradient, in (m/sec)/m, of the linear sound speed profile and θ is the angle of the ray with the horizontal when emitted from the source. In a temperature lapse or for propagation upwind, (Fig. 5 c) ray paths curve upward away from the ground causing an acoustical shadow region. If the sound speed profile is not linear, a caustic or sound-focusing region is formed (Fig. 5d).

Fig. 6 illustrates excess attenuation patterns in low frequency sound propagation for a variety of sound speed profiles measured around Saturn rocket engine test sites [5]. The strong influence of the different sound speed gradient categories is very evident.

Another example of excess attenuation in sound propagation for average (i.e. – lapse) outdoor weather conditions shows a trend typical for upwind (shadow zone) or lapse conditions propagation with an initial fall-off in level which reaches a plateau, in this case, of about 16 dB. This limiting attenuation in the shadow zone can be attributed to scattering by turbulence and is fairly well predicted by theory (See Fig. 17 in Ref. [1]). Sound prediction models, used for evaluating refraction in sound propagation include the FFP, (Fast Field Program) and PE (Parabolic Equation) programs (used for the prediction just cited – See Ref. [3] for a review).

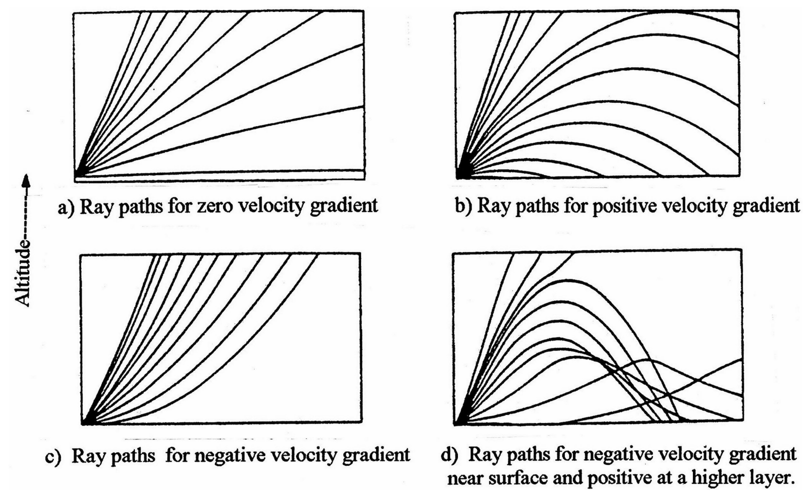


Figure 5: Sound ray patterns for various sound velocity profiles.

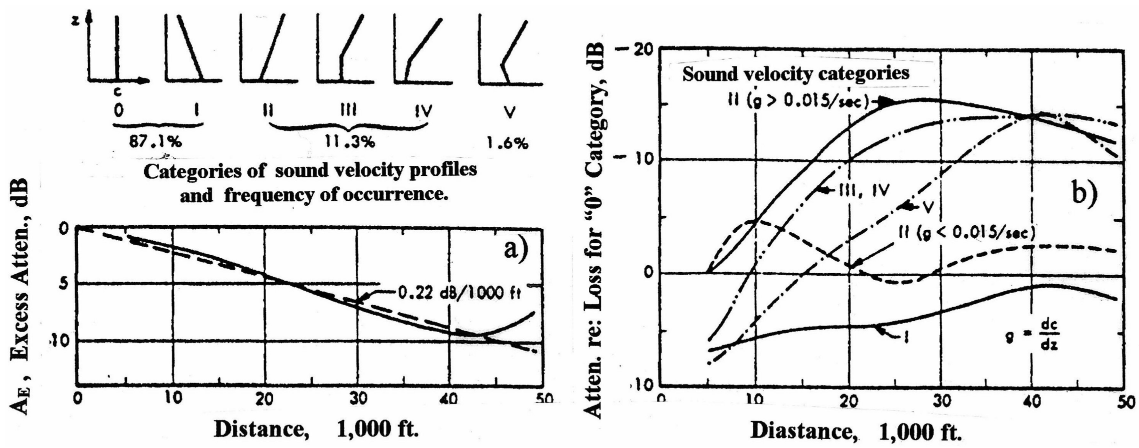


Figure 6: Measured low frequency excess attenuation for sound propagation from static rocket tests for: a) zero-gradient and b) attenuation relative to zero-gradient conditions [5].

6 - DIFFRACTION IN OUTDOORS SOUND PROPAGATION

The most significant manifestation of diffraction in outdoors sound propagation is that caused by atmospheric turbulence. In addition to the example shown in Fig. 7, other aspects, reviewed in Ref. [3] include definition of signal fluctuation during propagation through turbulence and extraction of atmospheric parameters from sonic probing of the atmosphere (i.e. – sodar). The other major diffraction effect in outdoors sound propagation is the attenuation of barriers. The barrier attenuation due to diffraction is governed by the Fresnel number proportional to the ratio of the path length difference with and without the barrier to the sound wave length [3].

7 - SUMMARY

A wide range of prediction methods are available for the evaluation of attenuation of sound during propagation outdoors. They range from uncomplicated models for spreading loss to sophisticated but well verified models for atmospheric absorption, propagation over ground, through turbulence and over barriers. Less well defined models, some empirical, are used to predict propagation through foliage, through built-up areas and for statistical models of the atmosphere for prediction of statistical patterns in outdoor noise environments. Much more needs to be done in this area to provide practical models for assessment of outdoors sound propagation from a statistical viewpoint.

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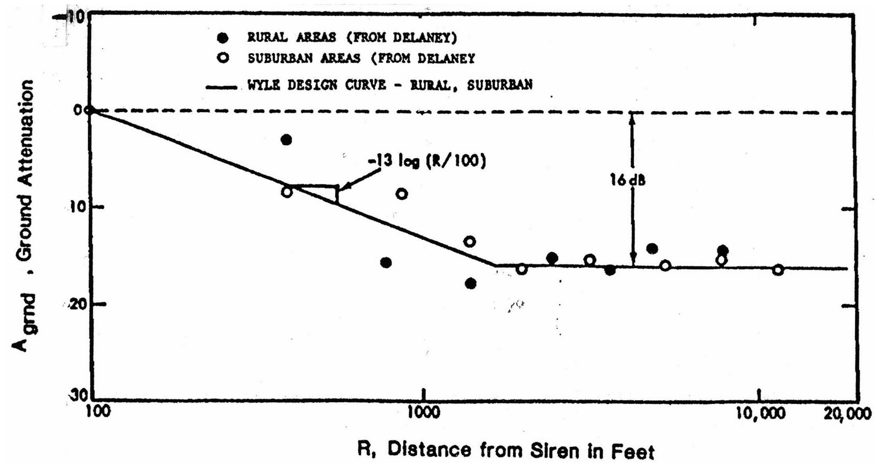

Figure 7: Excess attenuation for sirens in rural and suburban areas showing the combined effect of ground attenuation, refraction and limiting of shadow-zone attenuation by turbulence scattering (Data from Ref. 58 in Ref. [2]).

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