Most people have experienced nonstandard sound propagation conditions. You may have noticed sounds from a very distant source that are not usually audible. Or you may have been camping on a lake and heard voices on the other side of the lake that seemed much closer than they actually were. The propagation of sound in the atmosphere depends on many variables. The basic relationships are included in common acoustical modeling systems. Sophisticated sound level models include secondary variables, such as absorption by the ground material, partial screening by nonsolid obstructions, and reflections from large surfaces in the area. Yet almost all modeling methods assume a homogeneous atmosphere, where sound is propagated uniformly in all directions. This is never the case!

Certain atmospheric conditions produce dramatic deviations from typical propagation assumptions causing wide variations in the sound received by distant sources. They include a wind gradient, which has the potential of causing higher than expected sound levels in downwind directions and lower sound levels in upwind directions; a thermal gradient, which has the potential to channel sound; and atmospheric turbulence, which can alter the wave propagation differently under different conditions. This article focuses on the thermal structure of the atmosphere and its implications to sound propagation. It introduces some fundamental relationships between sound propagation and the atmospheric structure and the tools that have allowed some studies to correctly account for these atmospheric effects.

Sound waves travel through the atmosphere from the source to the receiver as omni-directional waves of sound. Since the area of the sphere increases exponentially as the distance increases from the source, the sound level at any point on the sphere would also decrease as the sphere gets bigger. The sound level in decibels (dB) will decrease with distance from the source by the following relationship: 

\[-20 \log_{10} x \text{ (ratio of distance)}\]

The decrease in sound level by spherical divergence produces the familiar rule of thumb, that the sound level decreases 6 dB with each doubling of distance from the source. The simplicity of this model is based on several sweeping assumptions about the source, transmission paths, and atmospheric conditions.

**ATMOSPHERIC THERMAL STRUCTURE**

The “standard” atmosphere is defined by national and international convention as an average condition of the atmospheric vertical profile. The familiar illustration of the standard atmosphere in Figure 1 shows its several distinct layers.
layers. The only layer relevant to our discussion of sound propagation is the troposphere, which is the layer closest to the earth. The troposphere is defined to have a specific mean sea level temperature (20 °C), specific moisture content, and is stationary (i.e., no wind). The temperature also decreases with altitude by a standard lapse rate of -6.4 °C per 1000 m altitude (-3.5 °F/1000 feet). The standard atmosphere is a scientific construct to represent average conditions in the mid-latitude atmosphere. The actual atmosphere, at a given time and location, always varies from the standard atmosphere. The character of the vertical atmospheric profile is always changing due to air mass movement, diurnal changes, and seasonal variations.

The nonstandard temperature profile, moisture profile, horizontal, and vertical motion in and between air masses provides the variations that affect the propagation of sound through the atmosphere. A layer of the atmosphere where the temperature increases with altitude (i.e., lapse rate becomes positive) is termed an inversion. It occurs often and from several causes, including radiation cooling on a cloudless night, strong subsidence, and frontal transitions. Thermal inversions are commonly known for their trapping of air pollutants in the layer below the inversion. While the reasons are quite different, an inversion also traps acoustical energy in the atmosphere below it.

Since the relationships are understood, then why don’t the numerical models include the atmospheric considerations in the calculation of sound propagation? The atmospheric vertical profile is usually measured using radiosondes at designated reporting stations. The observed data are only valid for one location and one test period. The collective soundings from the widely separated stations are used to produce a regional snapshot of the vertical structure of the atmosphere for use in meteorological models. They document the general profile of the entire column of the troposphere. Therefore, small-scale or fleeting conditions are not documented in the process. In contrast, the data needed for sound propagation analysis are detailed real-time vertical structure in only the lower atmosphere.

**SOUND PROPAGATION**

The speed of sound waves is a function of density (i.e., how close the molecules are to one another), temperature (i.e., molecular motion), and composition (i.e., types of molecules) of the atmosphere. Atmospheric variations that affect horizontal or vertical density alter the speed of sound along individual paths. When the speed of sound along one path is different from that of a nearby path, it has the effect of bending the propagation path, or refraction. While this illustrates why more sound is received at distant locations under this condition, it does nothing to quantify the increase. A more refined view of the refraction propagation path is needed to quantify the inversion’s effect on the surface sound level.

Figure 2 shows the sound wave vectors interacting with the thermal inversion layer. The schematic shows that the inversion layer affects various wave vectors differently. The vectors that are normal to the inversion layer are not affected by it. As the impingement angle decreases, the wave vectors are bent to a greater degree. The increase in bending occurs because the path through the inversion layer is longer and also because the effective temperature gradient is greater. At some angle, the curve will actually return the wave toward the ground. Below the angle of capture, the sound emitted by the source is trapped below the inversion layer. Propagation of the sound from that source to more distant locations becomes quite different beyond the point of capture. The propagation no longer follows the pattern of spherical divergence. At locations beyond this point, the inversion layer acts as a reflective surface and the sound effectively propagates as a cylinder. Cylindrical propagation results in much less loss-with-distance than spherical propagation.

The equations that describe the surface areas are:

\[
\text{Area of Sphere} = 4\pi r^2 \quad \text{Lateral Area of Cylinder} = 2\pi rh
\]

Where

- \( r \) = radius (or distance from sound source)
- \( h \) = height of the cylinder (distance from ground to inversion layer).

Remember that the sound energy is distributed over the entire wave surface. The area of a sphere increases exponentially with an increase in radius (i.e., distance from source). The surface of a cylinder, conversely, increases in a linear fashion since the wave front increases in horizontal dimensions, but not in the vertical. When the inversion successfully traps the sound waves between it and the ground, the cylindrical propagation causes a dramatic increase in the
observed sound level at the distant receptors. Stated another way; cylindrical propagation can make the sound from a distant source much louder (or seem much closer).

Can the effect be quantified? The answer is yes, but some important information about the source and atmosphere must be known. It requires the typical information about the source, such as sound power, relative elevation, and relevant distances that are needed to characterize the source and standard propagation. It also requires an understanding of the current vertical profile of the atmosphere, the elevation and density gradient of the refracting layer, and the lateral distance from the source to the point of capture. As illustrated in Figure 2, the source will radiate in a hemispherical pattern out to the point of capture. The sound level in this region can be estimated using classical models. At greater distances, the sound energy that is trapped under the inversion will be propagated in a cylindrical pattern out to the receptor. The divergence can be estimated using the equation for the relative areas of two cylinders, one at the point of capture and one at the receiving location. The analysis of a fleeting event such as a nighttime radiation inversion would require a moment-to-moment characterization of the three-dimensional atmospheric profile. Herein lies the challenge, since such refined data are not generally available.

The technology for monitoring the vertical structure of the atmosphere is available, but remains relatively expensive. For example, temperature profiles in the atmosphere up to approximately 1 km can now be measured remotely using very sensitive microwave receivers. In 2007, a meteorological temperature profiler was available from Kipp & Zonen for around US$105,000. This is beyond the scope of most commercial or industrial environmental studies. Sonic Doppler systems (SODAR) do not directly measure the temperature, but can characterize the active gradients by measuring the wind field up to an altitude of approximately 600 m. Active laser Doppler (LIDAR) systems can also monitor the wind field up to several kilometers in altitude.

The relationship between inversion strength, layer depth, and sound propagation still require further clarification. In 2006, Waxler analyzed variations in the sound received in the very narrow bands below 20 m. The greatest obstacle in quantifying this propagation pattern is the transient nature of the atmosphere’s thermal structure. Thermal inversions formed by radiation cooling can break down with the passage of a single large cloud. Frontal inversions may pass through an area within hours, forming in minutes, changing elevation with time, and breaking down in minutes. Even light winds can quickly break down a mild inversion layer. For this reason, the characterization of the propagation relationship would require on-site continuous vertical profile measurements. As noted above, the equipment needed for such a study is now on the market. Such specialty equipment generally decreases in cost based on time-on-market and competition. Waddington employed real-time vertical profile data and a modulated carrier wave in a European study to evaluate sound levels over a large domain.

In the absence of available real-time or statistical data to evaluate the vertical structure of the atmosphere, it is not practical to expand modeling tools to include algorithms to predict the specific affect of the atmosphere and the resulting sound propagation variations. Some modeling tools include adjustment factors to account for features such as downwind conditions or atmospheric stability. For example, CONCAWE offers a methodology based on Pasquill stability categories. ISO 9613-2 also includes a tool to estimate the quantitative adjustment to be used in modeling meteorological factors. Importantly, the Pasquill stability class in widespread use in the acoustics literature is based on the full column of the troposphere rather than the limited area in the lowest layer that is relevant to sound propagation. Neither do the adjustment factors account for the large variations that are reflected in empirical studies. The adjustments for meteorology from CONCAWE methods ranges from +5 to -5 dB. In contrast, field studies have quantified short-term deviations of 20 dB or more, depending on the distance. This shortfall highlights the need for a better understanding with respect to the atmospheric effects on sound propagation over longer distances.

**CONCLUSION**

The vertical profile of the atmosphere can produce conditions in which sound is propagated very differently than in the classical prediction models. Distant sources can produce higher than normal levels in the presence of a strong thermal inversion. The general principles of propagation are reasonably well understood, but the modeling would require atmospheric profile information that is not widely available. For this reason distant sound levels under nonstandard atmospheric conditions cannot currently be predicted for even a single source. The varying location and fleeting nature of these nonstandard atmospheric conditions further complicates efforts to predict the resulting levels at distant receivers. While not widely available, equipment is currently on the market that would provide real time point-of-analysis vertical profile information for such studies. Because this equipment can be expected to be more available for future analyses, there is a current need for a clearer understanding of the quantitative relationships of sound propagation under nonstandard atmospheric conditions.

**REFERENCES**


