Sound Propagation in the Atmospheric Boundary Layer

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Advances in computational methods have helped to reveal the complex impacts of the atmosphere on sound propagation, and provide new approaches for quantifying these impacts.

Introduction

Sound propagation in the atmosphere impacts noise emissions from factories and highways, detection and location of sound sources, and even remote sensing of atmospheric turbulence. Scientific study of the subject can be traced back to the 1700s (Embleton, 1996; Ostashev, 1997; Beyer, 1999). A number of excellent review articles (e.g., Piercy et al., 1977; Embleton, 1996; Attenborough, 2002) describe the present state of understanding. Most of these reviews are structured as follows. Geometrical spreading of sound waves from a point source is first introduced, which causes the sound intensity to diminish as $1/R^2$, where R is the distance from the source (that is, a 6-dB loss per doubling of distance). The exponential attenuation of sound amplitude, resulting from heat conduction, viscosity, and molecular relaxation processes in air, is then described. Next, reflections from the ground are discussed, which may be conveniently conceptualized as emanating from an image source, the magnitude and phase of which is determined by the ground surface impedance. Refraction by vertical gradients of wind and temperature in the atmosphere are typically discussed thereafter.

Last, complications such as those produced as a result of the scattering of sound by atmospheric turbulence as well as from interactions with natural and man-made terrain features such as hills, vegetation, walls, and buildings may be introduced. Recent reviews also discuss the advances in numerical methods for outdoor sound propagation. Like many fields, progress during the past several decades has been coupled to advances in computational capabilities and numerical methods. In particular, the late 1980s saw the introduction of numerical techniques that do not depend on the high-frequency approximations inherent to ray tracing, namely the fast-field program (FFP) and the parabolic equation (PE). Recently, finite-difference time-domain (FDTD) methods, capable of handling complications such as multiple reflections from trees and buildings, have also been introduced.

The preceding ordering of topics is natural in the sense of introducing the subject as a sequence of increasingly complex phenomena. It also happens to correspond, loosely, to the historical progress of research in outdoor sound propagation. But, intentionally or not, the ordering of topics may convey the sense that sound propagation outdoors is primarily a deterministic phenomenon (i.e., geometrical spreading, ground interactions, refraction by mean gradients of wind and temperature) while deemphasizing propagation phenomena that are fundamentally random or predictable only with substantial uncertainty (i.e., interactions with turbulence and complex terrain features). This article attempts to reverse that perspective. Hopefully, by the end, the reader will have gained an appreciation for

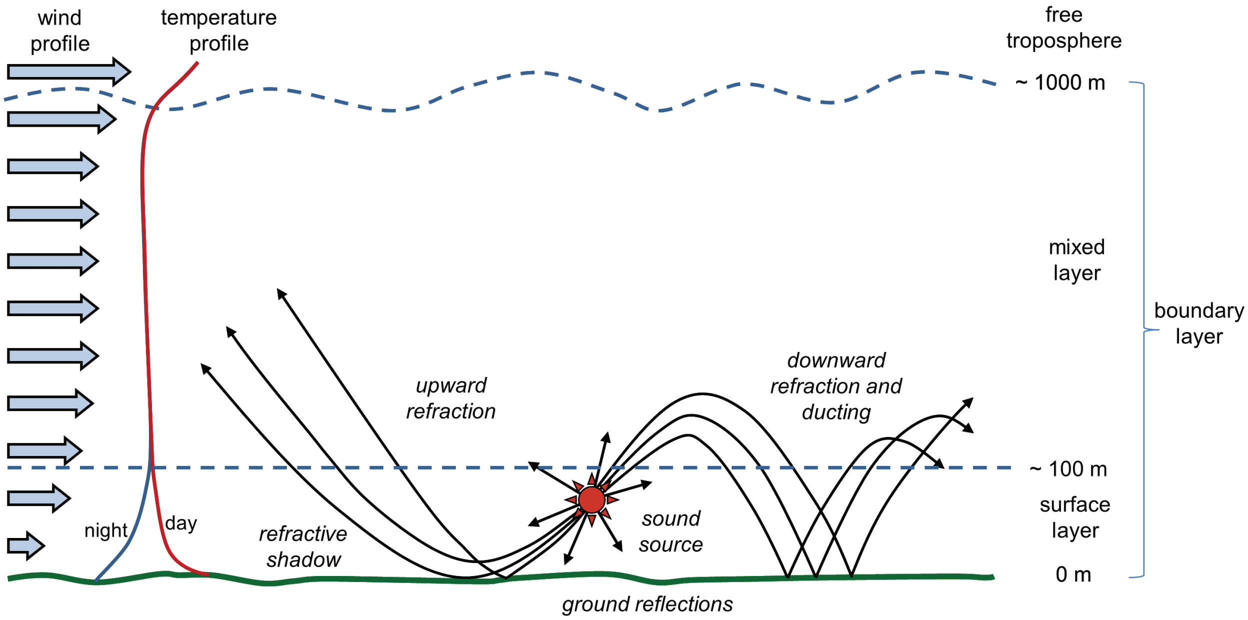

Figure 1. *Schematic of the atmospheric boundary layer (ABL) showing the atmospheric surface layer (ASL; between the straight dashed line and the ground), mixed layer, capping inversion (curvy dashed line), and free troposphere. Near-ground sound propagation for a high-wind condition, with the wind blowing from left to right, is depicted.*

the complexity and predictive challenges inherent to sound propagation in the atmosphere.

The variability of sound propagation in the atmosphere has actually long been recognized. King (1919; see also the account by Beyer [1999]) refers to the "…capricious behavior of sound-waves propagated in the open atmosphere [which] has been attributed to the existence of innumerable discontinuities of temperature, density and humidity, and to refraction by gradients of wind-velocity." Recordings by Ingard (1953) showed random variations in sound levels of 10-20 dB, which he attributed to the gustiness of the wind. Recent advances in the simulation of atmospheric turbulence and sound propagation enable dramatic visualizations of the variability identified by Ingard. [To view visual recordings visit: http://wp.me/p4zu0b-Qq]. Modern long-term experimental studies further demonstrate the challenge of predicting sound levels from atmospheric observations that are typically available in practice (e.g., Konishi and Maekawa, 2001; Valente et al., 2012).

The next section provides an introduction to atmospheric stratification and how it relates to the refraction of sound. Then we illustrate, using data from a nighttime experiment conducted on the US Great Plains, the challenge of accurately predicting sound propagation. Subsequent sections discuss representation and sampling of the atmosphere for sound propagation predictions.

Stratification and Refraction in the Near-Ground Atmosphere

Environmental phenomena occurring over a broad span of temporal and spatial scales influence sound waves propagating outdoors. Turbulent eddies and gravity waves in the lower atmosphere, which scatter sound, range in size from centimeters to kilometers. Weather phenomena on much larger scales also impact the propagation. The emphasis of this article is on propagation in the atmospheric boundary layer (ABL), more specifically the lowermost 10% of the ABL, which is called the atmospheric surface layer (ASL), as depicted in **Figure 1**. The ABL, which responds directly to surface processes on a diurnal timescale, is generally between 0.5 and 3 km deep depending on latitude and weather conditions.

When variations in terrain elevation and ground properties are weak, mean gradients of the atmospheric fields are usually much stronger in the vertical than in the horizontal direction. The atmosphere may then be described as horizontally stratified. Refraction of sound in such conditions can be most readily understood using the concept of an effective sound speed, which is defined as $c_{\mathrm{eff}} = c+u \cos \theta$, where c is the actual sound speed, u is the wind speed, and θ is the angle between the azimuthal direction of propagation and the wind vector. The sound speed itself is proportional to the square root of the absolute temperature; there is also a weak dependence on humidity (Ostashev, 1997).

A positive vertical gradient in c_{eff} leads to downward refraction of sound, whereas a negative vertical gradient leads to upward refraction. Temperature gradients and wind shear both contribute to gradients in c_{eff}. Depending on the atmospheric state and propagation direction, they may combine to strengthen or diminish overall refraction. Negative gradients may be caused by a temperature lapse condition, meaning that the temperature, and hence the sound speed, decreases with height. It may also be caused by a negative wind shear, meaning that the wind speed decreases with height as usually occurs for propagation in the upwind direction. A positive vertical gradient may be caused either by a ground-based temperature inversion, meaning that the temperature decreases with height, or by a positive wind shear, which usually occurs in the downwind direction.

Temperature stratification is related to the static stability of the atmosphere. When the temperature gradient equals –0.0098°C/m in air that is unsaturated by water vapor, the air column is said to be neutrally stratified. This value is referred to as the dry adiabatic lapse rate. If the temperature gradient is less (more negative) than the adiabatic lapse rate, the air column is buoyantly unstable in the sense that an air parcel, when displaced adiabatically from its original position, will tend to accelerate in the direction of displacement. When the temperature gradient is greater than the adiabatic lapse rate, the air column is buoyantly stable in that a displaced parcel will tend to oscillate about its original position.

If the wind speed is very high, stratification in the ASL is generally close to neutral due to the strong turbulent mixing induced by the wind shear. At lower wind speeds, stratification of the ASL will depend on radiative transfer between the ground and atmosphere. On a clear day, as the ground is heated by the sun, heat is conducted to the overlying air and unstable stratification develops. Conversely, on a clear night, cooling of the ground leads to stable stratification. A thick stratus cloud layer encourages near-neutral stratification. Hence we have the following four fundamental sound propagation "regimens" (and transitions in-between):

1. High wind (day or night): Temperature stratification is near neutral. Refraction depends primarily on wind shear and hence on the propagation direction.
2. Low wind, clear, daytime: Stratification is unstable and upward refraction prevails. Buoyancy instabilities create strong turbulence.
3. Low wind, cloudy (day or night): Weak refraction, generally upward, prevails in all directions. Turbulence tends to be weak.

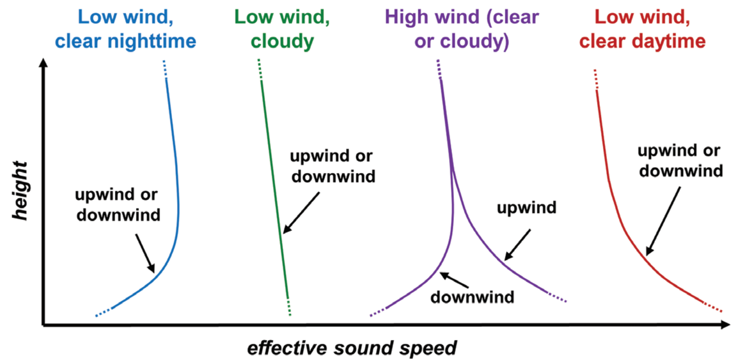

Figure 2. *Characteristic effective sound speed profiles for 4 limiting cases of the ASL. The profiles are arbitrarily offset along the horizontal axis so as to improve visibility.*

4. Low wind, clear, nighttime: Ground-based temperature inversions often form, which lead to the prevalence of strong downward refraction. Turbulence is suppressed by the stable stratification but may occur intermittently.

Characteristic effective sound speed profiles for these four cases are illustrated in **Figure 2.**

The Monin-Obukhov similarity theory (MOST) has been widely adopted in the atmospheric sciences (e.g., Wyngaard, 2010) for modeling mean profiles and turbulence statistics in the ASL and increasingly for sound propagation studies (e.g., Wilson, 2003). The basic scaling parameters of MOST are the friction velocity (u_*; which relates to the wind shear), the sensible heat flux from the surface to the overlying air (Q_H), the height from the surface (z), and the Boussinesq buoyancy parameter ($\beta = g/T_s$; where g is the gravitational acceleration and T_s is the temperature at the surface). MOST involves normalizing dimensional quantities by these scales. However, MOST cannot be used when turbulent mixing is suppressed, as happens in strong inversion conditions. MOST should also not be applied above the ASL where the wind direction rotates with height due to Coriolis forces.

Figure 3 shows Crank-Nicholson parabolic equation (CNPE; West et al., 1992) calculations of transmission loss (TL; which is defined as the difference, in dB, between the calculated sound pressure field and the field that would be produced by the same source at a distance of 1 m in free space) for wind and temperature profiles approximating the four conditions described above, namely $u_* = 0.6$ m/s and $Q_H = 0$ W/m^2 (high-wind, neutral conditions), $u_* = 0.1$ m/s and $Q_H = 200$ W/m^2 (low-wind, clear daytime conditions), $u_* = 0.0$ m/s and $Q_H = 0$ W/m^2 (low-wind, cloudy conditions), and $u_* = 0.08$ m/s and $Q_H = 0$ -10 W/m^2 (low-wind, clear nighttime conditions). In all cases, the source height is 5 m and its frequency is 250 Hz and the ground impedance (normalized by the characteristic impedance of air) is set to 8.77 + 8.39i,

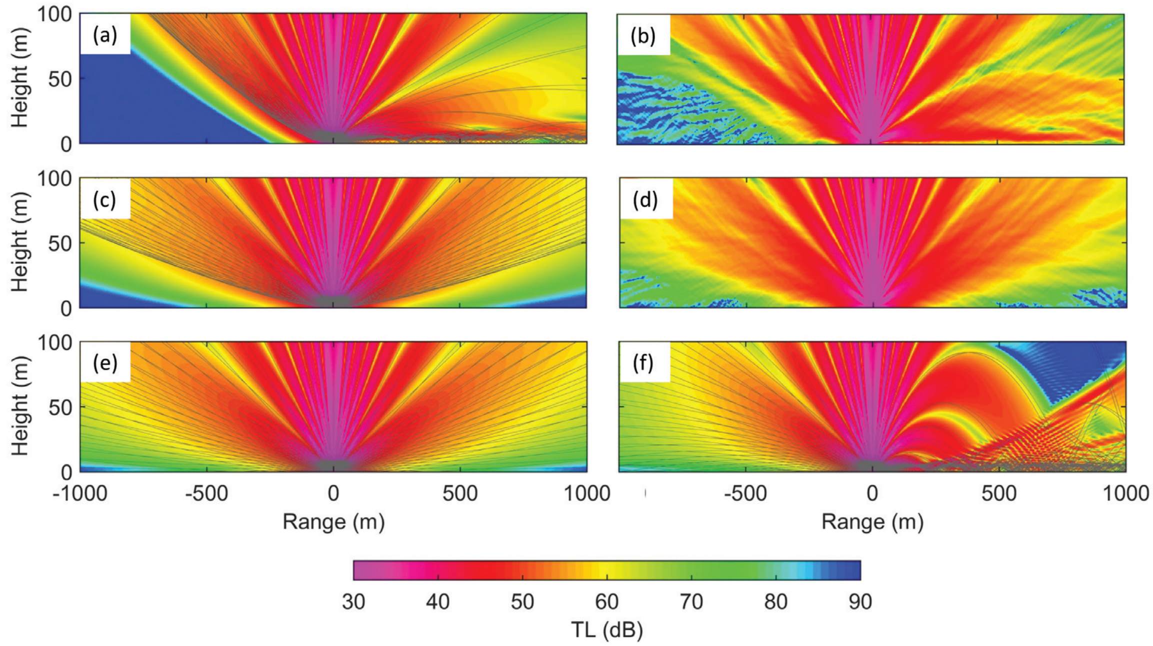

Figure 3. *Sound-field calculations for profiles approximating the 4 conditions shown in Figure 2. The source is at zero range, with upwind propagation negative (to the left) and downwind positive (to the right). (a) and (b) High-wind, neutral conditions. (c) and (d) Low-wind, clear daytime conditions. (e) Zero-wind, cloudy conditions. (f) Low-wind, clear nighttime conditions. Calculations (a), (c), (e), and (f) are without turbulence and ray traces are overlaid. Calculations (b) and (d) incorporate random scattering by turbulence. TL is the transmission loss.*

which is characteristic of a loose, grass-covered soil. For the high-wind case and the low-wind, clear daytime case, calculations are shown with and without turbulent scattering. The turbulence was synthesized by a kinematic method based on the von Kármán turbulence spectrum, as described later. For these two cases, turbulent scattering greatly increases sound levels in the refractive shadow zones. Turbulent scattering is weak for the low-wind, clear nighttime case and thus is not shown. (However, gravity waves may form in such conditions and significantly scatter sound; modeling of this phenomenon remains a challenge.) No turbulence is present for the low-wind, cloudy case because it was modeled as exactly neutral.

Sound Propagation at Night on the Great Plains

A pair of meteorological experiments conducted at sites on the US Great Plains in southwestern Kansas in 1968 and northwestern Minnesota in 1973 provided the foundation for modern similarity theories describing the structure and spatial statistics of turbulence in the ASL and ABL. In the ensuing decades, however, it became evident that a significant gap in understanding the lower atmosphere remained, namely, for clear nighttime conditions. Because stable stratification suppresses turbulence, conventional turbulence similarity theories such as MOST no longer apply. Hence a large new experiment was undertaken in southeastern Kansas in 1999 called the Cooperative Atmosphere–Surface Exchange Study or CASES-99 (Poulos et al., 2002). To leverage the extensive atmospheric observations available, a concurrent sound propagation experiment was also undertaken (Wilson et al., 2003). A series of five 6-m towers were placed along a linear path at ranges between 361 and 1,180 m from the source.

Offhand, one might expect the sound propagation conditions studied during CASES-99 to provide a best case scenario for accurately predicting sound propagation. The atmosphere was relatively stable and weakly turbulent. The ground was nearly flat and homogenous. Simultaneous, high-resolution wind and temperature data, collected at 5-m intervals on a nearby 60-m tower, were available. **Figure 4** illustrates the reality by comparing sound propagation measurements and predictions (based on 1-min average data from the 60-m tower) at 150 Hz during a 2-h interval up to and including sunrise. In both the measurements and predictions, deep fading episodes exceeding 20 dB are present. Despite the stable atmospheric stratification, sound levels can change by this amount in a matter of minutes. Although there are qualitative similarities between the data and the predictions, the timing and amplitude of the signal variations at the various microphone distances are not accurately predicted in a deterministic sense.

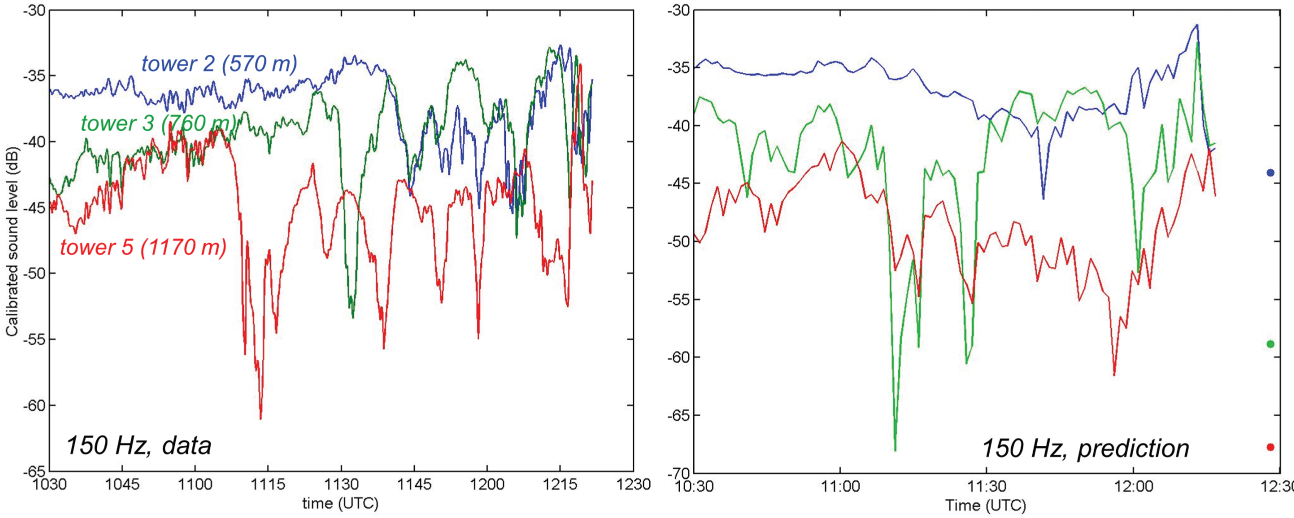

Figure 4. Sound propagation measurements (left) and predictions (right) at 150 Hz during CASES-99 intensive observation period 7 (October 18, 1999). Shown are 3 different ranges from the source: 570 m (blue), 760 m (green), and 1,170 m (red). Universal Coordinated Time (UTC) at the site precedes local standard time by 5 h. Reprinted from Wilson et al. (2003).

Representation of the Atmosphere

As illustrated by CASES-99, the atmosphere possesses a complex spatial and temporal structure that impacts sound waves strongly. Realistic high-resolution representation of the ABL is a particularly important and challenging aspect of simulating wave propagation in the atmosphere. One approach is to employ computational fluid dynamics (CFD) simulations of the atmosphere and turbulence as input to the sound propagation calculations. Among the various classes of CFD, large-eddy simulation (LES) generally best captures the dynamics of turbulence in the ABL (Galperin and Orszag, 1993). The main drawbacks of LES are its computational intensiveness (which may, in practice, far exceed the sound propagation calculation) and its resolution (which is typically no better than a few meters and thus most suitable for sound propagation at low frequencies). Besides LES, mesoscale numerical weather prediction (NWP) models can be employed (Lihoreau et al., 2006). Ordinary mesoscale models do not simulate turbulence and generally have a much lower resolution than LES. However, they are particularly useful for simulating flows in terrain with varying elevation and land surface properties.

Turbulence can also be synthesized with kinematic approaches, meaning that the fields are synthesized from prescribed spatial statistics, rather than by attempting to solve fluid-dynamic equations. Relative to CFD, the main advantages of the kinematic approaches are their efficiency, high resolution, and simplicity. Kinematic approaches have been commonly used in acoustical modeling since the 1990s (e.g., Gilbert et al., 1990). The lack of realistic dynamics may not be important for calculating second-order statistics of the scattered sound field, such as the mean square sound pressure. Most kinematic approaches involve spectral synthesis from a superposition of spatial Fourier modes (harmonic functions). The amplitudes of the modes are made proportional to the square root of the spectral density at that wave number, whereas the phases of the modes are independently randomized. Application of an inverse transform (from the wave number to the spatial domain) then yields a random field consistent with the desired spectrum. An alternative to the spectrally based methods, but nonetheless a kinematic method, involves representing the turbulence field as a collection of randomly positioned, eddylike structures (Goedecke et al., 2004).

The kinematic spectral methods as well as theories for wave propagation through turbulence require a model spatial spectrum for the turbulence. Although Gaussian spectral models have often been used in outdoor sound propagation, the Kolmogorov or von Kármán spectrum are more realistic (e.g., Ostashev, 1997). MOST and other turbulence similarity theories can be useful for predicting parameters in the turbulence spectra from available atmospheric measurements. The CNPE calculations shown in **Figure 3,b** and **d**, incorporated turbulent scattering based on single realizations of a von Kármán spectrum with height-dependent parameters, as detailed by Wilson et al. (2008).

Sampling of the Atmosphere

Rarely, if ever, are measurements of the atmosphere and terrain available with the subwavelength resolution necessary to accurately predict the sound field in a deterministic sense (e.g., Wilson et al., 2008; Gauvreau, 2013), thus hindering validation of computational models. This motivates a number of important practical questions regarding the use of meteorological data in outdoor sound propagation predictions. What types of meteorological data are most suitable, i.e., data from a vertical tower, weather balloons, weather radar or LIDAR, or a numerical weather prediction (NWP) model? How should the data be averaged and otherwise processed before usage in acoustic models?

Suppose, for example, we wish to predict the sound exposure level associated with a short-duration event such as an explosion. It may seem reasonable to use a single instantaneous set of vertical profiles recorded at the same time as the event. However, such profiles include the random turbulence present at the time of the observation. In effect, one is assuming that the turbulence extends infinitely in a horizontal plane, as illustrated in **Figure 5**. This has been aptly called a "plywood" model (Wyngaard et al., 2001).

For simplicity, we distinguish here between event and mean prediction. An event is short compared with the timescale over which the propagation effects decorrelate due to atmospheric variations. Examples are sound from an explosion and sound produced by a steady source but observed over an interval of several seconds or less. Mean predictions, in practice, refer to an average over a time interval long enough to remove the variability associated with individual events. In the atmospheric sciences, it is recognized that time intervals of roughly 30 min or longer are needed for good estimates of means and even longer averages for second-order statistics such as variances and spectra (Lenschow et al., 1994). Regarding sound propagation, spatial averaging along the propagation path and the frequency diversity in broadband signals may possibly mitigate the need for such long averaging times.

Wilson et al. (2007, 2008) examined the predictability of event and mean sound levels using high-resolution (1- to 4-m) LES as a surrogate atmosphere. After numerically propagating sound through the turbulence simulations, the results were statistically compared with predictions based on lower resolution but more typically available atmospheric characterizations such as mean vertical profiles and instantaneous vertical profiles at a location near the propagation path. The main conclusions were:

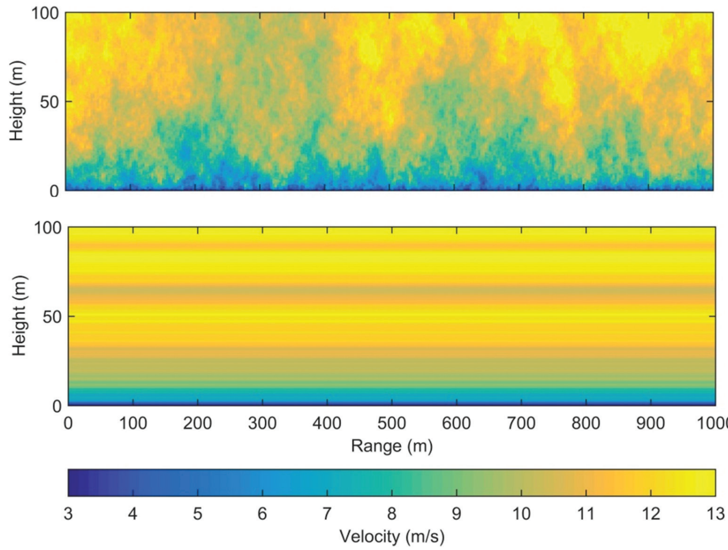

Figure 5. *(Top) Example of a realization of a turbulent velocity field (fluctuations plus mean vertical profile) in a vertical plane. (Bottom) Plywood model based on extending the fluctuations at a single range to the entire domain.*

1. Mean vertical profiles produce the most accurate predictions of both mean and event sound levels.
2. Predictions of mean sound levels from mean vertical profiles have relatively low root-mean-square (rms) errors, typically less than 2 dB, except in shadow zones and interference minima, where scattering by turbulence is important.
3. Predictions of mean sound levels based on averaging individual propagation calculations from many instantaneous vertical profile samples results in overprediction of sound levels in upward refraction due to the plywood atmosphere effect.
4. Event propagation is highly random and predictions have rms errors of 8-10 dB, even when they are based on local vertical profile data synchronized to the time of the propagation event.

Incorporating and Quantifying Uncertainty

In complex high-fidelity simulations, such as those for outdoor sound propagation, imperfect knowledge leads to errors at many stages of the modeling process. The error budget cannot be uniquely specified or computed exactly because the sources of error are not always known or quantifiable. However, an agreed-upon framework for the error budget can provide a useful starting point for describing uncertainties in a thorough self-consistent manner. Ghanem (2005) suggested the following hierarchical decomposition of modeling errors:

1. Errors reducible through better physics models.
2. Errors reducible through better data, e.g., more accurate and precise measurements.

3. Errors reducible through better statistics and probability models.
4. Errors reducible through better numerical methods and grids.

Regarding the physics models (item 1), the basic physics underlying sound propagation outdoors are now well understood. Regarding data (item 2), as discussed in the previous section, it remains challenging if not impossible to characterize the environment at a sufficiently high spatial and temporal resolution so as to accurately predict outdoor sound propagation in a deterministic sense. The statistics and probability models (item 3) relate to our previous discussion of the spatial spectrum and simulation of atmospheric turbulence. However, these models, even though quite complicated mathematically, still neglect commonplace features such as ground property variations, sloping of the terrain, interactions of the flow with objects such as trees and buildings, gravity waves, and intermittency of turbulence.

Numerical methods and grids (item 4) were not discussed much in this article beyond the **Introduction**. Much progress has been made in numerical methods for sound propagation in recent decades, and this will likely continue to be an active and productive area of research. A key to utilizing numerical methods effectively will be to employ them in an overall predictive framework that addresses uncertainties in data and statistics for the environment (items 2 and 3). This is where stochastic methods such as Monte Carlo integration come into play. Conventional methods for propagating errors and uncertainties, based on linear expansions and small perturbations, usually do not apply because the relationship between the parameters and the predictions is complex and highly nonlinear. Monte Carlo methods are now frequently employed in other related fields such as numerical weather forecasting, where ensemble forecasting is regularly used to assess the uncertainties in the forecasts.

Considering the prediction problem broadly, the received sound level will depend on a set of stochastic variables, which can include many different inexactly known parameters such as the source and receiver heights, the horizontal separation (range), the source level, wind speed and direction, thermal stratification, ground impedance, vegetation, topography, building positions, and material properties. The gist of the Monte Carlo approach is to specify (based on either empirical data or theoretical considerations) probability distributions for these parameters, randomly sample from the distributions, and perform a propagation calculation for each random sample. Quantities of interest, such as the mean square sound pressure and its variance, can then be estimated. The more direct approach of numerically integrating over the distribution for each of the parameters would require discretizing integrals into a finite number of intervals along each of the variable axes. Unfortunately, the number of evaluations of the integrand would then increase exponentially with the number of parameters and thus quickly become computationally impractical. Suppose, for example, there are 8 parameters to be sampled, and the integration for each is partitioned into 64 discrete intervals. That would amount to $64^8 = 2.8 \times 10^{14}$ evaluations of the integrand (e.g., solutions of a parabolic equation). If each evaluation takes 1 s, almost 9 million years would be needed to finish! A further disadvantage of this approach is that if only a few of the parameters dominate the end result, most of the evaluations of the integrand become unnecessary.

Rarely, if ever, are measurements of the atmosphere and terrain available with the sub-wavelength resolution necessary to accurately predict the sound field, in a deterministic sense.

Monte Carlo methods are particularly valuable in such situations (Evans and Swartz, 2000). In ordinary Monte Carlo sampling (MCS), each random sample of the parameter space (from which the integrand is then evaluated) is drawn independently of the other samples. A disadvantage of ordinary MCS is that it tends to randomly undersample certain parts of the input parameter space while oversampling others. Stratified sampling is commonly employed to ensure that important regions of the parameter space are adequately sampled. The overall parameter space is partitioned into strata (subvolumes) and then each stratum is sampled independently. The strata should be mutually exclusive and exhaustive. The overall statistics are then determined by appropriately weighting statistics as calculated from the individual strata. In the context of outdoor sound propagation, atmospheric conditions have often been categorized into acoustical classes based on the wind speed, propagation direction relative to the wind, and atmospheric stability. Such schemes exemplify stratified sampling.

Latin hypercube sampling (LHS) is a general and widely used scheme for stratified sampling. In LHS, the domain for each variable is first partitioned into *N* equal-probability intervals, where N is the number of samples to be drawn. A grid consists of N^M cubes, where M is the number of random variables. One sample is then randomly drawn from each row and each column in the grid so that each interval of a variable is sampled once.

Variables that would not normally be considered stochastic, such as frequency, can be incorporated into the Monte Carlo integration. This approach provides a substantial computational benefit: one can simultaneously sample over frequency and the uncertain variables (Wilson et al., 2014). LHS can be particularly useful in assuring that some parts of the frequency spectrum do not go undersampled. For example, the strata can coincide with octave or one-third octave bands. Temporal integrations (over time of day or season) can be handled by the same approach.

Let us consider a numerical example illustrating the impacts of uncertainty. The model atmosphere is neutrally stratified, and refraction and scattering by turbulence are included in the calculations using a CNPE and kinematic turbulence realizations. The vertical profiles and turbulence spectrum are modeled with MOST. The source is harmonic, with a frequency of 100 Hz. To represent uncertainty in the environmental state, six model parameters are assumed to be randomly distributed: source height, ground porosity, ground static flow resistivity, ground roughness, friction velocity, and wind direction. Because the first five of these parameters are positive definite, they are modeled with log-normal distributions. The medians are 5 m, 0.27, $2\text{x}10^{-6}$ Pa s m^{-2}, 0.01 m, and 0.6 m s^{-1}, respectively; the log deviations are all set to 0.4. The wind direction is modeled with a normal distribution, with a mean of 0° and a standard deviation of 40°. Additional details regarding the calculations can be found in Wilson et al. (2014). Root-mean-square (rms) errors for prediction of the mean sound level are shown in **Figure 6**. Shown are upwind and downwind predictions in which the integrand is evaluated using MCS (with 16 random samples) and LHS (8, 16, and 32 random samples). The errors are about twice as large in the upwind as in the downwind direction; this is likely due to the variable position of the shadow-zone boundary. The errors scale approximately as $1/\sqrt{N}$, as is characteristic of independent normally distributed samples. LHS provides about a 25% reduction in the rms error relative to MCS, without any increase in calculation time. More advanced sampling strategies, such as importance and adaptive sampling, can also be beneficially applied to this problem (Wilson et al., 2014).

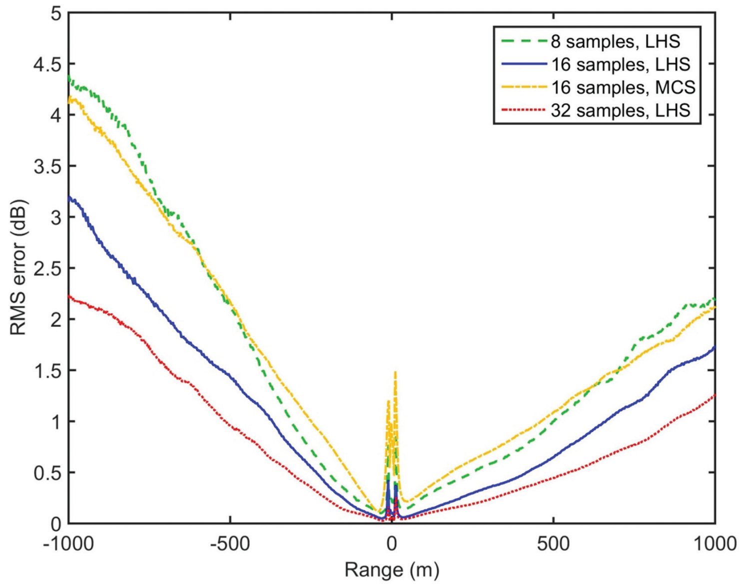

Figure 6. *Root-mean-square (RMS) errors for the prediction of the mean sound level at a single frequency (100 Hz) resulting from various parametric uncertainties. The number of random parameter samples and the sampling method (ordinary Monte Carlo sampling [MCS] or Latin hypercube sampling [LHS]) were varied.*

Conclusions

Sound waves propagating outdoors undergo many complex interactions with the atmosphere, the ground, and natural and man-made terrain features. As a result of steady improvement during the past several decades in theories and computational models, randomness and uncertainty in the propagation environment often determine the accuracy of predictions. However, advances in computing capabilities and MCS methods also provide new opportunities for quantifying the impacts of environmental uncertainties. These techniques can also be applied to propagation in other complex environments such as the ocean and architectural spaces.

Issues related to predictive uncertainty will likely increase in importance as computational capabilities and fidelity of models improve. By quantifying the model sensitivities, we can better understand the true accuracy of the predictions and determine whether increases in computational effort actually lead to better predictions. Effort should not be expended attempting to predict details of the propagation that are, in essence, unpredictable.

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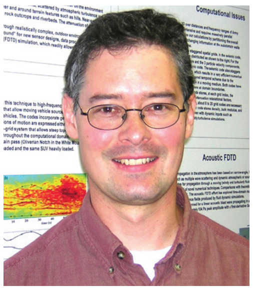
Biosketches



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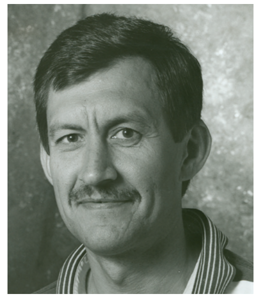

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