OUTDOOR PROPAGATION

REVIEW OF PHYSICAL MECHANISM AND COMPUTATIONAL MODELS

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INTRODUCTION

Propagation of noise in the atmosphere is governed by a number of interacting physical mechanisms including geometrical spreading, molecular absorption, reflection from a porous ground, curved ray paths due to refraction, diffraction by ground topography and scattering by turbulence. Accurate predictions of noise levels from a distant source must somehow account for all of these phenomena simultaneously. Although this goal is still beyond current capabilities, developments in computational tools for predicting sound propagation through the atmosphere have increased dramatically during recent years. The computational techniques now include analytical solutions for selected atmospheric profiles, ray tracing techniques which include interaction with the ground and meteorological conditions, and more sophisticated numerical solutions to the full wave equation; the fast field program (FFP) and the parabolic equation (PE). With modern computers, it is now becoming practical to incorporate some of these new computational tools into predictions schemes with advantages such as calculated noise contours based on observed meteorological patterns.

All noise prediction models include the attenuation due to geometrical spreading and, if required, molecular absorption. Where the empirical based models differ from computational models is in the incorporation of the other attenuation mechanisms. The empirical models tend to rely on general tendencies found in experimental databases. They often work well as long as the specific situation of interest falls within the bounds of the databases. Computational models on the other hand rely on our mathematical origin and in the way some of the physical mechanisms are incorporated. For example, some of the models incorporate the boundary condition Eq. (2) in some way. The purpose of this paper is to review the new computational models. The paper summarizes their limitations, their advantages, and shows a benchmark comparison of predictions. A complete and detailed description of each model, including comparison with experimental data, can be found in the cited references.

THEORETICAL BACKGROUND

The computational models assume simple harmonic time dependence $\exp(-i\omega t)$ and begin with the Helmholtz equation

$$[\nabla^2 + k^2]p(r,z) = -4\pi\delta(r, z - z_0)$$

(1)

where the wavenumber $k(z) = \omega/c(z)$, $r$ is the horizontal range and $z$ is the height above the ground. Reflection from a porous ground is described by the boundary condition

$$[\partial p/\partial z + ik\beta p]_0 = 0$$

(2)

at the ground surface where $\beta$ is the normalized complex surface admittance. In general, the speed of sound varies with height resulting in curved ray paths due to refraction as shown in Fig 1. During nighttime or downwind propagation, ray paths are curved downward leading to multiple rays and favourable propagation conditions. During daytime or upwind propagation, ray paths are curved upward leading to an acoustic shadow with increased attenuation. The atmosphere is also turbulent, requiring the wavenumber to be separated into deterministic and stochastic parts, $k(z) = k_0(n + \mu)$, where $n$ is the refractive index and $\mu$ a small perturbation. Turbulence scatters sound energy into shadows produced by barriers or refraction, limiting the amount of attenuation. Finally, terrain, such as hills or barriers, can be incorporated through boundary conditions or range dependence.

DESCRIPTION OF THE MODELS

The computational models describe below differ in their computational origin and in the way some of the physical mechanisms are incorporated. For example, some of the models limit the scope to a specific functional form for the sound speed profile. Some of the models do not include turbulence. All the models incorporate the boundary condition Eq. (2) in some way. The different approaches are presented following Ref. [2].

Analytical wave solutions

The Helmholtz equation (1) can be solved with a zero-order Hankel transform

$$p(r,z) = \int H_0^0(Kr) P(K,z) K dK$$

(3)

Residue series solutions to Eq. (2) can be found when the sound speed is assumed to vary linearly with height. The residue solutions do not incorporate turbulence (i.e., $\mu = 0$). The downward refraction solution is called Normal Modes [3] while the upward refraction solution is described in terms of Creeping Waves [4]. The solutions usually converge rapidly. An example of how noise levels of a few hundred Hz are predicted to decrease with distance (Transmission Loss, TL) according to the Normal Mode solution is shown in Fig. 2(a).

In the case where the sound speed is constant with height above the ground, ray paths are straight and the solution Eq. (3) reduces to the more familiar sum of direct and ground reflected waves [5]

$$p(r) = A_d \exp(ikr_1)/r + Q(\beta, \phi) A_r \exp(ikr_2)/r$$

(4)

where $r_1$ and $r_2$ are the path length of the direct and reflected path, respectively, $Q$ is the reflection coefficient and $\phi$ is the angle of incidence. In reality though, ray path are rarely straight and Eq. (4) is usually not valid at distances beyond a few hundred meters.

Ray tracing solutions

The effects of curved ray paths can be described from general principles. The curved ray modifies the angle of incidence and Eq. (4) can be used along with basic ray theory to construct heuristic physical solutions. Ray tracing solutions are computationally efficient. We note, however, that ray theory will not work beyond the shadow boundary in the case of upward refraction. The TL predicted from such a heuristic solution is usually not valid at distances beyond a few hundred meters.

The Gaussian beam approach [7] is another variation of ray tracing solutions. The basic concept of the theory is to launch a fan of ray-centered beams from the source and to trace the propagation of these beams through the medium. The wave equation is solved

Fig. 1 Sound rays in the atmosphere
non-turbulent atmosphere seriously restricts the use of the FFPs in ground. The FFPs generally provide accurate prediction out are horizontally stratified atmosphere where the sound speed is an arbitrary function of height. The Helmhotz equation in cylindrical coordinates is factored motion for a particular problem is always directed away from the barrier edge due to refraction [7].

The Parabolic Equation (PE) employs an assumption that wave propagation is laterally unbounded. Writing $U = \rho \frac{\partial p}{\partial t}$, the Helmholtz equation in cylindrical coordinates is factored into propagation of incoming and outgoing waves. Considering only the outgoing wave leads to the one-way wave equation

$$\frac{\partial U}{\partial t} = iq U$$

where $q = \frac{\partial^2}{\partial z^2} + k^2$. Most implementations of the PE can be traced back to Eq. (5). The approach for advancing the field in range is the point of departure for the PE methods. Two popular software implementations are called FINITE-PE [12] and FAST-PE [13]. The FINITE-PE method numerically integrates Eq. (5) using a Crank-Nicolson approach. The boundary condition Eq. (2) must be satisfied at each step requiring several integration steps per wavelength to model the large variations of the field close to the boundary and results in computation times comparable to the FFPs. The FAST-PE uses a Green's function approach and a split-step operation that factors $\nabla q$ into an operator for a homogeneous medium and another operator for propagation through the inhomogeneous perturbation. In addition, there are efficient terms for the field reflected from the ground allowing range steps of several wavelengths which results in dramatically decreased computation time.

The PEs allow the prediction of noise levels in a turbulent atmosphere [15] where the sound speed is an arbitrary function of height. Current developments are aimed at incorporating terrain [16,17]. In the case of the downward refraction benchmark case the PEs yield the curve in Fig. 2(c). In the case of upward refraction, models that neglect atmospheric turbulence predict large attenuations at longer ranges that are not supported by experimental data [18]. In the case of an upward refracting turbulent atmosphere the curves in Fig. 3 are typical levels [14] predicted for three values of the parameter $\mu$. In essence, the relative sound pressure levels (SPL) in Fig. 3 represent the attenuation in excess of the transmission loss shown in Fig. 2 due to upward refraction.

**SUMMARY**

When experimental data is sufficiently documented to allow comparison with the computational models, good agreement is obtained for a wide variety of situations and conditions [8,18,19]. The speed of modern computers, the increase in accuracy and reliability are making the use of computational models cost effective. Various alternatives for the field noise prediction schemes are beginning to see effort directed at predicting the hourly, daily, or seasonal variations in noise levels due to changes in environmental conditions by incorporating local weather into predictions schemes using computational models.

**REFERENCES**