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PUTTING METEOROLOGY INTO OUTDOOR SOUND PROPAGATION CALCULATIONS

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ABSTRACT

Accurate prediction of noise impacts at distances greater than a few hundred meters requires modeling or measurement of the atmospheric wind and temperature fields. In this paper, we summarize the many methods available for characterizing the atmosphere, including: (1) surface measurements from towers; (2) upper-air measurements derived from balloons and ground-based remote sensing systems such as sodar, radar, and RASS; (3) turbulence similarity theories; and (4) numerical turbulence and weather simulations. The relative merits and drawbacks of the various methods are discussed, and examples of their previous application to sound propagation in the atmosphere are provided.

1 - INTRODUCTION

The importance of atmospheric conditions in determining sound levels depends in part on the propagation distance. For distances less than 100 to 200 meters, the effect of atmospheric conditions is usually negligible. At distances longer than about 500 m, however, atmospheric conditions can have a very significant impact on sound levels. Therefore prediction of noise levels at long distances requires accurate modeling or measurement of the atmosphere, along with sound propagation models that can incorporate this information. Of main interest is refraction caused by the mean vertical profiles of the wind velocity and temperature, although other atmospheric variables may be important in some situations. For example, humidity plays an important role in the absorption of sound at high frequencies. Scattering by turbulence (the random fluctuations superimposed on the mean profiles) is the main mechanism by which sound penetrates behind barriers and into refractive shadow regions.

Many methods are available for characterizing the atmosphere. To determine which is most appropriate to a given problem, it is helpful to make a distinction between propagation in the atmospheric *boundary layer* as opposed to the *surface layer*. The boundary layer is usually defined as that part of the atmosphere whose structure changes directly in response to radiative heating and cooling of the ground as occurs over the course of a day [1,2]. It is generally between several hundred and several thousand meters in vertical extent, with top often identifiable by flattened clouds. The surface layer is usually defined as the lowermost one-tenth of the boundary layer.

A reasonable rule of thumb is that the wind and temperature profiles should be known up to a height of about 1/5 or 1/10 the horizontal sound propagation distance. Taking 1 km as a characteristic value of the boundary-layer thickness, propagation is therefore confined to the surface-layer when the propagation distance is 0.5 to 1 km or less. For longer propagation distances, out to about 5 or 10 km, boundary-layer structure above the surface layer must be modeled or measured.

Most common problems in noise control are confined to the boundary layer, and sometimes to just the surface layer. (A notable exception is large explosions, whose energy can propagate hundreds of kilometers.) Generally speaking, propagation confined to the surface layer can be handled with relatively simple tower-based measurements and turbulence similarity theories. Boundary-layer propagation requires a radiosonde, tethersonde, ground-based remote sensing system, or numerical weather simulation. In the following sections we summarize the relative merits and drawbacks of these methods for characterizing the atmosphere. Examples are provided of previous studies where these methods were applied to sound propagation.

2 - SURFACE MEASUREMENTS

Tower-based anemometers and thermometers are generally inexpensive and come with software that makes them easy to use. They have been widely employed previously to collect data for sound propagation calculations at short ranges. Kaimal and Finnigan [3] discuss in some detail the various types of instruments and their operating characteristics. Here we only summarize some main points relevant to sound propagation.

Standard cup (or propeller) and vane anemometers are accurate (except at very low wind speeds) for measuring the wind velocity averaged over time scales of about 1 min or longer. They are therefore satisfactory for determining the near-ground mean wind velocity profile, but their slow response makes them unsuitable for characterizing the turbulence spectrum. A hot-wire or ultrasonic anemometer is required for turbulence measurements.

There are many types of thermometers, with a correspondingly wide range of response times. If one is attempting to measure mean temperature profiles for sound refraction calculations, the thermometers should be set up in a bridged configuration to accurately characterize temperature gradients.

Ultrasonic anemomenter/thermometers can be very valuable by providing structural information on turbulence as well as the vertical profiles for temperature and wind velocity. The sampling rate of these systems is typically 0.1 s. This rate is normally adequate for characterizing the energy-containing subrange of the turbulence spectrum and the beginning of the inertial subrange. Since the inertial subrange can be extrapolated to smaller scales, this response time is normally suitable for audible-range sound propagation calculations including scattering. (See Wilson et al. [4] for a discussion of the various subranges of atmospheric turbulence and their role in acoustic propagation.)

Surface wind, temperature, and humidity data can also be obtained over the internet. For example, hourly data for locations throughout the United States can be downloaded from the National Climatic Data Center (http://www.ncdc.noaa.gov/ol/climate/climatedata.html). The same site also has global surface data available on a daily update cycle.

3 - UPPER-AIR SENSING

Measurement methods capable of characterizing the region of the boundary layer above the surface layer are discussed in this section. These include in situ sensors on balloons such as tethersondes and radiosondes, and remote sensing systems such as radar, sodar, and RASS.

A radiosonde is a free-flying balloon carrying an instrumentation package to measure pressure, temperature, and relative humidity. A positioning system (Loran-C or GPS) is used to locate the position of the balloon, from which the wind speed and direction can be inferred. Data are transmitted to a base station for processing. Radiosondes have been the preferred method of measuring atmospheric profiles up to 30 km, due to the low-cost of the balloons and instrumentation packages. The launch procedure is a relatively simple two-man operation. From the standpoint of acoustics, there are several disadvantages to radiosondes. A single launch provides only an instantaneous vertical snapshot of the atmosphere, which includes local random (e.g., turbulent) fluctuations that can cause misleading predictions in propagation models. Also, since the sonde is a free flying system, it will move out of the area of interest eventually, so that the upper level data may not be very well correlated with the current state of the atmosphere over the area of interest. Another problem is poor accuracy of the wind data within the first kilometer of the atmosphere.

As the name implies, a tethersonde is a tethered balloon with a package of sensors for measuring pressure, temperature, relative humidity, wind speed and wind direction. (Unlike the radiosonde system, the tethersonde has its own sensors for measurement of wind speed and direction.) Current tethersonde systems allow up to 6 sensor packages to operate from one tethered balloon. The balloon can be maintained at a fixed height, or raised and lowered at regular intervals to obtain profiles at different times. The tether may extend up to 3 km in height, but typical operation is within the first kilometer. Unlike the radiosonde, the sensor packages and balloon are reusable. A tethersonde is more labor intensive to set up and operate than the radiosonde. It is also limited to operating in wind speeds less than 10-15 m/s. An interesting study involving a tethersonde is described by Di et al [5], who included a microphone with the other instrumentation, and thereby simultaneously characterized the sound, wind, and temperature fields in the vicinity of an atmospheric refractive shadow.

SOund Detection And Ranging (sodar) systems are ground-based remote sensing instruments that emit acoustic pulses. Wind speed is derived from the Doppler shift encountered by the pulse when it is scattered by turbulence. Altitude is derived from the elapsed time between pulse transmission and echo reception. Thermal turbulence (the temperature structure function parameter) can be derived from the amplitude of the received signal. Most sodars have three-beam or phased array designs. Once set up, they have very low maintenance requirements. The wind measurement is a volume average, as opposed to the point averages provided by balloon systems. Performance of sodars is limited by interference of environmental noise with the received signal. Noise and the varying state of the atmosphere will cause the maximum height coverage to vary from 100 m to 700 m, with a typical value of 200 m.

Wind-profiling radars also make use of the Doppler effect. The signal for a 915-MHz profiling radar scatters primarily from moisture gradients in the atmosphere. These radars provide wind measurements at altitudes from 100 m to 4 km, with a typical maximum height of 2 km. The vertical resolution for commercial 915-MHz systems is usually between 100 and 400 m, as opposed to 15 to 50 m for sodars. Radio-frequency devices such as cell and portable phones interfere with wind-profiling radars. Cost is about 2 to 4 times as much as a sodar.

To measure temperature remotely, a radar can be equipped with a Radio Acoustic Sound System (RASS). Generally 3-4 loud speakers are arranged around a radar emitting pulses vertically into the atmosphere. The radar signal is scattered from the acoustic wave fronts, thereby allowing measurement of the local sound speed. Temperature can then be inferred from the sound speed. Typical RASS coverage is from 100 m to 1 km with a vertical resolution of 100 m. Raspet et al [6] have previously used RASS data to calculate sound levels.

4 - SIMILARITY SCALING METHODS

In similarity theory, a group of key variables, thought to be dynamically the most significant, is identified and used to nondimensionalize other quantities. Because of the complexity of atmospheric turbulence, there is no known similarity theory that applies well to all situations, and many similarity theories have been developed. Among the most useful are *Monin-Obukhov similarity* for the atmospheric surface layer, and *Deardorff* (or *mixed-layer*) *similarity* for boundary-layer turbulence produced during unstable conditions. (*Unstable* here refers to a positive air density gradient sufficiently large to produce spontaneous mixing of air. Such conditions typically arise when the ground is heated by the sun [1]).

In the Monin-Obukhov (MO) similarity theory [7], the key variables are the friction velocity u_*, the surface kinematic heat flux Q_s (units of temperature times velocity), the Boussinesq buoyancy parameter $\beta = g/T_s$ (where g is gravitational acceleration and T_s the surface temperature), and the height from the ground z. Since there are only three unique physical dimensions in this group (time, distance, and temperature), Buckingham Pi analysis [1] predicts that quantities nondimensionalized by three of these variables are a function of a dimensionless ratio involving the fourth. Monin and Obukhov used for the dimensionless ratio z/L_0, where $L_o = -u_*^3/k_v \beta Q_s$ is called the *Obukhov length*, and k_v is von Kármán's constant. From the standpoint of sound propagation predictions, MO similarity provides a valuable framework for modeling mean vertical profiles of wind speed and temperature. However, the similarity theory does require empirical determination of various constant factors along with the unknown function of z/L_0, for which many alternative formulations have been proposed. Most commonly used is the formulation due to Businger et al. [8].

Given similarity equations for the surface-layer wind and temperature profiles, one can measure the wind speed and direction at just one height along with the temperature at two heights, and then use these values to determine the underlying parameters u_* and Q_s [9]. If desired, a surface energy-balance model can furthermore be used to estimate Q_s from inputs such solar insolation and the ground properties [1,2]. Then wind and temperature measurements at only a single height are required. Because surface data are relatively inexpensive to obtain, combining these surface measurements with MO similarity and optionally a surface-energy balance model is very attractive way to determine the refractive profiles. The main drawback of MO similarity theory is that it is valid only in the surface layer, thereby limiting the valid distance of propagation calculations to 0.5 or 1 km. Furthermore, MO similarity can fail at night when highly stable conditions (strong temperature inversions) develop.

Besides the mean profiles, similarity theory can be applied to the problem of determining turbulence spectra for use in acoustical scattering calculations. A temperature spectral model based on MO similarity was developed by Ostashev and Wilson [10]. However, MO similarity is known to work poorly for modeling the horizontal velocity spectrum, due to the presence of boundary-layer scale convective eddies ("thermals") in unstable conditions. To model these large eddies, one must turn to Deardorff similarity. There are three key variables Deardorff similarity, namely Q_s, β, and z_i, the boundary-layer inversion height. Wilson [11] developed a von Kármán turbulence model for the surface-layer velocity field based on a combination of neutral similarity (the MO set without Q_s) and Deardorff similarity.

5 - TURBULENCE AND WEATHER SIMULATION

Numerical simulation of the atmosphere is a highly developed area of research. There are two main types of simulation that are promising for application to sound propagation: large-eddy (LES) and mesoscale.

The former is used to simulate turbulence within the boundary layer. A typical domain for LES is about 5 km by 5 km in the horizontal, and 2 km in the vertical. Mesoscale models (sometimes called regional forecast models) are used to simulate weather in domains intermediate between LES and large-scale (synoptic) numerical forecasting models. Mesoscale domains are typically 10 to 1000 km in the horizontal directions.

LES uses a formulation called a subgrid closure to mimic the transfer of turbulent energy from the resolved simulation scales to the smaller, unresolved scales. The lower limit for resolution is typically 5 to 50 m. Since the turbulence field should be resolved to a scale finer than the acoustic wavelength of interest, LES can be applied directly only to very low frequencies in the audible range. A further problem in applying LES to acoustics is that the profiles near the surface are inaccurate because of deficiencies in the subgrid model there. The main effect is that the wind and temperature gradients are not as sharp as in reality.

Wilson [12] used LES to calculate phase and log-amplitude variances of acoustic signals. Because of the finite resolution of LES, however, the amplitude statistics in particular were unrealistic. Gilbert et al. [13] developed a technique to circumvent the resolution problem, by adding synthesized inertial-subrange structure to the LES fields. Although Gilbert et al. dealt with radio-wave propagation, their technique can be applied equally well to acoustics.

Mesoscale models have even lower resolution than LES, making them impractical for simulation of turbulent scattering. But they still can be valuable for simulating wind and temperature profiles above the surface layer. The lowermost grid levels can also provide input to a surface-layer similarity scheme or energy balance model to determine profiles there.

Example applications of mesoscale models to sound propagation can be found in Heimann and Gross [14], and Hole and Mohr [15]. Magill and Swanson [16] dynamically retrieved mesoscale data over the internet from the U.S. National Oceanic and Atmospheric Administration's Rapid Update Cycle model, in order to create "nowcasts" of acoustic detection footprints.

6 - CONCLUSION

All of the methods for characterizing the atmosphere described in this paper have their own relative advantages and disadvantages. The best choice is particular to a given application. We anticipate that similarity scaling and mesoscale models will become increasingly popular due to rapidly expanding technologies for sharing data over the internet.

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