Predicting Sound Propagation in the Atmosphere

D. Keith Wilson

My career in acoustics began with an instance of serendipity. On receiving a BA degree in physics from Carleton College, Northfield, Minnesota in 1985, I was inclined toward applied physics, with optics and electromagnetics seemingly good possibilities. So I enrolled in the master's program in electrical engineering at the University of Minnesota, Minneapolis. While searching for a research assistantship, I serendipitously met Robert F. Lambert, a long-time member of the Acoustical Society of America (ASA), who was investigating the nonlinear properties of acoustic porous media. This turned into a master's thesis, and soon I took on the professional identity of "acoustician."

But this article is mainly about a different instance of serendipity in my career, namely, how my research in acoustics came to focus on the randomness and challenges of predicting sound propagation through the atmosphere. This focus arose largely from a couple formative experiments early in my career, which then set the stage for a key serendipitous encounter. In the following, I describe the two experiments followed by the serendipitous encounter.

The first of the experiments occurred as a PhD student. I had enjoyed my initial foray into acoustics so much that I enrolled in the Pennsylvania State University Graduate Program in Acoustics, State College, for my PhD. My thesis advisor was Dennis W. Thomson of the Meteorology Department, with whom I studied the intersection between acoustics and the weather. I found atmospheric acoustics compelling because it involves phenomena that can be experienced in our day-to-day lives if we observe closely enough, for example, hearing a distant train or roadway when the wind direction is right or the quiet of a soundscape with freshly fallen snow.

The experiment was simple. A subwoofer and a very powerful amplifier were placed near a barn at the Penn State agronomy research center, with microphones 750 m away. The purpose was to study the variation of long-range sound transmission with changing weather conditions. The sound level was monitored around the clock over several consecutive days during the summer and then during the fall. My main task was to write the BASIC program that retrieved and logged the data every minute from a spectrum analyzer.

When plotted over the course of several days, the data showed a clear trend, with the sound level rising each night and falling each day. This was not unexpected. At night, radiative cooling of the ground often leads to a temperature inversion (cold air near the ground, with a positive vertical temperature gradient), thus leading to downward refraction and ducted propagation. During the day, solar heating of the ground creates a temperature lapse (negative temperature gradient) condition, leading to upward refraction. Rather more surprisingly to me, superimposed on these trends were frequent, strong, random variations up to about 10 dB. Although some previous researchers, such as Ingard (1953), had noticed and remarked on this variability, by the 1980s, researchers had only begun to

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work systematically on experiments and theory to describe it (e.g., Daigle et al., 1986).

That was the first experiment I mentioned earlier. For the second experiment, fast forward about 10 years from my PhD student days. I was then working at the United States Army Research Laboratory. The Army Research Office organized a large, multinational experiment called CASES '99 to study the nighttime near-ground atmosphere. Dozens of organizations collaborated to deploy, at a site on the Great Plains in southeast Kansas, an array of tall, heavily instrumented towers, weather balloons and kites, and remote-sensing systems such as radar and sodar. Recognizing this opportunity to leverage the high-resolution atmospheric characterization, my colleagues John Noble and Mark Coleman simultaneously fielded loudspeakers and microphones to measure sound propagation over distances up to 1,300 m. Large, seemingly random variations in sound levels were observed as in the experiment I had analyzed years earlier. Astoundingly, even with the excellent coincident meteorological observations extending to hundreds of meters above the ground, the observed levels and their variations could not be consistently predicted, even with a state-of-the-art numerical method such as the parabolic equation (Wilson et al., 2003). This experiment had seemed like the best-case scenario from the standpoint of achieving good agreement between acoustic propagation model predictions and sound level measurements: flat, homogeneous ground, stable nighttime atmospheric conditions, and the best meteorological data feasible.

Now the instance of serendipity to which I have been leading. A few years later, on a dreary, muddy December day, I found myself at Ft. Drum in upstate New York. By this time, I had become involved in programming graphical interfaces to help nonexpert users such as soldiers apply the latest acoustic propagation models to real-world scenarios. It's not often that a PhD scientist trains soldiers directly! But the brigade commander was quite enthusiastic about having his unit learn new things. During the training, I serendipitously happened to overhear two soldiers converse about whether they should place any trust in the slick software I had worked so hard to develop. As I recall, I provided a cursory response that, of course, no model is perfect, but this was state-of-the-art and had been extensively compared with experiments. Reflecting later, I realized the inadequacy of my response. Sure, the physics of the wave equation is well established and numerical methods are available that can solve it accurately. But lacking suitable input data, even good models can produce poor results. And, as I learned during those earlier experiments, sound propagation exhibits considerable randomness and has limited predictability. As an expert, I had a decent sense of the model limitations. But how could that understanding be conveyed to nonexperts? Can the limitations due to uncertainties in inputs such as the atmosphere and ground state be meaningfully quantified? I had gone to Ft. Drum to instruct the soldiers but received an unexpected assignment from them.

For an initial effort at addressing the predictive limitations of the propagation models (Wilson et al., 2008), my collaborators and I made extensive use of large-eddy simulation (LES), a computational technique used to simulate turbulence in the atmosphere. The LES, when combined with the acoustical modeling, provided "ground truth" for propagation through a dynamic, fully three-dimensional atmosphere, which could then be compared with predictions based on more limited meteorological data as would typically be available in practice.

Here are some of the practical questions we aimed to answer: What happens when, say, there are variations in the wind and temperature profiles along the propagation path that cannot be observed? Or when the profiles are, say, half-hour averages around the time of the actual sound level measurement or event? Or when the profiles are from a nearby but different location? We found, for example, that even with accurate meteorological measurements from a location and time very close to the propagation path, sound level predictions have inherent random errors of about 6-8 dB. Fortunately, the errors do generally diminish when *mean* meteorological measurements (over an interval of, say, a half hour) are used to predict *mean* sound levels over the same time interval. But random variability of the atmosphere and the sensitivity of sound waves to this variability make it infeasible to accurately predict the propagation at a particular time and place.

In a further instance of serendipity, it was around this time that I first met Chris Pettit, then a new faculty member at the United States Naval Academy, Annapolis, Maryland, who had responded to a solicitation I put out regarding atmospheric acoustics research. Chris had previously performed research on uncertainty quantification (UQ) in aerodynamics and turbulence and quickly grasped that the methods he had learned for statistically characterizing errors of predictions from complex, nonlinear models would be valuable for sound propagation because the models are highly sensitive to inputs varying in time and space that cannot be exactly characterized. Together, we worked on a number of approaches to reducing the number of model runs needed to accurately predict sound levels, while efficiently quantifying the impacts of uncertainty in the wind and temperature profiles, turbulence spectra, and ground properties (e.g., Wilson et al., 2014; Martinelli et al., 2023).

An *Acoustics Today* article (Wilson et al., 2015) provided an opportunity to summarize the perspective I had formed over the previous couple of decades. Looking back, I arrived at this perspective through a serendipitous sequence of events, beginning with experiments having initially surprising results. These experiments provided a context for later interactions with soldiers who wanted to know if they could rely on "black box" computer models. The questions that arose developed into productive research thanks to seemingly chance collaborations and discussions with many outstanding colleagues. Unexpected results and challenges become valuable opportunities for new learning and discovery when we are prepared to see them through a different perspective.

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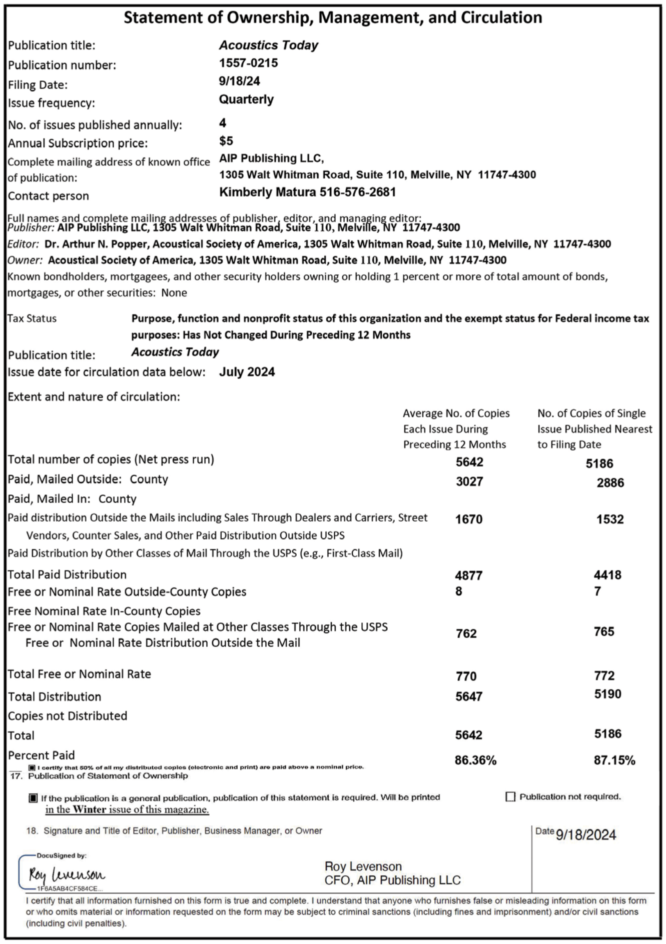

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