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SOURCE LOCALIZATION IN THE ATMOSPHERE BY MEANS OF BEAMFORMING AND TOMOGRAPHY

K. Wilson*, V. Ostashev, A. Voronovich**, S. Collier***

* U.S. Army Research Laboratory, 2800 Powder Mill Rd., 21114-1097, Adelphi, MD, United States Of America

** NOAA/Environmental Technology Laboratory, 325 Broadway, R/ET4, 80303-3328, Boulder, CO, United States Of America

Tel.: 301-394-2099 / Fax: 301-394-1155 / Email: dkwilson@arl.mil

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ABSTRACT

This paper reviews progress made during the past decade for localizing audible-frequency-range sound sources in the atmosphere. The main techniques are array beamforming and tomography. Beamforming has been successfully demonstrated for both ground vehicles and aircraft. Tomographic methods are still in an exploratory stage, but have the potential advantage of providing simultaneous characterization of the atmosphere. Beamforming and tomography are similar in that both use time delays between signals recorded at a dispersed set of microphones. In this paper, we pay special attention to the limitations the propagation medium (the atmosphere) places on beamforming and tomography.

1 - INTRODUCTION

Acoustic systems for localization in the atmosphere have made great strides during the past decade. The main progress has been in beamforming and tomography. Modern digital signal processing technology has enabled the development of highly capable systems that are inexpensive in comparison to their electromagnetic counterparts. With the anticipated arrival of acoustic microsensors, the trend for lower cost and smaller packages will likely continue during the next several decades.

Although most of the recent progress in beamforming and tomography has occurred outside the realm of noise control, there are many potential applications to this area. Beamforming arrays could be used to monitor noise originating from a specific direction. Either beamforming or tomography could be used to determine the location of unknown noise sources. Aircraft take-off and approach trajectories could be monitored to assure compliance with regulations in situations where ground clutter interferes with radar. The main purpose of this paper is to review recent progress in beamforming and tomography, in order to provoke interest in possible noise control applications.

2 - BEAMFORMING

Acoustic beamforming arrays are commonly used underwater for localizing sound sources and reflective objects. Although such arrays have not achieved the same widespread usage in the atmosphere, there has been a substantial and growing interest in these systems during the past decade. Most new development has focused military applications such as sniper detection, ground-vehicle tracking, and aircraft tracking [1,2,3,4]. Research into infrasonic arrays for monitoring nuclear explosions and severe weather has been ongoing for decades [5].

The basic principle upon which the arrays operate is simple: by finding the relative time delays between the signals arriving at the individual sensors, the angle-of-arrival of the wavefronts can be deduced. Presuming that little refraction occurs as the wave propagates from the source to the array, the angle-of-arrival is the same as the direction of the source. This assumption is generally reasonable for estimating the horizontal (azimuthal) bearings of a source. If both the source and sensor are close to the ground, refraction by wind and temperature gradients has a substantial effect on the vertical (elevation) angle. Therefore the observed vertical angle of arrival is little use unless the refraction can be modeled accurately. To localize a source, the estimated bearing (azimuthal and/or elevation) angles from two or more arrays are combined. The intersection of the bearing lines provides the source location.

Typical atmospheric beamforming arrays for the audible-frequency range have microphone spacings of several meters or less. In specifying sensor spacing and geometry, designers usually balance the need for an adequate baseline against the cost and susceptibility to atmospheric effects of larger arrays. Scientific research into atmospheric effects on arrays, and the resulting implications for array design, is still at a very early stage. Ferguson and Criswick [6] and Wilson et al [7] demonstrated that atmospheric variability can produce substantial fluctuations in measured angles of arrival. Wilson [8] developed a theoretical model for the accuracy of angle-of-arrival estimates in the presence of random atmospheric variations and interference by background noise. The model can be used for systematic study of the trade-offs between array geometry and performance.

An example of refraction and turbulence effects on localization is shown in Fig. 1. Plotted is the elevation angle-of-arrival monitored with a 32-element, vertical planar microphone array during three 20-min trials conducted in varied meteorological conditions. The source radiated at 250 Hz, was about 750 m distant from the array, and was stationary at 0° elevation angle. (The experiment and data processing are described in more detail by Wilson et al [7].) The results illustrate how the apparent elevation of the source fluctuates over short time scales due to turbulence, and differs from trial-to-trial due to changing atmospheric refractive conditions.

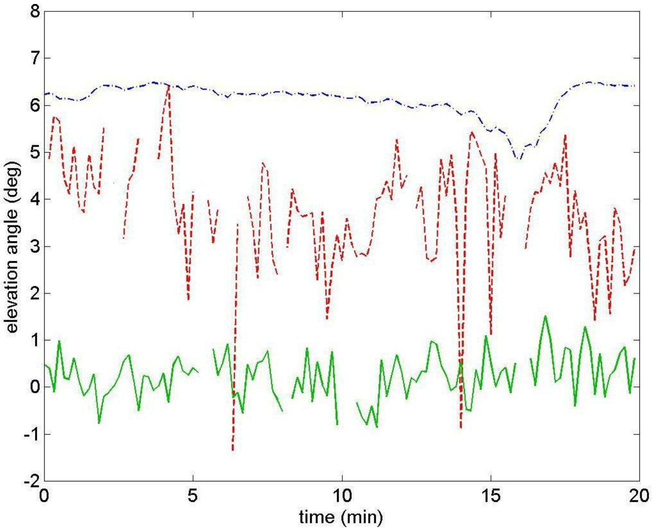

Figure 1: Elevation angle for waves arriving at a 32−element planar microphone array during three 20−min trials; dash-dotted (blue) line: trial conducted during still nighttime conditions; dashed (red) line: trial conducted during moderately windy daytime conditions; solid (green) line: trial conducted during low-wind daytime conditions.

3 - TOMOGRAPHIC LOCALIZATION

Tomography is the reconstruction of a field from projections through that field. In atmospheric acoustic tomography, the projections are the paths along which sound travels between source/receiver pairs. The field to be reconstructed is the atmospheric propagation medium. Most tomographic schemes for the atmosphere use the travel time along the propagation paths for the reconstructing the field. (Medical schemes, in contrast, usually use the wave attenuation.) Since the travel time along a path depends on the temperature and wind velocity in the intervening atmosphere, travel times from multiple source-receiver pairs can be used to approximately reconstruct the intervening wind and temperature fields. This application of tomography as an atmospheric remote sensing method was apparently first suggested by Greenfield et al [9]. Other discussions and implementations can be found in papers by Ostashev [10], Chunchuzov et al [11], Wilson and Thomson [12], and Ziemann et al [13]. Regarding localization, the source position can easily be incorporated into the tomographic inversion formulation, along with the unknown atmospheric wind and temperature fields. This idea was first proposed for localizing calling animals by Spiesberger and Fristrup [14] in 1990. Its practicality was demonstrated recently by Spiesberger [15], who tomographically localized calling birds.

We have also proposed a new tomographic scheme involving up to ten microphones on the ground for the purpose of tracking aircraft and other sources in the atmosphere. The main difference between this scheme and those developed by Wilson and Thomson [12], Ziemann et al [13], and Spiesberger and Fristrup [14] is that we model the atmosphere as horizontally stratified and try to retrieve the vertical profiles of the adiabatic sound speed $c(z)$ and wind velocity vector $\mathbf{v}(z)$ for heights z up to several kilometers.

In the proposed scheme (which will be described in more detail in a paper at IGARSS 2000), the N microphones including a reference one would be located on the ground at different locations. The microphones would be situated near an airport to record sound from ascending and descending aircraft. A standard cross-correlation technique (such as Ferguson's [16]) would then allow determination of the time interval Δt_i between the arrival of the signal at the i-th microphone and its arrival at the reference microphone. Using a small parameter $\varepsilon = \max\left(\left|c(z) - c_0\right|/c_0, v(z)/c_0\right)$ (where c_0 is a reference value for the sound speed), along with results from section 3.6.1 of Ostashev [17], we have obtained analytical equations for Δt_i in terms of $c(z)$ and $\mathbf{v}(z)$. These equations represent the forward-problem solution. The inverse problem can be solved by techniques similar to those in other schemes for atmospheric tomography. The minimal number of microphones needed for the inversion is either $N = 9$ or $N = 10$, depending on the solution method.

4 - ATMOSPHERIC TURBULENCE EFFECTS

From a signal processing standpoint, beamforming and tomography are similar in that they both make use of time (phase) delays between dispersed microphones. Both methods are also based on assumptions regarding the cause of the time delays that may not be valid for some sensor array configurations and atmospheric conditions. In particular, atmospheric turbulence can degrade the performance of both types of systems.

The main concern in beamforming is the *coherence* (consistent amplitude and phase relationship) of the signals received by the individual sensors. Atmospheric turbulence reduces coherence by randomly scattering sound waves. If the array elements are spaced too far apart, the resulting lack of signal coherence could disrupt efforts to localize a source. The variations in elevation angle illustrated in Fig. 1 exemplify coherence loss, since the phase between the sensors at different heights in the array is inconsistent.

We have recently developed a new spectral model for atmospheric turbulence that should be accurate for a wide variety of conditions [18]. The model is based on von Kármán's spectrum, with parameters estimated from well accepted atmospheric turbulence similarity theories. Contributions to scattering from both temperature and wind velocity fluctuations are incorporated into the model. Modeled coherence at 400 Hz for two different atmospheric conditions, as a function of range and sensor separation, is shown in Fig. 2 (these calculations are idealized in that they assume "line-of-sight" propagation: reflections from the ground, and refraction from atmospheric wind and temperature gradients, are not considered). The curves in Fig. 2 show that coherence is worst during windy, sunny conditions. Array apertures should be smaller than a few meters for beamforming at 400 Hz at a distance of 1 km. Even smaller apertures are needed for higher frequencies and longer propagation distances.

The microphone spacings for tomography are typically much larger than for beamforming arrays: from tens of meters in Spiesberger's [15] implementation, to several hundred meters in those of Wilson and Thomson [12] and Ziemann et al [13]. Despite this large spacing, a tomographic array is not affected by coherence loss in the same sense as a beamforming array. In fact, the purpose of the tomographic arrays is to monitor varying time delays between the sensors. Potential problems with source localization or atmospheric sensing can arise when the forward model (relating the properties of the propagation medium and receiver positions to the time delays) is incorrect. For simplicity, atmospheric tomography implementations to date have all been based on geometric (ray) approximations to the wave equation. Therefore, if the geometric approximations are invalid, these schemes can fail.

For geometric approximations to be valid, one must have $x/\left(kL^2\right) \ll 1$, where x is the propagation distance, k is the wavenumber, and L is the integral length scale of the effective index-of-refraction fluctuations [17]. According to the Ostashev and Wilson model [18], L can vary from about 20 m in windy, cloudy conditions to 200 m in calm, sunny conditions. The smaller value implies validity of geometric approximations at 400 Hz out to several km. We suspect that the actual range of validity is considerably shorter, mainly because the condition $x/\left(kL^2\right) \ll 1$ assumes line-of-sight propagation. Still, it does appear reasonable to employ geometric approximations out to several hundred meters near

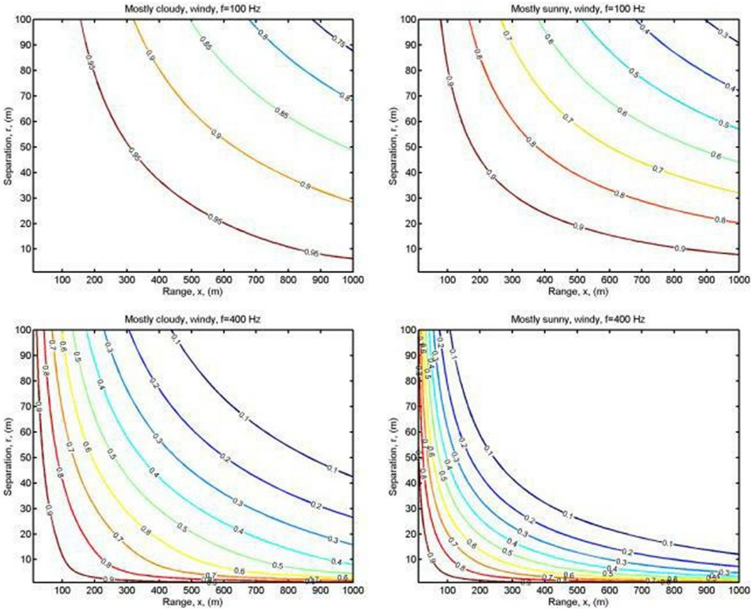

Figure 2: Modeled coherence for a 400-Hz sound wave propagating through the atmosphere; upper: sunny, windy atmospheric conditions; lower: cloudy, windy atmospheric conditions.

the ground, as was implicit to the tomography formulations of Wilson and Thomson [12] and Ziemann et al [13].

5 - CONCLUSION

Beamforming and tomography have many potential applications in noise control. This paper provides several references for those interested in exploring these applications. Some care must be taken to make ensure that new system designs are not based on false assumptions regarding the atmospheric effect on propagation of the sound waves.

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