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The influence of environmental conditions on estimation of source distance and height using a single vertical array

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ABSTRACT

The performance of microphone arrays outdoors is influenced by the environmental conditions. Numerical simulations indicate that, while horizontal arrays are hardly affected, direction-of-arrival (DOA) estimation with vertical arrays becomes biased in presence of ground reflections and sound speed gradients. Turbulence leads to a huge variability in the estimates by reducing the ground effect. Ground effect can be exploited by combining classical source localization with an appropriate propagation model (ground effect inversion). Not only does this allow the source elevation and range to be determined with a single vertical array but also it allows separation of sources which can no longer be distinguished by far field localization methods. Furthermore, simulations provide detail of the achievable spatial resolution depending on frequency range, array size and localization algorithm and show a clear advantage of broadband processing. Outdoor measurements with one or two sources confirm the results of the numerical simulations.

1. Introduction

Microphone arrays are a tool for localization and separation of sound sources and suppression of background noise. Outdoors, applications include the detection of persons and vehicles in a security or military context, like shooter/intruder detection, combined audio-visual traffic monitoring or determining source position on extended objects like (industrial) buildings.

Typically, outdoor source localization is characterized by a source-array distance which is much larger than the array size. Thus, and because of its computational efficiency, localization methods are generally based on a free field, far field assumption, so that a single array can only estimate the direction-of-arrival (DOA) of the incident sound. Source distance is obtained by triangulation using DOAs from two or more spatially separated arrays [1] or, preferably, by combining the data from these arrays directly [2].

There are cases in which range-dependent changes in the waveform or particular source signals can be exploited to obtain range information even with a single array. An example is shooter detection where the delay between the shock wave and muzzle blast and the change in the waveform of the shock wave generated by the supersonic projectile may be exploited [3].

Source height estimation, on the other hand, would require vertically separated arrays in a free field, far field scenario, something that is at least inconvenient if not impossible in many situations.

A free field is a greatly simplified description of the sound propagation in the atmosphere, several factors affect it. In Fig. 1, an overview is given of these phenomena. The direct wave is overlaid with the one reflected by the ground. Sound speed gradients caused by thermal layering of the atmosphere as well as wind shear change the inclination of the wave fronts. Turbulence leads to random fluctuations of sound pressure and phase. As a result, the wave front arriving at the array is distorted, phase (and pressure) relations between the microphone positions, which are the basis for any source localization technique, have changed in a deterministic (ground reflection, sound speed gradients) and random (turbulence) way. Additionally, absolute sound levels will increase or decrease depending on frequency.

As atmospheric sound propagation is historically well understood, a large number of models exist taking into account several or all of the above mentioned factors as well as others not considered here like irregular terrain or obstacles. For the purpose of this study it is sufficient to notice that for any situation there will be a (physical) model which predicts the complex propagation loss between source and receiver with arbitrary accuracy (assuming accurate input parameters), and that these models will differ significantly in their computational efficiency. In connection with source localization it is important to remember that it relies on the phase difference (and, less often, on the level difference) between closely spaced microphones. The absolute sound level,

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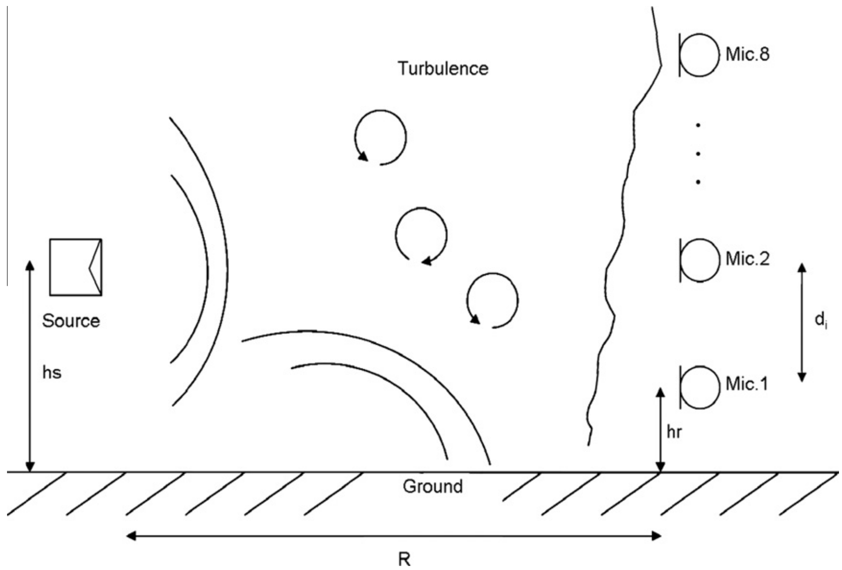

Fig. 1. Sketch of the measurement set-up showing the influence of ground reflection, vertical sound speed gradient and turbulence on the wavefront arriving at the (vertical) array.

which is the subject of numerous studies on the effect of environmental conditions on noise propagation, affects the array's performance by changing the signal-to-noise ratio (SNR) and consequently the uncertainty of the DOA estimation. Apart from propagation loss, the SNR at the receiver depends on the specific source strength and background noise level. In this study, we will consider the SNR to be a constant in order to assess which localization performance one could expect if one had a certain signal-to-noise ratio at the array.

Given the importance of (long range) source localization in the military, a number of studies dealt with the influence of atmospheric conditions on precision and variability of positions estimates. In general, estimates show random fluctuations due to the SNR dependent uncertainty of the estimator, on a short time scale, and fluctuations due to the change in atmospheric conditions (turbulence) on a longer time scale [4]. Likewise, fluctuations of the estimated source azimuth, elevation and level were observed during measurements with a large planar array and a 250 Hz source at a distance of 770 m, being strongest during windy conditions [5]. In the same study, a bias in the elevation measurement is observed in all but one trial which can be attributed to vertical sound speed gradients. These gradients were object of a numerical study on their effect on source position estimation by highly elevated (attached to aerostats) arrays [6]. Vertical gradients lead to biased positions estimates, but a correction is possible as long as the sound speed profile is known or can be deduced from meteorological observations. An effect of horizontal and vertical sound speed gradients on range and azimuth estimates is also found in the already cited study on localization by triangulation [1]. An interesting detail is that there's a larger effect on the apparent elevation (subsequently influencing the predicted azimuth) than there is a direct effect of horizontal gradients on the azimuth.

Theoretical background on the influence of turbulence on the Cramer–Rao bound as the lowest achievable variance of any angle-of-arrival estimator is given by [7]. Clearly, the variance increases with increasing index-of-refraction variance, propagation distance and decreasing scale of turbulence.

The predicted practical consequences of the turbulence effect vary. On the one hand, it is suggested that an increased array size will overcompensate the unwanted turbulence effect and lead to better localization performance [4]. On the other hand, simulations and measurements indicate that under adverse conditions, in this case in a refractive shadow, spatial coherence can be very low with correlation length as short as 1 m, so that larger arrays will no longer lead to better results [8]. Measurements under moderately complex environmental conditions [9] (shadowing by hills and upwind conditions) confirm these predictions: while small arrays were only suited to line-of-sight localization due to low angular sensitivity, very large arrays suffered decreased performance due to the spatial coherence decreased by turbulence; the authors recommend high population 1–8 m arrays, operating at low frequencies, to track sources under disrupted line-of-sight conditions.

A factor receiving less attention is the ground reflection, although studies by [10] demonstrate that multipath propagation, even with only two paths, can result in biased time-difference-of-arrival and consequently in biased position estimates.

To gain a better understanding of the relative importance of environmental factors regarding their influence on source localization performance and possible combination effects, we will, in a first step, check which factors have the widest influence on DOA estimation accuracy. This will be done by combining sound propagation models of increasing complexity with classical source localization methods to calculate the DOA misestimation for a number of geometries, frequencies and environmental conditions. Taken in mind that most existing studies address horizontal arrays, this study will concentrate on differences in the effects on horizontal and vertical arrays and the question of accurate source height determination.

In a second step, the effect of one of the (major) factors in outdoor sound propagation, the ground reflection, will be exploited to improve the localization methods and enable them to detect both the source elevation and range with a single vertical array of microphones even if the source is in the far field. This method – ground effect inversion – will consequently be an example of matched field processing popular in underwater acoustics. In a limited fashion this strategy has been used by [11] for solving the problem addressed here, source height estimation. However, the authors assumed the source distance to be known and used solely the difference in levels between the microphones instead of exploiting the phase differences as classical direction-of-arrival estimation does.

This study comprises both numerical simulations and outdoor measurements for their verification.