Assessing the Performance of Microphone Array Methods Using a Virtual Test Environment

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Introduction and Motivation

Phased microphone arrays offer the ability to localize and quantify the power of acoustic sources. In aeroacoustics, they are widely used in research in various applications. One of these application are flyover measurements. Here, they allow an assessment of the individual acoustic sources of aircraft in flight. Although the use here goes back a long way, it is still the subject of current research.

In order to be able to further develop and test beamforming techniques, synthetic data is required that represents real recordings as closely as possible. This contribution focuses on the reproduction of coherence loss due to atmospheric effects.

Characteristics of Flyover Measurements

Flyover measurements pose a set of challenges to the algorithms that evaluate the recordings of a microphone array that differs significantly from more common applications, e.g., on stationary machinery or wind tunnels. When analyzing flyovers, the algorithms must focus on fast-moving sources at a relatively great distance. The frequency shift due to the Doppler effect caused by the high source velocity must be taken into account. Additionally, the chosen length of the evaluated time segments is a consideration between the angular resolution of the source directivity and the amount of data available for analysis.This typically results in very short time signals (T <1s).

These challenges prevent the use of many microphone array methods developed for stationary or slow-moving sources. Methods that have proven their applicability are the very robust delay-and-sum beamforming in the time domain, which suffers from poor resolution at low frequencies, and a hybrid deconvolution approach based on DAMAS[1, 2]. Both typically assume the propagation not to be diffracted, i.e., in a straight line. Since the environmental parameters are usually only known at ground level, they are assumed to be constant.

Coherence Loss Due to Atmospheric Turbulence

One effect that has received little attention in simulating flyover microphone array measurements, is the loss of coherence due to atmospheric turbulence. Due to the different conditions on each respective propagation path, the signals from two microphones differ not only because of the different source-microphone distances. As the distance between the microphone increases, non-deterministic jitter causes a random phase shift that limits the spatial information available for reconstructing the acoustic field. This effect can be expressed by the coherence factor

$$\gamma^2(f) = \frac{|G_{XY}(f)|^2}{G_{XX}(f)G_{YY}(f)} \tag{1}$$

$$= \frac{\text{cross spectral density}^2}{\text{auto spectral density}^2} \tag{2}$$

which is a measure of the linear relation between two signals. $G_{XY}(f)$ and $G_{YY}(f)$ are the crossspectrum and autospectrum of two signals $x(t)$ and $y(t)$. γ lies in the interval $[0, 1]$, where $\gamma = 1$ characterizes the signals being fully coherent and $\gamma = 0$ them being fully incoherent (random).

Figure 1 shows the measured coherence between a large number of microphone pairs. Since coherence loss results in a loss of information at large microphone distances, it limits the effective aperture diameter of a microphone array. This effect increases with the considered frequency.

Method

Virtual Test Environments

Virtually generated data can be a vital tool for the assessment of the quality of microphone array methods[3]. So far, the loss of coherence has not been considered in synthetic data. Lincke et al. [4] have developed a model description for the mechanisms that cause coherence loss in the atmosphere and proposed a method to include it in a virtual test environment (VTC).

The three identified causes of coherence loss are spatial fluctuations in temperature, shear-produced wind velocity fluctuations, and buoyancy-produced wind velocity fluctuations.

The resulting model for each is based on the scaling parameters friction velocity u_*, specific heat flux σ_T^2, and atmospheric boundady layer height z_i.

The model defines the microphone distance as the projected distance perpendicular to the emission (see Fig. 2).

The steps for simulating microphone array data are:

1. calculate coherence factors of all $M \times M$ microphone pairs based on u_*, σ_T^2, and z_i
2. generate M fully incoherent signals
3. combine signals according to a mixing matrix calculated from the coherence factors

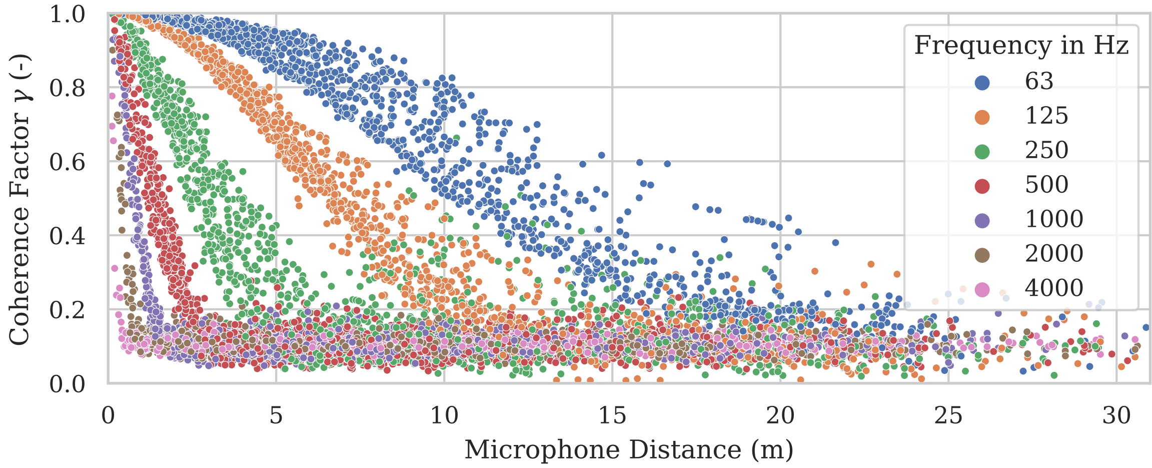

Figure 1: Measured coherence factors γ for microphone pairs at their the respective distance d. The values are based on a 2016 Flyover Microphone Array Measurement [5, 6]. For this particular recording, the aircraft was 186m above the array. The 0.5s time segment was chosen so that the aircraft's sound emissions originated directly above the array.

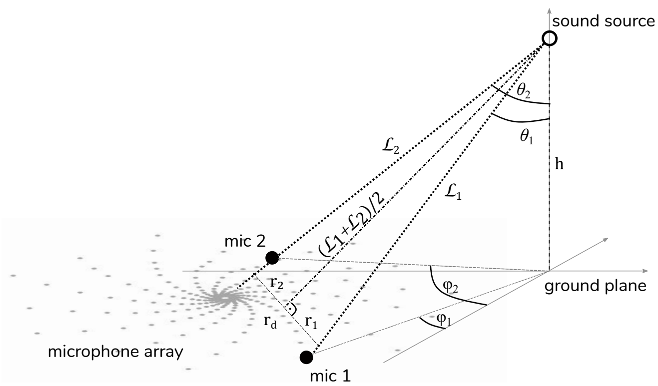

Figure 2: The geometry of the sound paths. For the modeled coherence loss between microphone pairs, only the lateral separation r_d was considered. Diagram first published by Lincke et al. (2023) [4]

A more detailed description of the model is beyond the scope of this manuscript. Interested readers are referred to the original paper.

As described in table 1, four sets of scaling parameters were chosen to represent the meteorological conditions: *low winds with little solar radiation* (a), *low winds with high solar radiation* (b), *high winds with low solar radiation* (c), *high winds with high solar radiation* (d). In general, the induced coherence loss increases from (a) to (d).

Table 1: Turbulence scaling parameters for conditions (a)-(d).

Condition	**(a)**	**(b)**	**(c)**	**(d)**
u_* (m/s)	0.1	0.1	0.5	0.5
Q_H (W/m²)	50	200	50	200
z_i (m)	500	2000	500	2000

Model Aircraft

This work represents a first step of using the new propagation model for simulating flyover measurements. Thus a simplified source configuration is defined. This source configuration only loosely represents typical aircraft engines noise sources, but does include the characteristic superposition of both tonal- and broadband noise.

The source signal consists of a mixture of three base signals, representing typical broadband noise, a tone at the blade-pass-frequency and buzz-saw noise respectively. The microphone data was generated individually for each base signal, allowing the creation of many VTCs by recombining the data sets . Figure 3 shows the spectrum of each base signal calculated by a dedopplerization of the data sets.

In this work, the broadband signal was placed at the inlet and nozzle of the engine. The buzz-saw signal was placed only at the inlets, the BPF-signal was placed only at the nozzle. The distance between the engine inlet and nozzle is 5.5m. The sources are simulated with a height of 180m and travel at 88m/s. The microphone positions correspond to the microphone array used in the Low-Noise ATRA project [5, 6], with 238 microphones arranged in a logarithmic spiral with a diameter of 35m.

The obtained data sets were processed with the delay-and-sum beamforming (Fig. 6-4) as well as the deconvolution approach (Fig. 5).

Results and Conclusion

Figures 6 and 7 show a contour plot of the results of the delay-and-sum method. The localization of the four sources works similarly well for all atmospheric conditions. However, the estimated sound pressure levels are slightly reduced. This observation is confirmed by figure 4 showing the total sound pressure levels of the four source positions. Especially at high frequencies, where the effect of coherence loss is most pronounced, the results systematically underestimate the correct levels (considering the coherent condition as baseline).

The deconvolution method proposed by Brook and Humphrey [2] and adapted to flyover measurements by

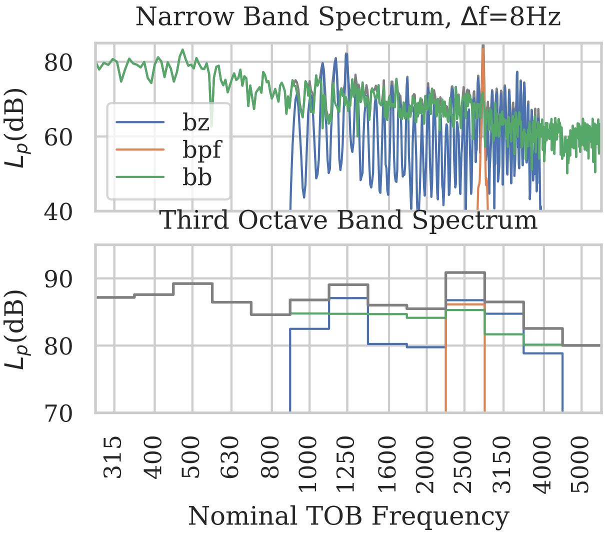

Figure 3: Dedopplerized signals which were used to generate the VTCs. They loosely represent buzz-saw noise (bz), a blade-pass-frequency (bpf) tone, and broadband noise (bb).

Guérin and Weckmüller [1] does not take a coherence loss into account. Figure 5 shows the result of the deconvolution for selected third-octave bands and that the underestimation cannot be corrected by applying the standard deconvolution used here.

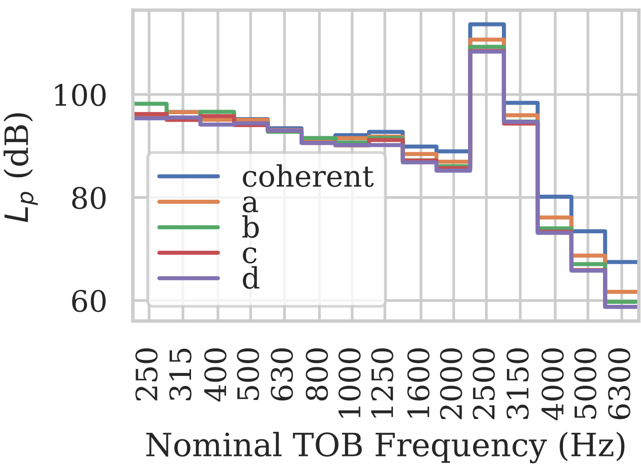

Figure 4: Total source power at the correct source positions, estimated with a delay-and-sum beamforming approach. (*coherent, a, b, c, d*) represent the conditions listed in table 1.

The presented work applies the propagation model of [4] to tonal and broadband point sources. It can show, that there is no impact on the localization of either sources type. The underestimation by the delay-and-sum beamforming method is to be expected. The random phase shift caused by the coherence loss prevents the *delay* step to correctly realign the phase of the microphone recordings.

For true virtual test cases for flyovers, the source model must be extended to accurately represent real aircraft sources. This includes spatially distributed sources, as

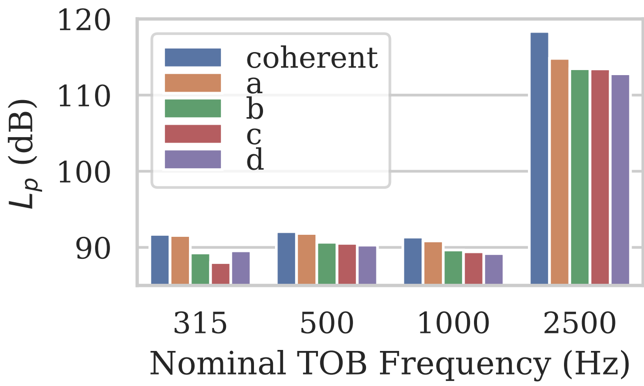

Figure 5: Total source power at the correct source positions, estimated using a decovolution approach [7]. A region of 1.25m around each of the sources was used for integration.

well as partially coherent sound emissions from aircraft components e.g., the inlet and the nozzle. However, the presented approach can already be used for pre-planning of measurement campaigns. It can also serve as a tool to define a set of atmospheric conditions to be met when performing phased array measurements.

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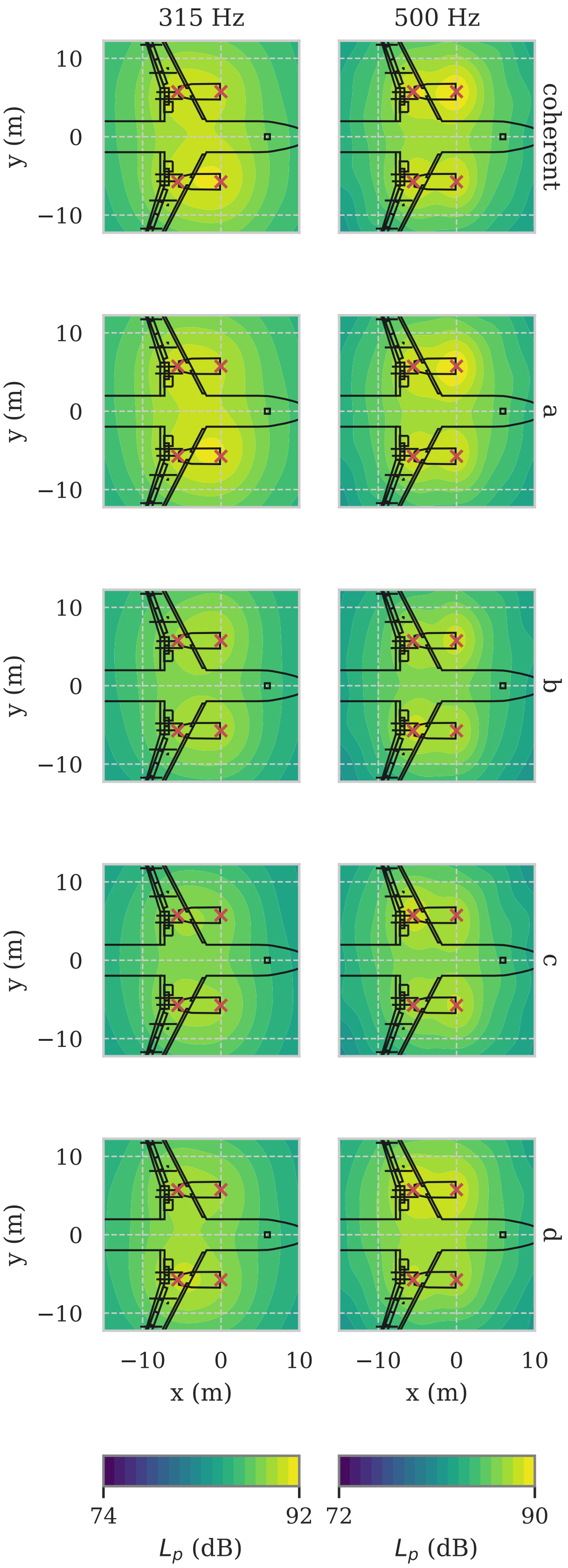

Figure 6: Beamforming results for the one-third octave bands 315Hz and 500Hz. No coherence loss was applied to (coherent), (a)-(d) correspond to the conditions in table 1. While the coherence loss has little effect on the source localization, the results of conditions (b) and (c) underestimate the source strengths.

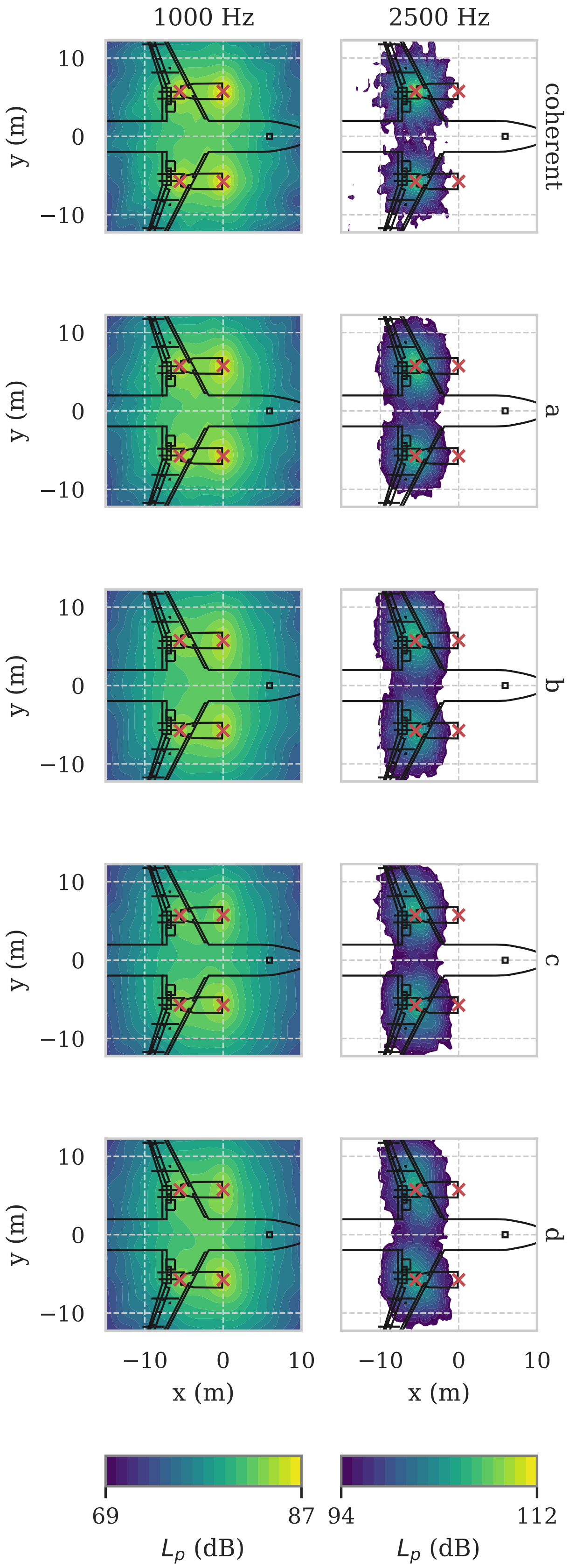

Figure 7: Beamforming results for the one-third octave bands 1000Hz and 2500Hz. The conditions are as in figure 6. At 1000Hz, the buzz-saw noise is visible at the inlet, and at 2500Hz, the BPF signal is visible at the nozzle. Thus, the delay-and-sum approach correctly localizes the sources for all conditions. The coherence loss affects the shape of the main lobes.