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A data base of outdoor transfer functions

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ABSTRACT

In many outdoor acoustic applications, the propagation channel can be modeled as a transfer function. For propagation above a flat ground, the environmental conditions vary, and a representative data base of transfer functions is needed. This study addresses the challenges of forming such a general data base. It uses a three-dimensional, Finite-Difference, Time-Domain (FDTD) model for propagating a reference wideband signal up to 250 m above a finite-impedance ground, over a range of wind strengths and directions, with consistent turbulence fluctuations. The database provides the amplitude and phase of the transfer function at fine spectral resolution. The sensitivity of the transfer functions to the various environmental parameters is analyzed. The present database can be used to readily connect any near-field signature to its propagated counterpart, in a variety of open, flat environments. The signatures of an illustrative impulse sound at 200 m in the various considered environments reproduce the large expected modulations and randomization due to the ground, atmospheric stratification and turbulence. The database can easily be enlarged to other environmental conditions with further computational resources.

Keywords: Propagation, Outdoors, Simulation

1. INTRODUCTION

Outdoor acoustics has an extensive scope of applications. In source sensing, the sound is used to extract information on the emitting source (e.g. vehicle tracking, explosion localization etc.). In these applications, knowledge is required of the relationship between the signature emitted at a source, and the signature received at a sensor or a sensors' array. By extension, noise monitoring applications (for industries, transports, entertainment, etc.) regard the human ear as sensor and the received sound as an annoyance. Last, outdoor acoustics intervenes in environmental remote sensing. The environment-induced alterations of a (known) source sound are then used to characterize the environment.

How does the environment alter a source sound to form the acoustic signature at the receiver? Formally, this issue can be assessed in the temporal or spectral domains, respectively with a convolution by the environment impulse response, or a multiplication by the environment transfer function. In simple environments, analytical solutions exist. In realistic outdoor environments, complex (e.g. 3D) propagation effects take place, and numerical solvers of sound propagation can calculate the transfer function of a perfectly known environment.

The key challenge is the computation of the transfer function *in the general case*. Indeed, the function dramatically depends on the environment – which changes with place and time (if only due to weather), and is never perfectly known. One thus needs to calculate a database of transfer functions, which spans over all considered environmental parameters, and to the best of knowledge.

Numerical approaches have been proposed for propagation in many weather conditions, for average sound level predictions in open, ground-to-ground propagation scenarii. These approaches focus on the amplitude of the transfer function, averaged over relatively large frequency bands. For impulse sounds, however, the phase of the transfer function is also required, on fine frequency bands. Besides, because it is a heavy challenge, the description of the atmospheric turbulence is often limited to a simple threshold parameterization. The oversimplification of turbulence effects may lead to biased estimates of the instantaneous and average noise level predictions (Cheinet, 2012), and biased and/or randomized sensing performance of impulse sounds (e.g. Cheinet et al. (2018).

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The present paper follow the same strategy of investigating a variety of near-surface atmospheric conditions, within a ground-to-ground propagation scenario. It is meant to illustrate that overcoming the above limitations becomes possible with present-day knowledge and resources. Specifically, it demonstrates that one can form a database of transfer functions (1) including the amplitude and phase information, (2) with explicit description of the ground and atmospheric effects (including turbulence). It illustrates some salient results of such a database.

The paper is composed as follows. Section 2 presents the sound propagation scenario and numerical models used for the calculations. Section 3 illustrates the calculated transfer functions and subsequently predicted sound signatures. Section 4 gives a conclusion.

2. NUMERICAL MODELING APPROACH

2.1 Overall scenario

The following scenario is hereafter considered, which is inspired from the ADVISE experiment (Atmospheric-Driven Variability of Impulse Sounds Experiment, Cheinet et al., 2018). A near-surface sound source (1.75 m height) emits a known sound, in the frequency range from 20 to 1250 Hz (wavelengths from 0.27 m to 17 m). The signature is desired at ranges up to 250 m – which implies atmospheric heights of relevance to sound propagation up to 25 m. The ground is composed of long grass. This scenario is rather simple, in that the source is punctual and omnidirectional, with no non-linear propagation effects. Besides, the environment is flat and open, e.g. there are no obstacles which could alter the acoustic or atmospheric fields. Last, at the considered ranges and frequencies, gaseous absorption of sound is negligible compared to other propagation effects, and is ignored.

2.2 Sound propagation model

The sound propagation model used in this study is a Finite-Difference, Time-Domain (FDTD) solution of the Linearized Euler Equations. The studies of Cheinet et al. (2012) and Ehrhardt et al. (2013) have demonstrated the relevance of this solution for sound propagation modeling through complex atmosphere and turbulence. An extensive description of the present FDTD model is given in Cosnefroy (2019); the set-up used in this study is now discussed.

- The model uses a Cartesian grid of resolution 5 cm, with a 13-points interpolation scheme in space. The spatial resolution used (0.2 times the smallest source wavelength) provides a major computational gain compared to previous versions of the model.
- The calculation is made for a moving window for each selected propagation direction. The window volume has 768 points (38.4 m width) x 512 points (25.6 m height) x 512 points (25.6 m depth). There are 7500 time-step iterations, with a Courant number of approximately 0.7, so the maximal range exceeds 260 m. Figure 1 sketches the computational approach.
- The lateral and top boundaries are modeled with perfectly matched layers (PMLs). The PML parameterization is optimized for absorption at grazing angles, after Cosnefroy et al. (2019). The front and back boundaries of the moving window also use PMLs.
- The source is taken to be a derivative-of-Gaussian pulse. It is implemented as an isotropic spatial distribution of the acoustic pressure, with full-width at half maximum 10 times the resolution.

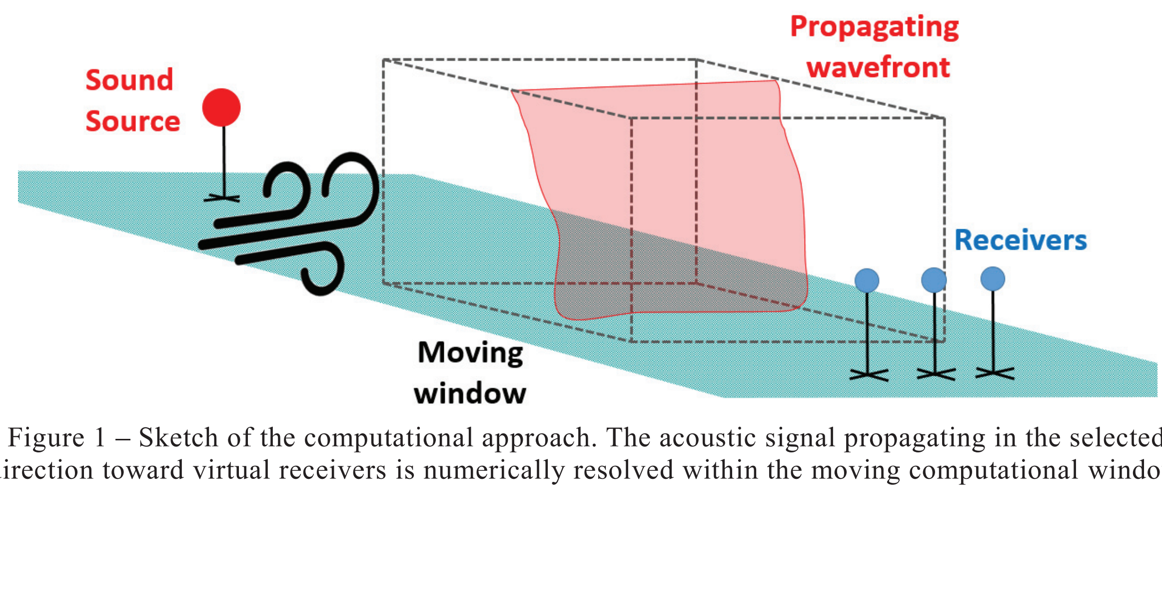

Figure 1 – Sketch of the computational approach. The acoustic signal propagating in the selected direction toward virtual receivers is numerically resolved within the moving computational window.

2.3 Environmental model

In the model, the environmental conditions respectively appear through the boundary conditions at the bottom layer (ground) and inside the model domain (atmosphere). The ground is assumed not to vary from simulation to simulation, and is taken to be horizontally homogeneous. After Cosnefroy (2019), it is modeled with a reflexion coefficient, with physical parameters fitted to the ADVISE measurements. Model-wise, the complex frequency dependence of the reflexion coefficient is approximated with a rational expansion, which allows for an efficient implementation with auxiliary differential equations in the FDTD model.

The 3D atmosphere (wind, temperature) directly enters into the Linearized Euler Equations. An appropriate first-order model is a superposition of a mean vertical stratification (horizontal wind, temperature), and homogeneous and isotropic turbulence fluctuations. The parameterization of both aspects combines the approaches of Cheinet (2012) and Cheinet et al. (2012), and is now recalled.

In the considered scenario, the atmospheric heights of relevance pertain to the surface layer, where the Monin-Obukhov Similarity Theory (MOST) generally holds. Accordingly, the stratification in mean horizontal wind and temperature is modeled with MOST relationships, with a buoyancy forcing of 0.01 mK/s, a temperature of 283 K at 2 m height, and a roughness length of 0.005 m. The friction velocity is given three values: 0.15 m/s, 0.3 m/s and 0.6 m/s, to model low, moderate and strong winds. The mean horizontal wind is assumed not to turn with height. The azimuthal angle between the mean horizontal wind and the acoustic propagation direction is given three representative values: downwind, crosswind and upwind propagation.

A turbulence model is used to generate random realizations of 3D wind velocity fluctuations. The selected von Karman spectrum has parameters (intensity, length scale) calculated with the MOST parameters above – whereby a consistent prescription of the turbulence and stratification. For each set of MOST parameters, a Monte Carlo approach is adopted with 30 turbulence realizations. An additional simulation with no turbulence is also performed. The temperature turbulence is ignored, as it usually has a lesser effect than wind turbulence. Since the turbulence realizations are uncorrelated, the temporal coherence of the atmospheric field (and of the propagated acoustic field) is ignored.

Overall, the database includes 3 wind forcings, 3 directions, 30+1 turbulence realizations, which gives 279 simulations. The calculations are run on a high performance computational cluster, with a massively parallel interface programming. For each simulation, the pressure time series at many, predefined receiver positions are stored in the database. Once this computational effort is carried out, the database takes the form of a lookup table, which provides the transfer function, for each simulation and each receiver's position.

3. RESULTS

3.1 Transfer functions

We start the analysis with a discussion based on the transfer function amplitude. Figure 2 shows the environmental gain (in dB) with frequency, obtained at 200 m and at a height of 1.75 m. The spherical spreading is compensated, so with no ground, the gain would be zero (dashed line), and with constructive interferences above a perfectly reflective ground, the gain would be + 6 dB.

The case which minimizes the atmospheric effects has low wind, crosswind propagation, with no turbulence (panel d). The departure from the no-ground case reveals the impact of the ground: increased lower frequencies, with a dip at 250 Hz and larger frequencies. Turbulence tends to randomize the gain compared to the no-turbulence case - a process called scintillation. The scintillation rate increases with frequency. The crosswind, no-turbulence simulations remain virtually unchanged as the wind increases, as the mean wind projection is nulled in crosswind propagation. On the other hand, an enhanced wind implies an enhanced turbulence (by virtue of MOST relationships), which in turn implies more scintillation. Hence, the wind increase has the indirect effect of increasing the crosswind scintillation. The obtained result also illustrates the importance of a quantitative description of atmospheric turbulence, if one is to consider the variability of the pressure field.

In a general sense, the downwind direction features an increase of the highest frequencies, with a slightly more pronounced dip around 200 Hz. Both effects increase with the wind strength. Given the modest solar forcing, the downwind propagation essentially stands for downward refraction, which causes the noted features. Upwind propagation leads to upward refraction, with opposed effects.

The simulations with no turbulence ignore scintillation. Still, they provide a viable model of the mean gain with turbulence, in configurations outside a shadow zone (downwind, crosswind, upwind with low wind). However, as the wind becomes non negligible, the no-turbulence simulation gain undergoes a dramatic loss at high frequencies in the upwind case. Conversely, the simulations with turbulence feature a plateau between -25 to -20 dB. Hence, in such shadow zones, the no-turbulence prediction becomes a poor estimator of the expected gain.

Qualitatively, the above effects are known. Their quantitative capturing in a systematic set of 3D FDTD simulations appears to be original. Indeed, the present approach makes far less approximations than, e.g., the study by Cheinet (2012). Among others, his parabolic equation approach (like many others) has a limited frequency range. It is solved on a 2D (range, height) domain, while the transposition to 3D is not trivial in presence of turbulence. The solved stochastic equation makes use of the Markov approximation. None of these assumptions is required in the present 3D FDTD approach.

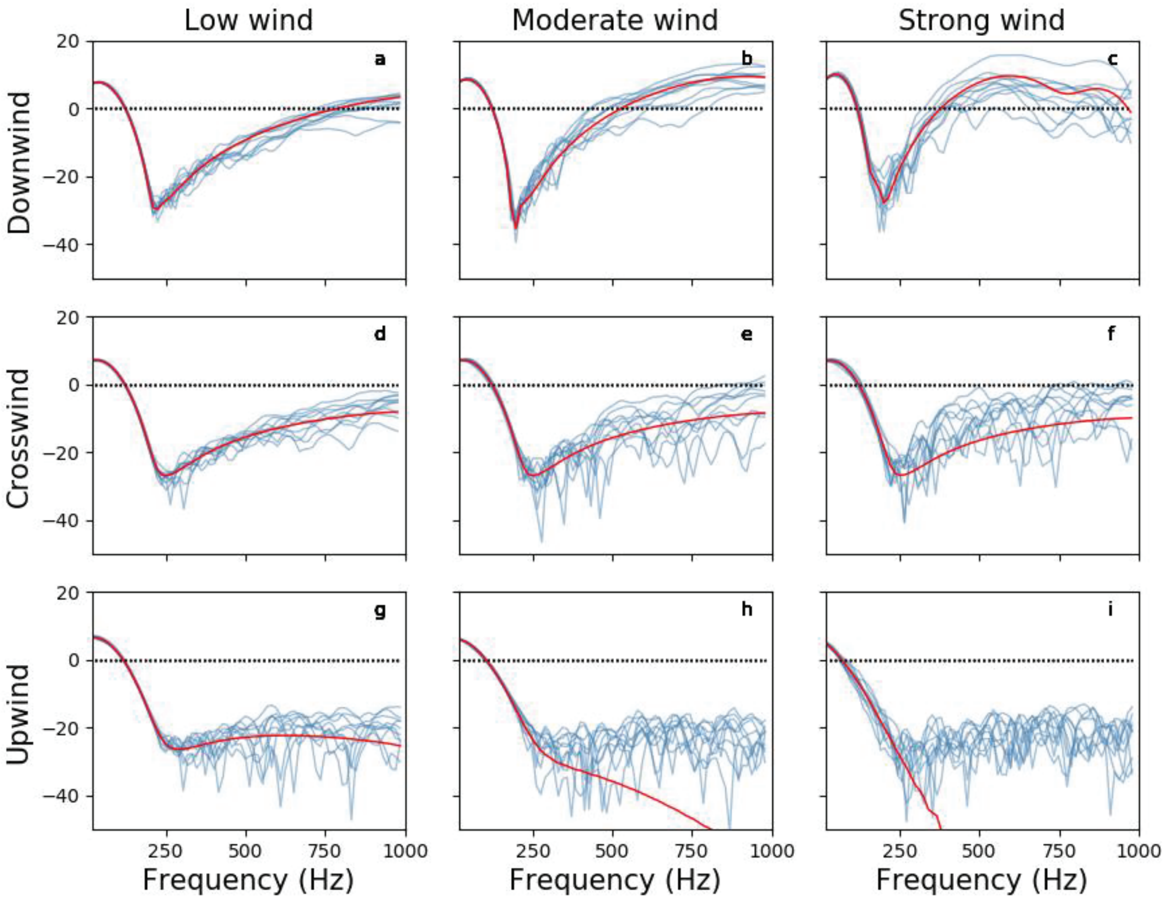

Figure 2 – Environmental gain (in dB, taken as 20 $\mathrm{Log}_{10}(A_{FDTD}/A_{FF})$, with A_{FDTD} the amplitude of the transfer function simulated with the environment, and A_{FF} the amplitude of the free field transfer function), with varying wind directions and strengths, at range 200 m and height 2 m. The dotted line is in free-field, the red line is without turbulence, the blue lines show 10 simulations with turbulence.

3.2 Propagated signatures of arbitrary sounds

The above section considered the amplitude of the transfer function. The phase of the transfer function further carries further time-domain information. Combining the two, one can readily derive the time-domain signature at any receiver's position, for any desired source signal and scenario (Sec. 1). A refinement is introduced for a more stable calculation of the transfer function at low frequencies (Cosnefroy, 2019).

As an example, the source signal is taken as the loudspeaker impulse sound measured in Cheinet et al. (2018). The near-field signature spans over the spectral range 150 – 1100 Hz, within the frequency range under scope with the formed database. Figure 3 shows the derived signatures at 200 m, for the moderate wind case, in the upwind and downwind directions.

The sound convection by the mean wind explains the shorter times-of-arrival in the downwind propagation, compared to upwind. At 200 m, the fluctuations in time-of-arrival are smaller than the duration of the first peak. As a result, the wander of the pulses in presence of turbulence is not too marked. Larger ranges may lead to larger wander. In the downwind direction, the pressure peak typically reaches 0.15 Pa. The upwind peak is of the order of 0.005 Pa. Thus, the overall effect of a changing wind direction induces a difference of 30 dB in the peak pressure at 200 m. This can be understood in light of the +6 dB versus -20 to -25 dB amplitude gains noted downwind versus upwind.

Downwind, the signatures are dominantly driven by the deterministic mean downward refraction. Thus, the downwind signature prediction without turbulence is rather representative of the averaged signatures with turbulence. The scatter due to turbulence is of several dB, still. Conversely, the deterministic contribution of mean refraction is a poor estimator of the transfer functions in the upwind propagation case (see above). Hence, the predicted signature without turbulence is poorly informative of the upwind signatures with turbulence. For example, there is a 12 dB difference between the peak of the no-turbulence pressure time series, and the largest peak obtained among the simulations with turbulence (not shown here). The turbulence results also feature notably more high-frequency oscillations than the result without turbulence. The impact of such differences is major for applications like (impulse) noise pollution or source classification.

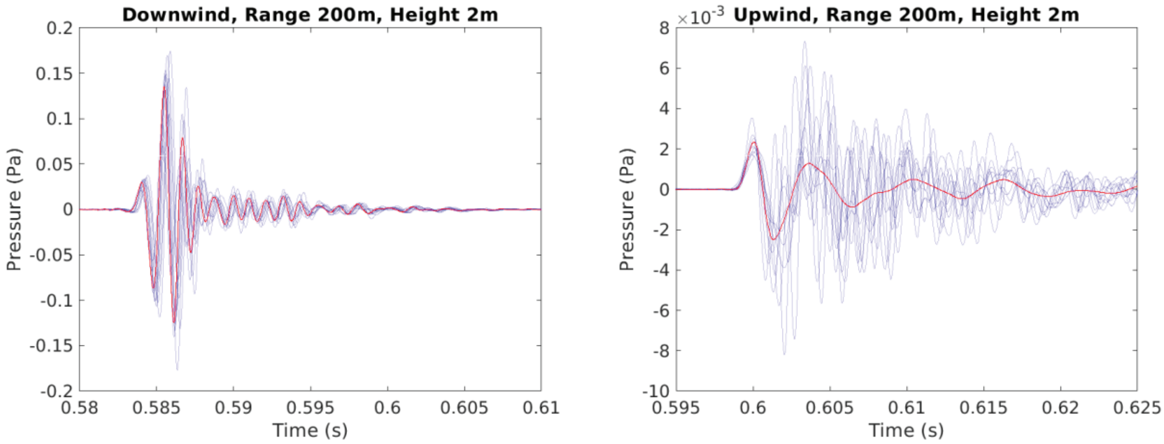

Figure 3 – Acoustic signatures derived from the database for an impulse sound at range 200 m. The red line is without turbulence, the blue lines show 10 simulations with turbulence.

4. Conclusions

Many, if not all, applications of outdoor acoustics require the relationship between a near-field source signature, and the signature received at distant receivers. Forming databases of such transfer functions for representative outdoor conditions has been investigated for decades. Previous proposals in this line focus on the ground and meteorological effects, in a ground-to-ground propagation scenario. They generally suffer from limitations, such as missing information on the time-domain content of the propagated signal, missing information due to averaging over frequency bands, or absence of significant propagation effects due to turbulence (scintillation, and scattering in shadow zones).

The present paper pursues the strategy of spanning over a representative variety of environmental conditions in a ground-to-ground propagation scenario. It demonstrates that one can form a database of complex transfer functions with explicit description of the turbulence effects. To this purpose, the environmental conditions are consistently modeled, with physical descriptions of the ground reflexion, meteorological gradients and 3D wind turbulence. The source sound is propagated with a 3D FDTD model which correctly predicts sound propagation in presence of complex ground and atmospheric effects.

The formed database provides the complex transfer function at ranges up to 250 m, over 1 ground type, 3 wind strengths, 3 wind directions, without and with turbulence (30 realizations). It can be used to readily derive the signature at a distant receiver, for any desired source signal within the frequency range of relevance. Analysis reveals the major effects of the environment (including turbulence) on an exemplary impulse sound.

Now that the transfer functions database is formed, it can be applied to analyze other source signals, and the signals at other receiver’s ranges and heights, at no additional computational expense. This opportunity appears to be original and of notable practical significance. In effect, it implies that the present database can cover, or give a good approximation, of a very large number of propagation scenarii in open, flat environments.

There are some assumptions in the present approach, which may require careful considerations if to be revised: punctual and omnidirectional source, applicability of MOST and of the selected model of turbulence, flat and horizontally homogeneous ground etc. On the other hand, the present database could readily include other parameters of sensitivity, e.g. the buoyancy forcing (due to e.g. surface heat fluxes), the ground type or the source height. Adaptations of the source, model domain and resolution would also extend the frequencies and ranges of interest. Such extensions raise no other challenge than the available power for computation.

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