

## On-Going ISL Research in Modeling Acoustic Propagation in the Atmosphere

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### ABSTRACT

*Atmospheric boundary layer processes, like wind, stratification, or turbulence, strongly affect the acoustic propagation. In the context of sensor development, they must be accounted for, to determine the effective sensor performance. Field experiments are the essential method to derive these sensitivities. However they face high costs and the difficulty of measuring the many relevant parameters. Hence realistic modeling of acoustic propagation is a very useful complement.*

*In the last decades, the research Institute Saint-Louis (ISL) has developed and used some modeling tools that can handle the impact of a mean atmospheric stratification. Modeling the acoustic propagation in the time domain is a recent development, still computationally intensive, which further enables to deal with turbulence and obstacles. This method has been developed at ISL following Wilson and Liu (2004). The results can be compared with other codes in standard benchmark cases.*

*Sensitivity to atmospheric features can then be analyzed by off-line coupling with atmospheric models. A difficulty there is to model the atmospheric features at the adequate resolution. ISL efforts in that direction are based on synthetic fluctuations generation and Large-Eddy Simulation. Preliminary tests will be presented, including the impact of turbulence on acoustic propagation.*

### 1. INTRODUCTION

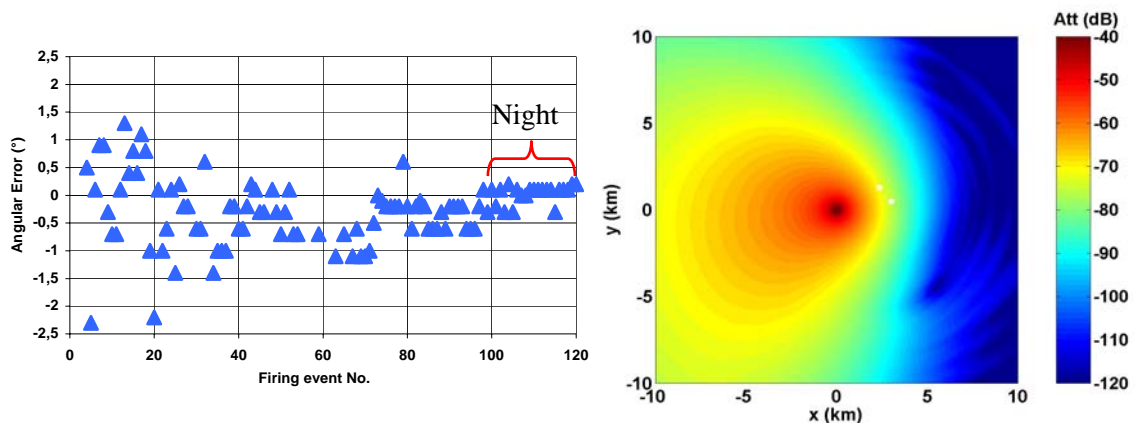
The propagation of acoustic signals has been intensively studied, due to environmental considerations (traffic noise, airport noise), and to its interest in terms of military applications. In the domain of Intelligence, Surveillance and Reconnaissance (ISR), acoustic sensing provides a low-cost, passive and omni-directional assessment of the battlefield environment. It is particularly appropriate as an unattended system (or network), disposed on or near the ground, effective at audible or near audible ranges (50-500Hz). From a sensor development point-of-view, optimizing the acoustic sensing performance requires long-term R&D efforts in three complementary directions: (1) documenting the sources characteristics (signature, geometrical divergence, etc), (2) analyzing the environmental impact on the signal propagation, (3) improving the sensing technology.

It is well-recognized that the environmental conditions largely modulate the acoustic propagation. For ground-based sensors, the nature of the ground, the vegetation and the terrain features (obstacles) play an important role at high acoustic frequencies. The propagation medium (air) can also alter the acoustic signals, through refraction, diffraction or absorption. This is especially true in the atmospheric surface layer, characterized by strongly varying wind gradient, temperature stratification, and turbulence intensity.

Cheinet, S.; Naz, P. (2006) On-Going ISL Research in Modeling Acoustic Propagation in the Atmosphere. In *Battlefield Acoustic Sensing for ISR Applications* (pp. 19-1 – 19-12). Meeting Proceedings RTO-MP-SET-107, Paper 19. Neuilly-sur-Seine, France: RTO. Available from: <http://www.rto.nato.int/abstracts.asp>.

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As now illustrated, this issue has direct implications on military purposes. An acoustic sensor array has been designed at ISL in order to detect artillery guns and estimate their azimuthal direction [1]. Its performance was experimentally evaluated. Figure 1a presents the raw angular error, showing that a global error of one degree was achieved during the experiment. Noteworthy, the localization strongly improves with time. Actually, the wind velocity decreased during the experiment, and the last estimates were performed at night in still conditions. The meteorological conditions affect the signal-to-noise ratio and the apparent sound phase, which in turn affect the localization. With simple diagnostics, it is not possible to determine whether the scatter in the first part of the experiment is due to the daytime turbulence, to the temperature gradient or to the synoptic wind. More generally, assessing the impact of the atmospheric features in a quantitative manner is a major difficulty in acoustic sensing. The basic reason is the number of relevant parameters, and the difficulty to characterize them simultaneously.



**Figure 1: (a) Azimuthal error of the ISL array retrieval with the firing event number i.e. with time. The meteorological conditions changed during the experiment. (b) Map of sound attenuation at the ground level (at 10Hz), as predicted by the FFP model (through an angular scan of the 2D vertical planes computations around the source, see text). After [1].**

In that respect, the development of physical models of acoustic propagation seeks to provide controlled and reproducible numerical testbeds. The realism of these models depends on the understanding and representation of the physics at work (including atmospheric processes) and on the available computer power. Numerical models are also the cornerstone of another application of interest to military applications. The decision aid aims at predicting the sensing performance in order to optimize the operation decision (which sensor, which schedule, which mission...). R&D efforts in this respect are to develop fast and reliable modeling tools for the evaluation of the sensor performance, and to feed them with an appropriately documented / predicted atmospheric state. Figure 1b shows the sound attenuation field at the ground level as predicted with a propagation model fed with in-situ meteorological observations. This type of diagnostics is of great help for practical applications. Combined with the intrinsic directivity of the source, it allows to estimate the noise level map, and/or to predict the detection range. Of course, a critical pre-requisite is that reliable atmospheric profiles are available.

ISL has a well-established expertise in conceiving some acoustic sensors for ISR applications. It also regularly performs some field experiments to better characterize the military sources signatures. In this paper, we present the ISL research on the topic of acoustic propagation in the atmosphere, with emphasis on the modeling side. First, we will discuss the experimental results collected over the past decades, and the propagation models used at the institute to interpret them. It will be shown that complementary models are needed to analyze some data. In the second part of the paper, we will discuss the recent efforts in these directions, presenting preliminary results of the models under development. The last part will briefly outline some future research topics.

## 2. ACOUSTIC PROPAGATION AT ISL

### 2.1 Experimental characterization

The strong impact of the atmospheric conditions on acoustic propagation has motivated a number of dedicated experiments, among which those conducted in the context of the NATO RSG 11 group. The JAPE-91 experiments were dedicated to measure the propagation of acoustic waves under carefully documented meteorological and terrain conditions [2]. A substantial instrumentation (acoustical, meteorological, etc.) was brought into operation on the field, with pure and mixed tones being broadcast by two pairs of loudspeakers distant from 1km. Figure 2 shows the sound pressure level measured when the wind was along the experimental set-up. The wind conditions appear to result in a difference of 30dB at 1000m, due to upward (resp. downward) refraction in the upwind (resp. downwind) direction. This difference increases with the frequency and decreases with the height of the source.

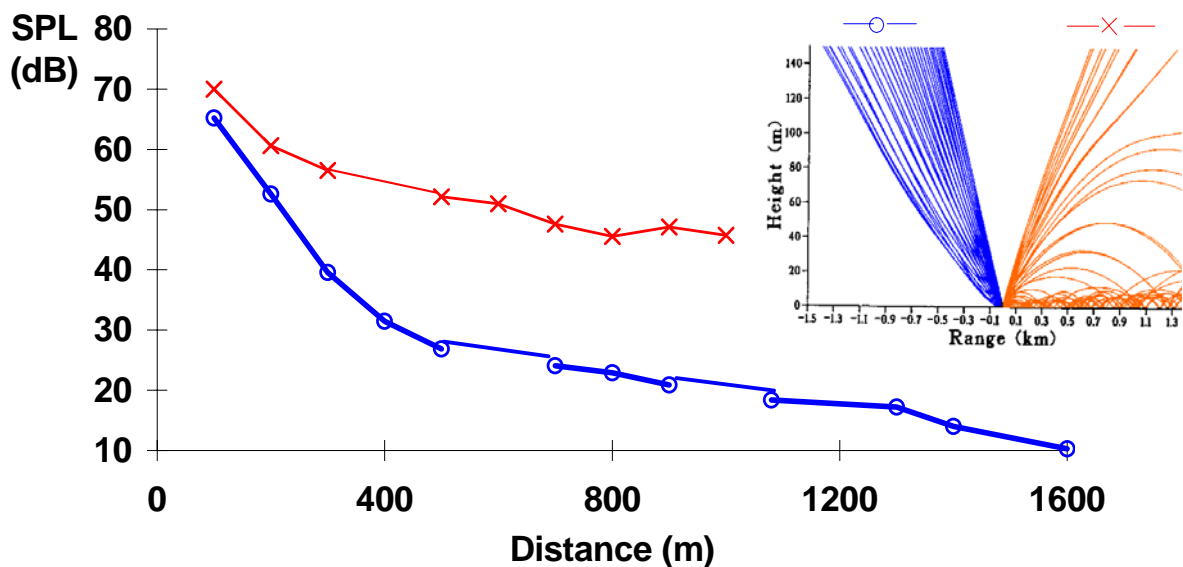


Figure 2: Influence of the wind direction on the acoustic level at 500 Hz, with upwind direction in blue, downwind direction in red. The upper-right panel shows a ray-tracing simulation of the impact of wind direction on ray trajectories with height (see below). After [2].

Another recent experimental campaign took place in the Autumn 2005 in Yuma (Arizona), as part of the NATO/RTO/SET/TG53 effort. The ISL participation was dedicated to examine the frequency ranges usable for the detection of small arms and mortar firing with the acoustic array presented above. As discussed in [1], it appears that the maximum energy is around 10-50Hz for artillery guns, 50-100Hz for small mortars, and above 100Hz for infantry rifles. During the experiment, the meteorological features were observed to result in major disturbances in the signals. The combined effects of temperature and wind gradients resulted in a greater sound attenuation in the middle of the day than at sunset or sunrise, in full consistency with the above result on localization. Specifically, the wind advection leads to the deflection of the acoustic waves, the sound is more attenuated upwind and reinforces downwind. The temperature gradient refracts the acoustic rays, resulting in shadow zones as well as focusing zones.

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### 2.2 Standard models used at ISL

Two pre-existing models are available at ISL, a ray-tracing algorithm [2] and a so-called Fast-Field Program (FFP, see [3]). These two models were evaluated in the benchmark cases of [4]. As mentioned above, for practical applications or comparisons with data, the vertical profiles of the atmospheric parameters (wind, temperature, pressure, etc.) must be available at a relatively high resolution (locally determined, several times every day). These meteorological profiles are used as input to the acoustic propagation models, assuming that the atmosphere is horizontally homogeneous.

The ray-tracing approach computes the trajectory of acoustic rays emitted by the source, with a constant-phase ray being computed from the coupled equations :

$$\frac{d\vec{r}}{dt} = \vec{V}_E + \frac{\vec{k}}{\|\vec{k}\|} \cdot C$$

$$\frac{d\vec{k}}{dt} = -\|\vec{k}\| \cdot \vec{\nabla} C - k_j \cdot \vec{\nabla} V_{E_j}$$

with  $C$  the sound speed,  $k$  the wave vector,  $t$  the time, and  $V_e$  the wind velocity. This set of equations results in the modulation of the ray curvature by the meteorological profiles. The ground is treated as perfectly reflecting. Note that the acoustic pressure at a given point is not a direct product of the model, although it can be indirectly derived, at least far from caustics. Figure 3 shows the ray-traces simulated with varying temperature gradient, with downward refraction under stable stratification (early morning), and shadowing under unstable stratification (afternoon).

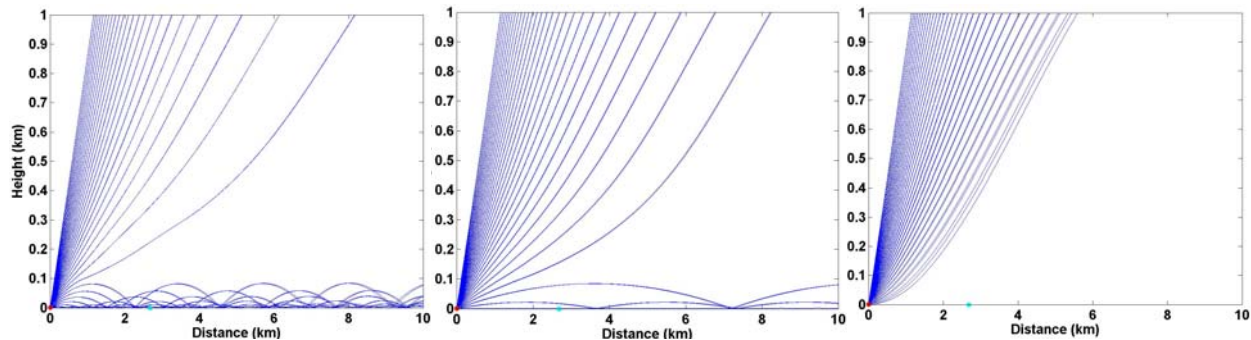


Figure 3 : Ray diagram simulated with the meteorological conditions of one particular day of the TG53 experiment, according to: left: 7a.m., center : 9a.m., right: 1p.m. After [1].

The FFP approach assumes that the acoustic pressure can be described by a cylindrical wave, slowly modulated by the distance of propagation. The wave equation can be written in the parabolic form :

$$\nabla^2 p - \frac{1}{C_e^2} \cdot \frac{\partial^2 p}{\partial t^2} = -4\pi \cdot \delta(x) \cdot \delta(y) \cdot \delta(z)$$

with  $\delta$  the delta function (with the source at the origin), and  $C_e$  the effective sound speed (accounting for the wind in the propagation direction). Applying the Hankel transform, the obtained differential equation is discretized and solved numerically in a vertical plane (2D). The integration is done for each elementary frequency, after the introduction of the adequate Green function. The model uses dedicated propagation equations inside the ground, and assumes that the atmosphere is horizontally homogeneous.

Overall, the model-to-model and model-to-data comparisons lead to the following conclusions. Under downward refracting conditions (downwind, stable stratification), the sound pressure levels computed with the two models are close to the observations, at least for low frequencies and short

propagation ranges. Figure 4 compares the FFP model prediction with some measurements performed during the AMI-2 experiment [2]. In the downwind direction, typical model errors are of 5 dB up to ranges of 4 km. In that context, the ray-tracing (not shown) is still useful even at the limit of validity of its high-frequency underlying approximation. For longer ranges or upward refracting atmospheric conditions (upwind, unstable stratification), the results are more contrasted. These deficiencies are more important if the sound level is influenced by the diffraction of sound waves by turbulent eddies, a process that is structurally ignored in both models.

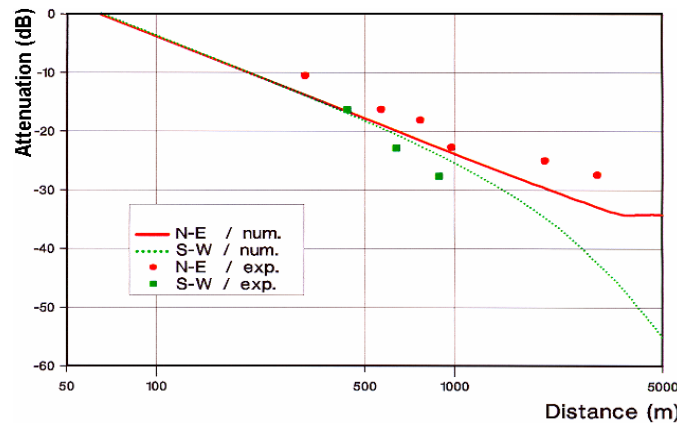


Figure 4: Sound attenuation during a summertime day with a S-W wind (AMI-2 experiment, at an helicopter main frequency). Lines: FFP simulation, symbols : observations. After [2].

### 3. ON-GOING MODELING DEVELOPMENTS

The limitations of the above models motivated us to develop a scheme that is able to account for sound speed and wind fluctuations. Contrary to frequency-domain approaches, the time-domain technique operates one signal in one calculation, and can readily incorporate the atmospheric fluctuations and the obstacles geometry. For these reasons, it was decided to opt for a time-domain approach. The numerical cost presently limits the applications to shorter ranges / lower frequencies, but is to be challenged by the continuous increase in the computer power.

#### 3.1 Description of the model

The model we developed is based on [5] (Wilson and Liu, 2004, hereafter WL), in which the reader will find an extensive discussion on the algorithmic choices. In the time-domain, the acoustic signal is represented by four prognostic variables, updated at each time step on a 3D grid. The prognostic variables are the acoustic pressure  $pa$  and the three coordinates of the acoustic particle velocity  $ua$ . The prognostic equations (which give the time evolution of the sound signal pattern) write as :

$$\frac{\partial pa}{\partial t} = -(v \cdot \nabla) pa - \rho c^2 \nabla \cdot ua + \rho c^2 Q$$

$$\frac{\partial ua}{\partial t} = -(v \cdot \nabla) ua - (ua \cdot \nabla) v - \frac{\nabla pa}{\rho} + \frac{F}{\rho}$$

where  $F$  and  $Q$  are the source terms corresponding to  $pa$  and  $ua$ , respectively. All the other variables are specific to the atmospheric conditions:  $v$  is the wind,  $c$  is the sound speed,  $\rho$  is the density. In brief, the

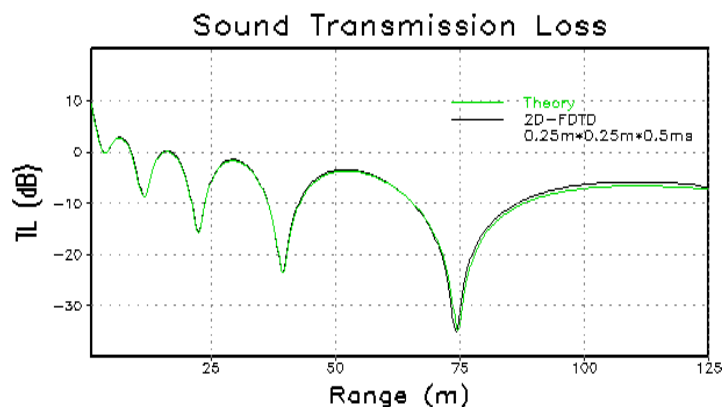


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first r.h.s. terms are the advective tendencies of the signal, whereas the second r.h.s. term in the second equation characterizes the impact of wind spatial variations.

The 3D grid is taken equidistant, with a half-level staggering of the velocity components. The spatial derivatives in the above equations are written as first-order finite differences (higher-order schemes may provide a greater robustness). Typically, the grid-spacing is chosen as one tenth of the signal wavelength, to allow a sufficient wave discretization. We use a fourth-order Runge-Kutta time integration. WL show that this choice, if not the most efficient, leads to a robust integration. The time-step is limited by the Courant criterion, which, combined with the grid-spacing, leads to one tenth of the signal period. At the domain boundaries, we use the equations of propagation in a porous medium proposed by WL. They formulate these equations in terms of standard ground parameters, and show that, with an artificially small static flow resistivity, the medium acts as an absorbing boundary (which avoids reflecting waves). Generally speaking, the model predictions close to the ground are very sensitive to the ground parameters. This realistic behavior calls for a quantitative calibration of the selected ground model and parameters.

In the present applications, we restrict to quasi-monochromatic sources, and prescribe the acoustic pressure at source point(s) as a tapered cosine function. The signal frequency is typically of 50Hz (a frequency useful to ISR, see above), with a spatial resolution of the order of 0.5m. For a single processor computer, the 3D version of the code makes it possible to address the short-range sound propagation (e.g. around obstacles). The treatment of longer ranges requires either to use parallel computing, or to use a 2D version of the code. This latter option is straightforward and is selected hereafter.

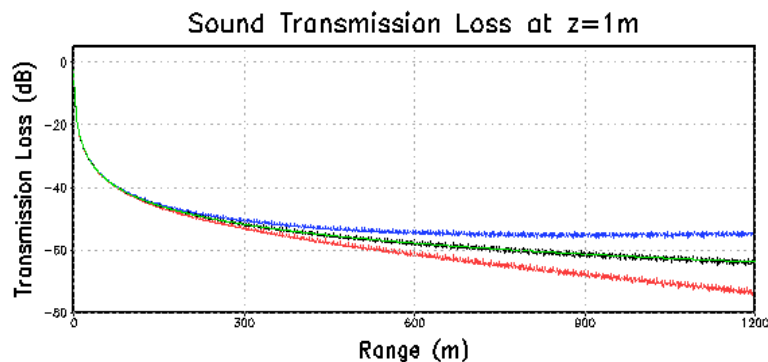


**Figure 5 : sound transmission loss along a horizontal path, for a 50Hz source continuously emitting at 20m high above a perfectly reflecting surface. Green: theoretical solution (based on the method of images), black: model prediction.**

As a first evaluation test, we have considered the academic case of a source emitting in a medium of constant sound speed, and compared the sound transmission loss with range against the theoretical (3D cylindrical) spreading that corresponds to our 2D problem. *NB: The sound transmission loss (in dB) is defined with respect to the acoustic pressure at a distance  $r_0$  from the source (usually taken as 1m), following  $TL(r) = 20 \log\{P(r)/P(r_0)\}$ .* The comparison gives an excellent agreement (see also below). We have included a perfectly reflecting surface, in order to simulate the Lloyd-mirror-like interferences pattern (e.g. upper left part of fig 7 panels). A 50Hz source is set at 20m height, the resolution is 0.25m, the time-step is 0.5ms. Figure 5 shows that the model quantitatively reproduces the theoretical variations with range. The sensitivity to resolution has been analyzed; the model remains quite reasonable in that respect (see WL).

### 3.2 Impact of atmospheric stratification

As discussed in the introduction, one motivation of the present study is to analyze the impact of atmospheric features on acoustic propagation. In this section, we focus on the impact of the mean structure, characterized by the vertical stratification (in the atmosphere, the mean horizontal variations are at scales much larger than those of interest to us). The atmosphere is felt through three parameters (see above):  $v$ ,  $\rho$  and  $c$  (proportional to the square-root of the temperature). The wind may be prescribed independently from the others (in the first approach). The temperature, density, pressure and height are related by the perfect gas and the hydrostatic laws. In order to illustrate the sensitivity of the acoustic propagation to the sound speed gradient, we break this physical coupling by imposing a null wind, a constant density with height, and set the sound speed gradient independently.



**Figure 6: Maximum over 4.1s of the transmission loss at 1m high, for a 34Hz source above a reflecting surface. The line color comes with the atmospheric gradient of sound speed ( $G$ ), according to : black:  $G = 0 \text{ s}^{-1}$  (green: theoretical result), blue:  $G = 5 \text{ s}^{-1}$ , red:  $G = -5 \text{ s}^{-1}$ . Results are divided by the square root of range in order to account for the three-dimensional spreading.**

Figure 6 is generated from a simulation over a domain of 1600m\*450m (resolution of 1m, time step of 2ms), with a 34Hz source at 1m high. The zero-gradient case matches the analytical spherical spreading. A negative sound speed gradient, as found at daytime over a sun-heated ground, produces an upward sound refraction, leading to a loss in the signal propagation. Conversely, a positive sound speed gradient, as expected in the nocturnal stable surface layer, leads to downward refraction and reflection at the surface, i.e. ducting in the lowest 50m. At the considered ranges, the loss decreases less than the asymptotic cylindrical spreading, suggesting that some acoustic rays are still bent downward from higher levels. Overall, the atmospheric vertical structure has a strong impact on detection ranges, and the model is able to address this impact in a quantitative manner.

### 3.3 Impact of turbulence

One strength of the time-domain approach is the ability to ingest any background atmosphere without changing the core propagation model. This section focuses on the impact of atmospheric turbulent fluctuations (of  $v$ ,  $\rho$  and  $c$ ) on sound propagation. Obviously, a statistical analysis based on 3D considerations is necessary in quantifying this impact, because there is no homogeneity in the direction perpendicular to any 2D plane, and because of the intrinsic variability of turbulent fluctuations. Keeping this in mind, we hereafter present our efforts oriented towards generating a realistic snapshot of the atmospheric state at the appropriate scales. For a wavelength  $\lambda_o$ , the main sound scatterers at the angle  $\theta$  are the eddies of scale  $L_B = \lambda_o / \{ 2 \sin(\theta/2) \}$  (see [6]). According to the applications,  $L_B$  typically ranges from one to several hundreds of meters. Such micro-meteorological scales can not be forecast in a deterministic sense (by weather modeling), nor can they be modeled with a simple unified approach.

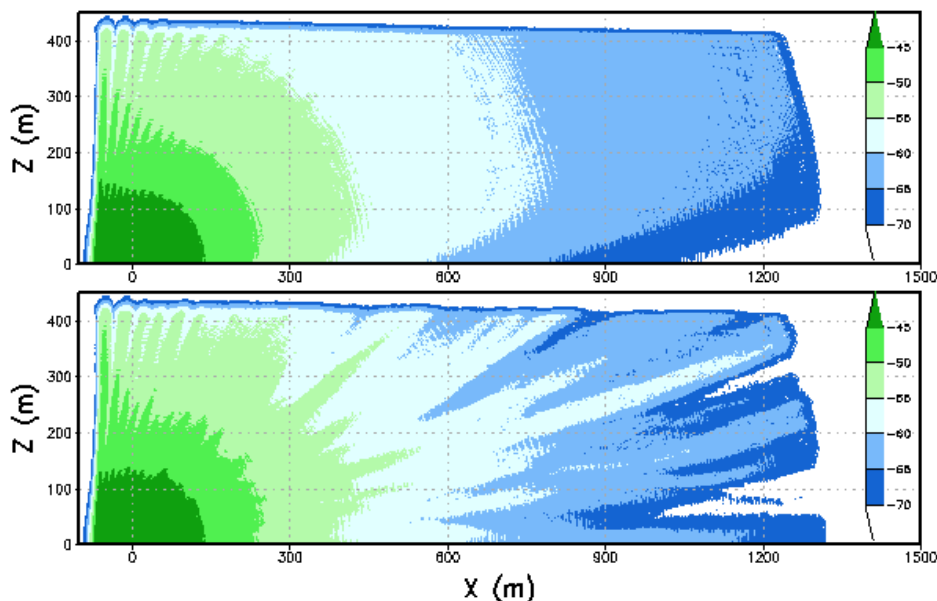
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The smaller-scale turbulence is standardly described as an energy cascade that transforms larger eddies into smaller, eventually dissipated by viscosity. The self-similar behavior at intermediate scales (far from energy input as well as from viscous dissipation) defines the inertial range. Assuming that the inertial range turbulence is homogeneous and isotropic, some theoretical arguments (supported by experimental data) specify the variance distribution in terms of the eddy size. More precisely, the 1D spectrum  $E$  of the (2<sup>nd</sup>-order) auto-correlation function of a scalar can be approximated e.g. by a Von Karman form :

$$E(k) = G \sigma^2 \frac{k^4 l^5}{(1+k^2 l^2)^{\frac{17}{6}}}$$

where  $k$  is the wave number ( $2\pi/\lambda$ , with  $\lambda$  the eddy size),  $\sigma$  is the r.m.s. of the fluctuations,  $G$  is a numerical constant, and  $l$  (the so-called integral length) scales the size of the most energetic eddies. In the inertial range, this expression decreases as  $k^{-5/3}$ .

From this basis, we have developed a Random Fluctuation Model (RFM) that takes  $\sigma$  and  $l$  as input, and sorts a scalar 3D distribution that matches the Von Karman spectrum (e.g. see [7]). Our treatment of 3-components wind fluctuations follows [8] for the incompressibility of the flow. This method allows to generate controlled fluctuations of each quantity of interest separately. Figure 7 shows the qualitative impact of 2D wind fluctuations (of r.m.s. 1.5m/s, a relatively strong value) in the upward refraction case above. Turbulence affects sound levels through refocalisation / defocalisation of the acoustic paths. Clearly, such modifications would have a strong impact on the detection range. A closer examination shows that the angle-of-arrival of the acoustic wave changes, which would affect the localization / reconnaissance of the source.



**Figure 7 : spatial distribution of the sound transmission loss (in dB). Top : same simulation as the upward refraction case of Fig 6. Bottom : same simulation except with 2D fluctuations of the wind from a 3D RFM simulation (r.m.s. 1.5m/s, integral scale 20 m).**

Whereas our implementation of the RFM reveals the sensitivity of the propagation to the fluctuations of one parameter, it suffers from structural flaws in the simulation of atmospheric turbulence. For example, the imposed fluctuations have no height-dependence, which is strongly unrealistic. Besides,



it does not account for the correlation of temperature and wind fluctuations. This feature is at the basis of the daytime turbulence over land [7], and is of importance to acoustic propagation [8]. Non-trivial developments have been proposed in the literature in order to palliate these deficiencies. These attempts have to face the fact that the larger-scale boundary layer turbulence is largely anisotropic and inhomogeneous, and that its characteristics dramatically vary with the wind, temperature and humidity profiles, and the surface, radiative and tropospheric forcings.

An alternative approach to describe the larger scales of turbulence is to perform the full integration of the Navier-Stokes equations, using a Large Eddy Simulation (LES). LES have a typical resolution of 20m (with domains of several kilometers). In the last decade, they have been shown to realistically simulate the larger-scale turbulence structure in a number of boundary layer types (except very close to the surface). We have performed a propagation simulation with the atmospheric fields (2D slab of the wind, density and temperature) of the LES of [9]. We use the same case study, except for the wind profile and forcing (set to 0), and the surface heat fluxes (latent flux set to  $35\text{W}\cdot\text{m}^{-2}$ , sensible flux set to  $500\text{W}\cdot\text{m}^{-2}$ ). The lower 500m characterize a convective, non-sheared boundary layer. The general propagation picture (Figure 8) gives a slightly upward refraction, with fluctuating noise levels (less than in the RFM-based case, which has stronger fluctuations close to the surface). This type of simulation has the potential to give many insights on the acoustic propagation in real boundary layers. On the other hand, it is difficult to isolate the sensitivity to one atmospheric parameter.

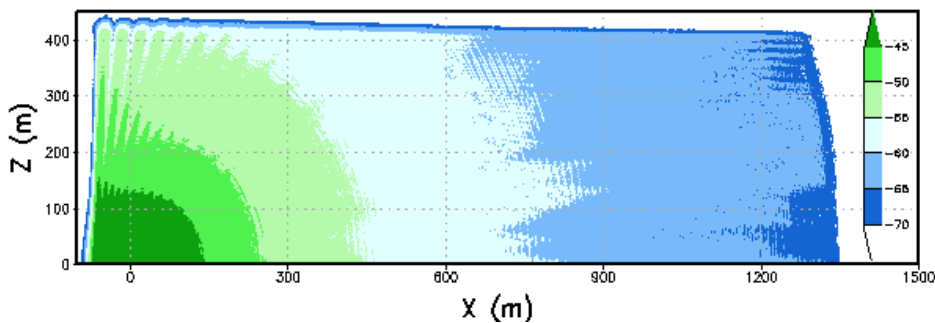


Figure 8 : spatial distribution of the sound transmission loss (in dB) with same set-up as Fig 7, except with fluctuations of the wind, temperature and density extracted from a LES simulation (snapshot of a 2D slab after 2 hours of run).

#### 4. SUMMARY AND PERSPECTIVES

This report aims at introducing the problems met at ISL in the domain of outside sound propagation, and the modeling efforts accomplished to address them. It has been shown that acoustic sensing is quite useful and efficient to ISR tasks. Recent ISL realizations in the domain include the detection and localization of artillery shots. The ISL experience confirms the well-known issue that a major limitation of acoustic sensing is its strong modulation by atmospheric properties. The complexity of the subject requires to use models to perform controlled (numerical) experiments. Fed with appropriate meteorological measurements, the models available at ISL can capture the impact of downward refracting atmospheric conditions (stable stratification, downwind). However, they misrepresent the sound propagation in upward refracting conditions, especially when it is affected by the atmospheric turbulence.

To face this issue, the time-domain model developed at ISL follows the recent scheme by WL. Considering the sensitivity to atmospheric stratification, the model shows correct qualitative trends, e.g. the upward/downward sound refraction according to the sound speed gradient. Quantitative estimates in standard benchmark cases are to be performed in the near future. The analysis of the impact of turbulence

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requires some dedicated developments in order to simulate the atmospheric fluctuations (at least not too close to the surface). The Random Fluctuations Model provides controlled fluctuations characteristic of small-scale turbulence, whereas the Large Eddy Simulation has the potential to realistically reproduce the larger-scale eddies. Preliminary tests demonstrate that the time-domain model is sound to quantify the effects induced by turbulence on the propagation of acoustic signals. However, the required 3D treatment may be rather demanding in terms of computer resources.

Whereas the time-domain technique provides an up-to-date phenomenological assessment of sound propagation, it is clearly a research tool, with some limitations (e.g. numerical cost). In comparison, the pre-existing codes (e.g. ray-tracing) provide a quick response, with identified domains of validity (see above). They are appropriate to a number of applications, like decision aid. One purpose is to use the time-domain model to develop and calibrate parameterized improvements of these codes, e.g. to reliably account for turbulence effects. One remaining critical point is the interface with synoptic weather predictions, that drive the boundary layer structure. Numerical weather models contain many information on the boundary layer structure [12], but the standard weather outputs are partly inadapted to acoustic propagation requirements (e.g. vertical resolution, no data on turbulence). Improvements are probably accessible towards a more appropriate match between these modeling tools.

In the context of ISL activities, our development of a time-domain model calls a number of future specific researchs. First, one can study the propagation of sound around obstacles (diffraction, multiple-paths, etc). This is particularly interesting in the light of some military needs, e.g. to detect and localize threats in urban areas. In the same line, we have mentioned that the representation of ground or buildings needs a thorough evaluation. The representation of military sound sources (weapons, vehicles) may require further investigations. For example, it is not clear how to represent impulsional noises, i.e. sounds characterized by a pseudo-discontinuity of the acoustic pressure at the source.

### **Acknowledgments :**

Our special thanks to the US Army Yuma Proving Ground and ARL members for hosting the experiment in Yuma, Arizona and for their support during the NATO/TG-53 field trials in october 2005, and to the French Ministry of Defense, Délégation Générale pour l'Armement, Service des Programmes de l'Armée de Terre (DGA/SPART) for the NATO/TG-25 field trial (ETBS, Bourges 2002) .

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