Comparative study of two methods for generating realistic turbulence for electromagnetic wave propagation in the atmospheric boundary layer

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***Abstract*—The 2D parabolic wave equation (PWE) is widely used to model terrestrial radiofrequency (RF) links. In this iterative method, the contribution of a turbulent atmosphere is classicaly modeled through a statistically homogeneous vertical phase screen generated from a Kolmogorov-type scintillation spectrum. This study proposes a comparison between two methods for generating phase screens representative of a marine atmospheric boundary layer (MABL), both based on large eddy simulation (LES) data. Preliminary results indicate that a purely statistical approach of turbulence tends to underestimate its impact on the propagation of RF signals.**

I. Introduction

The scintillation phenomenon is characterized by fast variations in both the amplitude and phase of an electromagnetic (EM) signal caused by small-scale fluctuations of the atmospheric refractive index. This turbulent phenomenon often develops in the atmospheric boundary layer (ABL) due to the occurrence of strong temperature and humidity gradients between the surface and the first kilometers of the troposphere. Its impact is cumulative with range and may induce additionnal losses to the propagation signal at frequencies above the X-band. Therefore, a precise modeling of turbulence appears crucial to anticipate its impact on the performance of radiofrequency (RF) systems.

The 2D parabolic wave equation (PWE) is classicaly used to model electromagnetic (EM) propagation in diverse complex media [1]. In this iterative method, a phase shift is applied to the signal at each propagation step to account for the contribution of atmospheric conditions. These are modeled by a 1D vertical phase screen theoretically calculated by integrating the refractivity field over the entire propagation step. In the case of a turbulent atmosphere, phase screens are usually randomly generated from full-scale homogeneous scintillation spectra representative of the inertial range of scales of the classical Kolmogorov's K41 theory [2].

In this study, we propose to compare two methods for generating realistic turbulent phase screens based on the large eddy simulation (LES) of an ABL. The LES-Kolmogorov method is a full-scale statistical approach that relies on the same principle as the usual technique except that a realistic vertical inhomogeneity in turbulence intensity is *a-posteriori* introduced using LES data. The X-LES method [3], on the other hand, is a more realistic approach : the contribution of larger scales is directly computed from the refractive index fluctuations generated by atmospheric simulations, while a statistical modeling is only used for the contribution of the sub-grid scales.

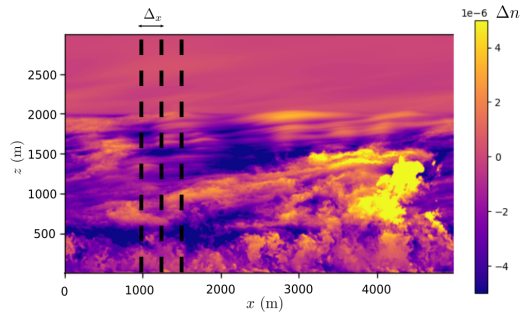

Fig. 1. Generated refractive index fluctuations from LES. Dashed lines indicate the integration step used to compute phase screens.

In the following, both used methods are briefly introduced in Section II while Section III shows some numerical results.

II. Methods

In this section, the LES-Kolmogorov and X-LES methods for generating vertically inhomogeneous phase screens are successively presented. Both techniques are applied to a commonly studied case of tropical MABL [4]. The atmospheric simulations are performed with the open-source LES code MicroHH [5] to study a $5\times5\times3$ km atmospheric domain using a $5\times5\times5$ m grid resolution. Figure 1 shows a 2D mapping of refractive index fluctuations for the generated case. It notably indicates a concentration of turbulence between 500 m and 1500 m.

A. LES-Kolmogorov method

Following [6], the turbulent phase at an altitude z can be given by

$$\Phi(z) = \sqrt{C_n^2(z)}\tilde{\Phi}(z), \tag{1}$$

where C_n^2 indicates the structure constant of the refractive index and $\tilde{\Phi}$ is an artificial phase screen generated from a homogeneous Von-Karman Kolmogorov spectrum of $C_n^2 = 1\ \mathrm{m}^{-2/3}$.

LES-Kolmogorov method consists in obtaining the variable term $C_n^2(z)$ via atmospheric LES. The one corresponding to

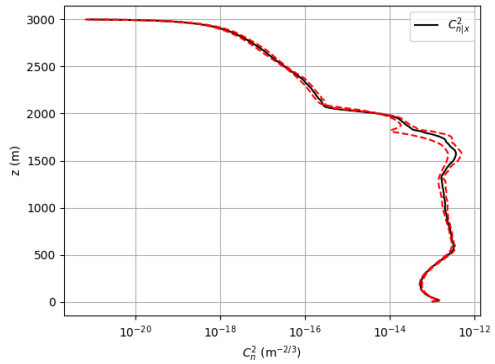

Fig. 2. Structure constant of the refractive index mean vertical profile. Red dashed lines indicate the temporal variability.

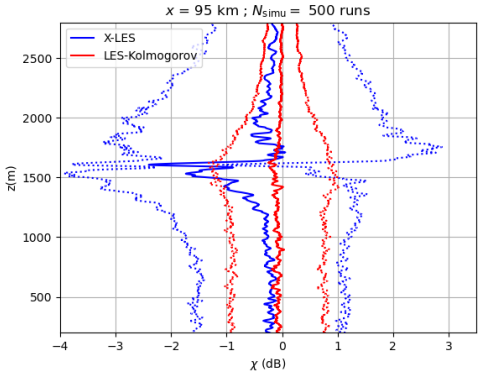

Fig. 3. Log-amplitude profiles at 95 km. Dotted lines indicate the standard deviation interval.

the present case is plotted in Figure 2. Therefore, the turbulence intensity with respect to altitude is accurately reproduced on phase screens. A similar approach with a parametric $C_n^2(z)$ profile has been proposed in [7].

B. X-LES method

In the X-LES method [3], each phase screen is generated by summing two contributions so that

$$\Phi = \Phi_{\mathrm{r}} + \Phi_{\mathrm{s}}. \tag{2}$$

Φ_{r} indicates the effect of scales directly resolved by LES and is computed from simulation outputs by integrating the refractive index fluctuations over a propagation step Δ_x as illustrated in Figure 1.

To model the entirety of the scales of the turbulent flow, Φ_{s} adds the contribution of sub-grid scales and is computed following the same principle as the LES-Kolmogorov method. More details on this generation technique can be found in [3].

III. Numerical results

The aim of this section is to compare the propagation of a spherical wave emitted by a 10 GHz frequency complex source point through two turbulent media. Phase screens are generated by either the LES-Kolmogorov or X-LES method. Note that the source is located at an altitude $z = 1600$ m.

The log-amplitude profiles obtained for both methods after a propagation over 95 km are plotted in Figure 3. Results are averaged over 500 runs. This metric gives a local quantification of the impact of turbulence on RF propagation that is particularly suitable in such an inhomogeneous case. It is defined as

$$\chi(z) = \ln\left(\frac{|\mathbf{E}_{\mathrm{t}}(z)|}{|\mathbf{E}_0(z)|}\right), \tag{3}$$

where $\mathbf{E}_{\mathrm{t}}$ and $\mathbf{E}_0$ indicate the propagated electric field across the turbulent medium and the one that would have been obtained in an atmosphere without turbulence, respectively.

Figure 3 first indicates that the obtained profiles show the same evolution with z. Both methods show a maximum impact around the source altitude. However, the turbulence effect appears to be more pronounced in X-LES than in LES-Kolmogorov.

IV. Conclusion

In this preliminary study, two methods for generating phase screens representative of a MABL based on LES have been compared. These initial numerical simulations seem to indicate that a purely statistical modeling of the phenomenon tends to underestimate the effect of turbulence, even with a very accurate C_n^2 profile.

This shows a potential limitation of the stochastic approach and suggests a need for a better way to generate synthetic turbulence data.

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