Numerical predictions for environmental acoustics: simulation of atmospheric fields and integration in a propagation model

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Outdoor sound prediction is both a societal stake and a scientific issue. Thus this paper deals with numerical simulations of micrometeorological (temperature and wind) fields for environmental acoustics. This is carried out through new developments in the reference mesoscale meteorological model at Météo-France ("Meso-NH"). Meso-NH predictions at very fine scales (up to 1m) including new developments (drag force approach) are validated both numerically and experimentally under stable, unstable and neutral conditions.

Then, this information can be used as input data for acoustic models. Our time domain acoustic model is based on the Transmission Line Matrix method (TLM). Its development has been carried out in order to be applied to outdoor sound propagation, *i.e.* in order to take into account topography, ground impedance, meteorological conditions, etc. The numerical validation of the TLM method by comparison with other models shows the relevance of its use in the context of environmental acoustics.

Finally, thanks to these models, simulated noise levels in different propagation conditions were compared to *in situ* measurements. Satisfying results were obtained regarding the observed phenomena variability. A feasibility study on a more complex experience (LTMS) leads to consider the TLM as a promising method in the context of environmental acoustics.

1   Introduction

Regarding environmental acoustics, outdoor sound prediction is both a societal stake and a scientific issue. It is now considered that from 50m from the sound source, the meteorological effects on the sound propagation shall be taken into account [1]. In order to qualify and quantify this influence, various acoustical propagation models have been developed. The meteorological information is carried on through atmospheric model of different complexity (from the simple linear vertical profile of wind and temperature to a complex representation of the atmospheric boundary layer). In order to get such a complex representation of the boundary layer, the purpose of this paper is to use the simulations results of the mesoscale meteorological model Meso-NH in Large-Eddy Simulation configuration (LES). Then this information can be used as input data for the (time domain) acoustical propagation model: The Transmission Line Matrix (TLM) method.

In order to evaluate this approach potentiality, the two different models (acoustical and meteorological) are compared with experimental data issued from the Lannemezan-2005 campaign.

Thus in this paper, the experimental campaign of Lannemezan-2005 is first presented. Then the mesoscale meteorological model Meso-NH and its configuration (in our context) are presented. The results obtained by this model over the Lannemezan site are next compared with the meteorological measurements during the experimental campaign. In the last chapter, we present the TLM temporal propagation model. Finally, the results of the TLM method using Meso-NH simulated meteorological fields as input data are shown and discussed.

2   Lannemezan 2005

Lannemezan-2005 was an experiment conducted by the Laboratoire Central des Ponts et Chaussées (ex-LCPC, now Ifsttar), Electricité De France (EDF), Société Nationale des Chemins de Fer (SNCF) and Ecole Centrale de Lyon (ECL) near the city of Lannemezan (France) [1]. It was designed to be a three-month experiment (in June, July and August 2005) in order to study meteorological and ground effects on outdoor acoustic propagation. Figure 1 shows the Lannemezan-2005 main site, its topography and the location of a selected set of sensors. The Lannemezan-2005 site is flat and covered with prairie grass. There are tree

barriers around 10m high on each side of the domain studied. The sound level of a broad-band omnidirectional sound source had been measured during the whole duration of the campaign by a bunch of microphones following 3 direction of propagation: DP1, DP2, DP3 (and DP4, not considered in this paper because of non flat ground). In addition to microphones, a large number of meteorological sensors were deployed in this area. For the meteorological part of the study, a 3D ultrasonic anemometer and two 10m high fully equipped meteorological towers (Wind speed, wind direction and temperature at a height of 1m, 3m and 10m) were placed respectively at 125, 75 and 175m from the source in each direction. Moreover, a 60m high meteorological tower with 3 3D ultrasonic anemometers, 3 temperature sensors and 3 humidity sensors was located at 200m northbound from the source. Information about turbulence kinetic energy was given by the 3D ultrasonic anemometers and one 60m mast with a measuring sampling rate of 10 Hz averaged over 10 minutes. The meteorological towers gave temperature and wind measurements every 10 seconds, averaged over 15 minutes samples. Regarding noise measurements (L_{eq1s} for each 1/3 octave bands on [100Hz;5kHz]), the different microphones were located at 50, 100 and 150m from the sound source in the different propagation directions (see Figure 1). For further details about this experiment, see [1].

In order to validate the meteorological model, 3 typical clear-sky conditions were chosen in the Lannemezan-2005 experimental database. As presented in Foken [2], the dimensionless stability parameter ς ($\varsigma=z/L_{MO}$) has been used to define the stratification degree of the surface layer (Unstable, Neutral and Stable atmospheres correspond respectively to a $-1<\varsigma$, $-1<\varsigma<0$ and $0<\varsigma$). This parameter values have been calculated from averaged measurements (15min) of the 3D ultrasonic anemometers. The 3 days chosen were:

- 17th June 2005 during day-time, corresponding to unstable conditions ($\varsigma=-0.3$) , to unfavourable propagation conditions following the DP1 direction and to homogeneous ones following DP3.
- 03rd July 2005 during night-time, corresponding to very stable conditions ($\varsigma=0.3$) and to favourable propagation conditions following the DP3 direction.
- 16th June 2005 during night-time, presenting neutral-stable atmosphere characteristics ($\varsigma=0.1$) andfavourable propagation conditions following the DP1, DP2 and DP3 directions.
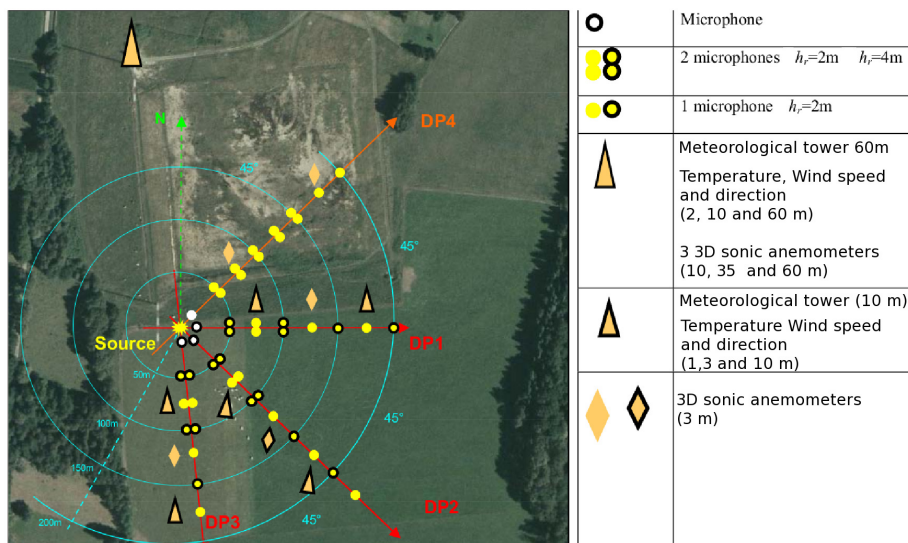
Figure 1: Lannemezan-2005 experiment, acoustical and meteorological sensors locations

3 Meso-NH

3.1 Presentation

Meso-NH is the non-hydrostatic mesoscale atmospheric model of the French research community [3]. It is intended to be applicable to all atmosphere scales, ranging from large (synoptic) scales to small scales (Large-Eddy Simulation). The model can use a 3D 1.5 order turbulence scheme, with two different mixing length parametrization (Deardorff [4][5] or Bougeault and Lacarrere [6]). Its performance for several boundary layer regimes has been tested successfully [7–9]. The model allows all types of boundary layers (stable, neutral, unstable) to be investigated over different types of surface cover and provides a resolution of the order of 1m. However, for such high resolutions, a description of the effects of the canopy on flow using a roughness approach (as it is usually done in large-scale atmospheric models) was not sufficient. Thus a new development has been done in order to take into account the drag force of the high vegetation. A detailed description of the basic equations of the Meso-NH model is available into the Meso-NH scientific manual [10].

3.2 Configuration

Simulations were conducted using 3 grid-nested 200x200x80 domains centred on the main domain of Lannemezan-2005 site. The domain size was chosen large enough to resolve the large scale eddies. Large-eddy simulations (LES) are performed with horizontal resolutions of 50m, 10m until 2m in order to resolve the smallest eddies. A vertical terrain-following stretched grid is used with 50 levels in the first 100m above the ground. Table 1 contains a resume about model configurations. It

can be noticed that for the unstable case (17-06-2005), the vortices are large enough to make the third model unprofitable

Surface fluxes were informed by the surface model ISBA [11]. The covers positioning came from interpolation of the Corine database [12] (horizontal resolution of 250m) except on the field experiment of Lannemezan-2005 where the data have been completed manually in order to better describe the position of trees.

In order to initialize the Meso-NH simulations, wind and temperature vertical profile have been assumed using ARPEGE analysis [13] above 60m and observations of the 60m tower below. Then, this profile is interpolated vertically and horizontally over the whole domain taking into account the orography.

Table 1: Configuration of the nested models (DEAR: Deardorff mixing length, BL89 : Bougeault Lacarrere mixing length)

Horizontal Resolution / Mixing length	1st Grid	2nd Grid	3rd Grid
07-03-2005 04:30 AM Stable	50m (10x10 km)	10m (2x2 km)	3,3m (500x400 m)
	BL89	BL89	DEAR
06-16-2005 04:30 AM Neutral	50m (10x10 km)	10m (2x2 km)	3,3m (500x400 m)
	BL89	BL89	DEAR
06-17-2005 04:00 PM Unstable	50m (10x10 km)	10m (2x2 km)	X
	DEAR	DEAR	X

3.3 Results

Figure 2 shows the comparison between simulation and experiment results for the profile of wind speed, temperature and turbulent kinetic energy the 06-16-2005 at 04:30 AM. The mean vertical profile is calculated from a space and time averaging over the different masts (on DP1, DP2 and DP3), and over 15min time periods.

In this particular case, we observe a good agreement between experimental results and Meso-NH simulations. It can be particularly noticed the good representation of the inflection point in the wind speed and the very good representation of the TKE mean vertical profile.
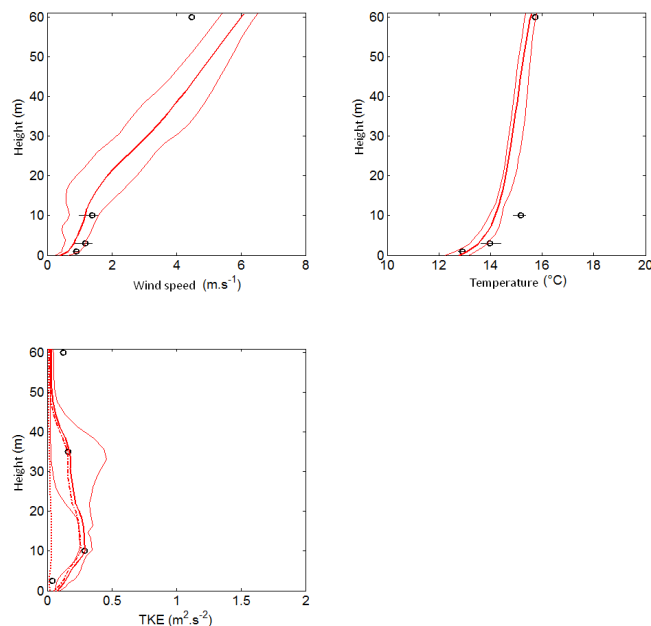
Figure 2: Mean vertical profiles and dispersion of the wind speed, temperature and turbulent kinetic energy measured (black) and simulated (red) the 06-16-2005 at 04:30 AM.

The comparison for the three different cases had shown that [14]:

- For the neutral and unstable cases (06-17-2005 and 06-16-2005), there is a good agreement between Meso-NH simulations and experimental results.
- For the stable case (07-03-2005), Meso-NH simulations produces a too high wind speed value, which induces overestimated TKE values.

Finally, Meso-NH is considered as a relevant model to provide input data for propagation simulations with the TLM method.

4 TLM

4.1 Presentation

The TLM method is often presented as a numerical approach of the Huygens' principle [14][15]. The method scheme in 2D, originally purposed by P.Johns [17], in electromagnetism is exposed Figure 3.
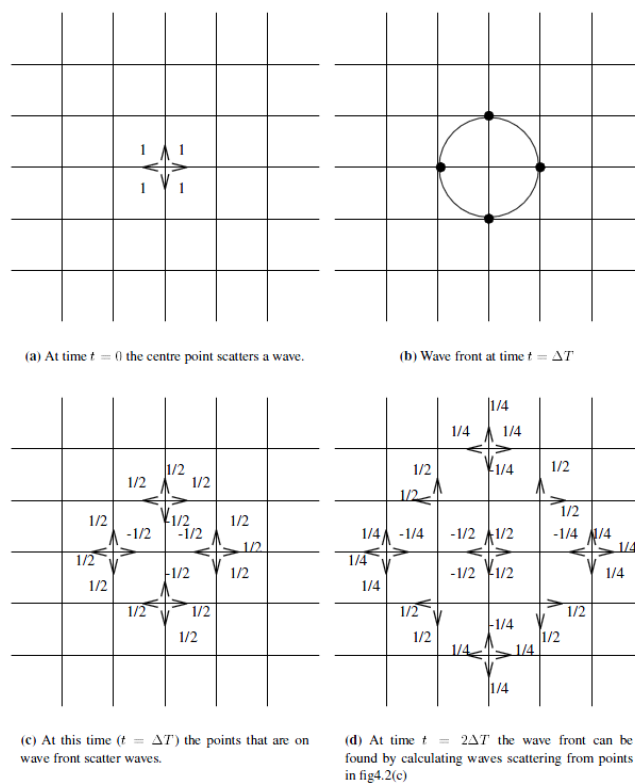
Figure 3: Propagation scheme in 2D of an impulsion in a TLM network.

Sound propagation is described by means of incident and scattered pulses at each junction of a transmission lines network. At each time increment t, incident pulses allow to compute scattered pulses through a matrix relation and these scattered pulses are diffused towards neighbour nodes by means of connexion laws which initialize the incident pulses for the next time increment. It can be shown that this concept is analogous numerically with a 2nd order discretization of the acoustic equation of propagation.

Recent developments of the TLM method have been carried out and validated in order to take into account different ground impedance characteristics [15], fully-absorbing boundary layer [18], the third dimension in space [18], and meteorology [13][18][20].

In the Figure 4, we present a validation example in 2D. The point source is situated at 50 m underneath an absorbing boundary layer and at 0.15m, 2.05m and 5.05m above a flat absorbing ground (ground impedance model from Miki [15]). The results of the TLM simulations are compared with analytical solutions after normalization by a reference microphone located 10m from the sound source. A very good agreement between analytical solutions and TLM simulations can be observed in this case. Other studies have shown that the TLM model is able to reproduce numerous of academic tests [14]. This allows us to consider the TLM as a reference method for the simulation of outdoor sound propagation.
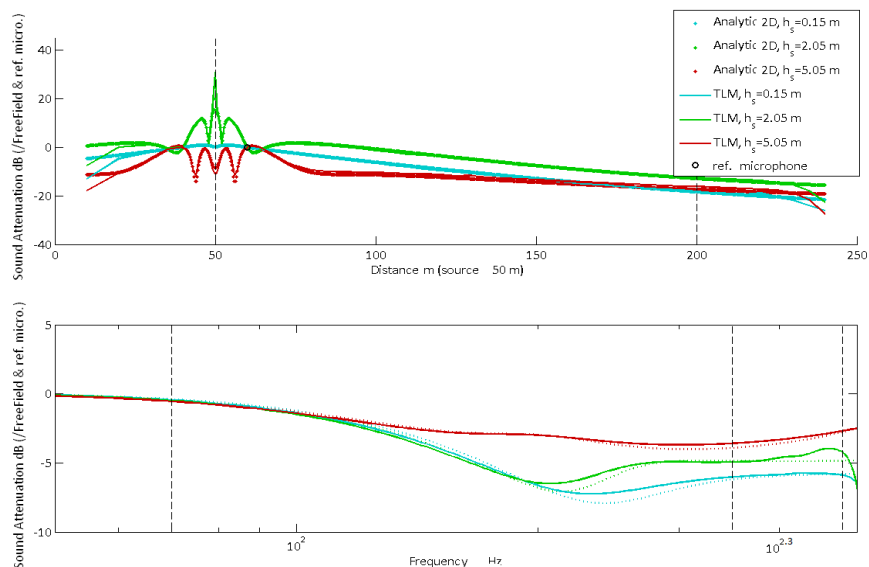
Figure 4: TLM validation over flat absorbing ground (σ=100k.N.s.m^{-4}). Sound attenuation (normalized by a reference microphone) as a function of distance (high, dist.=150m) and frequency (low, f=200 Hz)

4.2   Configuration

For the following simulations, the spatial resolution of the TLM method is 0.04m and performed in 2 dimensions during 0.65 seconds. The central frequency of the sound source (Gaussian pulse) is 500 Hz. Perfectly absorbing boundary layers are set around the space domain except at the bottom side where ground impedance conditions are assumed to be absorbing: In the Miki impedance model [15], the air flow resistivity is set to 150k.N.s.m^{-4}. which is the measured mean value during Lannemezan-2005 experiment [21]. The meteorological fields (temperature and wind) are extracted on each propagation direction and integrated in the acoustic model. Because of the important difference in time scales between acoustics and meteorological fluctuations (*e.g.* speed sound ~340m.s^{-1} *vs* flow speed ~10m.s^{-1}), it has been chosen to use fixed meteorological variables during the time of the simulation (0.65sec).

4.3   Results

In this paper, only 315Hz, 400Hz, 630Hz and 800Hz third octave bands results are presented and only for the 06-16-2005 case in the DP3 propagation direction. For more exhaustive results, see [14].

Almost perfectly homogeneous conditions (vertical speed sound gradient < 0,015s^{-1}) have been extracted from the Lannemezan-2005 database in order to be compared with TLM simulations in such conditions, *i.e.* without meteorological effects. This comparison is reported in grey on Figure 5, which shows a very good agreement between simulated and measured values at any distances and for all frequency bands. It confirms that the choice of the ground impedance parameters is sufficiently accurate and relevant.
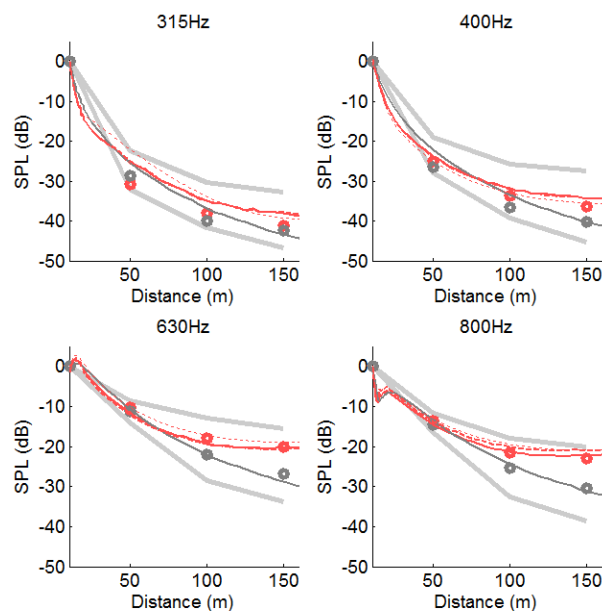

Figure 5: Sound attenuation (normalised by the free field and by a reference microphone located 10m from the sound source) as a function of the distance from the source, for 315Hz, 400Hz, 630Hz and 800 Hz third octave bands. Comparison between TLM (full line) and experiment (points) during the experimental campaign of Lannemezan 2005, the 16-06-2005 at 04:30 AM (red) and in nearly-homogeneous conditions (grey). The bold grey lines correspond to the experimental dispersion over the three-month measurements. The dotted red lines stand for TLM predictions using rough (linear) vertical profiles of sound

Then, the meteorological variables (wind and temperature) of the TLM model are informed by Meso-NH simulation results on the same site and for the same dates. Those comparisons between TLM simulations and experimental data are presented in red in Figure 5 (full red line for "exact" profiles directly issued from Meso-NH and dotted red line for linearly fitted profiles on Meso-NH predictions). Those comparison results generally show a very good agreement, and especially show the interest to take into account meteorological effects during acoustic propagation, even with only roughly fitted (linear) meteorological profiles.

Finally, the different study cases have shown that [14]:

- if the atmospheric boundary layer simulated by Meso-NH is sufficiently in agreement with the observation during Lannemezan-2005 experiment, then the TLM simulations are also in good agreement with the corresponding experimental data.
- the sound pressure levels are very sensitive to the meteorological fields and, in the case of low quality of Meso-NH simulations, the TLM simulations can be far removed from the experiments.

5   Conclusion

This paper deals with the use of the mesoscale meteorological model (Meso-NH) in order to inform the time domain acoustical model (TLM) in temperature and wind speed profiles. Thanks to the comparison between simulation results and experimental data issued from the Lannemezan-2005 campaign, this study has shown the strong sensitivity of the acoustical model to the vertical profiles of temperature and wind speed, and thus the necessity to make use of accurate meteorological simulations as input data.

By the way, the Transmission Line Matrix (TLM) method appears to be relevant in the context of outdoor propagation. Thus this prospective work improves the interest in the perspective of acoustical and meteorological models coupling.

More recently, some Meso-NH and TLM calculations have been realized in 3D on the Ifsttar (ex-LCPC) Long Term Monitoring Site (LTMS) located at Saint-Berthevin (F) [22]: Experimental field of ~500mx500m, until 250 Hz (~20h for calculation on 4 GPU) [14]. Those additional results will be presented during the presentation.

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