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Sound propagation over an irregular terrain with complex meteorological effects using the parabolic equation model

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Abstract [161] Sound impact of road and railway infrastructures are more and more severely regulated by European laws: acceptable thresholds in emission and reception are decreasing. This implies to develop propagation models able to take many phenomena into account at the same time (meteorology, uneven ground, impedances discontinuities...). The parabolic equation (PE) is one of those numerical methods. Its main purpose is to predict long-range sound propagation under range-dependant environment. Despite of its efficiency, this method shows a number of limitations to study complex outdoor situations. This paper aims at presenting ATMOS (Advanced Theoretical Models for Outdoor Sound propagation). This GFPE (Green's Function Parabolic Equation method) based calculation code is dedicated to complex outdoor situations which can not be solve with a classical PE approach. Usually PE neglects backscattering and complex topography can not be considered. ATMOS takes those phenomena into account by new several techniques: complementary Kirchhoff approximation, BEM-GFPE hybrid method, referential rotation. Numerical examples of road traffic configurations that illustrated those effects are presented here.

1 INTRODUCTION

ATMOS is a GFPE-based code developed at CSTB (Grenoble, France). It is dedicated to complex outdoor sound propagation considering combined effects of meteorology and topography. Using new methods, it can perform studies of numerous realistic road traffic noise configurations which are not solvable with the classical PE codes. Three new techniques are presented in this paper. The complementary Kirchhoff approximation is used to take backscattering and multiple reflections into account. The BEM-GFPE hybrid method is employed to consider complex obstacle as T-shape barrier with meteorological effects. The referential rotation approach is applied to deal with uneven ground in an inhomogeneous atmosphere.

2 THE PARABOLIC EQUATION

The parabolic approximation was introduced in the forties to solve electro-magnetism problems. Then it was used in many scientist domain as ocean acoustic and was adapted by Gilbert [1] for outdoor sound propagation. Starting from the Helmholtz equation in cylindrical (r, z) coordinates for

the sound pressure $P(r, z) = \frac{1}{\sqrt{r}} u(r, z) e^{jk_r r}$:

$$\left(\frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{\partial^2}{\partial z^2} + k(r, z)^2 \right) P(r, z) = 0 \quad (1)$$

an initial field is propagated step by step from the source to the receiver. After developments described in Gilbert's article [2], the field at $u(r + \Delta r, z)$ is solving by:

$$u(r + \Delta r, z) = \left[\frac{1}{2\pi} \int_{-\infty}^{+\infty} (U(r, k') + R(k')U(r - k')) \times e^{j\Delta r(\sqrt{k_r^2 - k'^2} - k_r)} e^{jk'z} dk' \right. \\ \left. + 2j\beta \times U(r, \beta) \times e^{j\Delta r(\sqrt{k_r^2 - \beta^2} - k_r)} e^{-j\beta z} \right] \times e^{\frac{j\Delta r \delta k^2(z)}{2k_r}} \quad (2)$$

where $U(r, k) = \int_0^{+\infty} e^{-jkz'} u(r, z') dz'$, $\beta = \frac{k_r}{Z_g}$ and Z_g is the normalized ground impedance.

PE is a powerful computational method able to calculate the sound propagation in inhomogeneous atmospheres. Even if this method is able to deal with varying ground impedance and simple obstacles (steps, barriers), it shows a number of limitations intrinsic to the parabolic equation itself. For example, configurations with backscattering or complex topography can not be directly solved with PE approach.

3 THE GFPE-KIRCHHOFF APPROACH

The classical PE method is unable to take backscattering into account. In this approach, backscattering created by reflections on vertical obstacle is considered by using a complementary Kirchhoff approximation called GFPE-Kirchhoff [3]. "Complementary" to the one used for the diffraction by a straight barrier, this method allows solving multi-reflection problems.

An image-source S' is built relatively to barrier vertical plane. The sound pressure at any calculation point above the obstacle is set to zero (see Table 1). The ones on the screen are multiplied by the plane wave reflection coefficient calculated from the barrier impedance and then propagated to the receiver.

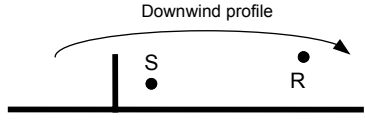
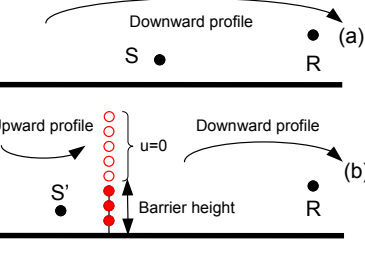
	Real configuration
	GFPE-Kirchhoff method : $P_{total} = P_{(a)} + P_{(b)}$

Table 1: GFPE-Kirchhoff method applied to a barrier located behind the source with a downwind profile

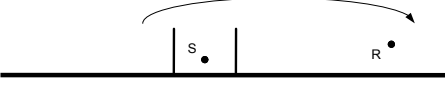
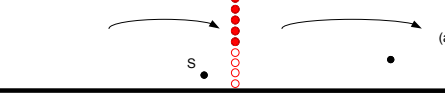
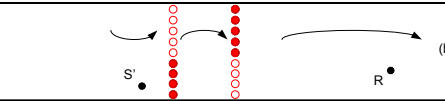
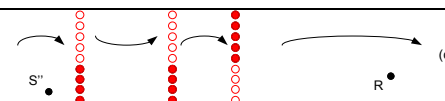
	Real configuration
	Diffraction
	Simple reflection + diffraction
	Double reflection + diffraction

Table 2: Principle of calculation with 2 parallel barriers at the order 2 with downwind profile,

$\circ u = 0$, $\bullet u = u(r, z)$

We are dealing here with a wind blowing from the source to the receiver. To insert the atmospheric refraction in the GFPE-Kirchhoff method, an upwind sound speed profile is built. This profile,

symmetric relatively to c_0 of the downwind sound profile is applied for the propagation from the image source S' to the obstacle. Then the “initial” downwind sound speed profile is used for the propagation from the obstacle to the receiver (see Table 1).

The total pressure at the receiver is the sum of the “direct field above ground” calculation (a) and the one obtained in case (b).

3.1 The multi-reflection

The GFPE-Kirchhoff method can be extended to multi-reflections due for instance to the presence of 2 parallel barriers. The calculation for an order of reflection of 2 is described Table 2. In this case, the total pressure at the receiver is the sum of 3 fields: (a) diffracted, (b) simply reflected and diffracted and (c) double reflected and diffracted.

3.2 Numerical simulations and validation

A realistic road traffic noise configuration with two parallel and absorbent barriers ($\sigma = 180$ cgs Rayls, Delany and Bazley’s formulation [4]) is studied with and without meteorological effects (see Figure 1). A strong sound speed gradient described by $c(z) = c_0(1 + 4.9 \times 10^{-3} z)$ corresponding to a wind blowing from source to receiver is chosen to point out the influence of refraction.

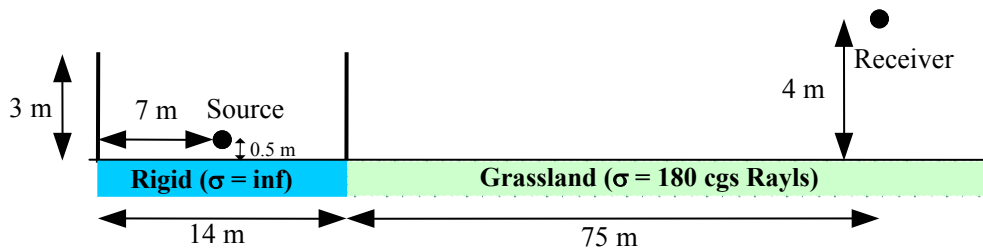


Figure 1: Configuration studied using the GFPE-Kirchhoff method

A measurement campaign above 1/20 scale models has been undertaken to validate the theoretical results. The meteorological effects are introduced using the analogy between sound propagation above a flat surface along curved ray paths and sound propagation above a curved surface along straight ray paths [4] (see Table 3). Results in homogeneous atmosphere are also compared to a reference solution obtained with BEM (Boundary Element Method) calculations [5]. Scale model measurements are performed between 2000 Hz -14000 Hz which corresponds to a frequency range of 50 Hz – 700 Hz at scale 1. Grassland and barriers absorption is achieved by a layer of felt ($\sigma = 3600$ cgs Rayls) corresponding to $\sigma = 180$ cgs Rayls at 1/1 scale. The measurement method is the sine swept technique [6].

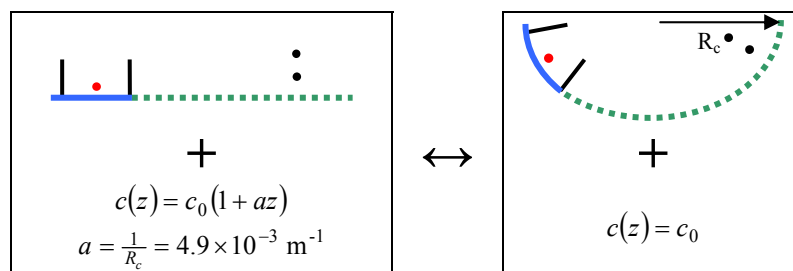


Table 3 : analogy between sound speed profile and curved surface

3.3 Results

Results discussion is almost the same for both receivers so that only results for the higher one are presented here. The agreement between calculations and measurements (see Figure 2, Figure 4 and Figure 5) is very good either in homogeneous or inhomogeneous conditions. As expected especially in homogeneous case, the 24 Hz step which separates two interferences is well correlated with the distance between the 2 barriers. Figure 3 points out the importance of meteorological effects. The global excess attenuation due to barriers for a typical traffic noise spectrum at emission is about 9.7 dB(A) in homogeneous conditions. It increases at 19.0 dB(A) in upward atmosphere but falls down at 0.3 dB(A) in downward conditions. Even if a very strong the sound speed profile has been chosen to point out the meteorological effect, it is really interesting to spot that barriers can become ineffective in downward conditions.

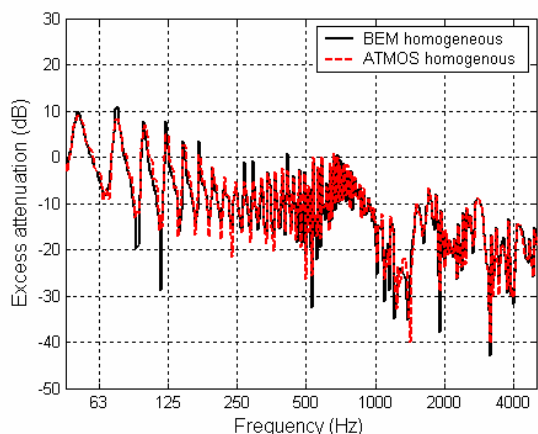


Figure 2: Comparison of BEM and ATMOS calculations in homogeneous atmosphere for the configuration detailed in Figure 1

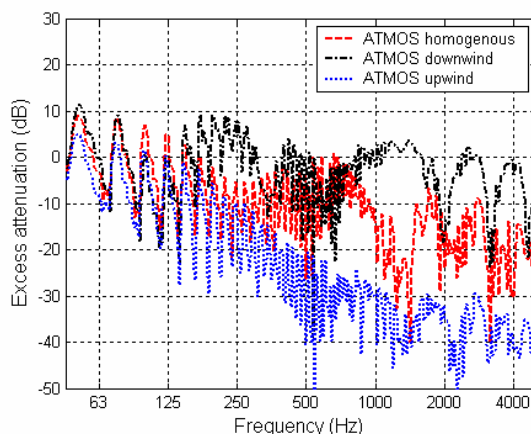


Figure 3: Comparison of calculations in homogeneous ($c(z) = c_0$), downward ($c(z) = c_0(1 + 4.9 \times 10^{-3} z)$) and upward ($c(z) = c_0(1 - 4.9 \times 10^{-3} z)$) sound speed profiles for the configuration detailed in Figure 1

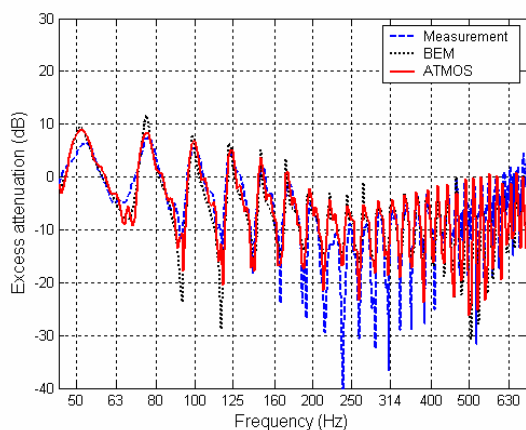


Figure 4: Comparison between ATMOS, BEM and scale model measurements for the configuration detailed in Figure 1, $c(z) = c_0$

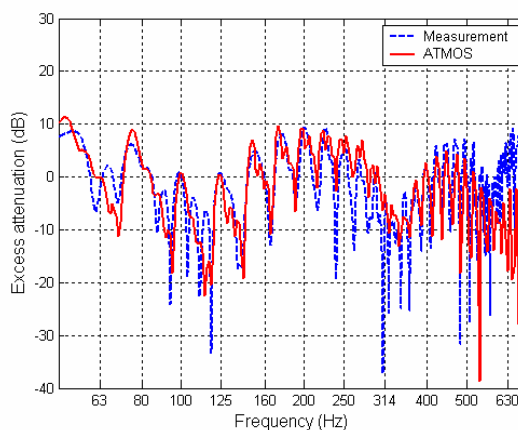


Figure 5: Comparison between ATMOS and scale model measurements for the configuration detailed in Figure 1, $c(z) = c_0(1 + 4.9 \times 10^{-3} z)$

4 THE BEM-GFPE HYBRID METHOD

No low time consuming method is able to calculate outdoor sound propagation when uneven terrain and various meteorological conditions are present. In the BEM-GFPE hybrid method [7], we choose to couple GFPE with a BEM code [5]. On one hand, BEM is a powerful method able to calculate sound pressure at any point of the space with complex topography but it does not deal with meteorological effects. On this other hand, GFPE is efficient for long range sound propagation in inhomogeneous medium but no more when the terrain is complex. Then, the aim of this technique is to use the advantage of one method to compensate the lack of the other.

The calculations are divided in 3 steps. First, the sound pressure nearby obstacle (barrier, hill) and ground irregularities are computed with BEM neglecting meteorological effects. Secondly, the calculated sound field is adapted and introduced as the starter for GFPE. Finally, GFPE PE is used for the long-range propagation to the receiver above a flat ground with meteorological effects. (see Figure 6).

4.1 Numerical simulations and validation

A 3 m high T-shaped barrier covered on its top with 5 cm of an absorbent layer ($\sigma = 30$ cgs Rayls, Delany and Bazley's formulation [4]) is studied with and without meteorological effects (see Figure 7). A source is located 5 cm above the rigid ground. Several receivers are located 15 to 300 m from the source and 2 m over the ground. The meteorological effects are represented by 2 logarithmic sound speed profiles ($c(z) = c_0 \pm \ln(1 + z/z_0)$) with $c_0 = 340 \text{ m.s}^{-1}$ and $z_0 = 0.1 \text{ m}$).

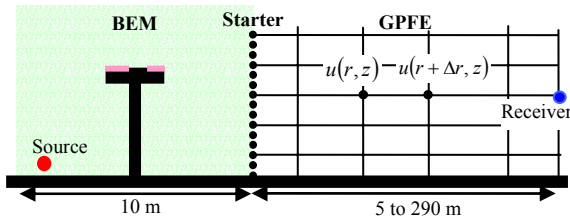


Figure 6: *BEM-GFPE hybrid method applied to T-shaped barrier*

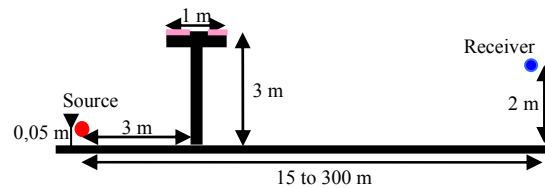


Figure 7: *Configuration studied with the BEM-GFPE hybrid method*

4.2 Results

Figure 8 and Figure 9 present the excess attenuation relative to the free field as a function of the distance for a frequency of 1000 Hz. Results are given in a homogeneous atmosphere as well as 2 logarithmic sound speed profiles. Sound pressure is calculated with BEM on a vertical axis (starter) 10 m from the source in homogeneous medium. GFPE is used from this starter axis for the propagation to the receiver in inhomogeneous atmosphere.

Before computing any calculations in inhomogeneous medium, results obtained with ATMOS have been validated in homogenous atmosphere. These results were compared with reference calculations achieved with BEM. We can see that results from ATMOS and BEM are very close to each other in homogeneous medium (see Figure 8).

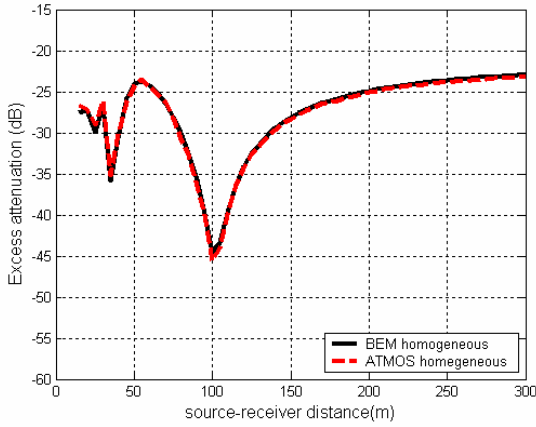


Figure 8: Comparisons of BEM and ATMOS calculations for the excess attenuation as a function of distance at 1000 Hz in homogeneous conditions.

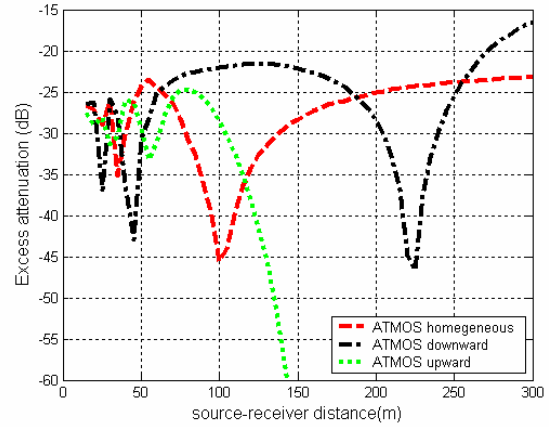


Figure 9: Comparison of calculations in homogeneous ($c(z) = c_0$), downward ($c(z) = c_0 + \ln(1 + z/0.1)$) and upward ($c(z) = c_0 - \ln(1 + z/0.1)$) conditions

Effects of meteorological conditions are also pointed out for the case of long range sound propagation. Figure 9 shows that meteorological effects can be neglected near the source. This is not true anymore when distance between source and receiver increases. For example, 150 m from the source, the excess attenuation relative to free field for homogeneous condition is 5 dB higher than in downward condition but 30 dB lower than in downward conditions.

5 THE REFERENCIAL ROTATION

Several methods already exist to take uneven ground into account in PE [8-10], but no one is dedicated to the study an embankment with the GFPE approach. In this approach, we choose to approximate the terrain with a succession of flat domains (see Figure 11). Above each of them, the sound field is propagated from an initial vertical sound field starter parallel to the slope. To switch from one slope to the other, the sound field is calculated at the boundary between two successive zones. Boundary location is determined by a rotation of the referential:

$$\begin{cases} r2 = d1 - z1 \times \sin(\phi) \\ z2 = z1 \times \cos(\phi) \end{cases} \quad (3)$$

with $d1$ the horizontal distance between the source and the beginning of the new domain and ϕ the angle between the two slopes (see Figure 10).

This approach can be extended to more complex topographies. The same principle is use for change of calculation domain.

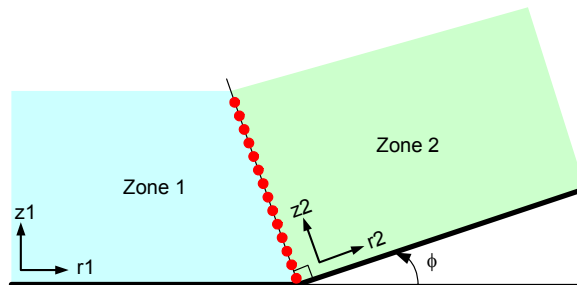


Figure 10: referential rotation approach applied to a positive slope

5.1 Numerical simulations and validation

A 10 m long rigid embankment of 15° is studied (see Figure 11). A 0.5 m high source is located 4 m from the embankment bottom. The sound pressure level is calculated at a receiver positioned 15 m from the embankment top. In this configuration, the receiver is masked from the source by the embankment.

Topography is divided in 3 slopes. Zone 1 is the domain between the source and the embankment bottom. Zone 2 is located between the base and the top the embankment. Zone 3 is the domain from the top of the embankment to the receiver. For each change of zone, the rotated referential method described below is applied.

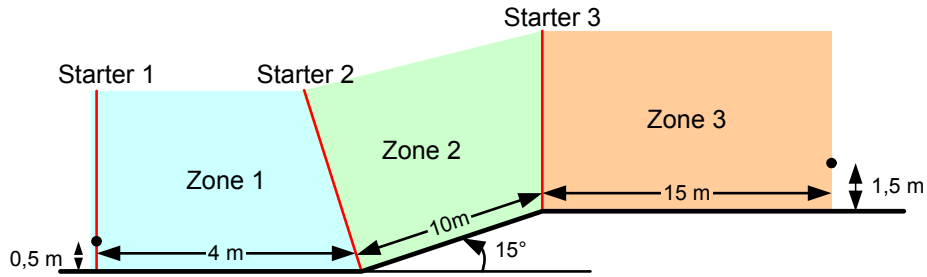


Figure 11: embankment studied with the referential rotation approach.

5.2 Results

First, calculations in homogeneous medium have been carried out. Results obtained with ATMOS have been compared to the BEM ones in terms of excess attenuation relative to free field as a function of frequency. Figure 12 shows a good agreement between both methods. Those results make us confident for further investigation.

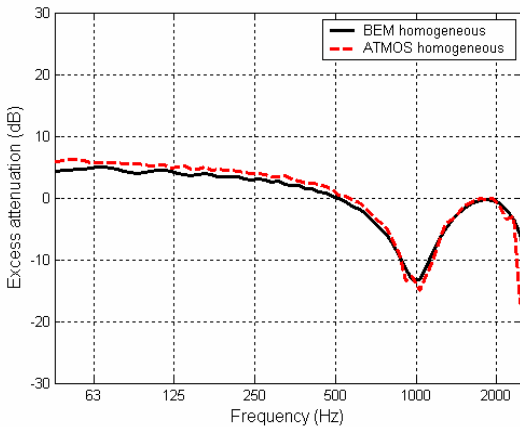


Figure 12: Comparison of BEM and ATMOS calculations in homogeneous conditions

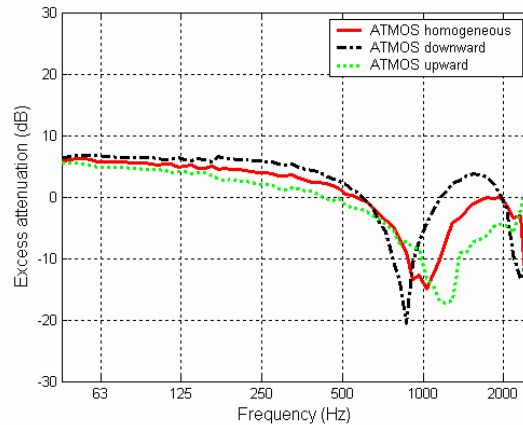


Figure 13: Comparison of calculations in homogeneous ($c(z) = c_0$), downward ($c(z) = c_0(1 + 4.9 \times 10^{-3} z)$) and upward ($c(z) = c_0(1 - 4.9 \times 10^{-3} z)$) conditions

Therefore, calculations have been completed in downward ($c(z) = c_0(1 + 4.9 \times 10^{-3} z)$) and upward ($c(z) = c_0(1 - 4.9 \times 10^{-3} z)$) conditions (see Figure 13). This point out the meteorological effect on sound propagation, even if the distance between source and receiver is relatively short (≈ 30 m).

The interference location moves due to the meteorological conditions: positioned 1000 Hz in homogeneous medium, it shifts 800 Hz in downward conditions and 1200 Hz in upward conditions. Thus, L_{acq} calculation for typical road traffic noise spectrum at emission gives -1.5 dB(A) in homogeneous atmosphere, -2.2 dB(A) for downward conditions and 0.8 dB(A) for upward conditions.

6 CONCLUSION

Results show that ATMOS is efficient in numerous complex road traffic noise configurations not solvable with classical PE approaches. It is adapted to take backscattering into account as well as multi-reflections effect created by face to face impedant vertical obstacles. It also deals with uneven ground. The study of embanked roads is now possible by using a referential rotation technique. To extend ATMOS abilities to more complex topographies, a BEM-GFPE hybrid method has been developed and validated. In conclusion, ATMOS can deal with many road traffic noise configurations coupling complex meteorological and topography effects. Work is in progress to better understand the terrain outcome on the aerodynamic effects and thus used more realistic range dependant wind speed profile for long range sound propagation.

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