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OUTDOOR SOUND PROPAGATION IN MOUNTAINOUS AREAS: COMPARISON OF REFERENCE AND ENGINEERING MODELS

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ABSTRACT
In this study, a comparison is made between reference and engineering models for the simulation of sound propagation in mountainous areas. Cross sections with a valley slope configuration pose a specific challenge on engineering models. Two reference models are used: the Green's Function rotated Parabolic Equation method and the Finite Difference Time Domain method. They are compared to the engineering model proposed in the Harmonoise/Imagine project. Both accuracy and performance aspects are discussed. The comparison focuses on road and railway noise with low sources, situated in a valley. Propagation distances up to one kilometer are considered. Both realistic and artificial cross sections are investigated, the former captured from the Unterinntal region in Austria.

INTRODUCTION
Outdoor sound propagation simulations are faced with specific challenges in mountainous areas with valley-slope cross sections. Compared to flat terrain, additional screening by the terrain and specific meteorological conditions are possible, and the ground effect can drastically be altered. The line of sight between source and receiver points can be blocked by undulations of the terrain, causing additional shielding. When the source and/or the receiver is positioned higher up a slope, attenuation due to the ground effect may be significantly reduced. Meteorological conditions in mountainous areas are complex, and are characterized by a large variability in space and time.

As part of a large study in the Unterinntal region in the Alps, in the western part of Austria [1], this paper focuses on the consequences of the valley-slope cross sections for noise mapping. As reference models are too slow to be used for noise mapping purposes, it is investigated how well an engineering model can cope with the complex situation. The focus is on the Harmonoise/Image propagation model in particular as it is a modern model that is relatively fast and promises linear complexity.

This paper focuses on the direct influence of a non-flat terrain. For an engineering model to be suitable for simulations in mountainous areas, it has to be capable of accounting for both the additional shielding and the altered ground effect. The engineering model of the Harmonoise/Imagine project is designed to take into account complex geometrical effects, processing arbitrary 1.5D polylines[1] as cross sections,.

In this article, the Harmonoise/Imagine model will be tested against two reference models, in both realistic and artificial cross sections. The reference models are the Green's Function rotated Parabolic Equation method [2] and Finite Difference Time Domain method [3, 4]. The Unterinntal region in Austria is used for the realistic cross sections of valleys.

REFERENCE MODELS
In this paper, two different reference models are used to eliminate uncertainties on the reference solution caused by approximations inherent to the numerical approach.

[1] 1.5D polyline: a polyline connecting a set of vertices $\mathbf{p}_k(x_k, y_k)$ with the restriction that the x-coordinates form an ordered set: $x_k < x_{k+1}$

Green's Function rotated Parabolic Equation
In the Green's Function rotated Parabolic Equation (GFrPE) model [1, 2], the undulating terrain is approximated as a succession of flat domains with different slopes. GFPE (Green's Function Parabolic Equation) [5, 6] calculations are performed in each domain. The sound field simulation in each domain starts from an array of pressure values, orthogonal to the local slope. The starting field for domain *n+1* is constructed based solely on calculations in the previous domain *n*. If there is a change in the slope angle between successive domains, a number of reduced propagation steps are needed in domain *n* near the transition to the next domain, in order to obtain the pressures at the correct height for constructing the starting field for domain *n+1*.

GFrPE has the same benefits as GFPE. Range-dependent refraction can be modelled. Large step sizes are allowed, except near the transition of domains. The ground impedance may be changed along the propagation path. GFrPE requires linearization of the cross section however, but as this is often the case in noise mapping anyway, this is not much of an issue for the comparison made in this article.

The GFrPE has been validated by comparing to detailed measurements, including meteorological observations, for sound propagation in a valley-slope configuration [1].

Finite-Difference Time-Domain
The Finite-Difference Time-Domain (FDTD) method [3, 4] has shown to be an excellent tool for solving the inhomogeneous moving medium sound propagation equations outdoors. Because it is a direct discretisation of the linearised Euler equations, it can easily take care of complex wind and temperature fields, typically found in outdoor situations.

The FDTD simulations presented in this article, were only available from simulations with a basic Cartesian FDTD. This has some limitations in representing the undulations of the terrain, because a staircase approximation of slopes has to be made. This can be circumvented by using a non-Cartesian FDTD [7, 8], though the comparison with GFrPE indicates that the cartesian approach has proven to be sufficient. The FDTD simulations have only been performed for the profiles with perfectly reflecting ground surface, though complex ground impedances can also be modelled [9]. Using a moving window FDTD may allow extending the propagation calculation over longer distances [7].

Expected inaccuracies for the FDTD model include scattering on staircase approximation of smooth slope and shift of ground dips at larger distance due to phase error.

HARMONOISE/IMAGINE ENGINEERING MODEL

The engineering model used for this article, hereinafter referred to as the Harmonoise model, has been developed as part of the Harmonoise/IMAGINE project [10, 11]. Driven by the European Noise Directive COM 2000/49, the project provided new prediction models for environmental noise mapping. Where the Harmonoise project concentrated on road and railway noise, the IMAGINE project studies the extension of this model to aircraft and industrial noise.

The Harmonoise model is not the first propagation model that is able to fully take into account cross sections modelled by 1.5D polylines. The Nord2000 [12] project already provided an extensive prediction model combining ground reflection, Fresnel weighting, diffraction and meteorological conditions. The Harmonoise model borrows many implementation details from Nord2000, but promises better performance. This is in particular true for cross sections with a lot of diffracting edges. The Harmonoise model promises a complexity linear to the number of diffracting edges, whereas Nord2000 has an exponentially growing complexity.

For the purpose of this paper, the implementation by CSTB was used. Most of the options in the Harmonoise model were disabled, in order to compare more directly to the reference models. Air absorption and scattering were disabled because they were not included in either of the reference models. Spectral averaging was disabled because the reference models also compute selected frequencies only.

RESULTS AND DISCUSSION

Convex cross section: declining slope with shielding

For the first cross section, the acoustic source is put on a horizontal plateau that looks over a lower valley with a linear declining slope in between. The source and receiver are both 2m above the ground which is assumed perfectly reflecting. The source is positioned at *x*=0m, while the receiver is moved along the x-axis. The slope starts 50m from the source, extending over 150m distance with a descend of 40m. As the receiver moves away from the source, the line of sight gets blocked by the edge of the plateau. This will test the model's effectiveness of handling shielding by the terrain.

In Figure 1, a comparison is made between both reference models and the Harmonoise model. The level plotted is the sound pressure level relative to the free field. Up to 50m, the agreement is very good, what is to be expected for a flat terrain situation. On the slope, the level first shortly spikes due to fully constructive interference where the receiver crosses the horizontal line of the plateau, and then drastically decreases due to shielding by the plateau edge. On the slope, the agreement between GFrPE and Harmonoise is very good, while the FDTD drops slightly faster, accumulating in 3dB difference over 150m. This might be explained by some energy loss due to scattering on the staircase edges of the terrain profile. Note however that the perfectly flat slope chosen in this example is ideal for the GFrPE but not very realistically in practical situations.

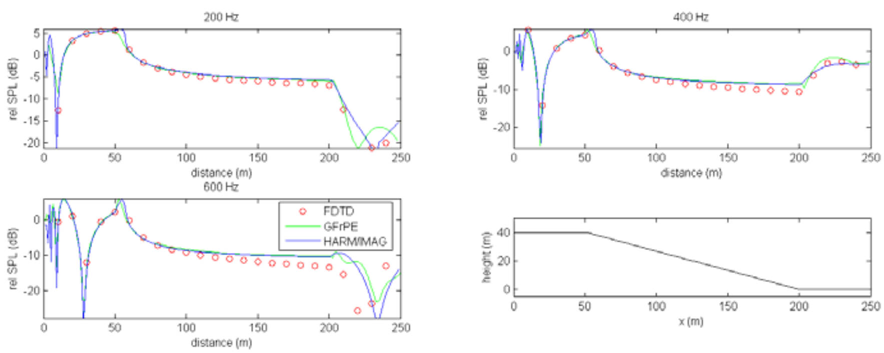

Figure 1.- Comparison of GTrPE, FDTD and Harmonoise/Imagine for a declining slope with shielding. Relative sound pressure level, hsrc=hrec=2m, σ=200000kNsm^{-4}.

Concave section: inclining slope without shielding

A typical situation in many Alpine valleys consists of a road centered in a valley while dwellings are found on the slopes. The source is positioned in a horizontal section at *x*=0m. The slope starts at 100m from the source, raising to 20m over a distance of 150m. Again, source and receiver are put 2m above the ground.

In Figure 2, the comparison is made between the models using the relative sound pressure level for propagation above a hard surface. Again, up to 100m, the agreement is very good as can be expected for a flat terrain situation. On the slope, FDTD and GFrPE are still in agreement, while the Harmonoise model yields totally different results. This is due to a simplification in the model to only handle first order reflections. This means that a sound path can only reflect on a single ground segment[2]. However, the cross section at hand also allows for second order sound paths, bouncing on both segments. Because of the hard ground surface, this path still is an important contributor, while it is completely neglected by the model.

However, hard surfaces in valley slope configurations are rather exceptional, especially for noise mapping purposes. If we use a soft ground surface instead, the situation improves considerably as shown in Figure 3. For 200Hz, the ground still acts as relatively hard, so Harmonoise is still off, but starting from 400Hz, the Harmonoise predicts the same levels as GFrPE.

[2] If the cross section contains diffraction edges, they can be seen as intermediary sources/receivers as well.

Ignoring higher order reflections reduces computational complexity to O(N) where N is the number of segments, whereas second order reflections increase this to O(N^2) and higher order reflections make it even worse. For noise mapping, computation speed is of high importance, and in case of soft ground surface, the simplification is thus justified.

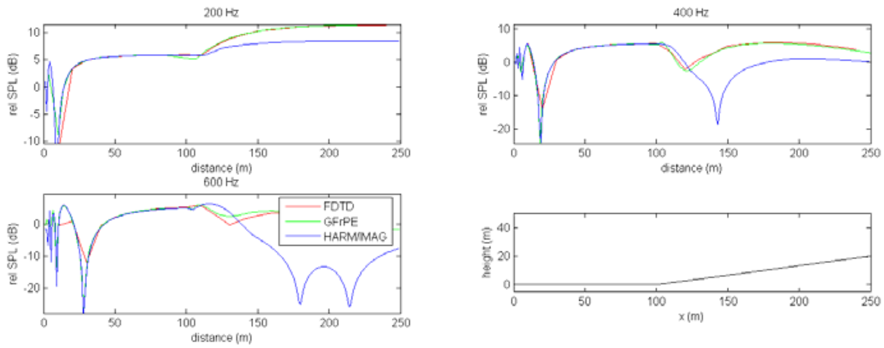

Figure 2.- Comparison of GTrPE, FDTD and Harmonoise/Imagine for a inclining slope without shielding. Relative sound pressure level, hsrc=hrec=2m, σ=200000kNsm^{-4}.

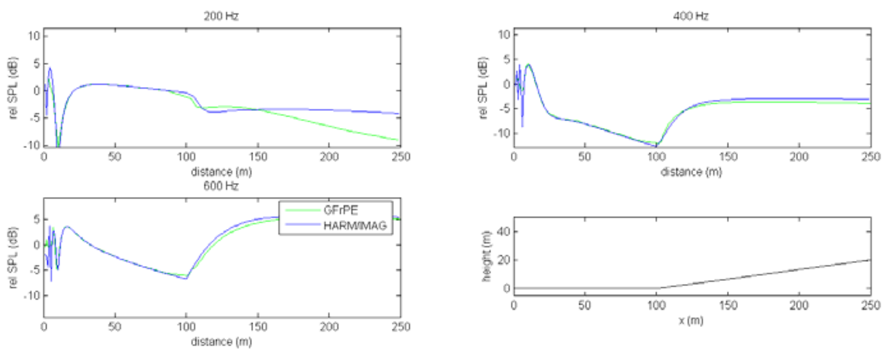

Figure 3.- Comparison of GTrPE and Harmonoise/Imagine for a inclining slope without shielding. Relative sound pressure level, hsrc=hrec=2m, σ=200kNsm^{-4}.

Smooth hill

A third artifical profile is a smooth hill [13], height=10m and width=250m, starting at *x*=50m. The source and receivers are put 2m above the ground, the source being at x=0m. The hill is composed of three circular arcs. For the purpose of the simulations, it is linearized into line segments as follows: for the GFrPE simulation, a horizontal resolution of 15 m is used, for the Harmonoise simulation, the technique described in appendix B of [10] has been used.

The overall agreement between Harmonoise and GFrPE is good. The ground can be considered as acoustically quite hard for 200Hz, and that's where the difference is largest. However, it can be seen that Harmonoise makes local jumps of 5 to 10 dB in the shadow area. The locations of these jumps are the vertices used for the linearization of the profile. It is not yet identified if these jumps are caused by limitations in the model or by the implementation.

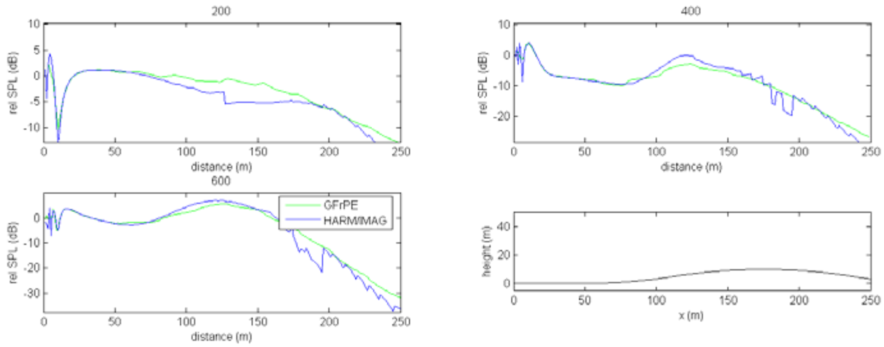

Figure 4.- Comparison of GTrPE and Harmonoise/Imagine for a smooth hill. Relative sound pressure level, hsrc=hrec=2m, σ=200kNsm^{-4}.

Real-life profiles

Lastly, the Harmonoise model is compared to GFrPE for some realistic cross sections, taken from the Unterinntal region, in the Alps, in the western part of Austria. The calculations are part of a larger study. More information on the specific measure points can be found in [1].

The source is positioned half a meter above the ground at *x*=0m, and represents a highway centered in the valley. The receivers run from left to right, 2m above the ground. The simulations run over longer distances and at higher frequencies than for the previous artificial profiles, since the comparison is against GFrPE only so that it is no longer constrained by FDTD limitations.

In Figure 5, the relative sound pressure level is plotted for two selected profiles: profile 25 of measure point 3 and profile 12 of measure point 5. The overall agreement between GFrPE and Harmonoise is good for both profiles, considering the large propagation distance.

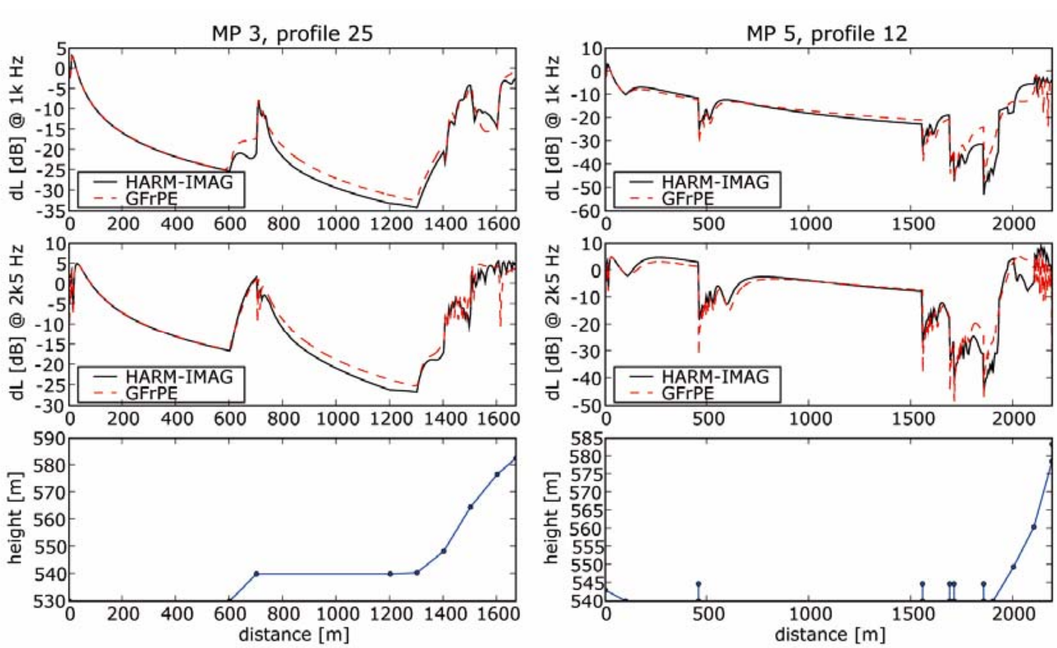

Figure 5.- Comparison of Harmonoise and GFrPE for two selected profiles in the Unterinntal region. Relative sound pressure level, h_{src}=0.5m, h_{rec}=2m, σ=30kNsm^{-4}.

CONCLUSIONS

From the selected profiles, it can be seen that the engineering model of the Harmonoise/IMAGINE project is quite good at predicting sound pressure levels in more complex cross sections in valley-slope configurations. Shielding by undulations in the terrain is fully accounted for.

In concave cross sections with hard ground surfaces however, the Harmonoise model underestimates the sound pressure level by neglecting higher order reflection paths. This is due to a trade off in complexity vs. accuracy. To fully account for second or higher order reflection paths, one needs quadratic or even exponential complexity, severely reducing the applicability of the model for noise mapping purposes. However, for concave cross sections with soft ground surfaces, this situation gets better because of the reduced importance of higher order reflections, justifying the simplification made by the Harmonoise model.

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