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The sound propagation model of sonRAIL

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ABSTRACT
The basic features of the sound propagation model of sonRAIL, the new Swiss railway noise calculation model, are presented [1]. An overview is given with the focus on newly developed parts such as the solutions for tunnel openings and railway line cuttings, the incorporation of meteorological effects on sound propagation and the coverage of reflections at buildings and other plane surfaces as well as diffuse reflections at forests and cliffs.

1. INTRODUCTION
The sonRAIL calculation model is composed of an emission model that describes the generation of railway sound and a propagation model. Both are defined in one-third-octave bands from 100 Hz to 8 kHz. The emission model yields sound power levels for five predefined source heights along the vehicle surface for each vehicle in dependence of infrastructure and operation conditions [2], [3]. Track sections with constant properties, i.e. track superstructure, traveling speed, traffic volume and composition, are combined to line sources that can be described by their total sound power.
The propagation model calculates the attenuation of sound radiated from such line sources to a receiver location. The propagation part can be operated entirely autonomous from the emission model with only the geometrical properties of the line sources as interface. The resulting sound exposure can then be calculated as a simple division between the sound power of a source and its corresponding attenuation. This clear distinction of sound emission and propagation is important as it allows separating the time consuming propagation calculation from the less laborious steps.
As the quality of calculation results not only depends on the correctness of the applied algorithms but also on the accuracy of the input data, great attention was also paid to the latter. Most of the necessary data is geo-referenced and geographical information systems feature potent tools to prepare the data and to present and analyze the results. Therefore it was decided to attach the calculation model to a GIS-platform. While the emission model was directly implemented in the GIS-system, the sound propagation model is designed as a separate application that is started and controlled by the main program but works independently from the rest. This allows a multi-processor-structure where many calculation tasks can be handled at the same time on different computers.
The propagation model is organized in four different modules that are operated independently from each other. The module ‘Basic’ is mandatory for each calculation as it performs a calculation of direct sound propagation under the assumption of a homogenous atmosphere (see section 2). In the second module meteorological effects on sound propagation are accounted for (see section 3). The results of the module ‘Meteo’ are added to the ‘Basic’ calculation as a correction, implying an increase or decrease of sound exposure as a

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consequence of meteorological conditions. The third and fourth module yield independent contributions, one for reflections at buildings, walls and other rigid surfaces and one for diffuse reflections at forest edges and cliffs (see sections 4 and 6).
In principle sound propagation is independent of the type of sound source. Nevertheless there are phenomena that are specific for a certain source type. For railway noise this is for example the case for the ground effect close to the source that shows a distinct behavior as a consequence of the specific properties of the ballast bed. In sonRAIL an extended ground effect model is implemented for this situation which is explained in detail in [4]. Also typical for railway noise are situations with hard surfaces in close vicinity of the vehicles that lead to additional reflections. This is for example the case for tunnel openings or railway line cuttings. In order to reduce the calculation effort, these multiple reflections are not dealt with within the reflection module but are treated based on an engineering approach that is presented in section 5.

2. CALCULATION OF DIRECT SOUND

The propagation module for direct sound basically represents an implementation of the ISO Standard 9613 [5], [6]. Geometrical divergence, atmospheric absorption and barrier effects are directly taken from the standard. Foliage attenuation is also included. The limiting propagation distance is though only implemented as a free model parameter and not mandatory set to 200 m as this limitation is only valid for flat terrain and downwind conditions. The additional attenuation for housing is not implemented as propagation in urban environments is treated in a separate module.
The most important deviation from the standard concerns ground effect calculation. Ground reflections are calculated for spherical waves over flat and homogenous ground according to Chessel [7]. The ground impedance is defined frequency-dependent according to the model of Delany and Bazley [8] with the flow resistance of the ground as single free parameter. This solution is extended to uneven terrain and varying ground properties using a Fresnel-zone-approach (see Figure 1). The Fresnel-zone is defined as the area around the reflection point from where reflections exhibit an additional path length of half a wavelength at most. It is assumed that half a Fresnel-zone is needed to get a full reflection. The contribution of each ground reflection is weighted with the percentage of the segment length that is covered by half the Fresnel-zone.

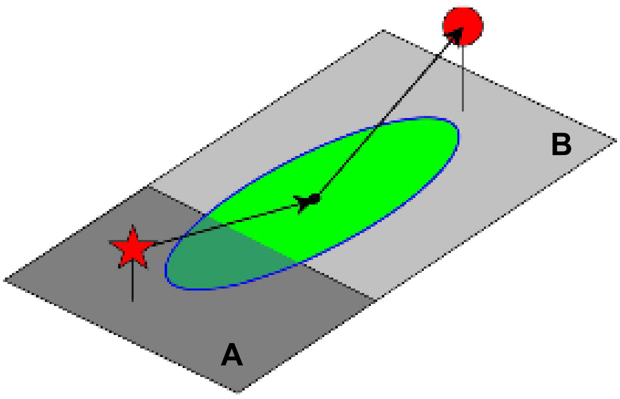

Figure 1: Fresnel-zone concept for the ground reflection calculation. The reflection on surface **A** is weighted with approximately 1/4 even though the reflection point is not on the surface.

Additionally the ground reflection model accounts for the coherence loss between direct and reflected sound in dependence of frequency and propagation distance [9]. The parameters for

this coherence loss factor were derived based on the work of Parkin and Scholes [10] and Daigle [11].
Shielding effects are calculated according to Maekawa [12] for the case with a separate consideration of ground effects. Only sound propagation paths with a single ground reflection are taken into account, i.e. the contribution of a path source-ground-barrier-ground-receiver is omitted. K_{met} is generally set to 1 as meteorological influences on shielding effects are dealt with in the module 'Meteo'. The shielding effect is limited to 20 dB in all frequency bands as higher barrier effects hardly ever occur under practical conditions as a consequence of turbulence-induced scattering.

3. METEOROLOGICAL EFFECTS ON SOUND PROPAGATION

Just as the 'Basic' propagation calculation the correction for meteorological effects is based on a vertical profile between a source and a receiver point including terrain and obstacles. As additional input data vertical profiles of wind speed, temperature and humidity are needed. These profiles can be generated in advance with a separate meteorological preprocessor.
While temperature and humidity are used to calculate air absorption, wind and temperature gradients with height in combination with a wind direction are used to derive effective sound speed profiles. Based on these sound speed profiles a ray tracing algorithm is applied that, starting from the source point, searches the sound ray that reaches the receiver. If barriers prevent a direct connection the ray to the barrier edge is taken and the search algorithm restarts from there. The resulting profile with curved sound rays and an original terrain is then dilated angle- and length-preserving, as demonstrated in Figure 2, resulting in a situation with straight sound paths but a converted terrain.

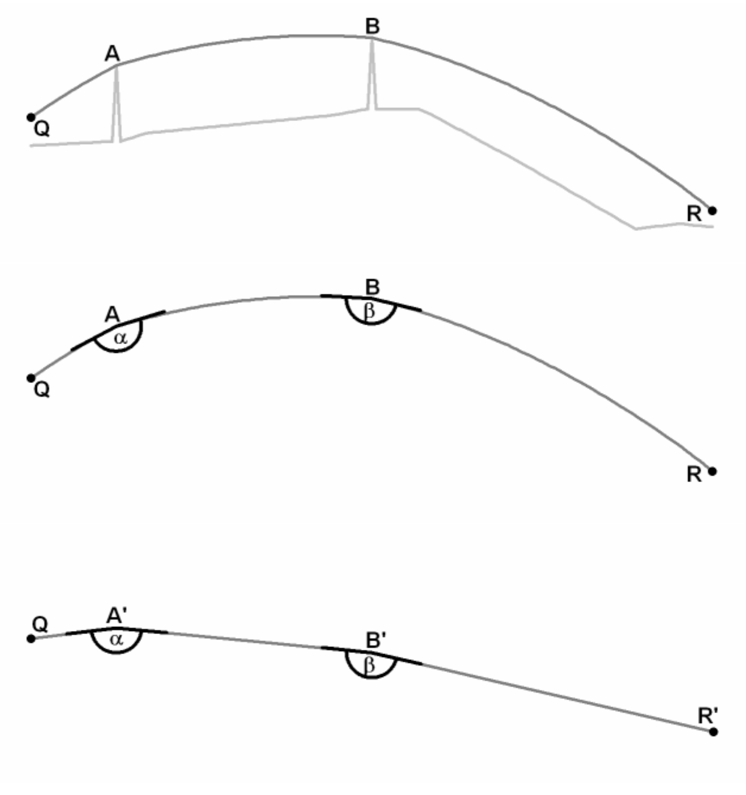

Figure 2: Determination of meteorological effect under downwind conditions: Transformation of the terrain from a situation with sound propagation along curved rays into a corresponding situation with straight sound paths.

For this transformed situation a recalculation of the shielding effect according to the algorithms of the 'Basic" propagation model is performed. The resulting meteorological effect is defined as the difference in level between the calculations with original and converted terrain.
Under upwind conditions it is though quite often the case that no sound ray can be found to reach the receiver. In these situations with an acoustical shadow zone, the ray is identified that comes closest to the receiver. Based on geometrical properties of this ray according to Figure 3 a correction for the decrease of level in the acoustical shadow zone is derived. The corresponding algorithms have been developed in comparison with numerous simulations with a Finite-Difference-in-the-Time-Domain-model and were published in [13].

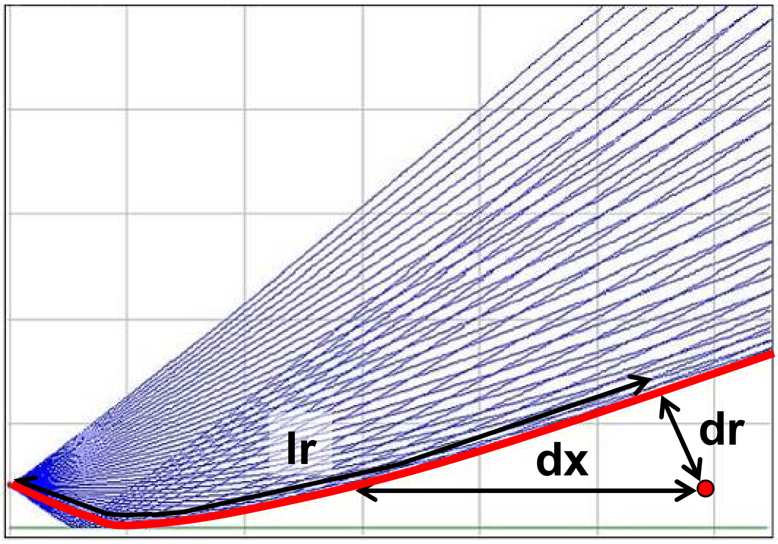

Figure 5: Determination of meteorological effect in shadow zones. The ray that comes closest to the receiver is highlighted. *lr*, *dx* and *dr* denote the geometrical properties used for the correction.

The sound paths from source to receiver derived by the ray tracing algorithms are also used to recalculate foliage attenuation. Based on these sound rays the total propagation distance over forested terrain with less than the average tree height of typically 20 m is derived. This distance is then multiplied with the damping factors according to ISO 9613-2.
Generally the influence of meteorology on air absorption and foliage attenuation is small in comparison to the presence of shadow zones and the change in shielding effect. The latter can yield a decrease of receiver level up to 20 dB and an increase of up to 15 dB relative to the 'Basic' calculation.

4. REFLECTIONS AT BUILDINGS AND WALLS

The model for reflections at buildings, walls and other rigid surfaces is designed for sound fields in urban conditions. The calculation procedure is based on two analytical solutions of the reflection problem, one for coherent reflections (mirror-reflections) and one for scattering. For frequencies below a certain threshold, set to 600 Hz as default, a solution of the Kirchhoff-Helmholtz-Integral is used to reproduce the coherent part. As these coherent reflections are phase-sensitive the calculation has to be performed for discrete frequencies and all involved areas have to be sub-divided in a small grid (see Figure 6). Integration is performed over sound pressure of all surfaces and is repeated iteratively to reproduce multiple reflections between the surfaces.

The incoherent model basically follows the same concept. As phase information has not be taken into consideration for scattering several simplifications can be applied: the integration over all surfaces is performed for sound intensity instead of sound pressure, all frequencies can be calculated in a single cycle and the grid for the surface discretization can be set much wider.
The chosen approach features several benefits in relation to traditional geometrical solutions of reflection problems. Most importantly reduced reflections as a consequence of finite reflector dimensions are automatically taken into account and contributions are considered even when geometrical reflection points are not on the involved surfaces.
The model is though quite demanding in terms of calculation effort. It was therefore decided only to perform a reduced propagation calculation. While air absorption is included according to ISO 9613-1 barrier and ground effects have been simplified substantially. Instead of calculating diffraction only a visibility check is performed. An exchange of sound pressure or sound energy is only performed for surfaces that exhibit free sight. The terrain is assumed to be plane and fully reflecting and the ground reflection is only incorporated incoherently.
A detailed description of the model and its validation has been submitted to Acta Acustica united with Acustica [14].

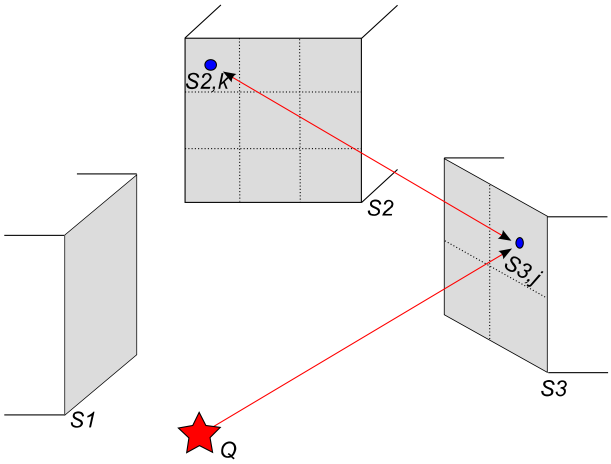

Figure 6: Reflection situation in an urban area with a source *Q* and several sub-divided surfaces that exchange sound pressure in the coherent case and sound energy in the incoherent case.

5. REFLECTIONS CLOSE TO THE SOURCE

As mentioned in section 1 reflections from tunnel openings and railway line cuttings are treated separately, apart from the reflection calculation procedure that was discussed in the previous section. For both situations an empirical correction was derived based on scale-model experiments and free-field-measurements [15], [16]. The resulting correction is applied to the attenuations that were determined in the module 'Basic' according to section 2.

A. Tunnel openings

For tunnel openings the calculation procedure distinguishes to types of contributions: direct sound from sources within the tunnel and contributions stemming from the diffuse sound field that establishes in the tunnel. Direct sound from inside of the tunnel is calculated based on the algorithms of the module 'Basic', including additional diffraction effects at the tunnel opening. The sound power emanating the tunnel opening that comes from the diffuse sound field is concentrated to a point in the middle of tunnel opening. From there a standard propagation calculation is performed to all receiver locations, taking into account an additional directivity pattern in dependence of Cosine squared of the radiation angle. Figure 7 shows the resulting sound field of the direct and diffuse contributions relative to an open track situation.

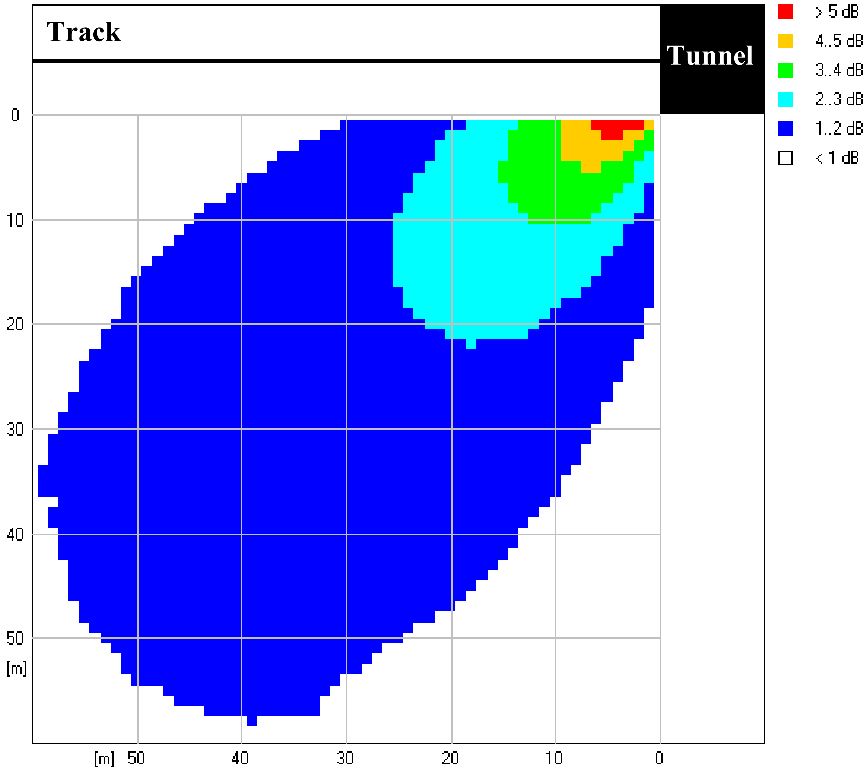

Figure 7: Level increase in the vicinity of a tunnel opening relative to an open track situation. (The tunnel opening has a rectangular shape with a height of 6.5 m and a width of 10.5 m.)

The sound power of the diffuse field source is primarily derived based on two questions: is the tunnel built with slab track or ballast track and is the tunnel opening partially equipped with absorbing material. For tunnels that are entirely mounted with absorbing material for the first 50 m of length the diffuse field source disappears.

B. Railway line cuttings

Railway line cuttings are defined as situations with a lowered track relative to the ambient terrain and predominantly reflecting side walls. Figure 8 visualizes the sound propagation phenomena that occur in such situations.

The calculation procedure distinguishes between single and multiple reflections. The latter occur between the vehicle and sidewalls in close vicinity. As there is hardly any absorption present, the radiated energy mounts to the roof section of the vehicle and propagates from there. The propagation from the roof is calculated by introducing two secondary sources which are placed on both sides of the vehicle on the roof (or in case of lower side walls at the height of the walls). The sound power of these sources is derived in dependence of the angle Φ, defined as the opening angle of the reflecting part of the side-wall seen from the centre of the wheel (see Figure 9). For these secondary sources as well as for the primary sound sources at the wheel-rail-contact a propagation calculation is performed that not only includes direct sound but also single reflections on the side walls, as indicated in the sketch on the right side of Figure 9. Similar to the approach for tunnel openings the secondary source, which represents the diffuse part of the reflection, features a directivity pattern that takes into account that the reflected energy primarily radiates in vertical direction.

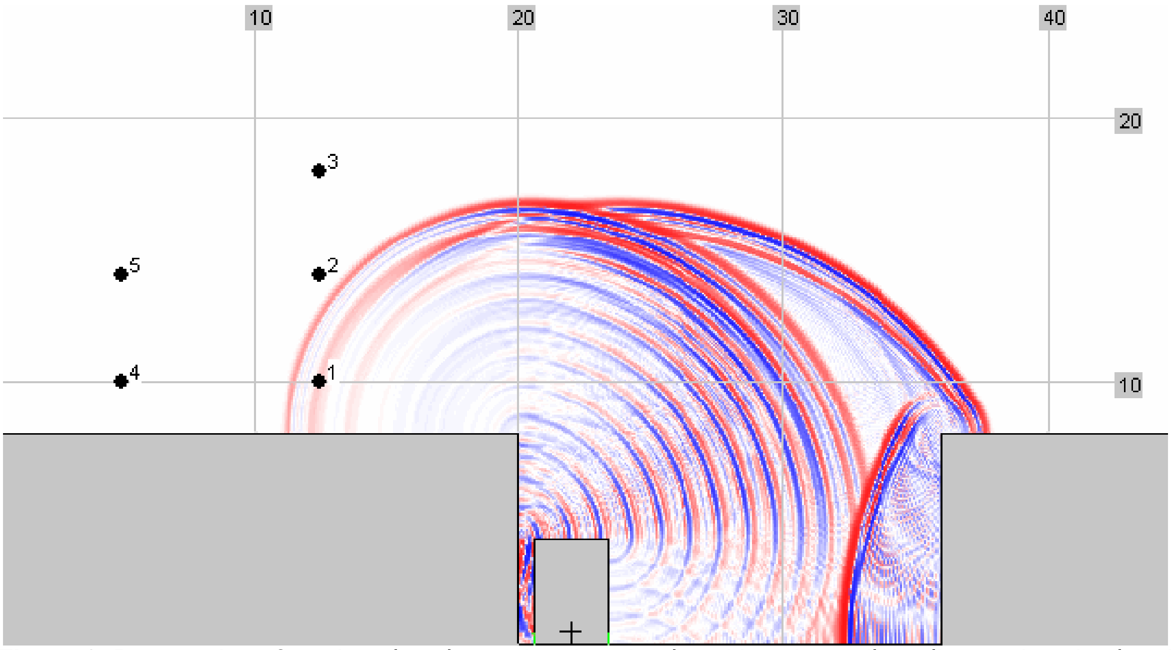

Figure 8: Propagation of two impulses located at the wheel positions in a railway line cutting simulated with a Finite-Difference-in-the-Time-Domain-Model. Multiple reflections between lateral walls and the vehicle body, reflections on the opposite wall and diffractions on the edges occur.

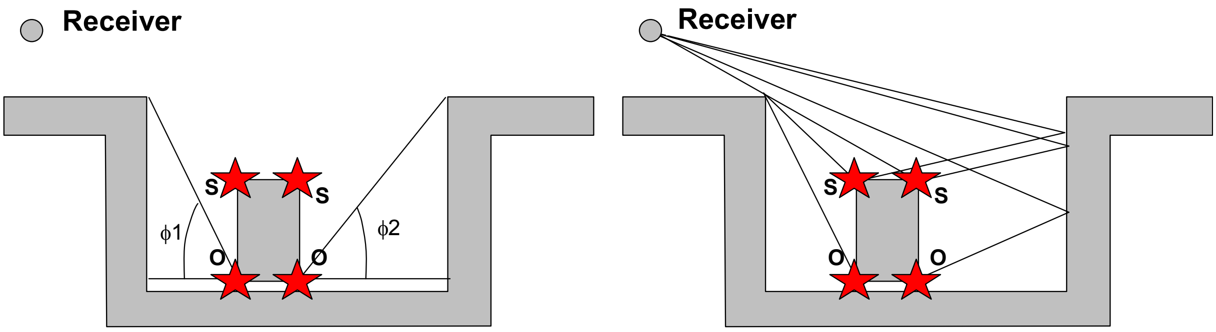

Figure 9: Left side: Definition of the angle Φ based on which the sound power of the secondary source *S* is derived. Right side: Propagation calculation for the original and secondary sources including single reflections at walls.

6. REFLECTIONS AT FOREST EDGES AND CLIFFS

Prominent reflections at forest edges and cliffs mostly occur in rural areas, especially in valley situations and are characterized by long drawn-out echoes. These diffuse reflections are calculated with two separate model approaches.

A. Reflection at forest edges

A single tree is modelled as a vertical cylinder. For the reflection at an infinitely long cylinder an analytical solution can be given based on the theory of scattering of spherical waves. Measurement results clearly support the assumption that the contributions of various trees can be summed up incoherently (see Figure 10). This conclusion allows important simplifications and accelerations of the calculation procedure. Instead of calculating the reflection of every tree in a forest in proper phase it is feasible only to do propagation calculations for a few representative cylinders and to account for the contributions of other trees by simple multiplications. Consequently the forest edge is divided into segments where only one tree on the forest edge is calculated per segment (see Figure 11). In order to determine the contribution of all the trees in comparison to the representative ones numerous calculations were performed where every single tree was explicitly calculated including air absorption and foliage attenuation as propagation effects. Based on these results an empirical correction was derived as a function of frequency and geometry to account for the contributions from the depth of the forest. The finite height of the trees is taken into account by a vertical efficiency factor. The analytical solution for the cylinder reflection already includes a directivity pattern in the horizontal plane. As a consequence of the finite height of the trees and of additional influences from the coppice the directivity in the vertical plane is not yet represented correctly. Therefore an additional vertical directivity pattern has been derived based on measurements.

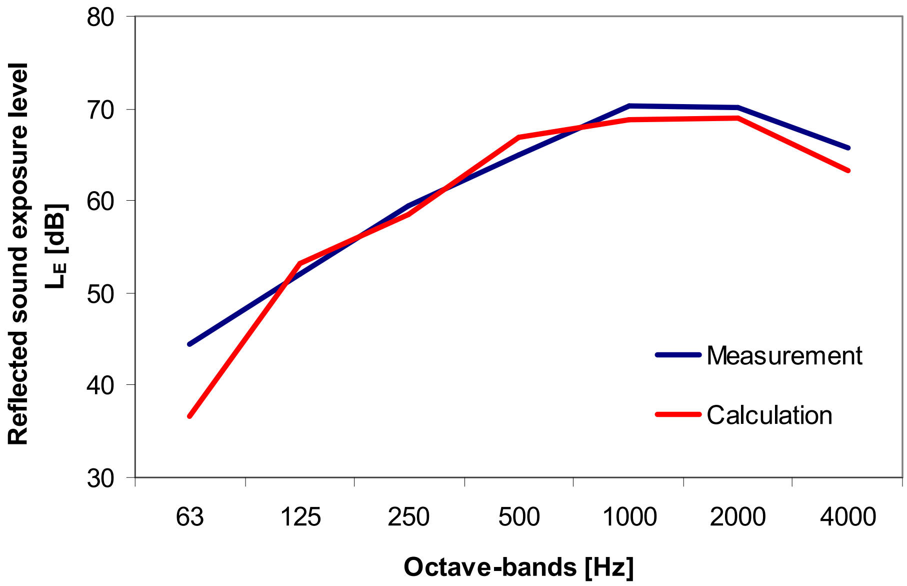

Figure 10: Comparison of measurement and calculation of a forest reflection with a point source in 30 m distance from a straight forest edge and a receiver in 20 m distance.

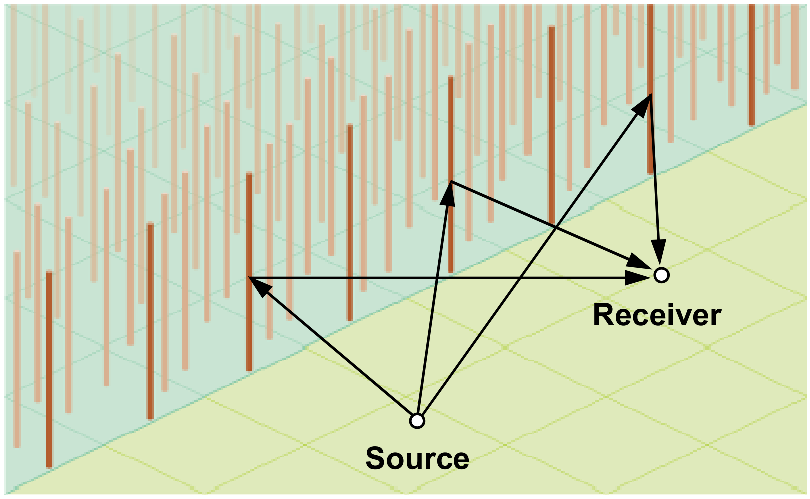

Figure 11: Calculation scheme for forest reflections where a propagation calculation is only performed for representative cylinders at the forest edge.

The forest reflection model has been published in Acta Acustica united with Acustica [17].

B. Reflections at cliffs

For reflections from cliffs a similar approach is followed. The entire cliff is divided in rectangular surfaces that are represented by secondary sources in the centres. A propagation calculation is performed from each source point to these secondary sources where the incoming sound energy is summed up. In a second step a propagation calculation is carried out from the secondary sources to all receiver points. Based on measurements a frequency-independent diffusivity factor of 0.8 was derived for the reflecting elements (Note: Additional validation measurements are planned to check this result.) For the diffuse reflection a directivity pattern according to the law of Lambert is assumed.

Mirror-reflections are neglected because of two reasons. On the one hand the typical geometrical situations generally exhibit source as well as receiver positions clearly lower than the reflecting cliffs. Only in very rare situations with either overhanging structures or in very narrow valleys mirrored reflection paths exist. On the other hand the available topographical data is neither capable of nor designed for giving accurate information on the orientation of the reflecting rock surfaces.

7. CONCLUSIONS

As mentioned in the introduction, the sonRAIL propagation model is designed to reach a high level of accuracy. Nevertheless its intention is an application as an engineering model and it therefore has to be able to cope with the demands for such models, for example the calculation of greater projects for the purpose of noise mapping within a reasonable time. Therefore analytical solutions were used where feasible and other aspects were dealt with empirical approximations, derived from calculations with reference models, scale-model-measurements or free-field-measurements. In comparison with the standard calculation model that is used so far in Switzerland, SEMIBEL, calculation time still increased by a factor of 1'000 to 10'000. SEMIBEL though only uses engineering formulas derived in the 80's of the last century and directly aims at reproducing A-weighted levels and does not meet with the state-of-the-art in railway noise calculation anymore.

The most recently published propagation model that can be taken as state-of-the-art was developed within the Harmonoise project [18]. When comparing the propagation algorithms of sonRAIL and the Harmonoise engineering model, similarities become obvious in many aspects. The 'Basic' propagation calculation is widely identical including in both cases a Fresnel-zone weighting for irregular terrain. To reproduce situations with refracting propagation conditions also a terrain transformation, called conformal mapping, is applied in Harmonoise. While in sonRAIL only barrier effects are determined for the transformed situation, Harmonoise performs an entire propagation calculation including ground effect. In Harmonoise sound rays are modeled as circles, an approach that was already implemented in the model Nord2000 [19]. The ray tracing algorithm of sonRAIL is significantly more laborious than this analytical solution based on circles. The major advantage is that arbitrary sound speed profiles can be used while circular solutions only represent constant gradients with height – something that hardly ever occurs in reality.

Significant differences can also be found when looking at the way reflections are modelled. While in Harmonoise a classical geometrical approach is implemented to identify reflecting surfaces, sonRAIL uses a totally new approach. The latter again is more laborious, but the model has major conceptual advantages, as already discussed in section 4.

For several model parts of sonRAIL no counterpart can be found in Harmonoise. Namely the ground-effect model over gravel, the special solutions for tunnel openings and railway line cuttings as well as the reflection models for forest edges and cliffs cover new elements. Summing up it can be concluded that sonRAIL and Harmonoise have a common basis, but that sonRAIL has gone a few steps further in several aspects.

ACKNOWLEDGMENTS

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