Adapting a sound ray model of the atmosphere to simulate sound propagation in urban environment

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Introduction

More than 50% of the world population is living in urban settlement areas. Additionally, the trend of urbanisation increases in many regions worldwide [1]. Noise exposure in urban areas is an important environmental factor which influences the well-being and quality of life of urban residents. According to recent studies the population is most frequently disturbed by road traffic noise. Particularly in residential areas near main roads this problem is essential, because prescribed noise levels are often exceeded here. Results of measurements in and around cities clearly demonstrate the temporal variability of the sound level mainly caused by the variable atmospheric structure [2]. This conclusion motivates us to study the influence of the atmosphere on sound propagation under specific urban environmental conditions.

Thereby we used the geometrical sound propagation model SMART (sound propagation model of the atmosphere using ray-tracing) to include on one side the vertical state of the atmosphere adequately and to minimize on the other side the computing time compared with physically and numerically more sophisticated models [3].

Atmospheric influence on the sound propagation in an urban environment

Urban atmospheric boundary layer

The complex composition of buildings in urban areas causes changed fluxes of energy and therewith modified vertical profiles of meteorological quantities like temperature and wind vector. To simulate the effect of a modified atmospheric structure on the sound propagation it is necessary to consider at first the special properties of the urban atmospheric boundary layer (UABL).

In comparison to the rural environment the UABL reaches greater height levels of about 1.5 km above the ground. The thickness of the UABL increases with a raising roughness height [4]. Consequently, the vertical gradient of the mean horizontal wind speed is maximal for a flat terrain and minimal for a very rough surface. On average and without the influence of the thermal stratification the wind speed in urban areas is smaller than in the rural environment. Especially during situations with small wind speeds the height of the UABL depends additionally on the temperature profile. A decreasing temperature with height results in a further decrease of the wind speed gradient and therefore a higher UABL (and vice versa).
There are different methods to simulate the meteorological regime in an urban environment. One possibility is the use of atmospheric models which numerically solve the system of equations describing the impulse and energy balance.
Furthermore it is possible to use computationally economic analytical models of the atmosphere. Such a two-layer model was developed by Emeis et al. [5] using long-term measurements in Hannover. Using this model mean wind speed profiles were calculated depending on typical thermal stratification during daytime and nighttime. In the near-surface layer of the UABL (up to a height of 20 m) the wind profiles were derived applying analytical formulas of Salomons [6]. Therewith the influence of obstacles (mean height: 10 m) on the air flow is approximated. The resulting wind profiles are shown in Figure 1.
The wind direction is also height-dependent above 150 m during the day and 30 m nighttime, respectively.

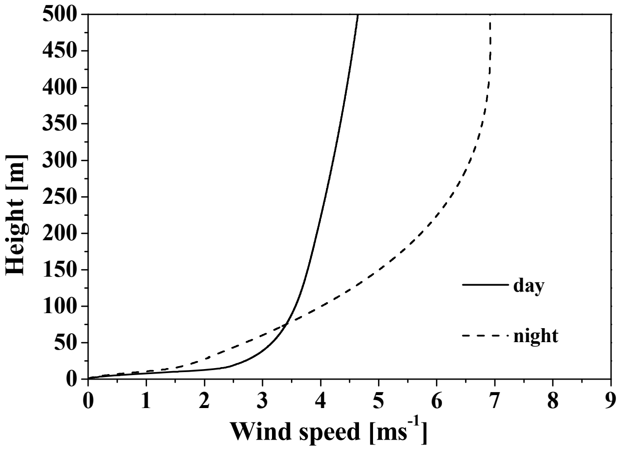

Figure 1: Mean urban wind speed profile daytime and nighttime. The roughness height was 1 m.

Besides the wind profile also the thermal stratification is changed in urban environments. Inside the urban obstacles layer the temperature decreases during daytime with maximal gradients near the surface. The above situated mixing layer is neutrally stratified on average. Beyond this well mixed layer an inversion layer can be observed which denotes the transition to the free atmosphere above the UABL. Because of the high thermal capacity of the buildings and anthropogenic heat sources it is possible that the mixing layer remains partially during the nighttime. Above this mixed and relatively thin layer a temperature inversion develops similar to the rural environment but with a smaller vertical layer thickness.

As a first approximation different linear temperature profiles were used in this study. During the day negative temperature gradients of -0.01 Km^{-1} as well as -0.006 Km^{-1} were applied. During nighttime both positive and negative gradients were used: -0.01 Km^{-1}, -0.006 Km^{-1}, +0.01 Km^{-1}, +0.006 Km^{-1}.

Outgoing from these typical atmospheric stratifications the vertical profile of the effective sound speed was calculated (see Figure 2 and Figure 3, exemplarily in upwind direction). The effective sound speed is derived from the adiabatic sound speed and the wind speed component in the direction of sound propagation [6].

In the daytime the effective sound speed decreases throughout the UABL. However during nighttime the gradient of the effective sound speed can reach positive values at a height level of 350 m above ground surface. For upwind conditions the stable stratification during nighttime results in an increasing effective sound speed up to a height of 0.3 m and above 250 m. These structures of the vertical profiles effect the sound propagation through the urban atmosphere.

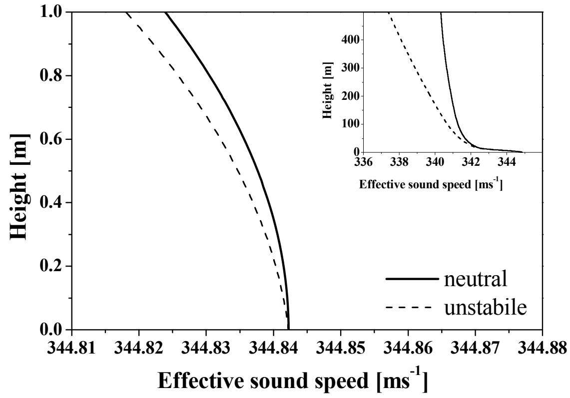

Figure 2: Mean urban profiles of the daytime effective sound speed in upwind direction with temperature gradients: -0.01 Km^{-1} (unstable), 0 Km^{-1} (neutral).

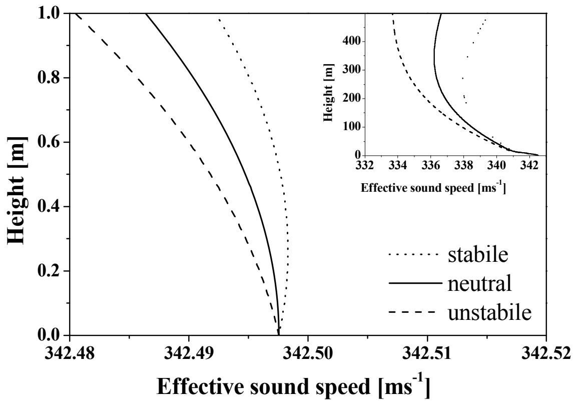

Figure 3: Mean urban profiles of the nighttime effective sound speed in upwind direction with temperature gradients: -0.01 Km^{-1} (unstable), 0 Km^{-1} (neutral), +0.01 Km^{-1} (stable).

Sound propagation model for urban areas

Outgoing from a point source at the ground the sound level attenuation at a height of 1.5 m (noise exposition of a pedestrian) is simulated using the model SMART. The simulations were carried out for an area with a maximal distance to the single sound source of 2 km. Therefore, the investigations can be considered as representative for the urban environment, e.g. near highways.

The above explained wind speed and temperature profiles (see Figure 1-3) are used as input data for the model. Thereby, a high vertical resolution of at least 0.1 m is required to trace the rays exactly. Especially in the near of the source, that means near the ground surface, a high vertical resolution is necessary. Exemplarily, a few of the totally 2009 traced sound rays are plotted in Figure 4. During nighttime conditions with a stable atmospheric stratification and a sound propagation in upwind direction a few sound rays emitted near to the horizontal direction are refracted downwards. These sound rays don't reach the immission level at a height of 1.5 m. In comparison to this behaviour sound rays with the same angles of emission pass through the 1.5-m level in the case of a neutral or unstable stratification.

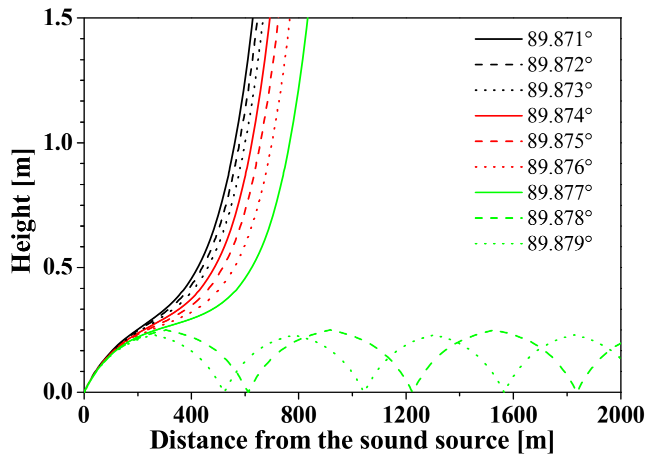

Figure 4: Sound rays with different emission angles during stable nighttime conditions (see Figure 3) in upwind direction.

Outgoing from the tracing of several thousands of sound rays the model SMART calculates the sound attenuation level. The change of the sound intensity level, i.e. sound attenuation level, at one height is only dependent on the relation between the cross sections of a sound ray tube in a reference distance and in another distance from the sound source if sound energy conservation can be assumed. The geometrical quantities of sound rays forming this ray tube at a distinct height are used to determine the sound attenuation level influenced by geometrical spreading and refraction. The sound attenuation level relates for SMART simulations to a distance of 1 m from the sound source. It is calculated dependent on the horizontal distance to the sound source. If the model SMART is applied for several horizontal directions (different azimuth angles), a horizontal map of sound attenuation results. The difference between the sound attenuation level for an actual atmospheric structure and for an atmosphere without refraction results in the meteorological excess attenuation as a measure for the influence of atmospheric refraction on the sound immission.

Simulation results

Using the adapted model SMART maps of the meteorological sound attenuation were calculated to estimate the atmospheric influence on the sound propagation up to a distance of 2 km to a sound source (see Figure 5 and Figure

6). Values around 0 dB characterize an inexistent influence of refraction. Negative values (hatched in the figures) symbolize an enhanced noise immission because of the atmospheric influence. Values greater than 20 dB (in light green) display a shadow zone.

Figure 5 and Figure 6 show that the onset of the shadow zone in the upwind direction depends on the thermal stratification. In the case of an unstable stratification this zone is greater and starts near the sound source. Otherwise, in the case of a stable stratification the shadow zone begins at a distance of about 500 m. This result can be explained by the sound rays (see Figure 4) which are refracted upwards at a larger distance from the sound source. In the downwind direction greater differences between different stratifications especially in the near of the sound source are detectable. An unstable stratification results in a larger area with enhanced noise exposure in comparison to stable stratification.

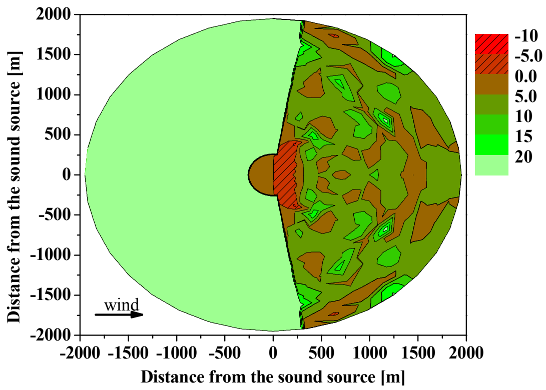

Figure 5: Meteorological excess attenuation [dB] during nighttime conditions and an unstable stratification.

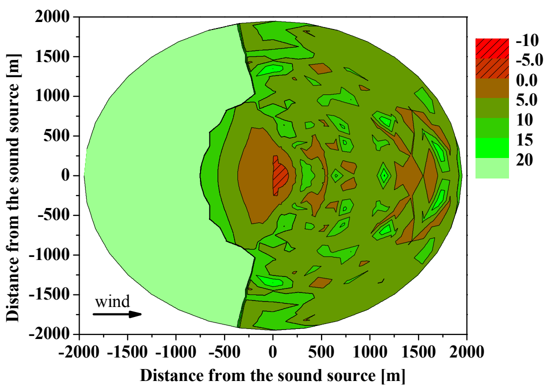

Figure 6: Meteorological excess attenuation [dB] during nighttime conditions and a stable stratification.

To estimate the influence of the complex urban profiles of meteorological quantities on the sound propagation in all 36 directions around the sound source, the frequencies of different meteorological excess attenuations are displayed in Figure 7.

A changed thermal stratification produces a considerably changed frequency especially for positive excess attenuations. This result is mainly caused by the different behavior of sound rays in the upwind direction during conditions of stable and unstable stratification. The nighttime wind profile combined with a positive temperature gradient of 0.01 Km^{-1} effects the most values in the range between 5 and 15 dB. Therewith an additional noise reduction is associated. Otherwise the ‘perfect’ acoustic shadow zone is reached for more locations, up to 47%, in the cases of negative temperature gradients. Furthermore, more negative values of the excess attenuation can be detected for a unstable stratification. It can be therefore concluded, that the urban heat island during nighttime causes a higher noise exposure in comparison to the rural environment.

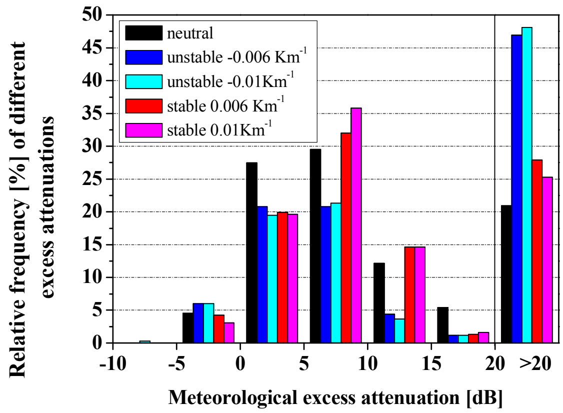

Figure 7: Relative frequency of different meteorological excess attenuations during nighttime conditions and several thermal stratifications (temperature gradients).

Atmospheric influence on the sound propagation near noise barriers

As a consequence of noise exposure near residential areas, noise barriers are often installed along busy roads. Obstacles within the sound ray path lead to a decreased sound level at the location of immission. The primary protection effect of noise barriers can be superposed by meteorological effects. To quantify these effects, measurements and simulations were carried out [7].

Measurement results

Two measurement places at a highway near Chemnitz in distances of 25 m and 150 m to the highway were used to study the effect of atmospheric stability and wind profile on the frequency-resolved sound level. A variation of the averaged (over 60 minutes) sound level dependent on the atmospheric structure is clearly visible in the results [7]. Thereby, the difference between a measured and a calculated sound level was analysed in a distance of 150 m to the highway. The synthetic sound level was calculated by VDI 2714 [8] which includes the atmospheric influence only by a simple and constant measure. Positive values of this difference sound level mean that the VDI model underestimate the measured sound level. Such results must be critically discussed regarding the noise protection of residents.

Exemplarily, the influence of different wind directions is demonstrated in Figure 8. The measurements were carried out daytime on the 5th of March and 29th of May in 2008 during a slightly unstable stratification of the atmosphere and wind speeds around 3 m/s at a height of 2 m.

Mean differences up to 5 dB for different wind directions result. A considerably higher sound level occurs during downwind conditions in comparison to upwind conditions. The VDI model underestimates the measured sound level by maximally 4 dB for frequencies in the middle part of the analysed audible spectrum.

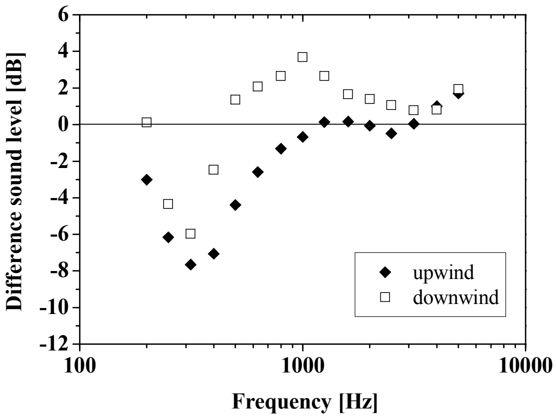

Figure 8: Difference sound level (60-min mean) from measurements and VDI model at a distance of 150 m from a highway with a noise barrier during daytime conditions in upwind and downwind direction.

Sound propagation model including a screen

The protection effect of noise barriers can be simulated in the easiest way using measures like the insertion loss [9]. Thereby the insertion loss is described as an additional attenuation level. This concept was integrated into the model SMART [10]. At first a SMART run without a noise barrier is performed. The second step includes the analytical calculation of the insertion loss mainly dependent on the geometrical properties of the noise barrier. Additionally the atmospheric influence is described by a correction parameter that amounts values in the range between 0 and 1. The value of 1 means straight line sound rays without refraction, smaller values are used under downwind conditions when the sound rays bent towards the ground surface. Using, e.g., a barrier of 4 m height, the insertion loss amounts to maximally 10 dB. Nearest the barrier the insertion loss decreases noticeably up to 4 dB at a distance of 55 m behind the screen [10]. After this calculation the insertion loss is added to the attenuation level simulated by SMART if the sound rays hit the noise barrier.

Another way to explain the atmospheric effect on the sound propagation is the direct simulation of sound rays including a noise barrier. The sound ray which hits the screen is not further traced and consequently don't contribute to the sound level behind the screen. In this way a perfectly absorbing noise barrier is simulated. Although realistic noise barriers are partly or totally reflective this approximation can be used for the investigation of sound levels behind the screen regarding the sound source. This area is especially interesting for the noise protection. Furthermore the sound rays are traced over several 10 m up to this area and therefore the meteorological influence on the sound propagation is important.

If one apply a 4 m high thin noise barrier at a distance of 55 m to a sound source a perfect sound shadow results behind this screen in the case of an atmosphere without refraction. Thereby, the simulations were carried out without diffraction effects at the screen which cause a dilution of the acoustic shadow. Otherwise, applying a temperature inversion and downwind conditions, the sound attenuation map shows no region with a shadow zone. That means that the protection effect of the noise barrier was cancelled by the atmospheric influence.

Further investigations will include the effect of diffraction to calculate more realistic values of the sound attenuation behind a noise barrier. Additional effects of changed wind profiles regarding the influence of obstacles should be included too [6]. Nevertheless, already the first simulations and measurements showed the remarkable influence of the atmospheric structure on the noise protection.

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