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Meteorological effects on the 3D sound propagation inside an inhomogeneous forest area

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Abstract

The influence of trees on sound propagation is currently discussed to reduce the sound exposure near transport infrastructure or industrial areas. This influence is direct due to reflection and scattering at the trees themselves as well as indirect through meteorological and ground effects modified by the trees. Previous investigations provide a mixed picture of sound attenuation within forested areas, in particular for the temporally and spatially variable meteorological influence. Thus, a three-dimensional model chain of atmospheric and acoustic models was adapted and applied to special meteorological and vegetation-specific conditions. A meteorological mesoscale model was applied to simulate temperature and wind fields within an inhomogeneous forest site. The meteorological quantities are used as diurnally variable input data for the acoustic FDTD (finite-difference time-domain)-model to simulate the sound propagation. Thereby, the effects of vegetation elements, impedance ground surface, and sound refraction are considered. The simulations are related to outdoor measurements, which were performed in early autumn 2011 near Dresden (Germany). The sound propagation of artificial signals was measured along sound paths of up to 190 m length through a clearing as well as through an old spruce stand. Results of the comparison between measurement and model simulations are presented and possible applications of these results with regard to noise protection aspects are discussed. The model results confirm the measured diurnal cycle of sound levels at the receiver positions. Simulations with and without trees suggest an excess attenuation of the trees by about 4 dB per 100 m already for low frequencies.

Keywords: atmospheric acoustics, forest meteorology, sound propagation, noise protection, acoustic measurements, three-dimensional acoustic model

1 Introduction

Negatively perceived or even unhealthy sound, i.e. noise, is still a topical and urgent environmental problem. Areas of forest are presently discussed as possible noise protections because direct (scattering, reflection of vegetation elements) and indirect (reflection at ground surface, refraction due to temperature and wind profiles) effects of vegetation contribute to sound attenuation.

The sound propagation through forest areas is affected by various phenomena. They include the distance-dependent spherical wave divergence and the air absorption, which is frequency-dependent and dependent on meteorological variables (temperature, humidity). These effects, which occur also for a sound propagation outside of forest areas, always lead to a sound attenuation.

In general, sound attenuation due to a forest stand increases with increasing frequency, however not continuously (Bies and Hansen, 1996; Price et al., 1988). Depending on sound frequency, different effects dominate (e.g. Aylor, 1972; Fricke, 1984).

Direct sound attenuation occurs due to reflection and scattering by trunks as well as absorption due to needles or leaves. This influence leads to a reduction of sound level after passing the forest and increases with increasing frequency. Scattering due to vegetation elements affects sound attenuation even at sound frequencies greater than 100 Hz (e.g. Fricke, 1984; Swearingen and White, 2007). The scattering effect can be examined explicitly by 3D modelling using FDTD models (Heimann, 2003). The direct effect is determined by the forest characteristics like tree density and trunk diameter.

Beyond, sound waves interact frequency-dependently with the ground surface (Embleton et al., 1976; Attenborough et al., 2011). Acoustic flow resistance, an important parameter for impedance modelling, decreases significantly compared with grassland and covers a wide range of values within forests (Martens et al., 1985). Hence, ground impedance is usually low in forest areas, leading to increased attenuation due to the indirect ground effect. In addition, the meteorological influence must be considered, especially sound refraction (Piercy et al., 1977; Heimann, 2013). This indirect effect can result in attenuation or amplification.

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Meteorological parameters have a significant influence on sound propagation (Aumond et al., 2012). Vertical gradients of temperature and wind velocity determine sound speed gradients and thus lead to the refraction of sound, one of the most important meteorological influences on sound propagation. Already Wiener and Keast (1959) measured the additional sound attenuation due to sound propagation in upwind direction (or for decreasing temperature with height). They quantified this acoustic shadow effect with maximal 35 dB as well as more recent studies by Heimann and Salomons (2004) and Cheinet (2012). The temporal variability of measured sound levels is also affected by the turbulent variability of temperature and wind profiles and includes a range of 10–25 dB within 30 s (e.g. Wiener and Keast, 1959; Cheinet, 2012). Even averaged sound level values over 15 min measured at a distance of a few 100 m away from road traffic show a high variability up to 20 dB for different meteorological situations (Gauvreau, 2013). Hohenwarter and Mursch-Radlgruber (2014) found differences between different temperature profiles up to 10 dB for the A-weighted sound exposure level, which was measured in a distance of 200 m from a railway noise source.

Vertical temperature and wind profiles show significant differences in forest stands compared to surfaces without vegetation (Finnigan, 2000). Due to changing temperature and wind fields in forests, different refraction of sound waves and thus a different sound immission and temporal variability in comparison to grassland are expected (Tunick and Swearingen, 2009).

Since the middle of the 20th century (e.g. Eyring, 1946), the shielding effect of vegetation strips and forests in terms of noise pollution from traffic is investigated (overview by van Renterghem et al., 2015). In recent years, a rising number of studies are specifically designed for protection against blast noise (Swearingen et al., 2013a, b). Meanwhile, there are numerous publications on measurements available. The sound attenuation values cover, depending on vegetation characteristics, measurement geometry, frequency spectrum, and method of investigation, an extended range of a few tenths dB/100 m (e.g. Embleton, 1963) up to a few 10 dB/100 m (e.g. Swearingen et al. 2013a; Tyagi et al., 2006). The results of these studies cannot be generalized simply, due to different boundary conditions, methods, and study areas. Thus, it is difficult to transfer the results received so far for noise control applications. For some years, therefore, the number of theoretical studies using models is growing significantly. Models have the advantage that some effects of sound propagation in forest areas can be distinguished and examined under 'virtual' laboratory conditions (Heimann, 2003; van Renterghem et al., 2012). In comparison to previous studies of narrow tree belts (e.g. Tarrero et al., 2008; van Renterghem et al., 2012), longer propagation distances up to 190 m and an inhomogeneous forest area with a clearing are considered in this paper. The investigation of sound propagation through such types of inhomogeneous forest areas are interesting for controlling noise pollution due to traffic routes or wind turbines in managed forests.

Despite many publications on the overall forest impact, the strength of meteorological influence on the sound propagation through forests and the temporal and spatial variability of this influence are unclear. Additionally it is questionable, which uncertainty due to meteorological influence must be applied for a constant value of forest sound attenuation used in guidelines and standards (e.g. ISO 9613-2). Furthermore, sound-channelling effects may occur depending on the vegetation parameters and enhance the meteorological influence on sound propagation (Tunick, 2003). Their impacts, e.g. on sound propagation of wind turbines and traffic noise sources within forest areas, are even not clear.

The paper therefore intends to answer the following questions:

- What is the meteorological influence on the propagation of sound through an inhomogeneous forest with clearing?
- Is it possible to reproduce the forest influence on sound refraction, reflection at the ground surface, scattering at trees with a 3D model chain connecting meteorology and sound propagation and to differentiate between the single acoustic effects of the forest?
- Which similarities and differences result from the comparison between the model chain and outdoor measurements?
- Is it possible to generalize the simulated results and to derive recommendations for practical applications and uncertainty of sound attenuation constants in guidelines?

2 Methods

2.1 Measurements

The area under investigation is a clearing and an adjacent stand of spruces in the forest "Tharandter Wald" (coordinates: 50 ° 57 ′ 49 ″ N, 13 ° 34 ′ 01 ″ E). The forest covers an area of about 65 km^2 and is situated about 15 km southwest of Dresden (Germany). Around the clearing a line of chestnut trees (height: about 20 m) forms the transition to an old spruce stand with a canopy top height of around 33 m. Further information about the site can be found e.g. in Queck et al. (2012).

Measurements were carried out in the late summer and early autumn of 2011. In this time of the year, the highest temporal variability of the vertical gradients of sound speed is expected. The topographical situation of and around the measurement site is shown in Fig. 1.

The propagation of acoustic signals was recorded along a sound path of 115 m in the clearing and 75 m in the old spruce stand. Besides the acoustic measurements, the atmospheric state was measured using 40 m high micro-meteorological masts in the clearing and

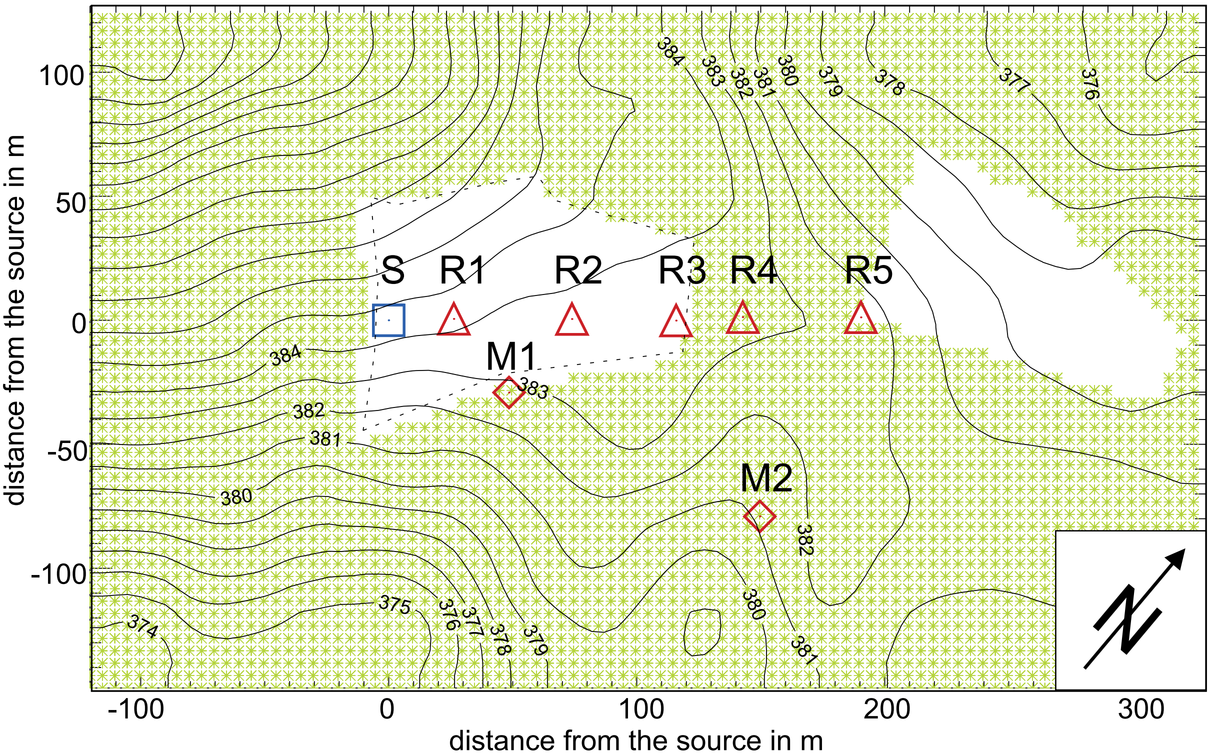

Figure 1: Experimental area "Tharandter Wald". Forested areas are green, clearings are white. The "Wildacker" clearing is framed by a dotted line. S denotes the acoustical source (loudspeaker). R# indicates the receiver positions (microphones) and M# the meteorological 40-m masts. Isolines represent the terrain elevation in m above sea level (increment 1 m). The area shown is identical with the meteorological model domain.

inside the forest. The present study focusses on measurements of low-frequent sound for the following reasons. The sound absorption in air is negligible for low frequencies and the considered sound path lengths. In this way, only the effects of refraction, reflection at the ground surface as well as reflection or scattering due to tree trunks have to be modelled and incorporated into the analysis of measured data. The signal/noise-ratio of the measured low-frequent sound signals is high enough for a sound source far away and for relatively small source strength. It is possible to provide model studies with different parameters (e.g. with/without forest) using low frequencies for the simulated sound wave propagation: the higher the sound frequency, the higher is the computational effort and time requirement. Furthermore, the low-frequency spectrum is of special interest for noise protection studies regarding traffic noise and noise of wind turbines.

The low-frequent sound was generated with a subwoofer (Raveland HBP 1028) about 1.35 m above the ground (output loudspeaker). The loudspeaker transmits every 20 s a short signal with ten oscillations of six sequent frequencies (40, 50, 63, 80, 100, 125 Hz). The frequency of 125 Hz is not further discussed, because of strange measurement results, which are not yet sufficiently explained. The sound propagation effects, especially the important ground effect, are similar for the remaining frequencies (Ziemann et al., 2013).

Brüel&Kjær 1/2″ free-field microphones with wind screens were used to measure the sound pressure level at distances of 26.3 m (R1), 74.4 m (R2), 115.9 m (R3), 143 m (R4), and 190.1 m (R5) from the source, at about 1.6 m above the ground. Before and after each measurement series (about 1.5 days) the microphones were calibrated. The sound signals were recorded by a frontend 3560-B (Brüel&Kjær). The frequency spectrum was analyzed by the software PULSE (Brüel&Kjær) and independently by a FFT analysis using an own MATLAB algorithm. Ziemann et al. (2013) provided detailed information on the measuring set-up, the equipment, and the execution of the measurements.

The present study refers to the 24-hour environmental situation of 3 September 2011, a day with unhindered radiation and high temperature amplitude.

2.2 Simulations

A coupled 3D meteorological-acoustical modelling system was applied to cover the full daily cycle of the measurement period. First, the meteorological mesoscale model FITNAH (Gross, 1992) is used to simulate details of the wind and temperature fields, which are influenced by the terrain (orography and surface roughness) and by the forest. The latter does not only act as a resistance to the airflow, but it also modifies the heat budget near the ground (Gross, 1993). Consequently, forested areas and clearings differ with respect to the vertical gradients of wind and temperature, which again are relevant to the propagation of sound because they determine the strength of refraction. The results of the meteorological model are hourly stored and coupled to an acoustic model to simulate the propagation of sound emerging from the loudspeaker. The acoustic model accounts for both the direct effect of the topography (terrain elevation and ground impedance, trees in the forest areas) and the indirect effect through the topographically induced modifications of the wind and temperature field. Sound propagation was simulated with finite-difference time-domain (FDTD) solutions of the linearized Euler equation of motion and the conservation laws of mass and energy (e.g. Heimann and Karle, 2006). All simulations are performed in three dimensions because of the horizontally inhomogeneous topography (e.g. clearings within the forest). The three-dimensionality enables the acoustic model to consider horizontal diffraction and scattering and the explicit representation of tree trunks. The model domains are aligned with the acoustic sensor chain, i.e. counter clockwise rotated by 39.1 degrees from the west-east direction.

2.2.1 Meteorological simulations

The prognostic model FITNAH was applied for this study. It is a 3D non-hydrostatic model suitable for simulating the distribution of meteorological variables even in small domains. The basic framework for this model consists of the equation of motion, the continuity equation, the first law of thermodynamics, and conservation equations for air constituents.

The vegetation is taken into account with special source or sink terms in the basic equations of motion, temperature, humidity, and turbulent kinetic energy. In this way, the interaction of the vegetation with the airflow is parameterized for the impulse, turbulence production, and radiation fluxes. At the ground surface, the model simulates the energy balance including the radiation balance.

The meteorological modelling domain (Fig. 1) is discretized by $90 \times 55 \times 25$ numerical grid cells with a horizontal spacing of 5 m. The vertical spacing within the acoustically interesting layer increases from 1 m near the ground to 5 m at 50 m above ground. Above, the vertical spacing further increases up to the top of the model at 1500 m above ground.

The model was initialized at 1800 local time (LT) on 2 September 2011 with a neutral (adiabatic) stratification and a geostrophic wind of 6.2 m/s from 230 degrees, i.e. nearly along the acoustic source-receiver line. With the long and short wave radiation scheme evoked, the simulation was continued until 4 September 2011 at 0000 LT with a numerical time step of 0.4 s. The large-scale forcing was kept constant during the simulation period. According to synoptic analyses, the geostrophic wind turned slightly towards southerly directions.

The model results were stored in 1-hour intervals for subsequent acoustic modelling over a full 24-hour diurnal cycle starting from 3 September 2011, 0000 LT. Two sets of boundary conditions were used: simulation 1 considers the forest while simulation 2 serves as a reference without forest.

2.2.2 Acoustic simulations

The FDTD sound propagation model is capable of simulating time-dependently the propagation of linear acoustic waves in a prescribed wind and temperature field that, in our case, is pre-determined by precursory meteorological simulations. The sound propagation model accounts for a finite impedance ground using the time-domain scheme proposed by Heutschi et al. (2005). The acoustic impedance is parameterized by the flow resistivity of the ground according to Delany and Bazley (1970).

The model includes the effects of spherical divergence, reflection, refraction, and diffraction. The air absorption is neglected because only low-frequency sound is regarded in this study. Trees can be directly considered if the numerical grid is fine enough to resolve at least the trunks.

In this study a $250\,\mathrm{m} \times 175\,\mathrm{m} \times 50\,\mathrm{m}$ large domain inside the domain of the meteorological model was defined. With a spacing of 0.4 m this corresponds to almost $35 \cdot 10^6$ numerical cells. The spatial resolution of 0.4 m also admits the representation of single tree trunks by blocking out grid cells, i.e. setting the particle velocity components to zero. The spacing in combination with the application of 7-point-stencil spatial differences (Bogey and Bailly, 2004) and a 6-step Runge-Kutta time integration (Hu et al., 1996) allows a resolution of a wave length by 6 grid cells. Hence, wavelengths down to 2.4 m or frequencies up to about 141 Hz can be handled in sufficient accuracy. This includes all 1/3-octave-bands up to the centre frequency of 125 Hz and covers the spectrum, which was used by the loudspeaker. Logarithmic classification of the frequency spectrum is typical of acoustics in the audible frequency range. Frequently, the band width of 1/3-octave is used, that means a frequency band with an upper boundary frequency of $2^{1/3}$ of the lower boundary frequency.

The forest is characterized by the area density of trees (8 m distance between trees on average), the diameter of the trunks (corresponding to grid cell size: 0.4 m), and the height of the trunks (33 m on average with a standard deviation of 5 m). According to Attenborough et al. (2011) the flow resistivity of forest floor is set to the rather low value of $50\,\mathrm{kPa\,m^{-2}\,s^{-1}}$ while for the ground of the grass-covered clearings it is set to $200\,\mathrm{kPa\,m^{-2}\,s^{-1}}$. This agrees with the fact that the forest ground is normally softer (less reflecting and more absorbing) than the ground of clearings because of littered leafs and needles.

Sound propagation simulations were performed for all 25 simulated meteorological situations between

3 September 2011, 0000 LT, and 4 September 2011, 0000 LT. Again, two main sets of boundary conditions were used: simulation type 1 with forest and simulation type 2 without forest as reference.

3 Results

3.1 Meteorological model results and their effects on sound propagation

Fig. 2 and Fig. 3 provide examples of simulated wind and temperature fields near the ground showing the situation at noon (1200 LT). At this time, the wind speed at 10 m above ground varies between 1.7 m/s in the forest and up to 3 m/s in the clearings. The wind direction varies by about 40 degrees because the wind flow is slightly diverted towards elevated areas. The air in the sunny clearings is up to 4 K warmer than in the shaded layer beneath the forest canopy.

Refraction is largely determined by the vertical gradients of the effective sound speed c_{eff}, i.e. the sum of the horizontal wind-speed component in the direction of sound propagation and the temperature-dependent adiabatic sound speed (e.g. Ostashev, 1997).

Fig. 4 shows the vertical profiles of the effective sound speed above the receiver positions at midnight (0000 LT) and noon (1200 LT). The difference between the clearing (R1, R2, and R3) and the forest (R4 and R5) is evident. Near the ground of the clearing, the vertical gradient of c_{eff} amounts to maximal 0.6 s^{-1} during night and $-0.6\,\text{s}^{-1}$ during day.

If circular sound rays are assumed as a first and rough approximation, then the maximum gradient corresponds to a radius of about 560 m (for horizontal sound propagation and a sound speed of 340 m/s). This is a very strong gradient and curvature in comparison to values used by standards, i.e. ISO 9613-2 (1999), where a sound ray radius of 5 km is characteristic for downwind conditions.

The sound speed gradients decrease significantly with increasing height at the grassland site. In general, there are lower vertical gradients inside the forest in comparison to the clearing. However, all values are positive during the nighttime hours. A lifted maximum of the sound speed gradient is a typical phenomenon developing inside the crown space of the forest that also occurs on daytime hours.

Negative gradients develop at 0700 LT, at first in higher layers above ground followed by air layers near the surface. They are associated with upward refraction. Extreme gradients occur again at the grassland site near the ground surface. Inside the forest, there are positive gradients also during the daytime with maximum values again in the crown space of the trees. This results in a distinct difference of the sound propagation between grassland and forest. If the first upward refracted sound from the loudspeaker in the clearing reaches the forest then a downward refraction can be caused with channelling effects for the sound wave below the crowns of the trees.

Fig. 4 also shows that the magnitude of positive gradients in the clearing is higher than that one for negative gradients. The main reason for this is the wind direction that was approximately in the direction of sound propagation. At nighttime, temperature inversion together with a wind speed increasing with height result in higher gradients in comparison to daytime where temperature and wind effects are acting in opposite direction.

3.2 Acoustic model results

The results of the acoustic simulations are discussed with respect to the following effects:

- effects of the forest on the horizontal broad-band (< 141 Hz) sound field,
- effects of the diurnal cycle on the horizontal broad-band (< 141 Hz) sound field,
- effects of the forest on the spectral distribution (35.5–141 Hz).

The total effect of the forest, i.e. the direct one of trees and the indirect effect of ground and the forest-induced meteorological fields, is visualized in Fig. 5, which shows the horizontal distribution of the broad-band 24-hour average sound level with the consideration of the forest relative to that without forest. In the clearing the sound field benefits from reflections and backscattering at the trees so that it slightly increased (by up to 0.3 dB) due to the forest. The greatest amplification is simulated where the sound impinges on the forest edge with a rather steep angle. Inside the forest the sound level is significantly attenuated by about 4 dB per 100 m in excess to the simulation without forest.

Please note that CET is the time base for all subsequent evaluations. There is a difference of about 6 minutes between LT and CET.

Fig. 6 and Fig. 7 display the effect of the diurnal cycle. The figures show the deviation of sound levels at midnight (0006 CET, Fig. 6) and at noon (1206 CET, Fig. 7), respectively, from the 24-hour average sound level.

Downward refraction during night leads to values of up to 1.3 dB above the average. The highest increase is simulated in downwind direction where both the wind effect and the temperature contribute to a positive vertical gradient of the effective sound speed. Moreover, the clearing is elongated in downwind direction so that the strong positive c_{eff}-gradient above the clearing acts over more than 100 m. In cross-wind direction the wind effect vanishes and the rather strong temperature induced sound speed gradient in the clearing is effective only for a short distance of a few tens of meters. The highest increase is simulated near the forest edge. This follows from the fact that the simulated vertical gradient of the sound speed is rather weak inside the forest.

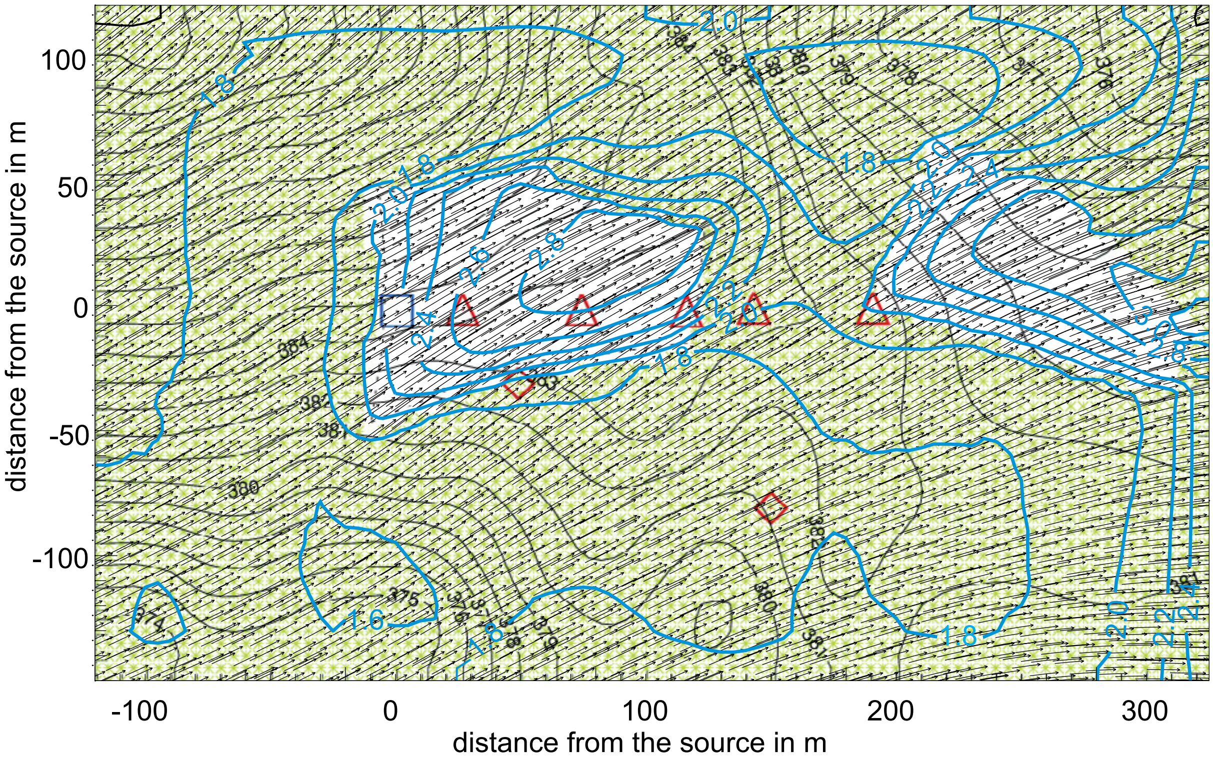

Figure 2: Simulated wind field (6-s traces) 10 m above ground at 1200 LT. Blue isolines show the wind speed in m/s (increment 0.2 m/s). Black isolines indicate the terrain elevation (increment 1 m). Symbols as in Fig. 1.

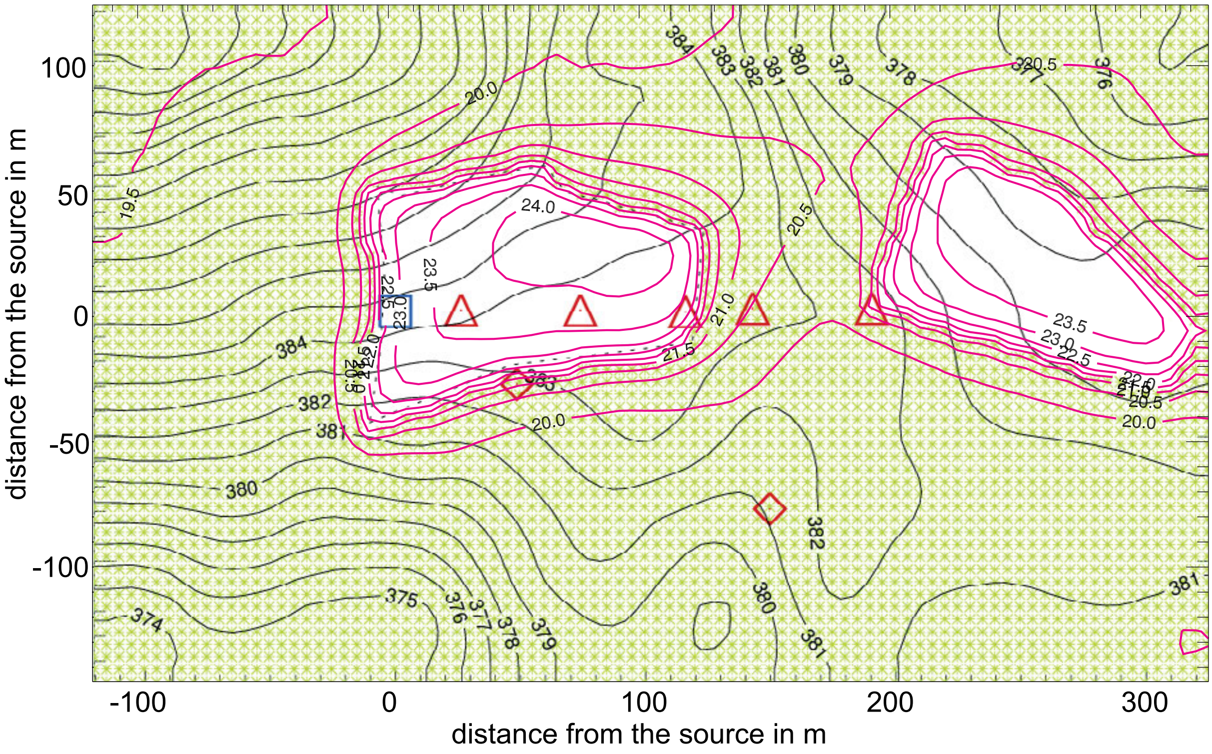

Figure 3: Simulated air temperature in °C (red isolines, increment 0.5 K) 2 m above ground at 1200 LT. Black isolines show the terrain elevation (increment 1 m). Symbols as in Fig. 1.

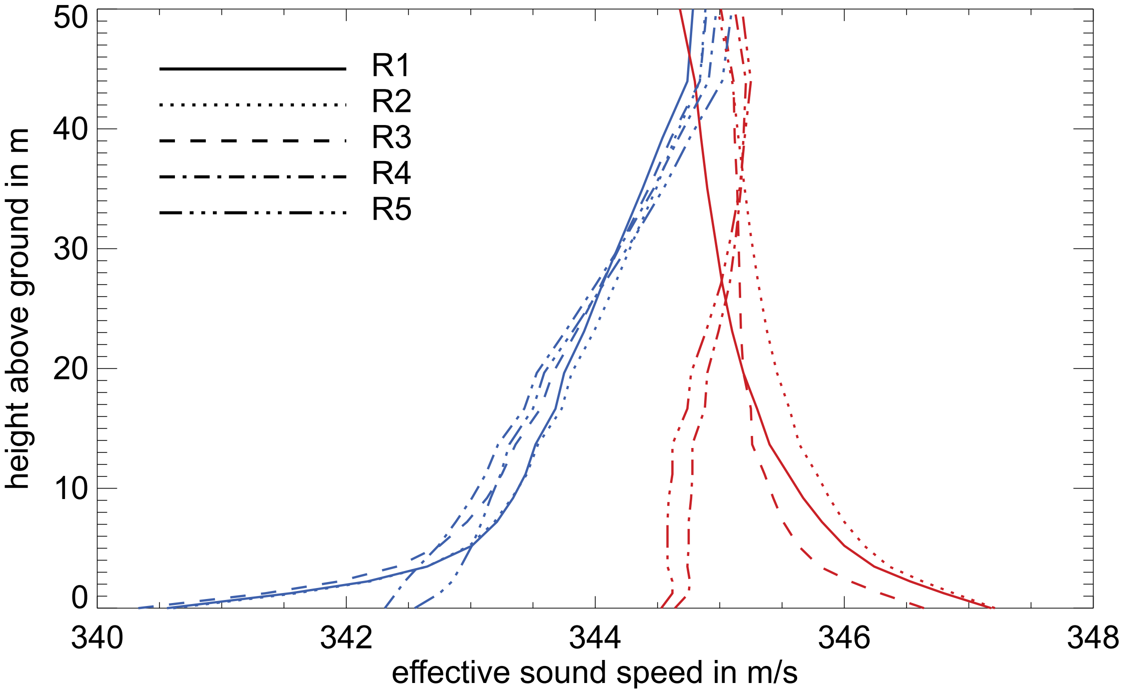

Figure 4: Vertical profiles of the simulated effective sound speed at the receiver positions R1–R5 (see Fig. 1) at 0000 LT (blue) and 1200 LT (red). Receivers R4 and R5 are inside the forest.

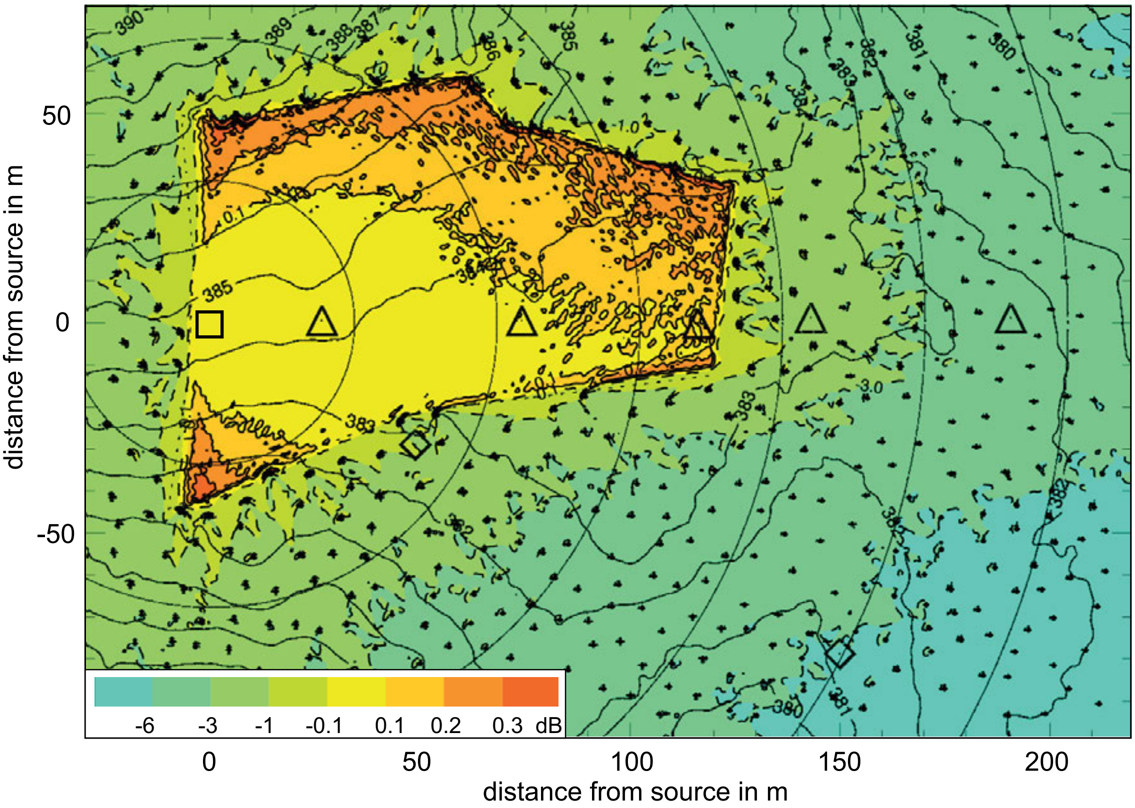

Figure 5: Simulated broadband (< 141 Hz) sound-level difference averaged over 24 hours 'with forest' minus 'without forest' 1.5 m above ground (contour level in dB, increment 3 dB for sound attenuation and 0.1 dB for amplification). The circles are concentric around the source. The square at position (0, 0) denotes the sound source. Generic trees are indicated by black dots.

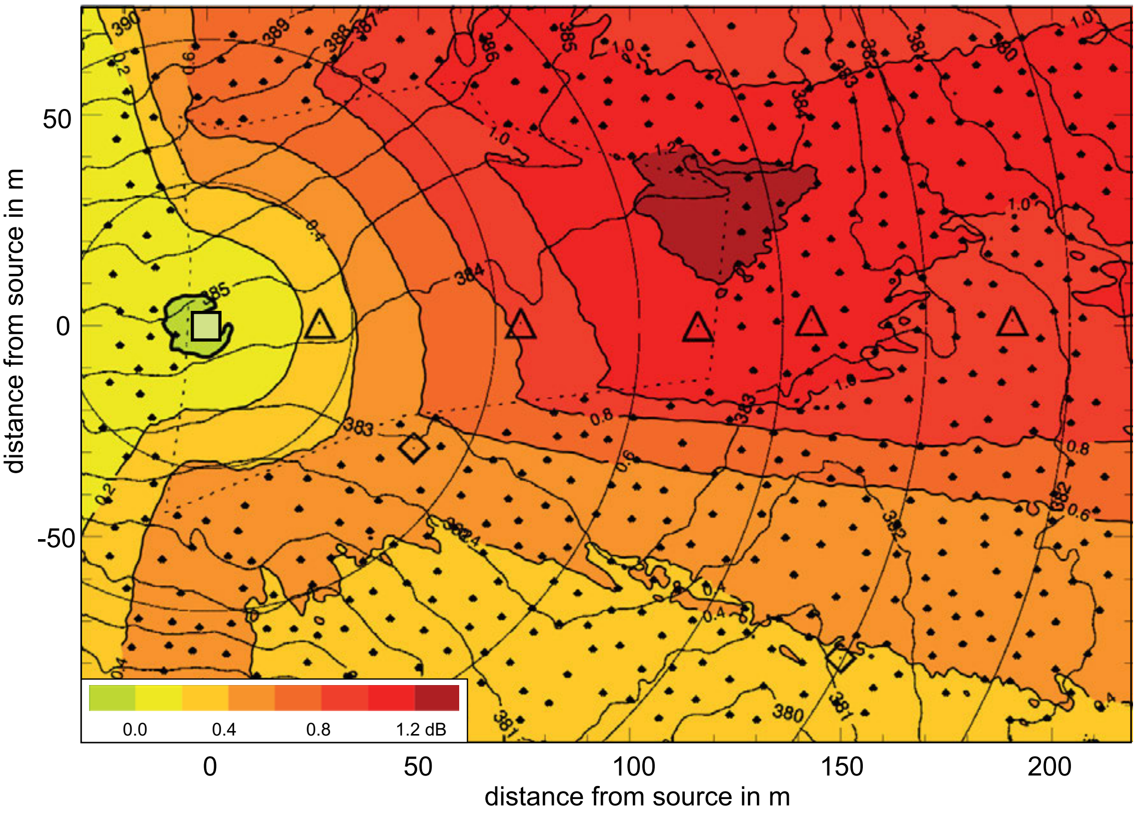

Figure 6: Simulated deviation of the broadband (< 141 Hz) sound level at 0000 LT from the respective 24-hour average sound level at 1.5 m above ground (contour levels in dB, increment 0.2 dB). Symbols as in Fig. 5.

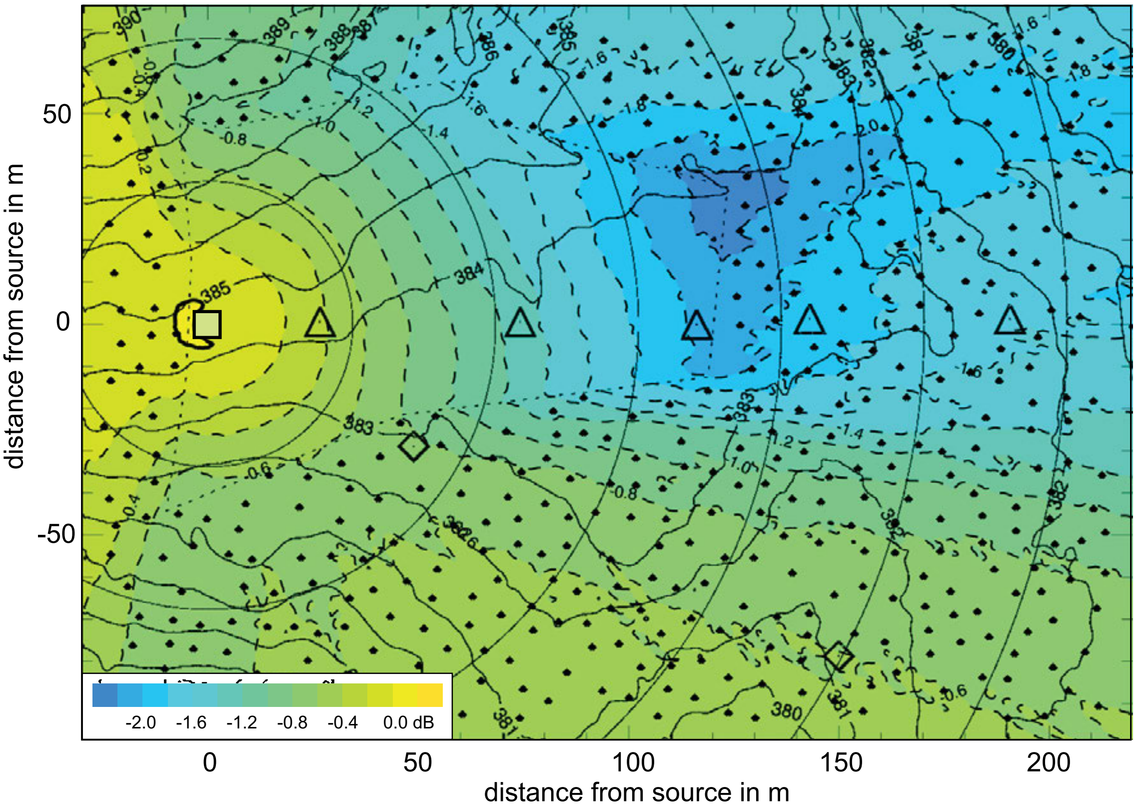

Figure 7: Simulated deviation of the broadband (< 141 Hz) sound level at 1200 LT from the respective 24-hour average sound level at 1.5 m above ground (contour levels in dB, increment 0.2 dB). Symbols as in Fig. 5.

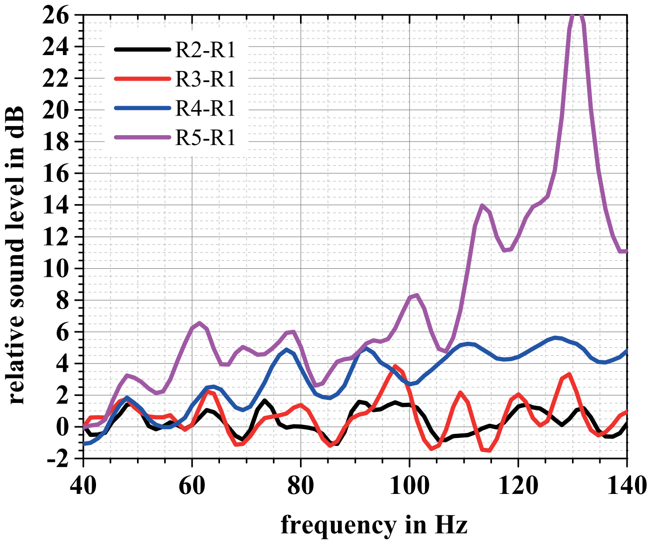

Figure 8: Relative sound pressure level (difference between simulated sound level attenuation with and without forest) at 1200 LT.

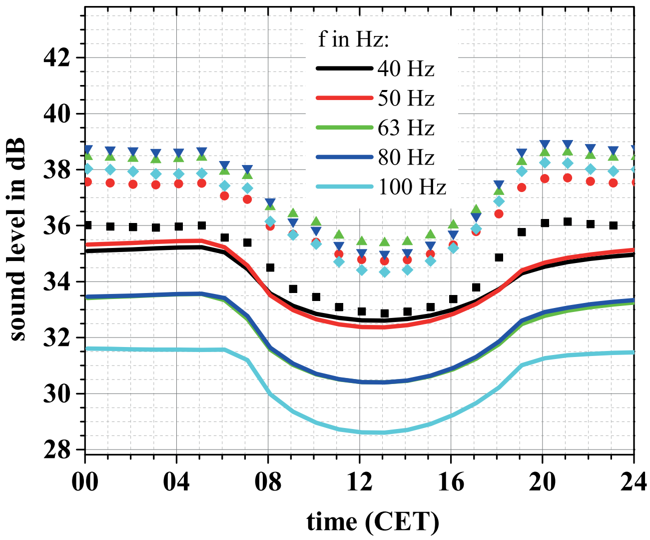

Figure 9: Daily variability of simulated sound levels at 1.5 m above ground at the position R5 for several frequencies with (solid line) and without forest (symbols). Please note: curves for 63 Hz (green) and 80 Hz (blue) with forest are nearly identical due to source characteristics and propagation effects.

During day the effect is inverted and leads to a sound level, which is by 2.2 dB lower than average. Again, the highest values are simulated in the downwind area. This is not only because of the long fetch inside the clearing, but also because the average sound level is dominated by the increased nightly sound level in this sector.

To be independent of characteristics of the sound source, the sound level attenuation between measurement points was evaluated. Position R1, located closest to the sound source in the clearing, was used as reference. A spectral investigation of the forest influence for this sound attenuation results in Fig. 8. The sound attenuation is displayed as a relative sound pressure level $(L_{f,\mathrm{R}x} - L_{f,\mathrm{R1}})_{\text{without forest}} - (L_{f,\mathrm{R}x} - L_{f,\mathrm{R1}})_{\text{with forest}}$, where the index f denotes the frequency and Rx the receivers R2, R3, R4, or R5. Positive values indicate an excess attenuation by the forest between the positions Rx and R1. The propagation from R1 to the positions R2 and R3 in the clearing is hardly affected by the forest, except by backscatters from the clearing edge. The propagation from R1 to R4 and R5 inside the forest is increasingly attenuated by the forest, mainly in the frequency range $>$ 100 Hz (up to 27 dB at 131 Hz at position R5).

An important advantage of a model chain is the possibility to use it as a virtual laboratory to control a changing set of parameters. In this way, it was possible to compare sound levels at the position R5 with and without forest influence (combination of ground effect and meteorology), see Fig. 9. At first, the typical behaviour of the sound level during a cloudless day can be derived: higher sound level in evening and nighttime hours and smaller values around noon and afternoon as a result of downward refraction due to the nighty temperature inversion and upward refraction by superadiabatic vertical temperature gradients during day, respectively. In comparison to grassland a sound attenuation results for all frequencies at this position inside the forest (190 m away from the sound source). The excess attenuation is on the whole growing with frequency with a maximum obtained for 100 Hz 1/3-octave-band: it amounts to 6.3 dB in average with a range of daily variability of 1.3 dB. Thereby, maximal forest effects occur in the morning (1000 CET) and in the evening (2000 CET).

3.3 Comparison to measured quantities

The measured sound pressure spectrum was investigated by a FFT analysis, where a time window of 40 ms and shift of 40 ms were used. Based on the maximum amplitude of distinct frequencies (40, 50, 63, 80, 100 Hz) the sound level was calculated. These independently derived data were compared with CPB (constant percentage bandwidth) analyses using the commercial black box software PULSE. Thereby, a digital band pass filtering is applied regarding the central frequency of the band, i.e. for 1/3-octave bands a bandwidth with always 23.156 % of the central frequency. This bandwidth is equal to the sensitivity of the human hearing process. A linear averaging of 40 ms was applied with central frequencies of 40, 50, 63, 80, 100 Hz. For the further analysis, only the data derived by software PULSE were used, but there are no qualitative differences to the FFT analysis.

In this way, the measured sound level at the same five positions was analysed just like using the model chain. In Fig. 10 the sound level at the receiver position R2 is shown, i.e. 74 m away from the sound source. The measured sound level was averaged over 30 min and plotted together with standard deviation. The local sound level depends on the strength and spectral characteristics of the sound source, which differ between measurement

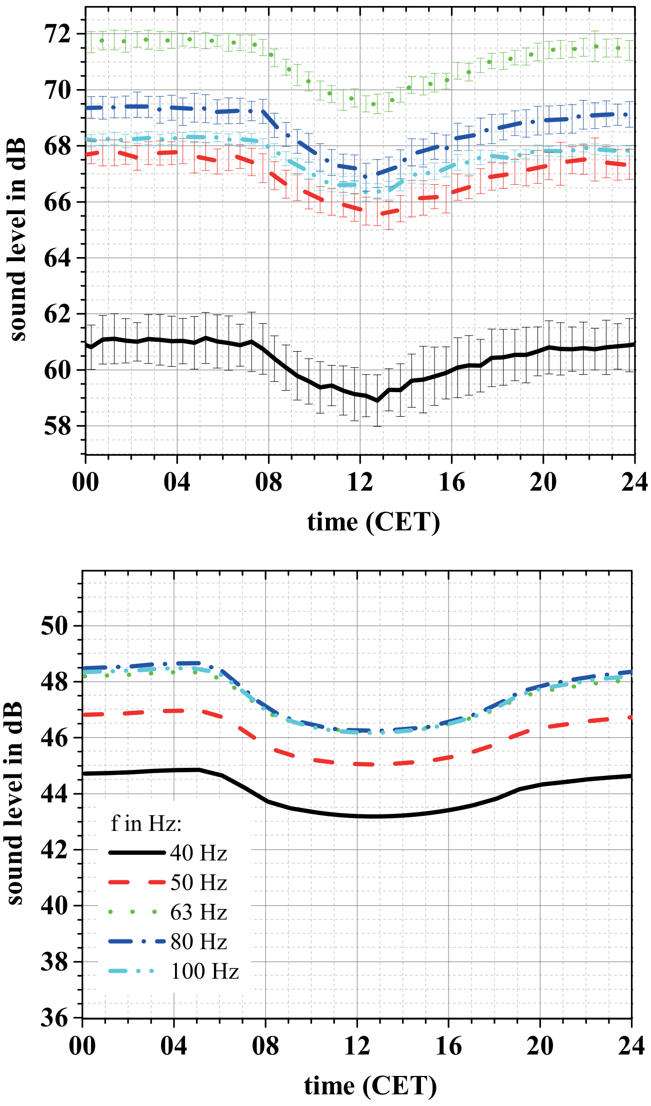

Figure 10: Daily variability of sound level at position R2 (clearing): measurements (above) on 3 September 2011 and simulations (below). Please note (Fig. 10 below): curves for 63 Hz, 80 Hz, and 100 Hz are nearly identical due to source characteristics and propagation effects.

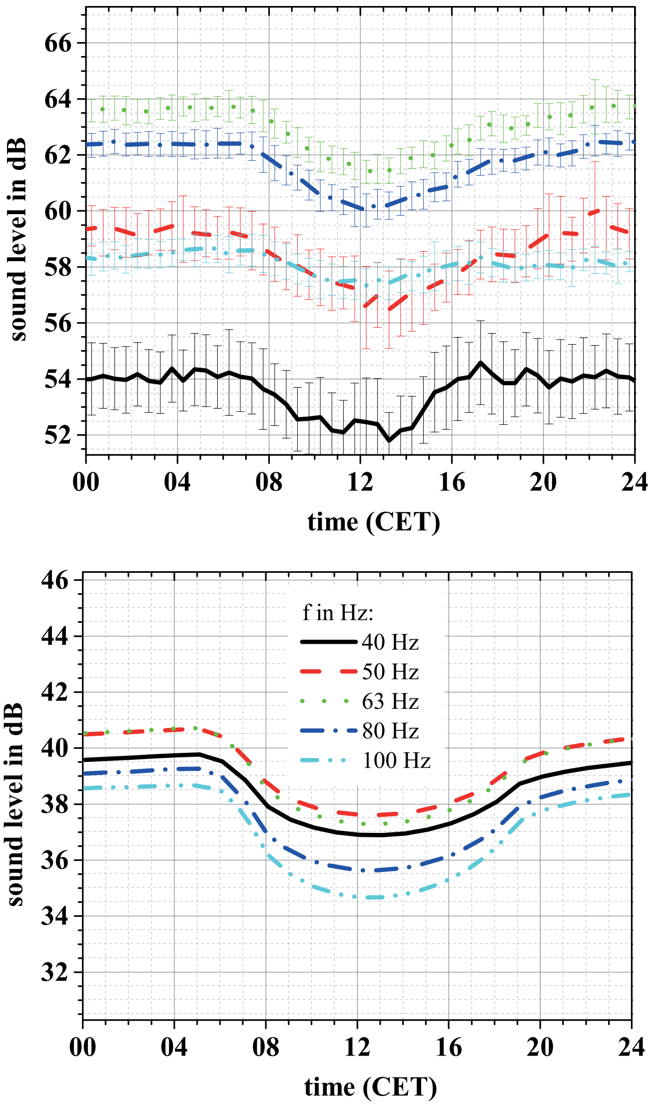

Figure 11: The same as in Fig. 10 but at position R4 inside forest. Sound level scale includes the effect of spherical divergence.

and simulation. Nevertheless, a similar daily variability of 2 dB occurs for both data sets.

The sound level at the position R4, i.e. inside the forest 143 m away from the sound source, is shown in Fig. 11. The daily variability in measured data amounts to 2–3 dB and is slightly smaller than for the simulated data (3–4 dB), but the direction of change is consistent for both data sets. Comparing the sound levels at the two positions it results that almost all signals are attenuated more than one would expect from the effect of spherical spreading (is included in the sound level scale of Fig. 11), especially for higher frequencies (> 40 Hz).

In a next step, the sound attenuation between two measurement points was calculated. Again, the position R1 in the near of the loudspeaker in the clearing was used as reference. Subsequently, a normalized sound attenuation was derived using the difference between the sound levels at two positions ($L_{f,\mathrm{R1}} - L_{f,\mathrm{R}x}$) divided by the distance between the positions. Such values are often used in guidelines to quantify several effects of outdoor sound propagation.

The measured data in the clearing show that only higher frequencies are more attenuated than by the spherical spreading of 0.19 dB/m between R2 and R1 (Fig. 12). This behaviour is partly in contrast to simulations where especially during daytime the attenuation values of several frequencies are equal or higher than spherical spreading. This can be a hint that the real meteorological effect on the sound propagation was not completely described by the model chain. Because of stronger sound speed gradients, the refraction effect in downwind direction is possibly enhanced resulting in a decreased attenuation of measured sound levels. It is assumed that the ground effect plays only a minor role as the simulated sound amplification for frequencies between 40 Hz and 100 Hz is very similar for positions R1 and R2. Nevertheless, attenuation effects of the natural

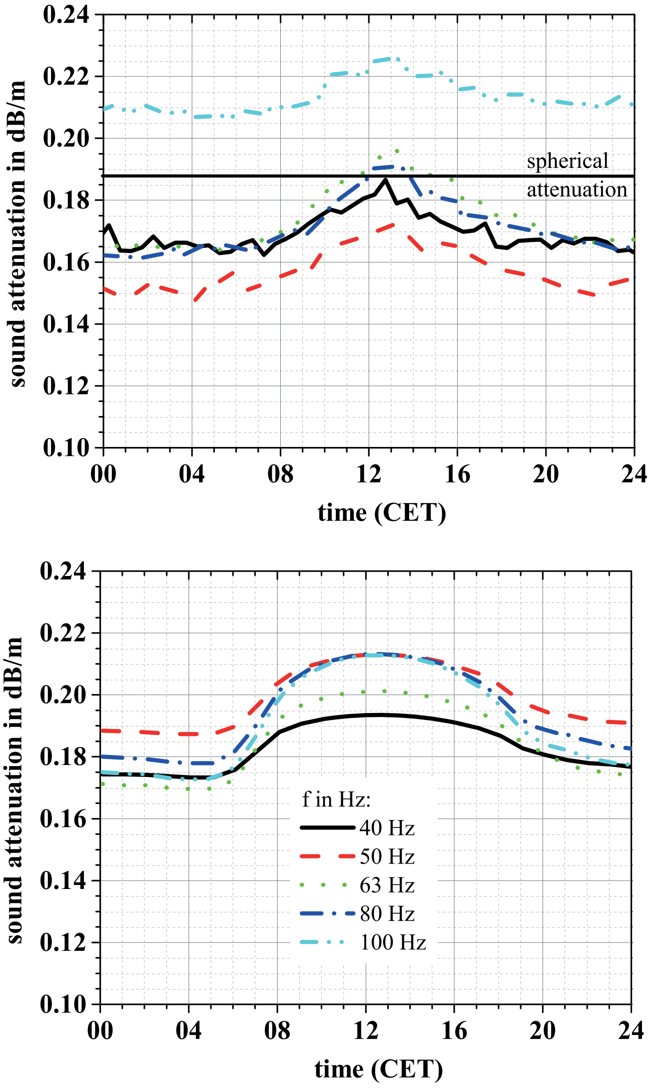

Figure 12: Normalized sound attenuation at position R2 in the clearing (reference: R1): measurements (above) on 3 September 2011 and simulations (below).

ground between R1 and R2 are not excluded because the 100-Hz-signal shows a significantly stronger attenuation probably due to surface inhomogeneity.

Inside the forest (Fig. 13), the measured attenuation of low frequencies agrees roughly with the spherical attenuation of 0.13 dB/m between positions R1 and R4. That means that direct effects of trees influence the sound waves to a lesser extent at these frequencies. The ground surface in forests is acoustically softer and results in a higher attenuation in comparison to grassland. The difference between the ground effect at position R1 and R4 is growing with increasing frequency.

Simulations show a qualitatively similar result, but the sound attenuation is more frequency-dependent for 40–80 Hz. The daily variability of the simulated attenuation is higher due to the nearly constant sound level at the reference point R1. In comparison to that, a daily variability of the sound level already at position R1 occurs in the measurements.

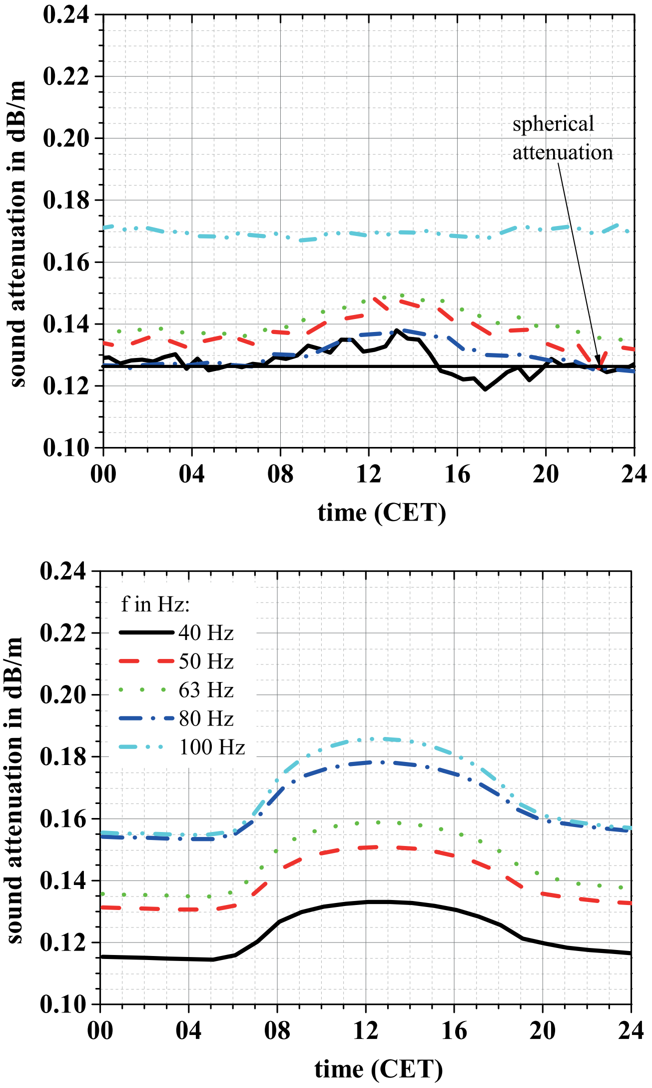

Figure 13: The same as Fig. 12 but at position R4 inside forest.

The excess attenuation effect of the forest is significant for higher frequencies (measurement: 100 Hz, simulation: 80 and 100 Hz) and amounts on average to 4 dB/100 m at the position R4.

4 Conclusions

Previous studies of noise barrier effects by forest showed a wide range of attenuation values, which are very difficult to compare due to their heterogeneity in many respects. In particular, the study of meteorological conditions is not included in most studies or set too simplified. In measurement results, the various effects are coupled and are in most cases inseparable. Only with the aid of corresponding simulation models the single effects of refraction, scattering or reflection at the ground surface can be considered as dependent on certain vegetation properties, transmitter-receiver geometry, and frequency spectra of the sound source. Therefore, a 3D model chain was applied in the study to a case of real outdoor measurements. The study focused on the indirect meteorological effect as well as on the direct influence of forests on the sound propagation in comparison to a grassland site.

The refraction due to vertical gradients of the effective sound speed differs between forest and grassland. The values of sound speed gradients decrease significantly with growing height at the grassland site. In general, the simulations result in lower vertical gradients inside the forest. Thereby, a lifted maximum of the sound speed gradient is developing inside the crown space of the forest as a typical phenomenon that can lead to a channelling of sound propagation due to the height of sound source. Numerical simulation with enhanced spatial resolution using more detailed information on the leaf area density of trees as well as the comparison to measurements could further confirm the calculated sound speed profiles.

The daily variability of the low-frequent broadband level (< 141 Hz) amounts to 3.5 dB in the downwind area, an especially interesting region for noise protection applications. The comparison with measurements (1/3-octave band) shows similar values. This amount of daily sound level variability has to be added as an uncertainty to calculated sound level data using engineering models without meteorological influence. Thereby, the meteorological excess attenuation during daytime is higher than the growing sound level during nighttime.

The 24-hour average sound level is significantly attenuated by about 4 dB per 100 m in excess to the simulation without forest. A similar value of forest excess attenuation results from the comparison between measurements and simulations for the single frequency of 100 Hz always in a small distance from the forest edge and it can be expected that the attenuation effect grows up for higher frequencies (e.g. Pal et al., 2000). This value nearly lies in the range of measured total attenuation for a road traffic noise spectrum (e.g. Pal et al., 2000: 6.6–12 dB(A)/100 m; Fang and Ling, 2003: 5–47 dB(A)/100 m) and highlights therefore the impact of forests for noise protection purposes. Thereby, the simulated daily variability of the forest excess attenuation amounts to a range of 1.3 dB due to meteorological effects. In comparison to our 3D model chain and measurements, the standard for outdoor sound propagation (ISO 9613-2, 1999) recommends a lower forest attenuation of 2–3 dB/100 m for the investigated low-frequency octave bands. The study results encourage therefore the discussion and evaluation of standardized recommendations to forest excess attenuation together with uncertainty values due to meteorological effects.

To generalize the results, the analysis of measured data will be extended to other frequencies (250 Hz–8 kHz), other measurement times (in 2012 and 2013) and other measurement setups (completely inside old spruce forest and beech forest). Thereby it is intended to study relatively homogeneous forest areas with one and the same set of vegetation parameters. The 3D model chain will be used again for a comparison with measured data sets.

In future, achieved study results will be evaluated and summarized in terms of the influence of various effects in the propagation of sound, having regard to their variation by meteorological influences. Derived parameterizations of these effects could be provided in a manner that allows a direct application in standardized models for outdoor sound propagation (e.g. ISO 9613-2, 1999). Based on such a study, a validated recommendation for the optimal design of sound protection forests should also result to reduce pollution from traffic noise. In addition to the applications for noise protection, the outcomes may also be used for the evaluation of sound propagation from wind turbines. Wind energy will be produced in Germany increasingly in managed and commercial forests. Thus, there is a pressing need for research on the effects of wind turbines in forests with respect to noise protection.

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