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The sound amplifying forest,

with emphasis on sounds from wind turbines

Master Thesis in the Master Degree Program, Sound and Vibration

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Cover: The front page picture shows a part of the investigated and measured forest, relevant for this master thesis. Measured at Fjällhult, Lerum on the 9th of December 2009.

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Abstract

In the future, more wind turbines may be located in forest terrain. Sound from wind turbines located in open terrain has been under study by many researchers and models for determining the noise level of receivers at different distances exist. But sounds from wind turbines located in forest terrain is a rather new field, which have not been under study to the same extent. After measurements performed by Elforsk 09:22[1] of a wind turbine located in forest terrain it was discovered that the sound level measured in the forest was higher than expected. The calculation software used was Sound Plan 6.4, in which Nord2000 is implemented, but did not treat the effect of forest.

The lacking understanding of the cause of why the calculated level was lower than the measured level created the need for this master thesis. Various hypotheses have been compiled which may explain a possible increase of the sound pressure level inside the forest. Promising hypotheses are the reverberation in the forest, refraction due to local climate, scatter effect from the tree trunks that contributes to the reverberation and also reduces the damping of the ground effect.

Measurements were made at different times, places and meteorological conditions. The main measured parameters are: reverberation time for different distances in the forest, the attenuation of noise for different distances in the forest, wind speed and temperature for different heights of the forest, the average diameter of trees, number of trees per hectare and humidity of the air inside the forest.

A calculation method has been developed and compared with measured data. The calculation method has integrated a model used within room acoustics to combine the reverberation with the direct sound pressure level in the forest. Thus, the forest has been regarded as a room. Its weakness is that it is difficult to determine the dimensions of the "forest room". A scale factor has been used to model forest room volume. Results from this comparison shows that the calculation model using reverberation is in relatively good agreement with measurements, if the volume multiplied by the square of the measurement distance is used in the calculation model.

The calculation model C.N.P.E. (Crank Nicholson Parabolic Equation) has been used to calculate the noise in the distance under the action of Refraction; created by wind and temperature gradients with height.

By: Elis Johansson

Keywords: acoustics, outdoor sound, sound propagation in forest, reverberation in forest, sound increase in forest, refraction, CNPE, master thesis

Titel:”Den ljudförstärkande skogen med betoning på ljud från vindkraftverk”

Sammanfattning

I framtiden kan fler vindkraftverk komma att placeras i skogsterräng. Ljud från vindkraftverk som är placerade i öppen terräng har studerats av många forskare och modeller finns för att bestämma ljudnivå hos mottagare på olika avstånd. Men ljud från vinkraftverk som är placerade i skogsterräng är ett relativt nytt område som inte studerats i samma utsträckning. Efter mätningar av Elforsk 09:22 [1] av ett vindkraftverk i skogsterräng upptäcktes att den uppmätta ljudnivån inne i skogen var högre än beräknad ljudnivå. Använda beräkningsverktygen var SoundPlan 6.4 med Nord2000 implementerat, men som inte tog hänsyn till skog.

Oklarheten varför beräknad var lägre än uppmätt nivå skapade behov av detta examensarbete. Olika hypoteser har sammanställts som kan förklara en ev. ljudnivåhöjning inne i skog. Lovande hypoteser är efterklang i skog, refraktion från skogens lokala klimat, spridningseffekt från trädstammarna som bidrar till efterklangen men som samtidigt reducerar markeffektens dämpning.

Mätningar har gjorts vid olika tillfällen, platser och väder. De huvudsakliga parametrar som mätts är: efterklangen för olika avstånd i skog, dämpning av ljudnivå för olika avstånd i skog, vindhastighet och temperatur för olika höjder i skog, trädens medeldiameter, antal träd per hektar och luftfuktighet för luften inne i skogen.

En beräkningsmodell har utvecklats och jämförts med uppmätta data. I beräkningsmodellen har en rumsakustisk modell integrerats för att kombinera efterklangen med ljudtrycksnivån i skogen. På så vis har skogen betraktats som ett rum. Dess svagheter är att det är svårt att bestämma dimensionerna på ”skogsrummet”. En skalfaktor har därför använts för att modellera skogsrummets volym. Resultat från denna jämförelse visar att efterklangen har relativt god överensstämmelse om volymen multipliceras med mätavståndet i kvadrat.

Beräkningsmodellen C.N.P.E. (Crank Nicholson Parabolic Equation) har använts för att beräkna ljudnivån på avstånd under inverkan av refraktion, som skapats av vind och temperatur gradienter med höjden.

Av: Elis Johansson

Nyckelord: akustik, utomhusljud, ljudutbredning i skog, efterklang i skog, refraktion, ljudökning i skog, CNPE, examensarbete

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1 Introduction

1.1 Background

Sound from wind turbines can be perceived as annoying and may lead to a deterioration of the living environment and the quality of life for people exposed by the noise. It is therefore important to ensure a good sound environment in the process of environmental permission of new wind turbines. Homes are rarely settled in the forest, but sometimes a target value of 35 dBA for the sound level is set in quiet outdoor areas. This is identified in the general plan of the municipality. On the website of Environmental Protection Agency's of Sweden, (will from this point and on in the text be referred as E.P.A. of Sweden, i.e. Naturvårdverket in Swedish) the target values of noise from wind turbines are described [2]. In recent years there have been discussions about the establishment of wind turbines in forests. The knowledge on how a forest reduces and scatters the sound is important in the establishment of new wind turbines in forests. Experts do not always agree about this establishment whether it is efficient regarding production and sustainability. Some promote it by saying that the development of increased hub heights during the last years makes it possible to better use the wind over forests [3]. Some other says that the production will be less good and the turbines will be exposed to worse detritions by placing wind turbines in forests [4]. However, an increasing number of wind turbines are planned to be located in forests. The Swedish company Vattenfall has built two wind turbines at Ryningsnäs, close to Hultsfred in Småland. They have been built in connection to a wind measuring mast. The purpose of these turbines was to gain sufficient experiences of wind turbines in forests in order to establish larger wind turbine projects more efficiently [5].

To understand more about the complexities when planning new wind turbines a research program called Vindforsk has been initiated, over which the Swedish company Elforsk has responsibility. In a project called V-164 within Vindforsk, the company ÅF-Ingemansson measured the sound from a wind turbine in a forest terrain. The measurements were made inside the forest; see [1]. Both sound emission (sound power level, SWL or L_W) from the wind turbine and the sound immission (sound pressure level, SPL or Lp) inside the forest were measured. The measurements were compared with predictions of the noise level by commonly used calculation models e.g. Nord2000 (a Nordic propagation model for outdoor sound), but without treating the forest. Forests usually have a scattering, i.e. dissipating impact on the sound and calculation models for forests thus predicts a decrease of the sound level compared to open areas.

However, from the measurements it was discovered that the sound immission in the forest was 1 to 2 dB higher than expected from calculations. A conclusion of the project of V-164 was that the available calculation models do not predict the sound immission in the forest correctly and further investigation needs to be done. The exact reason for the difference between the calculation model and measurements is not fully known. However, various hypotheses exist trying to explain the higher levels of sound immission in the forest. Two examples of possible hypotheses are the reverberation in the forest and due to strengthened wind and temperature gradient with height in the canopy. When regarding the hypothesis of reverberation one may compare the forest with a room. In a room the reverberation stores the sound energy, which decay with time, and can increase the sound pressure level. When regarding the temperature gradient in the canopy it can be explained that the speed of sound increases with increasing temperature, which leads to a refraction of the sound towards the ground. Refraction can therefore increase the reverberation in forests, one can say that the refraction will store more sound energy towards the ground; hence the reverberation can depend on the refraction. The topic of this master thesis will be to investigate the reason to why the sound immission in the forest is higher than predicted by calculation models. The purpose will be to compile different hypotheses and also to develop a calculation model that can predict the sound immission better.

1.2 Purpose and objective

The difference between the purpose and objective is that purpose aims for a longer time and wider perspective, when objective aims more close in time and is often stated with practical targets.
The purpose of this master thesis was to come closer to the understanding of why the noise from wind turbines, which are placed in a forest terrain, can cause higher sound levels than expected inside the forest.
A question that has been asked is: What is the reason to the increased sound pressure level in the forest? The understanding is expressed through a compilation of various possible hypotheses. In order to restrict the work, the compilation of hypothesis has primarily treated reverberation in the forest and wind together with temperature gradient in the canopy. Secondly other possible hypotheses for the sound pressure level increase can be investigated.
The objective of this master thesis was to compile the major hypotheses and confirm them by measurements.
The objective was also to develop a calculation model that can predict the increased noise level in forest, e.g. may take the reverberation in the forest into account.
Finally the objective of the master thesis was to present, discuss and argue for the developed calculation model and the compilation of hypotheses to the sound level increase.

1.3 Method

The objectives are achieved through literature studies (relevant to the reverberation and sound propagation in the forest), studies of the Nord2000, and review of project report by Vindforsk, and introduction to measurement equipment. Practical experience of outdoor sound measurements is achieved when performing measurements in forest. By contact and consultation among supervisors Jens Forssén (at school of Applied Acoustics, Chalmers University of Technology) and Martin Almgren (ÅF-Ingemansson), knowledge and understanding have been achieved. Through modelling and calculations in the software Matlab, the hypotheses may be accepted for now or rejected by comparing measured and calculated data. Report writing is progressed in parallel with the compilation of the hypotheses and measurements.

1.4 Restrictions

The master thesis is concentrated on the theories of reverberation and theories of sound speed gradient, and how to model this in Swedish forests. The thesis work has therefore mainly considered coniferous forests in Sweden. Deciduous and mixed forests have not been regarded as important, because the establishment of wind turbines in Sweden tends to be more usual within coniferous forests. Since the thesis work progressed during the winter season, the meteorology of summer conditions in the forest has not been considered adequately. Therefore, further investigations may be carried out, which make it possible to consider sounds for a whole year.
Measurements have been carried out with the restrictions:
- limited amount of microphone positions during measurements of the reverberation time of the forest
- not considered sound further than 150m from the wind turbine
- not considered sound with level below 30 dBA

The calculation model will only regard the frequency range (50Hz-10kHz),

2 Outdoor sound propagation

2.1 Introduction to sound propagation

The sound propagation outdoors has been under study for many years. The propagation is complex and influenced by many factors. The main factors are attenuation due to geometrical divergence, wind and temperature changing the speed of sound, air absorption, absorptive properties within vegetation and ground. Scattering and reflective properties are due to geometry, shape and material of reflecting obstacles. These factors are presented below.

2.1.1 Attenuation from geometrical divergence

The most common approach to regard the sound source from a wind turbine in a forest terrain is as a point source in the centre of the hub. The sound energy is distributed on the surface of a sphere with increasing distance from the source. Due to that the area increase the sound diverges and the intensity is reduced. This is the attenuation from the geometrical divergence.

With a simplified approach the sound pressure level can be determined from the wind turbine sound power level with equation, if the reference sound power is 1pW and the reference sound pressure level is 20µPa:

$$L_p = L_W - 10\, log\frac{S}{S_{ref}}$$

where L_p= sound pressure level, L_w = wind turbine sound power level, S_{ref} = reference surface (often assumed to 1m^2) and where S is determined from the equation of sphere:

$$S = 4\pi r^2$$

where r is the distance to the source. Assuming S_{ref} =1m² the equation can be simplified to

$$L_p = L_W - \left(10\, log(4\pi r^2) - 10log\left(S_{ref}\right)\right) \quad \rightarrow \quad L_p = L_W - (10log(4\pi) + 10log(r^2) - 0)$$

$$\rightarrow \quad L_p = L_W - 11 - 20log(r)$$

When the distance is being doubled, the sphere will become four times as big, which will decrease the sound pressure level with 6dB.
At far distances (>1km) the spherical wave can locally be perceived as a plane wave. But during propagation in forest the sound is affected by other factors, e.g. refraction.

2.1.2 Wind changing the speed of sound profile

The wind speed can be very high at high altitudes, (1km and up). Closer to the ground (1km and down) the wind speed varies largely with the height, most due to that the wind speed is limited by irregularities, e.g. as mountains and forests, at the surface of the earth.
Instead of measuring the wind speed for every height of interest a profile can be obtained with calculations. The concept of (aerodynamic) roughness length is introduced in order to estimate the irregularities which the wind will pass over. The roughness length is denoted z_0 and is an average quantity for a relatively large area of ground surface.[6 s. 287] It corresponds to the dimensions of the irregularities at the ground surface and can be used to calculate the wind profile [7 s. 378]. The characteristic value for an open field of grassland is in the range of 0.01 to 0.1 m, here grass causes the irregular surface. If larger obstacles, e.g. forest, are present the roughness length increases [6 s. 287]. A typical value of z_0 in forest is 0.3. The wind speed can be calculated, as following:

$$u_{wind}(z) = b \cdot \ln\left(\frac{z}{z_0} + 1\right)$$

$u_{wind}(z)$: wind speed at z height [m/s]

b=-1 [m/s] for upwind *z_0: air roughness length [m]*
b=1 [m/s] for downwind *z: height above ground*

The result from previous equation will give a wind speed which has a logarithmic profile, see Figure 1 below!

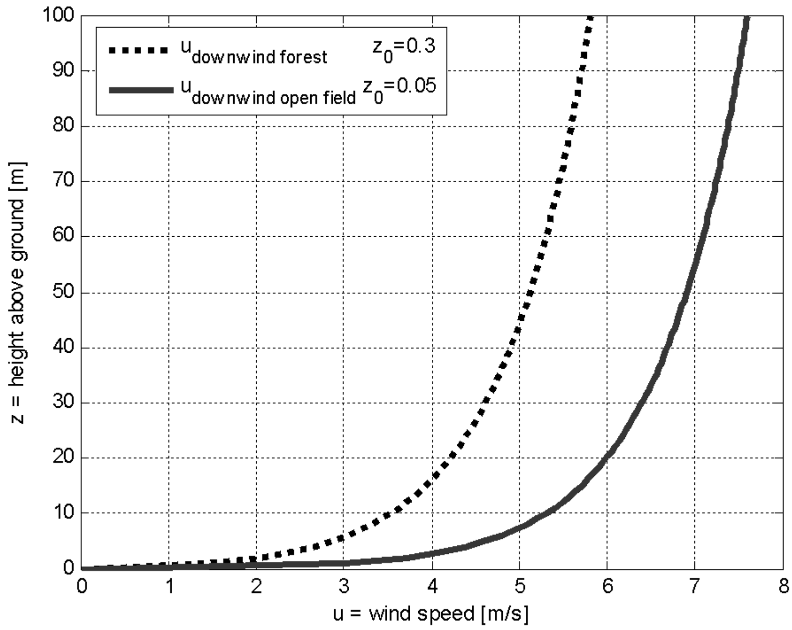


Figure 1. Example of logarithmic wind speed for two cases with different surface roughness (z_0), dotted = forest and continuous =open field, as function of height over ground

The difference between the forest and the open field can clearly be seen. The greatest increase change in wind speed occurs in range of 0-20 m height. In this region the speed of wind varies in the range 0-6m/s for open field and 0-4.3m/s for forest. Both these cases cause downwind refraction if the propagation direction is assumed along the wind. Upwind refraction will occur if the sound propagation is assumed to go opposite of the wind direction.
When determining the wind speed one measures the wind speed at two heights and calculates the profile assuming a linear or logarithmic shape. A linear profile may be easier to calculate but the logarithmic may provide a more realistic estimation.

2.1.3 Temperature changing the speed of sound profile

The speed of sound fluctuates with the temperature and can be determined with the following formula when regarding air under neutral and static conditions:

$c_{temp} = c_0\sqrt{1+\frac{T}{T_0}}$	*c_{temp}: speed of sound due to temperature*	*[m/s]*
T	*T: tempterature in celcius*	*[C]*
T0=273.15	*T: temperature in Kelvin corresponding to 0^oC*	*[K]*
c0=331.3	*c_0: speed of sound at ground level at 0^oC*	*[m/s]*

At zero degrees the speed of sound in air is 331.3 [m/s], which is why this is included in the formula as a reference. In Figure 2 below the speed of sound is plotted for temperatures 0-30 ^oC.

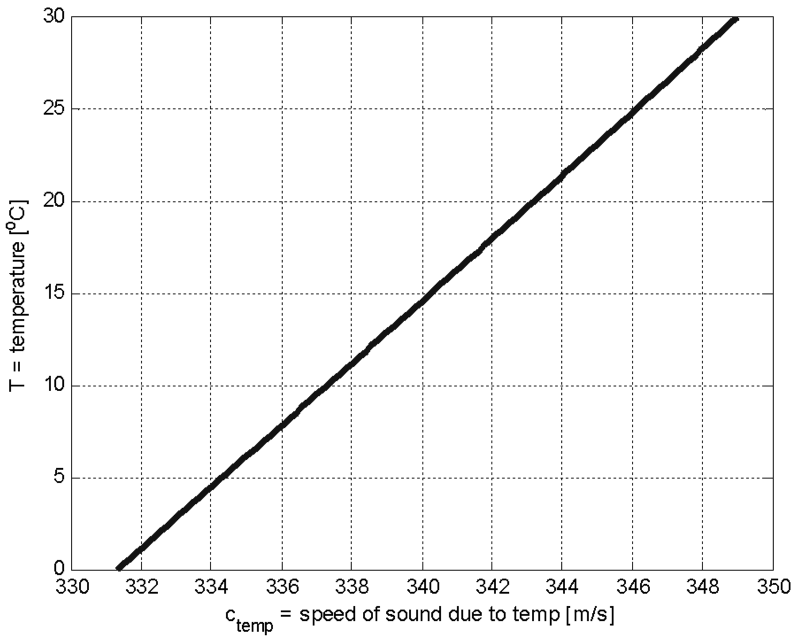


Figure 2. Speed of sound due to temperature

In natural conditions the temperature *T* of air also varies with height above ground, which is why it is usually mentioned as a height function of, *T(z)*. At very high altitudes the temperature is cool, but at ground level the sun is heating surfaces which are heating the surrounding air. The phenomenon creates a temperature gradient. The temperature gradient may also change over the day due to that ground materials absorb and radiate heat more quickly than the passing air. The continuous air movements in the atmosphere between the earth and the space, creates totally a negative temperature gradient with height, i.e. warm close to the ground and cold close to the space. The temperature gradient varies with weather and terrain conditions, i.e. it is different between open field, oceans and forests.
Since the speed of sound varies with temperature, the temperature variations with height will also, as the wind, induce a "bending" of the sound propagation, i.e. refraction. When the temperature is lower at ground level than higher up, i.e. positive temperature gradient, it creates downwards refraction. In the same way it will induce upwards refraction when the temperature is higher at ground level than higher up, i.e. negative temperature gradient.

2.1.4 Speed of sound due to height

To combine the influence of wind speed and temperature, the sound speed variation with height can be described. This is called effective speed of sound. The effective speed of sound can be obtained when combining previous formula and sum them together. The basic concept to calculate the speed of sounds due to the wind and is simply just to add the wind speed (in appropriate direction) to the speed of sound in air for the actual temperature. Here it is important to specify the direction of the wind, because the wind speed depends on the direction.

$$c_{eff}(z) = c_{temp}(z) + u(z)$$

$c_{eff}(z)$: *effective speed of sound over height*	*[m/s]*
$c_{temp}(z)$: *speed of sound due to temperature over height*	*[m/s]*
$u(z)$: *speed of wind at height z*	*[m/s]*

Reference: [6 s. 41]

Wind and temperature causing combined cases of propagation. The different propagation cases are schematically visualized in the table below. The sound is illustrated with sound rays, along which the sound waves propagate:

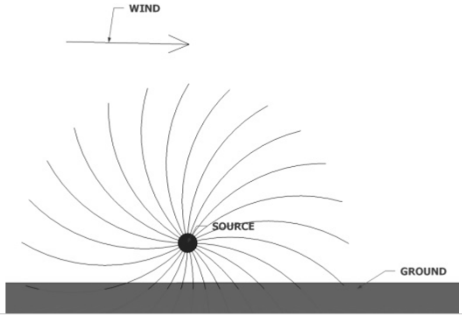
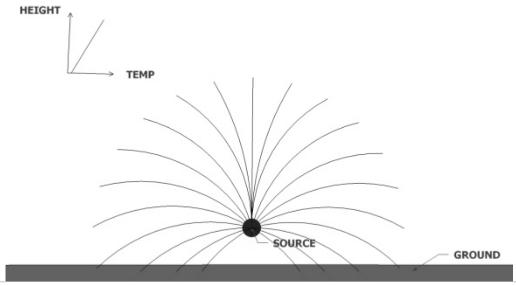
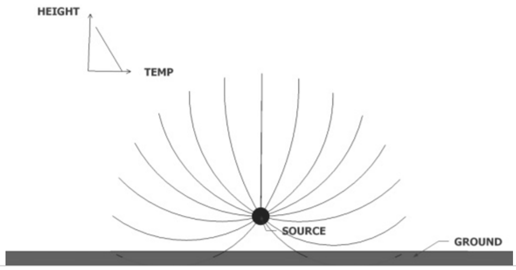
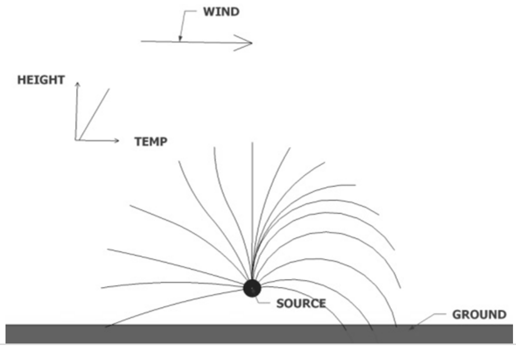
CASE	*VISUALIZATION*
1. WIND *Sound propagation along the wind causing downward refraction and towards the wind causing upward refraction, i.e. the propagation direction of importance.*	
2. TEMPERATURE INCREASE WITH HEIGHT *Sound will refract downwards in all directions*	
3. TEMPERATURE DECREASE WITH HEIGHT *Sound will refract upwards in all directions*	
4. POSSIBLE COMBINATION OF WIND AND TEMP *Propagation towards the wind (left of source) will be compensated and therefore almost horizontal. Propagation along the wind (right of source) will bend the propagation downwards, adding the case of wind and case of temperature with height.*	

Table 1. Different propagation cases of sound

In case no 3 a sound shadow can occur when the sound is bent upwards and not heard at all at some distances, see Figure 3 below.

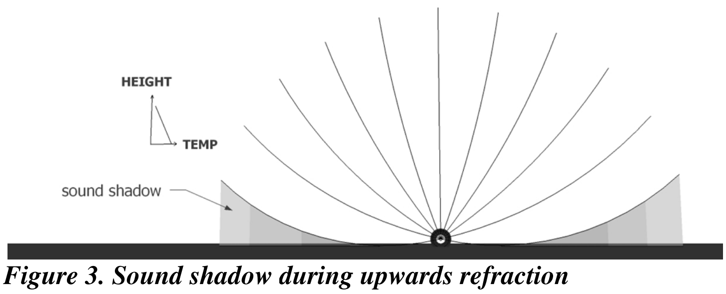
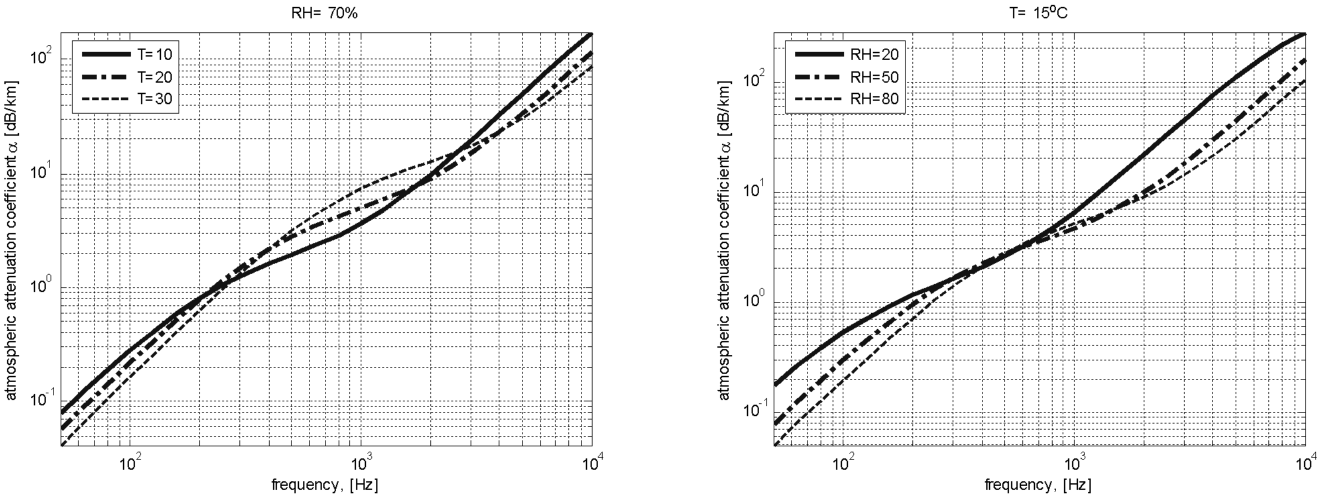


Figure 3. Sound shadow during upwards refraction

But wind and temperature are not the only factors determining the speed of sound profile. It is important to know the direction (mentioned before), relative humidity and barometric pressure as a function of height near to the propagation path in order to determine the speed of sound [8 ss. 14-15]. The influence on the speed of sound of relative humidity and barometric pressure is however small close to the ground.

2.1.5 Attenuation by air absorption

Sound is partly absorbed by the air; this is therefore called air absorption or atmospheric sound absorption. The absorption depends mainly on the temperature, the relative humidity and the frequency. It is strongly frequency dependent, with little absorption for low frequencies and high absorption of high frequencies. At distance closer than 100m to the source the air absorption does not affect the sound so much hence it may be neglected but at farther distances it has too large influence to be neglected. In large rooms the air absorption will have an influence on reverberation time at high frequencies.
The air absorption can be calculated with the international standard ISO 9613-1 [9 s. 3]. The absorption coefficients for different conditions calculated with ISO9613-1 can be seen below:



RH =70 % with Temp = 10, 20 and 30 °C ***Temp = 15 °C, with RH = 20, 50 and 80 %***

Figure 4. Atmospheric attenuation coefficients for different conditions.

In order to calculate the influence of air absorption on SPL, an atmospheric coefficient can be added to the previously presented sound pressure formula, equation 1. This is proposed in ISO9613-part1 and explained by Salomons; see [6 s. 109], as:

$$L_p = L_w - 10\log\left(S/S_{ref}\right) - \alpha r$$

If S_{ref} is assumed to 1m^2 this equation can be formed, as the analogous equation in ch 2.1.1, like this:

$$L_p = L_W - 11 - 20\log(r) - \alpha r$$

The fully explanation of calculating α is described in appendix Appendix A at page 1.

2.1.6 Attenuation due to ground for open field

The attenuation due to ground is of great importance in outdoor acoustics and is usually referred as the ground effect. In order to make a simple presentation of this effect, it is here presented for the case of open field.
Simplified approaches of the ground effect regard the ground as “acoustically hard”, which means that the ground has good reflection properties, or “acoustically soft”, which means that the ground has poor reflecting properties (i.e. good absorptive properties). Many situations do however need an extended model for treating the ground properties in the range between “hard” and “soft”. The concept of ground impedance (Z_s) is introduced and gives an estimation of the reflection coefficient of the ground. The reflection coefficient for the ground is notated as R_p for plane waves and Q for spherical waves.

The relation between the Z_s and R_p can, for a given plane sound wave with incidence angle θ normal to the ground, be represented by eq (D.13) in [6 s. 126] as:

$$R_p = \frac{Z_s cos\theta - 1}{Z_s cos\theta + 1}$$

Usually an empirical one parameter model developed by Delany & Bazley is being used [10]. The ground impedance is determined for fibrous absorbing materials. The normalised impedance (Z_s) can be represented as following formula: (with time dependency $e^{-j\omega t}$)

$$Z_s = 1 + 9.08\left(\frac{1000f}{\sigma}\right)^{-0.75} + i \cdot 11.9\left(\frac{1000f}{\sigma}\right)^{-0.73} \qquad \sigma{:}\, flow\ resistivity\ [Pa \cdot s \cdot m^{-2}]$$

$$f{:}\, frequency\ [Hz]$$

This model is generally used in the comprehensive Nord2000, but other models can also be used [11 s. 25]. Other models may be phenomenological models like models by Mores and Ingard or Thomasson, [8 s. 63].

An approach to model the sound propagation based on stronger scientific basis is to take the influence of viscous and thermal effects that exist in the pores of the ground. One of these is a pore-based microstructural model, which express the properties of a rigid porous medium with porosity Ω and tortuosity T containing slit-like pores [12] and [8 s. 63]. The model can be expressed with the following relations:

$$Z_c(\omega) = \frac{1}{\rho_0 c_0}\sqrt{\left(\frac{q^2}{\Omega^2}\right)\frac{\rho(\omega)}{C(\omega)}} \qquad \rho_b(\lambda) = \left(\frac{q^2}{\Omega}\right)\rho_0\left[1 - \frac{\tanh(\lambda\sqrt{-i})}{(\lambda\sqrt{-i})}\right]^{-1}$$

$$\lambda = s_A\sqrt{\frac{3\rho_0\omega q^2}{\Omega R_S}} \qquad H(\lambda) = 1 - \frac{\tanh(\lambda\sqrt{-i})}{(\lambda\sqrt{-i})}$$

$$k(\omega) = \omega\sqrt{q^2\rho(\omega)C(\omega)} \qquad C(\omega) = \frac{1}{(\gamma P_0)}\left[\gamma - (\gamma - 1)H\left(\lambda\sqrt{N_{PR}}\right)\right]$$

$$\frac{1}{(\gamma P_0)} = \frac{1}{(\rho_f c_f^2)} \qquad \rho(\omega) = \frac{\rho_0}{H(\lambda)}$$

$$R_s = \frac{2\mu q^2 s_0}{\Omega r_h^2}$$

The ingoing parameters of these relations are explained in the table below:

Symbol	Name	unit	Typical value
Z_c	characteristic ground impedance		
ρ_0	density of air	kg/m^3	1.2
c_0	sound speed of air	m/s	340
N_{PR}	Prandtls number	-	0.7
q^2	tortuosity	m	1.7
Ω	porosity	m	0.4
R_s	flow resistivity	$Pa\ s\ m^{-2}$	
k	propagation constant, wave number	m^{-1}	
ω	angular frequency	s^{-1}	
γ	ratio of specific heats	-	1.4
f	frequency	Hz	
λ	dimensionless parameter to $C(\omega)$	-	
$C(\omega)$	complex compressibility	$(m\ s^2)/kg$	
r_h	hydraulic radius	m	
s_0	steady flow shape factor		
s_A	pore shape parameter		$0.745 < s_A < 1$
$\rho(\omega)$	complex density	kg/m^3	
$k(\omega)$	bulk propagation constant	m^{-1}	

For hard grounds the flow resistivity takes high values e.g. concrete= 200'000 [$kNsm^{-4}$] and for soft grounds low values e.g. snow= 12.5 [$kN{\cdot}s{\cdot}m^{-4}$], [11 s. 26]. Elaborating with σ one founds that for high

resistivity the impedance takes high values (=∞) giving the $R_p = 1$, for low resistivity the impedance takes low and finite values giving the $R_p = -1$.
Sometimes the unit of the flow resistivity appear differently $\left[\frac{kPa \cdot s}{m^2}\right]$ and $\left[\frac{kN \cdot s}{m^4}\right]$. This can be understood by the difference in notation for pressure $\left[Pa = \frac{N}{m^2}\right]$.
The determination Q has a more complicated solution. According to [6 s. 133] Q can be determined using formula *D.54*:

$$Q = 1 - 2\frac{k_1}{Z}\frac{R_2}{e^{(ik_1R_2)}}\int_0^\infty e^{\left(-\frac{qk_1}{Z}\right)}\frac{e^{\left(ik_1\sqrt{r^2+(z+z_s+iq)^2}\right)}}{\sqrt{r^2+(z+z_s+iq)^2}}dq$$

Here the ingoing parameters are:

k_1	=	*wave number*	*[1/m]*
Z	=	*ground impedance*	
R_2	=	*reflected path*	*[m]*
q	=	*Integral operator*	
r	=	*receiver position*	*[m]*
z	=	*height of receiver*	*[m]*
z_s	=	*height of source*	*[m]*

According to [6 s. 23] the complex pressure amplitude of the free field is

$$p_{free} = S\frac{e^{(ikR_1)}}{R_1}$$

S=constant
R_1=direct path from source to receiver
R_2=reflected path from source to receiver
k= wave number

The relative sound pressure can be determined using the free field and adding the reflected field.

$$p_c = S\frac{e^{(ikR_1)}}{R_1} + QS\frac{e^{(ikR_2)}}{R_2}$$

This equation can have a more efficient form, like this:

$$p_c = p_{free}\left[1 + Q\frac{R_1}{R_2}e^{(ikR_2 - ikR_1)}\right]$$

So if the sound pressure level is desired it can be obtained:

$$L_p = L_W - 10log(4\pi R_1^2) - \alpha R_1 + \Delta L$$

where the term ΔL is called *relative sound pressure level* and has the following relation

$$\Delta L = 10\log\left(|p_c|^2 / |p_{free}|^2\right)$$

The often used expression, *excess attenuation*, is equal to $-\Delta L$, i.e. the attenuation in excess of divergence air absorption. If S_{ref} is assumed to 1m^2 this equation can be formed, as the analogous equation in ch 2.1.5, like this:

$$L_p = L_W - 11 - 20\log(R_1) - \alpha R_1 + \Delta L$$

With this approach it is possible to find the sound pressure level for a spherical sound wave, when taking geometrical divergence, air absorption, speed of sound gradient with height and ground effect into account.
When the ΔL is positive a constructive interference between direct and reflected waves occurs. The maximum of +6dB of constructive interference can occur for hard and rigid grounds, when Q=1. For absorbing grounds, when $|Q| < 1$ the increase is less than 6dB. In some occasions the so-called surface wave contribute to a higher values $|Q| < 1$ and therefore also can increase the sound pressure level more than 6dB[6 s. 26] The coming parts will extend this approach including other effects that can appear in the forest.

2.2 Sound propagation in forests

Sound propagation in forests has been a topic for many researches during the years, e.g. in 1946 by Eyring headline “Jungle acoustics” [13] and 1963 by Embleton “Sound propagation in Homogenous Deciduous and Evergreen Woods” [14].
In Sweden there are 182’000 km^2 of coniferous forests, i.e. forest mainly with pine trees and spruce [15 s. 45]. Globally there are many different species of spruce and pine. In Sweden the most common spruce species is *picea abies* and pine is *pinus sylvestris*. The sound propagation in forests is very complex and influenced by many factors and the main factors are explained here. Some factors create changed conditions for the propagation, e.g. changed wind and temperature profile. Other factors are how well obstacles absorb and reflect sounds. Some factors may even at rare occasions increase the sound pressure level.

2.2.1 Changed wind profile in the forest

Just above the canopy in forests the air can be very turbulent causing large deviations in the wind speed. Inside the forest it is often calm and the wind speed is dramatically decreased to find a speed which is much lower compared with open field at same height.
Swearingen and White calculated the wind velocity profile for open field and forest, using a model by Heimann [16]. which is shown below: and compared them in a figure, An example of differences between wind speed at open field and in forests can be seen in Figure 5 [17 s. 4].

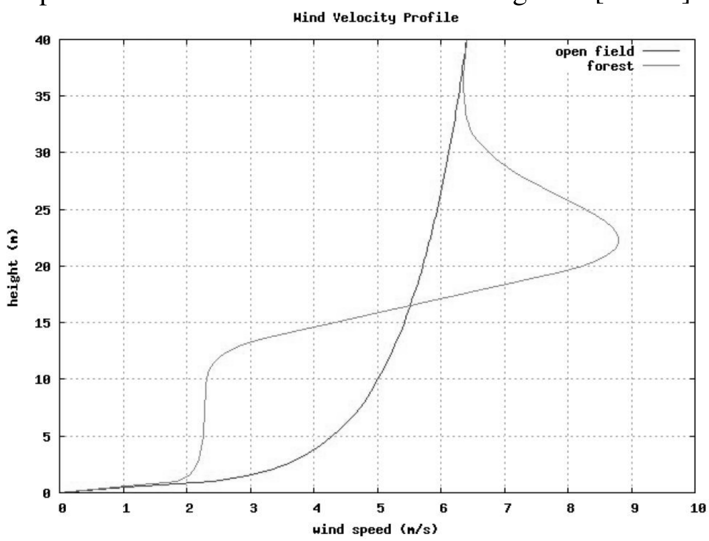


Figure 5. Wind profile over open field and forest, by Swearingen & White (16)

In Figure 5 it can be seen that the wind velocity for the open field has a logarithmic shape, but the wind velocity inside the forest has a more varying shape. The in data used by Swearingen & White states that the canopy starts at 10 m height, seen from the ground, and making the total tree height of 15m. In Figure 5 the canopy is exposed to very rapidly increasing wind velocity between 2.4-4.4 m/s. The wind velocity increases even more above the canopy, ranging 2.5-8.7m/s. At 40m height the open field and the forest reaches the same value. The differences can be regarded as two layers, one below the canopy and one above. The difference will with big probability cause an extreme downwards refraction, i.e. sound reaching the ground of the forest will undergo refraction and the sound intensity will be increased close to the ground.

2.2.2 Changed temperature profile in the forest

The temperature in the forest may have a large vertical variation, which is usually different from the case of open field. Surfaces directly exposed by the sun are heated faster compared with the surfaces lying in the shade. Temperature differences want to be compensated but the process will be delayed, which creates variations over the day.
Phenomenon of this daily variation is described by A. Tunick [18], for deciduous trees explaining how different trees are able to balance the surface temperature to the ambient air temperature. This is shown in Figure 6 below:

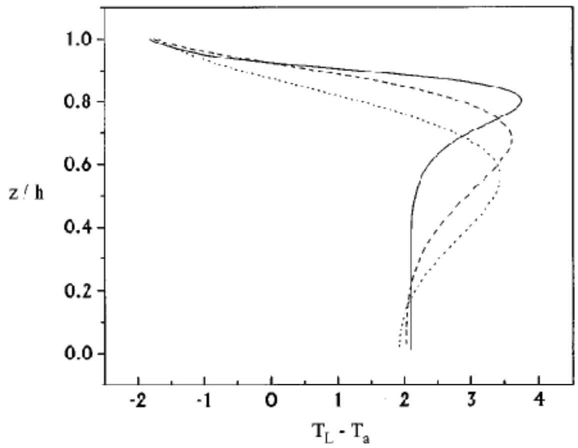


Figure 6. Profiles of the leaf-to-ambient temperature (T_L-T_a) differences (°C) for different trees, z=height above ground, h=height of canopy, picture from A. Tunick [18 s. 1799]

In Figure 6 one can see the difference between leaf (T_L) and ambient air (T_a) temperature. Close to the ground the T_L is 2^0C higher than T_a. At height of half the tree (*z/h*=0.5) differences can be seen among the trees. The dotted line has the peak in temperature difference of 3.5^0C at *z/h*=0.55, the dashed line has a value of 3.6^0C at *z/h*=0.68, and the solid line has a value of 3.75^0C at *z/h*=0.8. After each peak all tree types strives towards a negative temperature difference, at *z/h*=1.0 (the top of the tree) all trees has a value of -1.7^0C. At this height the curves from the different tree types gather together. A reason for this may be that the balance between incoming solar energy absorbed by leafs in canopy and the outgoing long-wave energy emitted is negative, (18 s. 1799). At the height of $z/h \approx 0.9$ the temperature difference is zero. Here the incoming solar energy and the outgoing heat from the leaves are balanced.
In [18] it is not clearly mentioned which type of trees they have been investigated, however branches and leaves indicates it is a deciduous forest stand. However, from the differences between the curves in Figure 6 some guesses can be made. The solid corresponds to trees with main canopy high up and a big part of the trunk with almost no foliage (e.g. pine), the dashed line corresponds to a foliage from the top to the middle of the tree (e.g. asp) and the dotted line corresponds to a foliage all the way from the top to ground (e.g. spruce).
In [19] the diurnal variation of temperature gradient in a pine forest is described. In this paper Figure 7 is presented:

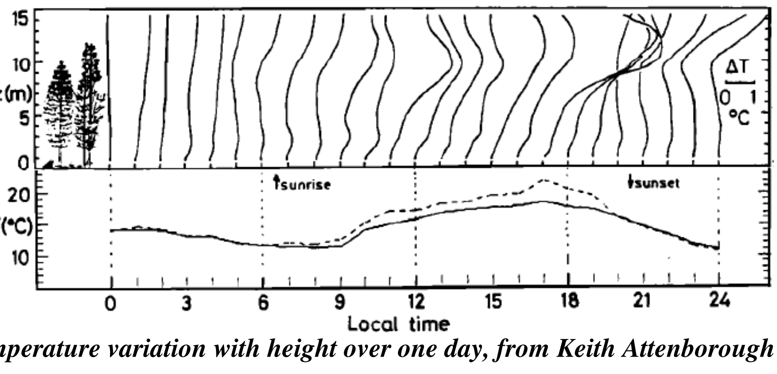


Figure 7. Temperature variation with height over one day, from Keith Attenborough [19 s. 2666]

In the upper part of Figure 7 the temperature difference, ΔT (horizontal), for different heights (vertical, z) is described. The lower part of Figure 7 shows the temperature variations over a day. It can be seen that the greatest influence of positive temperature gradient occurs in the hours around sunset, but also at noon. The main effects can be seen in the height range between z=8-12m.

2.2.3 Changed speed of sound profile with height in forest

Due to changed wind profile and temperature profile the speed of sound will have a resulting profile which usually is different compared with sound propagation over open field. Under these conditions the sound propagation will be influenced by refraction. An example of downwards refraction for an assumed sound speed profile can be seen in Figure 8 below:

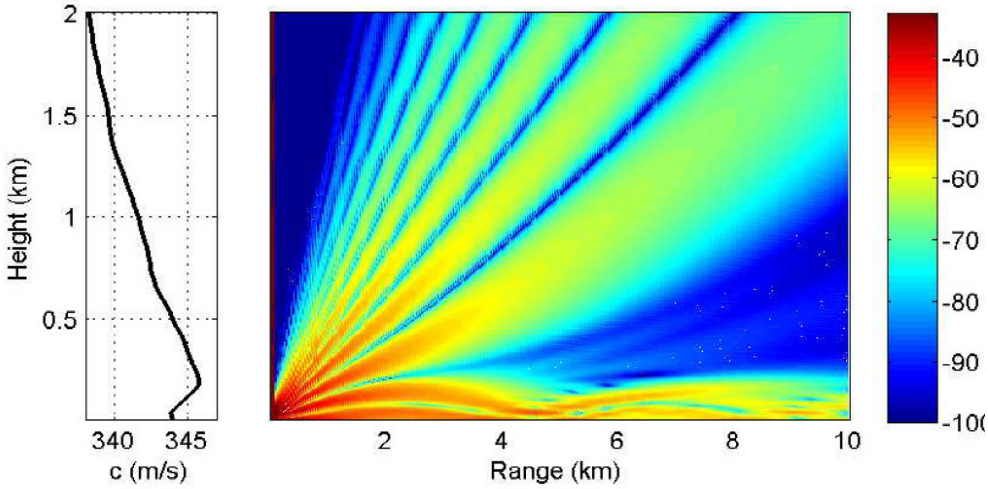


Figure 8. Propagation for an assumed speed of sound profile [3 s. 25]

The left part of Figure 8 shows the speed of sound profile with height. Close to the ground (0-200m) the sound speed increases, above 200m it decreases. The right part of Figure 8 shows the calculated sound pressure level for the corresponding sound speed profile. The sound pressure level is plotted over a horizontal range (x-axis) and height above ground (y-axis). The highest sound levels are marked as red and lowest levels as blue. In the figure it is showed how the downward refraction causes an increased level compared with other areas, as can be seen close to the ground. In these areas a vertical concentration of the propagated sound is occurring close to the ground. The downward refraction is caused by the characteristic speed of sound profile, which is seen to the left as a function of height. From ground level to about 200m height there is a positive gradient, which also can be seen in the color plot. At higher levels the gradient becomes negative, hence the color plot shows an upwards refraction.

2.2.4 Attenuation due to forest floor (Ground effect)

When the sound is propagating in the forest the ground will have a major influence on the resulting sound pressure level, except for very short distances <1m. The general theory of the ground effect can be understood when reading ch 2.1.6 at page 7.
In forests grounds have varied properties. The properties vary among different forests but also within a single forest. In order to find a good method to estimate this effect, a general approach is needed but also a technique or method for characterizes the properties of the single unique forest. From an acoustical point of view the forest floor is very complex. Some floors are thin and hard others are thick and soft. Sometimes the floor may be regarded as layered, where there e.g. is a rather hard foundation with soft shrubberies above.
As described above the ground can be described through its ground impedance, which depends on the flow resistivity. A table of flow resistivity and porosity for some common forests has been compiled by [20], see Figure 9 below.

Surface	Soil layer	Flow resistivity (R_s; 10^3 Pa s m^{-2})	Porosity (%)
Lawn	R, layer with roots	237 ± 77	50.5 ± 9.3
Bare sandy plain	A, mineral soil	366 ± 108	36.2
Soil layer with roots	R, layer with roots	114 ± 53	55.2 ± 4.5
Grass covered soil	R, layer with roots	189 ± 91	–
Beech forest	L, litter layer	22 ± 13	82.3 ± 1.9
Pine forest	L, litter layer	9 ± 5	67.5 ± 4.1
Mixed forest with beech and pine	L/F, litter/fermentation layer	13.3 ± 3.0	–
	F/H, fermentation/humus layer	52 ± 24	76.3 ± 3.2
	H, humus layer	210 ± 93	–
	A, mineral soil layer	102 ± 60	54.7 ± 6.8
Mixed deciduous forest with oak and beech	L/F, litter/fermentation layer	30 ± 31	–
	H, humus layer	375 ± 69	84.6 ± 5.6
	A, mineral soil layer	540 ± 92	51.5 ± 4.8

Figure 9. Measured values of flow resistivity (R_s) and corresponding porosity for different soils [20 s. 47]

In Figure 9, the lowest flow resistivity can be found in the pine forest, with value of 9±5. The feeling is that the "harder" the surface gets the higher values of the flow resistivity. The table may be related to the empirical impedance model by Delany and Bazley or other ground effect models.

2.2.5 Attenuation due to absorption by vegetation

A strip of forest can be an effective sound barrier. A 30m thick area of dense planted leaf trees can decrease the sound pressure level as much as 7-11 dB [21 s. 263]. The attenuation is mostly due to the sound absorbing of leafs and branches. For deciduous forests the amount of leafs varies with season. Other conditions can be found in coniferous forests. Here the amount of needles is approximately constant over the year. The forests of Sweden are in majority of coniferous type. Embleton [14], have studied pine and spruce trees, and also some deciduous tree species, e.g. cedar. From his paper one can e.g. understand the excess attenuation of cedar, pine, spruce and some common deciduous trees for different distances. For short distances 0-50ft (0-15m) the pine and spruce shows a very fluctuating behaviour of the excess attenuation, i.e. varies a lot. The highest value of the attenuation, value of 15dB, occurs at distance of around 100ft for sounds around 200Hz. On the other hand the lowest attenuation of -4dB occurs at distances around 100ft and frequencies. 630-800 Hz. A negative attenuation is a sort of amplification.

The average for pine, spruce and ceder is also very fluctuating for short distances with some negative attenuation. At other distances the attenuation is always positive. For the different measured forest types, Embleton suggest that the averaged excess attenuation at close distances (0-50ft / 0-16m) is due to refraction, absorption and scattering, while at further distances the excess attenuations are due to absorption and scattering alone [14 s. 1122].

At high frequencies (>1 kHz) there can be attenuation in the forest due to viscous friction in the foliage [8]. This may mostly related to the needles and leafs on the trees in the forest. The thermoviscous absorption occurs in the boundary layer of the air surrounding the needles. In a study of white pines it was found that the fundamental resonances for 8.8cm needles were about at 4Hz and for 2.3cm needles at around 49Hz, [22 s. 660]. But it seems that the scattering by trunks is one of the dominant high frequency absorptive mechanisms in forests, as stated by Donald Aylor [23]

3 Compilation of hypotheses for higher levels in forest

In this chapter a compilation of different hypotheses related to the sound pressure increase is presented. The hypotheses should possible apply for the special case of Elforsk 09:22 but also be generalized to apply on other cases. First a short re-evaluation of by Elforsk 09:22 performed measurements and predicted sound is described, after the introduction. Secondly generalized hypothesis for the sound level increase are presented.

3.1 Introduction

As described in the chapter Background at page 1 it was discovered after measurements that the sound pressure level was higher than expected from calculations. Why? What are the possible reasons? How can this be described?
The addressed sound level increase in forest can be treated as a negative excess attenuation, which is helpful when looking on the problem.
A shortcut to an answer can be found using an empirical equation suggested by Hoover, 1961, *"Tree zones as barriers for control of noise due to aircraft operations",* quoted by [24 s. 227]. The equation was developed from many measurements and gives the excess attenuation in a heavily wooden area:

$$A = 0.01 r f^{1/3}$$

Here r = range from source [m] and f = frequency [Hz]. As can be understood by the formula this empirical equation results in that the excess attenuation increase linearly with distance and exponentially with frequency. The result is very regular and follows a simple pattern. The attenuation here is never negative, i.e. it does not give an answer to sound increase. The attenuation of forest includes several parameters and the complexity of the sound propagation is not summarized in this equation. And the background and behaviour of the forest cannot be found from this empirical model. Instead it is interesting to try to find the reason behind possible sound increase in forests.

3.1.1 Performed measurements by Elforsk 09:22

All measurements and calculations presented in Elforsk 09:22 are addressed to one wind turbine of the two existing at Ryningsnäs. Measurements have been performed partly when both wind turbines being activated, partly when only one wind turbine is activated, and partly when both wind turbines are deactivated. When analyzing the measured sound, the background noise was subtracted from the measured wind turbine sound.
The measurements of sound emission were performed according to the international standard IEC 61400-11 [25]. The microphone was placed on a hard board on the ground. The microphone was protected from wind by a primary windscreen and also by an additional secondary windscreen. The meteorological aspects of has been regarded. The wind speed has been calculated from the electrical power produced at the time by the wind turbine, which is a procedure recommended in the report by the E.P.A. of Sweden; see [26 s. 24]. The wind speed has been recalculated to represent a wind speed at 10 m height. It was assumed that the ground was flat and that the wind had a logarithmic profile.
According to equation (9) in IEC 61400-11 the equivalent sound power level was determined using the following equation

$$L_{WA,k} = L_{Aeq,c,k} - 6 + 10log\left(\frac{4\pi R_1^2}{S_0}\right).$$

$L_{Aeq,c,k}$ = equivalent continuous A-weighted sound pressure level corrected for background noise at each integer wind speed and corrected to reference conditions, where k = 6, 7, 8, 9, 10
R_1 = direct path between source and receiver
S_0 = reference surface (=1m^2)

The contribution of 6dB is due to that the microphone is placed on a hard board. The measured $L_{Aeq,c,k}$ can be seen in Figure 10. The resulting $L_{WA,k}$ can be seen in Figure 11.

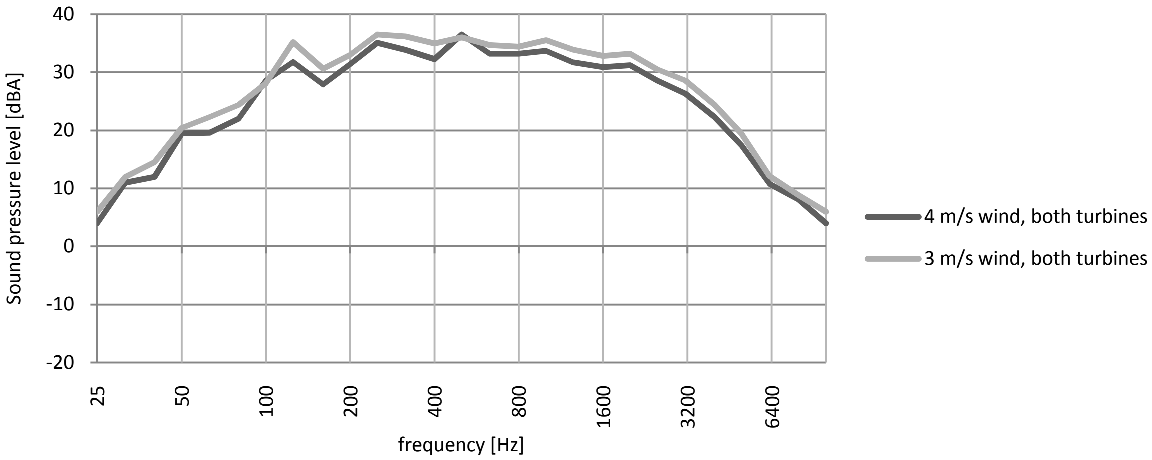


Figure 10. Spectra of sound pressure level [dB(A)] measured at 153m distance, a copy of fig 6 in [1 s. 12]

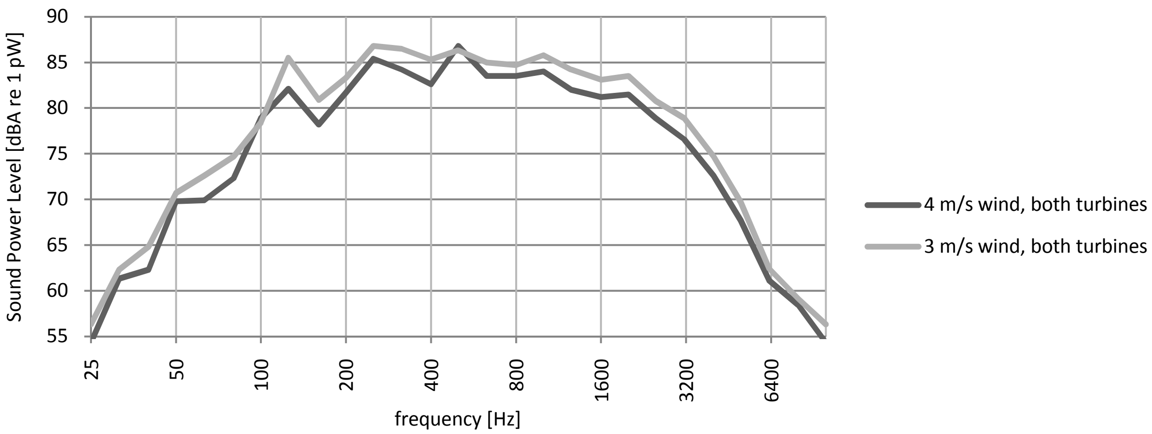


Figure 11. Spectra of sound source over frequency in [dB(A)], a copy fig 7 in[1 s. 13]

The recommended sound emission measurement according to [25] does not include corrections for atmospheric absorption or the effect of trees when measuring inside a forest. The measured sound pressure level, used for calculating the source level, may therefore be lower than the free field. This may cause an underestimation of the actual sound source level of the wind turbine. The possible underestimation is also discussed in the report [1 s. 17]. An underestimation of the sound source will also cause an underestimation of the predicted sound pressure level. So the actual sound source may have been higher and therefore the predicted sound pressure level also higher, which may concur better with measured level.
The sound immission has been measured according to a Swedish standard Elforsk 98:24 [27]. During the measurements the height of the microphone was between 1.2-1.5m. The microphone pointed in the direction towards the wind turbine and was protected with a wind screen.
The measured sound pressure level at 150, 330 and 520m distance, averaged over frequency and A-weighted are shown as single number values in the table below:

Location	***Height above ground***	***SPL [dBA] at wind 6 [m/s]***
EM 150m	0	46,5
IM1 330m	1,4	37,3
IM2 520m	1,5	34,5

Table 2. Single number values of SPL at different distances [1]

3.1.2 Predicted sound through calculations by Elforsk 09:22

The sound immission calculations were performed in the software SoundPlan 6.4. The predicting scheme of Nord2000 was used in SoundPlan 6.4, in order to model the sound field. Here ground class C and F was used with $\sigma_C = 80$ respectively $\sigma_F = 2000$. SoundPlan uses automatically a ground class with corresponding flow resistivity, but in the case of forests SoundPlan does not use the algorithm proposed in Nord2000, "Scattering zones", instead it uses the older approach included in standard ISO 9613 called "Attenuation due to sound propagation through foliage". The concept treating sound propagation through forests in Nord2000 and ISO9613 are more closely presented in chapter 5.3 at page 49.
The calculations used four different scenarios to predict the sound. The first scenario used data from the wind turbine supplier, modelled as a point source. The second used measured data as a point source in the centre of the wind turbine hub. The third used measured data as a surface source, caused by ten point sources located at the circumference of the rotor. The fourth had the same approach as scenario three, but used the influences of forest modelled in the software by the calculation model ISO9613.
In Figure 12 to Figure 14 the predicted sound pressure levels in dBA for the different calculation variants are shown.

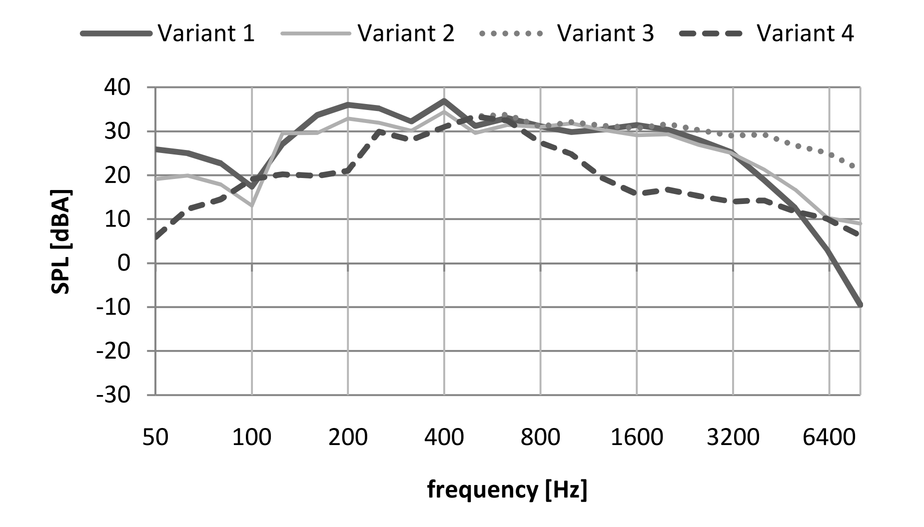


Figure 12. Predicted SPL at 150m

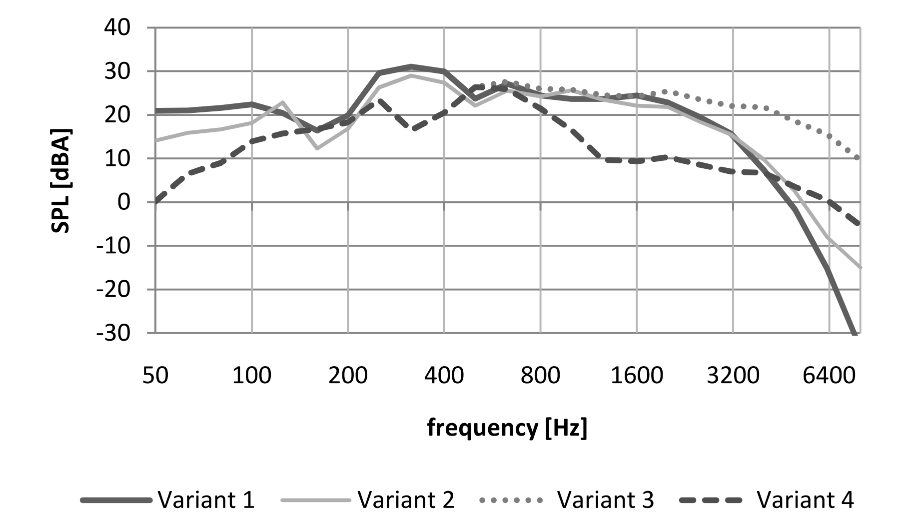


Figure 13. Predicted SPL at 330m

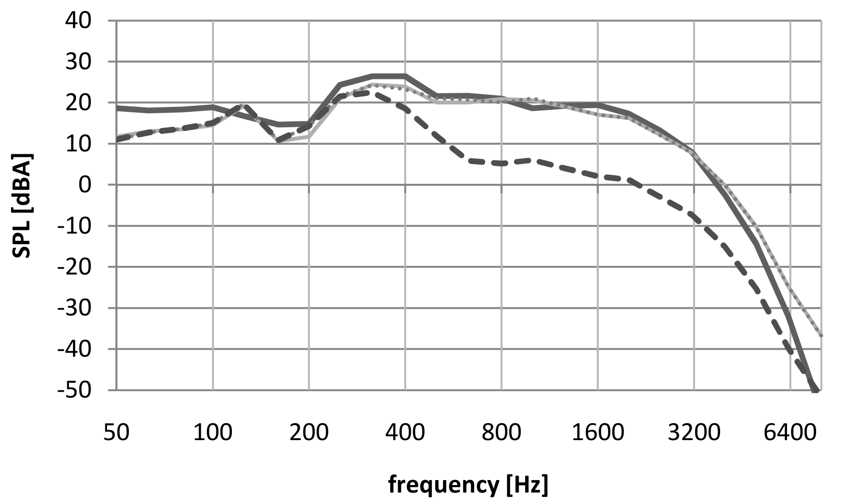


Figure 14. Predicted SPL at 520m

In Figure 12 the predicted SPL at 150m is shown. The fourth variant/scenario shows a more unique character compared with the others. Variant 1-3 follows each other quite well with some exceptions for low frequencies and very high frequencies. In Figure 13 also the fourth variant shows a deviation from the other curves. Figure 13 and Figure 12 are very similar, with ground dip around 160 Hz and the account for atmospheric and scattering effects at quite high frequencies as exceptions. Lastly Figure 14 shows the level at 520 distances. As previous figures the fourth variant shows a pattern of its own. The reason for this behaviour must be related to the influence of forest in variant 4. The calculation of ISO9613 attenuates proportional to the distance, which can be seen in at longer distances.

To calculate the sound power level of the source, the sound pressure level was measured at 150m distance on a hard board. It was also compared with results from a prediction scheme of Swedish EPA. The results can be seen in Table 3.

	Measured	***Calculated with the prediction scheme of Swedish EPA***[26]	
EM 150m hard board	***46.5***	***46.8***	***[dB]***

Table 3. Measured and calculated SPL [1]

Together with the four different prediction variants explained above the measured and predicted levels can be compared with the prediction scheme of Swedish EPA and results from the software of SoundPlan 6.4, in where the prediction scheme of Nord2000 is implemented.

The results showed that the highest levels was given by the first scenario, the lowest levels was given by the fourth scenario. Scenario two and three gave approximately the same levels.

The fourth scenario can be regarded as closest to the reality, treating the forest and the wind turbine in an extended way. The results from the fourth scenario gave the values of Table 4.

	Measured	***Calculated with software: SoundPlan 6.4 where the prediction scheme of Nord2000 is implemented.***	***Calculated with the prediction scheme of Swedish EPA*** [26]	
EM 150m	***42.2***	***42.7***	***43.8***	***[dB]***
IM1 330m	***37.3***	***35.9***	***37.3***	***[dB]***
IM2 520m	***34.3***	***31.8***	***32.7***	***[dB]***

Table 4. Measured and calculated SPL for different distances for the fourth variant/scenario by Elforsk [1]

So the calculations were performed with evaluated software (SoundPlan 6.4) giving satisfyingly accurate values. However, from this table the results from EPA give better agreement with measured even though the forest is not treated. Just as expected before, the increased sound pressure level may be caused by something else, e.g. due to the special conditions inside the forest.

3.2 Sound pressure increase in forests

In order to study the phenomenon with sound pressure increase inside forests, it would be interesting to investigate if this is a common phenomenon, if it is known since earlier.
According to [20 s. 16] forests has an attenuating effect, but may in some cases induce increased sound pressure levels. Also in presence of a solid barrier, the complex mechanisms of sound propagation may local conditions create unstable increased or decreased sound pressure levels.
Also Defrance [28 s. 5], writes about increased sound levels in the forest. It is described that for long distances sounds forests can be increased when unfavourable conditions are present. On the other hand it is also described that this phenomenon is of little importance because the levels of these distances are relatively low.
According to [29 s. 22], sounds containing frequencies mainly below 1 kHz “perceive” the forest as being transparent, i.e. parts limiting the horizontal propagation are not present, e.g. scattering obstacles or absorptive surfaces. Sounds above 1 kHz attenuate mostly due to absorption of the forest.
One clue to the problem may therefore be that the potential noise increase inside the forest mostly occurs at low frequencies or at least is frequency dependent.
Researchers have discovered that animals communicate acoustically in specific frequency ranges. Many birds communicate in 1-3kHz. This may be because that sounds in this frequency range is more easily propagating and less attenuated. [30]. Therefore it can be assumed that low and mid frequency regions may be used by large mammals in the forest. This may indirectly show that some frequency ranges make sound propagation easier.

3.2.1 Reverberation inside the forest

When walking inside a forest, it is easy to perceive a characteristic “sound of the forest”. When making noise e.g. as a gunshot it can be heard how the sound is attenuating quite slowly with time. At some occasions the attenuation takes very long time. This attenuation may be described as the reverberation in the forest and it may have a contribution to the increased sound pressure level discovered by Elforsk.
The reverberation is usually measured, but can also be estimated for a regular room using Sabine’s equation. According to [31] the formulation of Sabine’s equation at normal room temperature (22 ^{o}C) is as following:

$$T_{60} = \frac{0.161V}{(A + 4mV)}$$

where T_{60} = reverberation time, i.e. RT [sec], V = volume of the room [m3], A =absorption area [m2], m = energy attenuation constant for sound travelling through air (damping in air) [1/m]. Here the contributors can be described by the following relations:

$A = \alpha_{tot} S_{tot}$	A: *absorption area*
$\alpha_{tot} = \left(\alpha_T S_T + \alpha_R S_R + \sum \alpha_i S_i\right) / S_{tot}$	α_{tot}: *total absorption coefficient*
$S_{tot} = S_T + S_R + \sum S_i$	S_{tot}: *total surface area*
$\alpha_T = \left(\alpha_{tot} S_{tot} - \alpha_R S_R - \sum \alpha_i S_i\right) / S_T$	S_T: *acoustical audience area*

Table 5. Important relations when regarding RT

When regarding the reverberation in the forest, forest may be treated partly as a room and partly as being free field. This can be simplified. An ordinary room has clear and obvious dimensions, but the forest room is geometrically unclear, because of no definite points where walls, ceiling or floors starts and ends. Therefore it is not for certain that the Sabine formula can at all be applied to a forest. However, if so assumed, some dimensions of the forest must be assumed, in order to make the calculation model possible. The layer between the ground and the lower part of the canopy contain a temperature gradient which limits the sound energy in this layer. Sound from e.g. wind turbine is then concentrated in the area under the canopy and attenuates horizontally. This attenuation will occur more slowly with time compared with the one for open field, because of higher concentration of sound energy due to backscattering from tree trunks.

The classical calculation of indoor reverberation assumes that there is sufficient sound energy to create a diffuse sound field in the room. It is also often assumed that the air absorption is negligible. This may also be a problem when trying to apply the reverberation concept into forest. As mentioned before, when a large amount of sound scatters shall be regarded, the problem shall be treated as a classical diffusion problem, i.e. statistical approach [29]. This assumption may make it possible to meet the problem from a reverberant-perspective, which uses statistical calculations. This is closely related to the interference concept further explained in chapter 3.2.4 in where Elizabeth Lindqvist investigates how the reverberation can be modelled inside very large factories.
There exists an approach to model the reverberant field with scattering from tree trunks [19 s. 2671]. The approach models a large amount of scattering cylinders representing the tree trunks. When the trees are totally absorbing, all sound that reaches the receiver is related to the direct field. When the trees are totally reflecting the sound field at a receiver position is created by both direct and reverberant field. And when the cylinder reflects only a part of the incident energy, the sound field at a receiver is created by attenuated sound reflections by tree trunks and direct field. The model is partly base on a stochastic model by Kuttruff, but questioned by Attenborough and Huisman [19].
An effective trunk diameter has been developed when measuring the reverberation [19 s. 2671]. It should help representing the three dimensional sound propagation in a two dimensional domain. Measuring with different trunk dimensions it was found that, when the reflection factor was low, see Figure 15, a small diameter creates an initially increased attenuation (curve b) causing a quick drop but then flattens out causing a long reverberation, compared with a larger diameter (curve a). From this it may be assumed that young forest stand, with small trunk diameter may have longer reverberation time compared with old, assuming that other conditions (e.g. distance between trees, amount of vegetation) are the same.

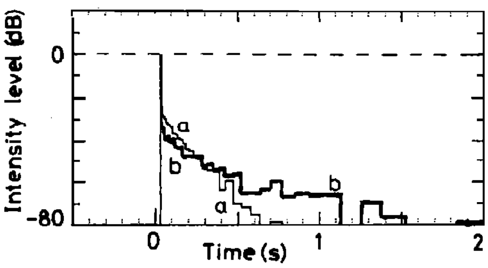


FIG. 12. The influence on simulated pulse response of the effective trunk diameter if the reflection factor is low. Effective trunk diameters D_e: (a) $D_e = 0.16$ m; (b) $D_e = 0.02$ m. Parameters: Range $X_r = 10$ m; density $n = 0.19$ trunks/m^2, air absorption 3.3 dB/s; reflection factor $R_e = 0.1$.

Figure 15. Attenuation over time.[19 s. 2672]

Bucur mention that there can be typical zones for sound propagation in the forest when noise from aircraft is being regarded[20]. The different vertical zones influences the sound propagation in different ways and the free space between trees can act as a noise amplifier, due to reverberation in the resonance zone. The author von Wendorff, mentioned by Bucur, call this the “trumpet effect”.
Factors influencing the reverberation in a forest stand are “the directivity of the source and receiver, the carrier frequency and the wavelength of the sound in relation to the dimension and shape of the scattering surfaces” [20 s. 93].
No commonly used prediction scheme for predicting outdoor sound in forests use the reverberation as a contributor for resulting SPL.

3.2.2 Temperature and wind gradient causing downward refraction

In forests there is usually a different temperature gradient compared with open field, see page 11 above. The possible refraction caused by the temperature gradient may increase the sound at an observer. The phenomenon with refraction is very sensitive in forests due to the sometimes very strong temperature gradient; see Figure 7 at page 11.
The temperature gradient can limit the vertical sound, as Figure 8, page 12, shows. Horizontally the sound is not limited and propagates in all directions. Vertically the sound is limited due to the

refraction and therefore not propagating as to higher altitudes in the same extent, e.g. causing sound shadow.
Compared with other effects influencing the sound propagation, e.g. scattering by trees or ground reflection, the atmospheric profile is the most important [32 s. 117] and is affected by the temperature gradient.
Wind turbines located at oceans is expected to have higher levels during spring and beginning of summer. This is due to that a positive temperature gradient is created between the cold sea water and the warm air. This causes a downwards refraction of the sound. The sound is in this way concentrated close to the surface of the ocean. In contrast a negative temperature gradient during the autumn is causing upwards refraction of the sound. The sound from wind turbines located at the sea is therefore season dependent. In analogy this season dependency could be seen in the forest, but to a much lower extension. Although the same effect could appear during sound pressure measurements of wind turbines close to lakes in forests.
The variation of attenuation between summer and winter for a stand of spruce and oak can be seen in Figure 16 below.

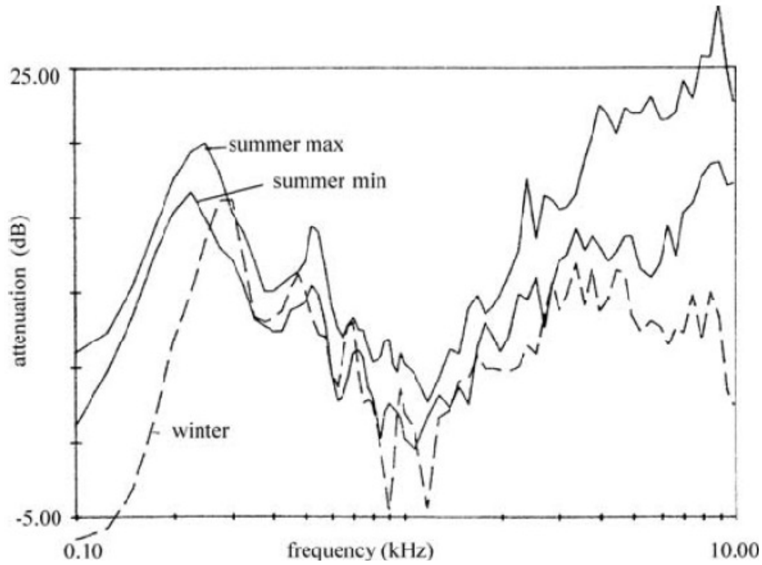


Figure 16. The variations in attenuation over frequency for a stand of spruce and oak trees, corresponding to a horizontal measurement range of 72m and a receiver height of 1.2m [33 s. 1838]

In Figure 16 at around 200Hz the curve of “summer max” has a peak, then a dip is occurring at around 1200Hz and thereafter the attenuation increases with increased frequency. The “Summer min”- curve follows the “Summer max” rather parallel, with the largest deviations at around 1kHz and from 4kHz and up. The “winter”- curve shows here the largest difference compared with the other curves. The first peak occurs slightly shifted up in frequency to about 300Hz. Then the curve dramatically decreases in several steps until it finally reaches almost -5dB attenuation at 900 and 1200Hz. Here the sound pressure level may be higher compared with the free field. At high frequencies the winter attenuation never reaches higher than 10 dB which is lower than both summer curves.
The reason for this is probably due to the difference in amount of leaves and vegetation in the forest between summer and winter.

3.2.3 Scattering effects (turbulence, horizontal, vertical)

Scattering is caused when the sound is reflected at a surface or when reaching turbulent air and hence the propagating direction changes randomly. The reflected sound interferes with direct sound or other reflections and can build a diffuse sound field.
If a sound source is put inside a forest the horizontal sound propagation will be affected by scattering from trunks. This horizontal scattering may theoretically be separated from the vertical scattering through the canopy layer, because of the differences in propagation direction. Within the horizontal scattering the sound is being reflected by the trunks, which have cylindrical shape, and extend the sound horizontally in the forest. The trunk scattering is mainly a phenomenon in mid frequency

region, i.e. the wavelength is approximate the same as trunk diameter. The effect caused by scattering is mainly attenuating, but the reverberation, turbulences or interference effects caused by scattering may increase the sound pressure level [20 s. 53]. The possible increase of sound in forests can be related to that the sound is trapped as reflections between the trunks. The trunks are rather hard compared with the porous ground, which will make reflections possible. Statistically the forest may be regarded as a room, i.e. treat it as a classical diffusion problem.

The attenuation by tree trunks increases linearly with increasing trunk diameter. It also increases with increased tree height. Trunk scattering reduces the ground effect, because it disturbs the coherence between direct and reflected waves. In favourable conditions the ground effect dip may therefore be reduced and the sound pressure level can be underestimated.

The vertical scattering is different from the horizontal scattering [20], in the sense of direction. The vertical scattering may involve the ground reflection, and it mostly addresses the mid-/high frequencies. The vertical scattering is affected by the canopy layer, where the sound is spread by vegetation. The vertical scattering depends mainly on the density of the canopy, in where scattering stems, branches, leafs and needles exists. A single leaf produces little scattering, but if the leaves are numerous, the acoustical properties are changed, and the waves arriving at any point may interfere constructively, increasing the sound pressure level. The forest can be divided into layers, all with unique, characteristics. The layered property of the forest create a "tube" or volume, between different surfaces which acts as wave guides, in where the sound waves are concentrated. In these regions and at these conditions (wind and temperature have great influence) a negative excess attenuation can occur for certain frequencies [20 s. 64].

From the experimental studies by [34 s. 70] it is suggested that the high levels in mid frequencies for different forest species work as a kind of amplifier. The frequency region may have evolutionary been started to used by animals because of its advantage in better propagation.

As [23 s. 202] describes, the energy transmitted through a canopy is scattered many times. The high probability of multiple scattering between leaves, the canopy can be represented by a single thin wall of unknown surface density. The attenuation through a solid thin wall can be described as following:

$$A_e = 20log(\pi s f/41.5) \quad s: density\ times\ the\ thickness\ of\ the\ wall \quad [kg/m^2]$$
$$f: frequency \quad [Hz]$$

It was shown that the atmospheric effect is very large compared with the scattering effect [32 s. 117]. An investigation of how the transmission loss (calculated by the GFPE-model by Swearingen) changes when adding parameters. At long distances the scattering effects have greater impact on the. See Figure 17 below:

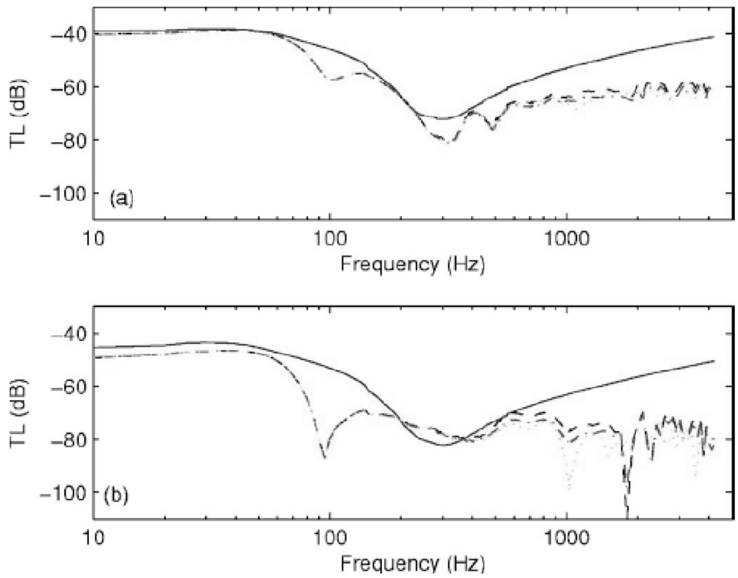


Figure 17. Figure from [32 s. 117]. The figure shows the TL=Transmission loss (dB) over frequency as following: "Cumulative contributions of components, upwind case. In each graph, (solid) is a homogeneous atmosphere with forest ground impedance. (dashed) adds the upwind forest profile, (dashed-dotted) adds the trunk scattering, (dotted) adds canopy scattering. The source to receiver to receiver distance is 174m in (a) and 315m in (b)"

In Figure 17 it can be seen that adding the upwind forest profile (i.e. including wind and temperature gradients which gives the efficient speed of sound profile with height) the transmission loss changes radically, generally for frequencies 80Hz and up. Adding the effects of scattering by trunk and canopy will change the TL almost equally but not as much as adding the upwind forest profile. Comparing the distances (comparing graph *a* with *b*) a difference between trunk and canopy scattering can be seen. The trunk scattering follows the upwind profile quite well, while the canopy scattering shows unique character at some frequencies, e.g. 1000Hz and 3500Hz.
Due to heavy wind the air flow over forests can have a turbulent character. This induces scattering effects when sounds are transmitted into a turbulent layer of air. In the case of upwards refraction, i.e. where a sound shadow after a distance may appear, the scattering of sound in the turbulent air in the atmosphere can reflect the sound to the shadow, hence make the sound shadow reduced. The predicted sound shadow may therefore underestimate the measured sound level.
Other phenomenon linked to this problem is that turbulences can cause higher sound power levels. In the report by the E.P.A. of Sweden [26 s. 24], it is described that wind turbines placed in a hilly terrain can emit higher sound power levels than open field, because of more turbulent and unbalanced air streaming towards the turbine. So here the importance of locating the wind turbine in an appropriate position can be seen, in order for the wind turbine to not emitting high sound power levels.

3.2.4 The ground effect and interference effects

Interference effects may occur when a direct sound wave interact with a reflected sound wave and form a merged sound wave, which can increase the sound (constructive) or decrease the sound (destructive). This interference may occur when the direct and reflected sound waves have good coherence, i.e. both have same phase relative to each other. So he reflected sound will be influenced both in amplitude and phase.
The ground in the forest consists of many different things, e.g. soil, rock or vegetation. The surface is irregular both in the sense of variations in terrain, but also smaller irregularities with regards to vegetation. These differences will cause a frequency dependency of the reflected sound.
The ground is an important contributor to the interference, especially at low frequencies. The low frequencies are not disturbed by the vegetations and irregularities to the same extension as higher frequencies. From studies by the Canadian researcher [35], the ground effects are less important at higher frequencies because of the loss of coherence due to scattering by turbulence, according to [19].

The probability for sound increase is different between different soil and ground conditions. For soft ground the sound can be more easily absorbed. For hard ground the sound will be reflected better and the sound level can be locally increased [20 s. 44]
Elizabeth Lindqvist presents in her report [36], that the sound field in large factories can notbe treated as diffuse because of the large distances between the walls. She states that the sound will attenuate with distance that differs from usual conditions inside rooms.
This can be understood when regarding figures in Table 6 below.

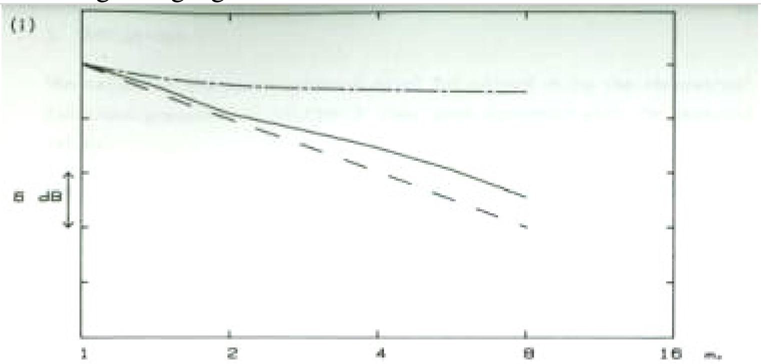
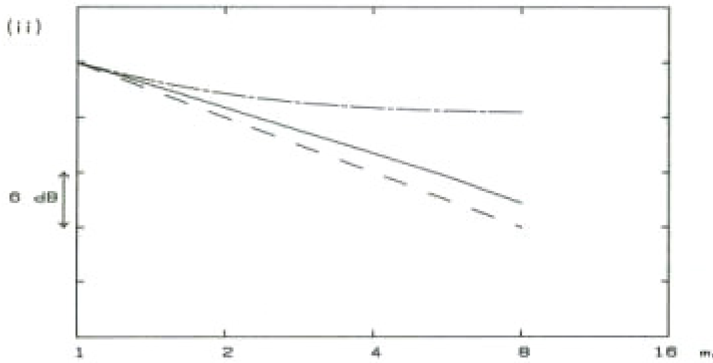
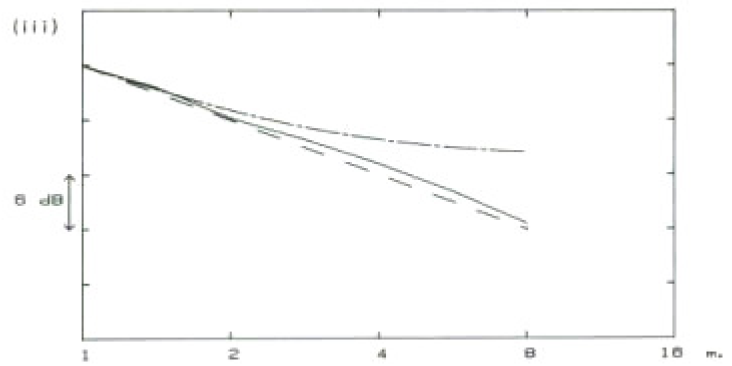
Absorbents on end walls	
Absorbents on end walls and ceiling	
Absorbents on all walls and ceiling	

Table 6. Figures from (Lindqvist, 1981 s. 33). The pictures show: Sound pressure level as a function of distance along the centre of the hall an omnidirectional source in the model hall according to the "Room equation" (dash-dotted), Model by Lindqvist (solid), and 6dB

Elizabeth Lindqvist refers to the "Room equation", with the following form [36 s. 28]***:***

$$L_p = L_W + 10\log\left(\frac{1}{4\pi r^2} + \frac{4(1-\alpha)}{A}\right)$$

L_P	=	sound pressure level
L_W	=	sound power level of the source
r	=	distance from the source
α	=	average absorption coefficient of the room
A	=	total absorption area

The curve from the room equation [36 s. 28] is first decaying due to the direct sound field but after a distance flattens out due to the reverberant sound field, i.e. the sound attenuates due to geometrical divergence close and then hardly no attenuation. Comparing this with the model developed by Lindqvist for large factories, one can see that the direct field continues to dominating and the sound attenuates with distance. Probably the same appearance as in large factories can be seen in the forests. Here the forest can be seen as a large “factory” with ceiling below canopy and scattering obstacles, i.e. machines, as trees, ground, stones or shrubs.
As described by Salomons the maximum level of a constructive interference is limited to +6dB unless the surface wave is not present [6 s. 26].

3.3 Discussion of hypothesis

In the Elforsk 09:22 the reasons for the unexpected high sound pressure levels are discussed. If the sound power level from the wind turbine would have been underestimated, this would give wrong reference when comparing with measurements. When the sound emission was determined the standard scheme in IEC61400 was followed. But the standard does not take attenuation due to air absorption, ground and scattering into account. The factor affecting the calculation of sound emission level which is indirectly discussed in Elforsk 09:22 is the attenuation of vegetation and scattering. The calculated level could be underestimated due attenuation of forest.
The background level measured during 9th April (see chapter 0) shows that the level in the forest varies a lot depending on wind and external sound sources, e.g. traffic, aircraft or animals. This implies that the measured sound pressure level of Elforsk 09:22 may be somewhat the same as the background level and the signal to noise ratio may be equal to one or even less than one, which may give inaccurate results.
If the reverberation should enhance the SPL this effect must be related to the amount of absorption existing in the forest. The backscattered sound must retain the energy from the direct sound in such extent that it can cause an increased level. A more likely case is that the backscattered energy is so weak due to surface absorption that it hardly is noticed, especially at a long distances. The decay with time can still increase with distance, but the level will become lower.
The temperature and wind causes refraction which refracts the sound. In the case of downwards refraction the sound is focused towards the ground and therefore increases the sound immission level at a receiver position compared with predictions. The typical meteorology of forests creates the typical wind and temperature variations with height in the forest. The focusing effect is most clearly at large distances, which make it possible for the two more distant cases of Elforsk, i.e. at distance 330m and 520m. The situations of refraction at these distances are investigated in chapter 6.1.2 together with a numerical model, i.e. CNPE-model. The advantage of predicting the sound immission taking meteorological effect into account is that wind and temperature is somewhat easy to measure. One needs a mast with two thermometers and a windspeed-meter. This is often measured at one position at a time and averaging over time, but when the sound immission is measured at different distances the meteorological conditions may vary from position to position and therefore give slightly inaccurate results. The fact that the meteorology varies with distance, height and time shows that the sound propagation is a complex problem, involving many factors.
Scattering effects can focus sounds after reflections from surfaces. This focusing causes a higher immission level than predictions. When regarding the horizontal scattering the tree trunks are the most important contributors. The importance of knowing the sound absorption properties of the trunk bark can be understood when estimating the scattering. For planted uniform forest, e.g. forests with majority of pine trees, the scattering may be estimated with average trunk diameter, average distance between trees and height of trees. This needs to be measured or investigated from place to place. In forests that contain a mixed population of trees, both deciduous and coniferous trees, estimating the scattering is much more difficult. The average trunk diameter has a bigger standard deviation, the absorption property varies and the amount of vegetation, which scatters and absorbs sounds, varies between the seasons. For mixed forest stand the prediction of scattering may therefore involve a larger content of errors, compared with uniform forests with one or two major species.

The ground effect may possible cause a constructive interference and increase the immission level of maximum 6dB. This effect occurs most at low frequencies and at low grazing angle, i.e. when the difference between the direct and reflected sound is small.
The coherent ground effect can be disturbed by scattering. It is quite easy to determine the flow resistivity (σ) of the ground and forest floors, following the method of Nordtest Acou 104 [37]. The method was used during measurements on the 9th of April, see more in chapter of 0. The flow resistivity (σ) is later used to calculate the ground impedance (Z) of the forest floor. The ground impedance is seldom determined for the whole range over which the measurements take place. Instead this estimated using average of at least two different positions. The procedure can cause problems when the ground impedance of the forest floor can vary from place to place.

4 Measurements of sound in forests

In order to understand more about what possible caused the difference between the measured and predicted levels for Elforsk 09:22, I have visited and investigated different forest in the surroundings of Göteborg. The purpose was not to simulate the sound from a wind turbine, but rather to understand more about the phenomenon influencing the sound propagation in forests. The measurements have been performed at two locations, the first at Fjällhult during 9th Dec 2009, north of Lerum, and the second at Holmevatten, north of Kungälv close to the nature reserve of Svartedalen during the 19th of March and 9th and 13th of April.
Another purpose of the measurements was also to compare it with predictions, making better conditions for verifying or developing a calculation model.

4.1 Measurements the 9th Dec 2009, at Fjällhult

Wednesday the 9th of Dec 2009 measurement of the reverberation time and temperature gradients in a forest were made. The measurements were made outside Lerum in a place called Fjällhult. Equipment was borrowed from ÅF-Ingemansson in Göteborg and was transported by car to Fjällhult
In order to measure the reverberation time, a reverberant sound field needs to be created. This can be made with a powerful loudspeaker. There are a lot of objects that can absorb sound inside the forest, which means that it will need more sound energy to excite a reverberant sound field with sufficient level. This give higher demands on the loudspeaker. Taking this into account a big loudspeaker from ÅF-Ingemansson, able to create high levels also at low frequencies, was chosen.
During measurements of reverberation time, a signal during some seconds excited the reverberant sound field. When there was enough reverberation the signal was turned off distinctly, making it possible to measure the time of 60dB attenuation. The signal is provided with the B&K 22 60, which includes an application performing the reverberation measurement. The microphone is connected directly onto the investigator. Equipment used:

Object	*Model*	*Serial no*	*Intern note*
Microphone, Electric Con	Brüel & Kjaer 4189	2294499	-
Acoustic analyser	Brüel & Kjaer, 2260	2290678	AL 124
Calibrator	Brüel & Kjaer, 4231	2292469	KU 75
Loudspeaker	Gallien-Krueger 1200CEB	79939	FK021
Thermo graphical camera	FLIR- i series	278006443	GBG-12

Table 7. Equipment used during measurement 9th of Dec

4.1.1 About the measurements

The area of Fjällhult was chosen because of its seclusion, the property is located alone in the woods away from noise sources, such as highway, industries and airport, but it was also chosen because there was access to electric power to the loudspeaker. The forest was fairly hilly with some variations in altitude.
A suitable placement in the forest for the speaker was assumed to be where it could create as good diffuse sound field as possible. The Investigator (B&K2260) together with the microphone was placed some distance from the loudspeaker and the distance was measured to 10.4 m. The microphone together with the B&K2260 was calibrated with the calibrator to 93.9dB at 1kHz, which was considered acceptable. A pre-programmed reverberation application was carried out by B&K2260. The application produced a white noise at high level for 2 seconds, then the signal was cut-off very quickly, and the reverberation time was measured by the microphone. The data was stored in the memory of B&K2260.
During the second measurement the volume on the loudspeaker was increased and reverberation measurements were carried out again. The measurement of the reverberation time was repeated for six different microphone positions. For each position two measurements with different speaker volumes. Thus, twelve measurements were carried out with six different microphone positions for the loudspeaker position no1. Then the loudspeaker was moved and the twelve new measurements were carried out at the same six microphone positions.

The weather at occasion of measurement was just above zero degrees. At 6 AM the temperature was 2 ^{o}C, at noon, i.e. 12 AM the temperature hade increased to 3.5 ^{o}C and at the end of the day around 6 PM the temperature had decreased to 2.5 ^{o}C. There was no precipitation that day, but the ground was moist and wet. The sky was misty and cloudy; no sun was seen during measurements. Just before sunset the sun appeared at the horizon.
The properties of the forest were investigated. The trunk perimeter was measured with measuring tape, the area of the measured forest was estimated and the number of trees was calculated. The number of trees was 94, the area of measured forest was 1340m^2 and the mean trunk diameter was 0.25m. That gave a tree density of an average distance between the trees of 3.77 m, according to this formula

$$d_m = \sqrt{\frac{A}{n_{trunk}}}$$

where d_m = mean distance between trees, A = forest area, n_{trunk} = number of trees. The average height of trees was estimated to 18m.
The results from measurements are shown in the following chapter.

4.1.2 Results from measurements of reverberation in Fjällhult

From the measurements of reverberation in Fjällhult the 9th of Dec the quality of the results varied.
Some peculiar measurements had values far above the mean value, with extremely high RT over 10sec. The variation indicates that some of the measurement may not have been performed correctly. The erroneous can be related to many things, e.g. equipment, handling or treatment of data.
In order to get a better perspective of the measurements, the most sever peaks have been removed and the cropped result is shown in Figure 18 below. The mean value is shown as a thick curve. The chosen results are from measurements on position no. 5, 6, 11, 14, 15 and 23. These all belongs to positions closest to the loudspeaker. The distance to source were: pos 5,6 = 9m, pos 11 = 7m, pos 14 = 9.2mm, pos 15 = 10.5m and pos 23 = 10.2m.

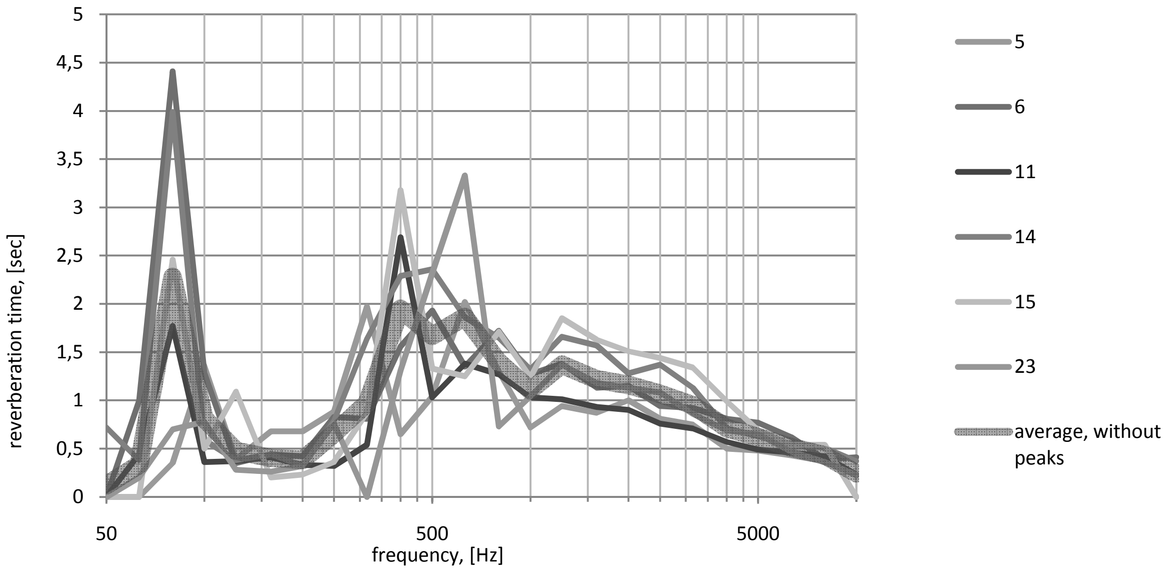


Figure 18. Measured RT without peculiar peaks

Here it is possible to see that the maximal reverberation time is around an interval at lower frequencies, around 63-80Hz. In this interval the mean values of reverberation time can be seen in Table 8 below:

Frequency (Hz)	***50***	***63***	***80***	***100***
Reverberation time, T_{60} (sec)	*0,12*	*0,34*	***2,28***	*0,81*

Table 8. RT mean value, 50-100 Hz

According to Table 8 there can be noted a significantly peak at 80 Hz. At this frequency the wavelength is about 4.3 m. Why this frequency is not absorbed in the same extent as other frequencies is not yet fully understood.
After a dip in RT the values start to rise again at higher frequencies. The RT values from 250-500 Hz are described in Table 9 below:

Frequency (Hz)	***250***	***315***	***400***	***500***
Reverberation time, T_{60} (sec)	*0,66*	*0,97*	*1,95*	*1,67*

Table 9. RT mean value, 250-500 Hz

Above 500 Hz the general evolution is declining, some variations exist, but the overall picture is that the reverberation time decreases with frequency.

4.1.3 Reasons to the character of reverberation time

Probably there are many reasons for the character of the reverberation time. According to the Sabine's formula the reverberation time is directly dependent on the amount of absorption, i.e. long reverberation is due to little absorption [31]. If this concept would be used for characterization of results in Figure 18 the frequencies containing highest values of reverberation also contains the smallest amount of absorption. This means that the sound has been absorbed as most in frequencies 125-315Hz but also to a great extent at high frequencies. At very low frequencies (<100 Hz) the sound treats the forest as being transparent and the reverberation is long. Vegetation, trees and ground absorb sound from the loudspeaker and decrease the reverberation. Also the long wavelengths of low frequencies generally demands large dimensions of the absorbing surfaces. But this does not concur with the results in Figure 18, where there must have been some measurement error. This could be caused by that the loudspeaker lacked the ability to excite the sufficient reverberation at low frequencies, which also resulted that the reverberation could not be measured and become RT=0 sec.
According to Fricke [38], the mid frequencies (250-1000Hz) are more sensitive to scattering. Fricke shows that sometimes an increased absorption give slower attenuation, hence giving long reverberation time despite much absorption. According to Bullen & Fricke [29], it is not probable that this interference appear a distance inside the forest, due to that the sound is assumed to be received from a random direction.
In Figure 18 there are very high levels at around 80 Hz. The measurements giving these high levels are no 6 and no14 with RT:s of 4.41 respectively 3.99 seconds. Measurement no 6 correspond to a distance of 9m from the loudspeaker and measurement no14 correspond to a distance of 7m. These two microphone positions belong to the positions closest to the loudspeaker.
In Figure 19 and Figure 20 the attenuation of the sound pressure level over time for positions no6 and no14 are shown. In both these figures the attenuation drops dramatically around 0.6-1 seconds. Around 1.1 seconds a small peak can be seen. The peak can belong to noise in the background and therefore could have affected the determination of the reverberation to be longer than normally.
However, still it can be difficult to interpret results of reverberation time measured in forests. This is due to that the curve does not need to be linear, instead it can have unknown decay evolution. The physical reverberation progress in forest might not be correctly described using the usual T60 (or T20 or other RT-time basis).

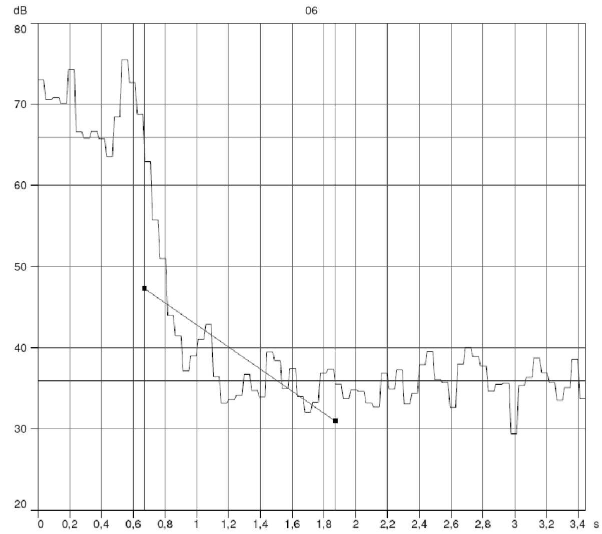


Figure 19. Attenuation over time, measurement no 6, 80 Hz

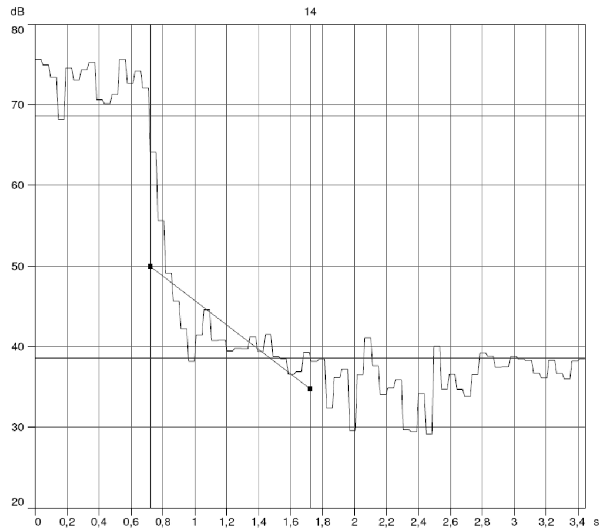


Figure 20. Attenuation over time, measurement no 14, 80 Hz

As mentioned before, the ability of the loudspeaker to excite the reverberation sound field at low frequencies may not be sufficiently. The frequency response of loudspeakers is somewhat proportional with frequency at low frequencies. Theoretically the reverberation time should be long, because of less absorption ability at these frequencies. This was predicted by the investigator, B&K 2260, see Figure 21 below!

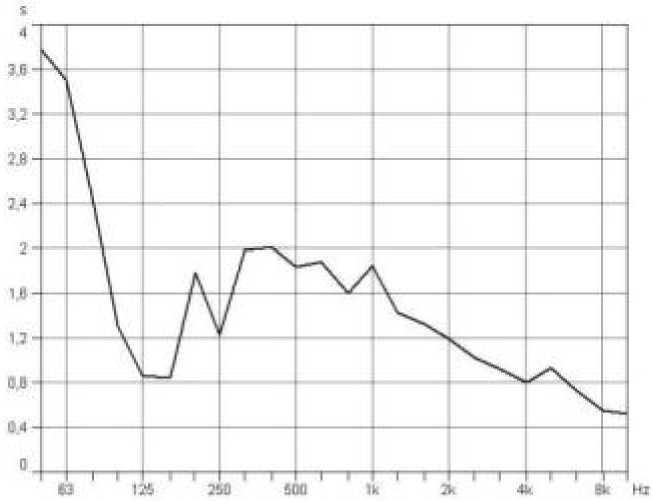


Figure 21. Average RT, obtained from B&K Investigator 2260

In Figure 21 the same appearance as Figure 18 can be seen, except for low frequencies. Comparing the figures one can see that in Figure 21 very long RT of around 3.6 seconds at 63 Hz have been obtained, but in Figure 18 the RT is around 0.3 seconds at the same frequency.
It would be interesting to measure the reverberation time at a location or occasion where it is possible to measure an area with and without the forest.
During the measurements the meteorological conditions may have affected the reverberation time.

4.1.4 Measurements of the surface temperature gradient

At the same occasion when the reverberation was measured the surface temperature with height was also measured. The temperature was measured with the help of a Thermo Camera, model FLIR i-serie. The camera made it possible to measure the surface temperature with height under the canopy inside

the forest. The error margin of the camera is quite large +/- 2 ^oC, but it was assumed that tendencies of the temperature differences could be discovered.
Figure 22 shows the measured trees in an ordinary photo and Figure 23 shows a thermo graphical picture with temperature shown at points on the trunk.

Figure 22. Ordinary photo of trees, trunks

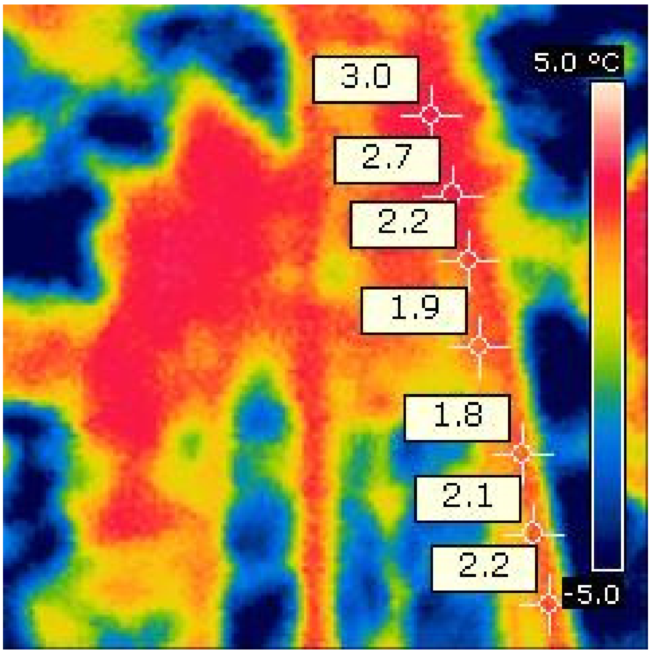


Figure 23. Thermo picture.
Temperature at points on the trunk

The thermo picture shows the point temperature along the trunk of the tree. Starting from the ground the temperature varies from 2.2 to 3.0 ^oC. The lowest temperature can be found a couple of meters up along the trunk; here the temperature was 1.8 ^oC. The highest temperature can be found in the canopy, here the temperature was 3.0^oC. The overall view of this section may show positive temperature gradient, which causes a downward refraction.
Similar tendency can be found in Figure 24 and Figure 25where the warmest section is located on the ground close to the foot of the tree and the coolest is some distance up along the trunk.

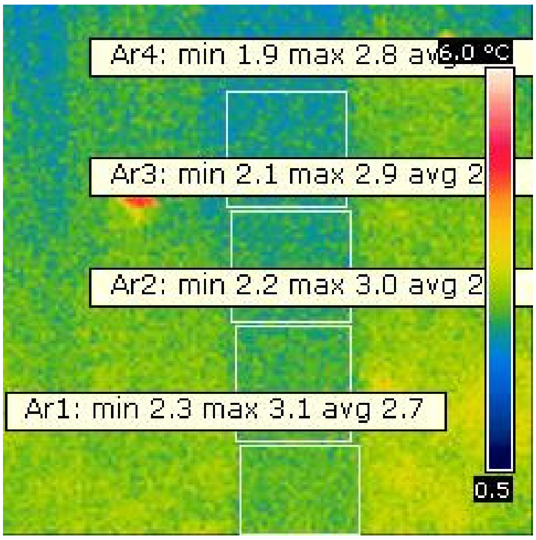


Figure 24. Area temperature on the trunk close to the ground

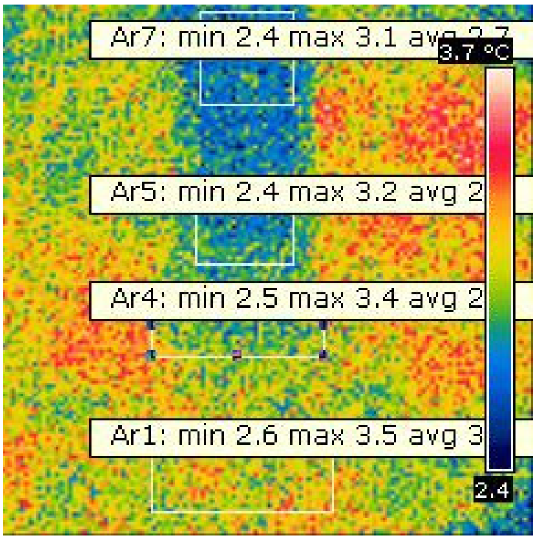


Figure 25. Area temperature at the foot of the tree

4.1.5 Conclusion from the thermo graphical pictures

It is obvious that the temperature varies with height in the forest. At a first glimpse it seems to be probable that the temperature increases with height around the tree, but close to the ground it is often higher temperature than at a small distance up along the trunk. Therefore it seems that the lowest temperatures along the trunk can be found some meter up. The highest temperature can be found in the canopy, but relatively high temperatures are found at ground level.
The temperature measurements were performed a cloudy day. A day with a lot of sunshine should possible have greater influence on the temperature variations. Measurements during such day would possible show tendencies of temperature gradient.

4.2 Measurements the 19th Mar 2010, at Holmevatten

The measurements of a forest were performed the 19th March, 2010. The measuring site was located close to the dwelling of Holmevatten, Romelanda in the municipality of Kungälv.
The forest was chosen because of its remote location, without any disturbing contributions from other external sound sources. The weather condition was not optimal. The snow depth was 70cm so it was decided not to perform all measurements, e.g. wind and temperature gradients, accurate flow resistivity of the ground. The only measurement that was performed was the reverberation for different distances. Equipments used were:

Object	*Model*	*Serial no*	*Internal*
Analyser	Norsonic 140		AL 167
Analyser	Norsonic 140	1402896	AL 172
Microphone	Norsonic 1209	12323	AL 172
Revolver	Arminius HW15	1157169	R4

Table 10. Equipment during measurements 19th March

First source position 1 was used and the receiver were placed in a dense part of the forest, see Figure 26. The distance was 30m respectively 35m between source and receiver. Here totally four measurements of the reverberation time was performed, i.e. two measurements for each position.
Secondly and later the receiver and source were moved to a sparse part forest, see Figure 27. Here the measured distances were 10m, 50m and 100m, also here two measurements for each position were performed.

Figure 26. Dense forest

Figure 27. Sparse forest

For every measurement the revolver were fired and the analyser registered the reverberation. The analyser performed calculation of reverberation time and the results can be understood in coming part after this.

4.2.1 Reverberation with distance

The reverberation with distance was measured and the results can be seen in Figure 28 below.

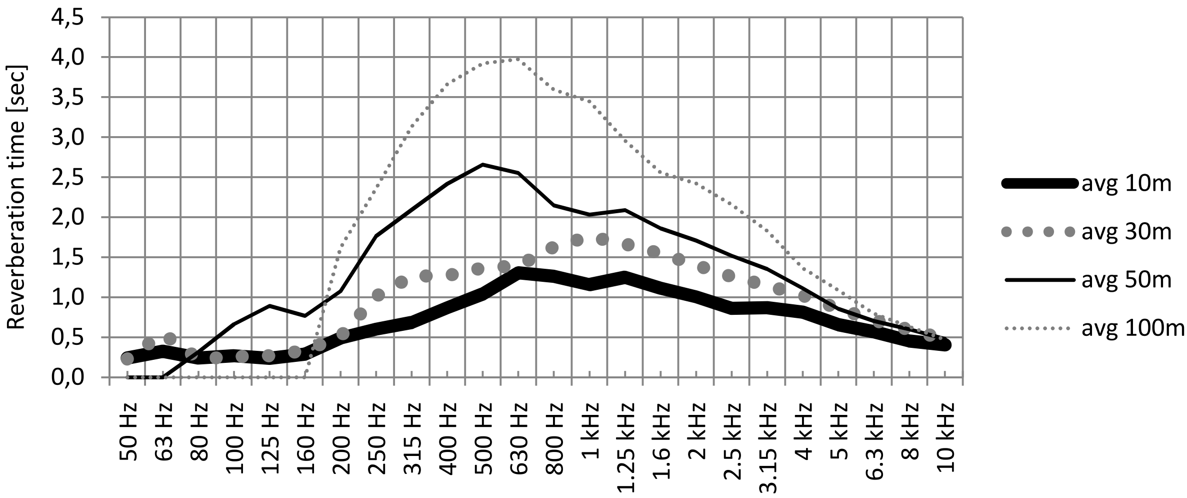


Figure 28. Average reverberation time (T_{30}) for different distances

In Figure 28 it can be seen how the RT have a peak at around 500 and 630 Hz for the case of 100m distance. Here the RT reaches a value of almost 4 seconds. Comparing the different distances it can be seen that for frequencies lower than 500 Hz, increased distance also give increased RT. And for frequencies higher than 500 Hz, decreasing almost linearly (in this logarithmic plot) with increased frequency, the longest distance decrease fastest. It should be noted again that the high levels of snow surely have an influence of the results the results may be compared to measurements at the same positions during periods without snow.

4.3 Measurements 9th April 2010 at Holmevatten

On the 9th of April measurements were performed again at Holmevatten. At this time the snow had gone and it was possible to walk and analyze the forest. This was measured: average trunk diameter, average distance among trees, ground impedance of forest and lawn field ground, the reverberation time and SPL with distance in forest and over the lawn field, wind and temperature over height by means of measuring in a mast, temperature at tree and ground surfaces (i.e. with the help of an IR-camera) and relative humidity of the ambient air.

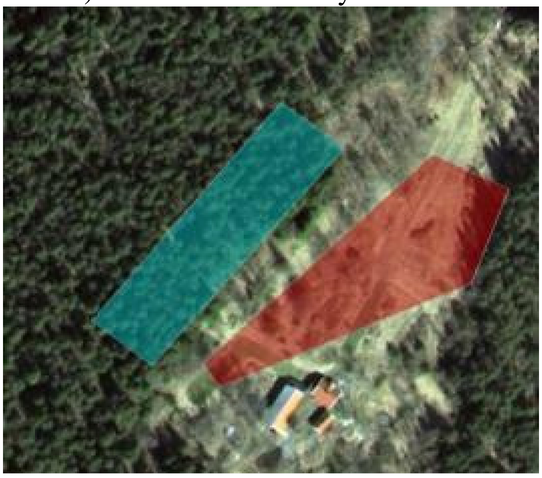


Figure 29. Measured area in forest (green) and lawn field (red), the lawn was regarded as open

4.3.1 General conditions

The measured forest area was assumed to have an area of 150x35m, i.e. approx. 0.5 hectare. In this area the average trunk diameter was determined through walking along the propagation path and measuring the circumference of each the tree. This means that not all trees were measured but after visibly inspection where I found that the tree diameter did not vary much, not measuring all trees saved a lot of time and increased the efficiency of the work. Totally 60 trees was measured and the average diameter was determined to 23cm. After this the number of trees was noted and resulted in 320 trees within the chosen area. The average distance between trees was calculated to 3.8m.
The ground was cool and wet. It consisted mainly of old needles, moss and sprigs from trees and shrubberies. The ground property varied in the forest and at some other places the ground was covered by a lot of small shrubberies. At the measured forest area several big trees have fallen, probably due to recent year storms. These wind traps or windfalls may influence the sound propagation, but is neglected in the coming result and discussion.
The background noise was in the morning a distant highway, probably E45, but after some hours the noise disappeared. Many small birds beeped and the forest was about to wake up from its winter sleep. Later the only background noise was the wind from the trees and an airplane at some occasions.
The equipment used is listed in Table 11 below:

Object	***Model***	***Serial no***	***Internal***
Analyser	Norsonic 140	1402896	AL 172
Microphone	Norsonic 1209	12323	AL 172
Analyser	Norsonic 118	31378	AL 147
Microphone	Norsonic 1206	30420	AL 147
Revolver	Arminius HW15	1157169	R4
Humidity and temp measure	Vaisala HMI31	34636	Ö9
Data logger, Campbell- Scientific	CR850	4602	Ö193
Thermometer	R.M. Young, USA	-	Ö193
Windspeed meter	Windsonic, option 1	1405-PK-021	Ö193
Loudspeaker	Gallien-Krueger 1200CEB	79939	FK021
Thermo graphical camera	FLIR- i series	278006443	GBG-12
Stands	-	-	-

Table 11. Equipment used during measurement 9th April

4.3.2 Measurement of ground impedance

The ground impedance was measured according to a method presented in [37]. Two microphones at 20cm resp. 50cm height registered the SPL from a known source with a white noise signal input, see Figure 30. This was measured for two different forest ground types.

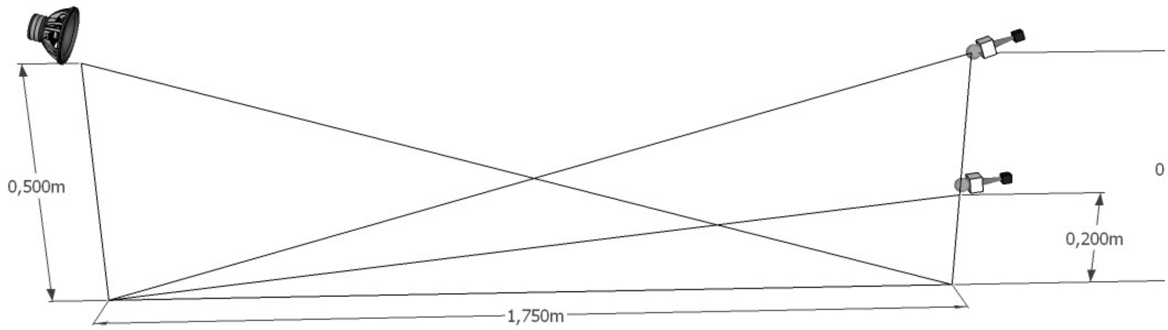


Figure 30. Recommended setup from [37]

In the Nordtest method it is assumed that the ground is flat. In reality the forest floor varies in height and shape, so it can be difficult to determine the level of the ground. The actual configurations can be seen in Figure 31 and Figure 32. The results were evaluated in accordance to the Nordtest method.

Figure 31. Ground impedance forest 1

Figure 32. Ground impedance forest 2

A third setup for measuring the ground impedance was performed for the lawn during open field measurements.

The reverberation time was measured both with gunshot and loudspeaker (13^{th} april) for different distances, i.e. 12m, 50m, 100m and 150m. The same time as the reverberation time was measured, the SPL for the mentioned distances was also measured.
The wind was measured at different height, i.e. moving the sensor to 4, 6, 8, 10 and 14m height.
The temperature was measured for 2m and 10m height.
To verify the ability of the IR-camera it was measured at different heights. The relative humidity was measured at different times.

Time	***RH [%]***	***Temperature [^{o}C]***
11:51	51	9.8
13:00	44	13
15:36	48	10.7

Table 12. Some climate data measured 9th April

Results from ground impedance measurements

The average (ΔL_M) of the level differences between the measured level for microphones at 50 and 20cm for each frequency has been calculated and the results can be seen in Figure 33.
Both forest1 and lawn field has a major dip at 400 Hz and a peak at 630 forest1 and at 800 Hz open field. The forest2 shows a different appearance with no dip at 400Hz and a much lower top at 500 and 630 Hz.

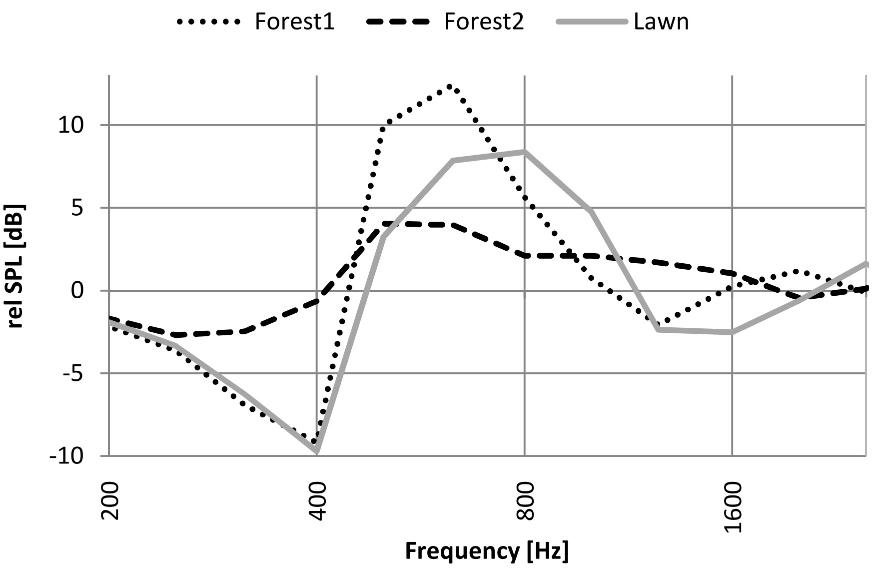


Figure 33. The average of level differences over frequency, measured according to Nordtest Acou 104

The flow resistivity can be obtained using the one parameter approach which calculates the minimum error from precalculated level differences for difference classes, see table B2 [37 s. 6].
The procedure is to calculate the minimum error from pre-calculated level differences ΔL_C, given in Table B.1 to Table B.8 in Annex B in Nordtest. Table B.1 gives the ΔL_C for temperatures between +5 to +30°C and table B2 from -20 to +5°C. The minimum error is not allowed to exceed 15 dB.
First table B1 was used because it fulfilled the proper temperature. The minimum error was determined to 40.7 dB for forest 1, 16.4 dB for forest 2 and 28.8 dB which definitely exceeded the condition of one parameter model of 15dB. Using table B2 instead the errors become less but still not satisfyingly. Because of that none of the models satisfied the criterion, “the modified one-parameter model with top layer of known thickness” was used. The top layer of the forest floor had a thickness of approximately 10cm. The values of Table B.7 made the forest 2 to be slightly lower than 15dB. The results from minimum error calculations from all tables with pre-calculated values are shown in Table 13 shown below:

	Forest 1 [dB]	σ [kNs/m^4]	Forest 2 [dB]	σ [kNs/m^4]	Lawn [dB]	σ [kNs/m^4]
Table B1	40.7	25	16.4	25	28.8	40
Table B2	38.3	25	**15.0**	25	25.8	40
Table B.3	26.0	25	23.0	40	22.6	40
Table B.4	42.6	25	15.8	25	31.4	*25*
Table B.5	41.0	25	16.7	25	28.7	40
Table B.6	27.7	25	22.7	40	21.5	40
Table B.7	40.3	*40*	**14.9**	25	26.8	40
Table B.8	38.3	25	15.6	25	25.8	40

Table 13. Results of minimum error calculation from [37].

Conclusion from the minimum error calculation is that only one satisfies the criterion of 15dB minimum error. The prediction of the flow resistivity of the forest may therefore not be completely accurate.

The resulting flow resistivity class and ground impedance at 1000 Hz is judged to σ_{forest} = 25 [kNs/m4] and σ_{lawn} = 40 [kNs/m4].

The sound pressure level relative the free field for different flow resistivities are plotted in Figure 34. The distance, d, was chosen to 1.75m, and the heights vary between 0.5 and 0.2m for respectively flow resistivity.

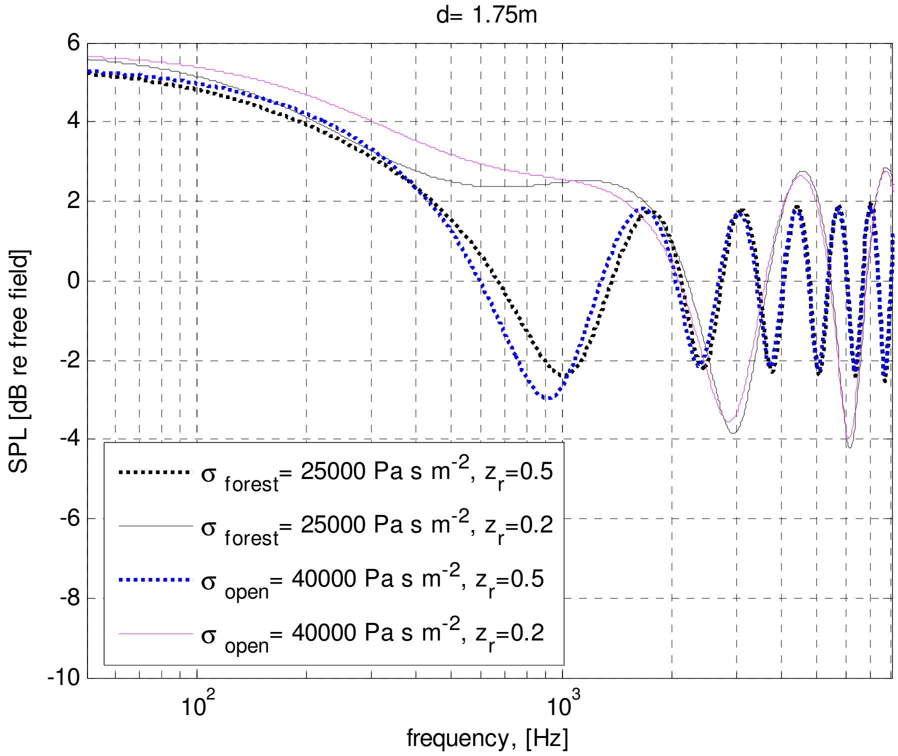


Figure 34. SPL re free field for calculated flow resistivities, forest and open field (lawn)

Some conclusion from the determination of ground impedance is that it may be difficult to accurate determining the flow resistivity of a forest floor. It is possible that soft grounds may cause greater deviations from the model suggested in Nordtest. The flow resistivity is used to calculate the ground impedance and may therefore be of great importance.

4.3.3 Measurements of the reverberation

The reverberation was measured with the acoustic instrument Norsonic 118 respectively 140. On Fri. the 9th the RT was measured using a gunshot as source and using a loudspeaker on the 13th. The RT was measured at 12m, 50m 100m and 150m distance in forest respectively over lawn, regarded as an open field. The measurement position at distance of 150m inside the forest was placed at the border of the forest, i.e. half in forest half at a more open part of the forest, which affected the result.

Results of RT

The results can be seen in Figure 35 to Figure 38, but it does not show a clear solution. The different evaluation time of T20 and T30 can clearly be seen, because of the changes in appearance. The plots show the average of measurement with gunshot and loudspeaker. Thus at low frequencies (50-200Hz) the loudspeaker would have greater impact and for higher frequencies (500Hz and up) the results is mainly caused by the gunshot. An alternative way of presenting the data would have to cut the result at, e.g. 400 Hz, letting the loudspeaker giving results for low frequencies and gunshot for high frequencies.

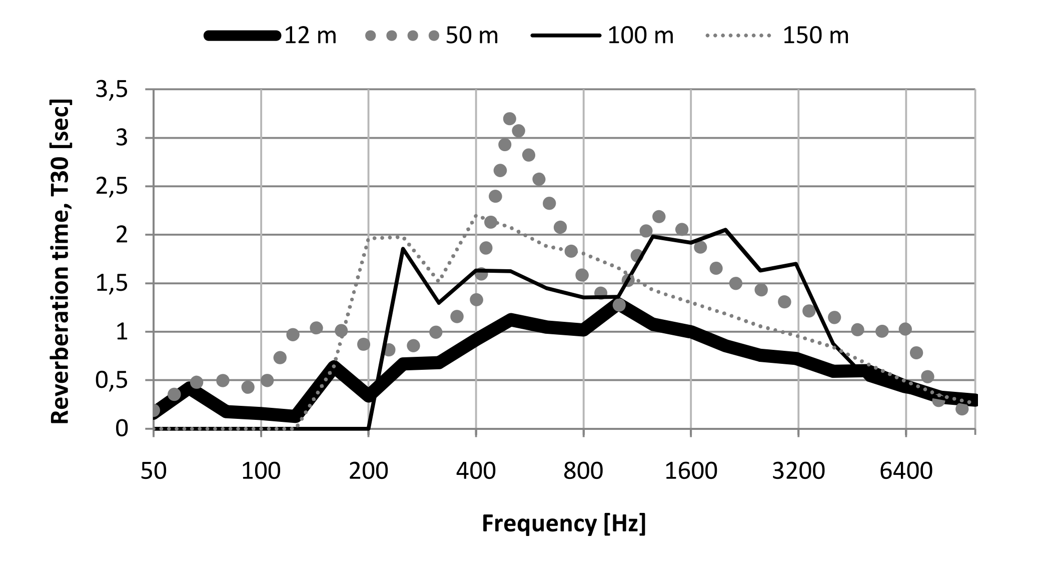


Figure 35. RT (T30) over frequency for different distances in forest

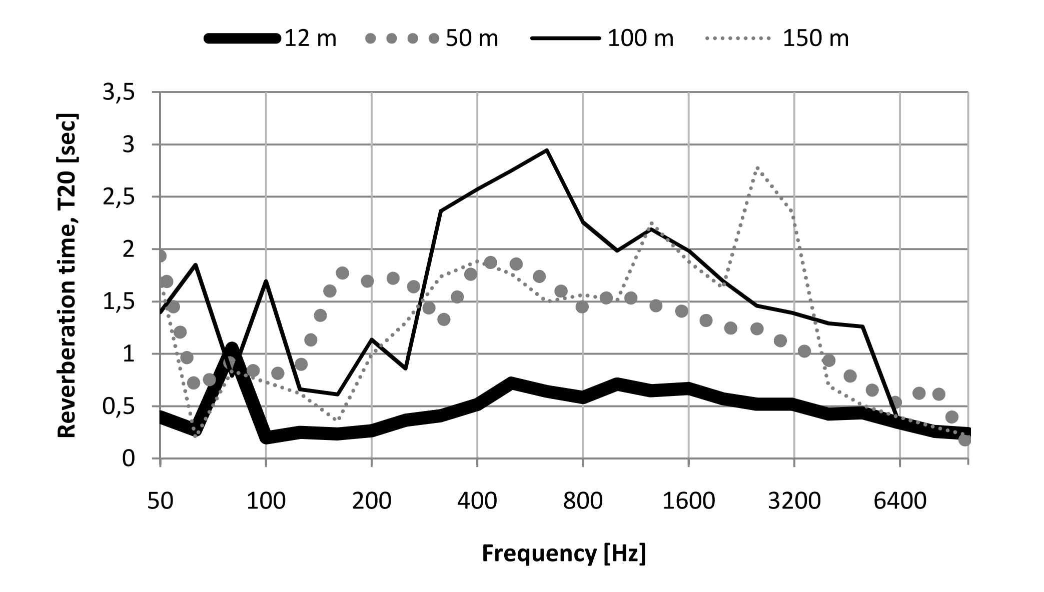


Figure 36. RT (T20) over frequency for different distances in forest

In Figure 35 the changes in RT (T30) between the distances over frequency is rather small, but the differences can be seen. Some major deviations can also be seen, e.g. peak at 50m at 500Hz and 150m between 200-400Hz.

In Figure 36 the RT of T20 is shown. Here the deviations between the distances may be more clearly. For low frequencies the behaviour is unclear. A peak for both 12m and 150m at 80Hz, but for 100m the peak is at 63Hz. At frequencies 315 and up the RT is higher for longer distance, except the case of 150m. This behaviour continues and the RT decay with increased frequency. The case of 150m distance is probably caused by its environment, being partly in forest and partly at a more open part of the forest.

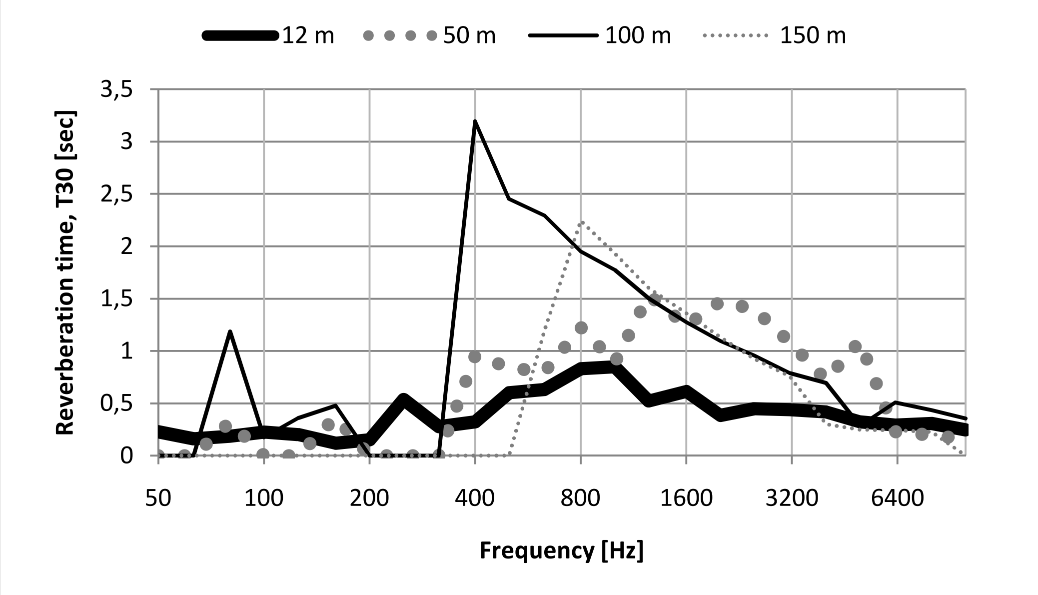


Figure 37. RT (T30) over frequency for different distances over lawn (open field)

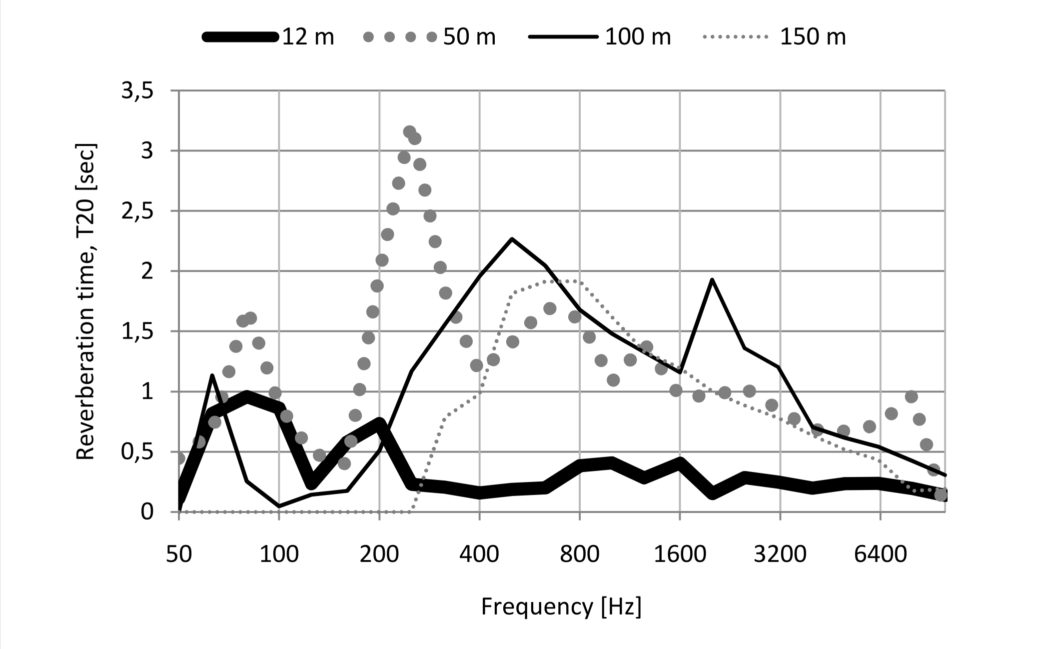


Figure 38. RT (T20) over frequency for different distances over lawn (open field)

In Figure 37 the RT (T30) is being low or not available at low frequencies, but for mid and high frequencies there is values registered. A small peak at 80Hz for 100m case can be seen. At 400Hz the 100m case gives values and very high, a peak of 3sec for the case of lawn! Some wrong settings, bad S/N- ratio or malfunctioning of the equipment is probably the main cause of this long RT. At 800Hz the case of 150m gives values of 2.2sec. The 150m case meets the 100m case and decays quite parallel with increase frequency.
In Figure 38 the RT (T20) can be seen. Compared with Figure 37 the RT at low frequencies are more represented. At 63 and 80Hz the cases of 12, 50 and 100m all have 1sec or more in RT, the 150m case gave no values, i.e. zero RT. A significant peak at 250Hz can be seen for the 50m case, which as the previous picture probably is represented by an error. All cases, except 12m, follow rather the same decay in RT from 500Hz and up.

Discussion of RT

The gunshots create higher levels but not so much low frequencies. The loudspeaker does create high levels but not as high as the gunshot, so with distance the RT is difficult to measure. But at close distances the loudspeaker gives better low frequency results.
The RT over lawn field is very discussable. Over a big lawn there should not be any RT, nothing would reflect the sound. Using the loudspeaker as source, gave no data to investigate. Here the RT is probably cause by echoes from surrounding forest borders, seen in Figure 29 right end of picture.
Other background noise, e.g. birds singing and beeping, can cause the RT, especially at high frequencies, to be shifted to a higher value. Some peaks at around 1600-5000Hz can be caused by birds, which at the occasion were really active.

4.3.4 Sound pressure level and excess attenuation with distance

The sound pressure level for different distances was measured. The distances were the same as the ones for measurements of RT, i.e. 12, 50, 100 and 150m. The SPL was measured during a 20sec long period, during the same time as the RT measurements. The source was the loudspeaker with same level for all measurements.
The background level was measured afterwards, which was assumed to be the same over time and for different positions in the forest and over the lawn. In order to find the level independent of the background noise, the background noise data was used to correct the level measured at different distances. Sometimes the background level was higher than the measured, especially at long distances over lawn. The measured background noise was much lower than the measured background noise over the lawn. The most probable reason for this is due to variations in background noise level during different times. During the measurements of background noise level over lawn there was heavy winds, causing the trees tops to generate wind blowing sounds. Anyhow, this problem means that the values of corrected levels over lawn must be neglected. Instead the values not corrected for background noise is used. However, the background noise influenced the level to a small extent.
The uncorrected results can be seen in Figure 39 to Figure 41 below:

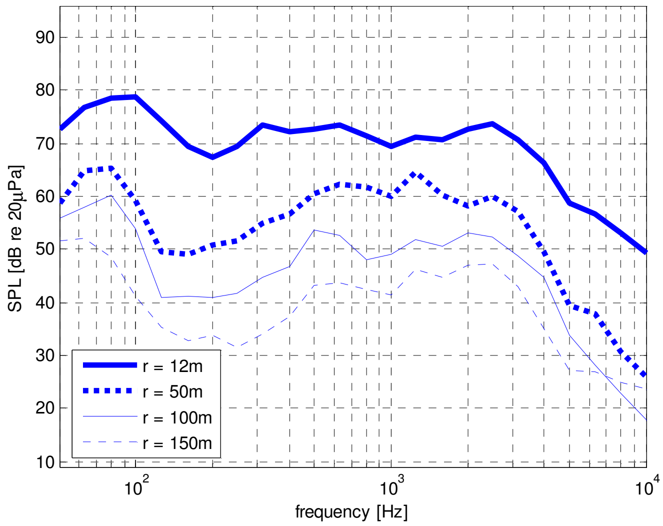


Figure 39. Measured sound pressure level in forest, not corrected for background noise

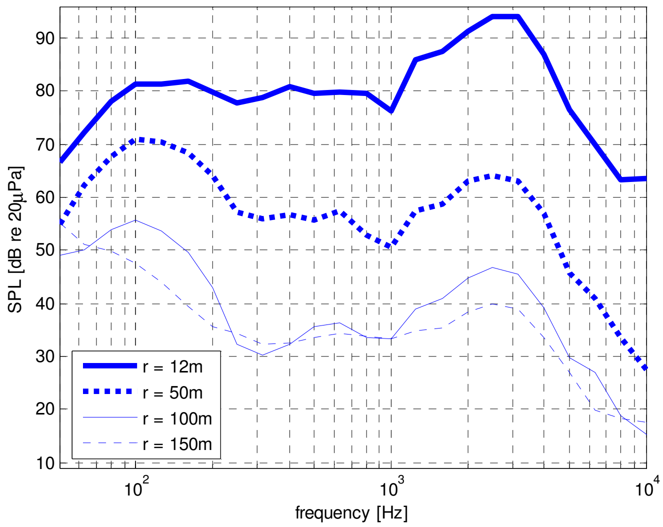


Figure 40. Sound pressure level over lawn field, not corrected for background noise

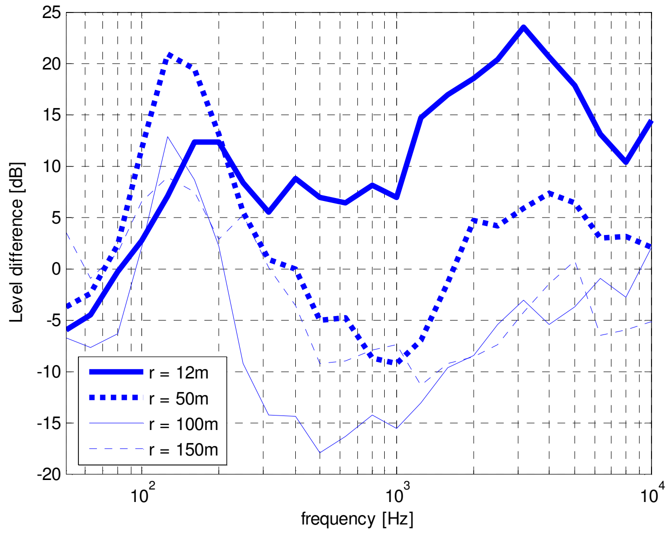


Figure 41. Level difference between lawn and forest for different distances

In Figure 39 the highest levels is obtained at 12m distance. Here the sound is almost unaffected and a typical loudspeaker frequency response can be seen. When the distance increases the level decreases, except for very low frequencies and some high frequencies in the case of 150m. This may be caused by background noise, since the loudspeaker lacking the power creates high levels at these frequencies. Instead the low frequencies may be caused by weather which makes the sound pressure to fluctuate.
In Figure 40 the levels are generally higher compared with Figure 39, at least for short distance, which is expected. In the case of 12m there is a peak at around 4000Hz. This shows that the open field (case of lawn) lacks the absorbing ability of forest, which is to absorb sounds containing high frequencies, i.e. branches, needles and ground surface. Looking at the long range cases 100m and 150m in Figure 40 the levels starts quite high, 55- 65dB at low frequencies and decrease down to around 35 dB at 200Hz. At high frequencies there is a dip, from 2500Hz with a level of 41 dB to 5000Hz with a level of 25 dB.
In figure Figure 41 the level difference is shown. It has been calculated using:

$$L_{p,diff\_lawn\_forest} = L_{p,lawn} - L_{p,forest} \qquad \text{[dB]}$$

When regarding the level difference in Figure 41 one sees that the levels are positive for very low frequencies around 20-40Hz, i.e. the levels in the forest are lower than the case of lawn. For case of 50m negative values occurs 400-1600Hz, case 100m at 250Hz and up, and case of 150m from source at 315Hz and up. A peak in the level difference occurs between 80-200Hz where all distances have positive values; the highest has case 50m with 21dB at 125Hz.
Finally, when comparing the levels measured outdoor it can be convenient to compare the measured levels with hypothetical values of the free field, expressed as the excess attenuation, see Figure 42 and Figure 43 below:

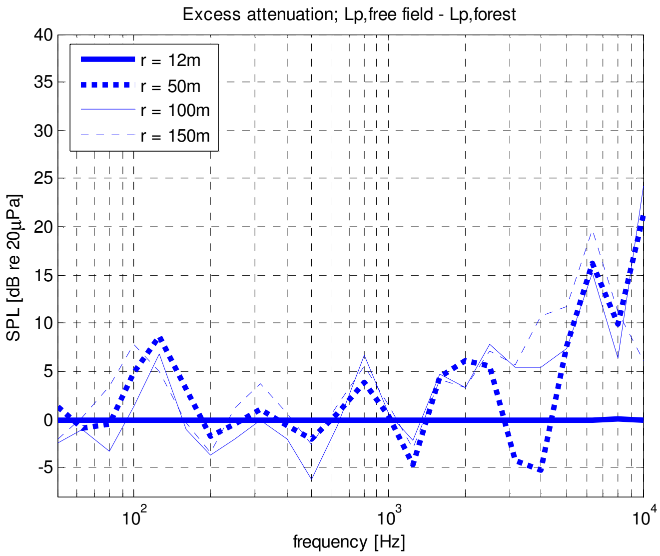


Figure 42. The excess attenuation of forest

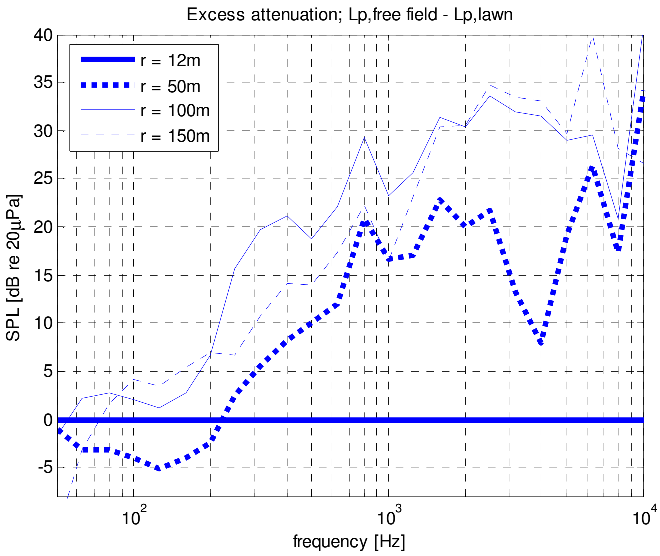


Figure 43. The excess attenuation of lawn

Here free field is a hypothetical level, which is calculated for the situation including the ground surface conditions. Therefore the excess attenuation can be expressed as following:

$$A_{excess forest} = L_{p,freefield} - L_{p,forest} \qquad \text{[dB]}$$

$$A_{excess lawn} = L_{p,freefield} - L_{p,lawn} \qquad \text{[dB]}$$

As, seen the excess attenuation can be calculated for the both the case of measured SPL in forest or over lawn for different distances. In Figure 42 the excess attenuation for distance 50,100 and 150m goes up and down for increasing frequency and the case of 12m is base to calculation, hence gives zero attenuation. For increased distance there is no clear patter. In Figure 43 the excess attenuation shows a clearer behaviour. Here it increases with increased frequency and distance.
Seen from the perspective of that the forest possible could amplify sound, one can observe that the case of forest is a less good attenuator, hence one can say that the forest is a better “amplifier” than lawn.

4.3.5 Wind and temperature with height

The wind and temperature was measured with height, using a steel frame mast, 16m high, which was available in the forest. The measuring equipment was a so called weather station using two thermometers, one at 10m and one at 2m, one ultrasonic wind meter and a data logger system. The wind was mainly coming from the west, which interfered with the measurement direction (northeast).
First the two thermometers were put at 2 and 10m height respectively. Then the wind meter was also put at 10m height. After little more than one hour the wind meter was lowered to 8m height. Continuing to lower to 6m after another hour and then to 4m height. Lastly the wind meter was put on 14m height in order to measure the wind speed as high as possible; the cables did not allow any higher heights. The results are presented as one minute average in Figure 44 and Figure 46.

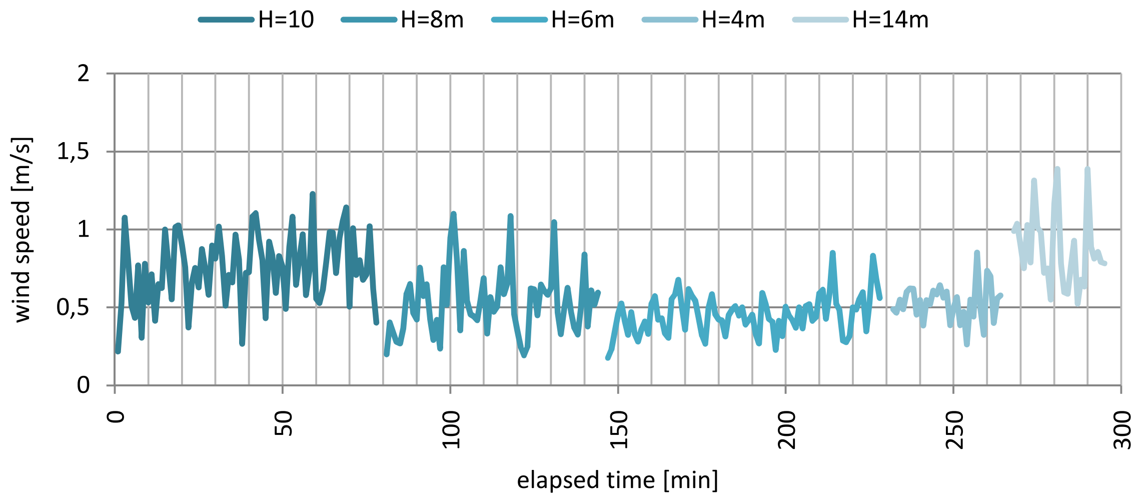


Figure 44. Wind speed over elapsed time, starting at 11:51am

In Figure 44 the wind speed are plotted for different times and heights. One can see that the wind speed varies more than 0.5m/s at each measured height. The variation increases with increased height, the standard deviation of the wind speed increases with height. At the occasion the average wind speed at 4m height was greater than that of 6m height. This may somehow be related to the relative short measurement time and an amount of greater wind will affect the average to a greater extent. This is clearly seen in Figure 45 below.

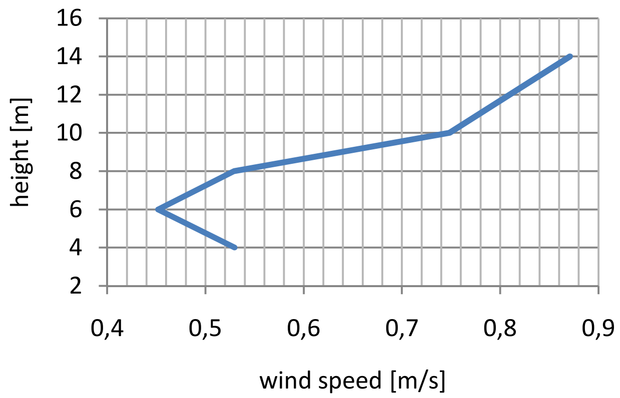


Figure 45. Average wind speed at different heights

The average wind speed in Figure 45 shows a positive wind gradient with height, except for heights below 6m. However, the small differences between the heights show that the wind inside the forest was quite weak during the measured day.

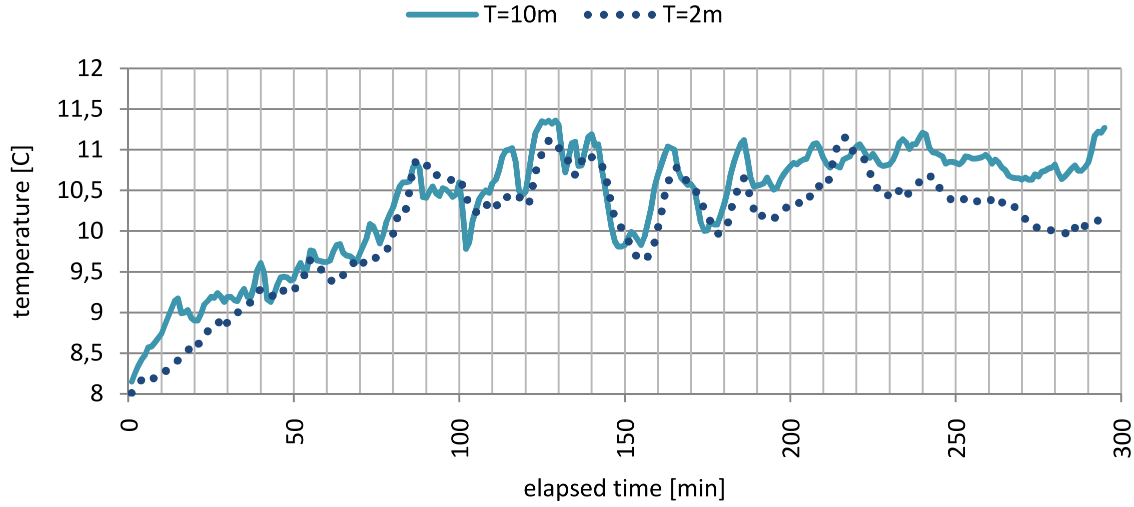


Figure 46. Temperature over elapsed time, starting at 11:51am

In Figure 46 the temperature is plotted for different times and for two heights, 10m and 2m. At noon the temperature increases from 8 °C up to 10.5 °C. Then the temperature flattens out and is continuous stabile at around 10.5 degrees. The difference between 2m and 10m is greatest just around noon (10min) and around 16:40 (290min). This can be seen in Figure 47 below.

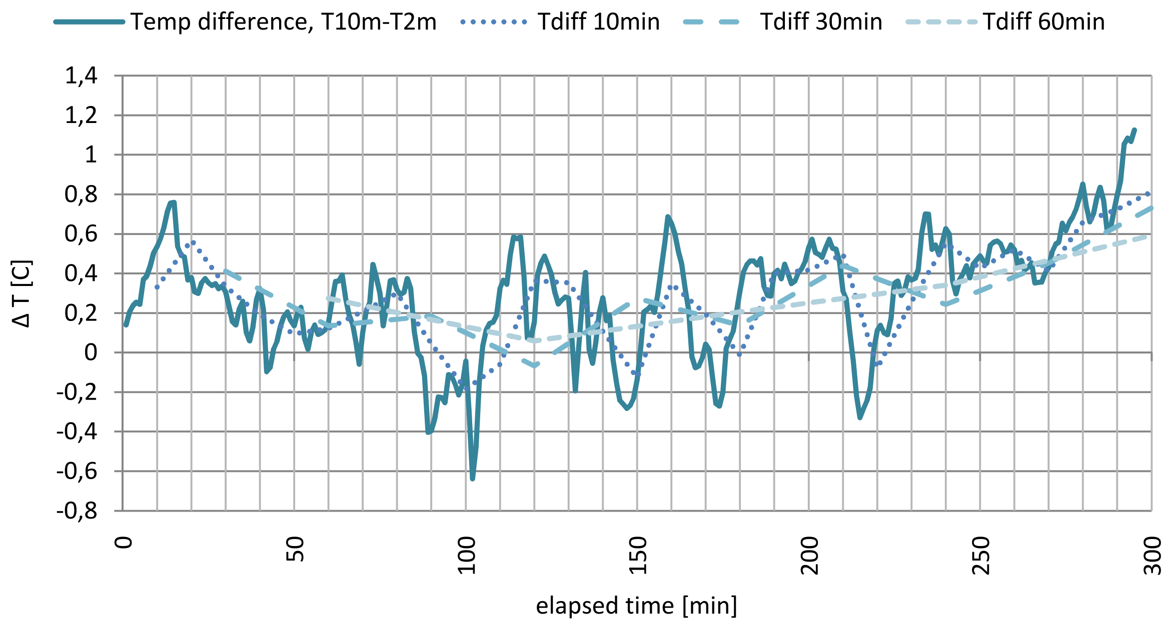


Figure 47. The temperature difference, ΔT=T(10m)-T(2m) for different time ranges

IR-Camera results

An Infrared-Camera was used in order to more convenient measure the temperature of different surfaces. In Figure 48 and Figure 49 below different photo types of a spruce trunk are shown.

Figure 48. Photo of the spruce trunk

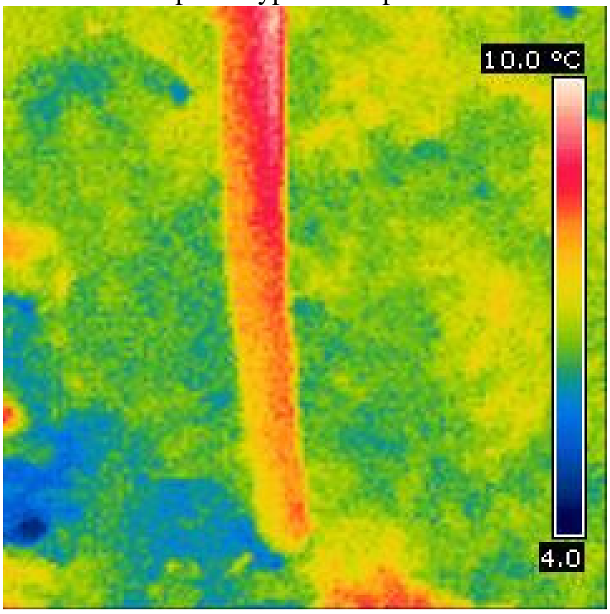


Figure 49. IR-photo of the lower part of a spruce trunk

In Figure 49 the lower part of a spruce trunk close to the steel mast is shown.
Here the temperature varies from 5-6 °C at the ground to 10 °C some meter up along the trunk.

Comparing Thermometer with IR-Camera

It could be interesting to understand how well the IR-camera can detect the ambient air temperature; therefore a comparison between thermometer and IR-camera can be seen in Figure 50 to Figure 55 on the following page:

Thermometer: Time 12:00, H=10m, 8.68 [°C]

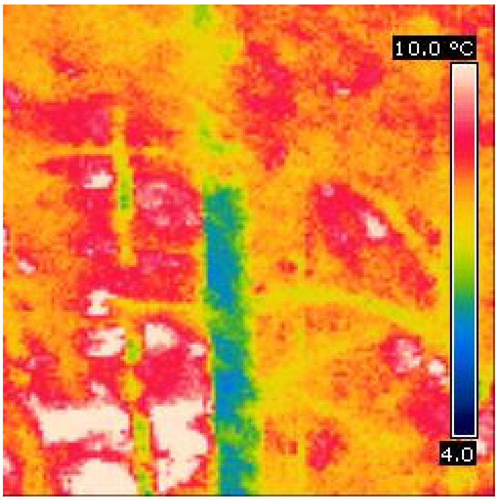


Figure 50. IR-Camera at 12:00 10m height

Thermometer: Time 11:56, H=2m, 8.23 [°C]

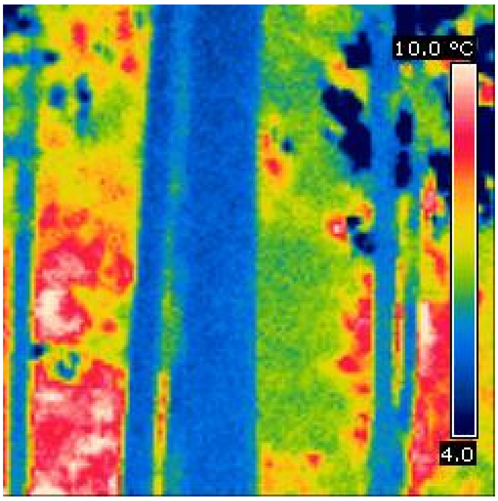


Figure 51. IR-Camera at 11:56 2m height

Thermometer: Time 14:38, H=10m, 10.66 [^{o}C]

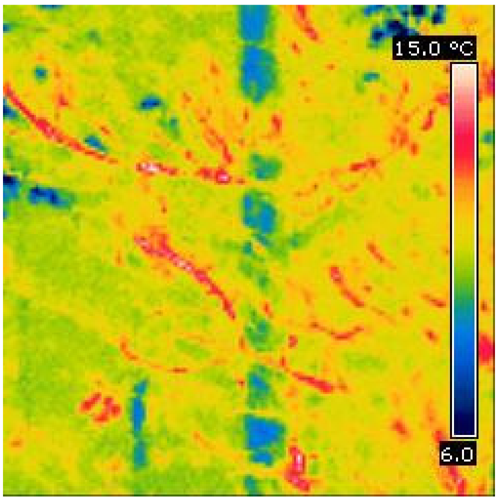


Figure 52. IR-Camera at 14:38 10m height

Thermometer: Time 14:35, H=2m, 10.7[^{o}C]

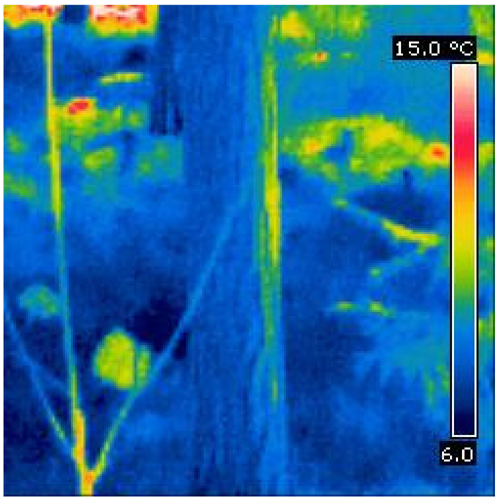


Figure 53. IR-Camera at 14:35 at 2m height

Thermometer: Time 16:46, H=10m, 11.27 [^{o}C]

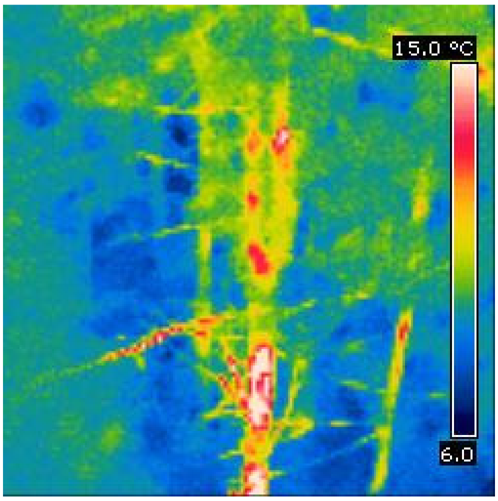


Figure 54. IR-Camera at 16:54 at 10m height

Thermometer: Time 16:46, H=2m, 10.14 [^{o}C]

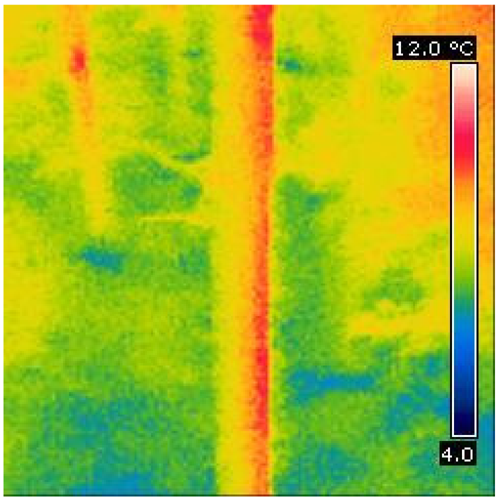


Figure 55. IR-Camera at 16:52 at 2m height

From Figure 50 and Figure 51 it can clearly be seen that the tree trunk surface temperature is definitely lower than the ambient air temperature measured by the thermometer. In Figure 50 the sun shining on the canopy may give the high temperatures to the left of the trunk. The trunk may have a surface temperature of about 5-6 ^{o}C. Figure 51 the cold sky may be shown as the dark spots to the right of the trunk. Sometimes the automatically adjustments of the emission of the camera makes the cases of sky difficult. When the sun is partly in the picture the temperature rises infinitely and when the blue sky is in the picture the temperature decrease. The trunk in Figure 51 is somewhat lower than in Figure 50, hence it may give a positive temperature gradient.

In Figure 52 the trunk is partly visible behind the canopy vegetation, here the temperature is around 8-9 ^{o}C, which is somewhat higher compared with previous picture. Some branches are exposed to directly sunlight and therefore are very red. In Figure 53 the trunk temperature is around 6-7 ^{o}C and the difference is large compared with the measured thermometer value. Here the sun did not reach the ground. Comparing the thermometer values one sees that the temperature gradient may be slightly negative during this time.

The last two pictures, Figure 54and Figure 55 were taken just after the weather station and the thermometers were inactivated. The last data from the thermometers during the day was at 16:46, which is why these are represented here. In Figure 54 the sun warms some parts of the trunk, but the

canopy is shadowed. Figure 55 shows how the sun has warmed one side of the tree, the left side may have 8 °C and the right side around 10 °C.
The IR-camera may not give a very good answer to the temperature of the ambient air, but can give a fast and efficiently glimpse of the temperature gradient if a larger part of the trunk can be seen. A quite large part of a tree trunk can be seen in Figure 56 below. Here the positive temperature gradient can clearly be seen.

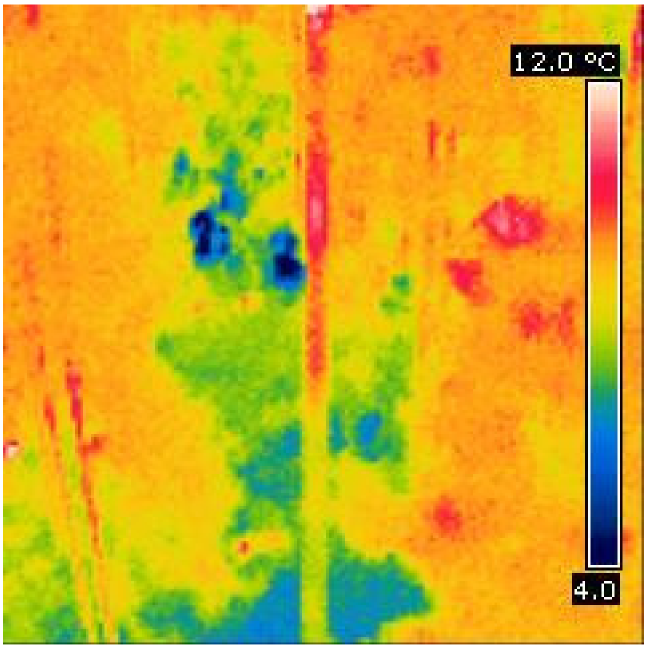


Figure 56. Temperature gradient on the surface of large part of tree trunk

Conclusions from the IR-camera measurements are that the camera is quick and visually efficient assessment, but lacks the possibility to exactly judge the temperature at different location in the ambient air and showing the variation over time.

5 Calculation model

According the project plan a calculation model should be developed, which can predict the increased sound pressure level. The model should take the reverberation and also wind- and temperature gradients into account. First, the approach to develop the calculation model is presented. Then some existing calculation models are presented, both for sound propagation outdoors and also the special case of sound propagation outdoors in forests. After that, a theoretical background to the calculation model is described. The last part of chapter 5 describes used calculation models. This part describes the calculation script of CNPE, used for comparative calculation, and also the developed calculation model, called RT-forest.
Sometimes it can be difficult to see the difference between the case of open field and of free field, but the difference is important. The free field should refer to a hypothetical value, calculated for the given situation. The open field refers to measured values over ground, which is the direct sound field plus the ground reflections.

5.1 Approach to develop a calculation model

When a new calculation model should be developed different approaches can been regarded. One approach is to try to take all the physical aspects into account. In this sense an analytical model could be developed. The diversity of the forest makes this very complicated. Another approach to predict the sound pressure level is to adjust results from measurements and in this way make a prediction based on experience. In this sense the calculation model would be empirically with the drawback of not being completely correct. Also another approach is to use already existing approaches and add the effects of reason for the sound pressure level increase. The advantage with this approach is that existing models can be used and only completed with some extra variables. The optimal approach chosen may be regarded to use existing calculation models and adjust or add complementary variables to take the increase level into account. The question whether an analytical, numerical or empirical model gives the best solution to the sound propagation have aroused and evaluated during the work of master thesis.

5.2 Existing calculation models predicting sound propagation outdoors

There exist almost as many models of sound propagation as there are cases of sound propagation. Some models have been developed with ambition to collect many cases and generalize the prediction of propagation, others just predicts special cases of sound propagation. Here some commonly used models are being presented.
According to [8] and as we have seen in this thesis so far the acoustics behind outdoor sound is very complex, which make empirical or semi-empirical models for predicting outdoor sound rather popular. The reasons for this may be the relative simplicity compared to non-empirical models, like a numerical method, e.g. the PE-Parabolic Equation or FFP-Fast Field Program, or an analytical method, e.g. the ray tracing model. Among empirical models is the international standard ISO 9613-2 [39] which exist as a Swedish standard SS-ISO9613-1:2006. It was developed during the beginning of the 1980's and has continuously being updated, lastly at 2006. It is a scheme for predicting noise outdoors in community environments and is intended to bridge the gap between two other standards (ISO 3740 and ISO 8297) in order to predict noise levels in a community from a known sound source. It consists of octave-band algorithms with centre frequencies 63-8000 Hz. The scheme is widely used by experts, customers and scientists.
Nord2000 is another predicting scheme and it was developed in the Nordic countries 1996-2001, and includes both empirical parts and analytical parts. Nord2000 is a model that makes it possible to predict noise from many different sources in 1/3 octave band with centre frequencies from 25-10000 Hz, including different profiles of terrain, different ground properties and taking meteorological conditions into account. Nord2000 has an advanced approach to model the sound propagation and gives good agreement with measurement [40]. But since it is a relative new model it may not be "calibrated" sufficiently, here ISO9613-2 may have had longer time to adjust to reality [41].

A model that was developed by the petrochemical industry in the Netherlands is called Concawe. It is more advanced than the ISO9613 in the sense that it better can take the meteorological conditions into account.
The European project of Harmonoise has developed a source-independent prediction scheme for outdoor sound. Like the Nord2000 the advanced estimation of the terrain, impedance model and meteorology have been developed.
Also the Swedish E.P.A. has developed a scheme for predicting sounds from wind turbines, [26].

5.3 Existing calculation model predicting sound in forests

Many of the previously mentioned prediction schemes can be used for predicting sound propagation in forests, e.g. ISO9613-2, Nord2000 and Harmonoise.
The used calculation model in Elforsk 09:22 [1], was partly Nord2000, which was implemented in the software of Sound Plan 6.4 and partly the calculation model used by the E.P.A. of Sweden [26]. Because of that the scattering effects in Nord2000 were not included in SoundPlan; a Matlab-script was created which calculates according to Nord2000's model for scattering zones.

5.3.1 Attenuation due to reverberation

The basic effects of reverberation may theoretically be related to the direct field and free field [20 s. 95] and [19 s. 2673]

$$A_s = 10log\left(\frac{E_d + E_r}{E_f}\right) \quad A_s{:}\, total\ scattering\ attenuation \quad E_d{:}\, energy\ of\ direct\ field$$

$$A_d = 10log\left(\frac{E_d}{E_f}\right) \quad A_d{:}\, direct\ field\ attenuation \quad E_r{:}\, energy\ of\ reverb\ field$$

$$E_f{:}\, energy\ of\ free\ field$$

Here it is obvious that the scattering is related to the reverberation. Having information about the source, the forest stand, the ground and geometrical conditions, the scattering and the reverberation may be obtained.

5.3.2 ISO 9613-2 Attenuation due to foliage

The international standard ISO 9613 includes attenuation from foliage when predicting the sound propagation, see annex A in [39 s. 15]. Here the foliage is regarded as dense, which means that it is impossible to see a short distance due to sight is blocked by foliage. The foliage may consist of trees and shrubs. For a given distance through the dense foliage the model gives attenuation in octave-band. The distance through the foliage can be calculated as the distance close to the source (d_1) and receiver (d_2) connected assuming a part of a circle with radius of 5000m. The distance in the foliage d_f is the sum of d_1 and d_2.

$$d_f = d_1 + d_2$$

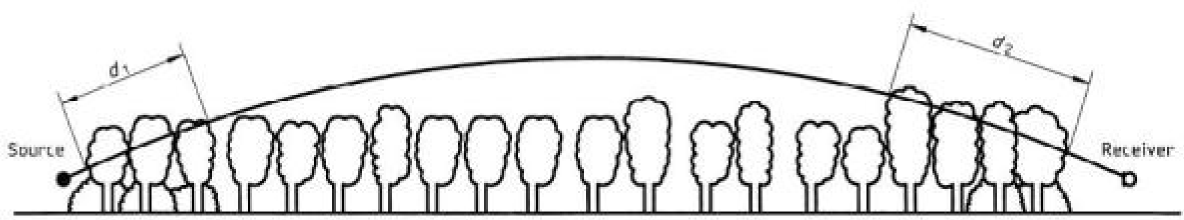


Figure 57. Distances in foliage, d_f [39 s. 15].

Propagation distance d_f	**Nominal midband frequency**								
[m]	63	125	250	500	1000	2000	4000	8000	
10 ≤d_f≤ 20	0	0	1	1	1	1	2	3	Attenuation, dB
20 ≤d_f≤ 200	0.02	0.03	0.04	0.05	0.06	0.08	0.09	0.12	Attenuation, dB/m

Table 14. Attenuation of an octave band of noise due to propagation as distance df through dense foliage [39 s. 15].

5.3.3 Nord2000

Nord2000 is a comprehensive method for calculating outdoor sounds. The basic equation is analogous with ISO9613-2, see eq. 3 and 4 in [39 ss. 3-4] and eq. 1 in [11 s. 12]. Both uses a simplified summation for finding the total sound pressure level [11 s. 12] where it is presented:
$L_R = L_W + \Delta L_d + \Delta L_a + \Delta L_t + \Delta L_s + \Delta L_r$
where the contributors are described as
L_R: $Sound\ Pressure\ Level\ at\ receiver\ for\ each\ frequency\ band$
L_W: $Sound\ Power\ Level\ for\ the\ frequency\ band\ of\ interest$
ΔL_d: $propagation\ effect\ of\ spherical\ divergence\ of\ the\ sound\ energy$
ΔL_a: $air\ absorption$
ΔL_t: $terrain\ effects$
ΔL_s: $scattering\ effects$
ΔL_r: $effects\ of\ obstacle\ dimensions\ and\ surface\ properties\ when\ calculating\ contributions\ from\ sounds\ reflected\ by\ obstacles$

The differences with ISO9613-2 arise when calculating each contributor, here Nord2000 uses an advanced and modern method, e.g. treating a varying terrain and extended frequency range.
The situation of regarding sound in forests will have an effect on many of the contributors in different ways compared with free field. The L_W can be affected by the air turbulences above the canopy, the L_d can be affected by the unique wind and temperature gradients in forests, L_a can be affected by temperature and relative humidity special for forests, L_t can be affected by the different ground classes of forests, L_s can be affected by the amount of trees, trunks and type of forest and L_r can be affected by ground class and vegetation in forests.
The two main contributors for the sound pressures level is ground effect and scattering effects [29].

Ground effect
As explained in chapter 2.1.6 and 2.2.4 the ground effect depend on the ground impedance, Z. The Nord2000 treat both terrain and screens for their special cases and the combination of them. It is a two dimensional model where the vertical cross section between the source and the receiver is treated and regarded for calculations [11 s. 17]. The terrain is simplified with segments, modelling the real terrain. The concept of Fresnel-zones is used in Nord2000. Its advantages can be used when treating sound propagation over ground with mixed impedance. The ground classification can be determined for each terrain segment using the empirical model by Delany and Bazely [11 s. 25]. In order to treat different sources, both a coherent and incoherent sources can be used in Nord2000.
The ground impedance classification for soft forests floor can be estimated using a flow resistivity of $\sigma_B = 31.5$, according to ground class B in Nord2000 [11 s. 26].

Scattering zones
In Nord2000 a method to predict sound from external sound sources in forests, e.g. wind turbines, is being described. Also in other calculation methods forests are being treated. In Nord2000 the approach [42 s. 39] is to use a statistical approach when regarding the scattering effects from reflections by trunks in forest. The scattering model in Nord2000 is mainly based on a report by Norwegian researcher Svein Å. Storeheier [43]. Analogous approach for treating the scattering forest can be seen among Twersky and Micelle Swearingen, i.e. they may have used related approach.
One of the parameters in Nord2000–scattering zones is the R_{SC} which is length of ray path, i.e. the sound travel distance in the forest. Other parameters are tree density, tree diameter and reflection

properties by scattering objects. A way to determine density and size is using the product of nQ. In the case of forests this is determined in Nord2000 by examine the type of tree and the mean trunk diameter.
The R_{SC} and nQ can together with knowing the absorption properties and height of scattering obstacles (i.e. the height of forest stand) be used to calculate the propagation effect of scattering zones, according to following formulas with corresponding explanation:

$$\Delta L_{scattering} = k_f T k_p A_e(R_{SC}) \qquad h' = nQh$$

$$A_e(R_{SC}) = \Delta L\left(h', \alpha, R'\right) + 20log(8R') \qquad R' = nQR_{SC}$$

$$T = min\begin{cases}\left(\dfrac{R_{SC}nQ}{1.75}\right)^2 \\ 1\end{cases} \qquad nQ = n''d$$

Symbol	*Name*	*unit*
$\Delta L_{scattering}$	*propagation effect of scattering zones*	[dB re 2µPa]
k_f	*weighting function*	[-]
T	*variable for calculating the coherence coefficient*	[-]
k_p	*weighting function*	[-]
$A_e(R_{SC})$	*level correction due to scattering*	[dB re 2µPa]
h'	*normalised scatter obstacle height*	[m]
h	*average scatter obstacle height*	[m]
α	*absorption coefficient of scatter obstacles*	[%]
R'	*normalised effective distance through the scattering zone*	[m]
d	*mean trunk diameter*	[m]
n''	*density of trees, i.e. [number of trees / area]*	[m^{-2}]
R_{SC}	*total sound path through the scattering zone*	[m]

These formulas can be found in first part of Nord2000 [11 s. 91], in where the tables for determining k_f, k_a and $\Delta L(h',\alpha,R')$ also can be found
The second part of Nord2000 [44] includes model for propagation in an atmosphere with refraction. But the model of Nord2000 is lacking the possibility to regard the local micrometeorological effects that occur inside forests, i.e. Nord2000 approximates the temperature and wind gradient linearly.
The scattering effect is plotted in Figure 58 below. The in parameters are:

d	=	0.3m
h	=	18m
R_{SC}	=	[100 200 300 400] m
α	=	0.1
n''	=	0.07

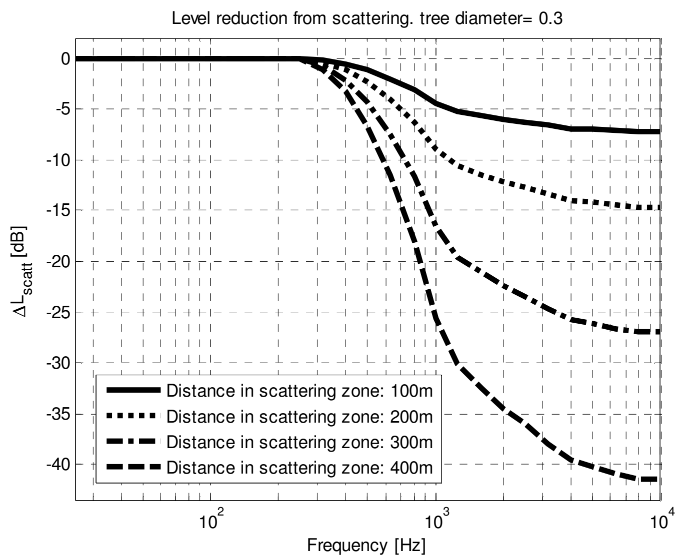
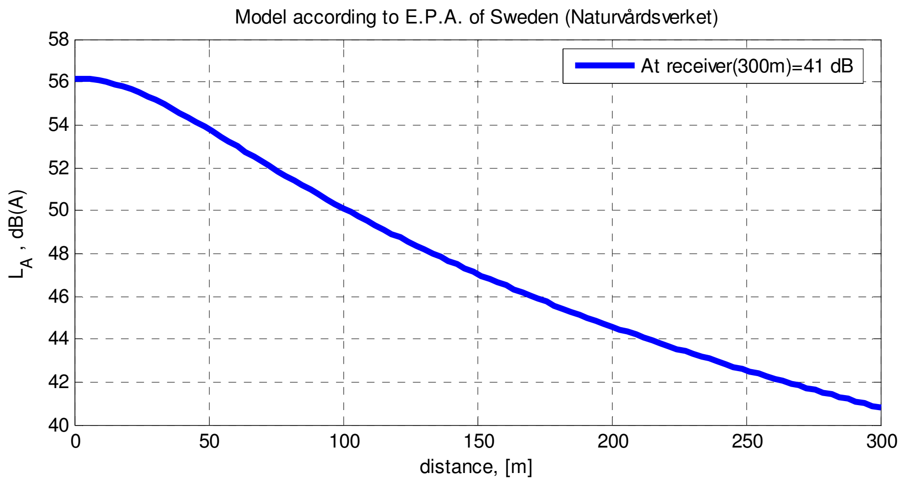


Figure 58. The effect of scattering according to Nord2000

In Figure 58 the clear dependence of distance can be seen. The scattering decrease the sound level difference with increased distance. A reason for this may be that the probability for the sound to be scattered by a tree increase the further one gets from the source.

5.3.4 The Swedish model – The model by the E.P.A. of Sweden (Naturvårdsverket)

The Swedish model was developed by request from the Swedish government, [26]. The model is appealingly simple but when compared to other prediction schemes like Nord2000 the Swedish model exist without a comprehensive algorithm for the complex sound propagation. The Swedish model is taking the forest into account when determining the roughness length, but there is no method for treating propagation through forest, e.g. lacking prediction due to scattering effects by trunks.
Example of calculation with the Swedish model can be seen in Figure 59 below:



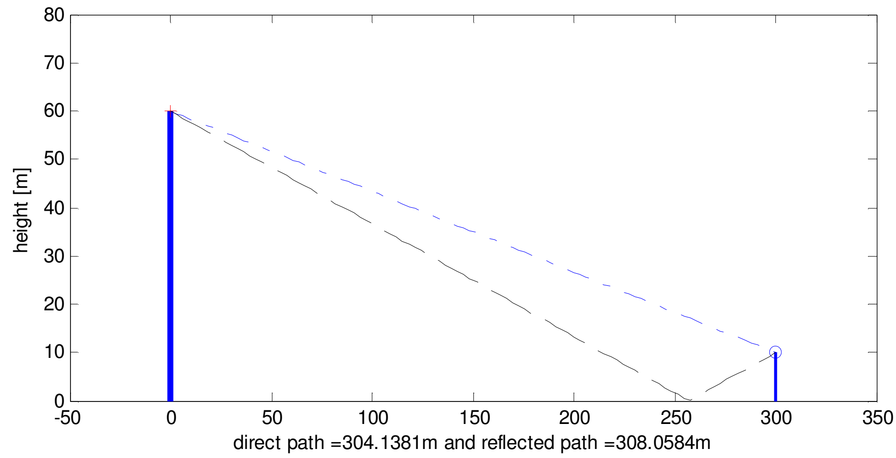


Figure 59. Calculation of SPL with noise from wind turbine according to E.P.A-model

In Figure 59 the source had a sound power level of L_W = 99dB, the hub height was H=60m, k=1dB per m/s, surface roughness assumed to z_0=0.3, the wind speed at 10m height v_h=8m/s, distance between tower and receiver 300m was assumed. The sound pressure level L_p at receiver 300m from source was calculated to 41dB(A). The calculation does not treat sound propagation in forest.

5.3.5 Numerical methods for predicting outdoor sound propagation

Numerical methods can solve difficult problems and give an approximate answer, which give a hint of the reality. The problem can sometimes be of other aspects, e.g. lacking computer calculation power or difficulties in understand the relations between each parameter. Three different numerical methods are described by Salomons [6 s. 48], in order to calculate the sound propagation. They take the effects of wind and temperature variations into account. These are FFP = Fast Field Program, CNPE = Crank-Nicholson Parabolic Equation and GFPE = Green's Function Parabolic Equation.
In the paper by Swearingen & White [32], an adjusted GFPE-model called “forest GFPE” is proposed. This model will predict the sound propagation and take the temperature gradient into account. Although the temperature gradient is accounted, it is also mentioned that the reverberation is not included in the model. By Michelle Swearingen it is recommended that a CNPE-model (Crank Nicholson Parabolic Equation) should be used [45]. Michelle refers to that: “The calculation will be much slower but more robust”.
The method of parabolic equation is that it gives a solution of the Helmholtz equation, here using the appropriate boundary conditions.

5.4 Used calculation models: CNPE and RT-forest

The used calculation models are first a developed model (RT-forest) which includes the reverberation and assumes the forest as kind of room. The second model is a C.N.P.E.-model supplied by supervisor Jens Forssén and used as a “black-box”, i.e. it is used as a unknown function with input giving some kind of output. In order to calculate the SPL for height and range a wind profile for forest has been assumed and the wind profile for free field has been calculated.

The developed model (RT-forest) regards the forest and predicts the sound pressure level at a distance in a forest stand. The developed model takes air absorption, ground effect, scattering by trees and reverberation into account. The input variables is the source and receiver geometry, the dimensions of the forest, meteorological conditions, measured RT and the sound power level used for calculations.

In the model the reverberation time (RT) is related to the sound pressure level by the classic room acoustic formula:

$$L_p = L_w + 10log\left(\frac{1}{4\pi r^2} + \frac{4}{A}\right)$$

L_p: $sound\ pressure\ level$	$[dB]$
L_w: $sound\ power\ level$	$[dB]$
r: $distance\ to\ source$	$[m]$
A: $apsorption\ area$	$[m^2]$

Here the RT is included in the absorption area. Changing the RT will also change the Lp.

The sound power level L_W is calculated from the sound pressure level at 12m distance, including ground effect and divergence. This also gives the nice optimal figure of G12, see Figure 85 at page 9.

The flow resistivity of $25*10^3$ was determined during measurements on 9th of April according to “Nordtest Method Acou 104”, see chapter about ground impedance at page 34. The basic formulas used are:

I $\quad L_P = L_W + \Delta L_{air} + \Delta L_{ground} + \Delta L_{scattering} + \Delta L_{divergence}$ *Excl. reverberation*

II $\quad L_P = L_W + \Delta L_{air} + \Delta L_{ground} + \Delta L_{scattering} + \Delta L_{divergence+reverberation}$ *Incl. reverberation*

The ground effect is using the on parameter model by Delany & Bazley and the scattering effect is modelled using the presented approach in Nord2000.

The RT-forest model can be understood when reading Appendix B, at Appendix page 2.

The C.N.P.E.-model has been used in order to take the wind and temp variations with height into account. For the case of forest, a profile obtained by Swearingen [17] was used and the case of free field a logarithmic profile was calculated. The results from a C.N.P.E.-script from Jens Forssén for wind profile in forest and the logarithmic wind profile for free field and the developed model compared with measurement from the 9th of April can be seen in chapter 6 at page 55.

6 Results and comparison between measurement and calculations

This chapter presents calculations through the C.N.P.E. (Crank-Nicholson Parabolic Equation) -model and then the comparison between measurements and the RT-forest model.

6.1 C.N.P.E. model

First predictions using the C.N.P.E. model are presented. It takes the effects of wind and temperature gradients into account. The C.N.P.E.-model was supplied by supervisor Jens Forssén in a Matlab-script in two versions. One version plotted the SPL in 2D with distance and height separately for single lines. The other plotted the SPL with distance and height together in the same plot, creating a colourful 3D-plot pattern representing the SPL for a range and height. The results for different cases are shown in the plots below. The used C.N.P.E. model is described in appendix 2D-C.N.P.E. model at page 16.
Below, the Figure 61 shows the relative sound pressure level for frequency f=250Hz and for a range between 0-550m. Here the 2D-model CNPE is used and the case of frequency 250Hz is chosen because the differences between case of no wind and refraction are shown quite clearly. The source and receiver height was chosen to 1.5m in the calculations. Figure 60 shows the corresponding speed of sound profile during free field conditions, here the logarithmic shape can be observed.

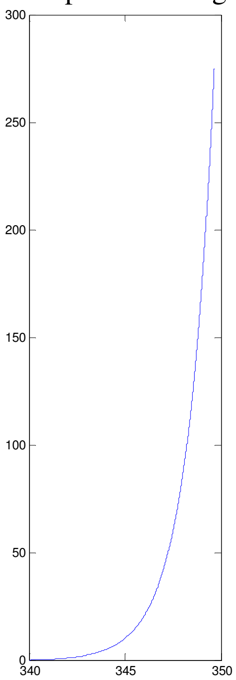


Figure 60. Free field sound speed profile, i.e. logarithmic wind profile

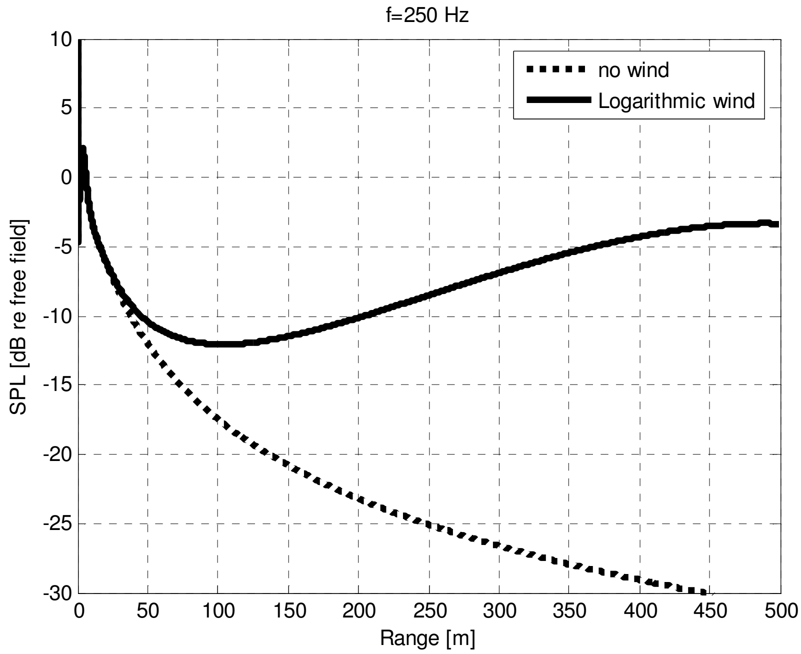


Figure 61. Rel SPL at f=250Hz for a range 0-550m for no and logarithmic wind profile

When analysing the resulting sound in Figure 61 one sees that the level is negative all the time, except for a peak at around 5m, which may be due to ground interference. At 100m distance the lowest value can be found, approximately -12 dB re free field.
When comparing sound propagation of free field with the case of forest, the change in wind profile can be introduced. Therefore, a wind profile possible for forest was incorporated into the 2Dmodel. This is shown in Figure 62 and Figure 63. Here the used profile is taken from Figure 5 at page 10. Also Figure 63 shows the relative sound pressure level (rel SPL) for frequency f=250Hz and for a

range between 0-550m but here Figure 62 shows the corresponding speed of sound profile for a forest. The source and receiver height was chosen also here to 1.5m. Here the sound profile has a different shape, a shape that may be obtained in forest.

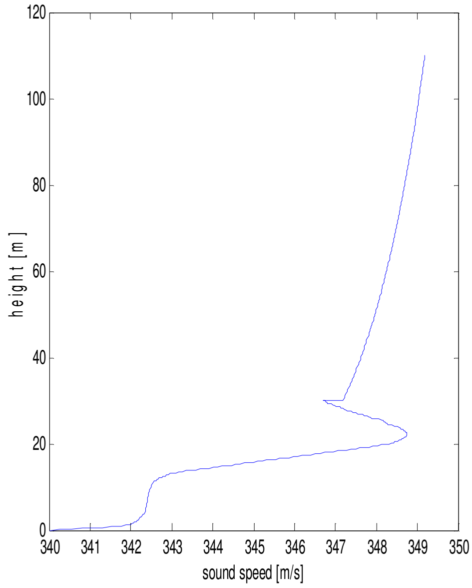


Figure 62. Forest sound speed profile up to 30m, above 30m logarithmic wind profile

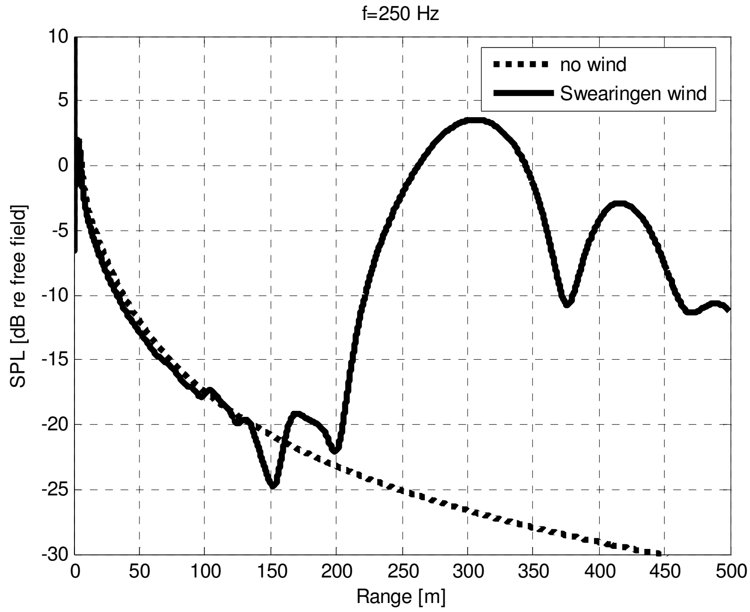


Figure 63. Rel SPL for f=250Hz and for a range 0-550m

In Figure 63 the resulting sound shows another pattern. The same peak as in Figure 61 can be observed at around 5m. The level drops and finds its minimum of -24dB at 150m distance. Then a dramatically increase of the sound appears and find a maximum of 4dB at 300m distance.
Comparing other frequencies one sees that this maximum level occurs in at low and mid frequencies, first in broad distance range at 50-80Hz, then peaks at 250-350 m for 250-315Hz.

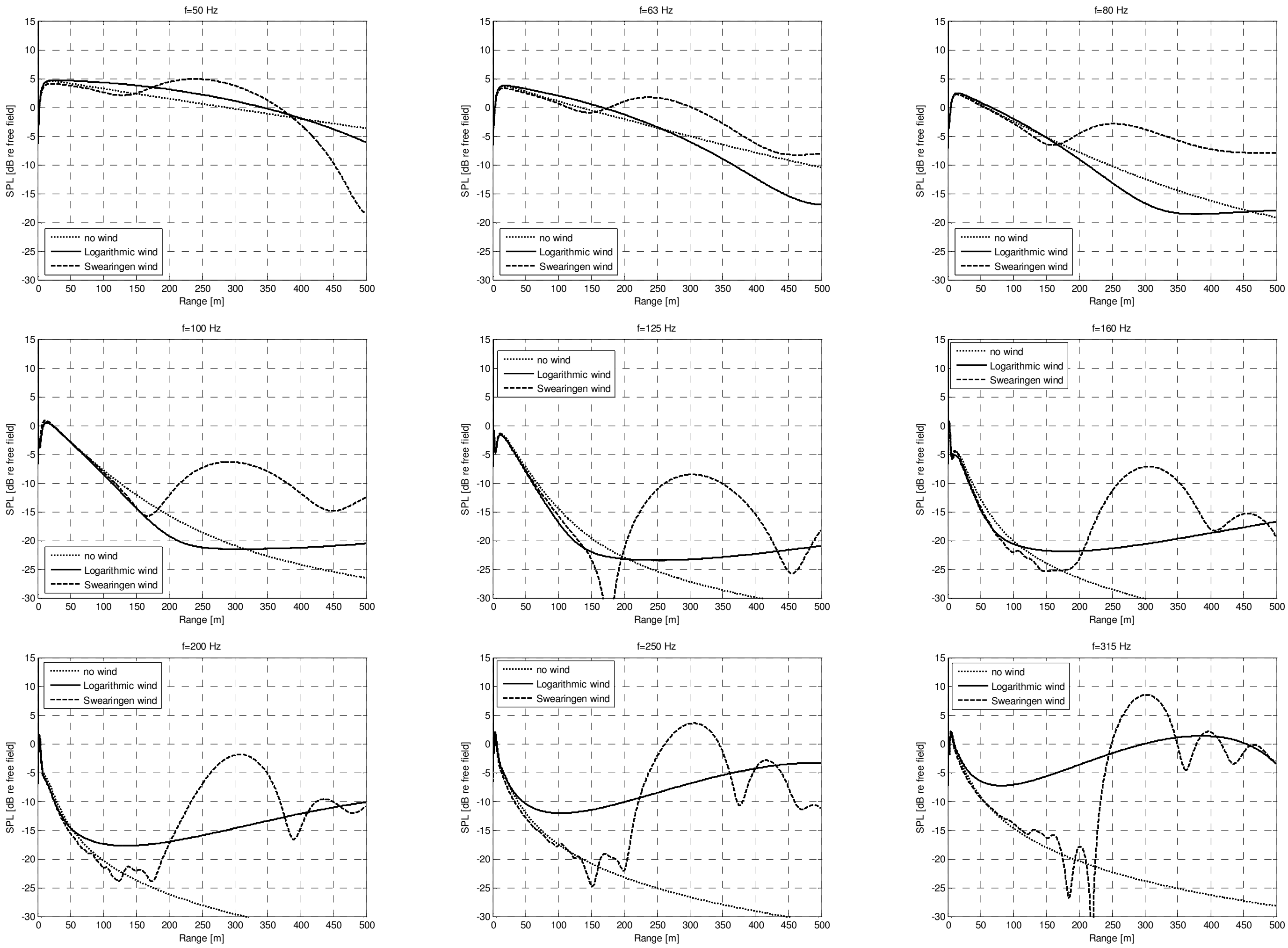


Table 15. Plots of SPL re free field for different frequencies

When running the other version of the C.N.P.E. model the relative SPL for a section with range 550m and height 100m could be visualized, see Figure 65 and Figure 67, with corresponding wind profiles in Figure 64 respectively Figure 66. The source and receiver was assumed to be at 1.5m. The surface roughness was in the forest assumed to be 0.3 and the ground impedance was assumed to be $\sigma = 25$ kPa s m^{-2} for both forest and free field.

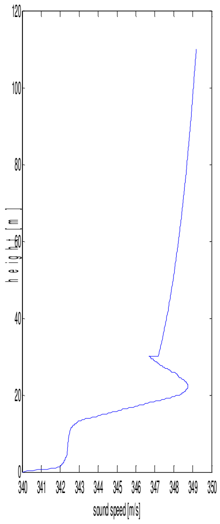


Figure 64. Forest sound speed profile up to 30m, above 30m logarithmic wind profile

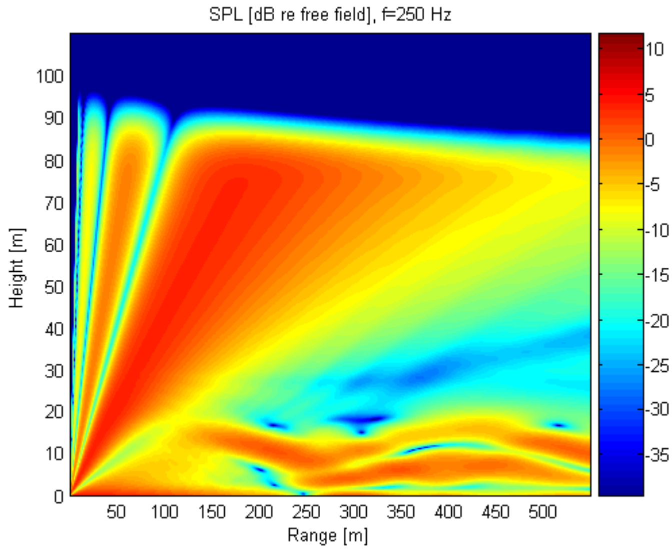


Figure 65. Rel SPL for range and height at 250Hz with forest wind profile

In Figure 65 the rel SPL varies from -35 to +10 dB and close to the ground the level, at (range=250, height= 0) a dip of around 20dB can be found. Little higher up at (200,7) dip comes at a shorter distance to the source. When z =10 the dip in dB has moved to 350m distance. The major dips are found at (280 to 350,15 to 20). The overall picture is that the sound speed profile causing both upward and downward refraction. A dramatically downwards refraction occurs up to z=15m. In the range z=20-30m an upwards refraction occur. Higher than z=30 a downward refraction occur, and here the sound speed profile has again adjusted to the free field case, i.e. this is sufficiently high above the canopy.

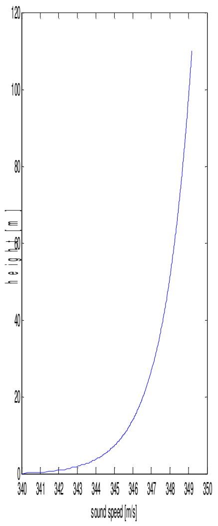


Figure 66. Free field sound speed profile, i.e. logarithmic wind profile

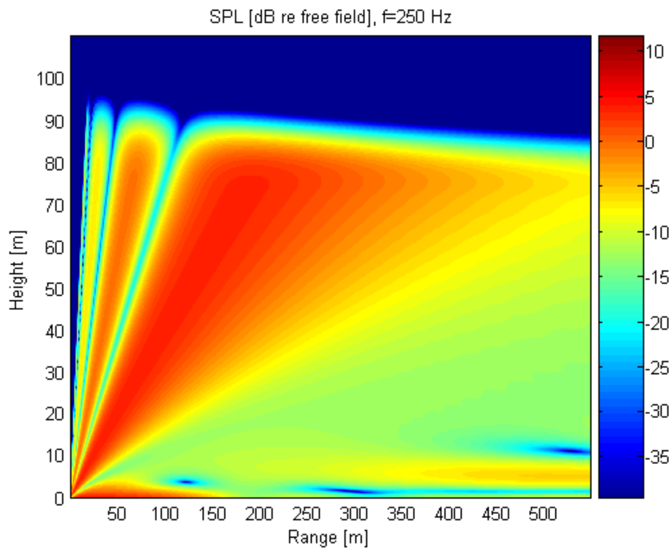


Figure 67. Rel SPL for range and height at 250 Hz with free field wind profile

In Figure 67 the logarithmic sound speed profile causing a downward refraction. Here some irregularities can be seen. There are some dips in the rel SPL at (130,5), at (250 to 350,2) and at (500 to 550,10)

Comparing Figure 65 and Figure 67 one can see that the downward refraction due to the assumed forest wind profile in Figure 65 causing higher levels close to the ground than the free field case. In Table 16 below the same conditions as in Figure 65 but for other frequencies are plotted.

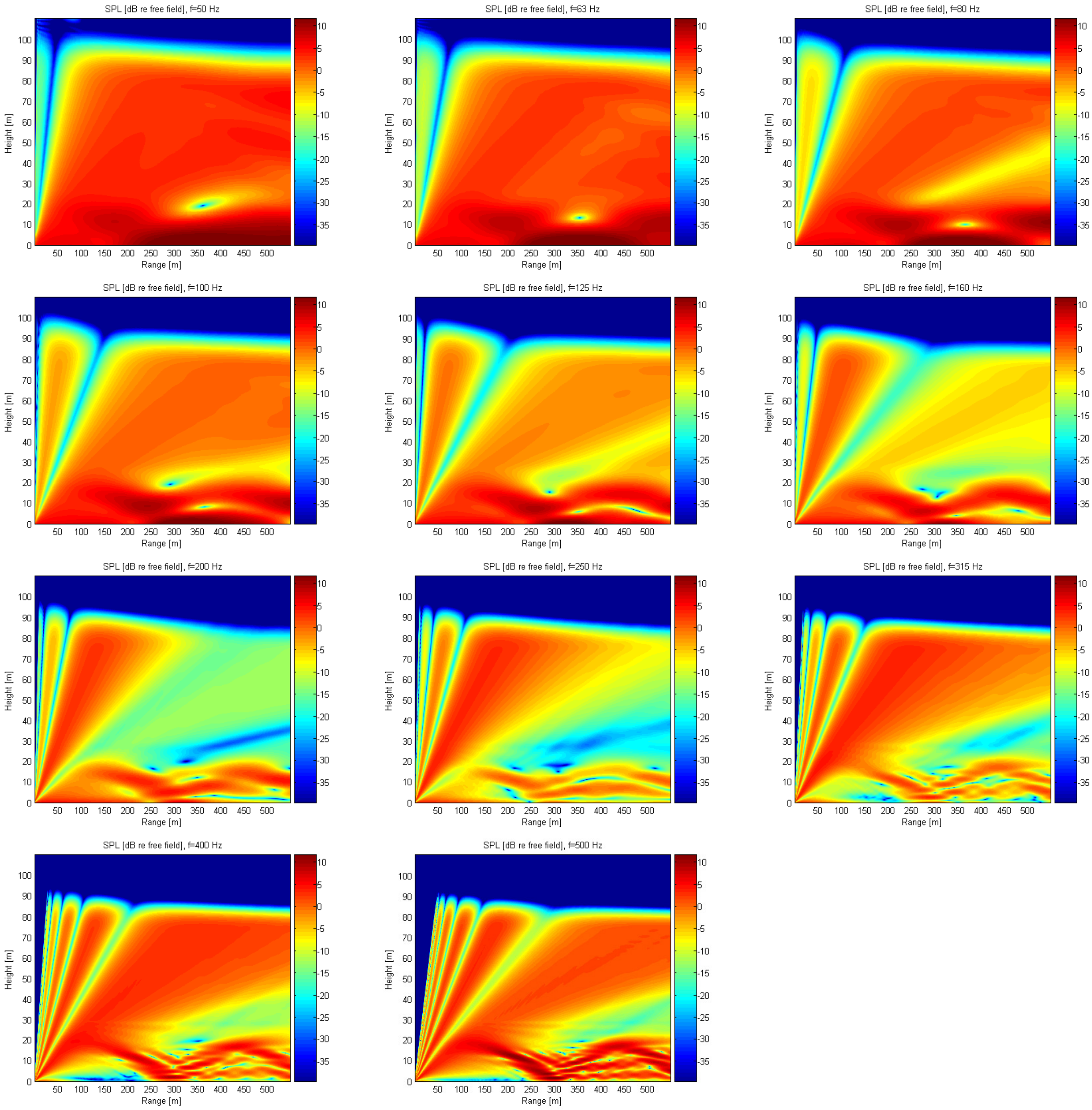
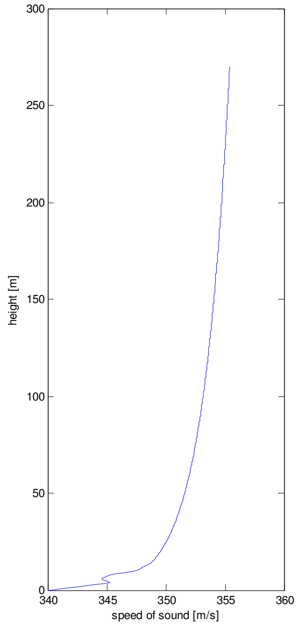


Table 16. Rel SPL for range and height at different frequencies with forest wind profile

During the measurement on the 9th of April a wind profile was obtained. The profile is quite weak compared with the one used in previous results. If the values of the obtained wind profile is multiplied with 10 and then used in the P.E.-model, the following results can be obtained at 250 Hz.



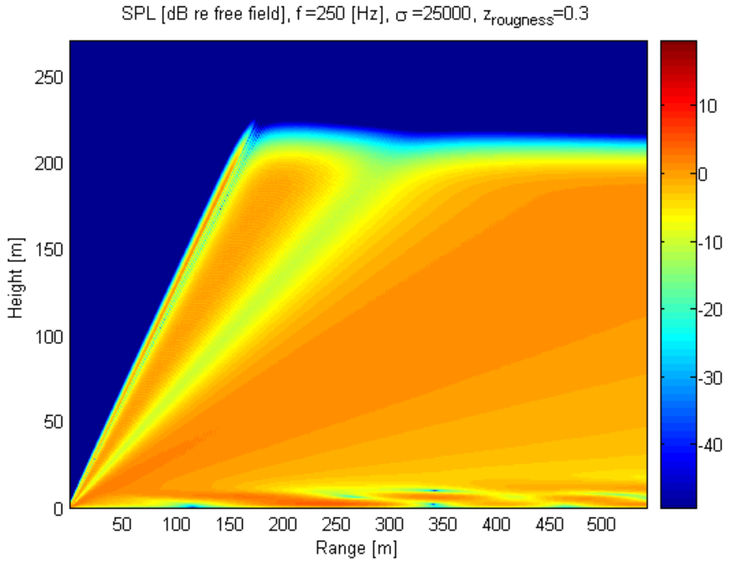


Figure 68. Measured sound profile up to 14m, above 14m logarithmic wind profile

Figure 69. Rel SPL for measured wind profile at 250 Hz

Here in Figure 69 the rel SPL is again plotted but now with the measured wind profile. The expected downward refraction occurs but not as clear as the one for the case of the assumed forest wind shown in Figure 65 above.
Conclusion from this is that the assumed forest profile in Figure 62 and Figure 64 may be exaggerated but during days of heavy winds it may happen. The measured wind profile may on the other hand be result of a very calm day.

6.1.1 Resulting levels at measured distances

The levels at the specific position for a microphone are interesting to investigate. Using the CNPE-model for different wind-profiles and distances these levels were obtained.

Logarithmic profile [dB re free field]				
Hz	*12*	*50*	*100*	*150*
50	4,3	4,6	4,4	3,9
63	3,7	3,3	2,2	0,7
80	2,6	1,0	-1,8	-5,3
100	0,8	-2,6	-8,3	-14,5
125	-1,7	-8,1	-17,5	-22,4
160	-5,0	-14,9	-20,7	-21,6
200	-6,2	-14,1	-16,5	-16,4
250	-3,7	-9,9	-11,1	-10,0
315	-0,4	-5,7	-5,7	-3,8
400	1,3	1,6	2,8	5,0
500	0,0	3,1	5,0	7,0
630	-2,2	4,2	6,4	7,1
800	-3,6	4,7	5,9	3,7
1000	1,2	3,4	2,2	3,7
1250	2,7	-3,0	4,6	4,3
1600	-5,1	-0,7	6,9	3,9
2000	3,0	6,2	6,0	2,9
2500	-4,0	1,9	9,2	2,7

Table 17. ΔL, log wind

Wind profile from Swearingen [dB re free field]				
Hz	*12*	*50*	*100*	*150*
50	4,1	4,0	2,8	2,7
63	3,6	2,8	1,0	-0,8
80	2,3	0,4	-2,7	-6,2
100	0,9	-2,8	-8,1	-14,3
125	-1,3	-7,6	-15,4	-22,5
160	[illegible]4,3	-14,	-22,7	-23,9
200	-6,1	-15,6	-21,9	-23,1
250	-4,5	-12,5	-17,9	-21,8
315	-0,8	-9,5	-14,1	-15,6
400	1,5	-1,1	-4,4	-6,2
500	0,8	0,1	-2,4	-3,8
630	-1,6	1,7	-0,2	-0,8
800	-4,6	3,1	2,0	2,1
1000	0,0	3,8	3,8	4,4
1250	2,9	3,0	4,1	4,7
1600	-3,6	-3,1	-1,3	-1,7
2000	2,5	-6,9	-2,7	-3,2
2500	-4,6	3,8	2,6	5,5

Table 18. ΔL Swearingen wind

Measured wind at Holmevatten [dB re free field]				
Hz	*12*	*50*	*100*	*150*
50	4,3	4,5	4,9	4,9
63	3,4	3,0	2,6	0,7
80	2,4	0,8	-1,3	-5,6
100	1,0	-2,7	-7,5	-14,4
125	-1,2	-8,1	-15,9	-17,9
160	-4,2	-15,4	-22,5	-14,8
200	-5[illegible]9	-13,7	-21,3	-9,7
250	-3,9	-7,9	-22,5	-7,8
315	-0,2	-2,0	-2,8	-14,0
400	1,7	4,5	5,9	4,3
500	1,0	5,4	6,6	4,7
630	-1,7	6,1	5,5	3,3
800	-4,2	5,5	6,2	3,3
1000	0,7	1,5	-1,7	5,7
1250	3,1	-5,0	1,4	6,4
1600	-4,8	7,5	2,2	0,7
2000	3,1	7,1	9,7	10,3
2500	-5,7	0,8	-1,7	1,0

Table 19. ΔL measured wind

When plotting the levels for each wind profile Figure 70 to Figure 72 was obtained.

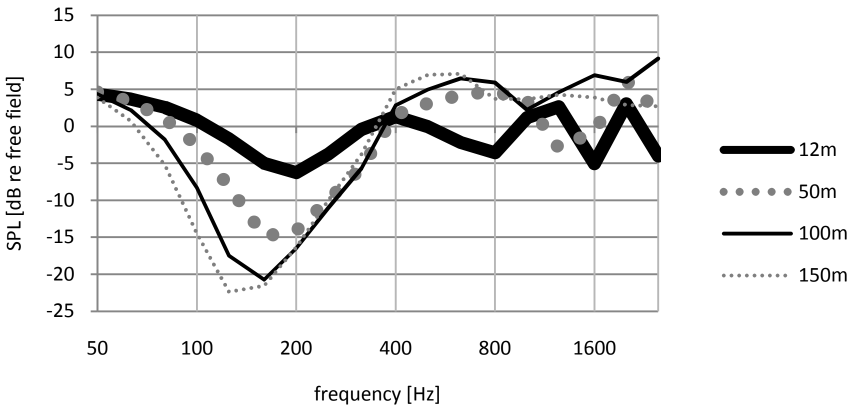


Figure 70. SPL rel free field for a logarithmic wind profile

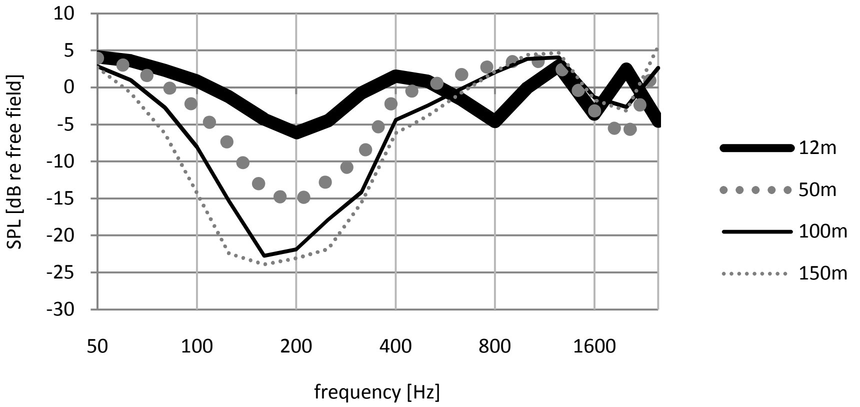


Figure 71. SPL rel free field for a wind profile obtained by Swearingen

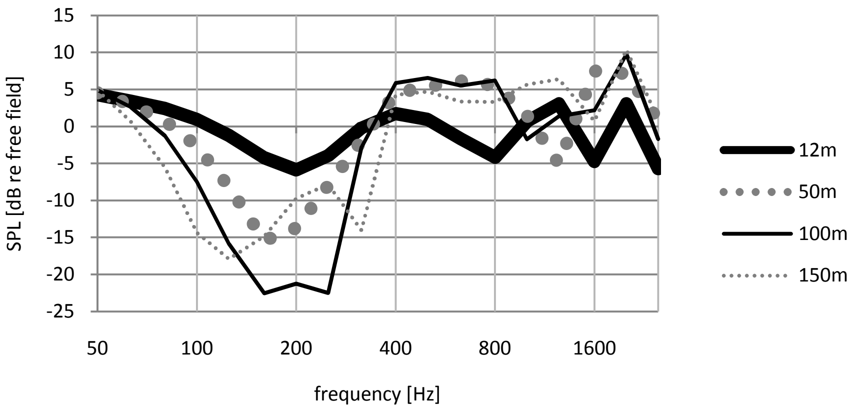


Figure 72. SPL rel free field for wind profile measured at Holmevatten

The results show values that are unlikely, especially when regarding substantial variations of the high frequencies. This is related to that the discretization had to be kept quite rough when running the Matlab-script, in order to avoid “Out of memory”-message. The results are assumed to accurate at least up to 800 Hz. The lacking of strong calculating power of the computer limited the best way of finding the results.

6.1.2 Case of Elforsk 09:22 in C.N.P.E.-model

The CNPE-model has been compared with the results from Elforsk. When adding the CNPE-result to the result from Elforsk it is possible to make a comparison, please see Figure 73.

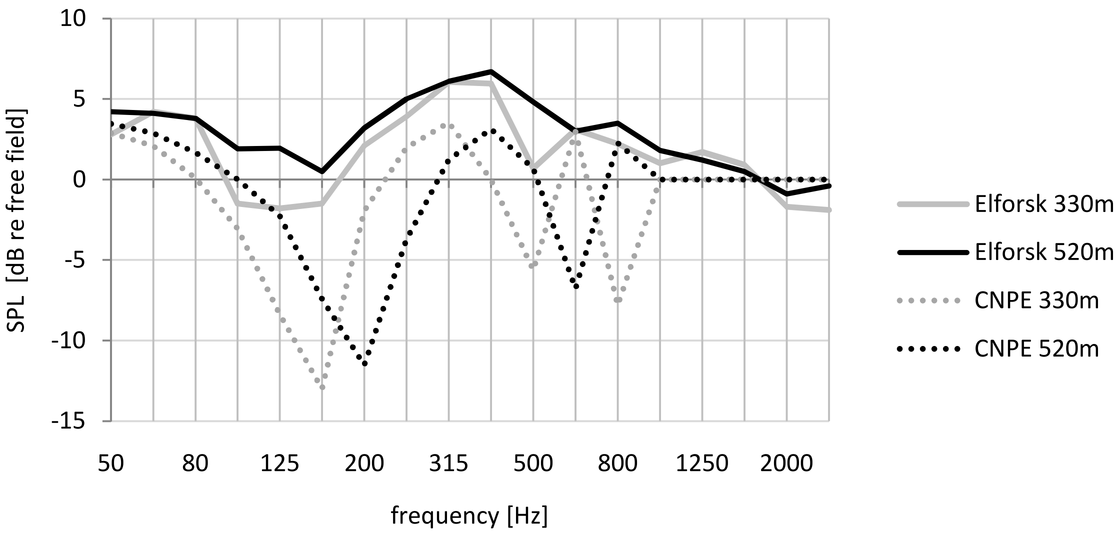


Figure 73. Comparing CNPE with results from Elforsk. Compared distances are 330m and 520m.

In Figure 73 four curves are plotted, which represent different cases. Two dotted CNPE-curves and two continuous curves by Elforsk, at distance 330m and 520m at wind speed 6 m/s [1]. The CNPE-results do not cover frequencies higher than 800Hz, here the dicretization of the CNPE-model limited the calculations.
The differences between the cases of curves are great. The dramatic curves from CNPE are not represented by Elforsk. The two Elforsk curves have a similar appearance, but the first ground dips are not as strong as the ones showed by CNPE-curves. The two CNPE-curves have a clearer distance dependency, where the first ground dip is moved up in frequency as the distance increases.
However, the similarities between CNPE and Elforsk can be found in the evolution. At low frequencies the curves start to decrease, they find a dip at 125-200Hz, and then they increase to a peak at 400Hz and at higher frequencies the curves have large differences.

6.2 RT-forest model

The model is presented and explained in chapter 5.4 "Used calculation models" at page 54. In this chapter an overview of some results are presented. The results from different cases can be seen in appendix: Results from the RT-forest calculation model at page 7.
The RT-forest model has been used for different cases at different distances. The model load data from measurements of forest from the 9th of April and calculate the SWL and a predicted SPL for the actual distance.
First the SWL was calculated using the closest case of 12m, taking geometrical and ground effect into account.

$$L_{W,source} = L_{P,measured12m} + 10\log\left(4\pi r^2\right) - \Delta L_{ground}$$

The effects of air absorption, scattering and reverberation were neglected because of the close distance. For the coming calculation this SWL was used.
In order to understand each sound propagation effect implemented in the model, e.g. how big the effect of atmospheric attenuation (air absorption) is, the effects have been plotted separately together with the measured level for different distances. Example of this is the case of 100m propagation in forest where Figure 74 to Figure 78 shows geometrical divergence, air absorption, ground effect, scattering and reverberation.

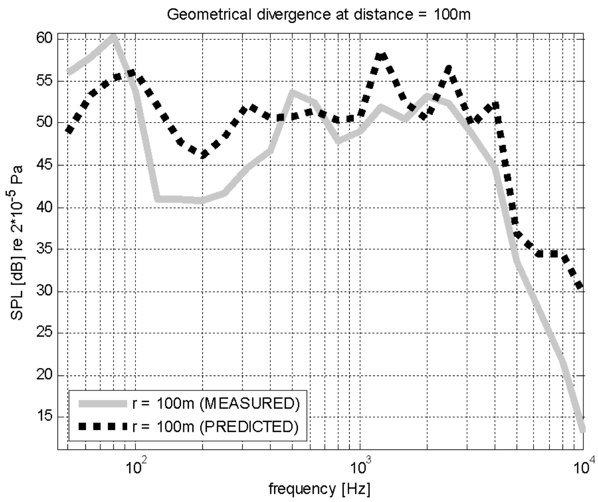


Figure 74. Geometrical divergence

$$L_p = L_{W,source} + \Delta L_{div}$$

$$\Delta L_{div} = 10\log\left(\frac{1}{4\pi r^2}\right)$$

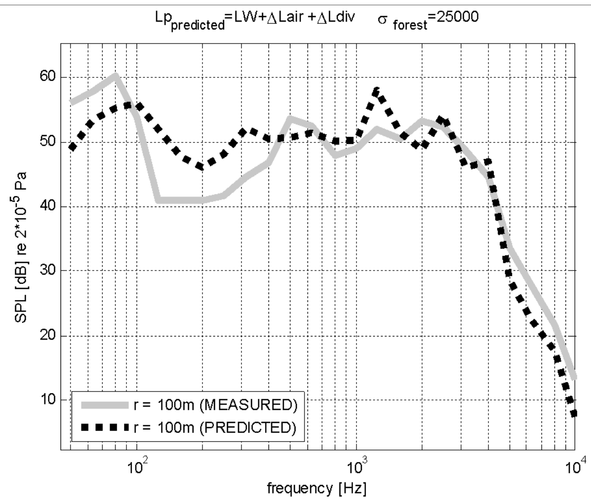


Figure 75. Air absorption

$$L_p = L_{W,source} + \Delta L_{div} + \Delta L_{air}$$

$$\Delta L_{air} = \alpha r$$

$$\alpha = 8.686 f^2 \tau_2^{0.5}\left(1.84\cdot 10^{-11}\rho_r^{-1} + \tau_r^{-3}[b_1 + b_2]\right)$$

α: pure tone sound attenuation coefficient in dB/m
r: distance in meter, through which the sound propagates

see Appendix A at 1 for a fully description of attenuation due to air absorption

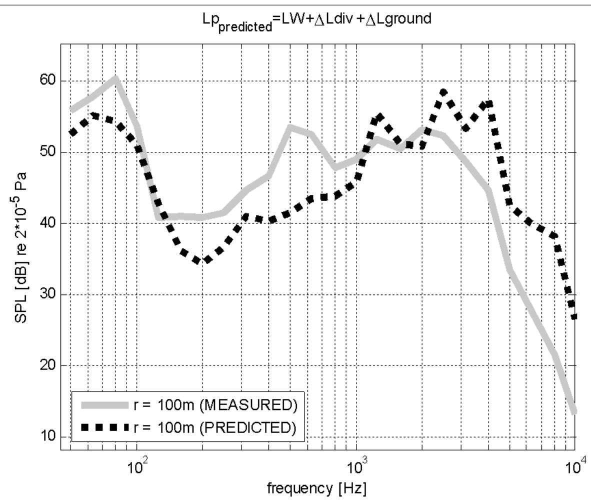


Figure 76. Ground effect

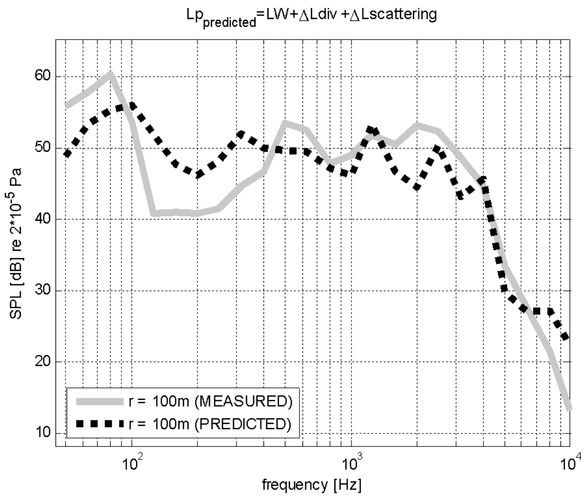
$$L_p = L_{W,source} + \Delta L_{div} + \Delta L_{ground}$$

$$\Delta L_{ground} = 20\log\left|1 + \frac{R_1}{R_2} Q e^{jk(R_2 - R_1)}\right|$$

$$Z = 1 + 9.08\left(\frac{1000 f}{\sigma}\right)^{-0.75} + i11.9\left(\frac{1000 f}{\sigma}\right)^{-0.73}$$

Input parameters to the ground model:
σ=25000

The spherical reflection coefficient is described in chapter 2.1.6 at page 7



$$L_p = L_{W,source} + \Delta L_{div} + \Delta L_{scattering}$$

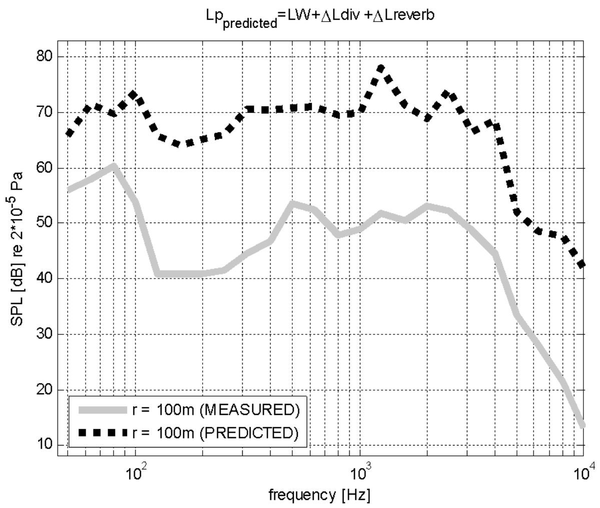
$$\Delta L_{scattering} = k_f T k_p A_e(R_{SC})$$

$$A_e(R_{SC}) = \Delta L(h', \alpha, R') + 20\log(8R')$$

Input parameters to the scattering model:
R_{SC}=100m
h=18 m
d=0.3 m
n"=700 m^{-1}
α=0.1

see chapter 5.3.3 at page 50 for further information of propagation effect on scattering zones according to Nord2000

Figure 77. Scattering effect



$$L_p = L_{W,source} + \Delta L_{div,reverb}$$

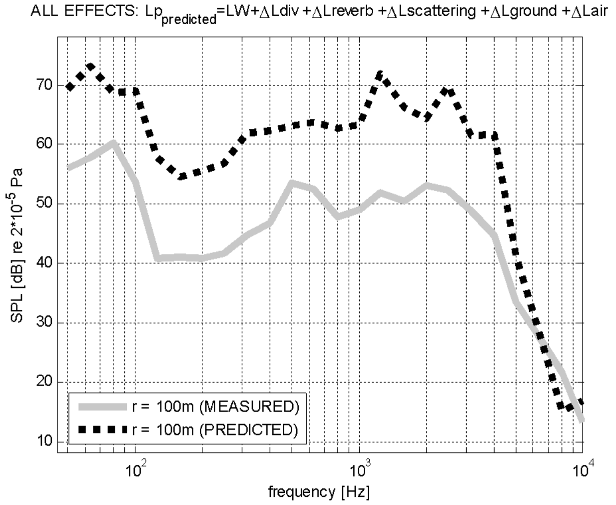
$$\Delta L_{div,reverb} = 10\log\left(\frac{1}{4\pi r^2} + \frac{4}{A}\right)$$

$$A = \frac{0.163V}{T}$$

Input parameters to the scattering model:
T=RT_measured

Figure 78. Divergence combined with reverberation effect

When all effects were combined, it was possible to obtain a single result and put into a plot. This is shown in Figure 79:

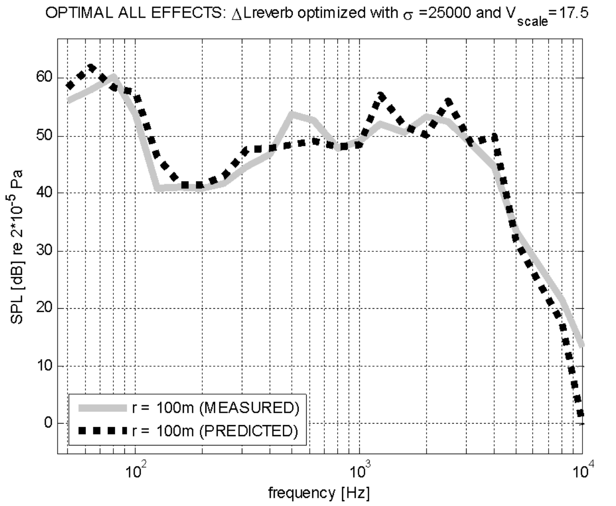


$$L_p = L_{W,source} + \Delta L_{div,reverb} + \Delta L_{scattering} + \\ + \Delta L_{ground} + \Delta L_{air}$$

$V_{scale} = 1$

Figure 79. RT-model all effects

Then the volume in the RT-model was adjusted so that the average difference came as close as possible to zero, i.e. the optimal prediction would be equal to measurement. This is seen in Figure 80 below.



$$L_p = L_{W,source} + \Delta L_{div,reverb} + \Delta L_{scattering} + \\ + \Delta L_{ground} + \Delta L_{air}$$

$V_{scale} = 17.5$

Figure 80. RT-model, all effects but with volume adjustments

In order to see the improvements of the optimal adjustment the level difference between predicted and measured have been plotted for both the case of Figure 79 and Figure 80. This can be seen in Figure 81 below. The average difference for the case of all effects and unadjusted volume became +12.33dB and for the case of adjusted volume +0.036dB. The parameter V_{scale} is a factor with purpose to change the volume and used in calculations as follows:

$$V = r * \frac{r}{2} * H_{trees} * V_{scale}$$

The parameter is chosen to an appropriate value, e.g. V_{scale} =1 the volume remains unchanged, V_{scale} =2 the volume is doubled or V_{scale} =0.5 the volume has half the size.

When finding an optimal adjustment to measurement, the parameter V_{scale} was chosen to 17.5, which means that when the tree height remain the same, the forest area for unadjusted model would be 5000m^2, i.e. half hectare, and for adjusted model about 90000m^2, i.e. 9 hectare.

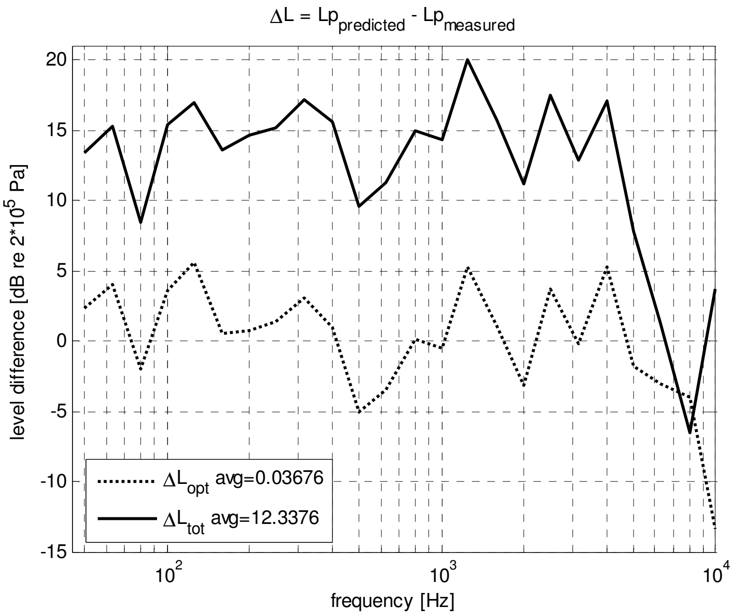


Figure 81. Level difference between predicted and measured, for two cases: all effects and all effects with adjusted volume

More about the RT-forest model can be seen in Appendix C.

6.3 Comparison measured level in forest with measured open field

In order to understand the effect of forest the measured level can be compared with the open field during the same condition, i.e. measured values of RT and SPL over lawn from 9th April. In this way the effect of forest may be seen from another perspective.
The measured distances on the 9th April at Holmevatten were 12m, 50m, 100m and 150m from the source. The equivalent sound pressure level during 20 sec was measured. The result is shown in Figure 82 and Table 20.

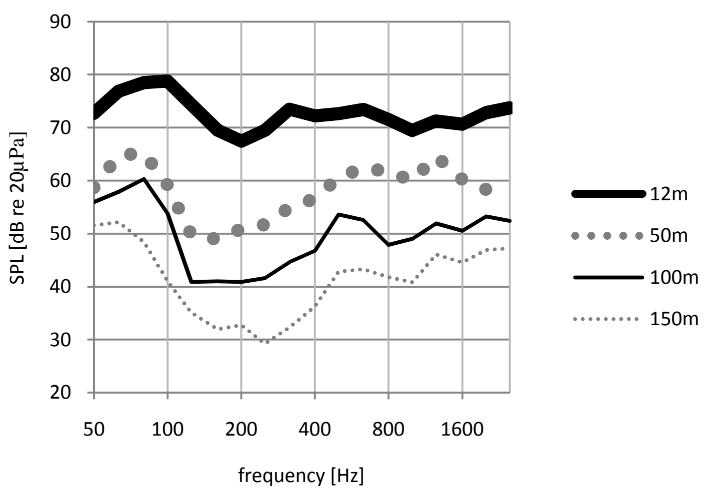


Figure 82. Measured level at different distances

Hz	12m	50m	100m	150m
50	72,7	58,7	56,0	51,5
63	76,9	64,8	57,9	52,2
80	78,5	65,2	60,3	48,4
100	78,8	59,2	53,8	41,0
125	74,3	49,7	40,9	35,1
160	69,5	48,9	41,0	32,0
200	67,5	50,9	40,9	32,7
250	69,5	51,7	41,6	29,2
315	73,5	54,9	44,6	32,3
400	72,2	56,6	46,7	36,2
500	72,6	60,6	53,6	42,8
630	73,4	62,4	52,6	43,3
800	71,5	61,7	47,9	41,8
1000	69,4	60,0	49,0	40,8
1250	71,2	64,6	51,9	46,0
1600	70,7	60,2	50,5	44,6
2000	72,8	58,3	53,2	46,9
2500	73,7	60,1	52,4	47,2

Table 20. Values of measured level at different distances

Starting with calculating the source level for the closest case (12m) the corresponding free field level can be calculated, including ground effect and atmospheric absorption. The results for the calculated free field level can be seen in Figure 83 and in Table 21.

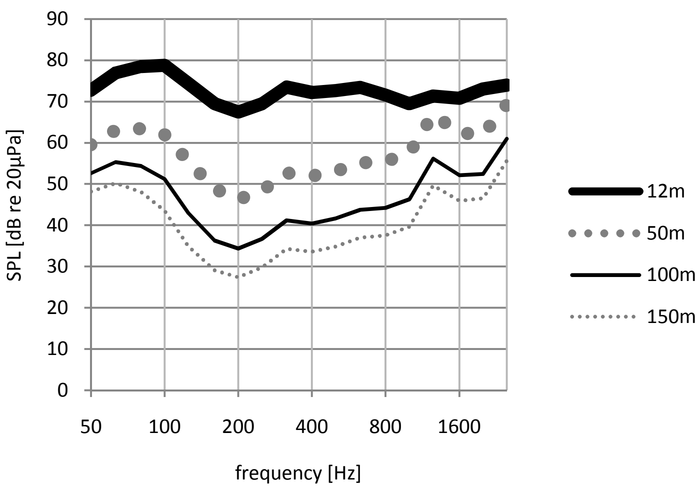


Figure 83. Calculated open field, incl. ground and air absorption

Hz	12m	50m	100m	150m
50	72,7	59,5	52,6	48,2
63	76,9	63,0	55,3	50,2
80	78,5	63,4	54,4	48,1
100	78,8	62,0	51,2	43,5
125	74,3	55,5	43,0	34,9
160	69,5	48,8	36,3	29,1
200	67,5	46,3	34,3	27,4
250	69,5	48,4	36,7	29,8
315	73,5	52,7	41,2	34,3
400	72,2	51,9	40,4	33,6
500	72,7	53,1	41,7	34,9
630	73,5	55,2	43,8	37,0
800	71,5	55,5	44,2	37,5
1000	69,5	57,4	46,3	39,7
1250	71,3	66,9	56,1	49,6
1600	70,8	62,4	52,2	45,9
2000	73,0	61,9	52,5	46,6
2500	74,0	69,2	61,0	55,6

Table 21. Values from calculated open field

Lastly the sound pressure level difference ΔL can be calculated between the levels, which are shown in Figure 84 and Table 22 below.

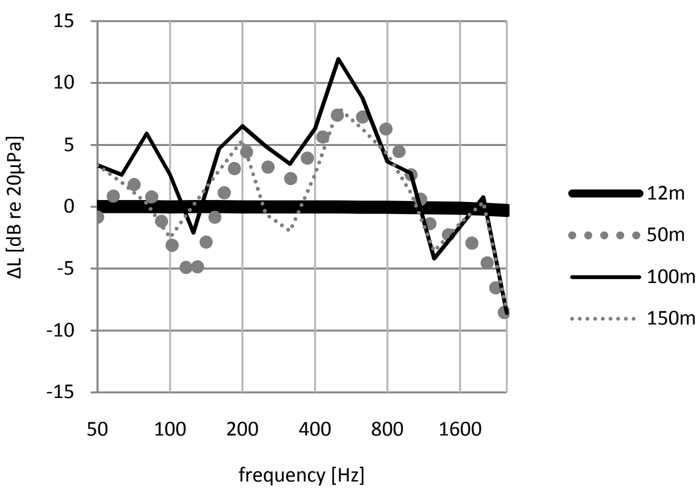


Figure 84. ΔL between measured and open field calculation

Hz	12m	50m	100m	150m
5	0,0	-0,8	3,4	3,4
63	0,0	1,7	2,6	2,0
80	0?0	1,8	5,9	0,3
100	0,0	-2,8	2,	-2,5
125	0,0	-5,8	-2,1	0,1
16	0,0	0,1	4,7	2,9
200	0,0	4,7	6,5	5,4
250	0,0	3,3	4,9	-0,6
315	0,0	2,2	3,5	-2,0
400	0,0	4,7	6,3	2,6
500	0,0	7,5	11,9	8,0
630	0,0	7,3	8,8	6,3
800	0,0	6,2	3,7	4,2
1000	-0,1	2,6	2,7	1,1
1250	-0,1	-2,3	-4,2	-3,6
1600	-0,1	-2,2	-1,6	-1,3
2000	-0,2	-3,6	0,8	0,4
2500	-0,3	-9,1	-8,6	-8,4

Table 22. Values from ΔL between measured and open field calculation

When analysing the results from Figure 84 one can see that the different distances follow each other roughly well over frequency. The level is positive when the measured level is higher than the free field case. The highest difference occurs at 630 Hz at 100m distance, with a difference of 8.8 dB. Here the forest may amplify the sound, probably caused by scattering among tree trunks or downward refraction due to the positive wind gradient during the measured day. The wind profile can be seen in Figure 45.

7 Discussion:

The reason for the sound increase depends on several combined reasons, which have been treated in the chapter Sound pressure increase in forests, see p. 18. But there is probably not one single reason for the increased level, but many different reasons combined. The possible hypothesis for sound pressure level increase in the forest shows clearly that the sound propagation inside forest is complex. The factors affecting the propagation are hard to quantify and sometimes it is difficult to address specific values to the parameters. In order to generalize the sound propagation in forest, it is required to carefully document the forest when measuring.

The reverberation is together with scattering a mixed phenomenon, created by backscattering from trunks. The reverberation depends on a lot of things, e.g. type of forest, type of source, type of meteorological conditions, desired distance. The reverberation increases with increased distance, as can be seen in Figure 28 at page 32. But as soon as the receiver comes out from the forest the reverberation disappears. This has been noticed when measuring at 150m distance in the border of the forest; see Figure 35 at page 37.

The scattering effects increase the sound pressure level both in the sense that it contributes to the reverberation but also indirectly when it disturbs the coherence of ground effect. Scattering reduces the coherence of ground effect and can take away destructive dips, which exclude a lowering of the sound pressure level. Here the medium in which the sound propagation takes place changes in temperature, flow and speed direction, relative humidity and pressure. All these parameters affect the sound propagation. Otherwise, the scattering reduces the sound energy over frequency, and the levels reduces even more with increased distance as can be seen in Figure 58 at page 52.

Often the wind is modelled as a property in one dimension, along a distance, but the more intuitive property would have properties in at least two dimensions, in the horizontal plane. This can be compensated with a projection calculation, giving the angle between propagation and wind direction. In reality it is important to remember that the wind propagates in three dimensions. When vertical wind occur it will affect the sound propagation, the sound will be bent in the direction of the wind. But measuring how the wind exactly is propagating is complex and difficult, especially high above ground. The three dimensional wind is difficult to quantify but it can be measured with the help of a Sodar ("Sound Detection And Ranging") system. This allows measuring wind up to 200m height without a mast using ultrasound technique. The propagation prediction with CNPE uses only horizontal wind propagation.

When regarding the SPL increase in the forest from measurements by Elforsk, it is clear that also here many reasons have interacted and contributed to the relatively high measured levels. The wind direction gave a positive contribution as it was downwind in three of four cases. The fact that also the upwind case had an increased level compared with predictions may hint that the reason is of another kind. A candidate for this is a positive temperature gradient in the forest giving downwards refraction in all direction seen from a sound source inside a forest.

Generally the propagation is affected by the time of the year, by differences in the forest over the seasons. The Elforsk-measurements taking place in December is a time of year where the excess attenuation often is less than during summer. The amount of leafs in the forest is the dominating reason for the annual differences; more vegetation will absorb more sound, please see Figure 16 at page 20 above, where the annual variation in attenuation of a stand of spruce and oak is plotted. The strongest effect of the special local temperature gradient inside forest may be during times when the trees have leaves, i.e. during summer. This effect is addressed to the deciduous trees, which have seasonal leaves. For coniferous trees, the local temperature gradient is somewhat equal over the year.

The fact that sounds from wind turbines are absorbed by the forest, from a distant perspective, and increased within the forest, from an internal perspective, make analogies with resonant absorbers. From a far distance the forest can be perceived as a big resonant absorber, with a covering forest stand as a layered medium and with a canopy with openings. This resonator keeps the sound from propagating in the surrounding space but increases the sound level within the resonator. But the dimensions of a normal pine tree forest make this theory only valid for very low frequencies.

The goal of the first measurement on the 9^{th} of Dec was partly for me to get more acquainted with the equipment and partly to analyze the forest. A mistake was that the wind and temperature in the air was

not measured. The thermo graphical camera gave an understanding of the temperature gradient in air below the canopy but since it showed the temperature of objects surfaces it was not an exact estimation. The goal of the second measurement on the 9^{th} of April was to analyze the forest, with respect to wind- and temperature profile with height and also to measure the impulse responses of the forest after a gun shot.
The differences between the measured forests with respect to climate, season, snow and forest type, make it harder to compare the forests.
The results from the measurements show a long reverberation time (RT) in the forest, with many RT_{30} over 1 sec. It also gives a hint of the scattering in the forest. But after evaluation of the determination of RT in post processing of the measurement system there are lot things to discuss. Only one position gave a resulting RT at low frequencies, the one very close to the loudspeaker. The process in where the RT is determined is questionable. The RT is determined as a linear approximation but the appearance of the sound pressure decay is usually strongly curved. In the instrument the RT is automatically determined, but was sometime concluded to make unrealistic estimations. This gives the need of proper measurement procedure in order to give good data to evaluate. Also the measuring conditions depend on several different factors, which all may vary with weather, time during day, and season. In order to better measure the sound field in forest, the measurements should be performed with a multichannel recording, and at the same time measuring the meteorological conditions at the location. This will take away the deviations from position and time, which have great affect on the results.
The perceived level is affected by the masking. During days with heavy winds the wind blowing in the canopy creates sounds that may mask the wind turbine sound. Masking of sound from forest can at windy locations allow for settlement of wind turbines. Otherwise it could allow for other regulations and restrictions.
When regarding measuring the temperature in the forest it is important to mention that the thermo graphical camera has a margin of error of about +/- 2 degrees.
The flow resistivity of the ground is not satisfyingly determined according to Nordtest, which also give that the ground effect may be incorrect.
Accomplished objectives are that a compilation of different hypothesis has been made, explaining how some phenomena may contribute to the sound increase and some may not.
Measurements have been performed, which have given a deeper understanding of the propagation in forests. Calculations have been performed with the CNPE-model and some interesting results have been obtained, e.g. concerning the influence of refraction on the received sound pressure level. The developed RT-model may have a theoretically weak basis, but gives a glimpse of the actual SPL in the forest. There may be errors in the results; mostly this can be related to rough assumptions. The RT-forest uses traditional outdoor sound propagation algorithms, inspired from Nord2000 and ISO9613. The CNPE uses an advanced algorithm and is in this master thesis regarded as a black box, i.e. the unknown function inside gives an answer directly related to the input. On the other hand the discretization of the ranging step when calculating the levels is not satisfyingly small. This is due to lacking of computer power in order to perform the calculation.
For the measurements, the desired extended frequency range 25Hz-10kHz has not been possible to achieve. Mostly this is due to the lack of a sound source (loudspeaker) that can create sufficiently high sound levels at the low frequencies. For example the RT:s from the measurements at Fjällhult included lot of missing data at 50Hz and 63Hz, so also for the RT measurement at Holmevatten. This was probably due to the loudspeaker which could not produce sufficient output at these low frequencies. A conclusion from this is that reverberation in forest is difficult to measure.

Suggestions of future work and improvements

Since the measurements during this master thesis were carried out during the winter it also only shows results during this period. But if a better overall picture of the sound propagation in the forest would be desired it is preferably to measure the forest during the spring and summer, i.e. when the air is warm and the temperature gives high levels. This would give a better prediction of the actual sound field in the forest. The calculation model can be better. The approach of meeting the reverberation and backscattering with room acoustic approach is not fully satisfyingly. Instead another approach can be

developed and used. The CNPE-model can give better estimation with powerful computer power. Therefore a future work can be to do more calculations with the CNPE-model and predict levels, taking both wind and temperature profile into account.
Another work is to improve the standard IEC61400, so it can include the effect of trees when measuring sound power level in forest.

Personal development

During this period of writing the master thesis I felt my knowledge about outdoor sound propagation has increased. Different theories, models and approaches have been studied and have left their markings and increased my experiences.
Concerning the process of the master thesis, one thing that has been very annoying is that the measurements have been delayed, due to an extremely long and cold winter. There have not been possibilities to measure the sound propagation inside the forest until the 9th of April. This caused a major delay in the work and problem with keeping the project plan.
It is been very useful to perform measurements. I have learned a lot when getting acquainted to equipment and then performing measurement. It is much easier to work with the equipment when knowing the techniques behind it rather than using it as just a black box. Also planning the measurement has been of useful knowledge. At school the access to the equipment could sometimes be taken for granted, but at the company of ÅF the equipment are being used more frequently by different persons and the need of good planning is important.
Also the setup of measurements has been evaluated and I feel I gained a lot of useful knowledge from this. Much thanks to my “colleagues” Stephan Schönfeld and Kristian Anderson who helped me with the equipment.

8 Conclusion

The two main results of this report are: First, that the compilation of different hypotheses presents reasons for the sound pressure increase in forest. The promising hypotheses are reverberation, scattering and sound concentration through refraction. The sound energy is trapped below the canopy due to horizontal backscattering from tree trunks and vertical scattering by the underside of canopy. The report shows that the reverberation in forest increases with distance. This is related to a larger amount of scattered sound energy and increased volume of the "forest room".
From the compilation part it can be understood that attenuation is at low frequencies due to the ground effect and at mid frequencies due to scattering effects. When the propagation is changed into favourable conditions due to downward refraction, the concentrated sound energy may increase the sound pressure level.
Secondly, the two main calculation models, RT-forest and the CNPE, have been presented. The basis for the RT-forest is weak and may not show an exact sound pressure increase. However, a good quality is that it gives a simple frequency plot and may easily be computed by amateurs. A different approach of modelling the reverberation can give some light onto the problem. The CNPE-model was a Matlab-script obtained from the MSc supervisor, but was modified to fit the different cases investigated. The CNPE-model uses an advanced approach and gives the results over range and height. But due to heavy data handling and lacking of RAM-memory, the calculations have been hard for the computer hardware to handle. The CNPE is more accurate than the RT-forest approach but the results have been harder to interpret.
The results from the calculations show that there can be a significant sound pressure level increase in forests, but mainly for low and mid frequencies. The ground effect may not increase the sound pressure level more than +6dB.
A conclusion from Elforsk 09:22 is that the difference in measured and calculated sound immission increases with distance. This conclusion is also shown in this report; from measuring sound at large distances in forests the uncertainties are large.
Another conclusion from this report is that the backscattering by tree trunks reduces the ground effect at medium and low frequencies, when the scattered sound disturbs the coherence between reflected and direct sound. However, the strongest reason for the increased sound pressure level is probably the microclimate inside the forest causing downward refraction of the sound.
The annual differences in Swedish forests are great. The summer forests may include leaves absorbing the main part of high frequencies. The winter conditions in the forests create less absorbing possibilities. During the winter a negative excess attenuation can occur, i.e. a sound level increase, in accordance with the Elforsk 09:22 measurements during December 2008.
A conclusion from measurements is that measuring the reverberation time inside the forest is quite difficult. At short distance a loudspeaker works sufficiently well, but at long distances the signal to noise ratio becomes too low. However, the overall signal-to-noise ratio for a gunshot is better but the frequency response is not reproducible to the same amount and it fails at low frequencies.

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8.2 Abbreviations

Symbol	*Name*	*Unit*
SPL or Lp	Sound Pressure Level	[dB] re $2*10^{-5}$ Pa
SWL or Lw	Sound Power Level	[dB] re $2*10^{-12}$ W
Lp,eq	equivalent SPL over time	[dB] re $2*10^{-5}$ Pa
Lp,ref	reference sound pressure level	$2*10^{-5}$ * [Pa]
T	reverberation time	[sec]
T_{ref}	reference T	1*[sec]
S	surface	[m^2]
S_{ref}	reference surface	1*[m^2]
RH	relative Humidity	%
Ws	wind speed	[m/s]
r	radius of sphere	[m]
V	volume	[m^3]
k	wave number	[m^{-1}]
α	air absorption	[%]
c_0	speed of sound in air	[m/s^2]
z	height above ground	[m]
σ	flow resistivity	[Pa s m^{-2}]
ω	angular frequency	[Hz]
A	attenuation	[dB] re $2*10^{-5}$ Pa
ΔL	propagation effect (ΔL=-A)	[dB] re $2*10^{-5}$ Pa
ΔL_{div}	propagation effect due to spherical divergence	[dB] re $2*10^{-5}$ Pa
ΔL_{air}	propagation effect due to air absorption	[dB] re $2*10^{-5}$ Pa
ΔL_{ground}	ground effect	[dB] re $2*10^{-5}$ Pa
$\Delta L_{scattering}$	scattering effect	[dB] re $2*10^{-5}$ Pa
$\Delta L_{div,reverb}$	spherical divergence combined with reverberation effect	[dB] re $2*10^{-5}$ Pa
Q	spherical reflection coefficient	[-]
R	plane reflection coefficient	[-]
Z	acoustic impedance	[Pa s/m^3]
k_f	weighting function	[-]
T	variable for calculating the coherence coefficient	[-]
k_p	weighting function	[-]
$A_e(R_{SC})$	level correction due to scattering	[dB re 2µPa]
h'	normalised scatter obstacle height	[m]
h	average scatter obstacle height	[m]
α	absorption coefficient of scatter obstacles	[%]
R'	normalised effective distance through the scattering zone	[m]
d	mean trunk diameter	[m]
n''	density of trees, i.e. [number of trees / area]	[m^{-2}]
R_{SC}	total sound path through the scattering zone	[m]

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Appendix A. Air absorption

The effects of air absorption is proposed in ISO9613-part 1 and explained by Salomons, see appendix B in [6].
The air absorption is treated as an attenuation of the sound power level, which is dependent on the distance. The sound pressure level can be calculated with formula below:

$$L_p = L_w - 10\,log\frac{S}{S_{ref}} - \alpha r$$

Here α is the air absorption coefficient in [dB per meter] and r [m] is the distance between source and receiver. The value of α can be obtained using

$$\alpha = 8.686 f^2 \tau_r^{1/2}(1.84 \times 10^{-11}\rho_r^{-1} + \tau_r^{-3}[b_1 + b_2])$$

Here $f: frequency\ in\ [Hz]$ and $\tau_r = \frac{T}{T_{20}}$ and $\rho_r = \frac{p_a}{p_r}$ are dimensionless quantities given by

$T: absolute\ temperature\ [K]$
$T_{20} = 293.15\ [K]$
$p_a: atmospheric\ pressure\ [Pa]$
$p_r = 101\,325\ [Pa]$
and b_1 and b_2 are quantities due to the relaxation frequency of nitrogen and oxygen. With $T_{20} = 293.15\ [K]$ and $p_r = 101\,325\ [Pa]$ b_1 and b_2 are given by

$$b_1 = 0.1068\frac{e^{\left(\frac{-3352}{T}\right)}}{\left(f_{r,N} + \frac{f^2}{f_{r,N}}\right)}$$

$$b_2 = 0.01275\frac{e^{\left(\frac{-2239.1}{T}\right)}}{\left(f_{r,O} + \frac{f^2}{f_{r,O}}\right)}$$

Here $f_{r,N}: relaxtion\ frequency\ of\ nitrogen\ [Hz]$ and
$f_{r,O}: relaxation\ frequency\ of\ oxygen\ [Hz]$, which are given by

$$f_{r,N} = \rho_r \tau_r^{-1/2}\left(9 + 280he^{\left(-4.17\left(\tau_r^{-1/3} - 1\right)\right)}\right)$$

$$f_{r,O} = \rho_r(24 + 40400h(0.02 + h)/(0.391 + h))$$

Here $h: molar\ contentration\ of\ water\ vapour\ in\ the\ atmosphere, in$ %, this is given by

$$h = \frac{r_h \rho_{sat}}{\rho_r}$$

Here $r_h: relative\ humidity\ in$ %

$$\rho_{sat} = 10^{C_{sat}}$$

$$C_{sat} = -6.8346(T_{01}/T)^{1.261} + 4.6151$$

$T_{01}: triple - point\ temperature\ of\ water\ [K]$

$T_{01} = 273.16[K]$

Appendix B. Matlab code for RT-forest calculation model

The calculations have mainly been performed in Matlab. Here is the main code for plotting the results, which are shown in latter appendix: Results from the RT-forest calculation model.

```
clear all
clc
close all
%%% Sound Pressure Level in Forest for 1/3 oct band
% Description
% In this program the following parameters are predicted or taken from
% measurements:
% Lp_measured = Sound pressure level    (measured)
% LW = sound power level               (measured)
% RT = reverberation time              (measured)
% Lp_predicted = sound pressure level   (predicted)
%
%%-----------------------
%% DATA FROM MEASUREMENTS:
%%-----------------------
f=[50 63 80 100 125 160 200 250 315 400 500 630 800 1000 1250 1600 2000 2500 3150 4000 5000 6300 8000 10000];
load data_measurement_9th_April.mat
%  LP_background_forest      background level of forest
%  LP_background_lawn        background level at lawn
%  LP_forest                 measured level in forest
%  LP_forest_corrected       measured level in forest, corrected for background noise
%  LP_lawn                   measured level at lawn
%  LP_lawn_corrected         measured level in lawn, corrected for background noise
%  LW                        calculated LW
%  RT_optimal                Reverberation times, 12 and 50m measured
%                            using loudspeaker, 100 and 150m measured using pistol
%%-----------------------------------
%% INPUT: CONDITIONS FROM MEASURMENTS
%%-----------------------------------
r=[12 50 100 150];          %desired distances for prediction
zs=1.5; zr=1.5;             %zs=source height, zr=receiving height, b=the width of the measured area
H_trees=18; avg_dist_trees=3.8; avg_diameter_trees=0.3; %=0.23;
%Geometrical setup and properties of forest dimensions
b=r/2;                      %width of measured area
l=130;                      %length of measured area
trees_per_hectare=700; trunkalpha=0.1;  %absorption coefficient of trees
alpha_e=25;
%Meteorological conditions
RH=50;T=6.5;           %RH=relative humidity, T= Temp in celcius
%Ground
sig=25*1000;           %According to Nordtest Method measurements at 9th April
c0=331.3+0.606*T;      %c0=speed of sound due to temperature
LP=LP_forest_corrected
%%-----------------------------------------------------
%% CONTROLLING PARAMETERS
%%-----------------------------------------------------
% Choose distance, as X:
% 1 = 12 m, 2 = 50 m, 3 = 100m,  4 = 150m
X=1;
active=0;      %0=RT not regarded, 1=RT is regarded
model=1;       %choose ground effect model
Vscale=1;           %a scale factor on forest Volume in the reverberation calculation
%%-------------------------------------------------------------
%% CALCULATIONS:
%%-------------------------------------------------------------
% STEP 1. Sound power level must be determined from the closest case, i.e. r(1)=12m
[R1 R2 theta]=geometry(r(1),zs,zr,H_trees);
model=1;
[dLground Q]=ground_effect(f,c0,theta,sig,R1,R2,r(1),zr,zs,alpha_e,model);
for i=1:length(f)
   LW(i)=LP(1,i)+10*log10(4*pi*r(1)^2)-dLground(i);
end
% STEP 2. When the SWL of the source is calculated, the SPL for different
% distances can be predicted. For easier understanding the distances is
% plotted separately and therefore the desired distance need to be chosen:
%%----------------------------------------------
%% DESIRED DISTANCE IS CHOSEN IN DIFFERENT VECTORS:
%%----------------------------------------------
r=r(X); Lp_measured=LP(X,:); RT=RT_optimal(X,:);
%%----------------------------------------------
```

```
%% EFFECTS:
%%-------------------------------------------------
dLdiv=divergence(r);
dLair=air_absorption(f,RH,T,r);
[R1 R2 theta R_sc]=geometry(r,zs,zr,H_trees);
[dLground Q]=ground_effect(f,c0,theta,sig,R1,R2,r,zr,zs,alpha_e,model);
dLscatt=scattering_by_trees(f,avg_diameter_trees,H_trees,avg_dist_trees,trunkalpha,r,zs,zr);
[dLreverb dLdiv]=reverb(RT,r,b,Vscale,H_trees,active,dLdiv);
%--------------------------------------------------------------
% DIVERGENCE-effect figure(1)
%--------------------------------------------------------------
%dLdiv=-10*log10(4*pi*r^2);
Lp_predicted=LW+dLdiv;
figure(1)
semilogx(f,Lp_measured,'c','LineWidth',5)
hold on
semilogx(f,Lp_predicted,':k','LineWidth',5)
legend(['r = ',num2str(r),'m (MEASURED)'],['r = ',num2str(r),'m (PREDICTED)'],'location','southwest');xlabel('frequency [Hz]');ylabel('SPL
[dB] re 2*10^{-5} Pa')
title(['Lp_{predicted}=LW+\DeltaLdiv = ',num2str(r),'m']);grid on
low=min([min(min(Lp_predicted)) min(min(Lp_measured))]);    %finds lowest value for plotting
high=max([max(max(Lp_predicted)) max(max(Lp_predicted))]);           %finds highest value for plotting
AXIS([min(f)-5 max(f)+5 low-2 high+2])
saveas(gcf,['D',num2str(r),'_divergence.emf'])
%-----------------------
% AIR-effect figure(2)
%-----------------------
%dLair=air_absorption(f,RH,T,r);
Lp_predicted=LW+dLair+dLdiv;
figure(2)
semilogx(f,Lp_measured,'c','LineWidth',5)
hold on
semilogx(f,Lp_predicted,':k','LineWidth',5)
legend(['r = ',num2str(r),'m (MEASURED)'],['r = ',num2str(r),'m (PREDICTED)'],'location','southwest');xlabel('frequency [Hz]');ylabel('SPL
[dB] re 2*10^{-5} Pa')
title(['Lp_{predicted}=LW+\DeltaLair +\DeltaLdiv']);grid on
low=min([min(min(Lp_predicted)) min(min(Lp_measured))]);    %finds lowest value for plotting
high=max([max(max(Lp_predicted)) max(max(Lp_measured))]);           %finds highest value for plotting
AXIS([min(f)-5 max(f)+5 low-5 high+5])
saveas(gcf,['A',num2str(r),'_air.emf'])
%-------------------------------------------
% GROUND-effect figure(3) (FREE FIELD CONDITION)
%-------------------------------------------
%[R1 R2 theta R_sc]=geometry(r,zs,zr,H_trees);
%[dLground Q]=ground_effect(f,c0,theta,sig,R1,R2,r,zr,zs,alpha_e,model);
Lp_predicted=LW+dLground+dLdiv;
figure(3)
semilogx(f,Lp_measured,'c','LineWidth',5)
hold on
semilogx(f,Lp_predicted,':k','LineWidth',5)
legend(['r = ',num2str(r),'m (MEASURED)'],['r = ',num2str(r),'m (PREDICTED)'],'location','southwest');xlabel('frequency [Hz]');ylabel('SPL
[dB] re 2*10^{-5} Pa')
title(['Lp_{predicted}=LW+\DeltaLdiv +\DeltaLground       \sigma _{forest}=',num2str(sig)]);grid on
low=min([min(min(Lp_predicted)) min(min(Lp_measured))]);    %finds lowest value for plotting
high=max([max(max(Lp_predicted)) max(max(Lp_measured))]);           %finds highest value for plotting
AXIS([min(f)-5 max(f)+5 low-5 high+5])
saveas(gcf,['B',num2str(r),'_ground.emf'])
%-------------------------------------------
% SCATTERING-effect figure(4)
%-------------------------------------------
%dLscatt=scattering_by_trees(f,avg_diameter_trees,H_trees,avg_dist_trees,trunkalpha,r,zs,zr);
Lp_predicted=LW+dLdiv+dLscatt;
figure(4)
semilogx(f,Lp_measured,'c','LineWidth',5)
hold on
semilogx(f,Lp_predicted,':k','LineWidth',5)
legend(['r = ',num2str(r),'m (MEASURED)'],['r = ',num2str(r),'m (PREDICTED)'],'location','southwest');xlabel('frequency [Hz]');ylabel('SPL
[dB] re 2*10^{-5} Pa')
title(['Lp_{predicted}=LW+\DeltaLdiv +\DeltaLscattering']);grid on
low=min([min(min(Lp_predicted)) min(min(Lp_measured))]);    %finds lowest value for plotting
high=max([max(max(Lp_predicted)) max(max(Lp_measured))]);           %finds highest value for plotting
AXIS([min(f)-5 max(f)+5 low-5 high+5])
saveas(gcf,['C',num2str(r),'_scattering.emf'])
%----------------------------------------------
% REVERB-effect figure(5)
```

```
%-------------------------------------------------
%[dLreverb dLdiv]=reverb(RT,r,b,Vscale,H_trees,active,dLdiv);
Lp_predicted=LW+dLreverb;
figure(5)
semilogx(f,Lp_measured,'c','LineWidth',5)
hold on
semilogx(f,Lp_predicted,':k','LineWidth',5)
legend(['r = ',num2str(r),'m (MEASURED)'],['r = ',num2str(r),'m (PREDICTED)'],'location','southwest');xlabel('frequency [Hz]');ylabel('SPL [dB] re 2*10^{-5} Pa')
title(['Lp_{predicted}=LW+\DeltaLdiv +\DeltaLreverb']);grid on
low=min([min(min(Lp_predicted)) min(min(Lp_measured))]);    %finds lowest value for plotting
high=max([max(max(Lp_predicted)) max(max(Lp_measured))]);           %finds highest value for plotting
AXIS([min(f)-5 max(f)+5 low-5 high+5])
saveas(gcf,['E',num2str(r),'_div_reverb.emf'])

%%-------------------------------------------------------
% TOTAL EFFECTS figure(6)
%%-------------------------------------------------------
Lp_predicted=LW+dLair+dLground+dLscatt+dLdiv+dLreverb;
figure(6)
semilogx(f,Lp_measured,'c','LineWidth',5)
hold on
semilogx(f,Lp_predicted,':k','LineWidth',5)
legend(['r = ',num2str(r),'m (MEASURED)'],['r = ',num2str(r),'m (PREDICTED)'],'location','southwest');xlabel('frequency [Hz]');ylabel('SPL [dB] re 2*10^{-5} Pa')
title(['ALL EFFECTS: Lp_{predicted}=LW+\DeltaLdiv +\DeltaLreverb +\DeltaLscattering +\DeltaLground +\DeltaLair']);grid on
low=min([min(min(Lp_predicted)) min(min(Lp_measured))]);    %finds lowest value for plotting
high=max([max(max(Lp_predicted)) max(max(Lp_measured))]);           %finds highest value for plotting
AXIS([min(f)-5 max(f)+5 low-5 high+5])          %finds highest value for plotting
saveas(gcf,['F',num2str(r),'_total_levels.emf'])
diff_tot=Lp_predicted-Lp_measured;
avg_tot=mean(diff_tot)

%%------------------------
% OPTIMAL EFFECTS figure(7)
%%------------------------
%Geometrical setup and properties of forest dimensions
zs=1; zr=1.5;             %zs=source height, zr=receiving height, b=the width of the measured area
b=r/2;
l=130;                    %length of measured area
H_trees=18; avg_dist_trees=3.8; avg_diameter_trees=0.3; %=0.23;
trees_per_hectare=700; trunkalpha=0.1;              %absorption coefficient of trees
%Meteorological conditions
RH=50;T=6.5;  %RH=relative humidity, T= Temp in celcius
%Ground
sig=25*1000;                  %According to Nordtest Method measurements at 9th April
active=1;
X=1
Vscale=17.5;          %a scale factor on forest Volume in the reverberation calculation
% ALL FUNCTIONS
dLair=air_absorption(f,RH,T,r);[R1                    R2                    theta                    R_sc]=geometry(r,zs,zr,H_trees);[dLground Q]=ground_effect(f,c0,theta,sig,R1,R2,r,zr,zs,alpha_e,model);dLscatt=scattering_by_trees(f,avg_diameter_trees,H_trees,avg_dist_trees,trunkalpha,r,zs,zr);[dLreverb dLdiv]=reverb(RT,r,b,Vscale,H_trees,active,dLdiv);
Lp_predicted=LW+dLair+dLground+dLscatt+dLdiv+dLreverb;
figure(8)
semilogx(f,Lp_measured,'c','LineWidth',5)
hold on
semilogx(f,Lp_predicted,':k','LineWidth',5)
legend(['r = ',num2str(r),'m (MEASURED)'],['r = ',num2str(r),'m (PREDICTED)'],'location','southwest');xlabel('frequency [Hz]');ylabel('SPL [dB] re 2*10^{-5} Pa')
title(['OPTIMAL ALL EFFECTS: \DeltaLreverb optimized with \sigma =',num2str(sig),' and V_{scale}=',num2str(Vscale),' ']);grid on
low=min([min(min(Lp_predicted)) min(min(Lp_measured))]);    %finds lowest value for plotting
high=max([max(max(Lp_predicted)) max(max(Lp_measured))]);           %finds highest value for plotting
AXIS([min(f)-5 max(f)+5 low-5 high+5])          %finds highest value for plotting
saveas(gcf,['OPT',num2str(r),'_optimal_levels.emf'])

figure(9)
diff_opt=Lp_predicted-Lp_measured;
semilogx(f,diff_opt,':k','LineWidth',2)
hold on
semilogx(f,diff_tot,'k','LineWidth',2)
avg_opt=mean(diff_opt)
low=min(diff_opt);    %finds lowest value for plotting
high=max(diff_opt);           %finds highest value for plotting
AXIS([min(f)-5 max(f)+5 -15 21])
```

```
title(['\DeltaL = Lp_{predicted} - Lp_{measured}'])
xlabel('frequency [Hz]')
ylabel('level difference [dB re 2*10^{-5} Pa]')
legend(['\DeltaL_{opt} avg=',num2str(avg_opt)],['\DeltaL_{tot} avg=',num2str(avg_tot)],'Location','Southwest')
grid on
saveas(gcf,['OPT',num2str(r),'_optimal_difference.emf'])
```

The codes of functions called by the script above are presented below. These functions are somewhat generalized and treats air absorption, geometry properties of the measured situation, attenuation due to divergence, ground effect, scattering effect and amplifying effect by reverberation.

Air absorption

```
% Sound Absorption according to Erik M. Salomons
% "Computational atmpspheric acoustics"
% based on ISO 9613-1:1993
function dLair=air_absorption(f,RH,T,r)
ht = RH;
pr=101325;                    % Reference ambient pressure
pa=pr;                        % Default ambient pressure
T=273.15+T;                   % Temperature in kelvin
T0=293.15;                    % Reference temperature
T01=273.16;
C=-6.8346*(T01/T)^1.261+4.6151;      % eq B.50, Eric
Salomons
psat=pr*10^C;                 % eq B.49, Eric Salomons
h=ht*psat/pa;                 % eq B.48, Eric Salomons   %
Molar conc of water vapour(%)
tao_r=T/T0;                   % Eric Salomons
rho_r=pa/pr;
frO=(rho_r)*(24+4.04*10^4*h*(0.02+h)/(0.391+h));
% eq B.47, Eric Salomons Relaxation freq of oxygen
frN=(rho_r)/sqrt(tao_r)*(9+280*h*exp(-4.17*((tao_r)^(-1/3)-1)));
% eq B.46, Eric Salomons
b1=0.1068*exp(-3352/T).*(frN+(f.^2/frN)).^(-1);            %
eq B.44, Eric Salomons
b2=0.01275*exp(-2239.1/T).*(frO+(f.^2/frO)).^(-1);          %
eq B.45, Eric Salomons
airalpha=8.686*f.*f.*sqrt(tao_r).*((1.84*10^(-11).*(rho_r)^(-
1)+tao_r^(-3).*(b1+b2)));% eq B.43, Eric Salomons
%Level calculation
for i=1:length(r)      %looping for each distance
   for ii=1:length(f)  %looping for each frequency
      dLair(i,ii)=-airalpha(ii)*r(i);
   end
end
```

Geometry properties

```
function [R1 R2 theta R_sc]=geometry(r,zs,zr,H_trees)
for i=1:length(r)
   R1(i)=sqrt(r(i)^2+(zr-zs)^2);     %direct ray path
   R2(i)=sqrt(r(i)^2+(zr+zs)^2);     %reflected ray path
   theta(i)=acos((zr+zs)/R2(i));     %angle of incidence

   if zs>H_trees
      a = ((H_trees-zr)/(zs-zr))*r(i);    %Horizontal distance to receiver
where sound from the source hits the tree tops
      R_sc = sqrt(a^2+(H_trees-zr)^2);    %How long does the sound go
through the forest
   else
      R_sc = sqrt(r(i)^2+(zs-zr)^2);      %How long does the sound go
through the forest
   end
end
```

Divergence attenuation

```
function [dLdiv]=divergence(r)
for i=1:length(r)
   dLdiv(i)=-10*log10(4*pi*r.^2);
end
```

Ground effect

```
% Function calculating relative sound pressure level generally
according to eq D.54 in
% Erik Salomons p.133
function [dLground
Q]=ground_effect(f,c0,theta,sig,R1,R2,r,zr,zs,alpha_e,X)
k=2*pi.*f/c0;
%alpha_e=25;      % rate of exponential decrease of porosity with
depth
gamma_air=7/5;      % ratio of specific heats
rho_air=1.2;
if X==1; %X=1 USE Delaney & Bazely model
   for m=1:length(r)
      for n=1:length(f)
         %%% Delaney & Bazely model
         %%% "Grass"
         % sigma=250000; % effective flow resistivity
         R=1+0.0511*(sig/f(n)).^0.75;
         X=0.0768*(sig./f(n)).^0.73;
         %ZG=1+9.08*(1000*f(n)/sig)^(-0.75)-
j*11.9*(1000*f(n)/sig)^(-0.73)
         ZG=R-j*X;     % Impedance
         betaG=1./ZG; % Admittance
         a=r(m);
         Q=get_q_bac_v1(zr,zs,a,k(n),betaG); % Spherical
reflection factor

dL(n)=20*log10(abs(1+Q*(R1(m)/R2(m))*exp(j*k(n)*R2(m)-
```

Scattering by trees

```
% Beräkning av utbredningsförlusten delta_L_s genom spridning från
träd vid ljudfält
% i skogar enligt Nord2000 modellen
% Autor: Stephan Schönfeld, 20090206
% Used as a function of Elis Johansson 20100415
%dLscatt=scattering_by_trees(f,avg_diameter_trees,H_trees,avg_dist_t
rees,trunkalpha,r,zs,zr)
function
dLscattering=scattering_by_trees(f,avg_diameter_trees,H_trees,avg_di
st_trees,trunkalpha,r,zs,zr)
for i=1:length(r)
c_0 = 343;     %[m/s] speed of sound @ 20 deg C
k_p = 1.25;    %[-] proportionality constant. 1.25 for forests
%% Constants and tables
ka_i = [0 0.7 1 1.5 3 5 10 20];
k_fi = [0 0 0.05 0.2 0.7 0.82 0.95 1];
R_i_i = [0.0625; 0.125; 0.25; 0.5; 0.75; 1; 1.5; 2; 3; 4; 6; 10];
alpha_i = [0 0.2 0.4];
h_i_i = [0.01 0.1 1];
delta_L_ha = [  6 6 6 6 6 6 6 6 6;
           0 0 0 0 0 0 0 0 0;
           -7.5 -7.5 -7.5 -6.0 -7.0 -7.5  -6.0 -7.0 -7.5;
           -14.0 -14.25 -14.5 -12.5 -13.5 -14.5 -12.5 -13.0 -14.0;
           -18.0 -18.8 -19.5 -17.3 -18.0 -19.0 -16.0 -16.8 -17.7;
           -21.5 -22.5 -23.5 -20.5 -21.6 -22.8 -19.3 -20.5 -21.3;
           -26.3 -27.5 -29.5 -25.5 -27.2 -29.0 -24.0 -25.5 -26.3;
           -31.0 -32.5 -34.5 -30.0 -32.0 -33.3 -27.5 -29.5 -30.8;
```

```
j*k(n)*R1(m))));
            QQ(m,n)=Q;
        end
        dLground(m,:)=(dL);
    end
    Q=QQ;
elseif X==2; %USE: Attenborough two-parameter model:
    for m=1:length(r)
        for n=1:length(f)
            %%% Attenborough two-parameter model:
            %%% Attenborough, JASA 92(1), pp. 418 (1992) "Ground
parameter
            %%% information for propagation  modeling"
            % But also in:
            %%% "Acoustical models and measurements treating the
ground as a
            %%% rigid", by Keith Attenborough eq 12 page 4 (613)
            %%% "Pine forest"
            % effective flow resistivity
            ZG=(1-j)/sqrt(pi*gamma_air*rho_air)*sqrt(sig./f(n))-
j*c0*alpha_e./(8*pi*gamma_air*f(n));
            betaG=1./ZG; % Admittance
            a=r(m);
            Q=get_q_bac_v1(zr,zs,a,k(n),betaG); % Spherical
reflection factor

dL(n)=20*log10(abs(1+Q*(R1(m)/R2(m))*exp(j*k(n)*R2(m)-
j*k(n)*R1(m))));
            QQ(m,n)=Q;
        end
        dLground(m,:)=(dL);
    end
    Q=QQ;
elseif X==3; %USE: Attenborough three-parameter model slit
pore model: Predicting outdoor sound page 62
    disp('Attenborough three-parameter model slit pore model!')
    T=2.5;  %T = Tortuosity (=1.7)
    omega=0.4;  %omega = porosity (=0.4)
    N_PR=0.715;     %Prandtl's number for air
    Rs=sig;         %flow resistivity
    rho_0=rho_air;          %fluid density [kg/m^3]
    sA=0.5;         %typical values between 0.745-1
    for m=1:length(r)
        for n=1:length(f)
            w=2*pi*f(n);
            lambda=sA*sqrt((3*rho_0*w*T)/(omega*Rs));
            H_lambda=1-tanh(lambda*(sqrt(N_PR))*sqrt(-
j))/(lambda*(sqrt(N_PR))*sqrt(-j));
%rho_lambda=(T/omega)*rho_f*H_lambda;
            rho_omega=rho_0/H_lambda;
            gammaP0=(rho_0*c0^2);
            C_omega=(gammaP0)^(-1)*(gamma_air-(gamma_air-
1)*H_lambda);
            c_lambda=C_omega*(c0/(2*pi*f(n)^2)); %omformar
omega till lambda
            k=w*(T*rho_omega*C_omega)^(0.5);
            Zc=(rho_0*c0)^-
1*((T/omega^2)*rho_omega/C_omega)^0.5;
            betaG=1./Zc; % Admittance
            a=r(m);
            Q=get_q_bac_v1(zr,zs,a,k,betaG); % Spherical reflection
factor

dL(n)=20*log10(abs(1+Q*(R1(m)/R2(m))*exp(j*k*R2(m)-
j*k*R1(m))))
            QQ(m,n)=Q;
        end
        dLground(m,:)=(dL);
        end
    Q=QQ;
else
    disp('ERROR: Specify ground model!')
    Q=0;
    dLground=0;
end
```

```
            -40.0 -42.5 -45.5 -37.5 -40.5 -42.9 -34.2 -36.0 -37.8;
            -49.5 -52.5 -56.3 -45.5 -49.5 -52.5 -40.4 -42.8 -45.5;
            -67.0 -72.5 -78.0 -62.0 -67.0 -72.0 -52.5 -56.2 -60.0;
            -102.5 -113.0 -122.5 -94.7 -103.7 -112.0 -78.8 -84.0 -89.7];
% table from appendix J
%% Calculation
% Distance in scattering zone
if zs>H_trees
    a = ((H_trees-zr)/(zs-zr))*r(i);    %Horizontal distance to receiver
where sound from the source hits the tree tops
    R_sc = sqrt(a^2+(H_trees-zr)^2);   %How long does the sound go
through the forest
else
    R_sc = sqrt(r(i)^2+(zs-zr)^2);   %How long does the sound go
through the forest
end
% Scattering
ka_interpol = 2*pi*f/c_0*avg_diameter_trees/2;
n_ii = 2/(avg_dist_trees^2*sqrt(3));%[number/m^2] tree density with
trees in hexagonal packing
nQ = n_ii * avg_diameter_trees; %parameter nQ from Nord2000
T = min(1,(R_sc*nQ/1.75)^2); %parameter T from Nord2000

k_f= interp1(ka_i,k_fi,ka_interpol,'linear',1);
%plot(ka_i,k_fi,'o',ka_interpol,k_f)
h_i = H_trees*nQ; %[m] normalized scatterer obstacle height
R_i = nQ * R_sc; %normalised effective distance through the
scattering zone
%Tricubic interpolation
delta_L_size = size(delta_L_ha);
    % interpolate along h_i
    for ii=1:3
        for jj=1:delta_L_size(1)
        delta_L_Ra(jj,ii) = interp1(h_i_i,delta_L_ha(jj,(ii-1)+[1 4
7]),h_i,'spline');
        end
    end
    % interpolate along trunkalpha
    for ii=1:delta_L_size(1)
        delta_L_R(ii,1) =
interp1(alpha_i,delta_L_Ra(ii,:),trunkalpha,'spline');
    end
    %interpolate along R'
    delta_L_haR = interp1(R_i_i,delta_L_R,R_i,'spline');
    A_e = delta_L_haR + 20*log10(8*R_i);
    dL = max([-15*ones(1,length(f)); (k_f*T*k_p*A_e)]); %result: level
reduction from scattering
    dLscattering(i,:)=dL;   %Making a matrix to export
end
```

Reverb

```
function [dLreverb dLdiv]=reverb(RT,r,b,Vscale,H_trees,active,dLdiv)
if active==1;
    dLdiv=0;
    V=(r)*(r/2)*H_trees*Vscale;          %the volume of the forest room
varies with distance
    for i=1:length(r)                %looping for each distance
        for ii=1:length(RT)          %looing for each RT (i.e. over
frequency)
            A(i,ii)=0.163*V(i)/RT(i,ii);
            dLreverb(i,ii)=10*log10(1/(4*pi*r(i)^2)+4/A(i,ii));
        end
    end
    disp(['dLdiv NOT active, RTfunction active'])
else
    disp(['dLdiv active, RTfunction NOT active'])
    dLreverb=0;
    dLdiv=dLdiv;
    return
end
```

Appendix C. Results from the RT-forest calculation model

Here the results from the RT-forest calculation model are presented. The code is presented in 0 at page 2. The result is a comparison between data from measurements on the 9th April and the calculation model, which take attenuation due to atmospheric absorption, ground, scattering, divergence and a combination of reverberation and divergence.

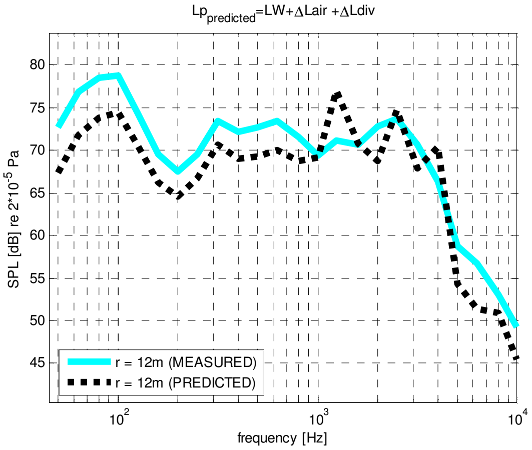
The sound power level LW is calculated from the sound pressure level at 12m distance, including ground effect and divergence. This also gives the nice optimal figure of G12 below. The flow resistivity of $25*10^3$ was determined during measurements on 9th of April according to Nordtest Method Acou 104, see chapter about ground impedance at page 34. The basic formulas used are:

I $L_P = L_W + \Delta L_{air} + \Delta L_{ground} + \Delta L_{scattering} + \Delta L_{divergence}$ *Excl. reverberation*

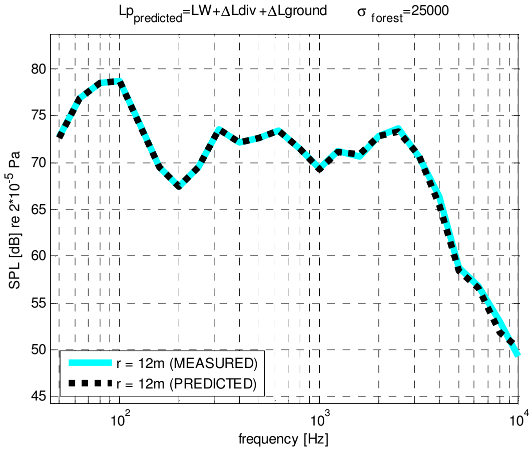
II $L_P = L_W + \Delta L_{air} + \Delta L_{ground} + \Delta L_{scattering} + \Delta L_{divergence+reverberation}$ *Incl. reverberation*

The basic formula (I) is borrowed from Nord2000 and ISO9613. Formula (II) is developed in this thesis and is derived from the Sabine's room equation. The name of each plot follows a system given in the table below. The table is divided into distances, effects and used equation. Most often equation I is used, but for cases A-E the effects are isolated together with LW, in order to show the influence of the single effect. For example the case when only the scattering effect at 100m distance is regarded is called C100:

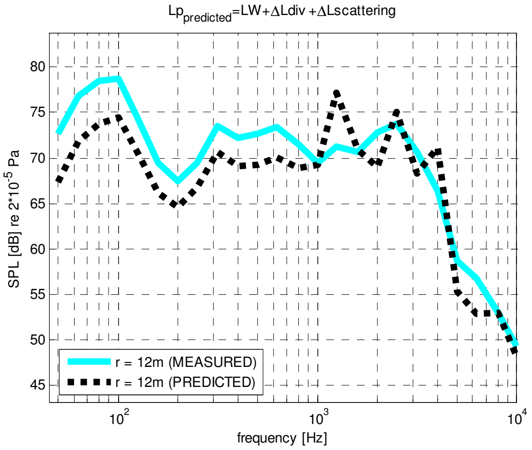
	ΔL_{air}	ΔL_{ground}	$\Delta L_{scattering}$	$\Delta L_{divergence}$	$\Delta L_{reverb} + \Delta L_{divergence}$	*All effects*	*Optimal*
r=12m	*A12*	*B12*	*C12*	*D12*	*E12-II*	*F12-II*	*G12*
r=50m	*A50*	*B50*	*C50*	*D50*	*E50-II*	*F50-II*	*G50*
r=100m	*A100*	*B100*	*C100*	*D100*	*E100-II*	*F100-II*	*G100*
r=150m	*A150*	*B150*	*C150*	*D150*	*E150-II*	*F150-II*	*G150*



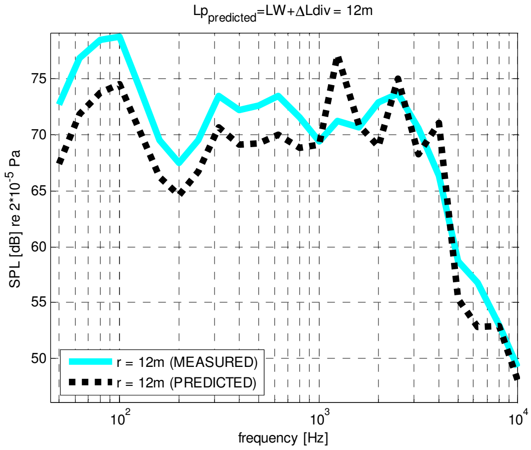
A12 = ΔL_{air}



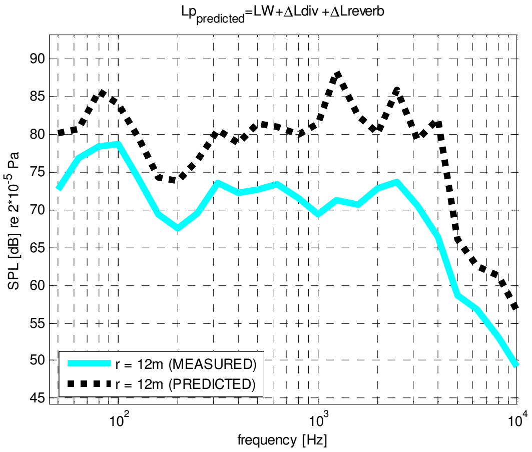
B12 = ΔL_{ground}



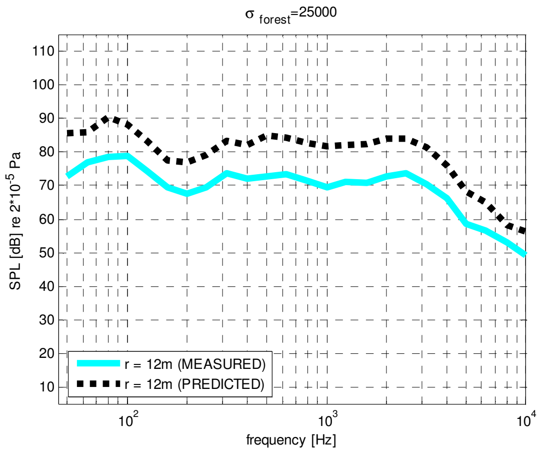
C12 = $\Delta L_{scattering}$



D12 = $\Delta L_{divergence}$



E12 = ΔL_{reverb}+ $\Delta L_{divergence}$



F12 = All effects

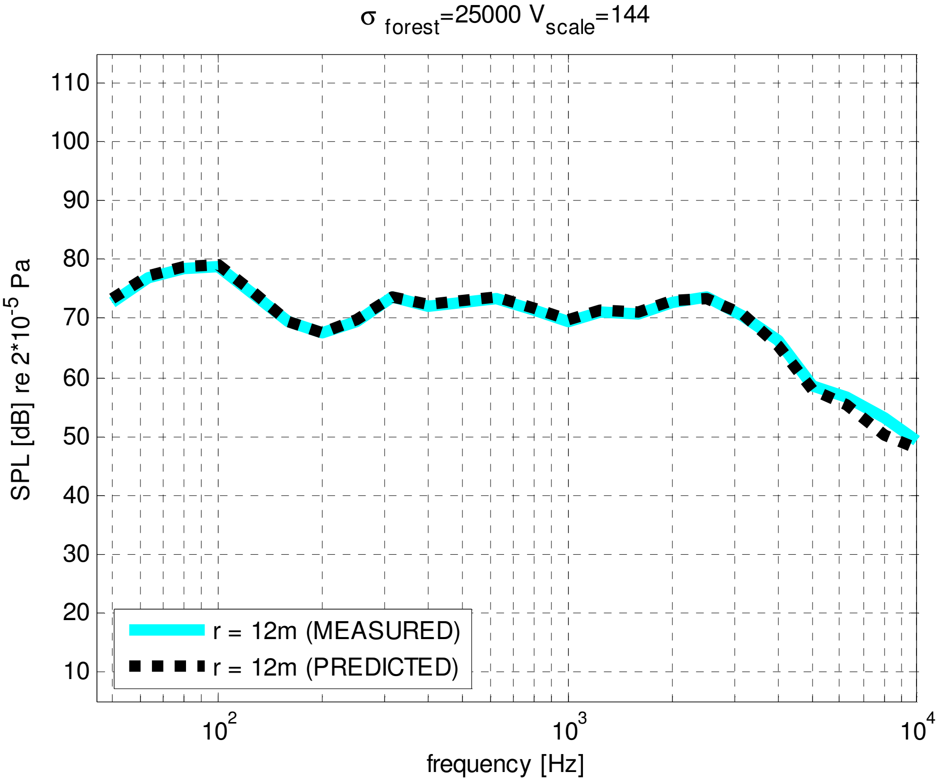
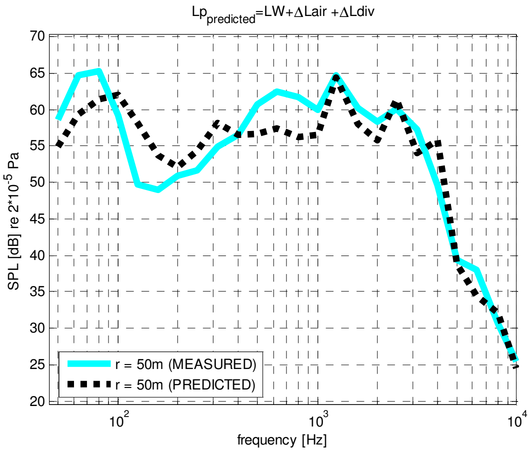
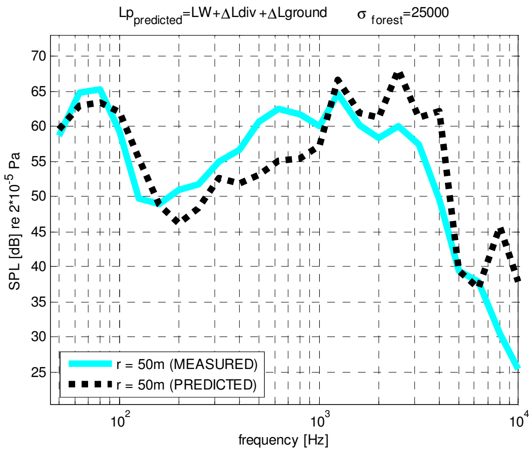


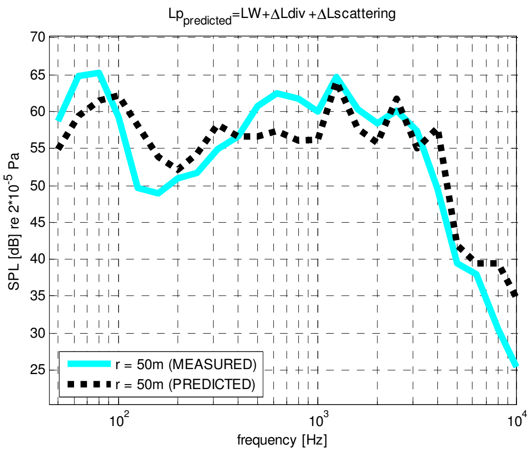
Figure 85. G12 = Optimal



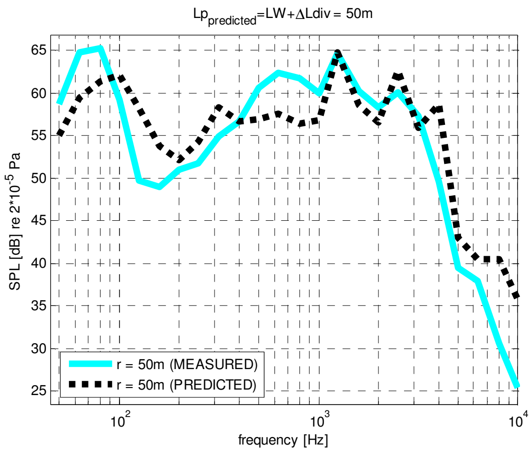
$A50 = \Delta L_{air}$



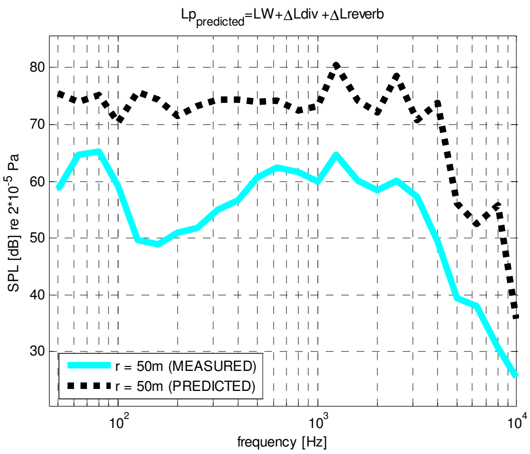
$B50 = \Delta L_{ground}$



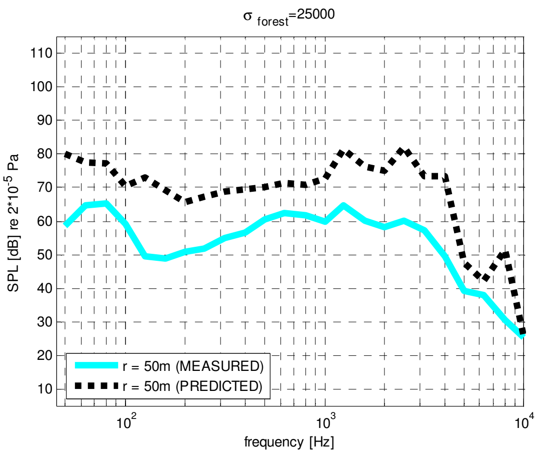
$C50 = \Delta L_{scattering}$



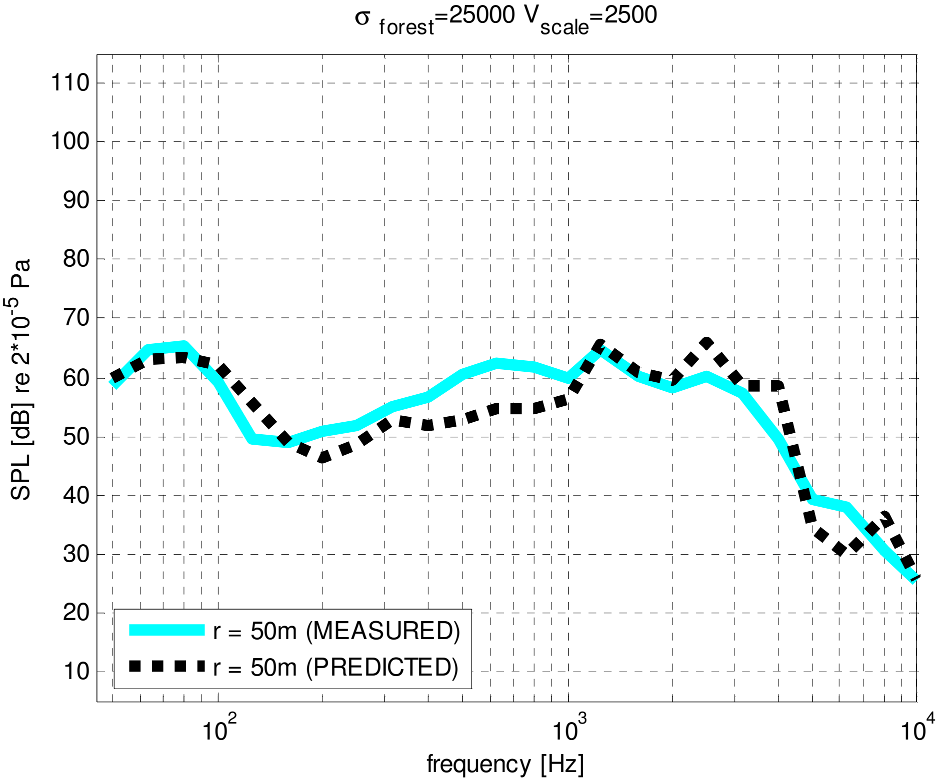
$D50 = \Delta L_{divergence}$



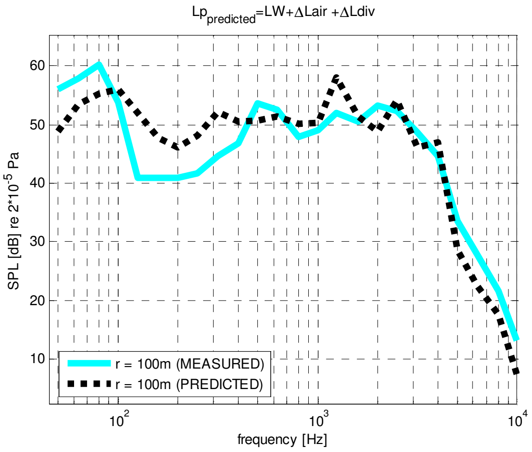
$E50 = \Delta L_{reverb} + \Delta L_{divergence}$



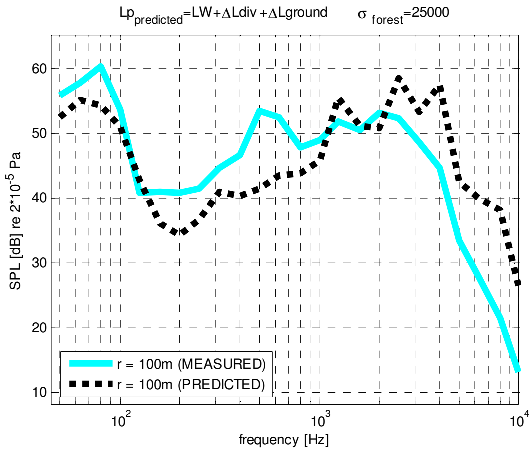
F50 = All effects


σ forest=25000 V scale=2500
110
100
90
80
70
60
50
40
30
20
10
SPL [dB] re 2*10^-5 Pa
r = 50m (MEASURED)
r = 50m (PREDICTED)
10^2
10^3
10^4
frequency [Hz]

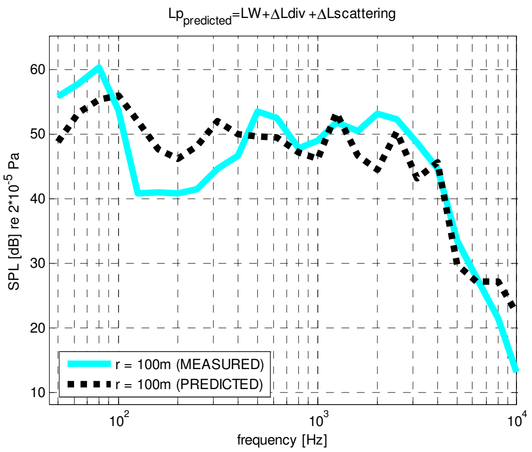
G50 = Optimal



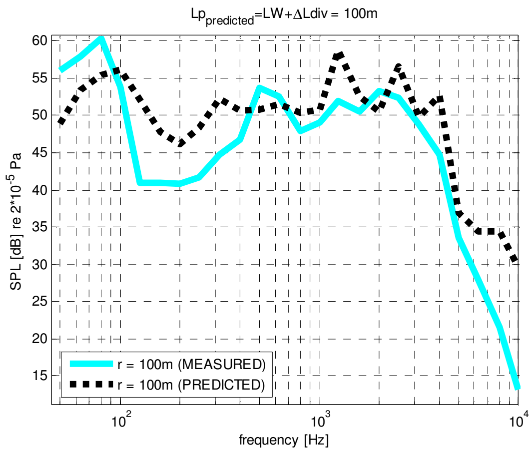
$A100 = \Delta L_{air}$



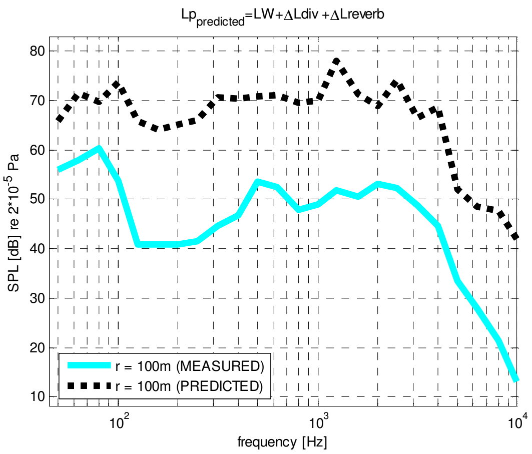
$B100 = \Delta L_{ground}$



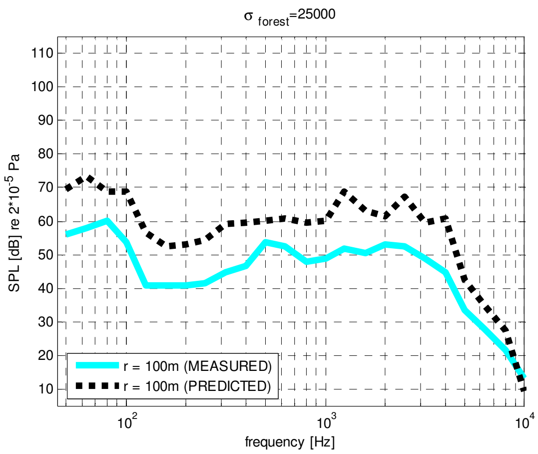
$C100 = \Delta L_{scattering}$



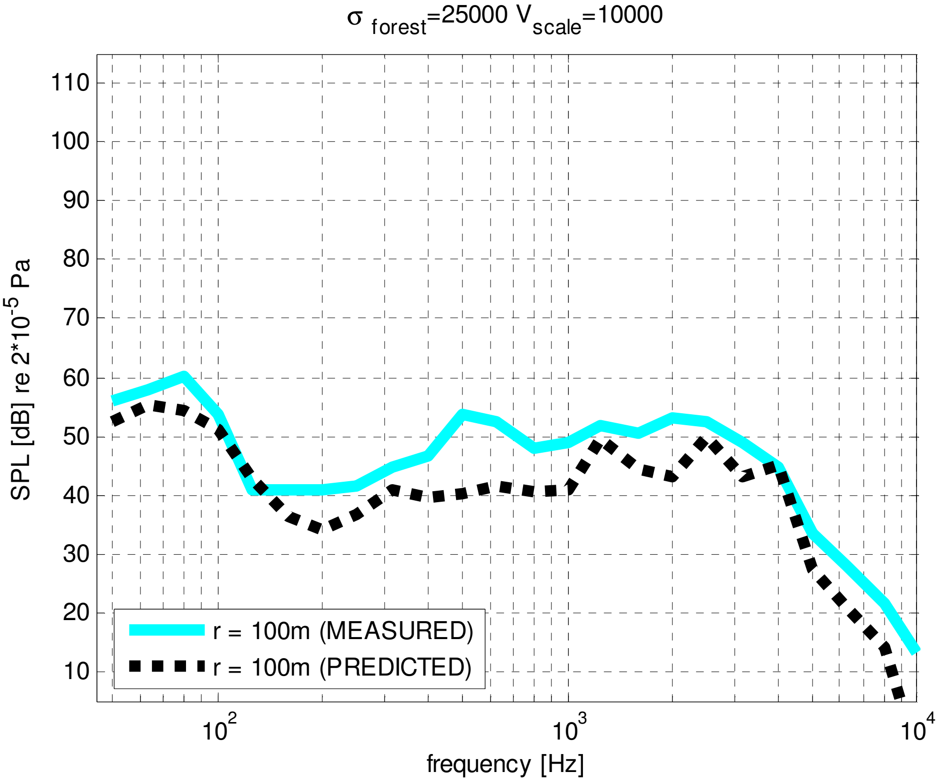
$D100 = \Delta L_{divergence}$



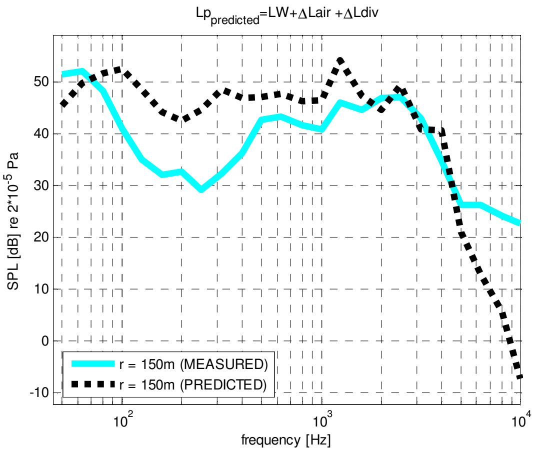
$E100 = \Delta L_{reverb} + \Delta L_{divergence}$



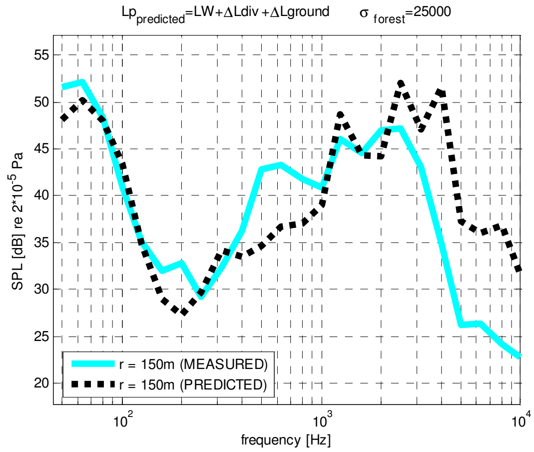
F100 = All effects



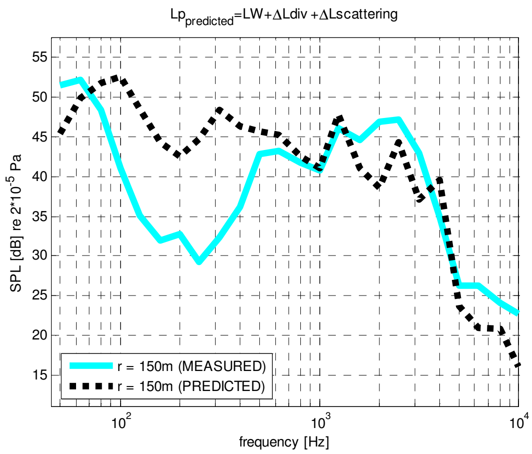
G100 = Optimal



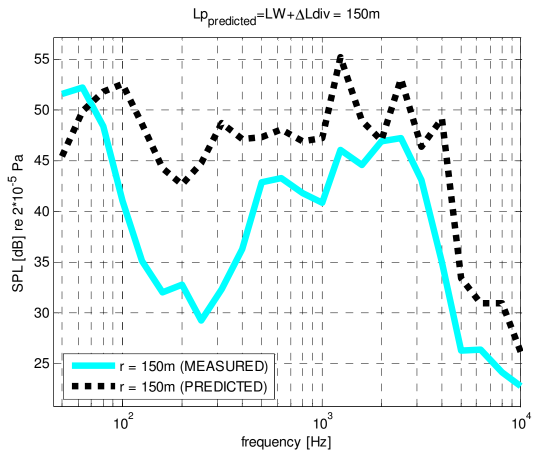
A150 = ΔL$_{air}$



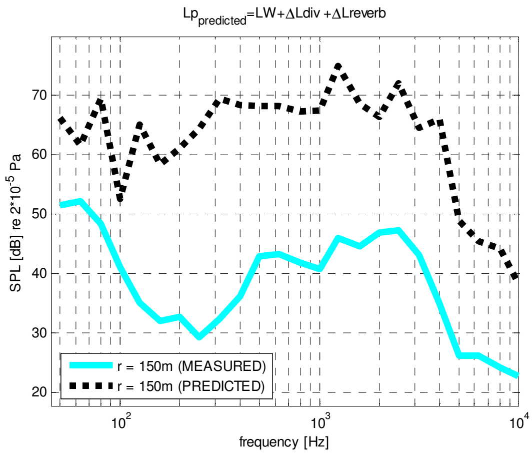
B150 = ΔL$_{ground}$



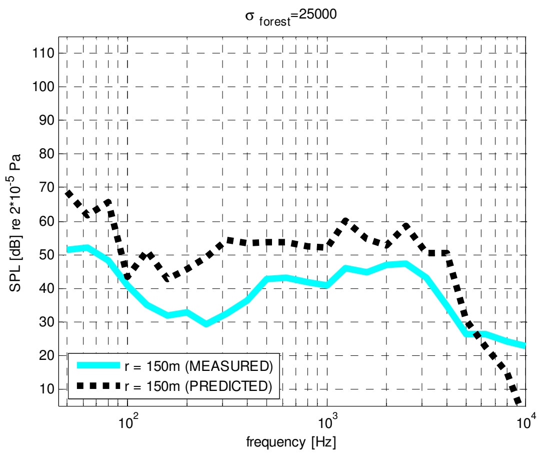
C150 = ΔL$_{scattering}$



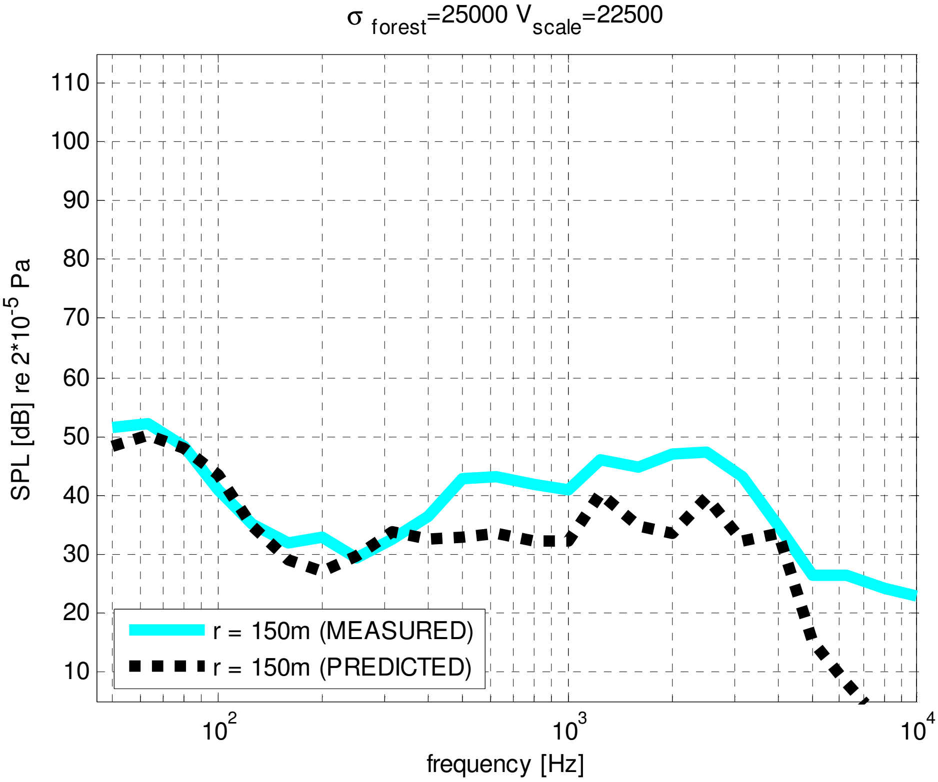
D150 = ΔL$_{divergence}$



E150 = ΔL$_{reverb}$+ ΔL$_{divergence}$



F150 = All effects



G150 = Optimal

Appendix D. 2D-C.N.P.E. model

In this section three different parts are presented in order to describe the used 2D-C.N.P.E.-model. The first part is the main file in where some input are inserted. The second part is a function (named *"callpe2_recarray"*), which constructs vectors used as input into a hidden script, *"pe_core_jf_v41"*. The third part is a script which saves the profile calculated by Swearing into a file called *"winddata.mat"*, which is loaded inside part 2. Returning to part 1 again, the resulting SPL is plotted over a range and over height.

PART 1

```
clear all
close all
clc

f_vec=[50 63 80 100 125 160 200 250 315 400 500 630 800 1000 1250 1600 2000 2500]';

Nf=length(f_vec);

LpPErel_band_mat=zeros(Nf,1);
LpFFPrel_band_mat=zeros(Nf,1);
LpPErel_mat0=zeros(Nf,1);

c0=340;
rho=1.2;

Rmax=550; % calc range
Zmax=0.5*Rmax; % calc height, could be reduced for some cases
zs=1.5; % sou height
zr=1.5; % rec height

sigma=25000; % effective flow resistivity for Delany and Bazely ground impedance model

zRough=0.3; %0.1; % roughness length of ground surface

b1=1/log(10/zRough+1);
windspeed=5; % wind speed at 10 m height, for log profile

tid_vec=zeros(Nf,1);
b=b1*windspeed; % wind strength, log profile
disp(['wind speed ',num2str(b*log(10/zRough+1))]) % wind speed at 10 m height
for i_f=1:Nf
   f=f_vec(i_f)
   k=2*pi*f/c0;
   lam=c0/f;
   dz=lam/20; % discretization; needs to be finer the stronger the wind

   Rimp=1+0.051*(sigma/f)^0.75;
   Ximp=0.0769*(sigma/f)^0.73;
   ZG=Rimp+j*Ximp; %normalized impedance acc to Delany and Bazely model

   tic
   my_mat=zeros(2048,2048);

[P_PE0_r,Lppe0_r,r_pe,P_PE0_z,Lppe0_z,z_pe,hr,soundspeedprofile]=callpe2_recarray(c0,f,Rmax,zs,zr,ZG,b,zRough,my_mat,Zmax,dz);
% Lp_pe is re free field

   tid_vec(i_f)=toc

   LpPErel_mat0(i_f)=Lppe0_r(end);

   savefilenametmp=['Lp_PE_f',num2str(i_f)]
   eval(['save ',savefilenametmp,' f P_PE0_r Lppe0_r r_pe P_PE0_z Lppe0_z z_pe hr soundspeedprofile'])
end

R1pe=sqrt((zs-zr)^2+r_pe.^2);
save Lp_rel_mat R1pe r_pe Rmax Zmax zr zs sigma zRough LpPErel_mat0 windspeed f_vec


% plot
for i_f=1:Nf
   figure(2*i_f-1)
   loadfilenametmp=['Lp_PE_f',num2str(i_f)];
   eval(['load ',loadfilenametmp,' f P_PE0_r Lppe0_r r_pe P_PE0_z Lppe0_z z_pe hr'])
```

```
    %figure(1), clf
    plot(r_pe,Lppe0_r,'k')
    title(['f=',num2str(f),' Hz'])
    hold  on;grid on
    axis([0 Rmax -30 10])
    xlabel('Range [m]')
    ylabel('SPL [dB re free field]')
    drawnow

    figure(2*i_f)
    plot(z_pe,Lppe0_z,'k')
    title(['f=',num2str(f),' Hz'])
    hold on;grid on
    axis([0 Zmax -50 10])
    xlabel('Height [m]')
    ylabel('SPL [dB re free field]')
    drawnow


end
```

PART 2

```
function [P_PE_r,Lppe_r,r,P_PE_z,Lppe_z,z,hr,c]=callpe2_recarray(c0,f,Rmax,zs,zr,ZG,b,zRough,Mmy,Zmax,dr)

Zabsorp=2/3*Zmax;
z=[0 dr/2:dr:Zmax]';
M=length(z);
r=(0:dr:Rmax)';     %avståndsvektor
r(1)=eps;           %for not getting warning
N=length(r);
c=c0+b*log(z/zRough+1);
%--------------
pos=find(z<30);
antal=length(z(pos));
Z=linspace(0,z(antal),antal);

load winddata.mat
WS= interp1(wh,ws,Z,'linear',1);

z(pos)=Z;
c(pos)=WS+c0;
%--------------

n=c0./c;

hindex=min(find(z>=zr-eps));    %
hr=z(hindex);                   %the receiver height

souidx=min(find(z>=zs-eps));    %source index
[P_PE_r,P_PE_z]=pe_core_jf_v41(hindex,c(souidx),ZG,zs,f,dr,r,N,Rmax,z,M,Zmax,Zabsorp,size(Mmy,2),n,Mmy);

R1pe=sqrt((zs-hr)^2+r.^2);
Lppe_r=20*log10(abs(P_PE_r))'+20*log10(R1pe);
Lppe_z=20*log10(abs(P_PE_z))'+20*log10(R1pe(end));
```

PART 3

```
clear all
wh=[0    0.5    1      1.5    2      2.5    3      3.5    4      4.5    5      5.5    6
         6.5    7      7.5    8      8.5    9      9.5    10     10.5   11     11.5   12
         12.5   13     13.5   14     14.5   15     15.5   16     16.5   17     17.5   18
         18.5   19     19.5   20     20.5   21     21.5   22     22.5   23     23.5   24
         24.5   25     25.5   26     26.5   27     27.5   28     28.5   29     29.5   30];
ws=[0    1      1.85   2.05   2.12   2.2    2.25   2.3    2.35   2.36   2.37   2.38   2.39
         2.4    2.41   2.42   2.43   2.44   2.45   2.47   2.49   2.52   2.55   2.6    2.7
         2.8    2.95   3.2    3.6    4      4.4    4.8    5.2    5.6    6      6.4    6.8
         7.2    7.6    8      8.35   8.5    8.6    8.7    8.75   8.75   8.7    8.6    8.5
         8.3    8.2    8.15   7.85   7.75   7.55   7.35   7.2    7.1    6.95   6.8    6.7];
save winddata.mat wh ws
```