STS 09007
Examensarbete 30 hp
Januari 2009

Sound from wind turbines in forest areas

– Are the sound propagation models used today adequate?

Mattias Wondollek

UPPSALA
UNIVERSITET

Teknisk- naturvetenskaplig fakultet
UTH-enheten

Besöksadress:
Ångströmlaboratoriet
Lägerhyddsvägen 1
Hus 4, Plan 0

Postadress:
Box 536
751 21 Uppsala

Telefon:
018 – 471 30 03

Telefax:
018 – 471 30 00

Hemsida:
http://www.teknat.uu.se/student

Abstract

Sound from wind turbines in forest areas

Mattias Wondollek

The Swedish model results in higher predicted sound levels, compared to international standard, which makes it more difficult for Swedish wind power developers to place their turbines optimal at forest sites. The aim of this study is to investigate the reasons for that, but also to cast more light on the potential forestal effect on sound emission and propagation from wind turbines.

The study reveals that the main reason behind the differences in predicted sound levels when comparing the models is due to a roughness correction formula in the Swedish model, returning an overestimated sound power level for roughness length's larger than 0.05 m, and vice versa.

Another important finding is that the end result is not only affected by the differences between the models, but can also be originated to the interpretations made by software developers and wind power developers. The Swedish land based model is a very simplified model, only suitable for non-refractive meteorological condition and flat hard ground with no obstacles or vegetation, when compared to more advanced sound propagation models such as Nord2000.

Overall forests probably have a damping effect on sound emission and sound propagation from wind turbines, especially for frequencies over 1000 Hz and during meteorological conditions favorable to propagation. The magnitude of the effect depends on a lot of variables such as the properties of the forest and meteorological factors, but also on the properties of the wind turbine.

Handledare: Angelica Widing, Nordex Sverige AB
Ämnesgranskare: Conny Larsson, Uppsala universitet
Examinator: Elisabet Andrésdóttir
ISSN: 1650-8319, STS 09007
Sponsor: Nordex Sverige AB

Populärvetenskaplig beskrivning

Naturvårdsverkets beräkningsmodell för ljudalstring och ljudutbredning resulterar i högre ljudnivåer jämfört med internationell standard vid projektering i skogsområden.

Syftet med detta examensarbete är att undersöka anledningen till varför naturvårdsverkets modell ger högre ljudnivåer, men även att studera och belysa skogens inverkan på ljudalstring och ljudutbredning för vindkraftverk i skogsmiljöer.

Arbetet visar att den största förklaringen till skillnaden mellan de estimerade ljudnivåerna kan häröras till en felapplicerad matematisk formel för råhetskorrigering i naturvårdsverkets modell. Användning av den formeln resulterar i överskattade ljudeffektnivåer för områden med högre markråhet än 0.05 m, såsom skog. Likaledes ger den upphov till underskattade nivåer vid områden med lägre markråhet, t.ex. vatten. Eftersom riktvärdet när det blåser 8 m/s på 10 m höjd är det som gäller för ljudalstring i Sverige och det motsvarar ett sorts värsta fallet scenario för ljudalstring, kan även poängen med råhetskorrigeringen ifrågasättas.

Ljudberäkningar med datorprogrammet WindPRO visade att skillnaderna mellan naturvårdsverkets modell och internationell standard, inte enbart kan härröras till skillnader mellan de olika beräkningsmodellerna, utan även beror på vilka antaganden och tolkningar programvaruutvecklare och vindkraftsprojektörer gör.

Naturvårdsverkets beräkningsmodell är väldigt förenklad jämfört med beräkningsmodellen Nord2000 och är egentligen endast applicerbar på hård, platt mark utan vegetation, där varken vinden eller temperaturen ökar eller minskar med höjden.

Ingen av beräkningsmodellerna tar någon hänsyn till fallet då vindhastigheten vid marken minskar i kombination med att vindhastigheten vid navhöjd fortfarande är stark och temperaturgradienten övergår i inversion. Detta fenomen leder till väldigt höga ljudnivåer samtidigt som bakgrundsljudet minskar.

Skogen har troligtvis en något dämpande inverkan på ljudalstring och ljudutbredning, framförallt för frekvenser över 1000 Hz och för väderförhållanden som normalt gynnar ljudutbredning. Hur stor skogens effekt är beror på många faktorer såsom skogens egenskaper och meteorologiska aspekter, men även på vindkraftverkets egenskaper.

Vanligast idag är att projekteringen i skogsmiljöer sker på höjder. Ett problem med vindkraftsprojektering på höjder är att varken den internationella standarden eller naturvårdsverkets beräkningsmodell tar hänsyn till de ljudfenomen som uppstår och leder till högre ljudnivåer för ljudkänsliga områden i dalen eller i foten av berget.

Det är hög tid att naturvårdsverket välkomnar mer avancerade beräkningsmodeller för ljudutbredning såsom Nord2000. Till skillnad mot Naturvårdsverkets modell, tar den hänsyn till vegetation och kuperad terräng men även en viss hänsyn meterologiska aspekter.

Table of contents

1 Introduction

1.1 Problem formulation

Because of the wind power mapping, showing better wind conditions than expected in the first place together with the increase in turbine size, the focus recently has shifted towards wind power development in forest areas. Still, sound emission and propagation from wind turbines in forest areas is a subject that needs further research.

The Swedish National Environmental Protection Agency advocates its own model for sound propagation (here on after called the “Swedish model”). Use of this model results in higher predicted sound levels compared to international standard, which makes it more difficult for Swedish wind power developers to place their turbines optimal at forest sites. When placing the turbines one has to make sure that the absolute noise limit of 40 dB(A) is not exceeded.

The Swedish model originates from the Danish model and consequently with Danish topography conditions. In Sweden we have a unique topography with a lot of forest areas, which makes the problem especially large (Berg, 2008).

1.2 Objectives

The aim of this thesis is to investigate in which ways the Swedish model differs from other sound propagation models and general theory of sound propagation.

My ambition is also to address the potential forestal effect on sound emission and propagation from wind turbines based on research done on forestal meteorology and sound propagation through forest areas, in order to cast more light on this unexplored subject.

1.3 Questions to consider

How does the Swedish model differ from the international standard?

Where are the lacks and weaknesses of today’s sound propagation models?

How is presence of trees and vegetation affecting sound emission and propagation?

1.4 Limitations

This work is delimited to cast a highlight on problems considering sounds from horizontal axis wind turbines. Tonality calculations and the uncertainty of noise emission measurements will not be taken under consideration, as well as screen and obstacle calculations in ISO 9613-2 and Nord2000.

Sound prediction calculations by hand would have been interesting to do, because by doing this the differences in the implementation of the models by the software developers would have been more obvious. However due to time restriction, manual calculations will only be performed to some extent.

When studying the forestal effect on sound emission and sound propagation, no considerations will be taken to the effects on animals or vegetation life.

Since the noise level limit of 40 dB is expressed as an absolute value instead of a relative, I will not consider the masking effect of the forest in this work, even though this is a very interesting issue. For further reading on this subject I recommend the work by Karl Bolin at KTH. See references.

2 Methodology

The work procedure contains the following steps:

1. Literature study
2. Interview with scientists and wind power developers
3. Sound calculations
4. Analysis

2.1 Literature study

The first step is to gain knowledge about how sound is created and distributed from wind turbines. It is of great importance to know what factors influences the sound path and in what ways. Also specific sound propagation theory for forest areas will be studied. After that, study of specific sound propagation models, such as the Swedish model, ISO 9613-2 and Nord2000 will be performed. But also other reports relevant to the subject will be studied.

2.2 Interviews with scientists and wind power developers

To be able to overlook the wide range of the problem and to explore different views of sound models, it is vital to interview the persons behind the calculation models, but also their opponents. Interviewing the wind power developers will reveal the consequences of using the Swedish Sound Prediction Model for introducing forestal wind parks in Sweden. The results from the interviews will be treated implicit all through the thesis.

2.3 Sound calculations

Further on calculations with WindPRO will be made, showing the differences in results for the Swedish model compared to the international standard, and this for minor (500 m) as well as large distances (1035 m).

2.4 Analysis

When the data collection and sound calculations are done, the last step is to analyze it. This will be done in the chapter called discussion. Initially aspects of sound emission will be discussed; this includes the “roughness correction formula” in the Swedish model. After that differences between sound calculation models and general theories will be analyzed. Assumptions behind the models will be analyzed in order to determine if the models give a reasonable result compared to reality. The next step is to compare the models with each other. In order to do that, the results obtained in WindPRO will be used.

The last step involves analyzing the potential forestal effect on the sound propagation from wind turbines. Since this is an unexplored area, findings regarding models and experiments, mainly developed in order to determine the traffic noise impact on the forest or other findings related to military purposes will be studied. This naturally implicates a speculative approach.

3 Sound emission and propagation theories

Today there are several calculation methods used to calculate sound from wind turbines. Even though standards like ISO 9312-6 and IEC 61400-11 are available, some countries have developed their own model or modified the standards, making them more suited for national policies and interest.

3.1 General theory of indoor sound propagation

From a point source, the sound can be considered to spread in all direction with the same magnitude. This is called spherical sound propagation. The sound intensity in one point, with the distance r from the emission point, can thus be described as the sound power level (in watt), divided by the area of a sphere:

$$I = \frac{S}{A} = \frac{S}{4\pi r^2}$$

Equation 1, Sound intensity, Larsson 2008

The sound intensity level, expressed in dB will be obtained by multiplying the right hand side with 10 times the logarithm of the intensity:

$$L_I = 10\log\left(\frac{S}{4\pi r^2}\right) = 10\log(S) - 10\log\,(4\pi r^2)$$

Equation 2, Sound intensity level (dB), Lundmark 2008

Now the sound power level, expressed in dB can be written as 10log(S):

$$L_I = L_W - 10\log(4\pi r^2) = L_W - 10\log(4\pi) - 10\log(r^2) = L_p$$
$$= L_W - 11 - 20\log\,(r)$$

Equation 3, Sound intensity level (dB), Lundmark 2008

The last expression is also called the sound pressure level L_p. Due to spherical spreading, each distance doubling will cause an attenuation of 6 dB. All other types of attenuation, which will be described in chapter 3.2 is called excess attenuation (Herrington, L., Brock, C., 1977).

3.2 General theory of outdoor sound propagation

When the sound power level has been determined, the next step will be to calculate how much the sound will vanish along its way to the receptor. In contrast to indoor propagation conditions, outdoor propagation is much more complex because of weather influence, vegetation, non plane ground and different ground types. The main factors influencing the outdoor sound propagation are: ground attenuation, atmospheric absorption, turbulence and refraction, caused by wind and temperature gradients. All together the weather effect on sound propagation can result in sound level differences up to 20-25 dB(A) (Larsson, 1999) The longer the transmission path, the larger are these fluctuations (Lamancusa, 2008)

3.2.1 Refraction

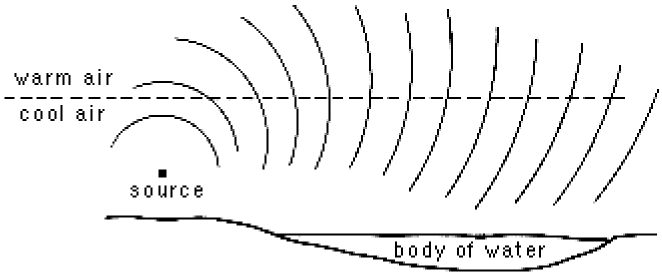


Figure 1, Refraction, Truax 1999

When the sound velocity and/or the wind speed change along the ray path, refraction will occur. The rays will be bent upwards or downwards, depending on the wind and temperature gradients. You could think about the rays as vectors perpendicular to the wave front.

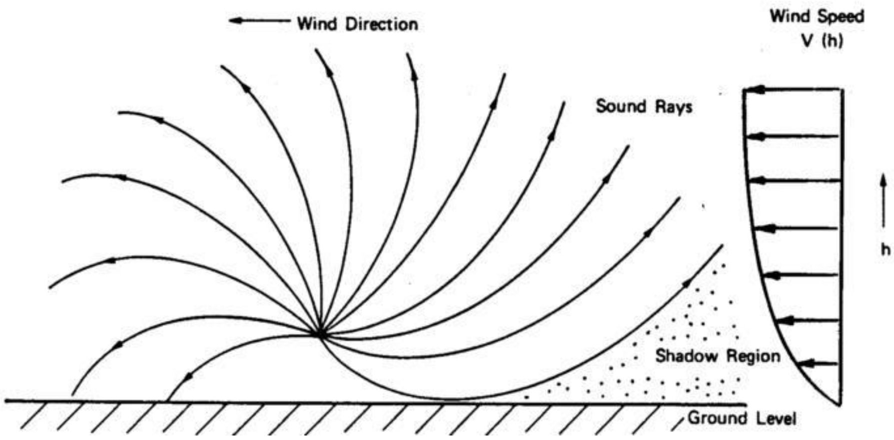


Figure 2, Refraction due to change in wind speed, Lamancusa 2008

The wind gradient says how much the sound rays bends down (in downwind situation) and up (in upwind situation), due to the fact that the wind blows stronger the higher up you are. The wind speed adds to the velocity of the sound wave, which causes the bending. As an example you could think of a car with a wheel pair running faster than the other. This will make the car turn right or left depending on the wheels position (Thorsson, 2008).

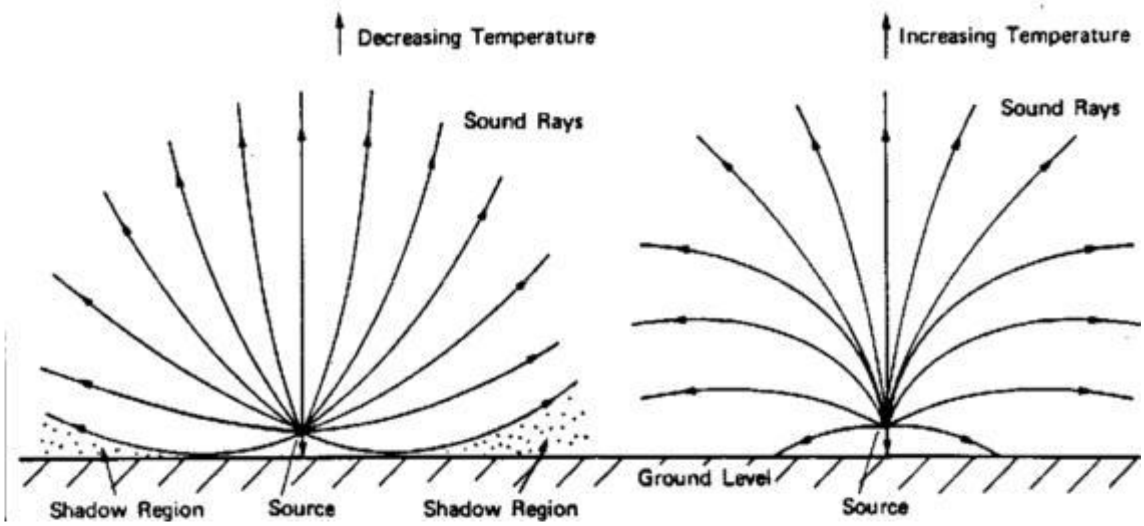


Figure 3, Refraction due to change of air temperature, Lamancusa 2008

The speed of the sound is also dependent on the temperature. Higher temperature means faster sound propagation according to the following formula:

$$c = 20.05\sqrt{T + e/p}$$

Equation 4, Temperature, water vapor and barometric pressure influence on sound propagation, Lamancusa 2008

Where e is the partial pressure of water vapor and p is the barometric pressure (Lamancusa, 2008).

Normally the temperature profile changes during day and night. If the temperature rises with increased height, which often is the case during night, the rays will be bent downwards (Figure 3, the right picture). This phenomenon is called inversion.

On contrary they will be bent upwards if the temperature falls with increasing height (the left picture). This is called lapse.

A neutral stratified atmosphere assumes a temperature falls 0.98 degrees Celsius per 100 m. This is however not the same as a non-refractive medium. In order to attain straight sound rays, the air has to show up an isothermal condition (constant temperature), and no difference in wind speed (Lamancusa, 2008). Straight rays can also be obtained for some combinations of positive wind gradient and negative temperature gradients, or negative wind gradient and positive temperature gradient (Larsson, 2008).

The temperature gradient also shows annual cycles. The highest noise levels occur during winter time, when the temperature increases with height, whereas the lowest noise levels are more frequent during summer time. Thus it is most silent during summer days and most noisy during night, evenings and mornings during in the winter (Larsson, 1999). See *Figure 4.* The explanation is probably a combination of the distribution of the temperature gradients and less atmospheric attenuation. Since the sun is up a shorter time period during winter than during summer, inversions are more common during the winter. (Larsson, 2008)

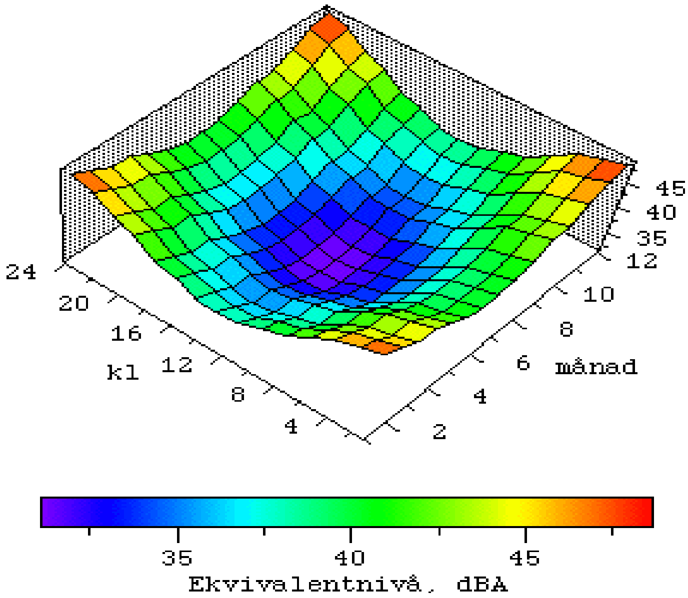


Figure 4, Sound profile over annual and daily sound level variations, Larsson 1999

Consequently the sound rays will be bent down if both the wind and temperature increases with height. If the temperature decreases with height, the rays can still however be bent down, if the wind gradient is enough large in comparison to the negative temperature gradient. With other words, a negative temperature gradient influence on the sound ray bending can be counteracted by the wind gradient for down wind conditions. One explanation is that a stronger wind gradient leads to more mixture of the air and consequently to a weaker temperature gradient (Larsson, 2008).

Compared to a uniform medium, assuming no refraction, upward refraction will cause less sound pressure level at the immission point because the sound is radiating upwards. Downward refraction will on the other hand cause higher sound pressure level at the immission point because the sound is focused along the ground (Lamancusa, 2008).

Refraction thus plays a crucial rule in reliable sound measurements at the immission point. Depending on weather condition, an unscrupulous consultant can choose to perform measurements when the conditions are favorable or unfavorable for sound propagation, depending on which side he or she is representing.

3.2.1.1 Stratified spreading

Due to refraction, the sound rays are not considered to be straight lines, for this reason the propagation isn't the same in every direction. For downward refraction conditions, the sound rays instead will stay under a certain maximum height and the propagation only occurs in the x and y dimensions. This phenomenon is often called *cylindrical spreading* but a more correct name would be stratified spreading, since the propagation takes place between two plates. The lower is the ground or surface and the upper, the temperature inversion or wind speed enhancement. The distance between the plates depends on the wind and temperature gradients, and is the same as the distance for which spherical spreading is turning into stratified spreading. Compared to spherical spreading, which as above mentioned assumes an attenuation of 6 dB per distance doubling; stratified spreading means an attenuation of 3 dB per distance doubling. This is one of the reasons why downward refraction leads to higher sound power levels at the immission point (Boué, 2007; Larsson, 2008). Downward refraction also causes multiple ground reflections, which leads to either an amplification or an attenuation, depending on the ground properties. See chapter 3.2.4

3.2.3 Atmospheric absorption

There are two different types of atmospheric absorption: viscous losses, resulting from the friction between air molecules. The friction causes heat generation, and thus energy loss.

Atmospheric absorption also occurs when sound energy is temporarily absorbed in the air molecules, which causes the molecules to rotate and vibrate. Partially interference can also occur because these molecules can re-radiate sound at a later instant, like small echo chambers.

Absorption of sound energy occurs for all sound propagation within the atmosphere, but increases with frequency and distance, and is dependent on the relative humidity, temperature and air pressure.

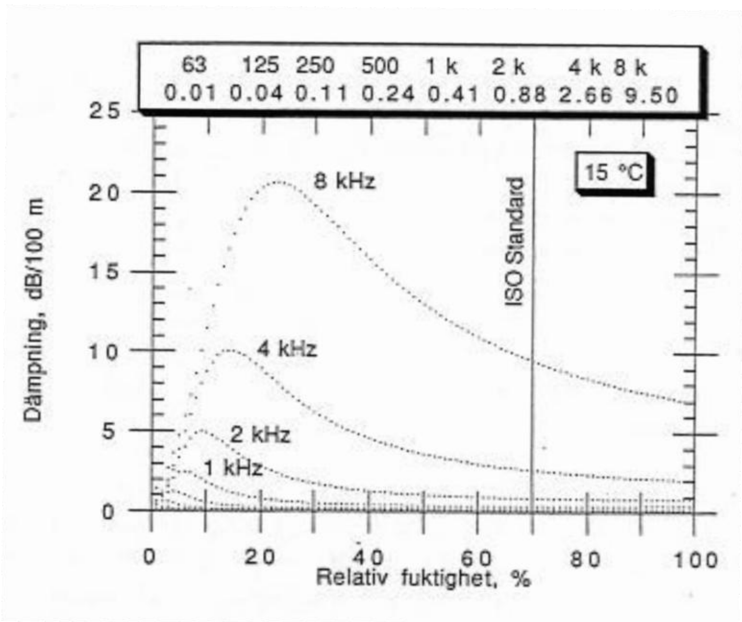


Figure 5, Attenuation vs. humidity for different frequencies, Larsson 1993

Figure 5 shows how the attenuation varies with frequency and humidity. The absorption is higher for higher frequencies, whereas absorption generally decreases with increasing humidity. Dry air is an exception, which has the least absorption (Lamancusa, 2008).

The atmospheric absorption is showing monthly and diurnal variations but also large geographic differences. For higher frequencies than 500 Hz, the atmospheric absorption tends to increase the further south we go, whereas the opposite trend is found for lower frequencies.[1]

[1] Only validated for six different stations in Sweden

	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
Luleå	0,8	1,3	1,6	3,3	7,9	21,8	39,4
Uppsala	0,3	0,6	1,4	3,2	7,9	22,3	73,6
Säve	0,3	0,7	1,4	3,2	7,9	22,0	74,4

Table 1, Geograpic distribution of atmopheric absorption in dB/km. 95% percentile values, Larsson 1996

For frequencies up to 500 Hz, the highest absorption mean value occurs during summertime afternoons and the lowest during wintertime. See *Figure 6*. For frequencies over 4000 Hz, the opposite relation is found, even though the absorption for 8000 Hz, still can be about 30 times higher than for 250 Hz. This conclusion is based on figure comparison in Larsson (1996).

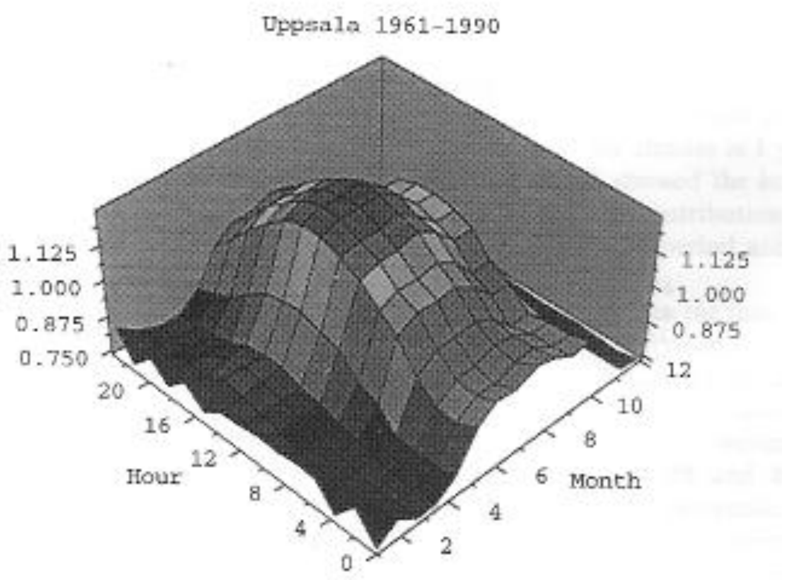


Figure 6, Arithmetic mean atmopheric absorption in dB/km at 250 Hz over a period of 30 years, Larsson 1996

3.2.4 Ground effect

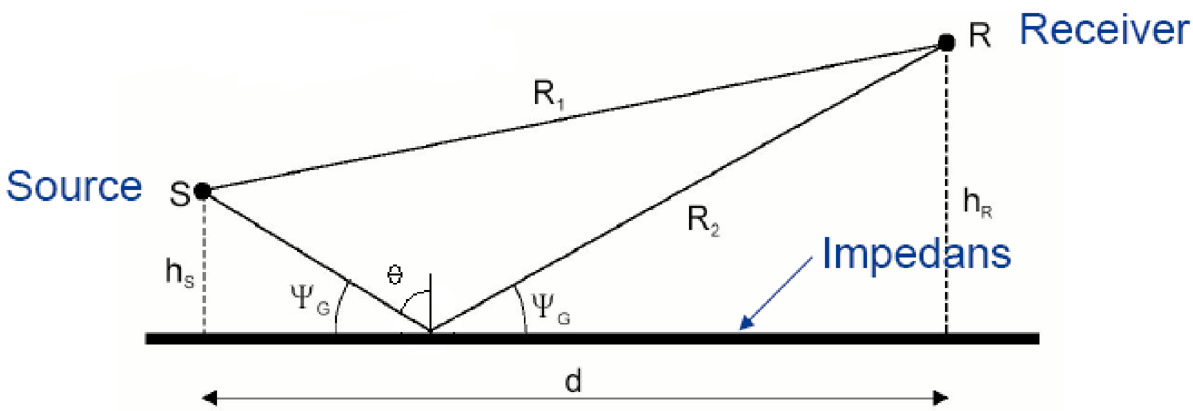


Figure 7, Ground reflection, Gustafson 2006 (slightly modified)

If the emission source placed over a reflective ground surface, some of the sound will be reflected against it and the energy of the sound wave will be absorbed by the ground. Direct and reflected sound wave will be added together and contribute to the sound pressure level at an observers point (Larsson, 1999)

Particularly for low grazing angles and frequencies, the ground surface itself also can provide a transmission path. The incident acoustic energy is transformed into vibration energy and is transmitted along the surface layer (Lamancusa, 2008).

Depending on the nature of the ground and the frequency of the air ways the interference will cause an amplification or attenuation (Bucur, 2005). When incidence wave leaves the surface as a reflected wave, its amplitude and phase has been modified by the impedance of the surface. The reflected wave meets the direct wave and either a constructive or a destructive interference will occur depending on their relative phases and amplitudes.

For perfect reflection, no atmospheric turbulence and both the source and receiver are near the ground, a sound pressure amplification of 6 dB will occur (Lamancusa, 2008). This I typical for hard, flat ground such as asphalt or water surface. A more soft ground such as grass or snow will absorb part of the sound energy and result in a phase displacement (Gustafson, 2006).

During strong downward refraction situations, multiple reflections occurs, which increases the ground effect.

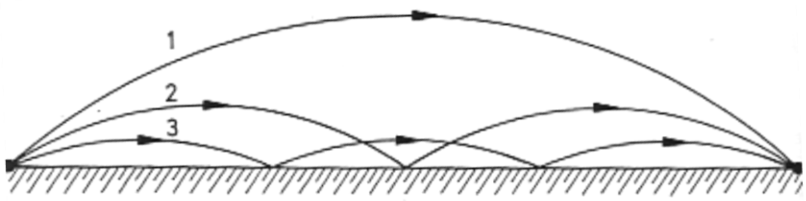


Figure 8, multiple reflections due to downward refraction, Larsson 1999

The sound pressure level at the observer for a spherical wave can be described by following formula:

$$\frac{p}{P_0} = \frac{1}{r_1} e^{-ikr_1} + \frac{R_p}{r_2} e^{-ikr_2} + \left(1 - R_p\right) \frac{F}{r_2} e^{ikr_2}$$

Equation 5, Larsson 1999

The first term on the right hand side is the sound pressure contribution from the direct wave source. The second term is the contribution from the reflected air waves, and the third term is called the contribution from the ground and surface wave. It accounts for the difference between the reflection of an actual spherical wave, and that of a plane sound wave (Lamancusa, 2008).

P_0 is the pressure amplitude in the reference point at the source, whereas R_p is the plane wave reflection coefficient defined as:

$$R_p = \frac{Z(w)cos\theta - \rho C}{Z(w)cos\theta + \rho C}$$

Equation 6, Larsson 1999

$Z(w)$, is the complex ground impedance, θ the angle of inflection and ρC is the impedance of air[2] (Lamancusa, 2008)

F is called the amplitude factor and describes the interaction between the bended wave front, ground and wave impedance. If the wave front is plane, F will be close to 0, and if the ground is acoustic hard it will take the value 1. In other cases will F be a function of r_2, the ground impedance, the angle of inflection and k (Larsson, 1999), where $k = 2\pi f/c$, r_2=the path length of reflected wave (Lamancusa, 2008).

Assuming the impedance model of Delany and Bazley the real component of $Z(w)$ is:

$1 + 9.08\left(\frac{f}{\sigma}\right)^{-0.75}$ Whereas the imaginary component is: $11.9\left(\frac{f}{\sigma}\right)^{-0.73}$,

Where σ is the flow resistivity of the surface in units of cgs rayls. It has been found that flow resistivity is a sufficient parameter to describe the absorptive ability of the ground (Lamancusa, 2008)

Stronger positive refraction will boost the importance of the ground effect. If the ground is soft, more attenuation will be achieved, whereas if the ground is hard and flat, more amplification will be achieved than would have been the case with straight sound rays, partly due to the ground dip shift towards lower frequencies and partly due to multiple reflections (Larsson, 2008).

In the case where the sound rays are bent downwards i.e. downwind and/or positive temperature gradient, the ground attenuation will be smaller than when the sound rays are bent upwards (Larsson, 1999). The Equations also say that the higher the source of sound is placed, the less is the sound pressure at the receiver point, due to larger values on r_1 and r_2. Thus the ground effect will only have a slight impact on the sound propagation for land based wind turbines if the wind turbines are high elevated and the distance to the receiver is short (Almgren, 2008; Larsson, 2008; Ljunggren, 2008; Thorsson, 2008).

[2] Normally 415 N-sec/m^3 at 20°C

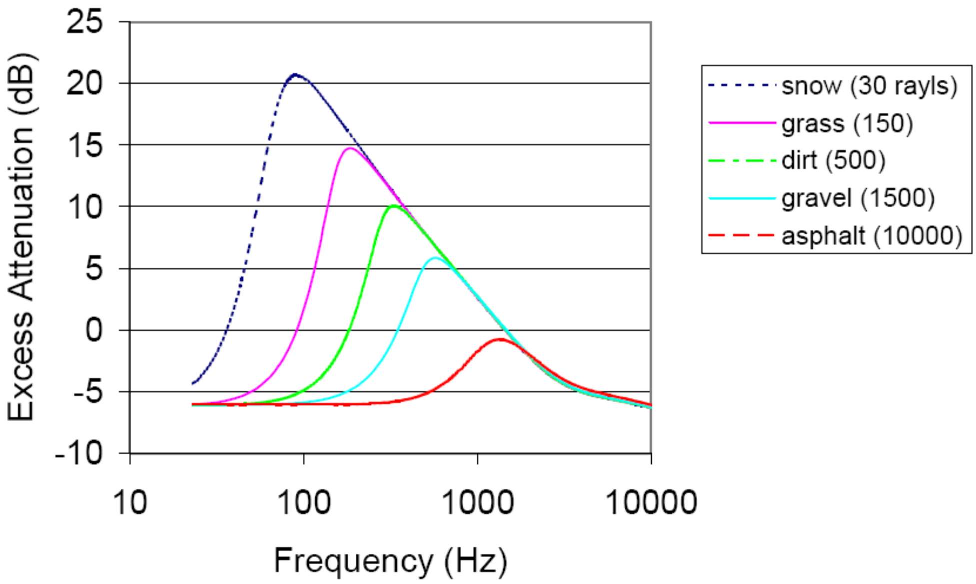


Figure 9, Ground attenuation for different ground types, Source and receiver at 1.5 m height, distance1 km, Lamancusa 2008

3.2.5 Turbulence

Turbulence causes fluctuations in phase and amplitude for the sound waves, which continually changes the interference effect, and thus reducing the ground effect. Turbulence can also make the sound enter shadow zones areas. The effect of turbulence is negligible small for distances up to a few hundred meters, and for low frequencies. (Larsson, 1999)

3.3 The forest effect on sound propagation

In forest areas, the sound propagation is different compared to open ground. Forests show up unique wind and temperature gradients, not following the daily and annual pattern you find over open ground. Their characteristics also differ extensively within and above the forest. Except meteorological factors, ground reflection and absorption, the sound propagation in forest areas is also influenced by scattering, reflections, and absorption due to foliage, trunks and branches. (Tunick, 2003; Swearinger and White, 2004)

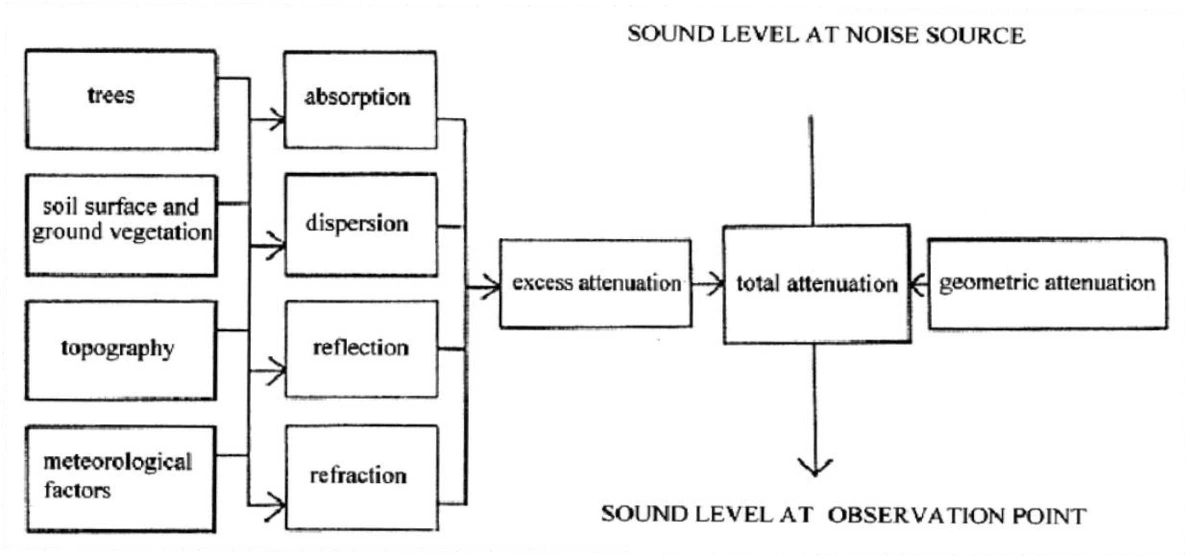


Figure 10, Factors influencing the SPL in forest areas, Bucur 2005

The above figure shows different factors influencing the sound pressure level at the observation point.

3.3.1 Wind profile of a forest

Large forest areas tend to have a wind speed decreasing and turbulence increasing ability (Gardiner, 2003). Besides a higher roughness, you also get a zero displacement height in forest. This is why the wind in general blows less hard on hub height over a forest than over open ground (Boddington, 2008).

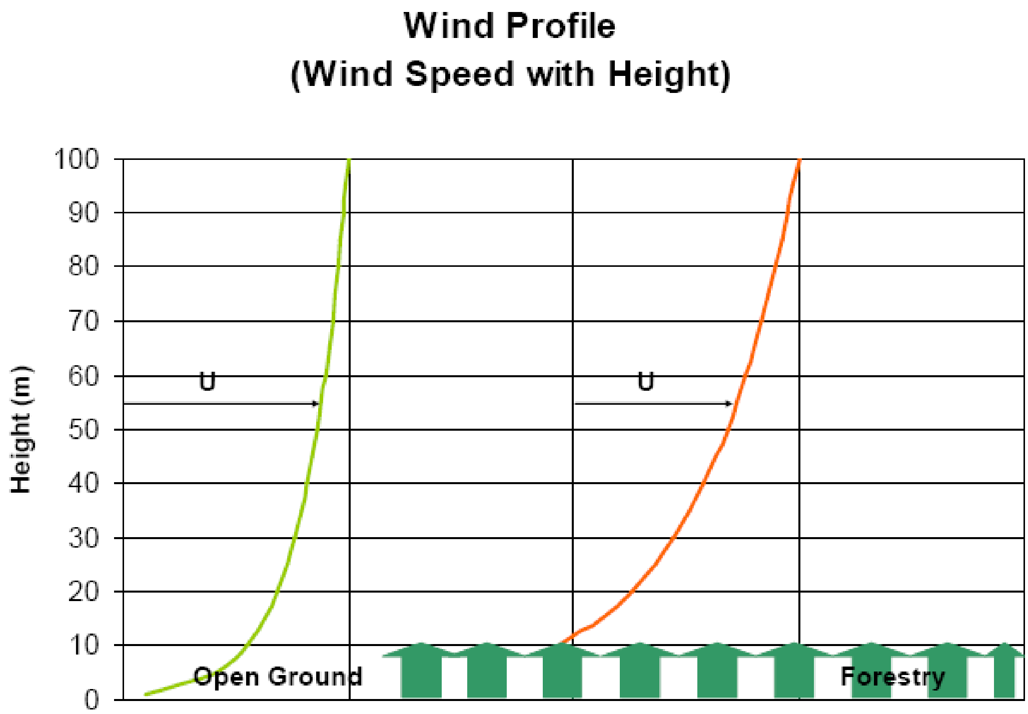


Figure 11, Wind profile over open ground and over forest, Boddington 2008

The above picture aims to illustrate the difference in wind speed over forest and open ground. Note that the forest height is only about 10 m here.

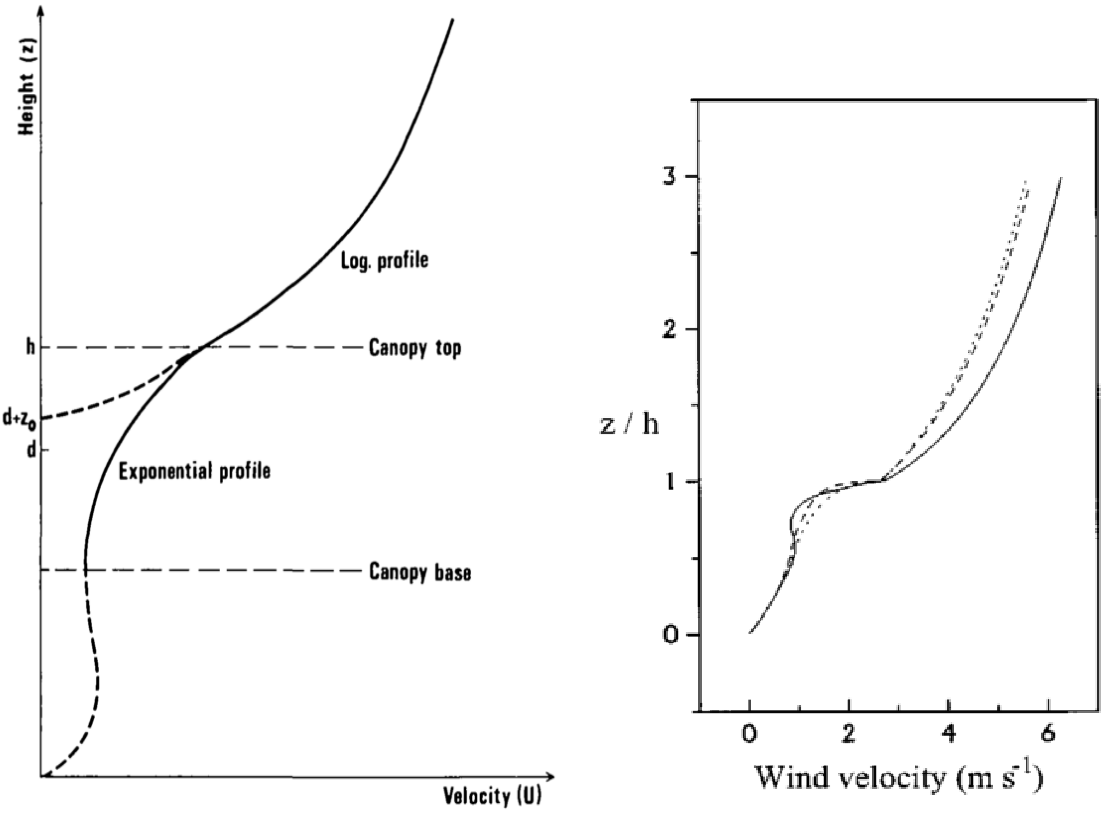


Figure 12, Modeled wind speed profiles, Oliver and Mayhead 1974 (left picture) and Tunick 2003 (right picture)

Within the forest, the average wind is not stronger than 1 m/s, in fact it is after a specific height d+z_0, the wind profile can be approximated by a logarithmic function, where d is the displacement height and z_0 the roughness level (Oliver and Mayhead, 1974) Modeled wind speed profiles are very similar to those of open ground. What can be seen in the right picture is the so called “skimming effect”. Each of the three lines has a specific leaf area index describing the leaf density of the canopy. A more compact surface result in a decrease in roughness for the canopy (compare the filled line with the dotted) (Tunick, 2003).

The roughness length can be determined through empirical observations of wind speeds at different heights. In practice however such determinations are seldom done. Instead one often uses a value that sounds realistic or a theoretically calculated value for the roughness length and zero plane displacement height. d=3/4*h or d=2/3*h are typical displacement height approximations, whereas z_0 =1/30*h or $z_0 = 0.3$ are typical roughness level approximation (Raftery, P., *et al.*, 2004; Bergström, 2007).

Markyta	Råhetslängd z_0 (m)	Råhetselementens höjd (m)
Slät sjö	0,00001	
Grov sjö	0,000015-0,0015	
Is	0,00001	
Snö	0,00005-0,0001	
Öken	0,0003	
Kort gräs	0,03-0,01	0,02-0,1
Långt gräs	0,04-0,1	0,25-1,0
Savann	0,4	8
Odling med grödor	0,04-0,2	0,4-2
Fruktodling	0,5-1,0	5-10
Barrskog	0,28-3,9	10,4-27,5
Tropisk skog	2,2	35

Table 2, Roughness lengths for different ground types and corresponding heights, Boddington 2008

This is problematic because many theoretical models tend to underestimate the "forest effect" since they normally not take the tree density or leaf area index into consideration (Raftery, P. *et al.*, 2004; Boddington, 2008).

Higher forests means higher roughness levels and zero plane displacement height (Boddington, 2008). Except for the forest height, also the wind speed influences the roughness lengths and zero plane displacement height. The roughness length tends to increase with increased wind speed, whereas the height of the zero plane displacement can decrease up to 50% with increased wind speed (Lo, 1995).

During neutral stratified atmospheric condition, the average wind speed with height z over a forest can be described by:

$$u(z) = \frac{u_*}{k} \ln\left(\frac{z-d}{z_0}\right)$$

Equation 7, Wind speed as a function of height of the forest, Lalic et al., 2002

k is the "von Karman" constant, d is the zero displacement height, z_0 the roughness length and u_* is the friction velocity over the vegetated area (Lalic *et al.*, 2002). u_* is usually determined through estimation of the other variables (Larsson, 1999).

The wind profile in non-neutral conditions differs from wind profile in neutral conditions. Under unstable conditions, eddy motions are stronger, causing higher displacement level and roughness length (Harman and Finnigan, 2006).

3.3.2 Temperature profile of a forest

According to a measurement study of a coniferous forest, where temperature data at four different heights within the forest was measured over a five year period, a temperature inversion was found during the day beneath the canopy and a negative laps rate above. During night instead, an isothermal layer or a minor lapse below the canopy and an inversion above are usual (Raynor, 1971).

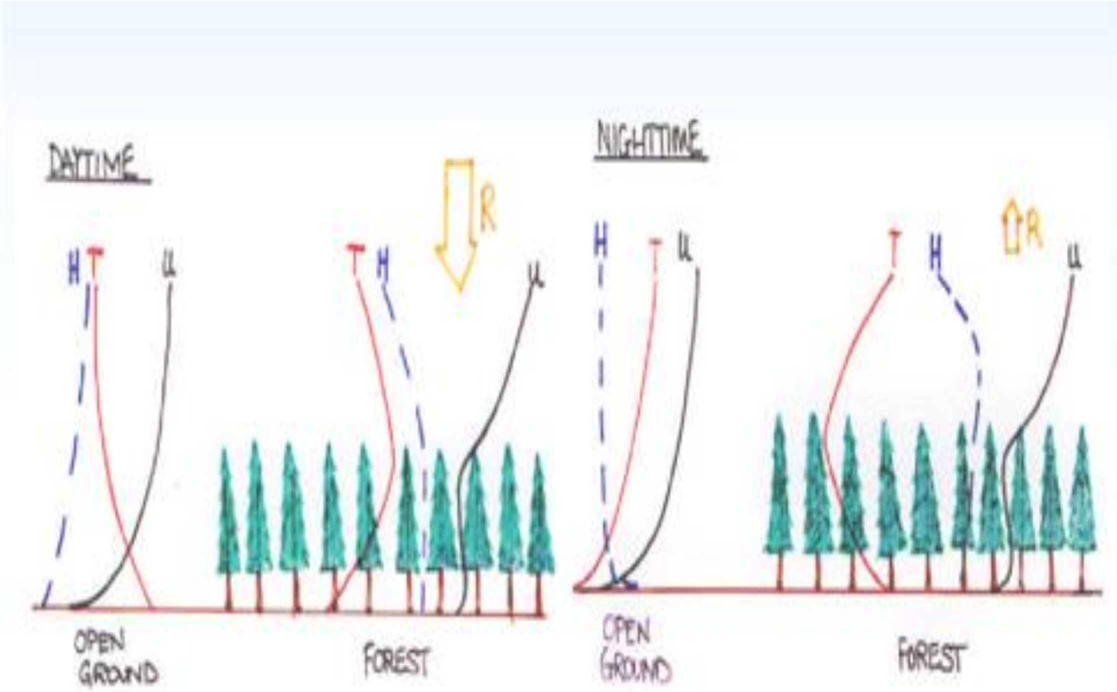


Figure 13, Temperature(T), humidity (H) and wind(u) profiles in and over a forest vs. open ground, Gardiner 2003

The canopy absorbs the solar heating during the day, while the forest floor is shaded. During night, the canopy thus is at a much higher temperature than the open night sky causing temperature transfer upwards and downwards from the canopy. On the morning, the forest floor then has a higher temperature than the canopy, shifting the temperature transfer upwards (Swearingen and White, 2004).

The Temperature profile over a forest as shown in *Figure 13* might be a bit exaggerated. According to a measurement study performed by Högström *et al* (1989) showed small average summer daytime temperature gradient being -2.3*10^-5 C° m^-1, which is very small compared to responding values under “ideal conditions” (low vegetation) (Högström *et al.*, 1989).

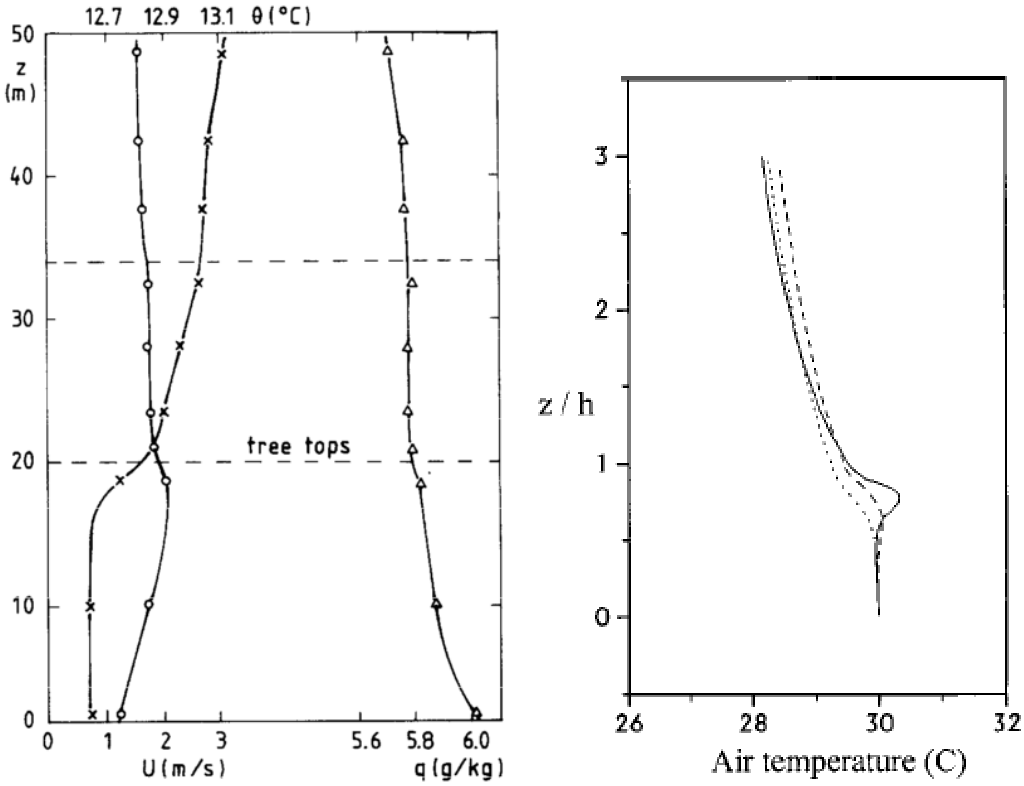


Figure 14, wind and temperature profiles, Högström et al. 1989 (left picture) and modelled temperature profile, Tunic 2003 (right picture)

The left picture shows the wind profile (x) and temperature profile (o) for one hour measurement September 9 between 15:00-16:00 at Jädraås Tower (Högström *et al.*, 1989).

It shall be noted that describing average wind and temperature profiles within forests are problematic, since it's difficult to isolate other variables affecting the measurement result. Generally, however it can be concluded that the temperature gradients above the forest canopy is small due to effective mixing above a rough canopy. (Halldin, 2008).

Also, denser canopy leads to somewhat greater temperature gradient, as can be seen in the right picture. The profile corresponds to a typical clear sky, midday atmospheric conditions. (Tunic, 2003).

3.3.3 Sound propagation through a forest

The sound propagation through a forest is from an acoustical point of view mainly influenced by scattering, reflections, and absorption due to foliage, trunks and branches(Defrance, J. *et al.*). But it is also influenced by micro meteorology which affects the vertical sound profile and the ground impedance (Swearingen and White, 2004). Studies also indicate an interaction between trunk scattering and ground effect that is more complicated than simple addition (Wilibrord *et al.* 1991). Thus sound propagation through a forest is a very complex subject.

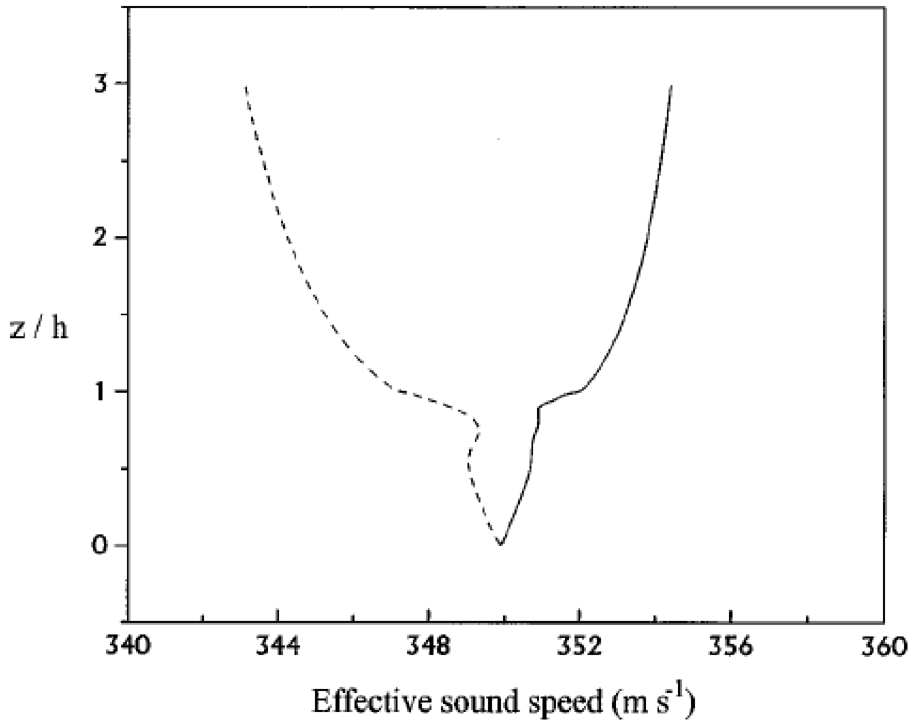


Figure 15, Modelled effective sound speed through and over a forest for downwind (solid) and upwind (dashed) conditions, Tunick 2003.

The above figure shows the effective sound speed, which is the sound speed as a function of air temperature, relative humidity and wind velocity based on the same assumptions as the right pictures in Figure 12 and Figure 14. As mentioned earlier, downward refraction occurs if the effective sound speed increases with height and vice versa. Less speed means more transmission losses (attenuation). As a result we will expect greater transmission losses at each frequency for upwind propagation (Tunic, 2003).

Trees can attenuate the sound by absorbing and reflecting the energy. The relevant forest variables for sound propagation are: trunk diameter, tree density, scattering and absorbing cross section, leaf area, the bark, the forest floor and the canopy (Bucur, 2008).

According to a measurement study, where the sound source was placed at 0.5 m height, 20 m away from a 100 m deep and 10.5m high forest strip with an average circumference of 0.16 m and density of 0.14 trunks/m^2, a measured value 100 m within the forest showed that sound propagation through a forest lead to an attenuation of -3 dB due to the decrease or cancellation of the positive temperature gradient inside the forest, particularly at night, compared to open ground, assuming favorable conditions [3]. For unfavorable conditions, especially for large distances instead an increase in SPL at the immission point is expected compared to open ground (Defrance, J. *et al.*).

[3] Positive temperature gradient and downwind conditions

Scattering, means that the incident waves are partially refracted and reflected. Scattering leads to more and more complex transmission paths, which causes absorption of acoustic energy.

Scattering and absorption by bark and foliage are strictly frequency dependent. It's been found that an acoustic wave of 1 kHz frequency has a wave length comparable to the diameter of a trunk (Bucur, 2005).

For frequencies below 1000 Hz, scattering is not occurring because the wavelength is too large compared to the trunks and branches diameter. According to Wiens, T. *et al.* (2008), for frequencies below 1kHz the vegetation is almost transparent and the attenuation it dominated by the ground effect (Wiens, T. *et al.*, 2008).

The larger the diameter, the lower the frequency for which the scattering becomes effective. It's also been found that higher stand density, mixed species of trees and larger quantity of leaves have positive influence on the noise attenuation, but also young stands and undergrowth of the forest. Winter time vs. summer time studies have shown that with absence of leaves, the attenuation is considerably low.

In a measurement study, an attenuation peak at 200 Hz was found due to the ground attenuation, whereas the attenuation then again gradually increased for frequencies over 1000 kHz, due to absorption and scattering. It has also been found that conifers aren't as good sound attenuators as broad-leaved trees (Bucur, 2005). On the other hand another study has shown greater attenuation during winter (Wiens, T. *et al.*, 2008). This probably is related to the presence of snow.

With the source and receiver at 1.2 m height, both placed within the forest, the highest excess attenuation in a coniferous spruce stand has been measured 10 dB/100m, and 7 dB/100 m if the receiver was placed at 3.9 m height (Bucur, 2005). Depending on if the source and /or receiver is placed outside the forest, entrance and exit losses will be obtained. It has been found that attenuation at the edges of a forest due to reflection of acoustic energy can result in an attenuation of 8.5 dB (Wiens, T. *et al.*, 2008). Furthermore the wind profile after the end of the forest strip becomes similar to the plain situation after a distance, 20 times the mean height of the forest (Defrance, J. *et al.*).

According to a measurement study performed during day time on a forest (23 trees) with average circumference of 621 mm and a line o sight of 20 m, the attenuation coefficient was found to be 0.352 dB/m if assuming spherical spreading. A measurement study performed by Swearingen showed 0,0086 dB/m if assuming spherical spreading and 0,00068 dB/m if assuming a spreading other than spherical or cylindrical (Wiens, T. *et al.*, 2008).

Another measurement study on sound propagation through a forest stand, showed differences in excess attenuation before and within the forest for different heights. They placed a speaker outside the forest and broadcasted a wide-band pink noise[4] in the direction of the edge of a coniferous plantation. Five microphones attached, each on

[4] A spectrum of noise, where every octave of frequency has the same energy

every five towers located as in *Figure 16* measured the corrected sound pressure level[5] (Herrington and Brock, 1977).

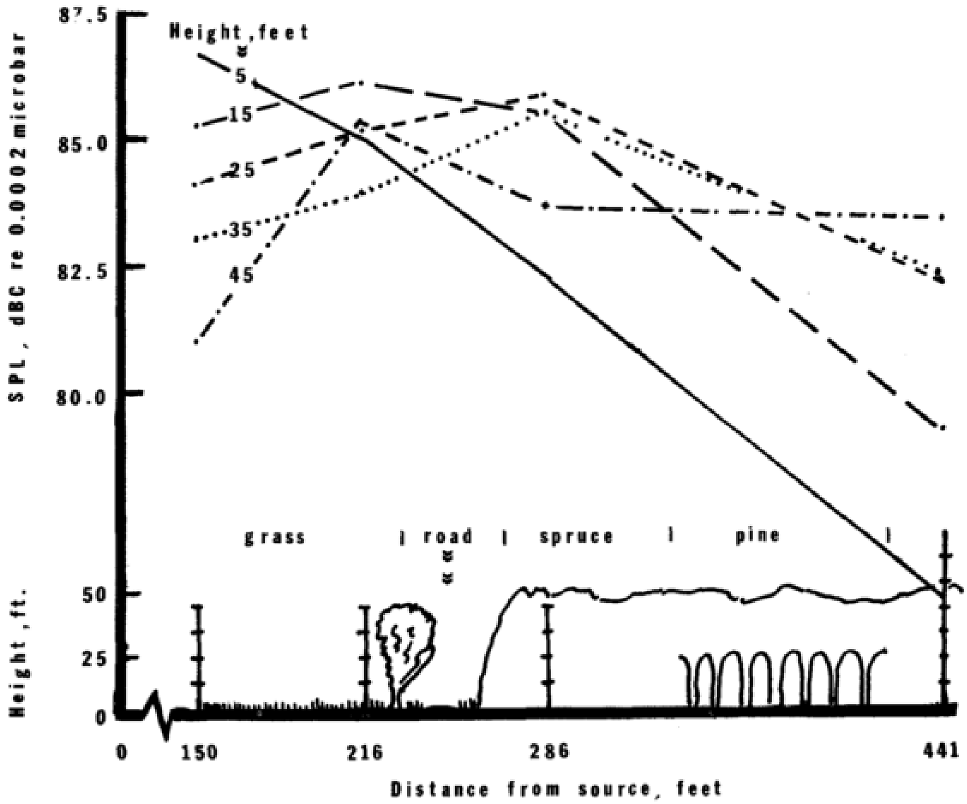


Figure 16, Herrington and Brock 1977

The reflection at the edge of the forest can be interpreted in the figure as the increase of sound pressure level between the 46 m and 66 m towers. Note the steady and rapid decrease in sound pressure level at 5-feet height within the forest, whereas the 45-foot height at the top of the canopy showed very little attenuation with distance. Herrington and Brock proposed that branches and tree stems scatters the acoustic energy and that the absorption mainly takes place at the ground surface, but also in the thickest part of the canopy (Herrington and Brock, 1977).

Swearingen and White performed a study of a predictive sound propagation model through a forest, taking account the ground impedance effects, scattering, spherical spreading, atmospheric absorption but also a simplified but realistic sound speed profile, assuming a scattering model by Twersky (1962) and impedance model by Attenborough (1992). An approximation of infinite cylinders were uses, where the density of trees were assumed to be 0.0124 m^-1 and their average tree radius of 0.0925. The canopy was then approximated by small and large branches. The small branches were assumed to be 1/8 of the trunk radius and 24 times the number of trunks.

The modeled attenuation rate, due to scattering can be seen in the below figure.

[5] A correction was made, adding the SPL loss due to spherical spreading of the wave front (Herrington and Brock, 1977)

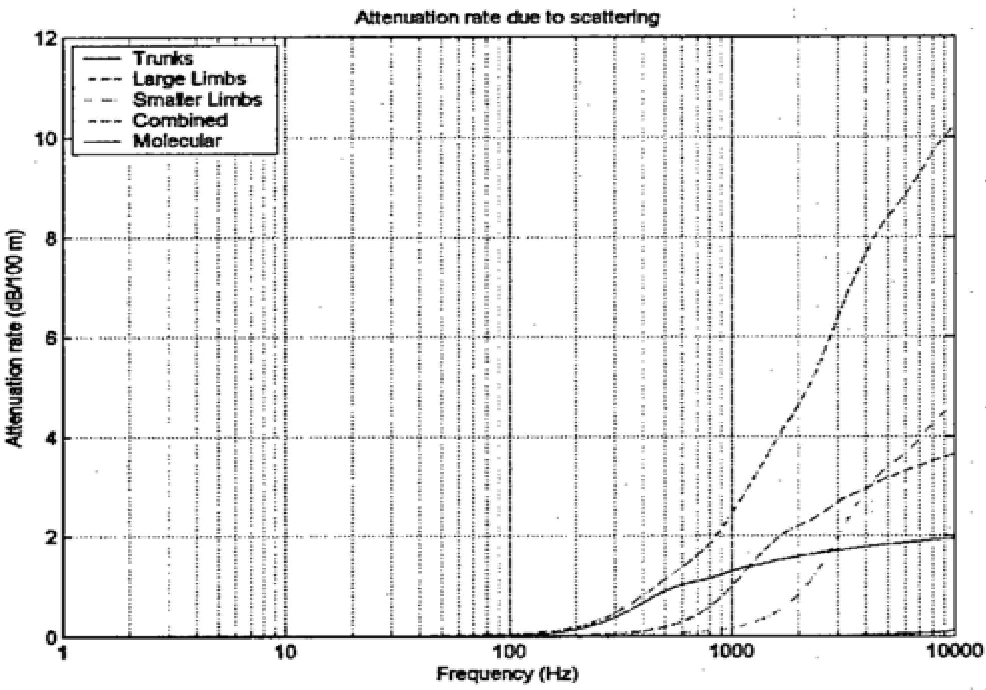


Figure 17, Swearingen and White 2004

The plot shows how the attenuation is expected to increase with frequency, and that it has a greater overall effect than atmospheric absorption.

In order to compare the model with the reality, explosives were detonated at a height of 2 m above the ground from four different locations. The receiver sources were placed at 174 Figure 18 resp. at 1400 m away from the source, Figure 19 (Swearingen and White, 2004).

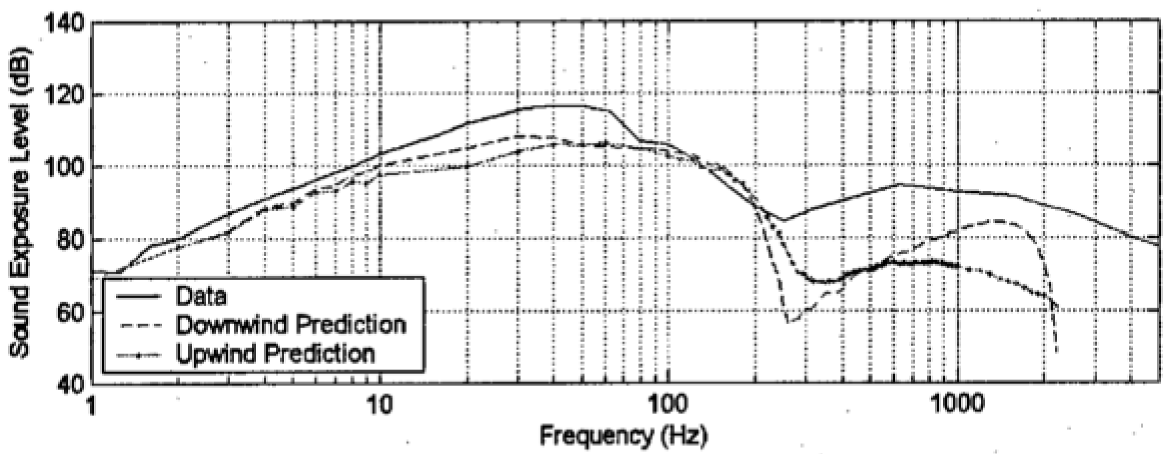


Figure 18, Predictions vs. measurements, Swearingen and White 2004

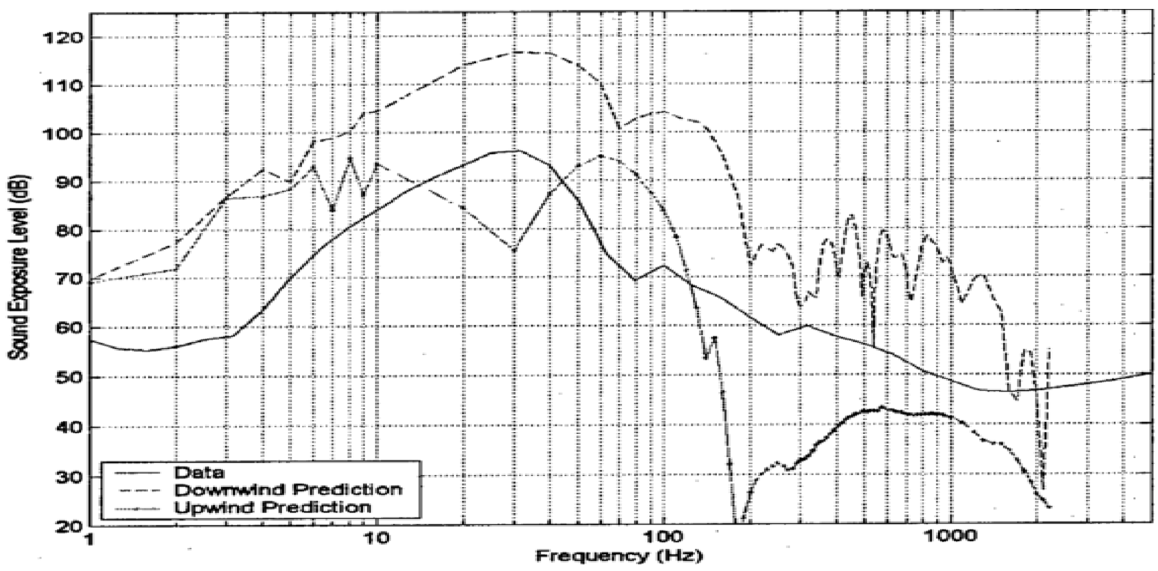


Figure 19, Predictions vs. measurements, Swearingen and White 2004

From Figure 18 you can tell that the measured data was generally higher in level than the predictions and that the apparent ground dip in downwind prediction can’t be observed in any of the figures. The general shape and trends fits pretty well, even though their magnitudes aren’t.

Also a comparison with predicted levels in forest was made compared to predicted levels in open field. See *Figure 20* on the next page.

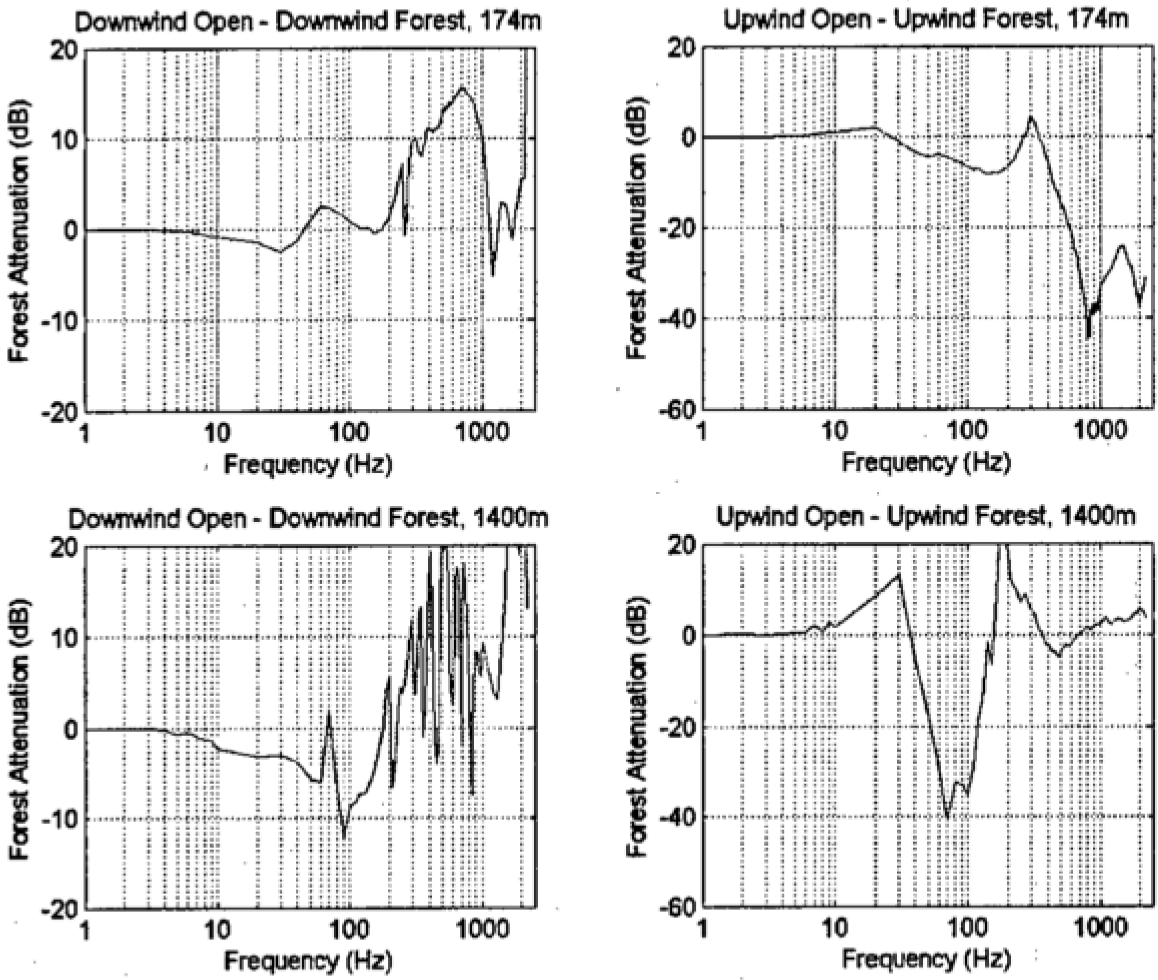


Figure 20, Forest vs. Open ground attenuation, Swearingen and White 2004

In large, the forest is slightly more favorable for sound propagation than open ground at short distance, downwind case for frequencies below 50 Hz, whereas the forest is providing more attenuation above 50 Hz. In the long range, the open ground is more favorable for propagation above roughly 200 Hz. The upwind open ground situation, produces much more attenuation than the forest across almost all frequencies.

It shall be noted, that the model is not taken atmospheric turbulence, that else would have caused a strong shadow zone in the upwind cases into consideration. Also note that these measurements and prediction was made under specific assumptions about the properties of the forest, and thus can't be generalized to an arbitrary forest. (Swearingen and White, 2004).

3.4 Sound emission

The most obvious determinant of how much noise one could hear from a wind turbine, is the noise generation itself. Turbines will generate two different types of noise: Mechanical and aerodynamic sound from the rotor blades. The former is nowadays seldom a problem, wherefore these sounds will be excluded in this report. In large the sound emission is dependent on the tip speed (Wizelius,2008). Since tip speed in turn is dependent on the wind speed, higher wind speeds in general also causes higher sound emission. (Sagrillo, 2004)

For modern pitch controlled wind turbines however, the blades begin to twist after a certain wind speed, leading to a decrease in tip speed ratio and to a constant sound power level for higher wind speeds. See Figure 21.

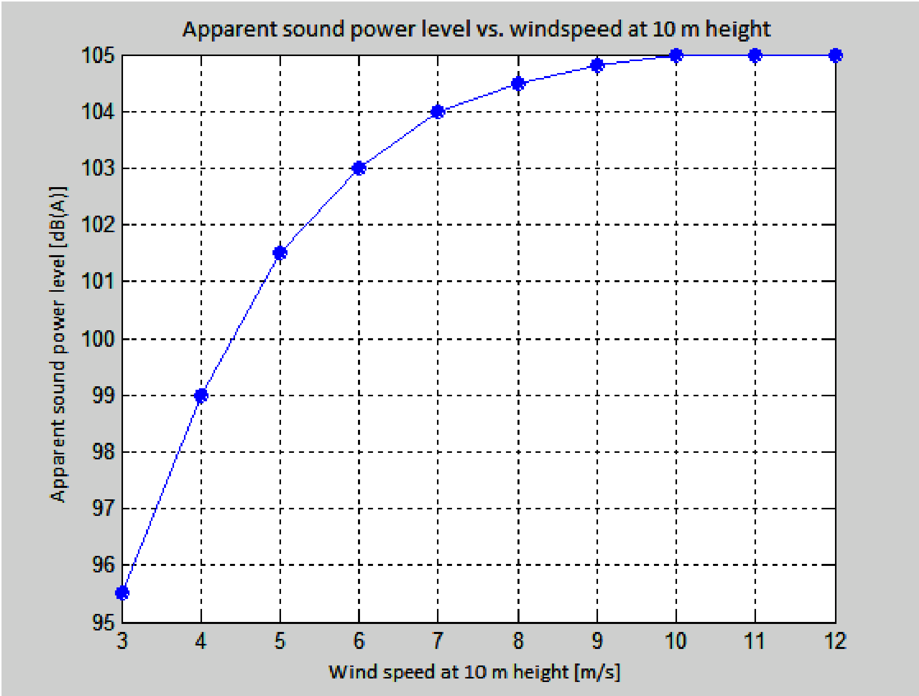


Figure 21, Apparent sound power level vs. windspeed at 10 m height for a typical wind turbine

Some modern turbines are programmed to run at lower tip speed ratio, minimizing the sound emission and thus making it possible to place those turbines more close to sound sensitive areas. This will off course on the other hand reduce the energy production and thus the economical benefits of the project (Wizelius, 2008). Experience has shown that aerodynamic sound normally is spreading with the same magnitude in all directions, except in the tangential direction of the rotor plane (Zhu, 2004). See *Figure 21*.

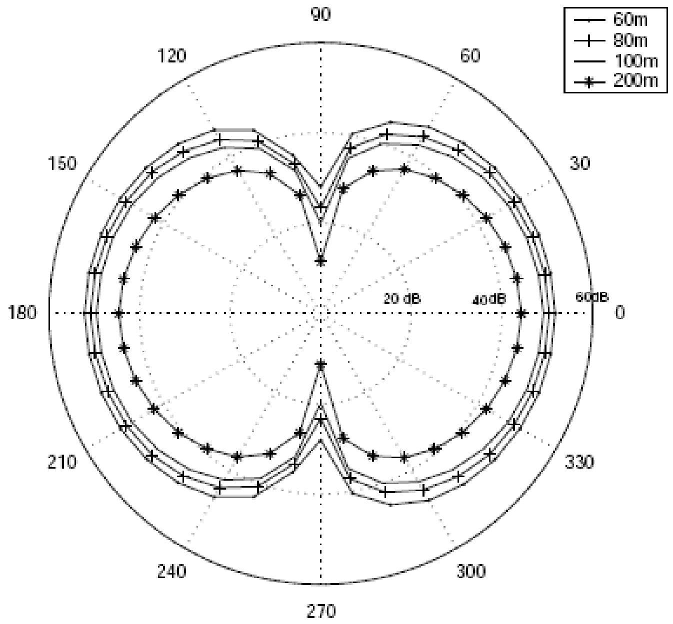


Figure 22, Sound pressure levels at different observer positions, Zhu 2004

Normally the sound emission from a wind turbine is assumed to behave like a point source.

The sound power level is expressed in dB(A) or decibel A, which is a corrected value adjusted to the sensibility of the human ear. The response of the human ear is not linear and has its maximum response for frequencies between 1000 Hz and 5000 Hz, whereas it is not sensitive to low frequencies. By adding a so called a-weighted filter to the sound power level, and adjustment can be made.

The aerodynamic sound of a wind turbine is often described by octave data in order to see the sound power contribution from each frequency to the total sound power level. Note that the octave-data in *Figure 23, sound power levels for different octave band frequencies, an example* is already a-weighted.

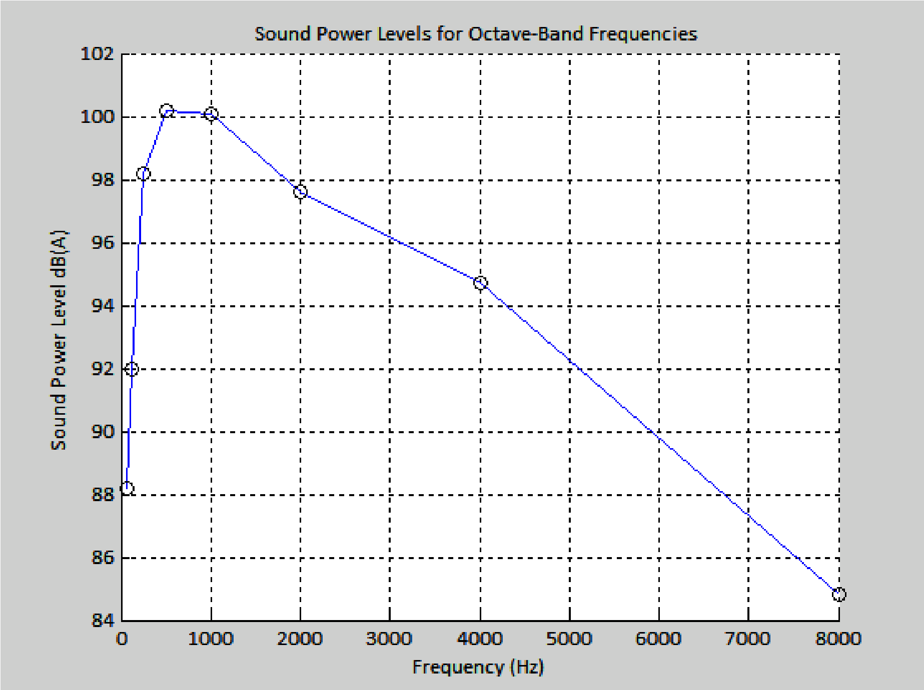


Figure 23, sound power levels for different octave band frequencies, an example

By tradition, the sound emission value used for sound propagation calculations today is the one corresponding to a wind speed of 8 m/s at 10 m height. The reason for this is unclear. One explanation might be the need for locking this to a specific height in order to perform control measurements (Ljunggren, 2005). Another explanation might be that worst case scenario is the starting point. 8 m/s almost corresponds to 95% of nominal power. [6], With higher wind speed the WTG might get noisier but you won't hear that because the ambient noise increases too (Marburger, 2008).

3.4.1 Measurement standards

Wind turbine developer often let a third party company measure how much sound their turbines generates. In Sweden there are two standards available for sound emission measurements: IEC 61400-11 and "Mätning av bulleremission från vindkraftverk". Both methods are very similar because there are about the same people behind the reports. The main exception is that the latter uses a linear regression method and the former a second order regression while calculating the noise dependence of the wind speed.

I will shortly explain the main algorithm of IEC 61400-11 below, because it's the newest and word wide most used one:

First one has to make sure that the electrical power for 95% of the time will not exceed rated power during the measurements. Then a power curve for the specific wind turbine is studied to see how much the wind blows at hub height. This value will first be corrected according to air pressure and temperature (Atmospheric conditions: T=288 K, P=101,3 kPa) and then corrected to the wind speed at 10 meters height, using Equation 1.

[6] 8.6 m/s for the reference turbine.

$$V_s = V_z \frac{\ln\left(\frac{z_{ref}}{z_{0ref}}\right)\ln\left(\frac{\mathrm{H}}{z_0}\right)}{\ln\left(\frac{\mathrm{H}}{z_{0ref}}\right)\ln\left(\frac{\mathrm{z}}{z_0}\right)}$$

Equation 8, IEC 61400-11:2002

z_{0ref} is the reference roughness length of 0,05 m, z_0 the roughness length, H the rotor centre height, z_{ref} the reference height 10 m and z is the anemometer height. If no anemometer measurement is done, z =H, and the Equation could instead be simplified to:

$$V_s = V_H \frac{\ln\left(\frac{z_{ref}}{z_{0ref}}\right)}{\ln\left(\frac{\mathrm{H}}{z_{0ref}}\right)}$$

Equation 9, IEC 61400-11:2002

If there are a lot of background noise, another method is preferred, which uses an anemometer placed at 10 meters height for wind speed measurements.

Background noise correction must also take place if the average background sound pressure levels are 6 dB or less below the combined level of the wind turbine and background. First a second order regression analysis for more than 30 data pairs will be done, where the sound pressure level is the dependent variable and wind speed the independent. Then a similar analysis will be done for the data pairs of the background noise measurements, and the sound pressure level for each integer ranging between 6 and 10 m/s will be calculated. The last step then will be to calculate the apparent sound power level for each integer wind speeds, which will be done using Equation 10, IEC 61400-11:2002:

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

Equation 10, IEC 61400-11:2002

$L_{WA,k}$ is the sound power level at each integer k, $L_{Aeq,c,k}$is the corrected A-weighted sound pressure level at each integer k, R_1 is the slant distance in meters from the rotor centre to the microphone, S_0 the reference area of one square meter and 6dB accounts for the approximate pressure doubling that occurs for the sound level measurements on a ground board.

Also tonality measurements should be done such as sound emission for different frequencies and tonal audibility criteria's shall be calculated.

3.4.2 Duration mean value

An alternative way of describing the sound emission level, that recently gained attention, is to use so called duration mean values[7]. That is the mean sound power level over a year, when taken into account how much of the time the wind blows with a certain magnitude (Figure 24), multiplied with the generated sound power level for that speed, and then all values weighted to an duration mean value as shown in Equation 11.

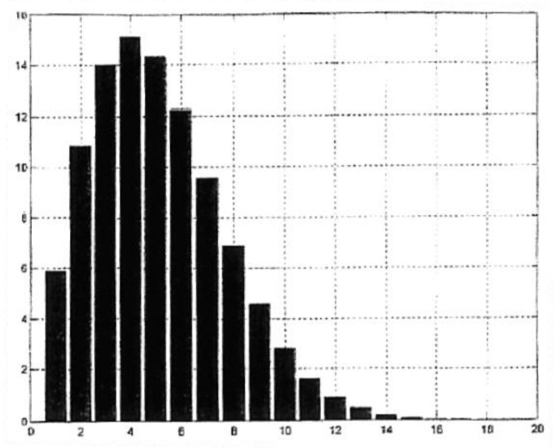


Figure 24, Wind speed distribution, Ljunggren 2005

$$L_{WA,dmv} = 10\log\left[\frac{t_6 10^{L_6/10} + t_7 10^{L_7/10} + t_8 10^{L_8/10} + t_9 10^{L_9/10} + t_{10} 10^{L_{10}/10}}{\sum_6^{10} t_n}\right]$$

Equation 11, Duration mean value calculation, Ljunggren 2005

$t_6$is the part of the time that the wind blows between 5.5 and 6.5 m/s at 10 m height. If the wind turbine starts at lower speeds than 5.5 m/s, the time for which the wind blows 5 m/s will be included in t_6. Likewise the part of the time the wind blows stronger than 10.5 m/s will be included in t_{10}. The duration mean value thus will tell how much noise the turbine on average generates on an annual basis (Ljunggren, 2005).

[7] In Swedish called driftsmedelvärde

4 Sound propagation models

Sound predictive models can either be theoretical, numerical, empirical or heuristic and they can vary in terms of complexity. Because the reality is very complex, assumptions always have to be made and some of the algorithms are therefore only applicability to certain situations. Some algorithms also assume incorrect fixed values for describing physical parameters. (Teague and Foster, 2006).

4.1 ISO 9613-2

ISO 9613-2 is a general method of predicting the sound levels in the community from sources of know sound emission. It is general in the sense that it may be applied to a wide variety of noise sources, and covers most of the major mechanisms of attenuation. The method predicts a long-term average A-weighted sound pressure level with respect to geometrical divergence, atmospheric absorption, ground effect, and reflection from surfaces and screening by obstacles, using octave data calculations. The model assumes downwind condition or moderate positive temperature gradient with wind speeds ranging from 1 to 5 m/s, measured at 3 to 11 m height (ISO, 1996).

The predicted sound pressure level is given by:

$$L_{fT}(DW) = L_W + D_C - A$$

Equation 12, Sound pressure level according to ISO 9613-2

L_W is the octave-band sound power level in decibels and D_C is the directivity correction in (dB), that describes how much the sound pressure level deviates in a specified direction from the level of an omnidirectional point sound source. If the pointsound source radiating into free space is omnidirectional, D_C will be equal to 0 dB, else D_C equals the directivity index, plus an index that accounts for sound propagation into solid angles less than 4 pi steradians (ISO, 1996).

A is the total attenuation when summarizing all the above mentioned attenuations:

$$A = A_{div} + A_{atm} + A_{gr} + A_{bar} + A_{misc}$$

Equation 13, Attenuation, ISO 9613-2

The divergence attenuation is given by:

$$A_{div} = 20\log(d) + 11$$

Equation 14, Divergence attenuation, ISO 9316-2

Here d is the distance from the source to the immission point in [m]. Note that the Equation is the same as the expression for the sound power level in Equation 3, **Sound intensity level (dB), Lundmark 2008** above.

The atmospheric absorption is expressed as:

$$A_{atm} = \alpha d/1000$$

Equation 15, Atmospheric absorption, ISO 9613-2

The atmospheric attenuation coefficient A_{atm} is expressed in decibels per kilometer for each octave band with nominal midband frequencies ranging between 63-8000 Hz. The values in table2 are given as average values based on temperature and relative humidity:

Temperature	**Humidity**	**Nominal midband frequency, Hz**							
°C	%	63	125	250	500	1000	2000	4000	8000
10	70	0,1	0,4	1,0	1,9	3,7	9,7	32,8	117,9
20	70	0,1	0,3	1,1	2,8	5,0	9,0	22,9	76,6
30	70	0,1	0,3	1,0	3,1	7,4	12,7	23,1	59,3
15	20	0,3	0,6	1,2	2,7	8,2	28,2	88,8	202
15	50	0,1	0,5	1,2	2,2	4,2	10,8	36,2	129
15	80	0,1	0,3	1,1	2,4	4,1	8,3	23,7	82,8

Table 3, Atmospheric absorption, ISO 9613-2:1996

ISO 9613-2 suggests two different ways to calculate the ground effect. The first should only be used for short distances and if the ground is flat, either horizontally, or with a constant slope, whereas the other method is preferred to use in other cases. The idea is to divide the whole distance from the source to the receiver, into a source region, a middle region and a receiver region, where the size of the middle region doesn't have any influence on the total ground effect. The ground type range between 0 and 1 and will be assigned for a constant G, where G=0 represent hard ground and G=1 porous ground (ISO, 1996).

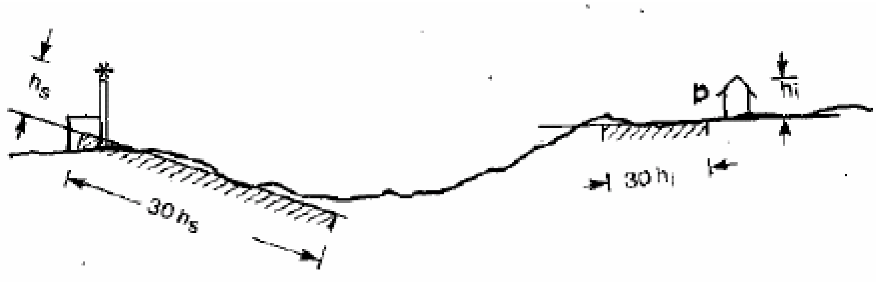


Figure 25, Classification of the ground properties, Gustafson 2006

The idea is to divide the whole distance from the source to the receiver, into a source region, a middle region and a receiver region, where the size of the middle region doesn't have any influence on the total ground effect. See Figure 25, **Classification of the ground properties, Gustafson 2006**. Then the roughness level ranging between 0 and 1 will be assigned for a constant G, where G=0 represent hard ground and G=1 porous ground (ISO, 1996).

Nominal midband frequency Hz	A_s or A_r 1) dB	A_m dB
63	$-1,5$	$-3q$ 2)
125	$-1,5 + G \times a'(h)$	$-3q(1-G_m)$
250	$-1,5 + G \times b'(h)$	
500	$-1,5 + G \times c'(h)$	
1 000	$-1,5 + G \times d(h)$	
2 000	$-1,5(1-G)$	
4 000	$-1,5(1-G)$	
8 000	$-1,5(1-G)$	

NOTES

$$a'(h) = 1,5 + 3,0 \times e^{-0,12(h-5)^2}\left(1 - e^{-d_p/50}\right) + 5,7 \times e^{-0,09h^2}\left(1 - e^{-2,8 \times 10^{-6} \times d_p^2}\right)$$

$$b'(h) = 1,5 + 8,6 \times e^{-0,09h^2}\left(1 - e^{-d_p/50}\right)$$

$$c'(h) = 1,5 + 14,0 \times e^{-0,46h^2}\left(1 - e^{-d_p/50}\right)$$

$$d'(h) = 1,5 + 5,0 \times e^{-0,9h^2}\left(1 - e^{-d_p/50}\right)$$

1) For calculating A_s, take $G = G_s$ and $h = h_s$. For calculating A_r, take $G = G_r$ and $h = h_r$. See 7.3.1 for values of G for various ground surfaces.

2) $q = 0$ when $d_p \leqslant 30(h_s + h_r)$

$$q = 1 - \frac{30(h_s + h_r)}{d_p} \quad \text{when } d_p > 30(h_s + h_r)$$

where d_p is the source-to-receiver distance, in metres, projected onto the ground planes.

Figure 26, Ground attenuation calculation method 1, ISO 9613-2:1996

The above equations shows that for example if the source is 80 m high (hub height) and the receiver is placed at 1.6 m height, with the distance 500 m between, on a hard ground A_{gr} will be constant -3 dB (63-8000 Hz) and 4,31 dB for porous ground (500 Hz). Over 125 Hz, A_{gr} will be about 0 dB for porous ground. Thus a porous ground will in this case lead to zero ground effect, whereas a hard ground will lead to amplification (note the change of sign when the values are entered in Equation 13). Also note that source height will not have any influence on the ground effect when greater than 10 m and the ground effect is independent on the size of the middle region.

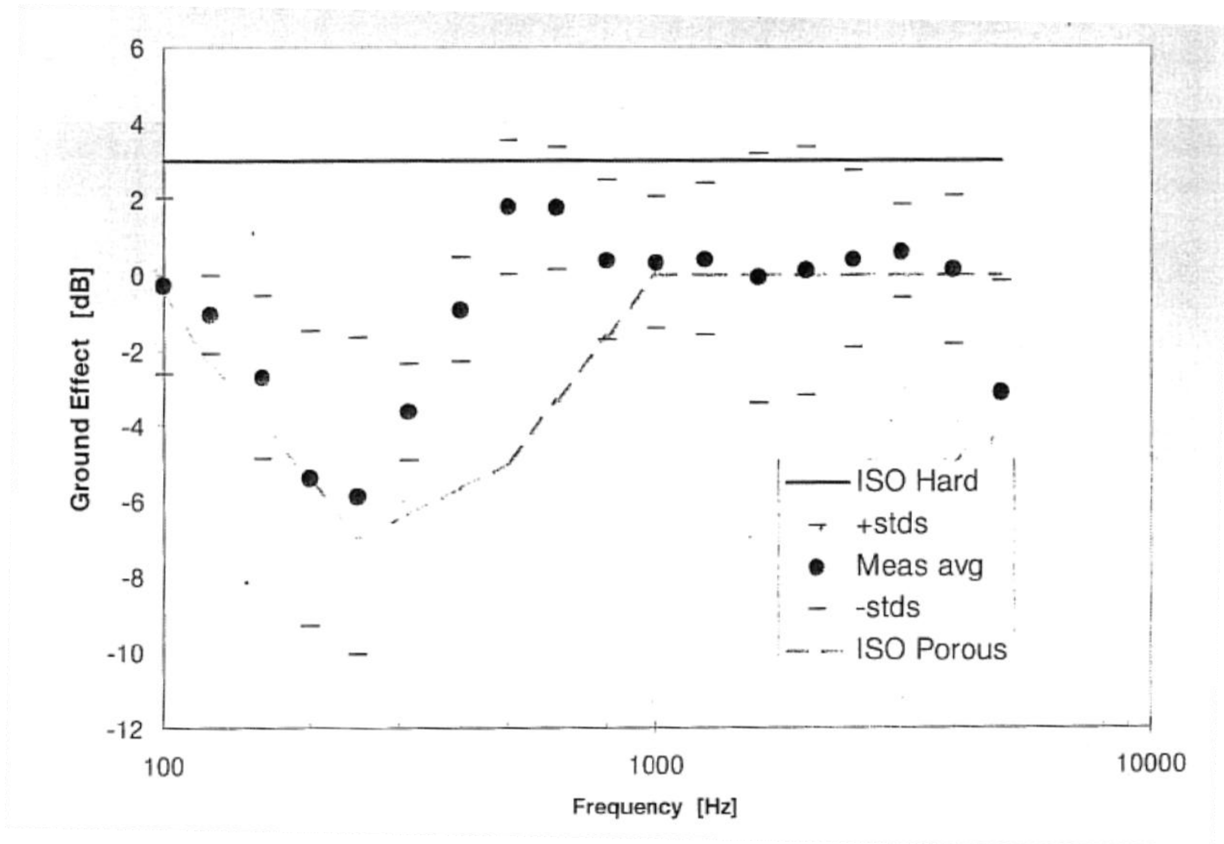


Figure 27, Ground effect prediction version measurement. Source 22m, receiver 1.5 m, distance 400 m, Ljunggren 2005

The above picture shows validation of the general ground effect prediction algorithm in ISO 9613-2. As you can see, using ISO Porous is more accurate in this case, than ISO hard.

A second method to calculate ground attenuation is through the following equation:

$$A_{gr} = 4.8 - \left(\frac{2h_m}{d}\right)\left(17 + \left(\frac{300}{d}\right)\right) \geq 0\ dB$$

Equation 16, Ground attenuation calculation method 2, ISO 9613-2:1996

h_m *is the average height of the propagation path above the ground, and d the distance from the source to receiver.* h_m *can be estimated by dividing d with the area between the ground and the propagation path line (ISO, 1996). See Figure 28.*

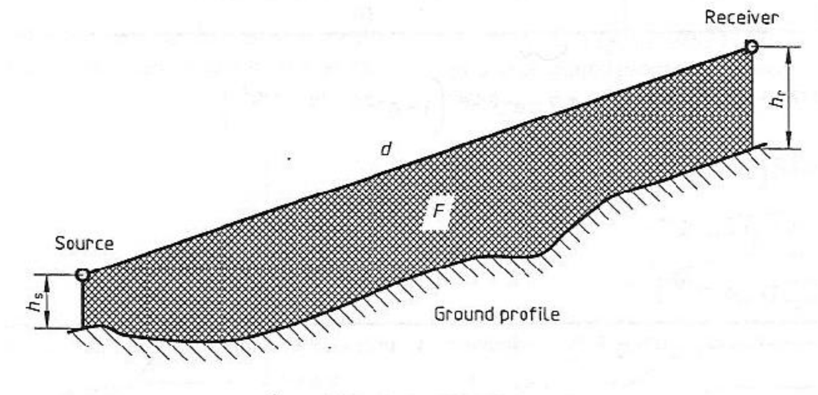


Figure 28, Estimation of h_m, ISO 9613-2:1996

If equation 16 returns a negative value, this value will be replaced by a zero (ISO, 1996). Thus the second method of calculating the ground effect can't result in ground effect amplification, which could be the case in method 1. This method presumes a mixed ground, most of which is porous. The reason why method 1 may be more accurate to use for short distances is that a small value on d, will result in no ground effect at all (ISO, 1996). Note that this method assumes the same attenuation for all frequencies.

ISO 9613-2 also shows different ways to calculate the effect which barriers and obstacles have on the sound propagation. Due to limitations I refer you to ISO 9613-2 for further reading.

As mentioned earlier ISO 9613-2 assumes moderate meteorological conditions that are favorable for sound propagation. Thus to obtain a long-term average A-weighted sound pressure level, a meteorological correction has to be done:

$$L_{AT}(\mathrm{LT}) = L_{AT}(DW) - C_{met}$$

Equation 17, Meterological correction, ISO 9613-2:1996

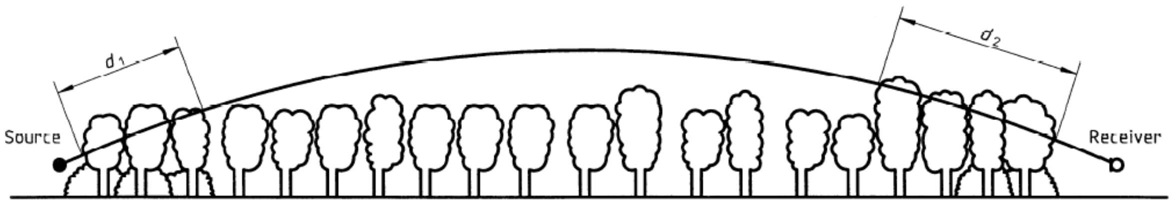
The time interval T is at least several months of a year, enough to include a variety of meteorological conditions, favorable or not favorable to propagation. Meteorological conditions have a small influence on the propagation for short distances and for long distances when the source and receiver are at greater heights (ISO, 1996). If the ground projected distance d_p is 10(h_s+h_r) or smaller, C_{met} = 0. Otherwise:

$$C_{met} = C_0\left(1 - \frac{10(h_s + h_r)}{d_p}\right)$$

Equation 18, ISO 9613-2:1996

where C_0 is a local meteorological factor in decibels, which depends on meteorological statistics for wind speed and direction, but also temperature gradients. Experience has showed that C_0 often range between 0 to 5 dB and that values exceeding 2 dB are exceptional (ISO, 1996).

ISO 9613-2 also offers a way to calculate attenuation due to propagation through foliage, industrial sites and houses.



NOTE — $d_f = d_1 + d_2$

For calculating d_1 and d_2, the curved path radius may be assumed to be 5 km.

Figure 29, Sound attenuation through foliage, ISO 9613-2:1996

If the forest is dense enough, that is so dense that it completely blocks the view along the propagation path, foliage attenuation for octave band frequencies can be used, given a certain distance d_f through the foliage. For $d_f \leq 20$ m, following attenuation values can be used:

Hz	63	125	250	500	1000	2000	4000	8000
dB/m	0	0	1	1	1	1	2	3

Table 4, Attenuation due to foliage, ISO 9613-2:1996

If $d_f \geq 20$ m, the following values are preferred be used:

Hz	6 3	125	250	500	1000	2000	4000	8000
dB/m	0,02	0,03	0,04	0,06	0,06	0,08	0,09	0,12

Table 5, Attenuation due to foliage, ISO 9613-2:1996

Measured values have been compared to calculated values for broad band noise sources giving ISO 9613-2 an accuracy of ±3 dB for distance 0 - 1000 m with mean height 0 - 5 m, ±1 dB for distance 0 – 100 m and ±3 dB for distance 100 – 1000 m with mean height, 5 - 30 m (ISO, 1996).

4.2 The swedish model

The year 2001 the Swedish environmental protection agency by order of the government published a report "Ljud från vindkraftverk", which contained two models for land based wind power and one for sea based. The first model is the same as the Danish Miljöstyrelsen's report from 1980 and is preferred to use for short distances, which is distances up to 1000 m:

$$L_A = L_{WA} - 8 - 20\log(r) - 0{,}005r$$

Equation 19, Sound pressure level calculation, Naturvårdsverket 2001.

L_A is the a-weighted sound pressure level, L_{WA} , the a-weighted sound power level and r the distance from source to receiver (Naturvårdsverket, 2001). This equation could be rewritten as:

$$L_A = L_{WA} - 11 + 3 - 20\log(r) - 0{,}005r$$

Equation 20

Now it’s easier to see which terms respond to which matter. +3 is the ground effect, -0,005*r the atmospheric absorption and the rest is the effect of geometrical divergence as we saw in equation 7.

What was new in the report from 2001 is the sound pressure level correction. During the emission level estimation, the estimator corrects the wind speed at hub height down to 10 m height given the roughness length 0.05 m (See Equation 8). For other roughness lengths the wind speed at 10 m height can’t be considered to be the same, and therefore a correction formula was introduced in the Swedish model:

$$L_{WA,corr} = L_{WA,meas} + k\Delta v_h$$

Equation 21, Sound power level correction, Naturvårdsverket 2001

Δv_h is the difference in wind speed at 10m height and the speed at hub height for the specific roughness length and is calculated through:

$$\Delta v_h = v_h \frac{\ln\left(\frac{\mathrm{H}}{z_0}\right)\ln\left(\frac{10}{0.05}\right)}{\ln\left(\frac{10}{z_0}\right)\ln\left(\frac{\mathrm{H}}{0.05}\right)} - 1$$

Equation 22, Wind speed correction, Naturvårdsverket 2001

Note the similarities with Equation 8

k is the sound dependence on the wind turbine at 10 m height in dB/m/s. The model thus assumes a linear dependency between the sound power level and the wind speed.

For distances over 1000 m, the other method will be used:

$$L_A = L_{WA,corr} - 10 - 20\log(r) - \Delta L_a$$

Equation 23, Sound pressure level for distances over 1000m, Naturvårdsverket 2001

Where:

$$\Delta L_a = 10\log\left(\sum 10^{\frac{(L_i+A_i)}{10}}\right) - 10log\left(\sum 10^{\frac{(L_i+A_i-ra_i)}{10}}\right)$$

Equation 24, Atmospheric absorption, Naturvårdsverket 2001

L_i are measured octave band values between 63 and 4000 Hz. These values often come with the emission report from the test institutions or companies for specific wind turbines.

A_i are A-weighted levels according to:

Frequency ,Hz	63	125	250	500	1000	2000	4000
A_i, dB	-26	-16	-9	-3	0	+1	+1

Table 6, A-weightening, Naturvårdsverket 2001

a_i are the air absorption values in octave band per meter according to:

Frequency ,Hz	63	125	250	500	1000	2000	4000
a_i, dB/m	0,0001	0,0003	0,0006	0,0014	0,0032	0,0079	0,0220

Table 7, air absorption for different frequencies, Naturvårdsverket 2001

Note that Table 7 shows exactly the same values as Table 1 for Säve measurement station, with the exception that value for 8000 Hz for some reason is missing here. The air absorption values are 95% percentile values, not average values.

The report also shows how to calculate the sound pressure level at a point, when there's more than one sound emission source. The total sound pressure level is obtained through the following formula:

$$L_{A,tot} = 10\log\left(\sum 10^{\frac{(LA_i)}{10}}\right)$$

Equation 25, Total sound pressure level from more than one wind turbine, Naturvårdsverket 2001

The Swedish land based model has only so far been validated for flat ground with an accuracy of ±1 dB (Naturvårdsverket, 2001).

4.3 Nord2000

With the increased computer power and development in acoustical understanding, the Nordic environmental authorities identified in the mid 90s a need for a more realistic sound propagation model, predicting noise from various types of sources. Nord2000, published in the year 2002, was a collaboration work between DELTA Acoustics & Vibration, SINTEF Telecom and Informatics and SP Swedish National Testing & Research Institute. Nord2000 is a general sound propagation model, but can be applicable for all kinds of sources, even wind turbines (Kragh, J., *et al.*, 2002).

Due to delimitations and the complexity of the model, I will only summarize the main characteristics of the model and thus exclude the mathematics behind it. Also screen and obstacle calculations will not be described.

Nord2000 uses the following formula for prediction of the sound pressure level at the immission point:

$$L_{R=}L_W + \Delta L_d + \Delta L_a + \Delta L_t + \Delta L_s + \Delta L_r$$

Equation 26, Kragh, J. et al. 2002

L_W is the sound power level, ΔL_d the spherical divergence attenuation, ΔL_a the air absorption, ΔL_t the effect of the terrain, $\Delta L_s$the propagation effect of scattering zones and ΔL_r the propagation effect of obstacle, depending on their surface and dimensions properties. As you can see the main variables to consider are about the same as for ISO 9613-2, even though the way they are interpreted and modeled differs a lot, except for ΔL_a. ΔL_d is the attenuation due to spherical divergence and is expressed by $1/R_0$. In case of refraction R_0 will be substituted by R, where R is the measured distance along the curved ray.

The ground effect ΔL_t, defined as: *the difference between the sound pressure level in the presence of the ground and the free-field sound pressure level* (Kragh, J., *et al.*, 2002). The ground effect calculations for a flat ground with different softness levels can be seen in *Figure 30* below.

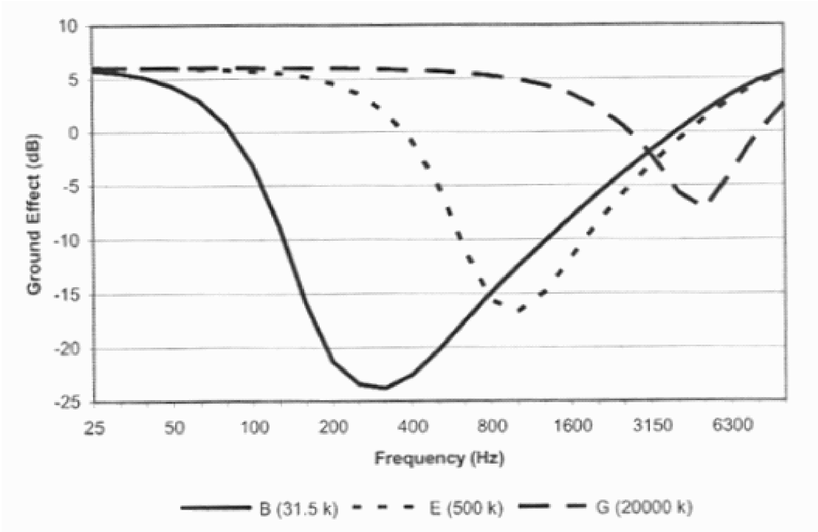


Figure 30, Ground effect of flat ground. d=100m ,hs=0.5m and hr= 1.5m, Kragh, J.,et al. 2002

The model uses the same theoretical assumptions as in 3.2.4. In the figure we see the relationship between the ground effect and the frequency. For small frequencies the phase difference between the direct and the reflected sound wave is small, hence we get an increase in amplitude (the sound pressure level), leading to a ground effect of 6 dB. When the frequency increases the direct and the reflected waves are interfering in a destructive way, leading to an amplitude reduction. The maximal reduction will occur when the phase difference is 180°. Due to difference in travelling distance and by the attenuation at the reflection, the direct and the reflected waves won't fully cancel out each other. As frequency increases, the phase difference becomes 360°, and they are in phase again. The differences in dip are due to the ground impedance. Nord2000 assumes the impedance model of Delany and Bazley. Thus the impedance will implicit specified by the resistivity flow of the ground surface, which is a parameter describing the hardness of the ground. In *Figure 30*, B = soft forest floor (short, dense heather-like or thick moss), E compacted field and gravel (park area, compacted lawns) and G hard surface (concrete, water etc). Normal forest floors is given the flow resistivity value 200 [kNsm^-4], which is between B and E.

In Nord2000 the area for which the ground effect will be calculated is given by the so called Fresnel-zone, which is the zone formed by the intersection between the ellipsoid and the plane. Only the sound field within this elliptic zone will contribute to the sound pressure at the immission point.

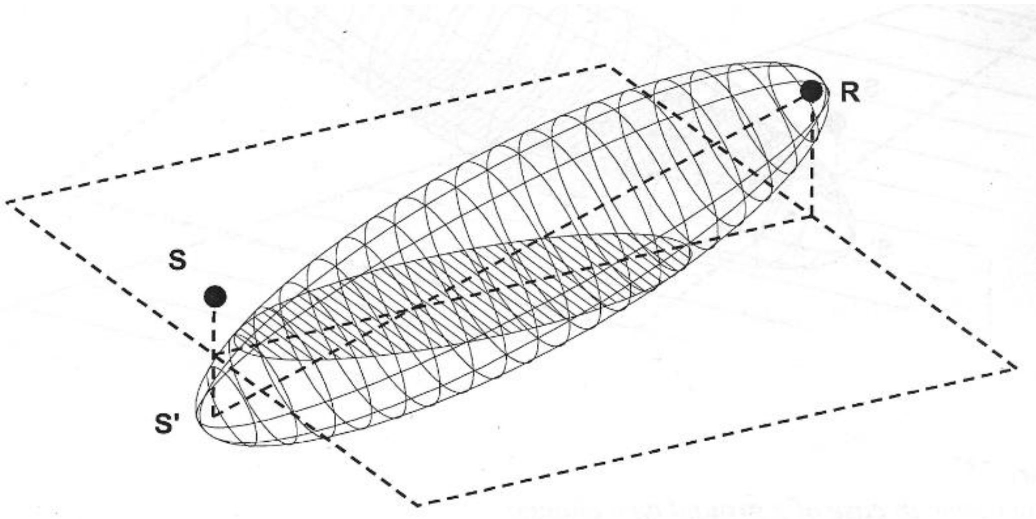


Figure 31, Fresnel zone, Kragh et al. 2002

The Fresnel ellipsoid is defined as: "*the locus of points P where the sum of the distances to the source S and receiver R minus the direct distance between S and R is a fraction F of the wavelength λ*"(Kragh, J., *et al.*, 2002).

$$|SP| + |RP| - |SR| = F\lambda$$

Equation 27, Kragh, J., et al. 2002

F will range between 1/16 and 1/2, depending on the purpose.

The idea of Fresnel zone is also applied in the case of different ground types between source and receiver. The size of each ground surface type is then calculated and used to interpolate between the ground effects contributions from each ground surface type.

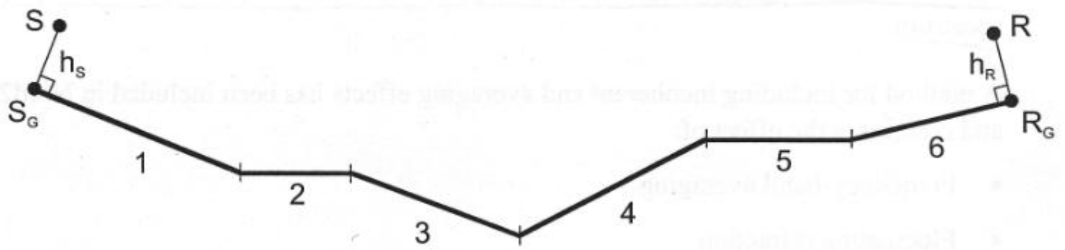


Figure 32, Non plane ground, Kragh et al. 2002

The ground effect can furthermore be calculated for non-flat terrain. The ground effect of each segment will then contribute to the total ground effect, by multiplying the calculated ground effect for each segment by the Fresnel-zone weight (Kragh, J., *et al.*, 2002).

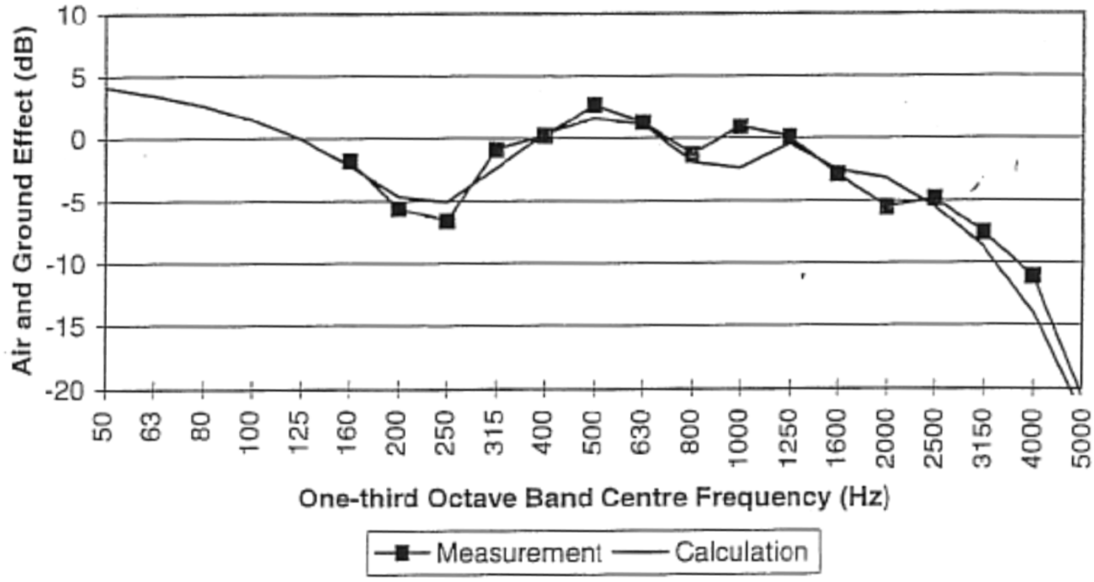


Figure 33, Validation of air and ground effect, Ljunggren 2005

The above figure shows validation for air and ground effect calculation of Nord2000. The hub height was 60 m, receiver height 1.5 m, distance 533 m, 9.5 m/s at hub height and the ground was soft with expected roughness length 0.02 (Ljunggren, 2005).

In Nord2000 the meteorological effect of sound propagation can be estimated for specific wind and temperature gradients. Input values for gradient estimations are: the average wind speed component in the direction of the propagation at a specific height, the standard deviation of variations in wind speed component, temperature at the ground, average temperature gradient, the standard deviation of temperature gradient variations and the turbulence strength parameters due to wind and temperature. In practice some of the above mentioned parameters will probably be difficult to know or determine and thus be fixed to realistic values.

The gradient values are then used to approximate the vertical sound speed profile, which causes downward or upward refraction depending on the gradients properties. Normally the wind profile increases logarithmic. In Nord2000 it's however a linear dependency is assumed, making the calculations easier.

The weather effect results in a change of frequency dips towards higher frequencies in upward refraction and towards lower frequencies in downward refraction situations.

Normally Nord2000 is only valid for modest refraction, thus multiple ground reflections in case of strong downward refraction and shadow zones in strong upward refraction situations are not taken into consideration. However according to Kragh *et al*. methods have been elaborated to take account for these effects.

ΔL_s is the effect of so called scattering zones, that is the effect of sound propagation through urban areas or vegetation. In forests the sound propagation is influenced by scattering, reflections, and absorption due to foliage, trunks and branches.

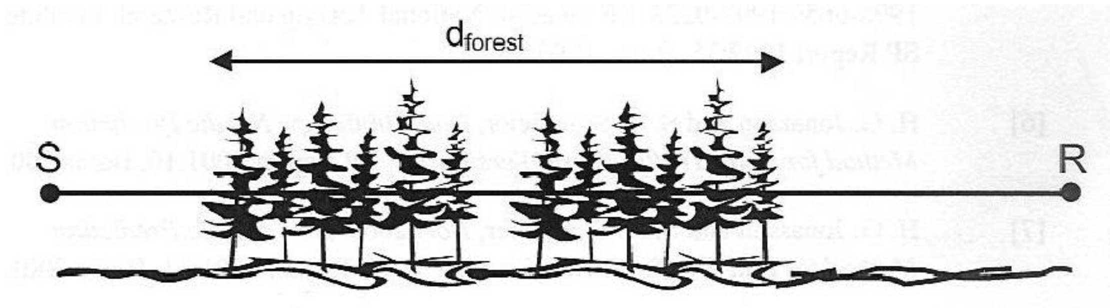


Figure 34, Forest scattering, Kragh et al. 2002

Because a deterministic approach is much too complicated, Nord2000 uses a statistical scattering model, a model that will not predict the exact sound pressure level, rather an averaged sound pressure level. ΔL_s depends on the size and density of the scattering objects, the wave number for each frequency, the total sound path length of the scattering zones and their absorption coefficients. Practical considerations have downward limited ΔL_S to -15 dB.

$$\Delta L_S = k_f T k_p A_e(R_{sc})$$

Equation 28, Kragh, J., et al. 2002

k_f is the frequency weighting function as a function of the wave number and the mean stem radius a according to:

Ka	k_f
0	0.00
0.7	0.00
1	0.05
1.5	0.20
3	0.70
5	0.82
10	0.95
20	1.00

Table 8, Ka and Kf, Kragh et al. 2002

$$T = \left(\frac{R_{sc} nQ}{1.75}\right)^2$$

Equation 29, Kragh, J., et al. 2002

nQ is used to describe the scattering effect. For forests, n is density of trees, whereas Q is the mean trunk diameter.

k_p is 1.25 and $A_e(R_{sc}) = \Delta L(h', \alpha, R') + 20\log(8R')$, where h' is the average scatter obstacle height, α the absorption coefficient and $R' = nQR_{sc}$. $\Delta L(h', \alpha, R')$ is determined using cubic interpolation. See Kragh, J., *et al.*, 2002

As you can see according to the formulas; larger stem diameter and height, higher tree density and longer propagation path will result in a higher attenuation due to scattering. Nord2000 also contains method for calculating scattering zones of varying types.

As mentioned previously, Nord2000 can only determine the weather influence on sound propagation for a specific weather condition, such as maximum levels or short-term equivalent sound pressure levels. If a long-term noise level such as the yearly average value is to be estimated, such a value can be obtained by combining the calculated short term noise level, with meteorological statistics.

Validation of the model has shows that Nord2000 is particularly accurate at distances up to 200 m for open ground (Kragh, J., *et al.*, 2002). Later validations of WiTuProp, which is a calculation program, using the Nord2000 theory for wind turbine noise prediction, have also shown high accuracy for distances up to 1000 m (Ljunggren, 2005). According to Søndergaard (2008), Nord2000 has been validated up to 1500 m for plane ground, showing really good results in downwind cases, but somewhat larger differences between measured and predicted values for upwind situations (Søndergaard, 2008).

Nord2000 is however not been validated for sound propagation from wind turbines in forest areas.

5 Sound calculation results using WindPRO

WindPRO is a software used by many wind power developers today in order to find appropriate places for energy production, with help of maps and wind statistics. After finding potential wind turbine locations, the next step often involves sound level predictions, that is the sound pressure level at nearest sound sensitive area, see Figure 35.

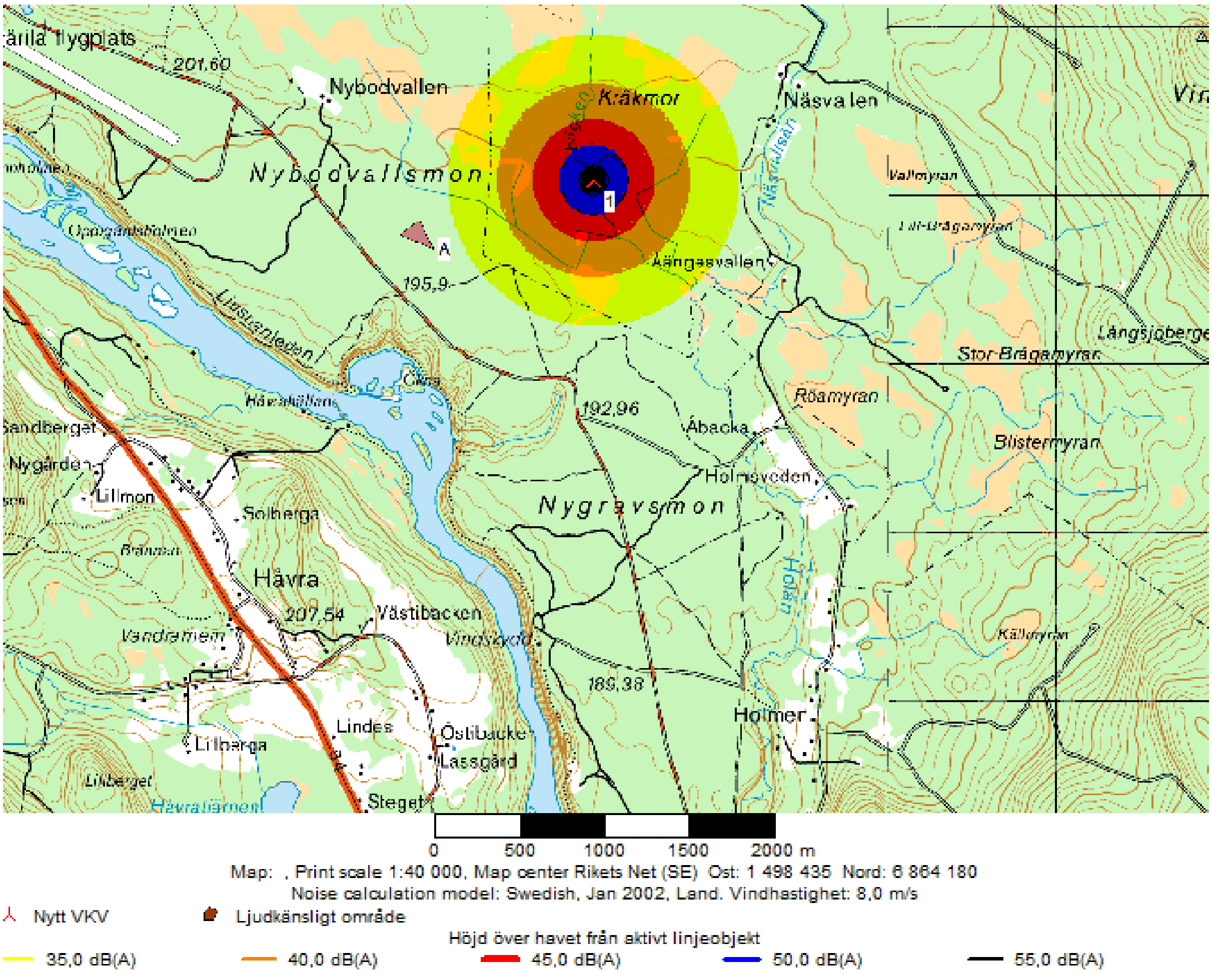


Figure 35, Sound calculation in WindPRO, "1" is the wind turbine and "A" an sound sensitive area, EMD

Several calculations were performed using the Swedish model and ISO 9613-2 in WindPRO for distances 500, resp. 1035 m assuming a plane forest area. The choice of these distances was mainly due to practical reasons. Unfortunately WindPRO also uses other roughness class definitions than Ljunggren proposes in (Naturvårdsverket, 2001). In order to compare the Swedish model with ISO 9613-2, the roughness classes have to be the same. Thus the calculations are made assuming the roughness class definitions in WindPRO. For detailed assumptions and results, see Appendix. The summarized result can be seen in the table below:

Model/Distance	Swe RC= 3	Swe no corr.	ISO Porous	ISO Hard	ISO Alt.
500 m	41.4 dB	39.8 dB	35.0 dB	41.0 dB	39.4 dB
1035 m	33.3 dB	31.8 dB	27.0 dB	34.0 dB	30.2 dB

Table 9, SPL calculations

Swe RC, is the Swedish model assuming roughness class 3. Swe no corr. the Swedish model assuming no correction for the roughness length, ISO Porous is ISO 9613-2 assuming porous ground, whereas ISO Hard assumes hard ground and ISO Alt. is the alternative method for ground attenuation.

Unfortunately at the moment of writing, I had no access to any software using Nord2000. The general opinion according to Almgren (2008), Heggies (2006), Teague and Foster (2006) and others however is that this model gives lower sound pressure level compared to both ISO 9613-2 and the Swedish model. One exception is when calculating propagation for a convex area such as a valley. The sound will then be focused on the dwelling (if placed in the valley). (Almgren, 2008).

6 Discussion

6.1 Sound emission

6.1.1 Duration mean value

Duration mean value is one way to take emission variations into consideration, instead of using a fix value of 8 m/s at 10m height as starting point. The idea behind it is good. Some problems with the formula however occurs for turbines which sound emission decreases after a specific wind speed. Also wind speed distributions above 10 m/s will underestimate the sound emission, whereas a wind speed distribution under 6 m/s will do the opposite since many turbines today starts at lower wind speeds than 6 m/s (Almgren, 2006). Even if a more accurate expression would be developed taking these effects into account, annual fluctuations due to weather and shifting wind directions will still lead to a great variety for the immission values at the receiver point. Hence, as long as these aspects are not combined there's in my opinion no point of using duration mean value as an emission value.

6.1.2 The sound power level correction formula

The idea behind the sound power level correction formula, given in the Swedish environmental authority report, was that developers could place wind turbines on other ground types with roughness lengths different than 0.05 m, without getting incorrect sound power levels (Ljunggren, 2008).

Unfortunately this formula is incorrect in many ways. To illustrate this, I will split the equation into pieces and describe what the mathematics say. I will use the values h=10, H=100 and z_0=0.4 m. I also name $V_1$the wind speed at height 100 for z_0=0.4, v_1 the wind speed at 10 m height (8 m/s), $V_2$the wind speed at height 100 for z_0=0.055, and v_2=the wind speed at 10 m height for z_0=0.055. What the formula actually says is that one start with assuming the wind speed to be 8 m/s height for a specific roughness length (in our example z_0=0.4). Then one calculates the wind speed at height H, given that condition.

$$V_1 = 8\frac{\ln\left(\frac{100}{0.4}\right)}{\ln\left(\frac{10}{0.4}\right)}$$

roughness - class / - length m	0.0 / 0.0002	0.5 / 0.0024	1.0 / 0.03	1.5 / 0.055	2.0 / 0.1	3.0 / 0.4	4.0 / 1.6
150 m	20	18.82	17.18	16.69	16.17	14.73	12.89
140 m	19.90	18.7	17.04	16.55	16.01	14.56	12.69
130 m	19.79	18.57	16.89	16.39	15.85	14.37	12.48
120 m	19.67	18.44	16.73	16.22	15.67	14.18	12.25
110 m	19.54	18.29	16.55	16.04	15.48	13.96	12.01
100 m	19.40	18.13	16.36	15.84	15.27	13.72	11.74
90 m	19.24	17.95	16.15	15.61	15.04	13.46	11.44
80 m	19.07	17.75	15.91	15.37	14.78	13.17	11.1
70 m	18.87	17.52	15.64	15.08	14.48	12.84	10.72
60 m	18.64	17.26	15.33	14.76	14.14	12.45	10.29
50 m	18.37	16.94	14.96	14.37	13.74	12	9.77
40 m	18.04	16.56	14.51	13.9	13.24	11.45	9.14
30 m	17.62	16.07	13.93	13.3	12.61	10.73	8.32
20 m	17.02	15.38	13.12	12.44	11.71	9.72	7.17
10 m	15.99	14.20	11.72	10.98	10.18	8	5.2

Table 10, Wind speed at different heights for different roughness lengths, Danish wind industry association 2008

As you can see in the table above, V_1= 13.72 m/s.

Next step is to multiply V_1 with the following expression:

$$\frac{\ln\left(\frac{10}{0.055}\right)}{\ln\left(\frac{100}{0.055}\right)}$$

By doing so, one assumes 13.72 m/s to be the value for z_0=0.055 at h= 100. ($V_1 = V_2$). According to the table, this value actually corresponds to 15.84 m/s for a wind profile with roughness length 0.055 m.

$$8\frac{\ln\left(\frac{100}{0.4}\right)}{\ln\left(\frac{10}{0.4}\right)}\frac{\ln\left(\frac{10}{0.055}\right)}{\ln\left(\frac{100}{0.055}\right)} = V_1\frac{\ln\left(\frac{10}{0.055}\right)}{\ln\left(\frac{100}{0.055}\right)} = v_2$$

roughness - class	0.0	0.5	1.0	1.5	2.0	3.0	4.0
- length m	0.0002	0.0024	0.03	0.055	0.1	0.4	1.6
150 m	17.32	16.3	14.88	14.46	14.01	12.76	11.16
140 m	17.24	16.2	14.76	14.34	13.87	12.61	10.99
130 m	17.14	16.09	14.63	14.20	13.73	12.45	10.81
120 m	17.04	15.97	14.49	14.05	13.58	12.28	10.61
110 m	16.93	15.84	14.34	13.89	13.41	12.09	10.4
100 m	16.8	15.70	14.17	13.72	13.23	11.89	10.17
90 m	16.67	15.55	13.99	13.53	13.03	11.66	9.91
80 m	16.52	15.37	13.78	13.31	12.8	11.41	9.62
70 m	16.35	15.18	13.55	13.07	12.55	11.12	9.29
60 m	16.15	14.95	13.28	12.79	12.25	10.79	8.91
50 m	15.92	14.68	12.96	12.45	11.9	10.4	8.46
40 m	15.63	14.35	12.57	12.05	11.47	9.92	7.91
30 m	15.26	13.93	12.07	11.52	10.92	9.3	7.21
20 m	14.74	13.33	11.36	10.78	10.15	8.42	6.21
10 m	13.86	12.3	10.15	9.51	8.82	6.93	4.51

Table 11, Wind speed at different heights for different roughness lengths, Danish wind industry association 2008

With the above values, we get $v_2$to be 9.51 m/s at 10 m height.

The final step in the Δv_h-formula is to subtract v_2 with v_1. With the above values, we get Δv_h to be 1.51 m/s. If we had chosen a roughness length below 0.051 m (for example water), we would have obtain a negative value for Δv_h.

To shed light upon what implications the above assumptions results in, I will start with discussing each assumption separately.

The first assumption was that the reference wind speed should be based on roughness length 0.4 m. This is totally wrong. According to IEC 61400-11 the wind speed values should be given for roughness length 0.05 m. In the same standard a similar correction formula is used (See Equation 8). I believe this formula is ripped without doing the necessary modifications to it, which is substituting 0.055 with 0.04 and vice versa in the formula. After reading about wind profiles in forest areas (chapter 3.3.1) you probably know by now that it is impossible to find such wind speeds for that height in a forest area if the wind outside the forest is considered to be 8 m/s at 10 m height.

The second assumption was that the wind speed at H=100 is the same, independent on roughness length. This is also wrong since different roughness length leads to different wind profiles. In the table below, you see that the wind speed at 10 m height for roughness length 0.4 is less than 8 m/s, and that the wind speed even at hub height with roughness length 0.4 is less than the wind speed at hub height for roughness length 0.055.

roughness							
- class	0.0	0.5	1.0	1.5	2.0	3.0	4.0
- length m	0.0002	0.0024	0.03	0.055	0.1	0.4	1.6
150 m	14.57	13.71	12.52	12.16	11.78	10.73	9.39
140 m	14.5	13.63	12.42	12.06	11.67	10.61	9.25
130 m	14.42	13.53	12.31	11.94	11.55	10.47	9.09
120 m	14.33	13.43	12.19	11.82	11.42	10.33	8.93
110 m	14.24	13.33	12.06	11.69	11.28	10.17	8.75
100 m	14.13	13.21	11.92	11.54	11.13	10	8.55
90 m	14.02	13.08	11.77	11.38	10.96	9.81	8.33
80 m	13.89	12.93	11.59	11.20	10.77	9.6	8.09
70 m	13.75	12.77	11.4	10.99	10.55	9.35	7.81
60 m	13.58	12.57	11.17	10.75	10.3	9.07	7.5
50 m	13.39	12.35	10.9	10.47	10.01	8.74	7.12
40 m	13.15	12.07	10.58	10.13	9.65	8.34	6.66
30 m	12.84	11.71	10.15	9.69	9.19	7.82	6.06
20 m	12.4	11.21	9.56	9.07	8.53	7.08	5.22
10 m	11.65	10.35	8.54	8	7.42	5.83	3.79

Table 12, Wind speed at different heights for different roughness lengths, Danish wind industry association 2008

If the reference wind speed instead is based on the roughness length 0.05 m we, will expect a value about 6.73 m/s assuming $V_1 = V_2$, and 5.83 m/s according to the table above.

Thus, the formula corrects the sound power level due to a higher wind speed at 10 m height by adding the value of Δv_h in dB to the sound power level, when in fact a lower wind speed than the reference value is expected. Hence we would expect a lower sound emission value in forest areas, not the opposite! With other words the formula favors wind power development i.e. sea-area, whereas it gives undeservedly high sound emission level, where the roughness length is higher, such as forest areas.

Furthermore, what actually is of the utmost importance is the difference in wind speed at hub height when using different roughness lengths. As we have seen in chapter 3.3.1, the mean wind speed is in general lower at the same hub height in a forest area, than open ground for hub heights up to at least 100 m due to the higher roughness length, but also because of the displacement height.

This is another problem with the formula, because it doesn't take any consideration to the displacement height of a forest. A more realistic value for i.e. a forest with roughness length 0.4 m and displacement height 15 would be if you add 15 m to the total height. Then you'll get a value between 9.81 – 9.7 m/s at 100 m height in the forest, which corresponds to 8 m/s at 10 m height with roughness length 0.055 m.

But as mentioned earlier, each forest is unique, hence it is problematic to use fixed values and other models describing displacement height and roughness length from the mean height of the forest, might underestimate the forest effect.

That assumption that the sound power level increases in proportion to the wind speed was a property older wind turbines had. The wind turbines under development today however doesn't have that characteristics, instead they only increases their sound power level up to a certain wind speed and after that produces a constant sound power level (See Figure 21)

Not only does an increased roughness length wrongfully lead to higher sound power levels, assuming k=1 will also make the error even larger. For example, comparing the sound power level for 8 m/s with the one for 9.51 m/s in *Figure 21*, we see that the difference in sound power level is less than 0.5 dB, instead of 1.51 dB. Assuming k=1, will result in an estimated sound power level that is even higher than the highest measured and warranted level for that turbine (105 dB), which is impossible to obtain! According to Berg (2008) EMD is aware of this problem, but are bound by a contract to follow the Swedish model. Hence it is not in their interest to do any modifications on the formula (Berg, 2008)

6.2 Sound propagation model compared to general theory

6.2.1 ISO 9613-2

According to the authors of ISO 9613-2, the model assumes moderate temperature inversion and wind speeds between 1-5 m/s in downwind direction. With other words, conditions that are slightly favorable for sound propagation. This implies slightly curved rays in downward direction. However the model assumes spherical spreading, which is contradictive and results in lower sound pressure levels at the immission point, especially for larger distances. Since the model only has been validated for source and receiver heights up to 30 m for distances up to 1000m with an accuracy of 3 dB, this is a weakness of the model.

The sound directivity correction is said to be the directivity index of the source, plus an index that accounts for the sound propagation into solid angles less than 4π steradians. Directivity index measurement is an optional task in IEC 61400-11. Since wind turbines in fact aren't omnidirectional point sources (as you can see in Figure 2), the idea behind directivity correction is good. Still it is how ever unclear why the latter index is only used in the correction, when using the alternative ground effect method.

When it comes to the ground effect I will start with analyzing the general method of ground effect calculation. For porous ground the ground effect will be zero and for hard ground + 3dB if the hub height is 80 m and the projected distance is less than 2445 m.[8] This is also implicit the criteria for which the size of the middle region plays any role. Moreover after 10 m, the height of the source position doesn't have any influence on the ground attenuation, which also sounds unrealistic. These are other examples of how the model is not applicable for long distances and when the source and receiver are at high altitude.

Only to be able to choose between two different types of ground types is a very simplified approach when predicting the ground effect. With other words the method lacks an impedance model taking the flow resistivity of the ground and the frequency of the sound waves into consideration.

The alternative method of ground effect calculation will result in attenuation or no attenuation at all. Thus it can't result in any amplification, since negative values shall be

[8] $q \neq 0$ if $d_p > 30(h_s + h_r)$, h_s=80, h_r=1.5 gives d_p=2445 m

substituted by zeros. For short distances and high elevation of the sound source (i.e. h_m =30 and d=200), the ground effect will be zero. According to chapter 3.2.4 the ground effect will be small for such conditions, the question is how small. However this method does only said to be valid for a “relative” soft ground. What about other ground types? Both ground effect calculation methods also lack the option of curved ray calculations and multiple reflection calculation.

Since ISO 9613-2 is only applicable for a special meteorological condition a correction to an average value, including a variety of meteorological conditions has to be made. However since the sound source of a modern wind turbine is at least 80 m, the distance has to be at least 815 m according to the formula for c_{met} , in order for c_{met} to be other than zero. That the meteorology effect is less at higher elevations is due to the fact that temperature and wind gradients are greatest close to the ground. The formula however doesn’t account for any displacement effect of the gradients in a forest and is thus only applicable on open ground.

c_0 can be determined using local weather statistics. It is however unclear exactly how the value should be determined. Furthermore it is unclear how often it has been showed that this value in practice range between 0- 5 and values above 2 dB are exceptional.

ISO 9613-2 also offers a way of determine foliage attenuation. An attenuation between 0.02 dB/m and 0.12 dB/m are preferred to use for D_f> 20. An increase in attenuation for higher frequencies is seen in Table 4, Attenuation due to foliage, ISO 9613-2:1996 and Table 5. According to 3.3.3 this is expected because higher frequencies means less wave lengths, which means a higher scattering probability. If we compare Table 4, Attenuation due to foliage, ISO 9613-2:1996 and Table 5 with Figure 17 we find that the attenuation rate for ISO 9613-2 is higher than the modeled one from Swearingen. Compared to the study of Wiens *et al*.(2008) the attenuation rate I smaller (0.352 dB/m) and compared to the study of Bucur (2005) the values are in the same range (0,07 dB/m-0,10 dB/m). Depending on the characteristics of the forest one will always obtain different values. A weakness of ISO 9613-2 is however that it is only guilty for a special type of forest and only for foliage attenuation. That is, the model doesn’t account for the diversity of the forest. Furthermore it is unclear if this foliage attenuation model is validated.

6.2.2 The Swedish model

The Swedish land based model for distances up to 1000 m assumes 8 m/s downwind condition. Nothing is mentioned about any temperature gradient condition but since the model assumes spherical spreading, an isothermal atmospheric condition has to be unstated.

The ground effect in the formula for distances up to 1000 m is +3 dB, which corresponds to hard flat ground. Thus no consideration is taken to non flat ground or other ground types than the one corresponding to this value. Since the value is constant, one can further assume the formula to overestimate the value for short distances.

The atmospheric absorption of 0.005 dB/m, is according to Ljunggren (2005), overestimated, but at the same time “making up” for the overestimation of the ground effect. According to results from a European project with 74 different measurements in six countries, a more accurate ground effect for short distances, flat ground is +1.5 dB.

An atmospheric absorption of 0.005 dB/m and a ground effect of 3 dB correspond to an atmospheric absorption of 0.002 dB/m and a ground effect of 1.5 dB (Ljunggren, 2005).

The Swedish model for distances over 1000 m will use a ground effect of +1 dB and an atmospheric absorption of 0.002 dB/m.

The atmospheric absorption is given in frequency dependent percentile values (95%), with other words not an average value or a value given for a specific temperature and humidity. Using a percentile value is in my opinion a more fair approach because of the diurnal and annual variations in sound energy absorption ability of the air. However since the model is only valid for a specific meteorological condition, a more consistent approach would be to use air absorption values corresponding to this condition.

Finally, the Swedish model doesn’t consider sound propagation through forest at all, as well as any directivity correction.

6.2.3 Nord2000

Nord2000 is probably one of the most detailed and thorough sound propagation model today. Calculations using curved sound rays and it’s consequence on ground effect, divergence and barriers are taking into consideration as well as the effect of different wind directions and forest on sound propagation.

The model uses the impedance model of Delany and Bazley in order to calculate the ground effect on the basis of the flow resistivity, which according to Lamancusa (2008) is an accurate way of describing that phenomenon.

Nord2000 uses the same method for describing the atmospheric absorption as ISO9613-2, which are average values for different temperature and humidity conditions.

The non-flat terrain calculation method and use of Fresnel-zones is unique, making such ground effect calculations more accurate than using flat terrain calculations or a mean height value. The ground effect calculation also features a selection between 7 different ground types, describing the softness level.

Meteorological aspects such as bending of the sound rays is taken into considerations also when it comes to spherical spreading, making the sound divergence more accurate.

Modelling of sound propagation through forest areas is done using a statistical prediction model. Assuming a specific tree radius and tree density for randomly placed parallel infinite cylinders is the same approach as Twersky’s multiple scattering model, used by Swearing and White (2004). It is not within the scope of this master thesis to the compare those scattering models against each others, but since there are not many statistical tree scattering models out there today, one could presume about the same underlying theory or thinking behind both models.

One disadvantage with Nord2000 is its linear approximation of the gradients. Large gradients near the ground will thus not be considered. Hence Nord2000 will only work with modest gradients, not temperature inversions (Larsson, 2008). According to Kragh, *et al.* methods have been elaborated to take these effects into account. It also doesn’t consider the invert meteorology of a forest which is another disadvantage.

Nord2000 shows as mentioned in chapter 4.3, really good with measured data for distances up to 1500, when consider plane ground. The model is however still not validated for complex terrain and forest areas. (Søndergaard, 2008)

Like ISO 9613-2 a yearly average value can be calculated using local meteorological statistics. A long-term level is thus a weighted average of a limited set of meteorological classes. Note that such values will only be true for a specific input value of the sound emission value of the wind turbine. A more realistic average value could be obtained if combining duration mean value with wind direction and magnitude data for the specific wind turbine site together with temperature gradients. In Nord2000 it is possible to calculate an annual equivalent value based on wind direction statistics and a fixed sound emission value (Almgren 2008).

6.3 Sound propagation model comparison

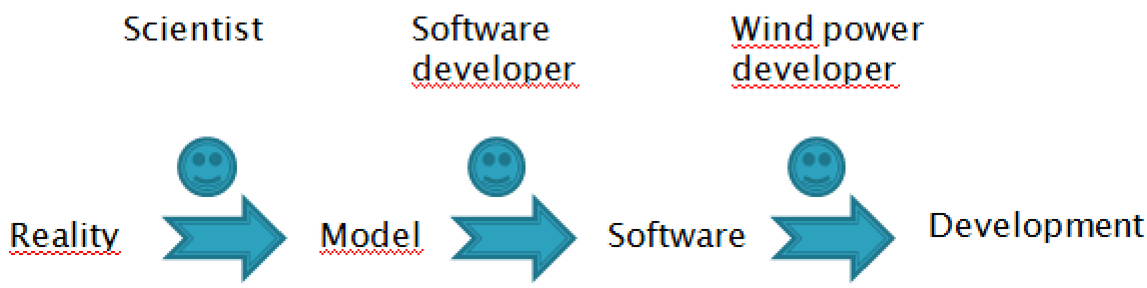


Figure 36

When it comes to comparison of different sound calculation models, one has to keep in mind that it is one thing what the difference in models suggest, due to different interpretations of the scientist behind the models. This difference might however not necessary correspond to the difference in the end result a wind power developer faces when predicting SPL with the help of software's, implementing these models. This is due to the fact that the software developers make their own interpretations of the model, and finally the wind power developer likewise its interpretation of how to best use the software. Every step along this path is associated with errors, and affects the end result of the sound prediction. In the previous chapter (6.2) I focused on comparing general sound propagation theory with the calculation models. That is similarly not the same as comparing the reality with the models, since theories are no absolute truths, but it is the closest to reality I get in this thesis. Next my focus shifts to comparing the models with each other.

Both the Swedish model as well as ISO 9613-2 uses a straight propagation ray, in which they take no consideration into the curve bending when it comes to the sound divergence or ground effect. ISO 9613-2 might however be more accurate sound propagation method than the Swedish model since it features a meteorological correction. However this correction should only be applied if the projected distance between the source and receiver is below 815 m, if the hub height is 80m and the receiver height 1.5m. It sounds reasonable that meteorological correction normally might not be necessary if the source is placed at great height and the receiver is not far away because of the decrease of gradients with increased height, when considering a long time average value. On the other hand, so called low levels jets causing temporarly irregular gradient patterns, leading to sudden extreme sound pressure levels at the immission point can occur.

Another phenomenon for which one can argue that average values is an unfair way of restricting noise levels is the fact that the wind speed at ground slows down, especially during summer evenings, whereas it remains strong at hub height. Together with shift in temperature gradient towards inversion, the SPL increases at the same time as the masking effect decreases, causing higher noise awareness for people living in nearby areas. This is something none of the above models take consideration to (Larsson, 2008).

Moreover one has to understand that using a wind speed of 8 m/s on a model that only is valid for wind speeds up to 5 m/s leads to problem and an underestimation of the bending of the sound rays effect, hence a meteorological correction might become necessary even for smaller distances.

With increased distance, the probability of multiple reflections increases when downward refraction occurs. To say that the wind is blowing 8 m/s at 10 m height without any information on the temperature gradients or isothermal condition (as in the case of the Swedish model) is problematic. How can one know how to validate a model if this information is missing? Moreover, without any meteorological correction a model is only valid for a certain meteorological condition.

Compared to ISO 9613-2 and the Swedish model, Nord2000 is a more complex model, taking refraction and its consequences into consideration, but also the wind direction effect on the sound propagation, which becomes very important if you have more than one wind turbine near a sound sensitive area. It is impossible for the wind to face all wind turbines with downwind at the same time, which is the consequence if you apply ISO9613-2 or the Swedish model with more than one wind turbine.

One major difference between the Swedish model and ISO 9613-2 or Nord2000 is that no consideration of barriers is taken and its effect on sound propagation. Barriers attenuation is probably one of the factors that have the most significant influence on the propagation when considering low elevated sources and receivers. However for high elevated sources such as wind turbines, barriers probably has only a minor influence on the sound, unless the obstacle is very high and/or placed near the receiver. Also foliage attenuation, resp. scattering and meteorological correction is missing in the Swedish model.

None of the models takes the wake effect into consideration. Wake effect means that the wind behind a turbine is slowing down behind the rotor blades due to the wind energy absorption of the turbine. The wind might not return to its initial speed until after about ten rotor diameters (Wizelius, 2008). This could have a significant impact on the SPL at the immission point, especially for short distances, since the speed of sound add s to the wind speed. One explanation why i.e. the Swedish model has showed good accuracy with measurement studies for wind speed 8 m/s at 10 m height, might be that the wake effect counteracts the refraction effect. Else higher measured value should have been obtained when using a model assuming spherical spreading instead of stratified spreading.

Looking at Figure 5 we find the following SPL order, starting with the highest: Swedish model Roughness class 3, ISO 9613-2 general method (hard ground), Swedish model no correction, ISO 9613-2 alternative method and ISO 9613-2 general method (porous ground). When considering the findings from the previously chapter, I'm not surprised the highest predicted level is the one obtained when using roughness class 3. Since the correction model is incorrect, there's no point analyzing the values obtained by that configuration. Excluding the Swedish model with roughness class 3, we find ISO hard to have the highest SPL level, closed followed by Swedish model no correction. In large the Swedish model for short distance is about the same as ISO hard. The only exception (excluding barriers, misc. attenuation and meteorological correction) is the difference in atmospheric absorption. The Swedish model uses an atmospheric absorption of -5 dB/km, whereas ISO 9613-2 uses -3.5 dB/km[9], which explains the somewhat higher SPL for ISO hard. There's probably no coincidence that the ground effect of the Swedish model (short distance) and ISO 9613-2 (general method, hard ground) are the same.

For distances over 1000 m, the Swedish model for large distance uses a 95% percentile value, which corresponds to an attenuation of about -2 dB/km. The explanation why this model still gives a lower value than ISO hard for distance=1035, is because it uses a ground effect of +1 dB, compared to +3 dB (ISO hard).

ISO alternative gives the second lowest SPL and ISO porous the lowest. Intuitive this might sound reasonable, since soft ground leads to attenuation. However as we saw in 4.1, a manual calculation will, according to the formula lead to no ground effect at all for porous ground. In the calculation result one can see that the ground attenuation is 1.3, resp. 3.11 dB/km, when using the alternative method. With other words, we would according to the model expect lower SPL for ISO general than for ISO porous, not the other way around! Use of the alternative method also features a directivity correction in its formula which should result in even less SPL, which makes the interpretation of the result even more confusing.

When comparing Figure 27, Ground effect prediction version measurement. Source 22m, receiver 1.5 m, distance 400 m, Ljunggren 2005 with Figure 33 one can find Nord2000 to be a more accurate model than ISO 9613-2. Not only because of better fit between the points and the measurements for the different source and receiver positions, but also (and more important) because of another reason. If the same measurement conditions as for Nord2000 had been for ISO9613-2, the latter would have, in case of porous ground predicted a ground effect of zero dB for each frequency. As you can see in the measured values for the Nord2000 validations, there's still a ground dip, even if it's not so big. Unfortunately I couldn't find any validation results for the Swedish model.

One also has to remember that these validations are only done for a specific meteorological condition. In order to validate a long term average value one has to do daily measurements over some years and then take a mean value of these measurements to compare with the predicted value. As far as I know, this hasn't been done yet. If that's the case, none of the predictions models discussed are validated for a long time average value. Hence they should only be considered to be credible for a short term use under a specific condition, everything else are speculations.

[9] Calculation based on *Equation 24* and given a frequency spectrum as the one in the Swedish model.

Going back to the initial discussion in this chapter, the reason why we obtained unexpected values using WindPRO in our calculations is due to wrongfully interpretations of the propagation model by the software develop, and/or by wrongfully interpretation of the software done by me.

There are several elements of ISO 9613-2, of some reasons not implemented in WindPRO. Neither barrier nor foliage calculations are possible to do. I think it is awkward how barriers are considered in the wind power calculations, but not when it comes to sound propagation.

Moreover, no input for the directivity index is possible when using the alternative ground effect method and there's no option for choosing temperature and humidity value other than (T=10°C, H=70%). They are used as a worst case scenario for the atmospheric absorption. However use of worst case scenario value is no demand in ISO 9613-2, instead it is an adjustment done by the programmer. Moreover the hardness of the ground in the general ground effect calculation can only adopt a value between 0 and 1, but it says nothing about which region it corresponds to (source, middle or receiver region). Consequently one has not the option to choose the ground hardness for different regions. Instead they will all have the same value.

Due to time restrictions I unfortunately can't tell what consequences calculations by hand would had have on the calculations result if one had taken considerations into presence of barriers, foliage and meteorological correction when using ISO 9613-2, compared to the Swedish model. Since they are sound attenuators[10], one however could assume the calculated value to be even lower than the result obtained in WindPRO.

Van Banda and Stapelfeldt (2005) have done research on this subject and stress how important clear definitions in the models are for the accuracy of the method. With vagueness and uncertainty the probability of wrongful interpretations during the implementation of the model increases. They also point out that nowadays the conversion to calculation input data is done more often done automatically by the software, especially GIS-reading software's. This leads to less manual inaccuracy, but at the same time to a source of uncertainty because the translation of multi-purpose GIS data to noise prediction data suited for numerical algorithms is not standardized yet. For further reading on this subject I recommend you to read Van Banda and Stapelfeldt (2005).

The last step in Figure 36, the one between software and developer is also far from unproblematic. I clarify this with an example. When I did the SPL predictions in WindPRO, I used the emission spectrum implemented in the software. This gives (using Figure 20) an atmospheric absorption of 2.4 dB/km, whereas the emission spectrum according to the Swedish model will result in an attenuation of -3 dB/km. If I had manually entered octave data measured for the wind turbine instead of generic values, the atmospheric absorption had resulted in -2 dB/km, that is 1 dB lesser attenuation than the Swedish model per km. With other words for 1035 m distance, depending on choose of emission spectrum for the turbine, the result is ± 1 dB SPL.
Unfortunately I had no access to a program using Nord2000 during my work. However as mentioned in 4.3 Nord2000 Nord2000 features more input data than the other

[10] Meteorological correction can also result in a higher SPL if the distance between the source and receiver is very large.

models, some of which might be difficult to know or measure, which the uncertainty and source of errors in the end result.

The benefits of the Swedish model over the other models are its simplicity and clearness. It is difficult to do wrongfully interpretations of it (even though it occurs, such as the sound emission spectrum example). However the simplicity has as I've showed also another side. It is too simple to being accurate for other situations than for plane, hard ground under a specific meteorological condition.

6.4 Forest impact on sound propagation from wind turbines

The studies presented in 3.4 are all performed with source and receiver at a relative small height, and with the receiver placed within the forest. The sound source of a modern wind turbine is however placed at least 60 m above the tree tops. Thus only a small part of the sound rays will be affected by the invert meteorology of the forests if the receiver is placed outside the forest. Hence the difference for favorable and non favorable conditions in forest compared to open ground as mentioned in chapter 3.3.3. is probably not as obvious when it comes to sound propagation from wind turbines, especially at short distances. For longer distances the sound rays comes “closer” to the forest, leading to more interaction with the forest. Because of the displacement of the wind and temperature gradients, one could expect stronger downward refraction to occur at corresponding height over open ground, causing more or less attenuation depending on the hardness and topography of the forest floor. Furthermore, for the same reason, one could expect multi reflections to occur at an earlier state (shorter distance) when considering downward refraction, compared to open ground for frequencies below 1000 Hz. On the other hand, this might not necessary be true because of the effective air mixture above the canopy.

For higher frequencies, one also has to consider the scattering effect. When the rays enter the forest canopy, high frequent sound waves will collide with foliage, branches and trunks leading to scattering. This phenomena is according to Swearinger and White, even a greater attenuator than atmospheric absorption. Much of the scattered sound will probably stay in the forest, instead of radiating out of the forest and interfere with direct sound rays. The forest thus acts as a high frequency filter, leading to a lower SPL at the immission point.

Unfortunately I couldn't find much information on the sound behavior when entering a forest. According to Wiens *et al.* (2008) the resulting effect can be an attenuation of 8.5 dB due to reflection. Such instant great attenuation effect can't be seen in the experiment by Herrington and Brock 1977 (Figure 37). According to this experiment, a decrease in SPL starts as soon as the sound rays enter the forest, especially for locations near the ground. In the same study an increase in SPL before the forest edge was measured. The authors behind the report claim that this is due to reflection. However according to Larsson (2008), he himself has once encountered such accumulation in sound, while doing sound measurement in other milieus. Thus a single measurement study is not enough in order to draw any conclusions from it. If the forest is very dense one however can assume some reflection to occur, leading to interference with the inflected rays. Since even a very dense forest top can't match the impedance of a flat ground such as asphalt or water, the interference, of any would probably be of destructive art.

How big the wake effect is for forestal wind turbines is also an unexplored subject. Due to the high turbulence over the forest, one could however expect the disbandment of the wakes to occur sooner over forest than over open ground. (Dahlström *et al.*, 2008). Thus the wake effect is probably less important factor in forestal areas than open ground calculations. With other words, the missing wake effect consideration in the sound propagation models might result in a smaller prediction error if used on forestal areas, than on open ground or water.

One issue I haven't discussed yet is the fact that much of the wind power development in forest areas takes place on hills. This is not unproblematic if dwellings or other sound sensitive areas exist further down the valley because of the wind restraining ability of the hill, leading to powerful downward refraction. Since less wind speed also means less masking of the sound, the sound from the wind turbines is more obvious to the human ear (Almgren, 2008). Neither ISO 9613-2 nor the Swedish model takes this issue into consideration.

The sound masking effect of the forest is due to limitations not included in this thesis. It has however in a loudness test been shown that the proportion of wind turbine noise is perceived as less than half of the entire noise at SNR[11] of 3 dB(A) and below, and that the masking effect is better for coniferous forests than other ambient noises. Furthermore in order for annoyance to occur, the sound from the wind turbine must exceed natural ambient noise by at least 3 dB(A) (Bolin, 2006).

When summarizing the above discussion the overall effect forest areas tend to have on sound emission as well as sound propagation is probably of damping kind, at least when not considering up wind and positive lapse condition.

[11] Signal to Noise Ratio is the ratio of a signal power to the noise power corrupting the signal.

7 Conclusions

Duration mean value is an interesting way of stating the sound emission value. It must however be combined with site specific meteorology statistics and advanced sound propagation models in order to obtain an annual average SPL value at the immission point. The roughness correction formula in the Swedish model for land based wind turbines, is in many ways incorrect to use, even for non forestal areas since it either underestimates or overestimates the sound power level.

ISO 9613-2 uses spherical spreading and is only valid for moderate wind speeds (up to 5 m/s) and temperature inversion, even though the wind condition used by wind power developers today even might result in stratified spreading. The ground effect lacks options for more than two ground types and when using non flat terrain calculations can only be done on relative soft ground. Similar the foliage attenuation is only valid for a specific type of forest and hence there's i.e. no choice for tree density or circumference input. The meteorology correction doesn't consider the gradient displacement effect of a forest nor has guidance to it. It is also unclear how to determine the value of C_0.

The Swedish model over land is only applicable for plane, hard, non vegetative ground under a specific meteorological condition, giving rise to straight sound rays.

Nord2000 is an advanced sound propagation model taking some of the consequences of refraction into account. It also features, among others an impedance model with choose between seven different ground types, non flat ground and scattering calculations, but also some meteorological correction.

When comparing ISO 9613-2 and the Swedish model, the Swedish model gives higher SPL when using roughness correction for a higher roughness length than 0.05 m. However, when no correction is done ISO 9613-2 returns the highest SPL level, when using the general method for ground effect calculation and hard ground. When using WindPRO, the choice of ISO 9613-2 hard ground, is the same as using the Swedish model, with the only exception the Swedish model uses percentile values instead of average value for the atmospheric absorption. Except the roughness correction formula in the Swedish model and the alternative method of calculating the ground effect in ISO 9613-2, barriers, misc. attenuation and meteorological correction are the main differences between these two models. However since barriers and misc. attenuation calculation is not an option in WindPRO and meteorological correction is recommended by the software developer not to use, the models becomes very similar. Besides own interpretations of the model by the software developers, also interpretations by the software users on which fields to fill and what values to use, i.e. choice of emission spectrum affects the end result of the sound prediction.

None of the models take consideration to the case when the wind speed slows down near ground but remains high at hub height at the same time as the temperature gradient is shifting to inversion, leading to a combination of higher SPL and lower ambient sound.

Overall forests probably have a damping effect on sound emission and sound propagation from wind turbine, especially for higher frequencies. The magnitude of the effect depends on a lot of variables: the properties of the forest and meteorological factors, but also properties of the wind turbine. Higher hub height means less influence from the forest. When building wind turbines on heights, SPL in nearby dwelling, further down the valley will probably be significant higher than both ISO 9613-2 and the Swedish model will predict, since they don’t consider refraction nor the sheltering effect of the hill.

8 Suggestions of improvement

The easiest and most reliable value for the sound power level is the one you obtain when using measured long time wind data from a mast in the area of development, measured from a height corresponding to that of the hub. Together with the original measured sound power levels at hub height for the given wind speeds, this could be used to state the average sound power level at hub height for the site specific turbine.

However since 8 m/s at 10 m height is still by tradition the reference value, and corresponds to a somewhat worst case scenario, a more safe and easy approach would be to use the warranted level for 8 m/s. This value corresponds to the maximum sound emission level, independent on the roughness of the ground, and without letting the masking effect taking over hand. Due to the incorrectness of the correction formula it is strongly recommended not to use it, since it results in false emission values for other roughness length than 0.05 m.

A third approach would be to use a proper correction formula, which also takes account for the displacement height. This however implies empirically observed values of the forest mean height and wind speeds at different heights in order to estimate correct roughness length and displacement height values, since analytical models describing these quantities today are insufficient. In that sense the whole idea behind the correction method is problematic and it might be better to use one of the two earlier mentioned proposals. As long as ISO 9613-2 and the Swedish model are used, I think it is better to use the worst case scenario approach. With more complex propagation models in the future, however it will be more natural to shift also the emission reference value towards a site specific mean or percentile value.

This thesis has shown the scarcity of traditional sound propagation models such as the Swedish model and ISO 9613-2 and the need for more advanced models, especially in a country like Sweden with a lot of forest areas and irregular, non flat terrain.

Today there are several advanced analytical methods for predicting outdoor sound propagation accounting for forest effects, such as Nord2000 and European project *Harmonoise*. I think it is time for the Swedish national environmental authority to leave the Swedish model behind and instead welcome these new advanced analytical models.

Since the reality is very complex, analytical methods have its limitations. In the long term perspective, I believe the improvement of advanced numerical methods, taking account all acoustical phenomena, even: wind- and temperature discontinuities, irregular terrain, turbulence and vegetation effects belongs to the future. With the increased computer power, programs will be able to use numerical methods together with satellite based GIS data and local meteorological statistics as input data to determine annual percentile values for wind power noise.

Moving the approach from simple worst case scenario calculations (at least for the sound emission) towards more advanced and realistic sound prediction modeling will in the end make it easier for wind power developers to place turbines more optimal without jeopardizing the health of nearby living people. This however requires a more clearness in the documentation from the authors behind the models in order to avoid misinterpretations by software developers and wind power developers.

9 Prospects

At the moment of writing a project with the purpose to link WAsP and WindPRO with Nord2000 is taking place at Delta Acoustics & Electronics in Denmark:

... it will be possible to exploit the 3D facilities in WindPRO and the wind-velocity distribution from WAsP. It then becomes possible to describe the dependence of the meteorology to the noise emission – both as snapshot values, e.g. wind velocity 8 m/s, wind direction 270 deg., and as annual mean values based on wind statistics for the site in question. It will also be possible to indicate how much a given location in fact is affected by noise levels of or above a given limit value and for how much of the time the noise level is higher/lower than the limit value. The system operates with complex calculations and results. During the project a prototype will also be constructed for a user interface which can facilitate easy operation and ensure clear presentation of the results. Stakeholders will be involved in defining the performance specifications and will be asked for their reporting and visualisation wishes… (Delta Acoustics and Electronics, 2008)

It shall be noted that WAsP doesn't take temperature gradients into considerations and climate tuning only works for average stability conditions (Larsson, 2008).

According to Thomas Sørensen at EMD, Nord2000 is planned for release medio 2009. At the moment they are working on validating it for wind turbines and implementing it in WindPRO. (Sørensen 2008)

Delta Acoustics and Electronics, the company behind Nord2000, have recently made measurements in complex terrain in Norway with the intention to validate Nord2000 for such terrain. When it comes to validations of Nord2000 for forest areas, the company have met some interest from energy companies in making new measurements on the noise reducing effect of vegetation specifically for wind turbines (Søndergaard, 2008) In Sweden, ÅF has been chosen by Vindforsk to do sound emission and propagation measurements in forest areas (Almgren, 2008).

When it comes to the wake effect, Delta Acoustics & Electronics will make a small measurement program on the wake effect and noise radiation during 2009 (Søndergaard, 2008)

10 Acknowledgements

I would like to thank Angelica Widing at Nordex Energy and Conny Larsson at Uppsala University for their support throughout the thesis. Martin Almgren, Jesper Berg, Sten Ljunggren and Gunnar Lundmark are acknowledged for letting me interview them. I am also grateful to Marcus Berg, Karl Bolin, Anders Björck, Sven Halldin, Bo Søndergaard and Tomas Sørensen for their help. Finally I would like to thank my fiancée, family and friends for their cordial support.

11 References

Almgren, M., 2006, Ljud från vindkraft, Utredning inför Naturvårdsverkets allmänna råd, Elforsk rapport 06:02

Bergström, H., Vindkartering över Sverige - version 2007, Avdelningen för Luft-, vatten- och landskapslära, Uppsala Universitet, http://www.geo.uu.se/luva/default.aspx?pageid=13152&lan=0

Boddington, R., 2008, The Effect of Forestry on Wind Regime and Energy Yield,SgurrEnergy, http://www.bwea.com/pdf/trees/Sgurr.pdf

Bolin, K., 2006, Masking of Wind Turbine Sound by Ambient Noise, Royal Institute of Technology, Department of Aeronautical and Vehicle Engineering, The Marcus Wallenberg Laboratory for Sound and Vibration Research, Stockholm. http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-4227

Bolin, K., 2008, KTH, mail contact

Boué, M., 2007, Final report for the Swedish Energy Agency project 21597-3 (TRANS) Long-range sound propagation over the sea with application to wind turbine noise, TRITA-AVE 2007:22 ISSN 1651-7660, KTH, Vindforsk.

Bucur, V.,2005, Urban forest acoustics, INRA, Centre de Recherches Forestières de Nancy, Champenoux

Bullen, P., Fricke, F., 1982, Sound Propagation Through Vegetation, Journal of Sound and Vibration, pp. 11-23.

CVI, 2004, Ljud från vindkraftverk, Faktablad 4, Centrum för Vindkraftsinformation, Högskolan på Gotland, Visby, http://mainweb.hgo.se/projekt/cvi.nsf/0/F745A5F5EBF886ABC1256EB500427D63/$FILE/Ljud%20fr%C3%A5n%20vindkraftverk.pdf?openelement

Dahlström, F., Bergström, C., Björck, A., Danestig, M., Engström, S., Hjort, J., Bergström, H., 2008, Kunskapsinventering kring vindar och vindkraft i skog, Statens energimyndighet, ER 2008:21, ISSN 1403-1892

Danish wind industry association, 2008, Wind Speed Calculator, http://www.windpower.org/en/tour/wres/calculat.htm

Defrance, J., Barriere, N., Premat, E., A diffusion model for sound propagation through forests, Centre Scientifique et Technique du Bâtiment, Saint-Martin-d'Hères. http://www.sea-acustica.es/Sevilla02/num06003.pdf

Delta Acoustics and Electronics, 2008, Project description, http://www.delta.dk/C1256EDD004E544A/0/A310DFF906AEEDFFC125738B0044306D

Gardiner, B., 2003, Airflow over forests and forest gaps, Forest research, http://www.bwea.com/pdf/trees/Barry_Gardiner.pdf

Gustafson, A., 2006, Mätmetoder och beräkningsmodeller – seminarium om vindkraft 11 oktober , 2006., SP Sveriges Provnings- och Forskningsinstitut

Halldin, S., 2008, Uppsala universitet, mail contact

Harman, I., Finnigan, J., 2006, A simple unified theory for flow in the canopy and roughness sublayer, CSIRO Marine and Atmospheric Research, Canberra, Australia

Heggies, 2006, Environmental Assessment: Proposed Wind Farm, Conroys Gap NSW, Report 40-1143-R2, Revision 4, Taurus Energy, Australia

Herrington, L., Brock, C., 1977, Propagation of noise over and through a forest stand, State University of New York, New York

Högström, U., Bergström, H., Smedman, A-S., 1989, Turbulent exchange above a pine forest, I: Fluxes and gradients,Department of Meteorology,Section of Hydrology and Department of Ecology and Environmental Research, Uppsala

IEC 61400-11:2002, Wind turbine generator systems- Part 11: Acoustic noise measurement techniques

ISO 9613-2:1996, Acoustics – Attenuation of sound during propagation outdoors – Part 2: General method of calculation, ISO 9613-2:1996.

Kragh, J., Plovsing, B., Storeheier, S-Å., Taraldsen, G., Jonasson, H-G., 2002, Nordic Environmental Noise Prediction Method - Nord2 000 Summary Report – General Nordic Sound Propagation Model and Applications in Source-Related Prediction Methods, Journal no. AV 1719/01, Nordic Noise Group.

Lalic, B., Mihailovic, D. T., Rajkovic, B., Arsenic, I. D., Radlovic, D., 2003, Wind profile within the forest canopy and in the transition layer above it, http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6VHC-48SPCC2-1&_user=651519&_rdoc=1&_fmt=&_orig=search&_sort=d&view=c&_version=1&_urlVersion=0&_userid=651519&md5=fd142be501340a7eb8d41224af2fec7e

Lamancusa, J.S., 2008 Outdoor sound propagation, noise control, Engineering Noise Control, Penn State University

Larsson, C., 1993, Långtidsmätning av flygbuller nor om Arlanda, Meterologiska institutionen, Uppsala universitet, Uppsala.

Larsson, C., 1994, Meteorological effects on sound propagation, Department of Meteorology, Uppsala University, Uppsala.

Larsson, C., 1996, Atmospheric Absorption Conditions for Horizontal Sound Propagation, Uppsala University, Uppsala.

Larsson, C., 1999, Vädrets inverkan på ljudutbredning – slutrapport, Institutionen för geovetenskaper, meteorologi, Uppsala universitet.

Ljunggren, S., 1998, Mätning av bullerimmission från vindkraftverk, Elforsk rapport 98:24.

Ljunggren, S.,2005, Ljud från vindkraftverk – en kritisk genomgång av dagens system för behandling av ljud omkring vindkraftverk, Institutionen för Byggvetenskap, KTH, Avdelningen för byggnadsteknik, arbetsrapport 2005:1, ISSN 1651-5579, Stockholm.

Lo, Kou-Fang, A., (1995), Determination of zero-plane displacement and roughness length of a forest canopy using profiles of limited height, Modelling and Integration Research Division, Atmospheric Environment Service, Environment Canada. Fulltext: http://www.springerlink.com/content/x65w66r504105v68/fulltext.pdf

Mann, J., Dellwik, E., Bingöl, F., Rathmann, O., Sogachev, A., Wind Profile Measurements over a Forest with Lidar, Wind Energy Department, Risø National Laboratory for Sustainable Energy, Technical University of Denmark, http://www.dffv.dk/vindkraftworkshop%202008/Jakob%20Mann%20-%20Wind%20Profile%20Measurements%20over%20a%20Forest%20with%20Lidar.pdf

Marberger, M., 2008, Nordex Energy GmbH, mail contact via Angelica Widing

Naturvårdsverket, 2001, Ljud från vindkraftverk, Boverket, energimyndigheten, naturvårdsverket rapport 6241

Oliver, H. R., Mayhead, G. J., 1974, Wind Measurements in a Pine Forest During a Destructive Gale, Institute of Hydrology Wallingford, Forestry Commission Alice Holt

Raftery, P., LeBlanc, M., Manning, J,., 2004, WASP Validation Study of Forestry effects, BWEA Tree Workshop, Garrad Hassan, Glasgow, http://www.bwea.com/pdf/trees/GH.pdf

Sagrillo, M., 2004, Residential Wind Turbines and Noise, Windletter the montly newsletter of the American wind energy association, vol 23. Issuo no. 3 http://www.renewwisconsin.org/wind/Toolbox-Fact%20Sheets/Sound.pdf

Swearingen, M., White, M., 2004, Sound propagation through a forest: a predictive model, US Army Engineer Research and Development Center, Construction Engineering Research Laboratory, Farber Driver Champaign, USA

Søndergaard, B.,2008, Delta acoustics, mail contact

Sørensen, T., 2008, EMD, mail contact

Teague,P., Foster,R., 2006, Acoustic Assessment of Wind Farms – A Practical Perpective, Proceedings of Acoustics, Christchurch, New Zealand

Thorsson, P., 2008, Svensk Vindkraft, Nr 4, Sep, Svensk Vindkraftsförening

Traux, B., 1999, Handbook for acoustic ecology, Second edition, Original published by the World Soundscape project, Simon Fraser University and ARC Publications, 1978, http://www.sfu.ca/sonic-studio/handbook/index.html

Tunick, A., 2003, Calculating the micrometeorological influences on the speed of sound through the atmosphere in forests, U.S. Army Research Laboratory, Computational and Information Sciences Directorate, Maryland, Journal of the Acoustic Society of America.Vol.114, No.4. Pt. 1

Van Banda, H., Stepelfeldt, H., 2005, Implementing prediction standards in calculation software – the various sources of uncertainty, Managing Uncertainty in Noise Measurement and Prediction, Symposium Le Mans, Den hag, Dortmund

Wiens, T., Bradley, S., George, K., 2008, Experimental characterization of Sound Propagation in a Dense New Zealand Forest, 37th , International Congress and Exposition on Noise Control Engineering 26-29 October 2008, Shanghai.

Wilibrord, T. , Attenborough, K., 1991, Reverberation and attenuation in a pine forest, The Journal of the Acoustical Society of America, Vol90, Issue 5, pp.2664-2677

Wizelius, T., Britse G., Widing, A., Vindkraftens miljöpåverkan – utvärdering av regelverk och bedömningsmetoder, Centrum för Vindkraftsinformation, Högskolan på Gotland

Wizelius, 2008, Vindkraft i teori och praktik, 2:a uppl.

Zhu, J. W., 2004, Modelling Of Noise From Wind Turbines, Mechenical Department, DTU,Lyngby

Interviews

Almgren, M., ÅF Göteborg, 081002

Lundmark,G., Lundmark akustik och vibration, 081001

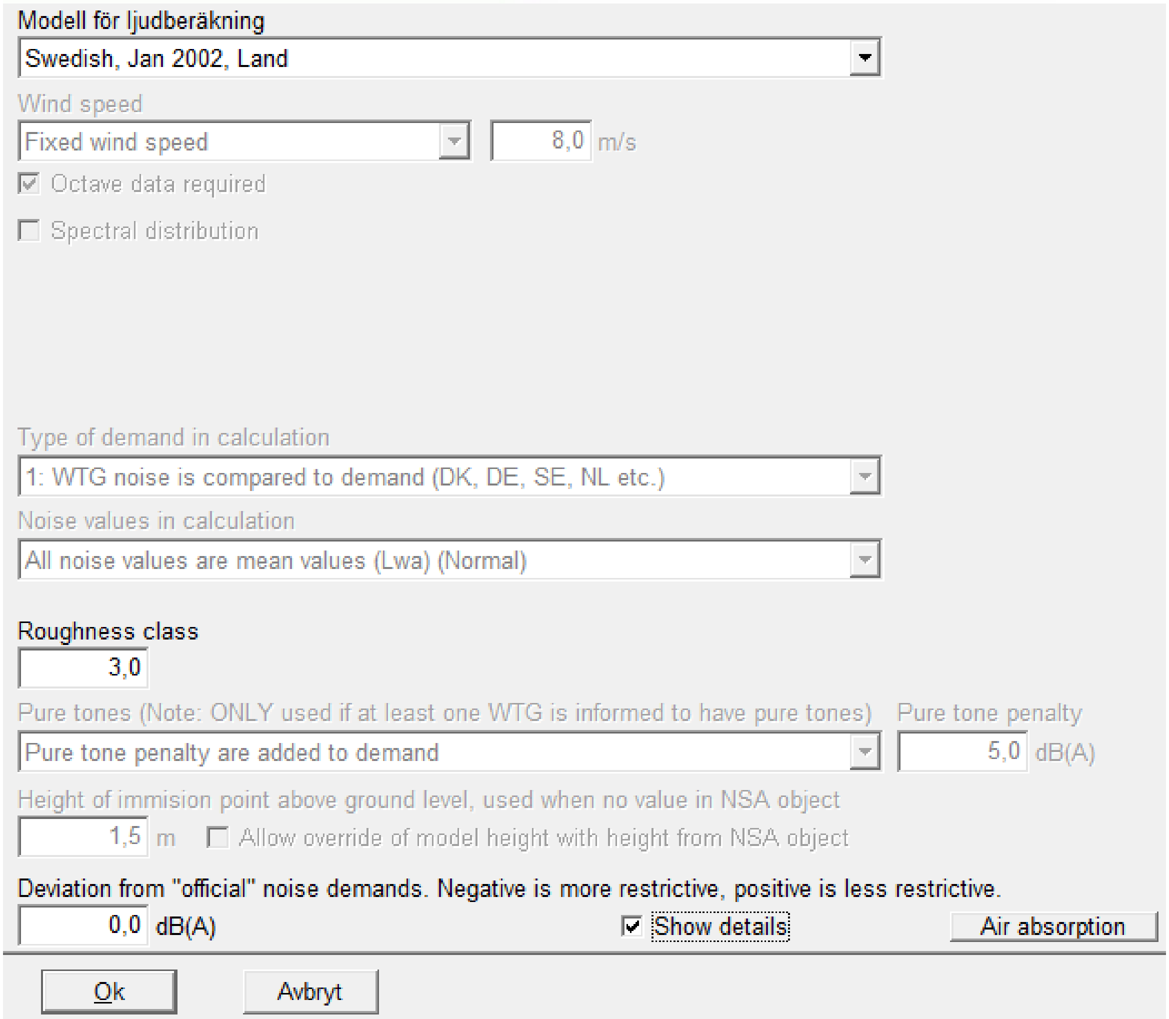
Ljunggren, S., KTH, 081014

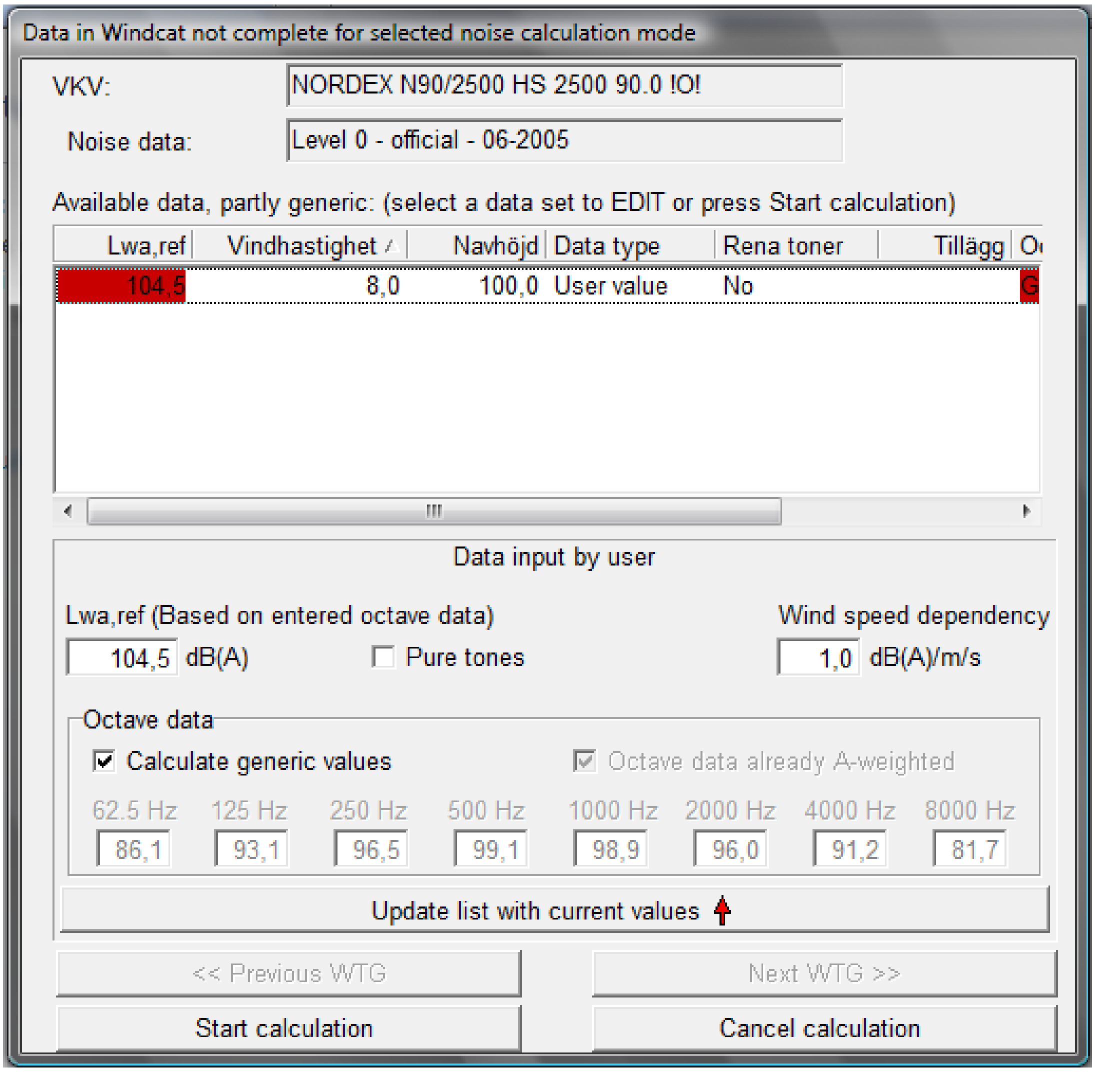
Jesper, B., Nordanvind vindkraft AB, 081030

Contact and exchange of ideas have been continuous with both instructor Angelica Widing as well as the revisor of the subject, Conny Larsson.

Appendix

Roughness class	Roughness length	Relative energy %	
0	0,0002	100	Water areas.
0,5	0,0024	73	Mixed Water and land area or very smooth land.
1	0,03	52	Open farmland with no crossing hedges and with scattered buildings. Only smooth hills.
1,5	0,055	45	Farmland with some buildings and crossing hedges of 8 m height and about 1250 m apart.
2	0,10	39	Farmland with some buildings and crossing hedges of 8 m height and 800 m apart.
2,5	0,20	31	Farmland with closed appearance and dense vegetation - crossing hedges of 8 m height and 250 m apart.
3	0,40	24	Villages, small towns, very closed farmland with many or heigh hedges, Forrest, many abrupt orographic changes, etc.
3,5	0,80	18	Large towns, cities with extended build-up areas.
4	1,6	13	Large cities with build-up areas and high buildings.




Data in Windcat not complete for selected noise calculation mode
VKV:
NORDEX N90/2500 HS 2500 90.0 !O!
Noise data:
Level 0 - official - 06-2005
Available data, partly generic: (select a data set to EDIT or press Start calculation)
Lwa,ref
Vindhastighet
Navhöjd
Data type
Rena toner
Tillägg
104,5
8,0
100,0
User value
No
Data input by user
Lwa,ref (Based on entered octave data)
104,5 dB(A)
Pure tones
Wind speed dependency
1,0 dB(A)/m/s
Octave data
Calculate generic values
Octave data already A-weighted
62.5 Hz
125 Hz
250 Hz
500 Hz
1000 Hz
2000 Hz
4000 Hz
8000 Hz
86,1
93,1
96,5
99,1
98,9
96,0
91,2
81,7
Update list with current values
<< Previous WTG
Next WTG >>
Start calculation
Cancel calculation

DECIBEL - Assumptions for noise calculation

Noise calculation model:
Swedish, Jan 2002, Land
Wind speed:
8,0 m/s
Ground attenuation:
None
Meteorological coefficient, C0:
0,0 dB
Type of demand in calculation:
1: WTG noise is compared to demand (DK, DE, SE, NL etc.)
Noise values in calculation:
All noise values are mean values (Lwa) (Normal)
Råhetsklass %d:
3,0 m/s
Pure tones:
Pure tone penalty are added to demand: 5,0 m/s
Height above ground level, when no value in NSA object:
1,5 m Don't allow override of model height with height from NSA object
Deviation from "official" noise demands. Negative is more restrictive, positive is less restrictive.:
0,0 dB(A)
Octave data required
Air absorption

63	125	250	500	1 000	2 000	4 000	8 000
[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]
0,1	0,3	0,6	1,4	3,2	7,9	22,0	50,0

VKV: NORDEX N90/2500 HS 2500 90.0 !O!
Ljud: Level 0 - official - 06-2005

Källa	Källa/Datum	Upphovsman	Redigerad
Manufacturer	2005.06.08	EMD	2005.11.21 15:35

Status	Navhöjd	Vindhastighet	LwA,ref	Rena toner		Oktavdata 63	125	250	500	1000	2000	4000	8000
	[m]	[m/s]	[dB(A)]			[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]
User value	100,0	8,0	104,5	No	Generic data	86,1	93,1	96,5	99,1	98,9	96,0	91,2	81,7

DECIBEL - Detaljerade resultat

Noise calculation model: Swedish, Jan 2002, Land 8,0 m/s

Antaganden

Calculated L(DW) = LWA,ref + K + Dc - (Adiv + Aatm + Agr + Abar + Amisc) - Cmet
(when calculated with ground attenuation, then Dc = Domega)

LWA,ref:	Sound pressure level at WTG
K:	Pure tone
Dc:	Directivity correction
Adiv:	the attenuation due to geometrical divergence
Aatm:	the attenuation due to atmospheric absorption
Agr:	the attenuation due to ground effect
Abar:	the attenuation due to a barrier
Amisc:	the attenuation due to miscellaneous other effects
Cmet:	Meteorological correction

Beräkningsresultat

Ljudkänsligt område: A Noise sensitive area: Swedish - User defined (5)

VKV Nej	Avstånd	Ljudavstånd	Wind speed: 8,0 m/s Calculated	LwA,ref	Dc	Adiv	Aatm	Agr	Abar	Amisc	A	Cmet
	[m]	[m]	[dB(A)]	[dB(A)]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]
1	500	510	**41,37**	104,5	0,00	0,00	-	0,00	0,00	0,00	-	0,00

Summa 41,37

- Data undefined due to calculation with octave data

Calculations with swedish model, distance 500 m, no correction

DECIBEL - Assumptions for noise calculation

Noise calculation model:
Swedish, Jan 2002, Land
Wind speed:
8,0 m/s
Ground attenuation:
None
Meteorological coefficient, C0:
0,0 dB
Type of demand in calculation:
1: WTG noise is compared to demand (DK, DE, SE, NL etc.)
Noise values in calculation:
All noise values are mean values (Lwa) (Normal)
Råhetsklass %d:
1,5 m/s
Pure tones:
Pure tone penalty are added to demand: 5,0 m/s
Height above ground level, when no value in NSA object:
1,5 m Don't allow override of model height with height from NSA object
Deviation from "official" noise demands. Negative is more restrictive, positive is less restrictive.:
0,0 dB(A)
Octave data required
Air absorption

63	125	250	500	1 000	2 000	4 000	8 000
[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]
0,1	0,3	0,6	1,4	3,2	7,9	22,0	50,0

VKV: NORDEX N90/2500 HS 2500 90.0 !O!
Ljud: Level 0 - official - 06-2005

Källa	Källa/Datum	Upphovsman	Redigerad
Manufacturer	2005.06.08	EMD	2005.11.21 15:35

Status	Navhöjd [m]	Vindhastighet [m/s]	LwA,ref [dB(A)]	Rena toner		Oktavdata 63 [dB]	125 [dB]	250 [dB]	500 [dB]	1000 [dB]	2000 [dB]	4000 [dB]	8000 [dB]
User value	100,0	8,0	104,5	No	Generic data	86,1	93,1	96,5	99,1	98,9	96,0	91,2	81,7

NSA: Noise sensitive area: Swedish - User defined (5)-A
Predefined calculation standard:
Imission height(a.g.l.): Use standard value from calculation model

Noise demand: 40,0 dB(A)
Distance demand: 0,0 m

DECIBEL - Detaljerade resultat

Noise calculation model: Swedish, Jan 2002, Land 8,0 m/s

Antaganden

Calculated L(DW) = LWA,ref + K + Dc - (Adiv + Aatm + Agr + Abar + Amisc) - Cmet
(when calculated with ground attenuation, then Dc = Domega)

LWA,ref:	Sound pressure level at WTG
K:	Pure tone
Dc:	Directivity correction
Adiv:	the attenuation due to geometrical divergence
Aatm:	the attenuation due to atmospheric absorption
Agr:	the attenuation due to ground effect
Abar:	the attenuation due to a barrier
Amisc:	the attenuation due to miscellaneous other effects
Cmet:	Meteorological correction

Beräkningsresultat

Ljudkänsligt område: A Noise sensitive area: Swedish - User defined (5)

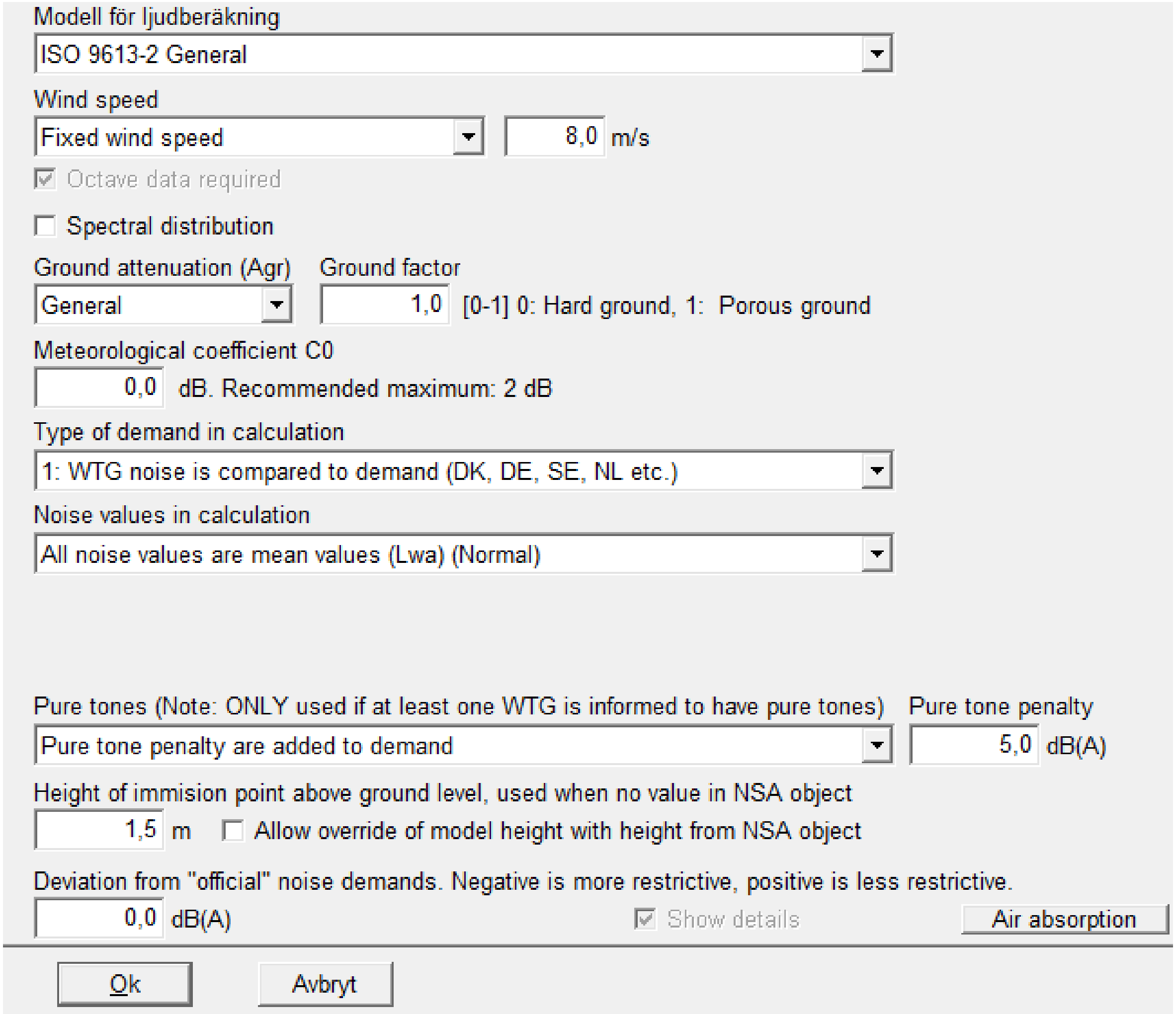
VKV — **Wind speed: 8,0 m/s**

Nej	Avstånd [m]	Ljudavstånd [m]	Calculated [dB(A)]	LwA,ref [dB(A)]	Dc [dB]	Adiv [dB]	Aatm [dB]	Agr [dB]	Abar [dB]	Amisc [dB]	A [dB]	Cmet [dB]
1	500	510	39,84	104,5	0,00	0,00	-	0,00	0,00	0,00	-	0,00

Summa 39,84

- Data undefined due to calculation with octave data

Calculations with ISO 9613-2, distance 500 m, porous ground assumption



DECIBEL - Assumptions for noise calculation

Noise calculation model:
ISO 9613-2 General
Wind speed:
8,0 m/s
Ground attenuation:
General, Ground factor: 1,0
Meteorological coefficient, C0:
0,0 dB
Type of demand in calculation:
1: WTG noise is compared to demand (DK, DE, SE, NL etc.)
Noise values in calculation:
All noise values are mean values (Lwa) (Normal)
Pure tones:
Pure tone penalty are added to demand: 5,0 m/s
Height above ground level, when no value in NSA object:
1,5 m Don't allow override of model height with height from NSA object
Deviation from "official" noise demands. Negative is more restrictive, positive is less restrictive.:
0,0 dB(A)
Octave data required
Air absorption

63	125	250	500	1 000	2 000	4 000	8 000
[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]
0,1	0,4	1,0	1,9	3,7	9,7	32,8	117,0

VKV: NORDEX N90/2500 HS 2500 90.0 !O!
Ljud: Level 0 - official - 06-2005

Källa	Källa/Datum	Upphovsman	Redigerad
Manufacturer	2005.06.08	EMD	2005.11.21 15:35

Status	Navhöjd	Vindhastighet	LwA,ref	Rena toner		Oktavdata 63	125	250	500	1000	2000	4000	8000
	[m]	[m/s]	[dB(A)]			[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]
User value	100,0	8,0	104,5	No	Generic data	86,1	93,1	96,5	99,1	98,9	96,0	91,2	81,7

DECIBEL - Detaljerade resultat

Noise calculation model: ISO 9613-2 General 8,0 m/s

Antaganden

Calculated L(DW) = LWA,ref + K + Dc - (Adiv + Aatm + Agr + Abar + Amisc) - Cmet
(when calculated with ground attenuation, then Dc = Domega)

LWA,ref:	Sound pressure level at WTG
K:	Pure tone
Dc:	Directivity correction
Adiv:	the attenuation due to geometrical divergence
Aatm:	the attenuation due to atmospheric absorption
Agr:	the attenuation due to ground effect
Abar:	the attenuation due to a barrier
Amisc:	the attenuation due to miscellaneous other effects
Cmet:	Meteorological correction

Beräkningsresultat

Ljudkänsligt område: A Noise sensitive area: Swedish - User defined (5)

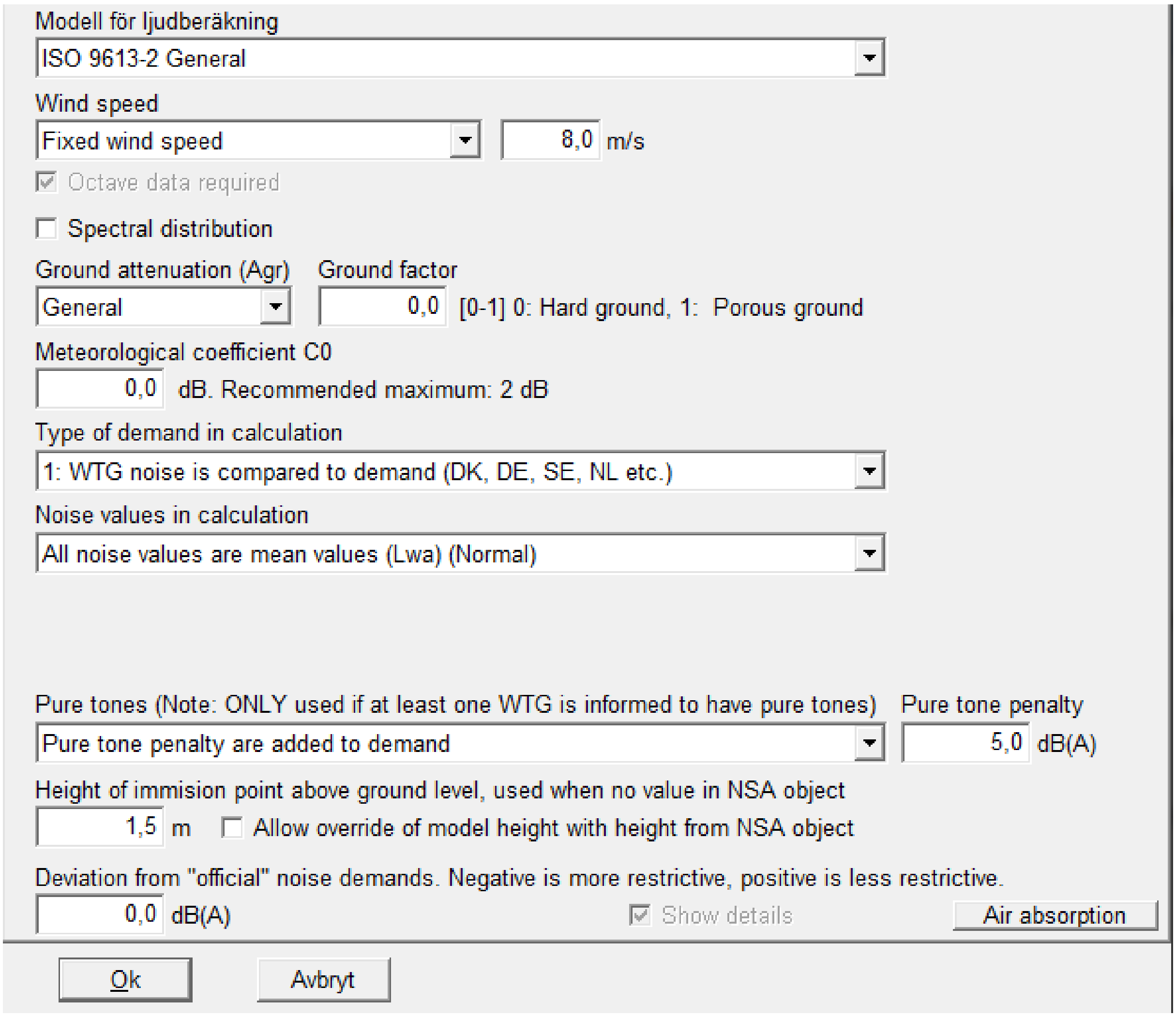
VKV — **Wind speed: 8,0 m/s**

Nej	Avstånd	Ljudavstånd	Calculated	LwA,ref	Dc	Adiv	Aatm	Agr	Abar	Amisc	A	Cmet
	[m]	[m]	[dB(A)]	[dB(A)]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]
1	500	510	**34,95**	104,5	0,00	65,15	-	-	0,00	0,00	-	0,00

Summa 34,95

- Data undefined due to calculation with octave data

Calculations with ISO 9613-2, distance 500 m, hard ground assumption



DECIBEL - Assumptions for noise calculation

Noise calculation model:
ISO 9613-2 General
Wind speed:
8,0 m/s
Ground attenuation:
General, Ground factor: 0,0
Meteorological coefficient, C0:
0,0 dB
Type of demand in calculation:
1: WTG noise is compared to demand (DK, DE, SE, NL etc.)
Noise values in calculation:
All noise values are mean values (Lwa) (Normal)
Pure tones:
Pure tone penalty are added to demand: 5,0 m/s
Height above ground level, when no value in NSA object:
1,5 m Don't allow override of model height with height from NSA object
Deviation from "official" noise demands. Negative is more restrictive, positive is less restrictive.:
0,0 dB(A)
Octave data required
Air absorption

63	125	250	500	1 000	2 000	4 000	8 000
[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]
0,1	0,4	1,0	1,9	3,7	9,7	32,8	117,0

VKV: NORDEX N90/2500 HS 2500 90.0 !O!
Ljud: Level 0 - official - 06-2005

Källa	Källa/Datum	Upphovsman	Redigerad
Manufacturer	2005.06.08	EMD	2005.11.21 15:35

Status	Navhöjd	Vindhastighet	LwA,ref	Rena toner		Oktavdata 63	125	250	500	1000	2000	4000	8000
	[m]	[m/s]	[dB(A)]			[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]
User value	100,0	8,0	104,5	No	Generic data	86,1	93,1	96,5	99,1	98,9	96,0	91,2	81,7

DECIBEL - Detaljerade resultat

Noise calculation model: ISO 9613-2 General 8,0 m/s

Antaganden

Calculated L(DW) = LWA,ref + K + Dc - (Adiv + Aatm + Agr + Abar + Amisc) - Cmet
(when calculated with ground attenuation, then Dc = Domega)

LWA,ref:	Sound pressure level at WTG
K:	Pure tone
Dc:	Directivity correction
Adiv:	the attenuation due to geometrical divergence
Aatm:	the attenuation due to atmospheric absorption
Agr:	the attenuation due to ground effect
Abar:	the attenuation due to a barrier
Amisc:	the attenuation due to miscellaneous other effects
Cmet:	Meteorological correction

Beräkningsresultat

Ljudkänsligt område: A Noise sensitive area: Swedish - User defined (5)

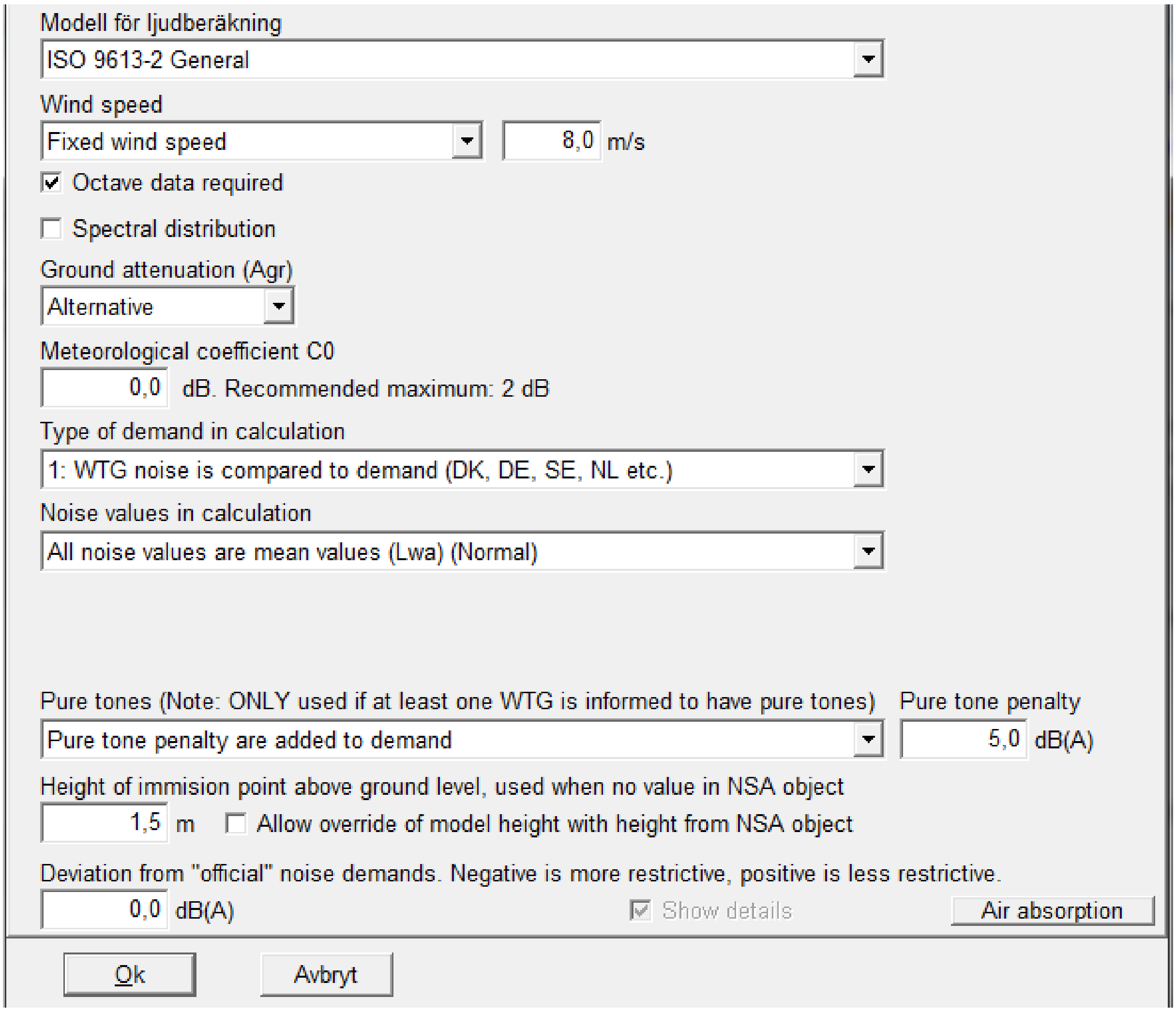
VKV — **Wind speed: 8,0 m/s**

Nej	Avstånd	Ljudavstånd	Calculated	LwA,ref	Dc	Adiv	Aatm	Agr	Abar	Amisc	A	Cmet
	[m]	[m]	[dB(A)]	[dB(A)]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]
1	500	510	**40,67**	104,5	0,00	65,15	-	-	0,00	0,00	-	0,00

Summa 40,67

- Data undefined due to calculation with octave data

Calculations with ISO 9613-2, distance 500 m, Alternative Agr method



DECIBEL - Assumptions for noise calculation

Noise calculation model:
ISO 9613-2 General
Wind speed:
8,0 m/s
Ground attenuation:
Alternative
Meteorological coefficient, C0:
0,0 dB
Type of demand in calculation:
1: WTG noise is compared to demand (DK, DE, SE, NL etc.)
Noise values in calculation:
All noise values are mean values (Lwa) (Normal)
Pure tones:
Pure tone penalty are added to demand: 5,0 m/s
Height above ground level, when no value in NSA object:
1,5 m Don't allow override of model height with height from NSA object
Deviation from "official" noise demands. Negative is more restrictive, positive is less restrictive.:
0,0 dB(A)
Octave data required
Air absorption

63	125	250	500	1 000	2 000	4 000	8 000
[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]
0,1	0,4	1,0	1,9	3,7	9,7	32,8	117,0

VKV: NORDEX N90/2500 HS 2500 90.0 !O!
Ljud: Level 0 - official - 06-2005

Källa	Källa/Datum	Upphovsman	Redigerad
Manufacturer	2005.06.08	EMD	2005.11.21 15:35

Status	Navhöjd	Vindhastighet	LwA,ref	Rena toner		Oktavdata 63	125	250	500	1000	2000	4000	8000
	[m]	[m/s]	[dB(A)]			[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]
User value	100,0	8,0	104,5	No	Generic data	86,1	93,1	96,5	99,1	98,9	96,0	91,2	81,7

DECIBEL - Detaljerade resultat

Noise calculation model: ISO 9613-2 General 8,0 m/s

Antaganden

Calculated L(DW) = LWA,ref + K + Dc - (Adiv + Aatm + Agr + Abar + Amisc) - Cmet
(when calculated with ground attenuation, then Dc = Domega)

LWA,ref:	Sound pressure level at WTG
K:	Pure tone
Dc:	Directivity correction
Adiv:	the attenuation due to geometrical divergence
Aatm:	the attenuation due to atmospheric absorption
Agr:	the attenuation due to ground effect
Abar:	the attenuation due to a barrier
Amisc:	the attenuation due to miscellaneous other effects
Cmet:	Meteorological correction

Beräkningsresultat

Ljudkänsligt område: A Noise sensitive area: Swedish - User defined (5)

VKV — **Wind speed: 8,0 m/s**

Nej	Avstånd	Ljudavstånd	Medelhöjd	Synlig	Calculated	LwA,ref	Dc	Adiv	Aatm	Agr	Abar	Amisc	A	Cmet
	[m]	[m]	[m]		[dB(A)]	[dB(A)]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]
1	500	510	50,7	Ja	**39,37**	104,5	3,01	65,15	1,69	1,30	0,00	0,00	68,14	0,00

Summa 39,37

Calculations with swedish model, distance 1035 m, roughness class 3

DECIBEL - Assumptions for noise calculation

Noise calculation model:
Swedish, Jan 2002, Land
Wind speed:
8,0 m/s
Ground attenuation:
None
Meteorological coefficient, C0:
0,0 dB
Type of demand in calculation:
1: WTG noise is compared to demand (DK, DE, SE, NL etc.)
Noise values in calculation:
All noise values are mean values (Lwa) (Normal)
Råhetsklass %d:
3,0 m/s
Pure tones:
Pure tone penalty are added to demand: 5,0 m/s
Height above ground level, when no value in NSA object:
1,5 m Don't allow override of model height with height from NSA object
Deviation from "official" noise demands. Negative is more restrictive, positive is less restrictive.:
0,0 dB(A)
Octave data required
Air absorption

63	125	250	500	1 000	2 000	4 000	8 000
[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]
0,1	0,3	0,6	1,4	3,2	7,9	22,0	50,0

VKV: NORDEX N90/2500 HS 2500 90.0 !O!
Ljud: Level 0 - official - 06-2005

Källa	Källa/Datum	Upphovsman	Redigerad
Manufacturer	2005.06.08	EMD	2005.11.21 15:35

Status	Navhöjd	Vindhastighet	LwA,ref	Rena toner		Oktavdata 63	125	250	500	1000	2000	4000	8000
	[m]	[m/s]	[dB(A)]			[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]
User value	100,0	8,0	104,5	No	Generic data	86,1	93,1	96,5	99,1	98,9	96,0	91,2	81,7

DECIBEL - Detaljerade resultat

Noise calculation model: Swedish, Jan 2002, Land 8,0 m/s

Antaganden

Calculated L(DW) = LWA,ref + K + Dc - (Adiv + Aatm + Agr + Abar + Amisc) - Cmet
(when calculated with ground attenuation, then Dc = Domega)

LWA,ref:	Sound pressure level at WTG
K:	Pure tone
Dc:	Directivity correction
Adiv:	the attenuation due to geometrical divergence
Aatm:	the attenuation due to atmospheric absorption
Agr:	the attenuation due to ground effect
Abar:	the attenuation due to a barrier
Amisc:	the attenuation due to miscellaneous other effects
Cmet:	Meteorological correction

Beräkningsresultat

Ljudkänsligt område: A Noise sensitive area: Swedish - User defined (6)

VKV			Wind speed: 8,0 m/s									
Nej	Avstånd	Ljudavstånd	Calculated	LwA,ref	Dc	Adiv	Aatm	Agr	Abar	Amisc	A	Cmet
	[m]	[m]	[dB(A)]	[dB(A)]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]
1	1 035	1 039	33,31	104,5	0,00	0,00	-	0,00	0,00	0,00	-	0,00

Summa 33,31

- Data undefined due to calculation with octave data

Calculations with swedish model, distance 1035 m, no correction

DECIBEL - Assumptions for noise calculation

Noise calculation model:
Swedish, Jan 2002, Land
Wind speed:
8,0 m/s
Ground attenuation:
None
Meteorological coefficient, C0:
0,0 dB
Type of demand in calculation:
1: WTG noise is compared to demand (DK, DE, SE, NL etc.)
Noise values in calculation:
All noise values are mean values (Lwa) (Normal)
Råhetsklass %d:
1,5 m/s
Pure tones:
Pure tone penalty are added to demand: 5,0 m/s
Height above ground level, when no value in NSA object:
1,5 m Don't allow override of model height with height from NSA object
Deviation from "official" noise demands. Negative is more restrictive, positive is less restrictive.:
0,0 dB(A)
Octave data required
Air absorption

63	125	250	500	1 000	2 000	4 000	8 000
[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]
0,1	0,3	0,6	1,4	3,2	7,9	22,0	50,0

VKV: NORDEX N90/2500 HS 2500 90.0 !O!
Ljud: Level 0 - official - 06-2005

Källa	Källa/Datum	Upphovsman	Redigerad
Manufacturer	2005.06.08	EMD	2005.11.21 15:35

Status	Navhöjd	Vindhastighet	LwA,ref	Rena toner		Oktavdata 63	125	250	500	1000	2000	4000	8000
	[m]	[m/s]	[dB(A)]			[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]
User value	100,0	8,0	104,5	No	Generic data	86,1	93,1	96,5	99,1	98,9	96,0	91,2	81,7

DECIBEL - Detaljerade resultat

Noise calculation model: Swedish, Jan 2002, Land 8,0 m/s

Antaganden

Calculated L(DW) = LWA,ref + K + Dc - (Adiv + Aatm + Agr + Abar + Amisc) - Cmet
(when calculated with ground attenuation, then Dc = Domega)

LWA,ref:	Sound pressure level at WTG
K:	Pure tone
Dc:	Directivity correction
Adiv:	the attenuation due to geometrical divergence
Aatm:	the attenuation due to atmospheric absorption
Agr:	the attenuation due to ground effect
Abar:	the attenuation due to a barrier
Amisc:	the attenuation due to miscellaneous other effects
Cmet:	Meteorological correction

Beräkningsresultat

Ljudkänsligt område: A Noise sensitive area: Swedish - User defined (5)

VKV **Wind speed: 8,0 m/s**

Nej	Avstånd	Ljudavstånd	Calculated	LwA,ref	Dc	Adiv	Aatm	Agr	Abar	Amisc	A	Cmet
	[m]	[m]	[dB(A)]	[dB(A)]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]
1	1 035	1 040	**31,79**	104,5	0,00	0,00	-	0,00	0,00	0,00	-	0,00

Summa 31,79

- Data undefined due to calculation with octave data

Calculations with ISO 9613-2, distance 1035 m, hard ground assumption

DECIBEL - Assumptions for noise calculation

Noise calculation model:
ISO 9613-2 General
Wind speed:
8,0 m/s
Ground attenuation:
General, Ground factor: 0,0
Meteorological coefficient, C0:
0,0 dB
Type of demand in calculation:
1: WTG noise is compared to demand (DK, DE, SE, NL etc.)
Noise values in calculation:
All noise values are mean values (Lwa) (Normal)
Pure tones:
Pure tone penalty are added to demand: 5,0 m/s
Height above ground level, when no value in NSA object:
1,5 m Don't allow override of model height with height from NSA object
Deviation from "official" noise demands. Negative is more restrictive, positive is less restrictive.:
0,0 dB(A)
Octave data required
Air absorption

63	125	250	500	1 000	2 000	4 000	8 000
[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]
0,1	0,4	1,0	1,9	3,7	9,7	32,8	117,0

VKV: NORDEX N90/2500 HS 2500 90.0 !O!
Ljud: Level 0 - official - 06-2005

Källa	Källa/Datum	Upphovsman	Redigerad
Manufacturer	2005.06.08	EMD	2005.11.21 15:35

Status	Navhöjd	Vindhastighet	LwA,ref	Rena toner		Oktavdata 63	125	250	500	1000	2000	4000	8000
	[m]	[m/s]	[dB(A)]			[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]
User value	100,0	8,0	104,5	No	Generic data	86,1	93,1	96,5	99,1	98,9	96,0	91,2	81,7

DECIBEL - Detaljerade resultat

Noise calculation model: ISO 9613-2 General 8,0 m/s

Antaganden

Calculated L(DW) = LWA,ref + K + Dc - (Adiv + Aatm + Agr + Abar + Amisc) - Cmet
(when calculated with ground attenuation, then Dc = Domega)

LWA,ref:	Sound pressure level at WTG
K:	Pure tone
Dc:	Directivity correction
Adiv:	the attenuation due to geometrical divergence
Aatm:	the attenuation due to atmospheric absorption
Agr:	the attenuation due to ground effect
Abar:	the attenuation due to a barrier
Amisc:	the attenuation due to miscellaneous other effects
Cmet:	Meteorological correction

Beräkningsresultat

Ljudkänsligt område: A Noise sensitive area: Swedish - User defined (6)

VKV **Wind speed: 8,0 m/s**

Nej	Avstånd	Ljudavstånd	Calculated	LwA,ref	Dc	Adiv	Aatm	Agr	Abar	Amisc	A	Cmet
	[m]	[m]	[dB(A)]	[dB(A)]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]	[dB]
1	1 035	1 039	33,28	104,5	0,00	71,34	-	-	0,00	0,00	-	0,00

Summa 33,28

- Data undefined due to calculation with octave data

Calculations with ISO 9613-2, distance 1035 m, porous ground assumption

DECIBEL - Assumptions for noise calculation

Noise calculation model:
ISO 9613-2 General
Wind speed:
8,0 m/s
Ground attenuation:
General, Ground factor: 1,0
Meteorological coefficient, C0:
0,0 dB
Type of demand in calculation:
1: WTG noise is compared to demand (DK, DE, SE, NL etc.)
Noise values in calculation:
All noise values are mean values (Lwa) (Normal)
Pure tones:
Pure tone penalty are added to demand: 5,0 m/s
Height above ground level, when no value in NSA object:
1,5 m Don't allow override of model height with height from NSA object
Deviation from "official" noise demands. Negative is more restrictive, positive is less restrictive.:
0,0 dB(A)
Octave data required
Air absorption

63	125	250	500	1 000	2 000	4 000	8 000
[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]	[db/km]
0,1	0,4	1,0	1,9	3,7	9,7	32,8	117,0

VKV: NORDEX N90/2500 HS 2500 90.0 !O!
Ljud: Level 0 - official - 06-2005

Källa	Källa/Datum	Upphovsman	Redigerad
Manufacturer	2005.06.08	EMD	2005.11.21 15:35

Status	Navhöjd [m]	Vindhastighet [m/s]	LwA,ref [dB(A)]	Rena toner		Oktavdata 63 [dB]	125 [dB]	250 [dB]	500 [dB]	1000 [dB]	2000 [dB]	4000 [dB]	8000 [dB]
User value	100,0	8,0	104,5	No	Generic data	86,1	93,1	96,5	99,1	98,9	96,0	91,2	81,7

DECIBEL - Detaljerade resultat

Noise calculation model: ISO 9613-2 General 8,0 m/s

Antaganden

Calculated L(DW) = LWA,ref + K + Dc - (Adiv + Aatm + Agr + Abar + Amisc) - Cmet
(when calculated with ground attenuation, then Dc = Domega)

LWA,ref:	Sound pressure level at WTG
K:	Pure tone
Dc:	Directivity correction
Adiv:	the attenuation due to geometrical divergence
Aatm:	the attenuation due to atmospheric absorption
Agr:	the attenuation due to ground effect
Abar:	the attenuation due to a barrier
Amisc:	the attenuation due to miscellaneous other effects
Cmet:	Meteorological correction

Beräkningsresultat

Ljudkänsligt område: A Noise sensitive area: Swedish - User defined (5)

VKV **Wind speed: 8,0 m/s**

Nej	Avstånd [m]	Ljudavstånd [m]	Calculated [dB(A)]	LwA,ref [dB(A)]	Dc [dB]	Adiv [dB]	Aatm [dB]	Agr [dB]	Abar [dB]	Amisc [dB]	A [dB]	Cmet [dB]
1	1 035	1 039	**27,02**	104,5	0,00	71,34	-	-	0,00	0,00	-	0,00

Summa 27,02

- Data undefined due to calculation with octave data

Calculations with ISO 9613-2, distance 1035 m, Alternative Agr method

DECIBEL - Detaljerade resultat

Noise calculation model: ISO 9613-2 General 8,0 m/s

Antaganden

Calculated L(DW) = LWA,ref + K + Dc - (Adiv + Aatm + Agr + Abar + Amisc) - Cmet
(when calculated with ground attenuation, then Dc = Domega)

LWA,ref:	Sound pressure level at WTG
K:	Pure tone
Dc:	Directivity correction
Adiv:	the attenuation due to geometrical divergence
Aatm:	the attenuation due to atmospheric absorption
Agr:	the attenuation due to ground effect
Abar:	the attenuation due to a barrier
Amisc:	the attenuation due to miscellaneous other effects
Cmet:	Meteorological correction

Beräkningsresultat

Ljudkänsligt område: A Noise sensitive area: Swedish - User defined (6)

VKV **Wind speed: 8,0 m/s**

Nej	Avstånd [m]	Ljudavstånd [m]	Medelhöjd [m]	Synlig	Calculated [dB(A)]	LwA,ref [dB(A)]	Dc [dB]	Adiv [dB]	Aatm [dB]	Agr [dB]	Abar [dB]	Amisc [dB]	A [dB]	Cmet [dB]
1	1 035	1 039	50,8	Ja	**30,18**	104,5	3,01	71,34	2,89	3,11	0,00	0,00	77,34	0,00

Summa 30,18

DECIBEL - Assumptions for noise calculation

Noise calculation model:
ISO 9613-2 General
Wind speed:
8,0 m/s
Ground attenuation:
Alternative
Meteorological coefficient, C0:
0,0 dB
Type of demand in calculation:
1: WTG noise is compared to demand (DK, DE, SE, NL etc.)
Noise values in calculation:
All noise values are mean values (Lwa) (Normal)
Pure tones:
Pure tone penalty are added to demand: 5,0 m/s
Height above ground level, when no value in NSA object:
1,5 m Don't allow override of model height with height from NSA object
Deviation from "official" noise demands. Negative is more restrictive, positive is less restrictive.:
0,0 dB(A)
Octave data required
Air absorption

63 [db/km]	125 [db/km]	250 [db/km]	500 [db/km]	1 000 [db/km]	2 000 [db/km]	4 000 [db/km]	8 000 [db/km]
0,1	0,4	1,0	1,9	3,7	9,7	32,8	117,0

VKV: NORDEX N90/2500 HS 2500 90.0 !O!
Ljud: Level 0 - official - 06-2005

Källa	Källa/Datum	Upphovsman	Redigerad
Manufacturer	2005.06.08	EMD	2005.11.21 15:35

Status	Navhöjd [m]	Vindhastighet [m/s]	LwA,ref [dB(A)]	Rena toner	Oktavdata	63 [dB]	125 [dB]	250 [dB]	500 [dB]	1000 [dB]	2000 [dB]	4000 [dB]	8000 [dB]
User value	100,0	8,0	104,5	No	Generic data	86,1	93,1	96,5	99,1	98,9	96,0	91,2	81,7