Appendix A. Theoretical background for noise propagation models

The International rule DIN ISO 9613-2, general

The ISO 9613-2 “Attenuation of sound during propagation outdoors, Part 2. A general method of calculation” describes the calculation of damping of the noise during propagation outdoors.

This text describes the theoretical basis of the ISO 9613-2 as implemented in WindPRO.

From version 4.1, the description is updated to include the ISO 9613-2:2024 edition.

Calculation formulas if octave data are not available

This is the calculation methodology if only the A-weighted noise source (without octave division/classification) is available for the noise record of the WTG. The damping values at 500 Hz are used to determine the resulting damping of noise emission. **The general method for calculation of ground attenuation cannot be used, only the Alternative method is available**. The resulting noise level from each source is thereafter calculated from the ISO 9613-2 as follows:

$$L_{AT}(DW) = L_{WA} + D_C - A - C_{met} \qquad (1)$$

LWA: Source noise, A-weighted.

D_c: Directional correction for noise source without directional effect (0dB), but taking the reflection from the terrain into consideration, D_Ω (Needed because the alternative method for calculating ground attenuation, Agr is used)

$$D_C = D_\Omega - 0 \qquad (2)$$

D_Ω is calculated as:

$$D_\Omega = 10 \lg\{1 + [d_p^2 + (h_s - h_r)^2] / [d_p^2 + (h_s + h_r)^2]\} \qquad (3)$$

Where:

h_s: Noise source height above terrain (hub height)

h_r: Noise receptors height above terrain (usually 5m, but can be set individually in the calculation setup)

d_p: Distance between noise source and recipient projected on level terrain

The distance is determined by the (x,y) coordinates for sources (index s) and recipient (index r).

$$d_p = \sqrt{[(x_s - x_r)^2 + (y_s - y_r)^2]} \quad (4)$$

A: Damping between the noise source (WTG-Nacelle) and the noise critical point:

$$A = A_{div} + A_{atm} + A_{gr} + A_{bar} + A_{misc} \quad (5)$$

A_{div}: Damping due to geometry

$$A_{div} = 20 \lg(d/1m) + 11 \text{ dB} \quad (6)$$

d: Distance between noise source and recipient

A_{atm}: Damping due to air absorption

$$A_{atm} = \alpha_{500} d / 1000 \quad (7)$$

α_{500}: Air absorptions coefficient (= 1,9 dB/km)

The value for α_{500} is based on the most optimal noise emission conditions (temperature 10 Gr. C and 70% relative atmospheric humidity). Note that if octave band data is available an octave band dependent air absorption can be combined with a dBA based alternative ground attenuation.

A_{gr}: Terrain damping:

$$A_{gr} = 4,8 - (2h_m / d)[17 + (300 / d)] \quad (8)$$

IF $A_{gr} < 0$ then is $A_{gr} = 0$

h_m: Average height above terrain (in meters) for noise emission

If there is no orography for the site:

$$hm = (hs + hr) /2 \qquad (9a)$$

If there is a DHM in the area between line of sight and the terrain surface between the WTG and the immission point, it will be calculated based on a grid (grid size set in the calculation setup) with a calculation for each grid point the line of sight passes through. The medium height is calculated by:

$$h_m = F/d \qquad (9b)$$

F: Integrated area from emission point to receptor (immission point)

$F = F_1 + F_2 + \ldots + F_{100}$

d: distance from emission point to receptor (immission point)

In order to calculate the integration of the area between the ground and line of sight windPRO uses the vertical distance from line of sight to the ground in each node. However the ISO 9613-2 can be interpreted so that the height in each node should be measured perpendicular to line of sight. windPRO allows that this interpretation can be used instead of the default approach.

A_{bar} : Damping due to shielding (noise protection). This is not implemented in windPRO assuming no shielding protection: A_{bar} =0.

A_{misc}: Damping due to different other effects (vegetation, buildings, industry). Usually these effects are not included in the calculation. A_{misc} =0.

C_{met}: A meteorological correction which can be applied to the calculation. The meteorological correction is the propagation deviation from downwind direction from the wind turbine. According to the ISO 9613-2 C_{met} is determined by means of the equation:

C_{met} = 0 for dp < 10 (h_s+h_r)

C_{met} = C0 [1-10(h_s+h_r)/dp] for dp > 10,

d_p: Distance between noise source and recipient projected on level terrain.

where the factor C0, dependent on weather conditions, can be between 0 and 5 dB. In exceptional cases, values over 2 dB may occur. In WindPRO, C0 can be defined individually for each noise calculation.

WindPRO includes two interpretations for calculating wind direction/directivity effects as described below.

Calculation method with octave-divided noise data

Using the ISO 9613-2 it is possible to calculate according to octave-divided noise figures for a WTG. If such data are available and entered into the WindPRO WTG catalogue, they will automatically be used in calculations. Using octave-band data also makes it possible to use the general ground attenuation method. In the following formula is only demonstrated the difference from calculation with 500 Hz frequency as average value. The resulting noise is calculated as follows:

$$L_{AT}\,(DW) = 10lg[10^{0,1LAfT(63)} + 10^{0,1LAfT(125)} + 10^{0,1LAfT(250)} + 10^{0,1LAfT(500)} + 10^{0,1LAfT(1k)} + 10^{0,1LAfT(2k)} + 10^{0,1LAfT(4k)} + 10^{0,1LAfT(8k)}) \qquad (10)$$

where:

L_{AfT}: A-weighted noise source for each noise sources at different frequencies (63, 125, 250, 500, 1000, 2000, 4000, 8000 Hz)

The A-weighted noise source L_{AfT} at average frequencies for each noise source is calculated from:

$$L_{AfT}\,(DW) = (L_W + A_f) + D_C - A \qquad (11)$$

where:

L_W: Octave noise source for non A-weighted point source. LW + Af constitute the A-weighted octave-divided noise source LWA according to IEC 651

A_f: standardized A-weighted from IEC 651. WindPRO calculates the A-weighted values for the noise source according to this.

D_c: Directional correction for noise source without directional effect (0dB), but taking the reflection from the terrain into consideration. If general ground attenuation is used $D_\Omega = 0$, which means $D_c = 0$. If alternative method is used D_c is calculated as in the non-octave band case.

A: Octave damping, damping between point source and recipient which is determined as described above by the following damping types:

$$A = A_{div} + A_{atm} + A_{gr} + A_{bar} + A_{misc} \qquad (12)$$

A_{div}: Damping due to geometry (= VDI 2714 Distance figure Ds)

A_{atm}: Damping due to air absorption, frequency dependent (=VDI 2714 air absorption figure DL)

A_{gr}: Terrain damping:(=VDI 2714 Terrain and meteorological damping figures DBM)

A_{bar}: Damping due to shielding (noise protection), worst case, no noise protection A_{bar} =0

A_{misc}: Damping due to different other effects (growth, housing, industry). Worst case A_{misc} =0

At octave-divided noise emissions, the damping due to air absorption depends on the frequency due to the air absorption:

$$A_{atm} = \alpha_f \, d / 1000 \qquad (13)$$

where:

α_f: absorption coefficient for each frequency band.

The air-damping coefficient depends strongly on the noise frequency, surrounding temperature and the relative atmospheric humidity. The most adverse conditions are at 10 degree Celsius and 70% relative atmospheric humidity. For this situation the following values are used:

Band, mean frequency, [Hz]	63	125	250	500	1000	2000	4000	8000
α_f, [dB/km]	0.1	0.4	1	1.9	3.7	9.7	32.8	117

Please note that this table was included in earlier versions of the ISO 9613-2 standard, but not in the current version.

It is possible to enter calculation specific air damping coefficients in the calculation setup.

Calculation of air absorption coefficients based on temperature, humidity and air pressure is described below.

For the terrain damping there is two methods available for calculation the ground attenuation, A_{gr}. The alternative method is as described for the non-octave band case above. The general method is calculated as:

$$A_{gr} = -10\log\left[1 + \left(^{-A'_{gr}}/_{10} - 1\right) * K_{geo}\right] \qquad (14)$$

Where

$$A'_{gr} = A_S + A_R + A_m \qquad (15)$$

$$K_{geo} = \frac{d_p^2 + (h_S - h_g)^2}{d_p^2 + (h_S + h_g)^2} \qquad (16)$$

A_S: The attenuation for the source region spanning $30h_s$, though max d_p. This region is described by the ground factor G_s, which gives the porosity of the surface, a value between 0 (hard surface) and 1 (porous surface).

A_R: The attenuation for the receiver region spanning $30h_r$ from the receiver. This region is described by the ground factor G_r.

A_m: The attenuation for the middle region. If the source and receiver region overlaps, then there is no middle region. This region is described by the ground factor G_r.

WindPRO can work with a fixed ground factor G, in which case the porosity is set in the calculation setup.

$G = G_s = G_r = G_m$ (17)

Or WindPRO can read an area object designating hard (0) and soft (1) terrain and through linear weighting assess G_s , G_r and G_m for each turbine – receptor pairing.

The below extract from the ISO 9613-2 document explains how the three ground attenuations are calculated.

Nominal midband frequency Hz	A_s or A_r [1] dB	A_m dB
63	$-1,5$	$-3q$ [2]
125	$-1,5+G\times a'(h)$	
250	$-1,5+G\times b'(h)$	
500	$-1,5+G\times c'(h)$	
1 000	$-1,5+G\times d'(h)$	$-3q(1-G_m)$
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 $d_p \leq 30(h_s + h_r)$

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

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

Long-term average noise level (resulting noise level)

Noise source figures and distances to noise critical points will be overlaid (superimposed) if the calculation contains n noise sources (wind farm). The resulting noise L_{AT} is calculated according to following:

$$L_{AT}(LT) = 10\cdot \lg \sum_{i=1}^{n} 10^{0,1(L_{ATi}-C_{met}+K_{Ti}+K_{Ii})} \qquad (18)$$

L_{AT}: Resulting noise at noise critical points

L_{ATi}: Noise at noise critical point from noise source i

i: Index for all noise sources from 1-n

K_{Ti}: Addition for pure tone content for a noise source i, depends on the local rules

K_{Ii}: Addition for impulse tone content for a noise source i, depends on the local rules

C_{met}: Meteorological correction which is determined by means of the equation:

$C_{met} = 0$ for dp < 10 (h_s+h_r)

C_{met} = C0 [1-10(h_s+h_r)/dp] for dp > 10,

d_p: Distance between noise source and recipient projected on level terrain.

where the factor C0, dependent on weather conditions, can be between 0 and 5 dB. In exceptional cases values over 2 dB may occur. In WindPRO the C0 can be defined individually for each noise calculation.

WindPRO includes two interpretations for calculating wind direction/directivity effects as described below.

Reflections

Additional noise contributions may be added from reflections. These will figure in calculation 20 as mirror sources, where the an alternative noise path is reflected off a wall on the receptor. Reflection from the ground is already factored into the ground attenuation.

A reflector is included as reflector in the calculation if the reflective surface has the right angle and is large enough to be a reflector. The test is done for each frequency band with the corresponding wavelength, λ, where:

$$\frac{1}{\lambda} > \left[\frac{2}{(l_{min}\cos\beta)^2}\right]\left[\frac{d_{s,o}d_{o,r}}{(d_{s,o}+d_{o,r})}\right] \quad (19)$$

λ: The wavelength at the midband frequency

$d_{s,o}$: Distance from source to reflection point

$d_{o,r}$: Distance from reflection point to receptor

β: Angle of incidence on the reflector

l_{min}: size of reflector (length)

The reflected sound is called the source image, $L_{W,im}$ and is calculated as

$$L_{W,im} = L_W + 10\log(\rho) + D_{Ir} \quad (20)$$

Where

L_W: the sound level from the source

P: The sound reflection coefficient, see below. This is a property of the obstacle object used as reflector.

$D_{I,r}$: The directivity index for the source, which is considered 0.

The attenuations for the propagation of the sound paths of the sound image is calculated the same way as the direct sound path.

Object	ρ
Flat hard walls	1
Walls of building with windows and small additions or bay	0,8
Factory walls with 50 % of the surface consisting of openings, installations or pipes	0,4
Cylinders with hard surfaces (tanks, silos)	$\frac{D \sin(\phi/2)}{2d_{sc}}$ *) where D is the diameter of the cylinder; d_{sc} is the distance from the source to the centre C of the cylinder; ϕ is the supplement of the angle between lines SC and CR.
Open installations (pipes, towers, etc.)	0
*) This expression applies only if the distance d_{sc} from the source S to cylinder C is much smaller than the distance d_{cr} from the cylinder to receiver; see figure 9.	

Calculation of air absorption coefficients

It is possible to calculate the atmospheric attenuation coefficients based on ISO 9613-1

For each frequency, f, the atmospheric attenuation coefficient, α, is calculated as:

$$\alpha = 8.686 f^2 \left(\left[1.84 * 10^{-11} \left(\frac{p_a}{p_r}\right)^{-1} \left(\frac{T}{T_0}\right)^{1/2} \right] + \left(\frac{T}{T_0}\right)^{-5/2} * \left\{ 0.01275 \left[exp\left(\frac{-2239.1}{T}\right) \right] \left[f_{rO} + \left(\frac{f^2}{f_{rO}}\right) \right]^{-1} + 0.1068 \left[exp\left(\frac{-3352.0}{T}\right) \right] \left[f_{rN} + \left(\frac{f^2}{f_{rN}}\right) \right]^{-1} \right\} \right) \quad (21)$$

Where

T: actual temperature in Kelvin

T_0: 293.15 K

p_a: atmospheric pressure

p_r: Reference pressure: 101.325 kPa

f: The frequency is the midband frequency and calculated for 1/1 octaves as

$$f = 1000 * \left(10^{3/10}\right)^k$$

Where k is the band number from -4 to 3.

The relaxation frequencies for Oxygen and Nitrogen, f_{rO} and f_{rN}, are respectively:

f_{rO}: $$f_{rO} = \frac{p_a}{p_r}\left(24 + 4.04 * 10^4 h \frac{0.02+h}{0.391+h}\right) \qquad (22)$$

f_{rN}: $$f_{rN} = \frac{p_a}{p_r}\left(\frac{T}{T_0}\right)^{-½} * \left(9 + 280h * exp\left\{-4.170\left[\left(\frac{T}{T_0}\right)^{-1/3} - 1\right]\right\}\right) \qquad (23)$$

where

h: the molecular concentration of water vapour, calculated as

$$h = h_r\left(\frac{p_{sat}}{p_r}\right) / \left(\frac{p_a}{p_r}\right) \qquad (24)$$

where

h_r: the relative humidity

p_{sat}/p_r: water saturation pressure divided by reference pressure calculated as

$$\frac{p_{sat}}{p_r} = 10^C \qquad (25)$$

Where

C: $$C = -6.8346\left(\frac{T_{01}}{T}\right)^{1.261} + 4.6151 \qquad (26)$$

Where

T_{01}: 273.16K

Calculation of attenuation as a function of wind direction / directivity.

WindPRO includes two functions for the calculation of attenuation due to wind direction /directivity.

ISO 9613-2 directional C0 adaption

LANUV NRW [LANUV NRW (2012): Empfehlungen zur Bestimmung der meteorologischen Dämpfung cmet gemäß DIN ISO 9613-2 from 26.09.2012; https://www.lanuv.nrw.de/fileadmin/lanuv/geraeusche/pdf/Cmet-Hinweise-2012.pdf, Access 08/2023] describe a method to calculate the average C_{met} value based on the directional components. In the WindPRO implementation these directional components are isolated to give the C_{met} values for each direction bin.

C_{met} is only calculated beyond a distance as a function of turbine and receptor height:

$C_{met} = 0$ for $d_p < 10\ (h_s+h_r)$

$C_{met} = C_0\ [1-10(h_s+h_r)/d_p]$ for $d_p > 10$

TA Lärm describes a method to calculate C_0 as

$$C_0 = -10 * \log \sum_i 10^{-0.1*\Delta L_i(\varepsilon)} * h_i(\alpha)/100 \qquad (27)$$

Which means that the damping ΔL_i is weighted with the probability of each sector h_i.

ΔL_i is then described as

$$\Delta L(\varepsilon) = 5 - 5 * \cos(\varepsilon - \frac{\pi}{4} * \sin(\varepsilon)) \qquad (28)$$

With $\varepsilon_i = \alpha_i - \beta$

α_i is the angle between north and the i'th sector and β is the angle between north and tailwind direction (opposite of the common convention in windPRO for wind direction)

Since we are not interested in average Cmet, but a direction specific Cmet, the expression for C_0 is simply ΔL_i

$$C_0 = \Delta L_i$$

The formula will therefore for a specific direction becomes

$$C_{met} = 5 - 5 * \cos\left(\varepsilon - \left(\frac{\pi}{4}\right)\sin(\varepsilon)\right)\left[1 - 10(h_s + h_r)/d_p\right] \qquad (29)$$

Note that method is only concerned by the C_{met} value and not directivity (direction dependent source noise level).

Institute of Acoustics method

The UK Institute of Acoustics (IoA) Good Practice Guide from 2013 (Institute of Acoustics: A Good Practice Guide to the Application of ETSU-R-97 for the Assessment and Rating of Wind Turbine Noise, 2013) suggests an empirical method for calculating the attenuation effect of wind direction and directivity combined. This value should therefore be applied alongside other attenuations in the calculation.

The IoA BPG states the following:

1. At far distance the directivity attenuation upwind is 10 dB and 2 dB crosswind
2. Downwind until 10 degrees before crosswind the directivity attenuation is 0 dB
3. For distances below 5 x total height there is no attenuation
4. From 5 to 10 time total height the directivity can be linearly interpolated between the two extremes.

This results in attenuations as presented below (flat terrain)

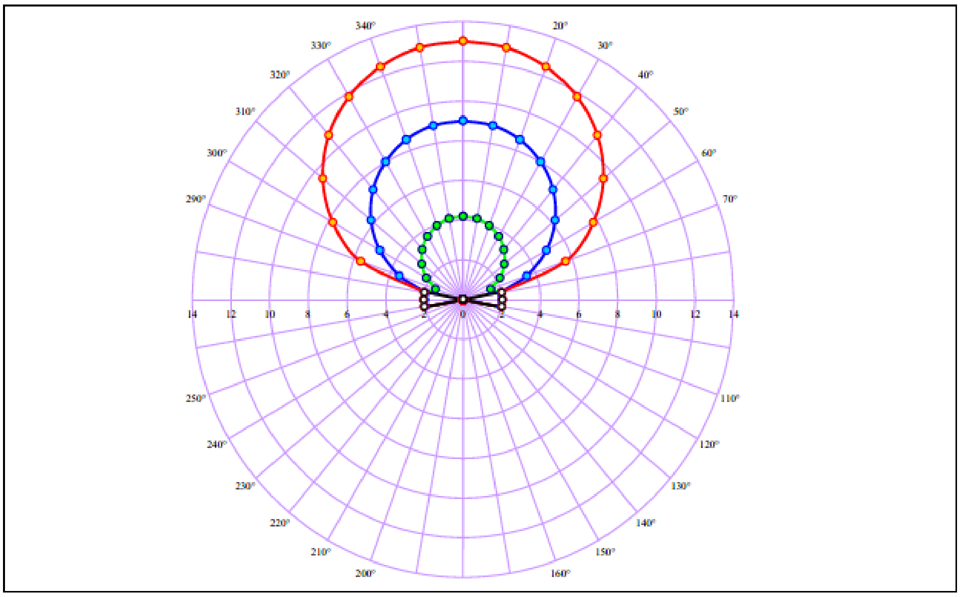

*Figure 1 The IoA BPG figure demonstrating the wind direction / directivity attenuation. 180˚ is where the receptor is downwind of the turbine. Black = 5.25 * tip height, Green = 7.5 * tip height, Blue = 11 * tip height, Red = 18 * tip height. (Institute of Acoustics: A Good Practice Guide to the Application of ETSU-R-97 for the Assessment and Rating of Wind Turbine Noise, 2013).*

Additional attenuations for the ISO 9613-2 model for use in the UK

The IoA (Institute of Acoustics) good practice guideline from 2013 recommends further adjustments to the ISO 9613-2 model as described in the ETSU-97 guideline.

Valley effect:

If calculated across a valley the noise impact is penalized with:

+3,0 dB if G=0,5

+1,5 dB if G=0,0

The criteria for a valley is:

$h_m \geqslant 1.5 \times (\mathrm{abs}\,(h_s - h_r)\,/2)$

where h_m is the mean height above the ground of the direct line of sight from the receiver to the source, and h_s and h_r are the heights above local ground level of the source and receiver respectively.

Topographic screening:

A reduction of 2dB is applied to the calculation of contribution if the receptor cannot see any part of the turbine

Only terrain contours are used for the assessment and tip height as well as receiver height (4m) are used as input.

The calculation is parallel to the ZVI calculation in the Shadow calculation. If the receptor in the calculation point cannot see the turbine in a ZVI calculation the contribution from this turbine is reduced 2 dB.

Additional attenuations for use in Germany (Interimsverfahren)

The ISO 9613-2 code for use in Germany, also known as Interimsverfahren, modifies the standard model in the following way:

A_{gr} = -3 dB

D_c = 0 dB

This means that formula 11 becomes:

L_{AfT} (DW) = (L_W + A_f) + 0 - A

And formula 12 becomes

A = A_{div} + A_{atm} + (-3 dB) + A_{bar} + A_{misc}

Other the calculation follows the methodology for ISO 9613-2 with octave band distributed data.

The German rule VDI 2714 (outdated)

Until 01.10.1998 calculations were performed from VDI-Guideline Directions "Noise emission in open air". The starting point for the calculation is a simple A-weighted noise emission. The formula below is the calculation formula for noise level at the distance S between the WTG and the noise-sensitive point:

$$LS = LW + DI + KO - DS - DL - DBM - DD - DG \quad \text{in dB(A)}$$

LS : Calculated noise level in distance S

LW : Noise emission for the WTG

DI : Directional impact figure (= 0)

KO : Solid angle figure (= 3 dB)

DS : Distance figure DS=10 log(4 π S2)

DL : Air absorption figure DL=α_L S

α_L = 0.00209 dB/m

DBM :Terrain and meteorological damping figure

DBM = Max(0, 4.8 - (hq+hA)/S(17+300/S))

hq hub height

hA Noise critical point height above terrain IP (= 5m)

DD : Vegetation damping figure (= 0)

DG : Build up damping figure (= 0)

Default values are shown in brackets. These are the so-called “worst case” values, which WindPRO uses. For instance, vegetation damping will normally always be >0 and therefore the measured noise should be below the value calculated.

If the noise originates from several sources (e.g. a wind farm) then each individual noise source contribution is added up and the resulting noise at noise critical points is calculated from there.

Danish noise codes

Danish codes 1991

The Danish rules are outlined in "Bekendtgørelse om støj fra vindmøller" (Statement from the Department of Environment) No. 304 of 14/5/91.

The key equation is:

$L_{pA} = {}_{LWA,ref} - 10 \times \log(l^2 + h^2) - 8dB - \Delta L_a$

Where
l is the distance between the WTG and the neighbor

h is the height difference between the nacelle and the neighbor (normally = hub height) and

ΔL_a is the air absorption.

ΔL_a is calculated as $\alpha_a\sqrt{(l^2 + h^2)}$

Where α_a is the damping coefficient (0.005 dB/m or from the table below).

Octave Band Damping Coefficient:

Center freq. (Hz)≤	125	250	500	1000	2000	4000	8000
α_a (dB/m)	0	0	0.002	0.004	0.007	0.017	0.06

If the noise emission from the WTG is given for each octave band (see Chapter 2, section 5 "WTG Catalogue" under WindPRO BASIS), the damping coefficient will be more correctly included in the calculations, but this is not a requirement.

Danish codes 2007

From 2007 new noise codes for Denmark are used in Denmark based on “Bekendtgørelse nr. 1518 af 14. December 2006, Bekendtgørelse om støj fra vindmøller”.

The propagation model here is changed with a separate damping for offshore wind turbines.

The central equation for is:

$L_{pA} = L_{WA,ref} - 10 \times \log(l^2 + h^2) - 11dB + \Delta L_g - \Delta L_a$

Compared to the former Danish codes the difference is in the damping.

The ground attenuation ΔL_g is 1,5 dB for onshore turbines and 3 dB for offshore wind turbines.

The air absorption ΔL_a is calculated as above but with revised damping coefficient as follows:

Center freq. (Hz)≤	63	125	250	500	1000	2000	4000	8000
α_a (dB/m)	0.0001	0.0004	0.001	0.002	0.0036	0.0088	0.029	0.1045

The noise must be calculated using 1/1 octaves.

The noise level from groups of turbines are added together using the formula:

$$L_{total} = 10 * \log\left(10^{\frac{L_{p1}}{10}} + 10^{\frac{L_{P2}}{10}} + \cdots\right)$$

Danish Codes 2011

For the normal noise calculation there is no change compared to the 2007 codes. The reason a separate noise code is available for 2011 is that default source noise levels for turbines with insufficient source noise information is different (see the user guide). Those changes are described in the in the guideline ”Støj fra Vindmøller, Vejledning fra Miljøstyrelsen nr. 1, 2012”.

Danish Codes 2011 Low Frequency

The low frequency codes are based on the same basic formula as the normal noise code of 2007 with a few changes. The formula for the damping is as follows:

$$L_{pA} = L_{WA,ref} - 10 * log(l^2 + h^2) - 11dB + \Delta L_g - \Delta L_\alpha - \Delta L_\sigma$$

Where
l = distance from base of turbine to calculation point
11 dB = correction for distance, 10 x log 4π
ΔL_{gLF} =correction for terrain at low frequencies (see below table)
ΔL_σ = noise insulation at low frequencies (see below table)
ΔL_a = air absorption, $(\alpha_a * \sqrt{l^2 + h^2})$ where the damping coefficient α_a can be found in below table.

frekvens	10 Hz	12,5 Hz	16 Hz	20 Hz	25 Hz	31,5 Hz	40 Hz
ΔL_{gLF} (dB) land	6,0	6,0	5,8	5,6	5,4	5,2	5,0
ΔL_{gLF} (dB) offshore	6,0	6,0	6,0	6,0	6,0	5,9	5,9
α (dB/km)	0,0	0,0	0,0	0,0	0,02	0,03	0,05
$\Delta L\sigma$ (dB)	4,9	5,9	4,6	6,6	8,4	10,8	11,4

frekvens	50 Hz	63 Hz	80 Hz	100 Hz	125 Hz	160 Hz
ΔLg_{LF} (dB) land	4,7	4,3	3,7	3,0	1,8	0,0
ΔL_{gLF} (dB) offshore	5,8	5,7	5,5	5,2	4,7	4,0
α (dB/km)	0,07	0,11	0,17	0,26	0,38	0,55
ΔLσ (dB)	13,0	16,6	19,7	21,2	20,2	21,2

For offshore turbines are used a separate terrain damping. In case the receptor is more than 200 m inland the onshore terrain damping is used. Receptors in the transition zone from offshore to onshore are calculated using an interpolation between the two values.

Danish codes 2019 and 2024

The Danish 2019 noise code is described by “Bekendtgørelse om støj fra vindmøller, Bekendtgørelse nr 135 af 07/02/2019”, from the Danish Ministry of the Environment.

This code extends and slightly modify the 2011/2015 code.

Danish code 2019 normal frequency range

The contribution from each wind turbine is calculated as

$L_{pA} = L_{WA,ref} - 10 \times \log(l^2 + h^2) - 11dB + \Delta L_g - \Delta L_a + \Delta L_m$

Where
l = distance from base of turbine to calculation point
h = hub height of wind turbine
11 dB = correction for distance, 10 x log 4π
ΔL_g = correction for terrain (1,5 dB for onshore wind turbines and 3 dB for offshore wind turbines)
ΔL_a = air absorption, $(\alpha_a * \sqrt{l^2 + h^2})$ where the damping coefficient α_a can be found in below table.

Center freq. (Hz)≤	63	125	250	500	1000	2000	4000	8000
α_a (dB/km)	0.11	0.38	1.02	2.0	3.6	8.8	29.0	104.5

ΔL_m = correction for multiple reflections (0 for onshore wind turbine, for offshore wind turbines see below)

The threshold distance for multiple reflections is calculated as

$$l_0 = 2000 * \frac{h}{30} * \sqrt{\frac{6}{v_{ref}}}$$

The normalized threshold distance, l’, is calculated as

$$l' = \frac{l_k}{l_0}$$

The correction for multiple reflections are then calculated as

$$\Delta L_m = \begin{cases} 0 \; for \; l' \le 1 \\ 10 * \log l' \;\; for \; 1 < l' < 2.512 \\ N * \log \frac{l'}{2.512} + 4 \; for \; 2.512 \le l' \le 5 \\ 10 * \log l' + (N - 10) * \log \frac{5}{2.512} \; for \; l' > 5 \end{cases}$$

Where N is a frequency dependent scale factor

1/3 octave center frequency (Hz)	<400	500	630	>800
N	20	16.8	13.4	10

At the coastline the sound path enters a 200 m transition zone. In this zone the ground attenuation is linearly weighted between onshore and offshore. More than 200 m from the coastline a receptor is calculated using onshore ground attenuation.

Multiple reflections do not increase after passing the coastline, but will remain unchanged across land as a base value of the sound.

The total noise level from a wind turbine is found by combining the contributions from each frequency.

$$L_{pA,tot} = 10 * \log \sum 10^{\frac{L_{pA,i}}{10}}$$

Danish code 2019 low frequency range

Low frequency noise at a receptor is calculated as the combined noise in the range 10 to 160 Hz as

$$L_{pA} = L_{WA,ref} - 10 * log(l^2 + h^2) - 11dB + \Delta L_g - \Delta L_\alpha - \Delta L_\sigma + \Delta L_m$$

Where
l = distance from base of turbine to calculation point
11 dB = correction for distance, 10 x log 4π
ΔL_{gLF} =correction for terrain at low frequencies (see below table)
ΔL_σ = noise insulation at low frequencies (see below table, distinction between normal dwellings and summerhouse areas (areas with light dwellings))
ΔL_a = air absorption, $(\alpha_a * \sqrt{l^2 + h^2})$ where the damping coefficient α_a can be found in below table.
ΔL_m = correction for multiple reflections (0 for onshore wind turbine, for offshore wind turbines, see above)

frequency	10 Hz	12,5 Hz	16 Hz	20 Hz	25 Hz	31,5 Hz	40 Hz
ΔLg_{LF} (dB) land	6.0	6.0	5.8	5.6	5.4	5.2	5.0
ΔL_{gLF} (dB) offshore	6.0	6.0	6.0	6.0	6.0	5.9	5.9
α (dB/km)	0.0	0.0	0.0	0.0	0.02	0.03	0.05
ΔLσ (dB) normal dwelling	4.9	5.9	4.6	6.6	8.4	10.8	11.4
ΔLσ (dB) light dwelling	8.8	3.9	0.4	-0.2	4.8	6.2	8.4

frequency	50 Hz	63 Hz	80 Hz	100 Hz	125 Hz	160 Hz
ΔLg_{LF} (dB) land	4.7	4.3	3.7	3.0	1.8	0.0
ΔL_{gLF} (dB) offshore	5.8	5.7	5.5	5.2	4.7	4.0
α (dB/km)	0.07	0.11	0.17	0.26	0.38	0.55
$\Delta L\sigma$ (dB) normal dwelling	13.0	16.6	19.7	21.2	20.2	21.2
$\Delta L\sigma$ (dB) light dwelling	10.5	11.9	11.9	16	17.5	17.9

At the coastline the sound path enters a 200 m transition zone. In this zone the ground attenuation is linearly weighted between onshore and offshore. More than 200 m from the coastline a receptor is calculated using onshore ground attenuation.

Multiple reflections do not increase after passing the coastline, but will remain unchanged across land as a base value of the sound.

From BEK 995 (2024), multiple reflections from wind turbines more than 20 km from the coastline should not be included in the low frequency calculation.

Swedish guideline, 2002.

By the end of 2001, new guidelines for calculating noise from WTGs were released in Sweden. They are called "Ljud från Vindkraftverk", Naturvårdsverket 2001, ISBN 91-620-6641-7. They replace former calculation methods and distinguish between onshore and offshore conditions.

Swedish, Jan 2002, Land.

For distances from the WTG up to 1000 m, the following formula is used:

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

where r is the distance from the receptor to the hub of the WTG.

$L_{WA,corr}$ is a corrected source emission value, which depends on the roughness of the terrain and noise as a function of wind speed.

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

Where $L_{WA,measured}$ is the measured, A-weighted noise emission level at hub height and 8 m/s at 10 m height.

k is the rate of change of noise with wind speed. In WindPRO k is set to 1 dB/(m/s).

Δv_h is the difference in wind speed at hub height compared to 10 m height and is calculated as:

$$\Delta v_h = v_h([\ln(H/z_0)/\ln(h/z_0)]*[\ln(h/0{,}05)/\ln(H/0{,}05)]-1)$$

where H is the hub height, h is 10 m and z_0 is the roughness length corresponding to a roughness class (see Chapter 3). In WindPRO, a general roughness class must be chosen for the calculation site.

If the distance between the receptor and the WTG is more than 1000 m, a different method is employed using octave-divided noise data. The noise level at the receptor is then calculated as:

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

Here the damping ΔL_a is calculated as:

$$\Delta L_a = 10*\log(\Sigma 10^{(Li+Ai)/10}) – 10*\log(\Sigma 10^{(Li+Ai-r*ai)/10})$$

where Li is the measured octave-band value and Ai is the A-weighting at the appropriate frequency.

r is the distance from the receptor to the WTG.

If no octave-divided data exists for the WTG, the calculation yields no result. This is true both for noise receptors and for the noise iso-line map.

Swedish, Jan 2002, Water

For the calculation of noise propagation over water surfaces, the Swedish guidelines recommends using a different formula.

$$L_A = L_{WA,corr} – 8 – 20*\log(r) - \Delta L_a + 10*\log(r/200)$$

where:

$$\Delta L_a = 10*\log(\Sigma 10^{(Li+Ai)/10}) – 10*\log(\Sigma 10^{(Li+Ai-r*ai)/10})$$

Thus octave-divided data is also required for calculation of noise emissions over water surfaces.

If no octave-divided data exists for the WTG, this calculation cannot be used (returns no values).

Swedish guideline, 2009.

The Swedish noise codes 2009 are arbitrarily dated as the Swedish Guideline “Ljud från Vindkraftverk” has been gradually updated over time. The changes referred to here are from 2009, 2010 and 2011. The latest are only available from the homepage of Naturvårdsverket:
http://www.naturvardsverket.se/sv/Start/Verksamheter-med-miljopaverkan/Buller/Vindkraft/Matning-och-berakning-av-ljud-fran-vindkraft/Berakningar-av-vindkraftsljud/

Compared to the original 2002 guideline there are three significant differences

1. Roughness correction has been abolished. The Swedish guideline has reverted to the standard IEC wind profile of 0,05 m. That means that source noise levels at 10 m height wind speed can be used directly in WindPRO if they are valid for the hub height of the turbine. There is no need to set a

roughness class anymore and therefore no controversy concerning the k value (noise with wind speed gradient)

2. Revised calculation of noise damping over sea. The calculation is now a three phase calculation
   a. Up to 1000 m offshore basic onshore calculation is used (see 2002 codes)
   b. Beyond 1000 m a revised offshore formula is used:
      LA = LWA – 8 -20 log(r) – ΔLa + 10 log (r/1000)
   c. At the transistion between land and water the formula change to the ordinary land formula >1000m.

   This basically means that noise level is calculated on the beach and then in a second step is calculated at the receptor.

3. It is allowed to replace the described calculation method with a NORD2000 calculation (see relevant chapter)

Norwegian 2012 guideline

The Norwegian 2012 guideline is described in Miljødirektoratet Veileder M-128 – 2014: Veileder til retningslinje for behandling av støy i arealplanlegging (T-1442/2012).

While describing a method for adapting the source noise level L_{WA} to the actual roughness it is suggested and indeed preferred to simply use the maximum noise level of the turbine as source noise level.

The propagation model is a very close adaption of the Swedish model except for the fact that only seven octaves are used (8000 Hz is omitted).

Noise calculation over land

For distances up to 1000 m from the turbine the formula used is:

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

Where r is noise distance and LwA,corr is the max noise level.

Distance above 1000m

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

Here the damping ΔL_a is calculated as:

$$\Delta L_a = 10*\log(\Sigma 10^{(Li+Ai)/10}) - 10*\log(\Sigma 10^{(Li+Ai-r*ai)/10})$$

where Li is the measured octave-band value and Ai is the A-weighting at the appropriate frequency.

Ai is air absorption

Frekvens 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

It is possible to enter custom values for air absorption as the guideline suggest that seasonal values can be used.

Noise calculation over water

Again the model is almost a copy of the Swedish codes.

Distance from turbine <700m

The land model is used:

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

For distances over 700 m:

$$L_A = L_{WA,corr} – 8 – 20*\log(r) - \Delta L_a + 10*\log(r/700)$$

where:

$$\Delta L_a = 10*\log(\Sigma 10^{(Li+Ai)/10}) – 10*\log(\Sigma 10^{(Li+Ai-r*ai)/10})$$

If the receptor is located on land and the noise propagates first over water and then over land then the following procedure is used:

The model for water is used until the shore and a value for LAshoreline is calculated here.

Then the formula on land >1000 m is applied with LAshoreline replacing LWA,korr and 20log(r/rshoreline replacing 20log(r).

Calculation of Lden.

L_{den} is a weighted average of the noise over a period of time. The den label refers to day-evening-night and means that the noise is calculated independently for each period with special penalties for evening and night.

The noise for each period is calculated as L_{eq24}, which corresponds to the standard L_{WA} noise calculated normally in WindPRO. The formula for converting L_{eq24} noise to L_{den} is given in the formula below, adapted from Statens Forurensningstilsyn's spreadsheet lden_lekv_driftstid.xls.

$$L_{den} = 10 * \log\left(\frac{10^{\frac{L_{day,y}}{10}} * t_{day} + 10^{\frac{L_{eve,y}+P_{eve}}{10}} * t_{eve} + 10^{\frac{L_{night,y}+P_{night}}{10}} * t_{night}}{24}\right)$$

Where t gives the number of hours in the periods day, evening and night respectively. Typical values are 12, 4 and 8 hours

P is the penalty for evening and night respectively. Typical values are 5 and 10 dB.

$L_{day,y}$ is the annual average of daytime noise given as:

$$L_{day,y} = 10 * \log\left(\frac{10^{\frac{L_{day,d}}{10}} * O_y}{365}\right)$$

Where O_y is the operation days per year. This value is set to 290 days in the former Norwegian guideline and 365 in the 2012 guideline.

$L_{day,d}$ is the daily average of noise. Typically this will the same as L_{eq24} or L_{WA}. If the turbine is stopped parts of the day $L_{day,d}$ can be calculated as:

$$L_{day,d} = 10 * \log\left(\frac{10^{\frac{L_{eq24,day}}{10}} * t_{day}}{12}\right)$$

L_{eve} and L_{night} are calculated the same way.

$$L_{eve,y} = 10 * \log\left(\frac{10^{\frac{L_{eve,d}}{10}} * O_y}{365}\right)$$

$$L_{night,y} = 10 * \log\left(\frac{10^{\frac{L_{night,d}}{10}} * O_y}{365}\right)$$

$$L_{eve,d} = 10 * \log\left(\frac{10^{\frac{L_{eq24,eve}}{10}} * t_{eve}}{4}\right)$$

$$L_{night,d} = 10 * \log\left(\frac{10^{\frac{L_{eq24,night}}{10}} * t_{night}}{8}\right)$$

Dutch, 1999.

The Dutch, 1999 method follows the guidelines described in “Handleiding meten en rekenen Industrielawaai” from Ministerie van VROM, Zoetemeer, 1999, ISBN 90 422 0232 7.

The section dealing specifically with noise from WTGs is Module C, method II.8.

Theoretical background

The basic formula is:

$$L_i = L_{WR} - \Sigma D$$

Where L_i is the noise level at the receptor

L_{WR} is the noise level at the WTG

And ΣD is:

$$\Sigma D = D_{geo} + D_{lucht} + D_{refl} + D_{scherm} + D_{veg} + D_{terrein} + D_{boden} + D_{huis}$$

Which are the different damping elements.

In this method octave-divided values are used. Where these are not available, a source noise emission value is used.

In WindPRO the following assumptions are made:

- The noise receptor point is 5 m above ground
- No shelter effects or reflection of noise
- No significant noise levels at low frequencies (31,5 and 63 Hz)
- The distance between the receptor point and the WTG exceeds 1,5 times the rotor diameter.

D_{geo} is the geometrical damping and is calculated as:

$$D_{geo} = 20*\log(d)+11$$

where d is the distance from the WTG to the receptor.

D_{lucht} is the damping due to air absorption. When using octave-divided data, a specific air absorption coefficient is used for each frequency. If only a source emission value is used, D_{lucht} is calculated as:

$$D_{lucht} = 0,002*d$$

D_{refl} is the damping from reflection. This is set to 0 in WindPRO.

D_{scherm} is damping from shielding. This is set to 0 in WindPRO.

D_{veg} is damping from vegetation. This is set to 0 in WindPRO.

$D_{terrein}$ is damping from industrial terrain. This is set to 0 in WindPRO.

D_{bodem} is damping from hardness (or softness) of the ground. It is possible in WindPRO to set the acoustic hardness B of the terrain with a value from 0 (hard terrain) to –3 (soft terrain, farmland with some trees). D_{bodem} is then calculated as:

$$D_{bodem} = -2 – B$$

D_{huis} is special case damping from houses. This is set to 0 in WindPRO

Dutch, 1999.

Dutch, 2011.

The 2010 Dutch noise code is described in "Reken- en meetvoorscrift Windturbines, 2/2-2010"

The Dutch codes require the calculation of an Lden value for each receptor.

The Lden value has the formula

$$L_{den} = 10 \lg \left(\frac{12}{24} 10^{\frac{L_{dag}}{10}} + \frac{4}{24} 10^{\frac{L_{avond}+5}{10}} + \frac{8}{24} 10^{\frac{L_{nacht}+10}{10}} \right)$$

The Leq noise value is calculated independently for the three situations: day, evening and night (L_{dag}, L_{avond}, L_{nacht}). In each case the formula is:

$$L_{eq} = 10 \lg \sum_{i=1}^{9} \sum_{n=1}^{N} 10^{L_{eq,i,n}/10}$$

"I" is the 8 octave bands,

"n" is the number of turbines.

The noise at each octave band is calculated as:

$$L_{eq,i,n} = L_E - D_{geo} - D_{lucht} - D_{ref} - D_{scherm} - D_{veg} - D_{terrein} - D_{bodem} - C_{meteo}, \text{ met}$$

Dref, Dscherm, Dveg and Dterrein can all be ignored.

Le

Le is the source noise emission. This is different from most other codes.

The Le is the average noise emission from the turbine. The formula is the below:

$$L_E = 10\lg\left(\sum_{j=V_{ci}}^{V_{co}}\left(\frac{U_j}{100}10^{L_{w,i,j}/10}\right)\right) + \Delta L$$

The summation is done for each wind speed bin from Vci (cut-in) to Vco (cut-out). At rated power it is assumed that the noise level does not change.

Uj is the frequency of the particular wind speed.

ΔL is a direction component, which is usually not available and is therefore set to 0.

From this it is clear that a weibull distribution is required at hub height for each turbine. This is done automatically with reference to https://www.mp.nl/actueel/nieuwe-windgegevens-voor-het-berekenen-van-geluid-van-windturbines-beschikbaar. The codes recommend to use this resource.

Dgeo

This is the geometric damping. It is identical to the ISO 9613-2 standard.

$$D_{geo} = 10 \lg(4\pi r_i^2) = 20 \lg r_i + 11,$$

"r" is distance from turbine to receptor.

Dlucht

This is the air absorption. The formula is the same as in ISO 9613-2 but the damping's are different.

$$D_{lucht} = a_{lu}(f)\, r_i$$

middenfrequentie octaafbanden [Hz]	31,5	63	125	250	500	1000	2000	4000	8000
a_{lu} [dB/m]	2.10^{-5}	7.10^{-5}	$2,5.10^{-4}$	$7,6.10^{-4}$	$1,6.10^{-3}$	$2,9.10^{-3}$	$6,2.10^{-3}$	$1,9.10^{-2}$	$6,7.10^{-2}$

Dbodem

This is the ground absorption. This is similar to the general ground attenuation of the ISO standard.

The regions are defined in the same way:

Near area:

$r_b = 30\ h_b$ als $r_i \geq h_b$

$r_b = r_i$ als $r_i < 30\ h_b$

Remote area:

$r_o = 30\ h_o$ als $r_i \geq h_o$

$r_o = r_i$ als $r_i < 30\ h_o$

Middle area:

Everything in between.

B is the ground porosity: B=1 absorbing, B=0 hard.

In WindPRO a universal ground porosity is selected by the user to cover all three regions for all turbine receptor couples.

The three components are added:

$$D_{bodem} = D_{b,br} + D_{b,ont} + D_{b,mid}$$

Unfortunately the dampings in each frequency is different from ISO 9613-2.

Middenfrequentie octaafband [Hz]	$D_{b,tr}$ of $D_{b,ont}$ [dB]
31,5	-3
63	-3
125	$-1 + B_b\ (a(h) + 1)$
250	$-1 + B_b\ (b(h) + 1)$
500	$-1 + B_b\ (c(h) + 1)$
1000	$-1 + B_b\ (d(h) + 1)$
2000	$-1 + B_b$
4000	$-1 + B_b$
8000	$-1 + B_b$
met	$a(h) = 3{,}0e^{-0{,}12(h-5)^2}(1 - e^{-r_i/50}) + 5{,}7e^{-0{,}09h^2}(1 - e^{-2{,}8\,10^{-6} r_i^2})$
	$b(h) = 8{,}6e^{-0{,}09h^2}(1 - e^{-r_i/50})$
	$c(h) = 14{,}0e^{-0{,}46h^2}(1 - e^{-r_i/50})$
	$d(h) = 5{,}0e^{-0{,}90h^2}(1 - e^{-r_i/50})$

h is hub height.

The Dmid is calculated as

Middenfrequentie octaafband [Hz]	$D_{b,mid}$ [dB]
31,5 en 63	$-3\,m$
125 en hoger	$+3\,m\ (B_m - 1)$
met $m = 0$	als $r_i \leq 30\ (h_b + h_o)$
$m = 1 - 30\ (h_b + h_o)/r_i$	als $r_i > 30\ (h_b + h_o)$

Cmeteo

Cmet is defined as

$$C_{meteo} = 0 \qquad \text{voor } r \leq 10(h_b+h_o)$$

$$C_{meteo} = 5\left[1-10\left(\frac{h_b+h_o}{r}\right)\right]\left[1-\frac{1}{2}\cos(\beta-45^\circ)\right] \qquad \text{voor } r > 10(h_b+h_o)\text{, met}$$

hb is hub height, ho is receptor height.

Beta is the angle from downwind from turbine to receptor.

Finnish guideline 2014

The Finish code (Ympäristöhallinnon Ohjeita 2, 2014, Modellering av buller från vindkraftverk) set up two phases of noise calculation. During the first the ISO 9613-2 model can be used, while during the second phase NORD2000 is required.

The first phase is divided into a standard noise calculation and a low frequency noise calculation.

Standard noise calculation

The standard noise calculation follows standard ISO 9613-2 principles. The only significant departure is a 2 dB penalty if the height difference between base of turbine and receptor is larger than 60 m.

Low frequency calculation

The calculation of low frequency noise is done by adding together contributions from each 1/3 octave in the range of 20 to 200 Hz.

Each frequency is calculated as:

Lp = LW – 20 dB • log10 (d1 / 1 m) – 11 dB + Agr – Aatm• d2

where

Lp is the 1/3 octave noise at the receptor.

LW is the 1/3 octave source noise of the turbine.

d1 is the distance from turbine hub to receptor [m].

Agr is frequency specific ground attenuation

Aatm is atmospheric attenuation at temperature 15 C° and 70 % relative humidity [dB/km]

d2 is the distance from turbine hub to receptor [km].

The attenuations are given in below table. Note a different set of ground attenuations for offshore.

Frekvens [Hz]	Markytans förstärkning A_{gr} [dB]	Vattenområdets förstärkning A_{gr} [dB]	Atmosfärens dämpning A_{atm} [dB/km]
20	5.6	6.0	0.0
25	5.4	6.0	0.02
31.5	5.2	5.9	0.03
40	5.0	5.9	0.05
50	4.7	5.8	0.07
63	4.3	5.7	0.11
80	3.7	5.5	0.16
100	3.0	5.2	0.25
125	1.8	4.7	0.38
160	0.0	4.0	0.57
200	0.0	3.0	0.82

There is a 200 m interpolation zone at coastline equivalent to Danish codes.

Low frequency noise in Finland is calculated as indoor noise, but fails to recommend noise insulation damping values. Instead the noise consultant must use their own values. In WindPRO it is possible to use the Danish 60% and 90% fractile values. Noise insulation damping is applied similar to the Danish model.