Investigation to determine the distance-dependency of C_{met} for sources in large height, e. g. wind turbines.

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The meteorological correction C_{met} for the calculation of equivalent long-term sound pressure levels

Due to the current development with regard to the preference of renewable energies and the necessary balance of measures for climate- as well as noise-protection, the inclusion of the A-weighted equivalent long-term sound pressure levels for wind turbines is becoming increasingly important. While the receiver level at night-time related to the rated power of a wind turbine and its comparison with the accepted limiting values is a kind of worst-case consideration, the A-weighted equivalent long-term sound pressure level $L_{AT}(LT)$ includes the frequency of occurrence and the timely variation during all nights of a year and can thus lead to a "fairer" distribution of the unavoidable noise impact regardless of known or suspected effect references.

According to ISO 9613-2:1996 [1], the A-weighted equivalent long-term sound pressure level $L_{AT}(LT)$ caused by a source is calculated by subtracting a meteorological correction C_{met} from the sound pressure level $L_{AT}(DW)$ that is based on propagation-favorable downwind and calculated according to the standard. This correction is defined by a formula that can be written as

$$C_{\mathrm{met}} = 0 \qquad for\ d_{\mathrm{p}} \le d_{p,0}$$

$$C_{\mathrm{met}} = C_0\left[1 - d_{p,0}/d_{\mathrm{p}}\right] \qquad for\ d_{\mathrm{p}} > d_{\mathrm{p},0} \qquad (1)$$

C_0 is a sound pressure level correction in dB, which indicates for longer distances the reduction of the level due to weakening of the sound during propagation due to different temperature and wind conditions. If the distance between the sound source and the receiver is smaller than a minimum distance – here referred to as $d_{p,0}$ – no deviation of the receiver level from the down-wind related level $L_{AT}(DW)$ is assumed even in the case of headwinds. Only at a greater distance does the correction C_{met} increase from 0 dB to the value of C_0 in dB due to the bracketed expression in equation (1) and its increase from 0 to 1.

According to the interpretation underlying the following detailed analysis, this attenuation results from the formation of a sound shadow, which is created with sound propagation in upwind direction due to the gradient of the horizontal wind speed directed in a positive z-direction. According to ISO 9613-2, for an average height of source and receiver up to 30 m, this minimum distance is defined by equation (2).

$$d_{p,0} = 10 \cdot (h_s + h_r) \qquad (2)$$

Since the application of ISO 9613-2 for the calculation of the sound pressure levels caused by wind turbines has proven its worth in recent years and this method is therefore used in most countries to predict noise caused by wind turbines, this experience was on request of ISO/ TC 43/SC 1 included as an informative annex in the draft ISO/CD 9613-2:2022 [2].

Investigation of the location of the acoustic shadow zone with sources in large height

However, there were often doubts in expert circles as to whether the dependencies postulated by equations (1) and (2) for lower altitudes can also be assumed for such high sound sources due to the gradients of the horizontal speed of sound, which are considerably dependent on the height above ground and the associated height-dependent curvature of the sound rays. Therefore, the author carried out an investigation of this dependency of the distance of the acoustic shadow zone in upwind direction on the source height with regard to sound sources in larger heights. To include the assessment of the equivalent long-term sound pressure levels caused by wind turbines, the night-time from 22°° to 6°° was taken as a basis. Figures 1 and 2 are a try to explain the physical principles behind the presented approach.

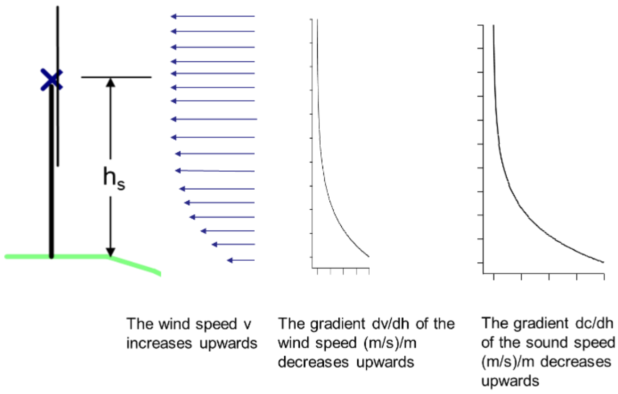

Figure 1:
On the left the acoustic model of the wind turbine with source height h_s and the wind speed increasing with the height above ground, in the middle the gradient of the horizontal wind speed decreasing with the height, on the right the gradient of the speed of sound also decreasing with the height above ground. *Grafik:Author*

From the wind speed gradients shown here and the temperature gradients, an altitude profile of the sound velocity gradient representative for the nights of a year was derived from measured values in [3] and proposed for normative purposes. The mean function is described by equation (3), where ∂c/∂h is the speed of sound gradient in s^{-1} and h is the height in meters.

$$\frac{\partial c}{\partial h} = 0{,}2 \cdot \exp\left(-0{,}03 \cdot h\right) \ \ [\mathrm{s}^{-1}] \qquad (3)$$

With this height dependency shown in Figure 2 on the left, the height-dependent radius of curvature of the sound rays is determined and used for the calculation of the ray geometry according to the method shown schematically in Figure 2 on the right.

Starting point is a ray-path from the source position P_1, which encloses the angle φ with the horizontal. From the diagram on the left the radius of curvature is determined based on the height -

curved upwards for upwind and curved downwards for downwind propagation. With the coordinates of P_1 and the slope known with angle φ, the geometry of the arc is determined and its intersection with a horizontal at a height reduced by dz can be determined. Thus, the position of P_2 is fixed and the following arc can be calculated using the link-condition that the slope of incoming and continuing ray path at each point P are equal.

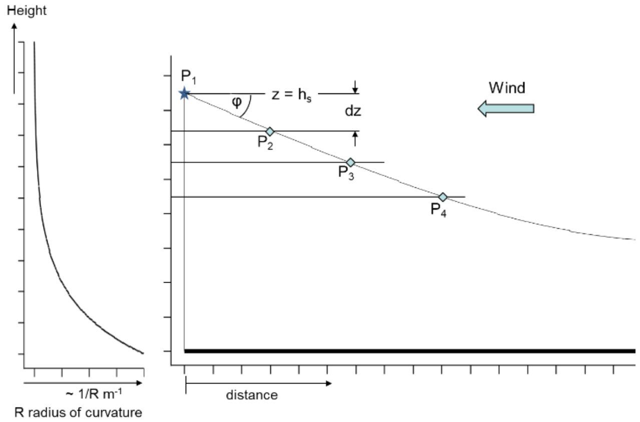

Figure 2: On the left the diagram with the relationship between the height and the reciprocal value of the radius of curvature and on the right the piecemeal construction or calculation of the ray emitted at an angle φ. *Grafik:Author*

This method, which is described here only principally, allows any functional dependencies of the sound speed gradient with height to be taken into account by a sufficiently fine subdivision in z-direction. For the underlying study, the vertical division was carried out with values dz from 0.25m to 1m. In order to determine the shadow-boundaries geometrically with the necessary precision, the ray paths were calculated with a starting angle staggered in 1/10 degree.
As an example, Figure 3 shows a bundle of rays calculated for downwind, Figure 4 for upwind with a source height of 150 m. The receiver R shown in each case is located in a distance of 2000 m at a height of 4m above the ground.

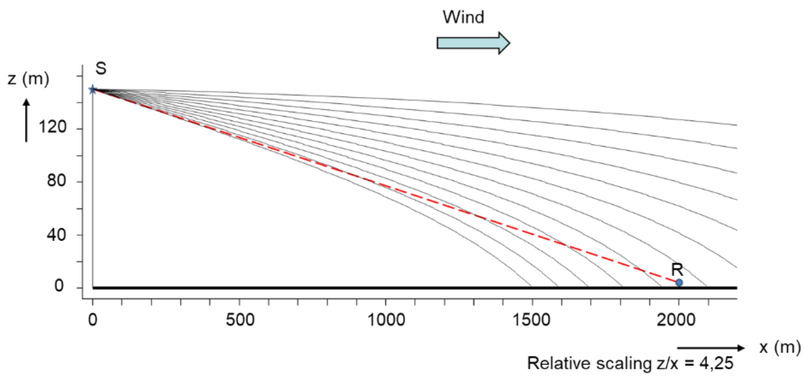

Figure 3: The paths of rays for propagation downwind based on a source height of 150m. *Grafik:Author*

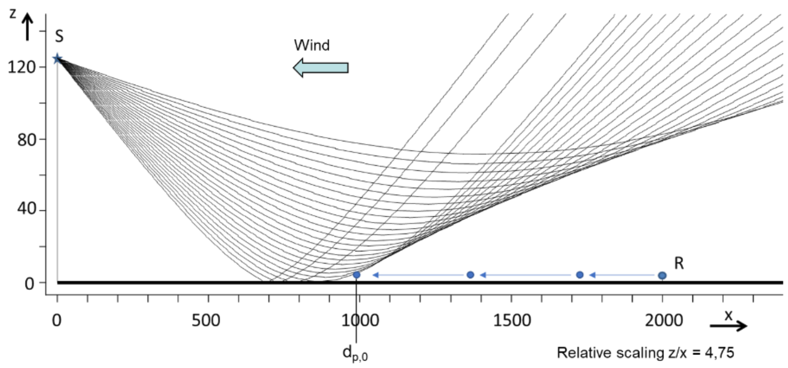

Figure 4: The paths of rays for propagation upwind based on a source height of 150m. *Grafik:Author*

The limit distance $d_{p,0}$ is further interpreted as the distance at which the receiver is located exactly on the edge of the acoustic shadow-zone – at larger distances there is an attenuation that increases from 0 to the value given by C_0. Therefore, for different hub heights typical of wind turbines and for several receiver heights, the ray bundle was calculated as shown in Figure 4 and thus the dependence of the distance $d_{p,0}$ on these heights was determined. Figures 5 to 8 show the rays for sound propagating upwind for some typical source heights and for a receiver height of 4 m.

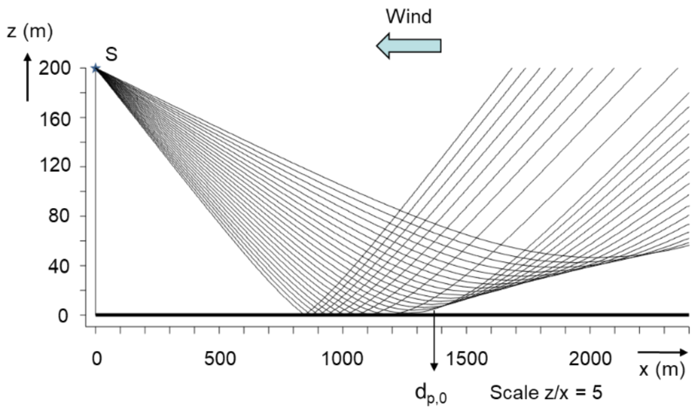

Figure 5: The ray-paths in upwind-direction with source-height 200m → $d_{p,0}$ with 1375 m. *Grafik:Author*

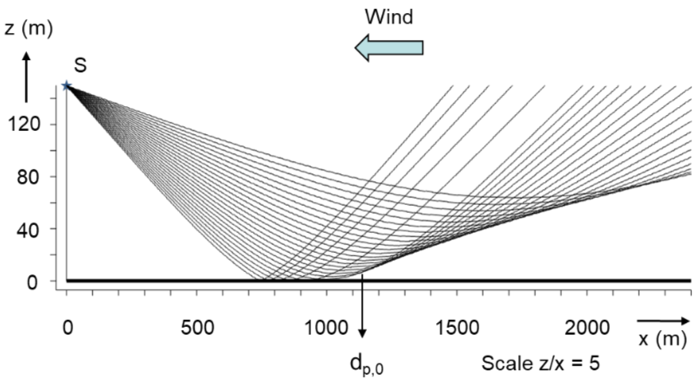

Figure 6: The ray-paths in upwind-direction with source-height 150m → $d_{p,0}$ with 1125 m. *Grafik:Author*

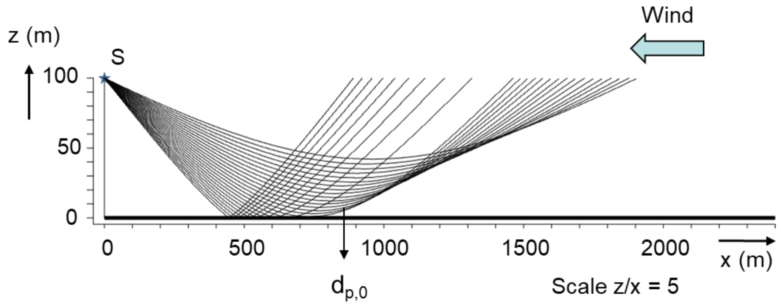

Figure 7: The ray-paths in upwind-direction with source-height 100m → $d_{p,0}$ with 875 m. *Grafik:Author*

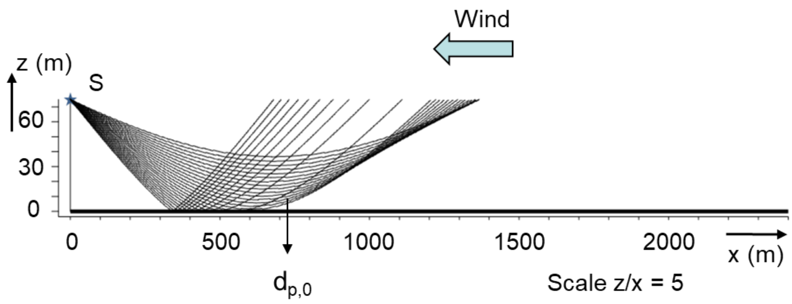

Figure 8: The ray-paths in upwind-direction with source-height 75m → $d_{p,0}$ with 725 m. *Grafik:Author*

The same scaling and relation z/x was chosen for figures 5 to 8. The calculation leads to an approximately linear dependence of the distance of the edge of the shadow-zone from the height of the sound source h_s in the range of 50m to 200m – it can be described with equation (4) in very good approximation.

$$d_{p,0} = 300m + 5{,}5 \cdot h_s \quad for\ h_s \geq 50m \qquad (4)$$

Based on the results of this study, equation (4) should be used in the formalism of equation (1) when determining the meteorological correction C_{met} for sound sources with a height above 50 m. The diagram Figure 9 shows that when these findings are taken into account, C_{met} becomes relevant for high sources even for smaller distances than when applying the distance formula of ISO 9613-2. The evaluation of the ray paths has also shown that the influence of the receiver height h_r no longer plays a role with the considered large values of the source height h_s. With sources in large height the receiver height h_r is therefore not a relevant parameter of the determination equation (4).

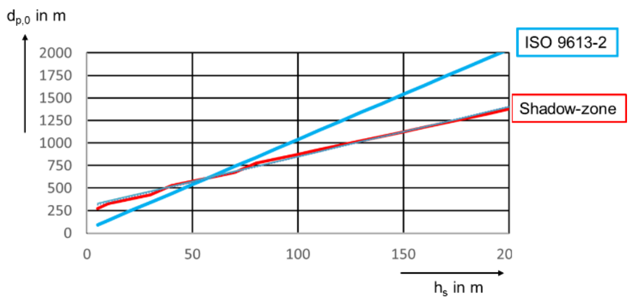

Figure 9: The dependence of the beginning of a meteorologically induced level reduction determined with the ISO distance formula and the shadow limit. *Grafik:Author*

As described, these results are interpreted in such a way that the distance $d_{p,0}$ determines the transition into the acoustic shadow at its boundary – for the levels in the acoustic shadow, which is defined by scattering at turbulences and diffraction processes in the impact zone, no further knowledge is available and therefore the distance-dependent formalism equation (1) is retained for this attenuation area.

These results were derived with mathematical methods from physical principles based on measured temperature- and windspeed-profiles. Even if the distance-equation according to (1) shall not be modified the results presented provide evidence that the description of the distance dependency of C_{met} with the formalism of equation (1) – or in paragraph 8 in [2] – holds principally also for sources in large heights above ground, e. g. wind turbines.

Literature

/1/ ISO 9613-2:1996, Acoustics – Attenuation of sound during propagation outdoors – Part 2: General method of calculation

/2/ ISO/CD 9613-2:2022 (E), Acoustics – Attenuation of sound during propagation outdoors – Part 2: General method of calculation

/3/ Vogelsang, B. M., Hirsch K.-W., Probst W., Zur meteorologischen Korrektur C_{met} in der VDI 4101 – Blatt 2: Windkraftanlagen, DAGA 2022, Stuttgart