UPPSALA UNIVERSITET

Noise analysis - Energipark Tjele

Prof. Ken Mattsson

November 11, 2025

Executive Summary

On behalf of the association *Borgergruppen*, we have conducted a comprehensive noise dispersion analysis of the area surrounding the proposed wind farm at *Energipark Tjele* by *BioCirc Group ApS*. The noise models currently used in environmental permitting—*Nord2000* and *ISO 9613-2*—were never intended for wind turbine assessments. They exclude infrasound and cannot simulate how low-frequency, pulsing noise actually propagates through the atmosphere and terrain. As a result, they systematically underestimate real sound levels, particularly under nighttime and inversion conditions. Similarly, using A-weighted levels (dBA) for wind turbine noise ignores the dominant low-frequency and infrasonic components that are most likely to influence health and well-being. To obtain accurate and reliable results, sound calculations and measurements must therefore include the full frequency range (down to at least 0.1 Hz) and use physically based models such as *SoundSim360*, which resolve the complete three-dimensional sound field without user-adjusted parameters. *Clarification: The information presented in this report is derived from research conducted by myself and my research group at Uppsala University and published in Applied Acoustics [30]. Recommendations regarding noise measurement, noise assessment, and limit values are based on our research findings, the prevailing body of knowledge in the field, and my professional experience. While Uppsala University supports this research, the recommendations and interpretations presented herein are my own.*

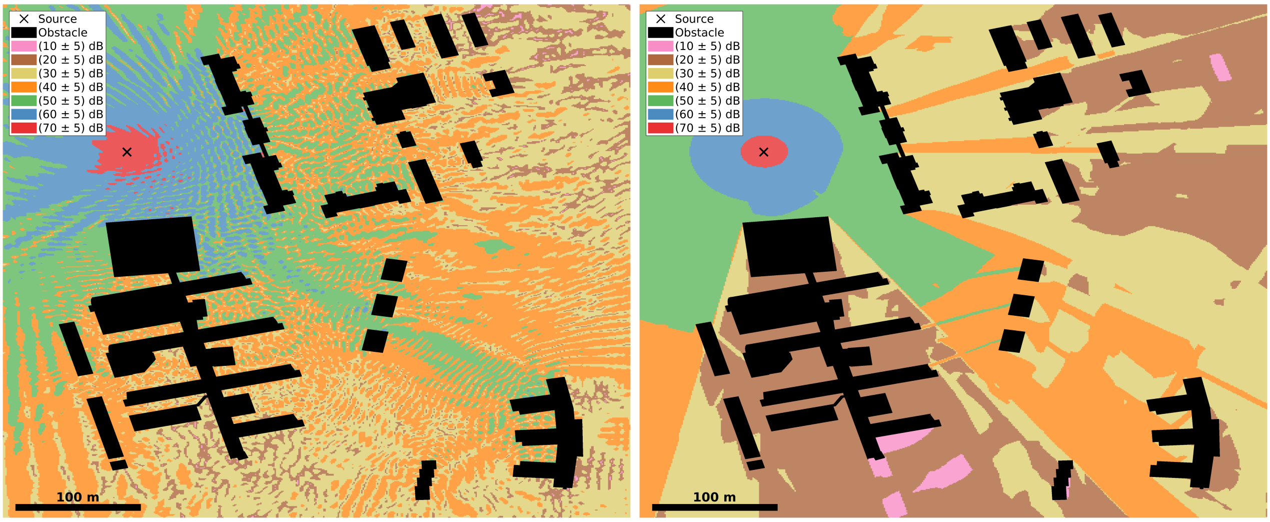
High-fidelity modeling of wind turbine noise using *SoundSim360*

Drawing on detailed measurements from several wind farms—including Målarberget and Lervik—we have calibrated a high-precision computational tool, **SoundSim360** [30], capable of simulating sound propagation over complex terrain and across the full frequency spectrum, including infrasound (frequencies below 20 Hz).

Sound propagation over large distances is governed by a range of interacting physical processes, including atmospheric stratification, topography, ground impedance, source geometry, and spectral content. Accurate modeling must therefore capture key physical phenomena such as diffraction, refraction, geometric scattering, absorption, transmission, reflection, and interference. If these processes are not represented correctly, noise dispersion cannot be reliably simulated. *SoundSim360* addresses these challenges by solving the full three-dimensional acoustic wave equation, incorporating real atmospheric profiles and high-resolution terrain data, with no user-adjustable “free parameters.” This ensures that simulation accuracy depends solely on the correctness of the physical input data, not on subjective calibration.

Over the past two decades, our research group has developed a suite of advanced numerical methods specifically for high-fidelity sound propagation modeling (see, e.g., [25, 34, 26, 31, 32, 24, 27, 3, 23, 28, 42, 29, 35, 20, 2, 49, 48, 33, 39]). These methods form the foundation of *SoundSim360*, which is implemented for efficient execution on modern high-performance graphics processors (GPUs), enabling detailed full-wave simulations of large acoustic domains. For details about SoundSim360 we refer to [30].

In contrast, the most widely used model for wind turbine noise prediction today is *Nord2000* [1], commonly implemented in commercial software such as *SoundPlan* and *windPRO*. *Nord2000* is fundamentally a ray-tracing model based on the assumption of high-frequency sound propagation. As a two-dimensional approximation, it cannot accurately represent low-frequency propagation, nor can it model interference between multiple sources. Its treatment of diffraction is also limited, which is particularly problematic in hilly terrain or near buildings and barriers. Previous work has demonstrated that *Nord2000* yields unreliable results in complex terrain [3]. To mitigate these shortcomings, the model introduces numerous empirical “tuning” parameters, making results heavily dependent on user settings and assumptions. Several independent studies, including those by Conny Larsson [17], show that *Nord2000* systematically underestimates measured sound levels by 5–7 dBA at approximately 1 km distance. Even more simplified models, such as the *ISO 9613-2* standard [10], generally produce similar or less accurate results.



(a) SoundSim360 (b) Nord2000

Figure 1: Low-frequency (31.5 Hz) sound simulation at Polacksbacken (105 dB point source at ×, 10 m above ground), comparing (a) SoundSim360 and (b) Nord2000. Shown are sound pressure levels 2 m above ground. Nord2000 cannot accurately model edge diffraction at low frequencies.

All of these traditional (simplified) models face inherent difficulties when simulating low-frequency or infrasonic sound, particularly over long distances and in non-flat terrain. Their reliance on user-adjustable correction factors introduces substantial uncertainty, which increases with turbine number, terrain complexity, and propagation distance. Because low-frequency and infrasonic components are only weakly attenuated by air and ground, they can travel many kilometers, making these modeling limitations especially critical.

For a computational tool to be broadly useful to the scientific and engineering community, it must satisfy three core criteria: 1) the underlying methodology must be rigorously validated and transparently documented; 2) results must be clear, interpretable, and visually accessible; and 3) the tool must be robust and user-independent, avoiding ad hoc parameter tuning.

These principles define the design philosophy of *SoundSim360*. Unlike conventional ray-tracing models such as *Nord2000*, which depend on empirical adjustments, *SoundSim360* directly solves the full three-dimensional acoustic wave equation, thereby eliminating the main sources of uncertainty. The four key deficiencies of ray-tracing approaches that our method overcomes are: 1) inadequate treatment of low-frequency sound (below 200 Hz), 2) difficulty in resolving complex geometries, 3) limited capacity to simulate sound transmission through structures, and 4) inability to capture transient or amplitude-modulated sources.

As an illustrative example, Figure 1 presents a comparison between *SoundSim360* and *Nord2000* (as implemented in *SoundPlan 9.1*) for a 31.5 Hz monopole source located at Polacksbacken, Uppsala University. The source is positioned 10 m above ground with a sound power level of 105 dB. Terrain and building data were obtained from Lantmäteriet [16], and the ground was modeled as a hard surface (impedance class H in *Nord2000*). All other *Nord2000* parameters were kept at default values. The resulting sound pressure level (SPL) distribution at 2 m height is shown for both models. The computational domain for *SoundSim360* spans 500 m × 600 m × 250 m. Significant discrepancies are evident in the shadow regions behind buildings, where *Nord2000* systematically underestimates SPL by approximately 20–30 dB. These deviations reflect the fundamental limitations of ray-tracing methods in the low-frequency regime and highlight the necessity of full-wave simulation approaches for accurate modeling of wind turbine noise.

Amplitude Modulation (AM) in Wind Turbine Noise

Numerous studies have demonstrated that atmospheric conditions and ground properties cause significant variations in noise levels—up to 20 dBA at a distance of 1 km from a wind farm [17, 38, 14]. Long-term measurements by Conny Larsson (2014) [17, 38] confirmed that these variations are most pronounced during evenings and nights, especially under snow-covered conditions.

One of the most perceptually disturbing characteristics of wind turbine noise is *amplitude modulation* (AM)—the periodic fluctuation in sound level commonly perceived as a "swishing" or "thumping" noise. The occurrence and intensity of AM are strongly dependent on propagation path and meteorological conditions, particularly during nighttime temperature inversions when sound refraction increases coherence between multiple turbine sources. This modulation can exceed 10 dB in peak-to-trough variation under certain atmospheric conditions. Measurements indicate that AM events are most frequent during stable atmospheric conditions—typically in the evening and at night—and can be detected over distances exceeding 10 km [37]. Long-term observations by Conny Larsson [17, 38] showed that amplitude-modulated noise occurred approximately 19% of the time at a 1 km distance from a wind farm, with the highest occurrence during winter evenings and under snow cover.

From a psychoacoustic perspective, AM is more annoying than continuous broadband noise of the same average SPL [46]. The slow temporal fluctuation in loudness increases detectability and prevents habituation, especially in quiet rural environments. This means that conventional dBA-based assessments, which average energy over time, substantially underestimate the perceived impact of AM noise. New metrics, such as modulation depth and modulation frequency weighting, have been proposed to better represent human annoyance and sleep disturbance caused by wind turbine AM noise.

It is also well known that annoyance increases with increasing energy content in the low-frequency range [46]. This means that a sound level of 40 dBA with a higher proportion of low-frequency content is considerably more annoying than 40 dBA with predominantly high-frequency content [53].

Seismic Vibrations Generated by Wind Turbines

There is growing concern regarding seismic vibrations generated by wind turbines. Unlike airborne acoustic waves, seismic waves propagate through the ground and may travel several kilometers depending on local geological conditions. These low-frequency ground vibrations can interact with airborne acoustic waves, potentially creating combined disturbance effects that are not yet fully understood. Despite the relevance of this phenomenon, empirical data on seismic emissions from wind turbines remain scarce.

However, at least one study [12] has investigated low-frequency vibration propagation and reported the following key findings: *(i)* most seismic waves generated by wind turbines operations propagate as Rayleigh waves; *(ii)* these microseismic waves can influence measurements at seismological centers up to 15 km away from a wind farm; *(iii)* the strongest disturbances occur within the 5–10 Hz frequency range; and *(iv)* turbine operation under strong winds can produce microseismic vibrations capable of causing perceptible annoyance to nearby residents.

Further research is needed to fully understand the implications of such vibrations. In particular, indoor measurements of low-frequency vibrations are important, as these can couple into the human body as body-conducted sound—effectively perceived as infrasound. Accurately modeling the real impact of ground-borne seismic waves would require advanced numerical techniques, such as full-waveform modeling, finite-difference, or finite-element methods, combined with high-resolution seismic data collected under controlled conditions. To our knowledge, no such comprehensive study has yet been performed.

Our present work therefore focuses solely on airborne acoustic waves and does not include seismic coupling effects. Depending on future research funding, we hope to address this important issue in subsequent studies.

Why Reported Sound Power Levels from the Wind Industry Are Not Reliable

The sound power levels (L_w) reported by the wind industry are often treated as reference data in environmental impact assessments and regulatory noise calculations. However, several factors make these values unreliable for accurate prediction of real-world sound exposure, particularly in the low-frequency and infrasonic ranges.

First, the sound power levels provided by turbine manufacturers are typically determined under highly controlled test conditions specified by standards such as IEC 61400-11. These measurements are performed at limited distances (usually 100–200 m) and under near-ideal meteorological conditions, with flat terrain, homogeneous ground impedance, and steady inflow turbulence. Such settings do not represent the complex, turbulent, and stratified atmospheric conditions encountered in actual wind farm operation, where refraction, interference, and ground reflection significantly modify the emitted sound field.

Second, the IEC standard prescribes the use of *A-weighted* levels (dBA), which heavily suppress low-frequency and infrasonic components—precisely the frequencies that dominate wind turbine noise at large distances. As a result, the reported values systematically underestimate the true acoustic energy output below 100 Hz. Manufacturers rarely publish unweighted or G-weighted spectra, making it impossible to assess infrasound contributions from public documentation.

Third, many wind turbine sound power measurements rely on short averaging times and exclude operating conditions with high turbulence or blade-tower interaction noise. Transient phenomena such as amplitude modulation (AM), wake interference, and partial stall events are thus excluded, even though they are the main contributors to the perceived annoyance and low-frequency pulsations experienced by nearby residents.

Fourth, in complex terrain or multi-turbine configurations, aerodynamic interaction between turbines can amplify low-frequency emissions due to constructive interference. These effects are not included in the manufacturer's declared sound power levels, which typically correspond to a single, isolated turbine operating under idealized conditions.

Finally, several independent measurement campaigns have demonstrated discrepancies between predicted and observed sound levels near wind farms, often exceeding 5–10 dB [17, 38, 14]. This systematic underestimation confirms that industry-provided source data are insufficient for accurate environmental noise assessments. To obtain reliable results, sound power levels should instead be derived from independent broadband and infrasonic field measurements conducted under representative atmospheric and operational conditions. In Figures 2 and 3, we compare the Nord2000 noise emission maps provided by the industry with SoundSim360 calculations based on real measurements from the Sötterfällan wind farm in early 2025.

Audible Sound Measurements

As an illustrative example of the unreliability of sound emission maps provided by the wind industry, we examine the Sötterfällan wind farm in Sweden, consisting of ten Vestas V136-3.45 MW wind turbines (hub height 190 m). Numerous A-weighted sound pressure level (dBA) measurements have been performed at this site.

The environmental impact statement commissioned by **Eolus Vind AB** is documented in **19-367-R1 Ljudemissionsmätning Sötterfällan**, prepared by the acoustics consultant **Akustikverkstan Konsult AB**. This report details the measurement locations and sound power levels (as specified by Vestas), and uses the *Nord2000* model to compute dBA noise emission maps, as shown in Figure 3.

On 5 January between 18:00 and 19:00 CET, two measurements were performed at locations **A** and **B**, both indicating sound pressure levels of approximately 60 dBA, as illustrated in Figure 2. Based on these measurements and the available atmospheric data, we solved the inverse problem to estimate the source sound power levels using *SoundSim360*, which yielded a value of 119.1 dBA at the time of measurement, whereas Vestas reports a value of 106.1 dBA.

The computed (simulated) dBA noise map for the region surrounding Sötterfällan, based on the two measured points, is presented in Figure 2. For completeness, we also include in Figure 2 the SoundSim360 simulation using the Vestas-specified sound power levels presented in Figure 3. In the SoundSim360 calculations, the atmospheric data correspond to 2025-01-05 at 18:00 CET (weather data obtained from the THREDDS Data Server). Soft ground surfaces are modeled as ordinary ground (Impedance Class E) and hard surfaces (water, asphalt, etc.) as fully reflecting (Impedance Class H), following the specifications in Nord2000 [1]. Atmospheric attenuation effects are incorporated in accordance with ISO 9613-1 [9].

In Figure 2, the dBA maps are shown as contour domains representing specific sound levels, including model uncertainty. For example, the red contour in the right subfigure (b) indicates the area where the sound level is 40 dBA ± 1.5 dBA (i.e., within the range 38.5–41.5 dBA). This uncertainty arises from parameter variations such as ground impedance, atmospheric attenuation, and interference patterns. We interpret all regions (in the measured simulation) within the red contour as approximately 40 dBA; areas enclosed by the inner rim exceed this level, while those outside the outer rim are below 40 dBA.

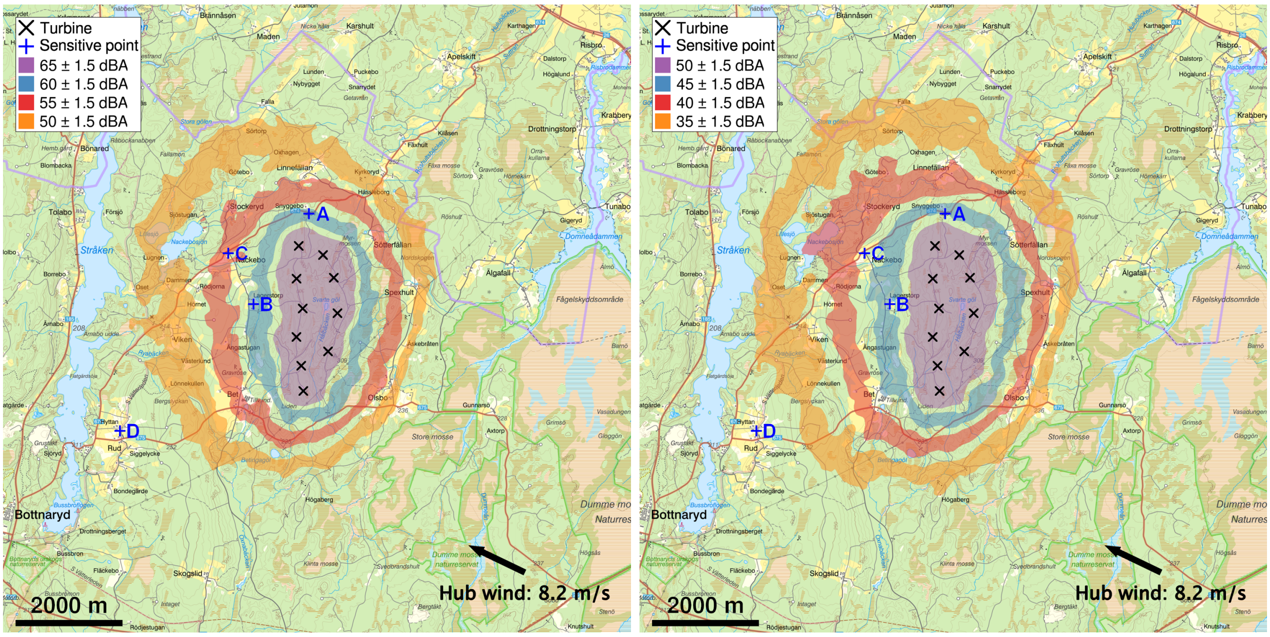
For the SoundSim360 computations, we used elevation data provided by *Lantmäteriet* [16] (1 m spatial resolution). The upper limit for the simulation domain was set to 5 km. For large-scale outdoor sound propagation, it is particularly important to incorporate atmospheric data into the model. The SoundSim360 simulations utilize MEPS atmospheric data from the *Norwegian Meteorological Institute*, which provide hourly temporal resolution, 2.5 km spatial resolution, and 65 vertical levels up to approximately 10 km altitude. The atmospheric attenuation coefficient is defined as a function of temperature, pressure, humidity, and frequency [9]. The speed of sound and air density are calculated from temperature, pressure, and humidity following the formulations presented in [40].

The computed A-weighted sound pressure levels at four residential receiver locations (**A**–**D**) are presented in Table 1. Two cases are considered: (1) using the measured sound power level (119.1 dBA), and (2) using the sound power levels provided by Vestas, as shown in Figure 3. The corresponding sound pressure levels computed with the Nord2000 model (by **Akustikverkstan Konsult AB**) are also included for locations **A**–**C** (note that location **D** was not included in the Nord2000 computations, as it lies outside the model domain).

A substantial discrepancy of approximately 22 dBA is observed between the measured sound pressure levels and those predicted using Nord2000. This large difference is primarily attributed to the unreliable sound power levels provided by Vestas, but also to inherent limitations of the Nord2000 propagation model, which typically underestimates sound levels by 5–10 dB [17, 38, 14]. This underestimation is also confirmed by our independent SoundSim360 calculations using the Vestas-provided sound power data (see Figure 2 and Table 1).

Sensitive point	Coordinates	Nord2000 [dBA]	SoundSim360 (Vestas) [dBA]	SoundSim360 (Measured) [dBA]	Nearest turbine [m]
A	[436134.863,6409794.411]	38	46.6	59.8	633
B	[435100.529,6408103.176]	37.6	46.7	60.2	922
C	[434628.846,6409055.159]	34.9	43.0	56.5	1323
D	[432604.586,6405734.605]	-	30.3	43.6	3508

Table 1: Measured sound levels (dBA) on 2025-01-05 at 18:00 CET at locations A and B, showing 60 dBA. Based on these measurements, we calculated the sound pressure levels (SPL) using SoundSim360 (see Figure 2), here SoundSim360 (Measured data). The results are compared with the industry-provided noise emission map computed using the Nord2000 model (see Figure 3). We also include SoundSim360 computation with sound power levels from the industry-provided noise emission map.



(a) SoundSim360 (Measured)

(b) SoundSim360 (Vestas)

Figure 2: Calculation of noise levels (dBA) using SoundSim360 for the Sötterfällan wind farm: (a) based on two measurement points (locations **A** and **B**), that showed 60 dBA on 2025-01-05 at 18:00 CET, (b) using the specified (Vestas) sound power levels, presented by **Akustikverkstan Konsult AB** in Figure 3.

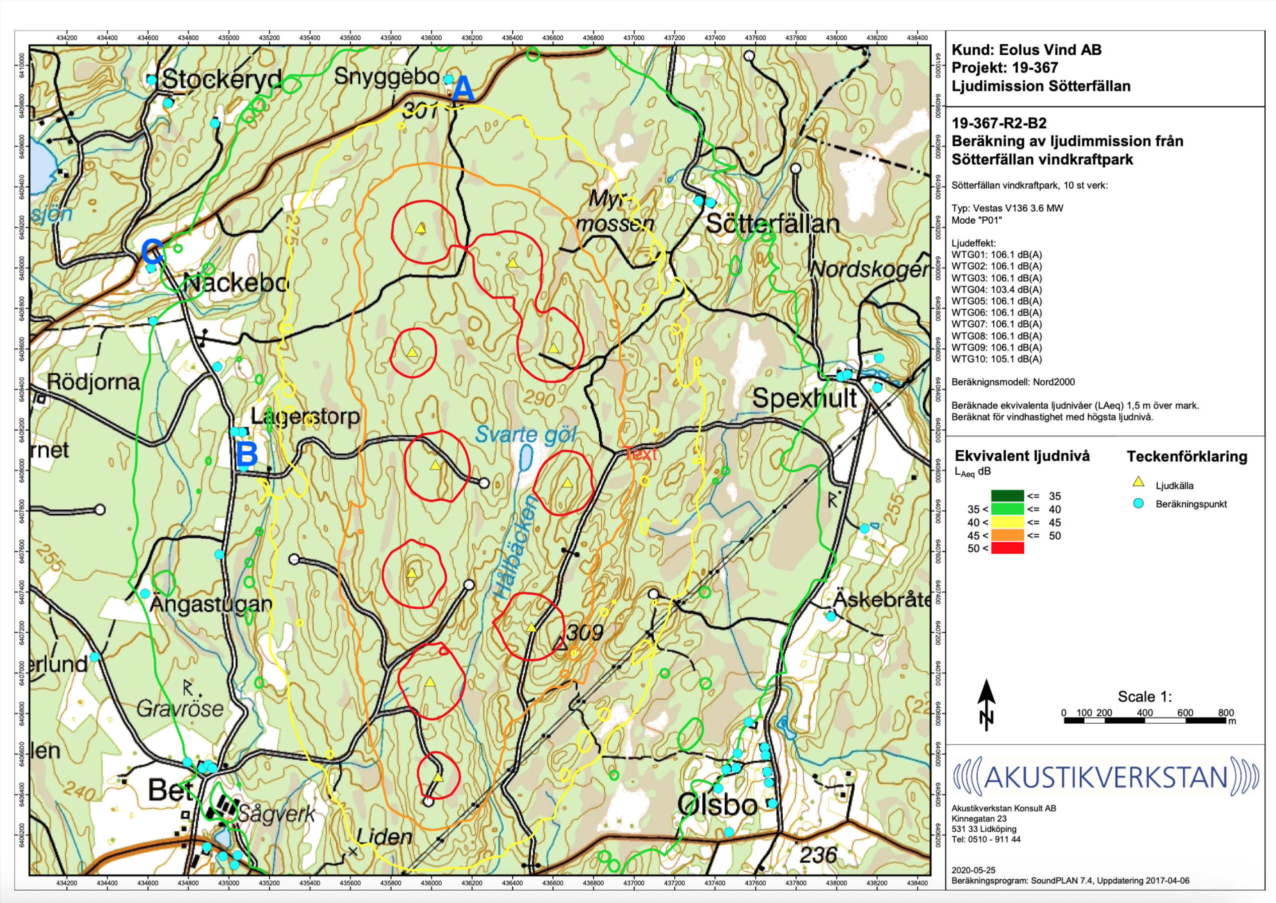


Figure 3: Calculation of noise levels (dBA) using the Nord2000 model for the Sötterfällan wind farm, as presented by **Akustikverkstan Konsult AB**.

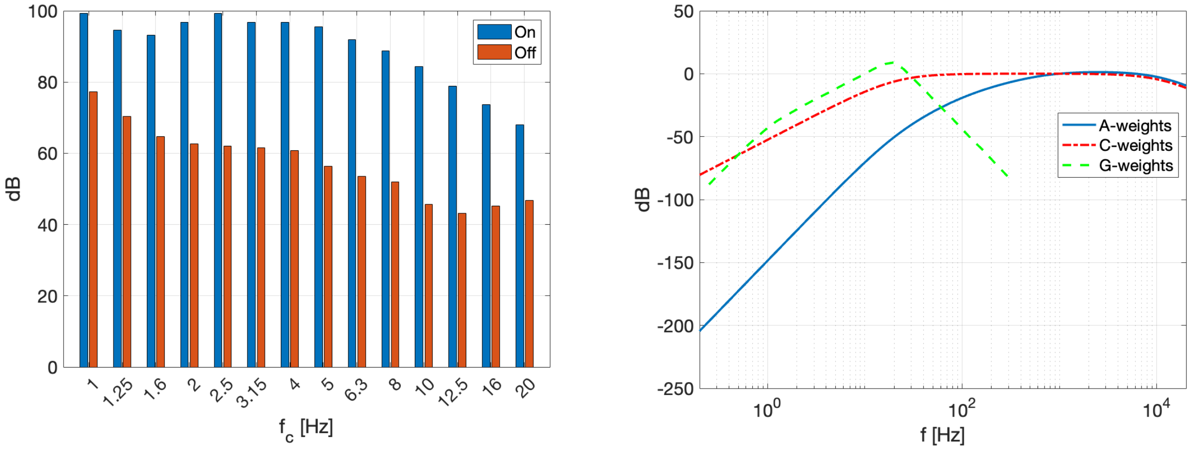
Measured Infrasound and Low-Frequency Noise from Wind Turbines

When evaluating SPL from wind turbines, broadband spectra are ideally divided into third-octave bands (f_c) covering the full frequency range from 0.1 Hz to 20,000 Hz. In practice, however, the wind industry typically reports only octave bands between 31 and 10,000 Hz, thereby excluding the infrasonic and very low-frequency components most relevant to large modern turbines. Møller and Søndergaard [36, 47] demonstrated that the relative proportion of low-frequency noise (below 100 Hz) increases with turbine size. This can be described as a downward spectral shift, meaning that larger turbines produce proportionally more acoustic energy at low frequencies and infrasound.

Wind turbine noise is inherently dominated by low-frequency components, with the highest energy typically below 6 Hz. The absolute maximum levels generally occur below 1 Hz and are expected to increase further as turbine dimensions and blade lengths grow. Measuring such low frequencies using *A-weighting* (dBA) is therefore physically meaningless, since this weighting curve almost completely suppresses energy below 20 Hz. Even *C*- and *G*-weightings, while somewhat improved, significantly underrepresent true infrasonic energy content. Figure 4 illustrates the attenuation introduced by the A-, C-, and G-weighting filters—showing how much energy is effectively "subtracted" from each frequency band.

At the Målarberget wind farm, we conducted infrasound measurements on 23 October 2024, both during turbine operation and immediately after all turbines were shut down due to negative electricity prices (see Figure 4). The results clearly demonstrate that the turbines are the dominant source of infrasound in the area: the background level (1–20 Hz) was approximately 27 dB lower when the turbines were off. A similar pattern was observed at the Lervik wind farm on 21 May 2024.

Summing all frequency bands in the 1-20 Hz range yields an overall level of 106.4 dB during turbine operation, corresponding to 22.7 dBA, 73.9 dBC, and 92.1 dBG. With the turbines off, the corresponding values were 79.1 dB, −2.8 dBA, 44.5 dBC, and 59.3 dBG. These values represent the effective infrasound levels across different weighting scales (below 20 Hz). Frequencies below 1 Hz were not included, as they cannot be measured reliably with existing instrumentation; however, model predictions and field experience suggest that peak levels likely occur around 0.2-0.6 Hz, depending on turbine size. Several independent studies have also shown that indoor infrasound levels are typically 3-5 dB higher than outdoor measurements [13, 4, 5, 7], indicating that building structures can amplify or resonate with the low-frequency pressure field.



(a) Sound pressure

(b) A- , C- and G-weighting

Figure 4: (a) Accurate measurement of infrasound with and without turbine operation, (b) illustrating the effects of A-, C-, and G-weighting.

The Impact of Infrasound on Human Health

Infrasound generated by wind turbines exhibits a distinctly pulsating character, fundamentally different from the broadband and largely stochastic infrasound produced by natural sources such as atmospheric turbulence and ocean waves. It is well established that amplitude-modulated or pulsating sounds are perceived as more annoying and intrusive than continuous broadband noise of equal average sound pressure level. We therefore propose that the pulsating nature of wind turbine infrasound constitutes a critical factor that should be explicitly considered in future health-related studies on infrasound exposure.

Several reports are frequently cited as *proof* that infrasound from wind turbines poses no adverse effects on humans, notably the studies in [22, 21]. However, after a thorough review of these and numerous earlier publications (e.g., [6, 52]), it is evident that none have investigated the exposure levels that we have measured near modern wind farms. Furthermore, none of these studies involved neurophysiological expertise, which is essential for interpreting potential neurological or vestibular effects. Importantly, none of the studies have addressed the effects of *pulsating* infrasound, which is a defining characteristic of wind turbine emissions.

Recent research has linked infrasound exposure at levels between 80–90 dB to altered brain activity [54, 11]. According to specialists in otoneurology, such as Håkan Enbom and Professor Alec N. Salt [43, 44, 45], there is strong evidence that inaudible, pulsating infrasound can trigger migraines in approximately 30% of the population—those with a highly sensitive nervous system [18, 41]. This sensitivity appears to be highly individual, consistent with clinical observations.

Both I and another member of our measurement team have personally experienced transient insomnia (lasting up to a week) and migraines following infrasound measurements near wind turbines. In these cases, we were exposed to infrasound levels exceeding 95 dB near the 1 Hz frequency band for several hours, corresponding to approximately 103 dB when integrated across the 1–20 Hz range (see Figure 4). Similar symptoms have been reported by other infrasound researchers [4], even at lower exposure levels.

Physiological responses to infrasound were documented as early as 1985, when Danielsson and Landström [8] demonstrated that exposure at 95 dB for one hour increased diastolic blood pressure while decreasing systolic blood pressure and pulse rate. More recent ecological studies indicate that many animal species—particularly deer and birds—avoid wind farms, often relocating more than 5 km away [50], consistent with observations from residents reporting reduced wildlife near turbines.

Between October 2023 and December 2024, our measurements around the Målarberget and Lervik wind farms recorded infrasound levels between 92–115 dB at 1 Hz, at distances of 500–1000 m from the nearest turbine. By comparison, the Finnish study [21] exposed participants to 73 dB at 1 Hz (approximately 89 dB total) for 10 minutes, and the Australian study [22] used 87 dB for three days—both representing significantly lower exposure levels than those recorded near operating wind farms. Moreover, neither of these studies examined realistic, *pulsating* infrasound representative of actual wind turbine emissions, despite their claims of using turbine-derived infrasound.

We therefore propose that the health effects of infrasound should be investigated through

a controlled study involving a statistically representative volunteer group (approximately 1000 individuals, including those with known migraine sensitivity) exposed to pulsating infrasound in the frequency range 0.5–16 Hz at levels of at least 95 dB for several days. The study should be conducted under the supervision of medical experts in otoneurology to ensure appropriate clinical assessment and monitoring. Until such a scientifically rigorous investigation is carried out, we recommend temporarily halting further expansion of wind farms.

Instrumentation and Calibration for Infrasound Measurements

Accurate measurement of infrasound down to (and below) 1 Hz requires instruments that are demonstrably calibrated within this frequency range. Reliable calibration around 1 Hz can be performed at **NORSAR** using their Hyperion reference system at the certified CTBTO infrasound station in Elverum, Norway. In our work, we employed four **Lidström infrasound microphones**, originally developed in Sweden during the early 1980s for helicopter detection [19]. These sensors are extremely sensitive and mechanically robust, well suited for harsh outdoor environments. They have previously been used by the Swedish Defence Research Agency (FOI) and the Royal Institute of Technology (KTH, Prof. Thomas Lindblad), and are currently utilized by the Institute for Space Physics (IRF) in Kiruna under the leadership of Johan Kero [51], who has generously lent us three of these microphones. All four Lidström microphones were calibrated at NORSAR against their Hyperion reference system.

During our field campaigns, we also tested the commercial **Nor140** and **Nor145** sound level meters, which are commonly used by acoustic consultants. Although the Nor145 specification claims sensitivity down to 0.4 Hz, our results clearly demonstrate that it is not accurately calibrated at such low frequencies; below 3 Hz, the readings are approximately 20 dB too low. This shows that instruments not calibrated at 1 Hz cannot be used for reliable infrasound measurements from wind turbines. Accurate infrasound monitoring therefore requires *professionally calibrated sensors*. Leading manufacturers such as **Hyperion** and **Chaparral** provide systems capable of accurate measurements between 0.01 and 200 Hz. We have recently acquired two Hyperion microphones to enhance measurement precision below 1 Hz. It is also crucial to perform *indoor* measurements, as infrasound levels are often higher indoors than outdoors due to structural amplification and reduced atmospheric damping.

The measurement campaigns used to calibrate and validate our numerical model, and to inversely estimate the infrasound source strength of wind turbines, were conducted at two sites: the **Lervik wind farm** (21 May 2024 and 10 September 2024) and the **Målarberget wind farm** (26 October 2023, 23 October 2024, and 16 December 2024). At each site, measurements were performed at one to three locations. During each campaign, concurrent atmospheric data were recorded and incorporated into the inverse modeling. Access to operational data from the wind farm operators (e.g., turbine on/off status) was essential for accurate interpretation, and both operators provided full cooperation.

A detailed scientific article describing the measurement methodology, data, and calibration procedures is found in [30]. Measurement data are available upon request. The turbines at Målarberget are of type **Vestas V150-4.3 MW**, while those at Lervik are **SG170-6.6 MW** units. An average value from the five different measurement days gives 163 dB source strength (SPL) at 1 Hz.

Calculations of dBA levels at energipark Tjele

We have calculated the sound dispersion for all third octave bands (normal noise) around energipark Tjele in dBA using SoundSim360. The proposed wind-farm consists of 14 wind turbines as presented in Bilaga 19 in the document *06-samlet-bilagsrapport-energipark-tjele-ved-vinge_del2* presented by Ramboll (Project: VINDMØLLER VED VINGE). Ramboll present 4 different alternatives:

- Alternativ 1 (A1): 14 stk. SG170-6,6 MW Siemens Gamesa vindmøller
- Alternativ 2 (A2): 14 stk. V162-6,2 MW Vestas vindmøller
- Alternativ 3 (A3): 14 stk. V162-7,2 MW Vestas vindmøller
- Alternativ 4 (A4): 14 stk. V172-7,2 MW Vestas vindmøller.

In the simulations, we used a representative atmospheric profile from 31 March 2023 (weather data obtained from the THREDDS Data Server) and performed calculations for nighttime conditions (04:00 AM) under tailwind scenarios of 4, 6, and 8 m/s, referring to wind speed measured at 10 m above ground level. The wind speed at hub height is approximately 2.5 times higher. Soft ground surfaces were modeled as ordinary ground (Impedance Class E), and hard surfaces (e.g., water, asphalt, and concrete) as fully reflecting (Impedance Class H), following the specifications in Nord2000 [1]. Atmospheric attenuation effects were incorporated in accordance with ISO 9613-1 [9]. Figures 5, 6, and 7 illustrate the simulated sound propagation for *Alternative 1* under tailwind conditions of 4, 6, and 8 m/s, respectively. The resulting A-weighted sound pressure levels (dBA) at four representative receiver locations (sensitive dwellings) are summarized in Tables 2–5 for *Alternatives 1–4*.

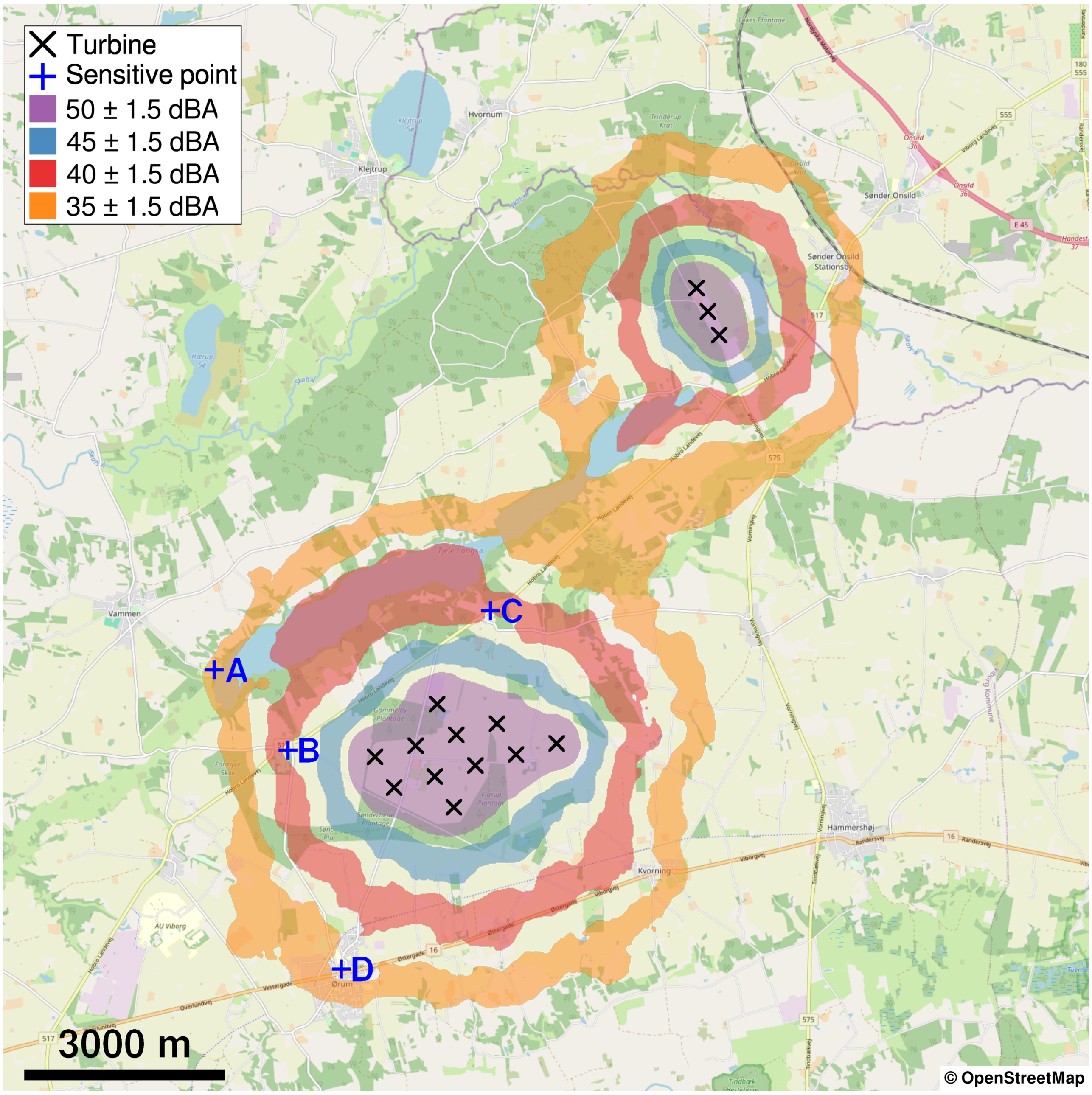


Figure 5: Calculation of noise levels (dBA) using SoundSim360 for Alternative 1 and 4 m/s.

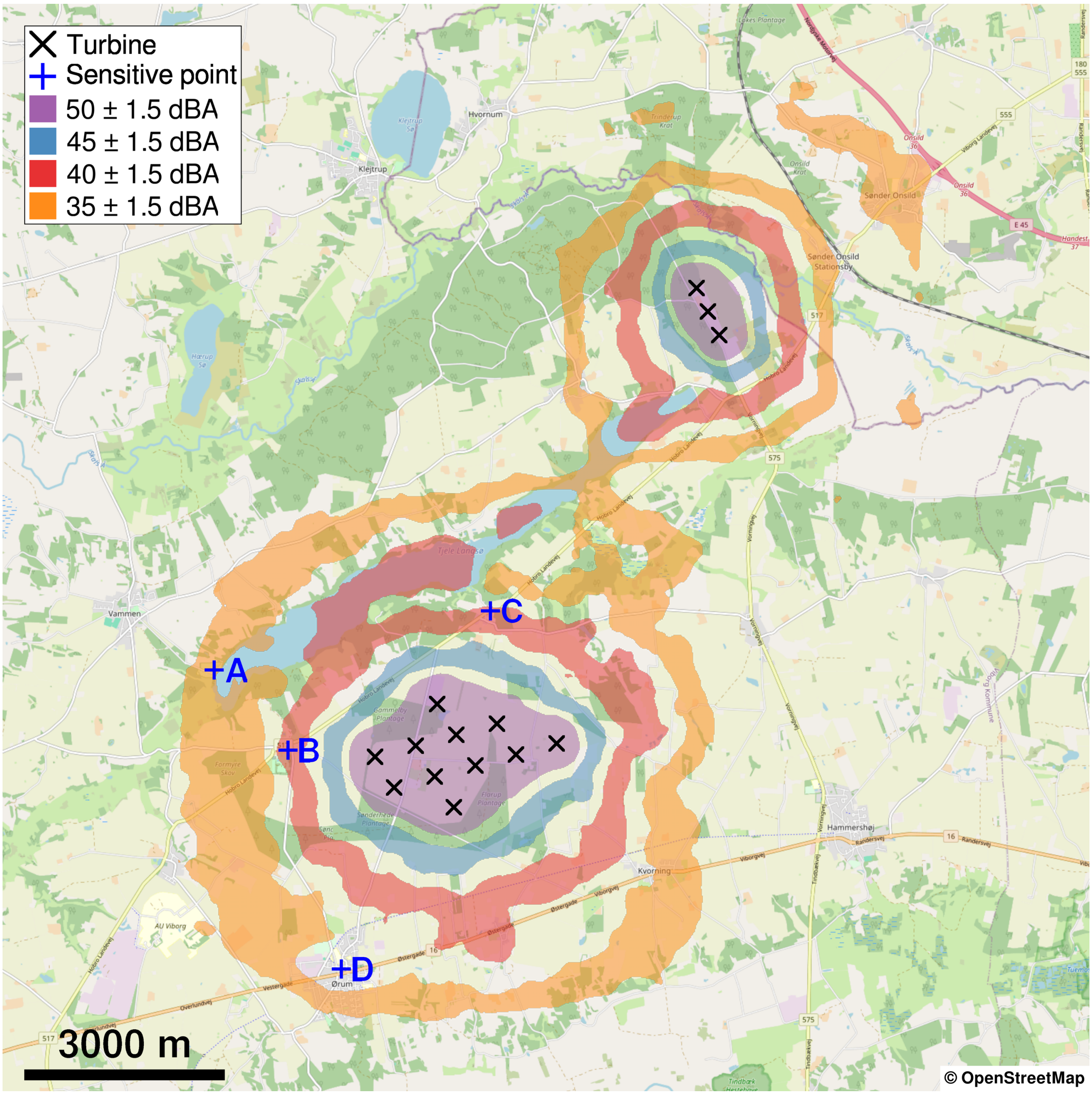


Figure 6: Calculation of noise levels (dBA) using SoundSim360 for Alternative 1 and 6 m/s.

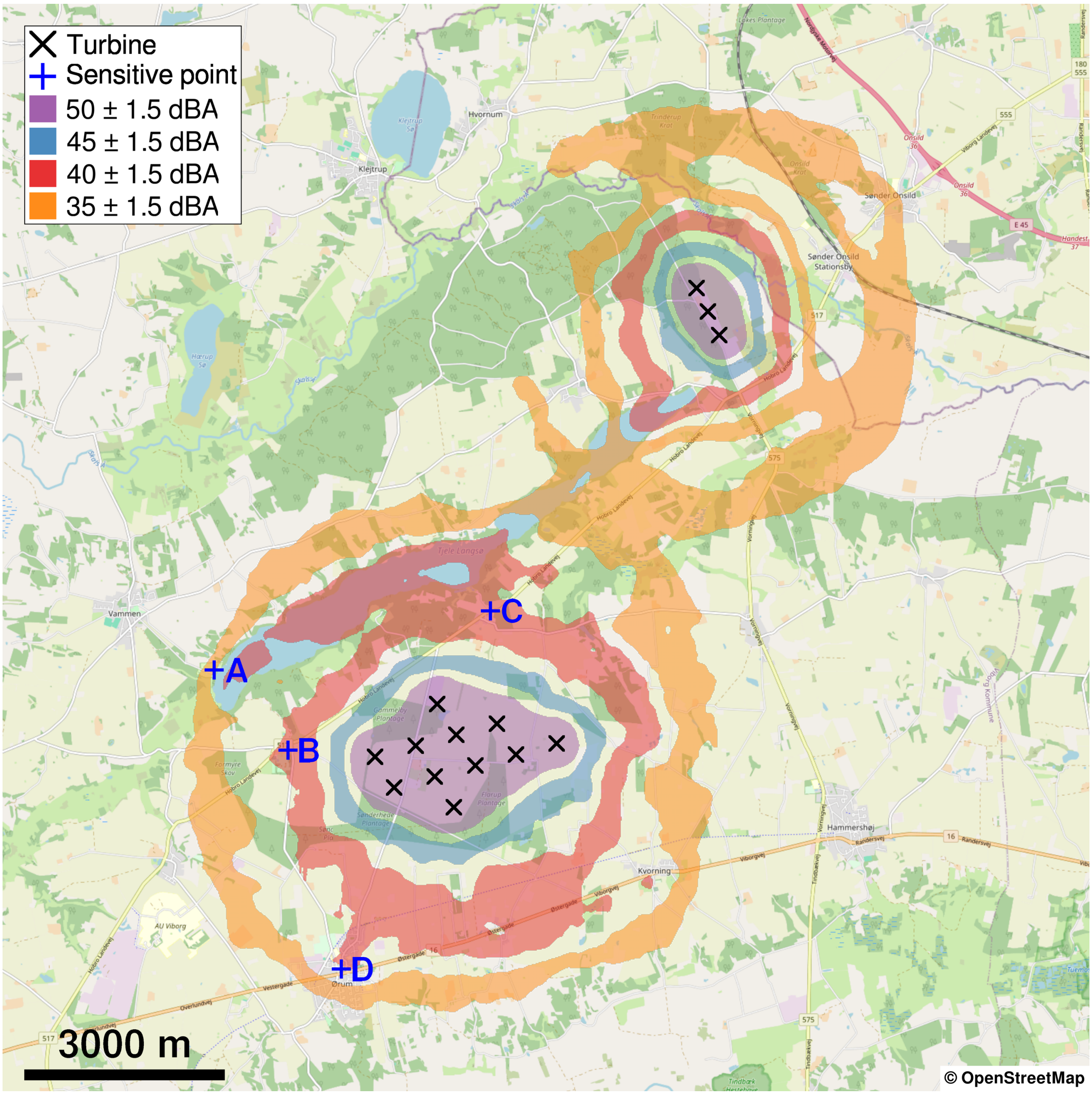


Figure 7: Calculation of noise levels (dBA) using SoundSim360 for Alternative 1 and 8 m/s.

Our simulations indicate that the noise level exceeds 42 dBA at a wind speed of 4 m/s for the sensitive receiver location *B* for both *Alternative 1* and *Alternative 4*, taking into account an uncertainty of ±1.5 dBA in the SoundSim360 computations. These A-weighted simulations are based on the sound power levels specified by *Vestas* and *Siemens Gamesa*. However, our experience shows that these manufacturer-provided values are not reliable. In particular, during evening conditions, amplitude-modulated (AM) noise [17] frequently occurs. This phenomenon produces an extremely disturbing audible "swishing" sound that can propagate over distances exceeding 10 km. When AM noise occurs, the actual noise levels in dBA become significantly higher than those predicted under stationary conditions. This underestimation is also confirmed by our independent SoundSim360 simulations using the Vestas-provided sound power data (see Figure 2 and Table 1).

Sensitive point	Coordinates	dBA (4 m/s)	dBA (6 m/s)	dBA (8 m/s)	Nearest turbine [m]
A	[536612.038397,6264417.583784]	35.0	36.0	**36.2**	2742
B	[537729.172883,6263224.527172]	**42.0**	40.4	39.5	1310
C	[540746.598861,6265340.465953]	**41.4**	39.2	39.6	1608
D	[538559.984452,6259949.801239]	37.1	**38.3**	38.3	2835

Table 2: dBA levels (normal noise) at the sensitive points (same locations and notation as in the document from Ramboll) calculated with SoundSim360 for Alternative 1. We compare the results with 4 m/s, 6 m/s and 8 m/s tailwind. See Figures 5, 6 and 7.

Sensitive point	Coordinates	dBA (4 m/s)	dBA (6 m/s)	dBA (8 m/s)	Nearest turbine [m]
A	[536612.038397,6264417.583784]	33.8	34.8	**35.0**	2742
B	[537729.172883,6263224.527172]	**40.8**	39.2	38.3	1310
C	[540746.598861,6265340.465953]	**40.2**	38.0	38.4	1608
D	[538559.984452,6259949.801239]	35.9	**37.1**	37.1	2835

Table 3: dBA levels (normal noise) at the sensitive points (same locations and notation as in the document from Ramboll) calculated with SoundSim360 for Alternative 2. We compare the results with 4 m/s, 6 m/s and 8 m/s tailwind. See Figures 5, 6 and 7.

Sensitive point	Coordinates	dBA (4 m/s)	dBA (6 m/s)	dBA (8 m/s)	Nearest turbine [m]
A	[536612.038397,6264417.583784]	33.7	34.7	**34.9**	2742
B	[537729.172883,6263224.527172]	**40.7**	39.1	38.2	1310
C	[540746.598861,6265340.465953]	**40.1**	37.9	38.3	1608
D	[538559.984452,6259949.801239]	35.8	**37.0**	37.0	2835

Table 4: dBA levels (normal noise) at the sensitive points (same locations and notation as in the document from Ramboll) calculated with SoundSim360 for Alternative 3. We compare the results with 4 m/s, 6 m/s and 8 m/s tailwind. See Figures 5, 6 and 7.

Sensitive point	Coordinates	dBA (4 m/s)	dBA (6 m/s)	dBA (8 m/s)	Nearest turbine [m]
A	[536612.038397,6264417.583784]	34.9	35.3	**36.1**	2742
B	[537729.172883,6263224.527172]	**41.8**	40.3	39.0	1310
C	[540746.598861,6265340.465953]	**40.8**	38.5	39.1	1608
D	[538559.984452,6259949.801239]	36.4	**37.8**	37.6	2835

Table 5: dBA levels (normal noise) at the sensitive points (same locations and notation as in the document from Ramboll) calculated with SoundSim360 for Alternative 4. We compare the results with 4 m/s, 6 m/s and 8 m/s tailwind. See Figures 5, 6 and 7.

Calculations of infrasound at at energipark Tjele

In the simulations, we used a representative atmospheric profile from 31 March 2023 (weather data obtained from the THREDDS Data Server) and performed calculations for nighttime conditions (04:00 AM) under an 8 m/s tailwind. Soft ground surfaces were modeled as ordinary ground (Impedance Class E), and hard surfaces (e.g., water, asphalt, and concrete) as fully reflecting (Impedance Class H), following the specifications in Nord2000 [1]. Atmospheric attenuation effects were incorporated in accordance with ISO 9613-1 [9]. A source sound pressure level (SPL) of 163 dB was used to compute the propagation of infrasound (at 1 Hz) in the area surrounding Tjele. The results are presented in Figure 8.

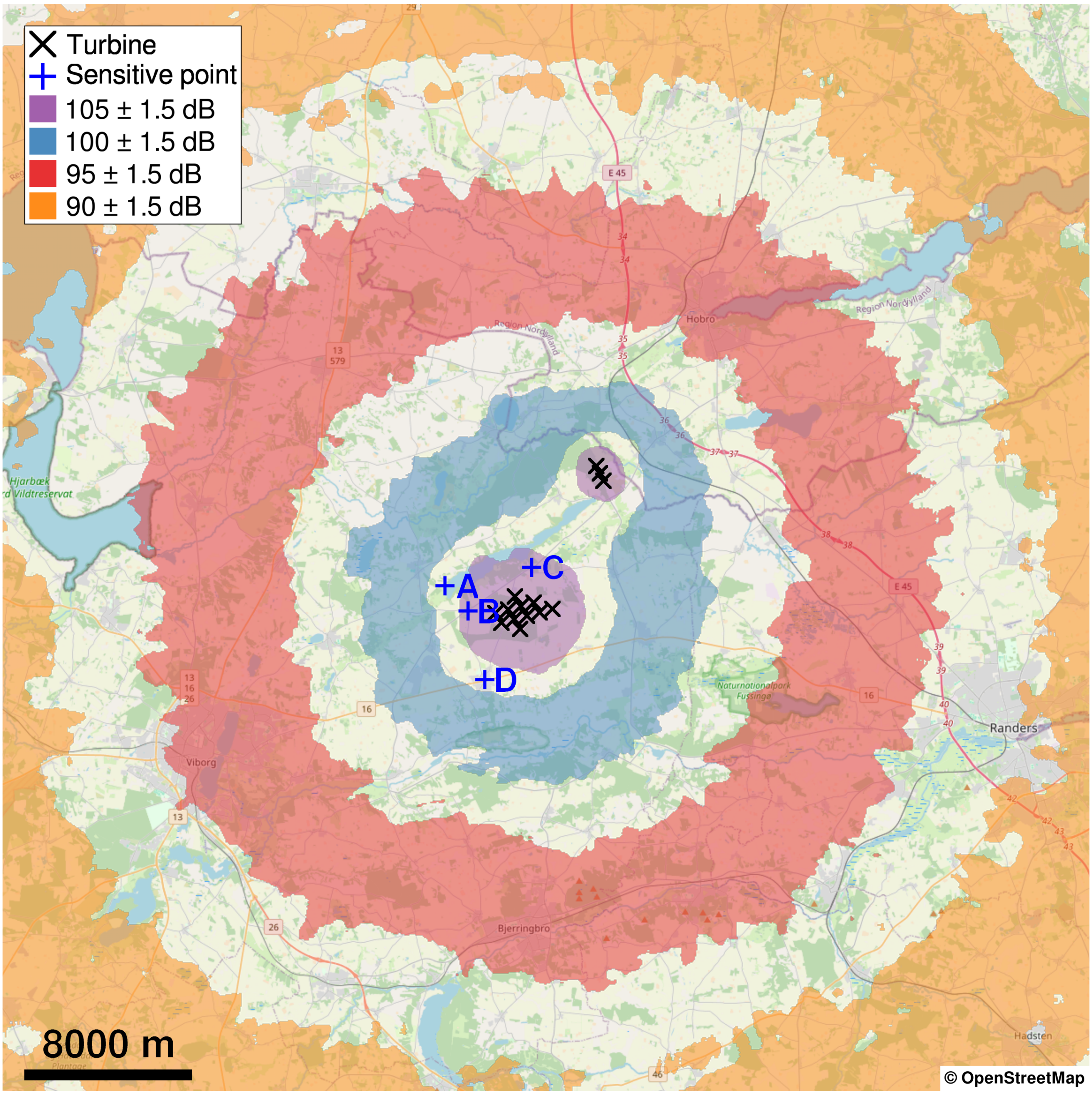


Figure 8: Calculation of the infrasound (at 1 Hz) noise level (dB) with soundSim360 for Tjele. All within outer edge of red is higher or equal to 95 dB at 1 Hz.

When we present the infrasound maps in Figure 8 we present domains with certain dB levels, including uncertainty. Red domain for example is an area where the sound level is 95 dB ± 1.5 dB (hence within the range 93.5-96.5 dB). This is due to uncertainties in the model parameters, such as grund damping, atmospheric damping, and interference pattern. I consider everything within the red to be 95 dB, and everything inside the inner rim of the red to be higher than 95 dB. Everything outside of the outer rim of red is less than 95 dB.

In Table 6, the calculated sound pressure levels (dB) at sensitive receiver locations (residential houses) for infrasound at 1 Hz are presented. It is estimated that the infrasound level at this frequency may fluctuate within approximately ±15 dB of the calculated values, depending on prevailing meteorological and ground conditions.

Sensitive point	Coordinates	dB [1 Hz]	Nearest turbine [m]
A	[536612.038397,6264417.583784]	102.5	2742
B	[537729.172883,6263224.527172]	104.6	1310
C	[540746.598861,6265340.465953]	104.6	1608
D	[538559.984452,6259949.801239]	102.3	2835

Table 6: Infrasound levels at 1 Hz were calculated at the sensitive receiver locations (same positions and notation as used in the Ramboll report) using *SoundSim360*. The sound power level was set to 163 dB. The resulting spatial distribution of the infrasound field is shown in Figure 8.

These represent **high sound pressure levels**, and it is therefore considered **inappropriate** to establish a wind farm in such close proximity to Tjele. This assessment is supported by several studies that have demonstrated measurable effects on both **blood pressure** and **brain activity** at infrasound levels of approximately 90–95 dB [8, 54, 11]. It should also be noted that an infrasound level of 95 dB at 1 Hz corresponds to a **total broadband infrasound level (1–20 Hz)** of approximately 103 dB.

Conclusions

Our calculations using *SoundSim360* at Tjele indicate that the infrasound levels for residents located within the outer border of the red-marked area in Figure 8 exceed 95 dB at 1 Hz. When accounting for all sub-bands between 1–20 Hz, this corresponds to an overall infrasound level of approximately 103 dB. The area experiencing at least 95 dB at 1 Hz extends several kilometers, potentially affecting a large number of residents. Based on findings reported in peer-reviewed literature [8, 43, 44, 45, 54, 11, 18, 41], such levels of infrasound exposure may be harmful for up to 30% of the population.

Our simulations also show that the A-weighted noise limits are exceeded at least at one sensitive receiver location (marked in boldface in Tables 2 and 5), when considering the uncertainty of ±1.5 dBA in the *SoundSim360* computations. The dBA noise emission maps are based entirely on the sound power spectra provided by the turbine manufacturer, which our findings suggest are unreliable. Of particular concern is the occurrence of amplitude-modulated (AM) noise [17], especially during nighttime and early morning conditions. This audible "swishing" sound is highly disturbing and can propagate over distances exceeding 10 km. When AM noise occurs, it can increase the A-weighted noise level by more than 10 dBA compared to the levels shown in standard noise maps.

Long-term measurement studies [38, 14] have further shown that noise levels can fluctuate by up to 20 dBA at distances of approximately 1 km from the nearest turbine, due to variations in meteorological and ground conditions. All identified sensitive receiver locations are therefore at considerable risk of exposure to elevated levels of AM noise, particularly during nighttime and early morning hours.

Policy Implications

Current regulatory frameworks for wind turbine noise are primarily based on A-weighted (dBA) metrics, which significantly underestimate low-frequency and infrasonic components. Our results demonstrate that these components can reach physiologically relevant levels at distances far beyond those typically considered in environmental assessments. To protect public health, it is therefore essential that future regulations incorporate frequency-dependent limits and explicitly account for infrasound and amplitude-modulated noise. The adoption of physically validated modeling tools such as *SoundSim360* would enable more accurate and transparent noise impact assessments, reducing the reliance on simplified or empirically tuned models such as *Nord2000* and *ISO 9613-2*. We recommend that national environmental agencies revise current noise assessment guidelines to include unweighted or G-weighted limits, nighttime-specific criteria, and long-term monitoring of infrasound exposure.

References

[1] Nina Aguilera, Henrik Naglitsch, and Katrin Olofsson. Beräkningsmanual Nord2000 : för bullerberäkningar i väg-och järnvägsplaner. Technical Report 2024:033, Efterklang, 2024.

[2] Martin Almquist and Eric M. Dunham. Non-stiff boundary and interface penalties for narrow-stencil finite difference approximations of the laplacian on curvilinear multiblock grids. *Journal of Computational Physics*, 408:109294, 2020.

[3] Martin Almquist, Ilkka Karasalo, and Ken Mattsson. Atmospheric sound propagation over large-scale irregular terrain. *Journal of Scientific Computing*, 61(2):369–397, 2014.

[4] Stephen E. Ambrose, Robert W. Rand, and Carmen M. E. Krogh. Wind turbine acoustic investigation: Infrasound and low-frequency noise – a case study. *Bulletin of Science, Technology & Society*, 32(2):128–141, 2012.

[5] Walker B, Hessler G, Hessler D, Rand R, and Schomer P. *A Cooperative Measurement Survey and Analysis of Low Frequency and Infrasound at the Shirley Wind Farm in Brown County, Wisconsin.* Report number 122412-1, 2012.

[6] K. Bolin, G. Bluhm, G. Eriksson, and M. E. Nilsson. Infrasound and low frequency noise from wind turbines: exposure and health effects. *Environmental Research Letters*, 6(3):035103, 2011.

[7] Richard A Carman. Measurement procedure for wind turbine infrasound. In *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, volume 250, pages 6143–6153. Institute of Noise Control Engineering, 2015.

[8] Åke Danielsson and Ulf Landström. Blood pressure changes in man during infrasonic exposure. *Acta Medica Scandinavica*, 217(5):531–535, 1985.

[9] International Organization for Standardization. *Acoustics: Attenuation of Sound During Propagation Outdoors.* International Organization for Standardization, 1993.

[10] International Organization for Standardization. *Acoustics-Attenuation of Sound During Propagation Outdoors: Part 2: General Method of Calculation.* 1996.

[11] Caroline Garcia Forlim, Leonie Ascone, Christian Koch, and Simone Kühn. Resting state network changes induced by experimental inaudible infrasound exposure and associations with self-reported noise sensitivity and annoyance. *Scientific Reports*, 14(1):24555, 2024.

[12] Theodore V. Gortsas, Theodoros Triantafyllidis, Stylianos Chrisopoulos, and Demosthenes Polyzos. Numerical modelling of micro-seismic and infrasound noise radiated by a wind turbine. *Soil Dynamics and Earthquake Engineering*, 99:108–123, 2017.

[13] N D Kelley, H E McKenna, R R Hemphill, C L Etter, R L Garrelts, and N C Linn. Acoustic noise associated with the mod-1 wind turbine: its source, impact, and control. Technical report, Solar Energy Research Inst. (SERI), Golden, CO (United States), 02 1985.

[14] Thomas Lagö and Bertil Persson. Wind turbine measurements in sweden. In *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, volume 259, pages 8151–8164. Institute of Noise Control Engineering, 2019.

[15] LantmÃ¤teriet. Map 1:50 000, raster. `https://www.lantmateriet.se/sv/geodata/vara-produkter/produktlista/karta-150-000-nedladdning-raster/`, 2018.

[16] LantmÃ¤teriet. Terrain Model Download, grid 1+. `https://www.lantmateriet.se/sv/Kartor-och-geografisk-information/geodataprodukter/produktlista/markhojdmodell-nedladdning-grid-1/`, 2021.

[17] Conny Larsson. Ljud från vindkraftverk, modell-validering-mätning : Slutrapport Energimyndighetens projekt 32437-1. Technical report, Uppsala University, LUVAL, 2014.

[18] Francesca Lionetti, Arthur Aron, Elaine N. Aron, G. Leonard Burns, Jadzia Jagiellowicz, and Michael Pluess. Dandelions, tulips and orchids: evidence for the existence of low-sensitive, medium-sensitive and high-sensitive individuals. *Translational Psychiatry*, 8(1):24, 2018.

[19] L. Liszka. *Infrasound: A Summary of 35 Years of Infrasound Research.* IRF scientific report. Swedish Institute of Space Physics, 2008.

[20] Lukas Lundgren and Ken Mattsson. An efficient finite difference method for the shallow water equations. *Journal of Computational Physics*, 422:109784, 2020.

[21] Panu P. Maijala, Ilmari Kurki, Lari Vainio, Satu Pakarinen, Crista Kuuramo, Kristian Lukander, Jussi Virkkala, Kaisa Tiippana, Emma A. Stickler, and Markku Sainio. Annoyance, perception, and physiological effects of wind turbine infrasound. *The Journal of the Acoustical Society of America*, 149(4):2238–2248, 04 2021.

[22] Nathaniel S. Marshall, Garry Cho, Brett G. Toelle, Renzo Tonin, Delwyn J. Bartlett, Angela L. D Rozario, Carla A. Evans, Christine T. Cowie, Oliver Janev, Christopher R. Whitfeld, Nick Glozier, Bruce E. Walker, Roo Killick, Miriam S. Welgampola, Craig L. Phillips, Guy B. Marks, and Ronald R. Grunstein. The health effects of 72 hours of simulated wind turbine infrasound: A double-blind randomized crossover study in noise-sensitive, healthy adults. *Environmental Health Perspectives*, 131(3):037012, 2023.

[23] K. Mattsson, M. Almquist, and M. H. Carpenter. Optimal diagonal-norm SBP operators. *Journal of Computational Physics*, 264:91–111, 2014.

[24] K. Mattsson and M. H. Carpenter. Stable and accurate interpolation operators for high-order multi-block finite-difference methods. *SIAM J. Sci Comput.*, 32(4):2298–2320, 2010.

[25] K. Mattsson, M. Svärd, M.H. Carpenter, and J. Nordström. High-order accurate computations for unsteady aerodynamics. *Computers & Fluids*, 36:636–649, 2006.

[26] K. Mattsson, M. Svärd, and M. Shoeybi. Stable and accurate schemes for the compressible navier-stokes equations. *Journal of Computational Physics*, 227(4):2293–2316, 2008.

[27] Ken Mattsson. Summation by parts operators for finite difference approximations of second-derivatives with variable coefficients. *Journal of Scientific Computing*, 51:650–682, 2012.

[28] Ken Mattsson. Diagonal-norm upwind SBP operators. *Journal of Computational Physics*, 335:283 – 310, 2017.

[29] Ken Mattsson, Martin Almquist, and Edwin van der Weide. Boundary optimized diagonal-norm SBP operators. *Journal of Computational Physics*, 2018.

[30] Ken Mattsson, Gustav Eriksson, Leif Persson, Chilo José, and Kourosh. Tatar. Efficient finite difference modeling of infrasound propagation in realistic 3d domains. *Applied Acoustics*, 2025.

[31] Ken Mattsson, Frank Ham, and Gianluca Iaccarino. Stable and accurate wave-propagation in discontinuous media. *Journal of Computational Physics*, 227(19):8753–8767, 2008.

[32] Ken Mattsson, Frank Ham, and Gianluca Iaccarino. Stable boundary treatment for the wave equation on second-order form. *Journal of Scientific Computing*, 41(3):366–383, 2009.

[33] Ken Mattsson and Ylva Ljungberg Rydin. Implicit summation by parts operators for finite difference approximations of first and second derivatives. *Journal of Computational Physics*, 473:111743, 2023.

[34] Ken Mattsson and Jan NordstrÃ¶m. High order finite difference methods for wave propagation in discontinuous media. *Journal of Computational Physics*, 220(1):249–269, 2006.

[35] Ken Mattsson and Pelle Olsson. An improved projection method. *Journal of Computational Physics*, 372:349 – 372, 2018.

[36] Henrik Möller and Christian Sejer Pedersen. Low-frequency noise from large wind turbines. *The Journal of the Acoustical Society of America*, 129(6):3727–3744, 2011.

[37] Phuc D. Nguyen, Kristy L. Hansen, Bastien Lechat, Colin Hansen, Peter Catcheside, and Branko Zajamsek. Audibility of wind farm infrasound and amplitude modulated tonal noise at long-range locations. *Applied Acoustics*, 201:109106, 2022.

[38] Olof Öhlund and Conny Larsson. Meteorological effects on wind turbine sound propagation. *Applied Acoustics*, 89:34–41, 2015.

[39] Pelle Olsson, Gustav Eriksson, and Ken Mattsson. Projection based summation-by-parts methods, embeddings and the pseudoinverse. *Journal of Computational Physics*, 524:113689, 2025.

[40] Vladimir E. Ostashev and D. Keith Wilson. Acoustics in moving inhomogeneous media. *The Journal of the Acoustical Society of America*, 105(4):2067–2067, 04 1999.

[41] M. Pluess, E. Assary, F. Lionetti, K. J. Lester, E. Krapohl, E. N. Aron, and A. Aron. Environmental sensitivity in children: Development of the highly sensitive child scale and identification of sensitivity groups. *Translational Psychiatry*, 54(1):51–70, 2018.

[42] Ylva Rydin, Ken Mattsson, and Jonatan Werpers. High-fidelity sound propagation in a varying 3D atmosphere. *Journal of Scientific Computing*, 77(2):1278–1302, 2018.

[43] Alec N. Salt and Timothy E. Hullar. Responses of the ear to low frequency sounds, infrasound and wind turbines. *Hearing Research*, 268(1):12–21, 2010.

[44] Alec N. Salt and James A. Kaltenbach. Infrasound from wind turbines could affect humans. *Bulletin of Science, Technology & Society*, 31(4):296–302, 2011.

[45] Alec N Salt and Jeffery T Lichtenhan. How does wind turbine noise affect people. *Acoustics Today*, 10(1):20–28, 2014.

[46] Beat SchÃ¤ffer, Reto Pieren, Sabine J. Schlittmeier, and Mark Brink. Effects of different spectral shapes and amplitude modulation of broadband noise on annoyance reactions in a controlled listening experiment. *International Journal of Environmental Research and Public Health*, 15(5), 2018.

[47] Bo Søndergaard. Low frequency noise from wind turbines: Do the danish regulations have any impact? an analysis of noise measurements. *International Journal of Aeroacoustics*, 14(5-6):909–915, 2015.

[48] Vidar Stiernström, Martin Almquist, and Ken Mattsson. Boundary-optimized summation-by-parts operators for finite difference approximations of second derivatives with variable coefficients. *Journal of Computational Physics*, 491:112376, 2023.

[49] Vidar Stiernström, Lukas Lundgren, Murtazo Nazarov, and Ken Mattsson. A residual-based artificial viscosity finite difference method for scalar conservation laws. *Journal of Computational Physics*, 430:110100, 2021.

[50] Anne Tolvanen, Henri Routavaara, Mika Jokikokko, and Parvez Rana. How far are birds, bats, and terrestrial mammals displaced from onshore wind power development? – a systematic review. *Biological Conservation*, 288:110382, 2023.

[51] Antoine Turquet, Quentin Brissaud, Celso Alvizuri, Sven Peter Näsholm, Alexis Le Pichon, and Johan Kero. Retrieving seismic source characteristics using seismic and infrasound data: The 2020 ML 4.1 kiruna minequake, sweden. *Geophysical Research Letters*, 51(12), 2024.

[52] Irene van Kamp and Frits van den Berg. Health effects related to wind turbine sound, including low-frequency sound and infrasound. *Acoustics Australia*, 46(1):31–57, 2018.

[53] Kerstin Persson Waye, Michael Smith, and Mikael Ögren. Hälsopåverkan av lågfrekvent buller inomhus. Technical Report 3, Sahlgrenska Akademin Medicinska Institutionen, 2017.

[54] Markus Weichenberger, Martin Bauer, Robert Kühler, Johannes Hensel, Caroline Garcia Forlim, Albrecht Ihlenfeld, Bernd Ittermann, Jürgen Gallinat, Christian Koch, and Simone Kühn. Altered cortical and subcortical connectivity due to infrasound administered near the hearing threshold - evidence from fmri. *PLOS ONE*, 12(4):1–19, 04 2017.