

# NOISE / NEWS INTERNATIONAL

Volume 34, Number 3  
2026 September

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- Towards Quieter Wind Turbines by Perception-Driven Design
- Recent Advances in Noise Reduction of Wind Turbine Blades
- Revising IEC 61400-11: Building Consensus for the Next Generation of Wind Turbine Acoustic Measurements
- ISO 9613-2:2024-01 Impact Assessment of Noise Modelling Procedure in Wind Power Projects
- Temperature Inversions and Wind Turbine Noise
- Open Research Data for the Investigation of Sound Propagation from Onshore Wind Turbines
- Hearing the Turbines: Wind Energy & Changes to Rural Soundscapes
- Integrating Acoustics, Perception, and Policy: IEA Wind TCP Task RESONATE
- What Goes Around Comes Around: NASA's 1970s–90s Turbine Research and Today's Infrasound Debate
- Eavesdropping on the Endangered Hawaiian Monk Seal
- Data Centers and Measurement of Low Frequency and Infrasound

## Wind Turbine Noise

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# Editor's Message

What's the loudest thing near your house that nobody else seems bothered by? For a lot of our readers, the honest answer is a wind turbine. If you've ever stood in a field explaining to a resident why 40 dBA is technically compliant while they insist the swish swish is ruining their sleep, you know that "compliant" and "acceptable" are two very different words. That gap is where this issue's wind turbine noise section lives.

We open with Roberto Merino Martinez arguing that our standard metrics are perceptually blind to what actually makes turbine noise annoying, and Goldwind's Yang Bing follows with hard wind tunnel numbers, 6.4 dBA of reduction from combining vortex generators with serrated trailing edges. Read them together and ask whether that's a win, given what Roberto just told you.

Then the standards fight starts. Lars Sommer Søndergaard and team are mid revision on IEC 61400 11, while Carlo Di Napoli and the AFRY team show the 2024 update to ISO 9613 2 can push predicted noise levels up by roughly 5 dB in real projects. Aeroustics tests a long assumed effect, temperature inversions, against long term field data and finds the relationship weaker than conventional wisdom suggests. Susanne Könecke and her Hannover colleagues hand the community an open, FAIR dataset built for exactly these questions.

Then we step back from the engineering. Eugene McKeown, writing with Eoin King and Denis O'Hora, asks what actually counts as an "acceptable" acoustic change in the pursuit of decarbonisation. A 40 dBA limit can sit close to daytime background levels in rural Ireland but dominate a night-time soundscape that drops below 25 dBA, and amplitude modulation, that rhythmic swish or thump, is consistently more annoying than steady noise at the same level. His piece asks acousticians to reckon with the fact that the communities hosting turbines are rarely the same communities receiving the electricity.

Eoin King then returns with Franck Bertagnolio to introduce RESONATE, IEA Wind TCP's new international task treating engineering, perception, and policy as one problem instead of three conversations that never talk to each other.

We close the section by looking backward. Isaac Old revisits the NASA Large Wind Turbine Program, acoustical research from the mid 1970s through the early

1990s that predates nearly everything else in this issue. As infrasound concerns resurface in today's debates, Isaac asks how much of that decades old research still holds up, and how much is being rediscovered.

From there we shift into departments. Jim Thompson offers field stories that will make you wince before you laugh, from the executive who didn't see the chain across the test track to the vibration crew chasing data through a tropical storm thirty feet off the ground. Send us yours. Kylfa and Salomon explain ultrasound and infrasound for readers of all ages, and Stig's reference cards revisit the physics of wind tones, a nice companion to this issue's "ABCs of Acoustics." Dr. Eric Ungar passed away this year, and the column you're about to read is likely his last, on organ pipes, written with the clarity and wit that defined his work. We're planning a longer tribute for a future issue, and if you have a memory of Eric worth sharing, we'd like to include it.

We save two pieces for the very end. Somewhere off the coast of Hawai'i, a monk seal is growling, groaning, and whooping in frequencies that overlap almost exactly with the noise humans make near it. Don't just read this one. Listen to it. We've embedded audio of Kekoa and Ho'ailona's vocal bouts directly in the piece, along with video of a wild seal vocalizing underwater. No spectrogram does that whoop justice.

We close on a warning shot. David Woolworth's piece on data centers and low frequency and infrasound measurement makes clear that this industry is growing faster than most communities can prepare for, and A weighted criteria still aren't up to describing what residents actually hear. Consider this our formal invitation: we want more voices on this topic in our next issue, case studies, regulatory gaps, community response data, whatever you've got.

Let us know what you think. ■



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# Towards quieter wind turbines by perception-driven design

Roberto Merino-Martinez, Faculty of Aerospace Engineering, Delft University of Technology, The Netherlands

## Introduction

Wind energy is one of the cornerstones of the global energy transition. Its installed capacity continues to grow steadily, both onshore and offshore, and so does the physical size of the turbines themselves: rotor diameters exceeding 200 m (roughly two football fields!) and hub heights above 150 m are no longer exceptional. Larger rotors capture more energy and, in general, reduce the cost per kWh, but they also raise a legitimate question for the acoustics community:

***“What does this upscaling trend mean for the noise experienced by the growing number of people living near wind farms?”***

## A relatively quiet source, but a large impact

Compared to aircraft or road traffic, wind turbines are relatively quiet sources in terms of sound pressure levels. Paradoxically, however, they generate a disproportionately large annoyance response [1], see Fig. 1. Whereas direct adverse health effects of wind turbine noise remain scientifically unproven, the

evidence on noise annoyance is unambiguous. Several acoustic characteristics help explain this “*annoyance penalty*”. Wind turbine noise is typically dominated by low-frequency content, which propagates over long distances with little atmospheric attenuation, penetrates building façades more easily, and is more poorly masked by everyday background sounds. Moreover, the periodic *swish* caused by the blade rotation introduces pronounced amplitude modulation (AM), which is repeatedly identified as a key driver of annoyance [2]. The trend towards ever-larger rotors is likely to shift the emitted spectra towards even lower frequencies due to lower rotation velocities and, hence, blade-passing frequencies, potentially aggravating precisely those features that communities often find irritating.

## Noise reduction measures at the source

On the engineering side, considerable progress has been achieved in reducing aerodynamic noise at the source. Turbulent-boundary-layer trailing-edge (TBL-TE) noise, the dominant aerodynamic noise mechanism in modern turbines, can be partially mitigated by trailing-edge



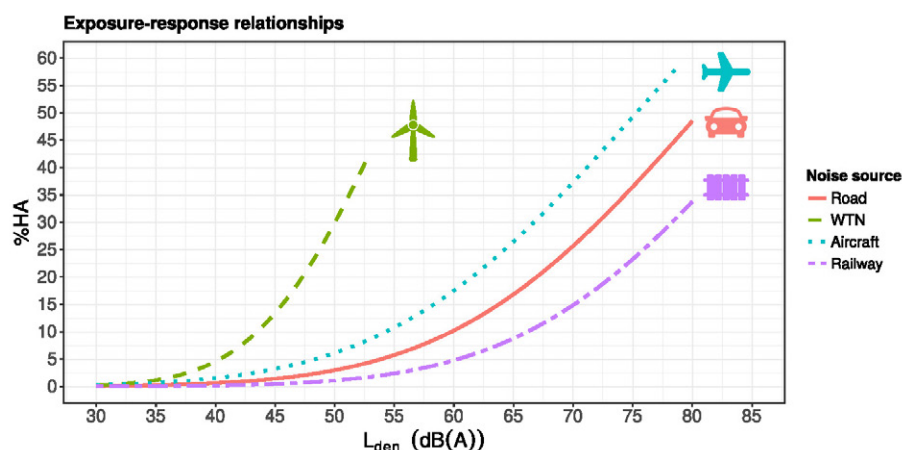


Figure 1 – Comparison of exposure-response relationships for people highly annoyed by road, railway, aircraft, and wind turbine noise (WTN) [1].

serrations, now standard on many commercial turbine designs, as well as by emerging concepts such as porous trailing-edge inserts, brushes, and combinations thereof. A holistic review of these technologies, connecting blade aeroacoustics all the way to annoyance estimation, is provided in [3].

There is, however, an important caveat: most of these additions are effective mainly from the mid-frequency range upwards (usually 300 Hz – 2 kHz), precisely where the human ear is most sensitive but not where wind turbine sound spectra concentrate their energy. Reductions of a few decibels in overall A-weighted level are certainly valuable for noise assessment, yet they may leave the low-frequency content and the amplitude modulation, the perceptually most critical ingredients, largely untouched. This mismatch between where we *can* reduce noise and where we *should* reduce it, perceptually speaking, is one of the central emerging challenges in the field.

## Beyond the decibel: psychoacoustic metrics

This challenge exposes a deeper methodological issue: the metrics we consider. Conventional indicators, such as the A-weighted sound pressure level or the day evening night level  $L_{den}$  were never designed for a source that is predominantly low-frequency and strongly amplitude-modulated. In fact, A-weighting heavily discounts low frequencies, and long-term energy-averaged metrics are essentially blind to temporal fluctuations. Two wind farm scenarios with identical  $L_{den}$  values can, therefore, evoke very different annoyance responses. Psychoacoustic sound quality metrics, such as loudness, tonality, sharpness, roughness, and fluctuation strength, capture these perceptual dimensions explicitly and can be combined into global psychoacoustic annoyance indicators [4]. Their application to wind turbine noise, including a psychoacoustic model for predicting noise annoyance, was presented in [5]. Such metrics offer a

more faithful proxy of human perception than a single decibel figure and are increasingly being adopted in acoustic research.

## Future directions: perception-influenced design and planning

These developments point towards a paradigm shift: *perception-influenced design*, see Fig. 2. Instead of simply minimizing an A-weighted level, blade designers and noise-control engineers can target the specific sound features that drive annoyance, i.e. identifying what to tackle “smartly” in perceptual terms. Psychoacoustic evaluation in the design loop enables ranking competing low-noise technologies not by decibels saved, but by annoyance and perceptual improvements. Auralization is a powerful enabler of this vision [3]. By synthesizing physically accurate, audible renditions of future wind farms, ideally reproduced in immersive listening facilities, developers and authorities can let local communities *hear* proposed scenarios before a single turbine is erected, instead of discussing decibel values, which are often confusing for the general public. This fosters transparency and trust in the planning process, as these tools provide actionable information for the optimal placement and operation of turbines around populated areas [6]. For example, a few large turbines might be energetically more efficient but emit more noise at predominantly lower frequencies, which is more challenging to mitigate (Fig. 3). On the other hand, several smaller turbines may require more land but produce lower noise emissions and mostly at higher frequencies, which attenuate more easily with distance. Which configuration is preferable from the residents’ point of view? Perception-based comparisons of exactly such trade-offs, using auralization, psychoacoustic analyses, and listening experiments, can help elucidate this dilemma [7].

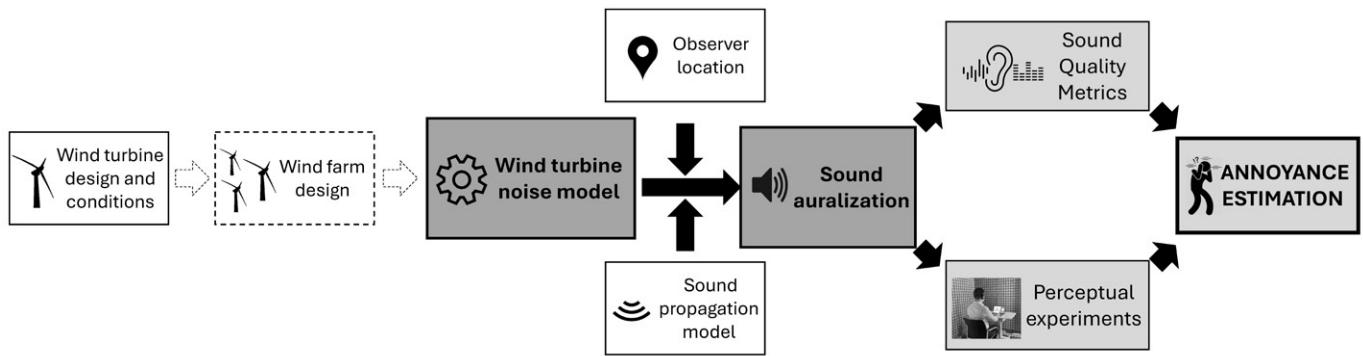


Figure 2 – Schematic of the proposed perception-influenced design framework for wind turbines and wind farms.

## Conclusions

Wind energy will keep expanding, and turbines will keep growing. Ensuring public acceptance requires placing human perception at the heart of the entire chain, from blade design, through noise assessment metrics, to wind farm planning and community engagement. The tools are maturing quickly. The main challenge for our community is to bring them into standards, regulations, and everyday engineering practice.

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Figure 3 - Conceptual comparison of two wind farm layouts with equal energy production: a few large turbines (left) vs. many smaller turbines (right).

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# Recent Advances in Noise Reduction of Wind Turbine Blades

Yang Bing, Beijing Goldwind Science & Creation Windpower Equipment Co., Ltd

Serrated trailing edges (STE) are currently the primary passive noise reduction technology for wind turbine blades. Consequently, most research efforts have focused on optimizing their geometric configurations. However, recent research by Goldwind has shown that vortex generators (VGs) can also reduce blade aeroacoustic noise. Moreover, combining VGs with serrated trailing edges yields superior noise reduction performance.

VGs are mainly used to enhance aerodynamic performance, such as suppressing stall in the root-to-mid span region and mitigating performance degradation caused by surface roughness. Consequently, VGs are typically installed in the root and mid-span sections of the blade. In contrast, serrated trailing edges are predominantly placed the outer one-third span, which is the primary source of aeroacoustic noise. This implies that VGs and STE are generally applied to different spanwise regions on wind turbine blades.

Since 2024, Goldwind has conducted a series of aeroacoustic wind tunnel tests for different airfoils applied in the outer part of blades in the Poul La Cour Wind Tunnel at DTU. These tests have demonstrated that

VGs with carefully optimized dimensions and placement can significantly reduce turbulent boundary-layer trailing-edge noise. Furthermore, when these VGs are combined with optimally designed serrations, the noise reduction effect is further enhanced. This combined approach is expected to become a mainstream research direction in aeroacoustics.

Figure 1 illustrates the wind tunnel acoustic test results for one of Goldwind's airfoils. The measurements were conducted at a constant wind speed of 80 m/s, yielding a Reynolds number of approximately  $4 \times 10^6$ . The results are presented as sound pressure level versus angle of attack. The clean airfoil, denoted as "Clean," and the airfoil with zigzag, denoted as "zz," are each evaluated with various combinations of VG and STE, with the results shown in the left and right panels, respectively. As can be seen from the figure 1, for the clean airfoil, VGs alone achieve a maximum noise reduction of 4.3 dBA at large angles of attack, while serrated trailing edges alone provide a reduction of approximately 3.8 dBA to 4.8 dBA across the tested angle-of-attack range. When combined, the two add-ons yield a maximum noise reduction of 6.4 dBA and a minimum of 4.6 dBA. For the airfoil with zigzag,

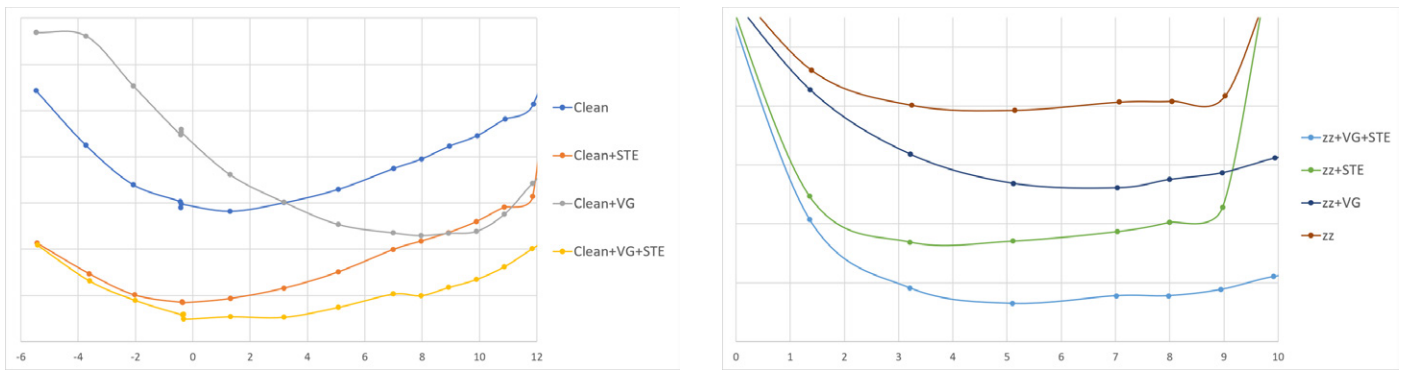


Figure 1: Comparison of wind tunnel noise measurements for the clean airfoil (left) and the zigzag airfoil (right) with various VG and STE configurations (vertical scale: 2 dBA per division).

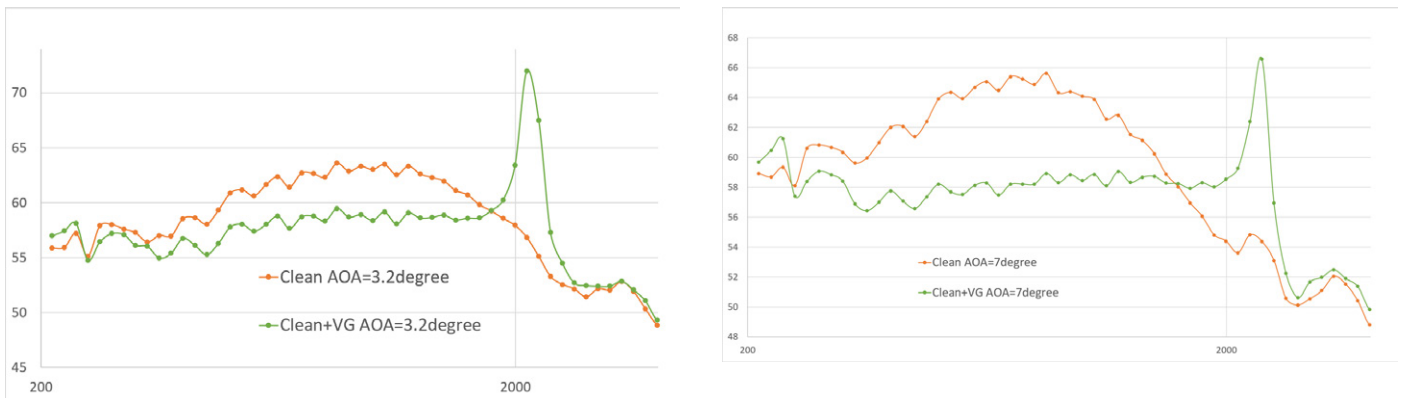


Figure 2: Spectral comparison for the clean airfoil without VGs ("Clean") and with VGs at angles of attack of 3.2° (left) and 7° (right).

the noise reduction performance of VGs remains similar to that observed on the clean airfoil.

However, it should be noted that at low angles of attack, the noise reduction effect of VGs is relatively weak and may even be negative for the clean airfoil, as VGs tend to excite blunt-trailing-edge shedding vortex noise. As can be seen from the spectral comparison in Figure 2, while VGs substantially reduce low-frequency noise, they simultaneously introduce high-frequency blunt-trailing-edge shedding vortex noise, which compromises the overall noise reduction. Whether VGs achieve a net noise reduction and to what extent depend on the trade-off between low-frequency attenuation and high-frequency excitation. It can also be observed from Figure 2 that as the angle of attack increases, the frequency of the blunt-trailing-edge shedding vortex noise rises while its sound pressure level decreases, and may eventually disappear which explains the more pronounced noise reduction effect of VGs at large angles of attack.

It should be noted that although VGs may excite blunt-trailing-edge shedding vortex noise at low angles of attack, this does not necessarily increase the overall noise beyond that of the clean airfoil. Whether the overall noise increases depends on the trailing-edge thickness and airfoil geometry. In Goldwind's tests, some airfoils show no noise increase with VGs. The results presented here are deliberately selected from cases where VGs do increase noise at low angles of attack, to better illustrate the potential impact of VGs, which will be further analyzed in the following discussion.

A series of noise test results on different airfoils with VGs and serrated trailing edges conducted by Goldwind all show similar trends and noise reduction performance. Based on the measurement results, the noise reduction mechanism of VGs is likely as follows: they inject streamwise vortices into the inner layer of the boundary layer, disrupting the spanwise vortex correlation at the trailing edge while simultaneously reducing the thickness of the spanwise-vortex-dominated boundary

layer. This results in a substantial reduction of low-frequency noise, which is a key contribution to the overall attenuation of turbulent boundary-layer trailing-edge noise. However, because the spanwise-vortex-dominated boundary layer is thinned, at angles of attack where the blunt-trailing-edge shedding vortex noise of the clean airfoil is not prominent, the addition of VGs renders blunt shedding vortex noise more noticeable.

Particular attention should be paid to the impacts of VGs on aerodynamic performance and structural loads when applying them to wind turbine blade noise reduction. Unlike serrated trailing edges, which can be designed to have essentially no impact on aerodynamic performance (e.g., lift-to-drag ratio), VGs exert a more pronounced influence in this regard. Nevertheless, judicious design can mitigate this impact. Therefore, a comprehensive trade-off among aerodynamic performance, structural

loads, and noise reduction is required when employing VGs. However, as the noise reduction capability of serrated trailing edges alone approaches its limit, the combination of VGs and serrated trailing edges emerges as a promising solution for future wind turbine blade noise control.

### About the Author

**Yang Bing** holds a Ph.D. in Aerospace Propulsion Theory and Engineering from Beihang University (BUAA). From 2007 to 2016, she worked at the Institute of Engineering Thermophysics, Chinese Academy of Sciences, focusing on wind turbine blade noise. In 2016, she joined Goldwind. From 2016 to 2022, she managed on-site noise measurements and noise reduction solutions for wind turbines and wind farms. Since 2023, she has been dedicated to blade noise reduction and aerodynamics. ■

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# Revising IEC 61400-11: Building Consensus for the Next Generation of Wind Turbine Acoustic Measurements

Lars Sommer Søndergaard, Project leader for IEC 61400-11 revision

For more than two decades, IEC 61400-11 has served as the internationally recognized framework for measuring and characterizing wind turbine acoustic emissions. The standard provides a common methodology that enables manufacturers, test laboratories, certification bodies, developers, regulators, consultants, and researchers to evaluate wind turbine noise in a consistent and comparable manner.

The current edition is based on Edition 3, published in 2012, and Amendment 1, published in 2018. Together, these documents continue to form the basis for most wind turbine acoustic emission measurements performed worldwide. As the newly initiated revision begins, it is worth reflecting not only on the technical evolution of the standard, but also on the role it plays in establishing confidence, comparability, and trust across the global wind industry.

## A Brief History of IEC 61400-11

The development of IEC 61400-11 has closely followed the growth of the wind industry. As turbines became larger and more widely deployed, the need for internationally harmonized acoustic measurement methods became increasingly apparent.

The 2002 edition established a globally accepted methodology for characterizing wind turbine noise emissions, including procedures for determining sound power levels, assessing tonal characteristics, and relating acoustic emissions to wind speed. A major revision followed in 2012 with Edition 3, introducing enhanced data reduction procedures and updated methodologies. Amendment 1, published in 2018, refined and clarified parts of the standard and remains part of the current consolidated version.

Today, IEC 61400-11 is the global reference for wind turbine acoustic characterization and is widely used for certification, environmental assessments, permitting, and noise prediction studies.

## Why IEC 61400-11 Matters

The continued relevance of IEC 61400-11 stems from its ability to provide a consistent and repeatable measurement methodology. By defining requirements for instrumentation, measurement locations, meteorological observations, operational data, and analysis procedures, it ensures that measurements performed anywhere in the world can be compared with confidence.

The standard enables fair comparison between turbine models, supports regulatory decision-making, and provides the acoustic emission data required for environmental noise prediction. In many respects, it forms the common language through which wind turbine acoustic performance is communicated internationally.

## The Measurement Principle Behind IEC 61400-11

At its core, IEC 61400-11 is an acoustic emission characterization standard rather than a community noise assessment standard. Its purpose is not to determine the noise level at a specific residence, but to characterize the noise generated by a wind turbine in a consistent and repeatable manner.

The principle is straightforward: measure the turbine close enough to minimize propagation-related uncertainties while remaining far enough away for the turbine to be treated as an acoustic source. Acoustic measurements are combined with meteorological and operational data to characterize turbine noise as a function of wind speed.

In its simplest form, the objective of IEC 61400-11 is:

**To determine the acoustic emission characteristics of a wind turbine by measuring sound, meteorological conditions, and turbine operation simultaneously, and expressing the turbine's noise emission as a function of wind speed in a manner that is repeatable, comparable, and independent of a specific project location.**

This principle has remained at the heart of the standard throughout its evolution.

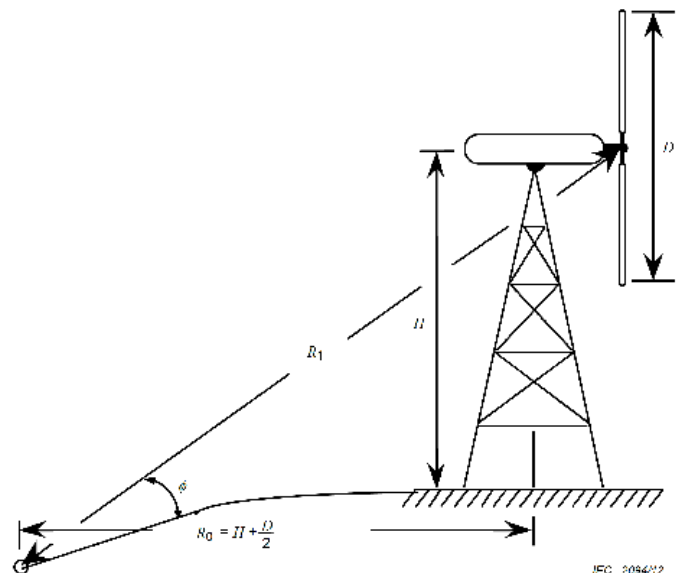


Figure 1: Showing the microphone measurement position for a horizontal axis turbine. The figure is from IEC 61400-11:2012+AMD1:2018 CSV "Copyright © 2026 IEC Geneva, Switzerland. [www.iec.ch](http://www.iec.ch)"

## From Simple Principle to Challenging Practice

Although the fundamental principles of IEC 61400-11 are relatively straightforward, anyone who has participated in a measurement campaign knows that their practical implementation is anything but simple.

At first glance, the objective appears clear: measure the turbine noise, measure the wind conditions, correlate the two, and derive a reliable characterization of the turbine's acoustic emissions. In reality, however, obtaining high-quality data often requires a combination of technical expertise, patience, and a certain degree of cooperation from the weather.

Unlike many other acoustic measurements, wind turbine noise measurements cannot be performed on demand. Wind is required to operate the turbine and generate representative acoustic emissions, but the same wind also creates challenges for the measurement itself.

Wind excites vegetation, buildings, and other environmental features, generating background noise that can influence the measurement. The stronger the wind becomes, the more difficult it can be to distinguish turbine noise from ambient sound sources. At the same time, great care must be taken to prevent wind-induced noise from contaminating the microphone signal. The use of windscreens is therefore essential.



*Figure 2: Photos from a measurement. Left: Photo of the microphone under a secondary wind screen on a plate on the ground. Right: Photo of a meteorology mast used for determining the wind speed during background noise measurements.*

Weather conditions rarely follow the measurement schedule. Forecasts may suggest ideal conditions only for reality to develop differently, while valuable measurement opportunities often arise unexpectedly. Successful campaigns therefore depend not only on instrumentation and methodology, but also on flexibility, persistence, and a measure of good fortune.

This combination of acoustic science, meteorology, and operational turbine behavior is one of the aspects that makes IEC 61400-11 both challenging and fascinating. It also explains why practical experience remains so important in the ongoing revision.

## Why Revise a Successful Standard?

If the standard works well, why revise it?

The answer is simple: the wind industry continues to evolve. Modern turbines are significantly larger than those considered when earlier editions were developed, often featuring rotor diameters exceeding 200 m, higher hub heights, advanced operating modes, and increasingly sophisticated noise management strategies.

At the same time, more than a decade of practical experience with Edition 3 has highlighted areas where clarification, simplification, or improvement may be beneficial. The goal of the revision is therefore not change for its own sake, but to ensure that IEC 61400-11 remains technically robust, practical, and internationally relevant.

The revision is being carried out by IEC TC88 Maintenance Team 11 (MT11), which currently consists of

42 experts from around the world representing a broad range of technical backgrounds and stakeholder groups.

## Current Topics Under Consideration

The revision is still in its early stages, and a number of technical topics are under discussion. These include:

- Wind speed ranges, measurement methods and devices
- Tonal analysis methodologies
- Background noise handling and correction
- Frequency range requirements
- Atmospheric absorption
- Windscreens
- Uncertainty
- Applicability to small wind turbines

Not all of these discussions will result in changes to the standard. As with any IEC revision, proposals must be evaluated on the basis of technical merit, practical applicability, reproducibility, and international consensus. The revision should therefore be viewed as an open technical discussion rather than a predefined set of changes.

## The Importance of Consensus

Perhaps the most important aspect of standards development is consensus.

IEC standards are developed through the participation of experts representing manufacturers, testing organizations, certification bodies, regulators,



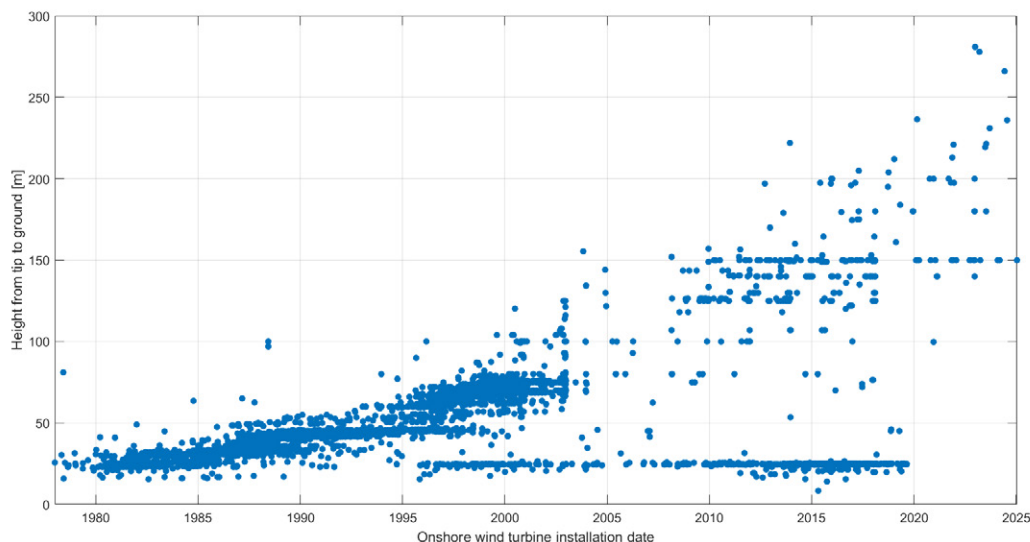


Figure 3: Plot showing the development of the total height (tip-to-ground height) of Danish onshore wind turbines between 1978 and 2025. Data source: the Danish Energy Agency (data merged from two tables).

consultants, researchers, and other stakeholders. Consensus does not mean that everyone gets exactly what they want; it means that different viewpoints are considered, technical concerns are addressed, and the final document achieves broad international support.

For IEC 61400-11, this is particularly important because acoustic measurements underpin certification, project development, environmental assessments, and regulatory approvals. Broad consensus helps ensure confidence in both the methodology and the resulting data.

## Invitation to Participate

One objective of this article is to raise awareness of the ongoing revision and encourage wider participation from the acoustics community.

The success of IEC 61400-11 has always depended on contributions from experts with different backgrounds and experiences. As wind turbine technology continues to evolve, broad international participation remains essential to ensure that future editions remain scientifically sound, practically applicable, and globally relevant.

Experts interested in participating should contact their national mirror committee for IEC TC88. Information on IEC National Committees can be found [here](#).

Participation in IEC technical work takes place through nomination by the relevant National Committee.

## Looking Ahead

The revision of IEC 61400-11 marks the beginning of an important and collaborative process. The objective is to

build upon a proven foundation while ensuring that the standard remains fit for purpose in an evolving industry.

The success of IEC 61400-11 has always rested on three fundamental pillars: **sound science, practical applicability, and international consensus**. Those same principles will hopefully guide the current revision and help ensure that IEC 61400-11 remains the trusted global reference for wind turbine acoustic characterization for years to come.

## Acknowledgement

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## About the Author

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# ISO 9613-2:2024-01 Impact Assessment of Noise Modelling Procedure in Wind Power Projects

M.Sc. Carlo Di Napoli, Principal Consultant, AFRY Finland Oy; Dr. Erkki Heikkola, Senior Consultant, AFRY Finland Oy; Dr. Mika Laitinen, Senior Consultant, AFRY Finland Oy

In Finland, the National Noise Modelling Guidelines for Wind Power Projects YM 2/2014 provide instructions for applying ISO 9613-2 standard in the environmental impact assessment (EIA procedure) and detailed zoning. The original version of the standard (Edition 1) is from 1996, which was in force at the time of publication of the guidelines until January 2024, when the latest version of the standard, ISO 9613-2:2024-01 (Edition 2), was published. Since then, the calculation procedures of the latest standard version have been implemented in various noise modelling software during 2024–2025.

Preliminary impact assessment calculations for three wind farms (Figure 1) indicated a need for a more detailed analysis. Comparison of the Edition 2 and Edition 1 calculation results showed roughly 5 dB higher results further away from the wind farm when calculating with Ed.2 standard. It was concluded that for certain projects, this could represent a moderate planning-phase risk.

The calculations were performed in a simplified test environment. The two ISO 9613-2 versions offer multiple modelling options. However, Finnish wind turbine noise

modelling follows the national guidelines (2014), which define how the standard is applied. As a result, only some of the changes made to the standard will cause changes to the noise modelling of wind turbines in Finland.

For wind turbine noise modelling, the most significant changes in the standard versions relate to obstacle modelling. Terrain obstacles prevent a direct line of sight between the noise source and the object exposed to the noise. The noise attenuation effect of a terrain obstacle is presented with the term 'Abar', described in chapter 7.4 of the standard documents, which is calculated using different formulas in the 1996 and 2024 standard versions.

The tests showed that the 1996 and 2024 editions model noise attenuation behind terrain barriers differently: The 1996 formulas generally produce greater attenuation, while the 2024 formulas result in higher predicted noise levels when a terrain obstacle lies between the turbine and receiver. The noise barrier attenuation seems unrealistically high in some situations with the 1996 formulas, and small changes in the location of the object exposed to noise can produce surprisingly sharp jumps



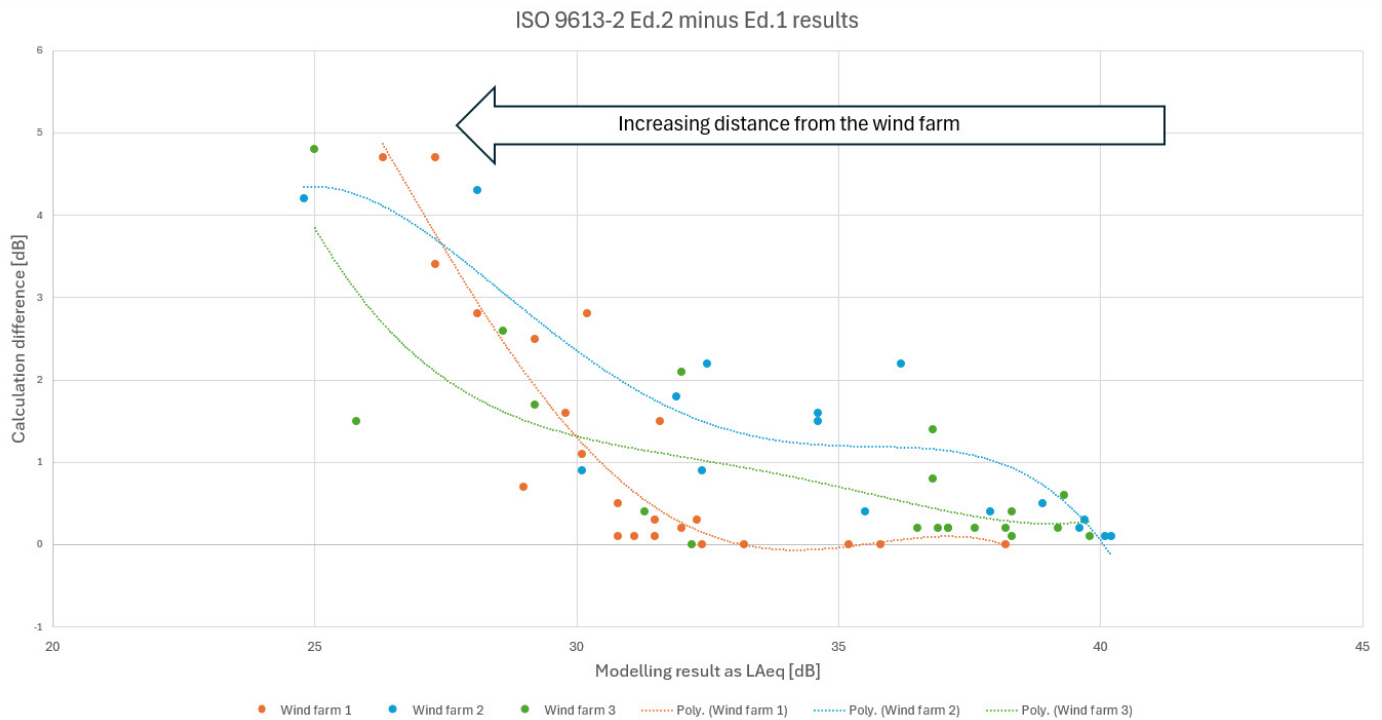


Figure 1: Modelling result difference of three different wind farms cases

in the attenuation. The 2024 standard version probably aims to avoid overestimating the attenuation caused by the obstacle and to produce a more consistent and reliable estimate of the noise level.

The 2024 standard version includes an informative appendix D related to wind power modelling, which was not included in the 1996 version. For example, it recommends limiting the terrain obstacle attenuation term (Abar) to 3 dB in hilly terrain to improve accuracy. The use of this limiter will clearly increase noise levels when the noise is heavily obstructed by terrain. However, this informative appendix is not considered as part of the current National modelling guideline.

The 2024 standard version also includes methods for modelling the effect of wind direction and the directivity of the noise source on noise. These methods have no effect on the noise modelling of wind turbines in Finland, because according to the noise modelling guide 2014, the noise of a wind turbine is modelled as a omnidirectional point source in downwind conditions.

## Methodology

In the test environment, artificial terrain elevation data has been generated, with 0–2 terrain obstacles between the wind turbine and the receptors. The point source describing the wind turbine is on the left side at the origin

of the coordinate system, the height of the obstacles varies only in one direction, and the shape of the obstacle remains constant in the transverse direction. There are 11 receptors at 500–1500 m from the sound source every 100 m. The calculation was carried out using AFRY's own wind power noise application AFRY-Numerola Noise, in which the simulation of the noise propagation of wind turbines has been carried out in accordance with the basic versions of the 1996 and 2024 standards.

## Results

The results of the 1996 standard version are presented in the graphs as large dots and the results of the 2024 standard version as smaller dots. The height of the obstacle is shown on the y-axis on the left side of the graph, and the result of the sound pressure is shown on the y-axis on the right side of the graph. In addition, the lower graph shows the difference in the sound level of each test (2024-1996).

In the left-hand test case (Figure 2), the difference between the standards reached 4.8 dB at 1100 m and exceeded 3.7 dB from 700 m onwards, where the turbine was no longer visible from the receptor. The difference remained significant at 1500 m, the limit of the modelling area. Similar results were observed in the right-hand test case, with differences increasing from 0.2 dB at 800 m to a maximum of 4.8 dB at 1100 m.

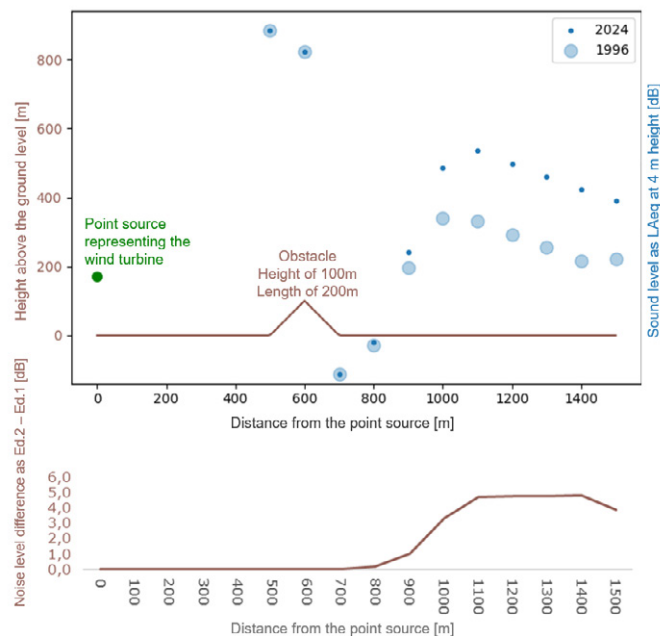
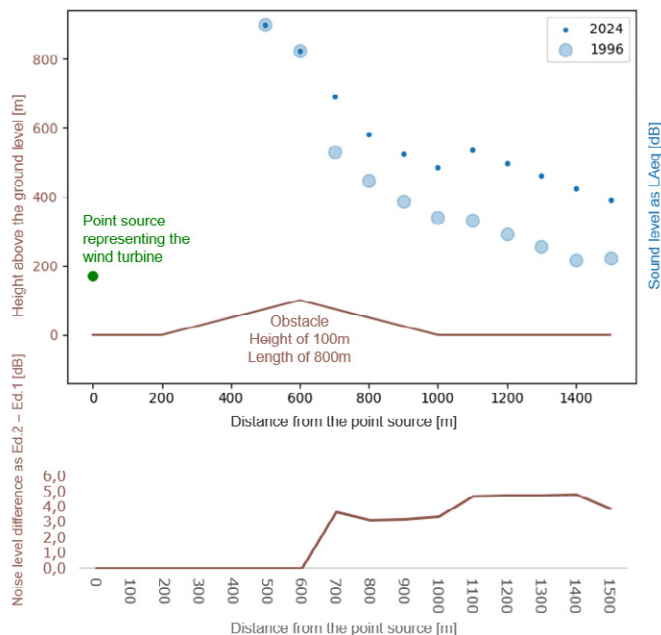


Figure 2: Modelling results of two different test cases

To verify the test observations, the calculations according to the ISO 9631-2 standard were carried out in addition to the AFRY program using two commercial software, SoundPlan and CadnaA.

## Conclusions

The calculation examples showed that ISO 9613-2:2024 predicts higher noise levels than the 1996 edition when there is a terrain obstacle between the hub of the wind turbine and the object exposed to the noise. The effect was evident even for gentle terrain and extended beyond the 1500 m test range in some cases. Maximum differences reached 4.8 dB, with the 2024 edition consistently producing higher results. On flat ground, both editions gave identical noise levels.

In August 2025, ISO's technical committee ISO/TC 43/ SC 1 has decided to start producing the 3rd version of the standard (ISO/AWI 9613-2).

## Acknowledgments

Financial support for this work was provided by Ministry of Environment Finland. The authors owe great thanks for the financial support.

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ISO/AWI 9613-2 - Acoustics — Attenuation of sound during propagation outdoors — Part 2: Engineering method for the prediction of sound pressure levels outdoors. International Organization for Standardization, Switzerland.

## About the Author

**Carlo Di Napoli** (M.Sc. Tech.) has over twenty years of experience in industrial noise assessments. These assignments have included 3D modeling, measurements, consulting, education and research covering especially wind, energy and mining industries. He has previous experience from the conventional power sector guarantee testing (gas turbines, steam turbines and boilers) and European Union emission trading auditing and verification as a Lead Verifier. Currently he is working as a Principal Consultant, Environment Vantaa, Finland. ■



# Temperature Inversions and Wind Turbine Noise: What Long-Term Field Data Shows

Brooklynn Bennitt, Duncan Halstead, Aercoustics Engineering Limited

Temperature inversions have long been considered one of the atmospheric conditions that can drastically increase sound levels at nearby receptors. The theory is straightforward: when the air temperature gradient is positive (temperature increases with height), sound refracts downward toward the ground, potentially increasing noise levels experienced by residents.

However, a long-term monitoring study conducted by Aercoustics Engineering Limited suggests the relationship may be more complex than conventional wisdom implies. Drawing on detailed acoustic measurements, turbine operational data, and meteorological tower data, the study found only a weak relationship between inversion strength and measured wind turbine noise levels. While stronger inversions were associated with higher sound levels, the effect was inconsistent and often overshadowed by other environmental and operational factors. These findings provide valuable real-world evidence for a topic that has historically been discussed largely through theory and modelling.

## A Question Worth Testing

Temperature inversions are a familiar concept to atmospheric scientists and acousticians alike. Under

typical conditions, temperature decreases with height, causing sound waves to refract upward. During an inversion, the opposite occurs: warmer air sits above cooler air, increasing sound speed with height and refracting acoustic energy downward.

Atmospheric stability effects are already incorporated, either directly or indirectly, into many commonly used environmental noise and dispersion modelling approaches, including ISO 9613-2, Nord2000, and Concawe/Harmonoise. For wind turbines, however, the situation is especially interesting because the source of the sound is elevated well above grade and turbine noise emissions are themselves closely tied to atmospheric conditions.

Despite widespread assumptions about inversion effects, relatively little long-term field data exists that directly compares inversion strength with measured wind turbine sound levels. An opportunity to examine a large monitoring dataset prompted the Aercoustics team to investigate whether inversion strength could be clearly linked to higher sound levels in practice.



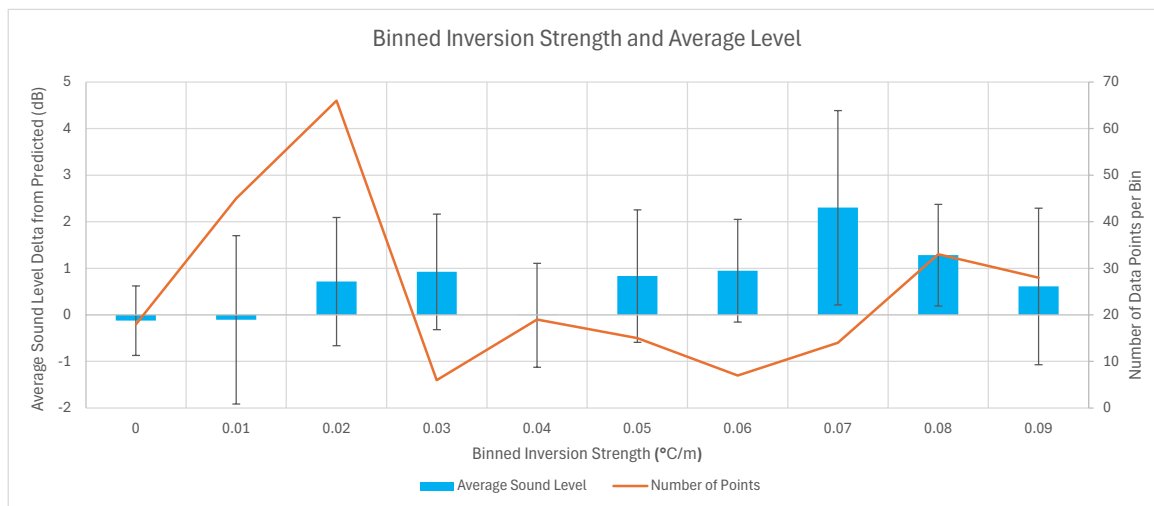


Figure 1: Average Different Between Measured and Predicted Sound Levels in the Downwind Condition, Binned by Inversion Strength.

## Measuring More Than Just Noise

The study was conducted at a rural wind farm characterized by relatively flat terrain. Analysis combined measurements from noise monitoring equipment, local weather measurements, turbine SCADA data, and a meteorological tower extending to near hub height. The acoustic monitoring campaign was supplemented by approximately 1.5 years of meteorological tower data, providing a broader understanding of atmospheric behaviour across the site.

To ensure the analysis focused on turbine-related sound, we carefully screened and filtered the dataset. We compared the resulting measurements against predictions from ISO 9613-2 modelling, allowing us to assess whether measured levels differed systematically under stronger inversion conditions.

## Binned Results: A Weak Overall Correlation

To look more closely at the trend, sound levels were grouped into bins based on inversion strength.

As shown in Figure 1, average sound levels generally increased as inversion strength increased. At first glance, this appears to support conventional expectations regarding atmospheric refraction. However, a closer examination revealed that the differences between inversion categories were relatively small and that variability within each category was substantial. Error bars representing the standard deviation often overlapped significantly between neighbouring bins.

The overall relationship between inversion strength and sound level was positive but weak. In practical terms, the results suggest that stronger inversions may contribute to elevated sound levels on average, but inversion strength by itself is not a reliable single predictor of what will be measured at a receptor location.

## Case Studies: Inconsistent Night-to-Night Behaviour

The limitations of relying solely on inversion strength became even clearer when individual nights were examined, displayed in Figure 2.

In one case study, as inversion conditions developed during the night, sound levels showed a weak upward trend with inversion strength, rising up to 4 dB above predicted levels at the strongest points in the period, though the inversions involved were modest enough that this magnitude of effect wasn't expected to be significant.

A second case study produced a different pattern. An increasing inversion strength resulted in lower measured sound levels, the opposite of the expected trend. This trend was present despite high observed inversions throughout the night.

Together, the two examples highlight a key takeaway from the study: atmospheric conditions do not operate in isolation. Wind speed, turbulence intensity, humidity, wind shear, and other meteorological variables can all influence measured sound levels, making it difficult to attribute changes to inversion strength alone.

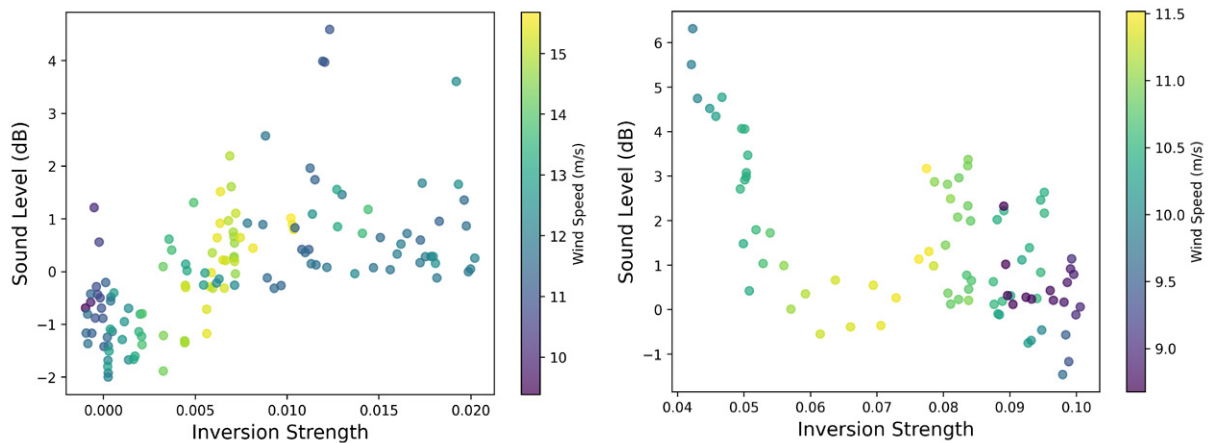


Figure 2: Sound Level Against Inversion Strength Coloured by Hub Height Wind Speed for Two Representative Nights

## Long-Term Meteorological Trends

The broader meteorological dataset helped to explain why inversion effects were difficult to isolate.

Analysis of approximately 1.5 years of MET tower measurements showed that strong temperature inversions occurred most frequently during lower wind speed conditions. Conversely, the higher hub-height wind speeds associated with maximum turbine sound emissions were much less likely to coincide with strong inversion events. In fact, strong inversions were relatively uncommon when hub-height wind speeds reached 10 m/s or higher.

This finding is important because it suggests that the atmospheric conditions most favourable to downward refraction do not necessarily occur at the same time as the operating conditions that produce the highest noise emissions of a wind turbine. As a result, the theoretical “worst-case” combination may occur less frequently in practice than is often assumed.

## Implications for Practice

The study confirms the underlying physics of sound propagation under temperature inversions, while showing that real-world turbine noise behaviour is shaped by a broader range of variables than inversion strength alone.

While stronger inversions were associated with slightly higher average sound levels, the relationship was weak and highly variable. The two case studies and the longer-term meteorological analysis both suggest that

atmospheric stability should be evaluated alongside other factors such as turbulence intensity, humidity, wind shear, and turbine operating conditions. Future studies may benefit from combining these variables to better quantify the complex interactions that govern environmental noise propagation.

Long-term field measurements remain essential for validating assumptions derived from theory and modelling. As increasingly sophisticated datasets become available, they may challenge long-held expectations and lead to a more nuanced understanding of how atmospheric conditions influence wind turbine noise.

## About the Authors

**Brooklyn Bennitt** is a co op student at Aercoustics Engineering Ltd, where she has contributed to projects related to wind turbine noise modelling and analysis, environmental noise modelling, architectural acoustics, and instrumentation testing. She is currently a fourth-year mechanical engineering student minoring in sustainable energy at the University of Toronto.

**Duncan Halstead** is Vice President of Operations at Aercoustics Engineering Ltd, where he leads technical and operational delivery across a range of environmental acoustics projects. His professional work focuses extensively on the assessment and management of wind turbine noise, supporting renewable energy developments through detailed noise modeling, compliance assessments, and expert interpretation of regulatory requirements. ■





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# Open Research Data for the Investigation of Sound Propagation from Onshore Wind Turbines

Susanne Könecke, Tobias Böhne, Raimund Rolfes, Leibniz University Hannover, Institute of Structural Analysis / ForWind

Experimental studies of sound propagation from onshore wind turbines are essential for understanding atmospheric sound propagation processes and for developing and validating numerical sound propagation models. However, long-term field measurements under real operating and atmospheric conditions are technically challenging and require considerable personnel and financial resources. At the same time, no comprehensive datasets are currently available to the scientific community, restricting reproducible investigations of different research questions.

Against this background, as part of research projects extensive acoustic field measurements were conducted (grant no. 0324134A) and resulting research data were systematically processed (grant no. 03EE3062). Selected datasets were made publicly available at the research data repository of the Leibniz University Hannover in accordance with the FAIR (Findable, Accessible, Interoperable, and Reusable) principles. In addition to a comprehensive one-month measurement dataset, a validated framework for identifying and characterizing wind turbine noise, and datasets for validating numerical sound propagation models, have been published.

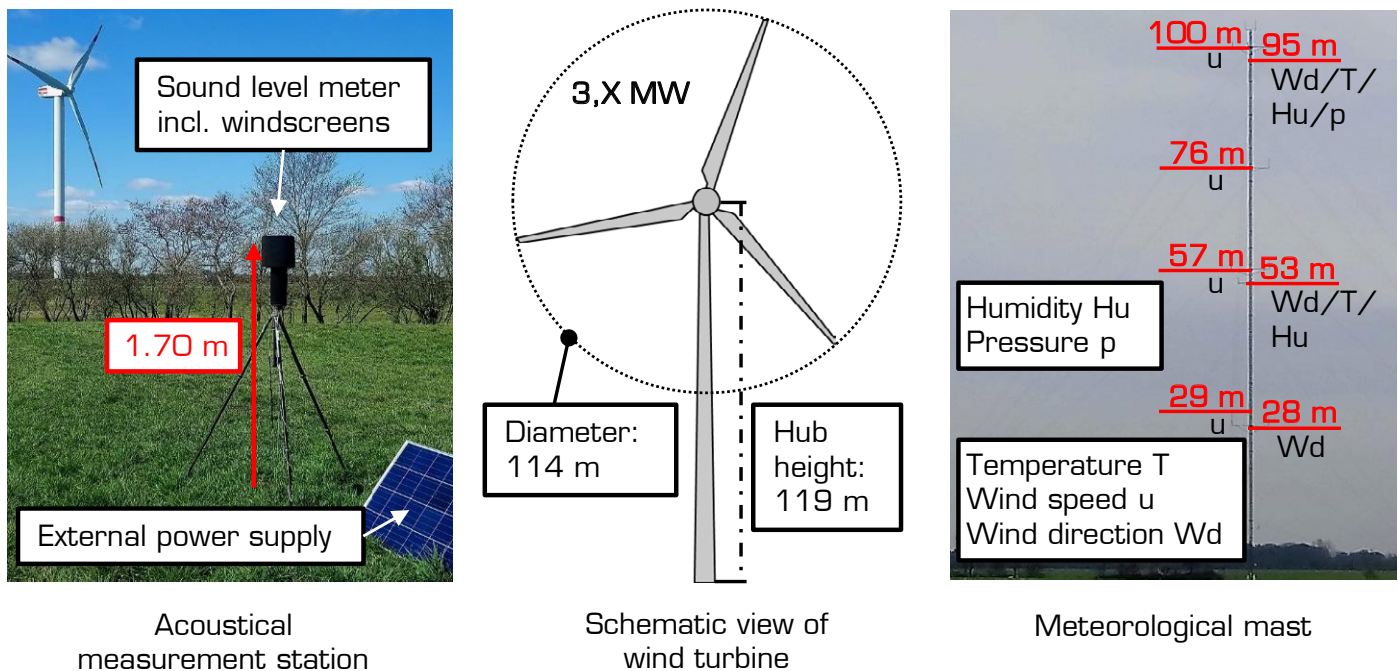


Figure 1: Overview of measurement systems and wind turbine [4].

This contribution provides an overview of the published datasets and their scientific applications. Further information on the datasets and the underlying scientific research can be found in the corresponding open-access journal articles referenced in the individual sections.

## Measurement Dataset for Sound Propagation Studies

Acoustic, meteorological, and wind turbine operational data were synchronously acquired during five measurement campaigns conducted near onshore wind farms in northern Germany. Acoustic measurement stations were installed at three distances from the wind turbine to record acoustic time signals as well as averaged sound pressure levels and third-octave spectra. In addition, meteorological measurements up to a height of 100 m were performed to characterize the atmospheric conditions, and SCADA (Supervisory Control and Data Acquisition) data from the wind turbine were recorded. An overview of the measurement systems is shown in Fig. 1.

A processed one-month dataset containing all measured parameters was published as open access, enabling a correlation between the measured acoustic signals, the operating state of the wind turbine, and the prevailing atmospheric conditions [1]. The dataset is suitable for investigations of sound propagation under varying

atmospheric conditions as well as for addressing questions regarding sound generation and the occurrence of physical phenomena such as amplitude modulation. By making the dataset publicly available, it can be reused in future research.

## Identification and Characterization of Wind Turbine Noise

Long-term acoustic measurements contain not only wind turbine noise but also numerous competing noise sources, such as wind-induced noise, vegetation noise, and traffic. The reliable identification of time periods dominated by wind turbine noise is therefore essential for further analyses.

For this purpose, a two-stage framework was developed (see Fig. 2). In the first stage, a preliminary selection is made based on acoustic criteria as well as meteorological and turbine-specific operating data. Subsequently, characteristic modulation frequencies extracted from the acoustic signals are compared with the blade passing frequency of the wind turbine to reliably identify periods dominated by wind turbine noise. Based on these selected periods, characteristic sound components such as amplitude modulation, tonal components, and high-frequency whistling noise can also be automatically determined. The framework was validated using a



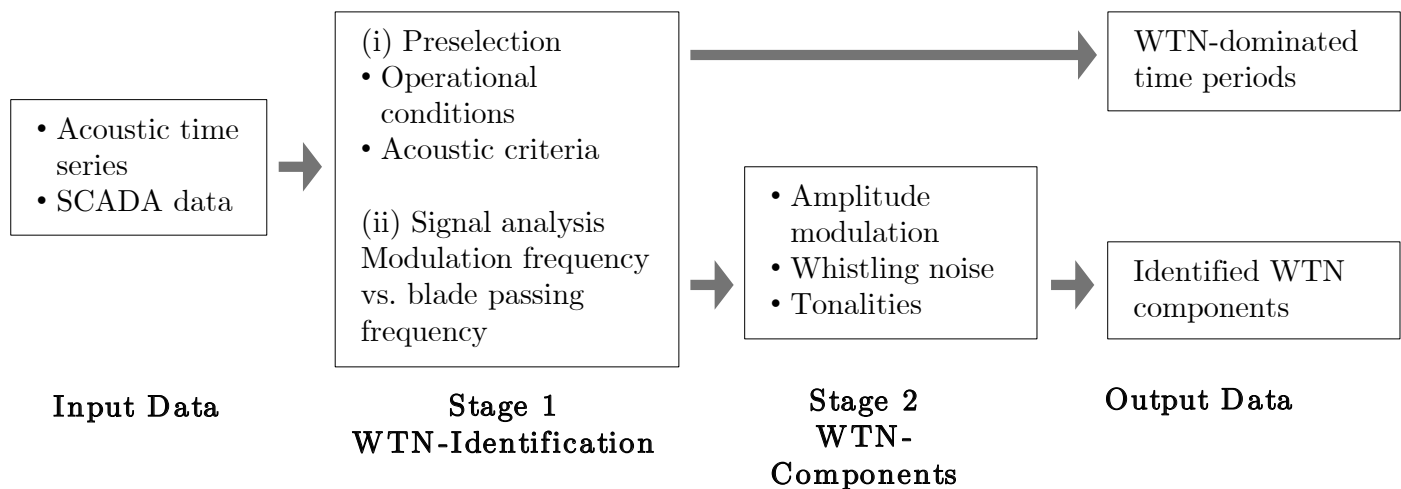


Figure 2: Overview of the two-stage framework for identifying and characterizing wind turbine noise in long-term acoustic measurements.

classified reference dataset derived from a structured listening test. [2]

In addition to the scientific publication, the framework, the listening test platform, and example audio files were made publicly available [3]. As a result, a validated method for identifying and characterizing wind turbine noise is now publicly available for the first time.

## Reference Dataset for Sound Propagation Model Validation

The measurement data were also used to validate a numerical sound propagation model based on the parabolic equation method. The validation comprises ten reference cases representing different atmospheric propagation conditions. The required model input parameters were derived from the measurement data, and the predicted sound propagation losses were systematically compared with the measured results [4]. As an example, Fig. 3 compares measured and modeled sound propagation losses for one-third-octave bands under crosswind conditions. In addition to the measurement data, the published dataset includes all model input parameters and numerical simulation results, thereby enabling reproducible model validation [5].

## Conclusions

The published datasets cover different stages of experimental investigations of sound propagation from wind turbines, ranging from measurement data acquisition and standardized data selection to the validation of sound propagation models. Together, they

provide the scientific community with a consistent research data basis for a broad range of studies in wind turbine acoustics.

We hope that the published datasets will be adopted by the scientific community, reused in future research, and supplemented with additional reference datasets. This will enable the development of new analysis methods, the reproducible validation of existing models, and the continuous advancement of experimental and numerical methods for investigating sound propagation from wind turbines.

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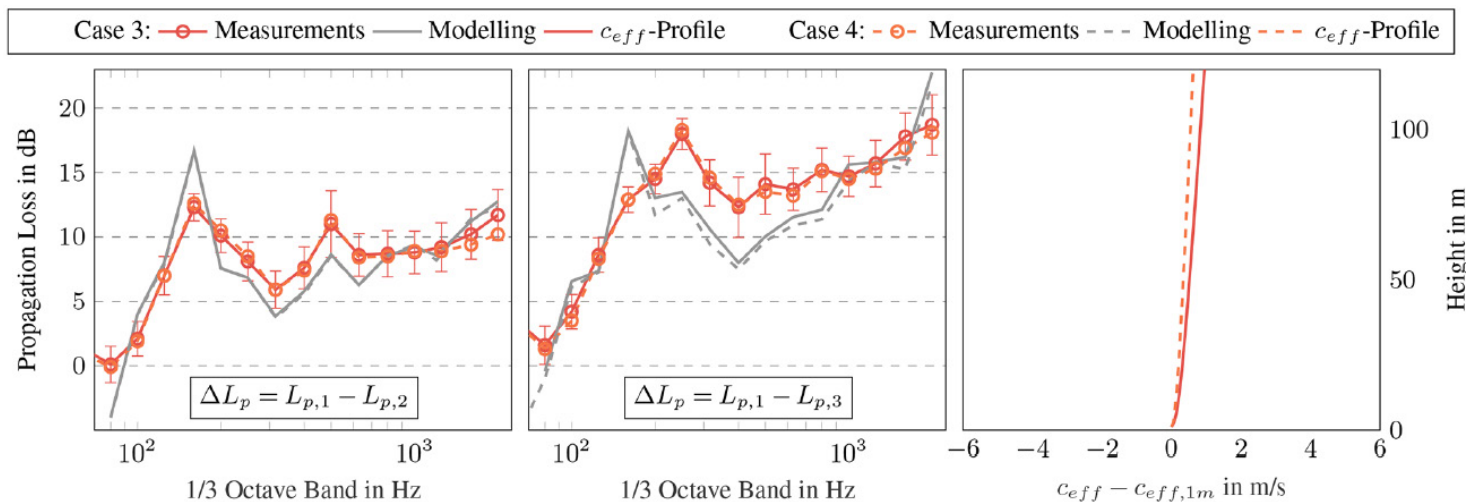


Figure 3: Comparison of measured and modelled sound propagation losses per one-third octave band under crosswind conditions (Case 3 and 4 in [4]). Left: propagation losses between Mic 1 (178 m) and Mic 2 (535 m) including standard deviation for one measurement case. Middle: propagation losses between Mic 1 (178 m) and Mic 3 (845 m) including standard deviation for one measurement case. Right: normalized profiles of effective sound speed.[4]

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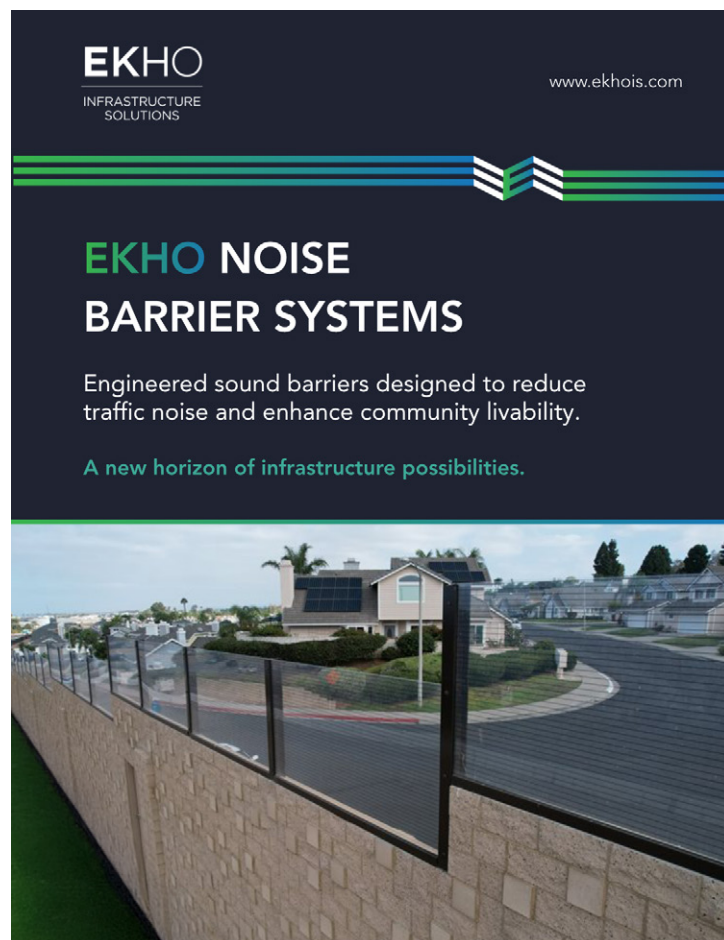
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# Hearing the Turbines: Wind Energy and Changes to Rural Soundscapes

Eugene McKeown, Eoin King and Denis O'Hora. Galway Sound Lab, University of Galway

For acousticians working on wind energy projects, compliance with regulatory limits is only part of the challenge. Equally important is understanding how new sources of sound alter existing acoustic environments and how those changes are experienced by impacted communities.

Wind turbines have become a familiar part of rural landscapes, but wind turbine noise remains a contentious issue. Current practice is to demonstrate compliance with planning regulations, standards, or technical guidance such as the UK's 'Assessment and Rating of Wind Turbine Noise' in the UK.

The UK and other international guidelines set wind turbine noise limits in the 35 to 45 dBA region, especially for night-time or in more mixed-use settings. A common approach is either a fixed limit such as 40, 43, or 45 dBA, or a background noise related rule such as 5 dBA above ambient sound levels. In rural landscapes (in Ireland) background noise levels are typically 35-45 dBA by day and lower at night. The daytime wind turbine noise turbine limit may therefore be close to existing background levels, making the change subtle but still noticeable. In quiet areas at night, background noise levels can drop below 25 dBA which sits well below the UK 43 dBA limit, so turbine sound could dominate and significantly increase perceived intrusion.

Wind turbine noise can be a steady broadband sound but sometimes it is characterised by amplitude modulation (AM). AM is a rhythmic "swish" or "thump" that draws attention

even at relatively low levels. Research consistently shows that amplitude-modulated sound is more annoying than other environmental noise at the same level because it is more noticeable [1].

Noise from wind turbines is also highly variable. Long range audibility depends on wind shear, atmospheric stability, terrain, and turbine operating conditions. At night, under stable atmospheric conditions, sound can travel further and be perceived as more prominent. This variability is difficult to capture in simplified prediction models, which often assume steady-state conditions and average meteorology.

## Regulatory Framework

Existing regulatory frameworks offer a consistent basis for assessment, but they do not capture how residents experience and respond to changes in their acoustic environment. Equally important is the preservation of amenity in settings where tranquillity is itself part of the character, such as national parks. Low levels of anthropogenic noise have been shown to support both ecological integrity [2] and human well-being [3]. Natural soundscapes allow species to communicate, forage and reproduce effectively and offer psychologically restorative experiences for visitors.

Distant noise sources such as air overflights, major roads, industry and renewable energy infrastructure can be audible for considerable distances across quiet landscapes. The addition of noise sources such as wind turbines, inverters, transformers and even smaller components such as cooling-fans subtly erode the acoustic character of quiet areas. This

creates a tension between climate-change mitigation goals and the preservation of acoustic amenity.

National parks and rural areas are commonly valued for their relative quiet, but “quiet” is not silence [Directive 2002/49/EC]. Such areas have an existing soundscape with wind and nature sounds, distant agricultural sounds along with road, air and sometimes rail traffic sources. Wind turbines introduce a new and persistent sound source into this environment. Studies in Northern Europe have found that wind turbine noise is more annoying in quiet rural settings than in already noisy environments, suggesting that context matters as much as level [4].

This raises an ethical question of what constitutes an “acceptable” acoustic change in the context of energy transition? Renewable infrastructure delivers clear public benefits, yet those benefits are not evenly distributed. Some communities host turbines and experience their acoustic presence directly, while others benefit from the electricity without encountering the sound. The WHO Environmental Noise Guidelines underline that health and quality-of-life impacts are not uniform and that environmental justice must be considered in noise policy.

Independent acousticians occupy a mediating position. They interpret data for planners and developers but also listen to residents and visit sites under different conditions. Their role is not only to verify compliance but to ask whether compliance is enough. Important questions remain regarding the suitability of current limits in low-background-noise environments, the treatment of amplitude modulation, and the extent to which operational strategies can reduce perceptual impacts without materially affecting energy yield. There are no simple answers. Quieter blade designs, operational curtailment during sensitive periods, and more nuanced planning guidance can help, but they cannot eliminate trade-offs.

The acoustician must balance data, policy, and lived experience while acknowledging that not all impacts can be fully resolved. The challenge for an acoustician is to recognise that some impacts may remain, and that society must decide what level of acoustic change it is willing to accept in pursuit of decarbonisation.

Planning processes are more likely to command public trust when potential noise impacts are openly acknowledged and clearly communicated [5]. Communities living closest to wind energy developments will experience the greatest acoustic change. Transparent assessment methodologies, inclusive engagement processes and acknowledging the disproportionate burden borne by these communities are critical in the pursuit of public trust.

Listening, in this sense, is not just a technical skill. It requires us to hold both climate imperatives and local experience in view, and to be clear about what each demands.

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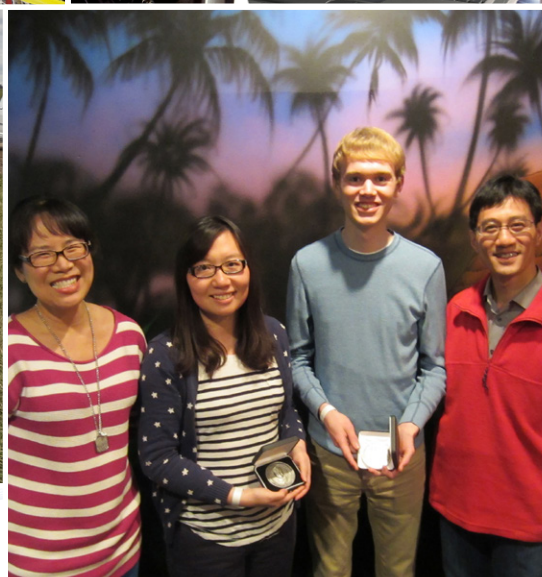
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# Integrating Acoustics, Perception, and Policy: Advancing Wind Turbine Noise Assessment Through IEA Wind TCP Task RESONATE

Eoin King, University of Galway, Ireland; Franck Bertagnolio, DTU WIND, Denmark

As wind energy continues to play an increasingly important role in the global transition to low-carbon energy systems, ensuring that developments are both technically effective and socially acceptable has become a key challenge. While modern wind turbines are significantly quieter than earlier generations, noise-related concerns remain one of the most important factors influencing community acceptance and planning decisions. Addressing these challenges requires more than advances in acoustical engineering alone. It also demands a better understanding of how wind turbine sound is perceived, interpreted, and experienced by people living nearby.

Task 64, RESONATE (Research on Emissions, Sound, Noise, Acoustics, Transmission & Community Experiences), is a new initiative of the IEA Wind Technology Collaboration Programme (IEA Wind TCP) that brings together experts in engineering, acoustics, psychoacoustics, psychology, and the social sciences to

advance international research in wind turbine noise assessment.

## Building on from Task 39 – Quite Wind Turbine Technology

RESONATE builds on the achievements of IEA Wind Task 39 – Quiet Wind Turbine Technology, which ran from 2017 to 2024. Task 39 established a unique interdisciplinary collaboration examining the complete pathway from wind turbine noise generation and propagation through to human perception and community response.

Among its achievements were benchmark studies for wind turbine noise propagation models, investigations of aerodynamic noise-reduction technologies such as trailing-edge serrations, studies of tip-noise generation, and important advances in understanding the relationship between sound quality and annoyance. The Task also helped identify several research challenges that would benefit from continued international collaboration.



Perhaps the most significant lesson from Task 39 was that wind turbine noise cannot be fully understood through engineering alone. Meaningful progress came from combining physical modelling with expertise in psychology and human perception, providing a more complete understanding of how sound is experienced by nearby communities. This interdisciplinary philosophy forms the foundation of RESONATE.

## Integrating Engineering and Human Experience

The primary aim of RESONATE is to improve understanding of both the physical characteristics of wind turbine noise and its societal impacts. From an engineering perspective, the Task will investigate noise generation mechanisms, near-field and far-field sound propagation, and the physical processes contributing to amplitude modulation. Research will also focus on strengthening the links between source and propagation models, reducing uncertainty in existing prediction methods and improving confidence in environmental noise assessments.

Equally important is the Task's focus on how wind turbine sound is experienced by communities. Planned activities include research into the mechanisms of annoyance, the development of advanced auralisation tools that allow realistic listening experiences, and the evaluation of regulatory approaches to tonal noise and amplitude modulation. RESONATE will also compare national assessment practices, identify areas of commonality, and explore opportunities for greater consistency in international methodologies.

## Looking Ahead

As wind energy deployment accelerates worldwide, the need for robust, transparent, and scientifically defensible approaches to wind turbine noise assessment has never been greater. RESONATE provides a timely opportunity to address many of the remaining scientific questions while strengthening collaboration between researchers working across traditionally separate disciplines.

By integrating advances in acoustical engineering with research on human perception, community response, and regulatory practice, the Task seeks to reduce uncertainty in current assessment methods and improve confidence in the evidence used by developers, regulators, and communities alike. Ultimately, RESONATE aims to support a more holistic understanding of wind turbine noise, one that recognises both the physical properties of sound and the human experience of living with it.

Through international collaboration and the sharing of best practice, the Task will help shape the next generation of wind turbine noise research, contributing to more effective environmental assessments, more informed policy development, and more socially sustainable deployment of wind energy around the world.

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**Dr. Eoin King** is a Lecturer in Mechanical Engineering at the University of Galway and Director of the Galway Sound Lab. His research examines the measurement, prediction, and mitigation of environmental noise, with a focus on developing evidence to support policy and sustainable development.

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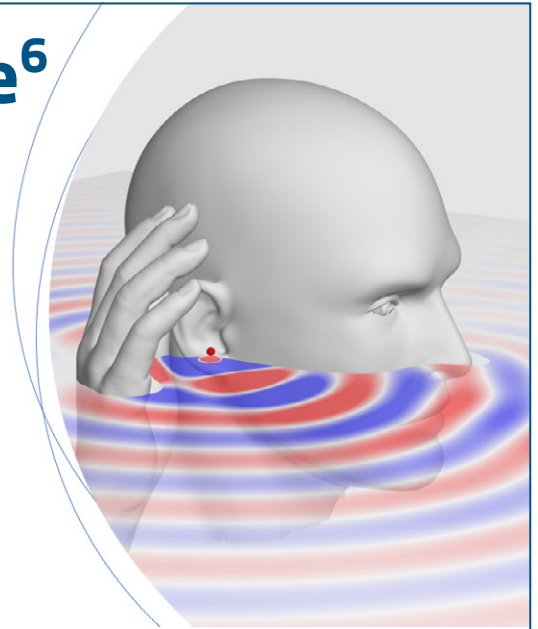


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# What Goes Around Comes Around: Acoustical Research on the NASA Turbines in Today's Infrasound Debate

Isaac Old, INCE Bd. Cert.

## Introduction

In the mid 1970s through the early 1990s NASA researchers conducted acoustical research on a series of prototype wind turbines, publishing the results in a series of research studies and technical papers. When complaints about wind turbine sound became more common with the rapid buildout of wind turbines across the world in the mid 2000s, a number of researchers, authors, and citizens searched for answers in this literature. This article will look into the content of these studies, calibrating their relevance to the current wind turbine acoustics debate.

## NASA Large Turbine Program Sound Research

By any measure the NASA large wind turbine studies were a tremendous accomplishment and they still rank among the most noteworthy and comprehensive wind turbine acoustics studies that have been performed by

any institution. Though the beginning and end of these studies is not well defined, we will look into papers released between about 1980 and 1990. These studies summarize research on a series of prototype horizontal axis wind turbines (HAWT) that include the MOD-0A, MOD-1, MOD-2, and WTS-4. These turbines were produced by a number of manufacturers including Boeing, General Electric, Westinghouse, and United Technologies. A comparison of these turbines is shown in Figure 1: Comparison of turbines in the NASA Large Wind Turbine program [1]. Note that this was published before the MOD-5B was constructed, so actual details changed [1]. The MOD-5A was never constructed. As these turbines were intended to be experimental there is some design variability. Output ranged from the 200 kW MOD-0A to the 4000 kW WTS-4.1 Three of the turbines were a design where the rotor spins downwind of the tower (a "downwind" turbine) and three were where the rotor spins upwind of the tower (an "upwind" turbine). Two

<sup>1</sup> Sources differ on what the actual output of the MOD-5B was.

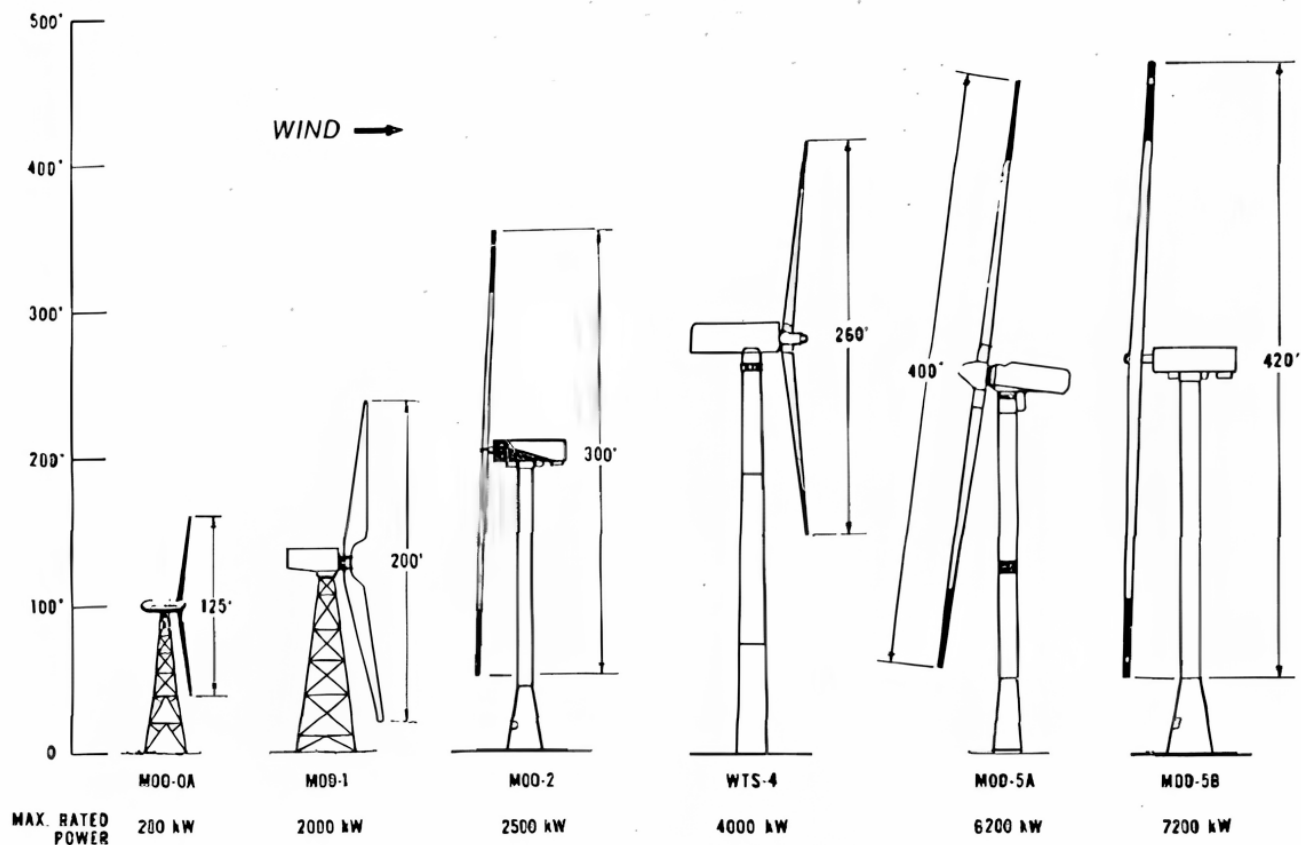


Figure 1: Comparison of turbines in the NASA Large Wind Turbine program [1]

of the turbines (the MOD-0A and MOD-1) used latticed towers and the remainder used monopole designs. Each of the turbines had two blade rotors instead of the current standard three blades.

Detailed acoustical studies of the turbines started after a string of noise complaints near installation of a MOD-1 turbine in western North Carolina. The complaints were from roughly a dozen residences that were located within 3 km of the turbine and centered around low frequency (sound with a frequency between about 20 and 200 Hz) thumping sound and some reports of vibration. From there, studies focused on diagnosing the issue using a combination of sound and vibration measurements, both near the turbines and at the residences, along with meteorological measurements. Field measurements, wind-tunnel studies, and analytical investigations demonstrated that rotor blades passing through the organized wakes of the cylindrical tower legs experienced transient aerodynamic loading fluctuations that produced coherent low-frequency sound impulses. The tower was creating substantial wind speed gradients that meant the

blades were encountering dramatically different wind conditions behind the tower compared to the rest of the swept rotor area. The rapid change in effective wind speed vibrated the rotor, generating the thumping sound. This effect was further exacerbated by the use of the latticed tower instead of a monopole tower, and the relatively close spacing between the rotor plane and the tower [2]. The latticed tower resulted in three wakes instead of the one that would occur with a monopole tower and the close spacing between the rotor plane and tower resulted in a more dramatic wind speed gradient.

Annoyance was due to the low frequency sound pulses making residential structures vibrate. Some of the sound was mitigated by slowing the rotor rotation (originally 35 rpm) and adding aerodynamic devices to the legs to break up the wind speed gradients. Additional testing was done later with the more adjustable MOD-0A turbine that included flipping the rotor upwind of the tower. Operation in the upwind configuration eliminated the impulsive low frequency sound that drove complaints. Later tests of the upwind configuration MOD-2 turbine



also did not find impulsive sound similar to the MOD-1 [3], [4].

A couple of years later a lab test was performed to develop a wind turbine annoyance assessment metric. The tests simulated wind turbine sound inside a residence under three different scenarios, two of which included impulsive low frequency sound [5]. The idea was to assess which metric provided the best correlation between sound levels and participant response. Two metrics provided the best correlation. The first was the C-weighting metric and the second was the LSL (Low frequency Sound Level) weighting metric. The C-weight metric emphasizes low-to mid-frequency sound, by de-weighting infrasound (sound with a frequency below 20 Hz) and high frequency sound. The LSL emphasizes low frequency sound while de-emphasizing infrasound and mid-frequency sound. The correlation coefficients of participant response for both of these metrics was similar. Unweighted sound levels, two proposed G-weighted metrics and A-weighted did not correlate as well with response as C-weighting and LSL. The G-weighted metrics were slightly different. The basic concept was the same, with audible-frequency sounds being de-weighted and the weighting following the audibility threshold curve in the infrasonic range. The basic differences are steeper de-weighting rates in the infrasonic range and a frequency shift of where it started de-weighting. The suggested annoyance threshold for wind turbine sound was 67 dBC for impulsive sounds and 75 dBC for non-impulsive sounds. The importance here is that both of the best performing metrics emphasize low frequency sound over infrasound. Due to common building façade attenuation characteristics, higher frequency sound will generally be attenuated more than mid- or low-frequency sound during transmission through the structure.

Additional NASA research focused on characterizing the acoustic emissions of the experimental turbine fleet and the propagation of wind turbine sound. Measurements of the WTS-4 showed that blade-passage-frequency harmonics could propagate long distances downwind, with attenuation rates influenced strongly by atmospheric refraction rather than simple spherical spreading [6], [7].

Overall, the NASA studies found that low-frequency noise generation, propagation, and structural response depend on turbine configuration, wake aerodynamics, atmospheric conditions, and the dynamic response of nearby buildings. Downwind turbines, particularly the

MOD-1, produced the strongest coherent low-frequency and impulsive emissions due to blade interactions with tower wakes, while upwind designs substantially reduced these effects [8].

Several findings remain relevant today. The studies showed that wind turbine sound radiation is directional at close range, that low- and mid-frequency emissions arise from a combination of mechanical and aerodynamic noise sources, and that low-frequency and infrasonic spectra commonly contain harmonics generated by periodic rotor loading at the blade-passage frequency.

## Current Positioning in the Wind Turbine Infrasound Discussion

In the past 15 years, the NASA wind turbine noise studies have repeatedly reappeared in the wind turbine acoustics literature and in regulatory, legal, and public discussions of wind turbine noise. Much of the attention has focused on the studies of the 2 MW MOD-1 wind turbine that were initiated in response to community noise complaints. As concerns about infrasound from modern utility-scale wind turbines grew, these studies were cited as evidence that complaints associated with turbine-generated low-frequency sound were not a new phenomenon and that large wind turbines had long been recognized as sources of significant infrasonic and low-frequency sound energy. The finding that low frequency sound could interact with residential structures has also been referenced. This in combination with increased audibility due to the impulsive coherent characteristic of the sound was used to explain how relatively low infrasound levels could result in human responses [9] [10].

## Comparison of Study Findings and the Current Debate

These discussions often overlook important distinctions between the early experimental turbines and modern commercial designs. The MOD-1 was a downwind turbine whose impulsive acoustic emissions were strongly influenced by blade-tower interaction, whereas nearly all modern utility-scale turbines employ upwind rotor configurations. In Hubbard and Shepherd they state “Impulsive noise is often associated with downwind rotors on HAWTs” [8]. Comparisons of the acoustic time series and spectra for the two turbine types show that the upwind turbine time series does show a modulated amplitude, but without the sharp impulses

of the downwind turbine. Overall sound levels from the upwind design in the low frequency sound range are also approximately 10 dB lower even for a physically larger turbine. Findings related to the MOD-1 that are generalized to contemporary turbines are done without consideration to what made its sound emissions unique. Some reviews of the NASA studies do acknowledge that the MOD-1 is different from current turbines, but then assert that the differences are irrelevant. The NASA researchers did not come to that conclusion.

Portions of the NASA lab studies on wind turbine annoyance metrics do not allow for simple application to infrasound. They indicate that sound in the low frequency range, particularly when impulsive, was the primary response driver. The metrics that best correlated with response are those that de-emphasize infrasound relative to low frequency sound. The NASA study also does not implicate infrasound as the issue, instead focusing on low frequency sound.

This difference is sometimes avoided in articles alleging infrasound as a driver of response through use of the phrase Infrasound and Low Frequency Noise (ILFN). Although infrasound is often reported as being the more harmful and unique portion of the sound spectrum, combining the two means previous research on low frequency sound tends to be applied to infrasound. In most cases this is an inappropriate application, particularly if the infrasound levels being referenced are below the audible range.

In the case of the NASA studies, the annoyance threshold was specified as being 67 dBC for impulsive sound and 75 dBC for non-impulsive sound. Wind turbine sound at these levels was audible. When findings of these studies are erroneously applied to inaudible infrasound, the disconnect should be apparent.

## Conclusion

Acoustical studies that were part of NASA's Large Wind Turbine program formed some of the earliest acoustical research on wind turbines, even today ranking as one of the most in-depth research projects on the subject. Topics ranged from wind turbine sound emission mechanisms, to sound measurement techniques, human response, and sound propagation. Recent discussions on wind turbine infrasound have focused on these studies due to a series of complaints near the installation of a MOD-1 prototype turbine in western North Carolina that were attributed to a strong low frequency thump emitted by the turbine. This

is often taken as evidence that high levels of infrasound are an intrinsic sound emissions of wind turbines and this characteristic has been known for decades. A close review of the NASA studies indicates the following:

High low frequency sound levels, particularly when impulsive, were primarily a characteristic of now obsolete downwind turbine designs. Upwind turbine designs were not the subject of complaints, had lower low frequency and infrasound levels, and showed much less impulsivity.

Low frequency sound was the primary driver of annoyance rather than sub-audible infrasound.

To understand the impact of infrasound from modern wind turbines, it is important to understand the findings of past and current research, and communicate it accurately to those affected.

## Acknowledgements

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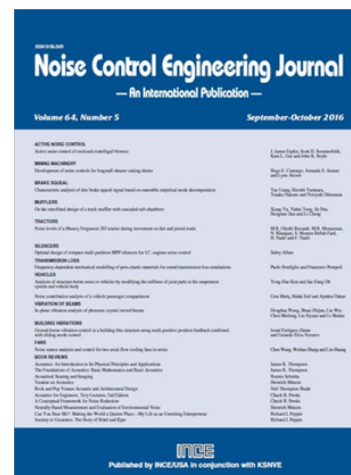
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# Funny stories somewhat related to noise control

Jim Thompson

**I am not sure how funny these stories are to others. I hope they are at least mildly amusing and perhaps there are some nuggets of information buried within the descriptions.**

## Visiting Japanese OEM Proving Ground

Many years ago, I was visiting the proving ground of a Japanese auto original equipment manufacturer (OEM). We had an up and down history with them. I was there because they had a new top-of-the-line car for which tire noise improvements were needed. I got to the proving ground, and they immediately took me to their noise test lab next to their test track. It was explained that the plan was a subjective ride for me to hear the noise they were concerned about. They had prepared a prototype with all production level components. It had just been detailed ready to be used for photo shoots later that day. We were waiting for the top manager to arrive because he wanted to demonstrate the noise to me.

When he arrived, there was a lot of etiquette. Evidently, he seldom visited the lab and was at a high level in the company. There were four of us in the car and the boss insisted on driving. We were on a short road that led to the test track. In front of us was a chain across the road to prevent people from randomly driving on the test track.

I guess the boss did not see it. The chain hit the hood about midway up and began to gouge paint and creased the hood. Following Japanese etiquette everyone was completely silent except the boss. I could have probably learned some Japanese profanity that day, but my translator did not dare speak.

Eventually, we backed up the car up, unlocked the chain, and went on the track. This was the quietest test drive I ever participated in. Only the boss and I were speaking, fortunately he spoke English. In the end he said goodbye to me and left the lab. All the other personnel were completely quiet. For a few seconds nothing happened. Then the lab supervisor sent a technician out to be sure the boss was gone. When the technician came back everyone heard the story in Japanese – I had no trouble understanding what they were talking about especially with dramatic reenactments and screeching sound. Some people in the lab were laughing so hard tears were running down their cheeks. One guy fell out of his chair. I will admit I was laughing along with them.

Certainly, there are some lessons here about prestige, etiquette, saving face, and knowing when to speak up. After this incident, we were awarded the business on this vehicle. For some reason, the demand for quieter tires seemed to disappear.



## Gathering Vibration Data

I was working for a large chemical company at the time. There were two groups focused on noise and vibration. Our group was primarily focused on noise and vibration related to noise. The other group focused on high-speed rotating equipment primarily concerned with monitoring, balance, and similar issues.

In one case, the rotating equipment group needed our help to measure vibration on new equipment at a plant in Texas. We sent an engineer and technician down to get the measurements. It was a real rush, the plant was about to go into production, and the data was needed to sign off the equipment.

The guys arrived, and the new unit was having problems. They spent three days trying to get the required data, but the plant kept having upsets. In one case the unit had to be evacuated due to a gas leak. In other cases, there were equipment failures, process segments with runaway temperatures, etc. On the fourth day a tropical storm came in and was predicted to last at least three days. I should have mentioned this turbine and compressor train is about 30 feet off the ground completely exposed with no shelter. The test equipment would not work and might not even survive exposure to the high winds and rain.

Eventually, the guys came back to the tech center and turned in the data. I did not find out until days later that the data acquisition process was a little irregular. Unable to get the measurements specified, these guys attached the accelerometers to the bed springs in their hotel room and jumped up and down on the bed. I never saw the data and did not want to see it. However, it had to have been obvious that this was not data from a 40,000-rpm turbine.

The funny part is that the other vibration group accepted the data, and we never heard a word of protest or a question about the data. Maybe they were too mad to even talk with us. I suspect that the data was filed away and never checked.

Again, there must be some lessons here. Maybe checking data from someone else is a good idea. I know I had a short but definitive talk with these two about never doing something like this again. Maybe someone should have checked with the plant to see how the startup was going before sending people to take measurements. Yes, several times after that these two offered to help when we were having measurement difficulties by going to a hotel in Texas.

I would like to hear your thoughts about these two cases. Were they funny to you or just to me? Do you have similar stories hopefully with some lessons learned? ■







# BACKGROUND NOISE THAT SPEAKS VOLUMES

TALES  
OF SONIC  
INEQUALITIES

Have you ever woken up in the middle of the night to the sound of a snowplow backing up or a motorcycle revving up?

Have you ever felt the need to escape the daily noise of the city?

If so, it's hardly surprising: the majority of people living in cities are exposed to dangerous levels of noise, according to the WHO\*. But we're not all equal when it comes to noise: a person is more likely to be exposed to it if they have a low income and/or are racialized.

These people tend to live near airports or freeways, for example, and work in more exposed occupations, such as factories or catering. What's more, not everyone has the time or opportunity to take a break in a park or find a quiet room at home to recharge their batteries.

Take a journey into the daily sound experience of three people from different backgrounds.

\*World Health Organization

## Team members

Students at McGill University

- Christopher Trudeau
- Valérien Fraisse
- Cynthia Tarlao



## Artist/Cartoonist

- Marina Leon





# BACKGROUND NOISE THAT SPEAKS VOLUMES

TALES  
OF SONIC  
INEQUALITIES











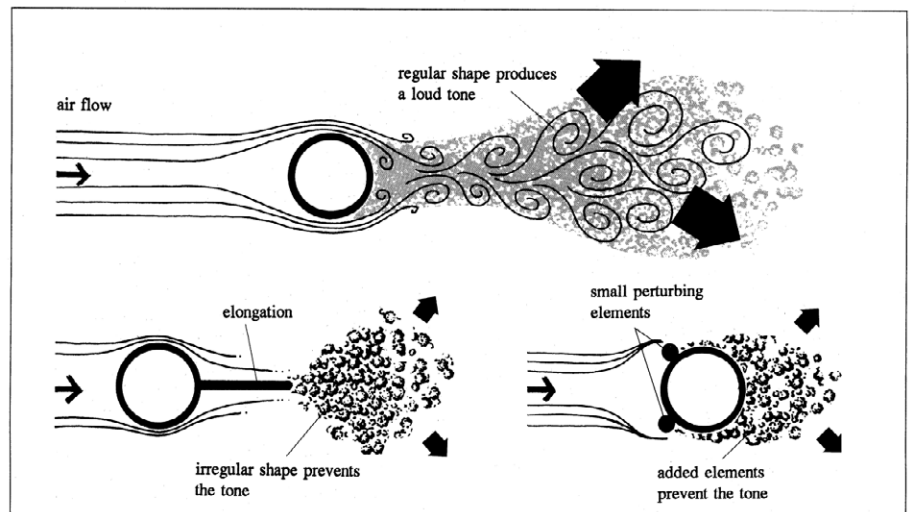
# Stig Ingamansson's Noise Control: Principles and Practice

## C1: SOUND PRODUCTION IN AIR OR GASES – WIND TONES

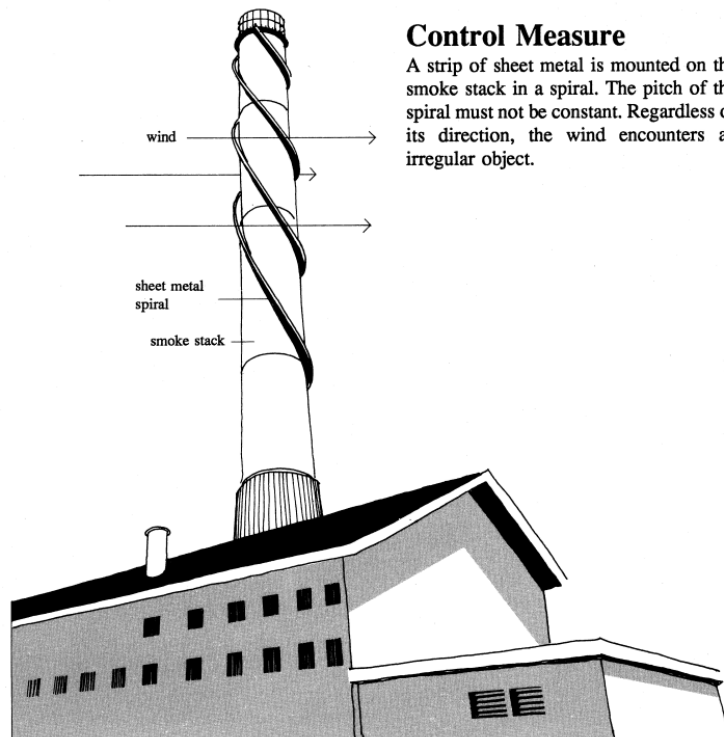
### Wind Tones can be Eliminated

When air passes by an object at certain speeds, a strong pure tone, known as a Karman tone, can be produced. This tone can be prevented by making the object longer in the direction of flow, such as with a "tail," or by making the object's shape irregular.

### Principle



### Application with Wind Currents



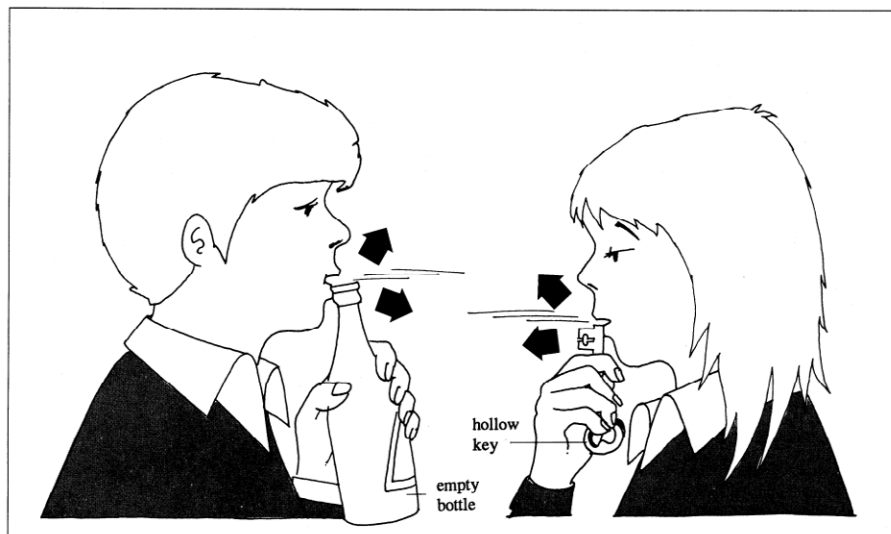


## C2: SOUND PRODUCTION IN AIR OR GASES – WIND TONES

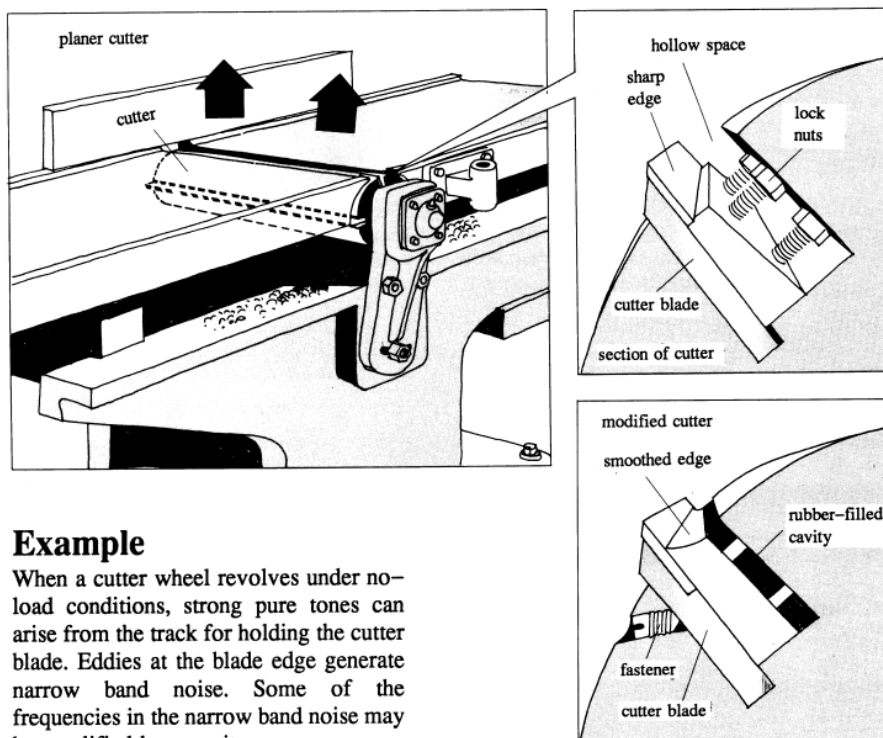
### Air Flow Past Hollow Openings Should be Avoided

When air or another gas is blown at certain speeds across the edges of an opening to a cavity, loud pure tones are generated. This is how wind instruments operate. The greater the volume of the cavity and the smaller the opening, the lower the frequency will be.

#### Principle



### Application with Air and Steam Jets/Objects in Rapid Motion



#### Example

When a cutter wheel revolves under no-load conditions, strong pure tones can arise from the track for holding the cutter blade. Eddies at the blade edge generate narrow band noise. Some of the frequencies in the narrow band noise may be amplified by a cavity resonance.

#### Control Measure

Smoothing the cutter edge and filling the empty space may reduce the broad band noise and may also eliminate the pure tones.



We offer this issue's ABCs of Acoustics with great sadness. Our author, colleague, and friend Dr. Eric Ungar has passed away. As we see with this series his work will live on for many years. Eric was a master of vibration, acoustics, and communication. His papers and books are informative, engaging, and easy to read and understand. He brought us the famous Vibration Criteria (VC curves) which are used throughout the building acoustics community to ensure vibration is within simple specifications. He and his colleagues, Kerwin and Ross, developed the famous RKU theory for estimating damping from constrained layer systems. These are far from his only contributions, and we're planning a longer tribute to Eric in a future issue. For now, please enjoy his poetry and musings on Organ sound and Propagation.

## Acoustics from A to Z

Eric E. Ungar

*An ORGAN pipe emits a tone  
When air into one end is blown.  
Its pitch is given by its length  
And somewhat by the blowing strength.  
In many instruments, indeed,  
The tone's established by a reed.*



Every introductory text on acoustics talks about organ pipes and how their lengths are related to the wavelengths and frequencies of the tones they produce. However, discussions of how steady blowing into a pipe produces oscillations generally are left to specialized texts. Clearly, if the injected airflow were entirely smooth, no oscillations would occur.

There are two basic types of organ pipes: flue pipes and reed pipes. In the former the incoming air stream passes through a narrow passage formed by a 'flue' and then impinges on the edge of a thin plate 'lip.' The resulting flow turbulence generates a rather broad band of frequencies in the pipe's air volume, which responds predominantly at its natural frequencies. The resulting oscillations then interact with the turbulent jet to stabilize both that jet and the acoustic oscillations. Reed pipes, as the name implies, use a vibrating brass reed to modulate the injected air, with the pipe and reed

generally tuned to the same frequency. More details can be found in the excellent books by Rossing, Strong and Plitnik [1,2]

The mechanism by which flutes produce sound is somewhat different: it is the same mechanism as that responsible for the whistle one hears as one blows across a bottle. A flute player essentially blows across a hole in the flute, resulting in some turbulence, which generates standing waves in the flute's volume and thus produces tones. A piccolo is a woodwind instrument that is about half the size of a standard flute. Its development has an interesting history. Professor Peter Schickele reports that a hungry Italian constructed the first piccolo by sautéing an ordinary flute in a frying pan until it had shrunk about fifty percent. This event later came to be known as the Mediterranean Flute Fry [3].





*In PROPAGATION through the air  
Indoors, outdoors, everywhere,  
Sound waves that spread out from a source  
Take energy away, of course.  
Pressure by spreading is abated  
And some by losses dissipated*

The basics of sound propagation in the atmosphere have been understood ever since the wave nature of sound has been recognized. Sound pressure decreases with increasing distance from a source because the energy injected by the source is spread over larger and larger areas at locations further away from the source, and also because acoustic energy is dissipated as sound passes through the air. The attenuation due to dissipation is more pronounced at high frequencies and when the humidity is high. As Philip Morrison [4] puts it: "Energy loss in sound transport is the result of internal diffusion that wipes away the contrast between compressed crests and rarefied troughs as any pressure wave advances. The longer the wavelength of the sound, the farther it can go."

One can easily visualize that winds whose speeds increase with increasing altitude tend to refract sound propagating in the windward direction toward the ground, because here the sound travels faster (with respect to the ground) in areas of higher wind-speed. Because the speed of sound in air is proportional to the square-root of the absolute temperature, an atmospheric temperature profile marked by increasing temperature with increasing altitude has a similar effect. Thus, wind (and temperature) gradients can result in focusing of sound downwind from a source and the formation of quiet "shadow zones" upwind. In the 1960s, test firing of large rockets at NASA's Marshall Space Flight Center in Alabama was found occasionally to damage some buildings in downtown Huntsville several miles away as the result of atmospheric focusing of the rockets' intense low-frequency sound. NASA eventually instituted the use of meteorological balloons to measure the wind and temperature profiles before each planned test firing and postponed the testing when calculations indicated a potential for focusing in built-up areas [5].

Since sound that propagates from an atmospheric layer with a lower temperature to one with a higher temperature is refracted back toward the cooler layer, sound can be "trapped" in a "sound channel" formed by a cooler layer that is located between two warmer layers. Such trapped sound decreases with distance much less than freely propagating sound, sometimes enabling acoustic phenomena to be

detected at very large distances. In the earth's atmosphere there exists a relatively permanent sound channel at high altitude, and it has been reported that the 1883 Krakatoa volcano eruption could be heard on the other side of the world. I have some doubts about that, because the audible components of the sound would have been attenuated over such long distances. However, the low-frequency components of the sound produced by the 1991 Mount Pinatubo eruption and by some nuclear explosions were detected by instruments thousands of miles away. Similarly, in the "Sofar Channel," a sound channel in the deep portions of the oceans, sound signals have been transmitted and received over great distances. [6]

As long as we are on the subject of atmospheric refraction, it is also interesting to consider wind blowing along the ground and across a noise barrier. The wind needs to accelerate to get over the barrier, resulting in a wind profile that may refract the sound toward the ground beyond the barrier - thus reducing its effectiveness.

1. The Science of Sound, T. D. Rossing, Addison-Wesley Publishing Co., New York, 2nd Edition, 1990.
2. Music Speech Audio, W. J. Strong and G. R. Plitnik, Soundprint, Provo, UT, 1992.
3. From "Bach to the Future," Diane Cyr, U.S. Airways Attaché, July 1999.
4. "Wonders: Double Bass Redoubled," P. Morrison, Scientific American, May 1998.
5. Rudy Volin wrote: "... During a visit to the Marshall Space Flight Center (Huntsville, Alabama) in February 1967 my hosts asked me if I wanted to visit a static test firing of a Saturn second stage ... I declined ... Sure enough, the motel began to shake, followed by a brief low-frequency rumbling noise ... I also heard, and I forget where, that occasionally focusing caused the noise from rocket firings at the Marshall Space Center to be transmitted to Birmingham, AL, which is a little over 100 miles southeast of Huntsville."
6. Sound Waves and Light Waves, W. E. Kock, Anchor Books, New York, 1965. ■



# The Noise Control Engineering Journal

Vol. 74, Issue 2, 2026 – Available now

[Noise Control Engineering Journal - Institute of Noise Control Engineering](#)

Here is an example selected from the papers in this issue.

**Case study: Deep Autoencoder Networks for Inverse Design of Broadband Acoustic Metamaterials in Low-Frequency Aircraft Noise Control Applications**

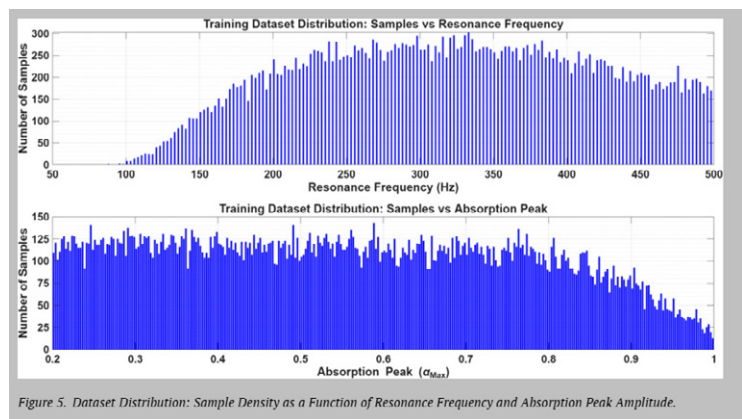
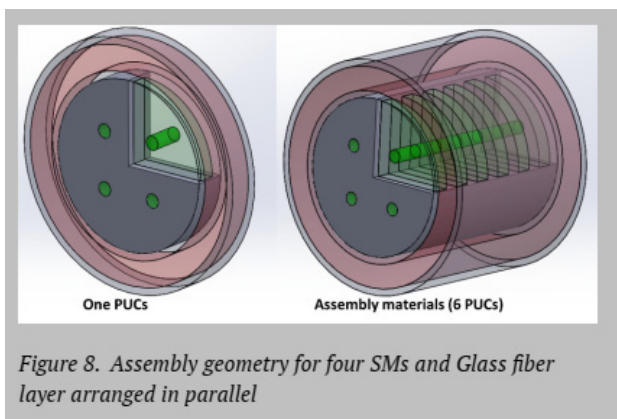
**Authors:** Kone, Tenon Charly; Ghinet, Sebastian; Ben Amar, Adam; Grewal, Anant ; Panneton, Raymond

**Source:** Noise Control Engineering Journal, Volume 74, Number 2, 1 June 2026, pp. 169-182(14)

**Publisher:** Institute of Noise Control Engineering

**DOI:** <https://doi.org/10.3397/1/377419>

Have you considered designing a metamaterial for a specific application with stringent performance criteria? You may want to look at this paper.







*Figure 1. An adult Hawaiian monk seal releasing bubbles through its nose as it vocalizes while swimming. Photo courtesy of Krista Jaspers.*

# Eavesdropping on the Endangered Hawaiian Monk Seal

**Kirby Parnell, Ph.D., Marine Mammal Research Program, University of Hawai‘i at Mānoa**

Beneath the surf of the tropical Hawaiian archipelago, the soundscape reflects the biodiversity of this remote coral reef ecosystem. Snapping shrimp crackle constantly, fish grunt, pop, and drum to defend territory, court mates, and warn off predators, and spinner dolphins whistle and click in protected bays. Among this cacophony, one can also hear low-frequency growling, whining, and the occasional whoop. These unique sounds are part of the endangered Hawaiian monk seal’s (Fig. 1) underwater vocal repertoire, and until 2018, they had only been described once, anecdotally, in the scientific literature.

For decades, scientists have recorded underwater sound throughout the Hawaiian Islands, drawn in large part by the song of the humpback whale, which visits Hawai‘i each winter to breed. Researchers have also used passive acoustics to study other marine mammals, including the insular false killer whale population which numbers fewer than 150 individuals, and spinner dolphins, which are disturbed by human activity roughly 80% of their resting period in shallow bays ([Tyne et al. 2018](#)). With this much underwater acoustic data collected in monk seal habitat, one might expect their vocalizations to be well described by now. For various reasons, this is not the case.

## Establishing a vocal repertoire

The first recordings and descriptions of Hawaiian monk seal vocalizations came from one adult male, Kekoa (KE18), living in human care. Kekoa was born at Kure Atoll, in the Papahānaumokuākea National Marine Sanctuary (PNMS), and was placed into human care by the U.S. National Oceanic and Atmospheric Administration (NOAA) – which oversees the species’ conservation – after he injured other seals in the wild population.

In 2017, researchers at the University of California Santa Cruz placed a small passive acoustic recorder (a SoundTrap) into Kekoa’s pool. With no other seals present, Kekoa regularly produced six distinctive low-frequency call types: croak, groan, growl, moan, rumble, and whoop, all named onomatopoeically (i.e., a word that copies or makes the sound of what it means). He produced these vocalizations in stereotyped “bouts”, or clusters of calls produced close together in time (Fig. 2). These call types were confirmed in a second captive male, Ho‘ailona (KP2), who produced the identical repertoire, again with no other seals nearby. Published in [Sills et al.](#)

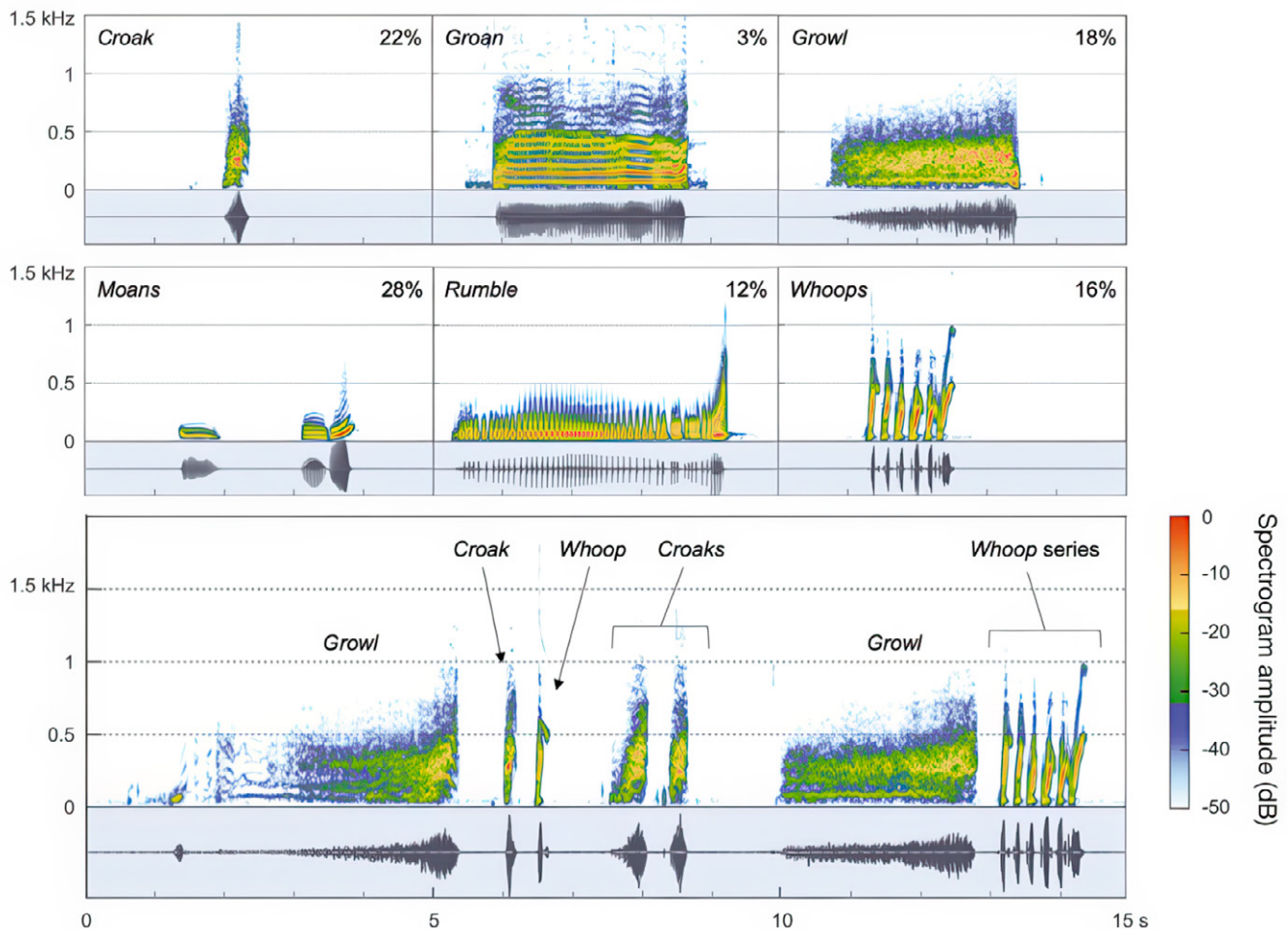


Figure 2. Spectrogram exemplars of Kekoa's underwater vocal repertoire and a representative vocal bout (from Sills et al. 2021). [Listen to Kekoa and Ho'ailona's vocalizations](#) in the supplemental material: Audio S1 and S2.

(2021), these findings provided the first description of the species' underwater vocal repertoire, along with its second underwater audiogram (i.e., hearing abilities). This audiogram revealed that monk seal hearing extends into the same low-frequency range as their calls and as common sources of manmade sounds (e.g., vessel noise).

These results mattered for two reasons: Hawaiian monk seals are endangered, with roughly 1,600 individuals remaining, and anthropogenic noise is a well-documented stressor for marine mammals. So the fact that monk seals vocalize and hear in the same frequencies as manmade sound raised a critical question: if seals depend on underwater vocalizations for essential behaviors, could noise pollution interfere with them enough to affect survival and reproduction? Before that question could be answered, however, researchers first needed to characterize baseline vocal behavior of wild seals. This meant establishing their repertoire and call characteristics, describing temporal and spatial patterns

in sound production, and determining the function of vocalizations.

### Confirming calls in the wild

To address these knowledge gaps, [Parnell et al. \(2025\)](#) deployed SoundTraps at five shallow-water sites where Hawaiian monk seals are known to rest and give birth: three in the main Hawaiian Islands (Kalaupapa, Moloka'i; Mānana Island, O'ahu; Lehua Rock, Ni'ihau), home to roughly 400 seals living alongside 1.4 million people, and two sites (Lalo and Manawai) inside the PNMS, where the majority of the population (~1,200 seals) lives and human access is restricted to research and cultural activities.

Across more than 4,500 hours of recordings, researchers manually detected over 23,000 vocalizations. Calls were low frequency (<1 kHz, peak frequencies 80 – 305 Hz), short-medium in duration (<7 sec), and often produced in bouts ([listen here](#)). Vocalizations were detected at all five sites, and at three sites with the highest seal



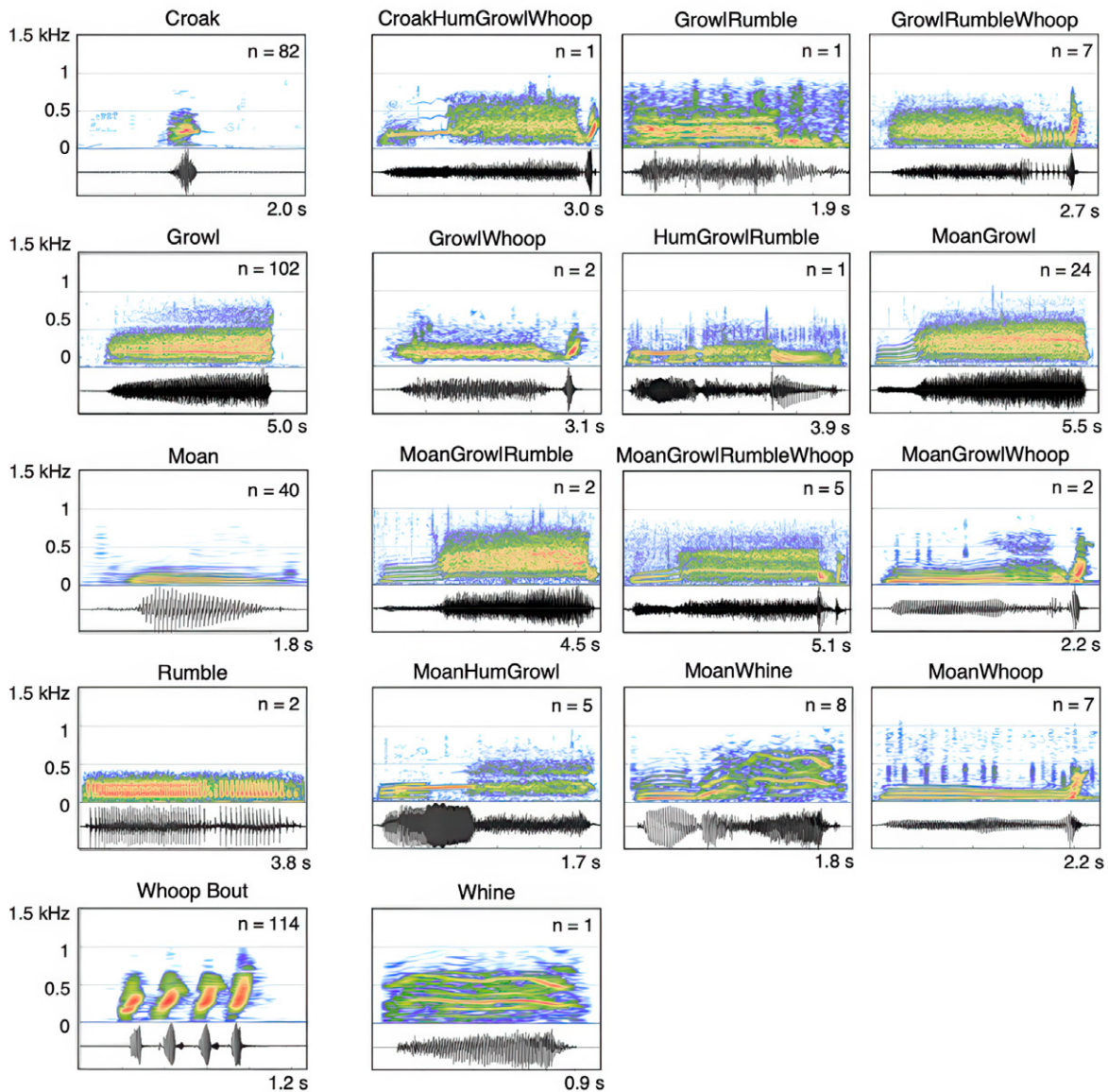


Figure 3. Spectrogram and waveforms of 18 underwater vocal types produced by wild Hawaiian monk seals. Elemental calls are shown in the left column, and all other spectrograms are novel combinational or elemental call types (from Parnell et al. 2025). Listen to these call types [here](#).

density, vocalizations were detected throughout the day, suggesting they play a key role in daily behavior. At Lehua Rock, ecotourism vessel noise overlapped in frequency with seal vocalizations, suggesting acoustic masking may occur (Parnell et al. 2024).

Wild seals produced five of the six previously described call types, but with a twist: they also combine these “elemental” calls into more complex “combinational” calls. For example, a quiet, low-frequency moan was often connected to the louder, harsher growl (MoanGrowl). In total, the repertoire now includes up to 25 call types: 6 elemental and 19 combinational (Fig. 3).

## What are the calls used for?

One call type tells a clear story. The whine, recorded only in the wild, is produced exclusively while seals forage, body inverted with their head near a coral or reef crevice. This behavior was first documented by recreational snorkelers and divers who posted videos online (watch video examples [here](#)). Researchers later confirmed it using paired video-audio data from multi-sensor tags attached to seals’ backs (Chapter 4 in Parnell 2025). It’s still unclear exactly why seals whine while foraging, perhaps to attract or flush prey out of hiding, but this makes the monk seal only the second phocid (true seal)



species known to produce a foraging-associated call. The monk seal's close relative, the northern elephant seal, was observed producing infrasonic sounds in a foraging context ([Frouin-Mouy et al. 2024](#)). Notably, adult and subadult female seals whine while foraging too, challenging the assumption that underwater calling is primarily a male behavior.

The whine is the exception, though. The exact function of most calls remains unclear. In other aquatically mating phocids, adult males call during the breeding season to attract mates, defend territory, and assert dominance over rivals. As monk seals mate aquatically, their underwater calls likely serve similar purposes. Kekoa's testosterone and calling rate both peaked during breeding season and dropped after his annual catastrophic molt, hinting at a reproductive function for calls. However, confirming this in wild seals requires more fine-scale behavioral research – a reminder that we are only beginning to understand the monk seal's communication system.

## Why this matters

Acoustic research on both captive and wild Hawaiian monk seals has shown that underwater vocalizations are integral to their at-sea behavior, used for critical functions including foraging and communication. These low-frequency calls overlap with the frequencies of human-generated noise from shipping, commercial fishing,

recreational maritime activities (e.g., ecotourism vessels), coastal construction, offshore windfarm development, and military activities. As Hawai'i's coastal waters grow busier, and the main Hawaiian Island population of seals increases, understanding how seal vocalizations and behavior are impacted by manmade noise is critical for conservation. Considering the multiple threats monk seals already face, from fisheries interactions and disease to shark predation and habitat loss, anthropogenic noise represents another potential stressor layered onto an already vulnerable population. Alongside NOAA's ongoing population monitoring and recovery efforts, the impacts of anthropogenic noise on this endangered and endemic species should now be a research priority.

## About the Author

**Kirby Parnell** is a marine bioacoustician who has studied Hawaiian monk seal underwater acoustic communication for the past decade, throughout her M.Sc. and Ph.D. work. She earned her Ph.D. in Marine Biology from the University of Hawai'i at Mānoa in 2025, following a B.Sc. in Marine Science from Eckerd College and an M.Sc. in Ocean Sciences from the University of California Santa Cruz. She is a co-founder of the nonprofit SMMILE ([Summer Marine Mammal Intensive Learning Experiences](#)) and currently serves as a 2026 Grau Fellow with NOAA's Office of National Marine Sanctuaries, Pacific Islands Region. ■



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# Data Centers and Measurement of Low Frequency and Infrasound

David Woolworth, Roland, Woolworth & Associates, Oxford, MS

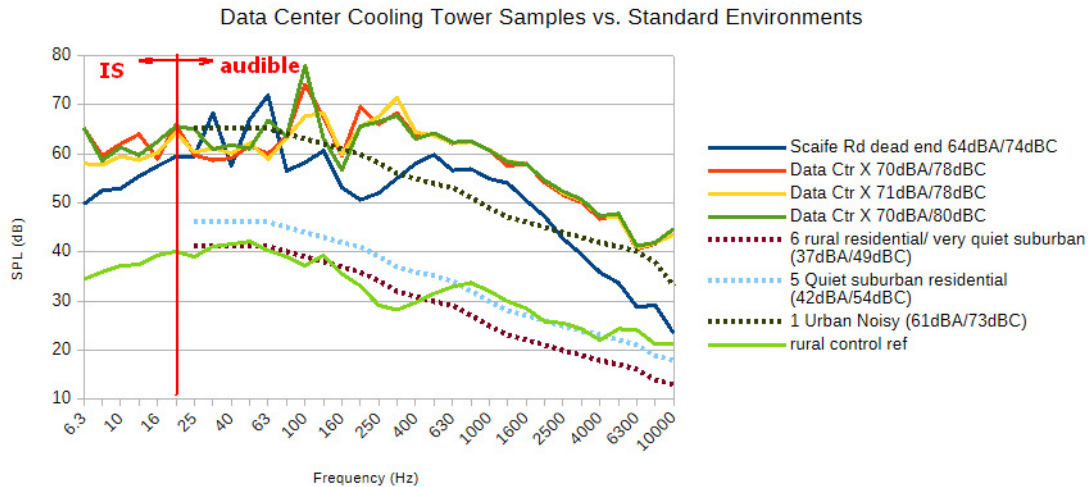
Data centers and their related power sources have become a hot topic in regard to noise among many other concerns. Each campus can be unique in size and composition, and in the resulting sonic signature and footprint. Data center noise sources consist of cooling systems (i.e. air or water cooling towers and chillers) which are well understood by themselves but can have interactions which may create unintended effects. In cases where power is generated nearby, the combination of sound sources poses an additional challenge to parsing out individual sources, in particular when power sources are permanent or temporary natural gas turbines, which are the fastest growing power sources for these centers [1,2]. In all cases the presence of low frequency sound is a concern, and poorly planned/rushed facility development can and do result in negative community impact stemming from low frequency and infrasound (LFIS). Many of the regulations (if there are any at all) utilize A-weighted criteria, which are insufficient to characterize LFIS.

Challenges for data centers sound level characterization through measurement are already numerous:

- Capturing baseline data (pre-construction) or allowable comparable baseline data
- Transience of data center/power sound sources, sometimes added to or altered over time, and cooling capacity requirements/energy demand change with the weather, time of day and year.
- Measuring long enough to capture the worst case propagation conditions, in particular at larger distances (1/2mile/0.8km+)
- By the time a consultant is onsite, there may have been multiple conditions that drove the original complaint that no longer exist. Barriers may be erected, and the systems, operations, and layout altered.
- The size of the campus and the access to the points in all directions at different distances around it to parse out multiple simultaneous sources, added to the challenge of transients.

As we are well aware, LFIS travel farther and penetrate building envelopes more easily than middle and high frequencies. Once inside a building it can be enhanced by resonances, and if levels are sufficient can set parts of the building into vibration. In the common example of thunder, we know that near a lightning strike there is a broadband crack sound that is attenuated by the





**Figure 1:** Examples of cooling tower noise at source/receiver property line. Scaife Rd (xAl) are a cooling towers along a building. Data Ctr X samples are extracted from a short term measurement to emphasize the fluctuating nature of cooling towers at middle and low frequencies. No significant infrasound is present, but low frequency tones are evident. Dotted lines represent typical noise levels expected in urban, suburban, rural residential in the evening, using ANSI S12.9 Part 3. [3] Rural control ref is included from the author's datasets and extends into the infrasound range.

atmosphere at long distances, leaving only the follow up low frequency rumble. The rumble following a lightning strike can be heard indoors distinctly and is capable of shaking buildings based on proximity to the source.

## Characterization of LFIS from data centers and related power sources.

**Figure 1** provides a look at characterization of cooling tower noise at two different sites. The graphs show the presence of low frequency tonal noise, at levels that can penetrate the facade of a residence. As an example, Data Center X exhibits pulsing or throbbing from interactions of fans, pumps and/or compressors, creating surges of low frequency noise that fluctuate at infrasound periodicity shown through short samples overlaid.

Natural gas turbine power sources are broken down into open and combined cycle (louder) and closed cycle, in order of increasing energy recovery systems. All systems can be fitted with attenuation measures, however in the case of a permanent installation, changes to the attenuation system require shutting the turbine down (prohibitive) and in temporary power generation, attenuation is often minimal due to the factors of expediency and cost. **See Figure 2.** The same pulsing or throbbing may be heard at power plants; over larger distances this audibility can be due to atmospheric effects.

As seen from **Figures 1 and 2**, tonal and broadband components can be present, note that measurement

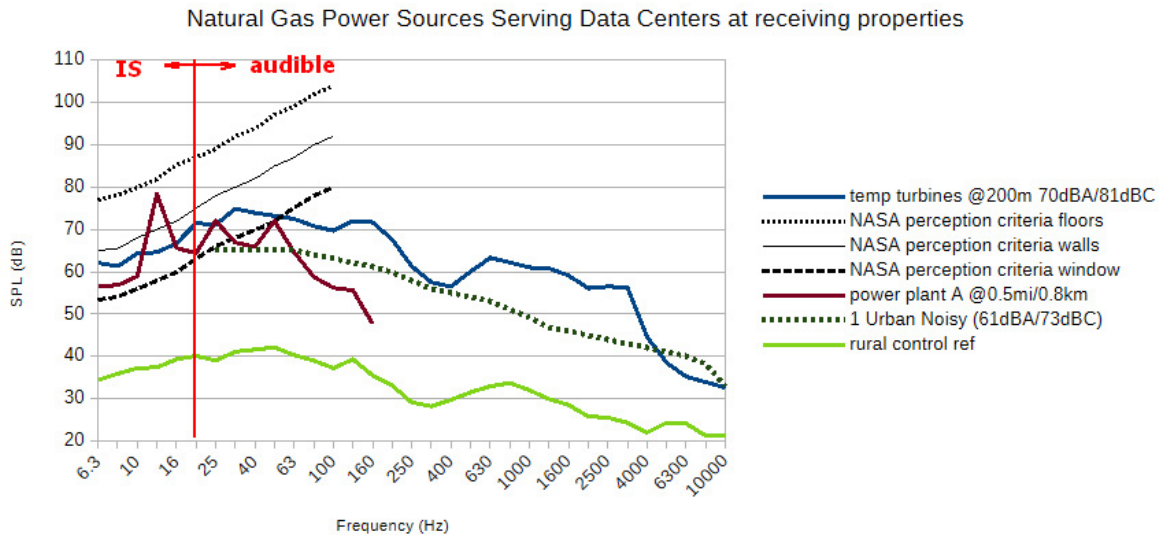
penalties should be assessed to address tonal concerns (and pulsing). Also note that common background sound levels are shown for reference (ANSI 12.9 part 3); while the all cases shown in **Figures 1 and 2** are real and are considered rather egregious, it should be noted that even lower levels of continuous noise from these sources directly impact the soundscape and quality of life experienced by residents indoors and outdoors. Single number regulations such as A-weight cannot properly quantify the human perception of this invasive and continuous sound in context, and this requires consideration. [4]

## Measurement of LFIS

Challenges exist in accurate measurement of LFIS, in particular due to a lack of capabilities of common sound level meters and microphones, availability of practical LFIS sensors for longer term observation [5], and wind screens.

- Microphone and sound level meter sensitivity and tolerances vary in the infrasound region. It is critical the accuracy and frequency range meet the needs of the measurement.
- Lab calibration of measurement microphones primarily will be 20Hz+, with an assumption that the microphone is functioning as per specifications in the IS range. Specialized IS calibration exists, but is not readily available; commercial IS sensors are available,





**Figure 2:** Examples receiving property sound levels from natural gas turbines (a) permanent natgas turbine installation/ tall stack and (b) temporary natgas turbines. The temporary turbines shown are under 30 units, increased to over 50 after the measurement (xAI Southaven, Mississippi). NASA -TM83288 provides perceptibility thresholds for vibration induced by airborne sound.

but this market is still developing. IS sensors can be calibrated, however this is also specialized and limited access. LFIS Sensors are ideal for deployments greater than short term measurements. [5]

- Wind noise is a special consideration with LFIS; the smaller the windscreen and the higher the windspeed, the higher the frequencies affected by wind induced noise (WIN); note that WIN consists of stagnation noise (the sensor interacting with the air flow) and non-acoustic pressure fluctuations caused by intrinsic turbulence. Larger windscreens can reduce intrinsic noise (see below). [6]

As many of you have seen in the field, LFIS windscreen noise can show up at different sites and times, all within, say, 1/8 mile (0.2km) of one another, and gusting is a factor. For those that fly small planes or sail boats, you are aware of localized fluctuations in wind direction and speed. None of the truly local wind conditions are borne out by nearby weather station data, suggesting that LFIS measurements would be well served by a weather station at each monitoring point, within practical limitations. **Figure 3** provides a graphical example of WIN/ turbulence noise.

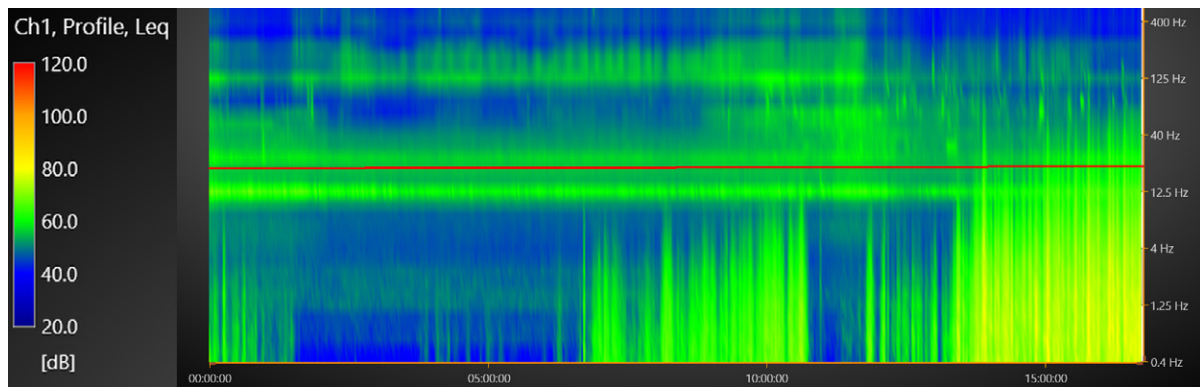
- Intrinsic turbulence is a non acoustic consideration that may be mistaken for infrasound or can easily

mask infrasound. Turbulence is generated by heat, turbulent eddies interacting, and eddies interacting with the wind shear layer near the ground.

Wavelengths of turbulence are a fraction of the size of the acoustic wavelengths of the same frequency, providing an opportunity to attenuate turbulent pressures with larger windscreens; turbulence effects increase drastically at the lowest frequencies. [5]

IEC 61400-11 wind turbine standard defines windscreens sufficient to provide WIN/turbulence noise attenuation down to ~4 Hz, and some government requirements exist to limit the use of windscreens to this standard, however there are opportunities to use smaller hemispherical screens on the ground if the lowest measurement target frequency is higher, noting that it must be characterized against a standard windscreen for corrections. The purpose is to get sufficient WIN/ turbulence attenuation to detect the presence of infrasound. Ideally we would use infrasound sensors with hemispherical screens at ground level.

- The LFIS standard ANSI S12.9 part 7 is adequate in its current state in terms of its prediction of wind noise based on windspeed and windscreen size/type, but there is room for improvement as these are minimum assumptions. [5] It is noted that S12.9P7 covers indoor and outdoor measurements.



**Figure 3: LFIS WIN/turbulence induced noise shown via heat map over a 17 hour period of a natgas power plant with a tall stack.** “Hot” surges along the bottom of the graph (lowest frequencies) are driven by wind fluctuations. Note on the right side of the graph WIN noise approaches 100Hz for this example. 12.5Hz, 25Hz, and 125Hz tones are evident, fluctuating over time (red line is ~20Hz). ½” microphone with 90mm windscreens- larger windscreens are critical in this range.

- It can be seen from the information presented that A weighted single number measurements are insufficient to characterize data centers and power plants; C weight is a start to address the audible sound spectra associated with data centers, but infrasound exceeds the typical local resources for measurement and legislation, creating a challenge for infrasound identification and management.

Single metric G weight is recommended by ISO 7196 but must overcome equipment limitations discussed above. Equipment limitations may be best accommodated by providing reportable data. ISO 7196 does not address perception of vibration related to high infrasound levels.

- Multiple sources may further require a parsing of the individual sound sources to inform needed noise control efforts. Arrays of microphones or sensors can aid in this process, but may not be practical for simpler investigations. [7] Triangulation around a source is less accurate, but may be sufficient for source identification.

## Propagation of LFIS

Commonly used outdoor noise modeling softwares utilize (a) temperature inversions and (b) assumed wind (gradient) profiles up to 100m based on windspeed at a given height above ground, and can be reasonably accurate up to 3km/2miles distance for a given condition and to predict worst case conditions (these models can be asked to calculate further, but accuracy suffers). The persistence of LFIS over greater distances suggests that we need to at least understand what can happen at longer

distances, as predicting and modeling the atmosphere above 100m may be impractical for practitioners.

Upward traveling sound entering the “duct” at an angle under 20 degrees to the horizontal can be redirected downward at some distance, the remainder of the sound continues toward the stratosphere. However, LFIS is capable of traveling larger distances upward where it can encounter wind traveling in different directions at different speeds, and these other ducts can cause LFIS to be deposited at great distances in different directions. See **Figures 4,5,6** real conditions taken from an investigation in Hutto, Texas.

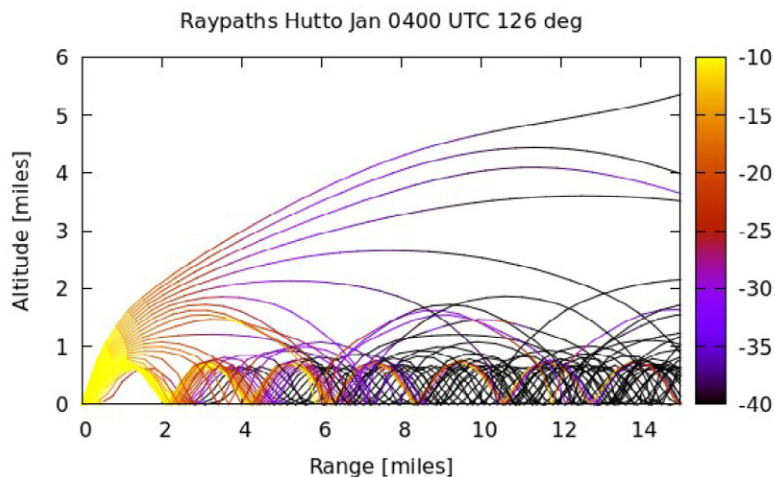
A rough estimate is if you have wind maxima/lobe at a given altitude, you can expect that sound to land 5x that distance downwind.

Returning to shorter range atmospheric propagation, if we look at the CONCAWE model, at 0.5miles/0.8km atmospheric effects can range from -12dB to +5dB at 1000Hz and -8 to +2dB at 63Hz. If we look at the potential fluctuations of perceived loudness (Fletcher-Munson), low frequencies and high frequencies are at least comparable in the perceived fluctuation (low to high 4x or ¼ as loud), however atmospheric absorption of middle and high frequencies leaves LFIS as the main concern at greater distances.

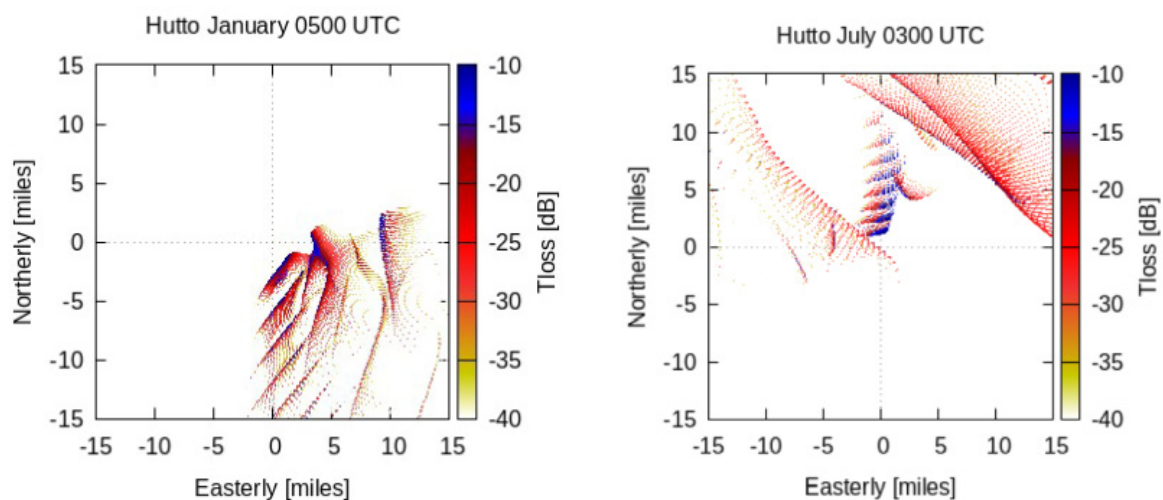
## Exposure to LFIS and standards

Thresholds of perception of LFIS vary physiologically between people such that one person’s threshold of perception is another’s of pain; these mechanisms infrasound perception are still being investigated [8], and there is not yet an agreement on what constitutes

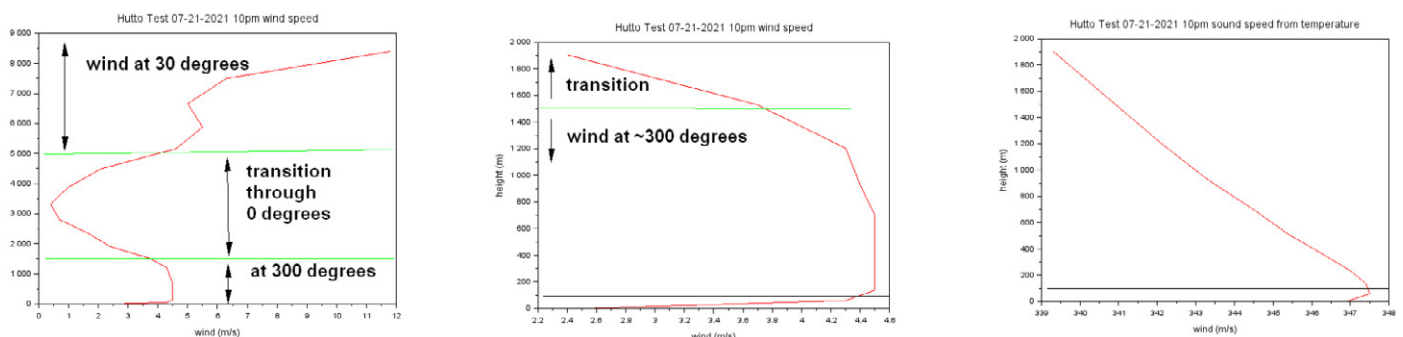




**Figure 4: Simplified ray propagation model of an outdoor concert, low frequencies.** Note that along the bottom of the graph we can see a duct where sound keeps re-arriving at the ground every 2 miles with only modest attenuation. This model is based on actual atmospheric conditions, but is only an approximation and does not include ground attenuation. On this particular evening wind was the dominant factor.



**Figure 5: Nighttime ray based analysis using wind and temperature (left) showing a strong southeasterly wind propagation with multiple “landing points” over 15 miles (11pm).** In the first 5 miles (south and southeast) there appears to be several strong landing points for sound that was projected upward. **Right, primarily wind based to the north and northeast (9pm).** Temperature effects can be seen to the north west. The model does not show the source sound (center 0,0) or the direct propagation, only approximate additive effects from the wind. Some other propagation phenomenon related to wind are not accounted for.



**Figure 6: Wind and temperature base sound speed profiles.** Left plot is wind speed and direction up to 8km, center to 2km, and right wind speed based on temperature. Under the black horizontal line (100m/328ft) is where ducting effects are considered to occur and is used by commercial computer models.

a maximum allowable exposure limit. Negative health effects of LFIS exposure can vary from person to person as well, and include sleep disruption, stress, hypertension, headaches, inability to concentrate, disorientation, and increased risk of cardiovascular failure.

As noted above, for LFIS measurements (and by association exposure criteria), the A-weighting metric comes up short and C-weighting can be useful but not at the lowest audible frequencies into infrasound. Our concerns are twofold: (a) what are the thresholds of community response to LFIS and (b) how do we regulate/manage LFIS? In regard to exposure/level limits we can certainly begin with DIN 45680, NASA-TM83288, ANSI S12.9 part 4, and DEFRA LFN criterion. David Nelson has recently presented a paper at Noise-Con 2026 that assesses these methods and proposes new criteria for consideration [9]; this has potential to inform a new U.S./international standard. In regard to local management of LFIS, this will require some innovative thinking: all regulations/laws are only as useful as the enforcement and judiciary resources permit, and the complexities of LFIS require specialized resources beyond most cities, let alone suburban and rural communities.

This article lightly covers a dense topic, I encourage you to dig into the referenced material (and their references) to get a more thorough understanding of LFIS. Accurately identifying, measuring, determining long range propagation of, and understanding exposure to LFIS from data centers, gas turbines, and other sources is critical to public health and safety.

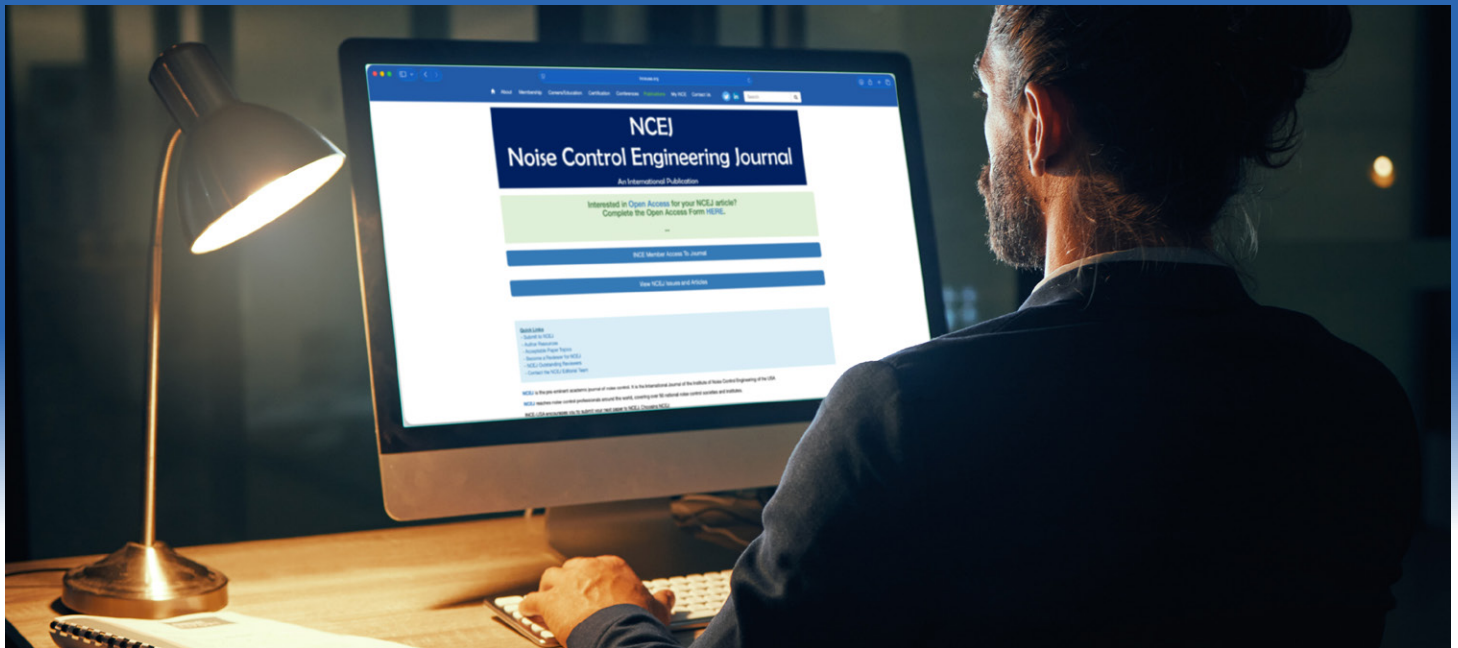
*Thanks to Roger Waxler and David Nelson.*

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- [2] <https://cleanview.co/reports/behind-the-meter-data-centers>
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- [4] Bray, Wade, "Relevance and applicability of the soundscape concept to physiological and behavioral effects caused by noise at very low frequencies which may not be audible", *J. Acoust. Soc. Am.* 132, 1925 (2012)
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## About the Author

**David Woolworth** is an acoustical consultant, educator, and researcher at Roland, Woolworth & Associates in Oxford, MS. An interest in low frequency community impacts was originally developed in response to managing entertainment sound and limits of standards and data addressing LFIS. Areas of research over the years include modal analysis of musical instruments, biomedical ultrasound, and other topics in physical acoustics. David is the chair of three ANSI standards S12.18, S12.9P7, S12.66, and is active in soundscape standards. ■



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## Social survey on wind turbine noise in Japan

**Authors:** [Kuвано, Sonoko](#); [Yano, Takashi](#); [Kageyama, Takayuki](#); [Sueoka, Shinichi](#); [Tachibana, Hideki](#)

**Source:** [Noise Control Engineering Journal](#), Volume 62, Number 6, 1 November 2014, pp. 503-520(18)

**Publisher:** [Institute of Noise Control Engineering](#)

**DOI:** <https://doi.org/10.3397/1/376246>

## Low frequency noise and infrasound from wind turbines

**Authors:** [O'Neal, Robert D.](#); [Hellweg, Robert D.](#); [Lampeter, Richard M.](#)

**Source:** [Noise Control Engineering Journal](#), Volume 59, Number 2, 1 March 2011, pp. 135-157(23)

**Publisher:** [Institute of Noise Control Engineering](#)

**DOI:** <https://doi.org/10.3397/1.3549200>

## Diagnosis of damaged wind turbine blade by noise characteristics

**Authors:** Wang, Chao-Nan; Chi, Tang-Yao

**Source:** [Noise Control Engineering Journal](#), Volume 68, Number 2, 20 March 2020, pp. 146-156(11)

**Publisher:** [Institute of Noise Control Engineering](#)

**DOI:** <https://doi.org/10.3397/1/376813>

## Nationwide field measurements of wind turbine noise in Japan

**Authors:** [Tachibana, Hideki](#); [Yano, Hiroo](#); [Fukushima, Akinori](#); [Sueoka, Shinichi](#)

**Source:** [Noise Control Engineering Journal](#), Volume 62, Number 2, 1 March 2014, pp. 90-101(12)

**Publisher:** [Institute of Noise Control Engineering](#)

**DOI:** <https://doi.org/10.3397/1/376209>



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