As the Wind Blows: Turbulent Noise on Outdoor Microphones

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Introduction

What does wind sound like? It certainly makes all kinds of noise. Wind is heard in the rustling of trees and whistling inside buildings. It can cause wires to sing a tone. Wind has been recorded as the rumbling in outdoor sound recordings for as long as microphones have been used. The motion picture industry has had to contend with it for at least a century. Infrasound recordings are routinely limited by noise from wind that goes mostly unnoticed by people. You may be surprised to hear, however, that not all these noises are sounds at all. This article explores the various sounds and noises produced by wind, their physical principles, and how these principles are used in reducing unwanted noise.

The Signal Is "Blowin' in the Wind"

Wind noise becomes unwanted whenever it overwhelms sounds of interest. Anyone who has struggled to understand a phone call made outside on a windy day has experienced the essential issue. Wind noise is also a common problem in video recordings made outdoors. Although a nuisance in these cases, for example, in users of digital hearing aids, wind noise is a serious limitation to hearing outdoors (Launer et al., 2016).

Wind noise occurs wherever there is wind, including on other planets. The Venera 13 and 14 probes that were landed on Venus by the former Soviet Union in 1982 (see go.nasa.gov/2VYTl0f) each included a microphone that recorded signals that Soviet scientists inferred to be wind noise. These recordings were used to estimate the wind speed at each landing site (Ksanfomaliti et al., 1982).

In addition, the NASA Mars 2020 Perseverance rover entry, descent, and landing camera (EDLCAM) system includes an omnidirectional microphone (Maki et al., 2020). One of the first recordings released from this microphone was of Martian wind noise (**Figure 1**) (National Aeronautics and Space Administration/Jet Propulsion Laboratory-Caltech, 2021).

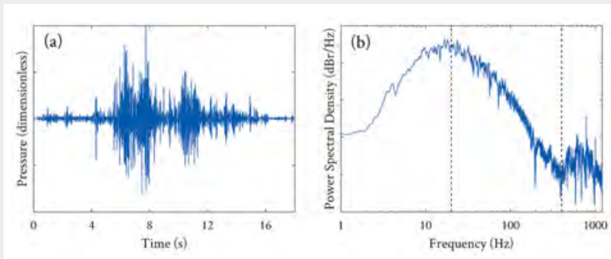

Figure 1. *Time series (**a**) and spectrum (**b**) of a wind noise recording from the entry, descent, and landing camera (EDLCAM) of the NASA Mars 2020 Perseverance rover. Wind noise contributions to the spectrum unaffected by microphone frequency response or rover noise fall between the vertical dashed lines at 20 and 400 Hz. Audio recording courtesy of National Aeronautics and Space Administration/Jet Propulsion Laboratory-Caltech (2021), available at go.nasa.gov/2WTC9t2.*

In physical acoustics, *wind noise* refers to a distinct type of noise made by the wind. In this definition, wind noise is the limiting noise recorded on microphones during windy conditions. Although a wide range of whistling, rustling, and rumbling noises are produced by and are readily associated with the wind, only a few are dominant sources of wind noise on microphones. This article focuses on microphone wind noise, with a limited discussion of other "wind sounds."

Atmospheric Turbulence

Before examining wind noise, it is helpful to first consider the wind itself. The atmosphere immediately above the ground is the *planetary boundary layer* (PBL). Although

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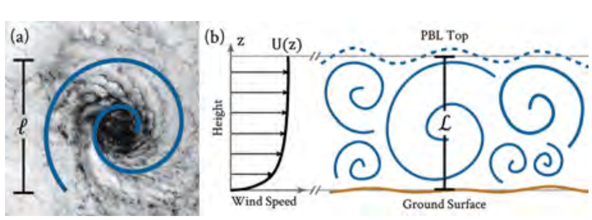
the PBL depth varies widely, from tens of meters to several kilometers, almost all outdoor sound is recorded in the PBL. Over land, the typical PBL wind speed varies diurnally, with higher wind speeds during the day than at night.

Wind in the PBL is almost always turbulent. This means that the wind velocity fluctuates continuously as a random process with irregularity in both space and time. Gusts are local peaks in this irregular wind. Averaging reveals a mean wind speed (U) that increases with height (z) above the ground. The *mean shear rate* (dU/dz), the gradient in wind speed with height, is approximately proportional to z^{-1} in windy conditions. Mean shear has an important role in the production of wind noise.

Turbulent wind can be thought of as a distribution of *eddies*, conceptual vortical structures spanning a wide range of length scales (**Figure 2a**). The largest eddies contain the majority of the turbulent kinetic energy, which is sustained by the mean shear. These large eddies have energy-containing length scales ($\mathcal{L}$) on the order of the PBL depth (**Figure 2b**). The smallest eddies, on the order of millimeters, are where turbulence dissipates into heat by viscous friction. A continuous spectrum of eddy length scales lies between these two extremes, with energy increasing rapidly as a power law with length scale.

To describe turbulence in time, one can use *Taylor's frozen turbulence hypothesis*: on average, eddies are carried along by the flow at nearly the mean wind speed. As a consequence, an eddy of length scale ℓ will produce a signal of duration ℓ/U_c, approximately, where U_c is a *convection velocity*, often taken as $0.7U$. The distribution of length scales can therefore be related to time-domain statistics, in particular the power spectral density, in the same way as an acoustic wave, with the sound speed replaced by the convection velocity (Wyngaard, 2010).

Figure 2. ***a:*** *Diagram of a conceptual eddy of scale* ℓ*, overlaid for illustration on a kilometer-scale horizontal vortex shed from the Juan Fernandez Islands off the coast of Chile on September 15, 1999. Image courtesy of National Aeronautics and Space Administration Earth Observatory, 2000.* ***b: Left:*** *Plot of a typical vertical wind speed profile* (U) *as a function of height above ground* (z)*;* ***right:*** *layer-spanning eddies with energy-containing scale* ($\mathcal{L}$) *in the planetary boundary layer* (PBL)*.*



Turbulence, however, is not a wave. It loses coherence in space and time much more rapidly than would an acoustic field with a similar spectrum of length scales (i.e., wavelengths). Although the flow does carry eddies along, they are not preserved but do distort and decorrelate. Distortion occurs most slowly at the largest scales, with decorrelation proceeding more rapidly with decreasing eddy scale (Mathieu and Scott, 2000). This loss of coherence can be exploited in wind noise reduction methods.

Noise Without Sound

Most wind noise recorded on microphones is not sound. In other words, the pressures that are most readily measured and associated with the blowing wind are not a result of propagating acoustic waves. Turbulent wind produces pressure fluctuations, which are recorded by an acoustic sensor regardless of whether they are acoustical. Although this distinction may seem academic, it has profound implications for how wind noise is measured and mitigated.

As with the turbulence that induces it, wind noise is broadband with a wide range of scales. Wind noise is observed most often over low frequencies, contributing typically below a few kilohertz (Luo and Nehorai, 2006). The largest eddies with length scale $\mathcal{L}$ ensure a broad peak in the wind noise spectrum near $U_c/\mathcal{L}$. Because this frequency can be less than a hundredth of a hertz, it is usually not observed, even on infrasound sensors. The spectrum then decreases as a negative power law with increasing frequency. Two distinct mechanisms contribute to wind noise: stagnation pressure and intrinsic pressure.

Stagnation Pressure

When a microphone is placed in the wind, it creates an obstacle for the flow. The wind must come to rest, or stagnate, on the sensor body. The turbulent momentum ahead of the microphone is balanced by an unsteady pressure along its surface. This category of wind noise is known as *stagnation pressure* (**Figure 3**). This source

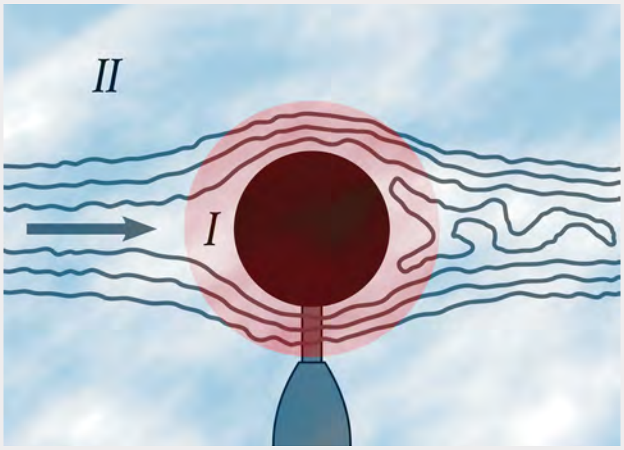


Figure 3. *Diagram of a screened microphone in atmospheric turbulence. Streamlines illustrate the stagnation and distortion of flow around the windscreen. The sources for stagnation pressure are localized to region I (**red**), whereas the intrinsic pressure sources dominate in region II (**blue**).*

involves not only the windward face of the microphone or its covering but also the wind diverted around it, in which the turbulence is distorted due to local acceleration. Stagnation pressure fluctuations can be modeled by a fluctuating Bernoulli equation such that pressure at the sensor is equal to the kinetic energy per unit volume that would be present in the flow if the sensor were not there (Raspet et al., 2008). Wind noise on a bare microphone will be primarily due to stagnation pressure.

Related to but distinct from stagnation pressure is the *self-noise*, which is caused by sensor-generated turbulence. Self-noise sources include the turbulent boundary layer on the surface of a microphone or its covering as well as the unsteady wake flow behind it. The largest scales in these secondary flows are significantly smaller than those of the atmospheric turbulence, on the order of the sensor dimension at most. For outdoor microphone measurements, self-noise is negligible in comparison with the stagnation pressure (Raspet et al., 2006).

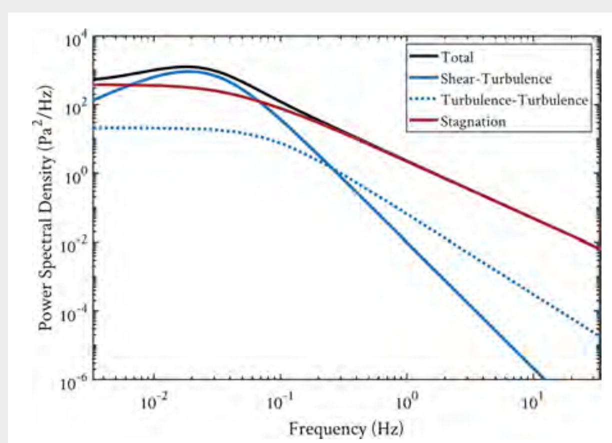
Intrinsic Pressure

Even if the stagnation pressure could be eliminated, wind noise would persist. Atmospheric turbulence produces its own static pressure fluctuations irrespective of the sensor body within the flow. This category of wind noise is termed *intrinsic pressure.* These pressure fluctuations are given by Poisson's equation in which the source terms are products of the velocity component gradients. A single linear source term in which the mean wind shear interacts with turbulent velocity gradients is called the *shear-turbulence* mechanism. The remaining contributions are second order in the fluctuating gradients. They represent a nonlinear interaction of the turbulence with itself called the *turbulence-turbulence* mechanism (George et al., 1984). **Figure 4** shows an example of contributions to a spectral model of wind noise from the stagnation and intrinsic pressures.

Unlike the stagnation pressure, the intrinsic pressure sources are not localized at the sensor. Unsteady pressure sources received by the microphone are distributed throughout the flow, a consequence of the intrinsic pressure Poisson's equation. The distance at which these sources are "felt" tends to increase with decreasing frequency so that low-frequency wind noise can be caused by turbulence tens or even hundreds of meters away from the sensor. For this reason, intrinsic pressure can been viewed as a lower bound for wind noise reduction (Raspet et al., 2006).

Because dU/dz is proportional to z^{-1}, the shear turbulence term becomes increasingly important near the ground (Yu et al., 2011a). Accurate modeling must account for variation in the shear rate with height, the structure of turbulence near the ground, and the nonlocal nature of sources (Yu et al., 2011b). The net outcome is that for wind noise at the ground surface, contributions to wind noise at frequency f are concentrated at a height

Figure 4. *Plot of contributions from the stagnation and intrinsic pressure sources to the total model power spectral density of wind noise one meter above the ground surface (Raspet et al., 2008).*



on the order of U_c/f, so that lower frequency sources are found at greater heights (Yu, 2009).

Aeroacoustic Sources

Wind does produce sounds, even if they are not significant sources of microphone noise. These *aeroacoustic* sources, sound generated by unsteady wind, commonly depend on the interaction of the turbulent wind with a surface. Lighthill's acoustic analogy provides the basis for our understanding of sound propagating from a turbulent fluid. Conceptually, turbulent eddies radiate as acoustic sources with a quadrupolar directivity (Lighthill, 1952, 1954). Jet noise is a common example, where the acoustic intensity scales according to the flow speed raised to the eighth power. Extensions of the acoustic analogy by Curle (1955) and Doak (1960) consider sound radiation from stationary surfaces embedded within turbulence. Pressure fluctuations on a surface radiate sound with dipole directivity. In this case, acoustic intensity scales according to the flow speed raised to the sixth power. Later, Ffowcs Williams and Hawkings (1969) extended the theory to account for moving surfaces.

A cylindrical body in the wind, such as a pole or a wire, will periodically shed turbulent eddies from its leeward side. The unsteady forces load the surface, causing sound radiation known as an *Aeolian tone*. Careful observations by Lord Rayleigh showed that a wire oscillates in a plane perpendicular to the direction of flow such that the sound radiates most strongly along the path of oscillation (Strutt, 1879).

Flow through outdoor vegetation generates a common source of natural noise. Trees generate sound aerodynamically, primarily as Aeolian tones from their leaves and branches and mechanically through unsteady contact between branches (Fégeant, 1999; Bolin, 2009). Low-frequency contributions in both coniferous and deciduous trees are due to mechanical contact between branches and unsteady aerodynamic forces. Fully leafed deciduous trees generate high-frequency noise through the unsteady contact of leaves with other leaves and branches (Fégeant, 1999).

Wind Noise Reduction in the Audible Band

In outdoor audio recordings, the stagnation pressure is typically the dominant wind noise contribution. For this reason, reduction methods focus on the wind flow around the microphone, typically with a covering known as a *windscreen*. Although varied in shape, size, and material, the intent of all windscreens is the same: reduce the stagnation pressure received at the microphone with minimal insertion loss for acoustic signals. Windscreens only mitigate turbulent pressure and generally cannot improve the ratio of any acoustic signal to acoustic noise because they will attenuate both equally. Distinct from windscreens, pop screens or pop filters are used in voice recording to shield a microphone from a burst of air generated in speech or singing, not to mitigate sustained turbulent flow (Wuttke, 1992).

As an alternative to windscreens, streamlined nose cones are commonly placed over microphones in indoor air flows to reduce stagnation pressure. However, the largest eddies of turbulence indoors, such as those generated by a fan or an exhaust duct, are several orders of magnitude smaller than those of atmospheric turbulence. The intensity of turbulence in such flows is also typically lower. As a consequence, when used in wind outdoors, these nose cones are not as effective (Webster et al., 2010).

Windscreen material properties that affect wind noise include porosity and tortuosity. Porosity is the amount of open space within the material. Tortuosity is an average measure of how twisted the network of pores is through the material. Permeability, a measure of resistance to flow through the open pores, is determined by porosity and tortuosity. Highly permeable materials have no effect on the flow or wind noise. As permeability decreases, the flow is impeded and diverted, resulting in wind noise reduction. If permeability is too low, however, the porous interface restricts flow to a degree that turbulent wake noise increases (Xu et al., 2011; Zhao et al., 2017). Porosity plays a role in dissipating turbulent vortices incident to a windscreen (Geyer, 2020).

Polyurethane foam windscreens are often used for wind noise reduction in outdoor acoustic monitoring applications. They are most appropriate for omnidirectional pressure transducers (Wuttke, 1992). Typical shapes include cylinders, spheres, and ellipsoids, which are chosen to accommodate to the shape of the microphone and its enclosure. Some of these shapes are seen in **Figure 5**. Characteristic dimensions are normally on the order of 10 cm, with larger windscreens selected for noise reduction at

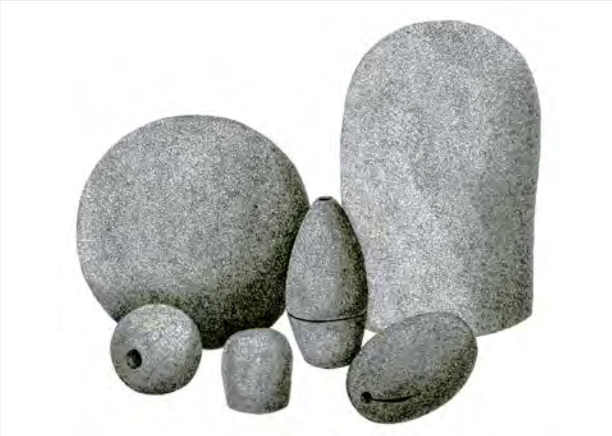


Figure 5. *A range of commonly used microphone windscreen types. Illustrated by Jessica Reeves.*

lower frequencies. Despite their use, accurate characterization of the acoustic environment is challenging, especially in windy conditions. Recordings are often censored when the mean wind speed at the microphone height is greater than a predetermined threshold (Mennitt et al., 2014).

In the motion picture industry, windscreens came into routine use once productions included sound recording outdoors. Early forms of "wind gags" were spherical or streamlined frames covered with one or more layers of fine-meshed muslin or silk (**Figure 6**) (Clark, 1931). The enclosed volume of air acts as a pressure chamber that maintains a high correlation between turbulent fluctuations entering the inlets of a pressure-gradient transducer (Wuttke, 1992). Due to their directional characteristics, these types of transducers are typically used in sound-recording practice.

Although the human eardrum is naturally shielded from wind noise by the pinna and ear canal, wind noise can be a significant problem for users of digital hearing aids. Unmitigated, wind noise can saturate hearing aid microphones, limit intelligibility of speech, and make outdoor sounds inaudible. Because windscreens are not feasible, wind noise mitigation has focused on digital signal processing. On a single microphone, wind noise may be detected from its statistical properties. In two-microphone algorithms, the relative incoherence of turbulent pressure is used to discriminate wind noise from sound. Once detected, wind noise is suppressed through a variety of algorithms, including single-channel noise reduction, microphone switching, or binaural algorithms in wirelessly paired hearing aids (Luo and Nehorai, 2006; Launer et al., 2016).

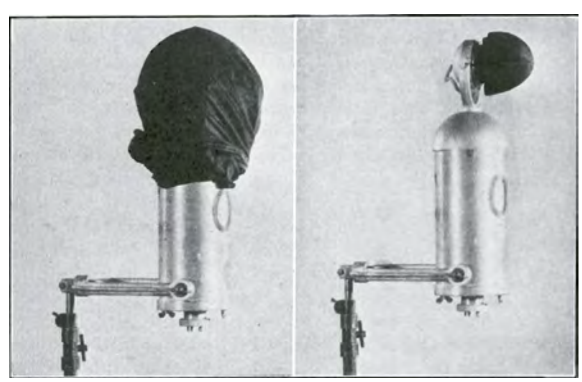
Windscreen Physics: Better Than Average?

The means by which windscreens reduce wind noise may seem obvious at first: the microphone is sheltered from the wind. However, wind stagnating on the windscreen still creates pressure sources on the surface that the microphone receives. At high frequencies, wind noise reduction is caused by averaging these sources over the surface. Eddies that are smaller than the windscreen will average with only partial coherence due to the properties of turbulence. Length scale considerations show that mean squared pressure fluctuations should decrease with the inverse square of frequency (van den Berg, 2006). Therefore, the bigger the windscreen, the greater the wind noise reduction.

The surface-averaging hypothesis fails at low frequencies, however, because significant wind noise reduction is also observed for eddy length scales much larger than the windscreen. To explain this, Phelps (1938) proposed that stagnation pressure fluctuations are distributed over the windscreen in the same way as the pressure field modeled by the mean flow. Morgan (1993) developed a model based on this hypothesis by using steady pressure distributions measured in a wind tunnel. Similarly, Zheng and Tan (2003) used computational fluid dynamics to consider a range of wind velocities under Phelps' (1938) hypothesis.

Phelps' (1938) hypothesis predicts a large negative correlation between the pressure fluctuations on the windward and

Figure 6. *Photographs of "wind gags" for wind noise reduction in early motion picture sound recordings (Clark, 1931).*



leeward sides of a windscreen. In measurements on a porous foam sphere, Raspet et al. (2007) instead observed that the surface stagnation pressure decorrelated over distances much shorter than the free atmospheric turbulence. They hypothesized that flow distortion around the windscreen reduces turbulent length scales. As a result, the spatial average over the windscreen surface is far more effective and the wind noise is reduced at lower frequencies than those predicted by spatial averaging alone (Raspet et al., 2019).

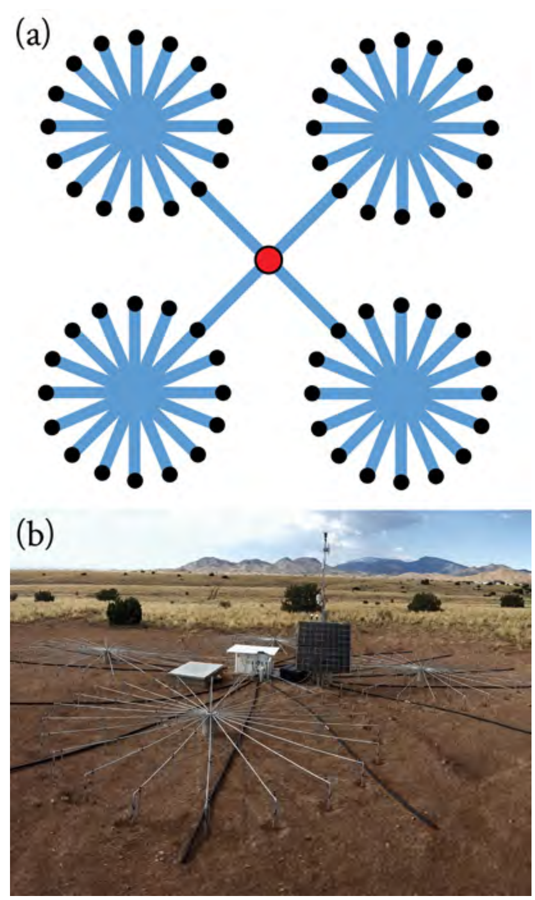
Wind Noise Reduction in the Infrasound Band

At frequencies below human hearing in the infrasound band, wind noise becomes more intense due to the increase in the turbulence spectral density with decreasing frequency. Infrasound sensors are used for measuring the geophysical and anthropogenic sources of sound, such as volcanoes, tornadoes, meteorites, and large explosions, at frequencies down to hundredths of a hertz. Because these sensors often are placed in sheltered locations on the ground surface or below it, intrinsic pressure will often dominate the wind noise. For long-range infrasonic sensing, such as that conducted by the International Monitoring System (IMS) for monitoring of atmospheric nuclear explosions, wind noise is the primary limitation to detection (Marty, 2019). Many methods exist for reducing infrasonic wind noise. The effective frequency band of these methods principally depends on the dimension of the filter system (Raspet et al., 2019). Because lower frequencies are caused by larger eddies, systems for infrasonic wind noise reduction tend to be much larger than the audio microphone windscreens.

One method for wind noise reduction for permanent infrasound sensor installments, known as a *pipe array*, consists of a branching network of interconnected solid pipes with inlets arranged over a wide area. A diagram and photograph of a common pipe array configuration known as a standard multiple rosette is shown in **Figure 7**, **a** and **b**, respectively, which covers an approximately 18×18-m^2 ground area. Yet again, the wind noise reduction results from the fact that for length scales less than the array aperture, atmospheric turbulence will be incoherent relative to acoustic waves. The acoustical response of pipe arrays is not uniform with frequency, however, because waves with a length near the array diameter or smaller will cause arrivals at the sensor from different inlets to be out of phase. Pipe arrays also suffer from resonance effects. Similar, but more portable, lengths of microporous "soaker" hoses can be attached to infrasound sensor ports and spread over the ground to act as a spatial filter (Walker and Hedlin, 2010).

Porous domes and wind fence enclosures are alternative types of wind noise mitigation that are free from the acoustical response and resonance issues affecting pipe arrays. For short-term use, small meter-scale-diameter domes are placed over infrasound sensors on the ground, which are effective for relatively high frequencies, above 2 Hz. Larger hemispherical domes ranging from one to six meters in diameter have been made from porous fabrics (**Figure 8a**) (Noble et al., 2014) and perforated

Figure 7. ***a:*** *Diagram of a standard multiple rosette variant of a pipe array wind noise filter system. Diagram courtesy of Thomas Gabrielson.* ***b:*** *Photograph of the same configuration at the Sandia National Laboratories Facility for Acceptance, Calibration, and Testing (FACT) Site Array. Photograph courtesy of John Merchant.*



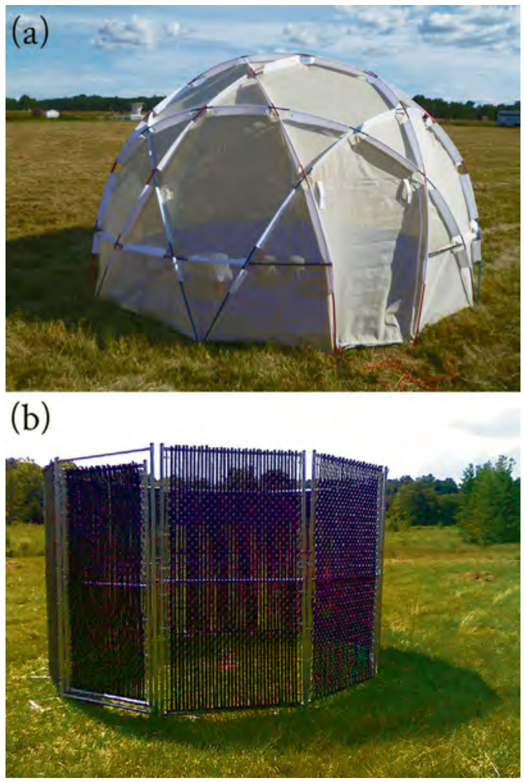


Figure 8. ***a:*** *Photograph of a porous dome windscreen from Noble et al. (2014). Photograph courtesy of John Noble.* ***b:*** *Photograph of a wind fence (Abbott et al., 2015). Photograph courtesy of John Paul Abbott, with permission of the Acoustical Society of America.*

sheet metal (Raspet et al., 2019). Cylindrical wind fences (**Figure 8b**) have also been investigated for a wide range of porosities, diameters from 5 to 10 meters, and heights from 3 to 6 meters (Abbott et al., 2015). These enclosures reduce intrinsic pressure sources within the sheltered interior at the expense of new stagnation pressure sources on the enclosure surface. As with audio microphone windscreens, measurements show that flow distortion around the enclosure significantly reduces near-surface correlation lengths. This leads to more efficient spatial averaging and wind noise reduction at lower frequencies than might be expected for the enclosure size (Raspet et al., 2019).

Conclusion

Within the topic of noise generated by wind, there are many other problems with a rich body of work that have not been discussed here, such as wind noise on mobile devices, noise inside vehicles in motion, and noise inside tall buildings. Wind noise is ubiquitous in outdoor sound measurements, which has led to many independent approaches to mitigation, whether mechanically or digitally. However, a common theme in the success (or failure) of noise reduction methods is exploiting the physical properties that wind noise inherits from atmospheric turbulence, most significantly its correlation structure in space and time. By recognizing that microphone wind noise is not sound, the physical and statistical tools by which it may be described and mitigated are realized.

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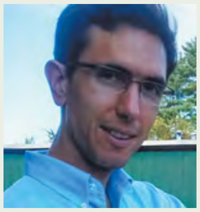

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