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Application of a spectral-based wind noise reduction method to acoustical measurements

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Wind-induced microphone self-noise is a non-acoustic signal that may contaminate outdoor acoustical measurements, particularly at low frequencies, even when using a windscreen. A recently developed method [Cook *et al.*, JASA Express Lett. 1, 063602 (2021)] uses the characteristic spectral slope of wind noise in the inertial subrange for screened microphones to automatically classify and reduce wind noise in acoustical measurements in the lower to middling frequency range of human hearing. To explore its uses and limitations, this method is applied to acoustical measurements which include both natural and anthropogenic noise sources. The method can be applied to one-third octave band spectral data with different frequency ranges and sampling intervals. By removing the shorter timescale data at frequencies where wind noise dominates the signal, the longer timescale acoustical environment can be more accurately represented. While considerations should be made about the specific applicability of the method to particular datasets, the wind reduction method allows for simple classification and reduction of wind-noise-contaminated data in large, diverse datasets.

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1. INTRODUCTION

Extraneous noise can contaminate or invalidate outdoor acoustical measurements. Contaminating noise can be caused by both acoustic sources and by non-acoustic signals, and therefore correctly measuring a source signal can be difficult. One particularly challenging source of outdoor contamination is wind, which not only creates additional acoustic sources—such as the rustling of leaves—but also introduces non-acoustic pressures, known as wind-induced microphone self-noise or hydrodynamic noise, that corrupt data.

Acoustic signals like the rustling of leaves caused by wind are a part of the acoustic environment and are not addressed in this paper. Conversely, wind-induced microphone self-noise—hereafter referred to simply as "wind noise"—is a non-acoustic signal which should not be considered as indicative of the acoustic environment.[1] For outdoor acoustic measurements in the audible frequency range, the dominant source of wind noise is the stagnation pressure fluctuations caused by atmospheric turbulence interacting with the microphone diaphragm or windscreen.[2,3] While microphone windscreens can reduce the overall amount of contamination measured by a microphone, they do not eliminate all wind contamination.

Various methods are used to mitigate the excess pressures resulting from wind noise,[4-7] such as using multiple microphone coherence to eliminate uncorrelated noise.[8] Another possible solution relies on measuring wind speeds along with acoustic data so that data taken during times of increased wind can be removed. For example, the National Park Service (NPS) Natural Sounds and Night Skies Division typically removes any data that were collected when the measured wind speed exceeds 5 m/s.[9] However, when considering datasets that contain only a single-channel recording and that do not include measured wind speeds, or even for relatively low but still relevant wind speeds, it is more difficult to determine which data are the result of acoustic sources and which are wind-contaminated data.

A recent paper was published to describe the development of a wind contamination identification and reduction method for one-third-octave band data taken with unobstructed, outdoor, screened microphones, based on known spectral characteristics of wind noise contamination.[10] The method uses the characteristic spectral slope of wind noise to classify individual spectral frequencies as either contaminated or uncontaminated. When several short-timescale measurements (e.g., several two-second spectra) are available, a decontaminated long-timescale average spectrum can be calculated (e.g., a spectrum composed of one-hour median spectral levels at each frequency, also known as an L_{50}). This method allows for automatic calculation of wind-noise-reduced or decontaminated spectra—and thus decontaminated overall sound pressure levels—for single-microphone data where wind speeds were not measured. By removing the wind-noise-contaminated data, the method can automatically estimate clean or decontaminated acoustic levels for a wind-noise-contaminated sound field.

This paper further explores the usefulness and limitations of the classification and reduction method by applying the method to spectral datasets where exact acoustic source characteristics and wind speeds are unknown. Different sized windscreens are used, and both natural and anthropogenic sources are considered. The method is able to remove not just high levels of low frequency wind noise contamination, but also lower-level contamination and wind noise at frequencies between multiple band-limited acoustic sources.

2. WIND NOISE THEORY

Wind noise is caused by non-acoustic turbulent pressure fluctuations on a microphone diaphragm. The sources of these pressure fluctuations may include turbulence that occurs naturally in the atmosphere or wake turbulence generated by the microphone and windscreen. In outdoor measurements, atmospheric turbulence is the dominant source of wind noise.[3] The magnitude of the pressure fluctuations produced by atmospheric turbulence depends on the wind speed, height above the ground, stability of the atmosphere, and frequency.

The frequency spectrum of atmospheric turbulent pressure fluctuations can be grouped into three frequency ranges: the energy-containing range, the inertial subrange, and the dissipation range. The energy-containing range occurs at low infrasonic frequencies (often less that a few hertz), which are below the frequencies of interest for the outdoor acoustic measurements considered in this paper. In the dissipation range, turbulent fluctuations rapidly dissipate into heat, so wind noise is typically negligible compared with the acoustic sources or instrumentation noise. The frequency of the dissipation range increases with wind speed and typically occurs above 100-1000 Hz.

For most outdoor acoustic measurements, contaminating wind noise in the inertial subrange is of primary importance. The inertial subrange lies between the energy-containing range and the dissipation range and can occur between high infrasonic and mid-range audible frequencies. In the inertial subrange, the stagnation pressure fluctuations caused by atmospheric turbulence interacting with the microphone diaphragm or windscreen are proportional to $f^{-5/3}$, where f is the frequency. Turbulent-turbulent pressure fluctuations, which are proportional to $f^{-7/3}$, are negligible compared with the stagnation pressure fluctuations.[311] Thus, the magnitude frequency spectrum of wind noise varies linearly with logarithmic frequency, i.e., $\mathrm{SPL} \propto \log(f)$, where SPL is the sound pressure level created by wind noise.

Windscreens are often used in an attempt to reduce wind noise in outdoor acoustic measurements. The pressure measured by a microphone at the center of a windscreen is a combination of the acoustic pressure and the turbulent pressure fluctuations as mitigated by the windscreen. Within the inertial subrange, the turbulent pressure fluctuations vary linearly with the fractional-octave band, which produces a characteristic spectral slope indicative of wind noise. However, the characteristic spectral slope changes at a crossover frequency of $f_c = V/(3D)$, where V is the mean wind speed and D is the windscreen diameter.[12] At frequencies below f_c in the inertial subrange, the turbulent pressure fluctuations are coherent over the entire surface of the windscreen, and the characteristic spectral slope is -6.7 dB per decade.[3] At frequencies above f_c in the inertial subrange, the turbulent pressure fluctuations are incoherent over the surface of the windscreen, and the characteristic spectral slope is -26.7 dB per decade, shown in Figure 1.[3,13] This result implies that a windscreen reduces wind noise at these frequencies by "averaging out" incoherent turbulent pressure fluctuations over its surface.[2,3]

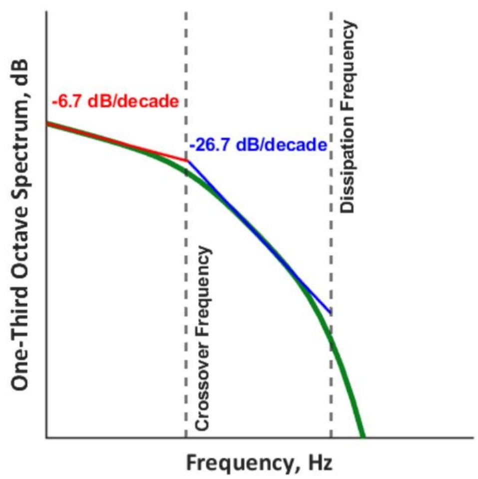

Figure 1. Visualization of spectral wind noise characteristics in the inertial subrange. Above the crossover frequency and before the dissipation range, the characteristic slope of wind noise is -26.7 dB per decade.

For many outdoor acoustic measurements with reasonably low wind speeds compared to the size of the windscreen, the crossover frequency occurs at infrasonic frequencies, and so the characteristic spectral slope is -26.7 dB per decade at audible frequencies. For example, for a windscreen with a diameter of 9 cm at a wind speed of 5.4 m/s, the crossover frequency is f_c= 20 Hz. Although an increase in wind speed results in higher measured sound pressure levels, the characteristic spectral slope is independent of wind speed above the crossover frequency. Thus, if the crossover frequency is generally below the lowest frequencies of interest, the characteristic spectral slope can be used to detect the presence of wind noise in acoustic measurements without requiring knowledge of the wind speed.

3. WIND NOISE CLASSIFIER

An implementation of the wind noise classification and reduction method is described in detail by Cook et al.[10] Given a particular spectrum, the algorithm seeks to find frequencies whose levels align with the characteristic spectral slope of wind noise of -26.7 dB per decade. Frequency data that match this spectral slope within a couple of decibels are classified as contaminated, while the other frequencies, which can be between contaminated frequencies, are classified as clean. No knowledge of microphone and windscreen setup, acoustic sources, suspected frequency range of wind contamination, or wind speed is necessary. By classifying multiple short timescale spectral data, longer timescale average spectra can then be calculated using only clean data. The automatic classification and reduction of wind noise can give a more accurate representation of the acoustic environment than that calculated using all the data.

To illustrate the effectiveness of this method, the variable wind speed was measured while recording a constant acoustic source, as described in Cook et al.[10]. Each 1-second spectrum is shown in Figure 2, colored by wind speed. At lower frequencies, increase in wind speed causes an increase in amplitude, though the spectral slope remains the same. The maximum crossover frequency during the data collection, based on windscreen size and maximum measured wind speed, was approximately 18 Hz, while on average was closer to 4 Hz, which is below the lowest 1/3 octave band used of 6.3 Hz. While it is not necessary for the crossover frequency of all 1-second spectra to be below the lowest frequency of interest, default algorithm parameters should be changed if thre crossover frequency is too high due to high wind speeds.

The method is able to correctly classify the contamination, and remove contaminated data when calculating the average spectrum. For comparison, two other average spectra are shown: one using all of the data, where the high levels at lower frequencies are the result of wind noise, and a second using only spectra where the measured wind speed was 0 m/s. The spectrum calculated using only the clean data approximates the no-wind spectrum, which is a more accurate representation of the acoustic environment than the average spectrum calculated from all of the data, as much of the data were contaminated by wind noise.

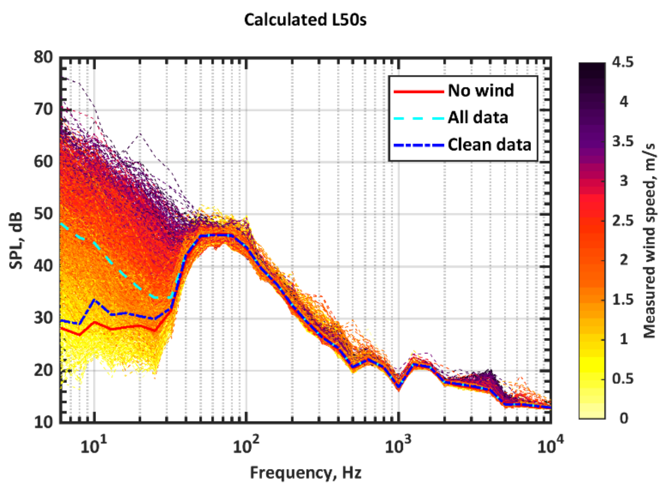

Figure 2. Wind contamination reduction results for a constant brown noise source. Below 50 Hz measured levels are primarily caused by wind contamination. The reduction method median level approximates the median level when wind speeds of 0 m/s were measured, indicating that the method is able to correctly classify frequencies where spectral data are a product of wind noise rather than acoustic noise.

In application, acoustic sources and wind speeds may not be known, and so while it has been shown that this method is effective with a known source and known wind speed, it is also instructive to show how the wind noise classification and reduction method works on spectral data of non-controlled sources with unknown wind speeds. Two different microphone setups are considered, which use different sizes of wind screens in different environments.

4. APPLICATION OF CLASSIFIER TO DATA

A. NATURAL AMBIENT ENVIRONMENT

Acoustic data were taken in the Bear River Migratory Bird Refuge using a ground-based microphone setup with a 30 cm windscreen.[14] While nearly 6 months of data were collected and run through the wind noise classifier, this paper focuses on a particular 90-minute period on the afternoon of May 10th, 2021, when there was evidence of variable amounts of wind noise contamination. Several natural and variable acoustic sources, both biotic and abiotic, were measured during this period. The wind noise classification and reduction method is applied to these spectral data and results are investigated.

The left plot in Figure 3 shows a spectrogram for the 90-minute period. The wind noise classification method is applied to each 1-second spectrum, and frequencies that show evidence of wind noise contamination are removed, resulting in the spectrogram in the right plot of Figure 3. Wind noise contamination is primarily found for frequencies below 160 Hz. While there appears to be higher-level wind noise after about 18:08, the classifier is able to not only classify these high levels of contamination, but also lower levels of wind noise contamination prior to this. With some exceptions, much of the visible wind noise in the spectrogram has been automatically removed successfully.

Something important to note is that there is additional noise in the 160-2500 Hz range after about 18:08, during periods of apparent high wind speed. This likely caused by the rustling of plants when there is wind, which itself is not wind noise contamination (wind-induced microphone self-noise) but is an actual acoustic source which is only present when there is wind. This noise is part of the acoustic environment, caused by physical sound sources, and should not be considered wind noise contamination. Because it is a physical noise source, it does not match the characteristic slope for wind noise and is not removed.

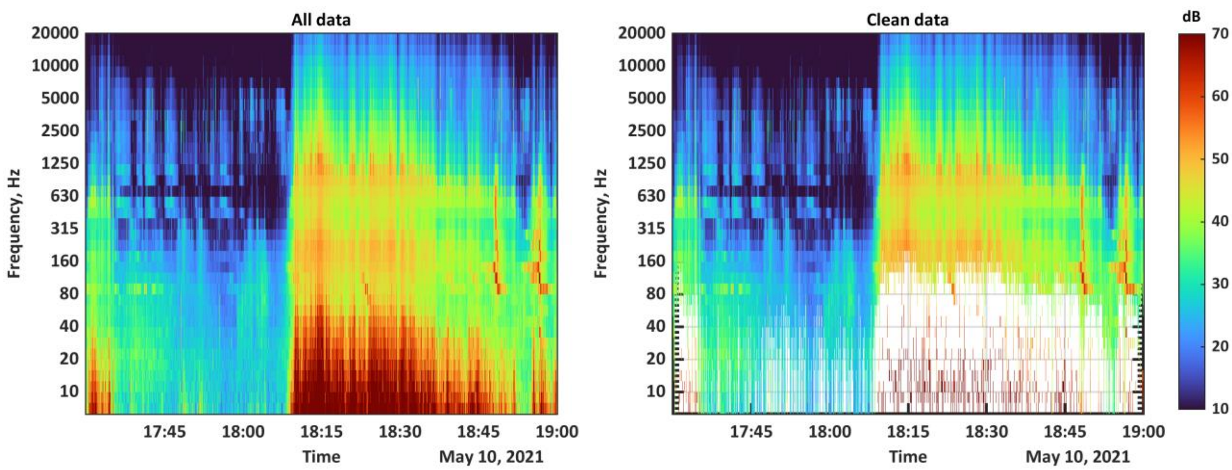

Figure 3. Wind noise classification applied to 90 minutes of ambient acoustic recordings at the Bear River Migratory Bird Refuge.

The classification alone, while useful in its own right, is further used to calculate median or $\boldsymbol{L_{50}}$ acoustic spectra. Median spectral levels are calculated for 15-minute intervals, as well as for the entire 90-minute duration. These can be compared to the median spectral levels for each corresponding time period when using all the data, and are shown in Figure 4. In each 15-minute period, it can be seen that the levels of the average spectrum of the clean data are less than or equal to the levels of the average spectrum of all the data. When applied to the entire 90-minute period, a reduction of up to 25 dB occurs at the lowest frequencies.

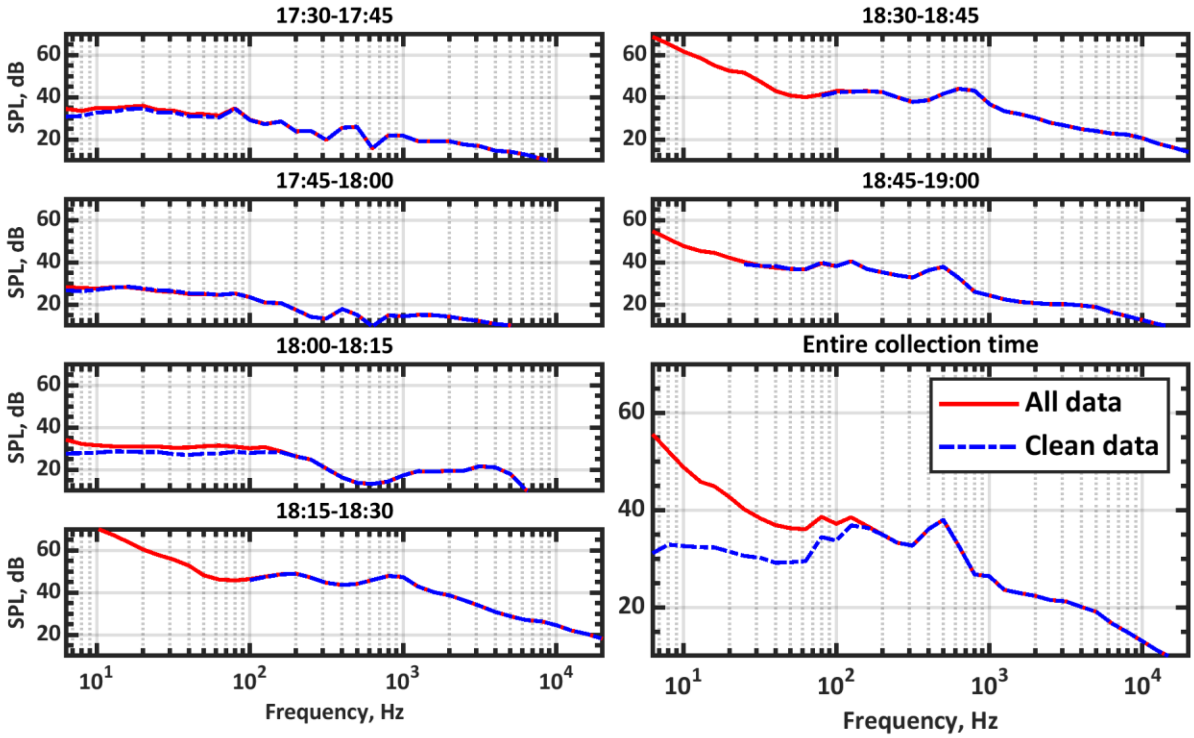

Figure 4. Wind noise reduction applied to the spectral data shown in Figure 3. Results are shown for 15-minute intervals, along with results for the entire collection period. For the clean data average, frequencies that were contaminated for more than 75% of the measurement period are omitted.

It is important to note than when calculating average levels using only the clean data, each frequency can be calculated using a different percentage of the total time period. Because wind noise contamination is not found at frequencies above 200 Hz in these data, the average spectrum at those frequencies represents 100% of the time duration; at lower frequencies, however, some of the data are contaminated. The exact amount of contaminated data depends on the particular frequency. If a high percentage of the data are contaminated, then it is possible that the ‘average’ spectrum at a particular frequency could be dominated by a very short time period. For this reason, frequenices where more than 75% of the data were classified as contaminated do not return an average level. For example, this is the case for frequencies below 100 Hz between 18:15-18:30.

Notably, if all spectral data had been removed when wind noise contamination was present instead of just the frequencies that were contaminated, the peak at 500 Hz—which is only present during time periods with higher wind—would also have been removed. This evidences that spectra calculated by the wind noise reduction method can give a more accurate representation of the acoustic environment than removing entire spectra that contain wind-contaminated data, all without having a measured wind speed.

In this natural ambient environment, the observed acoustic sources varied during data collection, and some acoustic sources were created by wind. Possible issues with too much of the data being contaminated by wind noise were seen, as well as how average spectra are calculated for a different percentage of the data collection time at different frequencies. The wind noise reduction method is able to preserve the acoustic sources while removing wind noise contamination, even though the wind speed during the collection was unknown.

B. ANTHROPOGENIC NOISE

To investigate other successes and limitations of the wind noise classification and reduction method, data containing anthropogenic noise is used. Acoustic data were taken on farmland using a microphone at a height of 1.5 m with a 9 cm diameter ball windscreen. This setup is more prone to wind noise contamination, due both to the microphone being higher off the ground, where wind speeds are greater, and to the smaller windscreen, where the crossover frequency is higher. However, for this particular time period, wind speeds were rather low, and so no more wind contamination is seen here than in the previous data set.

Figure 5 shows spectrograms for the two hours of data used, where the right plot removes data that were classified as contaminated. Sound sources observed include farm machinery, which exhibit some bandlimited or tonal behaviour, primarily at 13-16 Hz, and also at 31.5 Hz and 50 Hz. Acoustic data are consistent and of low level at higher frequencies, and so the frequency range shown is limited to below 315 Hz.

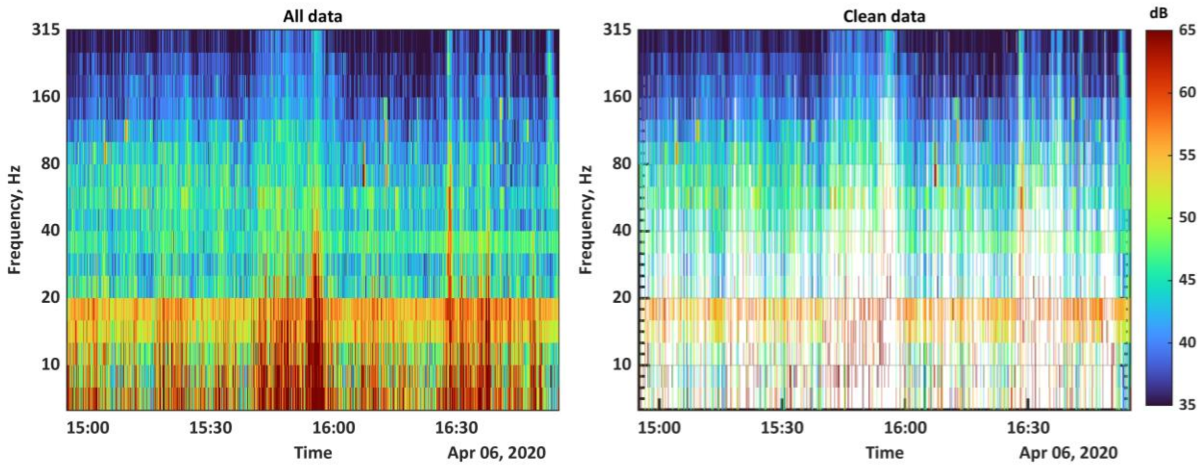

Figure 5. Wind noise classification applied to 2 hours of spectral data taken on farmland near machinery.

Median spectral levels are obtained for 20-minute intervals, and are shown in Figure 6. For each interval, the peaks at 13-16 Hz, 31.5 Hz, and 50 Hz are maintained, while wind noise at other frequencies—below, above, and also between the peaks—is removed. Note particularly 15:35-15:55, where all frequencies below 31.5 Hz except for 13-16 Hz are removed. These results show that source signals that are in the same frequency range as wind noise can be retained even when the wind noise is removed. This is significant, because even when there is wind noise, if the source levels are of higher than wind noise, the source signal is not removed with the wind noise.

In contrast to the previous data set, the average spectrum of the clean data is not always of equal or lesser level than the average spectrum of all the data. This is seen in the 31.5-80 Hz range for several of the time periods. This can happen in at least two possible situations: (1) when ambient sound levels are positively correlated with wind speed, e.g., a wind vane creaking when wind speeds pick up, or (2) when low levels of wind noise are removed but high levels of wind noise are not removed. In this case it is possible that the machinery was slightly louder when wind speeds were higher, as the higher levels of wind noise contamination appear to be removed successfully, though this is not certain. While results differ by less than 1 dB for this data set, this is an important limitation of the method.

Overall, sound levels at lower frequencies were reduced by up to 8 dB, while source levels were accurately maintained even during periods with high wind noise contamination. By removing the wind noise contamination, the peak at 13-16 Hz is seen to be more pronounced due to the reduction of wind noise at 10 Hz and below.

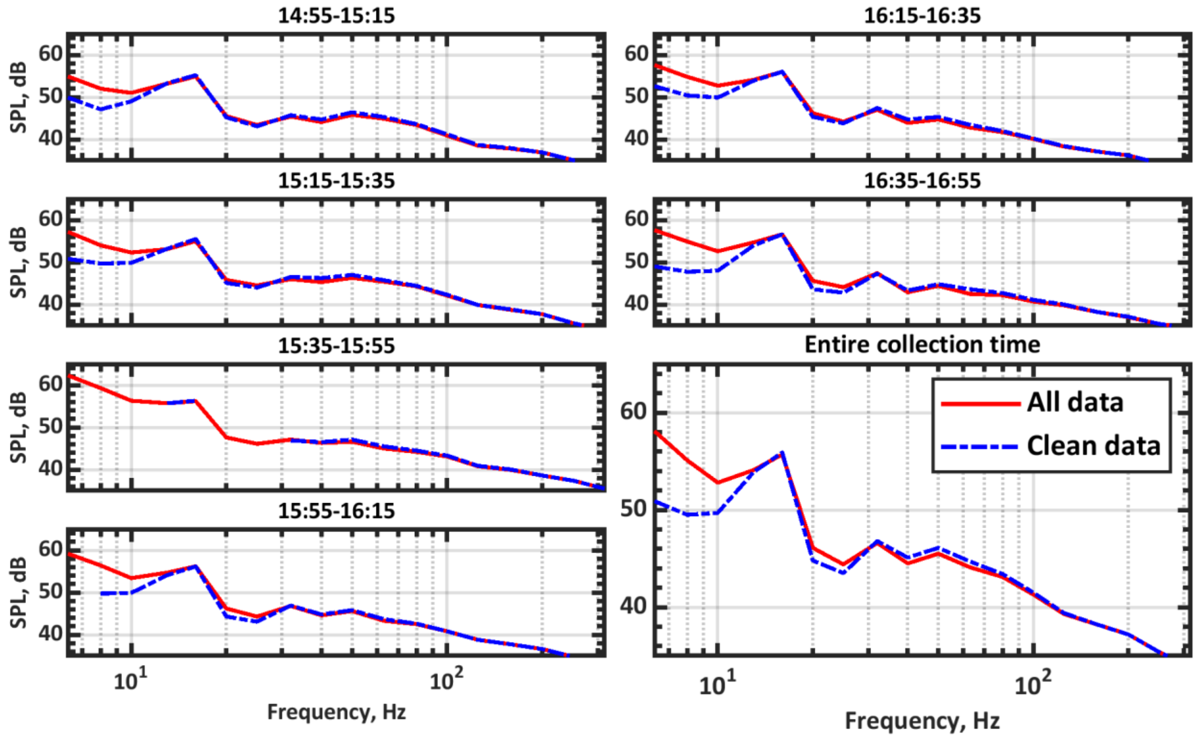

Figure 6. Wind noise reduction applied to the spectral data shown in Figure 5. Results are shown for 20-minute intervals, along with results for the entire collection period.

5. CONCLUSION

This paper has explored some application and limitations of the wind noise classification and reduction method published by Cook et al.[10] to spectral data where wind speed is unknown. The wind noise classification and reduction method is able to automatically detect and remove the negative effects of wind noise contamination in spectral data. While some care must be taken to ensure that spectral data are above the crossover frequency (when the windscreen is small compared to the wind speed), and while data must be taken using a windscreen, this method can be applied to many kinds of spectral data, even when specifics of data collection are unknown.

By using the characteristic slope of wind noise, levels at different frequency bands are independently classified so that acoustic data present during time periods with wind, and acoustic data in the same frequency range as wind noise contamination, is retained. This allows average spectra to be calculated that are better representative of the acoustic environment than those calculated by removing time periods of wind contamination and can be performed automatically without requiring a measured wind speed.

In practice, it may be infeasible to measure wind speeds while taking acoustic data. Even when wind speeds can be measured simultaneously, it is possible for wind speed measurement hardware to contaminate acoustic measurements. While the wind noise classification and reduction method is not applicable in every situation, it provides a simple, elegant way to classify and remove wind noise contamination in spectral data. It can be applied to spectra during data processing, and is performed automatically with minimal to no user input. This method can help anybody to improve outdoor measurements by removing wind noise from acoustic data.

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