Wind turbine low frequency and infrasound propagation and sound pressure level calculations at dwellings

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(Received 19 April 2018; revised 5 July 2018; accepted 5 August 2018; published online 27 August 2018)

This study was developed to estimate wind turbine low frequency and infrasound levels at 1238 dwellings in Health Canada’s Community Noise and Health Study. In field measurements, spectral peaks were identifiable for distances up to 10 km away from wind turbines at frequencies from 0.5 to 70 Hz. These measurements, combined with onsite meteorology, were in agreement with calculations using Parabolic Equation (PE) and Fast Field Program (FFP). Since onsite meteorology was not available for the Health Canada study, PE and FFP calculations used Harmonoise weather classes and field measurements of wind turbine infrasound to estimate yearly averaged sound pressure levels. For comparison, infrasound propagation was also estimated using ISO 9613-2 (1996) calculations for 63 Hz. In the Health Canada study, to a distance of 4.5 km, long term average FFP calculations were highly correlated with the ISO based calculations. This suggests that ISO 9613-2 (1996) could be an effective screening method. Both measurements and FFP calculations showed that beyond 1 km, ISO based calculations could underestimate sound pressure levels. FFP calculations would be recommended for large distances, when there are large numbers of wind turbines, or when investigating specific meteorological classes.

I. INTRODUCTION

Infrasound produced by wind turbines can be comparable to natural infrasound (Turnbull et al., 2012). Natural infrasound is typically dominated by long range pressure fluctuations from the ocean (microbaroms), short range pressure fluctuations due to local winds and eddies (Bowman et al., 2005; Garces and Willis, 2006), or from surf (Garces et al., 2003). Under certain circumstances wind turbine noise has the potential to exceed natural infrasound, making them a potential source of contamination to low frequency monitoring stations for the Nuclear Comprehensive Test Ban Treaty (see, e.g., Styles et al., 2005; Edwards, 2015; Marcillo et al., 2015).

Under specific conditions, wind turbine infrasound noise has been measured during stable, or very stable atmospheric conditions (e.g., during a temperature inversion at night) at distances of 4 km (Hansen et al., 2015; Zajamšek et al., 2016) and up to 90 km (Marcillo et al., 2015). Observations have also been made during high winds in the daytime to a distance of 20 km downwind (Willshire, 1985; Willshire and Zorumski, 1987; Hubbard and Shepherd, 1991). There are also a number of observations of favorable propagation (i.e., less attenuation, or the sound energy is channeled so that there is a longer distance propagation) of wind turbine noise over water (e.g., Sondergaard and Plovsing, 2005; Boue, 2007; Johansson, 2003). Propagation over even longer ranges (up to 2000 km) has been measured using explosive detonations as sound sources; empirical results (Whitaker, 1995) and Parabolic Equation (PE) simulation (Le Pichon et al., 2012) have shown that infrasound pressure levels from such sources involve mechanisms (e.g., stratospheric ducting and wind perturbations) that are not important for the distances that wind turbine noise propagates.

The previously indicated studies suggest that there may be some cases with sustained propagation that is more favorable than spherical spreading (a 6 dB decrease per doubling of distance) over land. This is not a common option in most commercially available sound propagation models, which were primarily developed for A weighted sound pressure level (SPL) from low sources (like vehicles), and for short propagation distances (up to 1 km). For example, the propagation in ISO 9613-2 (1996) assumes a 6 dB decrease per doubling of distance, although ground attenuation can add up to 3 dB to the levels at 63 Hz at long distances. The standard implementation of Harmonoise also does not provide for sustained propagation more favorable than a 6 dB decrease per doubling of distance; it does include localized SPL increases due to focusing of multiple ground rays, but it restricts each ray to a single ground reflection (van Maercke and Defrance, 2007; Jonsson and Jacobsen, 2008; Salomons et al., 2011). There are methods that allow results that may be comparable to a 3 dB decrease in SPL per doubling of distance (i.e., cylindrical spreading): The Swedish calculation method (SEPA, 2012), but only for conditions over water; and Nord2000 (Plovsing, 2006a,b)
which can be modified to allow coherent summation of multiple reflections (Hidaka et al., 1985; L’Espérance et al., 1992; Sondergaard and Plovsing, 2005).

The most sophisticated common commercially available propagation software use Nord2000 and the Harmonoise P2P models. These models use a simplification where a linear sound speed profile is assumed. In these models, sound speed profiles can be computed with weather classes based on common publically available weather forecasts of wind speed and cloud cover data (Eurasto, 2006; Heimann et al., 2007). For the Harmonoise project, between 100 and 630 Hz, at 1000 m, it was found that an accuracy of 2 dB with 90% probability could be obtained using 25 weather classes based on linear sound speed profiles (Heimann and Salomons, 2004). The simplifications used in these models have been validated at audible frequencies, but their validity at infrasound frequencies has not yet been established.

More powerful computational models such as the PE and the Fast Field Program (FFP) are based on numerical solutions to the wave equation. These methods can accommodate arbitrary sound speed profiles at all frequencies relevant for wind turbines (e.g., 0.5 Hz to 10 kHz), and have been used to predict and explain the long distance propagation from wind turbines (Johansson, 2003; Marcillo et al., 2015).

As part of Health Canada’s study (Keith et al., 2016a), yearlong measurements of wind turbine SPL below 70 Hz were compared to FFP and PE calculation methods for a distance up to 10 km (Daigle and Stinson, 2014; Edwards, 2015). To obtain a realistic estimate of the effect of FFP propagation calculations, measurements of wind turbine sound power were used with different calculation methods to obtain outdoor SPLs at dwelling locations from the Health Canada study.

II. METHODS

A. Site descriptions

Field tests of propagation over distances up to 10 km were made in the Canadian maritime province of Prince Edward Island (PEI). The PEI site was 200 km from the Atlantic Ocean and 20 km from the Gulf of Saint Lawrence (a semi-enclosed sea connected to the Atlantic Ocean). SPL calculations at dwellings were made in both PEI, and the inland province of Ontario. The two study areas had a moderate humid continental climate (southern to mid-boreal Dfb Koppen Geiger classification), flat rural agricultural areas with treed wind breaks on fence lines between fields, and occasional small settlements or copses of trees. In both locations the prevailing wind direction was generally from the west, and most locations were less than 15 km north or south of a large body of water (lake, strait, or sea).

B. Locations of dwellings used for calculation of outdoor SPL

The SPL from 399 wind turbines were calculated at the 1238 dwelling locations in the two provinces in the Health Canada study (Keith et al., 2016a; Michaud et al., 2016). Health Canada targeted all dwellings pre-identified within 600 m of any wind turbine in the study area and used a random selection of dwellings at larger distances out to 10 km. Half of the dwellings included in the study were within 1 km of a wind turbine. Within each province, 70 km was the maximum separation between any two turbines included in the study.

C. Weather statistics

In the Health Canada study area weather data were obtained from six weather stations (Environment Canada, 2016; Fisheries and Oceans Canada, 2016). These stations were chosen because they were the only ones within 200 km of a wind turbine that provided cloud cover data.

In the province of Ontario weather data were obtained from the Windsor airport with additional data from the London airport. The PEI weather data were obtained from the Charlottetown airport, with additional data from Nova Scotia at the Halifax airport, and from New Brunswick at the Bathurst and Moncton airports. The latter four stations reported cloud cover with an adjectival descriptive scale (i.e., Cloudy, Mostly Cloudy, Mainly Clear, and Clear), as well as cloud cover in 10% increments. The two Ontario stations only reported using the adjectival descriptive scale. For comparison, data were also obtained from Montreal, Quebec (1000 km away from the Ontario study area), as this was the nearest inland station that had cloud cover in percent. For the wind turbines (and dwellings) in the Health Canada study the nearest weather station was typically located at a distance of 56(29) km [where the number in parentheses is the standard deviation referred to the corresponding last digits of the quoted result per ISO/IEC Guide 98-3 (2008)]. Meteorology from the single nearest weather station was used to estimate wind turbine SPL. The statistics of the data from the other six weather stations were used to estimate uncertainty in weather data. Wind direction was binned in 10° increments.

D. TL calculation

Calculations were based on transmission loss (TL) as defined by the following formula:

\[
TL = -20 \log \frac{\text{total acoustic pressure at fieldpoint at ground level}}{\text{acoustic pressure of direct sound field at 1 m from the source}}.
\]  

The TL as a function of distance at 1.6 Hz and above was calculated using a full wave FFP (Raspet et al., 1985; Lee et al., 1986; Attenborough et al., 1995; Daigle and Stinson, 2014, 2016). The PE method was used at 0.5 Hz.
(Gilbert and Di, 1993). All calculations assumed an equivalent point source (Makarewicz, 2011) at a height of 80 m obtained from data measured at close range and a receiver height of 0.01 m.

In the TL calculations, sound speed profiles as a function of height were estimated from similarity theory (Monin and Obukhov, 1954; L’Esperance et al., 1993; Daigle and Stinson, 2014; supplemental material from Keith et al., 2016b). As described later, these data were extrapolated either using onsite weather data (for detailed checking of calculations), or based on the 25 general meteorological classes defined in Harmonoise (Table I).

 Typical applications using similarity theory or the Harmonoise meteorological classes do not require profiles for heights above 100–200 m since the propagation distances being considered are typically less than 1 km. Thus in some cases (i.e., Harmonoise classes W2S1, W3S1, W4S1, and W3S2) at heights above 100 m, extrapolation of the low altitude data on which similarity theory is based led to artefacts in the calculation of sound speed as a function of altitude, e.g., the wind would reverse direction. In some cases the temperature would also increase to unrealistic values. For these cases only the profile below 100–200 m was important so that it was not necessary to modify the profiles.

Detailed FFP calculations based on on-site weather station data used terrain elevation obtained from the GeoBase dataset (GeoBase Canadian Digital Elevation Data 1945 2010, 2010) with 1 m vertical resolution which was down sampled to obtain a grid with 3 arc min horizontal resolution (i.e., 92 m resolution north–south and 64 m resolution east–west). In the study areas, the ground was essentially flat and this simplification was used for general TL calculations based on generic Harmonoise classes. In all cases the ground impedance was based on uncultivated farm land.

### E. Use of ISO standards to obtain generic TL

For comparison with other calculations, the ISO 9613-2 (1996) TL calculations were extended to lower frequencies. For simplicity, the TL in octave bands from 0.5 to 32 Hz was assumed to have the same TL as calculated at 63 Hz using ISO 9613-2 (1996). This is expedient for the purpose of comparison with other calculations; at 63 Hz the ground absorption in ISO 9613-2 (1996) is reflecting for both hard and soft ground, and this situation would not be expected to change for frequencies below 63 Hz. In addition, the ground overestimates at 4 m receiver height were used for all frequencies.

The ISO A-weighted calculations were not performed if the wind turbine to dwelling separation exceeded 10 km, this created a large uncertainty in the ISO calculations when the nearest wind turbine was at a distance close to 10 km (i.e., the wind park associated with the nearest wind turbine could be excluded from calculations). To reduce this uncertainty, calculations were limited to dwellings within 4.5 km of the nearest turbine. This excluded 54 of the 1238 dwellings in the Health Canada study.

In calculations, the time at each wind speed was used to calculate the wind turbine source sound power, and the resulting long term average levels at dwellings. Weather class was not a factor in the TL calculations using ISO standards, and as is common in environmental assessments, the meteorological correction for wind direction (ISO 9613-2, 1996) was not included in the initial calculations.

### F. Field measurement validation of FFP and PE TL calculations

TL calculations were validated by field measurements acquired over a 13 month period near Summerside PEI (detailed description in Daigle and Stinson, 2014; Edwards, 2015; Keith et al., 2016a). On this site were four 3 MW Vestas V90 wind turbines (Vestas Wind Systems A/S, Aarhus, Denmark), which were located 40 km from the next nearest wind turbines.

Meteorology for these field measurements, including temperature, humidity, pressure, wind speed, and wind direction, was measured with two Vaisala WXT-520 weather transmitters (Vaisala Corp., Helsinki, Finland) mounted at heights of 2 and 10 m on a guyed aluminum frame tower 2.5 km east (downwind relative to the prevailing wind direction) of the wind turbines. Output data were transmitted and remotely monitored using two Avisaro RS232 Dataloggers (Avisaro AG, Hannover, Germany).

SPLs were obtained at four distances, 125, 2.5, 5, and 10 km from the wind turbines using Chaparral Physics model-25 microbarometers (Chaparral Physics, Fairbanks, AK). At the 125 m distance the microbarometer sensors were within 2 m of the transducers used to measure wind turbine
sound power (Sec. II G). For isolation from wind noise the microbarometer was mounted inside a 0.5 m diameter × 0.9 m high polyvinyl chloride plenum attached to four 15 m long, 1.9 cm outside diameter garden soaker hoses, which extended radially in 4 directions to form an orthogonal “X” shape. Data were recorded using a Nanometrics Trident 24 bit digitizer (Nanometrics, Ottawa, Canada) with a 200 Hz sample rate. These SPL measurements were made at ground level, matching the height used for FFP TL calculations.

In post processing signal enhancement of the sound pressure data used MATLAB (MathWorks, Natick, MA) software for power spectral density employing a “Welch” estimator (50% overlap) and a “Hamming window” with 8192 sample segment length, typically with a 1 h analysis sample time. Under target meteorological conditions, the data were examined at a 2.5 km distance for wind turbine spectral peaks, e.g., harmonics or other broadband spectral peaks. If spectral peaks were found, SPL data from other microbarometer locations were examined as well.

G. Field measurement of wind turbine sound power

Four day field measurements of sound power were performed on ten representative wind turbine models from areas in the Health Canada study (Keith et al., 2016a). This included three wind turbine models in PEI and seven models in Ontario. Measurements followed the methodology to determine the apparent sound power levels from IEC 61400-11 (2012). These procedures were extended to the 0.5 Hz 1/3 octave frequency band. The microphone frequency response below 6Hz was corrected based on manufacturer data included with the microphones. Microphones were set up at a distance of 60 to 125 m from the wind turbine base, depending on turbine height. As per IEC 61400-11 (2012), Bruel & Kjaer type 4165 microphones (Bruel & Kjaer Sound & Vibration Measurement A/S, Nærum, Denmark) were mounted on a ground board with a 95 mm diameter hemispherical foam primary windscreen and a 750 mm hemispherical polyester cloth secondary windscreen (Keith et al., 2016b).

Measurements were obtained over a range of downwind angles, but only measurements in the downwind direction were used to estimate wind turbine sound power. Wind turbines are approximately omnidirectional; the data of Friman (2011), Okada et al. (2016), and Buck et al. (2018) suggest the directivity index is less than 2 dB and that there is a 5 dB null in the crosswind direction.

For comparison, a soaker hose windscreen similar to those described in Sec. II F for long term measurements was also used; Bruel & Kjaer type 4165 microphones were mounted at the intersection of four 15 m long 3/4 in. diameter soaker hoses extending radially in 4 directions to form an orthogonal X shape. These data were simultaneously analyzed in 10 s time steps using 1/3 octave bands, and with narrowband fast Fourier transform (FFT), using Bruel & Kjaer PULSE V17 software. The FFT used 1600 lines resolution, a 100 Hz frequency span, a “Kaiser Bessel window,” and 3 linear averages with 66.7% overlap.

As described in Keith et al. (2016b) a weather station was set up 1.5 to 2 rotor diameters from each turbine base to measure wind speed, direction (Sutron Windsonic ultrasonic sensors 5600-0215, Sutron, Sterling, VA), and temperature (Sutron platinum probes with radiation shields 5600-0025) at 2 m and 10 m heights in 1 s intervals. Humidity (Sutron 5600-0312), and wetness (Sutron Decagon dielectric leaf wetness sensor) were also recorded at the 2 m height. Based on Monin-Obukhov similarity theory (Monin and Obukhov, 1954; L’Esperance et al., 1993; Daigle and Stinson, 2014; supplemental material from Keith et al., 2016b) these data were used to estimate wind speed at the nacelle height. Seven of the ten wind turbine models also had years of historical data available from the wind turbine nacelle for wind speed, yaw direction, electrical power output, and rotor rpm in 10 min intervals.

To improve the data quality of measurements made following IEC 61400-11 (2012) it was assumed that wind noise was not significant when the IEC 61400-11 (2012) wind screened measurements and adjacent soaker hose measurements agreed within 1 dB when averaged over the fundamental and first ten harmonics. For IEC windscreen FFT data meeting this criterion, the difference between the average peak dB level of the harmonics was compared to the average level of the noise at the mid frequency between adjacent peaks. This was used to create a criterion for IEC wind screened microphones when soaker hose windscreen data were not available. Additional criteria used to exclude measurements were rain, or gusts (i.e., changes between two sequential wind speed measurements greater than 1 m/s). Spectra were also rejected if the 10 s estimate of rpm was more than a factor of 1.8 lower than that in the corresponding 10 min average measured at the wind turbine nacelle (when available). In addition, for the data at 8 m/s wind speed, all audible noises were validated by listening to the recordings (Keith et al., 2016b).

H. Use of TL to calculate SPL at dwellings

Detailed on-site meteorological data were not available at most dwellings in the Health Canada study, and realistic yearly average SPL estimates at each dwelling were calculated similar to Eurasto (2006) using the 25 Harmonoise weather classes (5 wind speeds and 5 stability classes), and 36 wind directions. Meteorology was based on statistics for the Health Canada study area (Sec. II C). For each wind direction, the FFP and PE TL (see Secs. II D and II E for modeling parameters) based on weather classes was used with the measured wind turbine sound power (Sec. II G) to estimate the SPL at each dwelling. Each of the 1238 dwelling locations included a summation of the sound energy propagating from each of the 399 wind turbines in the Health Canada study.

FFP or PE was used to calculate TL (Secs. II D and II E for modeling parameters) using generic sound speed profiles based on the 25 weather classes from Harmonoise (Heimann et al., 2007) (Table I). The TL was calculated over a grid 20 km downwind and 5 km upwind with 26 m resolution. The grid spanned 20 km in each crosswind direction with 64 m resolution. Bilinear interpolation was used to estimate TL as a function of distance and direction. To reduce spatial fluctuations in the data, the grid data were smoothed using...
energy equivalent averaging over a sliding range, ±10% of
the radius and ±5° in bearing angle (in practice, long term
operational and meteorological changes would also be
expected to smooth this fine structure). Due to turbulence
upwind in the shadow zone, levels were not expected to drop
more than about 20–30 dB relative to inverse square law (Di
and Daigle, 1994). As a result, for distances upwind greater
than 5 km, the results at 5 km were extrapolated to a larger
distance using the inverse square law.

Based on the readily observable spectral peaks in pre-
liminary wind turbine data, TL data were originally calcu-
lated at five frequencies 0.5, 1.6, 4.8, 20, and 70 Hz.
Calculations in octave bands used the TL data at the nearest
frequency by geometric ratio. At and above 50 Hz atmospheric
absorption was estimated from ISO 9613-1 (1993)
for a temperature of 10°C and relative humidity of 70%.
Atmospheric absorption at lower frequencies was based on
data from Sutherland and Bass (2004, 2006).

The calculations were also repeated in the frequency
range from 0.5 to 63 Hz, using TL calculated by extending
ISO 9613-2 (1996) to lower frequencies (Sec. II E). The FFP
TL was not calculated at frequencies relevant for A-weighted
levels. However, since most wind turbine installations are
evaluated using A-weighting, the current infrasound and low
levels. However, since most wind turbine installations are
evaluated using A-weighting, the current infrasound and low
frequencies results were compared to overall broadband
(2016a). These last calculations were based on the same set of
residences and for turbines within 10 km of each of the
residences.

III. RESULTS AND DISCUSSION

A. Weather statistics

Figure 1 shows the relative time per day associated with
each Harmonoise meteorological class for data averaged over
one year. In this section the data for the seven weather stations
in the Health Canada study area are combined to simplify pre-
sentation of the data. As indicated earlier, in calculations at
dwellings, data from the single nearest weather station were
used.

In Fig. 1 only wind speed classes W3, W4, and W5 are
typically associated with wind turbine operation as W1 and W2
are generally below the wind turbine cut in speed. In this
figure the classes marked by asterisks show that favorable long
distance wind turbine noise propagation is most commonly
associated with the nighttime (S4 and S5). Wind turbines can
potentially operate for 8.7 of the nighttime hours (i.e., 75% of
the time between sunrise and sunset) when the wind speed is
above 3 m/s cut-in wind speed (i.e., wind classes above 3 m/s
such as W3, W4, W5, and W2S5). Weather statistics show
that wind typically blows 32% of the time in the prevailing
wind direction (±30°), and for any other compass direction
(±30°) approximately 14% of the time. Based on the wind
direction statistics and Fig. 1, on average a wind turbine is
operating 8.7 of the 11.7 nighttime hours (between sunset and
sunrise) relative to that turbine, favorable downhill propa-
gation (±30°) occurs on average 2.8 h for dwellings in the
prevailing wind direction and for 1.2 h for other dwellings.

During the daytime hours (classes S1, S2, and S3), classes
marked with asterisks and daggers in Fig. 1 show that the
most favorable propagation conditions only occur for 2.8 h,
and that is almost exclusively during conditions with wind
speeds W4 and W5. Combining this with wind direction sta-
tistics, favorable propagation of operational wind turbine
noise is found to occur on average 0.9 h for dwellings in the
prevailing wind direction and for 0.4 h for other dwellings.

B. TL calculation

Figure 2 shows a sample surface plot of the TL for the
generic class W3S5. In this plot the region above −65 dB (in
red, near 5 km Easting) shows TL near the wind turbine that
is associated with a 6 dB decrease per doubling of distance,
and toward the right this starts to approach 3 dB decrease per
doubling of distance. The red region forms a distorted ellipse
showing that this change in propagation is a function of the

FIG. 1. Annual average occurrence, relative to one day, of the 25
Harmonoise weather classes in the Health Canada study areas. Bars show
the average time (in hours) in each class for the seven stations where data
were available, and the whiskers represent one standard deviation of these
data. The bars sum to 24 h. Asterisks and daggers indicate conditions where
propagation at some frequencies below 70 Hz is at least 3 dB more favorable
than predicted by ISO 9613-2 (1996). Daggers also indicate low wind speeds
that are generally below the wind turbine cut-in wind speeds.

FIG. 2. Surface plot of TL for meteorological class W3S5 at 4.8 Hz as a
function of distance, Northing and Easting, from an 80 m high point source
(located at 1 km Northing, and 5 km Easting). The wind direction is from the
west (left-hand side of plot).
wind angle relative to downwind. At larger distances favorable propagation averaging a 3 dB decrease in SPL per doubling of distance occurs over a range of angles of approximately ±60° relative to the downwind direction. In these areas, there are large fluctuations in the calculated TL due to constructive and destructive interference (with a range of over 20 dB). These fluctuations are consistent with the results of Zajamšek et al. (2016) who also found the variation between minimum and maximum measured levels on the order of 20 dB.

Figure 3 shows smoothed data for frequencies from 1.6 to 500 Hz for the meteorological class W1S5, which along with downwind propagation in W2S5 or W3S5 are associated with the most favorable propagation of all classes. This figure takes into account geometrical spreading, ground reflection, ground impedance, and refraction in the case of the FFP. However, the figure excludes atmospheric absorption. The data have been plotted as the difference from results which would be obtained assuming a coherent +6 dB ground reflection, and a 6 dB decrease in SPL per doubling of distance.

Figure 3(a) shows the change in SPL downwind as a function of distance when calculated using generic FFP based on Harmonoise weather class W1S5. The spatial smoothing (averaging) of the data in this figure was found to have little effect at 1.6 Hz, but reduced the spatial fluctuations as much as 20 dB at higher frequencies. It should be noted that the sound speed profile used for calculations was not a function of frequency, so that the path of the sound rays is the same at all frequencies. For distances less than 1.7 km, the data for all frequencies tend toward horizontal lines which indicate a 6 dB decrease in SPL per doubling of distance. At higher frequency above 70 Hz, these curves are shifted down due to ground attenuation, and at 20 km the 500 Hz TL approaches a 9 dB drop per doubling of distance. All curves show some distances where SPL would be higher than expected with a 6 dB decrease in SPL per doubling of distance. Seventy Hz is the highest frequency where the data might arguably approach a 3 dB decrease in SPL per doubling of distance. For 70, 125, and 250 Hz, at a 1.7 km distance there is an observed jump of a few dB in TL, where multiple rays converge to increase the SPL.

Not shown in Fig. 3, the PE calculations at 0.5 Hz show that to a distance of 10 km the propagation is consistent with a 6 dB decrease in SPL per doubling of distance.

The right-hand panel, Fig. 3(b), repeats the calculation of relative levels using ISO 9613-2 (1996). Smoothing was not required for this data. Note that these calculations are for a height of 4 m, where ISO 9613-2 (1996) indicates there is more ground attenuation at 125 Hz than at 500 Hz. Below 0.5 km Figs. 3(a) and 3(b) suggest geometric spreading is comparable to a 6 dB decrease in SPL per doubling of distance and the main difference between panels is an approximate 3 dB reduction in SPL in the ISO 9613-2 (1996) calculations. The figure shows only the FFP results for the most favorable downwind propagation direction so this difference is to be expected as the ISO calculations give the same results both upwind and downwind. In the ISO calculations an underestimate of downwind levels is compensated by an overestimate in upwind SPL. Arguably, the results in Fig. 3 show consistency between ISO and FFP results for distances less than 1 km, which is the range over which the ISO standard was intended to be used (ISO 9613-2, 1996). Large differences between FFP and extended ISO 9613-2 (1996) calculations are only apparent at 1.7 km or more.

For comparison to Fig. 3, Fig. 4 shows similar smoothed data at 4.8 Hz for generic Harmonoise weather classes. Similar to Fig. 3, at distances less than 1 km, the relative difference from a 6 dB decrease in SPL per doubling of distance, +6 dB ground reflection is near zero. Table II shows numerical results for the same data at 10 km, and shows that for 8 of the 25 Harmonoise weather classes the deviation from the reference condition exceeds 8 dB (refer to Table I for class descriptions). Similar patterns were found at 1.6 Hz for all classes (data not shown). At 20 and 70 Hz, for the W4 and W5 wind speed classes, only W4S5 had TL more favorable than a 6 dB decrease in SPL per doubling of distance, but the patterns for W1 and W3 classes were similar to Table II.

![FIG. 3. Relative level directly downwind of a point source at 80 m height with reference to a coherent +6 dB ground reflection and a 6 dB decrease in SPL per doubling of distance. (a) Smoothed FFP calculations for meteorological class W1S5 in a downwind direction; (b) same calculations repeated using ISO 9613-2 (1996), which are not a function of wind direction. Frequencies used in calculations in (a) include Δ, 1.6 Hz; and ×, 70 Hz, ○, 125 Hz; +, 250 Hz; □, 500 Hz; (b) is similar except the lowest frequency is ×, 63 Hz. The angled dotted lines have a slope of 3 dB per doubling of distance. Higher relative levels in the figures are associated with higher SPL at dwellings.](image-url)
FIG. 4. Smoothed FFP data for a frequency of 4.8 Hz showing relative levels downwind for a single point source at 80 m height with reference to a 6 dB decrease in SPL per doubling of distance and coherent +6 dB ground reflection. From the uppermost to the lowermost curve, the classes represented include: $\Delta$, W1S5; $\times$, W3S5; $\bigcirc$, W4S2 (similar to W4S3 and W4S4); +, W1S2 (similar to W2S1); $\square$, W3S3; $\times$, W4S1; $\bigcirc$, W1S3. The data are for the direct downwind direction, i.e., the most favorable propagation direction. The relative levels shown in this figure at 10 km are summarized in Table II for all 25 Harmonoise classes.

IV. FIELD MEASUREMENT VALIDATION OF FFP CALCULATIONS

A. Identification of wind turbine noise

Figure 5 shows three measurements acquired 125 m from the wind turbine base measured using the microbarometer with soaker hose windscreen. The lowest red curve shows the ambient noise under a 15 min scheduled shutdown period when the wind speeds were about 4 m/s. The next highest blue curve shows the same conditions with the wind turbine operating at just above idle speed (0.5 Hz) at a fundamental frequency of 0.6 Hz. A comparison of levels with the wind turbine ON and OFF shows that wind turbine harmonics are readily visible from 0.6 to 6 Hz, with some broad peaks at higher frequencies. The next higher black curve in Fig. 5 is the wind turbine spectrum with the turbine operating at full speed (i.e., 16 rpm, which occurs for wind speeds at or above 8 m/s). At this speed the fundamental is at 0.8 Hz and a number of harmonics are visible, including some broad peaks at 20, 45, and 70 Hz. The harmonics and broadband spectral peaks seen in the upper curve were used when modeling the wind turbine noise propagation.

FIG. 5. SPL measurements of power spectral density made 125 m from the base of a wind turbine: Black curve (labeled max rpm), turbine operation at maximum rpm (0.8 Hz fundamental, Edwards, 2015); blue curve (labeled idle+), turbines operation slightly above idle speed (0.6 Hz fundamental); red curve (labeled turbine off), same conditions as blue curve, with turbines off. For reference, the ambient noise from Bowman et al. (2005) high ambient noise model (95th percentile) is shown in the uppermost curve; and the low ambient noise model (5th percentile) is shown in the lowermost curve.

In Fig. 6, harmonics associated with operation of the wind turbines are clearly identifiable at distances up to 10 km away. Near the wind turbine the noise is comprised of several harmonics of the fundamental blade passage frequency which are observed near 0.513 Hz for wind speeds less than 8 m/s, and transition to 0.806 Hz at higher wind speeds. These frequencies correspond to the nominal rotor rotation speeds of 10 to 16 rpm.

In Fig. 6, at 2.5 km and beyond, wind turbine SPLs would be expected to drop by more than 20 dB compared to the levels at 125 m. This makes the wind turbine harmonics more difficult to identify. At and beyond 2.5 km only the 16 rpm harmonics are visible, due to the higher sound power levels associated with this rpm. Particularly at night, the wind speed at hub height can be more than double the measured 10 m wind speeds shown in Fig. 6.

In Fig. 6, the upper 20 m/s wind speed curves show large contributions from wind noise at the 2.5 km station. At this location, at frequencies between 1 and 2 Hz the wind noise levels appear to be almost 15 dB higher than the levels at the 5 km station. The 2.5 km station was situated in an open field with a few trees, while the 5 km station was immediately adjacent to a long copse of trees to the north and a larger wooded area to the southwest.

One factor that affects the ability to measure and identify wind turbine spectral peaks is the ambient noise. Both Figs. 5 and 6 show the high and low noise models of Bowman et al. (2005), which characterize infrasound from 21 globally distributed, state of the art, infrasound arrays that are comparable to those in the current study (Sec. II F). At 125 m the high noise model by Bowman et al. (2005) passes through the peaks of the wind turbine noise. In the 4 Hz octave band, the high noise model (95th percentile) and wind turbine noise are both approximately 70 dB. This suggests that at the base of the wind turbines to have a 95% confidence of that wind turbine noise would be dominant,
narrowband filters would be required, and octave band filters
would not be sufficient. Conversely, the low noise model in
the figure is 4 to 6 orders of magnitude lower than the high
noise model, which suggests that under some conditions it
may be possible to measure wind turbine noise at large
distances. This is consistent with the results of Marcillo et al.
(2015), who measured wind turbine noise at a distance of
90 km.

Figure 7 shows spectra identified under well-defined
meteorological conditions. The measured wind speed is
5.0 m/s at 10 m height. In contrast to Fig. 6, where spectral
contributions from many meteorological conditions are aver-
ged, in Fig. 7 a number of harmonics stand out clearly from
the background noise.

The fundamental blade passage frequency was difficult
to observe at distances larger than 125 m. PE calculations at
0.5 Hz indicated propagation at this frequency was never bet-
ter than a 6 dB decrease in SPL per doubling of distance out
to a distance of 10 km.

B. Extrapolation of weather data

Figure 8 shows data from the on-site weather station
(Sec. II F) extrapolated to 1 km height using similarity theory
on an occasion when spectral peaks were readily identified.
The middle plot is the downwind wind speed, and the right-
hand plot is the effective sound speed in the direction of the
dwelling, which takes into account the wind direction.

Similarity theory was not developed for high altitudes,
and as a result the calculated profiles have an approximately
constant linear slope above 50 m. As seen in Fig. 8 this can
result in unrealistic profiles at higher altitudes. Despite this

FIG. 6. Adapted from Edwards (2015) inter-quartile means for measured 10 m
height wind speeds in 1 m/s intervals from 1 m/s (bottom curve in group) to
20 m/s (top curve in group) at a distance from turbine of (a) 125 m, (b)
2.5 km, (c) 5 km, and (d) 10 km. The uppermost curve is the high global
noise limit measured at infrasound monitoring stations (Bowman et al.,
2005) and the lowermost curve is the corresponding low global noise mea-
surement. Arrows above each set of curves show 0.8 Hz fundamental and
associated harmonics, and in (a) the arrows below the set of curves show
0.5 Hz fundamental and its harmonics.

FIG. 7. Averaged wind turbine spectrum at 10 km for a single weather con-
dition (wind speed 5 m/s @ 10 m height, 1.35 °C temperature difference, and
40° off downwind (from Daigle and Stinson, 2014).
C. Observations associated with class W3S5

always a good substitute for measured data. This shows that Harmonoise weather classes are not always a good substitute for measured data. In reality the sound speed gradient in Fig. 8(a)–9(c). Below 5 Hz the data are in good agreement with predictions. Between 5 and 20 Hz background ambient noise appears to be influencing the results at 10 km, and all distances seem to be affected by background ambient noise at 70 Hz. The FFP calculations based on onsite meteorology are closer to the measured SPL than those using the generic Harmonoise classes. Differences between the two calculation methods on the order of 5 dB are common.

Despite averaging over 1 h, the results vary in a range of up to 6 dB. This range is likely influenced by varying meteorological conditions along the propagation path, as well as the fluctuations seen in Fig. 2.

D. Seasonal changes in propagation

Snow cover can produce large changes in SPL near 300 Hz (Daigle and Stinson, 2005, Internoise). However, in the present study, measured over 13 consecutive months, for frequencies at and below 70 Hz, no systematic seasonal differences in SPL were found. In the W3S5 meteorological class in Fig. 9 measurements were observed in the months of June when crops were growing; in November after harvest; and in January when the study area had an accumulation of 1 m of snow.

E. Daytime

Based on measurements by Willshire and Zorumski (1987) it could be expected that the wind turbine signature would be frequently measurable during high W5 winds in the daytime (see also Table II). This was not the case in the Health Canada study area, in part because the W5 classes are not common (Fig. 1), and the Willshire and Zorumski (1987) measurements were facilitated by higher source power levels than found in the Health Canada study. Measurements were, however, identified for W4 wind speeds which compared to W5 classes, have similar TL and lower ground level wind speeds.

Wind turbine noise was also measured downwind at 3.2 Hz (Fig. 10) at 2.5 and 5 km distance. Due to the

FIG. 8. Data from the on-site weather station extrapolated using similarity theory to 1 km height early on a summer morning with a strong inversion [wind speed 5 m/s @ 10 m height, 1.4 °C temperature difference (between 2 and 10 m height), 40° off of downwind]. Left panel: Calculated temperature, middle panel: downwind wind speed, and right panel: effective sound speed in the direction of the dwelling. Note that the profiles become unrealistic at higher altitudes (from Daigle and Stinson, 2014).

limitation, the profiles in Fig. 8 were still usable; due to the high density of sound rays near the ground, the SPLs were found to be controlled by the sound speed profile below about 200 m. This was confirmed by systematically removing the higher altitude rays until the levels at the larger distances begin to change (i.e., drop). The rays above 200 m were found to be insufficient to alter the levels at all distances out to and including at 10 km.

Due to the 5 m/s wind speed measured at 10 m height, the data in Fig. 8 are clearly associated with Harmonoise wind speed class W3, but observations of cloud cover were not available to determine the stability class. The strong temperature inversion measured near the ground suggests this is a clear night so that the appropriate Harmonoise class would be W3S5. In reality the sound speed gradient in Fig. 8 is stronger than that found in any of the Harmonoise weather classes. This shows that Harmonoise weather classes are not always a good substitute for measured data.

C. Observations associated with class W3S5

Considering only those classes where the wind speed ensures the wind turbines are reliably operational (i.e., W3, W4, and W5), FFP calculations show the propagation conditions most conducive for long distance identification of wind turbine noise occurs for clear nights with relatively low wind speeds, i.e., meteorological class W3S5 (see Fig. 4). This class occurs on average 1.8(5) h in each 24-h period (Fig. 1). The ability to measure wind turbine noise would be expected to be maximal in W3S5 for a number of reasons: (1) at the wind turbine hub height this class includes the wind speed where the turbines produce near maximum sound power; (2) W3S5 has one of the most favorable TL (Table II, Fig. 4); (3) W3S5 has the highest wind shear (after W2S5) so that wind noise and background ambient ground level noise due to wind interacting with vegetation are low; and (4) W3S5 occurs at night when the anthropogenic background ambient noise is lowest.

Analysis of microbarometer SPL showed wind turbine spectral peaks were identified on 13 nights corresponding to strong inversion conditions (i.e., clear night) and wind speeds of about 5 m/s (measured on-site at 10 m height). The corresponding profiles are seen in Fig. 8. This corresponds to the W3S5 meteorological class, and based on Fig. 1 this class would be expected for approximately 360 h in the 200 nights in which the data were analyzed. The amount of data collected are consistent with the expected frequency of occurrence of this class because the analysis time in a given night was 1 h, and during this time the results had to be stable and free of excessive background noises.

Samples of data with identifiable spectral peaks (harmonics) measured on 10 nights in the summertime (typically in the early morning) during a downwind inversion condition are shown in Figs. 9(a)–9(c). Below 5 Hz the data are in good agreement with predictions. Between 5 and 20 Hz background ambient noise appears to be influencing the results at 10 km, and all distances seem to be affected by background ambient noise at 70 Hz. The FFP calculations based on onsite meteorology are closer to the measured SPL than those using the generic Harmonoise classes. Differences between the two calculation methods on the order of 5 dB are common.

Despite averaging over 1 h, the results vary in a range of up to 6 dB. This range is likely influenced by varying meteorological conditions along the propagation path, as well as the fluctuations seen in Fig. 2.
measured lapse, this suggests clear skies and W4S1 conditions. Both calculation methods underestimated the measured results by at least 5 dB. At other frequencies, e.g., 5.6 Hz in Fig. 10, the calculated levels were lower and no spectral peaks were observed. At 10 km the figures show generic calculations are almost 10 dB different from calculations using actual meteorological conditions.

Wind turbine noise was measured upwind of the turbines during a weak daytime inversion under W4 wind speeds in Fig. 11. Harmonics at 2.4, 3.2, 4.0, and 4.8 Hz were found at 125, 2.5, and 5 km from the turbines (Daigle and Stinson, 2014). This result closely matched the PE calculations based on onsite meteorology. Because of the daytime inversion, this condition is not part of the Harmonoise weather classes, and available generic calculations for the closest daytime W4 classes tended to underestimate the PE calculations.

F. Comparison of generic meteorological classes and on-site meteorology

As indicated above, sound speed profiles based on measured onsite meteorology can represent conditions that are not included in the Harmonoise weather classes. Figure 12 shows predicted SPL levels where onsite measurements had a weak temperature inversion, while the generic Harmonoise temperature profile was associated with a lapse. In this case calculations using the generic Harmonoise classes, although similar at a few hundred meters, differ by over 20 dB at 10 km distance. When studying specific weather conditions, particularly at large distances, the use of the generic Harmonoise classes could result in significant errors and would only be recommended when no other information is available.

V. COMPARISON OF CALCULATION METHODS AT DWELLINGS

A. Field measurement of wind turbine sound power levels

Figure 13 shows average octave band wind turbine spectra as a function of wind speed averaged over 9 of the wind turbine models (with 1.5 and 3 MW electrical power output and omitting the lowest power 660 kW model due to its reduced electrical power and size). In this figure octave band data are used to allow comparison to manufacturer’s specifications and to allow comparison of different wind turbines which may have different rotational speeds or different bandwidths for tones in their harmonics. When A-weighted, the results for a nominal 8 m/s wind speed at 10 m height (per IEC 61400-11, 2012) were on average 104.2(2.0) dBA, approximately equal to the average of the manufacturers specifications. At 8 m/s the unweighted sound power levels were 125.5(3.0) dB (where the sound power level for individual turbines ranged from 120 to 130 dB), and were typically 21(4) dB higher than the A-weighted sound power levels.

Below 4 Hz the standard deviation increases and spectral shapes are less similar as a function of wind speed. A large component of these differences is differing wind turbine rpm which changes the distribution of harmonics in the lowest frequency bands. Data are also less reliable in this range due to adjustment to compensate for low frequency cutoff of the microphones.

The wind turbine noise spectra shape shows little change as a function of wind speed. As the wind speed dropped from 8 m/s wind speed to 3 m/s the standard deviation increased to approximately 5 dB. This larger standard deviation is a result of increasing variation in turbine

![Fig. 9](https://example.com/fig9.png)  
**Fig. 9.** (a) Comparison between predicted and measured levels for strong inversion conditions during early morning in the summertime. Filled circles are onsite measured SPL data from ten nights. The thin black lines show the smoothed FFP calculated SPL for onsite conditions (wind speed 5 m/s @ 10 m height, 1.4 °C temperature change from 2 to 10 m height, 40 °C off from downwind) using similarity theory (from Daigle and Stinson, 2014). In all panels the thick gray lines are generic calculations for Harmonoise class W3S5 (40 °C off from downwind). The measurement at 125 m is influenced primarily by the single nearest wind turbine while the other measurements are equally influenced by 4 wind turbines. (a) Measured SPL and FFP calculations at 1.61 Hz compared to generic Harmonoise calculations at 1.6 Hz; (b) measured SPL and FFP calculations at 3.22, 4.03, 4.83, and 5.64 Hz compared to generic Harmonoise calculations at 4.8 Hz; (c) in the top panel, measured SPL and FFP calculations at 20 Hz are compared to generic Harmonoise calculations at 20 Hz, and in the bottom panels the generic Harmonoise calculations are made at a frequency of 70 Hz.
operating conditions, i.e., some idling at 3 m/s, some above cut-in, as well as to changes in rpm.

Near the base of the wind turbines, comparison of the two wind screening methods suggests that between 0.8 and 20 Hz the soaker hose provides approximately 20 dB more attenuation of wind noise than the IEC primary and secondary hemispherical windscreens. Because the IEC measurements were 1/3 octave band, and had a less effective

FIG. 9. (Continued)
windscreen, IEC measurements of wind turbine noise were effectively obscured by microphone wind noise for wind speeds above 8 m/s (measured at 10 m height).

B. Calculated SPL at dwellings

At each dwelling the SPL due to wind turbines was calculated using the sound power level for each wind turbine model (similar to Fig. 13) and the generic TL based on Harmonoise weather classes (e.g., Figs. 3 and 4). As an example, using the 31.5 Hz octave band the average sound power level is 111.3 dB. Assuming a 6 dB decrease in SPL per doubling of distance and a +6 dB ground reflection (Fig. 3), the corresponding SPL at a 125 m distance becomes 61.6 dB. This level approximates the average

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FIG. 10. Comparison between predicted and measured levels at 3.2 and 5.6 Hz for weak inversion conditions during the afternoon in the summertime. Circles are onsite measured data (note that there were no identifiable harmonics beyond 125 m at 5.6 Hz). The thin black lines show the smoothed FFP calculated levels for onsite conditions (8.4 m/s at 10 m height, −0.5° temperature lapse measured between 2 and 10 m height, 15° off downwind) using similarity theory (from Daigle and Stinson, 2014), and the thick gray lines are generic calculations for class W4S1 at 4.8 Hz (15° off downwind).

FIG. 11. Comparison between predicted and measured levels for weak inversion conditions during early afternoon in the summertime. Filled circles are onsite measured SPL. The thin black lines show the smoothed PE calculated levels for onsite conditions (7 m/s @ 10 m height, 0.5° temperature inversion measured between 2 and 10 m height, 125° off from downwind) using similarity theory (from Daigle and Stinson, 2014). The thick gray lines are generic calculations for class W4S3 at 125° off downwind.
The hearing threshold of 59.5 dB (ISO 226, 2003). The slope of the hearing threshold is 26 dB per octave, and this is many times greater than the slope of the wind turbine spectra (Fig. 13). This suggests that at frequencies below 31.5 Hz the noise from a single wind turbine would tend to be below the hearing threshold. At a distance of 10 km downwind, for common favorable propagation conditions at night, W3S5 (Table II, Fig. 1) the level from a single wind turbine would be 33 dB based on generic FFP calculations. At this distance and frequency, hundreds of wind turbines would be required to bring the noise to the average threshold of hearing.

For the overall G-weighted levels, the average sound power is 121.1 dBG, and at 125 m distance the level is 72.7 dBG. Near the base of the wind turbine this level is over 12 dB below the 85–90 dBG threshold typical for human perception (Broner, 2010; ISO 7196, 1995). The G-weighted levels are based on the infrasound perception threshold between 1 and 16 Hz, so that a very large number of turbines would be necessary before infrasound levels become relevant to wind turbine noise.

To obtain realistic estimates of wind turbine perceptibility, data from the 399 wind turbines in the Health Canada study can be used. Figure 14 shows the SPL for dwellings calculated for different frequency weightings using the generic Harmonoise classes for FFP calculations. Most environmental assessments currently use A-weighted values, so these A-weighted values are used as a reference for comparison. Compared to the generic FFP calculations the A-weighted data have a larger range because atmospheric absorption and ground absorption cause significant reductions in A-weighted levels at large distances, but has little effect on frequencies below 63 Hz.

Statistically there was little difference between calculated results in different frequency ranges. Figure 14 shows that compared to A-weighted values, the unweighted FFP
yearly average estimates had a Pearson’s $r$ greater than 0.75. Similar results were found for the 16, 31.5, and 63 Hz octave bands where $r$ was at least 0.87. The high correlations suggest that the data from the Health Canada study would not allow an evaluation to determine which frequency(s) are most relevant to a specific effect of wind turbine noise.

Figure 14 can be used to evaluate the perceptibility of the infrasound noise. The G-weighted levels do not appear to be relevant as they are below 68.0 dBG, more than 12 dB below the 85 to 90 dBG threshold typical for human perception (Broner, 2010; ISO 7196, 1995). Unweighted levels of 120 to 128 dB are used as limits for blast noise (e.g., ONMOE, 1978), and all levels in Fig. 14 are below 73.2 dB, far below these criteria.

Figure 15 shows a comparison of SPL calculated using FFP based on Harmonoise and extended ISO calculations for the same dwellings used in Fig. 14. There is a strong correlation between the two methods ($r \geq 0.90$), the slope is close to 1, and the scatter in the points is small compared to the expected 3 dB standard deviation in the ISO calculations. The agreement is better for the lowest SPLs, i.e., for longer distances.

ISO 9613-2 (1996) includes a meteorological correction for wind direction. For SPLs above the median in Fig. 15, the ISO 9613-2 (1996) correction would be near 0 and for the lowest levels in Fig. 15 the correction would approach 2 dB (to be subtracted from the levels). For the data in Fig. 15 this would improve the agreement at 31.5 Hz, and worsen the agreement in the unweighted levels. It should be noted that ISO 9613-2 (1996) was not intended for use at frequencies below 63 Hz.

The ANSI S12.2 (2008) criterion for moderately noticeable rattles is 65 dB in the 31.5 Hz octave band. This level is not exceeded in Fig. 14 where the highest calculated level was 58.6 dB at 31.5 Hz. The results are similar at neighboring octave bands; at 16 Hz 59.7 dB was the highest calculated level and 54.1 dB was the highest calculated level at 63 Hz. Both of these neighboring levels are also below the ANSI S12.2 (2008) criteria. In the Health Canada survey, of the 1238 subjects (in 1238 dwellings), 58 subjects noticed vibrations and 19 were highly annoyed by the vibrations. Rattle sounds can cause a large increase in annoyance (ANSI S12.9 Part 4, 2005) so the relatively small number of persons who noticed or were highly annoyed by vibrations in the Health Canada study is perhaps to be expected. The survey respondents who noticed vibrations tended to be at the higher calculated SPL and within 15 dB of the ANSI S12.2 (2008) criteria.

VI. SUMMARY AND CONCLUSIONS

Predictions verified by measurements show that under common meteorological conditions wind turbine noise can be measurable at 10 km downwind of wind turbines. Under these conditions, the downwind infrasound propagation (including air and ground absorption) is more favorable than a 6 dB decrease in SPL per doubling of distance, i.e., in class W3S5 which is estimated to occur on average 1.8(0.5) h a night in the area of the Health Canada study. Favorable propagation conditions could also occur throughout the night and during high winds in the daytime; however, under these conditions, measurement of wind turbine noise is made difficult by wind noise on the microphone and the noise from the wind interacting with vegetation.

The ability to measure wind turbine infrasound was influenced by ambient infrasound, the effectiveness of the windscreens, and the presence of shielding vegetation. Wind turbine SPLs are low enough that effective windscreens and narrowband analysis are required to ensure a 95% confidence of being able to distinguish wind turbine noise from ambient infrasound, even at the base of the wind turbines. For example, following the IEC 61400-11 (2012) wind turbine sound power standard, in 1/3 octave bands, using the specified windscreens near the base of the wind turbines it became difficult or impossible to measure wind turbine infrasound at wind speeds above 8 m/s. Conversely, background ambient infrasound pressure levels can also be significantly lower than wind turbine SPLs. Wind turbine noise was measured at a 10 km distance in the current study.

In the Health Canada study it was not possible to conclusively determine the frequencies having the largest effect on survey respondents. The shape of the spectra from the 9 wind turbines in the study were very similar, not strongly affected by wind speed, and the standard deviation in octave bands was 2 to 3 dB for frequencies between 4 and 2000 Hz. As a result, at the dwellings in the Health Canada study, individual frequency bands, or frequency weightings, are all

![Image](52x156 to 297x396)
correlated, i.e., Pearson’s $r$ was 0.75 to 0.93 for all comparisons of long term average data. In the Health Canada study, the infrasound levels were compressed into a smaller decibel range than found for the A-weighted SPL, so to effectively evaluate infrasound data high accuracy may be required. In the Health Canada study, improvements in accuracy required to evaluate infrasound would not likely be justified. Infrasound levels were found to be more than 17 dB below perceptible levels at all dwellings.

To determine if infrasound is close to perceptible levels it appears that ISO calculations can be extended to approximate the long term average infrasound SPL, provided that the most affected residences are within a few kilometers of the nearest wind turbines. If infrasound approaches perceptible levels, for calculations over long distances, or for specific meteorological classes, the improved accuracy of the FFP calculations using measured atmospheric properties as a function of height would be recommended.

ACKNOWLEDGMENTS

The authors acknowledge Wayne Edwards for his significant contributions to this work in its design, implementation, and interpretation of results. The authors also acknowledge Eric Lemay for his assistance in data collection. The authors appreciate the cooperation received from wind turbine manufacturers, operators, and landowners toward the completion of this study. The authors have declared that no competing interests exist.

1At 63 Hz, in ISO 9613-2 (1996) the ground reflection increases SPL by 3 dB near the source and the effect of the ground reflection monotonically increases to 6 dB at an infinite distance. For an 80 m height source, in the short distance range of 2.4 to 3.3 km, the ISO 9613-2 (1996) propagation appears to be more cylindrical than spherical.


