Acoustic and Geophysical Measurement of Infrasound from Wind farm Turbines

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ABSTRACT

An experiment was conducted to measure and characterize infrasound (and higher frequency acoustic energy) from turbines at a wind farm in Southern Alberta. Simultaneous telemetry and point measurements were acquired from three sensor types: low frequency geophones, acoustic microphones, and a precision sound analyzer. Measurements were recorded for three wind states: low, medium, and high. Down wind telemetry measurements were recorded for thirty (30) continuous 50m offsets, up to a distance of 1450 m from the wind farm. Point measurements, coincident with the telemetry measurements, were acquired with a low frequency precision sound analyzer for two offsets: 50m and 1000m from the turbines. The same measurements were recorded with the turbines on, and with the turbines off. The low frequency results of the experiment are presented in this paper.

RÉSUMÉ

Une expérience a été menée pour mesurer et caractériser les infrasons (et une forme d'énergie acoustique à hautes fréquences) provenant des éoliennes d'un parc dans le sud l'Alberta. La télémétrie simultanée et le mesurage par points ont été faits avec trois types de capteurs : géophones à basse fréquence, microphones acoustiques et un analyseur de son à haute précision. Des mesures ont été enregistrées pour trois états de vents : bas, moyen et élevé. Des mesures télémétriques ont été prises dans le sens du vent pour trente (30) déplacements continus de 50 m jusqu'à une distance de 1450 m du parc d'éoliennes. Des mesures par points, coïncidents avec les mesures télémétriques, ont été prises avec analyseur de son de précision de basses fréquences pour deux déplacements : à 50m et 100m des éoliennes. Les mêmes mesures ont étéUne expérience a été menée pour mesurer et caractériser les infrasons (et une forme d'énergie acoustique à hautes fréquences) provenant des éoliennes d'un parc dans le sud l'Alberta. La télémétrie simultanée et le mesurage par points ont été faits avec trois types de capteurs : géophones à basse fréquence, microphones acoustiques et un analyseur de son à haute précision. Des mesures ont été enregistrées pour trois états de vents : bas, moyen et élevé. Des mesures télémétriques ont été prises dans le sens du vent pour trente (30) déplacements continus de 50 m jusqu'à une distance de 1450 m du parc d'éoliennes. Des mesures par points, coïncidents avec les mesures télémétriques, ont été prises avec analyseur de son de précision de basses fréquences pour deux déplacements : à 50m et 100m des éoliennes. Les mêmes mesures ont été .

1. INTRODUCTION

The Castle River Wind Farm in southern Alberta, shown in Figure 1, contains one (1) 600 MW turbine and fifty-nine (59) 660 MW wind turbines. The terrain is relatively flat prairie to the east (downwind), and rolling hills to the foothills and Rocky Mountains to the west. The land is primarily agricultural, with grain farming to the east, and cattle ranching to the west. No other significant industrial activity is present in the vicinity.

The experiment employed sensors and methods to measure the acoustic (atmospheric), and geophysical (terrestrial) sound levels. Data was recorded for three wind states, low, medium, and high. For each wind state, data were recorded with the entire wind farm operating (turbines ON), and with the entire wind farm stopped (turbines OFF).

Figure 1. Castle River Wind Farm from the East.
Prevailing wind is from the West. (Photo © courtesy of Vision Quest WindElectric ®)

2. EXPERIMENTAL OBJECTIVES

Characterization of ambient noise levels, and sound emitted by turbines in the Castle River Wind Farm were the chief objectives of the study. Explicit measurements of any low frequency components, during different scenarios, were important. Six scenarios were investigated: low wind – turbines on and off, medium wind – turbines on and off, and high wind – turbines on and off. Calibrated point measurements of the acoustic environment were acquired with a Bruel and Kjaer (B & K) 2260 precision sound level meter. Experimentation and application of the geophysical data acquisition and processing techniques were also objectives of the test.

Measurements were taken to allow determination of the sound levels, dependence on wind speed, frequency content – especially below 200 Hz, 1/3 octave band levels, tonality, and attenuation with distance. Measurements included: voltage output from thirty 4.5 Hz geophones, voltage output from thirty calibrated microphones, and Leq and LIM (conforming to IEC 804 and IEC 804 Appendix B) with the B & K 2260 Precision Sound Analyser. Other data recorded included: wind speed and direction, atmospheric pressure, atmospheric temperature, and other turbine related data. Visual observations included: atmospheric conditions, extraneous sources of noise such as aircraft, trains, vehicular traffic, highway noise, bird song, crickets, and the rotational state of the turbines.

3. MICROPHONE CALIBRATION

The electret condenser microphones were calibrated prior to data acquisition, and also following data acquisition. The microphones were powered by new 9V batteries. Calibration equipment included: a Tektronix TDS 420A 4 channel Digitizing Oscilloscope, an HP 33120A 15 MHz Arbitrary Waveform Generator, a lab speaker with two ports for microphone insertion, and a TES 1352A Sound Level Meter. Several calibration runs were performed. For the pre- acquisition calibration, the microphones were measured for voltage output for the following 3 tests:

1 Constant Input Voltage and Constant Frequency Test
2 Constant Input Voltage and Stepped Frequency Response Test
3 Constant Speaker Output SPL Test.

Following data acquisition, all microphones were measured again for output voltage at 25 Hz 1.98 V RMS input, and for output voltage at 100 Hz 600 mV RMS input. Fourteen microphones were rejected due to nonlinear output voltage failures (with differences pre and post of >29%). Two post processing spectral analysis data sets were recorded to DVD, one with all microphones included, and one with the rejected microphones zeroed in the data set, to facilitate further analysis.

The appropriate response factors were applied to each microphone voltage response, in order to correct for response differences between microphones, and to normalize the microphones to the reference at ground station 102 (serial number 189). Normalization to the microphone at station 102 permitted comparison of the spectral analyses from the 30 electret microphones with the calibrated dB results from the B & K 2260 precision sound analyzer. Some differences were expected, due to variations in field acquisition conditions and near field effects. In addition, differences due to processing, particularly the spectral analysis, are expected between the electret microphone data, and the data from the precision sound analyzer.

4. PROJECT AREA DESCRIPTION

A cross country road runs East to West at the test site, near the South boundary of 36-6-1 W5M. The site map, details of instrument loction and schematics of test set-up are shown in Figures 2 through 4. The road is located east of Turbines 21 and 22 at the Castle River Wind farm, Alberta. It was

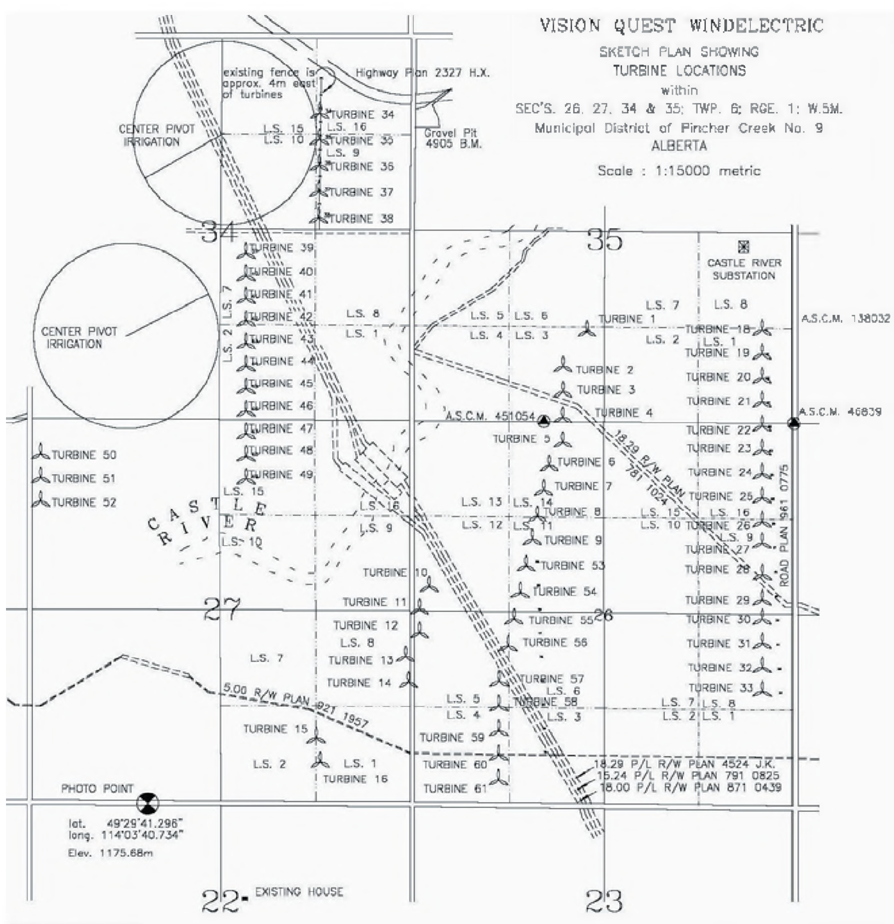


Figure 2. Map showing location of turbines.
(Map © courtesy of Vision Quest WindElectric ®).

decided that 30, 4.5 Hz geophones, would be planted in a linear array, parallel to the road, with a station interval of 50 m. The recording spread was 1450 m in length. The first station (101) was placed between turbines 21 and 22. The remaining stations were placed to the East, downwind from the wind farm.

5. METHODOLOGY AND PARAMETERS

5.1 Survey and Placement of Ground Stations

From the eastern most bank of turbines, a line was surveyed directly east, along the south side of the road allowance. Prior to data acquisition, the ground stations were placed with RTK (Real Time Kinematic) GPS survey equipment. Pin flags and flagging were placed at each station, with the appropriate station number marked on the flag. The survey data tolerance was +/- 20 cm. The survey data were processed and output in the form of a standard SEG P1 data file. The station interval was 50m, with stations numbered from 101 to 130 inclusive. Station 101 was at zero distance from the bank of turbines, and station 130 was 1450 m from the wind farm.

At each station, a hole with a diameter of 15 cm, was drilled to a depth of 30 cm. At the bottom of each hole, a 4.5 Hz geophone with a spiked base, was planted. The geophones were recorded as telemetry line 1. Coincident with each 4.5 Hz geophone was a calibrated acoustic microphone. The microphones were recorded as telemetry line 2. Both lines had identical station numbers and coordinates for those stations. The geophones were recorded on channels 1 to 30, and the microphones were recorded on channels 31 to 60.

The acoustic microphones were placed with care, to avoid any vibration from wind blown cables or connectors. The microphones were approximately 5 cm below ground level, in order to reduce effects of turbulent flow at the surface. The microphones were deployed in a systematic fashion, depending upon the measured response characteristics. The order of deployment placed the microphone with the highest output closest to the wind turbines at station 101, followed at the next station (102) 50 m away, by the microphone with the lowest output. At station 103, the microphone with the second highest output was placed, followed at station 104 by the microphone with the second lowest output. The purpose for the order of deployment was to allow statistical analysis between stations (if required) and to eliminate any systematic errors with a biased spread. The ground equipment was deployed in advance of data acquisition. Following post acquisition recalibration, it was evident that there was indeed a systematic failure mode for the acoustic microphones, and data from 14 microphones were rejected.

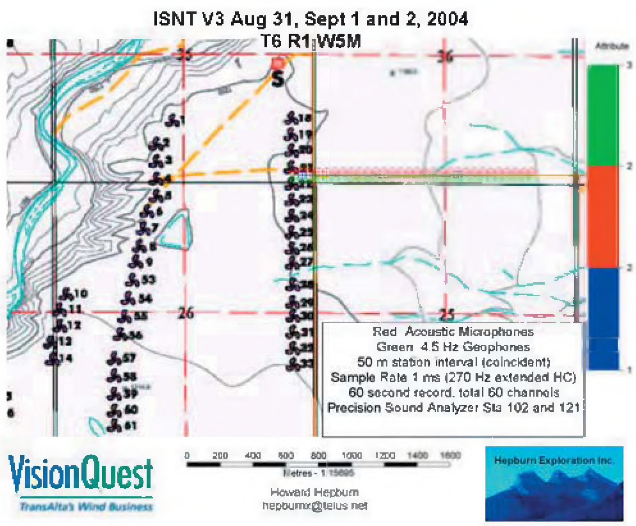


Figure 3. Topo map showing location of turbines, geophones, microphones, and B & K 2260.

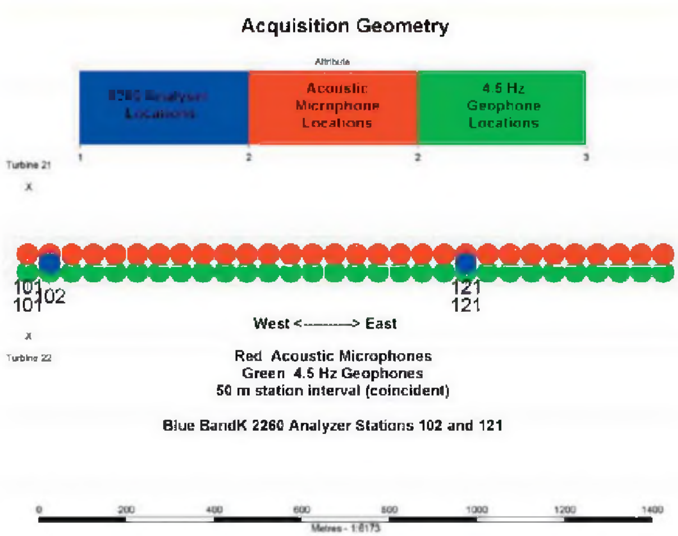


Figure 4. Schematic of acquisition geometry, location of turbines (on left), microphones, geophones, and B & K 2260.

5.2 Data Recording Methods

5.2.1 Telemetry Data Acquisition

It was decided that a 60 second record length would be used to allow sufficient sampling of any slow, low frequency events. Measurements were taken to quantify: sound frequency, sound amplitude, atmospheric pressure and temperature, wind speed, and from precise time measurements, terrestrial and atmospheric noise propagation velocities.

A truck mounted I/O System II seismic data recording system, rather than a smaller portable unit, was used, due to superior equipment, interior mounting, and software compatibility. Three sound data sets were acquired simultaneously, to provide verification and validation of the experimental method. The three data sets included: acoustic (atmospheric) records with the B&K 2260 Precision Sound Analyser at point locations, geophysical (terrestrial) records with 30 Mark Products L1B 4.5 Hz geophones, and acoustic (atmospheric) records with 30 calibrated electret condenser microphones coincident with the geophones.

The geophone and microphone data were acquired with the I/O System II telemetry recording instrument at a sample rate of 1 ms, which allowed for accurate recording of any signal and noise frequencies up to 270 Hz. The precision sound analyzer data were acquired with a B & K 2260, running software version BZ7206 ver 2.1. For each telemetry measurement (60 second records of 60 channels) of the geophone and microphone data, a measurement (60 second record) with either the dBA or dBL scale was made with the B & K 2260 (with correction for a 90 mm windscreen). Full data sets for the dBA scale and the dBL scale were acquired for all operational conditions. Details of the system and its parameters are outlined in Tables 1 and 2.

5.2.2 Precision Sound Analyzer Data Acquisition

The B & K 2260 Investigator Precision Sound Analyzer (running software version BZ7206 ver 2.1) was used to collect acoustic data sets concurrent with the telemetry data acquired from the 30 geophones and 30 electret microphones. The sound analyzer was calibrated prior to acquisition, according to the applicable ISO standards (including initial factory calibration traceable under ISO 9001), with a standard 1 kHz 94 dB calibrator at 30/08/2004 10:26:22 AM. The calibration and equipment meet the requirements of ANSI S1.4-1983 type 1, ANSI S1.43-2004 Type 1, S1.4A-1985, S1.1-1986 1/3 Octave Bands Order 4, Type 0-B, and S1.40-1984. Since the 2260 is a single sensor unit, the location of the 2260 data was limited to one station. The 2260 was moved to provide measurements at varying distances from the turbines. The data collected by the 2260 was concurrent with the other telemetry data, and the data sets can be compared with the assumption that the same time frame exists between data sets. The fast response sample rate was 125 ms, the slow response sample rate was 1 s.

Three stations used the B & K 2260: 101, 102, and 121, at distances from the turbines of 0m, 50m, and 1000m respectively. The B & K 2260 was mounted upon a tripod, with the microphone oriented directly west. The microphone was at a measured distance of 1.25 m above ground level, and had a standard 90 mm acoustic grade windshield. Sixty second records were acquired with the 2260, simultaneous with the 60 second records acquired with the I/O System II. The time stamps on the I/O System II and the B&K 2260 were calibrated to a GPS time signal, but may have drifted slightly, during the course of observations. In any event, the recording start times for both the B&K 2260 and the I/O System II were controlled by the GPS time signal which was announced with a radio. The data acquired with the B & K 2260 precision sound analyzer was processed with the Evaluator 7820 version 4.4 software.

5.3 Operational Conditions

Three scenarios existed for wind conditions: low wind, medium wind, and high wind. Two scenarios existed for the operational state of the turbines: on and off. B & K 2260 data were captured for dBA and dBL (Linear) scales for all three wind conditions (turbines on and off). The geophone and microphone data were recorded simultaneously with the precision sound analyser. Data acquisition was dependent upon weather, extraneous noise sources, and notification of the provincial transmission administrator.

Quantity	Item	Comment
1	I/O system II telemetry recording system	Truck mounted, 1 LIM
30	4.5 Hz geophones	Spike base, Kooter 2 pin connectors
10	LIUs (line input units)	6 channels per LIU
10	Cables, 50 m takeouts, Kooter 2 pin	
2	Line tap units Geophones on line 1 and	microphones on line 2
2	Line tap cables	1 line tap - geophones, 1 line tap - microphones
30	Acoustic microphones	Kooter 2 pin
1	Weight drop calibration mass	15.0 kg from 49.3 m height

Table 1. List of telemetry recording equipment for geophones and microphones.

Number of 4.5 Hz geophones	30
4.5 Hz geophone station interval (m)	50
Number of acoustic microphones	30
Microphone station interval (m) coincident with the 4.5 Hz geophones	50
Dimensions of hole for sensors – width (cm) and depth (cm)	15 and 30
Recording sample rate (ms)	1
Record length (s)	60
Recording format (SEG D Demultiplexed 8048) 24 bit	IEEE
Recording high cut filter, extended alias	270 Hz
Recording low-cut filter (implicit 3 Hz)	Out
Number of scenarios: Turbines on & off, for low, medium , & high wind states	6
Recording preamp gain (36 dB FFID 1 to 5) all other FFIDs:	48 dB
Recording gain	defloat
Geophones on line 1, stations 101 to 130, channels 1 to 30	
Microphones on line 2, stations 101 to 103, channels 31 to 60	Coincident w geo.

Table 2. Telemetry data acquisition parameters.

5.3.1 Low or no wind

Under low or no wind conditions, wind turbines will be either stationary, or will be idling without generating power at the optimum rate. The ambient wind noise will be at the lowest level for this condition. In addition, the sound emitted from the turbines will also be at the lowest level. Since blade tip speed in idle mode is far less than when operational, the noise emitted is negligible. In these zero or low wind speed conditions it can be presumed that the wind turbine will have little or no effect on the existing background noise level.

5.3.2 Medium wind

Medium wind conditions are those at which the wind turbine just starts to generate power and slightly above. As the turbines start to produce power, the emitted sound level will increase. With medium wind conditions, the ambient wind noise will still be relatively low, but increasing. Medium wind speed conditions (6 - 10 m/s) are the most critical, as far as audibility is concerned.

5.3.3 High wind

Sound emitted from wind turbines increase as wind speed increases. However, the increase in sound generated by the turbines is less than the increase in background noise levels. The rate of increased sound generation decreases at higher wind speeds, since the wind turbine does not increase rotational speed. Above a wind speed of typically 25 m/s, the wind turbines shut down and therefore do not emit any sound.

It is not straightforward to obtain accurate measurements of wind turbine noise. Noise reduction features have been considered in the design of most commercially available wind turbines. Some manufacturers have taken extensive steps to further reduce the aerodynamic noise. Sound levels emitted by wind turbines will be highest in the down wind direction.

Other data were also acquired during the sound data acquisition, including atmospheric and turbine data. That data may be incorporated into the results from the three acoustic data sets.

5.4 Data Acquisition and Processing Summary

The data were acquired on August 31, September 1, and September 2, 2004. Records with all systems were acquired for the three wind states, and for the two operational states of the turbines. Sound analyser values for the spectra were output from the Evaluator 7820 version 4.4 software. The output was transferred to a spreadsheet for graphical display purposes. For each wind state, and for the two turbine states (On and OFF), the 2260 spectral data are presented in section 6. For obvious reasons, two dB scales were used for data acquisition, the dBA scale, and dBL (Linear) scale. Due to the attenuation of low frequency amplitudes with the dBA scale, only the dBL data are presented. The graphs contain the data for the acoustic contributions of the turbines and the ambient sound levels.

5.5 Telemetry Data Processing - I/O System II for Telemetry Data

The geophone and acoustic microphone data were processed to be true amplitude, with all efforts made to quantify amplitudes relating to specific signal levels. The data were processed with ProMAX seismic data processing software. Further analysis will allow quantification of atmospheric and terrestrial noise levels in terms of frequency, amplitude, wavelength, velocity of propagation, and attenuation with distance. Details of the data flow are presented in Table 3.

6.0 RESULTS AND DISCUSSIONS

The data that has been accumulated is divided into three groups for discussion: The analyzer data; Distance attenuation and Telemetry sound data. The details of the three groups are presented below.

6.1 Low Frequency Analyzer Data

The sound pressure level spectra collected from the Bruel and Kajer precision sound level meter, type 2260, are presented in Figures 5 through 17.

Figure 5 shows the LLeqs for the ON and OFF conditions for low wind speeds, measured 50 m from the turbines. At 16 Hz and below, the turbines emit sound more than +20 dB above the ambient wind noise. Above 50 Hz the turbines do not contribute significant sound above the background. It is seen that ambient noise levels are fairly uniform from 6.3 Hz to 200 Hz. (File 30). For the low wind speed condition,

Data Input from disk (preamp gain applied data set)
FFID sort and kill, FFID Include: 4-23, 28, 31-37, 39-63, Trace Display
Trace Edits: according to visual inspection and to list of rejected microphones
Note geophones on line 1, stations 101 to 130, channels 1-30
Note microphones on line 2, stations 101 to 130, channels 31-60
Trace scalar amplitude normalization for microphones only, according to specified calibration scalars
Single function empirical trace scalar to match 2260 data at station 102 (1×10^6)
1/3 Octave band filtering, (each trace for geophones and microphones) according to ISO filters
Spectral analysis on 1/3 octave bands producing LLeqs for each band
Output of dBL values, relative to zero, maximum dB scale constant at 120 dB

Table 3. Telemetry data processing flow.

ambient wind noise levels are independent of distance from the wind farm.

Figure 6 shows the ON and OFF conditions for medium wind speeds, measured 50 m from the turbines. Above 50 Hz, the turbines emit sound about +20 dB above the ambient wind noise. Note that the lowest frequency components of the ambient noise levels have increased considerably (turbines OFF), compared to the previous figure.

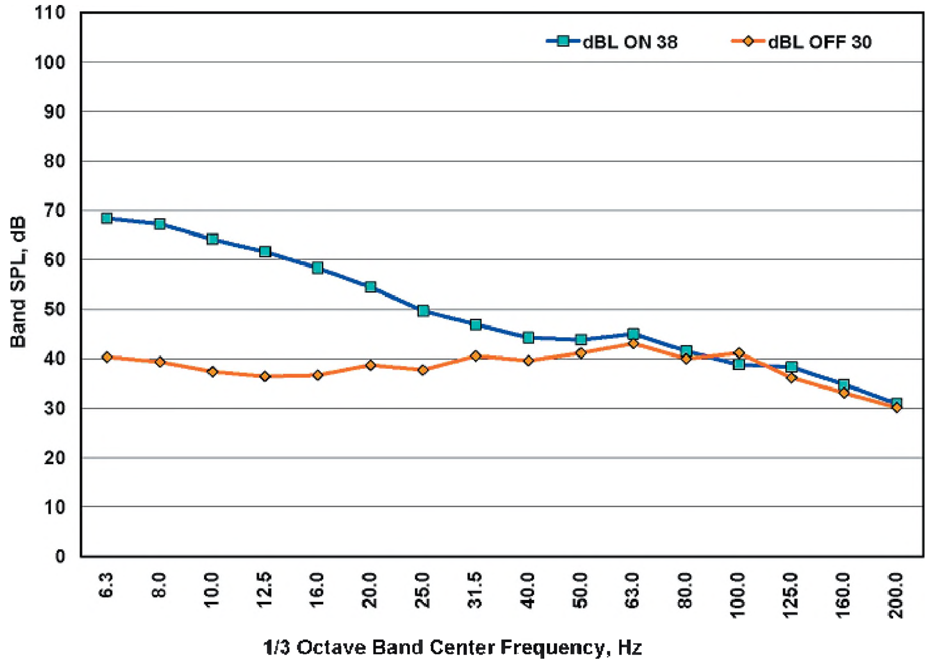


Figure 5. 1/3 octave LF spectra,
file 38: dBL, low wind, turbines ON, 50 m; file 30: dBL, low wind, turbines OFF, 50 m

Figure 7 shows the ON and OFF conditions for high wind speeds, measured 50 m from the turbines. Ambient wind noise exceeds sound from the turbines by approximately +8 dB up to about 50 Hz. Above 100 Hz, the turbines emit sound about +7 dB above the ambient wind noise. Below 80 Hz, turbine operation decreases ambient wind noise.

It must be pointed out that turbine rotational speed does not increase from the medium to high wind condition.

The effect of increasing wind speed at larger distance from the turbine farm is shown in Figures 8 and 9. Figure 8 shows the ON and OFF conditions for low wind speeds, measured 1000 m from the turbines. Below 25 Hz, the ambient wind noise exceeds levels when the turbines are ON by about +8 dB. The wind farm appears to decrease low frequency ambient noise levels at a distance of 1000 m. Above 50 Hz the turbines emit sound about +5 dB above the ambient wind noise.

For the same conditions, 50 m from the turbines (figure 5 above), the turbines emit sound about +20 dB above the ambient wind noise below about 16 Hz.

Figure 9 shows the ON and OFF conditions for high wind speed, measured 1000 m from the turbines. The turbines appear to contribute about +2 to +6 dB at most frequencies. However, ambient wind noise is the dominant factor at high wind speeds, and some variability in ambient noise levels may be a factor between the two conditions. The ON conditons for high wind speed, measured at 50 m and 1000 m from the turbines are shown in Figure 10. Negligible attenuation with distance confirms the dominant sound contributor is the wind.

The effect of wind speeds with distance on the resulting sound pressure levels are shown in Figures 11 through 13.

Figure 11 shows the LLeqs for the ON condition for medium wind speed, measured 50 m and 1000 m from the turbines. Significant attenuation at all frequencies is seen with an increase in distance from the turbines, from 50 m to 1000 m. As expected, attenuation with distance increases with increasing frequency, for medium wind speeds.

Figure 12 shows the ON conditions for high wind speed, measured 50 m and 1000 m from the turbines. It would ap-

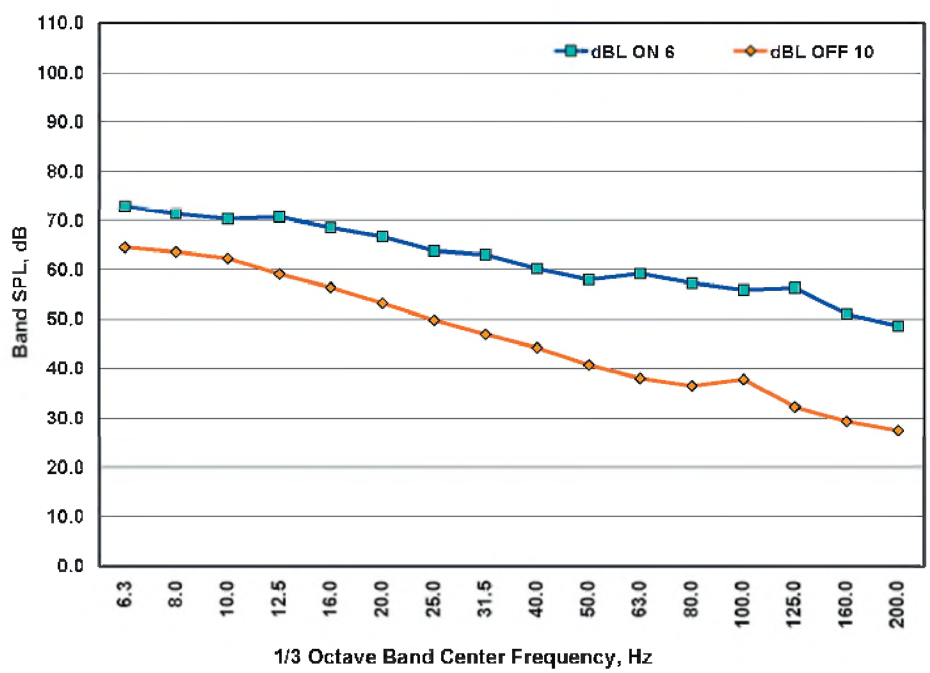


Figure 6. 1/3 octave LF spectra, file 6: dBL, medium wind, turbines ON, 50m
file 10:dBL, medium wind, turbines OFF, 50m

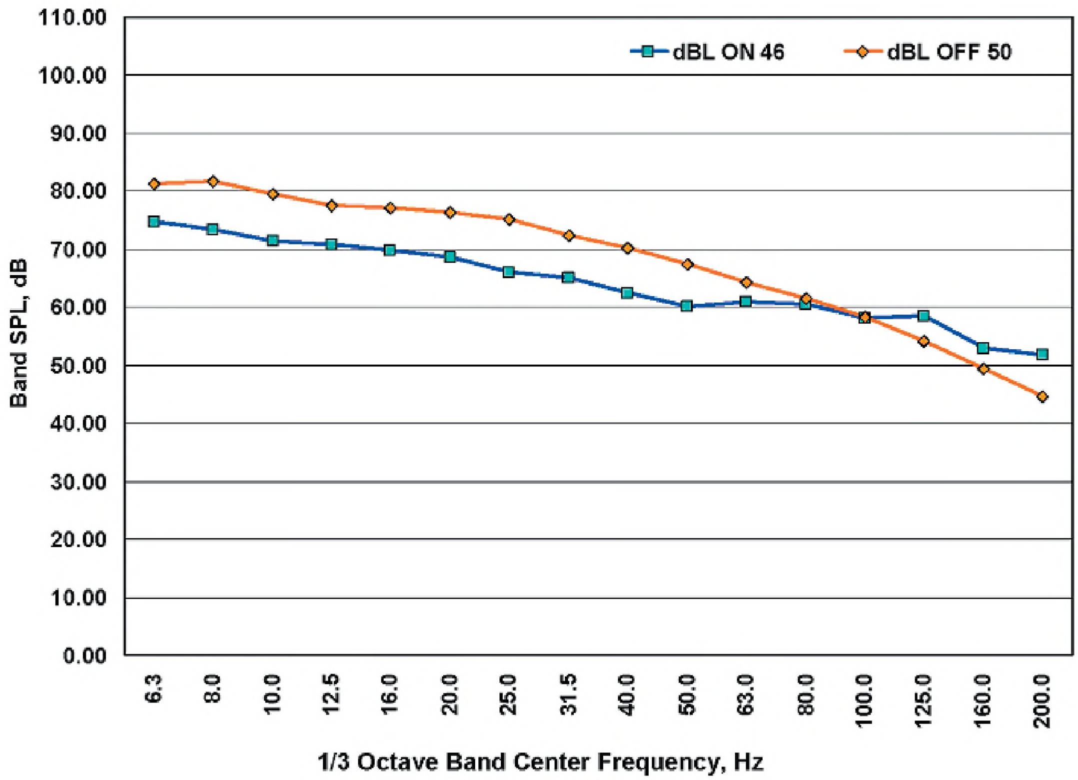


Figure 7. 1/3 octave LF spectra. file 46: dBL, high wind, turbines ON, 50 m; file 50: dBL, high wind, turbines OFF, 50 m

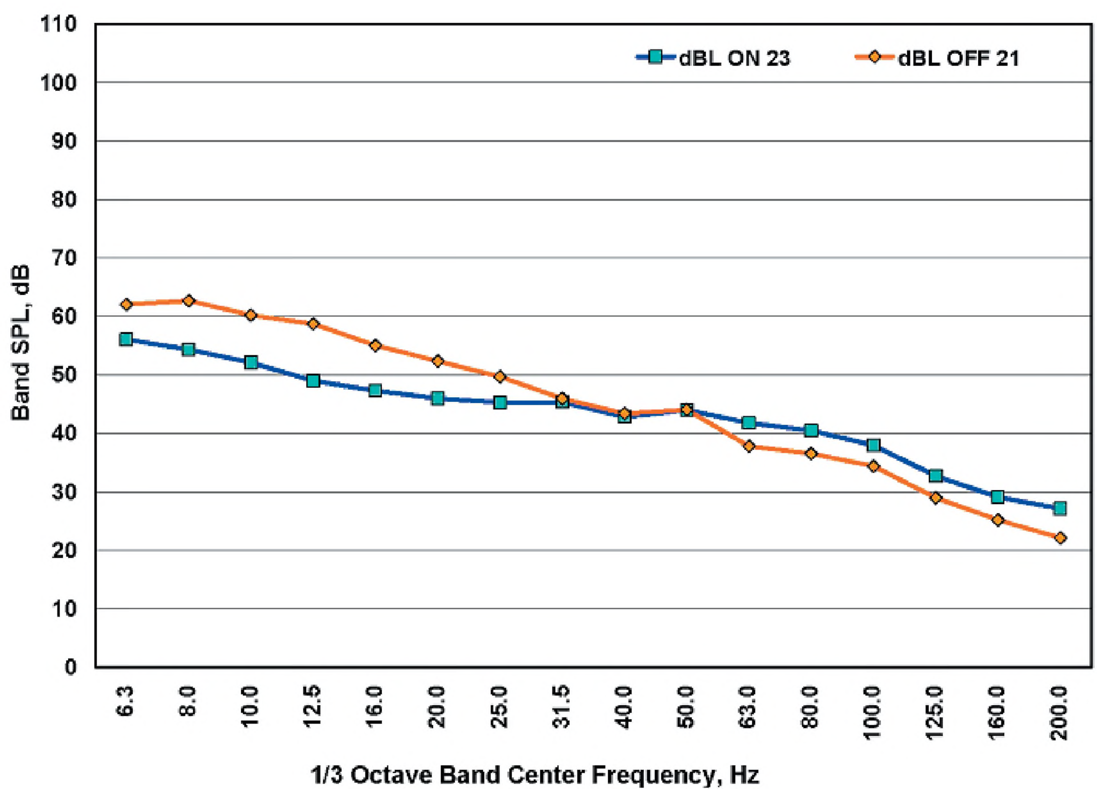


Figure 8. 1/3 octave LF spectra. file 23: dBL, low wind, turbines ON, 1000 m; file 21: dBL, low wind, turbines OFF, 1000 m

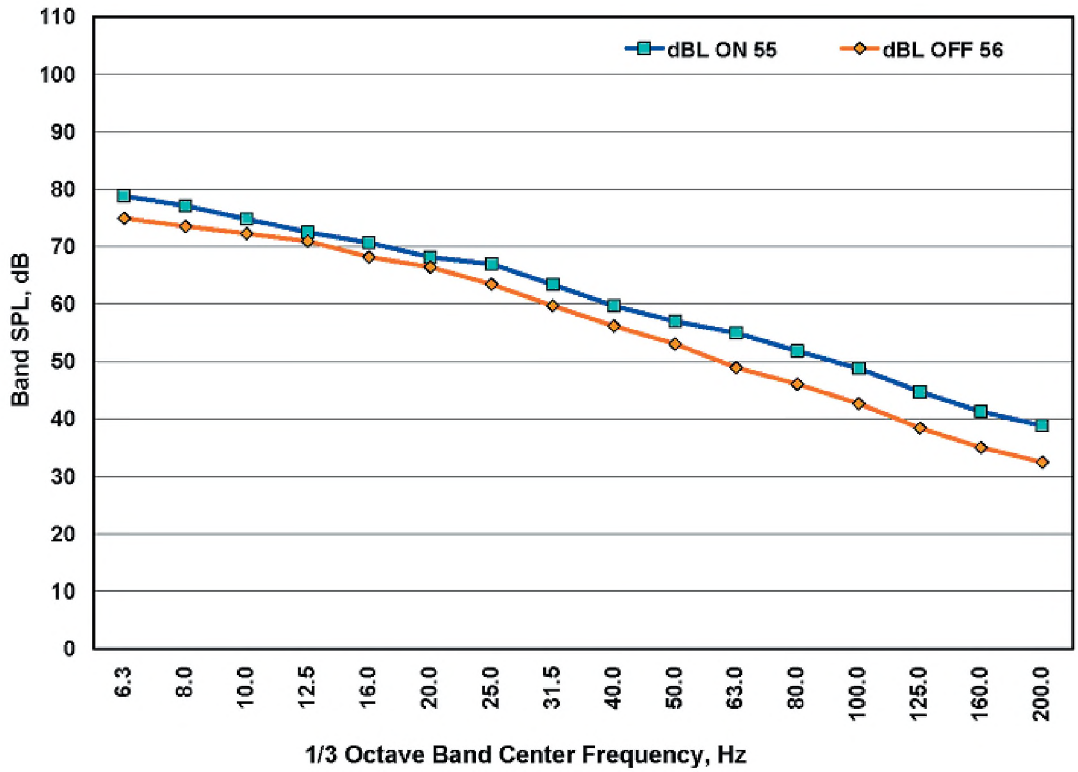


Figure 9. 1/3 octave LF spectra. file 55: dBL, high wind, turbines ON, 1000 m ; file 56: dBL, high wind, turbines OFF, 1000 m

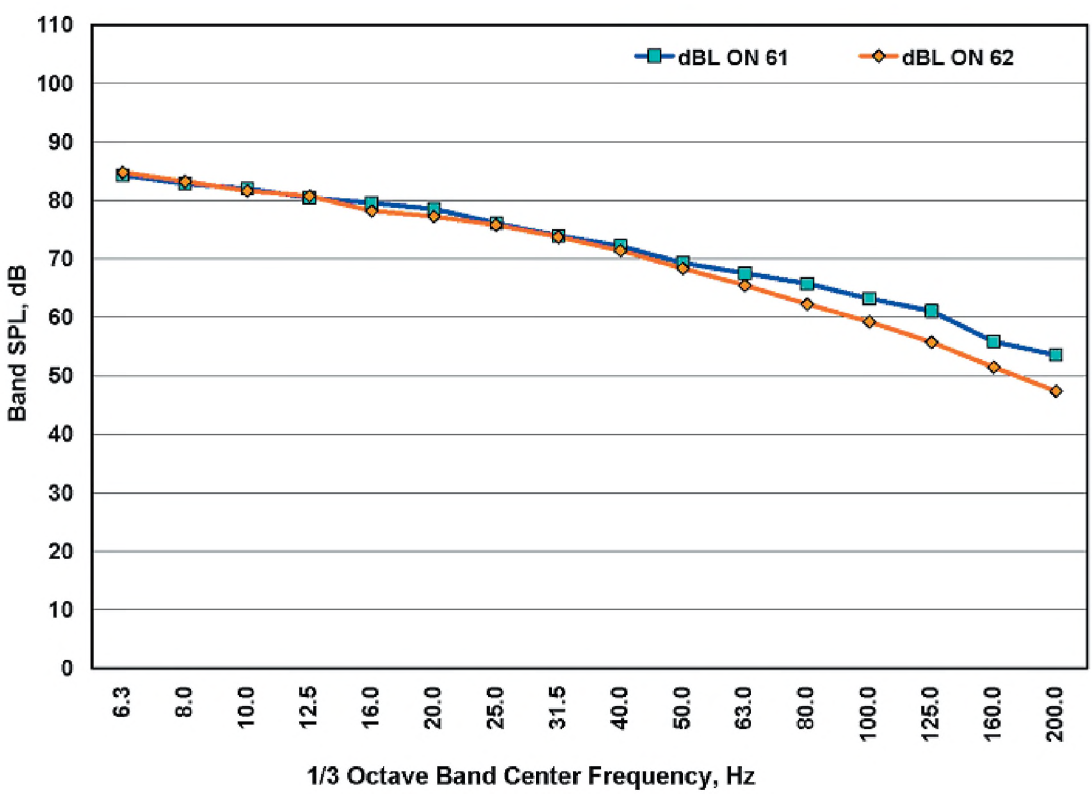


Figure 10. 1/3 octave LF spectra. file 61: dBL, high wind, turbines ON, 50 m; file 62: dBL, high wind, turbines ON, 1000 m

pear that very little difference exists from 50 m to 1000 m, however, the ambient wind noise is the main factor at high wind speeds. Wind noise is not attenuated with distance.

Some higher frequency attenuation of acoustic energy, with increasing distance, is seen with distance, above about 80 Hz.

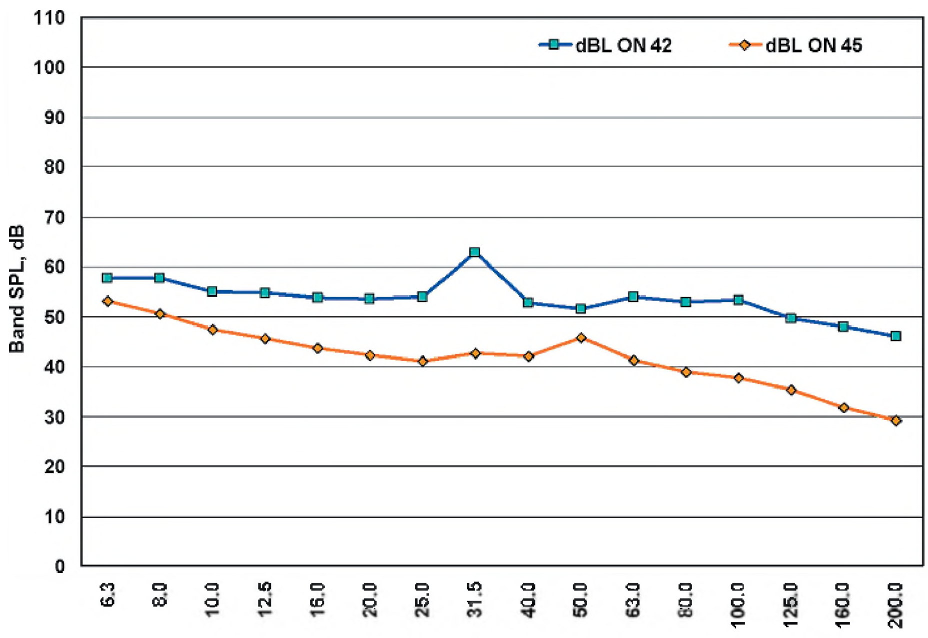


Figure 11. 1/3 octave LF spectra. file 42: dBL, medium wind, turbines ON, 50 m file 45:dBL, medium wind, turbines ON, 1000 m

Figure 13 shows the ON and OFF conditions for very low wind speed, measured 50 m (ON) and 1000 m (OFF) from the turbines. Below 31.5 Hz, less than +12 dB is contributed from the turbines. Above 31.5 Hz, very little contribution from the turbines is seen.

Figure 14 shows the effect of increasing wind speed (low to medium to high) at 50 m from the turbines, with all the turbines ON. Note that all LLeqs increase from low wind speed to medium wind speed, but do not increase appreciably from medium to high wind speed.

Figure 15 shows the effect of increasing wind speed (low to medium to high) at 50 m from the turbines, with all the turbines OFF. Note that the ambient wind noise, below about 50 Hz, increases from low wind speed to medium wind speed. With an increase in wind speed from medium to high, the ambient wind noise increases at all frequencies by about +20 dB. At high wind speeds, the ambient wind noise will exceed the sound output from the turbines. Note also that for the high wind condition, the LLeqs are higher when the turbines are OFF.

Figure 16 shows the LLeqs between low wind speed and high wind speed, with the turbines ON at a distance of 1000 m from the turbines.

Figure 17 shows the LLeqs between low wind speed and high wind speed, with the turbines OFF at a distance of 1000 m from the turbines.

An increase of +10 to +12 dB in ambient wind noise is apparent at most frequencies when the wind speed increases from low to high. The wind speed for file 56 was about 1.5 m/s lower than the wind speed for file 55 above (figure 16). Note that for the low wind condition, the ambient wind noise is higher than when the turbines are operating.

6.2 Attenuation With Distance: Calculated Vs Observed Laeq

For the three operational conditions: low wind, medium wind, and high wind, the median observed value for LAeq (turbines ON) at 50 m, as recorded with the 2260, was used as the starting point for the calculated attenuation. The observed data points are shown enlarged on the graph below. The attenuation due to distance was calculated for a line source, at –3dBA per dou-

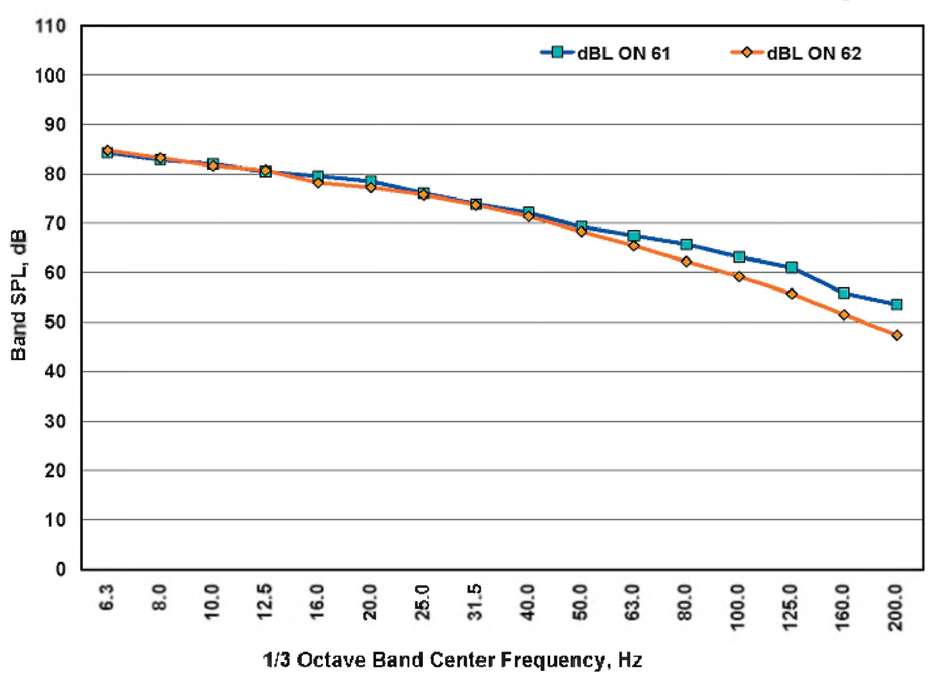


Figure 12. 1/3 octave LF spectra. file 61: dBL, high wind, turbines ON, 50 m file 62: dBL, high wind, turbines ON, 1000 m

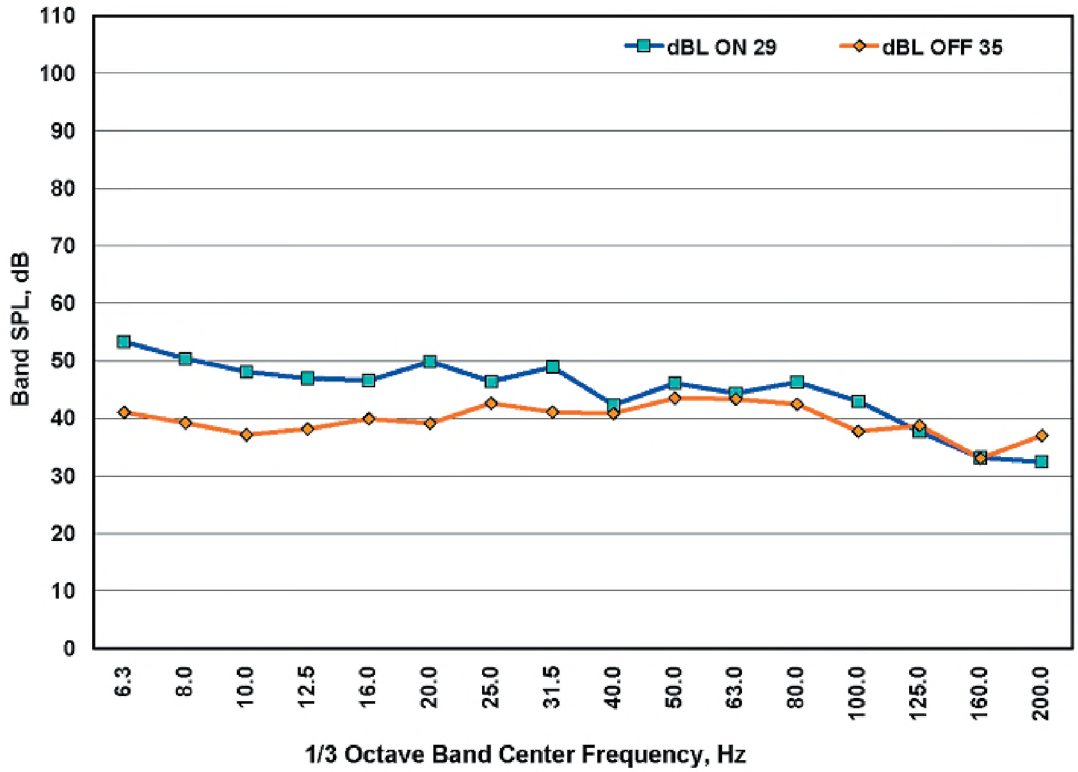


Figure 13. 1/3 octave LF spectra. file 29: dBL, very low wind, turbines ON, 1000m ; file 35: dBL, very low wind, turbines OFF, 50 m

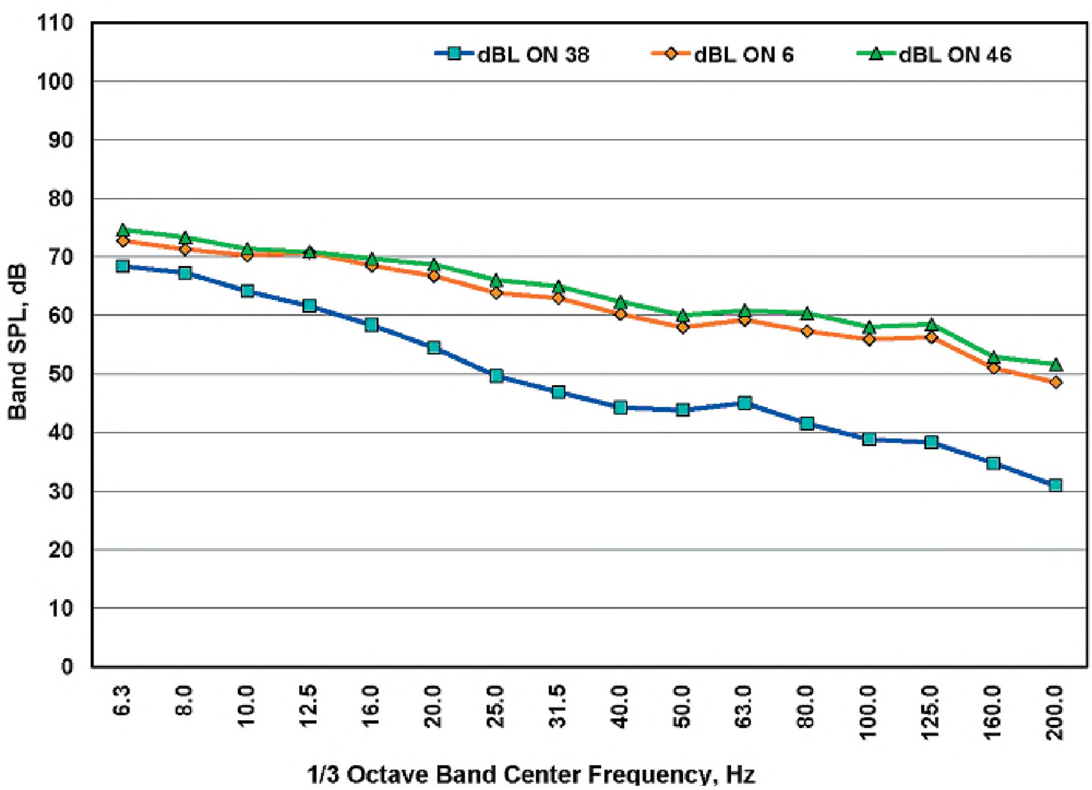


Figure 14. 1/3 octave LF spectra. file 38: dBL, low wind, turbines ON, 50 m
file 6: dBL, medium wind, turbines ON, 50 m; file 46: dBL, high wind, turbines ON, 50 m

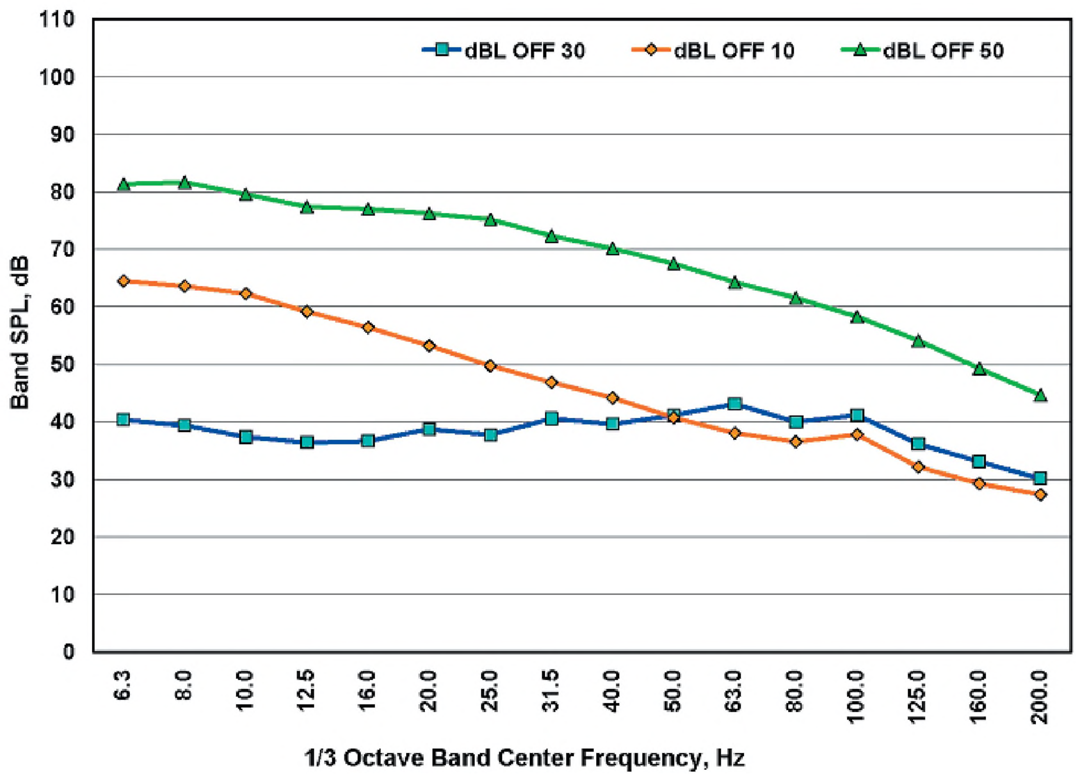


Figure 15. 1/3 octave LF spectra. file 30: dBL, low wind, turbines OFF, 50 m file 10: dBL, medium wind, turbines OFF, 50 m; file 50: dBL, high wind, turbines OFF, 50 m

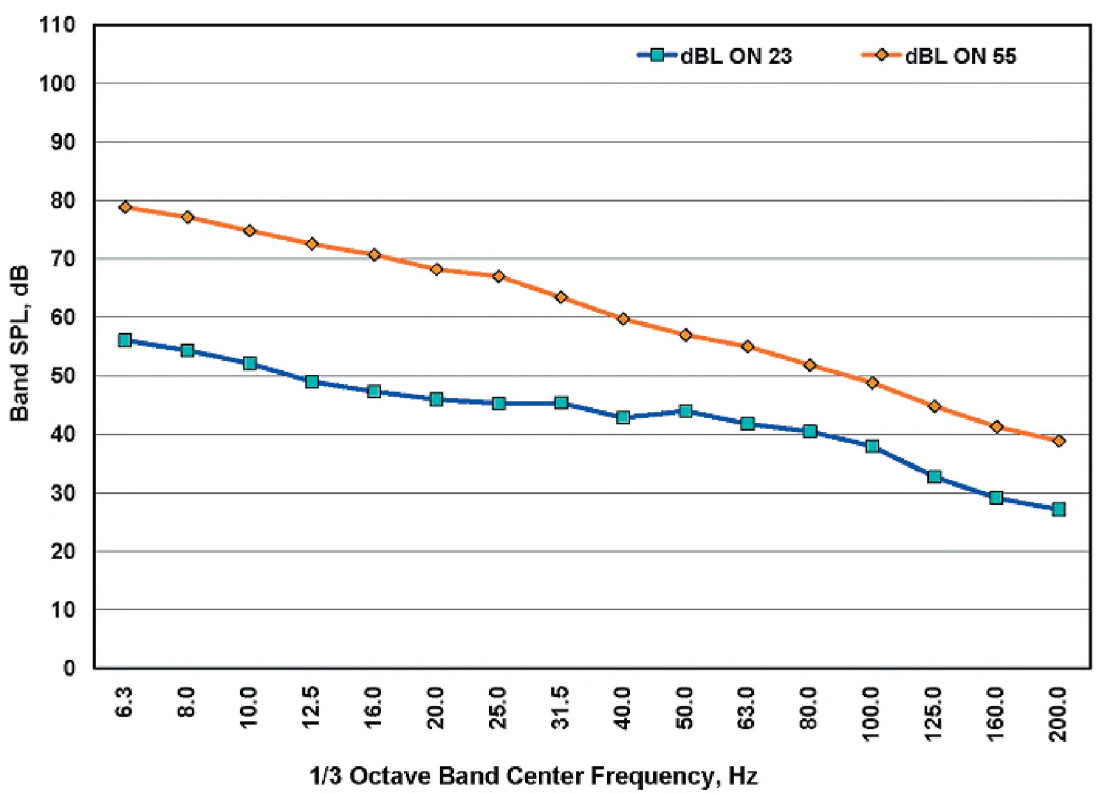


Figure 16. 1/3 octave LF spectra. file 23: dBL, low wind, turbines ON, 1000 m ; file 55: dBL, high wind, turbines ON, 1000 m

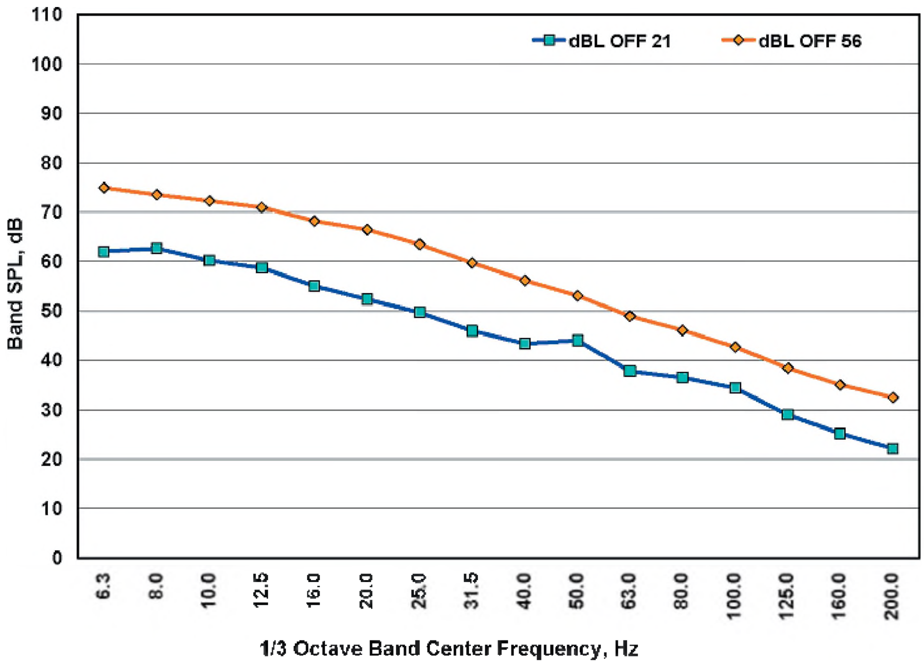


Figure 17. 1/3 octave LF spectra. file 21: dBL, low wind, turbines OFF, 1000 m file 56: dBL, high wind, turbines OFF, 1000 m

bling of distance. The following formula was used:

$$L(R2) = L(R1) - 10 \text{ Log10 } (R2/R1) \quad (1)$$

Where: R1 and R2 are distances in meters and L = dBA or sound level in dB for octave bands.

For the low wind condition, the observed dBA at 1000m exceeded the calculated dBA by 7.5 dB. The observed attenuation was less than the calculated attenuation since the ambient wind noise, albeit low, exceeded the output from the turbines at 1000 m. In other words, wind noise would not be attenuated with distance.

For the medium wind condition, the initial dBA at 50m was close to the measured initial dBA for high wind at 50m, since the turbines do not generate more sound at higher wind speeds. The behavior of the attenuation curve and observed values for the high wind condition indicates that the medium wind condition should behave in a similar manner, and attenuation for both conditions should closely follow the above formula. The observed dBA for high wind at 1000 m was actually lower than the calculated value, indicating an additional –3 dBA of attenuation. This indicates that the turbines decrease ambient wind noise. It is acknowledged that variability in wind speed and ambient noise could cause variability in measured LAeqs.

6.3 Telemetry Data Results and Analysis

The telemetry analysis provided time domain records for each of the three operational conditions of the turbines: low wind, medium wind, and high wind. In addition, for each operational condition, there were two operational states: ON and OFF. Those records are also shown. For each record, the first 30 traces (1 to 30 on the right) are the geophones, and the next 30 traces (31 to 60 on the left) are the acoustic microphones. The calibration scalars have been applied to the microphone data. The telemetry records are identified with an FFID (field file identifier).

Following the time domain records, the frequency domain amplitude spectra are presented, where possible, incorporating the calibrated data from the appropriate 2260 record. Data from the 2260 are identified as a file, rather than an FFID. The spectra are grouped for each of the three operational conditions. Within the spectra, data are often presented to compare operational states, ie. ON and OFF, or distance from turbines (50m or 1000m).

On each FFID, the first 30 channels (1 to 30 on line 1, stations 101 to 130) are 4.5 Hz geophones. The last 30 channels (31 to 60 on line 2, stations 101 to 130) are acoustic microphones. Stations on both lines have the same location (ie. Line 1 station 102 is the same location as Line 2 station 102). The line numbers differ to allow separation of the geophones and microphones on two cables in the field. The geophones and microphones were coincident on the stations. The vertical scale is time (ms). The horizontal scale is distance, with 50 m between traces. For all wind conditions, occasional

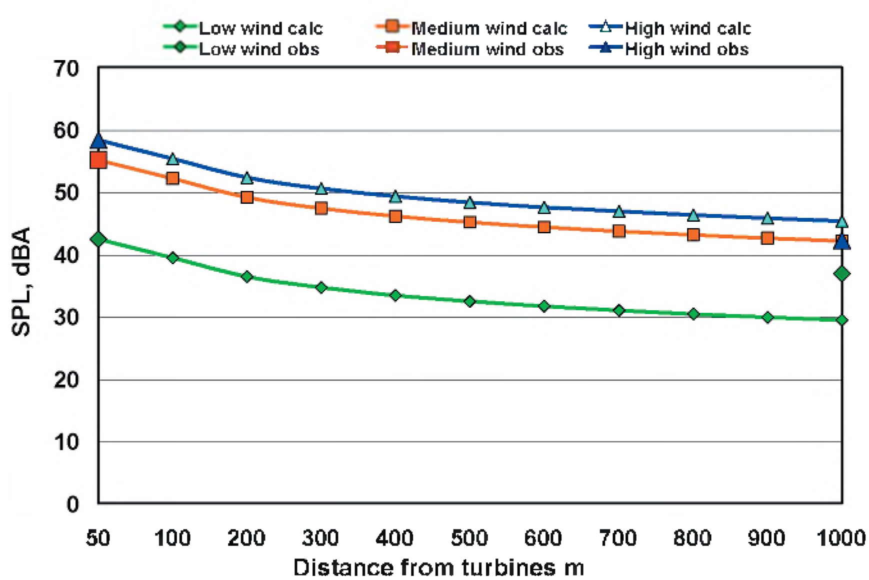


Figure 18. Calculated LAeq and observed LAeq: attenuation with distance.

noise bursts may be seen. These can generally be attributed to a wheat combine nearing the telemetry spread while working in an adjacent field.

The telemetry data analysis is presented only for the high wind conditions, since the dramatic variations are easily seen. Instead of the complete data set, only a discussion summary is presented for the low and medium wind conditions.

6.3.1 High Wind Conditions

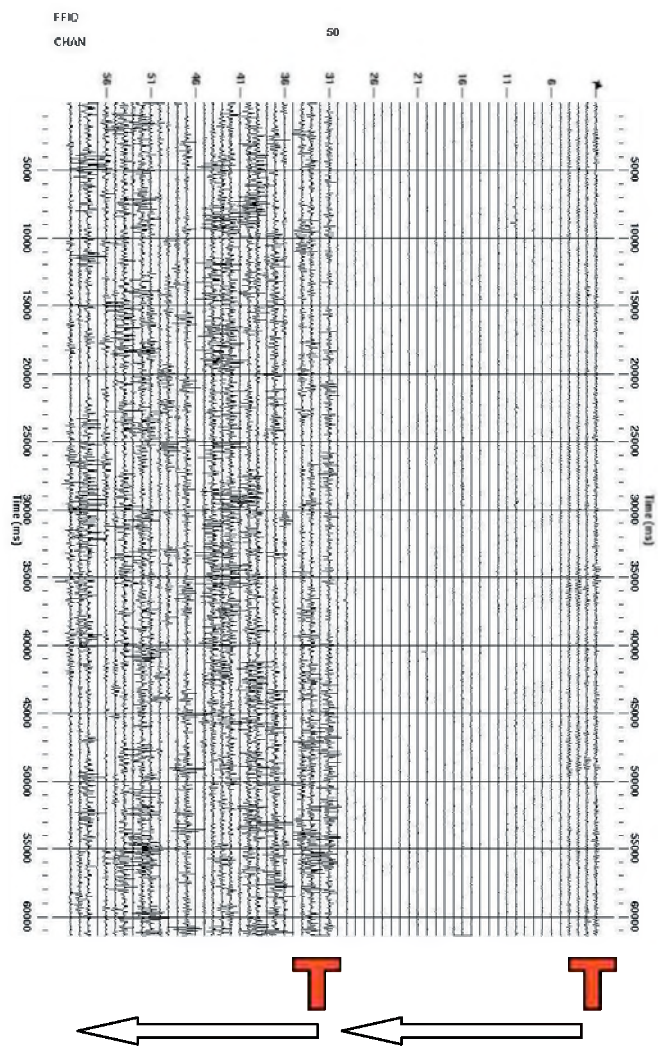
Fir the case of the turbines OFF, the microphones on the left half of figure 19 show that the wind noise at all offsets exceeds the sound levels for the same microphones on the left side of figure 20 (turbines ON). Similar results were found for the low and medium wind condiitons

The geophone traces on the right half of figure 19 are fairly quiet. The spurious events on the geophones close to the turbines were again caused by the wheat combine about 600 m north of the recording spread.

With the turbines ON, the acoustic energy recorded on the microphones has decreased at all offsets, due to the rotation of the turbines. The acoustic energy recorded on the geophones closest to the turbines has increased, due to the rotation of the turbines.

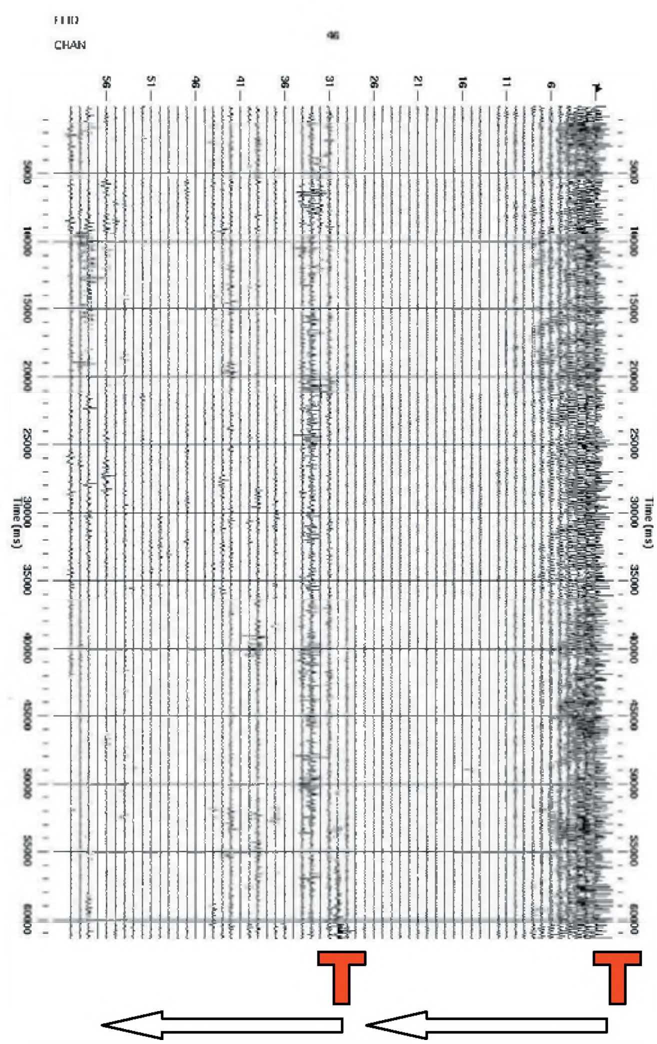
The above time domain records conclusively demonstrate that the wake effect of the turbines significantly decreases ambient noise for high wind speeds in the down wind direction, for the frequency band 3 Hz to 207 Hz.

Figure 21 shows the LLeqs measured at station 102 with high wind speed and the turbines ON. The data is out of range for B&K 2260 meter below 6.3 Hz, but were measured by the geophones and microphones. The telemetry data are empirically referenced to the 2260 data. Note that the geophone amplitudes decrease very rapidly with increasing frequency



Microphones every 50m Geophones every 50m

Figure 19. Time domain telemetry record (3 Hz to 207 Hz). FFID 50, high wind, turbines OFF.
Geophone traces 1 to 30, coincident with microphones on traces 31 to 60. The red T indicates the location of the closest turbines. Down wind direction to left of turbine location.



Microphones every 50m Geophones every 50m

Figure 20. Time domain telemetry record (3 Hz to 207 Hz). FFID 46, high wind, turbines ON.
Geophone traces 1 to 30, coincident with microphones on traces 31 to 60. The red T indicates the location of the closest turbines. Down wind direction to left of turbine location.

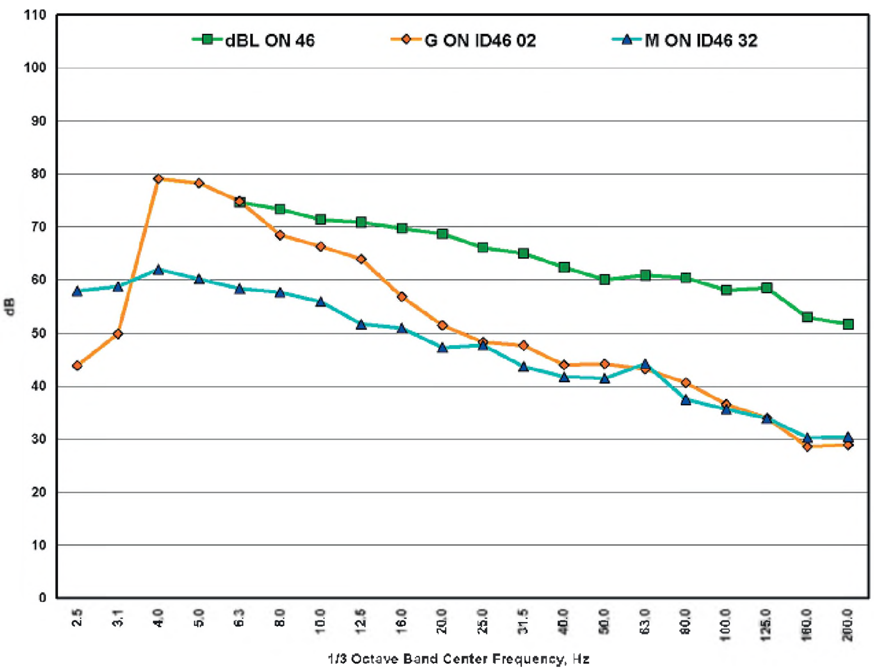


Figure 21. 1/3 octave LF spectra files: 46, FFID 46, ON, high wind, near trace LLeqs. file 46: dBL, 2260, high wind, turbines ON, 50 m, station 102 ; ID46 02: dBL*, geophone, high wind, turbines ON, 50 m, station 102; ID46 32: dBL*, microphone, high wind, turbines ON, 50 m, station 102; * indicates empirical calibration to 2260 acoustic data.

(-10 dB/octave). Microphone amplitudes also decrease with increasing frequency (-6dB/octave). 2260 LLeqs decrease with increasing frequency (-5dB/octave.) Interestingly, the amplitude dependence on frequency is almost identical to the medium wind case at 50 m.

Note that the microphone LLeqs for the high wind case are lower than LLeqs for the medium wind case, suggesting that the wake effect from the wind farm diminishes ambient noise, even at 50 m. The 2260 data are strongly affected by turbulent wind noise.

Figure 22 shows the LLeqs measured at station 121 with high wind speed and the turbines ON. The 2260 data were measured at station 102 (50m from the turbines). The telemetry data were measured 1000 m from the turbines. The attenuation due to distance for the geophones is not entirely linear, between 4 and 63 Hz approx -20 to -26 dB. The attenuation for the microphone data was about -5 dB, and was more linear with increasing frequency.

Figure 23 shows the LLeqs measured at 50m and 1000 m from the turbines, with high wind speed and the turbines ON. Figure 24 shows attenuation due to distance from 50m to 1000m, with high wind speed and the turbines ON. The microphone data are attenuated less than -10 dB over the range of 2.5 Hz to 200 Hz, with about the same attenuation at higher frequencies. The geophone data are attenuated from -5 dB to -32 dB over the same range, with more attenuation at lower frequencies. The attenuation with distance for the high wind case should be compared with the medium wind case. The attenuation for the geophones is very similar, however, the microphone amplitudes are not as strongly attenuated. Wind noise is more of a factor in the high wind case.

Figure 25 shows the LLeqs for the ON and OFF conditions, with high wind speed at a distance from the turbines of 50 m for the telemetry data, and 50 m for the 2260 data. The microphone data show largest decreases in amplitude, especially at low frequencies. The 2260 data show increases in amplitude at lower frequencies, showing the dominant effect of wind noise. Note the apparent tonal component at 63 Hz for OFF mic data (FFID50).

Figure 26 shows the difference between the ON and OFF conditions at a distance of 50 m from the turbines, with high wind speed. Geophone amplitudes decrease from –19 dB to +6 dB. Microphone amplitudes show a decrease in amplitude of about –30 dB for most frequencies, especially for frequencies below 40 Hz.

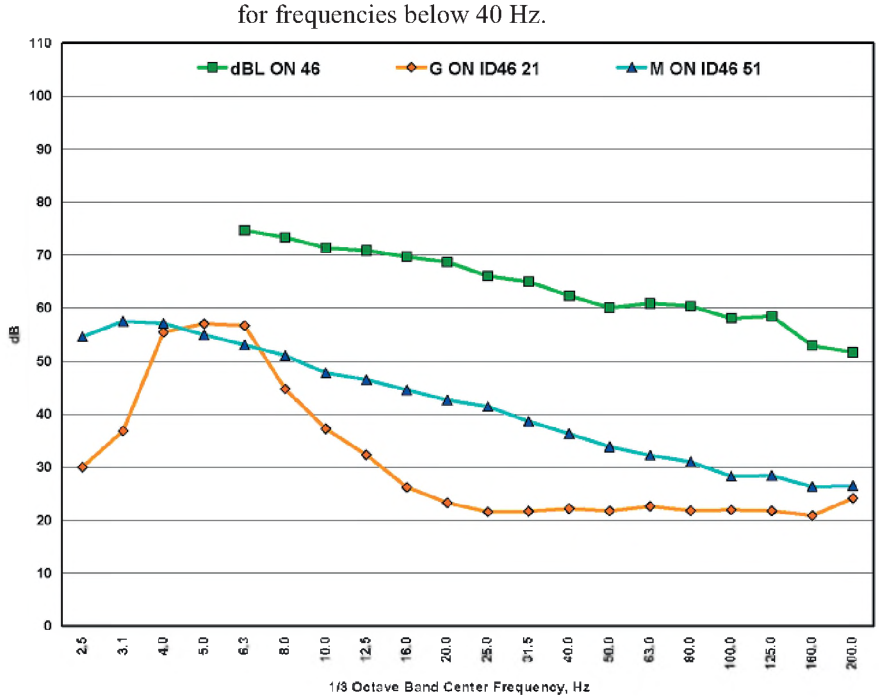


Figure 22. 1/3 octave LF spectra files: 46, FFID 46, ON, high wind, far trace LLeqs. file 46: dBL, 2260, high wind, turbines ON, 50 m, station 102 ; ID46 21: dBL*, geophone, high wind, turbines ON, 1000 m, station 121; ID46 51: dBL*, microphone, high wind, turbines ON, 1000 m, station 121

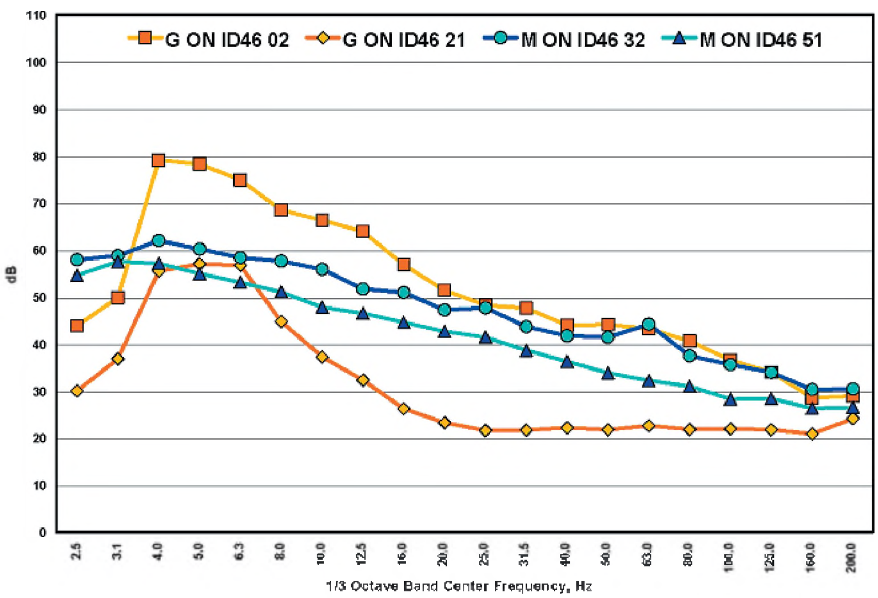


Figure 23 1/3 octave LF spectra

files: FFID 46, ON, high wind, near and far trace LLeqs.; ID46 02: dBL*, geophone, high wind, turbines ON, 50 m, station 102; ID46 21: dBL*, geophone, high wind, turbines ON, 1000 m, station 121; ID46 32: dBL*, microphone, high wind, turbines ON, 50 m, station 102 ; ID46 51: dBL*, microphone, high wind, turbines ON, 1000 m, station 121

The 2260 data show an increase in LLeqs from +6 dB to +9 dB for frequencies below 63 Hz, illustrating the dominance of wind noise at high wind speeds. The 2260 data confirm that wind farm operation at high wind speeds decreases the turbulent wind noise, even at 50 m. The microphones were protected from the turbulent flow, since they were about 2 inches below the surface.

Figure 27 shows the LLeqs measured for the ON and OFF with high wind speed at a distance of 1000 m from the turbines for the telemetry data, and 50m for the 2260 data. Amplitudes, as measured by the 2260 at 50 m from the turbine, are higher with the turbines OFF, as in figure 25 above. The geophone and microphone data at a distance of 1000 m, also show some increase in amplitude with the turbines OFF.

Figure 28 shows the differences measured for the ON and OFF conditions at a distance of 50m (2260 data) and 1000 m (telemetry data) from the turbines, with high wind speed. At most frequencies, the LLeqs increase when the wind farm is OFF, as measured with the 2260 at 50 m. The microphone amplitudes increase by about +12 to + 18 dB when the wind farm is OFF. The small decrease in amplitudes for the geophones, below about 8 Hz, confirm that there was not much coupled terrestrial energy from the turbines at high wind speeds. A +10dB increase in geophone amplitudes above 20 Hz confirm that wind noise, rather than sound output from the turbines, is a dominant factor.

9. CONCLUSIONS

Measurements of frequencies down to 6.3 Hz, obtained with the 2260, showed that infrasound emission from the Castle River Wind Farm is present in close proximity to the turbines, but is not a significant concern. Lower frequencies, down to approximately 2.5 Hz, were measured in the telemetry data set. The telemetry data demonstrate that in close proximity to the turbines, the largest infrasound levels are terrestrially coupled, and are detected on the geophones. The infrasound frequencies detected by the geophones are strongly attenuated with distance from the turbines. All data sets confirm that atmospheric infrasound emissions from the turbines are not significantly above the ambient wind noise levels at a distance of 1000 m, and that for the low wind and high wind conditions, infrasound levels are actually lower when the turbines are operating.

Ambient infrasound levels, when the turbines are not operating, are significant for the medium and high wind conditions. For the high wind condition, at a distance of 1000 m from the wind farm, infrasound LLeqs range from 76 to 82

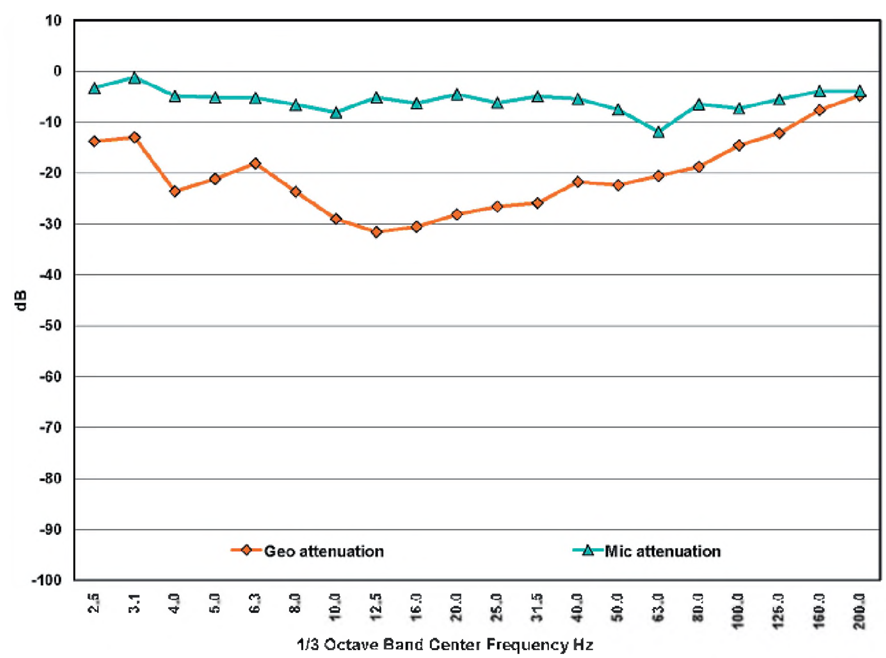


Figure 24. 1/3 octave attenuation.

FFID 46, ON, high wind, attenuation due to distance; FFID46: dBL*, geophone, high wind, turbines ON, attenuation from 50m to 1000m; FFID46: dBL*, microphone, high wind, turbines ON, attenuation from 50m to 1000m

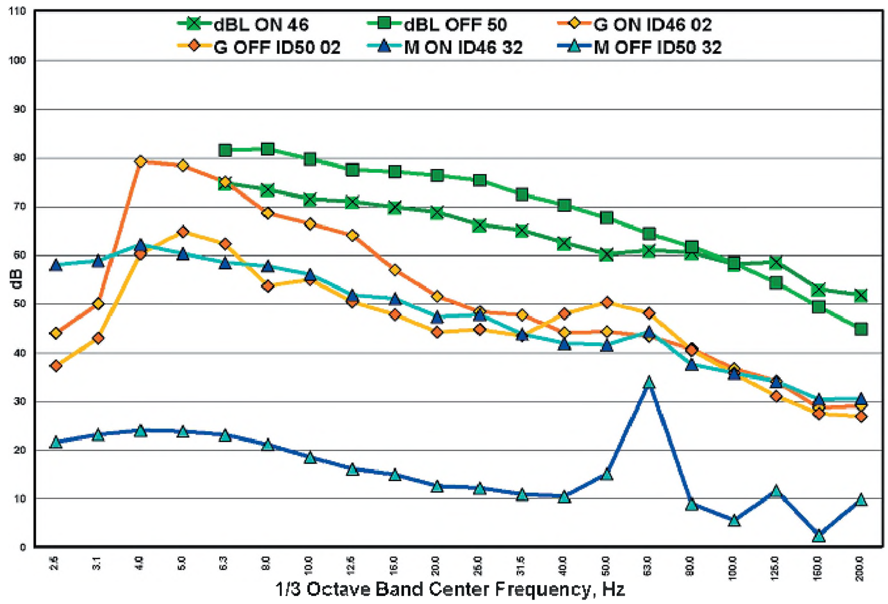


Figure 25. 1/3 octave LF spectra

file 46: dBL, 2260, high wind, turbines ON, 50m; file 50: dBL, 2260, high wind, turbines OFF, 50m; FFID46 02: dBL*, geophone, high wind, turbines ON, 50m; FFID50 02: dBL*, geophone, high wind, turbines OFF, 50m; FFID46 32: dBL*, microphone, high wind, turbines ON, 50m. FFID50 32: dBL*, microphone, high wind, turbines OFF, 50m.

dBL when the turbines are OFF, exceeding the infrasound LLeqs when the turbines are ON. The telemetry data confirm the 2260 data. For the medium wind condition, ambient infrasound LLeqs range from 53 to 65 dBL, when the turbines are OFF. For the low wind condition, ambient infrasound LLeqs range from 53 to 62 dBL, exceeding the infrasound LLeqs when the turbines are ON. The telemetry data confirm the 2260 data.

Attenuation of acoustic energy with distance was measured. The observed LAeqs at 1000 m, for low wind speed, was higher (+7.5 dBA) than calculated, due to the fact that ambient wind noise is not attenuated with distance, and the ambient wind noise exceeded the attenuated output from the turbines. The observed value at 1000 m, for high wind speed, was –3.1 dBA lower than calculated, indicating attenuation of the wind noise during operation of the wind farm. All data support the conclusion that some attenuation of wind noise occurs when the wind farm was operating in low and high winds. The time domain telemetry data for the frequency band of 3 Hz to 207 Hz support the same conclusion for all wind conditions, particularly at a distance from the turbines of 200 m and greater. Variation of environmental conditions may have introduced some variability into the data.

The full band (3 Hz to 207 Hz) time domain telemetry data clearly show the remarkable effect of wind noise reduction on the microphones, when the turbines are operating at all wind speeds. The 1/3 octave band spectra demonstrate that at low and high wind speeds, wind noise is attenuated when the wind farm is in operation. The ambient wind noise levels are higher when the turbines are not turning. Clearly, the wake effect is a significant factor in reduction of wind noise.

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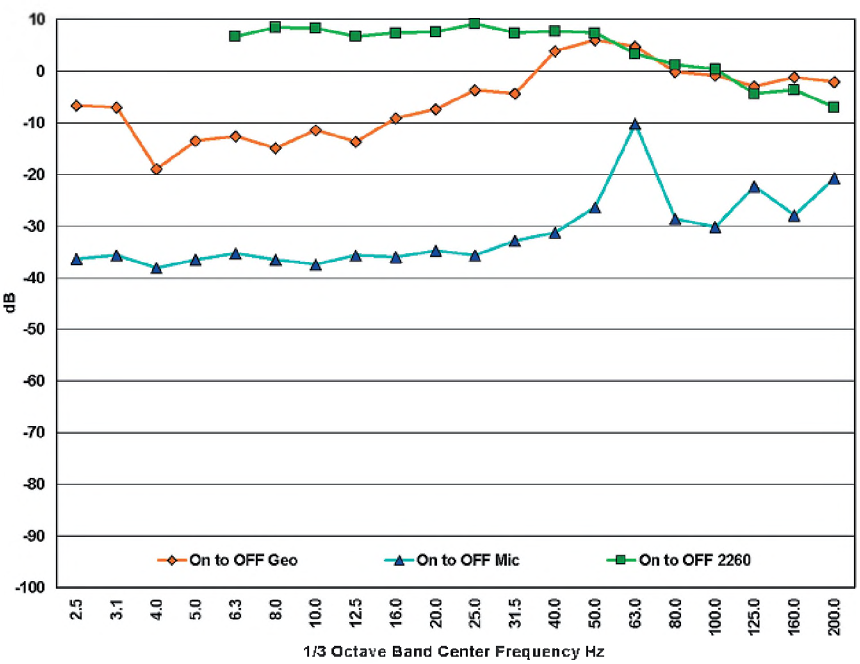

Figure 26. 1/3 octave difference

file 46, 50: dBL, 2260, high wind, turbines ON and OFF, 50m, residual above background; FFID 46, 50: dBL*, geophone, high wind, turbines ON and OFF, 50m, residual above background; FFID 46, 50: dBL*, microphone, high wind, turbines ON and OFF, 50m, residual above background.

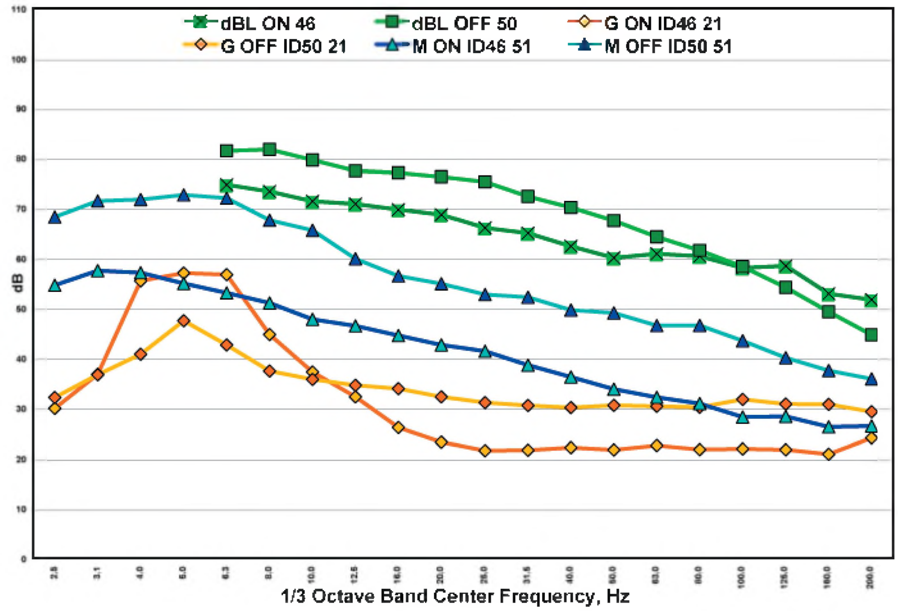

Figure 27. 1/3 octave difference

files: 46, 50, FFIDs 46&50, ON&OFF, high wind, far trace LLeqs. file 46: dBL, 2260, high wind, turbines ON, 50m; file 50: dBL, 2260, high wind, turbines OFF, 50m; FFID46 21: dBL*, geophone, medium wind, turbines ON, 1000m; FFID50 21: dBL*, geophone, medium wind, turbines OFF, 1000m; FFID46 51: dBL*, microphone, medium wind, turbines ON, 1000m FFID50 51: dBL*, microphone, medium wind, turbines OFF, 1000m.

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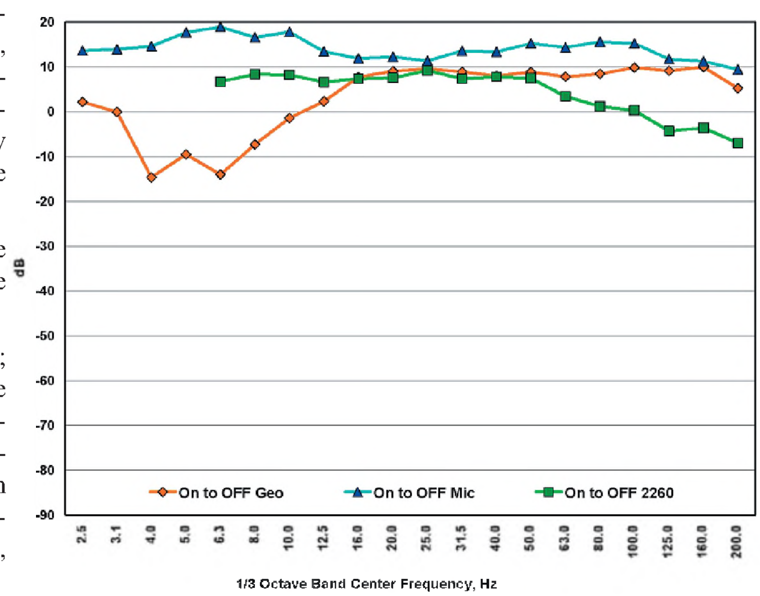

Figure 28. 1/3 octave difference

files: 46, 50, FFIDs 46&50, ON&OFF, high wind, far trace differences - file 06, 10: dBL, 2260, medium wind, turbines ON and OFF, 50m, residual above background; FFID 07, 11: dBL*, geophone, medium wind, turbines ON and OFF, 1000m, residual above background; FFID 07, 11: dBL*, microphone, medium wind, turbines ON and OFF, 1000m, residual above background.