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Characterization and Impact of Low Frequency Wind Turbine Noise Emissions

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Characterization and Impact of Low Frequency Wind Turbine Noise Emissions

by

James Finch

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Windsor, Ontario, Canada

2012

Characterization and Impact of Low Frequency Wind Turbine Noise Emissions

by

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DECLARATION OF ORIGINALITY

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ABSTRACT

Wind turbine noise is a complex issue that requires due diligence to minimize any potential impact on quality of life. This study enhances existing knowledge of wind turbine noise through focused analyses of downwind sound propagation, directionality, and the low frequency component of the noise. Measurements were conducted at four wind speeds according to a design of experiments at incremental distances and angles.

Wind turbine noise is shown to be highly directional, while downwind sound propagation is spherical with limited ground absorption. The noise is found to have a significant low frequency component that is largely independent of wind speed over the 20-250 Hz range. The generated low frequency noise is shown to be audible above 40 Hz at the MOE setback distance of 550 m. Infrasound levels exhibit higher dependency on wind speed, but remain below audible levels up to 15 m/s.

DEDICATION

This work is dedicated to my mother, Pamela Finch, and father, Douglas Finch, for their unwavering love, support and encouragement throughout my undergraduate and Master's studies and always. I will continue to strive for more and always make them proud.

I would further like to dedicate this to my grandfather, Roy Ellis, who instilled a passion for mechanical engineering from a young age with his RCAF experience and our remote control car races in Sussex, New Brunswick.

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Jeremy was a key part of the research as he volunteered himself and his truck to carry equipment to the site and around the field. His assistance was instrumental to the work, as were his feedback and knowledge of acoustics in ensuring that I was on the right path.

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His support and patience with carrying equipment around the field on multiple test days was a key to the success of the research.

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Joe was instrumental on the final and longest test day as he was patient and willing to help every step of the way through ground level and array measurements.

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ABBREVIATIONS AND NOMENCLATURE

AWEA	American Wind Energy Association
CanWEA	Canadian Wind Energy Association
CCW	counter-clockwise
CMOH	Chief Medical Officer of Health of Ontario
CPB	constant percentage bandwidth
dB	decibel
dBA	A-weighted decibel
dBC	C-weighted decibel
dBG	G-weighted decibel
FFT	Fast Fourier Transform
h_{hub}	hub height, metres
h_{ref}	reference height, metres
Hz	Hertz
LFN	low frequency noise
L_P	sound pressure level, decibels
L_W	sound power level, decibels
m	metres
MEASNET	Measuring Network of Wind Energy Institutes
MOE	Ontario Ministry of the Environment
P	sound pressure level, Pascals
P_0	reference sound pressure level, 20×10^{-5} Pascals
Pa	Pascals
s	seconds
U_{hub}	hub height wind speed, m/s
U_{ref}	reference wind speed, m/s
W	sound power, Watts
W_0	reference sound power level, 10^{-12} Watts
WRECE	Wind and Renewable Energies Centre of Expertise

CHAPTER I

INTRODUCTION

The wind energy industry is rapidly expanding globally as countries continually move to source an increased percentage of energy from renewable sources. The rapid development of wind farms is therefore likely to continue for many years to come. For example, as many as 500 wind turbines are to be installed in Southwestern Ontario alone by 2013. The benefits to harnessing the immense amount of energy available in the wind are numerous; however, as with most emerging technologies and industries, there are many challenges that must be given consideration as the technology continues to mature. One of the most controversial challenges is wind turbine noise and its potential to have an impact on quality of life.

Wind energy inherently lends itself to passionate supporters and defiant critics. This has led to the publication of many of articles, studies, measurement reports, health reviews, opinion papers and propaganda. The result is that it can be difficult to separate credible scientific analyses from well prepared reviews supporting one point of view or another. As wind turbine noise may impact human health, due diligence is required to improve understanding of the emitted noise and identify any potential risks.

The potential existence of a health-related noise issue is not the only motivation to perform an engineering investigation of wind turbine noise. The wind resource is often considered to be 'free', but the operation and maintenance of a multi-million dollar wind farm is costly. Regular noise condition monitoring or acoustic evaluations offer wind farm operators the opportunity to identify maintenance issues before they develop, and to improve efficiency through optimization of wind farm operational strategies. Decreasing the level of generated wind turbine noise consequently has the potential to satisfy nearby residents while improving wind farm profitability by ensuring a greater percentage of the energy in the wind is converted to electrical rather than acoustical energy.

The many emerging research opportunities as wind farm numbers continue to increase prompted the development of the Wind and Renewable Energies Centre of Expertise (WRECE) at the University of Windsor. The WRECE was established in partnership with Bruel & Kjaer – a world leader in acoustics and vibrations measurement technologies. This work is intended to build the foundation for future projects within the WRECE by providing a strong understanding of the fundamental characteristics of wind turbine noise, particularly across the low frequency spectrum.

Wind turbine noise is a broad subject with many years of research having been conducted into the mechanisms of wind turbine noise generation, simulation / prediction models and field measurements verifying noise emissions against existing hearing thresholds and regulatory limits. The resulting reports have provided significant insight into wind turbine noise generation, yet offer few definitive conclusions. Many of these reports will be discussed in Chapter 3. It is shown that broadband wind turbine noise is fairly well understood, while the low frequency component is often dismissed due to measured sound pressure levels being relatively low and often inaudible. Despite the low sound pressure levels associated with wind turbine noise, the potential for a low frequency or infrasound noise issue is often cited by the public as a great concern. As a result, the low frequency spectrum forms the basis of this study. It is important to focus on the low frequency domain in order to offer due diligence to those who may be affected and to enhance understanding of wind turbine noise in its entirety.

The concerns associated with wind turbine generated low frequency noise and infrasound date back to the wind turbines of the 1970's and 1980's. The majority of early wind turbines were downwind models in which the wind passed around the tower and nacelle before interacting with the rotor. These turbines were notoriously noisy and may have had significant infrasound noise emissions. Modern upwind turbines are have increased conversion efficiencies and generate less noise than the downwind turbines of the past, enabling more energy available in the wind to be extracted as electrical energy. There is reason to believe that as wind turbines continue to increase in size – offshore turbines will soon approach 10 MW – the low frequency component of the generated noise will continue to become more important.

The objective of this study is to improve understanding of the characteristics of wind turbine noise across the entire frequency spectrum. The work builds upon existing research through focused studies of downwind sound propagation, directionality, and the wind speed dependency of the noise. These studies enhance current knowledge of wind turbine noise and may assist communities, government agencies, and wind farm developers with siting of wind turbines, such that maximum efficiency can be achieved with minimal environmental impact. A second primary objective of the research is a detailed investigation of the low frequency and infrasound components of the noise. This can be controversial as sound pressure levels are sufficiently low that any further study is often dismissed, yet nearby residents remain concerned that low frequency noise and infrasound may have an impact on quality of life. This work develops important understanding of generated low frequency noise by identifying levels at key frequencies and assessing their relevance against the audible limits of humans, cattle, and goats.

This study involves three 2.3 MW class turbines located at different locations within a large wind farm development. Field measurements are performed on four separate days to assess the noise under varying weather conditions and turbine orientations. All measurements are conducted at ground level using primary and secondary windscreens to avoid the uncertainties associated with ground reflection if measurements were conducted at a specified height. For sound propagation, this study is unique in that measurements were recorded at 100 m increments moving downwind from the base of the turbine. The furthest measurements were land access limited, but at 550 m and 600 m were sufficient to provide insight into anticipated levels at the current MOE setback distance. Directional measurements were recorded every 45° at a radii of 100 m and 200 m from the base of the turbine. These measurements were repeated at different wind speeds, allowing for some definitive trends and characteristics of the noise to develop.

As conditions in the field change rapidly, fluctuations in wind speed and external noise sources are two of the greatest challenges to collecting valid wind turbine noise data. With consistent measurements recorded, comparisons are made between the characteristics of the noise under varying operating conditions. General trends are observed and characteristics defined through the comparison of overall sound pressure levels across measurement sets at different locations. The overall levels are valuable for understanding the downwind propagation and directional behaviour of the noise, but offer little information into where the noise sources are dominant in the frequency spectrum. Overall A-weighted levels are typically used for environmental noise assessments, including wind turbine noise. The author believes that the use of A-weighting is not suitable for wind turbine noise as it significantly attenuates the low frequency portion of the noise spectrum. A-weighted levels of wind turbine noise are generally quite low, so as long as they are within regulatory limits, no further consideration is often given to a potential noise issue. The problem is that if low frequency noise is present and significant, it may be highly attenuated by the A-weighted analysis and go unnoticed. It is possible that wind turbine noise may be audible with the potential for annoyance as low as 30 Hz. As such, the analytical techniques used in this study take a more holistic approach to ensure that the often high fluctuations in the low frequency spectrum are not discounted, and their impact on the perceived noise is included. This is performed largely through the analysis of linear (unweighted) sound pressure levels. To better represent the perception of noise in the low frequency and infrasound domains, C-weighting and G-weighting filters are applied. The results provide an opportunity to investigate the potential audibility of the low frequency noise as well as to consider the directional nature and propagation distance of infrasound and low frequency levels versus overall levels. This provides much needed understanding of the low frequency component and the general characteristics of wind turbine noise as a whole.

This study improves current understanding of wind turbine noise by focusing on propagation distance, directionality, and the low frequency component of the noise. The progressive design of experiments allows for the isolation of variables such that comparisons are made as accurately as possible in a changing environment. The conclusions developed in this report are significant as they identify key characteristics of wind turbine noise that have not previously been discussed at length. It is important to remember that studying wind turbine noise presents other opportunities, in addition to identifying whether there is a valid health concern. Those conclusions cannot be made from an engineering study alone and will require future correlation of data with medical experts. Noise condition monitoring presents an opportunity for the wind farm to monitor the performance of its turbines and identify maintenance issues early, or change operational strategies accordingly. These are among many areas which the WRECE will explore in the future, and this report provides the fundamentals on which much of that research will be based.

CHAPTER II

BACKGROUND INFORMATION AND THEORY

2.1 Sound and Noise

Knowledge of acoustic fundamentals is imperative to understanding the nature of wind turbine noise. The Oxford Dictionary defines noise as "a sound, especially one that is loud or unpleasant or that causes disturbance". [1] Noise issues are complex and may develop as a result of multiple factors including frequency spectra, level of intensity, tonality and the type and location of the source. The perception of sound then depends on such variables as the medium of sound transmission, background sound levels, the orientation of the receptor relative to the source and the path from source to receptor. For wind turbine noise in rural areas, background or ambient sound levels are relatively low and receptors – rural homes and businesses - may be several hundred metres from the source.

Sound is generated as small rapid pressure fluctuations are transmitted through a medium and perceived as sensations in the human ear. The speed of sound in air is approximately 343 m/s at 20°C and increases with a decrease in temperature. The human ear has a wide audible range from 20 Hz to 20 kHz, although lower frequencies may also be heard or perceived at very high sound levels. The ear is more sensitive to some frequencies than others and the sensitivity can vary from one individual to the next. In nature, pure tone sounds are not a normal occurrence. Each perceived sound is instead a composition of numerous sound waves where certain frequencies are prominent for a given source.

The octaves of a piano are one of the most easily identifiable examples of sound and how its tone and pitch vary with frequency. An octave is simply a doubling in frequency. Therefore, 500 Hz is one octave above 250 Hz and one octave below 1 kHz. Octaves are an important concept as they allow for the definition of frequency ranges over which analyses are conducted. It is common practice in acoustics for octave bands to be divided into 1/3 octaves for higher resolution analyses of sound levels that better represent the response of the human ear. These octaves can be further divided into narrower frequency bands down to the $1/n^{th}$ band, with smaller bands providing greater detail into the contribution of a given frequency to overall sound levels. The 1/24 octave is used extensively in this report as it offers a quick, relatively high resolution understanding of critical frequency domains, including a clear view of levels at the low frequencies of interest with wind turbine noise.

Noise was defined as an undesirable sound. The perception of noise depends on many factors including the location, amplitude and duration of the dominant frequency(s) in the overall sound spectrum. The way a sound is perceived can be analyzed based on perception limits or by using more specific psychoacoustic metrics such as loudness, sharpness, roughness, and fluctuation strength. Depending on the level and frequency content, noise has the potential to have a negative impact on humans ranging from annoyance to interference with daily activities to physiological effects such as hearing loss. The present state of art taken from existing published research on the potential impact of wind turbine noise is presented in Chapter 3.

2.2 Noise Measurement and Filters

While noise measurement data is most often given in terms of the sound pressure level of a source, reporting sound power level has advantages and is often used. Sound pressure level is a property of the noise source as well as the environment in which it is located. That is, the sound level measured at the receptor location will depend on many factors including source orientation, atmospheric conditions, ground absorption or reflectivity, etc. Alternatively, sound power level is a property of the source alone, independent of its surroundings, and is representative of its total acoustic power emission. As the ear responds nonlinearly to rapid but small excitations over a wide range of frequencies, it is inconvenient to present sound pressure levels in units of pressure alone. Because of this, sounds are presented logarithmically having units of the decibel (dB) with 0 dB representing the threshold of human hearing. The definitions for sound pressure level (L_P) and sound power level (L_W) in decibels are as follows. [2]

$$\boldsymbol{L_P = 20\, log_{10}\left({}^{P}\!/_{P_o}\right) \quad [dB]} \tag{1}$$

$$\boldsymbol{L_W = 10\, log_{10}\left({}^{W}\!/_{W_0}\right) \quad [dB]} \tag{2}$$

where the reference sound pressure level (P_0) is 20 x 10^{-5} Pa and the reference sound power level (W_0) is 10^{-12} W.

A relation is required between the decibel and perceived loudness to offer some understanding of the magnitude of a change in sound pressure level. A difference of 3 dB is generally required to barely observe a change in loudness, while a 10 dB increase results in an approximate doubling of loudness at the receptor. An ideal spherically propagating noise source is considered to decrease at a rate of 6 dB per doubling of distance from source to receiver, or 3 dB per doubling of distance with cylindrical propagation, such as for a line source. [2]

Acoustic weighting filters are another important concept for noise measurements, particularly when human perception of the noise is of interest. It has already been noted that the human auditory system perceives sounds at various frequencies differently and that the sensitivity to sounds at certain levels and frequencies is greater than at others. ISO 226:2003 defines the equal loudness contours which represent sound pressure levels at which the perceived loudness of pure tones is constant over the audible frequency range. [3] The shape of the equal loudness contours is similar at various levels of loudness and demonstrates the decreased sensitivity of the auditory system to sounds at low and high frequencies. Figure 1 shows the equal loudness contours of ISO 226:2003. Note that the 40 phon curve is one of the most commonly referenced in acoustics.

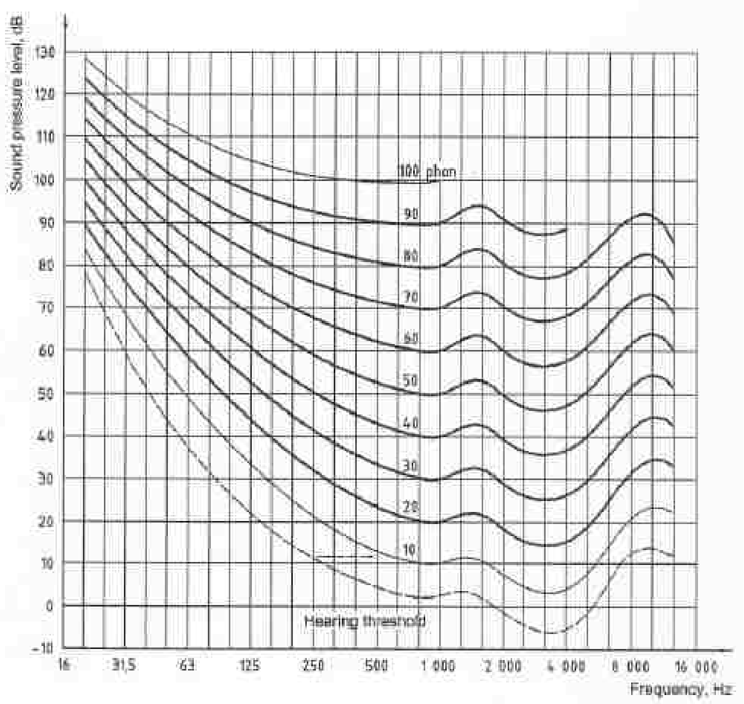


Figure 1: ISO 226:2003 Equal Loudness Contours [3]

To better relate a measured acoustic stimulus to the response of the human auditory system, a set of standardized weighting filters are defined in IEC 61672. [4] The filters were developed using the equal loudness contours of ISO 226 to represent the response of the human auditory system at constant loudness. The most commonly used environmental noise metric is the A-weighting filter (dBA) which is derived from an inversion of the of the equal loudness contour at 40 phon. [2] Additional filters exist to better emulate the response of the auditory system at low frequencies, such as the C-weighting and G-weighting schemes. These will be discussed in further detail in Chapter 3. The A-, B-, and C-weighting curves are displayed in Figure 2. [4]

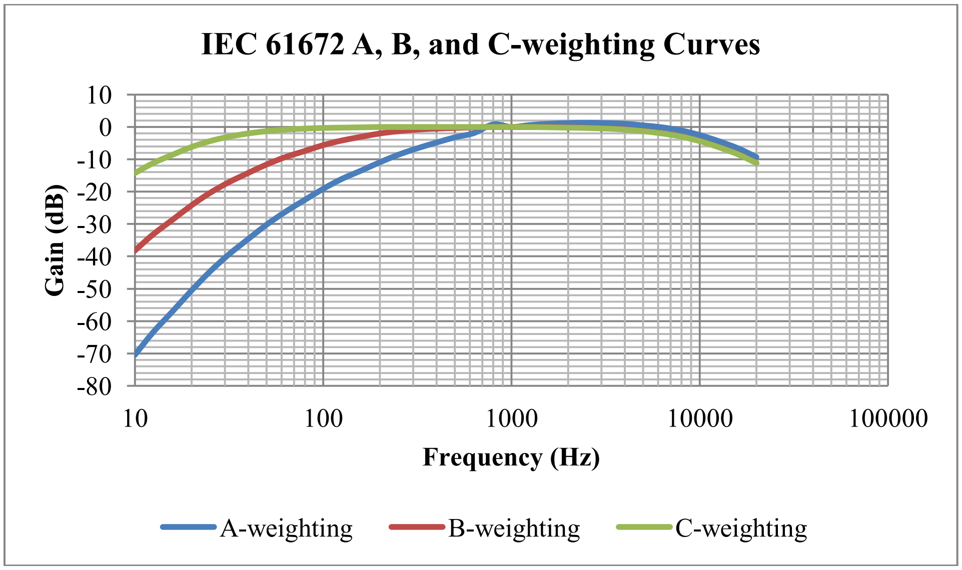


Figure 2: IEC 61672 A, B, C-weighting Curves

The A-weighting curve is shown to significantly attenuate noise below 100 Hz, which is well within the domain at which low frequency wind turbine noise is anticipated to be relevant. Minimal attenuation is applied with C-weighting, which makes it far more appropriate for low frequency noise evaluations. With only minimal weighting applied across most the frequency spectrum, C-weighted levels are typically close to linear (unweighted) levels.

CHAPTER III

LITERATURE REVIEW

As with many emerging technologies or industries in their infancy, wind energy projects have been subject to polarized opinions that either support or challenge their development. The potential for wind turbine generated noise to result in annoyance, unpleasantness or have a negative health impact on nearby residents are commonly cited concerns. The possibility of an infrasound or low frequency noise issue is often at the forefront of these discussions. Many involved or affected parties have conducted numerous sets of measurements, scientific studies, and summaries of existing literature, however few of these can be found to have truly addressed the complexities of wind turbine infrasound and low frequency noise, particularly in the absence of an ideological bias.

A detailed literature search was conducted to review many of these reports and gain an understanding of the research opportunities inherent in questions that remain unanswered. Many of the key findings and discoveries of these reports are reviewed in the sections that follow. It is first important to understand fundamental characteristics of the relevant frequency spectrum before reviewing its potential for human impact.

3.1 Infrasound

Infrasound is defined as sound in the acoustic spectrum up to 20 Hz and is present in the natural environment at frequencies of 0.01 Hz – 2 Hz [5]. As it is below the conventional frequency range of human hearing (20 Hz – 20 kHz), infrasound is often considered ‘inaudible’. While this may be true in most situations, at elevated sound pressure levels (typically greater than 100 dB) infrasound may actually be within the audible range of human hearing. [6] Much of the research work on infrasound in the literature has been conducted for these elevated sound pressure levels. It will be shown that this is not relevant to wind turbines as they generate much lower sound pressure levels across the entire frequency domain.

The fact that wind turbine generated infrasound levels fall below human thresholds of hearing does not indicate that the sound cannot be perceived in another manner. Below the approximate frequency of 15 Hz, it has been shown that there is a change in perception from ‘hearing’ to a ‘sensation’ or ‘presence’ of the sound. [6] The perception is described as a pressure type sensation at the ear or elsewhere on the body and may exist regardless of whether infrasound levels are above or below audible limits. There is an inherent spectral imbalance at low frequencies due to a rapid decrease in sound pressure level as frequency increases. [6] This spectral imbalance combined with large amplitude fluctuations is a contributing source to annoyance and unpleasantness. In extreme cases, these conditions can even lead to headaches and disorientation. [6] This leads to the possibility that low frequency noise may actually be of greater concern than infrasound, especially over the 20-50 Hz domain. The additional fact that the resonant frequency of human internal organs is below 5 Hz further reinforces the need for infrasound and low frequency excitations to be considered for their potential influence whether audible or not. This very low, infrasonic frequency domain is also the potential cause for other issues such as door and window rattles which may arise as additional sources of annoyance.

3.2 G-weighting

Although A-weighted sound pressure levels are most often used to assess environmental noise sources, the A-weighted filter is not sufficient to properly assess levels of infrasound as it significantly reduces sound pressure levels in the infrasound domain without regard to the other potential impacts from infrasound. Relatively low A-weighted sound pressure levels can still result in significant annoyance to receptors due to large amplitude, or temporal fluctuations, which may be lost in analysis, particularly if longer averaging periods are used.

A specialized filter for infrasound called G-weighting is defined in ISO-7196. The G-weighting curve is specified such that zero gain is applied at 10 Hz and is linear with a slope of 12 dB per octave over the range from 1 to 20 Hz, as shown in Figure 3. [7] Below and above the 1 Hz to 20 Hz domain are steep linear cut-offs with a slope of 24 dB per octave. [7]

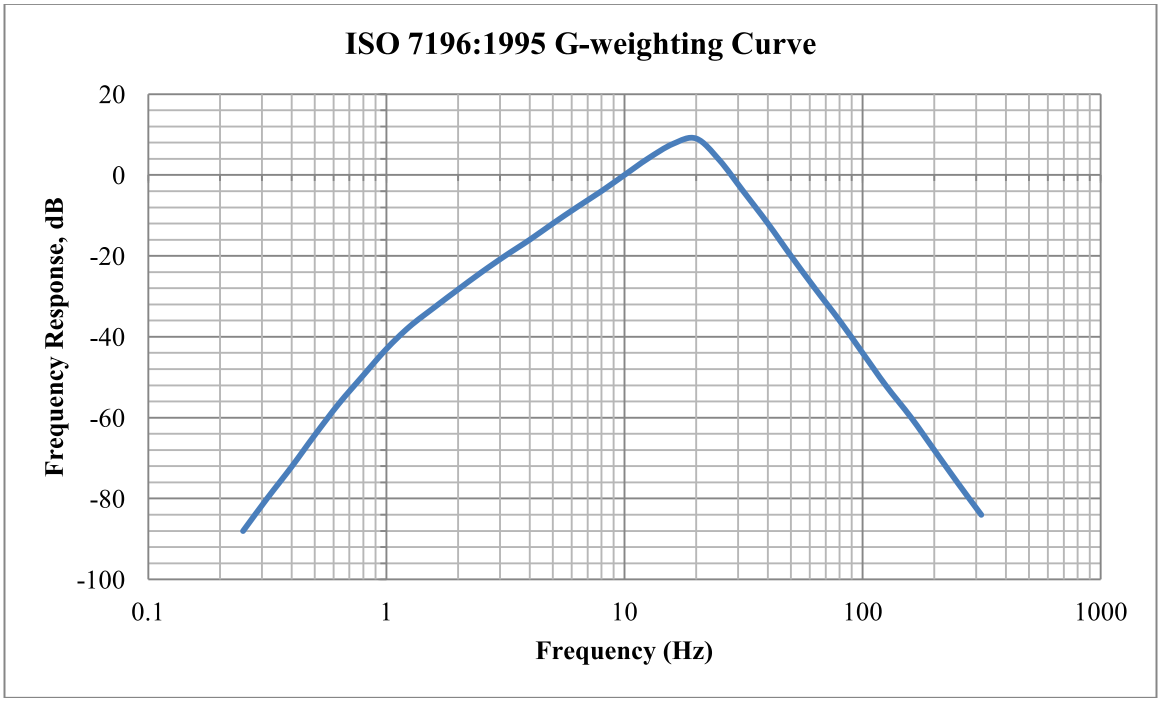


Figure 3: ISO 7196:1995 G-weighting Curve

Infrasound is generally not considered audible to humans below 85-90 dBG and limits in this range have been defined in some European standards. It is important to recall that there can be large standard deviations of hearing threshold in a sample population, and as such, levels which may disturb or annoy one person may have little to no impact on another. Broner notes that within the G-weighting spectrum, there may actually be an underestimation of loudness in the 16-20 Hz range. [6]

Another consideration is that stated hearing thresholds are generally given for pure-tone stimuli. Thresholds for complex noises may be much lower. Recent work in Japan has shown perception thresholds for pure-tones at 10 Hz and 20 Hz to be 94.0 dBG and 88.2 dBG, respectively. For a more complex noise signal, the perception thresholds decreased to 68.7 dBG and 64.3 dBG, respectively. [8] The hearing threshold for a complex noise signal can therefore be more than 20 dBG lower than pure tone audible limits. A percentage of the population is likely to be hypersensitive to infrasound and may be subject to additional annoyance at or below these levels. Recall that the thresholds define audible limits and the presence of a sound may still be experienced, as a pressure type sensation or otherwise, below these limits.

3.3 Low Frequency Noise?

Low frequency noise is commonly referred to as the audible frequency range from 20-100 Hz. [6] In regard to wind turbine generated low frequency noise, it is relevant to consider the low frequency domain to be approximately 20-250 Hz. Based on a review of previously reported data, it is expected that wind turbine noise may in fact be audible, with the potential for annoyance, over the range of approximately 40-200 Hz. Recent studies have shown that low frequency noise between 20-50 Hz is likely to have a greater impact on humans than infrasound and Broner suggests that the range from 30-80 Hz may be one of the most likely to lead to annoyance. [6]

Similar to infrasound, the potential for annoyance due to low frequency noise is greater than that at higher frequencies due to the degree of amplitude modulation and spectral imbalance involved. [6] A small change in low frequency noise may be perceived as a larger change in loudness than the same magnitude change at a higher frequency. This is important for the assessment of low frequency noise and infrasound as shorter time averaging periods are required to ensure that amplitude and temporal fluctuations are not lost. When assessing the audibility of low frequency noise, it must be kept in mind that hearing thresholds are average values and therefore often coincide with standard deviations as high as +/- 5-10 dB. [6] The hearing thresholds are typically based on pure-tone stimuli and, as discussed in the previous section on infrasound, it has been demonstrated that audible limits for complex noises can be much lower than pure-tone values. [8]

3.4 C-weighting

Despite its deficiencies, most low frequency noise studies are still analyzed using the A-weighting filter. Since A-weighting diminishes, or devalues much of the low frequency component, the C-weighting filter may be more appropriate in applications such as wind turbines where low frequency noise is suspected to be prominent. To date, this is not being done in the vast majority of wind turbine noise studies. When C-weighted levels are used, they are generally compared with A-weighted values as a metric to identify whether the potential exists for a low frequency noise issue. The metric is defined as low frequency noise having the potential to cause annoyance when the difference between A and C weighted levels (C-A) is greater than 15, 20 or 25 dB, depending on the jurisdiction or standard applied. [6] Similar metrics have been proposed and are sometimes used between linear and A-weighted sound pressure levels.

3.5 Mechanisms of Wind Turbine Noise Generation

Wind turbine noise generation can be separated into aerodynamic noise and mechanical noise. Mechanical noise refers to emissions from the gearbox, generator, cooling system or other accessory equipment. It is often predominantly tonal and can therefore be mitigated through design changes to the mechanical system. [9] Aerodynamic noise is far more complex and to date many aspects of it are not fully understood. Much of the existing theory on wind turbine aerodynamic noise is derived from aeroacoustic models for propellers and helicopters. The generated aerodynamic noise can be further divided into three categories: [9]

- Airfoil self-noise
- Inflow turbulence noise
- Low frequency noise and infrasound

Airfoil self-noise includes trailing-edge noise, flow separation from the blade at stall, and blade tip noise, among other conditions. These sources generally produce broadband noise and can be mitigated or avoided. Trailing-edge noise is often cited as the dominant source of broadband noise from wind turbines and can be identified in the 770 Hz to 2 kHz range. [9]

Inflow turbulence noise is still not well understood. It has been noted as contributing to broadband noise [9] in addition to being cited for potential low frequency noise issues when inflow turbulence is particularly high. [5]

The mechanisms of wind turbine low frequency noise and infrasound generation are additional areas that require further research and understanding. Much of the low frequency noise issue observed with older downwind turbines was associated with blade passage through the wake of the tower. [10] This is inherently no longer an issue with modern upwind turbines. It is believed that it may still be a contributing factor for larger wind farms where many turbines operate in the wake of neighbouring units. [9] Other potential sources of wind turbine generated low frequency noise and infrasound are not regularly identified or discussed because measured sound pressure levels are often determined to be sufficiently below audible levels for the issue to not warrant further investigation. In the cases where researchers have observed prominent levels of low frequency noise or infrasound, potential sound generation mechanisms are not often discussed.

Amplitude modulation is often cited as the characteristic of wind turbine noise that may pose the greatest risk for annoyance. [5] It is easily recognized as the audible swish-swish associated with passage of the blade by the tower. Opponents of wind farms commonly refer to amplitude modulation as a low frequency noise but may be confused with the blade passage frequency as the noise itself is typically in the 500-1000 Hz range. [5]

3.6 Existing Field Measurements of Wind Turbine Noise

Given the controversial nature of wind turbine noise, a number of supporters and opponents of wind energy have recorded sound level measurements, analyzed the data, and reported their results either in scientific journals or as a general service to the public. Many have conducted their measurements in accordance with the IEC-61400-11 standard or a variation of it. It would serve no purpose to review all of them here as the vast majority present similar results for measured sound pressure levels relative to the standard in a particular jurisdiction. Rather, those that looked more closely at the potential impact of low frequency noise and infrasound are considered in greater detail.

In 2009, Aercoustics Engineering Limited was contracted by Kruger Energy to assess its Port Alma, Ontario wind farm for compliance with Ministry of the Environment (MOE) standards and to comment on the potential noise impact for nearby residents. [11] A noise monitoring system was installed at a house 637 metres from the closest wind turbine and sound pressure levels were measured both inside and outside of the house over a three week period. Outdoor sound pressure levels were plotted against indoor sound pressure levels, revealing a trend of approximately 11.5 dBA difference between indoor and outdoor levels. [11] This is consistent with the general assumption of approximately a 10 dBA decrease in sound pressure level between indoor and outdoor measurements. Over the measurement period, outdoor sound pressure levels were commonly observed in the 37-47 dBA range, while indoor levels were between 25-37 dBA. [11] These values are consistent with those observed near wind turbines at many locations around the world and fall within, or slightly above current noise limits in many jurisdictions.

Aercoustics further analyzed noise emissions from the Port Alma Wind Farm to include data in the low frequency and infrasonic domain. Average levels of low frequency noise within the home were reported to range from approximately 40 dBA at 30 Hz to 35 dBA at 150 Hz. [11] Infrasound levels were reported outside / inside of the residence as 70 dBG / 60 dBG at 2 Hz, 64 dBG / 53 dBG at 10 Hz, and 59 dBG / 51 dBG at 20 Hz. [11] These measurements are characteristic of wind turbine infrasound emissions and, due to the fact that they are well below the pure-tone hearing threshold of 85-90 dBG, are generally considered to have no potential impact on nearby residents. As presented in the work involving audibility of complex noises conducted in Japan, it is possible that perception still exists at these lower levels of infrasound and may result in disturbance. [8]

In a report commissioned by the Canadian Wind Energy Association (CanWEA), HGC Engineering presented findings on the potential impact of wind turbine generated infrasound observed at three wind farms across Canada and one in Poland. The first measurements were conducted at Pubnico Point Wind Farm in Nova Scotia. Results showed linear sound pressure levels of 60 dB over the range from 5 to 25 Hz as well as overall levels of 79 dBG at 60 m, 81 dBG at 330 m and 74 dBG at 700 m from Vestas V80 1.8 MW turbines. [12] The results were deemed inconclusive due to difficulty separating infrasonic components from the sound of the ocean. Another assessment performed at a wind farm in Ontario reportedly revealed better results. The measurements observed near a GE 1.5 MW turbine were as follows: 80 dBG at 60 m, 67 dBG at 300 m, and 59 dBG at a distance exceeding 3 km from the turbine. [12] One final data set was reported from the Castle River Wind Farm in Alberta. Based on the presented measurements, the report concludes that “levels on the order of 80 to 90 dBG would typically be expected close to the wind turbines, falling off with distance from the wind turbines”. [12] It is further stated that at the distances where residences are located, “infrasonic levels are low enough to not be of concern”. [12]

Although the HGC Engineering report dismissed a potential infrasound issue, it proceeded to discuss the audible amplitude modulation component - recognized as the swish-swish. Near a Vestas V80 1.8 MW turbine and a GE 1.5 MW turbine, the data demonstrated an amplitude modulation frequency of approximately 0.8 Hz over the range from 250 to 1000 Hz. [12] Consistent with the work of Leventhall [5], it is reported that amplitude modulation may be the primary source of annoyance. Psychoacoustic research indicates that the perceived loudness is closely related to the level of amplitude modulation, with the greatest perception of loudness occurring at modulation frequencies around 4 Hz. [12] Fluctuation strength is the psychoacoustic metric used to quantify low frequency sound modulation up to about 20 Hz.

More recent work commissioned by the Japanese Ministry of the Environment in 2009 was to specifically investigate the possibility of a wind turbine generated low frequency noise issue. Measurements were taken within 100-150 m of a wind turbine as well as inside the houses of four complainants at 240 m, 210 m, 350 m, and 680 m from the nearest wind turbine. In all cases, infrasound levels were dismissed as they were determined to be at least 20 dB below human hearing thresholds at distances 100-150 m from the turbines. [13] The results for low frequency noise were much different. In the houses of the complainants at 240 m and 210 m, sound pressure levels exceeded the human hearing threshold at frequencies of 40 Hz and 80 Hz (and above), respectively. Inside the houses located at a distance of 350 m and 680 m, low frequency noise was also observed to be above the hearing threshold at frequencies of 100 Hz and 125 Hz (or more), respectively. [13] In the three residences nearest to the turbines, a tonal component was observed in the 160 to 200 Hz range and was deemed to be the cause of complaints in the residences. [13] Although the tonal component was not measured in the house 680 m from the nearest wind turbine, the complainants there were still able to recognize a difference in the on-and-off operation of the wind turbine. This perceived difference was also observed in residences nearer to the wind turbines. The observer in the house 350 m from the wind turbine indicated that the sound was most unpleasant immediately after the turbine begins to operate (after shutdown) and that the sound is more unpleasant in weak winds than in strong winds. [13] This supports the suggestion that low frequency noise may subject observers to additional annoyance when ambient sound levels are at their lowest (night hours as an example) due to a greater perception of loudness.

Research has also been conducted in South Korea to more closely study the relationship between wind turbine size, speed regulation mechanism and the emitted infrasound and low frequency noise. The research involved two turbines – the first a 1.5 MW stall-controlled machine and the second a 660 kW pitch-regulated turbine. Pitch control has recently become the dominant form of wind turbine power regulation as it lends itself to quicker and smoother adjustments in reaction to changes in the wind profile at various atmospheric conditions. Measurements were conducted under summer and winter weather conditions and at multiple wind speeds according to IEC 61400-11. One important observation made was the faster rate of decay, with increasing distance from the turbine, of sound pressure levels at frequencies above 200 Hz than at lower frequencies. [14] The average rates of increase of L_{Geq} and L_{Aeq} as wind speed increased from 7-13 m/s were computed for both turbines. The results showed average rates of increase in noise generation with wind speed for L_{Geq} of 1.07 dB/(m/s) and 0.65 dB/(m/s) for the 1.5 MW and 660 kW turbines, respectively. The results for L_{Aeq} were less comparable as only the 1.5 MW turbine showed a linear relationship (1.25 dB/(m/s)). The 660 kW turbine revealed a sound pressure level-wind speed relationship that was more quadratic, with levels decreasing after about 10 m/s. [14] It was suggested that the much larger rate of increase of sound pressure level with wind speed for the 1.5 MW turbine is largely due to its stall control strategy. As the turbine blade approaches stall, strong turbulence is generated around the blade, thus increasing broadband noise generation. [14] This may be one of many reasons why modern wind turbines are moving to pitch-regulated speed control.

The Korean study also analyzed the recorded data for its potential to validate complaints about infrasound and low frequency noise generation. Hearing thresholds proposed by Watanabe and Møller, ISO 389-7, and Japanese guidelines for low frequency window and door rattle were all used as assessment metrics. The results indicated that for both the 1.5 MW and 660 kW turbines, sound at frequencies above 30 Hz could be perceived by the average adult and may lead to annoyance. [14] It was also found that, according to Japanese guidelines, noise in the 5 to 8 Hz range may result in complaints due to door and window rattle or similar. [14]

Møller & Pedersen of Aalborg University in Denmark are prominent researchers at the forefront of low frequency noise research. In 2011, they published an extensive review in the Journal of the Acoustical Society of America of previous work conducted in the area of wind turbine noise, as well as measurements and projections for the noise impact of future larger wind turbines. The study utilized data from 45 wind turbines with outputs varying from 75 kW to 3.6 MW. Emitted sound power levels, one-third-octave band spectra, tonality, directivity, indoor sound insulation, and more were all considered and the data was used to predict sound generation from the much larger wind turbines currently under development. [15]

Møller & Pedersen separated low frequency A-weighted sound power levels (L_{WALF} < 200 Hz) from A-weighted sound power levels (L_{WA}) and compared the measured values with turbine size. It was found that low frequency noise levels increased more rapidly with increasing turbine size than did A-weighted broadband noise levels. [15] It should be noted that, over the data sets from approximately 40 wind turbines of varying size and output power, levels varied by as much as 20 dB. To look more closely at trends due to wind turbine size, the data was divided into wind turbines smaller than 2 MW and those with output greater than 2 MW. Averages of the data in the two categories revealed that the frequency spectrums for larger wind turbines fall lower in the frequency domain than those within the class below 2 MW. Møller & Pedersen noted that although the difference between sound power levels of the smaller and larger categories of wind turbines was only 1.5-3.2 dB, the differences may be sufficiently large to have an impact on human perception. [15] As small changes in sound power level can result in a large increase in the required distance from a turbine, a change of 3 dB could require 41% more distance. [15] Analyzing more closely the four turbines for which infrasonic data was available, Møller & Pedersen found emitted sound power levels to be 122-128 dBG, which equated to sound pressure levels of 69-75 dBG at a distance of 150 m from the turbine. [15] This is consistent with the previously cited levels of wind turbine generated infrasound.

Møller & Pedersen also presented one of the few studies reviewed to have considered the directivity of wind turbine noise. The data was inconclusive as levels higher and lower than those measured at the reference position were observed in front of and to both sides of the turbines. [15] It was noted that although directivity was expected to be low at the lower frequencies, this was not observed in the data. Future work is recommended in this area, with an emphasis on taking measurements at a level more commonly observed at neighbouring residences and thus closer to the horizontal plane of the axis of the rotor than current ground level measurements. [15]

In addition to directivity, propagation distance was considered in the study by analyzing the required distance from the wind turbine to achieve a sound pressure level of 35 dBA - the Danish and Swedish standard. Results for 2.3-3.6 MW turbines varied significantly from 629 m to 1227 m. [15] It was observed that at these large distances from the turbines, the shift to the lower portion of the frequency spectrum became more prominent. Within this spectrum, the highest A-weighted, one-third-octave-band levels were often observed below 250 Hz. The authors concluded that "It is thus beyond any doubt that the low-frequency part of the spectrum plays an important role in the noise at the neighbours and that the low-frequency sound must be treated seriously in the assessment of noise from large turbines". [15] This is in stark contrast to work produced by many other researchers including, most notably, that of Leventhall which said that "low frequency noise is normally not a problem, except under conditions of unusually turbulent inflow air". [5]

Indoor sound pressure levels at neighbouring residences were analyzed at various combinations of turbine and room type. Low frequency spectra (20-250 Hz) for each combination were compared with ISO 389-7 hearing thresholds, revealing that a significant portion of the low-frequency sound is audible at the levels present in many of the turbine/room combinations. A few combinations resulted in audibility above 40 Hz, while most exceeded hearing thresholds from 100 Hz onward. [15] This further supports the earlier statement on the relevance of the low frequency noise component and its potential to cause annoyance for neighbours of wind farms.

On the basis that large (> 2MW) wind turbines generate sound lower in the frequency spectrum than their smaller (< 2MW) counterparts, Møller & Pedersen attempted to project the magnitude of a shift downward in the frequency spectrum for even larger class wind turbines up to 10 MW. An approximate shift of one-third of an octave down in frequency was identified between the mean noise levels of the small turbines (average output of 650 kW) to those of the larger turbines (average output of 2.6 MW). [15] Thus increasing turbine output by a factor of 4 appears to cause a shift down in frequency by one-third of an octave. As such, the authors' projections suggest that 10 MW class turbines of the future would demonstrate an additional shift of one-third octave down in frequency [15], further emphasizing the impact of the low frequency component.

3.7 Potential Health Effects Associated With Wind Turbine Noise

Numerous allegations have been made relating wind turbine noise to a negative health impact for humans and animals living in the vicinity of a wind farm. Minimal scientific data exists to validate this relationship, especially information that relates engineering acoustical data to the physiological data of medical specialists. The reality is that whether widespread or isolated, affected populations should be treated seriously and due diligence is required to mitigate any issues that may exist.

From an engineering perspective, the focus is often on audibility – if a source does not emit noise at levels that surpass hearing thresholds over the audible frequency range, then it is not considered to be problematic. While this provides some understanding, it cannot entirely rule out the potential impact that a sound could have in other ways. In the infrasound section above, it was reported that a sound may still be perceived at levels below audible limits. Recall as well that hearing thresholds are mean values and can have standard deviations of 5-10 dB within which large percentages of the population may fall. [6]

From a medical perspective hearing thresholds remain important for assessment, yet the focus shifts toward psychoacoustics, physiological effects, and the mechanisms through which these effects may reduce quality of life. Both the engineering and medical fields overlap when sound data is used to correlate what has been observed under medical examination with that which has been measured in the field. This is rarely performed in the available literature, but is imperative for future studies.

Frits van den Berg categorized the numerous factors that affect the potential impact of wind turbine noise best in his paper, “An overview of residential health effects in relation to wind turbine noise” [16]. Van den Berg divided the effects into three basic categories [16]:

- Acoustic
- Non-acoustic
- Personal and Social

The categories are reviewed independently in the sections that follow, and include results from reviews and studies conducted by researchers around the globe.

3.8 Acoustic Effects

Acoustic effects, or the risk thereof, due to infrasound and low frequency noise are frequently assessed by relating measured sound pressure levels to hearing thresholds defined by ISO 389-7, ISO 7196 (infrasound), Watanabe and Møller, Inukai, Nakamura and Tokita, etc. Comparisons and analyses using hearing thresholds are often performed in a trivial manner. They are typically graphical comparisons with a coincident yes / no decision on whether or not residents are likely to be at risk. Based on measured data and existing definitions for human hearing thresholds, many existing studies have therefore concluded that there is limited or no potential risk to human health. The conclusions from these assessments for wind turbine noise have been discussed Section 3.6.

A 2010 report by the Chief Medical Officer of Health of Ontario (CMOH) stated that "low frequency sound and infrasound from current generation upwind model turbines are well below the sound pressure levels at which known health effects occur" and acknowledges that "while some people living near wind turbines report symptoms such as dizziness, headaches, and sleep disturbance, the scientific evidence available to date does not demonstrate a causal link between wind turbine noise and adverse health effects". [17] Referring to the work of Møller & Pedersen [15], it would appear that low frequency sound pressure levels generated by wind turbines may in fact be audible and thus subject residents to annoyance, contrary to the CMOH report. Annoyance is ultimately the most commonly cited impact due to wind turbine noise and may in some cases lead to other effects such as sleep disturbance, irritability, fatigue, etc. [16]

In 2007, Pedersen et al. completed a field study in the Netherlands that selected residences within 2.5 km of wind turbine installations across the country. Of those who were contacted, 725 completed surveys were returned and the reported perception and annoyance data was analyzed relative to predicted A-weighted sound pressure levels at the respective properties. [18] A dose-response relationship was developed to assess potential for annoyance due to wind turbine noise in comparison to other known noise sources. The data revealed that wind turbine noise was found to result in higher proportions of the population experiencing annoyance than due to aircraft, traffic, railway or other industrial noise. [18] Only rail yards were determined to cause potential annoyance in higher proportions of the population. The results demonstrated the following percentages of annoyed respondents according to sound pressure level [18]:

- 35-40 dBA: 8% annoyed, 2% very annoyed
- 40-45 dBA: 15% annoyed, 5% very annoyed
- 45-50 dBA: 25% annoyed, 15% very annoyed

The last two categories are levels at which wind turbines are likely to operate in Ontario.

Pedersen et al. postulated that one reason for high levels of annoyance due to wind turbine noise is the irregular and unpredictable nature of the sound. [18] Wind turbine noise can vary dramatically over small periods of time as a result of atmospheric changes. This is perhaps most notable during overnight hours when background noise levels are at their lowest, but wind turbine noise levels may be higher. Van den Berg reported that atmospheric conditions at night result in variations in the wind velocity profile such that although weaker winds are present at the surface, winds may be stronger than predicted at hub height. [19] This means that greater sound pressure levels may be emitted at night, with less background noise to mask the sound than during the day. Respondents to the surveys distributed by Pedersen et al. also indicated that the sound became more dominant at night. [18] This effect is expected to be more critical for larger wind turbines with higher towers and greater wind speed distributions over the diameter of the rotor.

To more specifically consider the low frequency and infrasonic component, Møller and Lydolf made publicly available a 45 question survey for residents of Denmark who had allegedly experienced annoyance or discomfort due to wind turbine noise. Respondents to the survey provided a variety of descriptions for the perceived sound with terms including: "a deep humming sound", "constant and unpleasant", "coming from a distant engine or pump", "affects the whole body", "pressure in the ears", etc. [20] The authors note that in many cases the sound may be perceived by only a single member of a household. A solution to the issue is often not found as that person may be considered to be more sensitive to the noise or a special case.

Of those who responded to the Møller and Lydolf survey, nearly 82% reported experiencing the sound everywhere in their home, while only 28% expressed disturbance from the sound around the outside of their home. [20] Consistent with the work of Pedersen et al, the overnight interval (22:00-7:00) was noted to be the time during which a disturbance from the sound was most prominent. Also of interest were the methods in which the sound was perceived. Respondents indicated that 92.9% could hear the sound with their ears, with 16.2% saying that it was perceived with the ears but not as a sound. Also, 43.9% of respondents indicated that they could feel vibrations in the chest, stomach, legs or some other part of the body and 28.8% felt vibrations through buildings or other objects. [20] While Møller and Lydolf note that it cannot be certain that these perceptions or human body responses are related to an external sound, the results do show consistency in that the vast majority of respondents perceive the sound in a similar manner. [20] The authors of the study intend to follow-up on this work by performing a more detailed investigation with 22 randomly selected cases that will include blind tests and medical examinations.

Despite the fact that noise measurements continue to conclude that levels are far below the pure-tone thresholds at which humans may be subject to annoyance, many people still appear to be affected by wind turbine noise. Dr. Swinbanks of MAS Research Ltd. in the United Kingdom presented research on the audibility of low frequency wind turbine noise which may at least partially explain an additional reason for the discrepancy. Swinbanks focused on the nature of the acoustic signal relative to that of pure tone sinusoids. The concern is that using the conventional method, the rms energy of the measured acoustic signal is compared with that of the pure-tone sinusoids without taking into account the larger crest factor of the measured signal. [21] Since measurements of low frequency noise from wind turbines contain acoustic energy from various bandwidths, the crest factors may be higher than those for the pure-tone sinusoids, even if overall rms energy is lower. [21] Thus, through extensive analytical work, Swinbanks concluded that “a clean impulsive low-frequency signal can be audible at levels 8-11 dB below the threshold defined by mean square energy” and that as broadband noise is mixed with the clean spectrum, audible levels may be approximately 5 dB below defined hearing thresholds. [21] This could prove to be significant for wind turbine noise as sound pressure levels are relatively low but are often not far from audible levels.

There appears to be only limited research available for review on the perception of sound below audible levels; however Salt and Lichtenhan do present a physiological analysis of some mechanisms through which the ear responds to infrasound. Salt and Lichtenhan describe how the outer hair cells of the ear (sensitive to low frequency stimulation) are mechanically coupled to inner ear hair cells (not sensitive to very low frequency). It is shown that although 'hearing' may be insensitive to infrasound and some low frequency noise, the entire ear is not necessarily insensitive to the stimulation and the coupling of inner and outer hairs may transfer the perception through the ear. [22] Salt and Lichtenhan show that although very low frequency noise may not excite auditory nerve fibres, it may actually modulate the auditory response of the ear to higher frequency sounds. Further, the presence of high frequency sounds may actually suppress the response of the ear to infrasound. [22] Perhaps this change in perception could further support the observations of a greater noise impact when background noise is low in rural environments and at night.

It can therefore be concluded that whether it is audible or not, wind turbine noise has the potential to affect nearby residents, with more research being required in this area. Most importantly, more medical data needs to be correlated with measured sound pressure levels to allow for a true assessment of the potential for impact.

3.9 Non-Acoustic Effects

In addition to potential acoustic effects of wind turbine noise, other variables warrant discussion. Two of the more prominent non-acoustical effects to have emerged as strongly influencing whether an individual may be subject to annoyance from wind turbine noise are economic benefit and visibility. [16] [18] Those who benefit economically from wind turbines have been shown to be less likely to report annoyance or to be disturbed during their sleep by the emitted noise. [16] These individuals are also often those who live closest to a wind turbine or wind farm. A similar effect is observed with visibility. Levels of annoyance increased in dwellings where at least one wind turbine was visible. [18] The visibility of a wind turbine has been associated with negative feelings toward them and thus may increase awareness of the emitted noise.

3.10 Social and Personal Effects

The underlying opinion that an individual has formulated on wind turbine development or the manner in which developers move forward with installations, has also proven to have a significant impact on the perception of noise from a wind farm. Pedersen et al. confirmed work conducted in previous studies that indicated a strong correlation between a negative opinion of wind farm development and noise annoyance. [18] Some of this is involved with the fact that an individual may not support wind energy development or may not enjoy having them in a rural area where the lifestyle does not lend to large scale industrial facilities.

Many negative opinions have however been proven to be more a function of the perceived fairness in the manner in which the developer approached local issues. This lack of perceived fairness may make individuals more sensitive to any wind turbine generated noise. A 2010 report by the Chief Medical Officer of Health for Ontario recognizes these “concerns about fairness and equity” and states that “these factors deserve greater attention in future developments”. [17] In his report entitled *Why Turbine Noise Annoys*, Dick Bowdler indicates that numerous government and manufacturer miscommunications of facts about wind energy, a developed paranoia of wind turbines for residents who may be affected, and exaggerations and misnomers on both parts have resulted in an ideological feud with no solutions developed for those who are actually affected by the noise and need assistance. [23] In the study by Møller and Lydolf, only 60.1% of cases where residents had contacted authorities about a wind turbine noise issue resulted in a visit to address the issue, and 14.8% of complaints were rejected immediately. The study also indicated that noise measurements were only taken in 48.4% of the cases, of which measurement difficulties (i.e. separating background noise) were often cited as an issue. [20] The result was that only 7.8% of those who had complained to authorities in the Danish survey actually had their issue at least partly solved. [15] This is consistent with the reports of Bowdler, Pedersen et al. and the CMOH that increasing the perceived openness and fairness of a wind energy project is likely to result in a reduction in noise complaints. As Bowdler stressed though, the noise issue is real for some people and the focus needs to be on providing due diligence to the issue in order to work toward a resolution. [23] Perhaps this helps establish the case for continuous noise condition monitoring at wind farms. Continuous noise monitoring would offer the transparency for a community to verify that a farm is operating within acceptable limits, while also providing farm operators with data which may provide early insight into maintenance issues or strategies for the farm to increase its operational efficiency.

3.11 Regulatory Standards for Wind Turbine Noise

Given that wind farm development is relatively new to many regions of the world and much research is still required to define appropriate regulatory noise limits, current regulations are continuously evolving or may or may not exist in a given nation. It is important to recognize that even where a country or province may define certain regulations, there may be additional local by-laws which have arisen due to concerns in a specific region. A summary discussion and table of regulatory limits imposed across several Canadian provinces and nations around the world is provided in this section, current as of August 2011.

Prior to analyzing regulatory standards for specific jurisdictions, consideration should be given to the World Health Organization (WHO) Community Noise Guidelines. [24] WHO recommended outdoor noise limits are 50-55 dBA (day) and 45 dBA (night). WHO further recommends limits of 35 dBA (day) and 30 dBA (night) for noise inside residential dwellings to avoid the potential for annoyance and sleep disturbance, among other effects.

The Ontario Ministry of the Environment (MOE) is responsible for the definition of environmental noise limits in Ontario. The MOE has developed a specific set of regulations for wind turbines that defines separate scales of wind speed dependent noise limits for rural and urban areas as shown in Table 1. [25]

Table 1: Ontario Ministry of the Environment Noise Limits

Wind Speed (m/s) at 10 m height	4	5	6	7	8	9	10
Wind Turbine Sound Level Limits Class 3 Area, dBA	40.0	40.0	40.0	43.0	45.0	49.0	51.0
Wind Turbine Sound Level Limits Class 1 & 2 Areas, dBA	45.0	45.0	45.0	45.0	45.0	49.0	51.0

There is no distinction between day and night limits and with a peak limit of 51 dBA at a 10 m/s wind speed, there is certainly the potential for WHO recommended indoor limits to be exceeded both day and night. The 10 m/s peak limit may itself be insufficient as most wind turbines operate up to a cut-off wind speed in the range of 15-18 m/s. The MOE further recommends a setback distance of 550 metres from a wind turbine to the nearest receptor. [26]

The province of Quebec does not have specific wind turbine noise legislation. Note d'instruction 98-01 [27] provides general industrial noise guidelines and is applied to wind farms. Quebec does make a distinction between day and night limits, which further depend upon the type of receptor in proximity to the noise source. At a single-family residential property, limits of 45 dBA (day) and 40 dBA (night) are mandated.

Nova Scotia and New Brunswick have yet to develop standards specific to wind turbine noise. Investigative consultations have been completed by Jacques Whitford Ltd. [28] to determine best practices for wind farm siting that may be developed into provincial standards. At present, many municipalities in Nova Scotia have defined their own standards with noise limits in the range of 40-45 dBA and setback distances of 2-4 times the height of the turbine. New Brunswick has indicated that wind farms must follow the CanWEA-recommended wind speed dependent noise limits of 40-53 dBA. [29] It appears that further legislation may be under development but is likely to be similar to the CanWEA recommended limits.

Alberta is another province to distinguish between day and night limits. The Alberta ERCB uses a different approach than most regions as the day limit is determined as a function of the night limit. Night limits in Alberta range from 40-56 dBA depending on the location and number of nearby dwellings. The day-time limit is defined as the specified night limit plus 10 dBA (i.e. 50-66 dBA). [30] Day limits in Alberta are in effect until 10pm as opposed to 7pm in Quebec. Where the potential for low frequency noise exists, the Alberta ERCB mandates that both A and C weighted measurements be analyzed. The province recognizes that low frequency noise may result in increased annoyance and has therefore implemented a penalty of 5 dBA from the limit if a prominent low frequency component is found to exist. Low frequency noise is said to be prominent if dBC – dBA is greater than 20 dB. [30]

British Columbia has specific documentation on wind power projects which limits noise emissions to 40 dBA (day or night). [31] Along with Quebec, this would appear to be one of the toughest in Canada as the limit is independent of wind speed.

In the United States, consistent legislation across larger jurisdictions is often not present or is difficult to find. The two states with the greatest number of wind turbines, California and Texas, do not appear to have legislation specific to wind turbine noise. Michigan has provided guidelines of 55 dBA (day and night) in addition to a setback distance of 1.5 times the turbine height [32], however some counties have decided to implement tougher regulations due to rising local concerns. The state of Massachusetts has defined regulatory limits similar to those in much of Canada, with a noise limit of ambient plus 10 dBA. [33] Oregon implemented a similar limit where ambient is assumed to be 26 dBA unless proven otherwise [34], making it one of the toughest regulations in North America. Oregon further enforces a setback distance of 350 m for consenting owners and 1000 m for non-consenting owners. [34]

Regulations in Europe also vary considerably. Denmark has imposed different limits for open land versus residential with the lowest being 37 dBA and 39 dBA at 6 m/s and 8 m/s wind speed. [35] The Danish EPA regulated low frequency noise until the publication of its current standard in 2006 when it decided that overall noise limits were sufficient to ensure that the low frequency noise present at defined sound pressure levels would not be of concern. There still appears to be an infrasound limit of 85 dBG.

Germany mandates 45-55 dBA during the day and 35-40 dBA at night [36], setting it below the Ontario standard and likely in coherence with WHO guidelines for indoor noise limits at night. Limits in the United Kingdom [37] are similar to those in

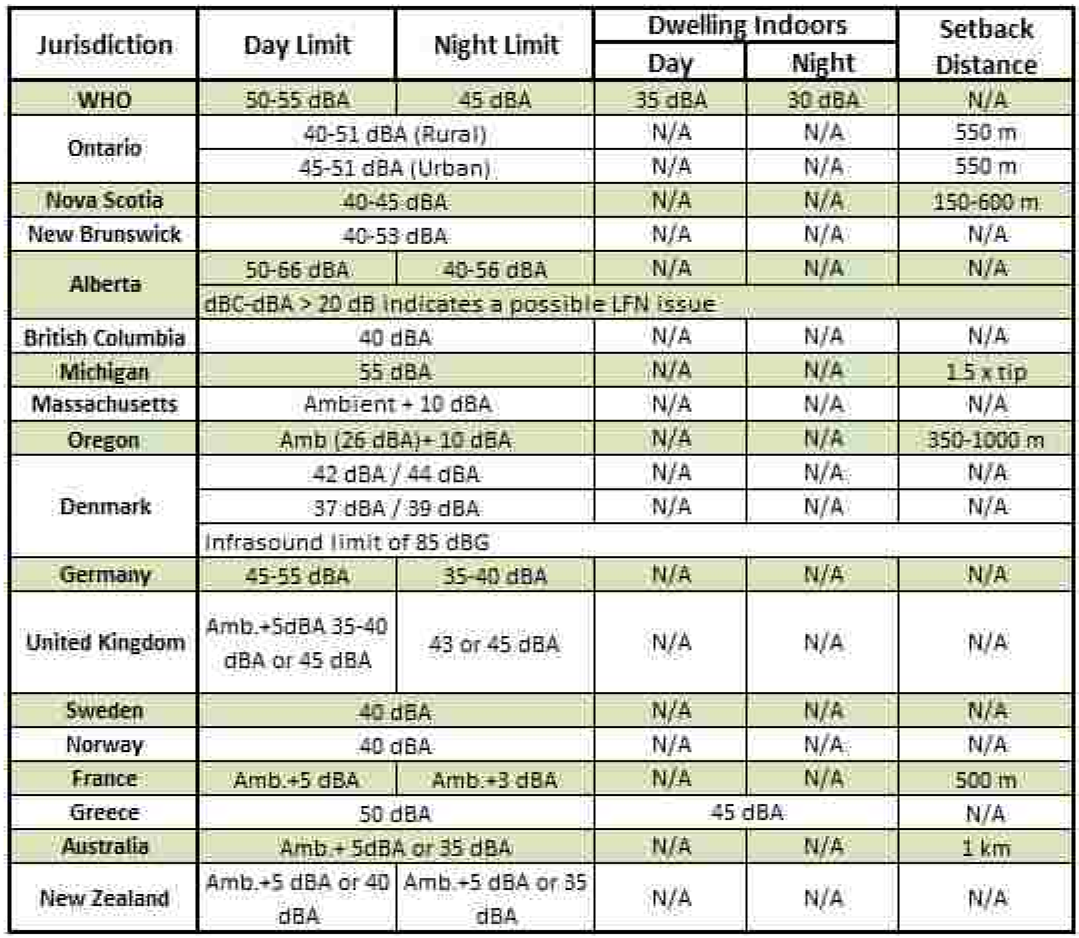
Ontario while Sweden [38] and Norway [38] have defined 40 dBA as the limit day or night (comparable to British Columbia). France mandates ambient plus 5 dBA (day) or plus 3 dBA (night) while recommending a 500 m setback distance. [38] Despite being well above WHO recommended guideline, Greece is perhaps the only country to define an indoor limit, at 45 dBA. [38]

Another region of rapid wind power development is Australia and New Zealand. Australia has perhaps the most stringent wind turbine noise regulations in the world at ambient plus 5 dBA, or 35 dBA. [39] The Australian standard further recommends a setback distance of at least 1000 metres. Much like Australia, New Zealand developed their most recent standard by taking WHO guidelines into special consideration. Although still one of the toughest in the world, the New Zealand limit is a little higher than Australia at ambient plus 5 dBA, or 40 dBA (35 dBA in special areas). [40] Both the Australian and New Zealand standards make note of the potential for annoyance by low frequency noise and infrasound yet no further limits are imposed.

It can be concluded that the standards of Australia, New Zealand and Oregon are presently the toughest in the world and are the only ones which appear to have been developed with the recommendations of WHO held at the forefront. It is interesting to note that these jurisdictions all recommend setback distances of at least 1000 metres as opposed to those in the range of 300-500 metres in many other parts of the world. This is representative of the increased distance required not only to achieve sufficiently low sound pressure levels, but also of that believed to be required to reduce the potential impact of low frequency and infrasonic noise. These long setback distances are only ‘recommended’ as the decay of sound pressure levels with distance may necessitate further setbacks in some regions.

One final important point about regulatory standards is that each jurisdiction employs similar acoustic predictive methods for wind farm siting, however only a few necessitate that predicted noise levels be verified after installation of the wind turbines. The majority of jurisdictions appear to only require verification upon receipt of a complaint or concern. Table 2 summarizes the standards discussed.

Table 2: Summary of Canadian and Global Wind Turbine Noise Regulations



Jurisdiction	Day Limit	Night Limit	Dwelling Indoors		Setback Distance
			Day	Night	
WHO	50-55 dBA	45 dBA	35 dBA	30 dBA	N/A
Ontario	40-51 dBA (Rural)		N/A	N/A	550 m
	45-51 dBA (Urban)		N/A	N/A	550 m
Nova Scotia	40-45 dBA		N/A	N/A	150-600 m
New Brunswick	40-53 dBA		N/A	N/A	N/A
Alberta	50-66 dBA	40-56 dBA	N/A	N/A	N/A
	dBC-dBA > 20 dB indicates a possible LFN issue				
British Columbia	40 dBA		N/A	N/A	N/A
Michigan	55 dBA		N/A	N/A	1.5 x tip
Massachusetts	Ambient + 10 dBA		N/A	N/A	N/A
Oregon	Amb (26 dBA)+ 10 dBA		N/A	N/A	350-1000 m
Denmark	42 dBA / 44 dBA		N/A	N/A	N/A
	37 dBA / 39 dBA		N/A	N/A	N/A
	Infrasound limit of 85 dBG				
Germany	45-55 dBA	35-40 dBA	N/A	N/A	N/A
United Kingdom	Amb.+5dBA 35-40 dBA or 45 dBA	43 or 45 dBA	N/A	N/A	N/A
Sweden	40 dBA		N/A	N/A	N/A
Norway	40 dBA		N/A	N/A	N/A
France	Amb.+5 dBA	Amb.+3 dBA	N/A	N/A	500 m
Greece	50 dBA		45 dBA		N/A
Australia	Amb.+ 5dBA or 35 dBA		N/A	N/A	1 km
New Zealand	Amb.+5 dBA or 40 dBA	Amb.+5 dBA or 35 dBA	N/A	N/A	N/A

3.12 Opportunities to Expand on Existing Work

The material reviewed in the sections above indicates that significant research has already been completed on wind turbine noise. Despite this, many of the reports and studies are found to be inconclusive and therefore present great opportunities to improve understanding of this important subject. Topics requiring further focused and detailed studies include: sound propagation behaviour, directivity, low frequency noise, infrasound, appropriate analysis techniques for infrasound, noise source identification, and correlation of engineering data with medical data.

Sound propagation behaviour is important as the majority of current studies present measurements at the IEC 61400-11 reference distance or at arbitrary distances further out. This is effective for the assessment of overall levels but is insufficient to fully understand the propagation of the sound over long distances as it does not identify the relevant components of the noise at specified distances. Sound propagation studies also present an opportunity to validate prediction models used to site wind farms and establish regulatory setback distances. A study of sound propagation at various wind speeds as measured in 100 m increments from the base of the turbine to the MOE setback distance is presented in this report.

Directionality is rarely considered in the existing work, but is an important concept as there may be significant differences in noise propagation at various angles to the turbine. Not only can sound pressure levels vary at different angles, but the relevant components of the noise, low versus high frequency, may change as well. Directionality therefore presents a great opportunity to enhance understanding of the characteristics of wind turbine generated noise. It is studied in detail at a 100 m and 200 m radius and various wind speeds in this report.

Low frequency noise and infrasound are perhaps the most misunderstood aspect of wind turbine noise. These topics are often the greatest cause for public concern, yet are dismissed by the majority of wind turbine noise experts due to measured sound pressure levels being sufficiently low to not be of concern. It was shown in the sections above that some researchers have concluded that low frequency wind turbine noise has the potential to cause annoyance, but more work is required to confirm. There are two opportunities here. The first is to analyze generated low frequency and infrasound levels to determine whether they are likely to be audible at current setback distances. The second is to develop improved metrics for the assessment of low frequency noise and infrasound by improving understanding of the mechanisms through which the noise is perceived by humans or livestock. Both are investigated in this report to offer an improved understanding of the characteristics of low frequency noise, the opportunities to use different analysis techniques, and the potential audibility of the low frequency component.

As important as understanding how wind turbine noise is perceived is how it is generated. Many existing studies have identified the broadband sources of wind turbine noise and theoretical models developed to predict generated levels in the design phase. Limited understanding exists however on the mechanisms of low frequency wind turbine noise generation. Noise source identification studies should be conducted to identify the key sources at low frequencies. This presents numerous opportunities for wind farm operators to gain further understanding of their machines as well, across the entire frequency spectrum. This could help farm operators become aware of maintenance issues before they fully develop or identify strategies to improve system efficiency. Noise source identification is beyond the scope of this study, but is highly recommended for future work.

Finally, to offer due diligence to the potential for a health-related wind turbine noise issue, engineering data must be correlated with medical assessments and reports. This is a crucial step that is not done in the existing work. It is beyond the scope of this study, but is required in the near future as it is the missing step to accurately assess whether there is a risk of annoyance or disturbance with current noise regulations. Cooperation with medical experts also facilitates the assessment of whether there is a potential impact for the broader population or a limited hypersensitive portion of it.

Numerous opportunities therefore remain to improve current knowledge of wind turbine noise. The Chapters that follow enhance existing knowledge of the characteristics of the noise source and begin to answer many of the questions that have arisen in this Chapter.

CHAPTER IV

EXPERIMENTAL METHODOLOGY

The present study is the first detailed wind turbine noise investigation performed as part of the recently established Wind and Renewable Energies Centre of Expertise (WRECE) at the University of Windsor in partnership with Bruel & Kjaer. Given this, it was necessary to define the scope of the experiment such that it allowed for the completion of an overall noise study, while considering the low frequency spectrum in greater detail. These experimental and analytical methods were defined to improve understanding of wind turbine noise across the entire frequency spectrum. It will be shown that a large portion of the noise falls within the low frequency domain and therefore becomes the primary focus of the study.

4.1 Measurement Standards

Many different measurement procedures are employed for the characterization of wind turbine noise with the majority of governmental regulations and scientific researchers using the methods of IEC 61400-11 or a variation of this standard.

IEC 61400 -11 for Wind Turbine Generator Systems defines the procedures and guidelines for acoustic measurements of wind turbines of any size as well as for both horizontal and vertical axis configurations. The standard is intended to be used by manufacturers, site planners/developers, site operators and consumers to ensure that wind turbines are built and maintained within the range of acceptable noise levels at a given location. IEC 61400-11 details recommended procedures for acoustic measurements where microphones are located at ground level at a reference distance equal to the height of the tower plus half the rotor diameter. [41] Detailed measurement procedures can be referenced in the standard. A selection of key elements follows: [41]

- For the equivalent continuous A-weighted sound pressure level:
    - A type 1 sound level meter according to IEC 60804
    - Microphone diameter less than 13mm
- For the 1/3 octave band spectra:
    - Constant frequency response for 45 - 11200 Hz
    - Filters must meet IEC 61260 Class 1 requirements
    - If low-frequency noise is measured the range must be expanded
- For the narrow band spectra:
    - Must meet IEC 60651 type 1 for the 20 – 11200 Hz range
- Mounting of the microphone:
    - At the centre of a hard circular board at least 1.0 m in diameter and 12 mm thick (wood) or 2.5 mm thick (metal)
    - Primary windscreen is mandatory consisting of half of an open cell foam sphere approximately 90 mm in diameter
    - Secondary windscreen may be used as required (and detailed in the standard)
- Calibrator:
    - The entire system must be calibrated before and after measurement
    - The calibrator must meet IEC 60942 class 1

- Anemometer:
    - Max. deviation of +/- 0.2 m/s over the wind speed range of 4 – 12 m/s
- Wind direction transducer:
    - Accurate to +/- 6°
- Other Instrumentation:
    - Temperature accurate to +/- 1°C
    - Atmospheric pressure accurate to +/- 1 kPa.

IEC 61400-11 also provides information on data reduction techniques and the data required to be included in a final report, including sound power level, 1/3 octave level, and tonality at 6, 7, 8, 9, and 10 m/s. [41]

Other measurement metrics such as low-frequency noise, infrasound, and directivity are not mandatory but may be reported as desired. Annex A of IEC 61400-11 recommends that G-weighting defined by ISO-7196 be used when infrasound is suspected to exist. [41] Annex A further notes that low frequency noise may not be properly quantified by A-weighting and may therefore still be a source of annoyance. Where the difference between A-weighted and C-weighted sound pressure levels is greater than 20 dB, it is recommended that 1/3 octave bands down to 20 Hz be considered. [41]

Although IEC 61400-11:2006 is one of the most widely used acoustic measurement standards for wind turbine noise, it has fallen under criticism for some deficiencies, and at the time of this writing, a new version of the standard is under review. Some expected changes include a move from wind speed measurements taken at a height of 10 metres to the data instead to be recorded from the nacelle anemometer, and a change from one minute averaging for A-weighted levels to a 10 second averaging period.

In addition to the IEC standard, other relevant standards are prescribed by the American Wind Energy Association (AWEA) and the Measuring Network of Wind Energy Institutes (MEASNET). MEASNET is a network of research institutes from around the world who are working together to establish common measurement techniques for the wind energy industry. The MEASNET Acoustic Noise Measurement Procedure [42] is based primarily on IEC 61400-11 with minor adjustments and/or measurement guidance offered. One aspect to note is that similar to the proposal for the revised IEC standard, MEASNET recommends a shorter averaging period of 10 seconds. [42]

The equipment used in this study was supplied by Bruel & Kjaer, and meets the specifications of the IEC 61400-11 standard. This complete wind turbine noise measurement and monitoring system has the ability to combine acoustic measurements, atmospheric conditions taken at the nacelle (or a separate weather station), and wind turbine operational data to provide a real-time assessment of wind turbine noise emissions over the range of wind speeds. This allows for easy measurements of the wind turbine noise in complete accordance with the IEC 61400-11 guidelines. The complete integrated system was not used in this investigation as an interface with the wind turbine control system was not permitted by the wind farm operator. As such, the IEC standard was used as a guideline and not applied in total compliance in this study. The complete Bruel & Kjaer wind turbine noise monitoring system is shown in Figure 4.

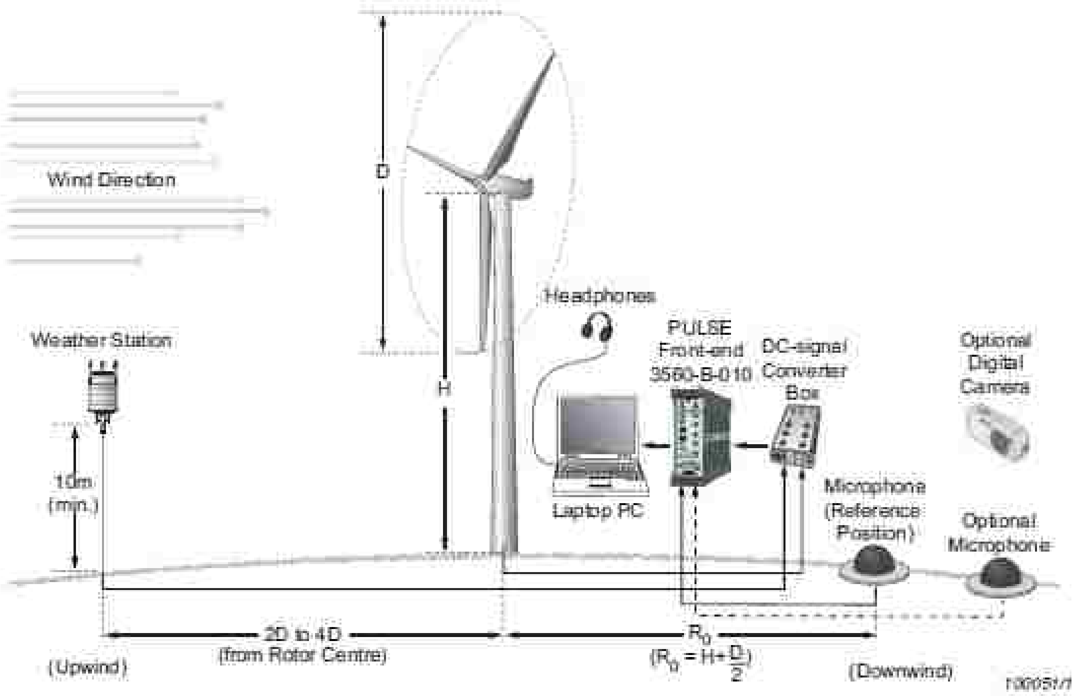


Figure 4: Bruel & Kjaer Wind Turbine Noise Monitoring System [43]

4.2 Design of Experiment

The field experiment was configured as an overall characterization of wind turbine noise where the low frequency spectrum did not become the primary focus until post-processing and analysis. Relevant measurement locations were selected such that the overall sound level investigation could develop scientific understanding of the nature of wind turbine noise directionality and propagation distances. Directionality and propagation distance have been explored in previous studies, yet few have specified a design of experiments where measurements are recorded at the same locations on different days and varying wind speeds. Having good access to wind turbines and lands surrounding for the measurement of noise is both essential and the greatest challenge. This is complicated by the fact that yaw adjustments to realign the turbine for maximum use of the wind resource can happen quickly in the field.

For this study, the experiment was defined such that as many of the following measurements could be completed as possible. All measurements were completed at ground level with the target to collect noise data on low (5 m/s), medium (8 m/s) and high (12 m/s) wind speed days.

- Downwind sound propagation from 100 m - 600 m, in 100 m increments
- Directionality at a 100 m radius, with 8 locations in 45° increments
- Directionality at a 200 m radius, with 8 locations in 45° increments

Due to some of the aforementioned challenges, it was not always possible to collect all of the data desired. It was initially intended that measurements would be completed for wind turbines of varying sizes. The end result was that measurements were only completed at 2.3 MW wind turbines in a single wind farm located in south-western Ontario. Select specifications for the 2.3 MW turbines are shown in Table 3.

Table 3: 2.3 MW Wind Turbine Specifications

Wind Turbine Specifications	
Nominal Power	2.3 MW
Hub Height	80 m
Rotor Diameter	93 m
Blade Length	45 m
Rotor Speed	6-16 rpm
Cut-in Wind Speed	3-5 m/s
Nominal Power Wind Speed	13-14 m/s
Cut-out Wind Speed	25 m/s
Rotor Weight	54 tons
Nacelle Weight	82 tons
Tower Weight	162 tons

One of the challenges to perform noise measurements in the months of March to June, 2012 was that these months experienced relatively low wind speeds. In fact, it was one of the lowest average wind speed seasons that the wind farm had experienced, making it difficult to get the variety of desired data at the target wind speeds. Ultimately, the following measurements were completed with wind speeds reported as the hub height equivalent, according to the power law wind profile.

- 6.5 m/s wind speed
    - Directionality at 200 m, with 8 locations in 45° increments
    - Downwind sound propagation 100 m, 200 m, 300 m
- 7 m/s wind speed
    - Directionality at 100 m, with 8 locations in 45° increments
    - Directionality at 200 m, with 4 locations in 45° increments
- 8 m/s wind speed
    - Downwind sound propagation 100 m – 550 m in 100 m increments
- 9 m/s wind speed
    - Downwind sound propagation 100 m – 600 m in 100 m increments
- 15 m/s wind speed
    - Directionality at 100 m with 8 locations in 45° increments
    - Downwind sound propagation 100 m, 200 m, 300 m at turbine A
    - Downwind sound propagation 100 m, 200 m, 300 m at turbine B

4.3 Equipment and Instrumentation

In order to complete the testing defined in the previous section, a range of equipment supplied by Bruel & Kjaer was employed. A list of the equipment used is detailed in Table 4.

Table 4: Test Equipment List

Equipment Name	Qty
LAN-XI Data Acquisition Hardware Type 3660	1
LAN-XI Battery Module Type 2831-A	1
1/2" Prepolarized Free-Field Microphone Type 4189-A-021	2
Sound Calibrator Type 4231	1
90 mm Hemispherical Foam Primary Wind Screen	1
Secondary Windscreen for Boundary Layer Microphone UA-2133	1
PULSE 16 and PULSE Reflex	1
10 m BNC Cable	2
LAN Cable	2
Davis Instruments Vantage Pro2 Wireless Weather Station	1
Weather Station Tripod	1
Laptop with Charger and Power Inverter	1
Garmin eTrex 20 Handheld GPS	1
Digital Camera	1

The Bruel & Kjaer LAN-XI data acquisition system is well suited for field measurements as it is light and compact making it easy to carry in a backpack. Its accompanied lithium-ion battery module provided enough power to perform over seven hours of measurements. Figure 5 displays the laptop, backpack containing LAN-XI, and wind screen in the field.

Figure 5: Wind Screen and Laptop in the Field

The Bruel & Kjaer Type 4189-A-021 microphone was selected as a high sensitivity IEC 61672 Class 1 microphone and is designed for application where high precision free-field measurements are required. Its specifications and calibration data are shown in Table 5.

Table 5: Bruel & Kjaer Type 4189-A-021 Specifications

Bruel & Kjaer 1/2" Prepolarized Free-field Microphone Type 4189-A-021	
Nominal Sensitivity	50 mV/Pa
Frequency Range	6.3 Hz - 20 kHz
Dynamic Range	14.6 - 146 dB
Temperature	-30 to +150°C
Serial Number	2779822
Calibrated Sensitivity	45.3678 mV/Pa
Serial Number	2779823
Calibrated Sensitivity	48.6668 mV/Pa

As specified by IEC 61400-11, the microphone is to have both a primary and secondary wind screen for ground level wind turbine noise measurements. Both were provided by Bruel & Kjaer with the primary wind screen being a conventional 90 mm foam hemisphere and the secondary wind screen being a 0.75 m diameter hemispherical dome which mounts on a 25 mm thick wooden base having a 1 metre diameter.

Figure 6: Secondary Wind Screen in the Field

The secondary wind screen is designed to isolate the microphone from wind induced noise such that the wind turbine generated noise is measured without the effects of the wind. The effectiveness of this wind screen is shown in Figure 7.

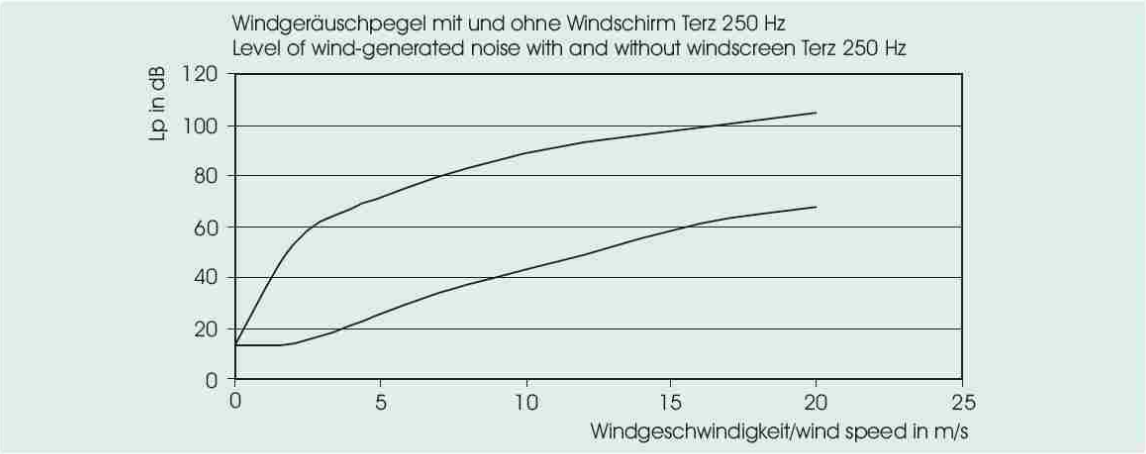


Figure 7: Effectiveness of the Secondary Wind Screen

In addition to the equipment used for the measurement of the noise, the measurement of the atmospheric conditions is also of critical importance as wind speed and turbine noise generation are directly related. A more detailed discussion of the wind speed dependency of turbine noise is presented in Chapter 5, while the equipment used is specified here. Most standards recommend that meteorological data is recorded either from a weather station with the anemometer located at a 10 m height or directly from the nacelle. In the absence of nacelle data or a costly portable 10 m tower, a more affordable weather station was used with the anemometer located approximately 2.5 m above the ground. It is recognized that this was not ideal as conditions close to the surface may result in inaccurate weather data due to a more fluctuating signal. The weather station used was a Wireless Vantage Pro2 by Davis Instruments. The specifications for the weather station are detailed in Table 6 and a photo of the deployed weather station is given in Figure 8.

Table 6: Vantage Pro2 Weather Station Specifications

Vantage Pro2 Weather Station				
	Resolution	**Range**	**Accuracy**	**Interval**
Barometric Pressure	0.01 kPa	54-110 kPa	+/- 0.1 kPa	1 min
Temperature	0.1°C	-40-+65°C	+/- 0.5°C	10 sec
Humidity	1%	1-100%	+/- 3-4%	1 min
Wind Speed	0.4 m/s	1-80 m/s	+/- 1 m/s	2.5 sec
Wind Direction	1°	0-360°	+/- 3°	2.5 sec

Figure 8: Weather Station and Equipment Set-up

4.4 Experimental Procedure

Given the relative simplicity of the experimental setup, the ability to repeat the measurements with similar operational conditions should not be difficult. The experimental procedure is provided as follows:

1. Set-up weather station such that the anemometer is pointing north at a height of 2.5 metres
2. Load PULSE LabShop on the laptop and configure project file as desired
3. Mount Type 4189 microphone on wooden wind screen base
4. Connect the LAN-XI to the microphone and laptop and ensure communication with PULSE LabShop
5. Calibrate microphone with Type 4231 sound calibrator
6. Record calibration signal in PULSE LabShop
7. Remove calibrator and install primary and secondary wind screens

8. LAN-XI and extra cable length can be stored in a backpack for ease of travel through the field while carrying the laptop
9. A helper is required to carry the wind screen assembly between locations
10. Mark the location of the base of the turbine on the GPS
11. Proceed to the desired measurement location by monitoring the distance from the base of the turbine on the GPS and orienting yourself at the correct angle (for directional measurements)
12. At each location, position the wind screen so that the microphone is directed at the wind turbine
13. Five 30 second measurements are recorded at each measurement location using PULSE LabShop
14. Ensure that there are no external noise sources such as road vehicles, airplanes, tractors, etc. over the course of the measurements
15. Once all measurements are complete, the equipment is carefully packed
16. Weather data must be exported from the wireless weather station display and is saved in 1 minute intervals (as an average for varying measures)
17. Post-processing is performed using the combined efforts of PULSE LabShop, PULSE Reflex and Microsoft Excel

In post-processing, a number of metrics are employed to develop understanding of the overall characteristics of wind turbine noise and to determine the potential significance of the low frequency component. PULSE LabShop and Reflex are used to apply CPB and FFT numerical methods to linear, A-weighted, and C-weighted data sets. Signal statistics are also performed within PULSE to reveal information about the variation of wind turbine noise. The 1/3 octave CPB identifies general trends in wind turbine noise at various wind speeds, and offers a means of comparison with hearing thresholds. The 1/3 octave data also permits the G-weighting filter to be applied in Excel in order to assess the significance of the infrasound component. The 1/24 octave CPB allows for a more detailed analysis of the narrow frequency bands that are most prominent. This is particularly relevant at the low frequencies of interest where differences between frequencies may be lost in the analysis of wider frequency bands. This increased understanding of low frequency noise when correlated to wind speed data is critical to assessing its potential significance.

Overall sound pressure levels at each measurement location and wind speed are exported to Excel for further analysis. This allows for a more general view of the variation between signals at a single measurement location as well as for plots to be generated comparing sound pressure levels at different measurement locations and wind speeds. Histograms demonstrate sound propagation behaviour while polar plots identify the directional nature of the noise. When these plots are created using various weighting schemes, the regions where low frequency noise is more prominent can be identified. The relative significance of the low frequency component is further assessed by the dBC-dBA > 20 dB metric. Finally, comparisons between measured signals and audible limits for humans and animals are made that allow for the true potential impact to be assessed.

CHAPTER V

ANALYSIS OF DATA AND OBSERVATIONS

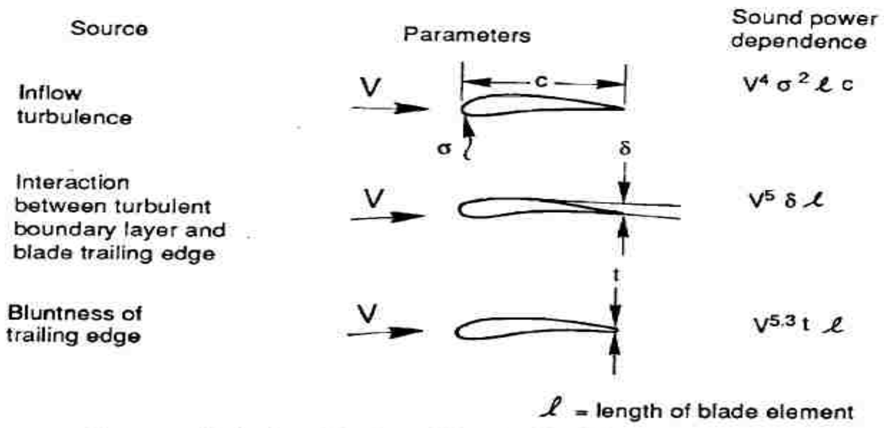
This chapter presents the analytical results used to reveal some interesting observations on the nature of wind turbine noise. General trends are developed to identify the prominent characteristics of the noise, its wind speed dependency, the significance of the low frequency component, and the relevancy of generated levels of infrasound. These observations are shown to often be related to one another, further emphasizing the complexity of wind turbine noise while leading to new perspectives on the behaviour of the noise source.

Using the handheld GPS as a field positioning guide, sound propagation and directional measurements were conducted on four separate days and at five wind speeds over a period of approximately two months, as defined in Chapter 4. The work presented a number of challenges as environmental conditions change rapidly in the field and land access did not always allow for the desired measurements to be recorded. Further, given the quiet background noise levels in the rural measurement environment, the affect from other noise sources including airplanes, tractors and automobiles can result in erroneous data or masking of the wind turbine noise. Despite the challenges, several good data sets were recorded with consistent analytical results that converged on expected trends.

Without an appreciation for the nature of wind turbine noise in the field, the generated sound pressure levels can be determined to be quite low and perhaps even insignificant. This is perhaps the greatest challenge with wind turbine noise as the detailed data, not simply overall levels, may not always be analyzed in sufficient detail to assess whether there is in fact a potential impact, especially at low frequencies. In this study, subjective field evaluations did reveal that, although quiet, wind turbine noise was in fact audible at a distance of 600 m from the turbine. It was also perceived to be highly directional with the sound at some angles from the axis of the nacelle observed to have greater potential for annoyance than others. The sections that follow will consider the objective data and analytical techniques in great detail and will examine the data trends to make the necessary conclusions. Hearing thresholds, audibility and the subjective field evaluation will be discussed in Chapter 6 – Perception and Potential Impact.

5.1 Atmospheric Conditions

There are a number of challenges involved with obtaining good measurements of wind turbine noise – not least are prime environmental conditions for turbine operation. Most turbines operate at hub height wind speeds of 4 m/s to 18 m/s or approximately 15 km/h to 65 km/h. This range is fairly common but can vary between models and MW classes. With the intricate pitch control systems of modern wind turbines, rotor speed is maintained relatively constant over the higher end of the wind speed range. Environmental conditions are constantly changing and atmospheric turbulence is always an issue, so wind speeds at a given site can change dramatically within a measurement period of only a few seconds. This has an immense impact on wind turbine noise and some theoretical models have shown as high as a fifth power relationship between wind speed and the generated sound power level. [44] Figure 9 shows this wind speed dependency for three mechanisms of wind turbine noise generation.



Sources of wind turbine broadband noise [Grosveld 1985]

Figure 9: Select Noise Generation Mechanisms and Critical Variables [44]

Over the measurement period for this study, the wind farm was experiencing the lowest average wind speed for spring months since it began operation. Wind farms are at the mercy of the wind and with such high wind speed dependency, as are generated noise emissions. For the 2.3 MW turbines under study, the cut-in wind speed is approximately 4 m/s with nominal power output at 13-14 m/s. Over the four days when noise measurements were completed, wind speeds were recorded to be approximately 7 m/s, 8 m/s, 9 m/s and 15 m/s at hub height. Without nacelle data or a tachometer it is difficult to determine rotor speed accurately. Rotor speeds were estimated to be 10-12 rpm while the measurements were being recorded but naturally varied to some degree with wind speed.

The wind speeds reported here and used throughout this report reflect estimated hub height values. These estimates are derived using wind speeds measured with the weather station at a height of 2.5 m and extrapolated by assuming a power law wind speed profile. The power law profile is widely used in the wind energy industry and is defined as Equation 3. [9]

$$\boldsymbol{U_{hub} = U_{ref} \times \left({h_{hub}}/{h_{ref}} \right)^{\alpha}} \tag{3}$$

U_{hub} and U_{ref} are the wind speeds at the hub height (h_{hub}) and measured reference height (h_{ref}), respectively. Alpha is a highly variable roughness coefficient but for fields such as those where the measurements were recorded, 0.143 is a common value. The weather station reported wind speed data in one minute average in addition to the peak wind speed observed during the averaging period. Figure 10 displays the measured wind speed data for one measurement day. The relatively small fluctuations in wind speed should be noted over the short time periods relative to the larger shifts in wind speed observed as the day progressed. There appears to be two dominant 'sustained' levels; one over the range of about 40 to 120 minutes and the other from 140 to 260 minutes. The solid lines represent ten-minute moving averages of the measured average wind speeds and peak wind speeds.

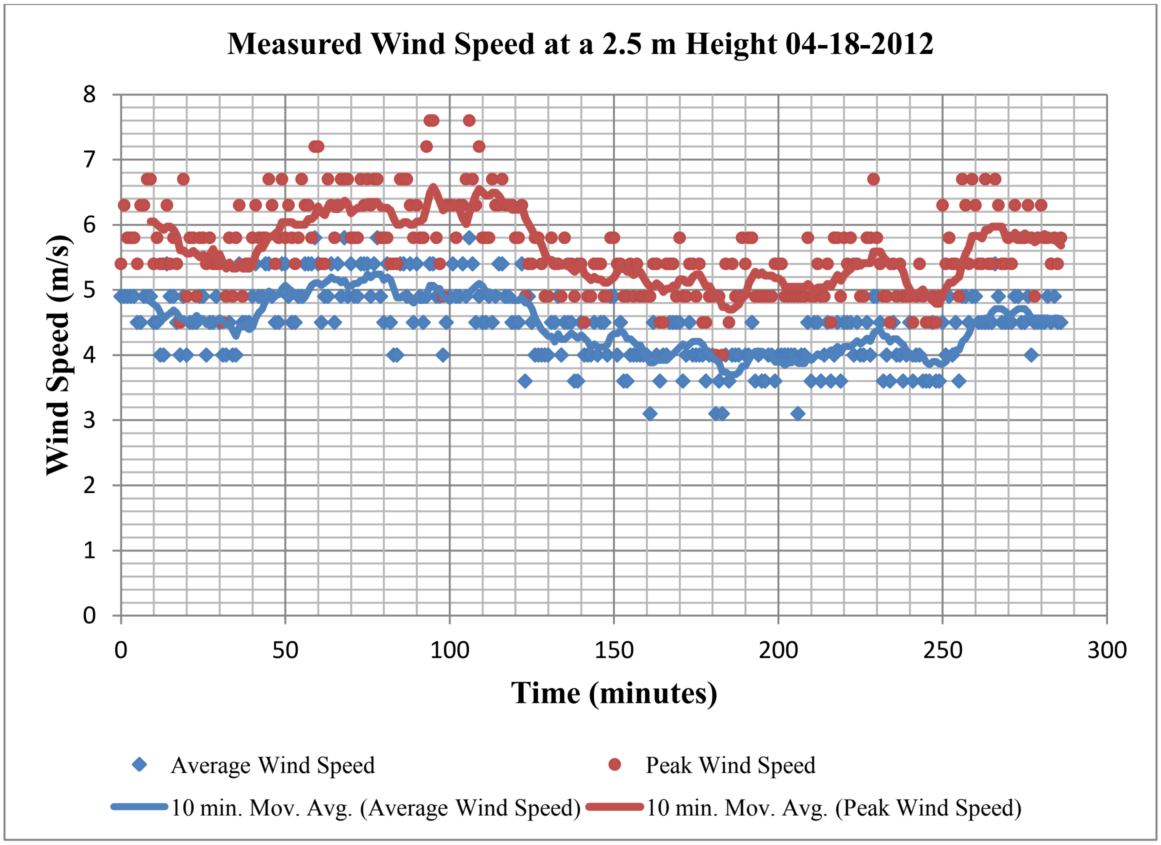


Figure 10: Measured Wind Speed Data at a 2.5 m Height

Given that the power law is simply a ratio raised to an exponent, the plot for estimated hub height wind speed takes the same general form, but at higher values. A hub height wind speed plot for a different day is shown in Figure 11. The wind speed is observed to fluctuate far more over short periods of time on this day, but a general shift to a lower 'sustained' wind speed later in the day does occur. These large fluctuations over short time periods will have an impact on measured noise emissions. An observer in the field can notice wind turbine generated noise levels increasing and decreasing over the span of a 30 second measurement. Because of this, subsequent measurements were sometimes delayed a few minutes in anticipation that the wind would rise again. Additional detailed wind speed and meteorological data can be referenced in Appendix A.

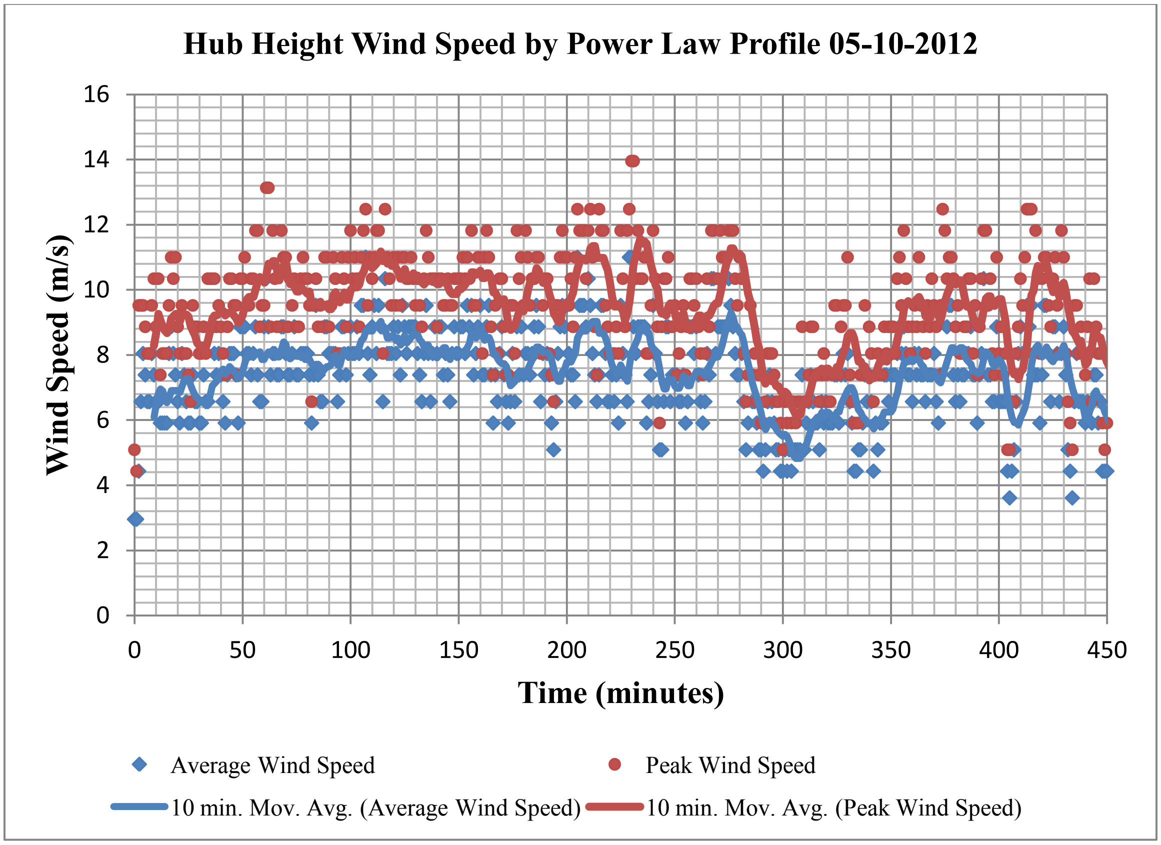


Figure 11: Hub Height Wind Speed Calculated Using the Power Law Profile

Wind speed is not the only important atmospheric variable. The speed of sound varies as a function of temperature. Temperature is assumed to not be a significant factor in the analysis given that over the four test days at the wind farm, the temperature was fairly consistent with two 9°C days and two 13°C days.

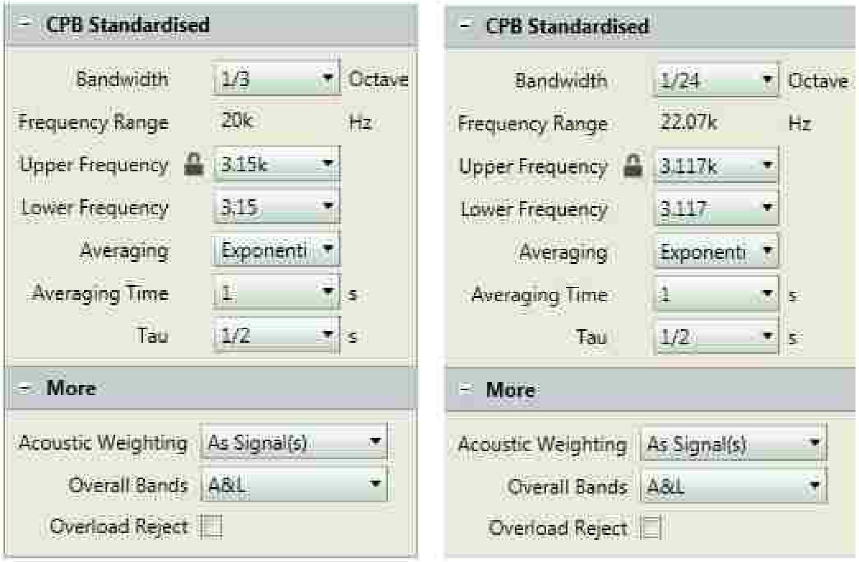
5.2 Analytical Methods

Depending on the nature of a sound and its frequency spectrum, there are numerous methods employed for analyzing acoustic data, within which many parameters can be adjusted to yield optimum results. One of the most common is the fast Fourier transform or FFT. An FFT decomposes a signal into its many component sinusoidal waves and therefore can assess noise levels according to the various frequencies. The FFT is not used extensively in this work as it can be difficult to configure a good FFT and it is not always best suited for the analysis of low frequency noise. Once the FFT is refined, the low frequency spectrum may appear similar to signal noise and therefore can make it difficult to draw conclusions on important frequencies. The FFT does see limited use in this study for contour and waterfall plots that present sound pressure levels as a function of frequency and time.

The second method is the constant percentage bandwidth (CPB) analyzer which separates the frequency spectrum into bandwidths of one octave or a fraction thereof (1/n octave). The 1/3 octave CPB with A-weighting is one of the more commonly used analyzers for the evaluation of environmental noise. The 1/3 octave and 1/24 octave CPB analyzers are used in this study. The 1/3 octave analysis allows for general trends to be observed as frequency bands are sufficiently wide to not be overly sensitive to large fluctuations between neighbouring frequencies. Linear 1/3 octave results are also necessary for the G-weighting filter to be applied, assessing the significance of the infrasound content of the noise. The 1/24 octave provides much more resolution of the time domain signal. It is similar to what can be observed from an appropriately applied FFT but is simpler to implement. For each data set, the following analyses were completed:

- 1/3 Octave CPB
- 1/24 Octave CPB
- FFT versus Time
- Overall Analyzer

Each analysis was post-processed in PULSE Reflex using linear, A-weighted and C-weighted data. The G-weighting filter for infrasound was applied to 1/3 octave data in Excel, following which overall G-weighted levels was computed. The configurations for each analysis are shown in Figures 12 & 13. A frequency range up to 3.2 kHz was defined for each analysis as the literature review suggested that little wind turbine noise is observed above 2.0-2.5 kHz. The wider range to 3.2 kHz provided a margin should relevant sound pressure levels be identified at higher frequencies. A lower frequency of 3.1 Hz was deemed sufficient as this was just below the capability limit of the microphone.



CPB Standardised

Bandwidth 1/3 Octave
Frequency Range 20k Hz
Upper Frequency 3.15k
Lower Frequency 3.15
Averaging Exponenti
Averaging Time 1 s
Tau 1/2 s

More

Acoustic Weighting As Signal(s)
Overall Bands A&L
Overload Reject ☐

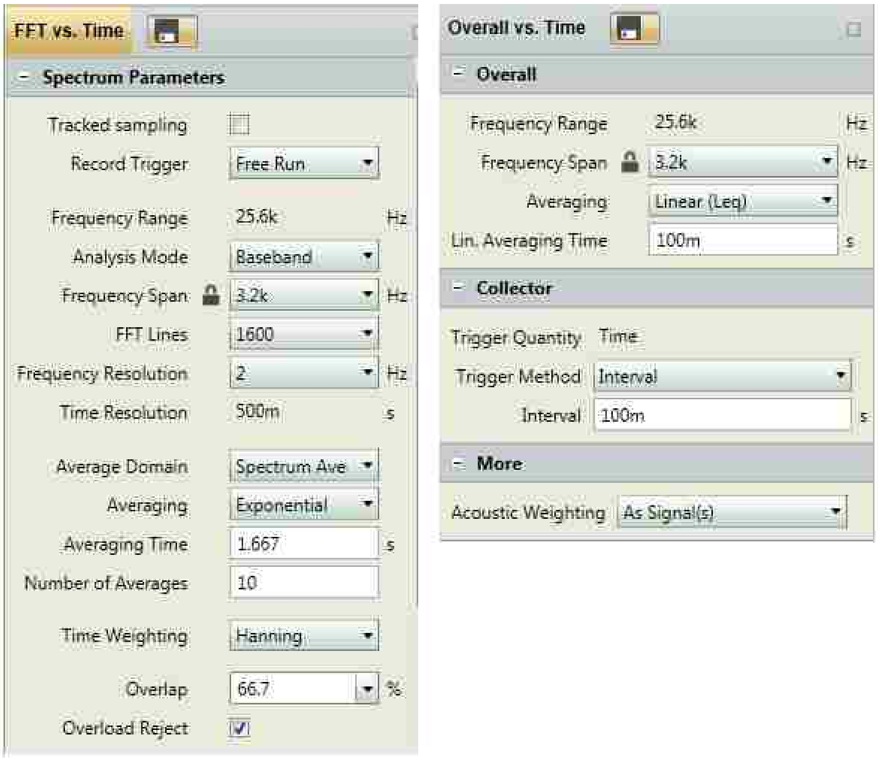
CPB Standardised

Bandwidth 1/24 Octave
Frequency Range 22.07k Hz
Upper Frequency 3.117k
Lower Frequency 3.117
Averaging Exponenti
Averaging Time 1 s
Tau 1/2 s

More

Acoustic Weighting As Signal(s)
Overall Bands A&L
Overload Reject ☐

Figure 12: 1/3 and 1/24 Octave Analysis Configurations



FFT vs. Time

Spectrum Parameters

Tracked sampling ☐
Record Trigger Free Run
Frequency Range 25.6k Hz
Analysis Mode Baseband
Frequency Span 3.2k Hz
FFT Lines 1600
Frequency Resolution 2 Hz
Time Resolution 500m s
Average Domain Spectrum Ave
Averaging Exponential
Averaging Time 1.667 s
Number of Averages 10
Time Weighting Hanning
Overlap 66.7 %
Overload Reject ☑

Overall vs. Time

Overall

Frequency Range 25.6k Hz
Frequency Span 3.2k Hz
Averaging Linear (Leq)
Lin. Averaging Time 100m s

Collector

Trigger Quantity Time
Trigger Method Interval
Interval 100m s

More

Acoustic Weighting As Signal(s)

Figure 13: FFT vs. Time and Overall Analyzer Configurations

5.3 Characteristics of the Signal

Subjectively evaluating wind turbine noise in the field, a few characteristics of the sound are quickly observed. The most dominant is the commonly referenced amplitude modulation or swish-swish. The sound may not be accurately described as a swish, but more of a distinct power stroke of the blade slicing through the air, like a propeller through water, and generating significant aerodynamic noise as a result of the speed at which the blade moves through the air medium. Although wind turbines may not appear to be moving very quickly, blade tip speeds for the 2.3 MW turbines studied were likely in the range of 170-200 km/h and can reach 270 km/h at peak rotor speed. The ‘power stroke’ or dominant ‘swish’ occurs as the blade is moving downward from its peak height and appears to end about three-quarters of the way to the bottom of the rotational cycle. As rotor speed increases, the resulting sound is very dominant and appears to be most audible coming from the outer half of the blade, which reflects the higher local particle velocity further out. At lower speeds this is not as apparent, and at close range, noise is more clearly audible from other sources including the hub, nacelle and heat dissipation fan at the base of the turbine. As recorded signals are played back in PULSE Reflex, the amplitude modulation of the ‘power stroke’ or ‘ swish’ sound can be identified, although noise from the generator and auxiliary equipment in the nacelle start to emerge as well. These sounds were likely not as well perceived in the field as they may have been masked by the wind noise.

Upon inspection of the 1/3 octave and 1/24 octave CPB analyses of select data, certain characteristics of the sound and trends become evident. Figures 14-15 show two individual measurements at 100 m downwind with an 8 m/s hub height wind speed. The 100 m downwind measurement location is frequently referenced in this report as it is close to the ‘reference distance’ commonly assessed according to IEC 61400-11. The true reference distance for the studied 2.3 MW turbines is approximately 125 m.

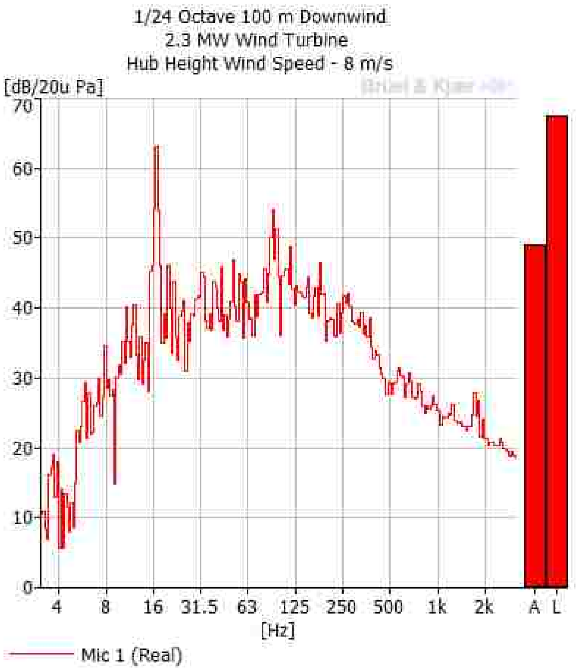


Figure 14: 1/24 Octave CPB at 100 m Downwind and 8 m/s

In both Figures, a trend is observed showing much of the wind turbine noise occurring over the range of about 10-500 Hz. Within that range, there is a fundamental frequency at approximately 16 Hz, with repeating harmonics near 31.5, 63 and 125 Hz. These are more prominent in some signals than in others. These harmonics also appear to shift up and down in frequency, perhaps as a function of wind speed, and therefore may not always be observed exactly at 16 Hz, 63 Hz, etc. For many of the analysed signals, a tonal source is present in the 1500 – 2000 Hz range. This can likely be associated with the aerodynamic noise of the blade, resulting from the 'power stroke' or 'swish' sound described earlier. The dominant tones at 16 Hz, 125 Hz, as well as those in between, appear to be present regardless of wind speed, and therefore, may not be associated with the broadband aerodynamic noise. It is likely that they may be related to sounds from mechanical equipment within the hub and nacelle. Further work with array acoustics for noise source identification is recommended to better pinpoint the source of these tones.

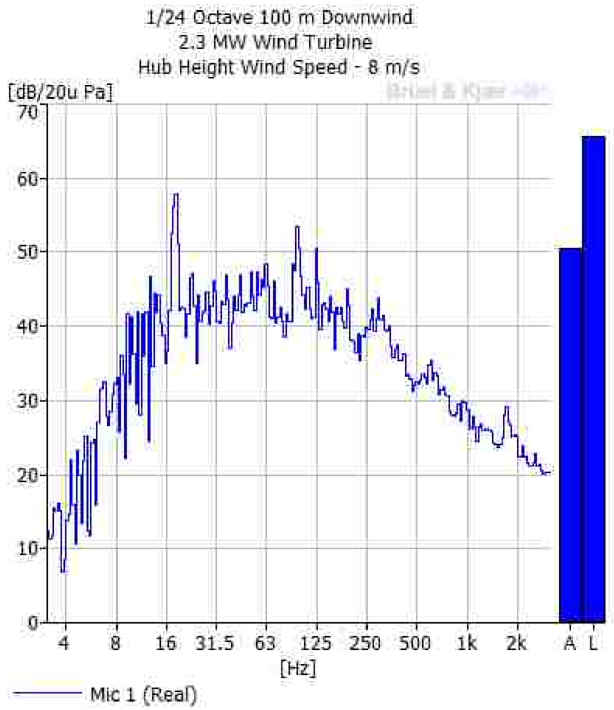


Figure 15: 1/24 Octave CPB at 100 m Downwind and 8 m/s

To assess the more general trends of the measured noise, the 1/3 octave results for the signals presented in Figures 14-15 are shown in Figure 16.

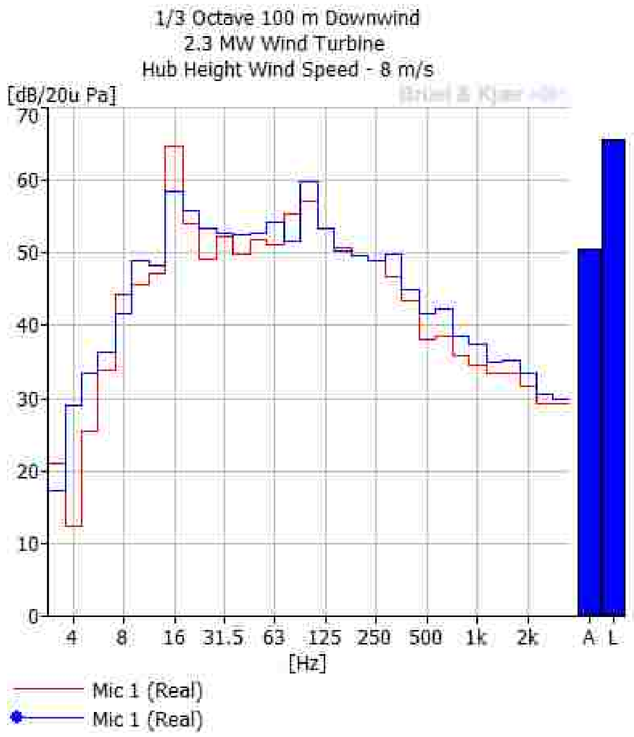


Figure 16: 1/3 Octave CPB at 100 m Downwind and 8 m/s

Although the fine details are not as evident in the 1/3 octave analysis, the trends for both measurements are similar and reveal definitive tones in the 16 Hz and 100 Hz regions.

To confirm what was observed at 8 m/s, sample results at 7 m/s and 15 m/s are shown in Figures 17-18. The tones at 16 Hz, 31.5 Hz, 100 Hz, and 1700 Hz are again prominent at a wind speed of 7 m/s, and overall values appear to be similar. It is important to note that the 7 m/s and 8 m/s data sets were recorded on separate days and at different wind turbines, suggesting that the observed tones are not related to a single turbine. The 15 m/s data set shows higher sound pressure levels across the spectrum in addition to much higher levels of infrasound. This may be related to a combination of increased wind turbine noise generation as well as additional energy in the environment due to the higher wind speeds. The tones are not as well defined but are still there and appear to have shifted up in frequency about 1/2 of an octave.

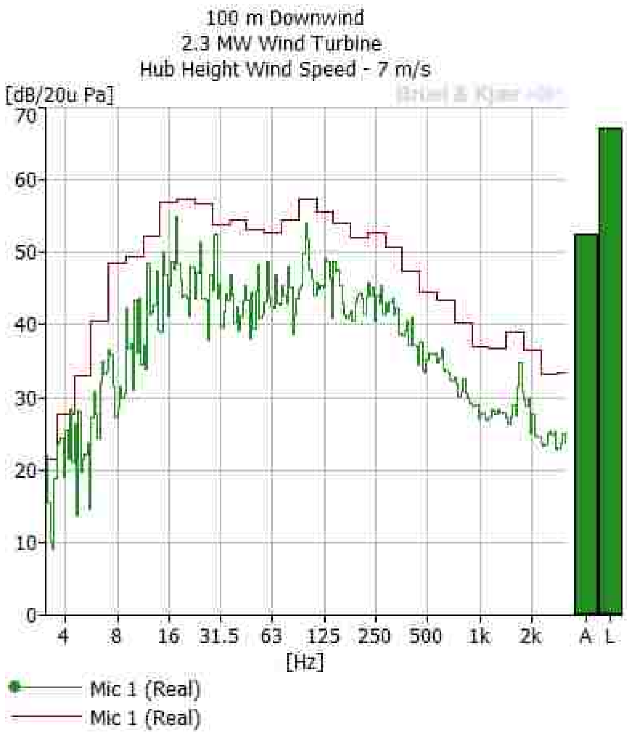


Figure 17: CPB Analysis for 100 m Downwind at 7 m/s

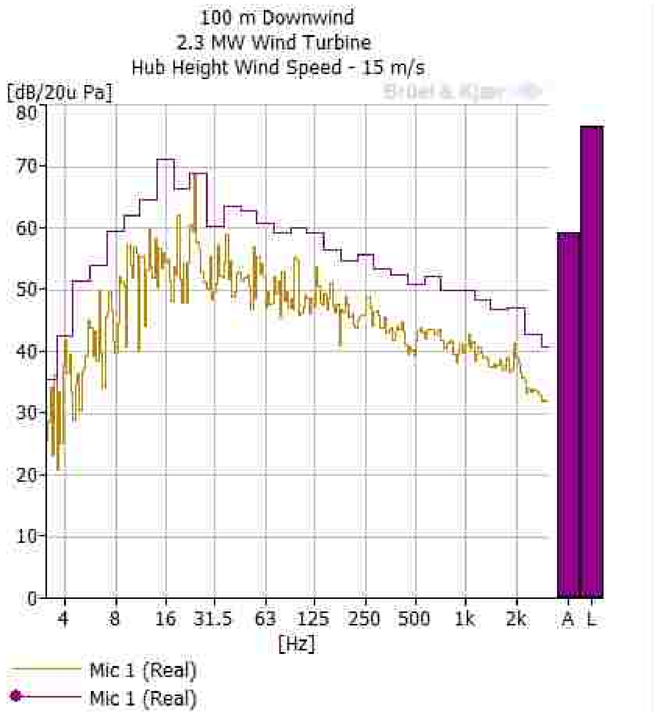


Figure 18: CPB Analysis for 100 m Downwind at 15 m/s

5.4 Background Noise

Given some of the general trends and characteristically low sound pressure levels of wind turbine noise, an assessment must be made as far as to what extent it is even relevant, or whether the noise may be masked by wind noise and other sources in the environment. Wind farms are generally located in rural areas where background noise levels can be quite low, especially at night, which allows for the wind turbine noise to be more audible. To evaluate this, background noise level measurements were recorded at 2 km and 5 km from the wind farm, at 7 m/s and 9 m/s. The results are shown in Table 7.

Table 7: Background Noise Levels

Background Noise				
	7 m/s		9 m/s	
Overall dB	58.9	59.4	56.4	60.6
Overall dBA	38.9	34.7	40.0	44.5
Overall dBC	55.9	55.8	52.8	58.0
Overall dBG	62.4	63.4	60.5	66.8

Overall sound pressure levels of 34.7 and 38.9 dBA were observed on the day having 7 m/s wind speeds while levels of 40.0 and 44.5 dBA were experienced at 9 m/s. With Ontario wind turbine noise limits of 43 dBA at 7 m/s and 49 dBA at 9 m/s, there is room for wind turbine noise emissions to increase background sound levels by 6-9 dB. This increase has the potential to be significant, but before conclusions are made based on overall levels alone, the signals should be assessed with background noise removed to verify which components of the noise can be attributed to the wind turbine. Figure 19 shows the 100 m downwind 8 m/s signals presented in the previous section with a 7 m/s background noise signal subtracted from them. Figure 20 is similar but for 7 m/s and 9 m/s, using minimum background noise levels at the respective wind speeds.

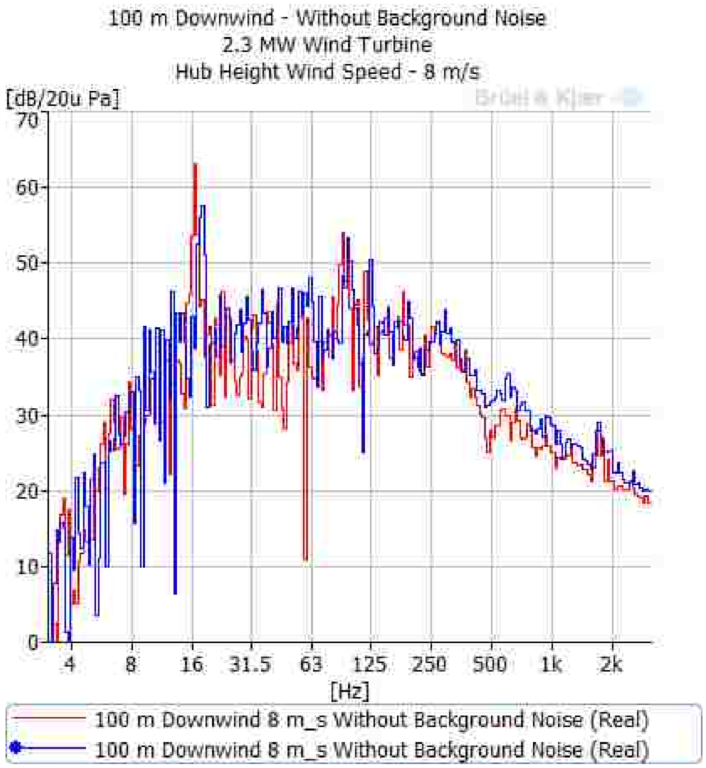


Figure 19: 100 m Downwind Without Background Noise at 8 m/s

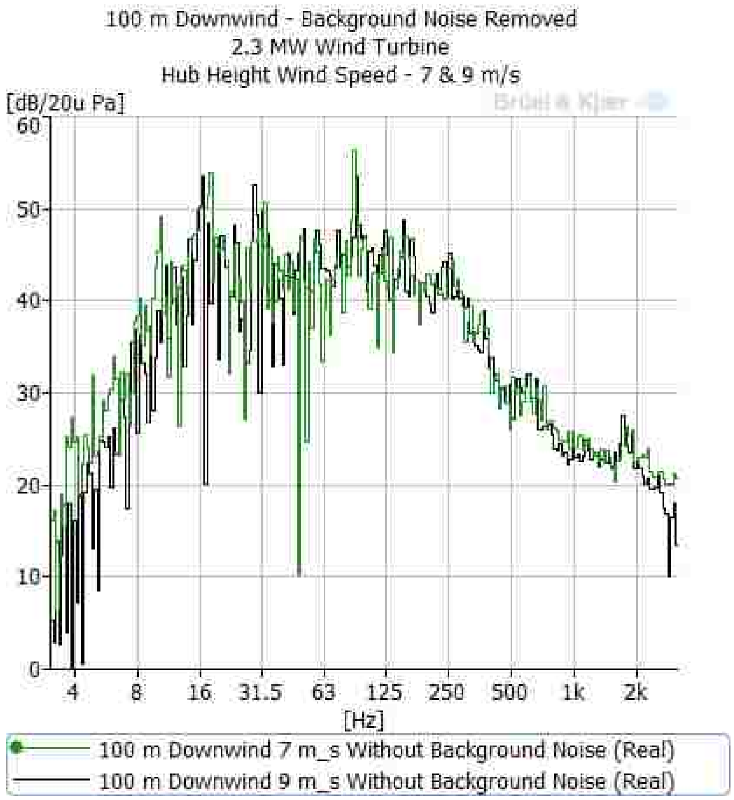


Figure 20: 100 m Downwind Without Background Noise 7 & 9 m/s

These figures show that subtracting background noise did little to diminish the dominant sounds at 16 Hz, 31.5 Hz, 100 Hz and 1700 Hz. It also appears that that there is another source in the vicinity of 250 Hz. This was not evident before subtracting background noise from the signal. Since there were no other external sources present at the time of measurement, and the data is consistent across separate days with different turbines and background noise removed, it is concluded that the sources at the identified frequencies can be attributed to wind turbine generated noise. The sources at these frequencies are further verified as being present (non-fluctuating) throughout the entire measurement period in Figure 21.

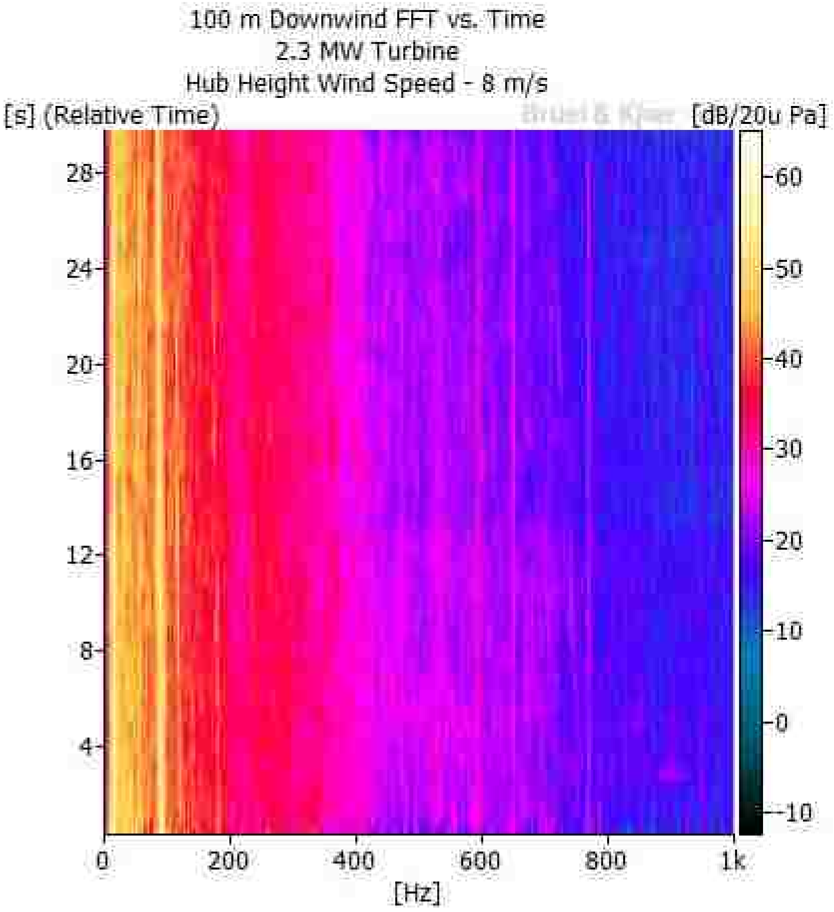


Figure 21: 100 m Downwind at 8 m/s FFT vs. Time

5.5 Measurement Statistics

A basic statistical analysis was conducted in order to further increase the confidence level in the above results. As discussed in the section on atmospheric conditions, there is accepted to be a fifth power relationship between wind speed and the emitted sound power level. With wind speed fluctuations as high as 1 to 2 m/s within some measurement periods, it is expected that this might be the cause of the majority of variations between measurements. The 30 second average overall levels should help to reduce the variation observed between signals and allow for better comparisons to be made.

Upon investigation of a set of six measurements 100 m downwind and a set of five measurements 550 m downwind, a few trends begin to emerge as far the characteristics of the measured signal. The six measurements for 100 m downwind at 8 m/s are shown in Figure 22. Although there is certainly some variation between each measurement, the general trend is maintained and the differences in sound pressure levels at each 1/3 octave are more than likely associated with changes in atmospheric conditions between measurements. In the absence of the alleged wind speed differences, most 1/3 octaves appear to overlay consistently between measurements. This provides additional confidence for the general trend and strengthens the argument for the key frequencies.

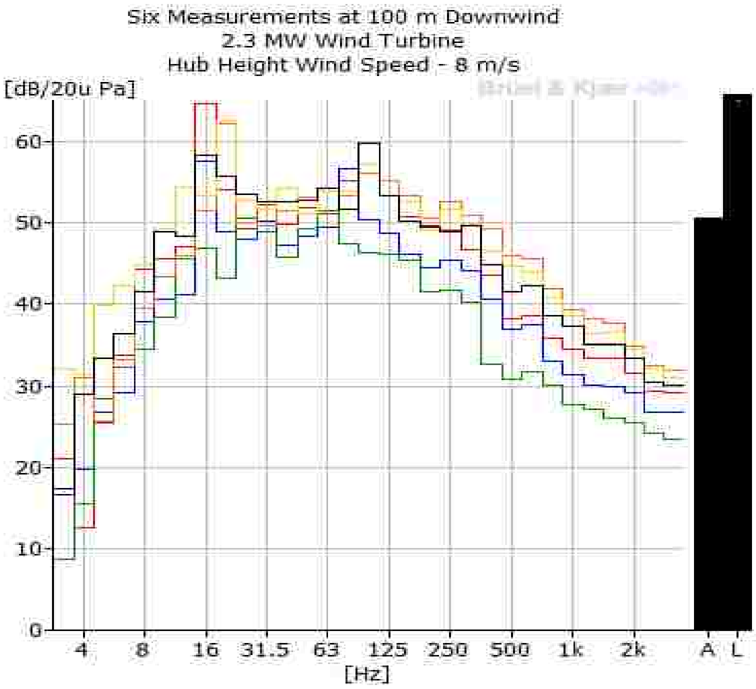


Figure 22: Six Measurements 100 m Downwind at 8 m/s

The measurements for a specific location (i.e. 100 m downwind at 8 m/s) were then analyzed to compute 1/3 octave mean, maximum, and minimum levels for the measurement location, as displayed in Figures 23-24. At measurement locations 100 - 300 m from a turbine, 1/3 octave mean sound pressure levels are near the maximum levels for a given data set. In these cases, the difference between mean and minimum levels is much larger across the frequency band. The 1/24 octave analysis shows a similar trend with mean and maximum levels very close together for a given data set. The proximity of mean to maximum levels can likely be associated with rapid changes in wind speed. The sustained wind speed is closer to peak wind speed levels than the momentary periods of calmer winds where sound pressure levels may be artificially low.

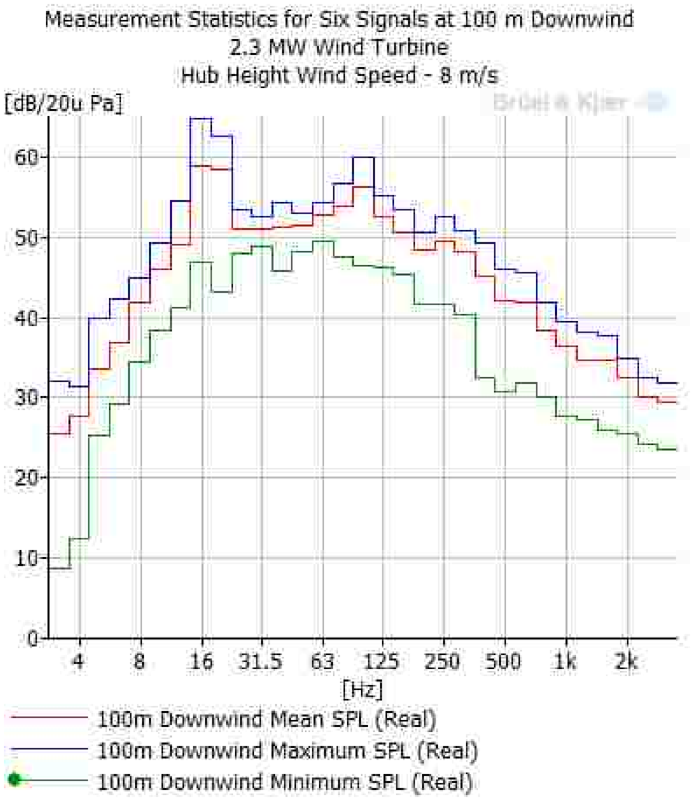


Figure 23: Measurement Statistics for Six Signals 100 m Downwind at 8 m/s

Although not as well defined as with measurements closer to the wind turbine, the observation that mean levels trend closely with maximum levels remains valid at distances out to 550 m, as shown in Figure 24. At longer distances, the difference between mean and minimum levels is reduced, especially at higher frequencies. This may be attributed to the attenuation of many of the high frequency fluctuations by air and ground absorption. Low frequency wavelengths are much longer and therefore travel further before being attenuated. Therefore, minimum and maximum levels of wind turbine noise at long distances are likely to be more dependent on the low frequency component and less dependent on wind speed. A worst case is preferred for analysis, so the 1/3 and 1/24 octave maximum levels are typically used for comparison in this report, but have been shown in this section to trend closely with mean levels as well.

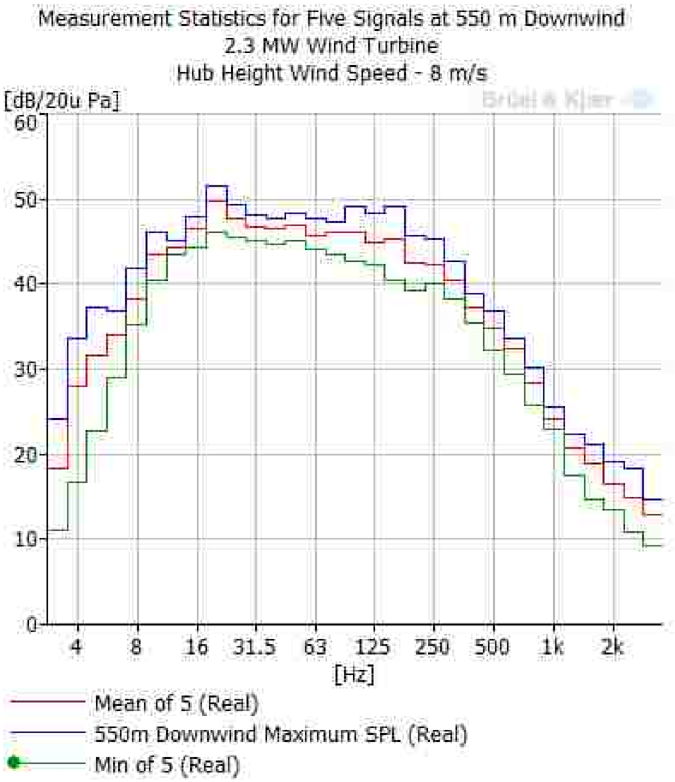


Figure 24: Measurement Statistics for Five Signals 550 m Downwind at 8 m/s

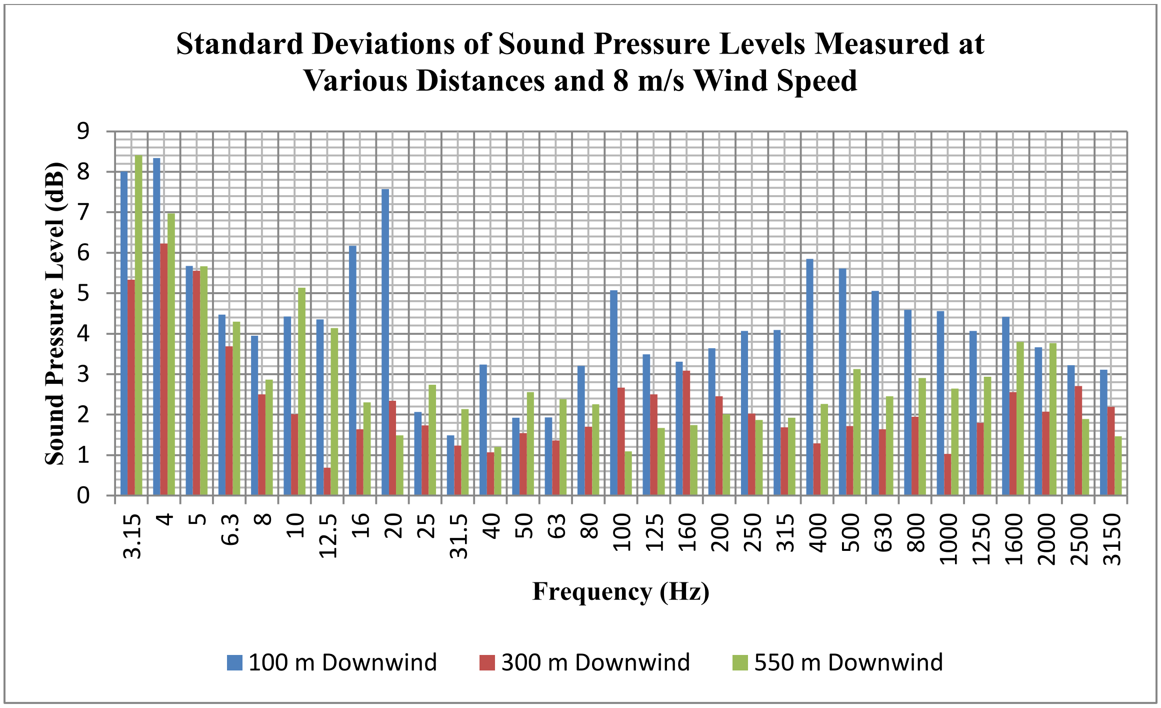


Figure 25: Standard Deviations at Various Distances and 8 m/s

Standard deviation was the final metric used to assess variation between measurements. The standard deviation was calculated for each 1/3 octave across sets of measurements at 100 m, 300 m, and 550 m downwind, as shown in Figure 25. The results are interesting in that the lowest standard deviations (1-3 dB), regardless of distance, tend to be in the range of 20 to 150 Hz. This is coincidentally also the range where low frequency wind turbine noise is most prominent. The extreme standard deviations (5-8 dB) below 6 Hz may be a combined result of fluctuations in the infrasound naturally present in the wind and the sensitivity limit of the microphone used.

The fact that the majority of the standard deviations fall below 3-4 dB suggests that the data is relatively consistent. Fluctuations of that magnitude may be barely noticeable as a perceived change in sound to the human ear and therefore may go unnoticed in the field. There also appears to be a distinct reduction in standard deviation as distance increases from the base of the wind turbine. This may be associated with additional acoustic energy close to the source that is being rapidly attenuated, particularly on the high frequency end, with increasing distance from the source. High standard deviations at 100 m over the 400–1600 Hz range may be related to the broadband amplitude modulation or swish-swish (power stroke) sound discussed above. There are audible changes in sound pressure level associated with this phenomenon but they are highly sensitive to wind speed.

5.6 Propagation Distance

Wind turbine noise propagation distance is controversial as minimum setback distances have been defined according to various prediction models and standards, causing disagreement over how far these distances should actually be. The issue is complicated by the fact that few enforced setback distances appear to have been validated by noise measurements at neighbouring residences following the installation of a wind turbine. It is understood that as sound travels through air from a source, the high frequency component is absorbed or attenuated much more rapidly than the large wavelength, low frequency and infrasonic components. Some reports indicate that wind turbine generated infrasound may be present up to 1-2 km from a turbine, whereas the high frequency component is well-attenuated within the first 500 m.

The collection of wind turbine noise propagation data can be challenging as the physical ability to measure further than 1 km from a turbine is often limited. Wind farms present a unique challenge in that shorter distances may be required to ensure that the recorded noise was generated by the intended turbine and is not influenced by another nearby. In this study, a distance of 1 km was aspired for but was unattainable given required land permissions for adjacent properties. The maximum propagation distance achieved was 600 m downwind, with measurements recorded in 100 m increments from the base of the turbine. Measurements were conducted at four wind speeds and involved two separate turbines. The incremental measurements of wind turbine noise propagation at various wind speeds appear to be unique to the literature available today. The data was first analyzed for general trends using average overall sound pressure levels. A more focused study was then performed to identify the relevant frequency bands and how they change as the receptor moves further from the turbine. This provides greater understanding of the characteristics of downwind turbine noise propagation and identifies the relevant components of the noise at distances up to the current MOE setback distance of 550 m.

Figure 26 presents average 1/3 octave overall sound pressure levels at a wind speed of 8 m/s, with measurements recorded 100 m to 550 m downwind. Only linear sound pressure levels have been considered thus far in the report. In Figure 26, weightings are applied to the recorded signal such that overall levels are displayed as linear, A-weighted, C-weighted, and G-weighted (for infrasound) values.

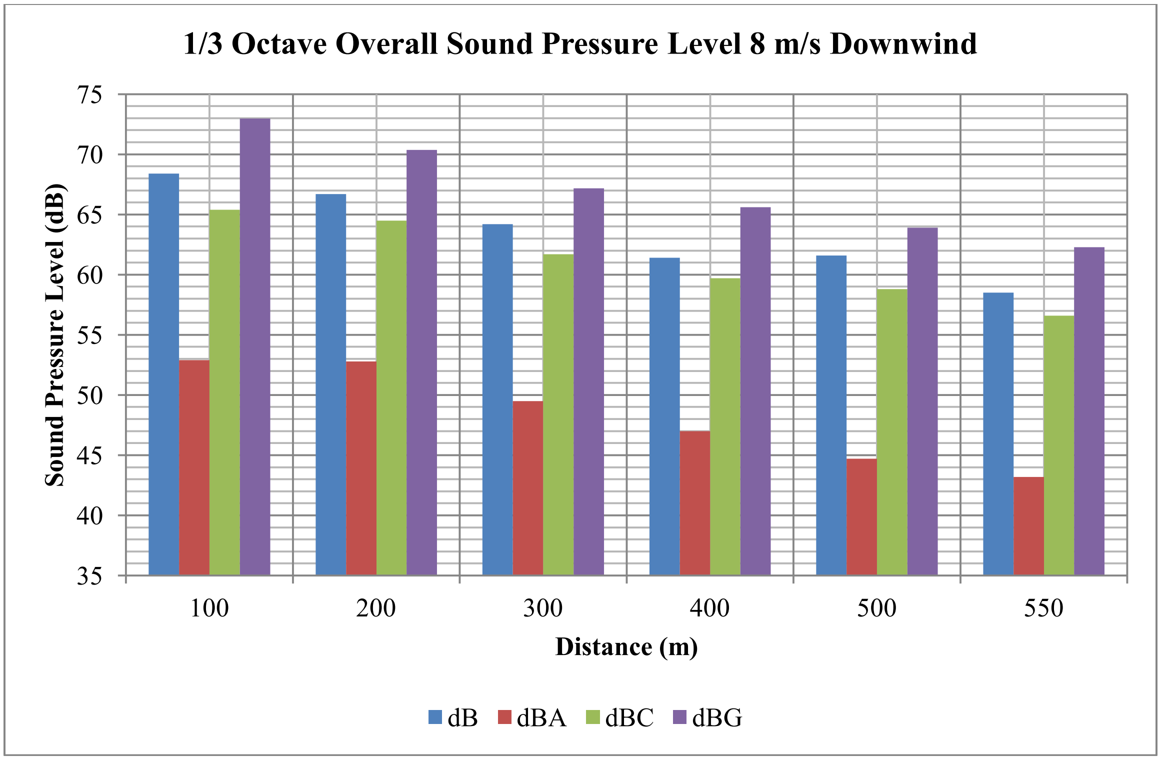


Figure 26: Overall Sound Pressure Levels Downwind at 8 m/s

Significant attenuation of the emitted sound is observed from 100 m to 550 m as linear levels decrease from 68.4 dB to 58.5 dB, and A-weighted levels are reduced from 52.9 dBA to 43.2 dBA. An attenuation of approximately 10 dB over the distance from 100 m to 550 m is observed independent of which weighting filter is applied. Sound attenuation of approximately 5 dB per doubling of distance indicates that spherical propagation is appropriate for wind turbine noise. Minimal attenuation is observed between 100 m and 200 m downwind which may be due to multiple factors. The 30 second measurement period may not be long enough for the low frequency component to fully develop at 100 m, or a change in atmospheric conditions may have occurred between measurement locations. Interesting though is that there is a 3 dB decrease in G-weighted infrasonic levels over the same distance.

G-weighted levels, even at 100 m downwind, are only 75 dBG at a wind speed of 8 m/s. That is 10 dBG below the 85 dBG limit for human perception, and is consistent with previous measurements of wind turbine noise discussed in the literature review. The A-weighted level at the MOE setback distance of 550 m was 43.2 dBA, which is well within the limit of 45.0 dBA at a wind speed of 8 m/s. The metric of dBC - dBA being greater than 20 dB for a potential low frequency noise issue was applied. Overall sound pressure levels showed a 12-15 dB difference, thus indicating that a low frequency noise issue is unlikely. Considering just the 20-125 Hz range, the difference between A and C weighted levels is much higher, reflecting both the shape of the weighting curves and the fact that the highest levels of wind turbine generated noise are observed in this range. The metric may therefore be insufficient as low frequency noise appears to be relevant despite not exceeding the 20 dB difference between A and C-weighted levels.

Measurements at 100-600 m downwind were also performed at a different wind turbine with an average hub height wind speed of 9 m/s. The results are shown in Figure 27. Despite a slightly higher average wind speed, overall sound pressure levels were found to be similar to the 8 m/s results detailed above. The results were consistent between the two data sets, so differences in sound pressure level may be attributed to such factors as the degree to which wind speed fluctuated over the measurement period or different operating parameters of the turbine (i.e. blade pitch angle and rotor speed). It would be beneficial in future studies to overlay operational parameters with noise measurements. This would provide greater understanding of the mechanisms of wind turbine noise generation while assisting the wind farm with its operational strategies. Although A-weighted levels are lower (as low as 39.2 dBA at 600 m), C and G weighted levels are consistent with the 8 m/s data set. This suggests that there may have been less acoustical energy present in the environment and may reflect fewer fluctuations in wind speed. As levels at higher frequencies diminished more between data sets, the dBC–dBA metric becomes more significant at 9 m/s with a difference of 15-18 dB observed. This was still not above the 20 dB difference, but reinforced the fact that the low frequency component of the noise is important and may be a significant factor for annoyance.

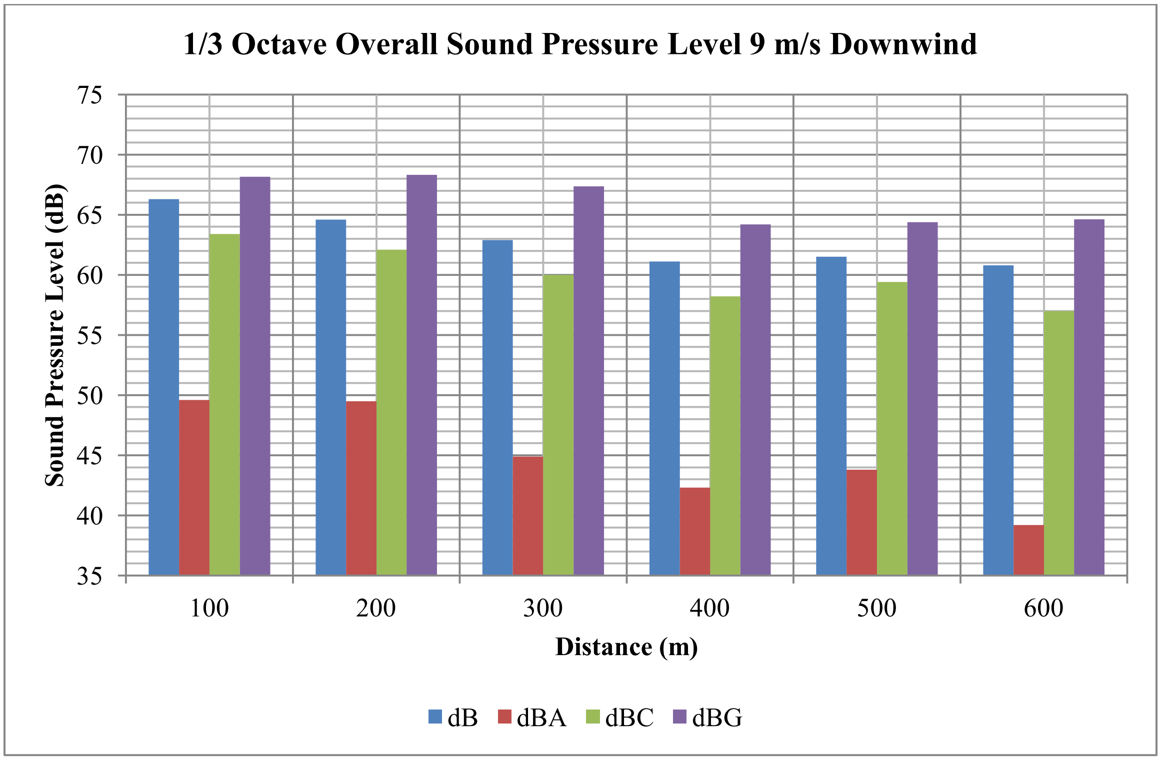


Figure 27: Overall Sound Pressure Levels Downwind at 9 m/s

A small change in wind speed increased confidence in the measured data as two turbines on separate days showed consistent results. The next step then is to understand what would happen if the wind speed were increased significantly. At a wind speed of 15 m/s, measurements were recorded at 100 m, 200 m, and 300 m downwind of two turbines about 400 m apart. The wind was blowing such that the nacelles of the two turbines were approximately parallel to one another and therefore Turbine A was not directly in the wake of Turbine B. The results are shown in Figures 28-29.

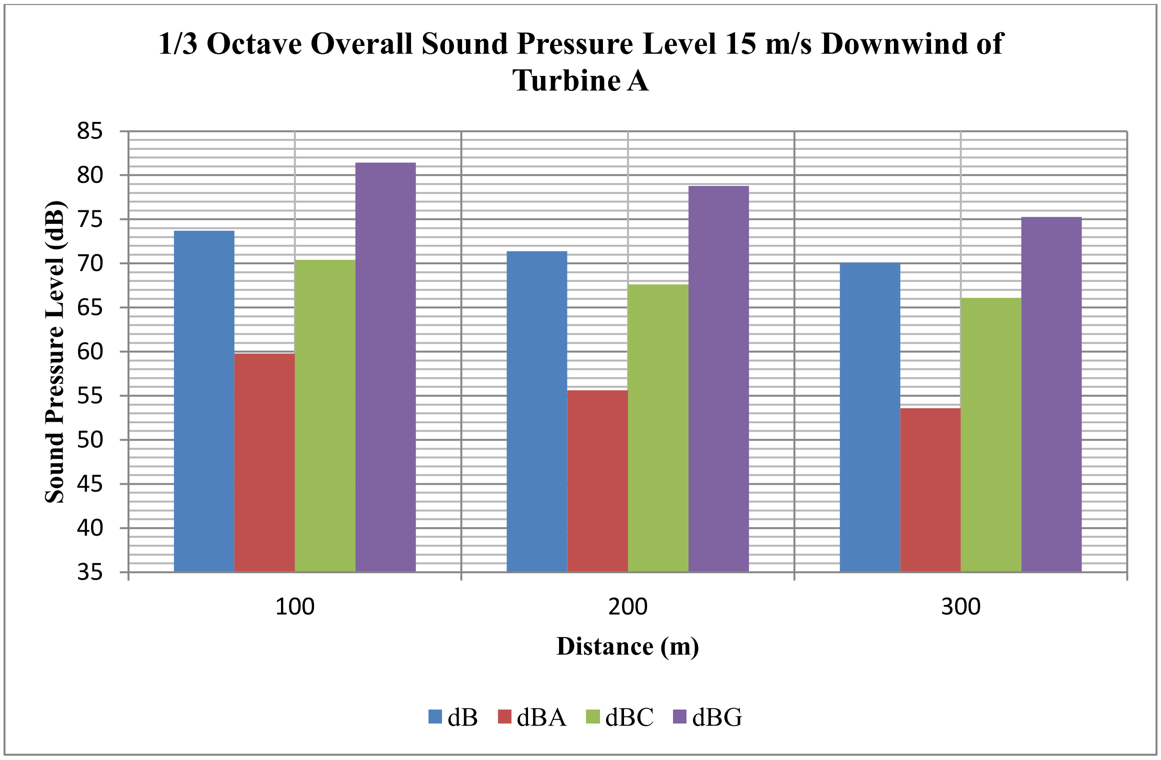


Figure 28: Overall Sound Pressure Levels Downwind at 15 m/s

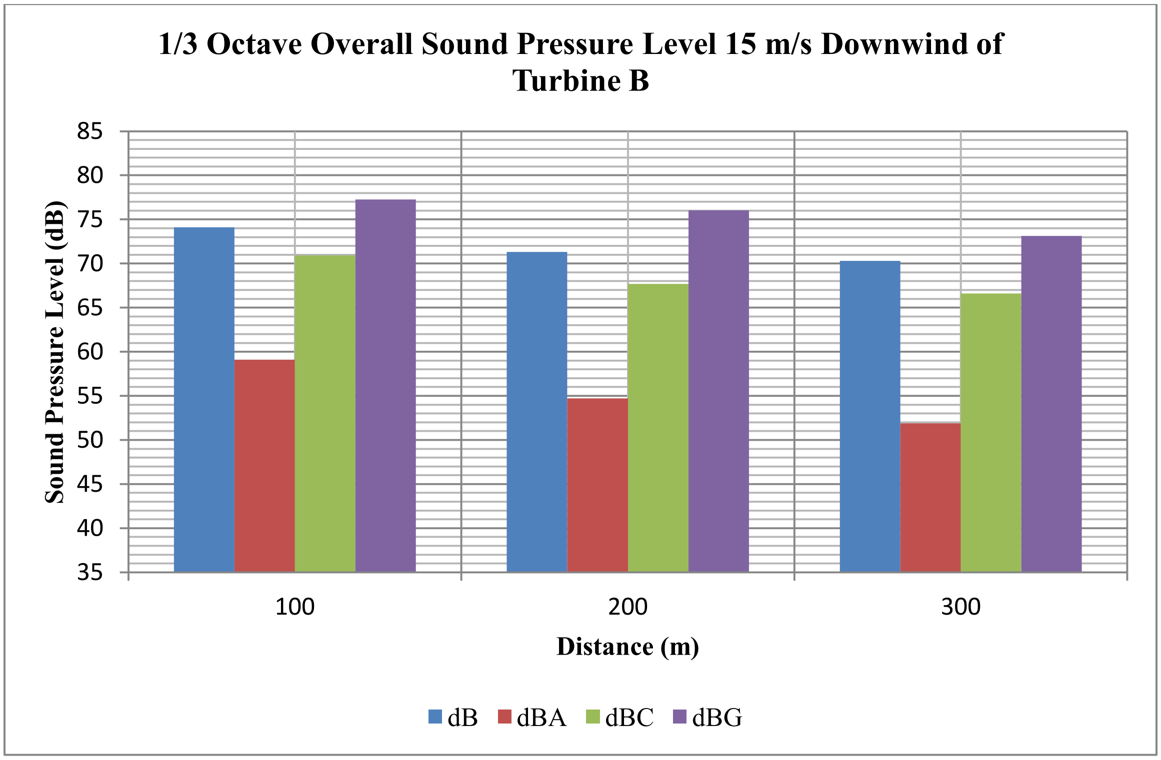


Figure 29: Overall Sound Pressure Levels Downwind at 15 m/s

Strong consistency is observed between the data for Turbine A and Turbine B. At a wind speed of 15 m/s, a decrease of about 3 dB is observed between 100 m and 200 m rather than remaining relatively flat as levels did at lower wind speeds. Measurements from additional locations are required to truly assess the propagation behaviour of the sound. Given that a 2-3 dB decrease occurs between 200 m and 300 m, it is likely that the trend would be consistent with that observed at 8 m/s, where a decrease of 5-6 dB is observed per doubling of distance.

Linear and C weighted levels at turbines A and B were within 0.5 dB of one another, yet A and G-weighted levels were approximately 2 dB higher at Turbine A than at Turbine B. Although the wind direction was such that inflow into the two turbines was nearly parallel, the offset may have been enough to have Turbine A experience some wake effects from Turbine B. It is suspected that the additional energy in the atmosphere as flow comes off B and moves toward A may be responsible for the higher A and G-weighted levels observed at Turbine A.

At a wind speed of 15 m/s, observed G-weighted levels of 81 dBG at 100 m were approaching the pure-tone limit for human perception of 85 dBG. This is nearly 10 dBG higher than the levels observed at wind speeds of 8-9 m/s and is in coherence with linear and A-weighted sound pressure level increases of 6-8 dB. The high levels of infrasound decreased to 73 and 75 dBG at 300 m and based upon the trends observed at lower wind speeds, are projected to be about 68-70 dBG at the Ontario setback distance of 550 m. Even when taking into account the complex noise hearing thresholds discussed in Chapter 3, these levels would only be considered barely audible. It is therefore unlikely that wind turbine generated infrasound has the potential for an audible human impact at wind speeds up to 15 m/s. Further research is recommended at higher wind speeds and current data correlated with medical information to assess the potential for non-auditory physiological responses to infrasound at these levels. Both are beyond the scope of this study.

Measured A-weighted levels of 53.6 dBA and 51.9 dBA at 300 m and a wind speed of 15 m/s suggest that levels at the MOE setback distance of 550 m are likely to be in the 46-49 dBA range. The dBC-dBA low frequency noise metric is reduced to 11-13 dB, suggesting that a low frequency noise issue is less imminent. This may be a result of masking by the additional wind noise of a high wind speed day. Measurements at high wind speeds and further distances are recommended for future work in order to assess whether the low frequency component remains masked as the high frequency component diminishes with distance from the turbine. The generated low frequency noise may then prove to be more prominent at lower wind speeds and quiet background noise, perhaps overnight, and less of an issue on high wind speed days when much of the noise is masked.

With an understanding of some of the characteristics of wind turbine noise propagation, the measured signals are analyzed in further detail to identify the components of the noise which remain important as a receptor moves further from the turbine. The 1/3 and 1/24 octave maximum levels for each measurement set are used in the results presented. Figure 30 presents 1/24 octave data for downwind measurements at 100-600 m. A detailed view of the low frequency spectrum is shown in Figure 31. The primary noise sources at approximately 16 Hz, 31.5 Hz, 100 Hz, 200 Hz and 1700 Hz discussed previously in this chapter and were observed at all measurement locations out to 600 m downwind. They were however more pronounced within 300 m and the peaks became gradually smaller as distance from the turbine increased. The 100 m and 200 m measurements were quite similar, with the exception of a minor decrease in levels above 1000 Hz at 200 m. This is likely attributed to the ground and air absorption of high frequency noise that occurs progressively with distance. Beyond 300 m downwind, noise levels above 250 Hz were observed to decrease quickly. Low frequency noise between 20-125 Hz followed a similar pattern but decreased at a slower rate, while the infrasound levels remained relatively constant. The 500 m downwind results were observed to trend higher than those at closer distances. Some irregularities were observed in all three measurements taken at 500 m and it is not clear whether there was a momentary increase in wind speed or interference from an external source in the field.

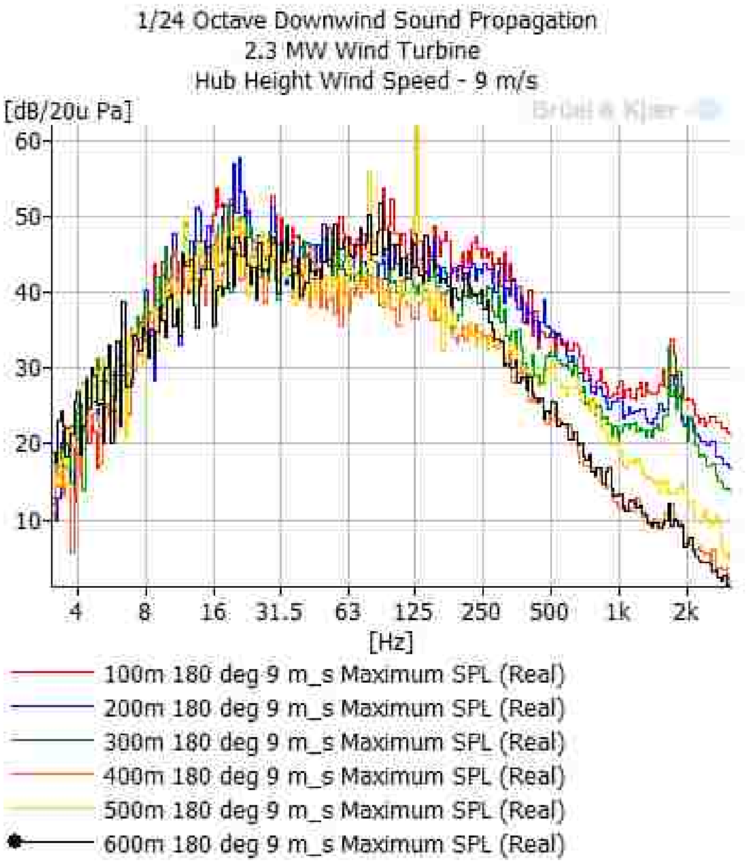


Figure 30: 1/24 Octave Downwind Sound Propagation at 9 m/s

Figure 31 reinforces some of the key frequencies at approximately 16 Hz, 31.5 Hz, and 100 Hz and demonstrates the relative consistency of infrasound levels with increasing distance from the turbine. The infrasound component should therefore be considered to be present at distances beyond 600 m, despite occurring at levels that are well below the audible threshold. Giving the low frequency spectrum additional consideration, levels at 600 m are observed to have the potential to be as high as those at 100 m, over the 31.5-125 Hz range. This indicates that noise below 125 Hz is not well dissipated or absorbed before reaching an observer at 600 m. Therefore, although overall levels have dramatically decreased 600 m downwind of a turbine, low frequency levels have not. In fact, the generated low frequency noise above 40 Hz may even still exceed audible levels. Audibility will be discussed in further detail in Chapter 6.

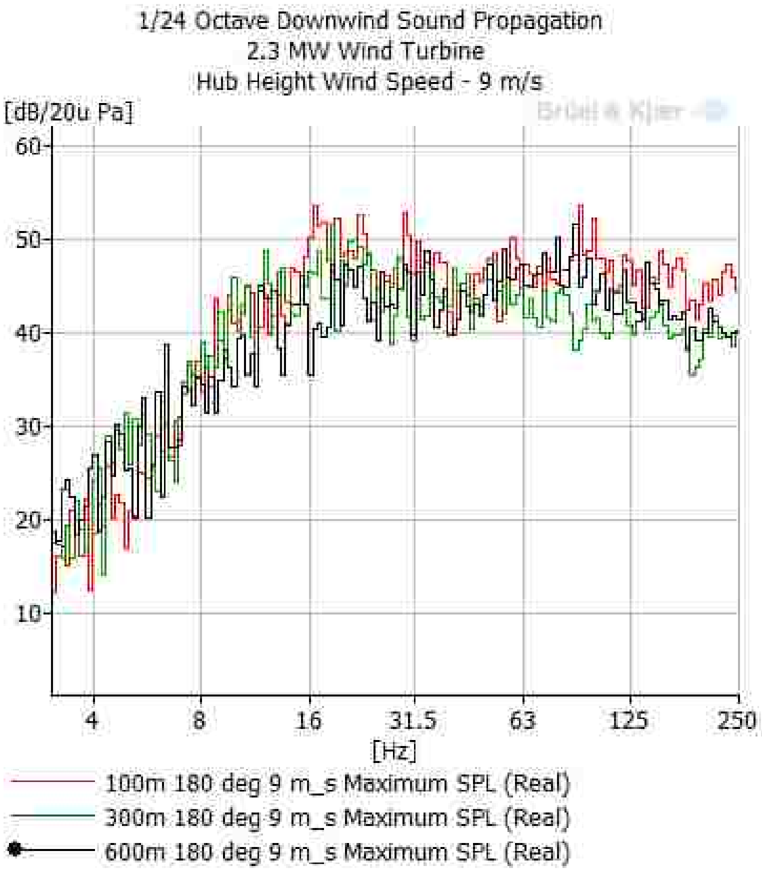


Figure 31: 1/24 Octave Downwind Sound Propagation at 9 m/s Up To 250 Hz

5.7 Directivity

Existing wind turbine noise research often involves measurements at specified distances downwind of the turbine, similar to the work presented in the previous section. Limited literature is available to review the directional characteristics of wind turbine noise in detail. The incremental nature in which this study was completed is believed to be unique and will offer new insight into best practices for wind turbine noise measurement. Measurements were conducted in 45° increments at 100 m and 200 m radii from the base of the turbine. The orientation directly upwind of the turbine is the reference and was defined as 0°. Measurements were recorded every 45° moving counter-clockwise from the 0° upwind location. The turbine view from measurement locations at 0°, 90°, 180°, and 360° are shown in Figure 32.

Figure 32: Directional Measurement Views at 0°, 90°, 180°, 360°

Similar to the analysis of sound propagation in the previous section, 1/3 octave overall sound pressure levels (dB, dBA, dBC, dBG) are used for comparisons of general trends between data sets, while maximum 1/3 and 1/24 octave levels in each frequency band offer more detailed understanding of the directional characteristics of the noise. Figure 33 is a polar plot of linear overall levels at a 100 m radius and three wind speeds. The plot suggests that wind turbine noise is directional, although it is difficult to assess to what degree. It does appear though that the noise is more directional at low wind speeds than at high wind speeds. To improve understanding of the degree of directionality, a histogram of the data is shown in Figure 34.

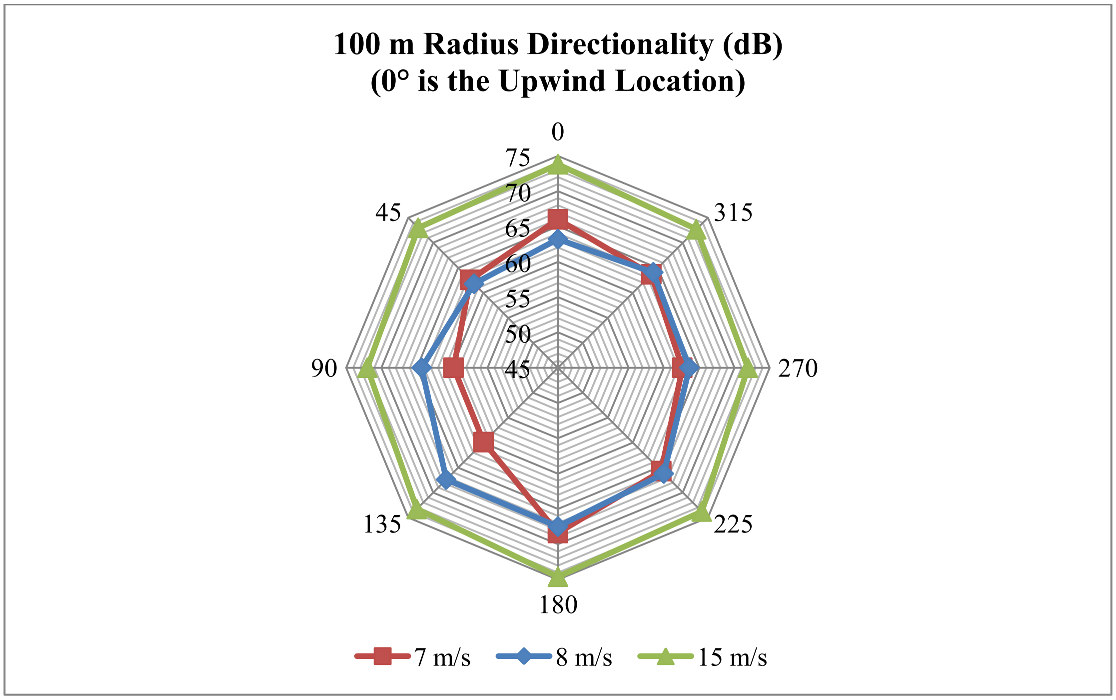


Figure 33: 100 m Directionality Polar Plot at Three Wind Speeds

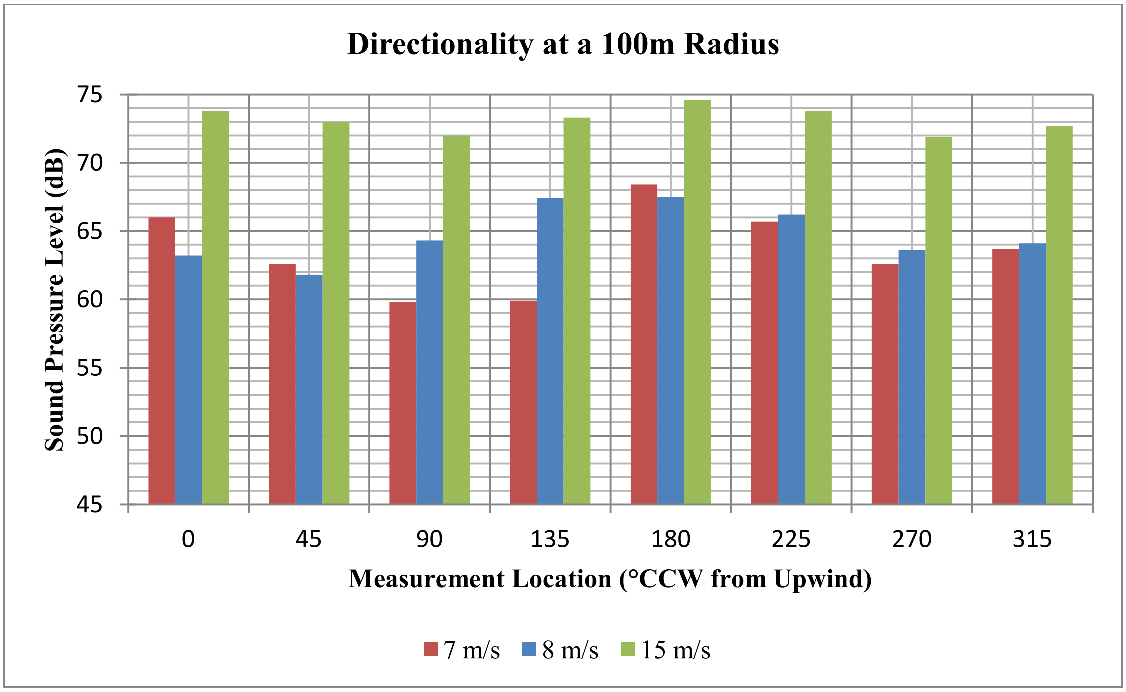


Figure 34: 100 m Directionality Histogram at Three Wind Speeds

In Figure 34, the directional nature of the 15 m/s data set is more evident than it was on the polar plot. At all wind speeds, the downwind, 180°, measurement location revealed the highest overall sound pressure levels. This observation supports the subjective field evaluation of the downwind region being the loudest location around the turbine. This further supports the standardized noise measurement location at the reference distance downwind of the turbine.

The wind turbine directional pattern appears to take the shape of an egg, where higher levels are observed directly upwind and downwind of the turbine, and lower levels are found perpendicular to the nacelle at 90° and 270°. This trend is consistent across most data sets, which can be reviewed further in Appendix C. The fact that overall sound pressure levels are lowest at 90° is interesting as the rotor rotates such that the blades are coming down through the 'power stroke' or 'swish' type motion on that side of the turbine. That distinct characteristic of the sound must propagate more in the direction of the wind than it does perpendicular to the nacelle. This may be due to the fact that the 'swish' occurs higher in the frequency spectrum. It may also be that the rotating blade directs the sound tangentially (flow over the blade and off the tip) towards the opposite side of the turbine, where higher levels are observed than on the 90° side.

Using the same data set at a 100 m radius, the directivity index was calculated with the downwind sound pressure level as the reference. The results are shown in Figure 35 and reinforce many of the preliminary observations. Recall that a difference of 3 dB is a noticeable change in perceived sound at the receptor. As the directivity index was determined to be close to or greater than 3 dB in many cases, wind turbine noise is concluded to be directional over a range of wind speeds. The directional nature of the noise does however decrease with an increase in wind speed. Following the downwind location, the 225° receptor is consistently one of the loudest places around the turbine. The same conclusion cannot yet be drawn at 135°, as the 7 m/s and 8 m/s data sets are contradictory, but more data is likely to prove that 135° is another prominent location. There appears to be more consistency in the trends on the 270° side of the turbine than on the 90° side. The sound is found to be highly directional at both locations and is certain to result in a change in perception for an observer. As directivity index is shown to be inversely proportional to wind speed, the change in perception is more significant at low wind speeds than at high wind speeds. This is consistent with previously discussed data that suggested that wind turbine noise has greater potential for annoyance when background noise levels are lowest, such as at low wind speeds.

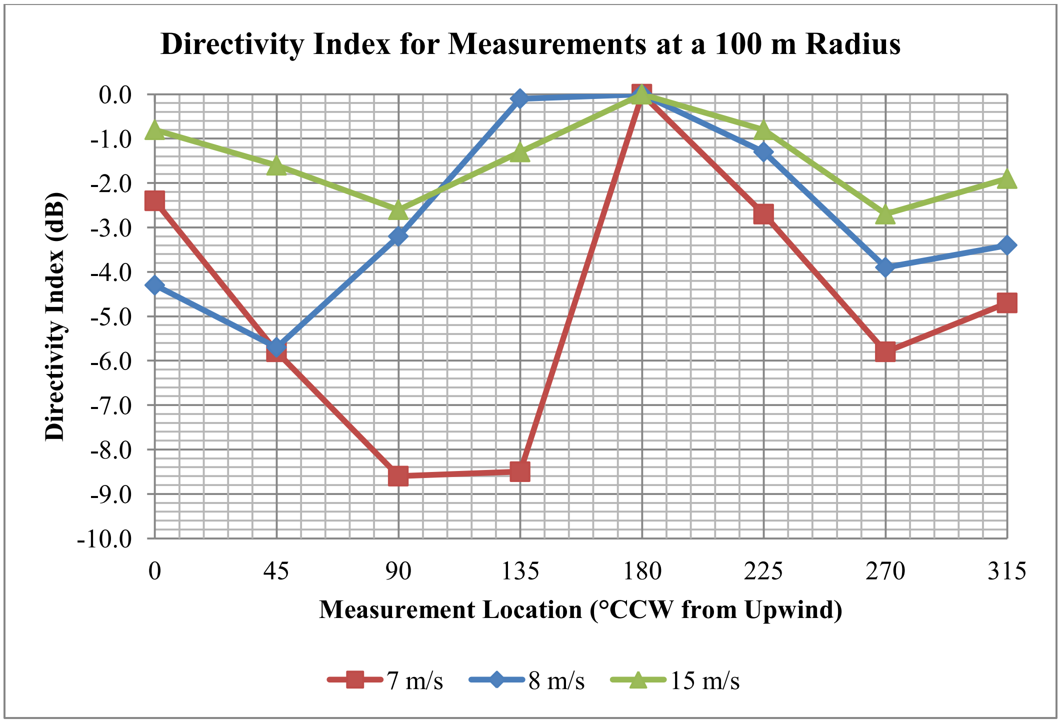


Figure 35: 100 m Directivity Index at Three Wind Speeds

The logical progression is to identify whether the directional nature of the sound remains true at a 200 m radius. Figure 36 is a polar plot that compares 100 m and 200 m overall levels at an approximately 8 m/s wind speed. A full data set was not possible at 200 m due to required access to unapproved land near to the turbine. The data is however consistent with that observed in the section on sound propagation where 100 m and 200 m levels are quite close. The 200 m polar plot follows a similar shape to that of the 100 m, with the exception being a dramatic decrease at 90° to near background levels. Perhaps this was influenced by a sudden lull in wind speed but further demonstrates the highly directional nature of wind turbine noise.

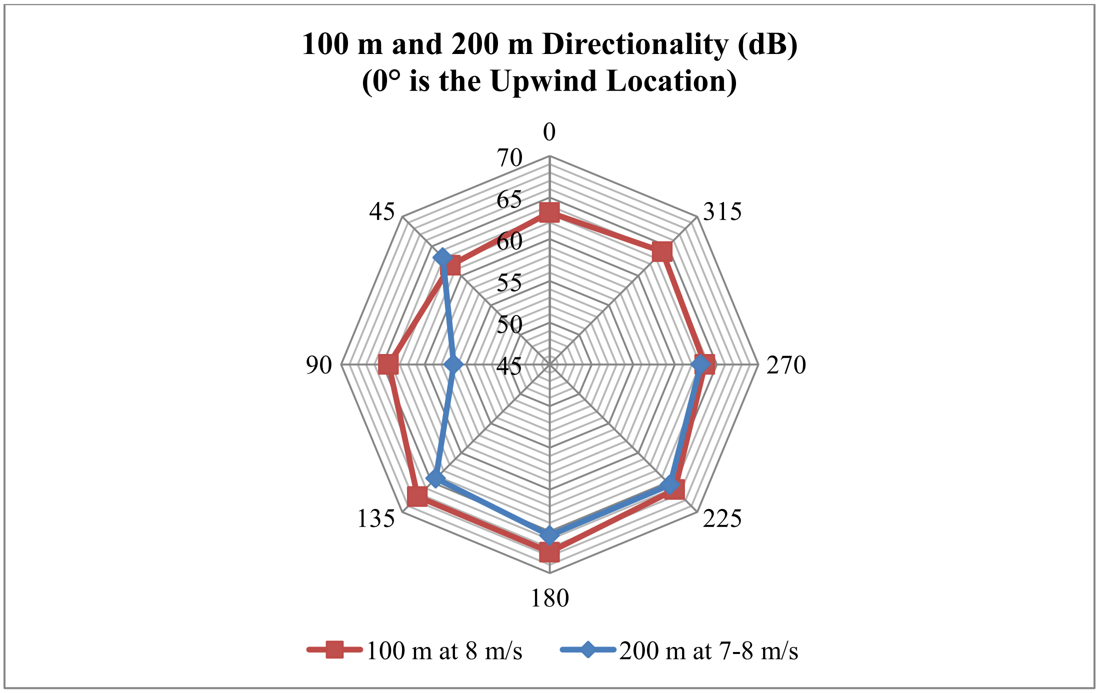


Figure 36: 100 m and 200 m Directionality at 8 m/s

A plot of directivity index comparing the 100 m and 200 m data sets is shown in Figure 37. Overall levels at 90° and 270° are again observed to be the most directional while 0°, 45°, and 315° also show directionality to varying degrees that are all sufficiently large to affect the perception of the noise by an observer. The 135° and 225° data reinforce the prior conclusion that sound pressure levels at those locations can be just as high as downwind levels.

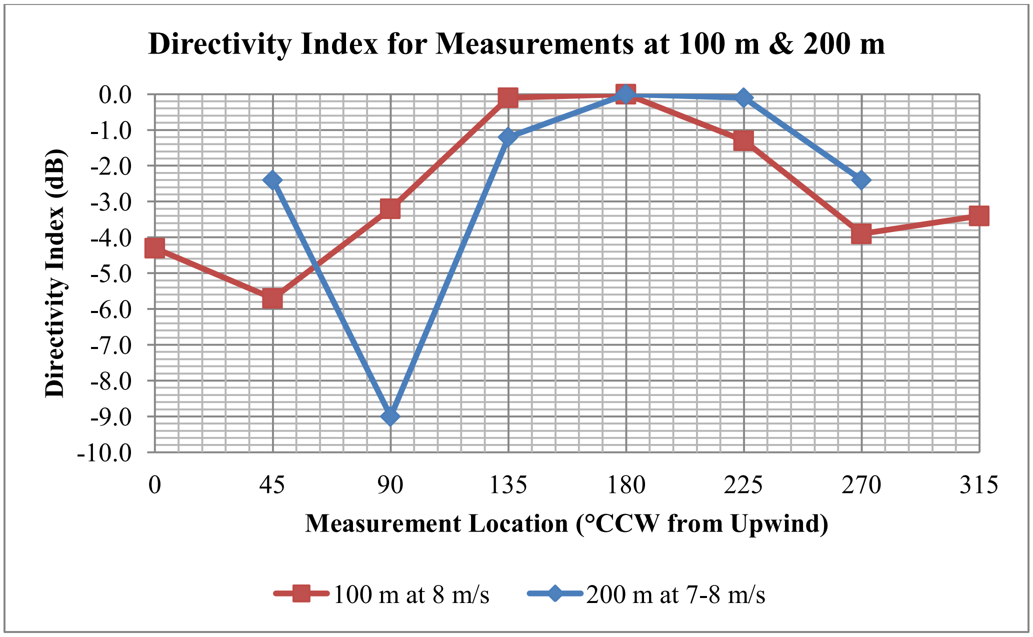


Figure 37: 100 m & 200 m Directivity Index at 8 m/s

With the understanding that wind turbine noise is directional, the question then arises as to whether this is true across all frequency bands or if certain portions are more directional than others. The question can be first addressed by reviewing the directivity index for overall levels using A, C, and G-weighting filters, as in Figure 38.

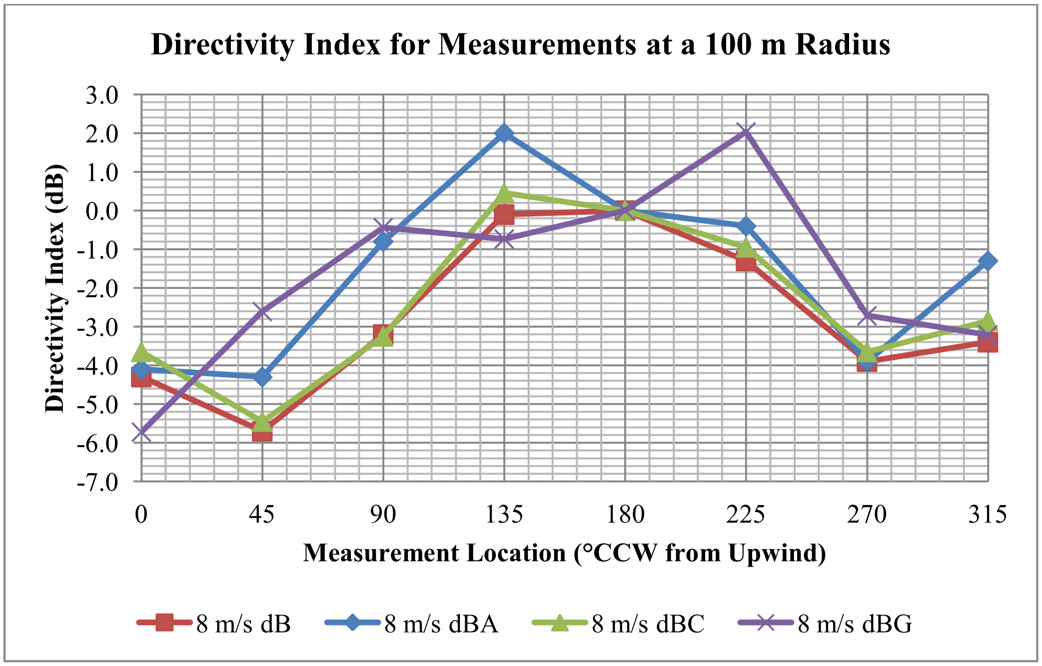


Figure 38: Directivity Index at 100 m and Various Weightings

A-weighting, which is the standard for most wind turbine noise measurements, indicated that the noise characteristic approaches having a directional characteristic at 135°, and in contrast to the linear analysis, the directional component may actually be higher than the measured level at 180° (downwind). As anticipated, C-weighted levels follow a directional trend that mirrors that of the linear values. This should support the cause for the use of C-weighting in wind turbine noise evaluation as there appears to be a significant portion of low frequency noise that is being lost or diminished with the application of the A-weighting filter. When G-weighting is applied, the infrasound component is not found to be as directional as the noise in the rest of the frequency spectrum. This is not surprising with the long wavelengths associated with infrasound and relatively short measurement distances used in this study. The dominant source in the vicinity of 16 Hz is within the infrasound domain and may not prove to be directional – meaning it may be just as relevant at 90° as at 180° and may be perceived at much longer distances than the rest of the emitted noise. The infrasound component does not appear to travel far in the upwind direction, but is otherwise within 3 dB of the 180° reference at the rest of the measurement locations. This is consistent with theory which suggests that infrasound is not highly directional, despite the fact that the rest of the frequency spectrum is. Further understanding of what frequency bands are important at each location around the turbine is gained from the spectral data in Figure 39.

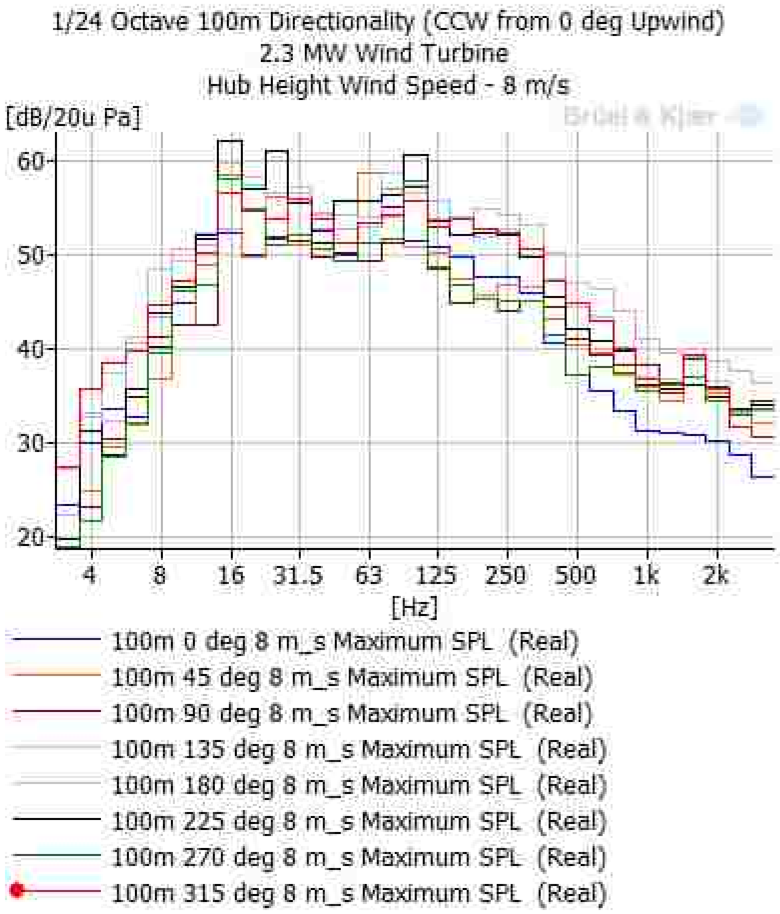


Figure 39: 1/3 Octave Directionality at 8 m/s

The 1/3 octave data supports the observation that 135°, 180°, and 225° are the receptor locations where the highest sound pressure levels are experienced. These three locations show results which are high across the frequency spectrum whereas other locations show high low frequency content but trail off above 125 Hz. Between 16-125 Hz, the prominent noise sources do prove to be directional. The levels at 225° are the highest, suggesting that this may be a measurement location of additional interest in the future. It may in fact prove to be a worse case than directly downwind, but more data is required to develop such a conclusion. To demonstrate consistency between multiple data sets, similar trends are observed in Figure 40 for a wind speed of 15 m/s. The levels at 225° are again the highest across much of the spectrum.

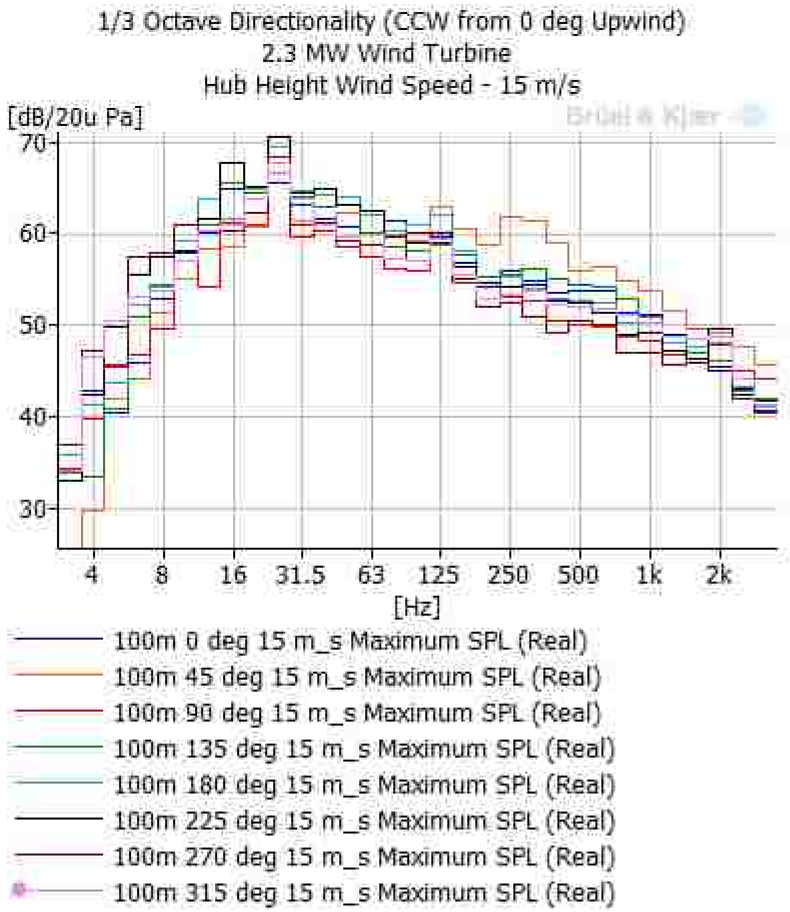


Figure 40: 1/3 Octave Directionality at 15 m/s

5.8 Wind Speed Dependency

Having considered the characteristics of wind turbine noise propagation and directivity, the final variable analyzed is the dependency of the emitted noise on wind speed. Emitted noise levels were shown in Section 5.1 to be highly dependent on wind speed. Several theoretical models contain a fifth power relationship between wind speed and sound power level. These models are often used to determine the contribution of particular higher frequency noise sources (i.e. trailing edge noise). Limited information exists for the contribution of low frequency sources and their relationship with wind speed.

It was observed empirically in the previous section that there is a definitive increase in sound pressure level with wind speed. The directional characteristic of the noise appears to be relevant at various wind speeds, although directivity index tends to decrease with increasing wind speed. It is then of value to understand whether increasing noise levels with wind speed occur at all frequencies, or perhaps the increases are most relevant in specific regions of the frequency spectrum.

Figure 41 displays 1/24 octave maximum sound pressure levels measured 100 m downwind at 8 m/s, 9 m/s, and 15 m/s. The 8 m/s and 9 m/s levels overlay well, as do the measurements at two turbines with a wind speed of 15 m/s. Across most of the frequency spectrum, an approximate 10 dB increase is observed between levels at 8 m/s and those at 15 m/s. A 10 dB increase represents a perceived doubling of loudness for an observer. Doubling the wind speed is therefore significant and results in a doubling of perceived loudness. Additional data is required to validate this observation, but the trend is observed here and in Figures 42-43 that follow. It was noted that this trend is valid over most of the frequency range, except at the frequencies where prominent noise sources were identified: 16 Hz, 31.5 Hz, 63-250 Hz, and 1700 Hz. At these points, the 8 m/s and 15 m/s data sets are much closer together and may differ by 5 dB or less. These sources are therefore found to be less dependent on wind speed than the rest of the signal.

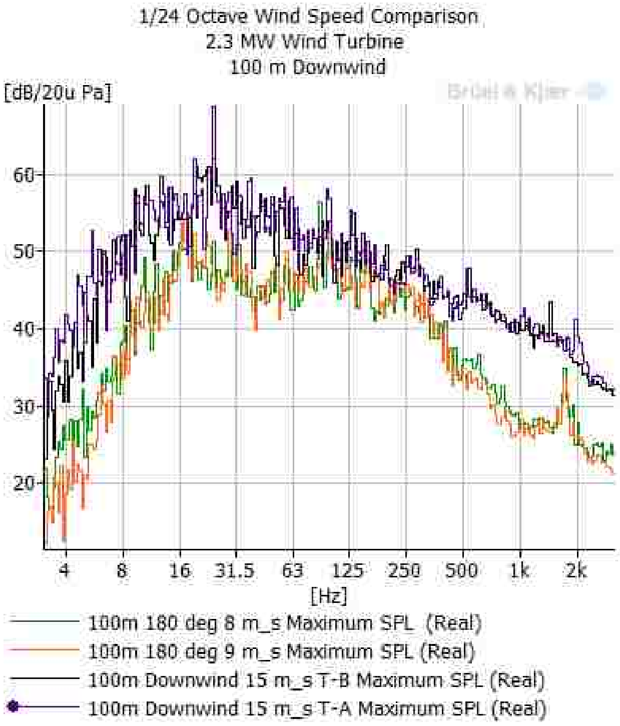


Figure 41: 1/24 Octave Wind Speed Comparison 100 m Downwind

The trends observed in Figure 41 are again evident in Figure 42 for measurements 200 m downwind at three wind speeds. The measurements at 6.5 m/s identified the primary sources to some degree, but were otherwise very close to background noise levels. At 200 m, a difference of about 10 dB between the 8 m/s and 15 m/s data sets is again observed. The separation remained larger at infrasound and high frequencies than the small differences in noise level observed over the low frequency band of 20-250 Hz. Infrasound levels at 100 m and 200 m were much higher at 15 m/s than at lower wind speeds. This cannot be completely attributed to wind turbine noise as a portion of it is likely infrasound present in the wind. The high wind speed lends in part to additional high frequency noise for similar reasons. A portion of the high frequency content would be related to the wind turbine, but the majority may actually come from additional acoustic energy in the atmosphere. Higher infrasound levels at 200 m than 100 m are noted, and may be attributed to long infrasonic wavelengths not having had sufficient time to fully develop over a 30 second measurement at 100 m. As the measurements were recorded, the infrasound component of the signal could be seen developing over the first 10-15 seconds and may have still been progressing at the end of the 30 second recording. A longer recording is highly recommended for future measurements interested in infrasound. If sufficiently long, this would also permit for the calculation of L_{eq}.

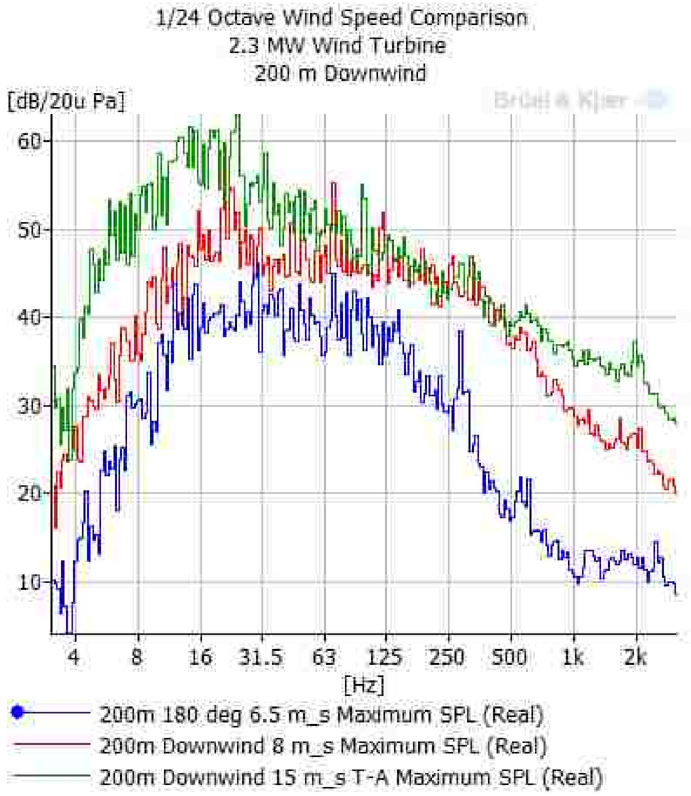


Figure 42: 1/24 Octave Wind Speed Comparison 200 m Downwind

One of the most interesting and perhaps relevant differences between the 100 m and 200 m data is in the low frequency domain. At 200 m, the range over which 8 m/s and 15 m/s levels are closer together is much wider, encompassing most frequencies between 16-500 Hz. In fact, sound pressure levels at both wind speeds overlay well from

63-500 Hz. This further reinforces the earlier observation that the low frequency component is less dependent on wind speed and is dominated by the primary sources identified at 16 Hz, 31.5 Hz, etc. The limited wind speed dependency at low frequencies suggests that the noise sources may be mechanical rather than aerodynamic in nature, although peak levels at 15 m/s do exceed those at 8 m/s. Future access to wind turbine operational data such as rotor speed, generator speed, and power output is likely to better support these conclusions. Assuming the rotor to have been operating at approximately a constant speed, the aerodynamic noise may prove to have more of a low frequency component than the current data reveals.

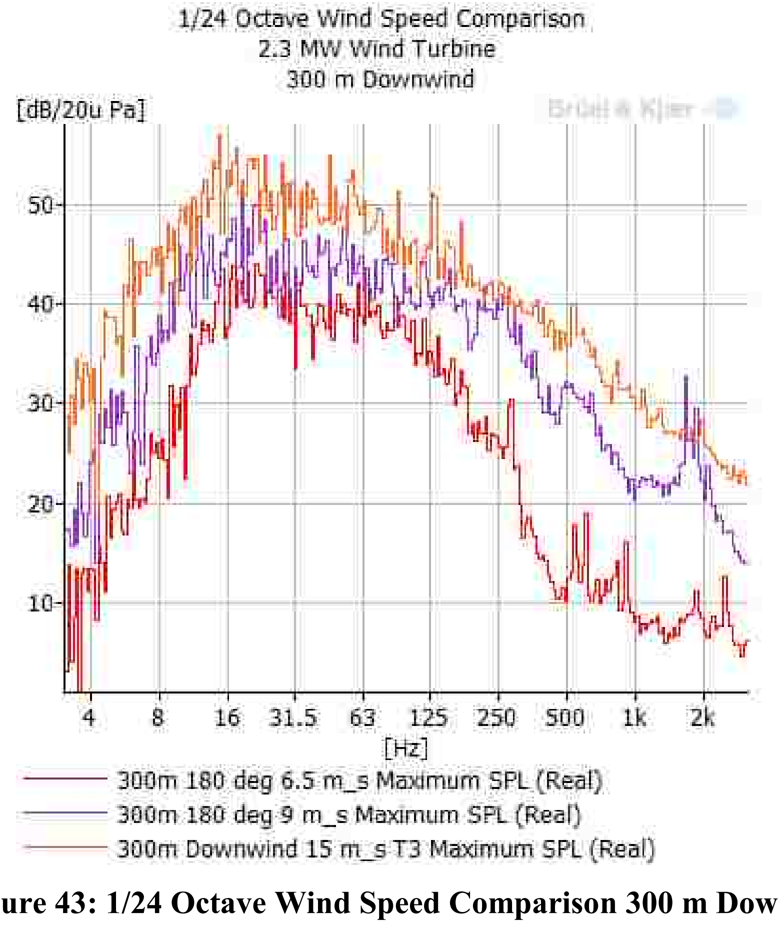


Figure 43: 1/24 Octave Wind Speed Comparison 300 m Downwind

The 300 m downwind data in Figure 43 represents similar trends to those observed at 100 m and 200 m. Infrasound and high frequency levels again reveal a 10 dB increase from 8 m/s to 15 m/s. The high frequency data begins to converge and often indicates a difference of only 5-8 dB between wind speeds. This can be attributed to much of the high frequency content having been absorbed or dissipated as the noise travels out to a 300 m receptor. Low frequency data between 16-125 Hz remains less dependent on wind speed than the rest of the frequency spectrum. This is consistent with the data at closer distances and is important because low frequency noise may occur in the audible range. The noise from low frequency sources has the potential to travel further distances than higher frequency emissions before being absorbed, and therefore may be relevant at long distances from a wind turbine, regardless of wind speed.

CHAPTER VI

PERCEPTION AND POTENTIAL IMPACT

The general trends, signal characteristics, downwind propagation, and directional properties of wind turbine noise were discussed in detail in Chapter 5. This information builds upon existing work to improve overall understanding of wind turbine noise. It offers some insight into opportunities to improve current wind turbine noise measurement practices and leads to additional research with noise source identification that could help wind farm operators improve operational efficiency. These are important moving forward but the most significant concern is whether the levels measured, under varying conditions, are relevant to a human or animal observer. This Chapter assesses the prominence of the sound and its potential impact on those in the vicinity of a turbine. The work presented focuses on audibility, particularly at low frequencies, and should be correlated with medical data in future research.

6.1 Field Observations

Numerous observations were made while recording measurements that support many of the trends discussed in Chapter 5 and reflect how the sound may actually be perceived. Three aspects of the subjective in-field evaluation were most prominent and reinforce the data presented in this study.

The first observation is the magnitude of the impact that variations in local wind speed have on wind turbine noise. Relatively small fluctuations in wind speed over a short time period resulted in a noticeable change in perception. It is not only small fluctuations in wind speed that effect perception, as the average wind speed also has an important role, especially for propagation distance. At wind speeds below 7 m/s, the noise appears to be relatively well masked by background levels and therefore is not well perceived beyond 200-300 metres. At wind speeds up to 15 m/s, the sound is masked to some degree by the louder background noise levels associated with high wind speeds. The conditions for the greatest potential for perception and thus impact on nearby residents appears to be a mid-range wind speed, when background levels are sufficiently low for the sound to be perceived at long distances. This may be even more important at night when background levels are often lower, but hub height wind speeds may be higher.

The second observation is the relative loudness of the 'power stroke' or 'swish' of a blade moving down from the top of a rotation, which is by far the dominant sound observed in the field. Given measured overall sound pressure levels of only 45-55 dBA, this sound can be much louder than expected, especially relative to the low background noise levels of rural areas. It is accompanied by a large amplitude modulation which makes the dominant source of wind turbine noise appear more like a non-steady signal.

A third important observation is that the directional nature of wind turbine noise is quite evident at different orientations to the axis of the nacelle. Limited higher frequency noise and some noise from the hub is audible at close distances and the 0°, 45°, and 315° angles. The audible noise is rapidly reduced between 45° and 90° before developing again moving toward a 135° orientation. In this quiet zone, the hum of the generator, cooling fans and other auxiliary equipment can be heard well at 100-200 m. Much less aerodynamic noise is audible in this range and in particular when at receptor locations perpendicular to the nacelle. The 135° to 225° range is generally perceived as the loudest with significant audible aerodynamic noise even at longer distances. From 225° through to 315° there is another quiet zone, although it is generally not as quiet as on the 90° side. These directional observations were all supported by the data presented in Chapter 5.

It can therefore be concluded that much of the analyzed data reflects the perceptions of the observed sound in the field. It is important to remember that wind speed is possibly the most important variable. At the mid-wind speed range, and at the MOE setback distance of 550 m, wind turbine noise was audible in the field to some degree. It was however, observed to be a fairly quiet distant noise source and it is unclear how well it would be perceived within a house at that distance. Field work at the MOE setback distance was only possible at low to mid-range wind speeds, as such, additional measurements are highly recommended. The following section analyzes the theoretical audibility of the noise with a particular emphasis on the low frequency noise sources discussed throughout this report.

6.2 Audibility

Audibility is important not only for human perception in the vicinity of a wind farm, but also for farm animals. Reports have emerged about illness, strange behaviour and decreased levels of milk production in cattle and goats. Animals can often hear much higher frequencies than humans, but may also see some impact at the low frequency end. Pure-tone hearing thresholds for humans [45] are presented in Figure 44 along with sample audiogram data for cattle and goats. [46]

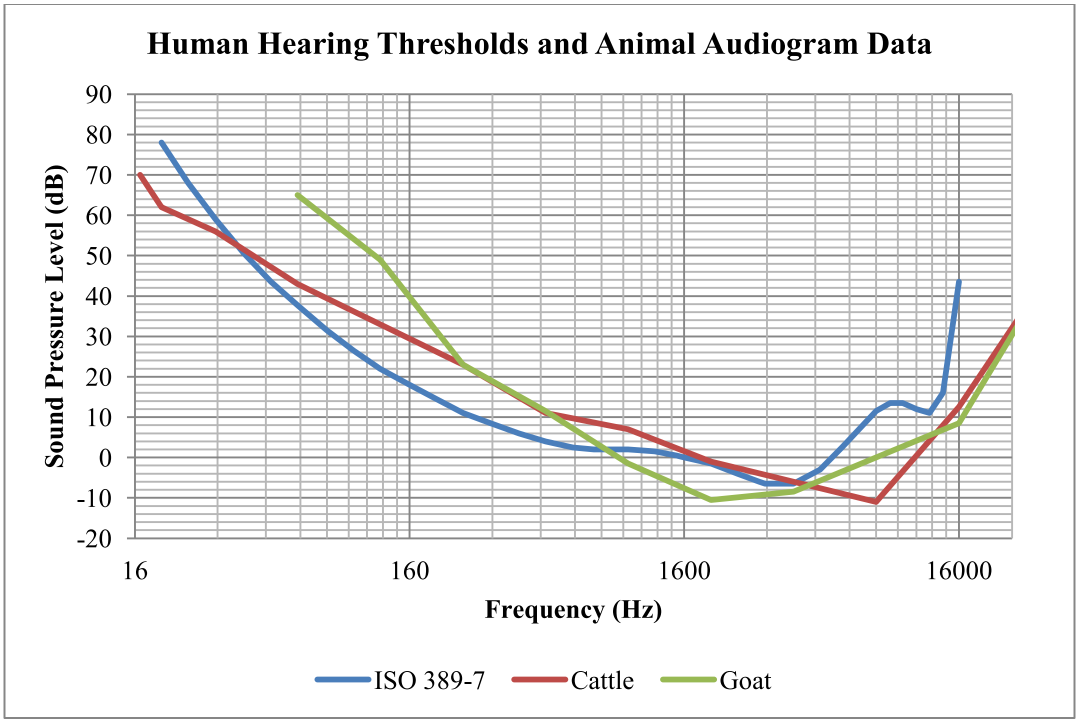


Figure 44: Human Hearing Thresholds and Animal Audiogram Data

According to the audiogram data, audible sound levels are lower for humans compared to that for cattle or goats over most of the low frequency range. The exception is below 40 Hz where cattle are more sensitive than humans. In the case of wind turbine noise, animals may be much closer to the turbines than the nearest human observer and would be subject to higher sound pressure levels. Figures 45-46 overlay 1/3 and 1/24 octave sound pressure levels with the hearing thresholds and audiogram data presented above. The data is presented at 550 m and 600 m to identify which components of the noise remain audible at the required MOE setback distance.

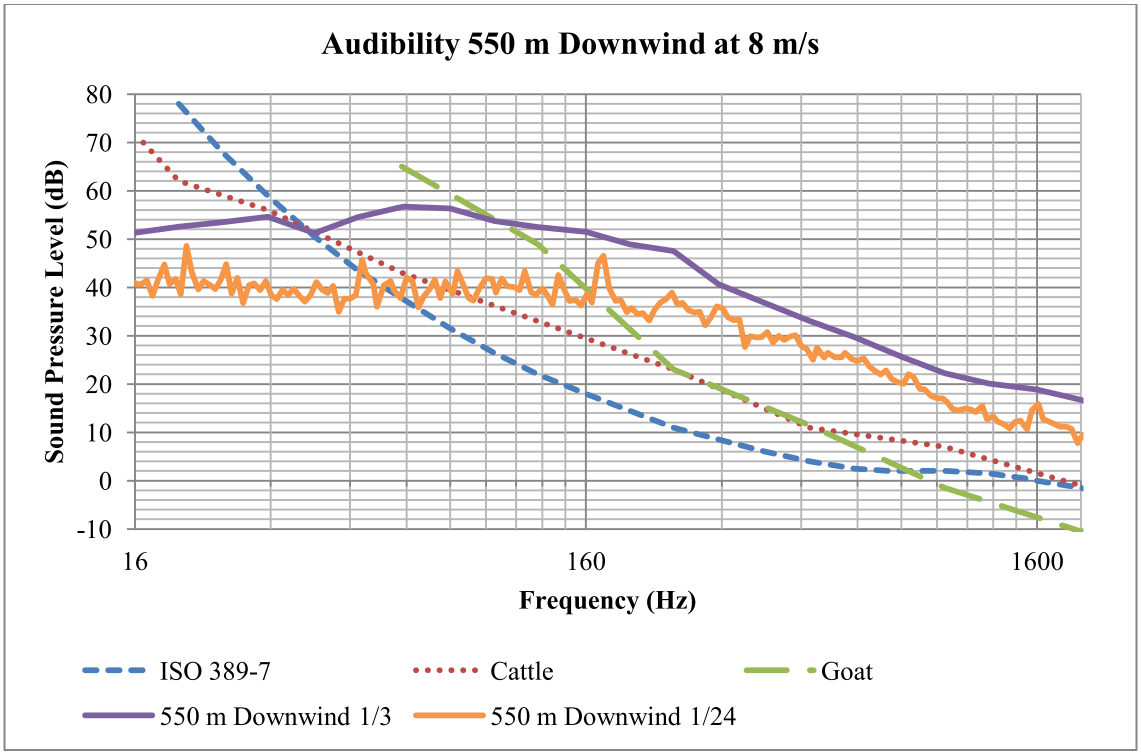


Figure 45: Audibility 550 m Downwind at 8 m/s

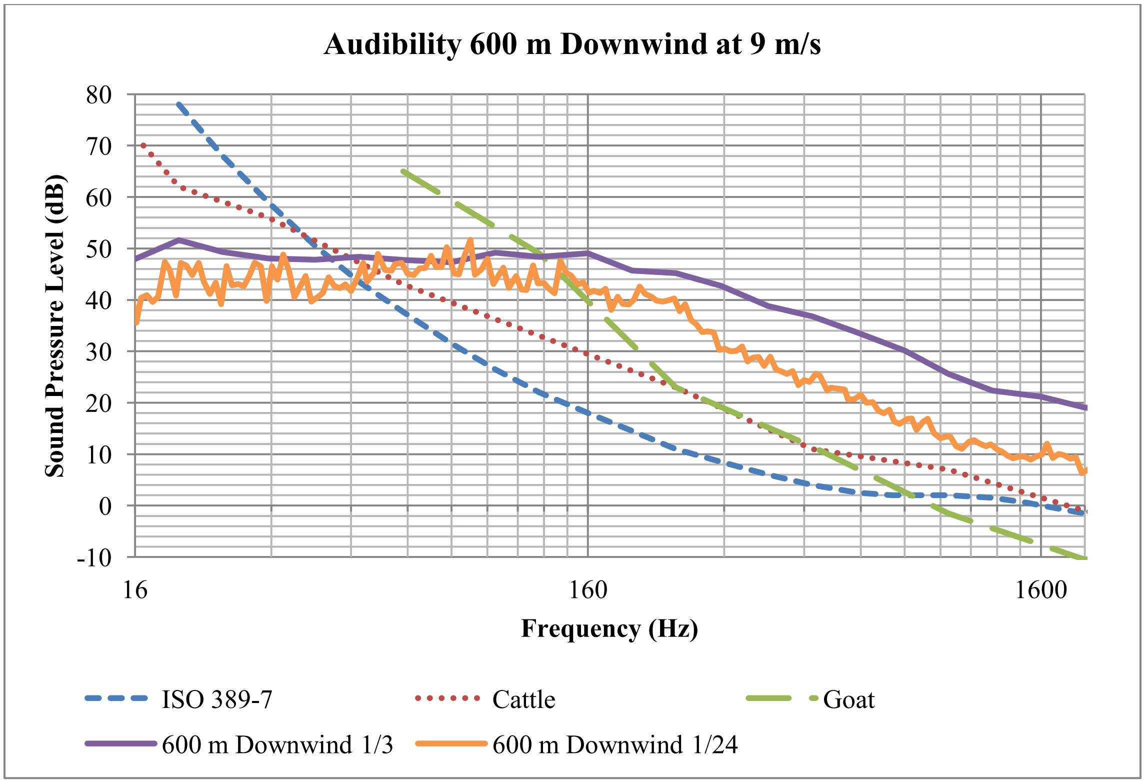


Figure 46: Audibility 600 m Downwind at 9 m/s

The 1/3 octave levels offer insight into general trends and characteristics of the noise, while 1/24 octave levels generally show lower levels but offer additional detail. Both are discussed here to increase the understanding of where wind turbine noise becomes audible. The 550 m and 600 m data sets display similar results with the noise becoming audible above 40 Hz (1/3 octave) and 50 Hz (1/24 octave). This is consistent with the hypothesis that wind turbine noise is likely to be audible above 30 Hz and indicates that the low frequency portion of the noise is in fact very important. Recall that at 550 m, overall A-weighted levels were within environmental regulations. A-weighting dramatically reduces the influence of the low frequency component, which in this case is observed to be significant over much of the low frequency range. The data further reveals that at the MOE setback distance, the noise is audible to cattle above 40 Hz and goats above 125 Hz. To gain improved understanding of the potential impact on animals closer to a wind turbine, the data for 200 m downwind is shown in Figure 47. In this case, the audibility limit shifts down to about 35 Hz for humans and 31.5 Hz for cattle.

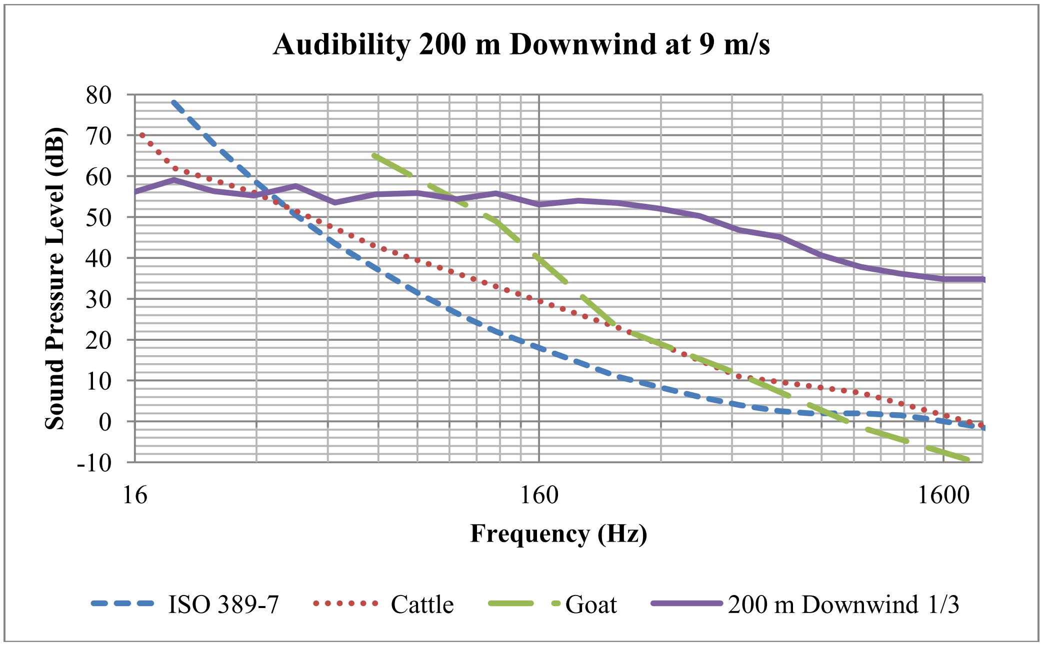


Figure 47: Audiblity 200 m Downwind at 9 m/s

It can be concluded that low frequency noise levels are sufficiently above 30-40 Hz to be audible by humans and cattle. Levels at identified key frequencies such as 63 Hz and 90-125 Hz are often as much as 10-20 dB above the audible threshold. The potential for an audible disturbance or annoyance due to low frequency noise is therefore quite real in the vicinity of a wind turbine. Fluctuations of 5-10 dB have been observed at key frequencies over the course of a noise measurement. Given that a small fluctuation at low frequencies can be perceived as a larger disturbance than the same fluctuation at high frequencies, the potential for impact on humans or farm animals exists. The potential impact is likely in the form of annoyance, which if unresolved, can lead to further complications.

Future research must consider the low frequency component more closely to amass additional data and correlate it with the data and understanding of medical experts. There is a further need to identify the mechanical or aerodynamic sources associated with noise at these frequencies. This presents an opportunity to not only mitigate the emitted noise, but perhaps increase the operational efficiency of the wind farm.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

As wind energy development continues to increase around the world, communities are looking for solutions and improved understanding of the effects of wind turbine noise issues. To identify opportunities and understand the issue in its entirety, unbiased scientific evaluations of the noise are required. The importance of this is reinforced by the fact that there are individuals who may suffer daily from the presence of wind turbine noise. Regardless of whether this is an issue that affects only a hypersensitive group within society or the larger population, due diligence is required to increase understanding. It is believed that the work reported here offers some additional understanding to this effect.

This research has implications beyond the potential for health issues. Further understanding may help farmers better understand why their animals behave a particular way, not just in the presence of wind turbine noise but also in the presence of other similar noise sources. A fundamental understanding of the characteristics of wind turbine noise, under an array of conditions, presents an immense opportunity for wind turbine operators and manufacturers as well. The fundamentals can be used to enhance understanding of noise source identification results that identify the particular noise sources on a turbine. These may lead to early detection of potential failures or changes in operational strategy that reduce noise and increase efficiency. Similarly, detailed noise studies have the potential to help manufacturers understand how their machines are operating in the field and identify opportunities for improvements with future models. From which ever perspective wind turbine noise is viewed, there are opportunities to build knowledge and keep driving the industry forward in a sustainable manner. The conclusions and suggestions and future work that follow serve to enhance current knowledge and present a few of the opportunities for the future.

7.1 Conclusions

Field noise measurements conducted as part of this study proved to be consistent between measurements on different days, at different turbines, and under changing conditions. The reported data was further found to be coherent with much of that observed in previous studies on wind turbine noise discussed in the Literature Review. Analyses were conducted to look at three key areas: sound propagation distance, directivity, and wind speed dependency. The data allowed for observations to be made on the wind turbine noise, particularly in the low frequency spectrum. It was shown that low frequency wind turbine noise is audible for humans and farm animals and has the potential to cause annoyance or other disturbances. This is contradictory to many other reports which often disregard the low frequency spectrum due to low A-weighted levels which may be in accordance with regional regulations. Many of the key noise sources were identified in the 20–250 Hz range, providing further justification of the important role low frequencies should have in future research and analyses.

Downwind sound propagation had been examined in previous reports, but this study is believed to be unique in that propagation was studied incrementally from the base of the wind turbine out to the required MOE setback distance of 550 m. The 100 m incremental measurement locations permitted the propagation behaviour and characteristics of the noise to be assessed in greater detail. The results indicated that spherical sound propagation is a good estimation as a decrease of 5-6 dB per doubling of distance was commonly observed in the field. Ground absorption is likely responsible for the sound level dissipation rate being slightly less than 6 dB per doubling of distance (for theoretical spherical propagation) in most cases. The exception was between 100 m and 200 m where the decrease was at most 3 dB and often barely changed at all, probably due to near field effects. Between 100 m and 550 m, a decrease of 10 dB or a halving of loudness was observed.

Infrasound and low frequency levels were analyzed in detail and showed relatively conclusive results. At a wind speed of 15 m/s and 100 m from the turbine, infrasound levels only reached a maximum of 81 dBG. This approaches the human perception limit at 85 dBG, but also decreases rapidly moving away from the turbine and thus is not believed to be relevant at distances where people reside. The low frequency component proved to be far more relevant, with results showing a fundamental frequency at 16 Hz and additional prominent sources at 31.5 Hz, 63 Hz, 90-125 Hz, 250 Hz and 1700 Hz. The vast majority of these occur within the low frequency domain and are often at levels which exceed audible thresholds. These low frequency sound pressure levels experience frequent fluctuations that increase the likelihood of disturbance or annoyance for an observer. It was further determined that wind turbine noise is audible for humans and cattle above 40 Hz at the MOE setback distance of 550 m. The audible threshold shifts to noise above 30-35 Hz at a distance of 200 m from the turbine. This indicates that the low frequency component of wind turbine noise is relevant and requires much additional study for complete understanding. The dominant source at 16 Hz was not included in this analysis as it occurs within the infrasound range and, by applying the G-weighted filter, is typically found to be inaudible. Nonetheless, sound pressure levels at

16 Hz are high and experience large fluctuations. It should be considered a source to analyze in further detail in the future for its possibility to be perceived by the body in other ways.

Wind turbine noise also proved to be highly directional. The location 90° counter-clockwise from upwind was consistently identified as one of the quietest and the range from 135° to 225° was found to be the loudest. Thus current downwind measurements and those suggested 45° either side of the downwind location are well selected for a ‘worst case’ noise measurement. The 225° measurement location may prove to be of additional importance if the data of this study is reinforced by future work at other turbines. It may in fact be a better measurement location for a worst case scenario than at 180° (downwind). To improve existing standards, it may be beneficial for measurements to be recorded at 135°, 180°, and 225° in order to ensure that the initial downwind (180°) measurements are accurate and representative of the true noise emissions.

Regardless of measurement distance, or orientation around the turbine, the data shows that wind speed is the most important variable. Wind turbine noise proved to be highly dependent on wind speed. An increase of 10 dB was observed across the frequency spectrum as wind speed doubled from 8 m/s to 15 m/s. Therefore, a doubling in wind speed is concluded to result in roughly a doubling in perceived loudness. This was demonstrated to be true at infrasound and high frequency levels, but not in the 20-250 Hz low frequency range. The low frequency range appeared to be relatively independent of wind speed. In fact, levels at wind speeds of 8 m/s and 15 m/s were within a few dB in the low frequency domain – a trend that remained valid at various distances from the turbine.

The analysis and results observed in this study offer additional significant insight into wind turbine noise. Improved understanding of the characteristics of wind turbine noise propagation and directionality should be used to assist with site planning for future turbines, or analysis and comparison of data measured at existing units. The key low frequencies (16 Hz, 31.5 Hz, etc.) detailed throughout the study must be pursued in future research to identify their mechanical or aerodynamic sources and whether they exist at similar frequencies for other turbine models and sizes. The acknowledgement that wind turbine noise is audible, with the potential for annoyance, in the low frequency domain is critical for future research. The low frequency component should therefore become a greater focus, not only of future research around the world, but also in the development of next generation measurement standards and governmental regulations.

7.2 Summary of Conclusions

Many variables were considered in this study of wind turbine noise. As such, numerous observations were made which lead to specific conclusions throughout the report. The most important observations and their resultant conclusions are summarized in the list that follows. These conclusions enhance current knowledge of the characteristics of wind turbine noise and lead to future research detailed in Section 7.3.

- Data was found to follow consistent trends at most wind speeds and distances and was repeatable across measurements at different turbines on separate days
- Prominent noise sources appear in the vicinity of: 16 Hz, 31.5 Hz, 63 Hz, 90 Hz, 125 Hz, 250 Hz, 1700 Hz
- Smallest standard deviations observed in the low frequency domain (20-150 Hz)
- A decrease of approximately 10 dB is observed between 100 m and 550 m
- Spherical propagation at 5-6 dB per doubling of distance
- Maximum infrasound level observed was 81 dBG at 100 m from the turbine
- dBC-dBA > 20 dB metric for low frequency noise issue varied between 10-18 dB
- Sound pressure levels between 20-125 Hz can be as high at 600 m as at 100 m
- The high frequency component of the noise decreases quickly beyond 300 m
- Wind turbine noise is highly directional, although infrasound is to a lesser degree
- Directivity appears to decrease with increasing wind speed
- 90° CCW from upwind observed to be the quietest while 180° and 225° loudest
- Wind turbine noise determined to be highly dependent on wind speed
- Doubling the wind speed resulted in a 10 dB increase, or a doubling in loudness

- The low frequency portion, and in particular the sources at 16 Hz, 31.5 Hz, 90-125 Hz, and 1700 Hz, was found to be almost independent from wind speed
- Wind turbine noise is audible at frequencies above 40 Hz (for humans and cattle) at the current 550 m MOE setback distance
- Closer to the turbine, at 100-200 m, wind turbine noise is audible above 30-35 Hz

7.3 Recommendations for Future Work

Wind turbine noise is a complex issue with many sensitive and not well understood variables. This study offered much additional insight into the characteristics of wind turbine noise and new developments into the relevance of its low frequency component. These are important to advancing the understanding of wind turbine noise and reveal many more research opportunities. A few research areas of importance to further this study in future work are presented in below, in no specific order.

1. Noise source identification techniques should be used to identify the mechanical or aerodynamic noise sources associated with the key frequencies at 16 Hz, 31.5 Hz, etc. presented in this study. A special microphone array and analysis techniques may be required as current measurement technologies are generally designed for higher frequencies.
2. In order to understand the various mechanisms of wind turbine noise and identify opportunities to increase the efficiency of turbine operation, noise source identification techniques should be used to identify sources across the entire frequency spectrum. The addition of continuous noise monitoring could further assist with identifying maintenance issues or potential failures before they occur.
3. To fully understand the noise sources and operational variables which impact noise emissions, the measured data must be correlated with the operational data of the turbine such as blade angle, rotor speed, generator speed, etc.
4. Incremental sound propagation measurements must be recorded at further distances, additional wind speeds, and during different seasons to validate the results observed in this study. The ability to measure the noise accurately at

distances up to 1-2 km will show how far the low frequency component can travel and may lead to the development of new setback distances.

5. Incremental directionality measurements must be performed at more angles, further distances, additional wind speeds, and during different seasons to validate the data presented in this study. The data may lead to better measurement locations for assessment than the downwind location specified today. The low and high frequency components should be separated in the analysis as it is likely that the high frequency component will demonstrate more directionality than the low frequency noise.
6. Health Canada and other medical research groups around the world are performing detailed reviews to assess the potential impact wind turbine noise may have on public health. Correlation of measured data with medical studies is imperative to accurately determine the degree to which wind turbine noise poses a risk for annoyance or other health impacts.
7. Low frequency wind turbine noise was determined to be prominent and audible in this study. Current metrics for assessing the potential for a low frequency noise issue (i.e. dBC-dBA > 20 dB) are insufficient. The development of additional metrics or methods for identifying potential low frequency noise or infrasound issues would be greatly beneficial. These could apply to applications beyond wind turbine noise.

It is anticipated that through the continuing work of the Wind and Renewable Energies Centre for Expertise at the University of Windsor, this study will help communities, individuals and operators better understand wind turbine generated noise. It will also lead to more focused research activities offering benefits to nearby residents with reduced noise emissions and to farm operators for increased efficiency. Wind turbine noise monitoring truly is a win-win situation for the community and the wind farm, and should always be viewed in that manner. This will ensure a strong future for the wind energy industry with a minimized impact on people and the environment.

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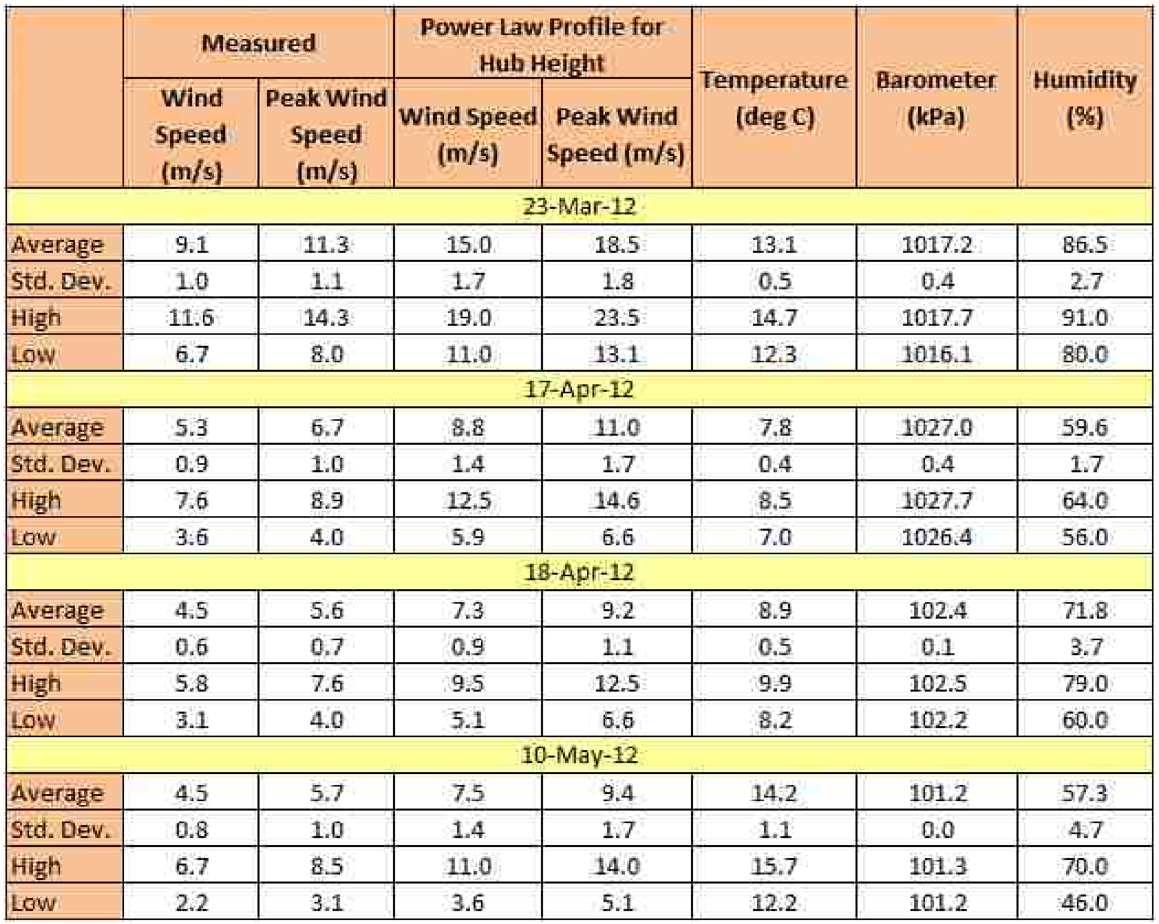
APPENDICES

APPENDIX A

Atmospheric Conditions & Meteorological Data



	Measured		Power Law Profile for Hub Height		Temperature (deg C)	Barometer (kPa)	Humidity (%)
	Wind Speed (m/s)	Peak Wind Speed (m/s)	Wind Speed (m/s)	Peak Wind Speed (m/s)			
23-Mar-12							
Average	9.1	11.3	15.0	18.5	13.1	1017.2	86.5
Std. Dev.	1.0	1.1	1.7	1.8	0.5	0.4	2.7
High	11.6	14.3	19.0	23.5	14.7	1017.7	91.0
Low	6.7	8.0	11.0	13.1	12.3	1016.1	80.0
17-Apr-12							
Average	5.3	6.7	8.8	11.0	7.8	1027.0	59.6
Std. Dev.	0.9	1.0	1.4	1.7	0.4	0.4	1.7
High	7.6	8.9	12.5	14.6	8.5	1027.7	64.0
Low	3.6	4.0	5.9	6.6	7.0	1026.4	56.0
18-Apr-12							
Average	4.5	5.6	7.3	9.2	8.9	102.4	71.8
Std. Dev.	0.6	0.7	0.9	1.1	0.5	0.1	3.7
High	5.8	7.6	9.5	12.5	9.9	102.5	79.0
Low	3.1	4.0	5.1	6.6	8.2	102.2	60.0
10-May-12							
Average	4.5	5.7	7.5	9.4	14.2	101.2	57.3
Std. Dev.	0.8	1.0	1.4	1.7	1.1	0.0	4.7
High	6.7	8.5	11.0	14.0	15.7	101.3	70.0
Low	2.2	3.1	3.6	5.1	12.2	101.2	46.0

Figure A1: Summary of Atmospheric Conditions and Meteorological Data

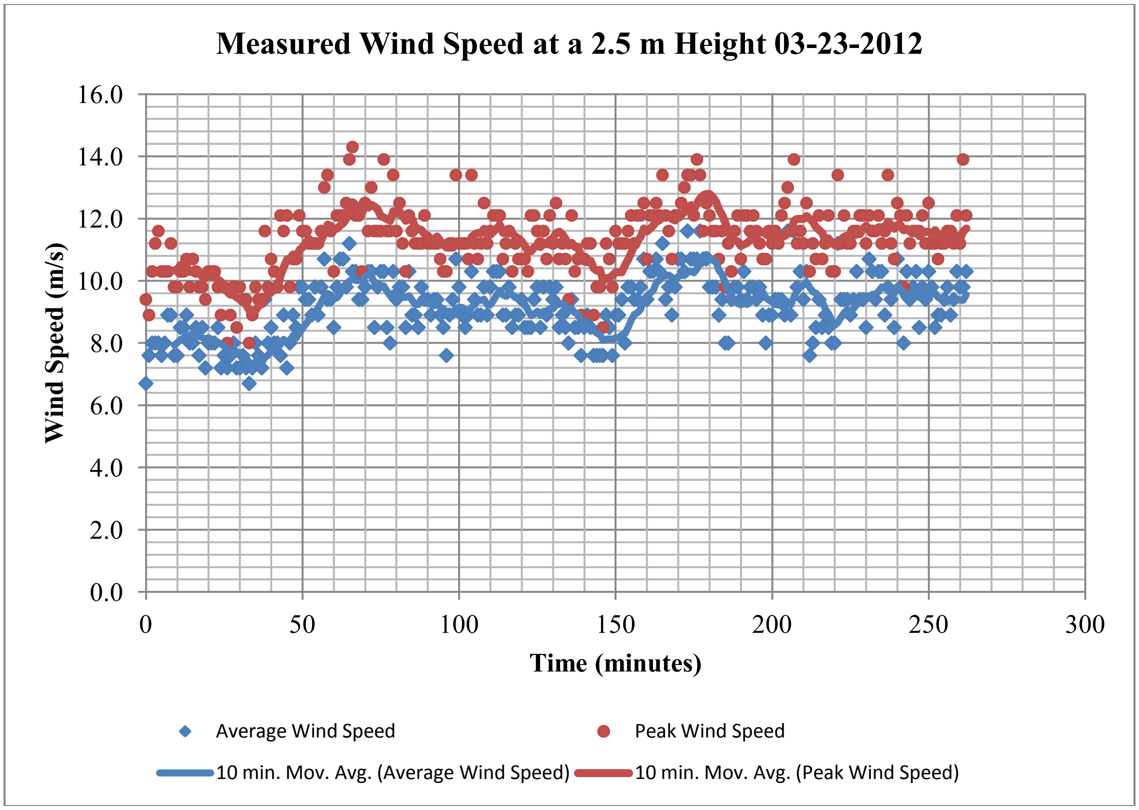


Figure A2: Measured Wind Speed 03-23-2012

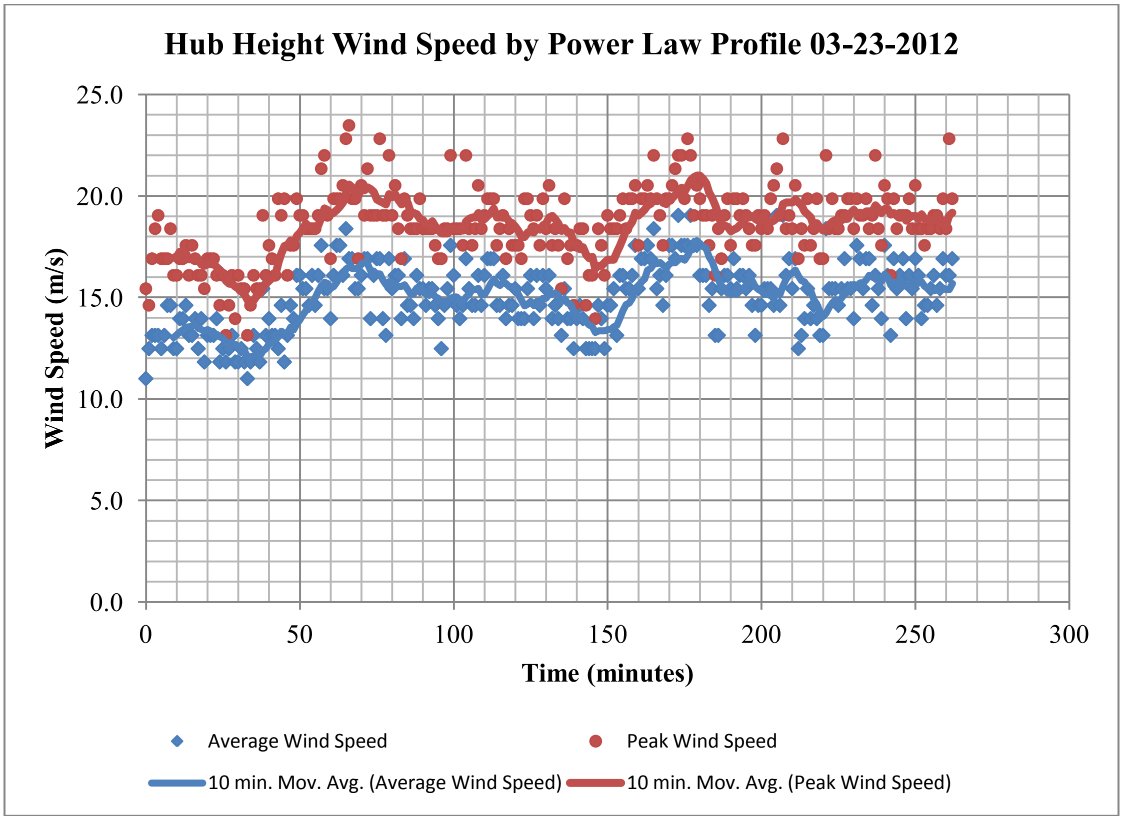


Figure A3: Power Law Hub Height Wind Speed 03-23-2012

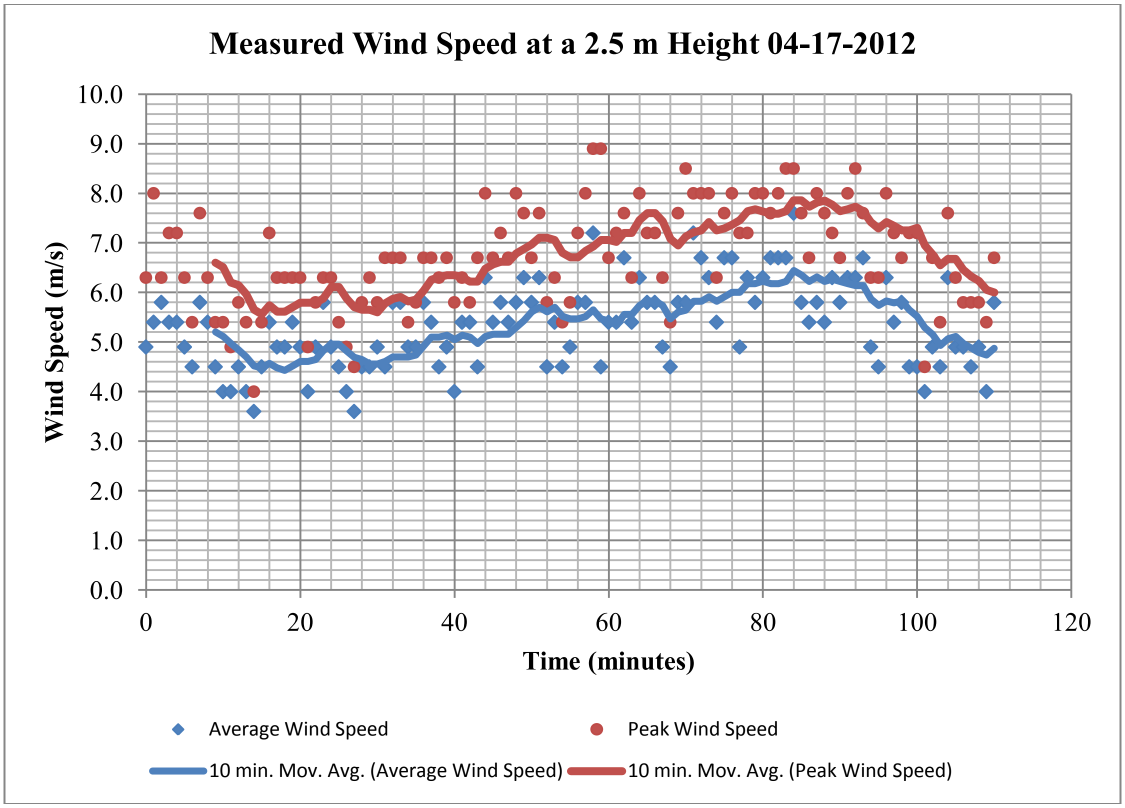


Figure A4: Measured Wind Speed 04-17-2012

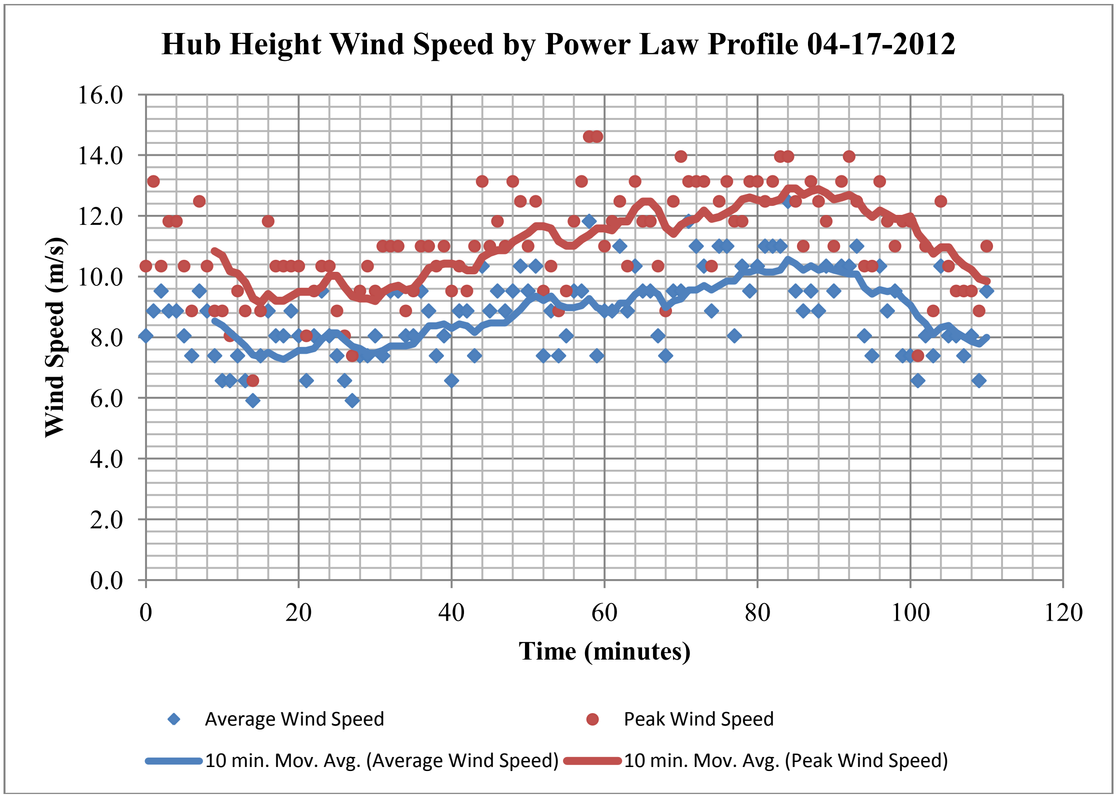


Figure A5: Power Law Hub Height Wind Speed 04-17-2012

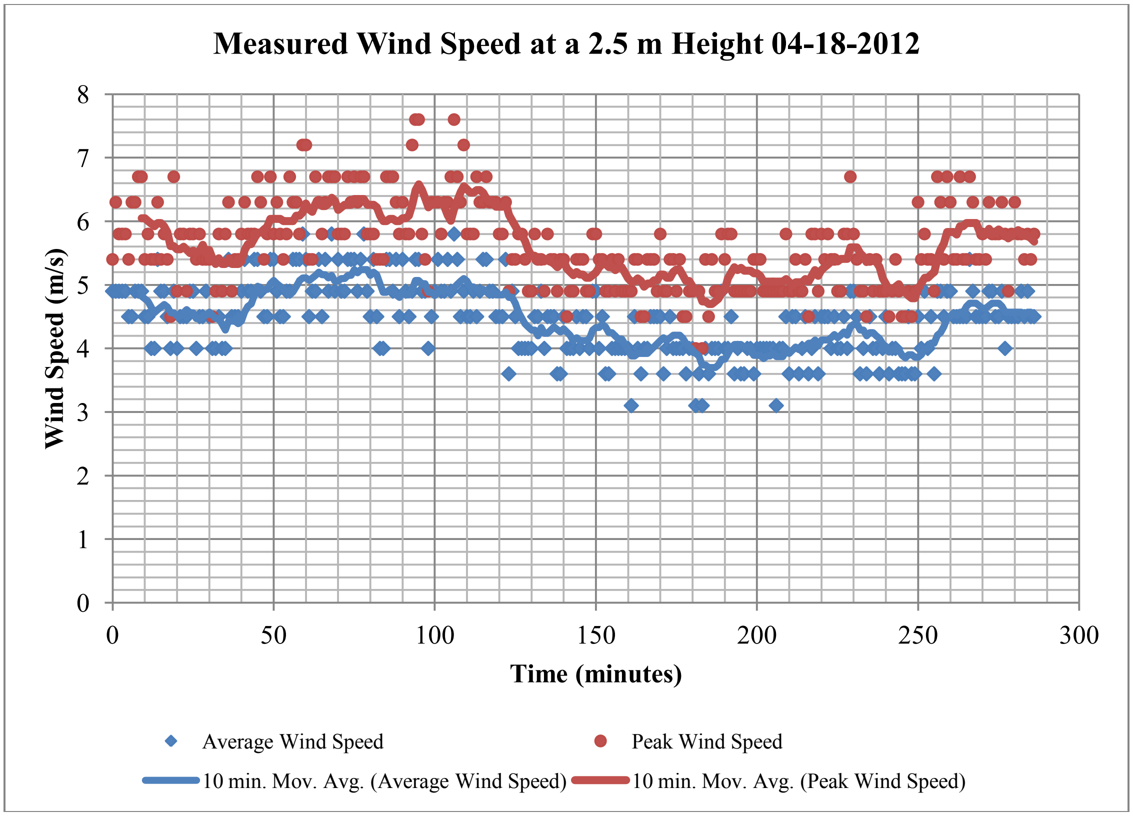


Figure A6: Measured Wind Speed 04-18-2012

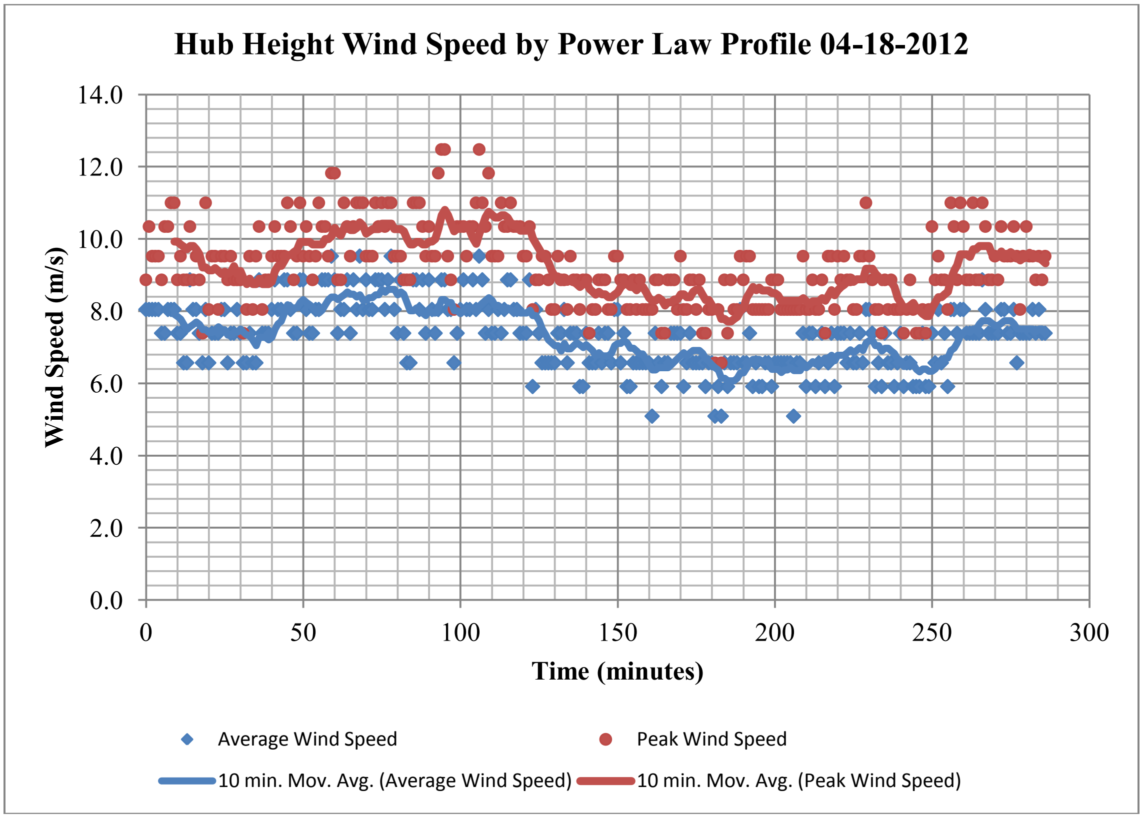


Figure A7: Power Law Hub Height Wind Speed 04-18-2012

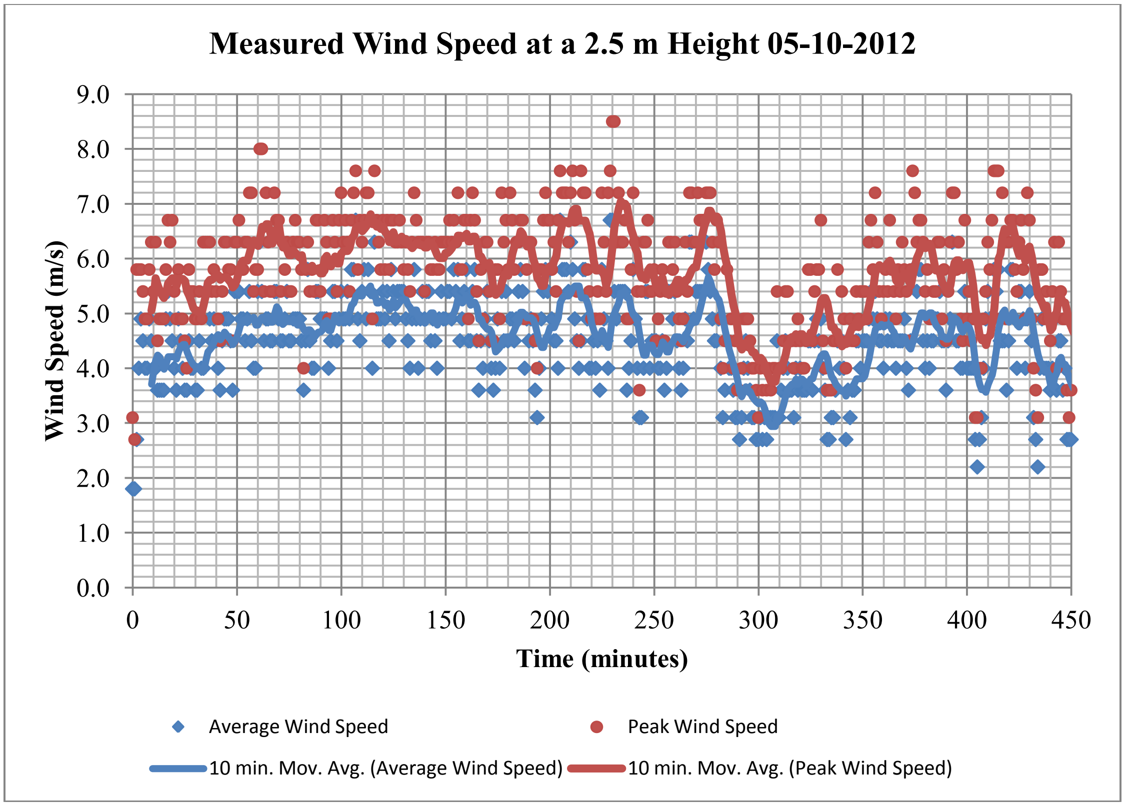


Figure A8: Measured Wind Speed 05-10-2012

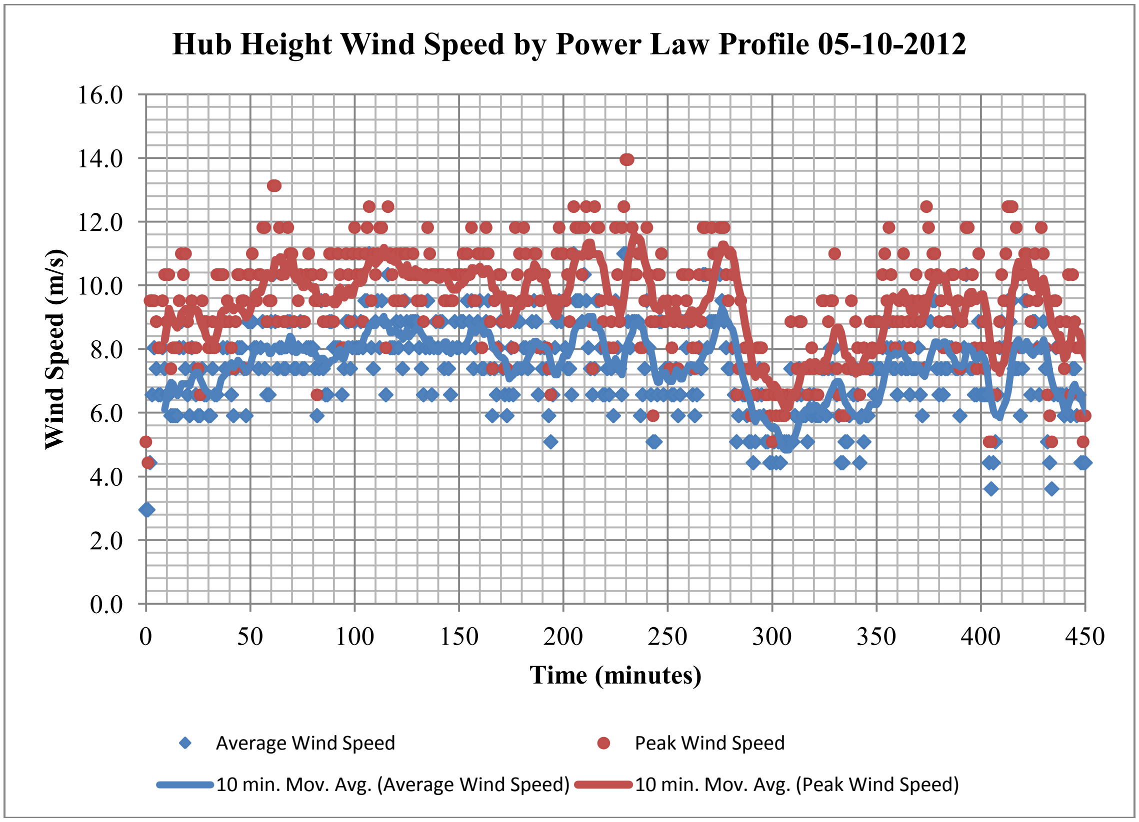


Figure A9: Power Law Hub Height Wind Speed 05-10-2012

APPENDIX B

Downwind Sound Propagation Data

100 m Downwind 8 m/s							**Max**	**Average**	
Overall L:	63.8	64.8	59.8	68.4	66.6	67.0	68.4	65.1	**dB**
Overall A:	47.4	48.0	42.3	52.9	51.3	51.6	52.9	48.9	**dBA**
Overall C:	61.4	62.0	57.3	65.4	64.4	64.2	65.4	62.5	**dBC**
Overall G:	73.0	66.3	59.4	71.6	69.0	72.4	73.0	68.6	**dBG**

Figure B1: 100 m Downwind Overall Levels at 8 m/s Hub Height Wind Speed

200 m Downwind 8 m/s						**Max**	**Average**	
Overall L:	63.1	65.4	65.5	66.7	64.0	66.7	64.9	**dB**
Overall A:	47.3	49.1	52.3	52.8	47.5	52.8	49.8	**dBA**
Overall C:	60.3	62.7	63.6	64.5	61.0	64.5	62.4	**dBC**
Overall G:	63.6	68.2	70.4	68.4	66.3	70.4	67.4	**dBG**

Figure B2: 200 m Downwind Overall Levels at 8 m/s Hub Height Wind Speed

300 m Downwind 8 m/s						**Max**	**Average**	
Overall L:	64.2	59.5	62.4	63.8	63.8	64.2	62.7	**dB**
Overall A:	48.9	43.0	48.5	47.6	49.5	49.5	47.5	**dBA**
Overall C:	61.6	57.0	60.4	60.8	61.7	61.7	60.3	**dBC**
Overall G:	66.0	64.0	63.8	66.2	67.2	67.2	65.4	**dBG**

Figure B3: 300 m Downwind Overall Levels at 8 m/s Hub Height Wind Speed

400 m Downwind 8 m/s						**Max**	**Average**	
Overall L:	60.5	60.0	61.0	61.4	59.7	61.4	60.5	**dB**
Overall A:	43.1	44.5	45.9	47.0	43.3	47.0	44.8	**dBA**
Overall C:	57.6	57.2	58.4	59.7	56.8	59.7	57.9	**dBC**
Overall G:	65.6	64.0	64.1	62.7	62.9	65.6	63.9	**dBG**

Figure B4: 400 m Downwind Overall Levels at 8 m/s Hub Height Wind Speed

500 m Downwind 8 m/s						**Max**	**Average**	
Overall L:	61.6	56.9	56.5	58.8	57.5	61.6	58.3	**dB**
Overall A:	44.7	40.1	38.6	44.1	40.4	44.7	41.6	**dBA**
Overall C:	58.8	54.3	54.0	56.5	54.5	58.8	55.6	**dBC**
Overall G:	63.9	62.2	57.4	61.2	60.9	63.9	61.1	**dBG**

Figure B5: 500 m Downwind Overall Levels at 8 m/s Hub Height Wind Speed

550 m Downwind 8 m/s						**Max**	**Average**	
Overall L:	58.2	58.5	57.7	57.4	57.4	58.5	57.8	**dB**
Overall A:	43.2	42.9	41.4	41.1	40.6	43.2	41.8	**dBA**
Overall C:	56.0	56.6	55.8	54.9	54.8	56.6	55.6	**dBC**
Overall G:	61.8	60.1	58.4	61.3	62.3	62.3	60.8	**dBG**

Figure B6: 550 m Downwind Overall Levels at 8 m/s Hub Height Wind Speed

1/3 Octave Maximum Overall Sound Pressure Levels Downwind 8 m/s				
m	**dB**	**dBA**	**dBC**	**dBG**
100	68.4	52.9	65.4	73.0
200	66.7	52.8	64.5	70.4
300	64.2	49.5	61.7	67.2
400	61.4	47.0	59.7	65.6
500	61.6	44.7	58.8	63.9
550	58.5	43.2	56.6	62.3

Figure B7: Summary of Maximum Overall Levels at 8 m/s Hub Height Wind Speed

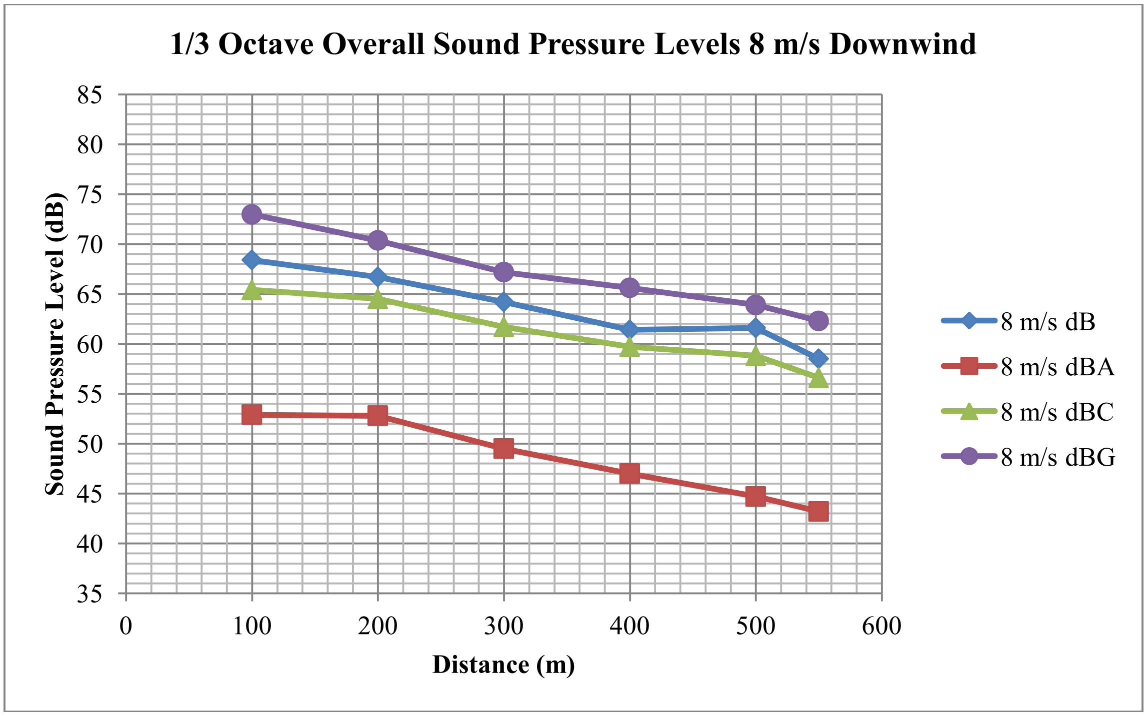


Figure B8: Downwind Maximum Overall Sound Pressure Levels at 8 m/s Hub Height Wind Speed

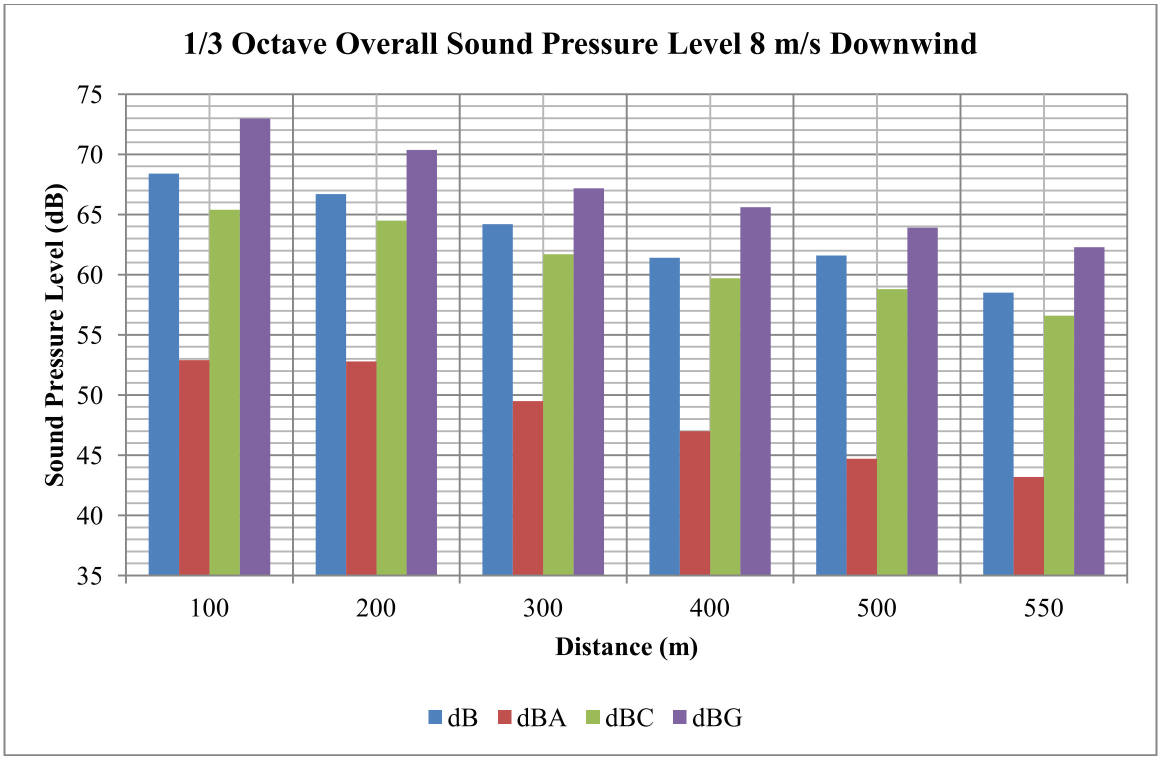


Figure B9: Downwind Maximum Overall Sound Pressure Levels at 8 m/s Hub Height Wind Speed

Downwind 9 m/s							
	100 m	**100 m**	**200 m**	**200 m**	**300 m**	**300 m**	
Overall L:	65.7	66.3	64.6	64.4	62.9	64.2	**dB**
Overall A:	49.7	49.6	49.5	48.2	44.9	46.6	**dBA**
Overall C:	63.4	63.4	62.1	61.5	60.0	61.0	**dBC**
Overall G:	69.2	68.1	68.3	69.6	67.4	64.8	**dBG**
	400 m	**400 m**	**500 m**	**500 m**	**600 m**	**600 m**	
Overall L:	60.7	61.1	61.5	61.6	60.8	63.7	**dB**
Overall A:	41.6	42.3	43.8	43.4	39.2	47.0	**dBA**
Overall C:	57.5	58.2	59.4	65.1	57.0	61.9	**dBC**
Overall G:	64.5	64.2	64.4	64.2	64.6	63.5	**dBG**

Figure B10: Downwind Overall Sound Pressure Levels at 9 m/s Hub Height Wind Speed

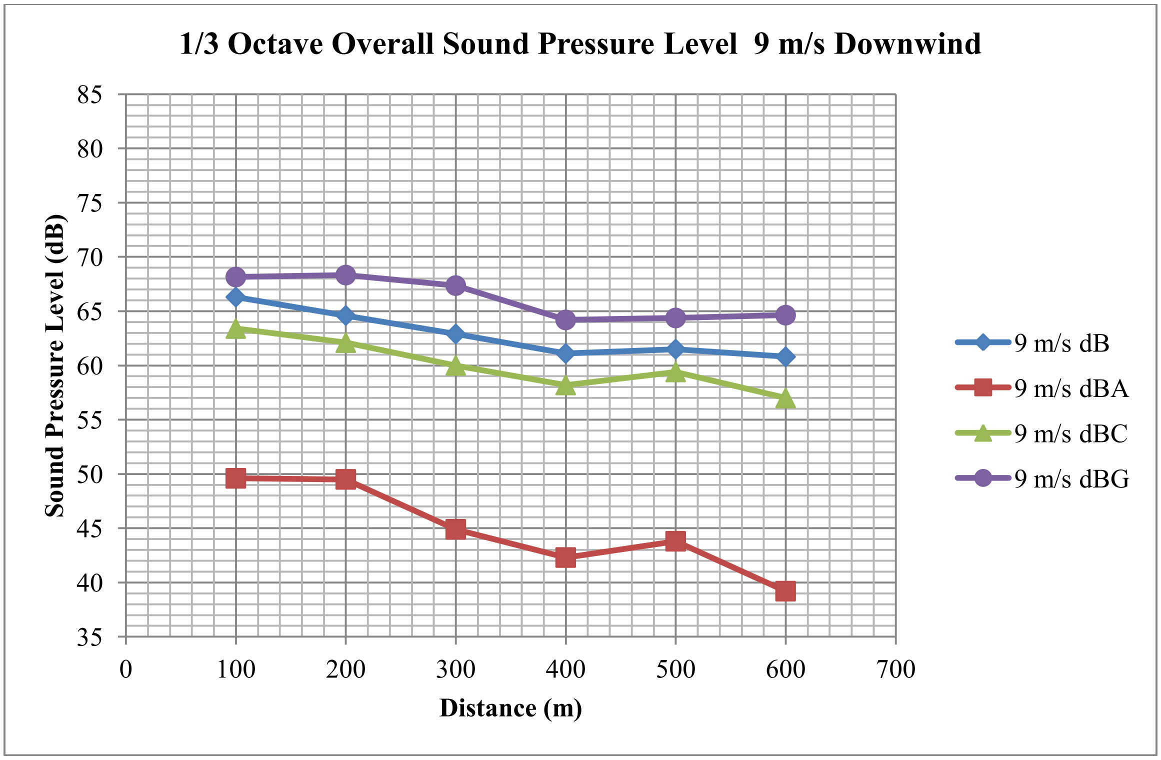


Figure B11: Downwind Maximum Overall Sound Pressure Levels at 9 m/s Hub Height Wind Speed

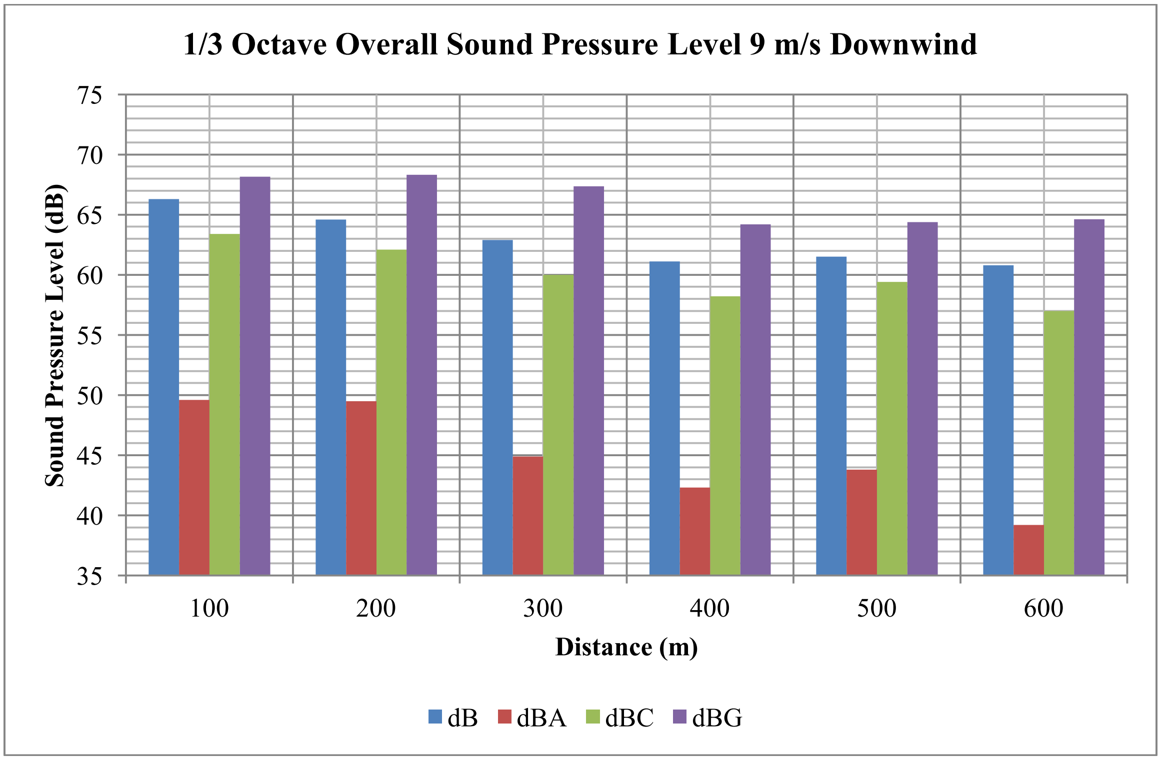


Figure B12: Downwind Maximum Overall Sound Pressure Levels at 9 m/s Hub Height Wind Speed

Downwind 15 m/s							
	Turbine A						
	100 m	**100 m**	**200 m**	**200 m**	**300 m**	**300 m**	
Overall L:	75.1	73.7	71.8	71.4	70.1	69.9	**dB**
Overall A:	59.9	59.8	55.3	55.6	51.9	53.6	**dBA**
Overall C:	71.3	70.4	67.7	67.6	66.5	66.1	**dBC**
Overall G:	80.1	81.4	78.8	78.8	75.3	73.1	**dBG**
	Turbine B						
	100 m	**100 m**	**200 m**	**200 m**	**300 m**	**300 m**	
Overall L:	74.1	74.5	70.9	71.3	70.3	70.8	**dB**
Overall A:	59.1	59.2	54.4	54.7	51.9	51.6	**dBA**
Overall C:	70.9	71.3	67.6	67.7	66.6	66.3	**dBC**
Overall G:	77.3	76.6	75.4	76.0	73.1	75.8	**dBG**

Figure B13: Downwind Overall Sound Pressure Levels at 15 m/s Hub Height Wind Speed

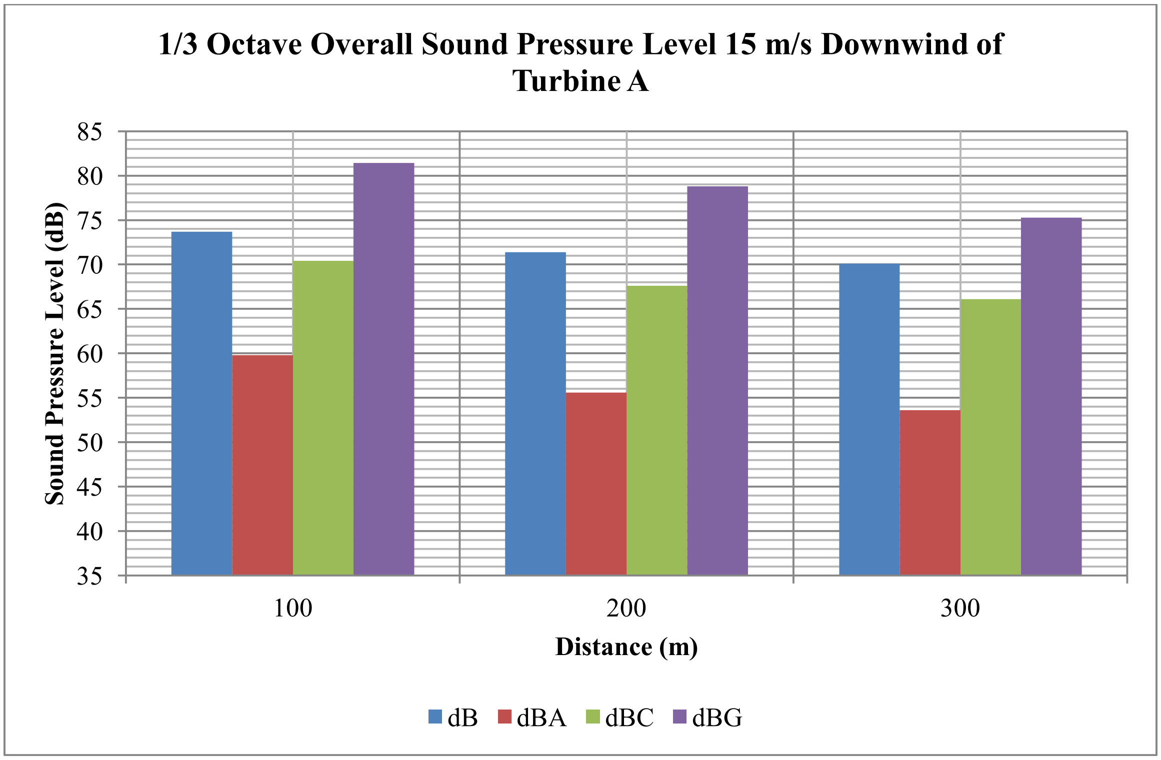


Figure B14: Turbine A Downwind Maximum Overall Sound Pressure Levels at 15 m/s Wind Speed

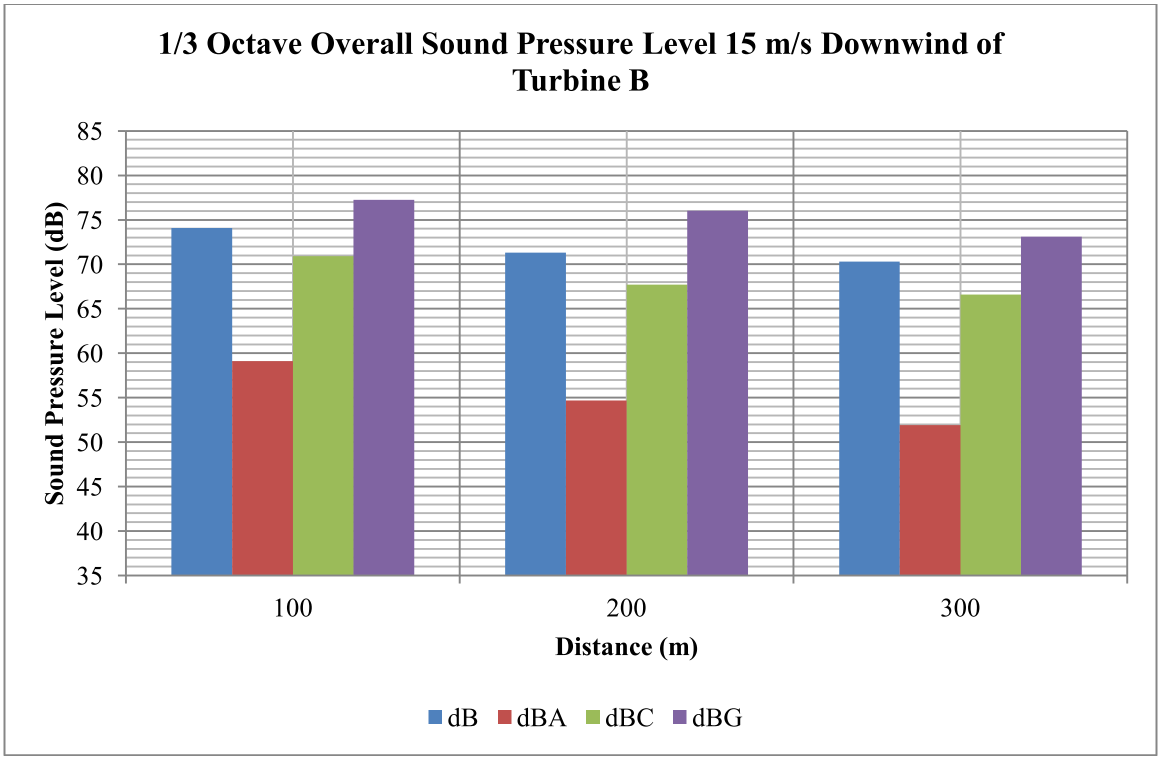


Figure B15: Turbine B Downwind Maximum Overall Sound Pressure Levels at 15 m/s Wind Speed

APPENDIX C

Directional Noise Data

100 m Directionality 7 m/s									
	0	**0**	**45**	**45**	**90**	**90**	**135**	**135**	
Overall L:	66.0	68.8	62.6	63.4	59.9	59.8	59.4	59.9	**dB**
Overall A:	50.5	56.1	49.1	50.8	44.5	45.0	42.0	42.7	**dBA**
Overall C:	63.6	66.6	59.5	60.5	57.0	56.6	57.6	58.0	**dBC**
Overall G:	68.8	69.0	64.4	62.2	63.8	65.1	60.9	60.1	**dBG**
	180	**180**	**225**	**225**	**270**	**270**	**315**	**315**	
Overall L:	68.4	66.6	65.3	65.7	61.0	62.6	62.1	63.7	**dB**
Overall A:	52.9	51.3	49.1	51.3	45.6	47.7	47.9	51.2	**dBA**
Overall C:	65.4	64.4	62.6	64.1	58.2	59.6	60.3	61.2	**dBC**
Overall G:	71.6	69.0	72.0	67.8	66.3	66.5	70.1	68.2	**dBG**

Figure C1: 100m Directional Overall Sound Pressure Levels at 7 m/s Wind Speed

100 m Directionality 8 m/s									
	0	**0**	**45**	**45**	**90**	**90**	**135**	**135**	
Overall L:	62.9	63.2	61.8	60.9	64.3	61.7	66.6	67.4	**dB**
Overall A:	45.4	47.7	47.5	47.2	51.0	47.5	55.1	53.8	**dBA**
Overall C:	60.9	61.2	59.4	58.9	61.6	59.3	64.5	65.3	**dBC**
Overall G:	62.0	63.8	67.0	60.6	69.1	67.1	68.5	68.8	**dBG**
	180	**180**	**225**	**225**	**270**	**270**	**315**	**315**	
Overall L:	67.6	67.5	66.2	66.6	62.6	63.6	65.6	64.1	**dB**
Overall A:	50.9	51.8	51.4	50.3	47.3	47.9	52.1	50.5	**dBA**
Overall C:	64.7	64.9	63.9	64.3	60.0	61.2	63.7	62.0	**dBC**
Overall G:	69.6	69.6	71.6	68.6	68.3	66.8	66.5	66.3	**dBG**

Figure C2: 100m Directional Overall Sound Pressure Levels at 8 m/s Wind Speed

100 m Directionality 15 m/s									
	0	**0**	**45**	**45**	**90**	**90**	**135**	**135**	
Overall L:	73.8	72.8	73.6	73.0	71.8	72.0	73.3	73.7	**dB**
Overall A:	60.1	60.1	62.3	62.9	59.0	58.4	60.6	60.6	**dBA**
Overall C:	70.8	70.0	71.0	70.7	68.8	68.7	70.5	70.7	**dBC**
Overall G:	76.6	75.5	72.8	73.7	73.4	76.6	78.1	75.1	**dBG**
	180	**180**	**225**	**225**	**270**	**270**	**315**	**315**	
Overall L:	74.6	74.2	73.8	73.2	71.8	71.9	72.7	73.1	**dB**
Overall A:	60.1	59.9	58.8	58.8	57.4	56.5	59.6	59.6	**dBA**
Overall C:	71.5	71.3	70.5	69.9	68.4	68.5	69.6	69.7	**dBC**
Overall G:	77.7	75.9	79.3	77.4	73.6	75.4	76.3	73.8	**dBG**

Figure C3: 100m Directional Overall Sound Pressure Levels at 15 m/s Wind Speed

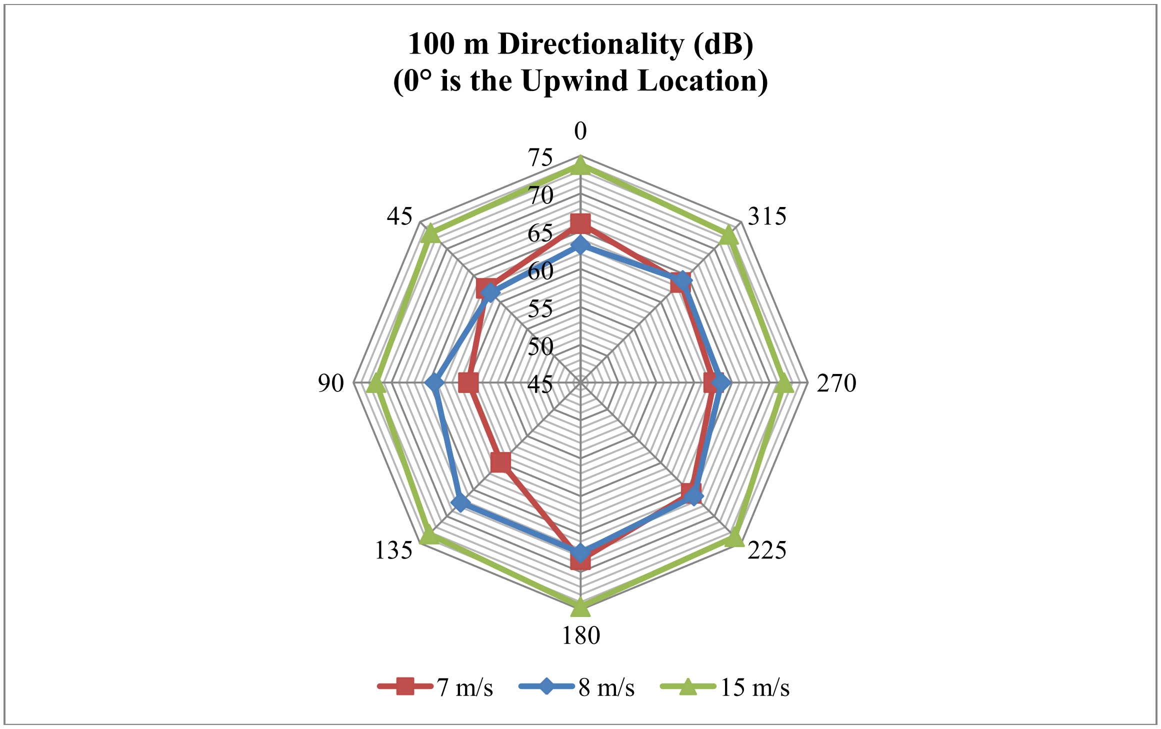


Figure C4: 100m Directional Linear Maximum Overall Sound Pressure Levels

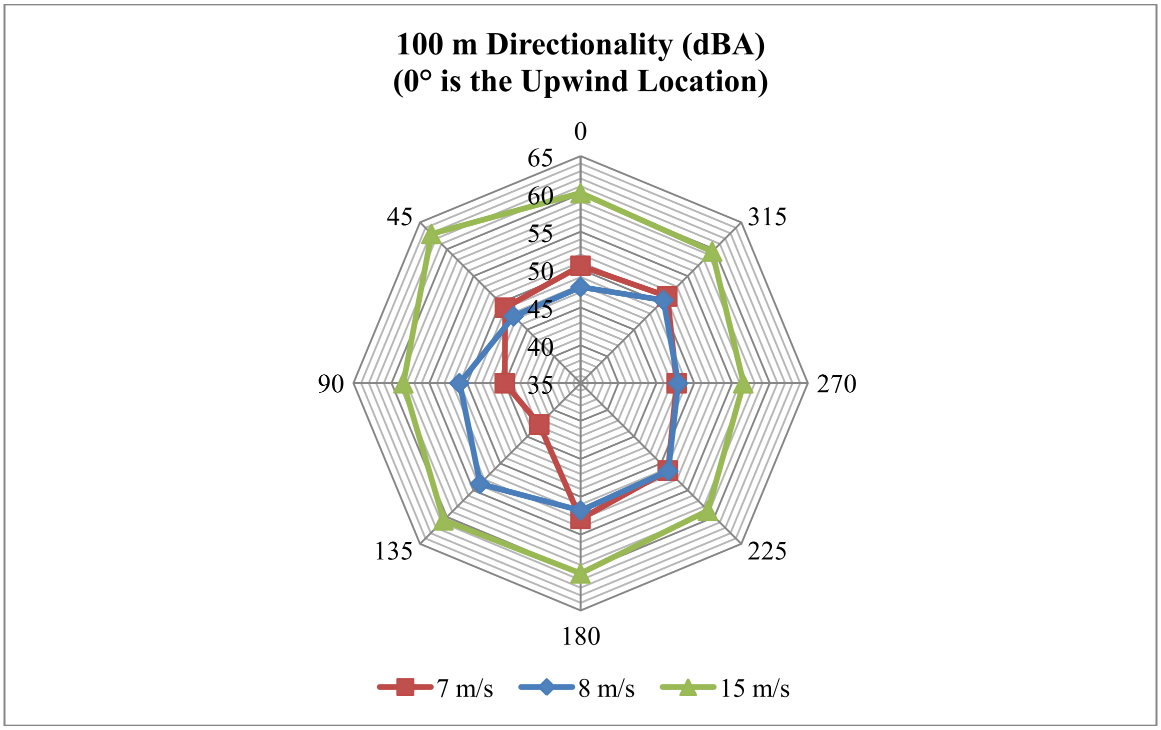


Figure C5: 100m Directional A-weighted Maximum Overall Sound Pressure Levels

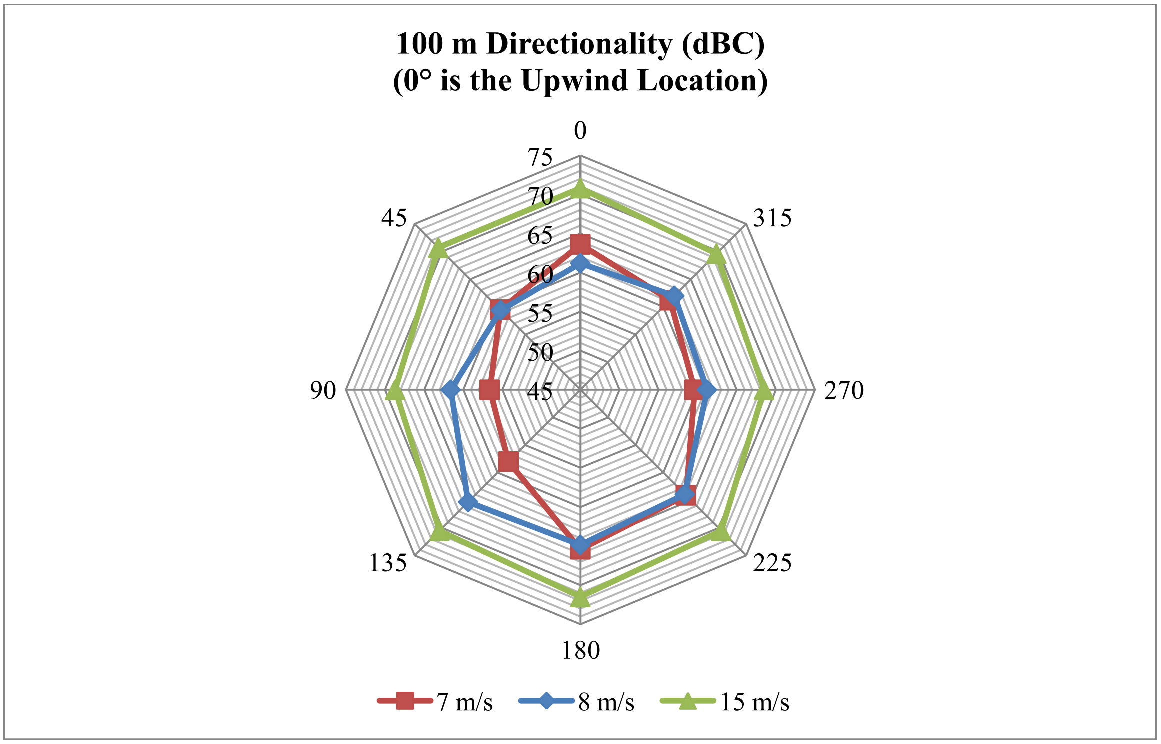


Figure C6: 100m Directional C-weighted Maximum Overall Sound Pressure Levels

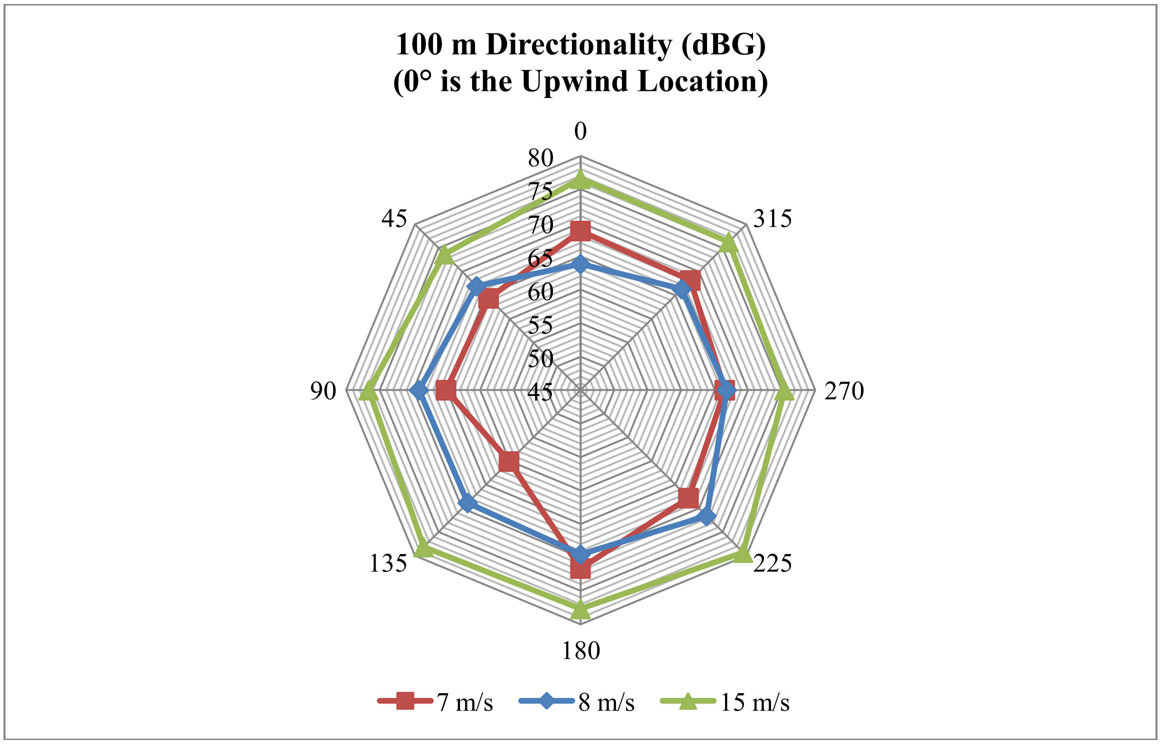


Figure C7: 100m Directional G-weighted Maximum Overall Sound Pressure Levels

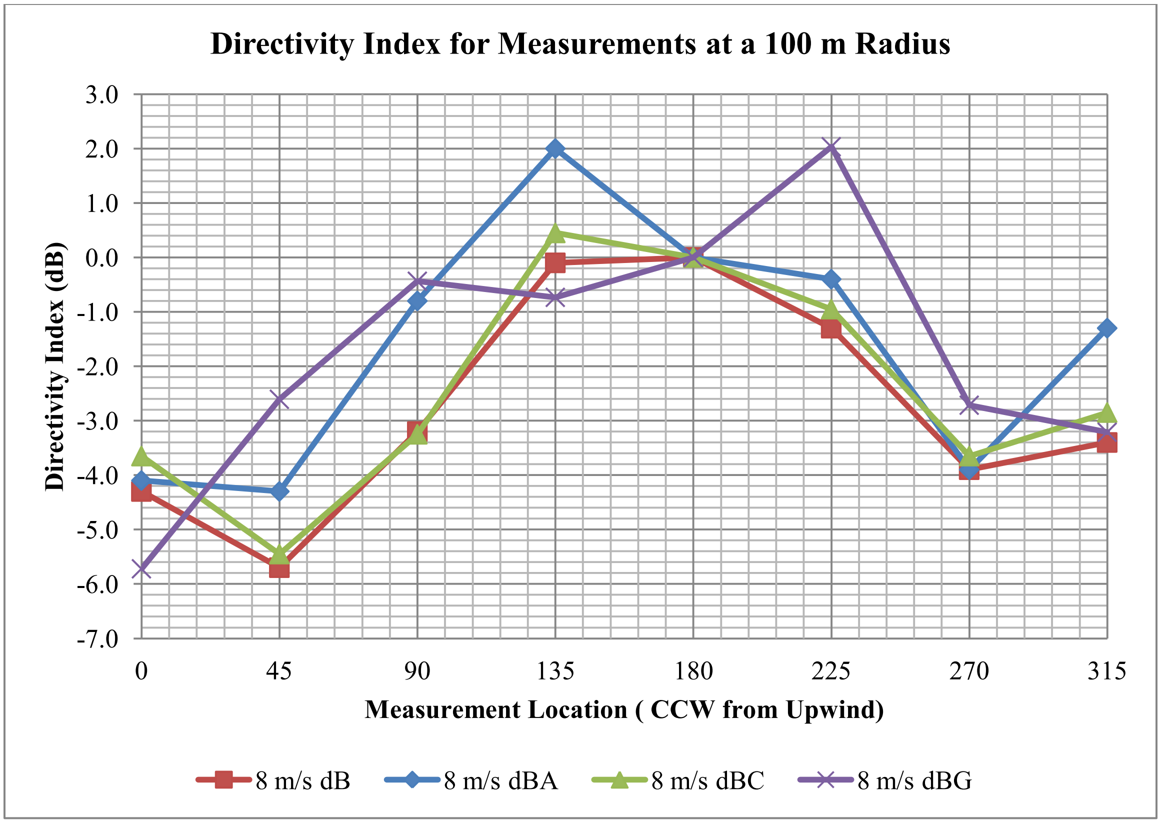


Figure C8: Directivity Index for Measurements at a 100 m Radius and 8 m/s Wind Speed

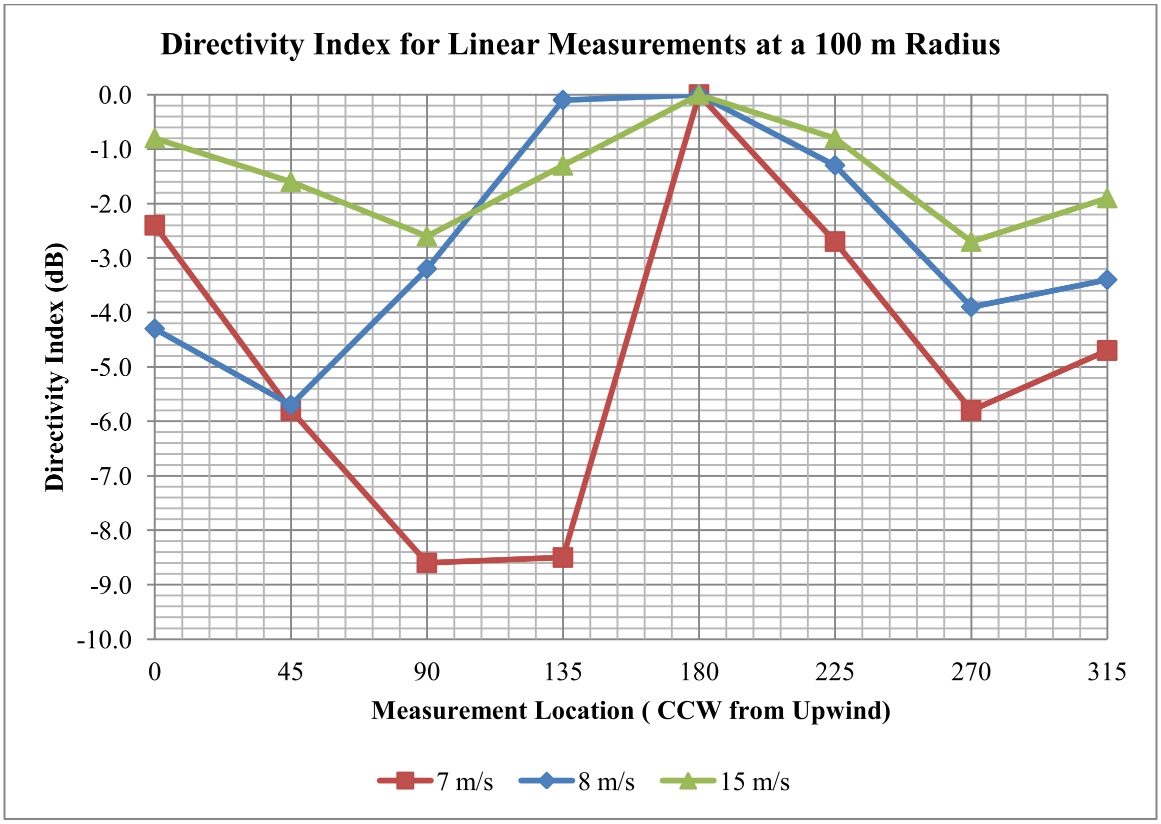


Figure C9: Directivity Index for Linear Measurements at a 100 m Radius

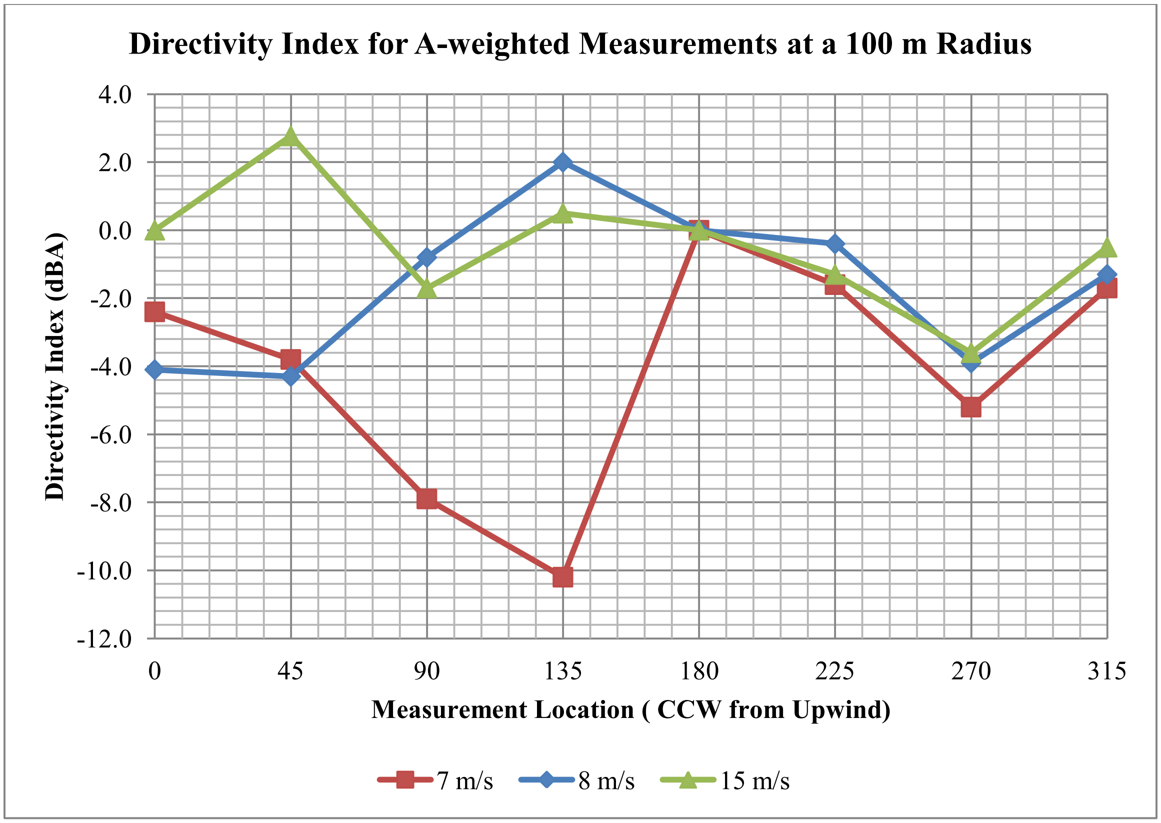


Figure C10: Directivity Index for A-weighted Measurements at a 100 m Radius

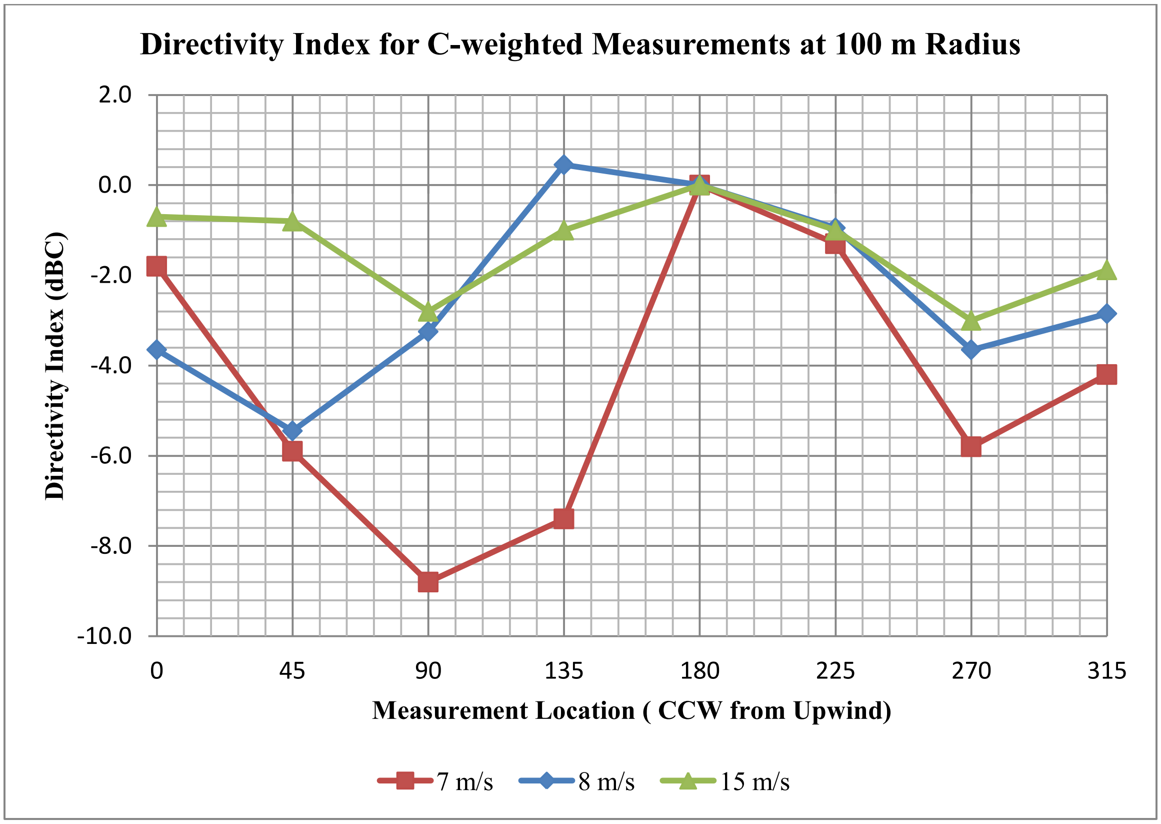


Figure C11: Directivity Index for C-weighted Measurements at a 100 m Radius

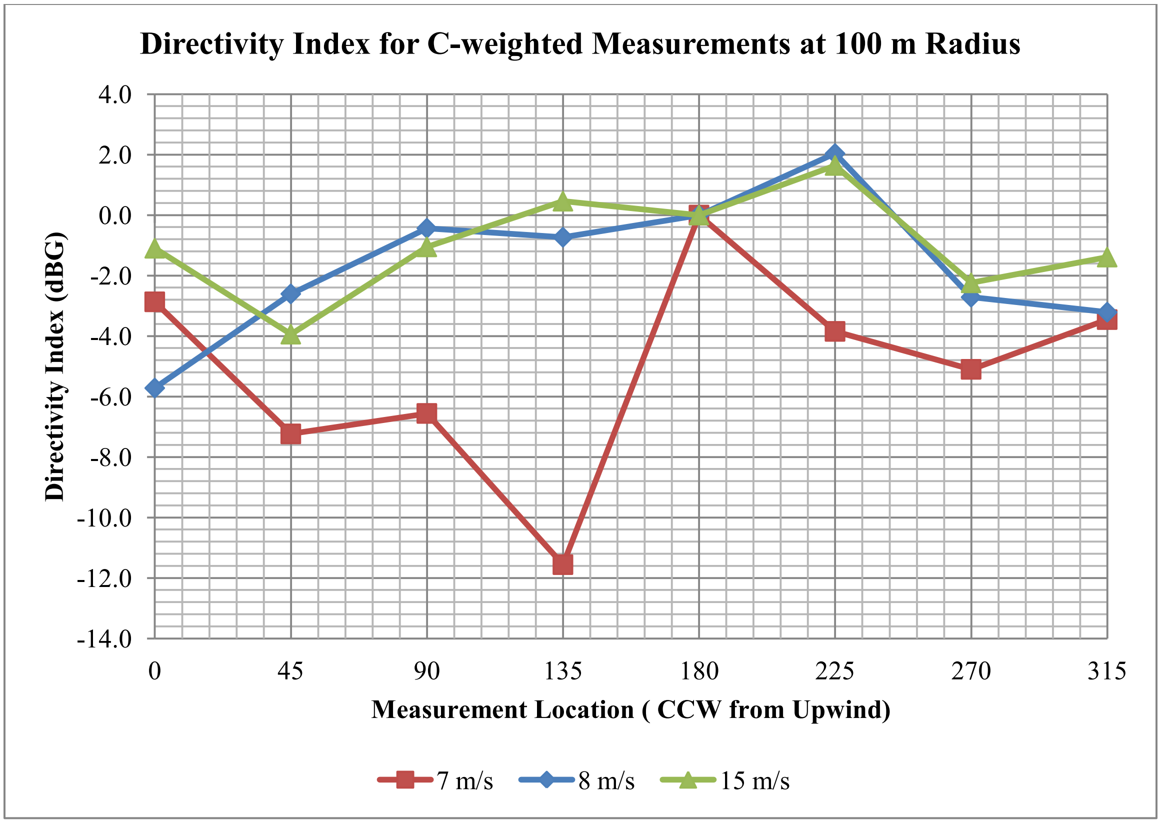


Figure C12: Directivity Index for G-weighted Measurements at a 100 m Radius

200 m Directionality 6.5 m/s									
	0	**0**	**45**	**45**	**90**	**90**	**135**	**135**	
Overall L:	59.9	58.6	58.4	57.6	57.4	57.1	58.6	59.0	**dB**
Overall A:	39.5	40.3	41.8	43.3	38.8	38.6	39.9	40.0	**dBA**
Overall C:	56.1	56.2	55.8	55.1	54.5	54.3	56.1	56.4	**dBC**
	180	**180**	**225**	**225**	**270**	**270**	**315**	**315**	
Overall L:	58.9	59.6	59.1	58.8	59.2	59.1	61.0	61.0	**dB**
Overall A:	40.1	39.0	40.1	38.6	41.5	40.3	43.3	42.9	**dBA**
Overall C:	57.2	56.4	56.4	55.9	56.5	56.0	58.4	58.5	**dBC**

Figure C13: 200m Directional Overall Sound Pressure Levels at 6.5 m/s Wind Speed

200 m Directionality 7 - 15 m/s									
	45 @ 7 m/s	**45 @ 7 m/s**	**90 @ 7 m/s**	**90 @ 7 m/s**	**135 @ 7 m/s**	**135 @ 7 m/s**	**180 @ 8 m/s**	**180 @ 8 m/s**	**deg**
Overall L:	63.1	62.8	56.5	55.6	64.3	60.2	65.5	66.7	**dB**
Overall A:	51.6	49.9	43.0	43.0	51.2	46.3	52.3	52.8	**dBA**
Overall C:	61.3	60.6	54.9	53.9	61.9	58.4	63.6	64.5	**dBC**
Overall G:	67.9	64.9	56.8	57.2	69.5	63.8	70.4	68.4	**dBG**
	225 @ 9 m/s	**225 @ 9 m/s**	**270 @ 9 m/s**	**270 @ 9 m/s**	**270 @ 15 m/s**	**270 @ 15 m/s**	**225 @ 15 m/s**	**225 @ 15 m/s**	**deg**
Overall L:	65.4	64.0	62.6	63.1	71.8	71.7	69.5	69.1	**dB**
Overall A:	51.2	47.7	50.3	50.7	53.7	54.2	52.1	52.1	**dBA**
Overall C:	62.7	61.2	60.2	60.7	67.3	67.8	66.1	65.8	**dBC**
Overall G:	69.9	67.4	64.6	65.1	77.0	75.5	72.0	71.5	**dBG**

Figure C14: 200m Directional Overall Sound Pressure Levels at 7-15 m/s Wind Speed

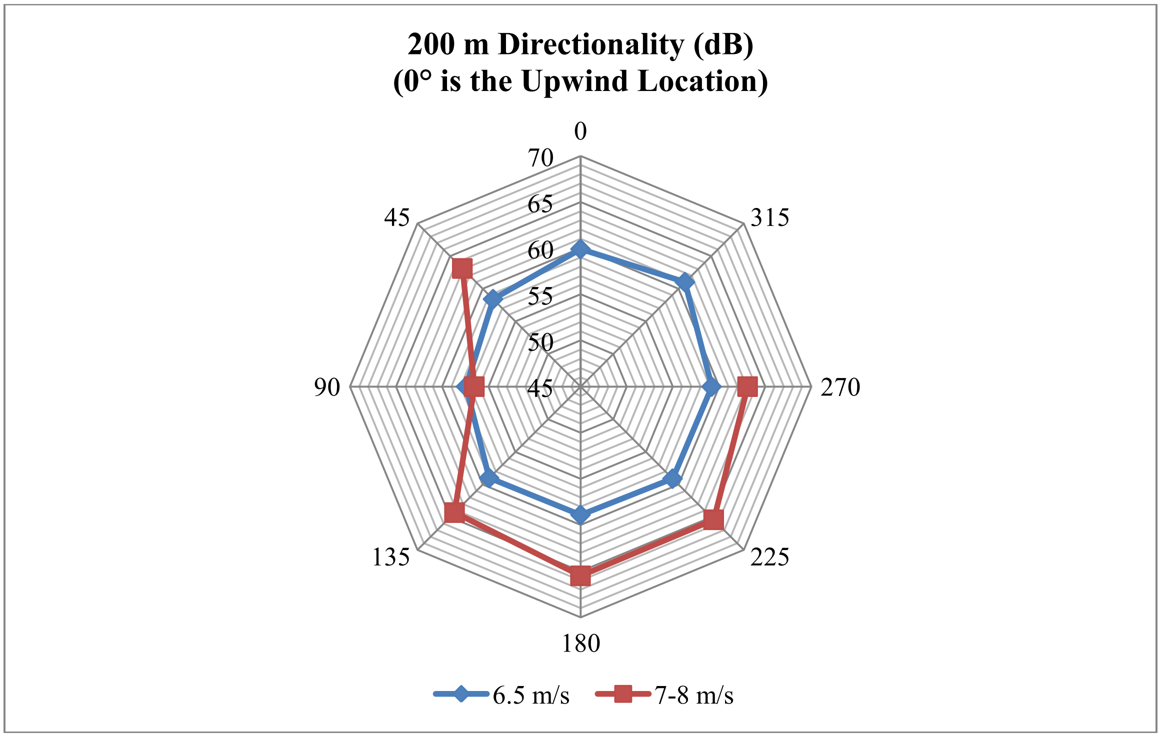


Figure C15: 200m Directional Linear Overall Sound Pressure Levels

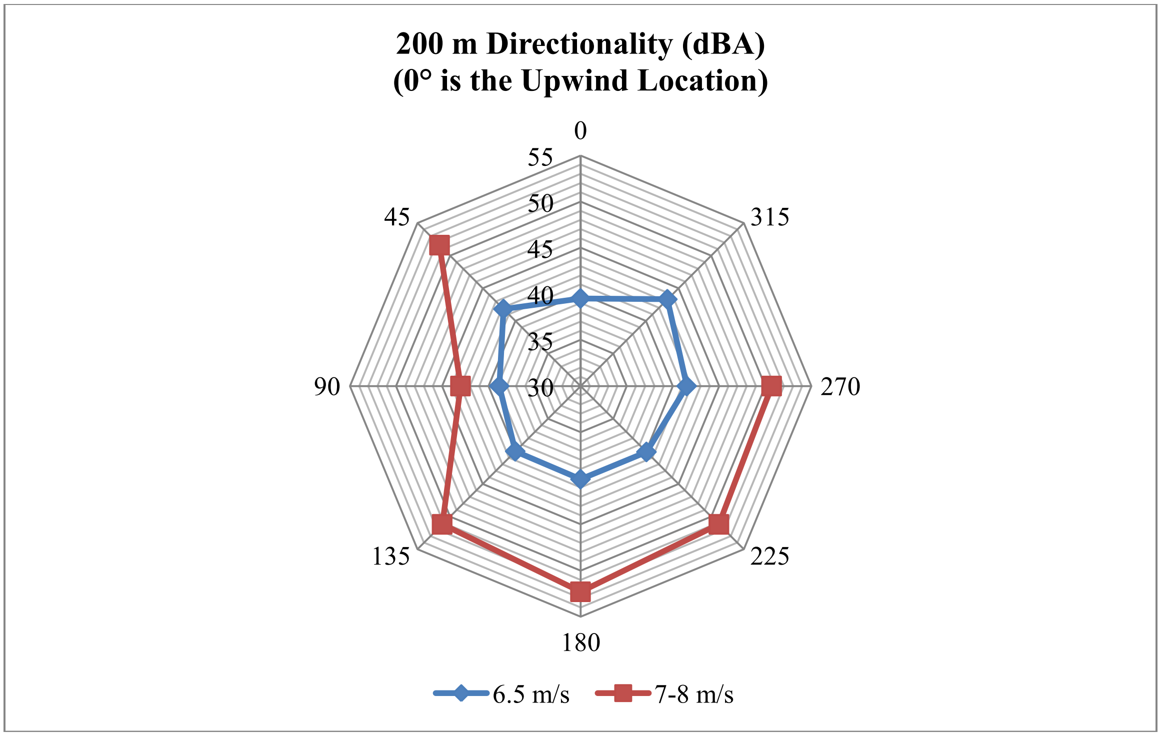


Figure C15: 200m Directional A-weighted Overall Sound Pressure Levels

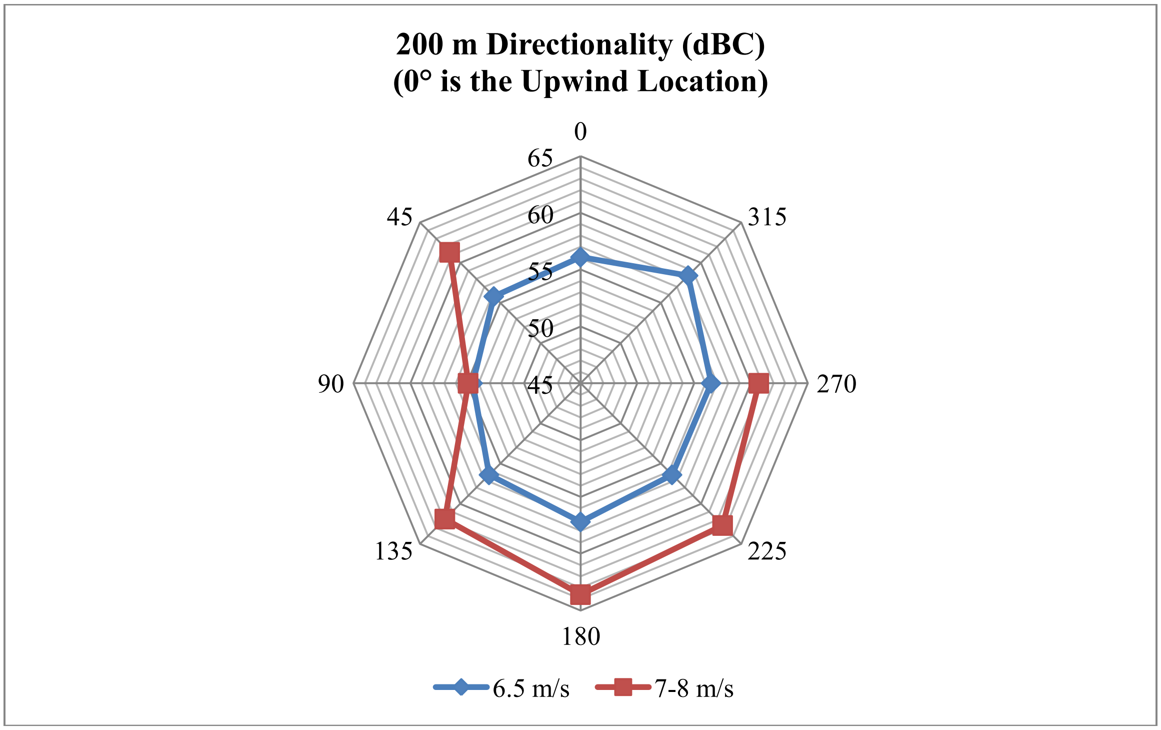


Figure C17: 200m Directional C-weighted Overall Sound Pressure Levels

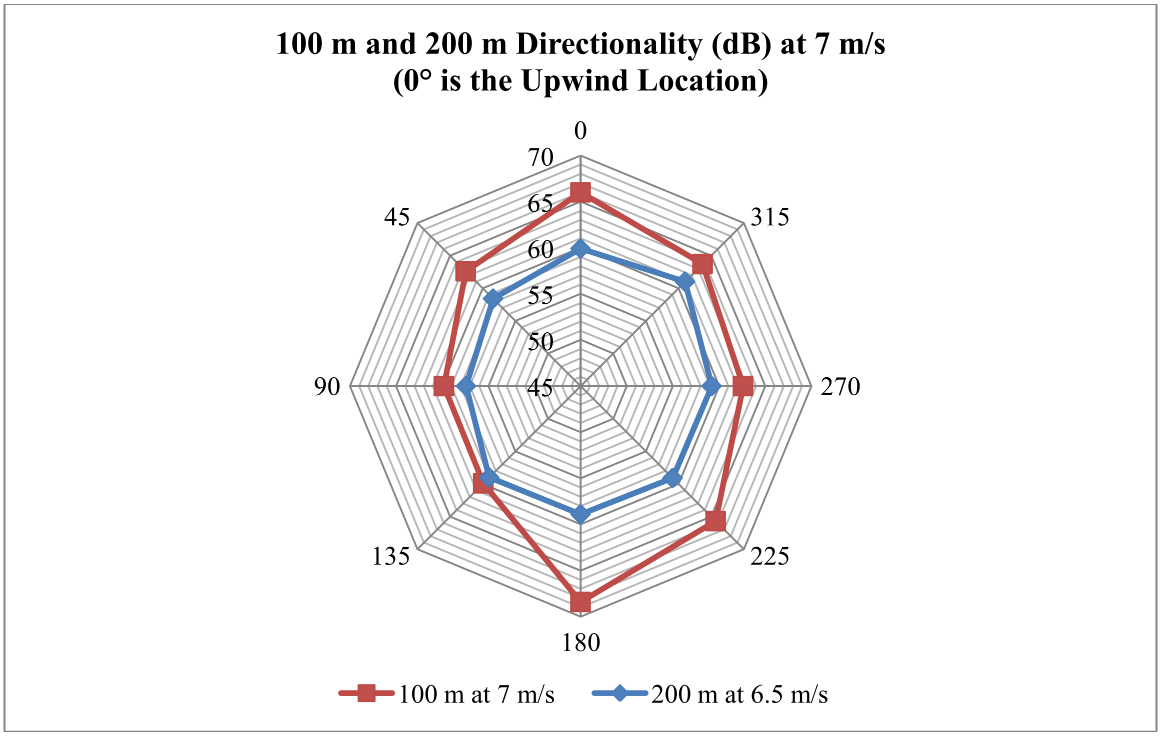


Figure C18: 100 m & 200 m Directional Overall Sound Pressure Levels at 7 m/s Wind Speed

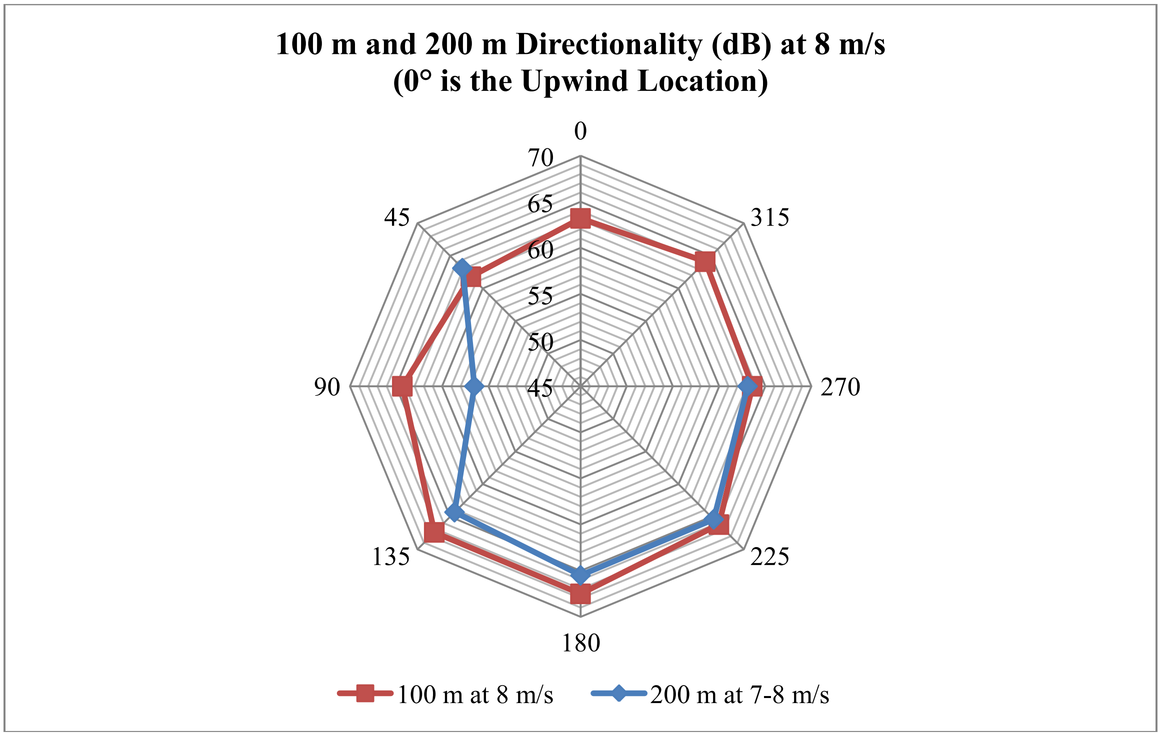


Figure C19: 100 m & 200 m Directional Overall Sound Pressure Levels at 8 m/s Wind Speed

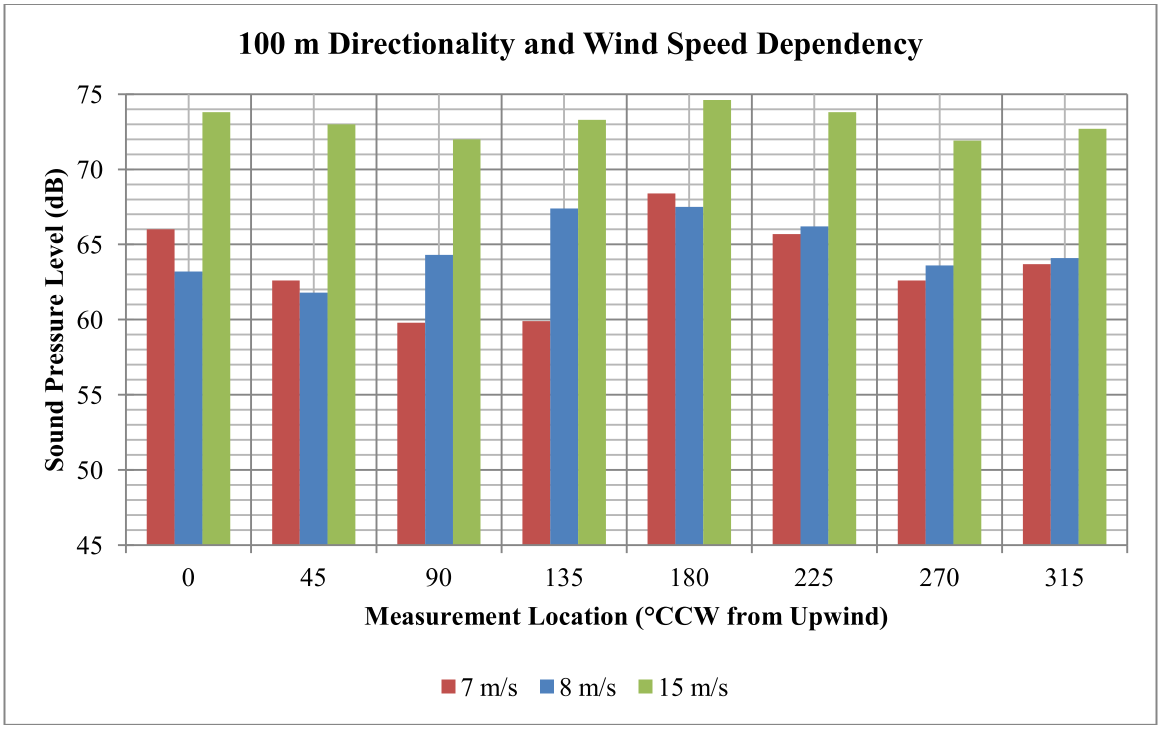


Figure C20: 100 m Linear Directionality and Wind Speed Dependency

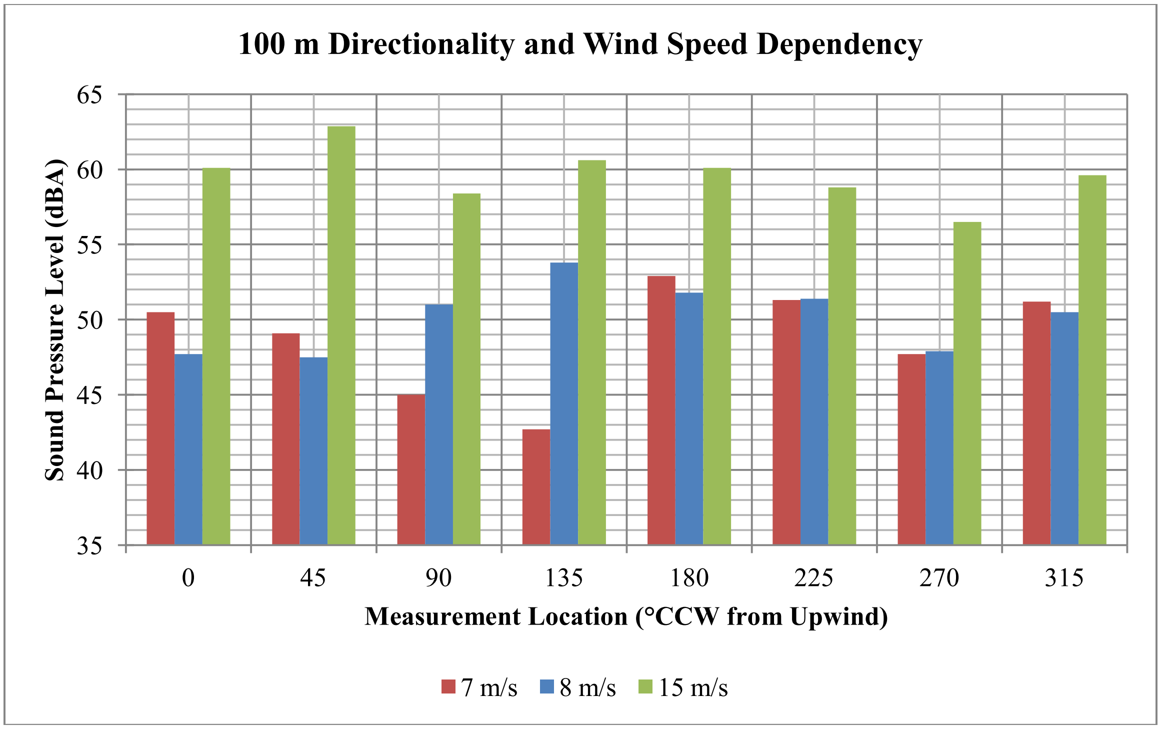


Figure C21: 100 m A-weighted Directionality and Wind Speed Dependency

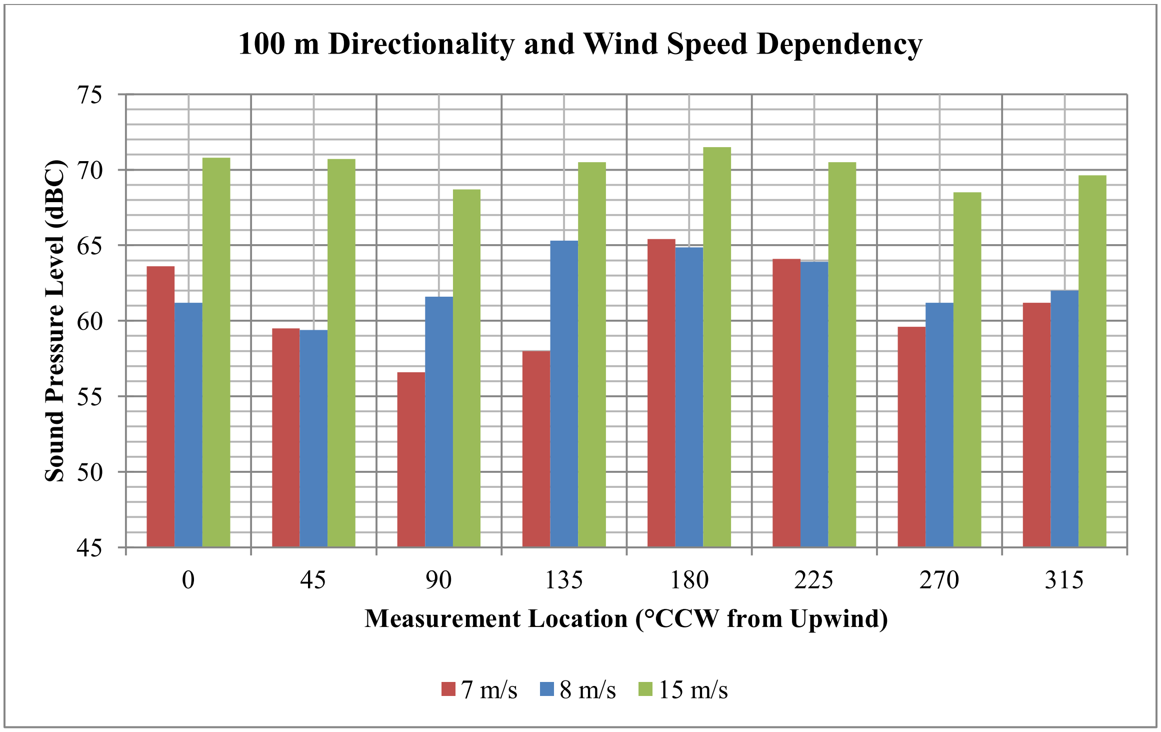


Figure C22: 100 m C-weighted Directionality and Wind Speed Dependency

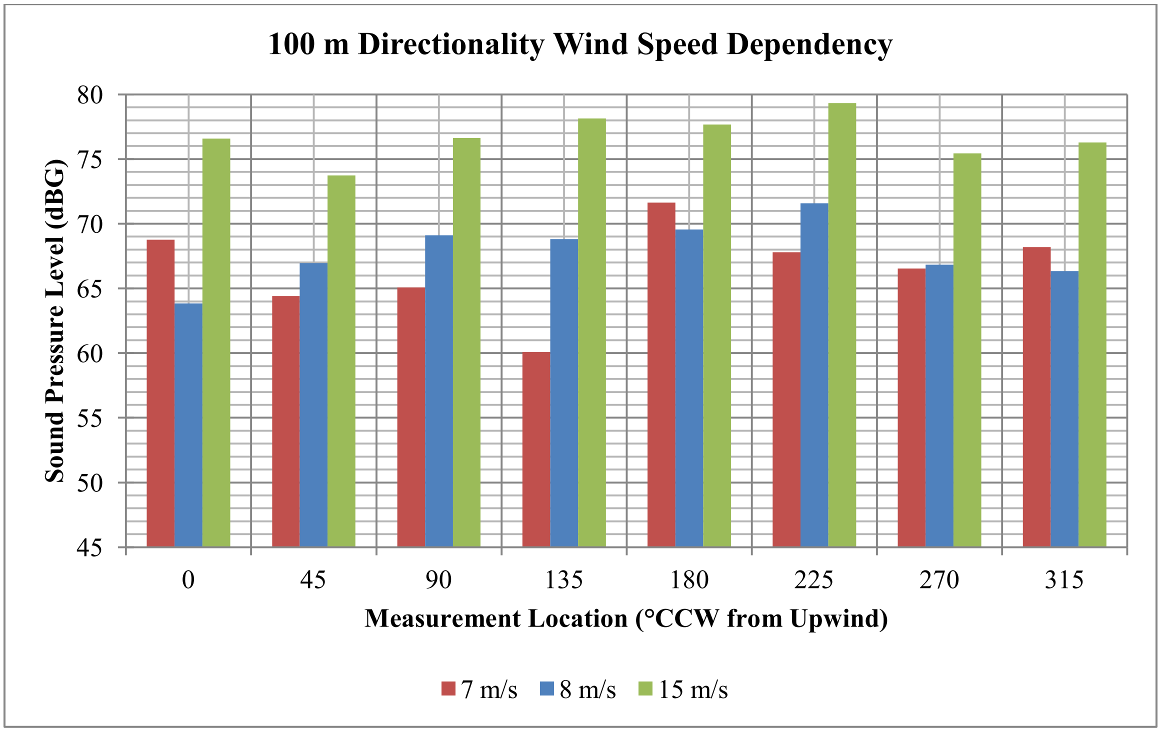


Figure C23: 100 m G-weighted Directionality and Wind Speed Dependency

VITA AUCTORIS

James Finch was born in 1988 in Saint John, New Brunswick. He graduated from St. Malachy's Memorial High School in 2006. From there he went on to the University of Windsor where he obtained a Bachelor of Applied Science degree in Mechanical Engineering – Automotive Option in 2010. He is currently a candidate for the Master's degree in Mechanical Engineering at the University of Windsor with expected completion in the Fall of 2012.