The Bruce McPherson Infrasound and Low Frequency Noise Study

Adverse Health Effects Produced By Large Industrial Wind Turbines Confirmed

December 14, 2011

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"The idea that infrasound doesn't or can't affect the ear is just flat-out wrong."

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Executive Summary

This study was commissioned through a private philanthropic grant created to determine why there were so many strong complaints about the loss of well-being and hardships experienced by people living near large industrial wind turbines operating in Falmouth, Massachusetts. The purpose of this study was to investigate and confirm or deny the presence of infrasonic and low frequency noise emissions (ILFN) from the "WIND 1", a municipally-owned Vestas V82 industrial wind turbine. In March of 2011, after many months of vigorous neighborhood complaints and strong appeals to the town, selectmen voluntarily decided to curtail WIND 1 operations when hub height wind speed exceeded 10 m/s. This required that this study focus on noise emissions from the nearby "NOTUS" wind turbine, an identical make and model.

Acoustics

This study was conducted at a representative neighbor's home in Falmouth and confirmed that there are dynamically modulated low frequency acoustic amplitudes and tones produced by the nearby wind turbine. Dynamic amplitude modulations occurred at 1.4 second intervals that were consistent with the blades rotating past the wind turbine tower (the blade pass rate). Dynamic amplitude modulations below 10 Hz were stronger indoors than outdoors. Modulations measured indoors were 0.2 Pascal peak to peak consisting mostly of energy below 20 Hz. Two tones were detected from both the NOTUS and the WIND 1 turbines, at 22.9 Hz and 129 Hz, and are considered signatures of the wind turbines' acoustic profile. Outdoors, the A-weighted sound level decreased at a predictable rate of 6 dB per doubling of distance from the nearest turbine. The linear unweighted sound level decreased according to cylindrical spreading at 3 dB per doubling of distance and was controlled by acoustic energy below 20 Hertz. A-weighting does not reveal this low-frequency information. Sound-level averaging with Leq for any time length hides the low-frequency dynamic amplitude modulations.

Health effects

The investigators were surprised to experience the same adverse health symptoms described by neighbors living at this house and near other large industrial wind turbine sites. The onset of adverse health effects was swift, within twenty minutes, and persisted for some time after leaving the study area. The dBA and dBC levels and modulations did not correlate to the health effects

experienced. However, the strength and modulation of the un-weighted and dBG-weighted levels increased indoors consistent with worsened health effects experienced indoors. The dBG-weighted level appeared to be controlled by in-flow turbulence and exceeded physiological thresholds for response to low-frequency and infrasonic acoustic energy as theorized by Salt. The wind turbine tone at 22.9 Hz was not audible yet the modulated amplitudes regularly exceeded vestibular detection thresholds. The 22.9 Hz tone lies in the brain's "high Beta" wave range (associated with alert state, anxiety, and "fight or flight" stress reactions). The brain's frequency following response (FFR) could be involved in maintaining an alert state during sleeping hours, which could lead to health effects. Sleep was disturbed during the study when the wind turbine operated with hub height wind speeds above 10 m/s. It took about a week to recover from the adverse health effects experienced during the study, with lingering recurring nausea and vertigo for almost seven weeks for one of the investigators.

Further epidemiological and laboratory research needed

The research is more than just suggestive. Our experiencing of the adverse health effects reported by others confirms that industrial wind turbines can produce real discomfort and adverse health impacts. Further research could confirm that these ill effects are caused by pressure pulsations exceeding vestibular thresholds, unrelated to the audible frequency spectrum but are instead related to the response of the vestibular system to the low frequency noise emissions. The vestibular system appears to be stimulated by responding to these pressure pulsations rather than by motion or disease, especially at low ambient sound levels. Dysfunctions in the vestibular system can cause disequilibrium, nausea, vertigo, anxiety, and panic attacks, which have been reported near a number of industrial wind turbine facilities. The study emphasizes the need for epidemiological and laboratory research conducted by medical health professionals and acousticians working together who are concerned with public health and well-being. This study underscores the need for more effective and precautionary setback distances for industrial wind turbines. It is especially important to include a margin of safety sufficient to prevent inaudible low-frequency wind turbine noise from being detected by the human vestibular system.

Acknowledgements

This study was initiated by the concerns of a private citizen, Bruce McPherson who enjoyed the many quality of life benefits of living on Cape Cod. He was disappointed that there were no efforts being made by developers or government agencies, to determine the real cause for the many complaints from Falmouth residents living near three new industrial wind turbines. He knew that neighbors were constantly complaining to town officials about receiving excessive noise, adverse health effects and the loss of well-being. Thanks are given by so many for the generosity of Mr. McPherson, who initiated and funded this independent investigation.

To the residents of Falmouth who welcomed us into their homes and lives, extended us their hospitality, told us their stories, and gave us their time and assistance, our deepest appreciation.

Sincere appreciation is given to Dr. Alec Salt, Dr. Timothy Hullar, Mr. Richard James, and Mr. Charles Ebbing for their insightful correspondence, professional reviews and comments.

Prologue

Falmouth is one of many communities having learned the unfortunate outcome for locating industrial wind turbines too close to residences in a quiet rural environment. The responses to wind turbines by neighbors close by are very similar to those experienced in other communities that have wind turbines improperly sited too close to homes; complaints that are vigorous and very vocal. Wind turbine complaints can be divided into two distinct categories; excessive noise and physiological symptoms. This study was launched with the mission of identifying for the presence or lack of low-frequency and infrasonic sound. Due to the direct exposure to adverse health symptoms experienced during the field measurements, this study was inspired to investigate further for the potential causes for these physiological symptoms. This involved looking for significant changes in the low and very low frequencies related to acoustic and atmospheric pressure fluctuations produced by wind turbines. It was not the intent of this study to determine the direct cause of the physiological symptoms. Yet there were strong correlations established.

Authors Comments:

> *This study is written in a format to assist the average reader. We need to understand why so many neighbors are having such a hard time living near industrial wind turbines located in quiet areas. We would like to start this report by sharing our experiences, which we ourselves did not fully acknowledge or even understand until the morning of the second day of our investigation.*
>
> *Our study began with our arrival at a nearby home. These neighbors had experienced and reported their many months of adverse health symptoms. Shortly after our first meeting and polite conversation, the homeowners invited us to use their home as the base of operations for our acoustical investigation. We respectfully accepted and were allowed to use their dining room for our field office.*
>
> *As is our custom on field surveys, we were enthusiastic and ready to begin our work. It was a beautiful spring afternoon, warm with a strong westerly wind aloft at the wind turbine blade height. We observed that there was a soft southeasterly*

wind extending from ground level to tree top (about 60 feet). Within twenty minutes of being inside their house, while setting up our instruments, each of us started to lose our initial enthusiasm and actually started to feel less well. As time went on, we got progressively worse. We each experienced unpleasant symptoms of motion sickness, including ear pressure, headache, nausea, dizziness, vertigo, especially when moving about. We had a sense that the room was moving or slightly displaced from where it appeared. We experienced a loss of appetite, cloudy thinking, fatigue, some anxiety and an inexplicable desire to get outside; similar to motion sickness we have experienced on a boat or plane. We felt slightly better when we did go outside.

> According to the conflict hypothesis (Brandt, 2003) motion sickness is the consequence of discordant (not in agreement or harmony) inputs to the brain information about the position and motion of the body from the vestibular and the visual systems, and from other sensory sources [1].

On the morning of the second day we left the house to go out for breakfast. About 30 minutes later and a few miles away we shared a light conversation about the night before... We talked about the difficulties we had staying motivated and the challenges we encountered performing our usual work. As time went we started to feel better, and then by the contrast in our state of mind, it hit us. We realized and understood the true extent of the debilitating symptoms expressed by neighbors; we had experienced many of them the previous evening.

[1] BRANDT T. (2003) Vertigo: its multisensory syndromes. London, New York: Springer, 2003.

1 INTRODUCTION

This study was commissioned through a private philanthropic grant created out of concern for strong complaints of hardships experienced at residences near large industrial wind turbines operating in Falmouth, Massachusetts. Our investigation grew in scope as we were performing our analysis. One lead led to another, and we found ourselves immersed in technical research bridging acoustics, otolaryngology, and neuroscience. Our ears do more than just listen; they play an integral part in sensing environmental conditions. The ear performs many interrelated functions that condition and inform our personal state of well-being.

1.1 Background

Low frequency sound may play an important part in the cause for adverse community reaction to large industrial wind turbines installed close to residences in quiet areas. However, this has been proven to be very difficult to determine based on only A-weighted sound level measurements, which is often the only quantifier used for compliance by local and state regulations. The A-weighting filter severely attenuates low frequency signals (the primary frequency range of most community noise complaints) and essentially eliminates acoustic signals below 20 Hertz where "infrasound" is located in the acoustic frequency spectrum. Wind turbine noise standards and most regulations require A-weighting which suppresses the amplitude of low frequency noise predictions in modeling and application submittals.

Research (detailed in Section 4) has established that infrasonic thresholds for human hearing are well below those previously assumed from traditional sinusoidal hearing tests.

It has been noted that other noise sources can generate infrasonic energy, such as surf and thunderstorms. However wind turbine low frequency energy presents a recurring and/or unpredictable pressure signature, with audibility or detectability occurring over a much longer period of time than other environmental sources of low frequency energy. When an audible or detectable acoustic or pressure signature is found, this is very valuable for subsequent monitoring system design and correlating with complaints.

1.2 Falmouth Wind Turbines

Over months of town meetings in 2009 and 2010, Falmouth approved the installation of two municipal wind turbines and one privately owned. These approvals required the town to receive sufficient information from the wind turbine applicants to make their decisions. We understand that during numerous presentations, town officials and neighbors were assured by the applicants, environmental engineers and scientists, that the proposed wind turbines would not cause an adverse public reaction or generate excessive noise impacts. Acoustic professionals concluded that any changes in the acoustic environment would not be sufficient to be found either objectionable or disruptive. These statements were based on assessments of the A-weighted sound level predicted for the wind turbines. (We have not seen community reaction assessments or discussions of low-frequency or sound quality comparisons to the existing environment.)

Strong appeals to stop the noise and complaints of health problems were voiced by neighbors after the municipal and privately-owned wind turbines started operating.

There are currently three industrial wind turbines (Vestas, Model V82, 1.65 MW each) installed in Falmouth with two, municipally-owned and operated, near the wastewater treatment facility. Figure 1 shows the locations for the two municipal wind turbines; WIND 1, WIND 2, and further east, the private NOTUS wind turbine owned by Daniel H. Webb and operated by NOTUS Clean Energy LLC, in the Falmouth Technology Park. All of the turbines are located east of Route 28, north of Blacksmith Shop Road and south of Thomas B Landers Road as shown on Figure 1. Commercial operation of the Town of Falmouth's Wind 1 turbine began on March 23, 2010, while WIND 2 is still waiting for start-up. The NOTUS turbine also started operation in 2010. For reference, the study measurement locations were at two residential homes, shown as ML1 (indoors and outdoors) and ML2 (outdoors).

Figure 1 - Wind turbine and measurement locations

1.3 Noise Complaints

We understand that shortly after WIND 1 became operational in 2010 several neighbors began to complain about excessive noise produced by the new wind turbine. The same reactions surfaced for homeowners living near the new NOTUS wind turbine when it started operating in 2010. Neighbors continued to complain for many months and they just could not adjust their lives to this new sound. The noise was reported to be constantly fluctuating with "swishing" or "thumping" sounds. Neighbors found this noise to be very annoying, intrusive and disruptive. During moderate wind speeds the noise was clearly audible outdoors and for some even indoors. At times the noise had an audible low-frequency tone that came and went. Neighbors commented that it was more annoying indoors and that it interfered with relaxation and sleep.

> *We believe that these complaints could have been predicted by using the results of studies funded by the United States Environmental Protection Administration (USEPA). These studies have a long history having been used as standard*

practice to predict the public response to a new noise source. At the beginning of an environmental noise assessment, it is appropriate to first develop a noise level design criteria to avoid producing an adverse community response. The documented community response to wind turbine noise expressed by nearby neighbors in Falmouth varies from "highly annoyed" to "strong pleas to stop the noise". This community reaction typically indicates at least a 10 to 20 dB increase over the background ambient sound level (without wind turbine).

Unfortunately, Falmouth officials were not made aware of these studies and the wind turbine project teams chose not include this information in their presentations.

Fortunately, the Town did respond to the numerous public complaints by requiring post-operational noise surveys. Noise measurements were also performed for and by adversely affected neighbors. Most measurements were performed by qualified acousticians near the impacted neighbors. The primary acoustical descriptor measured was the A-weighted sound level (dBA). The sound levels generally ranged from the mid-30s to mid-40s dBA. Some noise level variations were due to differences for time of day, wind speed and wind direction (upwind or downwind). The measured sound levels were fairly consistent from survey to survey. However, the interpretations of the measured noise levels were different for assessing neighbors' complaints. We understand that while complaints were logged by the Town, the complaints were not correlated by distance or noise level and the health complaints remained unaddressed.

Similar adverse health symptoms have been associated with noise complaints such as "sick building syndrome", correlated by field study to low-frequency pulsations emanating from ventilation systems [2,3]. That is, adverse health effects from low frequency noise exposure in buildings have been studied and confirmed by the acoustics profession. However: As of the date of this report we have not observed any substantive effort by the wind turbine industry and their acoustical consultants to acknowledge and investigate the mechanisms including

[2] Burt, T., Sick Building Syndrome: Acoustical Aspects, Indoor and Built Environment January 1996 vol. 5 no. 1 44-59. "Symptoms resulting from exposure to infrasound can include fatigue, headache, nausea, concentration difficulties, disorientation, seasickness, digestive disorders, cough, vision problems and dizziness."

[3] Shwartz, S., Linking Noise and Vibration to Sick Building Syndrome in Office Buildings, EM Magazine, awma.org, March 2008.

possible low frequency noise underlying the numerous documented complaints of similar adverse physiological symptoms by people living near large industrial wind turbines. We have not yet observed wind facilities designed with noise criteria selected by the wind acoustic consultant to prevent adverse health effects and complaints. With respect to the adverse impacts to indoors locations in homes near wind turbines, we have not yet observed the wind industry following the best practices of the HVAC industry as published in the ASHRAE journals. We have seen suggestions, from wind facility developers to learned acoustical scholars to state commissioners of health, to the effect that it is a "psychological" issue and that wind turbines do not emit excessive low frequency noise. Having experienced adverse physical health effects ourselves directly as a result of being indoors in a home near a large industrial wind turbine, as presented in this report, with dramatically increased low-frequency and infrasonic sound levels that exceed vestibular thresholds for detection and processing by the inner ear, we must emphatically reject any such dismissive notions.

1.4 Physiological Complaints

We understand that Falmouth neighbors reported having difficulties living in their home for a variety of unpleasant health-related experiences. They were no longer able to feel comfortable, at peace while at home, unable to relax; felt tense for unknown reasons, and had a strong desire to go outside or leave the area entirely. They were unable to concentrate or stay focused on normal, at-home activities.

Some complained about headaches, ear pressure, dizziness, nausea, apprehension, confusion, mental fatigue, lassitude (inability to concentrate, lethargy). These feelings occurred when WIND 1 and/or NOTUS were operating during moderate to strong winds.

Some neighbors experienced extreme discomfort. They moved their bedrooms into the basement in an attempt to get a good night’s sleep. Others left home altogether to sleep farther away with family or friends.

These complaints are clearly indicative of a serious adverse public health impact and the personal loss of well-being for those affected.

We understand that as of the date of this report, there been no substantive health investigations, medical evaluations, or epidemiological studies by public health officials of the health effects experienced by folks living near the wind turbines in Falmouth, Massachusetts[4]. In October 2011 the Falmouth Board of Health conditionally supported the intent of an article "to ease negative health effects" apparently only after repeated, strong pleas to stop the noise, while noting "wind turbines have to be studied before the causes can be known for sure"[5]. In November 2011, the Town decided to shut down WIND 1 for a period of six months, and start up WIND 2 with a complaint monitoring process.

2 STUDY OBJECTIVES

We understood prior to the study's launch that people were complaining more about discomfort indoors than outdoors. Typically, indoors the A-weighted sound level is *lower* than outdoors when human activity is at a minimum. This strongly suggested that the A-weighted sound level might not correlate very well the wind turbine complaints. This may be indicative of another cause such as low- or very-low-frequency energy being involved.

The attenuation and band-pass filters used for dBA and dBC weighting exclude the very low frequency energy below 20 Hz even when the background is quiet.

The purpose of this study therefore was to investigate for the presence of infrasonic pressure pulsations (acoustic amplitudes lower in frequency than 20 Hz) and low-frequency sound emissions (20-200 Hz) from the large industrial wind turbines; and, assess if they 1) are greater than or uniquely distinguishable from the ambient background levels, and 2) exceed human detection thresholds.

To date, wind turbine noise studies have focused on the A-weighted sound level and are set by international standards (IEC 61400) to use A-weighting for overall and octave and one-third octave band data. We have noticed that infrasonic emissions by wind turbines have been dismissed by the wind industry and their acoustical consultants as too weak to be of any consequence. Simultaneously,

[4] Todd Drummey, Falmouth, MA; personal communications, 2011.
[5] The Enterprise, Cape News, 18 October 2011.

many wind industry acousticians, by saying that it is everywhere in the natural environment, may have overstated the presence of naturally occurring infrasonic energy and missed the fact that wind turbine acoustic signatures are both tonal and regularly modulated. We have not seen evidence that naturally occurring infrasound is comparable to the strong dynamic amplitude modulations created by industrial wind turbines operating in quiet environments.

The scope of this study was conducted at one home that is representative of the many neighbors that have complained about noise and adverse health effects. We assessed differences between the outdoors and the indoors environment, where neighbors have said the wind turbines bother them the most and the discomfort is worst.

3 METHODOLOGY

Acoustic measurements were made with precision sound measurement instruments and dual-channel computer-based signal analyzer software. These instruments were capable of measuring very low frequency energy, as low as 1 Hz. Frequency response was flat (within 1 dB) to 2 Hz and 6 Hz for the two primary measurement channels. During computer analysis, response was compensated flat between 1 and 6 Hz using manufacturer specifications for microphones and preamplifiers and dual-channel end-to-end system response checks.

Outdoor measurements were conducted consistent with ANSI 12.9 [6] and ANSI 12.18 [7]. Simultaneous measurements were made using two microphones, one outdoors and one indoors, to determine the outside-to-inside level reduction (OILR) for the exterior walls and roof. The OILR measurements were performed in accordance with ASTM E966-02. The indoor microphone was fitted with a 4-inch windscreen and mounted on a microphone stand in the master bedroom at a location where the reported adverse symptoms were more pronounced. The outdoor microphone was fitted with a 4-inch windscreen and placed inside a RODE Blimp for improved wind and shock mount protection. The entire system was mounted on a tripod, positioned 5 feet above the ground, and located away from house and trees. Wind speeds were light at the outdoor microphone position.

3.1 Instrumentation

Instrumentation configurations are itemized in Table 1.

[6] ANSI/ASA S12.9-1993/Part 3 (R2008) - American National Standard Quantities and Procedures for Description and Measurement of Environmental Sound, Part 3: Short-Term Measurements with an Observer Present.

[7] ANSI S12.18-1994 (R2004) American National Standard Procedures for Outdoor Measurement of Sound Pressure Level.

Table 1 - Instrumentation List.

Description	Manufacturer	Model	Serial No.
Microphone	Bruel & Kjaer	4165	844497
Preamplifier	Larson Davis	2221	0107
Microphone	GRAS	40AN	27538
Preamplifier	Larson Davis	902	0235
Sound Meter	Larson Davis	824	0914
Calibrator	Bruel & Kjaer	4230	1103065
Audio Interface	Sound Devices	USBPre2	HB0411005004
Recorder	M-Audio	Microtrack II	139ADC8107245
Microphone	Svantek	SV22	4012682
Preamplifier	Svantek	SV12L	5552
Sound Meter	Svantek	949	6028
Calibrator	Larson Davis	CAL200	2425
Audio Interface	ROGA	DAQ2	06pnd0097
Recorder	TEAC	DR100	0030486

Each sound level measurement system was independently field-calibrated (end-to-end) prior to and verified after the survey measurements. Each system had its own acoustic sound level calibrator (Brüel and Kjær Type 4230 or Larson Davis CAL200), generating a 1-kHz tone of 1 Pa [94 dB sound pressure level (SPL) re 20 µPa root mean square (RMS)]. Sound level meters and acoustic calibrators had current laboratory calibration certificates traceable to NIST.

It is worth noting that Type 1 instrumentation's ANSI filter characteristics have a long impulse response time at low frequencies. At 1 Hz, the ANSI 1/3 octave band impulse response is close to 5 seconds! Thus, unfortunately, **ANSI filters do not capture the fast peak pressure changes occurring in the low and infrasonic frequencies** [8]. The RMS levels reported in this study are understating the true range and modulation of the levels obtained compared to *the time response of the human ear*. The octave-band and FFT results in this study should be considered suggestive of the possible range of pressure changes and detectability for the human ear, thereby prompting the need for more extensive field and laboratory research.

We were able to improve our ability to perform fast signal analysis by using an external digital filter in series with the digital recording playback output, and then analyzing the digital data with

[8] Bray, W., James, R., Dynamic measurements of wind turbine acoustic signals, employing sound quality engineering methods considering the time and frequency sensitivities of human perception, Noise-Con 2011.

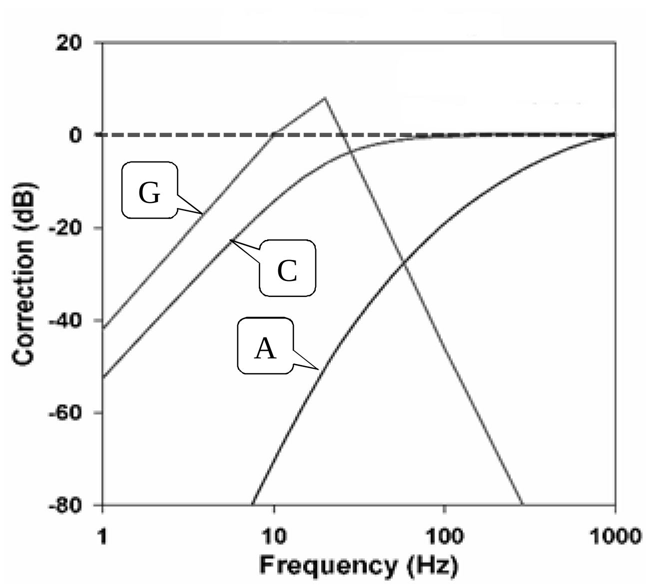
a faster response signal analyzer to observe the time history. This method revealed large modulations for the wind turbine tone at 22.9 Hz (see section 4.1.3).

The A- and C-weighting as well as octave band and FFT analysis were performed with Spectraplus software in real-time and recording mode on site. Later the recorded data was analyzed off-site using the post-processing features. G-weighted sound levels were computed using fast FFT settings for octave band analysis of the G-filtered 4, 8, 16 and 31.5 Hz octave bands using the following constants [9] which are the average value for the one-third octave bands comprising each octave band. While coarse in approach, the method was determined to be a usable trade-off between analysis time, accuracy, and computational requirements.

Octave Band, Hz:	**4**	**8**	**16**	**31.5**
dBG correction, dB:	-16	-4	7.7	-4

The A-, C-, G-weighting and un-weighted (dashed) functions are shown in **Figure 2** below [10].

Figure 2 – Weighting functions



The A-weighting filter cuts out most low frequency sound and gives the lowest reading. C-weighting includes more low frequency sound contributions and gives a higher reading than A-weighting. G-weighting measures infrasound frequencies centered in the 10-20 Hz range.

[9] ISO 7196:1995, Acoustics – Frequency weighting characteristic for infrasound measurements.
[10] Adapted from figure at http://oto2.wustl.edu/cochlea/wt4.html.

Un-weighted (dBL) measures include the entire sound signal and give the highest peak readings.

3.2 Weather Conditions

Outdoor measurements were made when weather conditions were favorable for measurements (ground level winds ≤ 9 mph and no precipitation) Publicly accessible long-term weather observation data was obtained from the nearest met tower at the Otis Air National Guard Base located a few miles away, as shown in Appendix A, B, and C.

The survey period commenced in the late afternoon of April 17, 2011 and concluded during the morning of April 19, 2011. The weather generally showed an early summer pattern with wind speeds at the hub of 20 to 25 m/s by midmorning. Low-level surface winds at the home were light and *southeasterly*, contrary to upper level *westerly* winds. At night, hub-height wind speed was light, with ground wind speed about zero. Wind speeds continuously exceeded 18 m/s during the evening of April 17 and the daytime hours of April 18. Wind gusts exceeded 30 m/s (66 miles per hour) on April 17, meaning that the NOTUS wind turbine was operating in “gale force” wind speeds at hub height, while ground level winds were generally light. This indicates "high wind shear", which is present in most of New England including the Falmouth area of Cape Cod. The conditions are summarized as follows:

> *Day 1: Changeable with wind speeds 25 to 30 meters per second at the hub, gusting to more than 35 meters/ second. Wind direction west–southwest. Barometer “low” and variable. Sunny and partly cloudy. Temperature 45 to 50 degrees Fahrenheit*
>
> *Day 2: Sunny with wind speeds 15 to 20 meters per second at the hub, gusting to 25 to 30 meters/second. Wind direction west–southwest. Barometer “low” and rising during the day. Temperature 45 to 50 degrees Fahrenheit*
>
> *Day 3: Winds stopped in morning and the field study concluded.*

3.3 Wind Turbine Operations

WIND 1 and NOTUS turbines were installed with nearest two residences having separation distances as close as 1300 feet and 1700 feet, respectively. In the spring of 2011, Falmouth imposed a maximum wind speed restriction on the WIND 1 turbine in an effort to reduce the noise levels and mitigate the adverse responses from neighbors. Wind 1's operational control software was modified to stop power generation whenever the hub-height wind speeds exceeded 10 m/s (22 miles per hour).

There was no noise reduction requirement imposed on the Webb-owned NOTUS wind turbine, even though NOTUS is as close to homes as WIND 1. The manufacturer's operational program includes a trip setting for a maximum hub-height wind speed at 32 m/s (70 miles per hour).

Thus when winds exceed 10 m/s at wind turbine hub height for any length of time, WIND 1 is shut down and NOTUS can continue to operate.

During this survey, the authors noted that the NOTUS wind turbine was clearly audible outdoors at ML1 and audible indoors at ML1 during the stronger winds. WIND 1 was not operating for most of the survey period. However, during the last day with very light wind conditions, NOTUS was seen as not turning, and WIND 1 blades were visibly rotating. This was a good opportunity for obtaining digital recordings at ML1 with only WIND 1 operating.

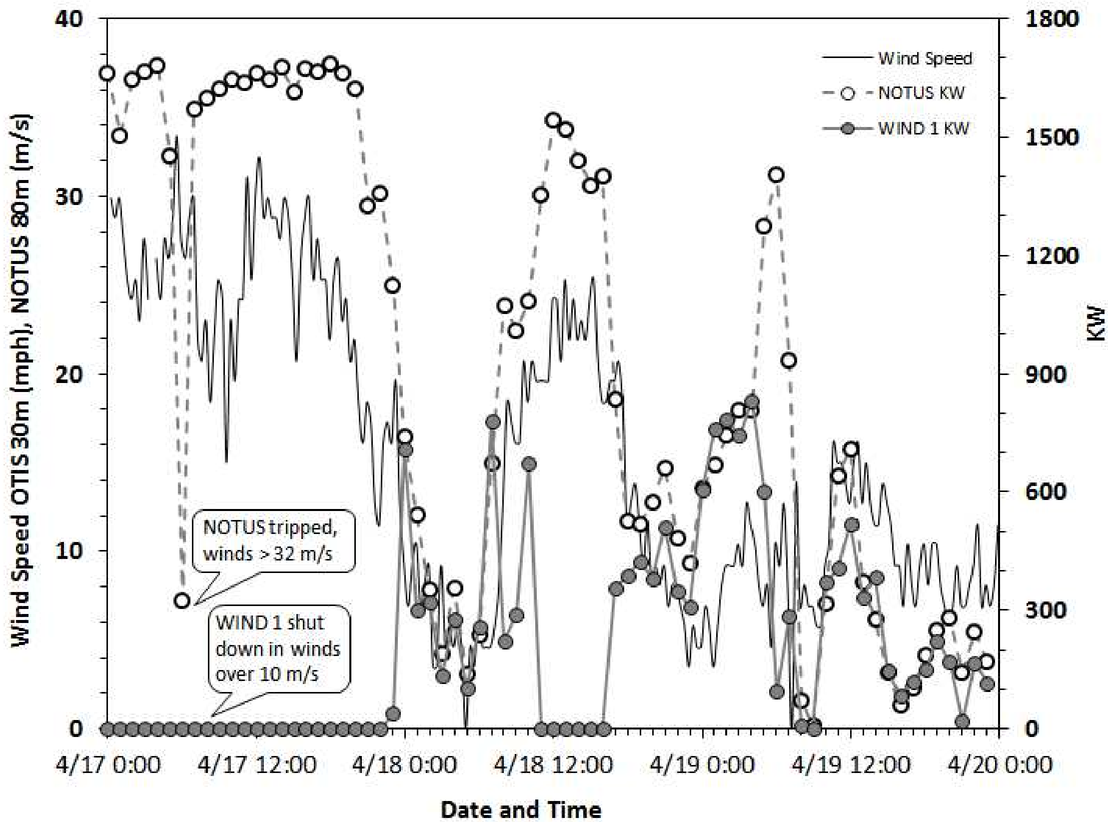
Wind turbine power outputs were obtained from the WIND 1 and NOTUS websites. Wind speed data was obtained from the nearest weather station tower at the Otis Air National Guard Base a few miles away. This data was then graphed by date showing the wind speed and correlating power output, as shown on **Figure 3**.

The wind turbines rotated at a nominal blade pass rate of 0.7 Hz or 1.4 seconds between blades passing by the turbine mast.

The NOTUS wind turbine dominated the acoustic environment the first and second day while operating. The third day, in the morning, with winds too light for NOTUS to turn, audible sounds included intermittent loading operations in a nearby sandpit, very distant traffic, and occasional cars passing by on the neighborhood roads several hundred feet distant.

Figure 3 - Wind Turbine Operations

(Showing dates, power output and wind speed)

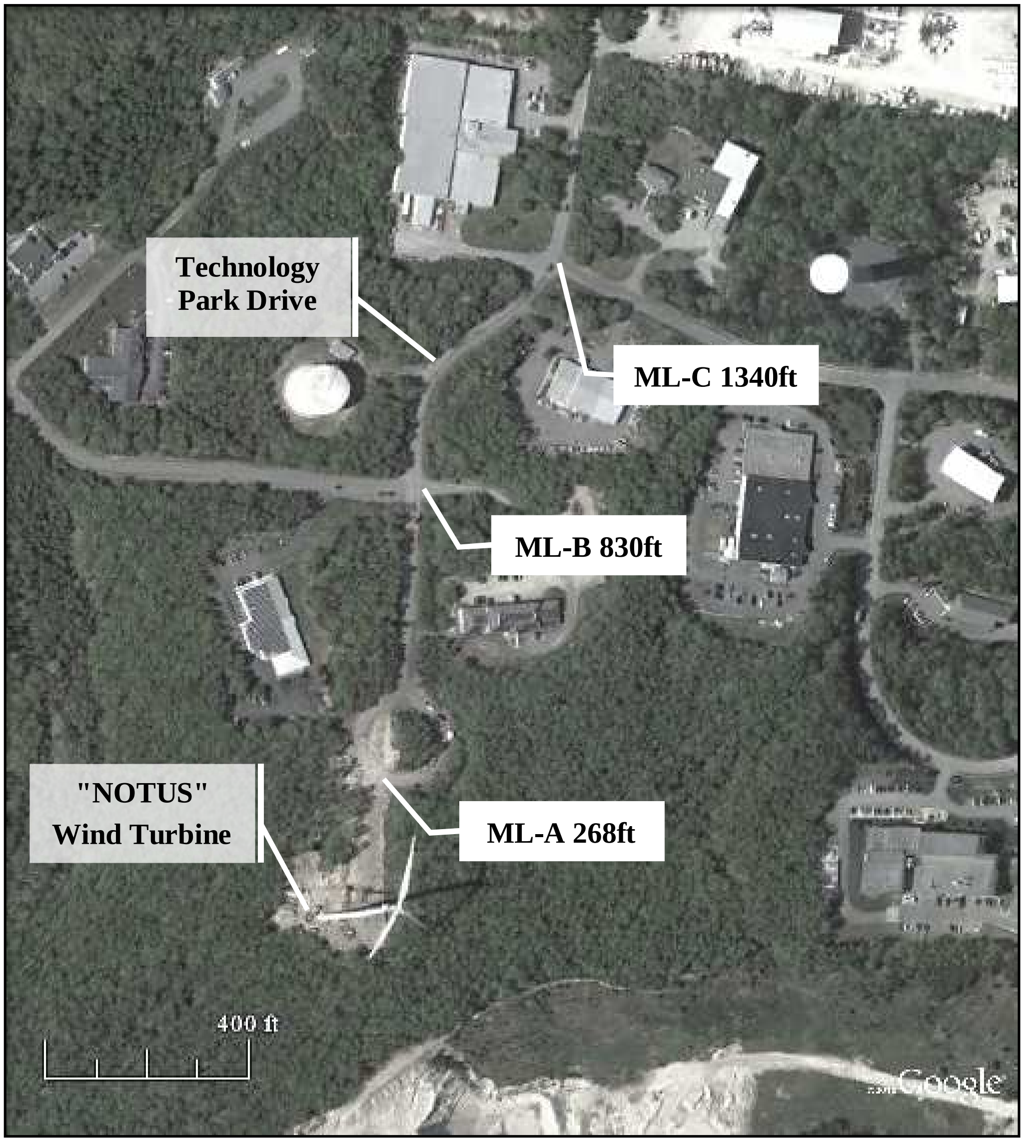


3.4 Sound Level versus Distance

Sound level measurements were made at different distances from the noise source to depict the noise level decrease with distance. This is a very useful method to use especially in quiet environments where the noise source under investigation is prominent at great distance. This measurement technique is referred to as; "level versus distance", "walk-away", or "stepped distance".

"Stepped distance" measurements were made at four locations; three in the Falmouth Technology Park (at 260, 830, 1340 feet) and one at 1700 feet at the residence under investigation (ML1) as shown in **Figure 4**. Distances from the wind turbine for the three closest locations were obtained with a laser range finder aimed at the tower base. A Google Earth satellite image was used to determine the separation distance between the wind turbine and residence (ML1). It is worth noting that noise from the wind turbine was always dominant at all measurement locations.

Figure 4 – Stepped Distance Measurement Locations



4 ANALYSIS AND RESULTS

4.1 Operations and adverse health effects felt

The survey took place over a three day period. We experienced adverse health symptoms within twenty minutes of starting the survey. Our health symptoms were tabulated with the measured data for wind speed, NOTUS output, locations, dBA, dBG & dBL levels as shown on Table 1.

Table 1 - NOTUS data and adverse health effects (ML1 at 1700 feet away from NOTUS)

Hub wind speed, m/s	NOTUS output, kw	Study	dBA	dBG	dBL	Symptoms Experienced
Day 1: 25 with gusts to 35	1600-1700	Indoors	n/a	n/a	n/a	Nausea, dizziness, irritability, headache, loss of appetite, inability to concentrate, need to leave, anxiety.
		Outdoors	n/a	n/a	n/a	Felt miserable, performed tasks at a reduced pace.
Night 1: 0-9	150-350	Indoors	18-20	n/a	n/a	*Slept with little difficulty*
Day 2: 20 with gusts to 30	1350-1500	Indoors	18-24	51-64 pulsations	62-74 pulsations	Dizzy, no appetite, headache, felt miserable; performed tasks at a reduced pace. Desire to leave.
		Outdoors	41-46	54-65 pulsations	60-69 pulsations	Dizzy, headache, no appetite. Slow. Preferred being outdoors or away.
Night 2: 4-12	150-350	Indoors	18-20	n/a	n/a	*Slept fitfully, woke up*
Day 3: 6 calm	OFF	Indoors	18-20	39-44 random	50-61 random	Improvement in health. Fatigue and desire to leave.
		Outdoors	32-38	49-54 random	57-61 random	Improvement in health. Fatigue and desire to leave.

During the start of the survey, we were attempting to perform normal activities associated with our investigation; setting up instruments, observing measurements, concentrating, using computers, leaving the house for late night, stepped-distance measurements and, returning to retire for the night. Within twenty minutes, we found ourselves having difficulties performing our ordinary tasks. For example, we had difficulty determining which wires to use and what components to connect together in what sequence. We were unsure about our calibrations, and checked them repeatedly. Within an hour, we were debilitated and had to work much harder mentally. As hours passed, the severity of the symptoms increased. We were unable to acquire meaningful data at ML1 during the first evening when winds were strongest. However, we believe that the levels not acquired on April 17 were probably similar to or several dB higher than those acquired on April 18.

Later that night after 11 PM, the winds dropped below 10 m/s. We were able to confirm calibration on our instruments and collect outdoor data after midnight at the NOTUS stepped-distance locations before it started to rain. We then retired for the night in the home under study; the winds remained under 10 m/s.

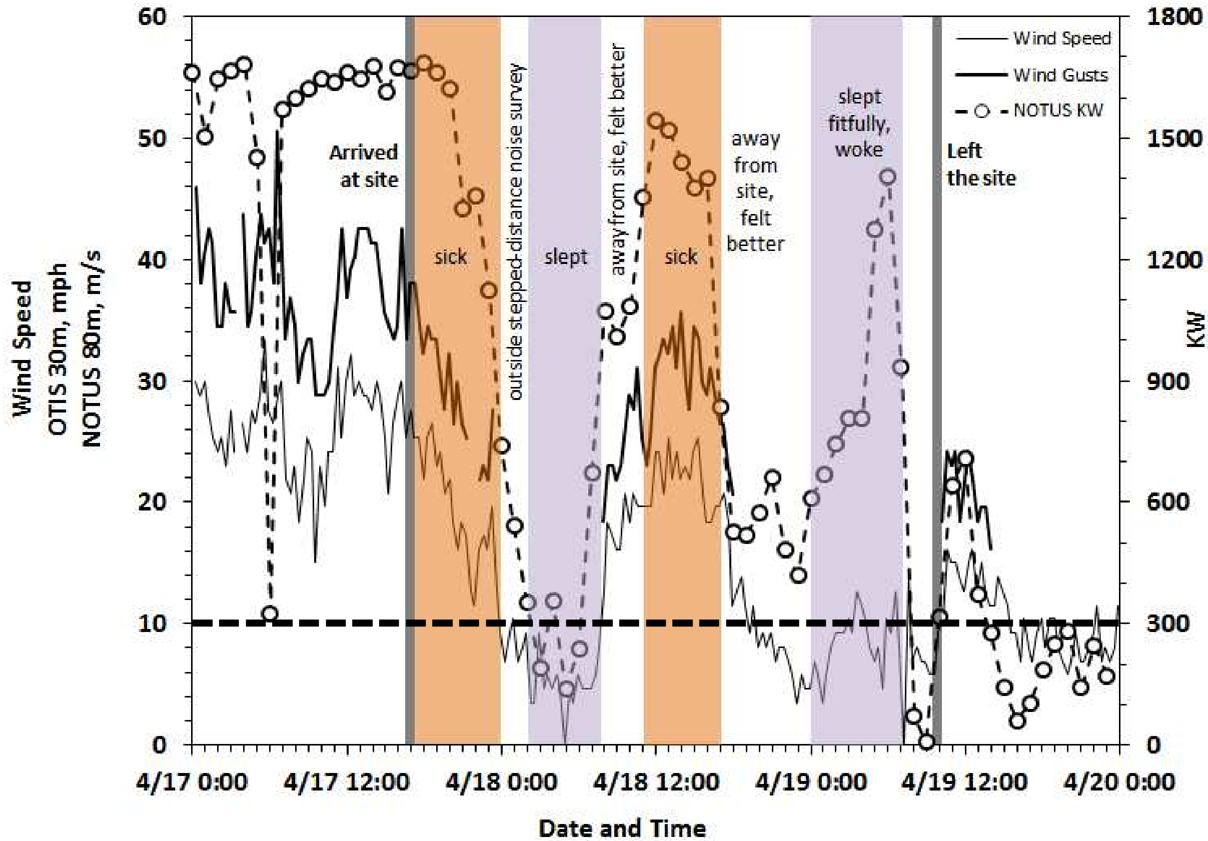
However, the adverse health symptoms at the house continued through the second day with wind speeds over 10 m/s, especially when indoors. We obtained partial relief when working outdoors.

We felt improvement in health on the morning of the third day when NOTUS was OFF and felt better over time when we left the area influenced by wind turbines. It took a week to recover, with recurring symptoms of nausea and vertigo over the next seven weeks for one of us.

We annotated Figure 2 data (NOTUS power output) with the physiological-symptoms and activities listed in Table 2, with the combined information presented on **Figure 5**.

Figure 5 - Survey Operations at ML1

(Average and gusty wind speeds)



We found that there is an *unexpected* correlation between our symptoms occurrences with the hub-height wind speed. It is worth noting that Falmouth had elected to set an operational cap on the WIND 1 at 10 m/s, *shown for reference* as a horizontal dashed line in Figure 5. *We were noticeably affected when the wind speeds were over 10m/s at hub height for NOTUS, 1700 feet from our study location.*

We found a strong correlation between the symptoms experienced by us with versus the wind speed and the NOTUS power output. The graph in Figure 5 shows that the most severe symptoms (labeled as "sick") occurred when the winds were the strongest (well above 10 m/s), as confirmed by power output. To our best knowledge, there have been no such physiological complaints made by neighbors in Falmouth *prior to* the installation of NOTUS (and WIND 1).

Further, the graph in Figure 5 shows when we were not severely affected. When the wind speeds dropped below 10 m/s the first night, we recovered enough to be able to go out and measure the stepped distance data. We also did not complain about sleeping difficulties during the first night with winds remaining below 10 m/s. However, we *both* experienced difficulty sleeping during the *second* night when the average hub-height wind speeds *increased to above 10 m/s several times* during the early morning hours.

4.1.1 Physiological Symptoms

During moderate to high wind speeds, we experienced adverse physiological symptoms very similar to those described by neighbors. We arrived fresh and ready to work, without the ill effects of missing a good night's sleep. We had no personal attachment to place, no concerns about shadow flicker or diminished real estate value. Instead we found ourselves encountering a very *visceral* discomfort (proceeding from instinct, not intellect), unexpected in this peaceful rural environment. The severity was directly related to the strength of the dBG-weighted and the un-weighted amplitude-modulated infrasonic acoustic pressure level that was proportional to wind speed.

> *We found that individuals prone to motion sickness (as both researchers are) can experience unpleasant physiological symptoms, especially indoors near a wind turbine. We also acknowledge the large body of medical evidence of vestibular medical conditions that can cause problems with balance and orientation, nausea, dizziness, anxiety, and other health effects, that that can be worsened by adverse environmental conditions.*

4.1.2 Current Research

From our experience in April, we know now that understanding the adverse health effects reported by neighbors living near large industrial wind turbines requires coordinated research involving several branches of science, including neuroscience, otolaryngology, and acoustics. We will not attempt here to present the vast areas of knowledge represented by the disciplines just listed. We will cover a very small portion in order to lay the basic framework for presentation of Dr. Salt's work on the response of the ear to infrasound.

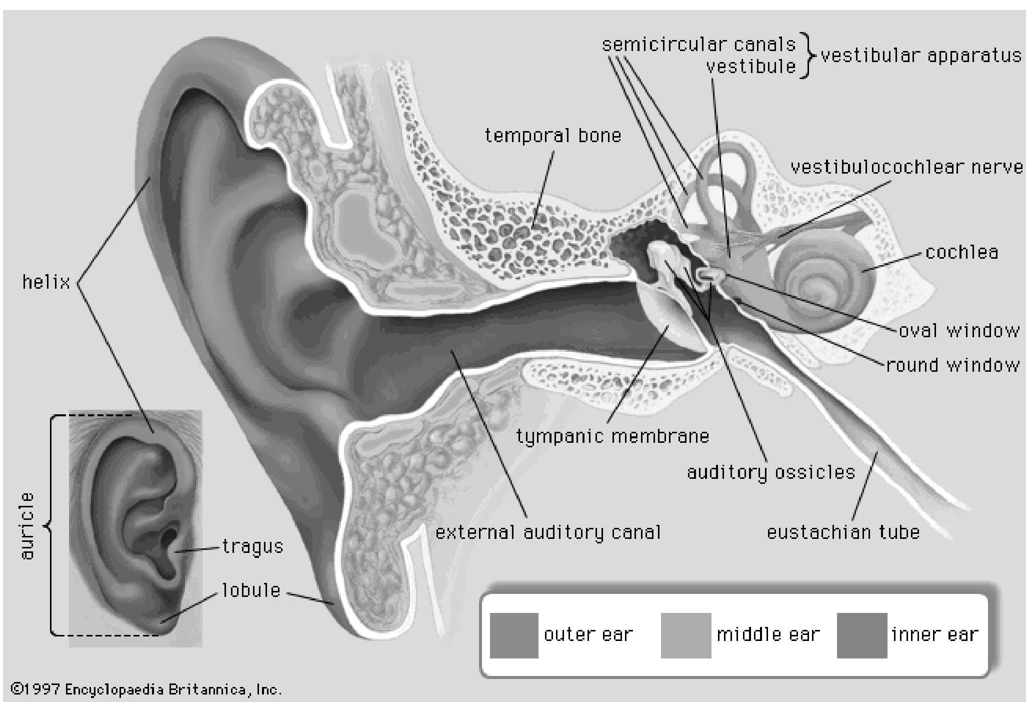
Sound pressure is the small alternating deviation above and below atmospheric pressure due to the propagated wave of compression and rarefaction. The unit for sound pressure is the Pascal (symbol: Pa). Sound pressure level (SPL) or sound level is a logarithmic measure of the effective sound pressure of a sound relative to a reference value. It is measured in decibels (dB) above a standard reference level. The commonly used "zero" reference sound pressure in air is

20 µPa RMS, which is usually considered the median threshold of human hearing (at 1 kHz). Some 16 percent of the population is about 6 dB more sensitive than the median. Frequency is measured by the number of waves per second or Hertz (Hz). The average range of hearing is 20-20,000 Hz with the greatest sensitivity in 1000-4000 Hz. At the most sensitive frequency around 4 kHz, the amplitude of motion of the eardrum is about 10^{-9} cm, which is only about 1/10 the diameter of a hydrogen atom. Thus, the ear is very sensitive, detecting signals in the range of atomic motion.

The term "infrasound", which refers to acoustic energy at frequencies below 20 Hz, is misleading for most, not being "sound" at all as we know it but either felt or inaudible. However as determined by Dr. Salt, the ear detects and responds to infrasound.

We present for reference a diagram of the ear in **Figure 6**. Note that the inner ear's vestibule and semicircular balance canals are as close to the eardrum as the cochlea which processes sound.

Figure 6 – Diagram of the ear



The vestibular system in the brain does more than just allow us to stand upright, maintain balance and move through space [11]. It coordinates information from the vestibular organs in the inner ear, the eyes, muscles and joints, fingertips and palms of the hands, pressors on the soles of the feet, jaw, and gravity receptors on the skin and adjusts heart rate and blood pressure, muscle tone, limb position, immune responses, arousal and balance. The auditory system is also highly involved in vestibular functions. The vestibular and auditory nerves join in the auditory canal and become the eighth cranial nerve of the brain. Anything that disrupts auditory information can also affect vestibular functioning.

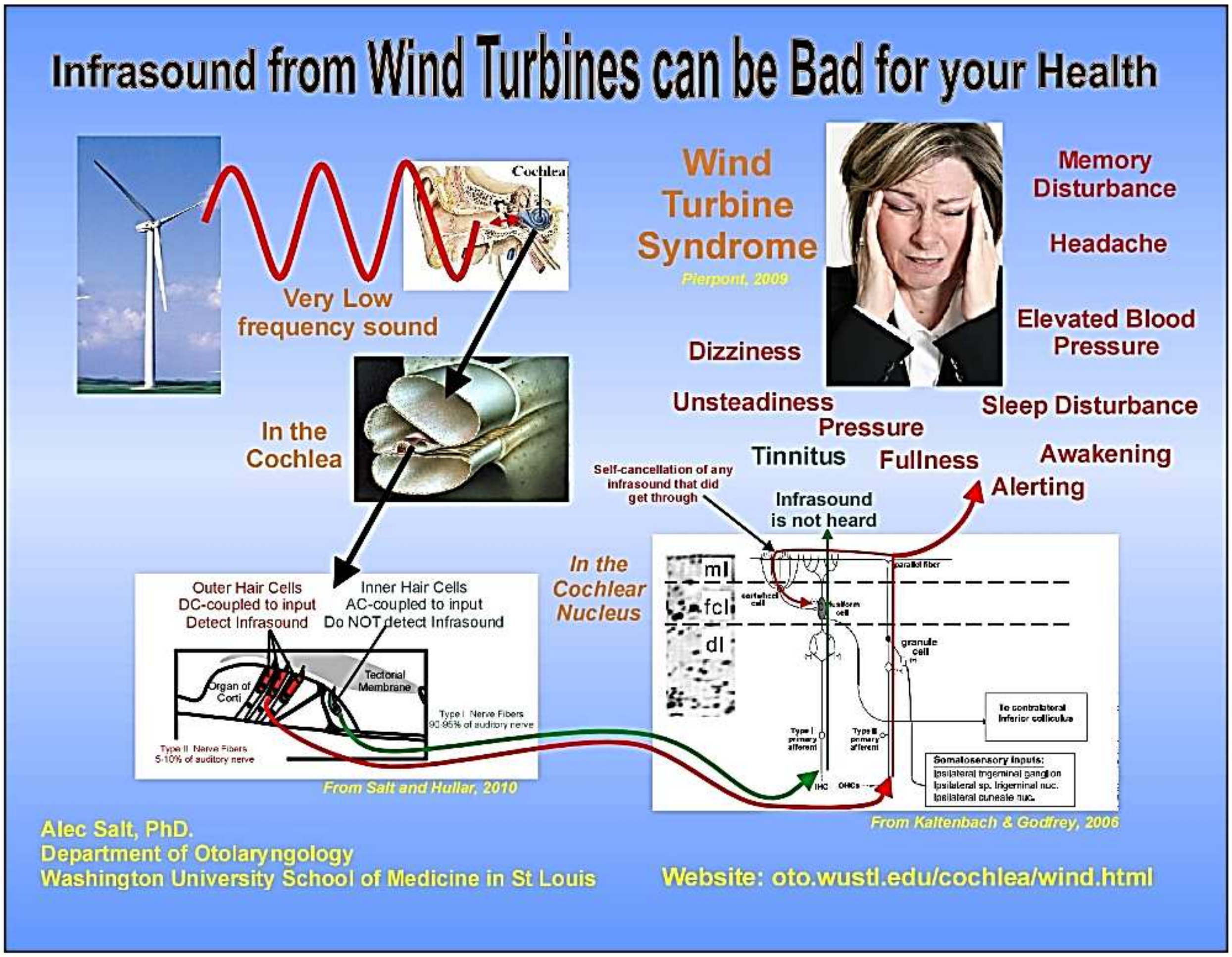
> *Our symptoms (ear pressure, dizziness, vertigo, anxiety) suggested that there was atmospherically transmitted energy that directly affected our vestibular systems. Yet we were puzzled by the fact that we were most severely affected when sitting relatively still indoors, not moving about. What were our vestibular systems responding to? Were the vestibular canals being moved? Were the otolithic crystals being displaced [12]? Was the endolymphatic fluid volume being affected? Was a vestibulosympathetic reflex involved? Was the ear triggering fight or flight reactions in response to low frequency sound?*

Dr. Alec Salt [13] has conducted extensive research into vestibular response to sound pressure pulsations. His research shows that ***the ear responds to sound we cannot hear***.

There are two types of hair cells in the cochlea, the inner hair cells (IHCs) and the outer hair cells (OHCs). The IHCs are fluid-connected and *velocity*-sensitive, responding to minute changes in the acoustic pressure variations based on frequency, with sensitivity decreasing at a rate of -6 dB per downward octave. ***IHCs detect audible sounds and they are insensitive to low frequency and infrasonic acoustic energy.*** In contrast, the OHCs are motor as well as sensory cells. OHCs are found only in mammals. OHCs are mechanically connected, responding to small changes in *displacement*, with a more uniform sensitivity across the acoustic frequency spectrum. ***OHCs respond to and contract with infrasonic stimulus*** and then act to reduce vibration stimulus at the IHCs. Thus there are actually *two* specialized receptors, or transducers, in each ear, as outlined in Dr. Salt's slide in **Figure 7**.

[11] http://www.braintraining.com/vestibular.htm.
[12] "...small crystals of calcium carbonate (also referred to as "otoliths" or "canaliths") that are normally attached to the otolithic membrane in the utricle of the inner ear.", http://www.vestibular.org.
[13] Department of Otolaryngology, Washington University School of Medicine, St. Louis, Missouri, USA.

Figure 7 – Ear response to very low frequency sound



Dr. Salt's research reported the following [14]:

- The ear is sensitive and responds to low frequency and infrasonic pressure modulations at levels that are not heard (sub-audible).
- Low frequency pressure modulations produce a *biological* amplitude modulation of nerve fiber responses to higher frequency stimuli. This biological amplitude modulation cannot currently be detected by even the most sophisticated sound level meter.

[14] Salt, A., "Responses of the Inner Ear to Infrasound" - presentation to the Wind Turbine Noise Conference, Rome, April 11-14, 2011.

- The outer hair cells of the ear are directly attached (DC-coupled) to movements of the sensory structure and respond to infrasound stimuli at moderate levels.

- Low frequency stimulation of the outer hair cells (OHC) may be used in the brain to eliminate infrasound from hearing (improving and optimizing the signal to noise ratio of the audible-range ear mechanism in most acoustic environments, except the very quiet.) Low frequency stimulation of the OHCs is also linked to the attention state and arousal, so stimulation could disturb sleep.

- Outer hair cell responses to infrasound are the most sensitive when ambient sound levels are low.

In summary, Dr. Salt indicates very simply,

> *"The idea that infrasound doesn't or can't affect the ear is just flat-out wrong."* [15]

Our field experience in Falmouth in April 2011 is consistent with Dr. Salt's research findings. As detailed in the following sections, we experienced the most adverse health symptoms indoors where the acoustic energy was 0.2 Pascal peak-to-peak, modulated at 0.7 Hz, with portions of the low-frequency energy modulated above the OHC threshold, while occurring in a very low background sound level of around 20 dBA. Our symptoms lessened somewhat outdoors, where the pressure pulsations at 0.7 Hz were slightly lower than indoors, and the background level was in the low 40s dBA.

We understand that some families living near wind turbines and experiencing similar effects indoors, yet not ready to abandon their homes, have resorted to sleeping outside in tents. This lessening of effects outdoors (compared to indoors) is consistent with findings of low-frequency noise effects documented in [2].

Dr. Salt formally identified in 2011 a number of areas requiring more research:

Stimulation of vestibular hair cells (saccule, utricle).

Vestibular hair cells are "tuned" to infrasonic frequencies.

No-one has ever measured sensitivity to acoustic infrasound.

Symptoms: unsteadiness, queasiness

[15] Salt, A., http://oto2.wustl.edu/cochlea/wt7.html.

Disturbance of inner ear fluids (e.g. endolymph volume).

Low-frequency sound at non-damaging levels induces endolymphatic hydrops (a swelling of one of the fluid spaces).

Infrasound does affect endolymph volume – it is the basis of a treatment for hydrops (Meniere's disease).

No one has ever measured what level of infrasound causes hydrops.

Symptoms: ear fullness, unsteadiness, tinnitus

Infrasound – affected structures and long-term exposure effects, ranked by sensitivity:

Outer hair cells — "Overworked, tired, irritated" OHC, type II fiber stimulation

Inner ear fluid homeostasis — Volume disturbance, endolymphatic hydrops

Saccular hair cells — Stimulation

Other, non-ear, receptors — Stimulation

Inner hair cells/hearing — None

Sensitivity and sensations remain to be quantified: ear pressure or fullness, discomfort, arousal from sleep; ear fullness, tinnitus, unsteadiness; unsteadiness; stress, anxiety.

4.1.3 OHC & IHC Sensitivity Analysis

A representative average (not peak) wind turbine noise spectrum, obtained during the second day (April 18, hub-height winds 20 m/s and gusting) when the researchers were experiencing moderate-to-severe adverse health effects, was compared with Dr. Salt's OHC and IHC threshold data [16]. When the wind turbine noise was dominating, the sound level was in the low 40s dBA outdoors and about 20 dBA indoors.

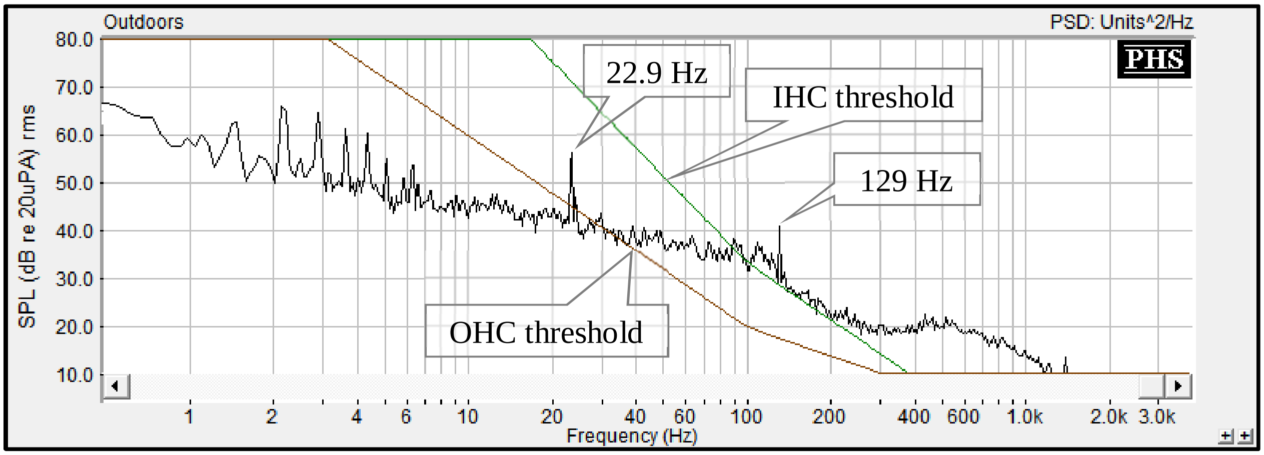
The outdoor RMS spectrum presented in **Figure 8a** shows that both the 22.9 & 129 Hz wind turbine tones exceed the OHC threshold levels along with all frequencies above 30 Hz. The 22.9 Hz tone was not audible outdoors. However, the 129 Hz tone was clearly audible outdoors since it exceeded the IHC audibility threshold.

The indoor RMS spectrum presented in **Figure 8b** shows that both the 22.9 & 129 Hz wind turbine tones exceed the OHC threshold levels. Again, the 22.9 Hz tone was inaudible indoors and the 129 Hz tone was frequently audible, more so than reflected in the averaged RMS level.

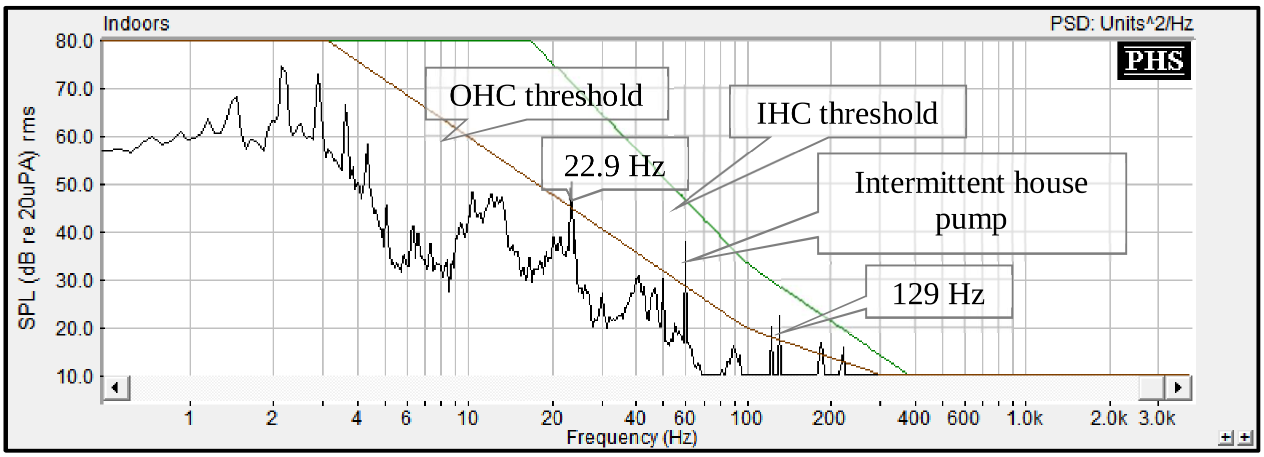
[16] Curves furnished by Dr. Salt via private communication, 2011.

Figure 8 – OHC & IHC Thresholds vs. RMS Wind Turbine Spectrum (4/18/2011)

8a – Outdoors (RMS)



8b – Indoors (RMS)



We were drawn to evaluating the potential significance of the 22.9 Hz tone. The amplitude modulation of the 22.9 Hz tone was evaluated using an external 10th-order digital bandpass filter (20 to 24 Hz) applied to the digital recording output and then analyzed with SpectraPlus software at 23 millisecond intervals using Hamming weighting. The time history presented in **Figure 9** shows that the indoors 22.9 Hertz tone modulates significantly above and below the OHC threshold of 45 dB SPL at 22.9 Hz.

Figure 9 – 22.9 Hz tone and its OHC threshold

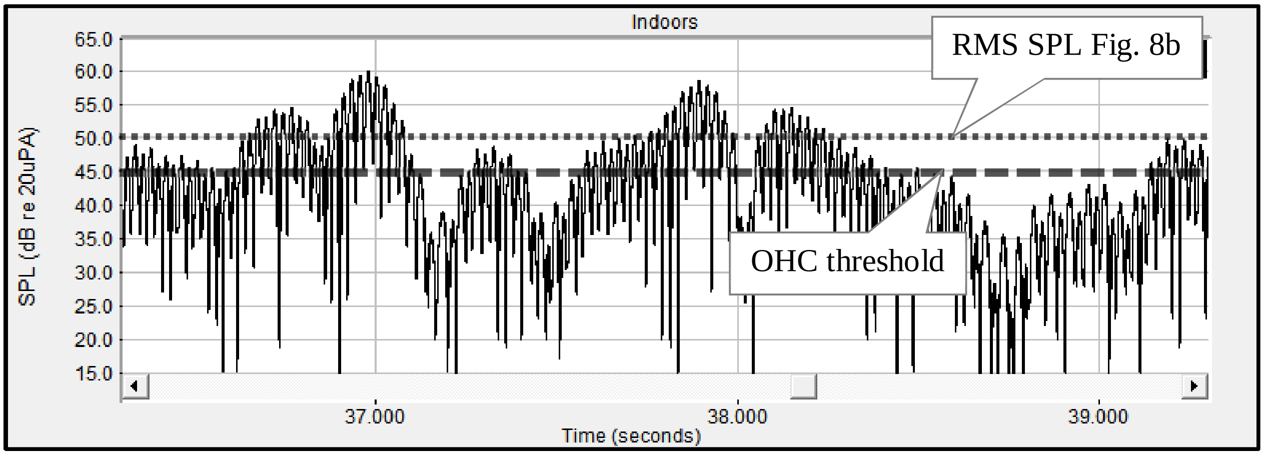


Figure 9 reveals a remarkable range of modulation in the 22.9 Hz tone, which peaks in this example time record as high as 60 dB SPL, 10 dB higher than the 50 dB SPL mean established by the FFT averaging. Nulls between peaks drop down several tens of decibels below the OHC threshold. The figure suggests that the inner ear OHC circuitry is receiving individual low-frequency pressure events 43 milliseconds apart at the 22.9 Hz driving frequency. The tone does not reach the IHC threshold (about 72 dB SPL at 22.9 Hz) and in fact we did not find the 22.9 Hz tone to be distinctly audible. Based on Dr. Salt's research, these 22.9 Hz pressure events are undetected by the IHC circuitry, yet strong enough to trigger the OHC circuitry which then drops gain on the IHC circuitry.

Example dBG-weighted time histories for the second day (4/18/2011) can be reviewed in **Figures 10a & 10b** with the 60 dBG guideline shown as a dashed line.

Figure 10a – dBG levels, indoors

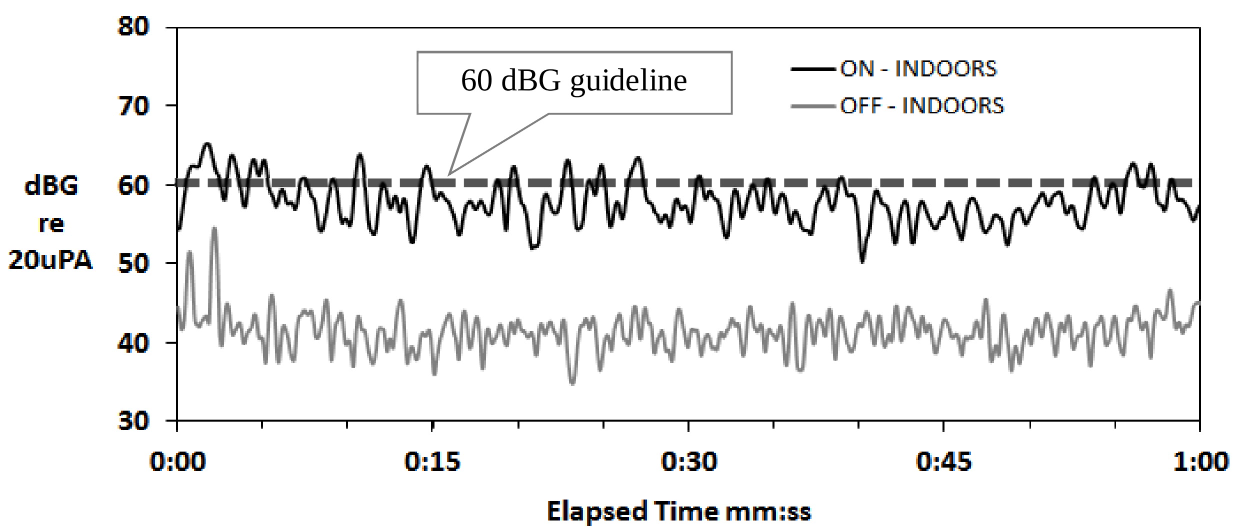
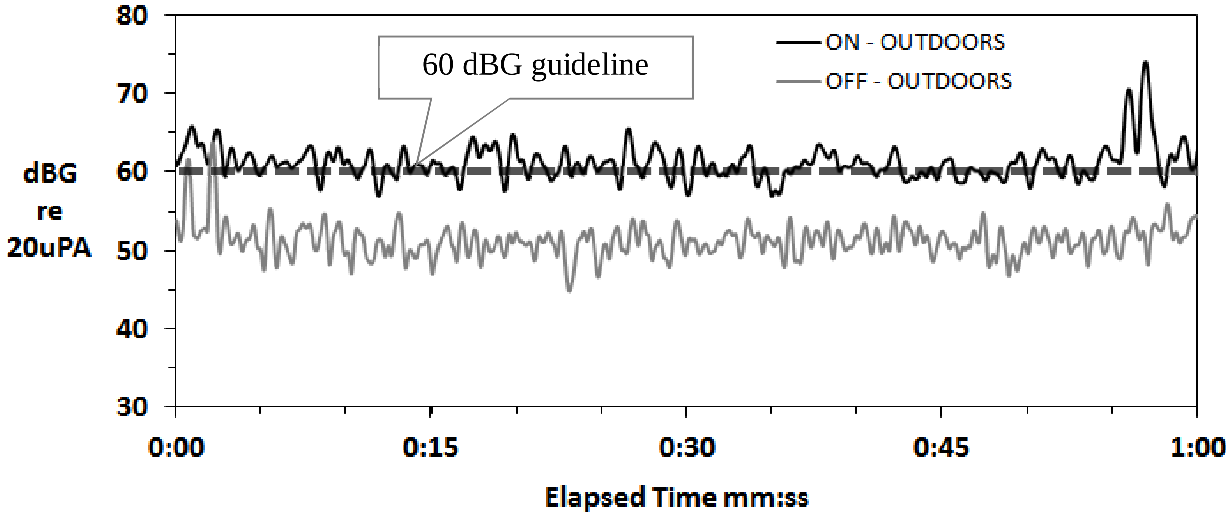


Figure 10b – dBG levels, outdoors



These figures (10a & 10b) clearly show the dBG-weighted levels exceeding Dr. Salt's 60 dBG guideline when the NOTUS wind turbine is operating. Again, based on Dr. Salt's research, these low-frequency pressure events are undetected by the IHC circuitry, yet strong enough to trigger the OHC circuitry which then drops gain on the IHC circuitry.

Indoors, the dBG level was modulated above 60 dBG with turbine ON and was down in the high 30s to low 40s (dBG) with turbine OFF. Indoors, we observed a 20 dB increase in dBG due to the wind turbine operation.

Outdoors, the dBG level was modulated above 60 dBG with NOTUS ON and was down in the low 50s (dBG) with NOTUS OFF. There we observed a 10 dB increase in dBG due to the wind turbine operation.

As a point of reference, relief started to set in for us when NOTUS was off with resulting dBG levels generally not exceeding 55 dBG outdoors and below 45 dBG indoors.

4.1.4 Discussion: Effects on Sleep and Wake States

Sleep Disturbance

We found that sleep was disturbed during the second night with hub-height winds above 10 m/s. However the background sound levels were low indoors, around 20 dBA. What could have been disturbing our sleep? This experience demands further study. We offer here a possible link.

> *From our direct experience that night, we hypothesize that sleep was disturbed when the wind turbine's principal modulation frequencies including the 0.7 Hz*

blade pass modulated in-flow turbulence pressure pulsations and 22.9 Hz tone became sufficiently detectable to the ear's vestibular system to engage the brain centers through the auditory frequency following response, or FFR [17,18]), and may have created conflict with the brain's sleep operations which would have its own sequences and frequency states during the night.

In sleep the brain is normally in Theta (4-7 Hz) or Delta (up to 4 Hz) states, as seen in **Figure 11**.

Figure 11 – Brain Waves

Type	Frequency (Hz)	Behavior
Delta	up to 4	• Slow wave sleep in adults, and some continuous attention tasks.
Theta	4 – 7 Hz	• Drowsiness or arousal in older children and adults, idling.
Alpha	8 – 12 Hz	• Relaxed/reflecting, closing the eyes.
Beta	12 – 30 Hz	• Alert/working, active, busy or anxious thinking, active concentration.
Gamma	30 – 100 +	• Perception which combines two different senses, such as sound and sight and short term memory matching of recognized objects, sounds, or tactile sensations.

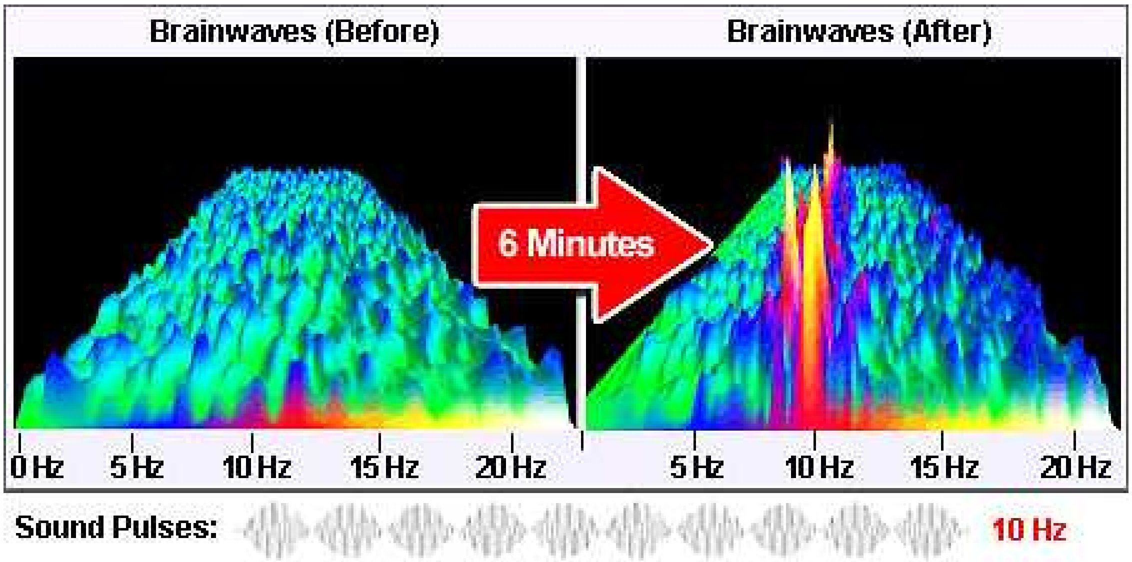
The wind turbine's 22.9 Hz tone lies in the "high Beta" range of brain wave frequencies (understood to be 23-30 Hz). Beta brain wave activity is understood to be associated with alert brain state, anxiety, and stress. Conversely, the wind turbine's blade pass frequency of 0.7 Hz, with which the wind turbine turbulence and tonal energy is amplitude-modulated, lies in the deep Delta brain wave range. We understand that medical researchers have established that entrainment to an external frequency when the brain would normally be operating at its own frequency requirements may result in brain activity conflict. That is certainly what we

[17] Frequency-following responses (FFRs), sustained evoked potentials based on precisely phase-locked responses of neuron populations to low-to-middle-frequency periodical acoustical stimuli.

[18] Du, Y. et al, Auditory frequency-following response: a neurophysiological measure for studying the "cocktail-party problem". Neurosci Biobehav Rev. 2011 Nov;35(10):2046-57. Epub 2011 May 27.

experienced. The brain entrains through FFR to external acoustic stimulus [19], example shown in **Figure 12**.

Figure 12 – Brain Response to 10 Hz Entrainment



This line of reasoning suggests that we may have experienced FFR with wind turbine acoustic emissions. We were unprepared to acquire brain wave (EEG) states during the field work to confirm FFR. If the medical protocols can be established, would EEG field testing be useful? It appears so.

Wake State

We experienced cloudy thinking, lethargy and difficulty with activities especially indoors during the daytime hours when wind speeds were strong at hub height. The wind turbine's 22.9 Hz tone increased in strength with increasing hub-height wind speed. Again, the 22.9 Hz tone is in the "High Beta" frequency band. There is clinical evidence that "synchronizing cortical activity in the beta frequency band slows voluntary movement" [20]. Other researchers [21,22] have investigated the abnormally high amounts of beta wave oscillatory brain activity in Parkinson's' Disease. Their research "demonstrated abnormally synchronized oscillatory activity at multiple levels of the basal ganglia-cortical loop. This excessive synchronization correlates with motor deficit".

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[19] Original source reference being sought.

[20] Pogosyan A, Gaynor LD, Eusebio A, Brown P., Boosting Cortical Activity at Beta-Band Frequencies Slows Movement in Humans. Curr Biol. 2009 Oct 13;19(19):1637-41. Epub 2009 Oct 1.

[21] Hammond, C., et al, Pathological synchronization in Parkinson's disease: networks, models and treatments. Trends Neurosci. 2007 Jul;30(7):357-64. Epub 2007 May 25.

[22] Eusebio, A., Brown, P., Synchronisation in the beta frequency-band — The bad boy of parkinsonism or an innocent bystander? Exp Neurol. 2009 May; 217(1): 1–3. doi: 10.1016/j.expneurol.2009.02.003.

We understand a number of people worldwide have experienced cardiovascular upset near wind turbines; pains in chest, heart racing, palpitations. Were our cardiovascular systems being influenced through entrainment during the Falmouth study?

> *According to the principle of entrainment [23], two systems will entrain or align their rhythms if exposed to each other for a sufficient length of time. At 42 modulations per minute, the 0.7 Hz blade pass frequency falls in the range of resting heart rates for athletes. Our heart rates are normally closer to 65-70 bpm. Could our heart rates have slowed? Could entrainment have spurred adaptive vestibular attention to signals from vascular baroreceptors for confirmation of the incoming pressure pulsations? We do not know. We were unprepared to monitor heart rate variability or cardiovascular condition during the study.*

What do these lines of thinking suggest?

First, they suggest that brain oscillations may synchronize to the wind turbine. Our experience told us that our mental functions shifted dramatically within a short period of exposure to the wind turbine noise. The effect may be more pronounced or occur more quickly when winds are strong, and from our own experience, can affect sleep and waking states. Anxiety could have emerged for the very reason that the incoming energy processed and reported by the vestibular system was inaudible.

Second, they suggest that a complex of physiological conditions may be triggered by the vestibular processing of the incoming low-frequency energy that is inaudible yet exceeds the vestibular threshold. These human responses strongly suggest that this is in fact *a medical problem*. Medical doctors and researchers should evaluate the health effects reported by neighbors living near wind turbines in Falmouth through epidemiological and laboratory work.

[23] "a synchronization of two or more rhythmic cycles," a scientific phenomenon discovered by Dutch scientist Christian Huygens in 1665. Following the law of the conservation of energy, when two closely related rhythmic cycles interact they synchronize with each other.

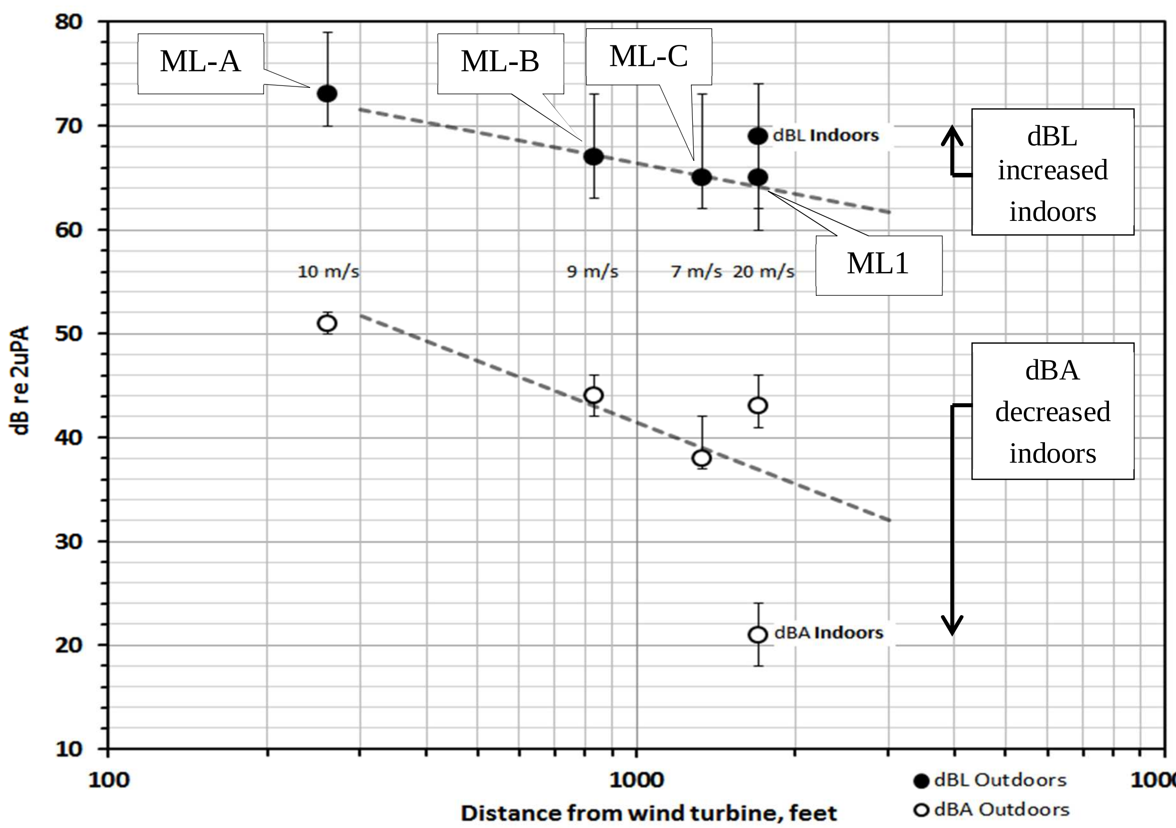
4.2 Sound Level versus Distance

Outdoor dBA sound levels decrease at 6 dB per doubling of distance (6 dB/dd) as depicted by the inverse square law for acoustic frequencies. Sound level versus distance measurements were plotted *using a semi-log scale for distance*. This graphing method typically shows the drop of sound level as a straight line as the distance increases.

The "stepped distance" data combined with the data at ML1 clearly show that the NOTUS noise level decreases with distance uniformly, as shown on **Figure 13.**

Figure 13 - NOTUS RMS Sound Level vs. Distance

(Showing wind speeds, and average noise levels with max-min ranges)



There are two trend lines; the lower dashed one showing the dBA decreasing at a predictable 6 dB/dd. The dBA trend line is faired through a wind speed of 8 m/s which is the wind turbine specification wind speed. The upper line is for the unweighted sound level, which is controlled in these measurements by energy at frequencies less than 20 Hz. The data indicate a decrease with distance consistent with cylindrical spreading; about 3 dB/dd.

> *Outdoor sound wave propagation generally occurs in one of three ways; spherical or hemispherical, represented by a decrease of 6 dB per doubling of distance, or cylindrical, with a decrease of 3 dB per doubling of distance.*

Measurements at the house were measured indoors and outdoors. The dBA measurements show that the indoor levels were more than 20 dB quieter than outdoors, depicting a well-built house with good noise reduction. A closer look reveals an important bit of information. The un-weighted linear (dBL) levels *indoors* were actually several dB *higher* than those *outdoors*. This indicates that the house is reinforcing and amplifying the very low frequency energy.

Analysis of the WIND 1 digitally recorded data using signal analyzer software shows that there are series of repetitive low-level infrasonic pulses with energy in the range of 0.7 to 6 Hz at multiples of the blade pass rate of 0.7 Hz. These are unique to the wind turbine, and we have not located similar data for environmental sources. They are presented in the sections 4.3 to 4.5.

4.3 House Noise Reduction

Field testing was conducted general accordance with the applicable ANSI Standards; ANSI Standards S12.18-1994 (Procedures for Outdoor Measurement of Sound Pressure Level, Method 1) and S12.9-1993/Part 3 (Procedures for Short-Term Measurements with an Observer Present) and ASTM E996-02 [24]. Measurements were made with the NOTUS wind turbine operating with hub height wind speeds averaging about 20 m/s. A simultaneous dual-channel analysis was performed using two precision condenser microphones; one located inside (master bedroom) and another outside (lawn well clear of house and trees). The one-minute time-averaged transfer function analyses are shown on **Figures 14a and 14b**, FFT and octave band, respectively.

[24] "Standard Guide for Field Measurements of Airborne Sound Insulation of Building Facades and Facade Elements", ASTM Designation: E 966 – 02. Definition: outdoor-indoor level reduction, OILR—in a specified frequency band, the difference between the time-averaged exterior sound pressure and the space-time average sound pressure in a room of a building.

Figure 14a - Outside-to-Inside Level Reduction (OILR), FFT

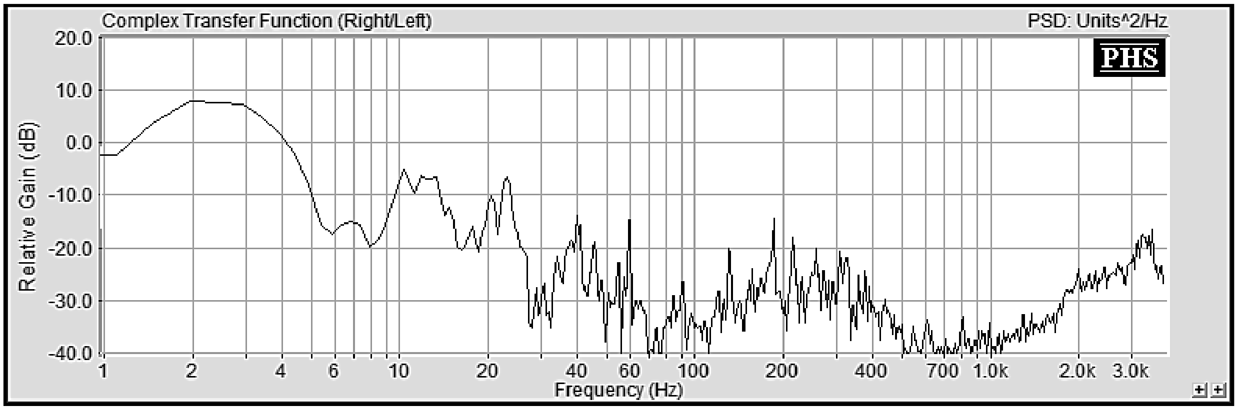
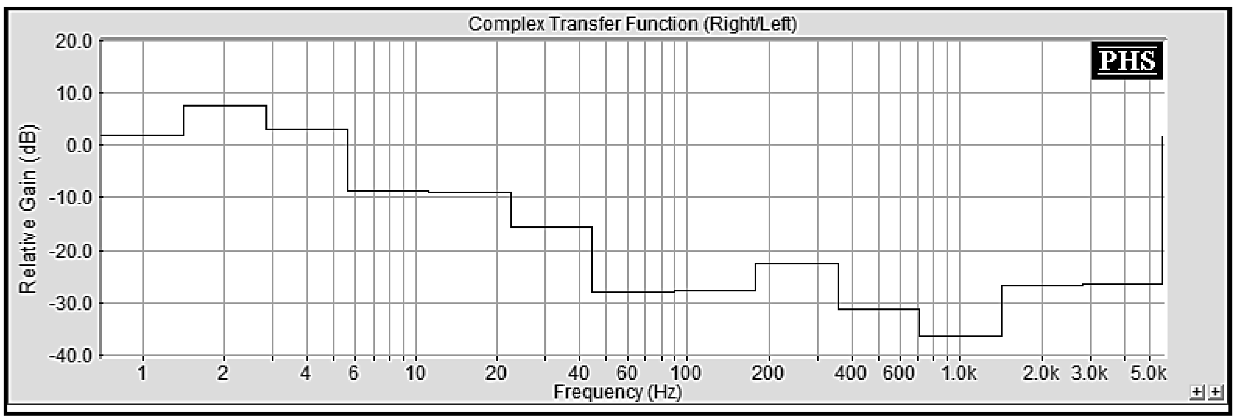


Figure 14b - Outside-to-Inside Level Reduction (OILR), Octave Band



The graphs in Figures 14a & 14b present a preliminary assessment of the outside-to-inside-level-reduction (OILR), or "noise reduction" (NR) provided by the house exterior walls and roof.

Negative values indicate attenuation or NR, while positive values indicate amplification. There is on average more than 20 dB of NR for frequencies greater than 31.5 Hz, and about 15 dB in the 31.5 Hz band. From 16 to 8 Hz the NR is reduced to 10 dB. However, below 8 Hz there is no NR, but rather there appears to be amplification for the very lowest frequencies. This is evident in a review of the octave-band sound pressure in Pascal shown in **Figures 15a & 15b**.

Figure 15 – Sound pressure, NOTUS ON (4/18/11)

Figure 15a - Outdoors

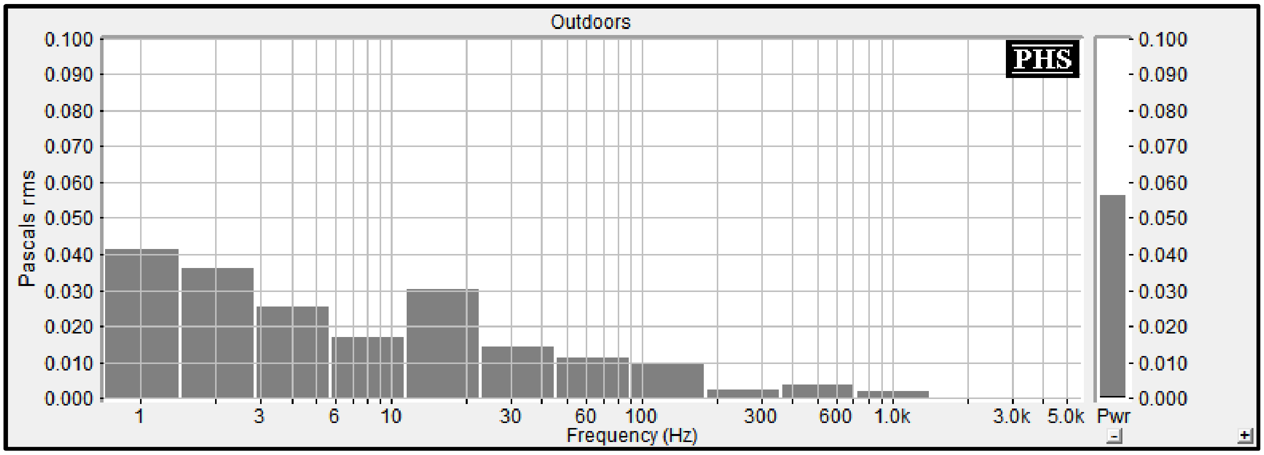
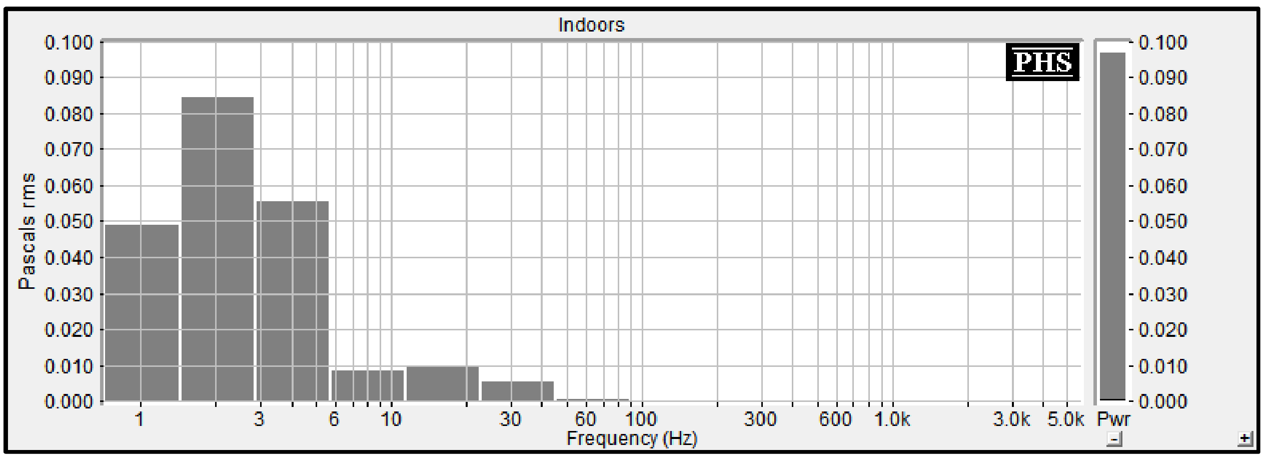


Figure 15b - Indoors



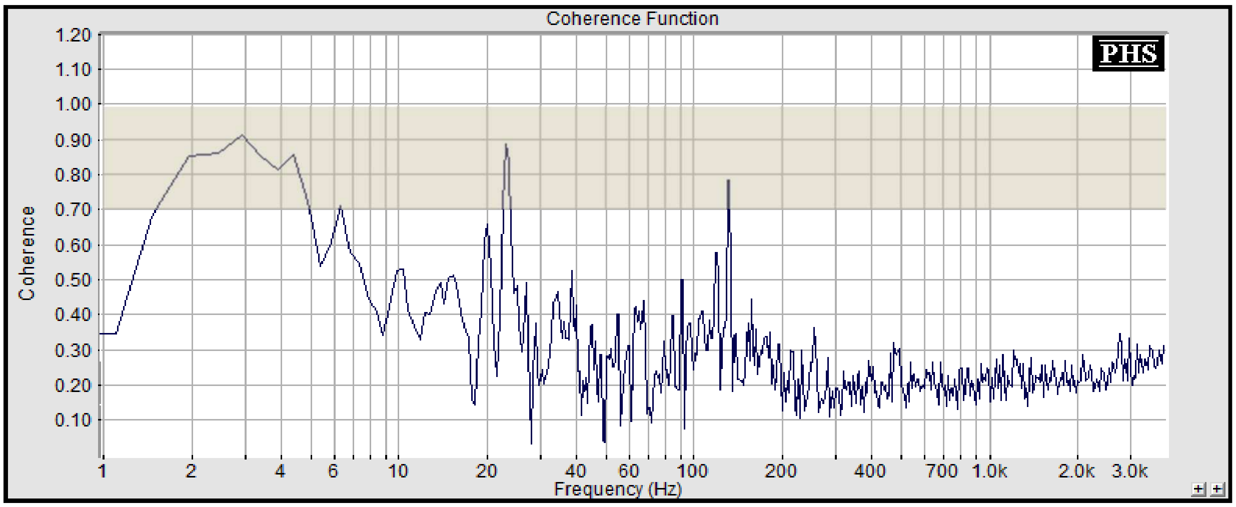
4.4 Acoustic Coupling to Home Interior

"It's like living inside a drum".

This comment has surfaced several times during wind turbine facility investigations. Is the wind turbine acoustic signature acting like a drum stick striking on the house-as-drum? Is the acoustic energy outside coupled into the interior space? To evaluate what acoustic energy emitted by the wind turbine was coupled into the house interior, a coherence analysis was conducted from a series of averaged frequency-amplitude measurements of the outdoor and indoor microphone signals (**Figure 16**). Coherence is the ratio of the squared magnitude of the cross-spectrum and the product of the auto-spectrum of both channels. It measures the *degree of linearity* between the channels and is analogous to the squared correlation coefficient used in statistics. Two perfectly coherent signals have a coherence value of 1.0. A coherence value of 0.7 or more (highlighted below) was considered for this analysis as indicative of strong acoustic coupling, the acoustic energy *indoors* highly correlated to the acoustic energy *outdoors*.

Figure 16- Coherence, Outdoors to Indoors

(April 18, 2011, 3:22 pm)

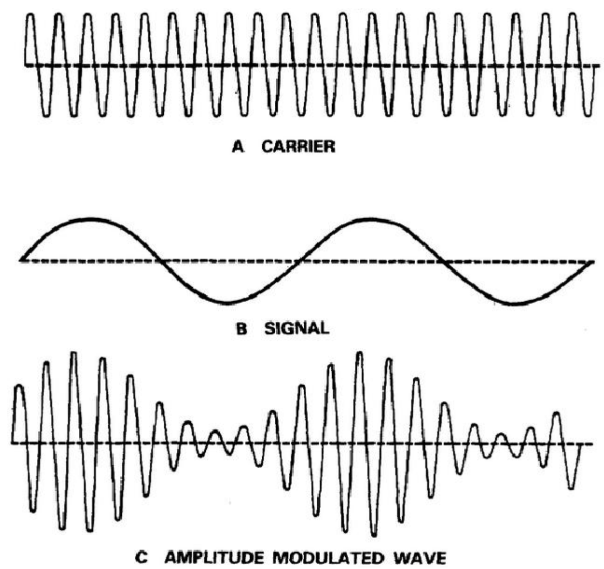


The coherence values indicate that the very-low-frequency energy found below 10 Hz was very-strongly coupled into the house interior, consistent with the indoors pressure amplification noted in section 4.3. This suggests a "whole-house" *cavity response* of the interior house volume. The 22.9 Hz and 129 Hz tones were also strongly coupled outdoors to indoors.

4.5 Dynamic Amplitude Modulation

Wind turbine noise presents a characteristic that distinguishes it from ambient noise; dynamic amplitude modulation. The process of amplitude modulation is familiar to those who understand the fundamentals of AM radio broadcasts. In amplitude modulation (AM), a carrier wave's amplitude is modulated by a lower-frequency signal (**Figure 17**). The frequency of the carrier wave remains unaltered but its amplitude is caused to vary by an amount proportional to the amplitude of low frequency signal and at the rate proportional to the frequency of the signal and the modulated wave obtained.

Figure 17 - AM modulation



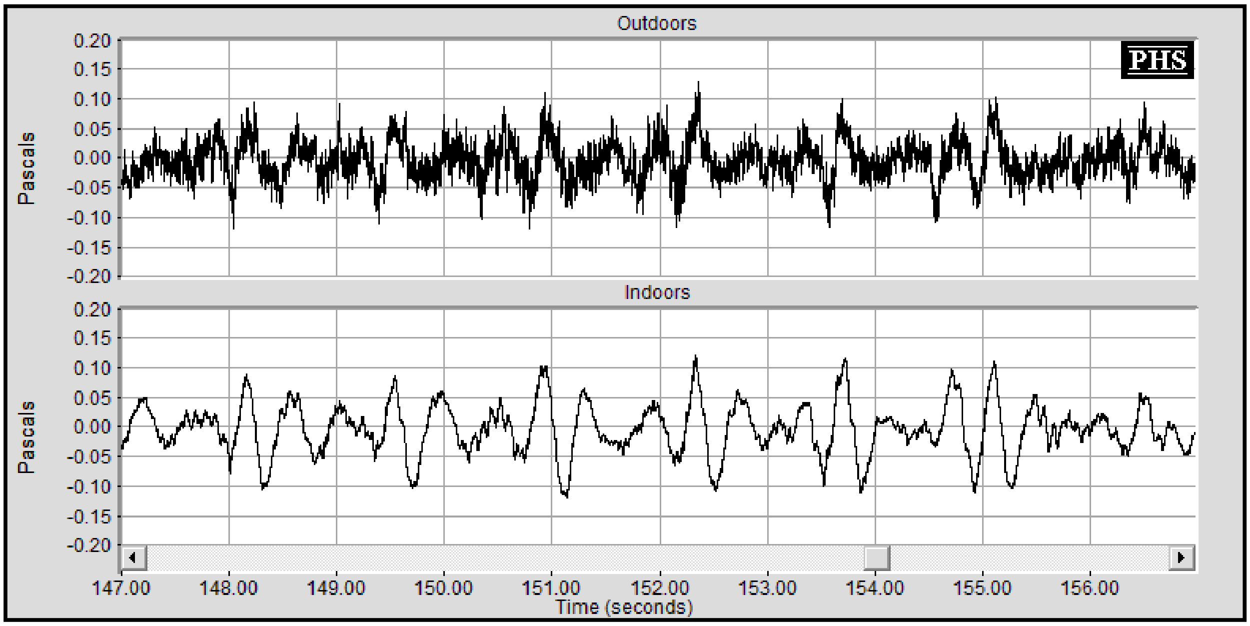
In AM radio, we do not hear the modulated broadcast carrier. For example, a medium-wave AM radio transmission uses a carrier frequency in the 520-1610 kHz radio frequency band which is beyond the range of human hearing. In contrast, the carrier signal for wind turbines is for the most part audible; and complex, consisting of the collective modal and aerodynamic acoustic emissions radiated by the wind turbine; *some in the infrasonic range, some in the audible acoustic range*. The "signal" consists of the dynamic sound pressure modulations recurring at the blade pass rate.

There are several acoustic components experiencing dynamic modulation at the blade pass rate; among these, very-low-frequency blade bending and twisting modes interacting with turbulence; vortex shedding off the end of the blades (interrupted or slapping against the wind turbine mast); dynamic stall along the blades (influenced by cyclical and abrupt variations of wind vectors along the blades); the in-flow turbulence (below 20 Hz for the large units- peak frequency dependent on blade length, affected by blade position during rotation through turbulent layers); gear and generator tones rising and falling with wind load and radiated by the mast and blades.

A sample time history "strip chart" in **Figure 18** shows the primary dynamic modulation at the blade pass frequency is clearly visible every 1.4 seconds. The modulation repeats but is not sinusoidal. Peaks and dips occur suddenly with rise and fall times exceeding 10 dB per second. The "Outdoors" graph shows the higher frequency details associated with the wind turbine's characteristic "swish" sounds. The "Indoors" graph shows the house-envelope-filtered-and-amplified very-low frequency content of the wind turbine sound. What is apparent is that the negative pressure swings (vacuum) are more pronounced indoors compared to outdoors.

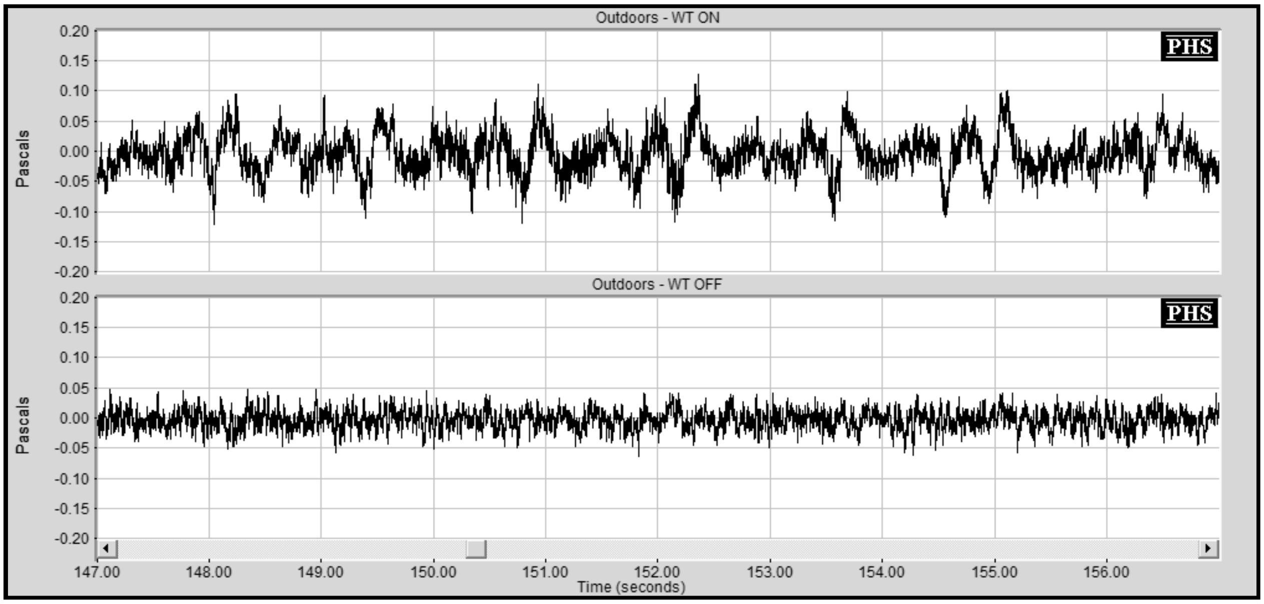
Figure 18 -Acoustic pressure fluctuation time-history

(Outdoors and indoors; April 18, 2011, 3:22 pm)



Despite the apparent increase in energy indoors, the wind turbine was almost inaudible indoors. The house envelope blocked most of the frequency content above 10 Hz, and amplified the remaining low frequency pulsations, *much like a drum*. The acoustic pressure swung from positive (compressed) to negative (rarified) 0.2 Pa peak-to-peak. As shown in the composite dual time history in **Figure 19**, the infrasonic AM signature was absent when the NOTUS was OFF.

Figure 19 – Outdoors, linear sound pressure, NOTUS ON (4/18/11) and OFF (4/19/11)



The infrasonic and low-frequency pulsations are *hidden* by the A-weighting filtering normally used by noise consultants to assess noise *levels*; yet, these pulsations are clearly visible in the linear, un-weighted time history in Pascal (Figures 18, 19). Pressure pulsations are even more evident in the *indoors* record in Figure 10, which is almost entirely composed of the "signal" dynamic amplitude modulation of the "carrier" wind turbine acoustic emissions below 10 Hz. A-weighting, then, serves to hide a large portion of the wind turbine acoustic emissions; the dynamically modulated sound pressures below 100 Hz.

Our instrumentation reported the Crest Factor at 11-12 dB outdoors and indoors. This suggests that **the RMS measurements reported on our graphs are well below the peak levels detectable by the human ear**.

The C- and A-weighted levels were compared to the un-weighted linear (dBL) sound level and shown in **Figure 20** below. Occasionally in this record, we heard the audible modulation of the upper-frequency "swish" sounds, which show up in the dBA record. However those were relatively small compared to the repetitive amplitude modulations in the linear sound pressure record which occur below 20 Hz. While the dBA and even the dBC filtered levels reveal little of the underlying "signal" from the NOTUS wind turbine, the linear sound level (dBL) contains the entire sound pressure signature, and clearly shows the extent of the variations in sound pressure. This is even more evident indoors, as shown in **Figure 21** below.

Figure 20 –Outdoors sound levels, NOTUS ON (4/18/11)

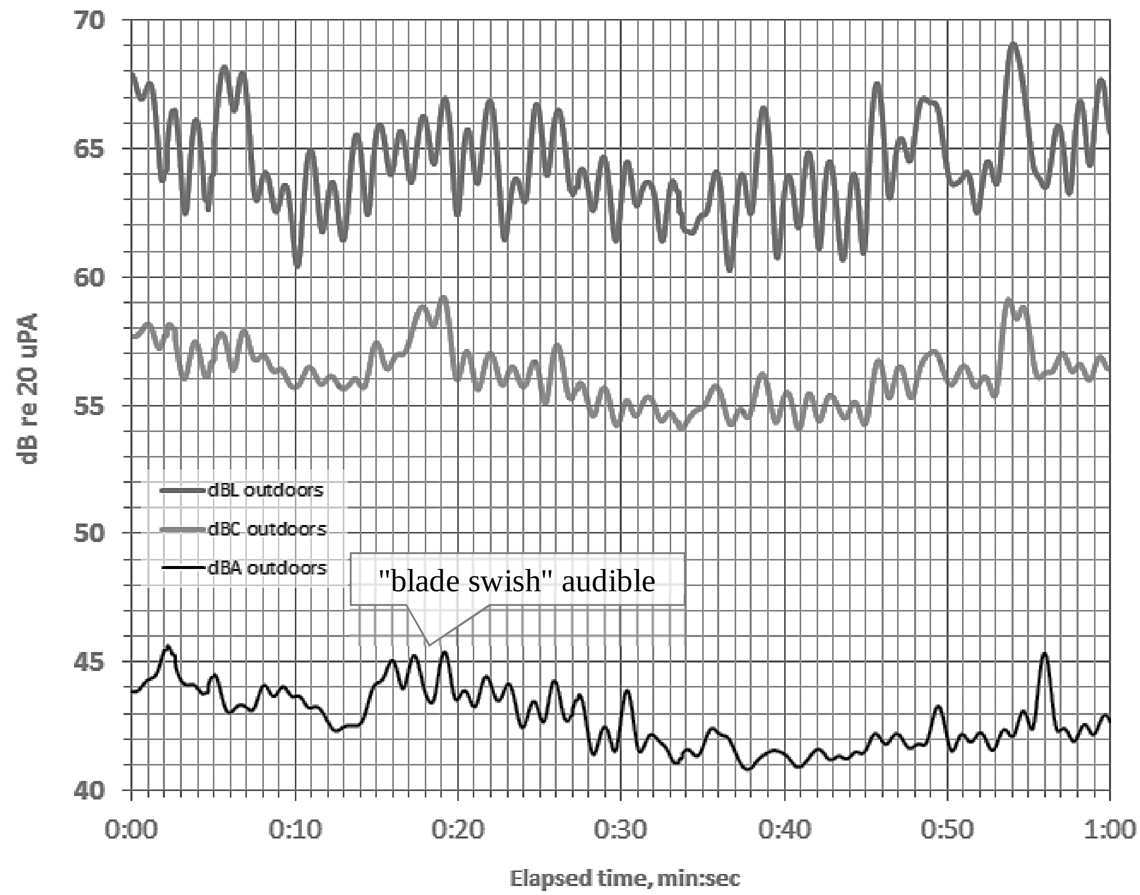
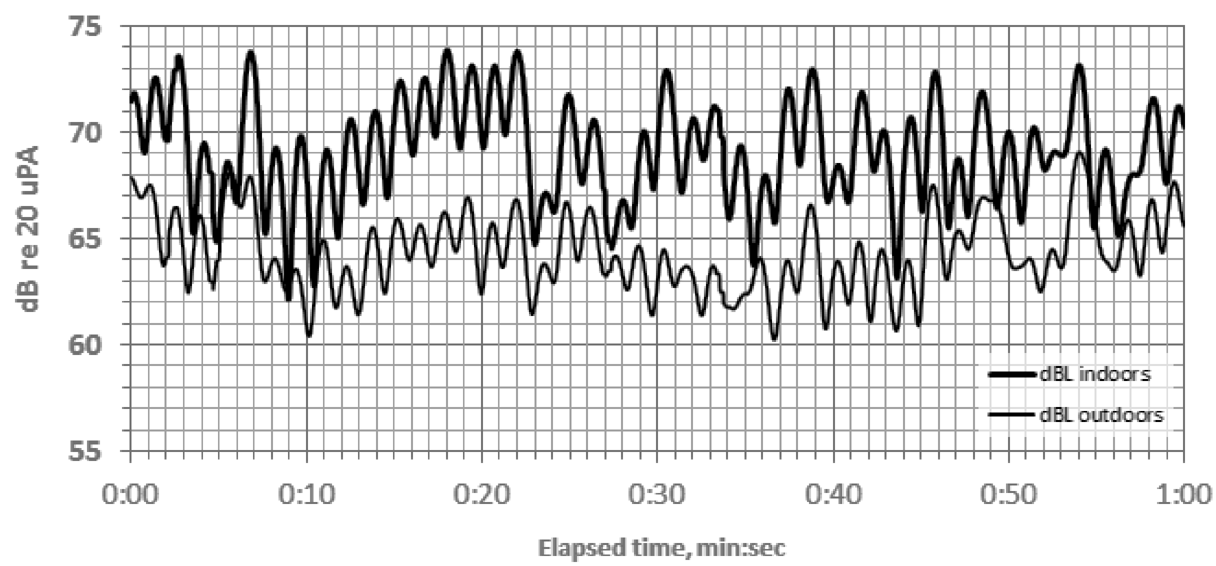


Figure 21 - Acoustic pressure fluctuation time-history

(Indoors versus outdoors; April 18, 2011, 3:22 pm)



The house amplification (the inaudible yet pervasive sound pressure "drum-beat") is clearly evident again in Figure 13, with increases of 2 to 6 dB, outdoors to indoors.

4.6 Pressure Pulsation Exposure and Dose-Response

It is generally accepted that human response and cumulative effects increase with the quantity and the peak level of intrusive noises. Peak noise events are additive. The relative impact of noise level and number on human reactions is measured by the decibel equivalent number effect (k) expressed as the number of decibels which have an effect equivalent to that of a tenfold increase in number of events [25]; 10log(n), where n is the number of events.

We experienced onset of adverse health effects shortly after starting our work indoors. Over the first fifteen minutes at 1.4 seconds blade pass rate, we estimate that we were subjected to a repetitive exposure of 642 peak pressure events. Over each hour we were exposed to an estimated 2571 pressure events. Over a period of five hours on the first day during the highest winds when we were most severely affected, we estimate that we were exposed to over 12,800 blade pass peak pressure events. Of those pressure pulsations, we estimate that well over fifty percent exceeded the 60 dBG threshold (from Salt).

The occurrence of pressure events at 22.9 Hz is much greater. Over a five-hour period, some 412,200 pressure events would have occurred 43 milliseconds apart, and we estimate that 1/2, or some 200,000 of those would have entered the ear (inaudibly to the IHC circuitry), then they would have been detected and processed by the OHC circuitry, repeatedly and rapidly changing gain on the IHC circuitry.

We would not automatically assign a conventional dose-response relationship to these low frequency inaudible pressure events compared with the health effects from nuisance and annoyance as commonly associated with *audible* sound events. However, we experienced vestibular impact or conflict which ramped up over time (within twenty minutes) and took time to dissipate (hours to days or more). The time to onset and recovery suggest that dose-response is involved with these pressure events.

[25] Fields, J., The effect of numbers of noise events on people's reactions to noise: An analysis of existing survey data. J. Acoust. Soc. Am. Volume 75, Issue 2, pp. 447-467 (1984).

5 CONCLUSIONS

5.1 Noise and Pressure Pulsations

The acoustic energy from the wind turbine was found to be:

1) Greater than or uniquely distinguishable from the ambient background levels, and
2) Capable of exceeding human detection thresholds.

This research revealed dynamically modulated low frequency and infrasonic energy from the nearby wind turbine occurring at the blade pass rate; energy which was found to be amplified indoors below 10 Hz. These dynamic infrasonic modulations were absent when the wind turbine was off. The wind turbine has tonal energy at 22.9 and 129 Hz. The wind turbine acoustic emissions were strongly coupled to the indoor environment at very low infrasonic pulsations and at the 22.9 and 129 Hz tones.

The dBA levels were inversely correlated to adverse health effects experienced; effects were more severe indoors where dBA levels were much lower (around 20 dBA). However the dBL (un-weighted) and dBG (infrasonic-weighting) levels were more strongly modulated indoors. This increase in modulation indoors was consistent with the stronger adverse health effects indoors. The increase in total sound pressure indoors appears related to a "whole-house" cavity response; the outside pressure pulsations exciting the interior acoustic pressure much like a stick hitting a drum. Especially, the degree of negative pressure increased significantly indoors compared to outdoors.

5.2 Adverse Health Effects

This research revealed that persons without a pre-existing sleep deprivation condition, not tied to the location nor invested in the property, can experience within a few minutes the same debilitating health effects described and testified to by neighbors living near the wind turbines.

The debilitating health effects were judged to be visceral (proceeding from instinct, not intellect) and related to as yet unidentified discordant physical inputs or stimulation to the vestibular system.

The dBG levels indoors were dynamically modulated at the blade pass rate and tonal frequencies and exceeded the vestibular physiological threshold guideline of 60 dBG provided by Dr. Salt.

Health effects moderated when dBG levels fell well below the 60 dBG guideline when the wind turbine was OFF.

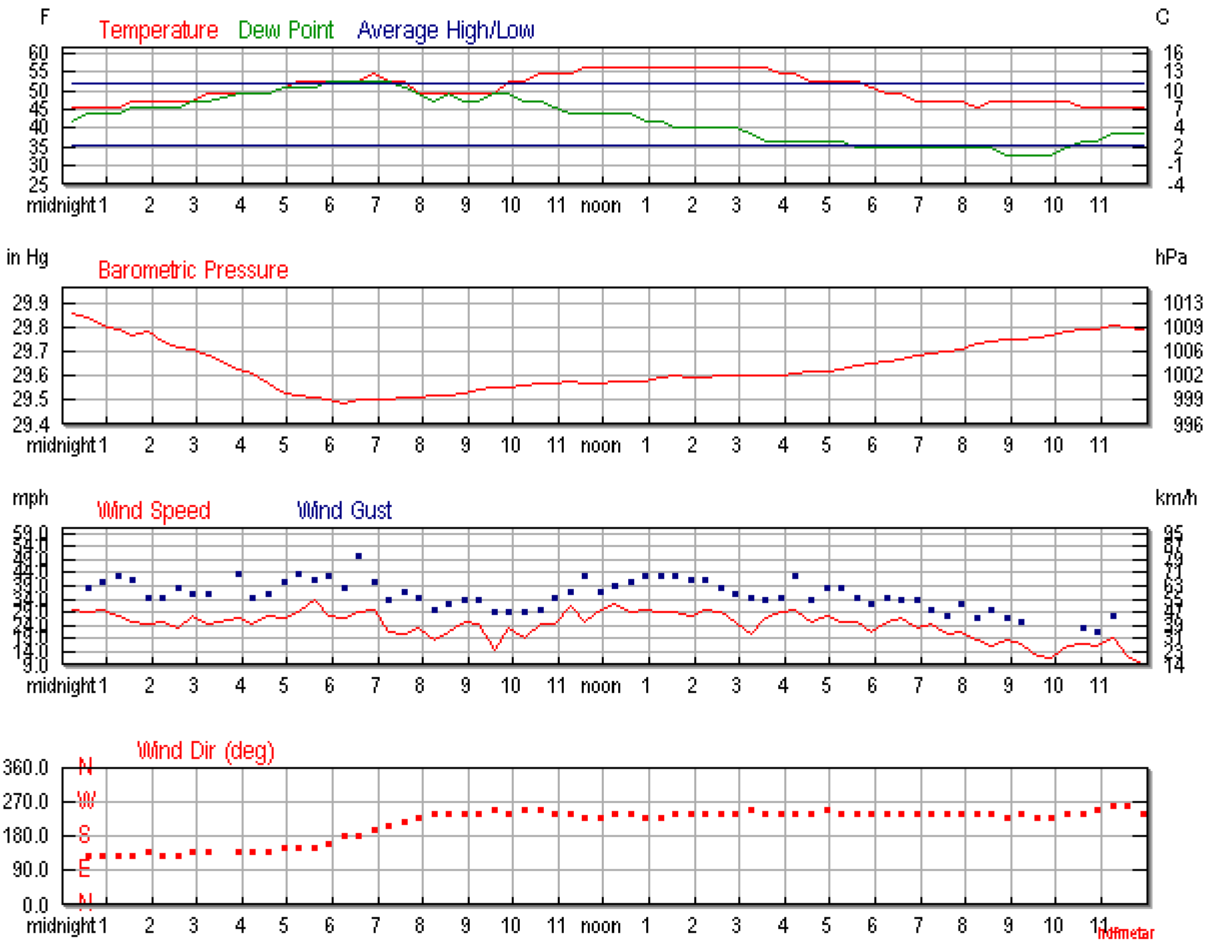
Wind turbine tonal energy at 22.9 Hz lies in the brain's "Beta" range which is associated with alert mental activity and anxiety; antithetical to sleep. The dynamic 0.7 Hz modulations of in-flow turbulence and tonal energy lie in the deep Delta range associated with deep sleep. Clinical evidence of frequency following response (FFR) in the brain suggests that entrainment with wind turbine modulations, pulsations and tones may pose conflict for the brain's natural rhythms, leading to stress when the conflicting signals (the wind turbine) cannot be turned off. Other physiological mechanisms may be in play. Medical epidemiological field and laboratory investigation is needed.

The study confirms that large industrial wind turbines can produce real and adverse health impacts and suggests that this is due to acoustic pressure pulsations, not related to the audible frequency spectrum, by affecting the vestibular system especially at low ambient sound levels. The study results emphasize the need for epidemiological and laboratory research by medical health professionals and acousticians concerned with public health and well-being. This study underscores the need for more effective and precautionary setback distances for industrial wind turbines. It is especially important to include a margin of safety sufficient to prevent inaudible low-frequency wind turbine noise from being detected by the human vestibular system.

Attachment A

Weather Conditions
April 17, 2011

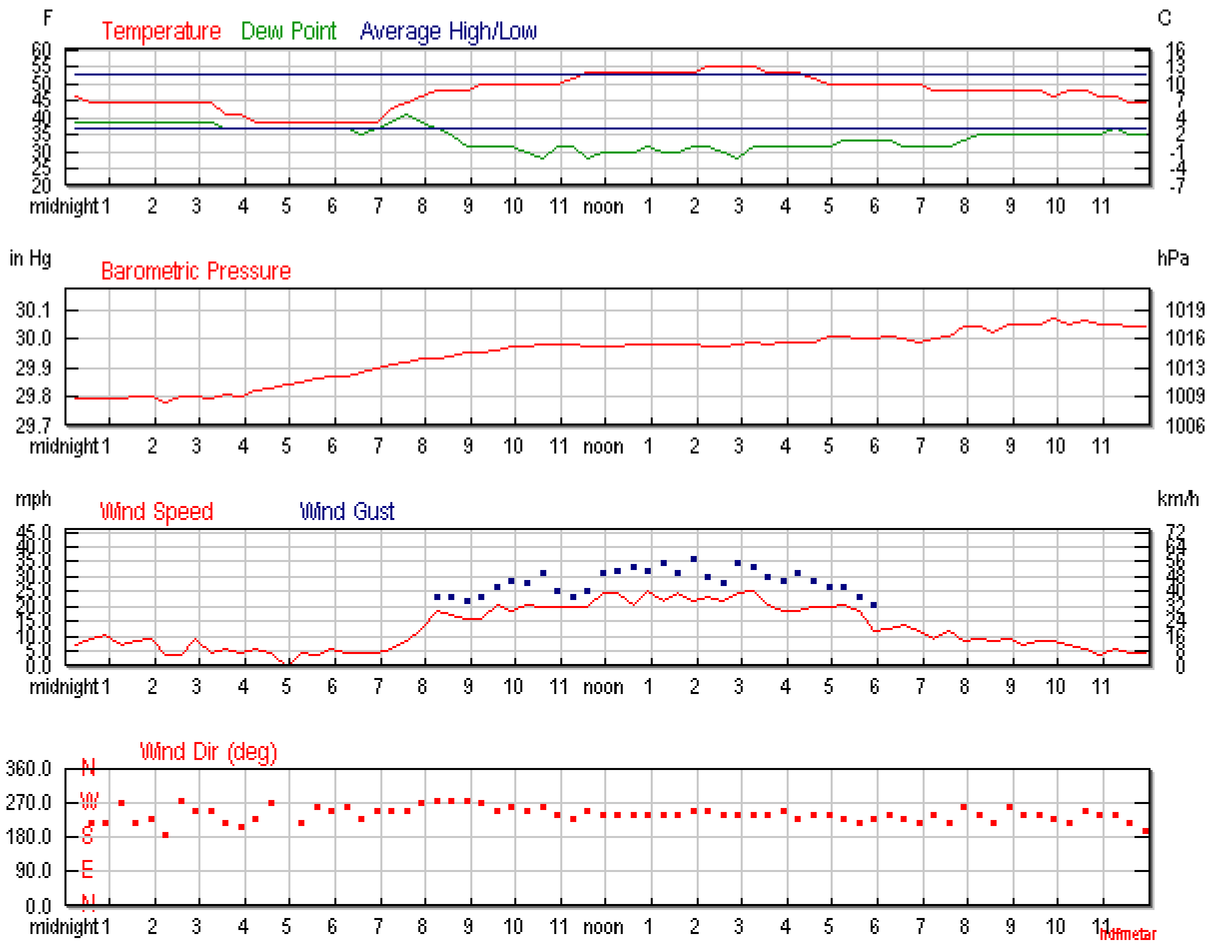
Otis Air National Guard Base
Falmouth, Massachusetts



Attachment B

Weather Conditions
April 18, 2011

Otis Air National Guard Base
Falmouth, Massachusetts



Attachment C

Weather Conditions
April 19, 2011

Otis Air National Guard Base
Falmouth, Massachusetts