Recent research on low-frequency noise from wind turbines

If AEI were a mass media outlet, publishing this on New Year's Eve would be considered an attempt to "bury" the story on a weekend when few people are following the news. But since our readership works on a longer time scale and are likely to find their way here over the next couple of weeks, I hope you'll instead consider this a New Year present! It's taken many (many...) hours of work, and I hope it helps all those working on wind farm noise issues – including local and state regulators, environmental consultants, wind developers, and community groups – to make sense of the insanely confusing world of low-frequency noise and infrasound. Here's to a constructive 2012 as we continue to work toward siting policies that protect residents from unwanted changes to their sense of place while encouraging responsible and widespread growth of wind energy!

As regular readers will know, AEI's wind farm coverage has focused primarily on the ways that nearby neighbors respond to the audible noise from wind turbines, with far less emphasis on infrasound. However, given the ongoing public dialogue about the contribution of infrasound and low-frequency sound to the annoyance, sleep disruption, or health effects reported by some wind farm neighbors, I do like to keep abreast of research into the lower end of the sound spectrum. In this post, I'll be summarizing several papers that have appeared in journals and conference proceedings over the past several months. This will be a much longer post than normal, but I encourage you to take the time to read through it, and to download the source papers for further study. What you'll find here is a close reading of work from both mainstream and more cautionary acousticians, which I believe will help you to understand the subtleties of our current state of understanding in a new and clearer way.

I think it's fair to say that the bottom line continues to be roughly the same as it's been: wind turbines clearly produce much of their sound energy at lower frequencies, including the low end of the audible spectrum (20-250Hz) and the infrasonic range (below 20Hz, which is generally below the range humans tend to hear, simply because it has to be very loud to be perceptible). Conventional wisdom continues to be that the infrasound in wind turbine noise is well below human perceptual limits, even of the more sensitive fringe of the population. This summary doesn't directly challenge that idea, though as you'll see, there are some indications that we may have been a bit too quick to entirely rule out any perception of infrasound produced by wind turbines. Still, I hasten to stress that any possible connection between physically perceptible infrasound and health effects remains beyond the scope of most of these papers (with a couple of exceptions).

More importantly, though, it's increasingly being recognized that low-frequency audible sound could very well be a key factor in widespread annoyance about wind farm noise. It's important to not conflate infrasound and low-frequency sound; while the former is (always or mostly) imperceptible, the latter is clearly very audible in many situations, and indeed, is the dominant sound component of wind farm noise at moderate and larger distances. It's quite likely that much of the annoyance people report could be triggered by very low frequency, moderately audible noise, which can be more ear-catching (or perhaps even cause physiological reactions) when it contains one or more dominant tones or fluctuates rapidly. Further, increasing evidence confirms neighbors' reports that moderate but extremely bothersome low frequency noise can be more perceptible inside their homes than outside.

Among the highlights of the recent research is Möller and Pedersen's finding that larger turbines produce more low-frequency sound (especially audible low-frequency), and that in many atmospheric conditions, sound levels will remain annoyingly high for much farther than often assumed by more idealized sound modeling. Also of note, Bray and James' field measurements of wind turbine sound, using equipment designed to capture very short time segments, reveals a remarkable variability and surprisingly high peak sound levels in the low-frequency and infrasonic sound, to a degree that raises questions about our tendency to rely on longer-time-period averages that suggest infrasound is always well below perceptual limits. As we look more closely into low-frequency and infrasound data, both the mainstream papers and the more cautionary acousticians' work suggest that these questions are far from settled.

(I should clarify that my use of the word "mainstream" is meant to simply mean studies by folks working with techniques and perspectives on bothersome noise levels that have been standard in noise control assessment for many community noise sources. And conversely, the use of the term "cautionary acousticians" does not imply they are less qualified or biased in any way. Indeed, most of them have decades of noise control experience and have been drawn to the study of wind farm noise only because of the unexpectedly robust complaints that have arisen, and are professionally interested in trying to ascertain the reasons, either by using innovative measurement techniques or closely assessing annoyance patterns. They may be more "cautionary" in their recommended noise limits simply because they've looked more closely at specific problems, rather than keeping their distance and approaching the issue through standard noise modeling and analysis techniques.)

Some of the papers I'm summarizing here address aspects of annoyance and sound characteristics of wind farm noise that are not limited to low frequency and infrasound issues (especially including acknowledgement of the extreme variability of the overall sound levels); these papers provide important perspectives that may help us to understand why wind farms are producing more annoyance reactions than we might expect, considering their moderate sound levels.

For more (much more...but worth it!), click on through to read lay summaries of the following recent papers:

- Möller and CS Pedersen. Low-frequency noise from large wind turbines. J. Acoust. Soc. Am. 129 (6), June 2011, 3727-3744.
- O'Neal, Hellweg, Lempeter. Low frequency noise and infrasound from wind turbines. Noise Control Eng. J. 59 (2), March-April 2011.
- Bolin et al. Infrasound and low frequency noise from wind turbines: exposure and health effects. Environ. Res. Lett. 6 (2011) 035103
- Bray and James. Dynamic measurements of wind turbine acoustic signals, employing sound quality engineering methods considering the time and frequency sensitivities of human perception. Noise-Con 2011.
- Stephen E. Ambrose and Robert W. Rand. The Bruce McPherson Infrasound and Low Frequency Noise Study: Adverse health effects produced by large industrial wind turbines confirmed. December 14, 2011.
- David Hessler, Best Practices Guidelines for Assessing Sound Emissions From Proposed Wind Farms and Measuring the Performance of Completed Projects. Prepared for the Minnesota Public Utilities Commission, under the auspices of the National Association of Regulatory Utility Commissioners (NARUC). October 13, 2011.
- Knopper and Ollsen. Health effects and wind turbines: A review of the literature. Environmental Health 2011, 10:78

- Kroesen and Schreckenberg. A measurement model for general noise reaction in response to aircraft noise. J. Acoust. Soc. Am. 129 (1), January 2011, 200-210.
- HGC Engineering, Low frequency noise and infrasound associated with wind turbine generator systems: A literature review. Ontario Ministry of the Environment RFP No. OSS-078696.
- Bob Thorne. The Problems with "Noise Numbers" for Wind Farm Noise Assessment. Bulletin of Science Technology and Society 2011 31: 262.

Let's start with a paper from Möller and CS Pedersen that got a fair amount of attention when it was published. The leading take-away from the paper in the popular and trade press was their finding that larger turbines (2.3-3.6MW) produce more low-frequency sound than smaller ones (below 2MW); specifically, the sound spectrum shifted downward by about a third of an octave. This has important implications moving forward, because of the push to increase turbine size in order to generate more electricity from each turbine; 3MW is becoming a common size in new wind farms. The increase in low frequency sound was moderate, just 1.5-3.2dB, but the authors remind us that at low frequencies, small dB differences are perceived as larger differences in loudness than at higher frequencies. And, the farther you go from the turbine, the more higher frequencies are dissipated while lower frequencies become the dominant component of the sound that remains.

But the Möller/Pederson paper is important for several other key reasons as well. Firstly, they stress that much of the information being promulgated by both sides of the wind turbine siting debate fails to distinguish between infrasound and low-frequency sound. As they say (parenthetical phrases are in the original, not editorial additions):

> Infrasound and low-frequency sound are often not properly distinguished, and, as a peculiar consequence, low-frequency noise is frequently rejected as the cause of nuisances, just because infrasound can be discarded (usually rightfully). Infrasound is (still) often claimed inaudible, and sometimes even low-frequency noise, or it is reported that both can only be heard by especially sensitive people—which is all wrong. Weighting curves are misunderstood or (mis)used to give the impression of dramatically high or negligibly low levels. Sometimes, political utterances (from both sides) are disguised as scientific contributions.

Infrasound is addressed only briefly in this paper, but their treatment provides a good foundation for understanding other papers. They use **G-weightened sound levels** in their consideration of infrasound, which, unlike C or A weighting, includes sounds below 10Hz, while accentuating the frequencies from 2-70Hz (though still adjusted in a way that lets one final dB number reflect a combined contribution of different frequencies' sound levels). The human hearing threshold is 95-100 dBG, with anything below 85-90 dBG generally considered imperceptible. Their measurements of wind turbine sound at 90-525m were below 65 dBG; the highest measurements they found in the literature were 80 dBG at 360m, still below perceptible thresholds. The paper includes an unusually thorough survey of research into individual differences in hearing sensitivity at low frequencies (including studies suggesting that we respond to peak sound levels when there are large fluctuations, a precurser to the Bray/James study below which found peaks of over 90dBG), though the authors conclude that except for the possibility of a very few people with anatomical abnormalities in the hearing organs, the variation found to date is modest and so infrasound is unlikely to be a contributing factor to wind farm annoyance.

But don't rest easy just yet: they also stress that downwind propagation of low-frequency noise, and overall turbine noise, is often vastly underestimated using standard models. Atmospheric refraction - sound bouncing back down from air density boundaries overhead, and sometimes (especially with low frequencies) bouncing off the ground as well, so it's channeled greater distances - can create much higher sound levels than we might expect at distances of beyond a few hundred meters. Sound just below the border of low frequency and infrasound (especially 8-16Hz) appears to dissipate much more slowly ("cylindrical" instead of "spherical" spreading), dropping by only 3dB with each doubling of distance, rather than 6dB as do most audible sounds. (Other papers included here, including the HGC/Ontario MOE report, also stress this factor, which the Ambrose/Rand field measurements confirm.) This means that at greater distances, the turbines noise that makes it that far will sound lower in frequency, and be louder than predicted by spherical spreading models.

Their measurements of actual wind turbines also led to some quite remarkable results. They measured the sound power levels of 9 large turbines, then did two rounds of sound modeling. The first assumed simply spherical spreading, sound dropping 6dB for each doubling of distance. They measured how far they had to be from individual turbines in order for the sound to drop to 35dB, the level above which E Pedersen and Waye found annoyance begin to spike beyond 5-10% of the population, and also the level required in quiet areas in Sweden. Because the nine turbines had distinctly different initial (source) sound levels, the variation in distance was stunning, with this quiet sound level reached at distances ranging from 629m (2063ft) to 1227m (4024ft). Interestingly, when modeling small wind farms of 12 turbines, they found that sound levels of 44dB (Danish wind farm noise limit at homes) were reached at a very similar wide range of distances, 530m-1241m.

But more striking still was the dramatic increase in setback distances necessary when they considered atmospheric conditions with a sound-reflecting layer. Here, they joined an emerging consensus in acoustics that propagation can be cylindrical beyond 200m, and found that homes would need to be anywhere from 1414m (4600ft) to 3482m (11,421ft / 2.16miles) in order for the sound to drop to 35dB. Again, they note that at these greater distances, as higher frequencies are absorbed and lower frequencies are less impeded, the sound becomes more dominated by lower frequencies, and that "Cylindrical propagation may thus explain case stories, where rumbling of wind turbines is claimed to be audible kilometers away." This also helps explain the fact, noted in both the Hessler and Thorne papers below, that noise levels well above those predicted by noise modeling can be expected to occur with some regularity.

Möller and CS Pedersen repeatedly stress that the audible low-frequency components of wind turbine noise, especially as distance increases, are likely a key factor in reported annoyance by neighbors. After modeling likely indoor noise levels, they note:

> If the noise from the investigated large turbines has an outdoor A-weighted sound pressure level of 44dB (the maximum of the Danish regulation for wind turbines), there is a risk that a substantial part of the residents will be annoyed by low-frequency noise even indoors. The Danish evening/night limit of 20dB for the A-weighted noise in the 10-160 Hz range, which applies to industrial noise (but not to wind turbine noise), will be exceeded somewhere in many living rooms at the neighbors that are near the 44dB outdoor limit. Problems are much reduced with an outdoor limit of 35dB.

Given all they found, Möller and CS Pedersen consider 35dB a "very reasonable limit for wind turbine noise," joining their Scandinavian colleagues TH Pedersen and Nielson, who recommend 33-38dB. As they also note, "A limit of 35 dB is used for wind turbines in Sweden for quiet areas... It is also the limit that applies in Denmark in open residential areas (night) and recreational areas (evening, night, and weekend) for industrial noise (but not for wind turbine noise)."

Note: If you, like I, have been wondering whether all these Scandinavian Pedersens citing each others' work are engaged in scientific nepotism, rest easy. I recently confirmed that none of them are related; they just share a common name (lots of family lines had Peder at the top of the lineage, I guess!)

A literature survey paper by Karl Bolin, et al, Infrasound and low frequency noise from wind turbines: exposure and health effects, generally affirms the conventional wisdom that infrasound is of minimal concern, but also includes several somewhat cautionary notes. The paper begins by focusing on the mechanism that creates the low frequency and infrasound components of wind turbine noise, zeroing in on inflow turbulence as the primary contributor in the 10Hz to several hundred Hz range, covering audible low-frequency noise and some infrasound. A quick look at measured low-frequency and infrasound levels finds them, per usual, well below typical perceptual thresholds. The authors twice note that studies cited by Salt et al to suggest that infrasound is commonly at high enough levels - 60dBG - to trigger outer ear hair cell responses took place at very close range (20-100m) from turbines, much closer than residential sites. *(Ed. note: however, see two studies below at residences where peaks of 60-90dBG were observed.)* The section of the paper on annoyance levels notes that the widely-cited E Pedersen-Waye et al annoyance surveys all focused primarily on outdoor annoyance, while the same studies found indoor annoyance levels to be about half of those found outside at each noise level.

Here, though, Bolin et al move toward a cautionary stance, summarizing annoyance studies as compared to other common community noise sources and concluding that today's 45-50dB turbine noise guidelines may be a bit too high:

> Overall, these comparisons suggest that guidelines for wind turbine noise in the interval 35-40 dB would correspond to the proportion of annoyed persons comparable to the proportion annoyed by road traffic noise at a typical guideline value.

The final section of the Bolin paper surveys sleep disturbance and other health effects, reporting on the health findings in the big Pedersen surveys, which found that while annoyance and some sleep disturbance were reported, there was no consistent association between noise levels and specific health factors, including chronic disease, headaches, tinnitus, or tiredness. At the end of this section, the authors report that cardiovascular risk has been found to be elevated near road noise of 55dB or more, which is "significantly higher than typical exposure from wind turbine noise." However, noting that these cardiovascular risks are considered to be largely related to stress, annoyance, and sleep disruption (i.e., not from direct physiological effects of the noise itself), and that wind turbines tend to trigger stress and annoyance at lower levels than road noise *(note: this is the basis for their suggestion of a 35-40dB guideline above)*, then "one cannot completely rule out effects on the cardiovascular system after prolonged exposure to wind turbine noise, despite moderate levels of exposure."

The most comprehensive look at low frequency sound and infrasound from turbines to come out in recent months appeared in the journal Noise Control Engineering, and was written by Robert O'Neal and two colleagues at Epsilon Associates, a consulting firm.

This paper includes an extensive literature survey, an indoor and outdoor field measurement program at a wind farm in Texas, and a comparison of the field measurements to several key noise control criteria. In short, they find that the low-frequency and infrasound components of the wind turbine sounds they measured meet all relevant standard criteria, including those from the International Standards Organization (ISO), American National Standard (ANSI), and UK and Japanese environmental agency guidance. Most of the findings are pretty straight-forward, as well as rather detailed, so I'll refrain from recounting them here, and encourage you to check out the paper yourself.

I'll note a few things that caught my eye as I read it through, though. Right off the bat, the authors stress that the widespread idea that sound below 20Hz or so is inaudible to humans "is incorrect since sound remains audible at frequencies well below 16 Hz provided that the sound level is sufficiently high....The division into 'low-frequency sound' and 'infrasound' should only be considered 'practical and conventional.'" *(Ed. note: still, we need to be attentive to perceptual thresholds, which range as high as well over 100dB a the lowest frequencies.)*

The discussion here of physical sensations in response to infrasound also shed some interesting light. The authors note that sensations in the chest, lower back, and thighs sometimes occur, but only at sound levels 20-25dB <u>above</u> the hearing thresholds *(Ed. note: this is very high indeed at low frequencies, unlikely to occur near wind farms even considering the more cautionary field studies below*); the ears are the most sensitive receptors even of sounds between 4 and 25Hz. Yet also, this observation may illuminate some neighbor reports: "Below 10 Hz it is possible to perceive the single cycles of a tone, and the perception changes into a sensation of pressure at the ears."

This paper relies on standard measurement procedures that average the sounds over relatively long periods of time (10 minute averages; sampling rate is not noted, though the "fast" rate typically employed is 125ms, with 1-second sampling also being common). As we'll see in the Bray/James paper below, this methodology may miss some of the dynamic, rapidly varying aspects of wind turbine noise. But for now, let's take this work at face value, and see that the authors note of ANSI outdoor criteria:

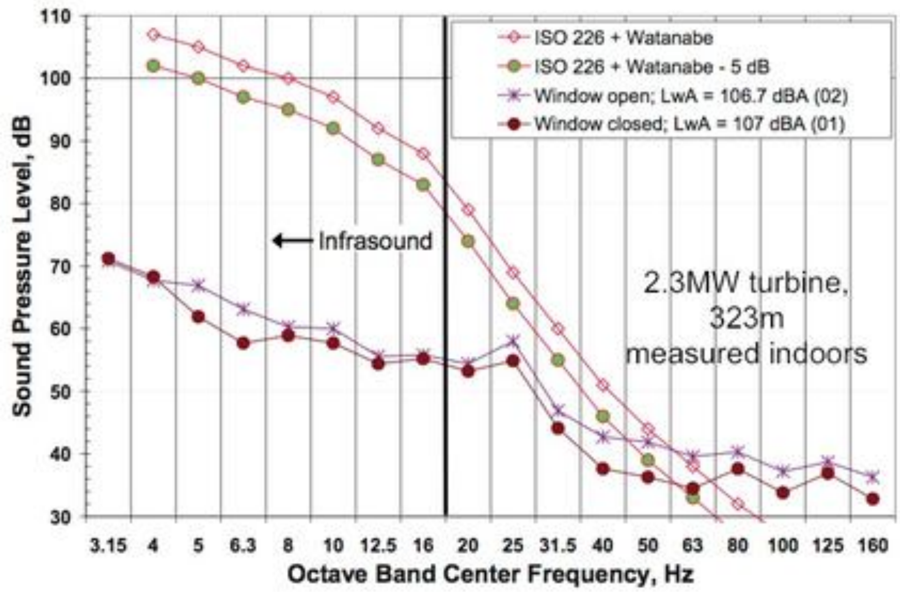
> annoyance is minimal when the 16, 31.5 and 63 Hz octave band sound pressure levels are each less than 65 dB and there are no rapid fluctuations of the low frequency sounds.

And, that according to UK standards, "A low frequency noise is considered steady if either L10 minus L90 (i.e., the difference between the loudest and quietest times) is greater than 5 dB or the rate of change of sound pressure level (Fast time weighting) is less than 10 dB per second" in the most extreme third-octave band.

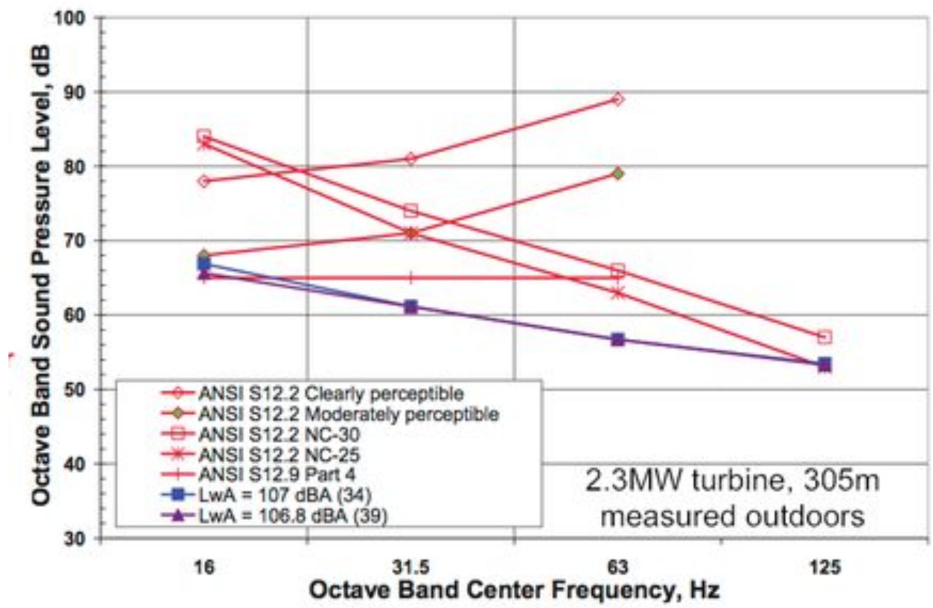
Ed. note: Bear these caveats in mind as we move to consideration of the faster time-averaged measurements reported below by Bray/James and Ambrose/Rand, both of which found significant variation of sound levels and rapid fluctuations in low frequencies.

Turning to the Texas field measurements of 1.5 and 2.3MW turbines, several things stand out. First is that the sound emissions from the Texas turbines was incredibly consistent: moderate sound output periods were only 2-3dB lower than maximum periods, and in the low-frequency one-third octave bands, the standard deviation in sound levels was under 1dB across six measurement periods. *(Ed. note: This suggests that, following on the Bolin paper above, inflow turbulence was likely quite low at this site (flat open land); I wonder whether the results would be applicable to sites with more rolling landscape or other factors that could increase localized turbulence.)*

Most of the Epsilon measurements came in well under the various criteria; this figure is representative of most of their results:



One measurement, however, was fairly edgy, bumping up against the "moderately perceptible" vibration level, as well as the ANSI standard that is modified for low-frequency noise (ANSI 512.9 Part 4); this one tracks sound only down to 16Hz, and one wonders what's going on in the deeper infrasound range below:



Overall, though, O'Neal and his Epsilon colleagues conclude that their measurements indicate:

> Infrasound is inaudible to even the most sensitive people 305 meters (1,000 feet) from these wind turbines (more than 20 dB below the median thresholds of hearing). Low frequency sound above 40 Hz may be audible depending on background sound levels.

At present, this paper is the clearest summation of this widespread conventional wisdom.

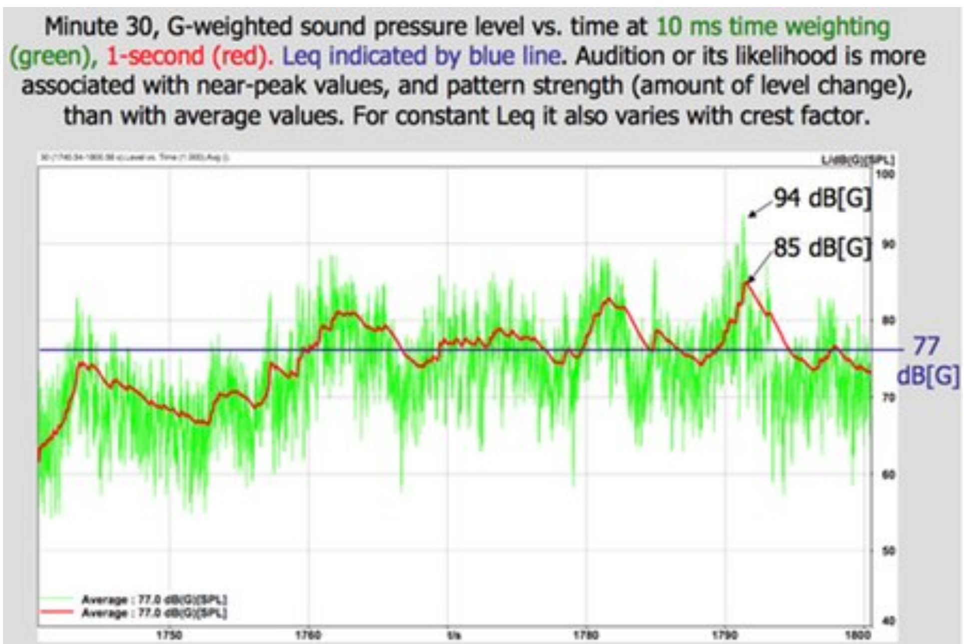
Well, dear reader, you're doing well to be hanging in this long! Your diligence will be rewarded, as the next few papers move the discussion forward in several interesting directions. We'll see some intriguing – and possibly troubling – sound measurements in very short time scales, an innovative approach to predicting annoyance reaction to noise, and a critique of typical noise measurement metrics. Alright, then, on we go!

Probably the most provocative and ground-breaking paper among this batch of new research is the paper presented by Wade Bray and Rick James at Noise-Con 2011, the annual conference of the Institute of Noise Control Engineering (INCE).

For years, Bray has stressed the need to assess sounds at time scales that reflect human auditory perception, and James has in recent years been on the forefront of investigating the sound of wind farms in locations where people have been especially bothered by the noise. In their recent paper and presentation, they worked together to assess the sound at a home in Ubly, Michigan 1500 feet from the nearest turbine (wind speeds were low, under 10mph, with temperatures of 17-22 degrees F, overcast skies, and no precipitation).

Given the innovative approach this paper takes toward assessing noise levels, it's especially difficult to summarize briefly; here I'll mention the key concepts and findings, but I encourage you to read the full paper for a more complete context as to why the authors think this approach is an important adjunct to traditional assessment techniques.

Typical noise assessment focuses primarily on measuring the sound levels at the full range of frequencies, with an emphasis on very fine resolution between frequencies (one-third of an octave is the typical resolution; so that spectrograms present the dB level for each third-octave). This works fine at higher frequencies, but as you move down the frequency scale, a trade-off has been made for historic and technical reasons: several third-octave bands are combined into "critical bandwidths" forcing the time scale of the measurements to be extended far beyond the time scale of human perception. While we perceive and respond to low frequency (20-100Hz) sounds on a timescale of about 10ms (miliseconds; one one-hundredth of a second), most noise assessment standards use "fast" time weightings of 125ms, or even levels averaged over as much as 1-10 seconds. These longer averaging times hide the peaks and troughs of the sound that occur at very short time scales:



For the one minute of the Ubly data graphed above, the sound level averaged across the entire 60 seconds was 77dBG. When averaged every second, the red line shows levels ranging from about 62dB to 85dB, and when averaged every 10ms, it ranged from about 55dB to 94dBG. (The G-weighted sound level primarily emphasizes sounds from 10-30Hz, and only moderately reduces the emphasis on sounds from 2-10Hz and 30-70Hz. While still not reflecting the pure, un-adjusted sound spectrum, dbG provides a better focus on low frequency and infrasonic ranges than A or C weightings.)

Ed. note: Because dBG weighting includes sound below 10Hz (unlike dBA or dBC weightings), some people tend to think this is a measure of primarily infrasound. Yet note that it actually includes a large chunk of audible low frequencies (up to 70Hz), while centering on that fuzzy transition between infrasound and low frequencies (10-30Hz).

A central point of this Bray/James paper is that human perception responds to the peak sound levels, rather than averages (as also affirmed in Möller/CS Pedersen's paper, above). In addition, sounds that are highly variable in short time spans (called a "high crest factor") are also more perceptible than sounds at a steady level or closely varying around the average, because human ears are very attuned to patterns in sound. These two observations, combined with the fact that the measured peak levels approach much closer to the standard human perception curves than do the averages (which are typically used to assess likely perceptibility of low frequency wind farm noise), suggest to the authors that the low frequency and infrasonic components of wind turbine sound could be more readily perceptible than is normally assumed. (The standard human perception curves are derived by playing pure-tone sounds at carefully controlled dB levels; this method suggests a perceptual threshold for infrasound in the range of 95-100dBG).

In addition to the very rapid pulses of sound over 90dBG (and much more often over 80dBG), which occur over a span of about 60ms, Bray and James reported several other variations in sound levels that they suggest may aggravate or increase the annoyance responses in nearby neighbors. They found tone-like higher sound levels at 30, 75, and 150Hz, pulsing a bit louder once per second (which corresponds to the "blade-pass rate," the rhythm at which one of the three blades either passes the tower, or sweeps across the top of its rotation, through higher wind speeds). And, they noted several other "periodicities," or fluctuations in sound level, including periods of 6-9 seconds of higher sound levels that came and went unpredictably *(Ed. note: perhaps corresponding to periods of high inflow turbulence)* and blade-pass rate sound peaks that varied in several frequency regions over time periods of less than a second, several seconds, and several minutes. This variability in the audible sound levels is likely a key reason that turbines trigger more annoyance than other noise sources.

I'll be very interested to see what other acousticians make of this new data, particularly the discovery of very rapid fluctuations and high peaks in the low frequency dB levels. It appears to my untrained reading that this is important new information, though I am far from conversant in the arcane details of short-time-period considerations of either human perception or sound levels. And while they didn't find peak dBG levels above the classic perception curves (though they were close), these field measurements clearly confirm that infrasound is present at relatively high and very dynamic levels in wind farm noise. Time and further research will tell whether this is part of the reason why wind farm noise seems to trigger more annoyance than other sound sources at similarly moderate average dB levels. I should also note that this paper makes no claims about health effects being triggered by the infrasound levels; its focus is on the fine-time-scale structure and sound levels of the measured wind turbine noise and the relation of their findings to human perceptibility.

Ed. note: While Hessler, below, suggests all infrasound recordings are contaminated by wind on the mic, Bray notes that his binaural mics provide a means to identify wind noise, which would be subtly different on each mic; and, the pulses of sound in synch with the blade-pass rate are clearly not wind noise.

Another study just released by two longtime noise control engineers, Stephen Ambrose and Rob Rand, offers a close look at noise levels and health effects, while also providing some detailed sound data that complements the Bray/James work.

This report is being circulated from Rand's consultancy website, so unlike the others here, is not peer reviewed, but the authors are operating exactly in the area of their decades of expertise, and the reporting is detailed enough to be worthy of full consideration. It presents a very short-term assessment of a particular location in Falmouth, Massachusetts where the resident was experiencing sleep disruption, headaches, and the like, located 1700 feet from a single operating turbine (a 2nd turbine nearby was shut down in high winds as a noise mitigation for neighbors). The authors were on-site for a bit under two days, and were surprised to experience the disorientation, difficulty in focusing, and sleep disruption reported by many Falmouth residents; they note that they are both prone to motion sickness, which may indicate some vestibular sensitivity.

Again, this paper contains much detail worth reading and evaluating for yourself, and I'll just mention several key points. They note a clear correlation between their physical symptoms and both the wind speed and the power output of the turbines; a correlation with the dBG sound levels is suggestive as well, with ill effects more prominent with higher dBG levels, and at times with dBG pulsations (they felt fewer ill effects when dBG variation was random). As interesting as their fatigue, headaches, and lack of appetite may be, this is clearly a very short period of study, and while providing a solid indication of the value of further similarly targeted research, is far from definitive proof of a health and turbine noise link at this point.

Near the end of their paper, though, the authors make an interesting observation. They note that the ramping-up onset of symptoms that they experienced, along with the more gradual dissipation of the symptoms after they left the site, both mimic a classic dose-response relationship; they suggest that the peak sound pressure events, which occurred on average once every 1.4 seconds, often over 60dBG (as reflected in their detailed measurements discussed below), can be considered the recurring "dose" that triggered their "response." They mention a standard dose-response equation for considering cumulative effects that could be used to explore this idea further.

Some of the actual sound measurements that were made are also particularly valuable. Their measurements found two tones with higher sound levels, at 22.9Hz and 129Hz; these are both low-frequency, not infrasound. The authors note that both tones exceeded the Outer Hair Cell stimulation threshold proposed by Alec Salt, both indoors and outdoors. They also point out that 22.9Hz lies at the high end of the range of the brain's "beta waves," which are associated with alertness, concentration, and active thinking.

Interestingly, a closer analysis of the 22.9Hz tone shows a high variability in peak levels as also found by Bray and James; in this case, the average sound level was 50dB (unweighted dB I believe, but unspecified in the paper), with faster time sampling showing sound ranging from 15 to 60dB over the course of just a second, with a rapid peaks occurring every 40ms or so. And, at this location, 1700 feet from the turbine, dBG levels were often over 60dBG indoors, and consistently over 60dBG outdoors. (some critiques of Salt's proposed 60dBG threshold for hair cell response to infrasound, including O'Neal, above, point out that Salt's examples of turbines producing these levels were taken much closer to turbines, with the implication that 60dBG is unlikely at typical residential distances over 1200 feet or more).

Finally, the authors made measurements at increasing distances from the turbine (268ft, 830ft, 1340ft, and 1700ft), and report that while the dBA decreased at a standard 6dBA for every doubling of distance (the assumption used in most sound modling), the unweighted sound levels (dBL) dropped at only 3dB per doubling distance, due to the slower dissipation of lower frequency components of the sound. And most interestingly, while at 1700 feet, the measured dBA was much lower indoors than out (43dBA outside, 21dBA inside), the unweighted sound level was actually higher inside than out (75dBL outside, 79dBL inside). This affirms many residents' reports that the low frequency sound can be more noticeable, and more bothersome, inside than outside their homes. As the authors note: "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....The acoustic pressure swung from positive (compressed) to negative (rarified) 0.2 Pa peak-to-peak." As they note, residents often say they experience these low frequency pulsations as if they are living inside a drum.

A recent addition to the pile of papers was **David Hessler's comprehensive guidelines for assessing sound emissions from proposed and completed wind farms, prepared for the Minnesota PUC and funded by the US DOE**.

A few things stand out here. First and foremost is the claim that all low-frequency and infrasound recorded near wind farms is simply flow noise of wind on microphones. Again, I'm not an acoustician or engineer, so can only make a few comments on that; you may want to read his logic yourself. He notes that tests of wind screens in quiet wind tunnels show high levels of LF and infrasonic noise (up to 70dB, unweighted at the lowest frequencies); he likewise presents some data showing near-identical dBC readings (averaging time not noted) at a residence surrounded by wind turbines and a location several miles from the wind farm, both of which vary with wind speed, and are seen by Hessler as further evidence that the dBC readings are nothing but wind noise.

Ed. Note: I can't help but note that the dBC levels reported by Hessler, as well as the dBG and dbL levels reported by Bray/James and Rand/Ambrose are well above the air-flow noise Hessler reports from the wind tunnel; this implies that there is additional low-frequency noise occurring above and beyond any microphone contamination noise. Also, much of the low-frequency and infrasonic sound measured at faster time scales (by Bray/James) show clear patterns in synch with the blade-pass rate, which would not be seen in air-flow noise on the mics. Finally, the problem of air flow on the mics can be bypassed by recording at times when wind is very low at the ground/recording level, and high at hub height. And, binaural systems (such as those used by Bray/James) allow a comparison of the two channels; wind noise will tend to be somewhat different at each mic, showing up as some incoherent measurements between the two, while turbine noise will be synched or similar in each mic (if the data shows perfect coherence between the two mics, you can be quite sure there is no wind noise contamination).

Beyond the low-frequency data and suggestions presented by Hessler, this set of guidelines includes several general recommendations for non-low-frequency noise that are worth noting. Most strikingly, the guidelines suggest keeping average dBA sound levels to 40dB at homes, and urges site plans that include many homes in the 40-45dB range to be adusted to minimize the number of homes receiving more than 40dBA. They also stress that for locations with ambient levels over 35dB (which includes most rural locations during the day), it is important to keep turbine noise to no more than 5dB louder than ambient; this is in contrast to many locales where 10dB over ambient is allowed. Both of these recommendations are based on reported annoyance and complaints at existing wind farms; while not going "all the way" to a 30 or 35dBA limit as suggested by some, this downward shift from today's norm of 45dB or more is notable.

Relatedly, Hessler stresses that the use of a mean sound level (full day and full night, or perhaps even full day-night 24-hour averages) is necessitated by the fact that sound levels vary quite notably, making peak levels difficult to predict and peak limits difficult to enforce:

> Extensive field experience measuring operational projects indicates that sound levels commonly fluctuate by roughly +/- 5 dBA about the mean trend line and that short-lived (10 to 20 minute) spikes on the order of 15 to 20 dBA above the mean are occasionally observed when atmospheric conditions strongly favor the generation and propagation of noise. Because no project can be designed so that all such spikes would remain below the 40 or 45 dBA targets at all times, these values are expressed as long-term mean levels, or the central trend through data collected over a period of several weeks.

Indeed, they also present some compelling graphs showing actual noise levels as the wind speed increases, which show that there is typically a 20dBA range of noise level at any given wind speed; this represents both variation in how strong the wind and ambient rustling of grass and leaves is when hub-height wind is creating turbine noise, and the impacts of various atmospheric conditions that change the noise level at the turbine and sound propagation in the surrounding environment.

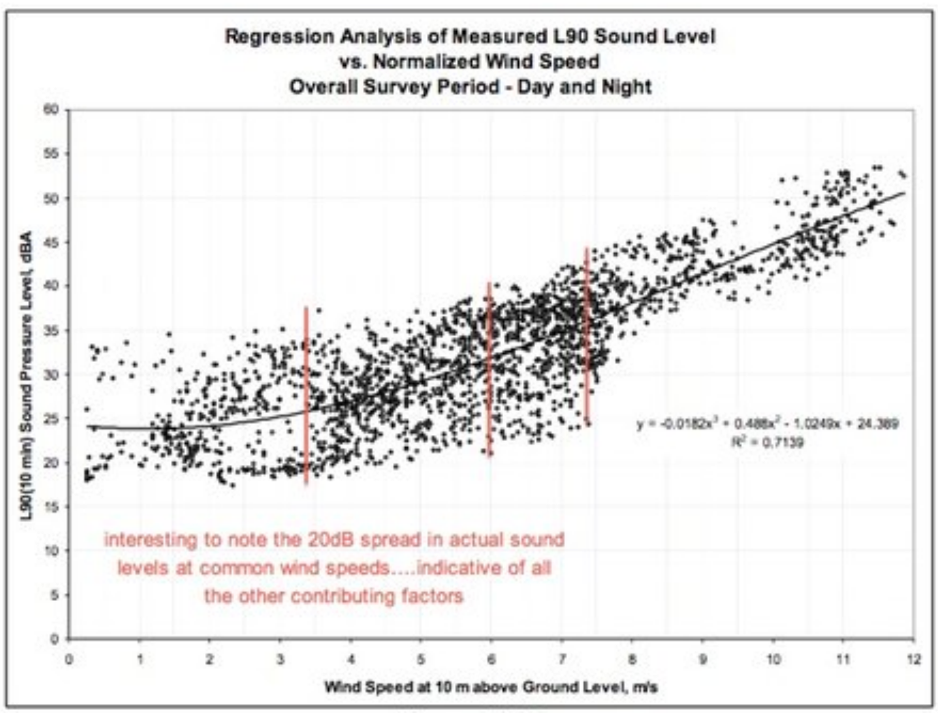


Figure 4.4.1.3

Hessler notes that "the possibility, even likelihood, that project noise will occasionally spike for short periods should be factored into regulatory limits....As a suggestion, it seems reasonable to conclude that a project is in compliance with an absolute regulatory limit if the measurements indicate that the project-only sound level is lower than the stated limit at least 95% of the time..."

Ed. note: While this seems logical, we should note that 5% of the time over the limit can translate into a chronic experience for neighbors, and may create significant impacts when *added to an already potentially marginal regulatory limit of 45dB or even 40dB, where "over the limit" can mean 10dB or more over background ambient. Five percent of the time translates to 72 days with 6 hours of excessive noise (20% of days), or 219 days with 2 hours of excessive noise (60% of days). For this reason, I'd lean to seeing this acknowledgement of the impracticality of 100% absolute limit be seen as a reason to set a somewhat lower average limit. If the limit were 30-35dB, it may be that we could tolerate more "over-limit" time, up to 10% or more.*

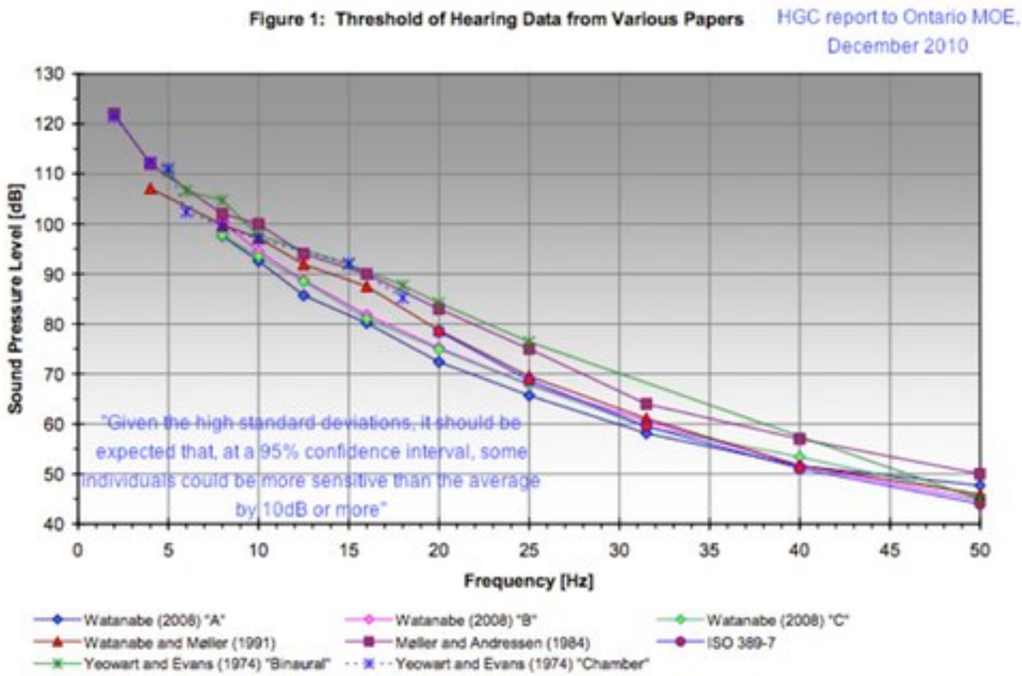
The final take-away of note from Hessler's assessment guidelines is the fact that Leq, or average sound levels, even at short 10-minute averaging times, is not appropriate for assessing existing background ambient noise levels or project sound levels; instead, Hessler stresses the use of the L90 level, representing the dB level that is exceeded 90% of the time, as more able to discern actual ambient levels and project noise levels (though again, he proposes long averaging times for the L90 noise criteria).

As I was completing this summary of recent low-frequency noise reports, a new one was released; while actually written in late 2010, in December 2011 the **Ontario Ministry of Environment released a literature review on low frequency noise and infrasound written by HGC Engineering**, a noise consultancy.

As usual, I urge you to check out the full report for more detail; the general tone and findings follows from most other similar overviews, concluding that while wind farms produce plenty of audible low-frequency noise, the infrasonic frequencies are below the levels necessary for human perception. **At the same time, though, the report contains a number of details that, to my eye, reinforce many of the other reports here in justifying the raising of a cautionary yellow flag, rather than relaxing into assurance that there are no low-frequency and infrasound issues to be further explored.** In particular, the literature references and recommendations dealing with low frequency sound inside homes, and the detailed references regarding wide individual variability in low frequency and infrasonic perceptual thresholds both bear close attention.

The Ontario report stresses the need to assess indoor low frequency noise, since many complaints come from folks who are more bothered inside their homes than outside. The Ambrose/Rand study (above) provides some initial data that confirms this experience. The HGC authors cite studies showing that transmission loss through walls is zero or near zero in low frequencies and infrasonic ranges (in contrast to the commonly assumed 15dB reduction in dBA full-spectrum sound). When combined with studies, also cited here, affirming just a 3dB reduction in lower frequencies with doubling of distance (rather than the 6dBA reduction presumed in most sound modeling, which focuses more on higher-frequency audible sound), the likelihood that neighbors at distances beyond 500m-1km may be experiencing elevated low-frequency sound in their homes becomes quite clearly understandable. Because of "the significant variation in sound impact from house to house as a function of room layout and sound transmission characteristics," the HGC team recommends that MOE develop a protocol for assessing noise indoors. The report notes that best practices for indoor recording are still in development; it is challenging, since sound levels can vary by 20-30dB in different parts of a room (due to complex interactions of sound reflected from the walls, floor, and ceiling). One current best-practices approach is to average the sound of 4 points in the floor or ceiling corners of the room.

This report presents a good, clear graph of the various studies of perceptual thresholds for low frequency and infrasound:



A few things bear noticing here. These curves show hearing thresholds only at very low frequencies (below 50Hz), and are measured in unweighted dB (which is sometimes called dBL and sometimes dBZ, and sometimes, just dB). The authors note that some (few) individuals are expected to be more sensitive than these curves "by 10dB or more." You can see the 95-100dBL thresholds at 10Hz, which dominate the dBG levels that result in the same threshold; remember here the Bray/James data showing dBG peaks of over 90dB, and more often, over 80dB.

Remember that these curves are the average thresholds found in each of these 8 different studies, and that the studies use simple pure tones at each frequency, gradually increasing the volume/amplitude of the sound until the subject reports being able to hear it. Bearing this in mind, the HGC report has a good set of literature summaries that address the individual variability within each of these average curves.

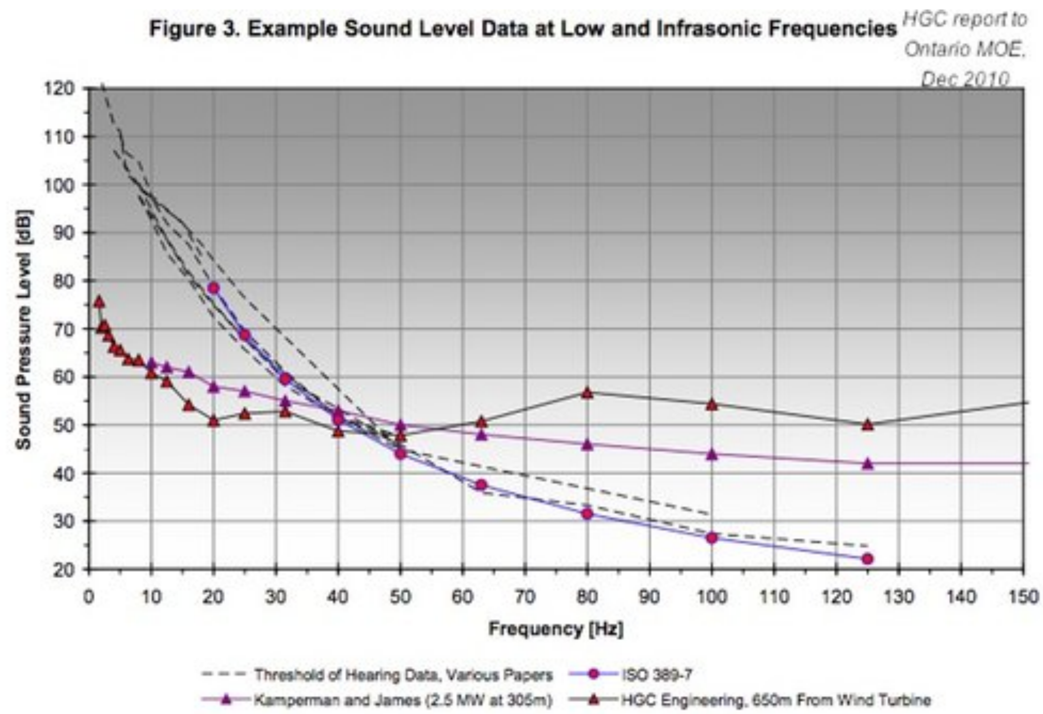
Individuals' hearing thresholds tend to not be nearly as smooth as these group averages would suggest; in fact, these studies show "an extremely diverse range of individual responses to low frequency noise." In some individuals, the curves flatten out at some of the lower frequencies rather than rising so sharply. Several other studies (not hearing/threshold tests) found sounds being perceived at levels below these traditional thresholds, especially when there is a combination of tones and frequencies more complex than the simple pure tones used in the threshold studies. *(Ed. note: Of course, wind farm sounds are also far more complex, with some tones and rhythms/pulses, and an overal sound that encompasses a broad spectrum of frequencies.)* HGC cites another lit review, by Schust (2004), which "highlights a few papers which identified possible effects ('somnolence, irritability, tiredness, tense and restlessness') which were associated with infrasonic noise at levels below (although close to) a level equivalent to the mean threshold of hearing less one standard deviation." *(Ed. Note: i.e., not just below the classic mean threshold, but just below a standard deviation quieter than that…which may really bring the Bray/James data into play)*

In sum, the HGC/Ontario report stresses that "it is clear that some caution is needed when judging the audibility of sound which approach the mean thresholds of hearing." Yet they also concludes that, below 20Hz, "sound pressure levels produced by modern upwind turbines will be well below (on the order of 20dB below) the average threshold of hearing, at the setback distances typical in Ontario." (setbacks are 550m/1800ft; bear in mind that beyond here, infrasound will drop by only 3dB per doubling distance, so that at 1.1km/3600ft, sound will be perhaps 23dB below the average thresholds). *Ed. note: To my eye, given the individual variability noted in this report and the emerging study of peak, rather than average, infrasound and low-frequency noise levels, this relatively close gap between (average) infrasonic and (average) hearing thresholds does suggest that peak sounds could easily approach the average thresholds and be above some individuals' thresholds.*

This report also notes the infrasonic sound levels of other things people are commonly exposed to, including riding in trains (with extreme infrasound, up to 150dB, as they enter and leave tunnels), and riding in a car, which commonly exposes us to over 100dB of infrasound. This may be reassuring, since even peak levels at homes near wind turbines are significantly lower. *(Ed. note: However, these reassurances don't take into account the difference between a few seconds of train/tunnel exposure, a few hours of being in a car (which most of us can affirm leads to mental and physical discomfort/fatigue), and chronic exposure at one's home. And more importantly, if the Bray/James and Ambrose/Rand data is representative of other locations, the rapidly pulsing nature of the infrasonic sound from turbines may well be of an entirely different nature, contributing to the fatigue and focus issues reported by Ambrose and Rand, even at lower intensities than we experience in trains or cars.)*

The HGC report also addresses the challenges of getting accurate low-frequency readings in windy conditions, as Hessler stresses. But rather than joining Hessler in considering low-frequency and infrasonic readings to be entirely unreliable or impossible around wind farms, HGC notes several approaches, including a NASA-designed wind screen and an in-ground system, both of which allow for accurate infrasonic readings, though they distort or miss higher frequencies. Indeed, while the HGC report concludes that infrasound is unlikely to be an issue, so need not be routinely measured as part of project permitting, they also note the ongoing investigations taking place by acousticians (as well as the public apprehension), and recommend that MOE adopt measurement procedures for infrasound, to be used in specific situations – presumably, when complaints arise, and perhaps also to provide for better comparison between studies that are performed in the coming years.

Finally, this graph presents a pretty good overview of the relationship between wind farm noise and hearing thresholds:



A few things are worth noticing here. The dotted lines show the same hearing threshold curves we saw in the previous graph, with an International Standards Organization standard overlaid on them; the two other curves, marked with triangles, are actual measurements of wind farm noise. The first thing I noticed was that the two studies of wind farm noise plotted here show surprisingly little difference in overall sound levels between 305m/1000ft (Kamperman and James) and 650m/2100ft (HGC) – this may reflect differences in the local topography or turbine size, or could be a reminder that simple sound propagation models (which would suggest that the darker triangles from HGC should be routinely 3-6dB below the purple Kamperman/James data) are not as reliable as we might wish. We can expect, once again, these low-frequency sound levels to continue to drop only 3dB at 4200ft, and 6dB at 8400ft.

The graph shows lots of easily audible low frequency sound from 50Hz on up, while it is likely that some individuals would be sensitive to the wind farm sound levels shown here at 25-50Hz. (Note that even these lower frequencies are not infrasound, but borderline-audible low frequencies.)

If we add to this graph the reminder noted by HGC of "strong, audible low frequency (but not infrasonic) tones from some turbines," it once again comes into clear focus that the lower frequency parts of the wind turbine sound spectrum are likely to be key factors in triggering annoyance among neighbors.

Ed. note: While some reports, including this one, tend to suggest that leaf rustling and wind in trees and ears will mask these lower frequencies (which are not that much above our hearing thresholds), the experiential reality in most situations is that the turbine noise remains clearly audible at a lower frequency than the wind and rustling sounds in vegetation; while the absolute dB levels may match or suggest that the turbines would be masked, the higher frequencies of the leaves do not in fact mask the generally lower overall frequency *content of the turbines.*

Finally, I want to mention a brief summary included in the HGC report of a very interesting detailed study by Møller, CS Pedersen, and Persson-Waye, which investigated a randomly selected sample of 21 cases of low-frequency noise complaints from a pool of 203 cases (these were not wind farm noise locations; just homes where people reported a bothersome low frequency noise). The study involved making recordings of sound in the homes of the complainants, after which the subjects were exposed to the sounds in blind listening tests at a low-frequency test facility. The study concluded that some of the complainants were annoyed by physical sounds, and others were suffering from low frequency tinnitus. That is, this latter group did not hear or respond to the actual sounds recorded in their homes. The authors stressed that physical sounds in the infrasonic range were not found to be responsible for the annoyance in any of the cases, which means that the ones who did hear and respond to the sounds recorded in their home were in fact being bothered by low-frequency noise, rather than infrasound.

Ed. note: of course, this is not evidence that no infrasound-related complaints are valid, especially if considering the new measurement methods being used by Bray/James. But we also must be cautious not to simply assume that the Bray/James work, or the Ambrose/Rand work (where the infrasound peaks were significantly lower than Bray/James) can be instantly and broadly applied to presume that any situation reporting no infrasound issue is inherently invalid, just because these new methods were not employed. Science moves slowly, to be sure, but it does move as evidence accumulates and is affirmed elsewhere. It's important to note the newest studies, but there needs to be far more investigation, using similar methods in different situations, before these provocative new results could support widespread changes in policy or standards.

While supporting the current Ontario MOE approach to wind farm noise assessment, which relies exclusively on dBA measurements, with penalties for tones, "which often occur in the low frequency range," the HGC report stresses that "there is a degree of disagreement and uncertainty in the literature of some of the subjects discussed in this review, and research efforts are ongoing." They recommend that any low-frequency or infrasound policies adopted by the province of Ontario should have some built-in flexibility, so as to incorporate new research findings in the future.

Okay, almost there! Just three more, each much shorter summaries than those we've covered so far.

Knopper and Olsen's paper in Environmental Health, which is a literature review of health effects of wind turbines, affirms the conventional wisdom that the noise from wind farms is not loud enough to directly trigger physiological reactions.

They do note that annoyance and sleep disturbance "have been statistically associated with wind turbine noise especially when found at sound pressure levels greater than 40 dB(A)," which lines up well with the emerging consensus we see in the mainstream papers here, encouraging project planners to limit exposures above that level at nearby residences. This annoyance and sleep disruption is also correlated with visual impact and attitudes to the local wind farm, as well as to general noise sensitivity. This literature review largely suggests that most of the annoyance reactions and health effects are caused indirectly, via anxiety or annoyance about the wind farm, citing a long history of studies of other community noise sources that show similar links between health effects and attitudes.

One key point in this paper caught my attention: this idea that most health effects are due to various cognitive stresses means to the authors that "it appears that it is the change in the environment that is associated with reported health effects, not a turbine-specific variable like audible noise or infrasound." What leapt out at me from this is that the change in the environment IS a "turbine-specific variable," the wind farm itself! Even if the sound is not directly triggering health issues (noting that these reviews of previous literature do not include any recent work on short time-averaging and higher peak levels), what we are seeing is that for many people, their sense of place and home is of such importance that the arrival of a wind farm in their rural landscape triggers a strong negative response that encompasses aesthetic, stress, sleep, and quality of life issues. Acknowledging that the change in the environment is a substantial impact in and of itself is an important insight to bear in mind.

A fascinating paper by Kroesen and Shreckenberg appeared in the Journal of the Acoustical Society of America in early 2011, which proposed a multi-faceted approach to understanding why noise can be annoying to people at their homes.

The paper focused on aircraft noise, but would seem to be applicable to our emerging inquiries into wind farm annoyance issues as well. Again, reading the paper itself is recommended, as it draws from rich research streams in psychological acoustics which cannot be adequately summarized here. The nut of it is the authors' suggestion that what they term a "general noise reaction" (GNR) can be calculated from assessing several different aspects of the individual's response to the noise source. "Residential satisfaction" and "perceived health" (both mental and physical health) are seen as being outcomes of the GNR, which has three main types of contributors: traditional noise annoyance, activity disturbance, and anxiety and fear related to the noise source. Activity disturbance can include specific activities such as relaxation, reading/concentrating, "domestic coziness or visitation," and sleeping. Anxiety and fear includes such factors as concern about stress-related health effects or impacts on property values. Overall, the authors found that mental health was more than twice as strongly affected as physical health, based on the GNR ratings obtained from their study, with direct noise annoyance and activity disturbance being the dominant factors, "while the anxiety and fear dimension operates at a more distant level."
This seems to be an important finding, for it is one of the more detailed investigations of the underlying factors in noise reactions; all too often, subjective factors such as anxiety, fear, and prior attitudes are assumed to be the primary drivers of negative reactions to wind farms, based either on assumptions or on simpler survey results. This study seems to point to more concrete experiences such as the noise itself being bothersome or intruding into valued activities as the core factors.

With the exception of the Pedersen non-clan in Scandinavia, most of the best-known research and reports on wind farm noise have come from the US and Canada. But a lot of important work is ongoing in Australia and New Zealand as well, where several large wind farms have spurred widespread complaints at greater distances than we commonly hear about elsewhere (2-4km). Bob Thorns is one one of the acousticians there who has investigated wind farm noise in as much detail as anyone here; his Ph.D. thesis on perception and annoyance in response to moderate noise plowed some very fresh ground.

This year, **Thorne published a paper that addressed *The Problems with "Noise Numbers" for Wind Farm Noise Assessment* that introduced a new hypothesis worthy of serious followup study: the concept of heightened noise zones (HNZ) as a key driver of unexpectedly high levels of annoyance.**

Thorne predicates this paper on a key, fundamental observation:

> Wind farms and wind turbines are a unique source of sound and noise. The noise generation from a wind farm is like no other noise source or set of noise sources. The sounds are often of low amplitude (volume or loudness) and are constantly shifting in character ("waves on beach," "rumble-thump," "plane never landing," etc.). People who are not exposed to the sounds of a wind farm find it very difficult to understand the problems of people who do live near wind farms...

This paper includes much of interest (including some consideration of health effects), but again, I'll focus in on just a few of its themes. There is a significant amount of focus here on the elevated low-frequency "thumps" experienced inside homes, generally 1.5-2km (5000-6500ft) from turbines. As Thorne notes, "Low-frequency sound and infrasound are normal characteristics of a wind farm as they are the normal characteristics of wind, as such. The difference is that "normal" wind is laminar or smooth in effect whereas wind farm sound is non-laminar and presents a pulsing nature." Residents studied by Thorne often report that the low-frequency sound is noticeably worse in their homes it is outside. Even more surprising, and frustrating for some residents, "rooms in a residence can and will show significantly different characteristics. What may be inaudible or not perceptible in one room can be easily heard or perceived in another room on the same side of the house."

Like many others, including the Hessler guidelines report above, Thorne stresses the wide variability in noise levels at different times, leading to his conclusion that "wind farm noise level predictions can therefore only be considered as approximations and cannot be given any weight other than this." More specifically, he notes that in sound modeling,

> the predicted values are given as a range, ±3 dB(A) at 1,000 meters for the most common prediction method with the predicted value being the "middle" of the range. The uncertainty increases with distance and the effect of two or more turbines operating in phase with a light/strong breeze blowing toward a residence. A variation of 6 to 7 dB(A) can be expected under such adverse conditions. Thus, on any given day the wind farm background LA95 or "source" time-average (LAeq) sound levels—assuming the wind farm is operating—could vary significantly in comparison with the predicted sound level. This is without the additional effect of any adverse wind effects or weather effects such as inversions.

As noted by Hessler, when considering all such effects, peaks of up to 20dB over the predicted (modeled) levels can be expected.

Thorne has monitored sound levels at many homes around a mile from wind farms. He notes that "in 60 seconds the sound character varies regularly by more than 20dB" and that "Sound from wind farms can easily be heard at distances of 2000 meters (1.24 miles); such sound was measured...over the range 29 to 40 dB(A) with conditions of calm to light breeze. The sound was modulating and readily observed and recorded. The sound can be defined as being both unreasonable and a nuisance." *(Ed. note: it's worth noticing these 40dB peaks at over a mile away; most sound modeling will suggest that such levels are common only within a third to half mile or so of turbines)*

Thorne also notes that he has often observed what he calls heightened noise zones, which "can be small in extent—even for low frequencies and infrasound—leading to turbine sounds 'disappearing' and 'appearing' in areas spaced only a few meters apart. The concept of HNZ goes a long way in explaining the problem of wind farm noise and its variability on residents." *(Ed. note: I've heard similar anecdotal reports from many residents and visitors to wind farms, though this is the first paper I've seen that's addressed this important and confounding factor)*

As an initial hypothesis, Thorne suggests that these HNZs are generated in part by the air vortex traveling downwind from turning turbine blades, which "travels downwind in the form of a helix, rotating about its axis with each vortex replacing the previous one in space at approximately 1-second intervals." If they encounter another turbine within 10 rotor diameters (1160m/3800ft for a 2.5MW turbine), these vortexes can cause turbulence that increases the noise output of the second turbine; in addition, they continue downwind with lesser power for much greater distances. Thorne hypothesizes that these vortexes and the increased sound they trigger in nearby turbines interact with the less directional audible sound waves emanating from each turbine, lensing in the air or ground, and interference between turbines' noise (audible) and vibration causing very localized patches of heightened noise and/or vibration. He reports that "the effect has been consistently measured at a residence 1,400 to 2,000 meters (roughly three quarters of a mile to a mile and a quarter) downwind from a row of turbines."

All of this leads Thorne to conclude that any compliance criteria based on a single value (including a low 35dBA Leq, a higher 40dBA L95, or an ambient-plus 5dB) are ineffective and "unacceptable" as protection from noise nuisance, because "current noise prediction models are simplistic, have a high degree of uncertainty, and do not make allowance for" the sorts of variables and effects reported above.

If all noise measurements are invalid, I'm not sure where that leaves us, in terms of generating siting policies. Thorne suggests setting siting standards based on observed reactions by residents, including sleep disturbance, anxiety, and stress, and suggests that these reactions are likely to begin to crop up as sound levels rise above 32dBA (Leq) outside homes, or above the individual's threshold of hearing inside. He concludes that setbacks of up to 3.5km may be necessary to achieve these low sound levels at homes, though also proposes that "no large-scale wind turbine should be installed within 2,000 meters of any dwelling or noise-sensitive place unless with the approval of the landowner."

This latter proposal dovetails nicely with an emerging "cautionary" consensus of trying to keep noise at non-participating neighbors homes to no more than 35dB. As AEI often emphasizes, such limits need not preclude development if they also include provisions to allow closer siting to neighbors who don't mind hearing turbines more often or more noticeably.

Phew! We made it. I appreciate your diligence in reading all this through, and

hope you'll agree that the details found in this wide-ranging set of papers add some important and helpful perspectives as we try to understand why wind farms are triggering more annoyance than most other community noise sources.

While the possible role of infrasound in community responses remains highly contentious, I'm struck by the increasing acknowledgement of the importance of low frequency components of wind farm noise (especially inside homes), and the move toward lower (40dB) noise limits even among mainstream acousticians. It appears that the common U.S. regulatory standards of 45-50dB are no longer considered appropriate in many situations, especially because of the low frequency considerations. While many acousticians continue to recommend limits of 30-35dB to effectively eliminate noise complaints, I'm struck by how the gap between the mainstream and cautionary views is rapidly shrinking. This bodes well for a more positive dialogue on these subtle but important questions surrounding noise annoyance, quality of life, and wind farm siting guidelines.

Even 40dB standards will require a new level of collaboration between wind developers and host communities - and in this lies the possibility of a gradual move toward what AEI sees as the obvious win-win path forward: adoption of lower noise limits (which will likely vary by community, based on the local sense of place and tolerance for moderate noise), in combination with negotiated easements allowing closer siting to homes where the residents don't mind somewhat higher noise levels.

Time will tell how siting policy will evolve, but it's clear that the conventional wisdom is shifting. Ongoing research and more informed public debate are likely to keep the process of learning, listening, and experimenting very interesting in the next few years. Here's to a constructive dialogue in 2012 and beyond!