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Long Distance Amplitude Modulation of Wind Turbine Noise

Carlo Di Napoli
Pöyry Finland Oy, Tekniikantie 4 A, 02151 Espoo, Finland
carlo.dinapoli@poyry.com

Abstract

This article explains in detail the results of the wind turbine noise measurement campaign, which took place around Olostunturi in the Finnish Lapland in 2009. Olostunturi is a single hill with a peak level height of 510 m above sea level. On the top of the hill there stand 5 x 600kW Bonus stall regulated upwind wind turbines erected in 1998 and 1999. A nearby hill only 14 km away from this site is under investigation for a new 30-45 MW wind turbine site where a holiday residential area lies about 1.6 km away from the nearest planned turbine. The purpose of the measurements was to provide general information on wind turbine noise in low background sound areas, typical of the Finnish Lapland with a small population and industrial density.

The measurements were carried out in different distances, locations, wind directions and time of day, but mostly during evening and night-time hours with low measurement level ground wind speed and moderate wind speed at the turbines. The measurement results revealed that even the smaller and older turbine types can produce significant amplitude modulation detectable about two kilometres away from the nearest turbine. On the basis of the results the atmospheric changes to the sound propagation and amplitude modulation were estimated by using simple and practical tools. The measurements also revealed issues related to pulsating infrasound emitted from the turbines, which was detected around the area.

1 Introduction

This paper discusses of some measurement results gathered in 2009 around a single hill located in the Finnish Lapland. The purpose was to estimate wind turbine sound in far field locations, since a new 30- 45 MW wind park site was under investigation with some noise sensitive holiday cottages situated at about 1.6 km from the planned site. Both hills have similarities (single hill) and the goal was also to gain more information about different local weather conditions influencing the sound propagation and wind turbine sound quality.

The hill under measurement study has 5 x Bonus 600 kW stall regulated upwind models erected in -98 -99 thus during the measurement period, the turbines had already serviced about half of their planned life time under tough and cold climatic conditions. Tower ground height is about 500 meters from the sea level and a skiing centre is located on the north side of the hill at approximately 200m lower level. The south side was mainly forest wilderness with few jogging/skiing routes made around the hill. Site was visited during the cold winter season but most of the measurements were undertaken during summer period mostly during evening and night time (and under the midnight sun) due to the presence of more stable atmosphere at the immission points (van den Berg, 2007). In this paper, only results from the amplitude modulation are presented.

2 Measurement setup

Far field noise measurements were carried out by using relatively lightweight equipment as the initial idea was to record far field wind turbine noise from many points around the hill and in different periods of time. The current turbine site has had an active period of research and development for blade heating technology with wind mast, but all such activities were just a memory when this project started. Thus wind and other atmospheric data had to be collected from the nearby hills and from a town 7 km west from this site by using the national weather service and its network stations which luckily had the same height as the turbines hub height providing valuable information especially for measurement planning prior to the start of each measurement date.

2.1 Emission measurements

Before far field measurements, one turbine (typically the closest one) was selected for simultaneous emission sound level measurement with flat 1m diameter round hard ground board and at the distance from the turbine according to the IEC 61400-11:2002. Also during day time additional turbine sound emission measurements were conducted by shutting down one turbine and by logging wind speeds or turbine power levels from the control unit. Since these stall regulated turbines have only two main rotational speeds (27 rpm and 17 rpm), it became quickly clear that the emission measurement SPL remained mostly stable even during long measurement periods (overnight) and it typically varied between 54 and 56 dB(A) thus giving sound power levels between 97-99 dB(A).

2.2 Immission measurements

Each far field immission point was selected mainly based on the wind speed and especially wind direction. Original plan was to select direct downwind, upwind and crosswind positions but due to the difficult landscape around the hill especially at the south side prevented sometimes for selecting such positions. Thus some measurement locations (or positions relative to the wind direction) were sometimes 20-30 degrees tilted. Also some locations were at the side such as some turbines were clearly closer compared to the rest of the turbines. However most of the far field measurements, especially downwind locations, were carried out during direct wind directions from the turbines to the immission point.

The equipment consisted of a B&K 2238 sound level meter with attached wind screen, a tripod and a memory card based 16 bit 44 kHz linear PCM sound recorder. Typical measurement periods were 1-2 hours at the same location. Since many measurements were pre-selected based on the lowest possible wind speed at the immission level, there was no practical need for continuous wind speed loggings and thus wind speeds were only randomly measured by using a hand held wind speed meter. Also low level wind speeds at the immission point measurement level were sometimes well blocked by the surrounding trees.

3 Some practical tools for assessing amplitude modulation

Before the measurements started it was decided to use a method which could reveal amplitude modulation (later “AM”) of wind turbine sound from A or C weighted SPL time domain data. Therefore it was necessary to obtain a far field measurement setup which fulfilled the Nyquist-Shannon theorem by using a sound recorder. The previous measurement case revealed that AM could be successfully measured and assessed under certain wind conditions for just one turbine. (Di Napoli, 2009)

3.1 Nordtest method

In time domain data amplitude modulation occurs as fluctuating SPL with roughly the frequency of the turbine rotation for three blades. One fluctuation peak consist of an onset rate (OR, measured as dB/s) and level difference (LD, as dB). A Nordtest method for assessing impulsive sounds objectively from A-weighted broad band recorded sound with fast- time constant was found to contain such parameters by using a function of Predicted Prominence P (Nordtest Acou 112, 2002).

$$P = 3 \cdot \lg(OR) + 2 \cdot \lg(LD) \qquad (1)$$

If the onset rate exceeds 10 dB/s and highest predicted prominence P > 5 for one impulse sound is found, a graduate adjustment K_I can be addressed to the measured L_{Aeq} level in order to assess the sound annoyance due to the impulsive character of sound. This method now fulfils the ISO 1996:1987 K_{2i} correction objectively by substituting a subjective approach for sound annoyance correction (ISO 1996-2:1987). If OR < 20 dB/s, LD must be > 3.5 dB for exceeding P>5. K_I correction

becomes > +1 dB if LD > 7 dB with 20 dB/s onset rates thus meaning that for wind turbine noise, AM of higher K_I corrections (> 3 + dB) is highly dependent on the level of OR.

3.2 Fluctuation Strength

The fluctuation strength model was introduced for quantitative assessment of the amplitude modulation and originally it was proposed by Fastl (Fastl, 1983) and the formula for calculation of the fluctuation strength contained average linear broad band level L. (Lenchine, 2009)

$$F = \frac{5.8 \cdot (1.25 \cdot m - 0.25) \cdot (0.05 \cdot L - 1)}{\left(\frac{f_m}{5}\right)^2 + \left(\frac{4}{f_m}\right) + 1.5} \qquad (2)$$

It is suggested in (Fastl and Zwicker, 2007) that perception of the amplitude modulation becomes significant if it reaches about 10% of the relative fluctuation strength (100% can be produced by amplitude- modulated broadband noise of 60dB SPL at 4Hz modulation frequency and modulation depth 40dB or greater). For amplitude modulated broad band noise it is achieved at about 0.2vacil. This number is suggested as criterion to decide if the amplitude modulation is a characteristic of the wind turbine noise. (Lenchine, 2009).

4 Measurement results

Annex 1 at the end of this paper has 3 pictures on each page representing broad band SPL changes as dB(A) in time-domain window from each main wind direction and different distances from the closest turbine. Each result represents a very short sample period from a wave format file recorded at those locations and typically are the ones with the maximum AM. From the sample files it can be concluded that for downwind samples, AM does not seem to vanish although the measurement location goes further away from the closest turbine. Upwind results show also surprisingly high levels of AM, but most of the crosswind results are without any AM.

By using the Nordtest method (chapter 3.1), some processed peaks were calculated into a single graph below.

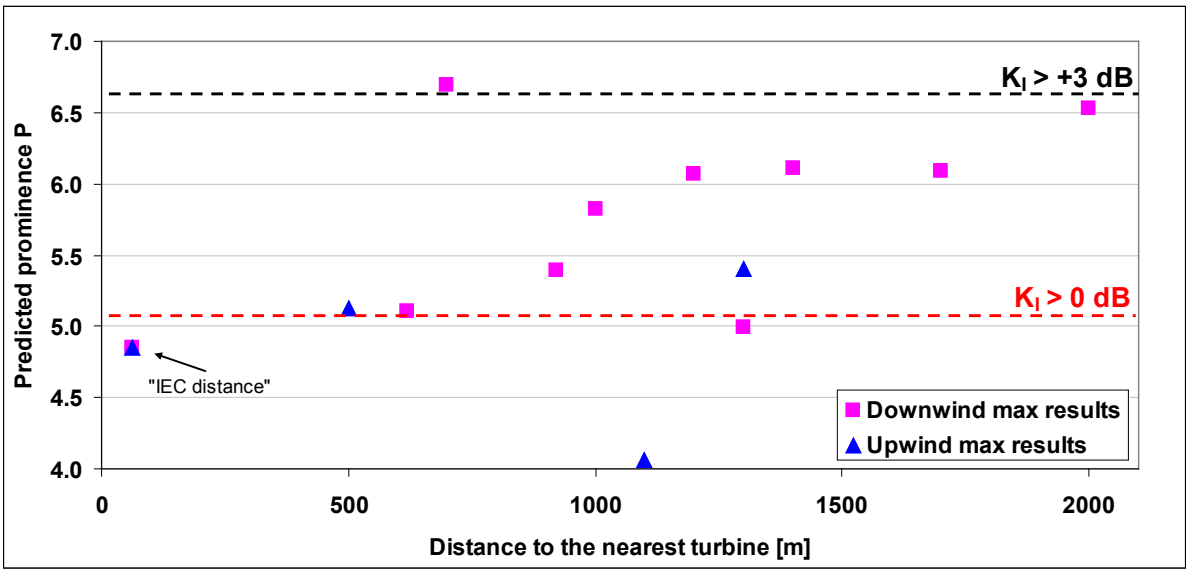
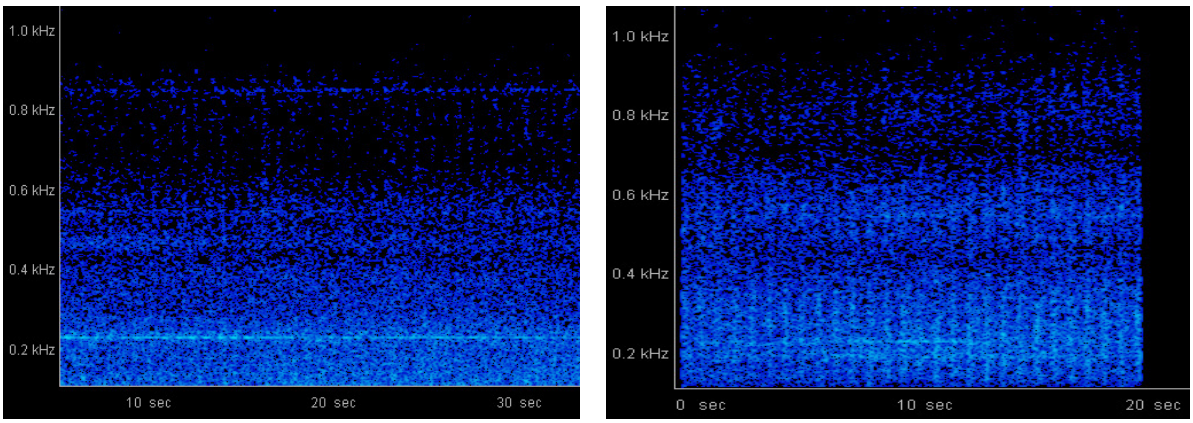


Figure 1. Predicted prominence of impulse sounds with increasing distance.

The K_I correction level is also drawn as a dotted line and from the graph it can be seen that most of the maximum broad band AM peaks at the downwind locations has at least one clear peak which has a prominence level so high, that also a low K_I correction to the measured L_{Aeq} level could have been used. The black dotted line is drawn (K_I > + 3dB) to represent a higher K_I correction, which could lead to a +5 dB correction in a typical Nordic noise assessment due to an impulsive character of sound for this particular time period (Nordtest Acou 112, 2002). This measurement location was about 630 m from the closest turbine, 150 m below the top ground height and also in the middle of the row thus giving many AM peaks where two or more turbines caused synchronized AM peaks.

The IEC distance location represents results from the emission measurement board, where LD was typically 3.5 dB to maximum 4 dB in broad band time domain data but always with relatively low OR of about 18-20 dB/s. Spectrogram analysis was performed to emission measurement recordings as well as to the immission point recordings which revealed that AM was typically more pronounced at far field locations in the broad band recorded noise (see pictures 2a and 2b).



Figures 2a and 2b. Spectrogram analysis from the emission measurement location (a) and from 2km location (b).

The fluctuation strength method takes account also the broad band sound level and thus is assumed to give a lower fluctuation strength in vacil scale with increasing distance. As an example only few maximum AM peaks were selected mainly from the emission measurement point and other downwind locations.

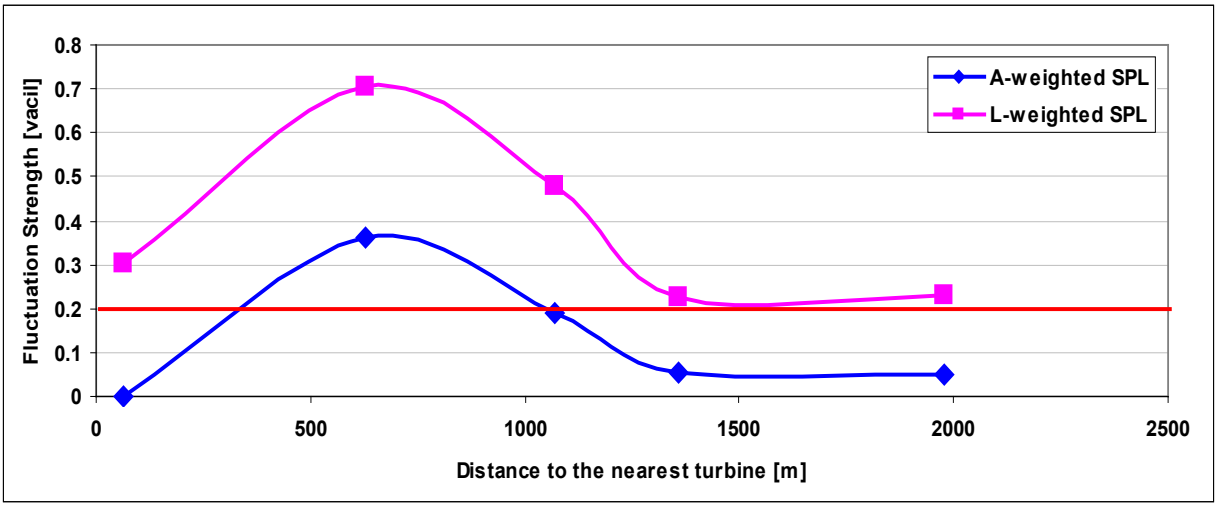


Figure 3. Fluctuation strength of AM peaks with increasing distance by using linear and A-weighted broad band sound levels. 0.2 vacil line is marked with red line.

Fluctuation strength F seems to decrease with distance but only after the 630m downwind location. Emission measurement point had the highest SPL but only 4 dB modulation depth versus the downwind 2km point, where a 6 dB AM in A-weighted time domain data was found (and clearly heard). Synchronized turbine rotation in terms of sound pulses in phase, seemed to play in important role together with low background sound level. Also a large difference of F between L and A-weighted SPL was discovered.

In annex 2, more sample plots are given to visualize what was clearly audible at the site: the dominance of the AM at downwind locations in different dates or opposite directions. In Figure 4, two audio files were fully investigated and all AM peaks calculated (as beats per minute) in order to extract the difference between upwind and downwind locations during the same measurement date.

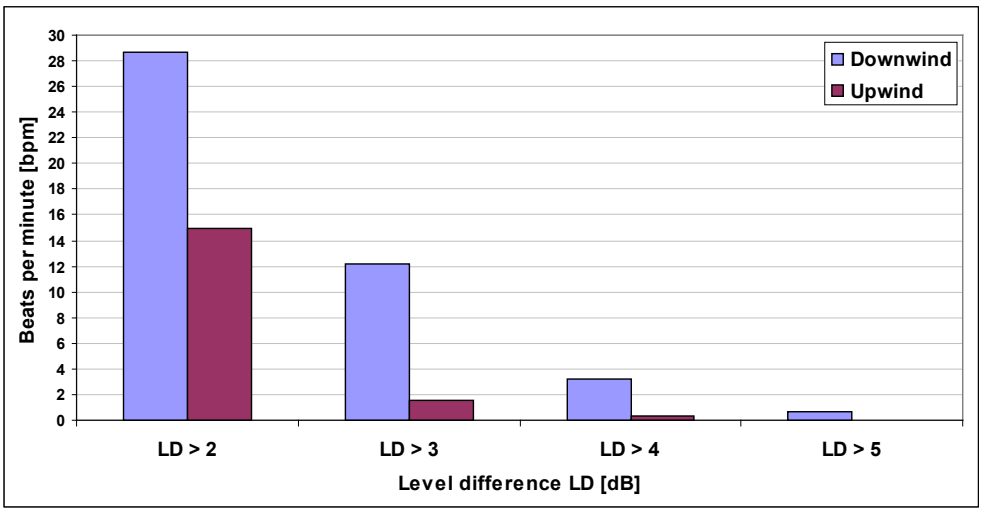


Figure 4. Number of AM beats per minute during one evening measurement at the opposite sides of the hill.

The stall regulated upwind turbine models under study also had a clear footprint of infrasound at a region from 6-10 Hz. This was accidentally discovered during one crosswind measurement period, where the wave form data showed a steady pulsation although the broad band modulation depth in time domain was minimal (see plots in annex 3). LD was now 10-14 dB and was found from many recordings analysed afterwards. Although the equipment used in field measurements was not optimized for such low frequencies, it gave interesting information regarding the phase difference of broadband SPL versus the infrasound level and modulation depth. A 30-32° blade rotation phase difference was found from the emission recording data and if it indeed is emitted when blade passes to tower (e.g. older downwind models, see Jakobsen, 2005), then it supports the idea that the highest broad band SPL is emitted from the downward blade movement presented by Oerlemans (Oerlemans, 2007).

5 Conclusions

Noise measurement campaign gave interesting results regarding the level of amplitude modulation at different distance in a complex terrain case. Two different methods for assessing AM were used to objectively measure the level of AM at different locations. AM of wind turbine broad band sound did not decrease with distance as was expected. Low night time immission point wind speed together with synchronized AM pulses increased the AM onwards from the emission point. The highest modulation depth with higher onset rates was typically found from the downwind samples and in particular at the far field measurement points which were located normal to a turbine row axis or at points directly downwind. By using two assessment methods of sound annoyance showed that a conservative approach assessing wind turbine noise in complex terrain cases is needed. This may especially be the case if the area has low nocturnal background sound levels. The Infrasound results indicate that the downward movement of the blade produces most the broad band modulation measured.

References

Acoustics – Description and measurement of environmental noise, Part 2: Acquisition of data pertinent to land use. International Standard ISO 1996-2. Switzerland, 1987.

Acoustics: Prominence of Impulsive Sounds and for Adjustment of LAeq. Nordtest Method NT ACOU 112, Nordtest, Finland, (2002).

Di Napoli, C. Case Study: Wind Turbine Noise in a small and quiet community in Finland. Conference Proceedings, Third International Meeting on Wind Turbine Noise, Aalborg, Denmark, 2009.

Fastl H., Zwiker E. 2007, Psyco- acoustics: facts and models, Springer, NY

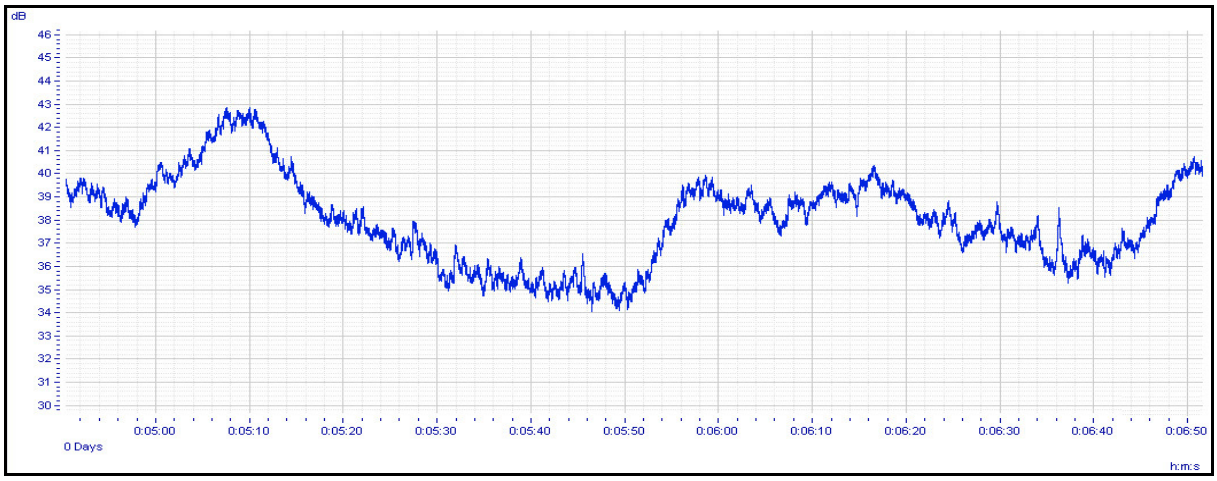
Jakosen, J. Infrasound Emission from Wind Turbines. Journal of low frequency noise, vibration and active control, 2005.

Lenchine, V. Amplitude modulation in wind turbine noise. Proceedings of Acoustics 2009, Adelaine, Australia.

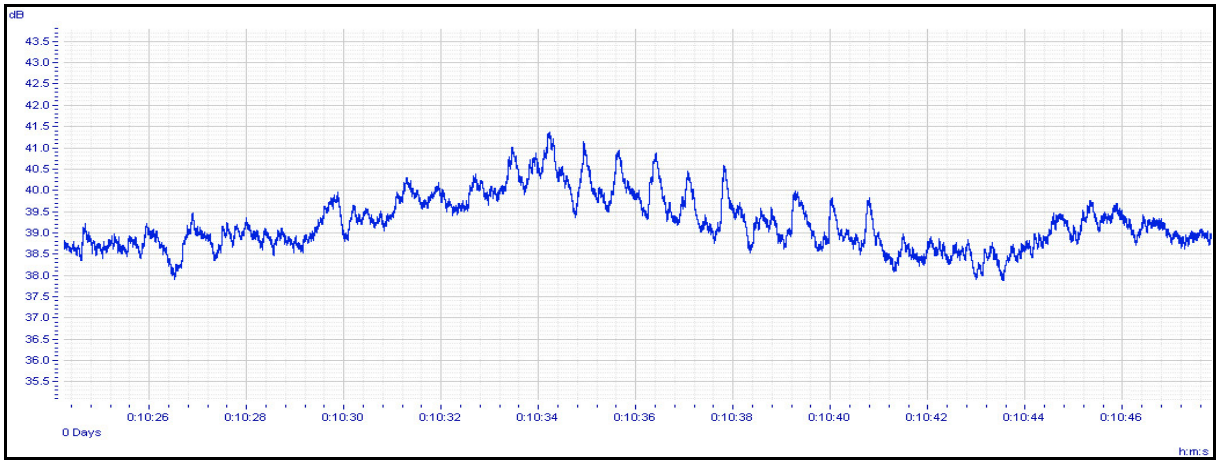
Oerlemans, S. Shephers, G. Prediction of wind turbine noise and comparison to experiment. Conference Proceedings, Second International Meeting on Wind Turbine Noise, Lyon, France, 2007.

van den Berg, F. Wind profiles over complex terrain. Conference Proceedings, Second International Meeting on Wind Turbine Noise, Lyon, France, 2007.

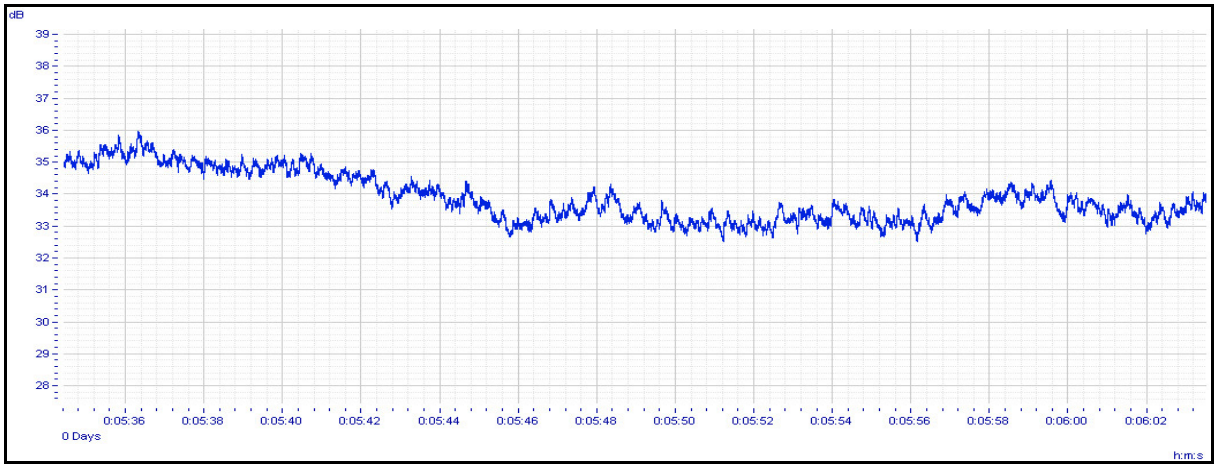
Annex 1 – AM sample plots



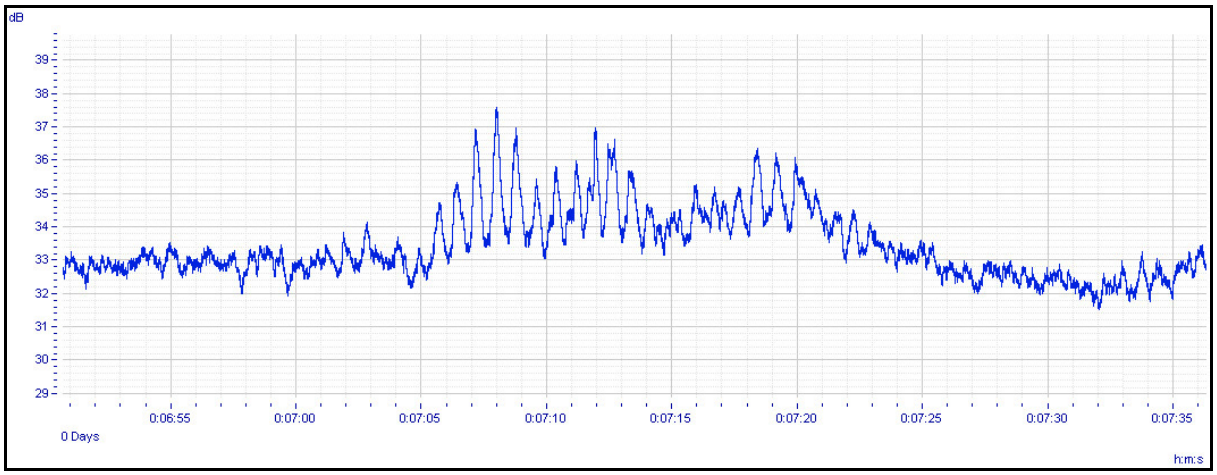
Plot 1. Crosswind sample @ 530 meters, dB(A) in time domain. 7m/s @ 510m, 4 m/s @ 230m.



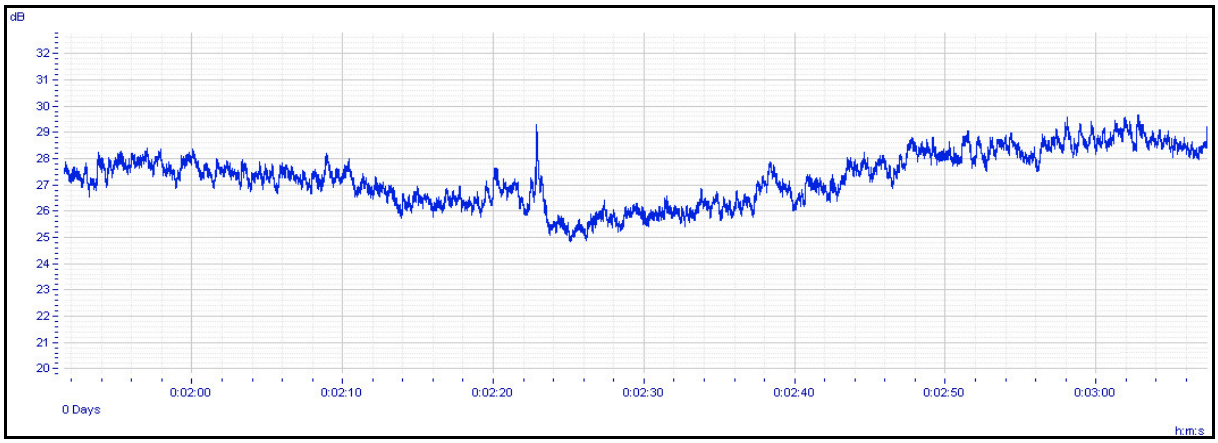
Plot 2. Crosswind sample at 1000 meters, dB(A in time domain. 14 m/s @ 510m, 5 m/s @ 230m.



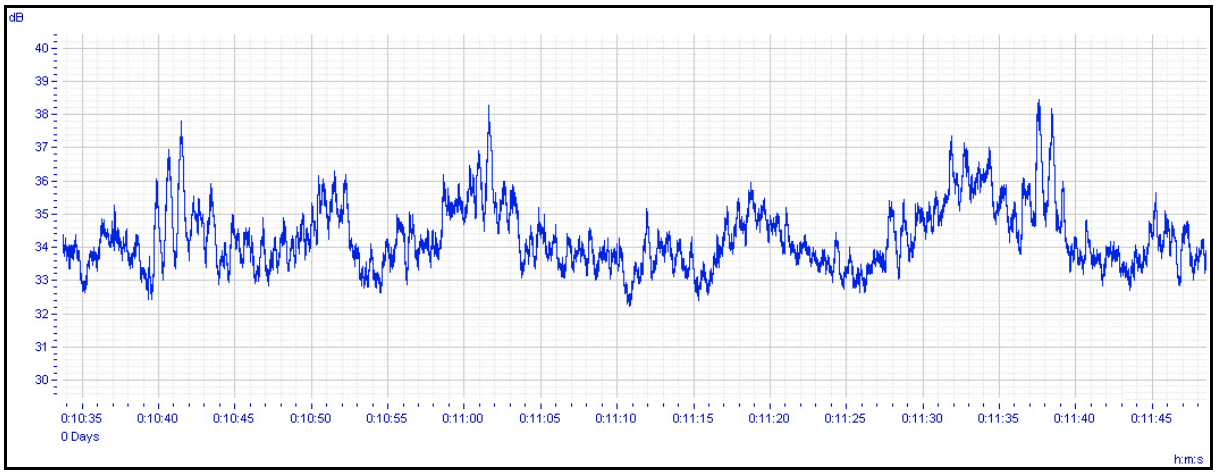
Plot 3. Crosswind sample at 1300 meters, dB(A) in time domain. 12 m/s @ 510m, 6 m/s @ 230m.



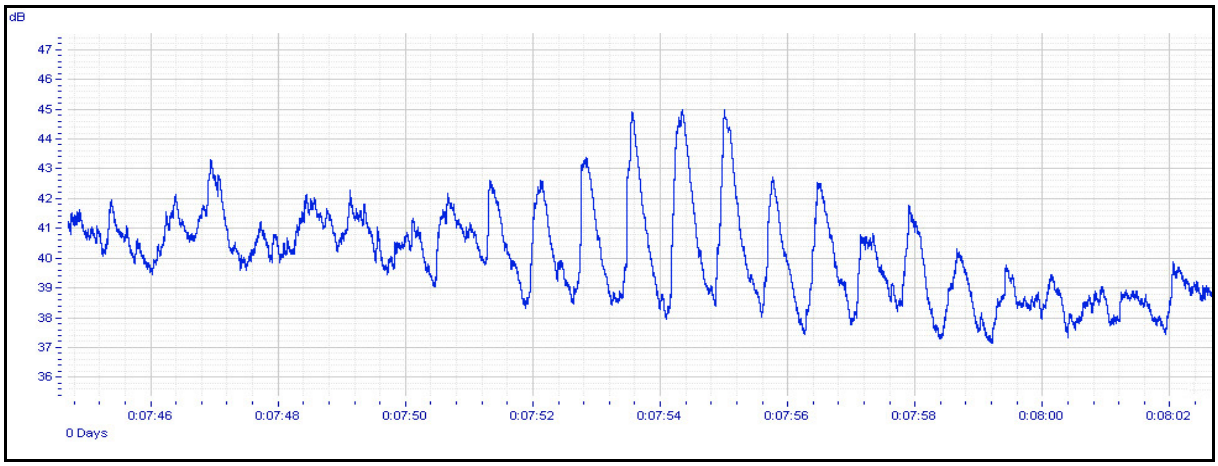
Plot 4. Upwind sample at 520 meters, dB(A) in time domain. 8 m/s @ 510m, 2 m/s @ 230m.



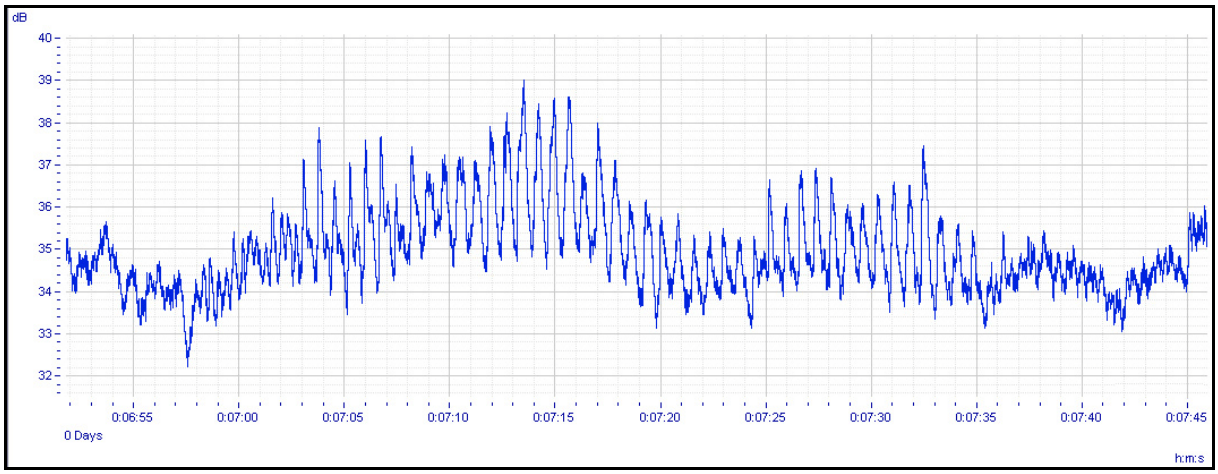
Plot 5. Upwind sample at 1000 meters, dB(A) in time domain. 7 m/s @ 510m, 4 m/s @ 230m.



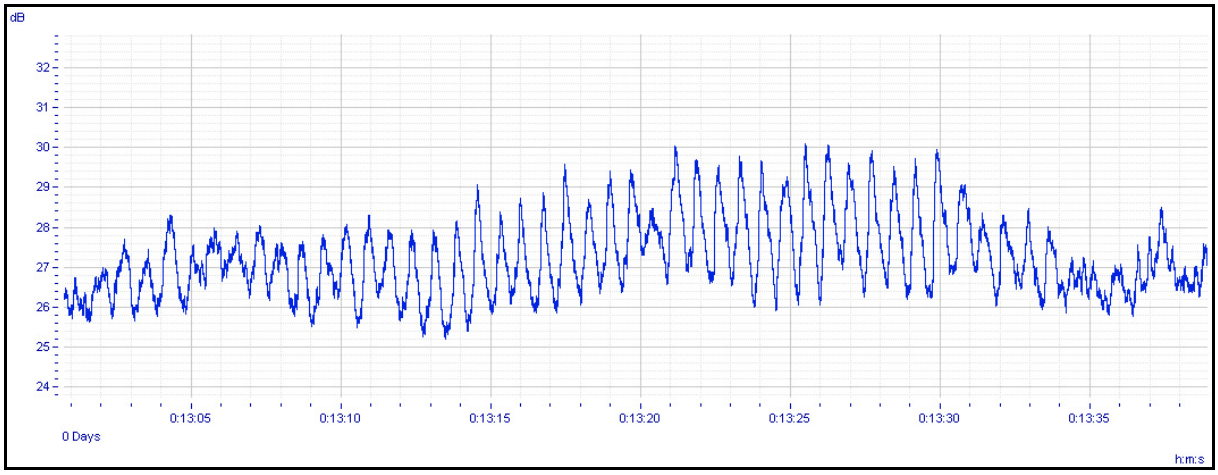
Plot 6. Upwind sample at 1300 meters, dB(A) in time domain. 8 m/s @ 510m, 2 m/s @ 230m. LD = 4.2 dB, OR = 20 dB/s, P = 5.4.



Plot 7. Downwind sample at 630 meters, dB(A) in time domain. 9 m/s @ 510m, 2 m/s @ 230m. LD was now 7 dB, OR about 42 dB/s => K_I = +3.1 dB

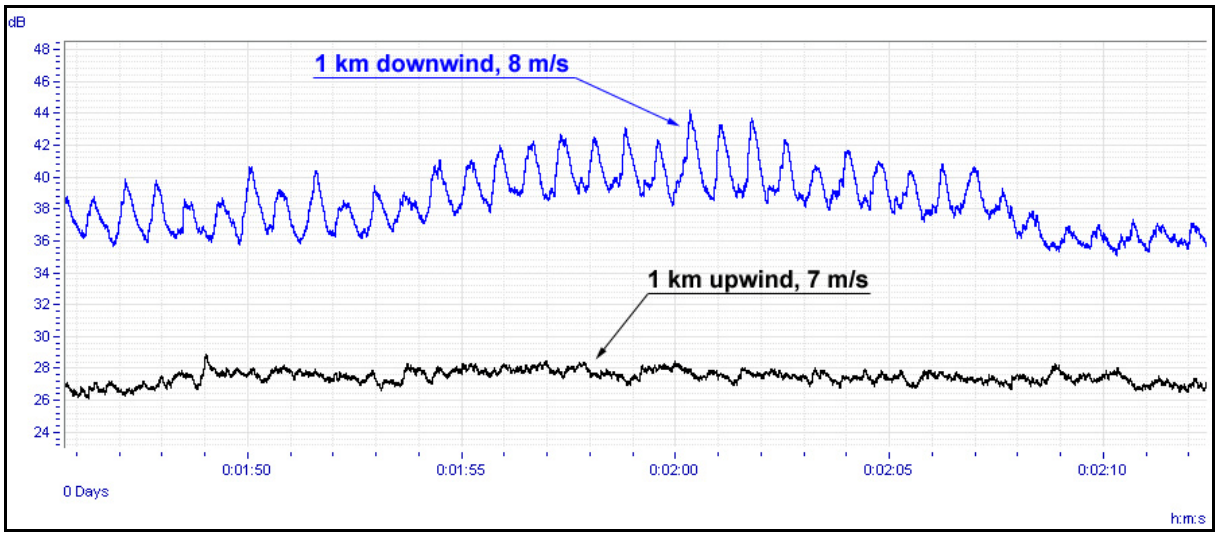


Plot 8. Downwind sample at 1000 meters, dB(A) in time domain. 9 m/s @ 510m, 2 m/s @ 230m.

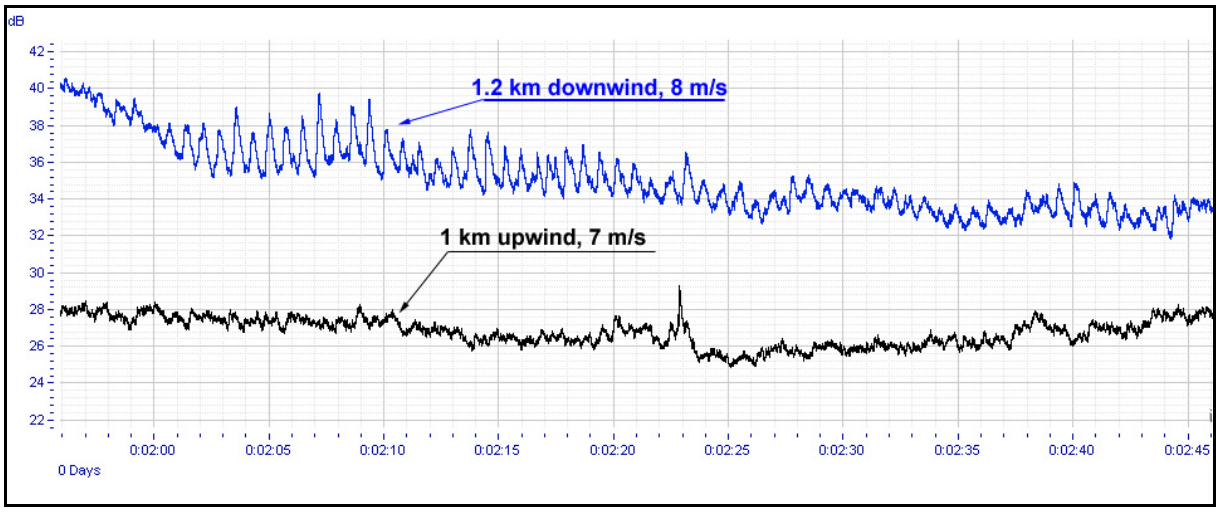


Plot 9. Downwind sample at 2000 meters, dB(A) in time domain. 8 m/s @ 510m, 0 m/s @ 230m.

Annex 2 – AM sample plots – Comparisons

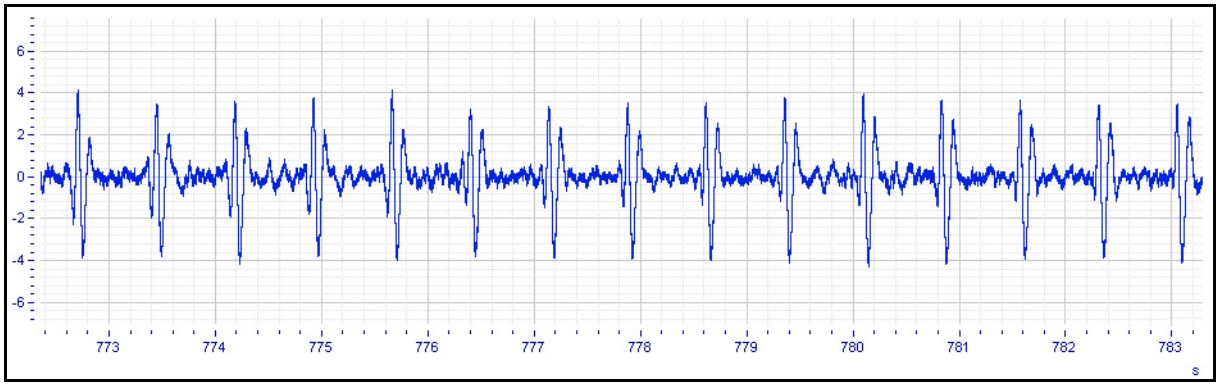


Plot 1. Immission point at 1000m, two different measurement dates, same location, opposite wind directions, same turbine rpm.

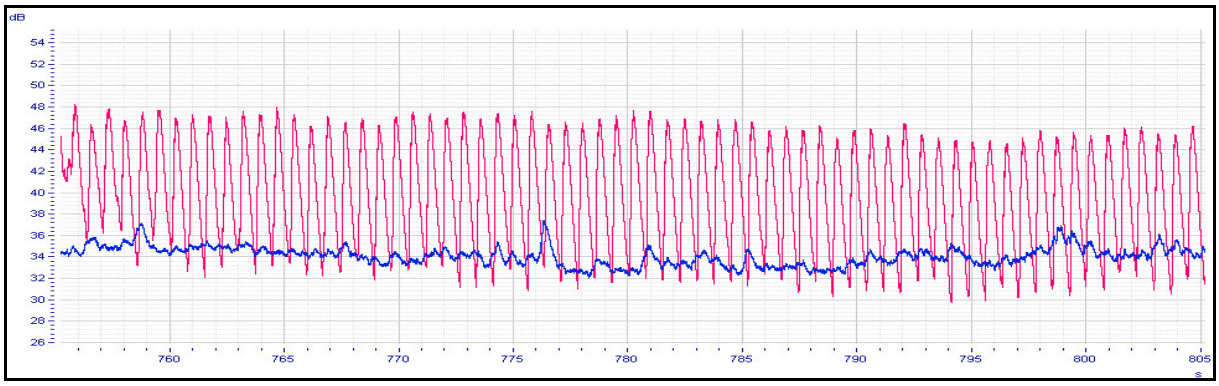


Plot 2. Immission points at 1000m upwind and 1200m downwind during the same night time measurement, same turbine rpm, opposite sides of the hill. At the 1.2 km immission point directly downwind from the turbine, the “famous” pile driving sound now was present with rapid onset rates and frequencies only up to 300 Hz.

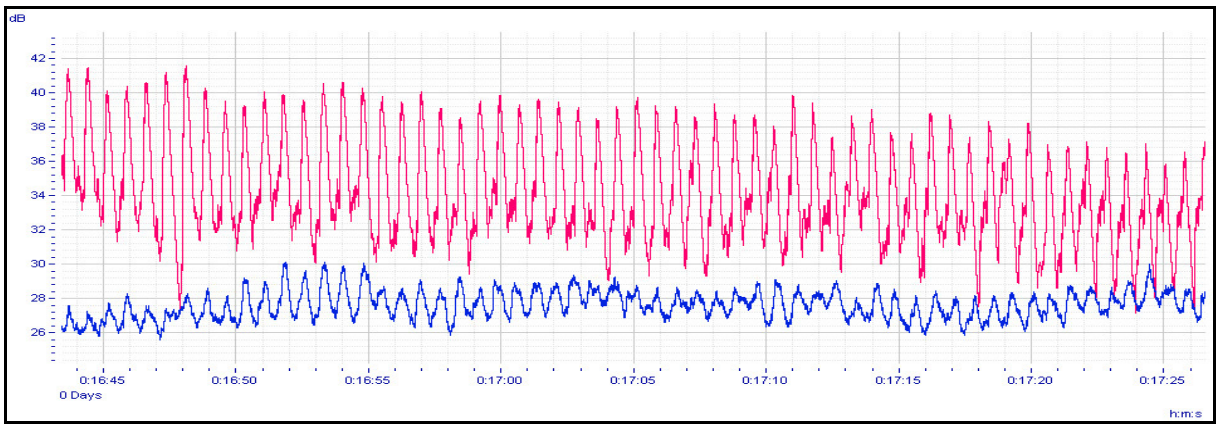
Annex 3 – Infrasound sample plots



Plot 1. Wave-format data showing infrasound pulsations during one crosswind measurement.



Plot 2. C-weighted infrasound as band bass frequency from 6 Hz to 10 Hz (red curve) during one crosswind measurement at 520m from the closest turbine. LD is about 14 dB.



Plot 3. C-weighted infrasound as band bass frequency from 6 Hz to 10 Hz (red curve) during the 2 km downwind measurement under stable atmospheric conditions. LD is about 10 dB.