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Time dependent changes in sound pressure levels caused by wind turbines at long distances

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Summary

Sound pressures levels caused by wind turbines typically show a lot of time-dependent changes. One obvious cause is the source itself, where the sound power of the wind turbine depends directly on the wind speed. Another obvious cause for changes in sound pressure levels at long distances is the wind direction, since the sound propagation depends on it.

Conditions for the source as well as the propagation and attenuation of sound can be classified to better understand the statistics of the sound pressure levels. But even choosing time sections with fairly constant wind speeds and wind directions at the wind turbine, there still is a lot of variability in the sound pressure levels.

On the very short time scale, this is partly due to the type of sound emitted by wind turbines. The aerodynamic sound from the rotor blades is band-limited noise, which results in fluctuations in sound pressure levels for purely statistical reasons.
Under some conditions, amplitude modulations (AM) occur, causing sound described with terms like whooshing or thumping. With 100ms-Leqs, the levels go up and down in synch with the rotor blades.
If the focus is on determining average sound pressure levels, and not on studying amplitude modulations, Leqs with integration times longer than the period of the AM can be used to suppress the effects of AM on the statistical distribution of the levels.

The variability and statistical properties of sound pressure levels caused by wind turbines at about 1000m distance for a two month long measurement project are presented.

1. Introduction

The sound pressure levels caused by wind turbine sound at long ranges vary for a number of reasons. The wind turbine itself emits sound that depends mostly on wind speed and the power produced, but may also change with turbine blade pitch angle, with the turbulence of the wind field, and the shape of the wind speed profile.

The attenuation due to the sound propagation also depends on the wind direction, the turbulence and shape of the wind field as well as the air temperature profile. The wind turbines

have an effect on the wind field itself that may also be relevant for the propagation of sound for several hundred meters.

And there may be many more reasons for variations in the wind turbine as a source of sound as well as the propagation of the sound. The present paper discusses some of the problems that are encountered when evaluating the varying and fluctuating sound pressure levels caused by wind turbines.

2. Sound pressure levels

2.1 100ms-equivalence levels

The sound from wind turbines mostly is a band-limited noise – with noise being used in the statistical sense. For a noisy signal, a calculated sound pressure level with a limited integration time is also noisy, i.e. it shows statistical variations. The shorter the integration time, the more the sound pressure levels fluctuate, even if the sound pressure is a stationary signal – stationary indicating that it has a constant amplitude.

The longer the integration time, the smaller the statistical fluctuations become. But using long integration times reduces the time resolution. For wind turbines, the sound pressure signal often is not stationary, but has a modulated amplitude. If the amplitude goes up and down each 1.5s – for example – the integration time needs to be much shorter to still see the amplitude modulations in the sound pressure levels.

In studies on the sounds from wind turbines, it is very common to look at $L_{Aeq,100ms}$, which are A-weighted levels, with a rectangular integration window of 100ms, which seems to be a good compromise between time resolution and statistical noise.

2.2 Long term sound pressure levels

A typical use of the measured levels might be the calculation of an equivalent continuous A-weighted sound pressure level [ISO9613-2], also called time-averaged sound pressure level [ISO1996-1].
Since ISO9613-2:1996, there were several revisions of ISO1996-2. The text for the source was changed, where it used to say (6.1):

> "*The source operating conditions shall be statistically representative of the noise environment under consideration.*",

the current text is much more fuzzy, and the *statistically representative* was dropped. But the requirement of determining the uncertainties was added.

And for the meteorological conditions, the requirement in 3.6 for a meteorological window had the minor change from

> "*set of weather conditions during which measurements can be performed with limited and known variation in measurement results due to weather conditions.*"

to

> "*set of weather conditions during which measurements can be performed with limited and known variation in measurement results due to weather variation.*"

For wind turbines, the source depends on the meteorology, as do the propagation properties that affect the measured sound pressure levels. Depending on national regulations, old or new versions of ISO 1996-2 are to be used. But in both cases, the requirement that the variations in results due to meteorological conditions need to be limited and known stands.

And whether paragraph 6 is taken from the old or new version, single measurements can not fulfill the requirements.
For the old version of ISO1996-2, a possible way to fulfill the *statistically representative* requirement would be to perform measurements for a very long time. The time would have to be long enough to be statistically representative – which might be a year, two years, or even three years.

The new version of ISO1996-2 does not require a *statistically representative* measurement time, but it requires the determination of uncertainties. And this goes hand in hand with the *limited and known* requirement for the effects of the meteorology.

An approach to satisfy these requirements would be to form classes of conditions for the source and sound propagation, and then use known statistics for these classes to calculate a representative long-term averaged sound pressure level.
For each of these classes, the measurement results need to have "limited and known variation". The following is a discussion on such classes and meteorological windows.

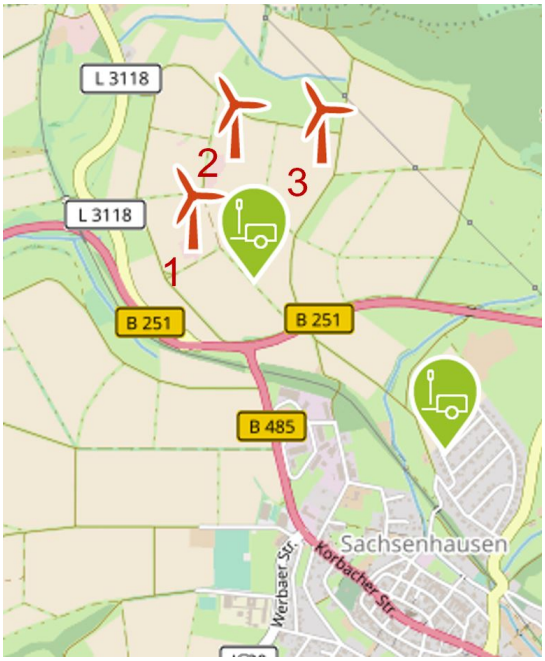

Figure 1 Location of the wind turbines and measurement positions

3. The measurements

The data used was measured in a project on the impact of sound from wind turbines funded by the German Environment Agency (Umweltbundesamt – UBA). It should be noted that this project does not focus on sound pressure levels, and that the following is not part of the project.

Outside of a small place called Sachsenhausen in Nordhessen, Germany, three wind turbines are about 1000m away from the residential area (see Figure 1). The wind turbines are:

- Wind turbine 1 and 2: Enercon E-82 with hub height 137 m,
- Wind turbine 3: Enercon E-101 with hub height 133 m.

Two measurement systems were installed by deBAKOM GmbH.
At 180m distance to wind turbine 1, meteorological data was gathered, including wind at several heights up to 10m. Operational data of wind turbine 1, including power and wind speed at hub height, was recorded at 1s intervals.

Figure 2 Measurements close to the wind turbines

Figure 3 Measurements at edge of residential area

A second measurement system was installed at the edge of the residential area, recording wind at two heights, and acoustical data at 7m height. All sound pressure levels discussed in the following were recorded in this location.
The measurement systems recorded from April 27th to June 26th 2018. Due to technical problems, not all systems ran for the whole time, but the acoustical measurements at the edge of the residential area are almost complete for the two month period.

4. Statistical classification

4.1 Background noise

As a very first step of looking at the measured levels, the distribution of levels is shown as a histogram in Figure 4. The vertical axis is labeled “relative density”, the values shown are just the number of levels in each bin, divided by the total count of levels. In histograms, this is often called “frequency”, the term “relative density” is used to avoid confusion.

Indicated in the histogram are also the 95, the 80, and the 50 Percentile. For the L50, the 50-Percentile, half of the measured levels are higher than this value, and half of the levels are lower. The L95, for which only 5% of the levels are lower than this value, is sometimes referred to as a background level.
The distribution shown in Figure 4 includes all the noise measured, which is not just from the wind turbines, but also from sources ranging from traffic to birds and mooing cows.

In the measurement location, the most quiet time of the night is the time from 23:00 to 04:00. Figure 5 shows the distribution of levels for this time. The shift of the distribution to smaller levels is very obvious.

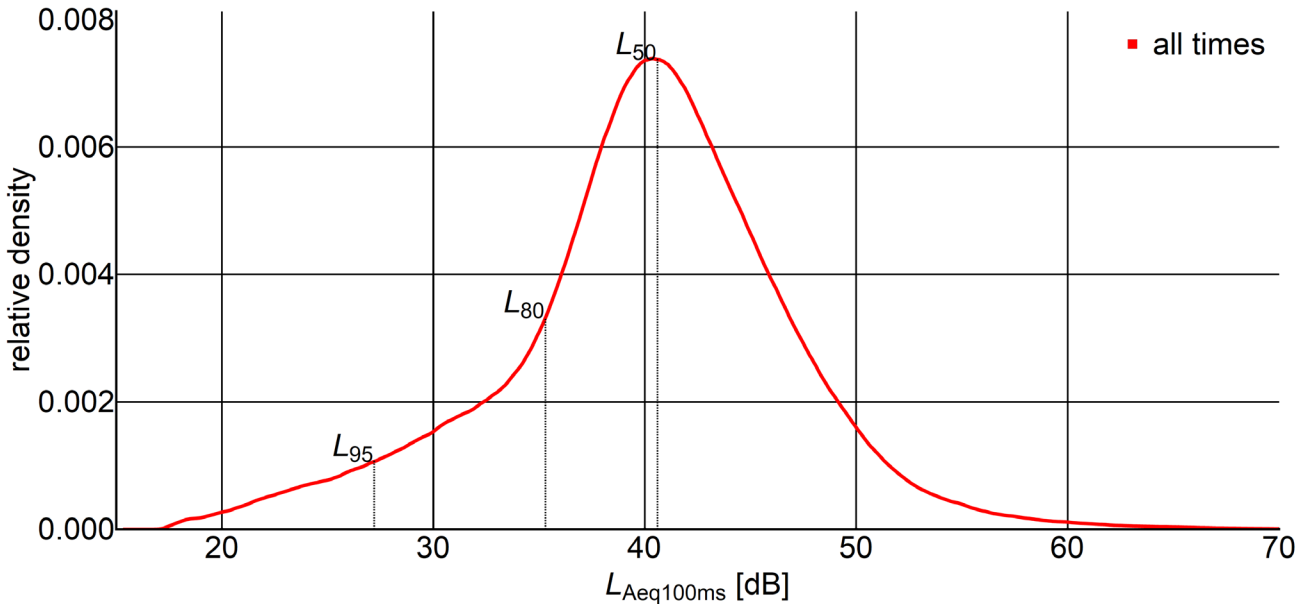

Figure 4 Distribution of $L_{Aeq,100ms}$ for all times

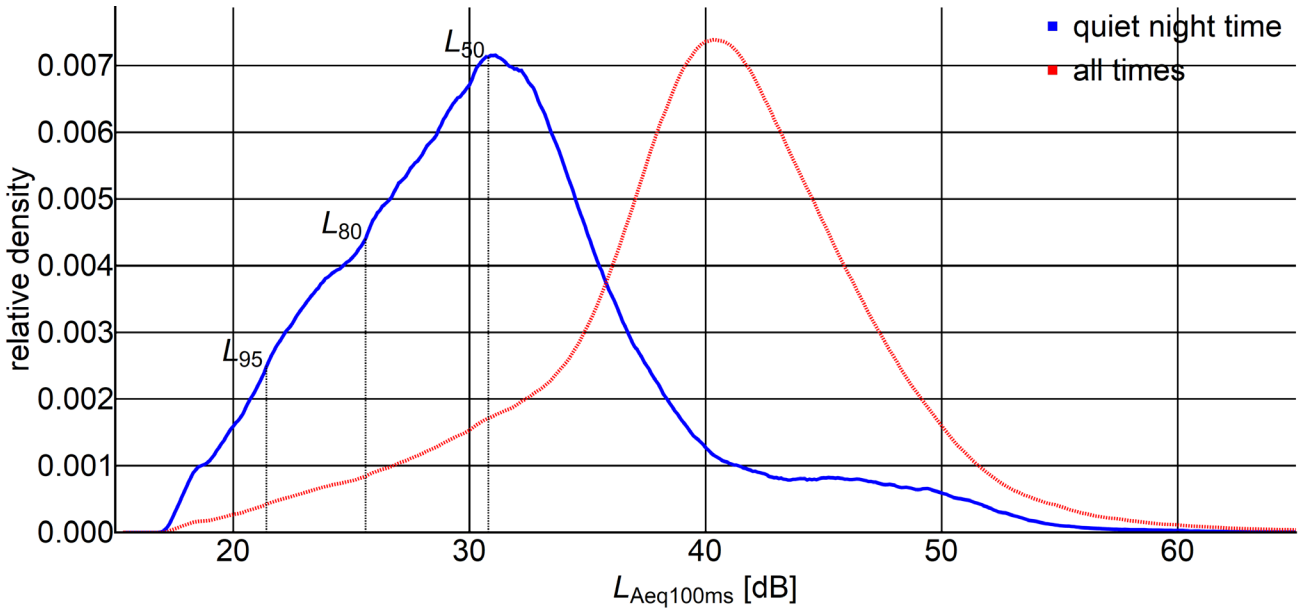

Figure 5 Distribution of $L_{Aeq,100ms}$ for the quiet night hours

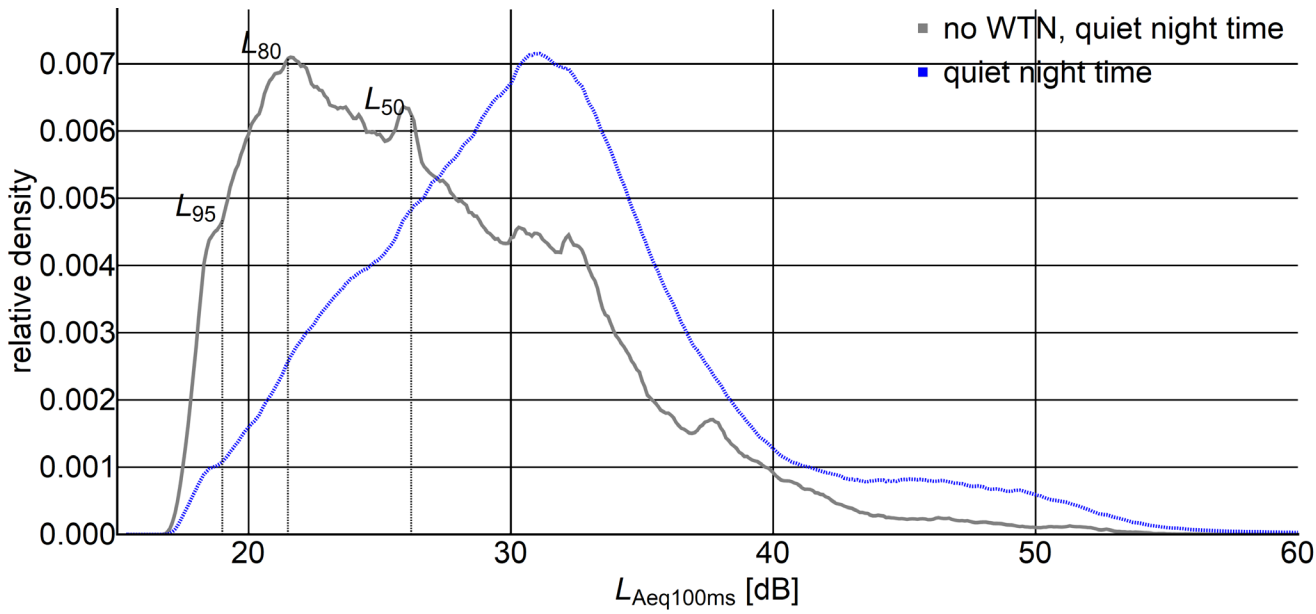

Figure 6 Distribution of levels for the quiet night hours without WTN

The next step is to reduce the times taken into account yet again, and only look at the quiet night hours where the wind turbines did not run, or - to be more specific - the times where wind turbine 1 produced less than 100kW power. Figure 6 shows this distribution, which should be a good approximation for what the night levels would be like it there were no wind turbines. With an L50 at about 26 dB(A), and an L95 at about 19 dB(A), the area is fairly quiet.

The levels in the absence of WTN mostly are so low, that for the following the measured levels under different conditions are looked at as if they were caused only by the wind turbines. Note that this is a very rough approximation, that is used to illustrate qualitative effects in this paper.

In the following, only data from the quiet time of the night from 23:00 to 04:00 is used.

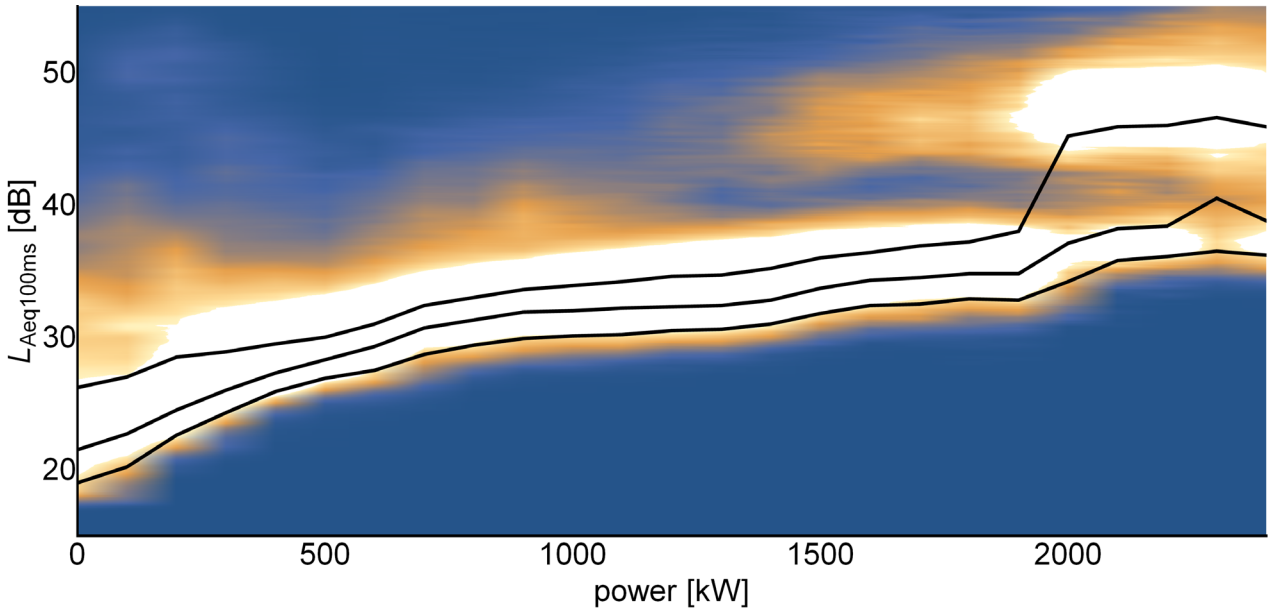

Figure 7 Distribution of levels for the quiet hours of the night vs power from WT 1. Black lines show the L95, L80 and L50.

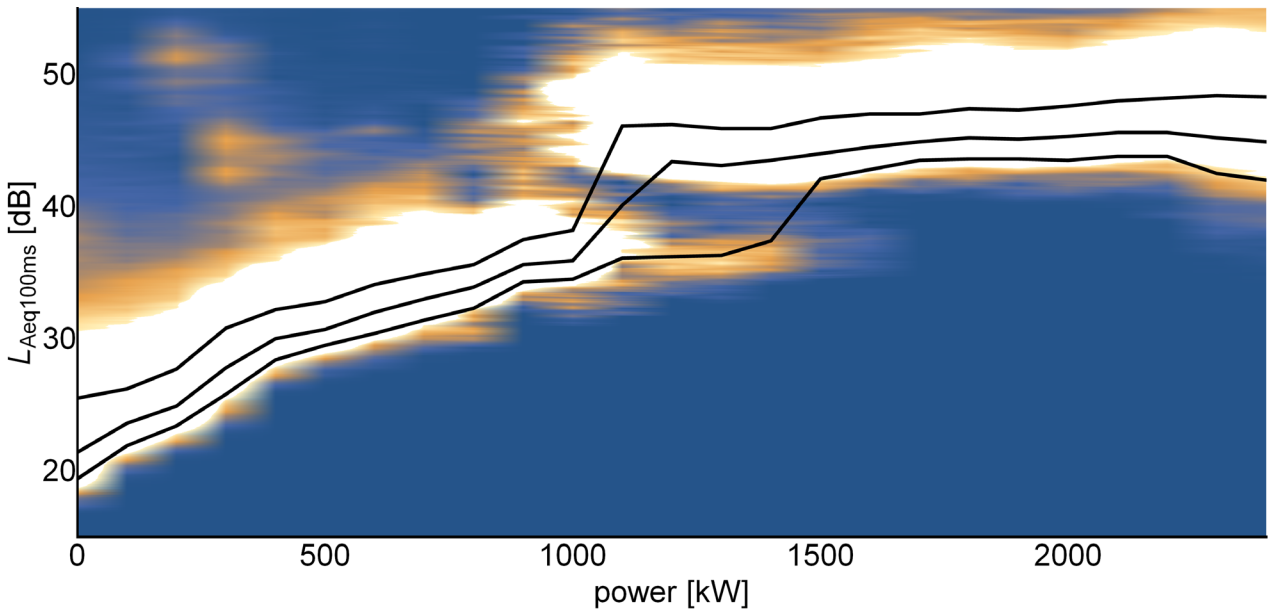

Figure 8 Distribution of levels for the quiet hours of the night and for favorable wind directions vs power from WT 1. Black lines show the L95, L80 and L50.

4.2 Levels vs wind turbine power

Some correlation of the sound pressure levels with the power from the wind turbines can be expected. Figure 7 show the distribution as 2D-plot for levels and power from wind turbine 1. The density of values is indicated by the color, with lighter colors for higher densities.
Up to about 1900kW the distribution of levels is smoothly shifted to higher levels, basically meeting the expectation that the levels depend on the power of the wind turbine.

Ignoring the discontinuity at 2000kW for now, another simple expectation that can be verified is the dependence of levels on the wind direction. Figure 7 shows levels for all wind directions, a distribution for favorable wind directions is expected to look similar, but with the distribution shifted to higher values. In the actual distribution for favorable wind directions shown in Figure 8, the levels are indeed distinctly shifted up – but the discontinuity that was at 2000kW for all wind directions is now between 1100 and 1200kW. For now, the reason for the discontinuities is unclear, but the distinct difference between Figure 7 and Figure 8 can be taken as warning on how deceptive the statistics for such measurements can be.

Figure 7 and Figure 8 also show L95, L80 and L50. Since the distribution of levels might be a bit asymmetric due to other noise, 2*(L50-L95) might be taken as a measure for the width of the distribution. This width of the distribution is about 8dB or higher for all wind turbine powers. So the width of the distribution is not limited in the sense of ISO1996 requirement, and the reason for the variations is certainly not known as per the same paragraph in ISO1996-2. Classification by wind direction and turbine power clearly is not good enough.

4.3 Levels vs wind at the wind turbines hub height

The distributions shown in Figure 7 and Figure 8 are plotted versus the power from wind turbine 1, and there is the inherent assumption that the other two wind turbines have similar power, and hence similar sound power levels.
Another approach would be to look at the wind speeds as the main classification parameter, which is also what is done in IEC 61400-1 for the sound pressure levels close to the wind turbines.

Figure 9 shows the distribution of $L_{Aeq,100ms}$ vs the wind speed at the hub of wind turbine 1, during the quiet hours of the night and with favorable wind directions. Similar to the plots versus power, the plot versus wind speed shows how the distribution is shifter to higher levels as wind speed increases, and a discontinuous jump to higher levels at 9 m/s wind speed.
The level distributions vs wind speed still show a width of 8dB or more, so a classification of source and propagation conditions just by wind speed and wind direction would be insufficient.

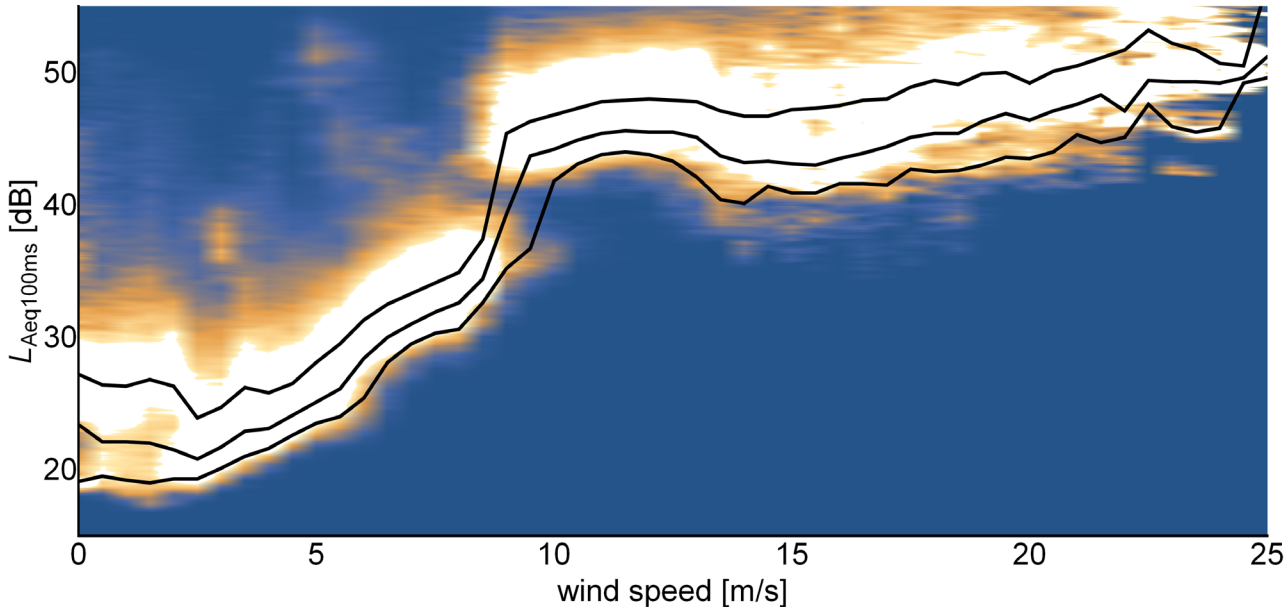

Figure 9 Distribution of levels for the quiet hours of the night and for favorable wind directions vs wind speed at hub height of WT 1. Black lines show the L95, L80 and L50.

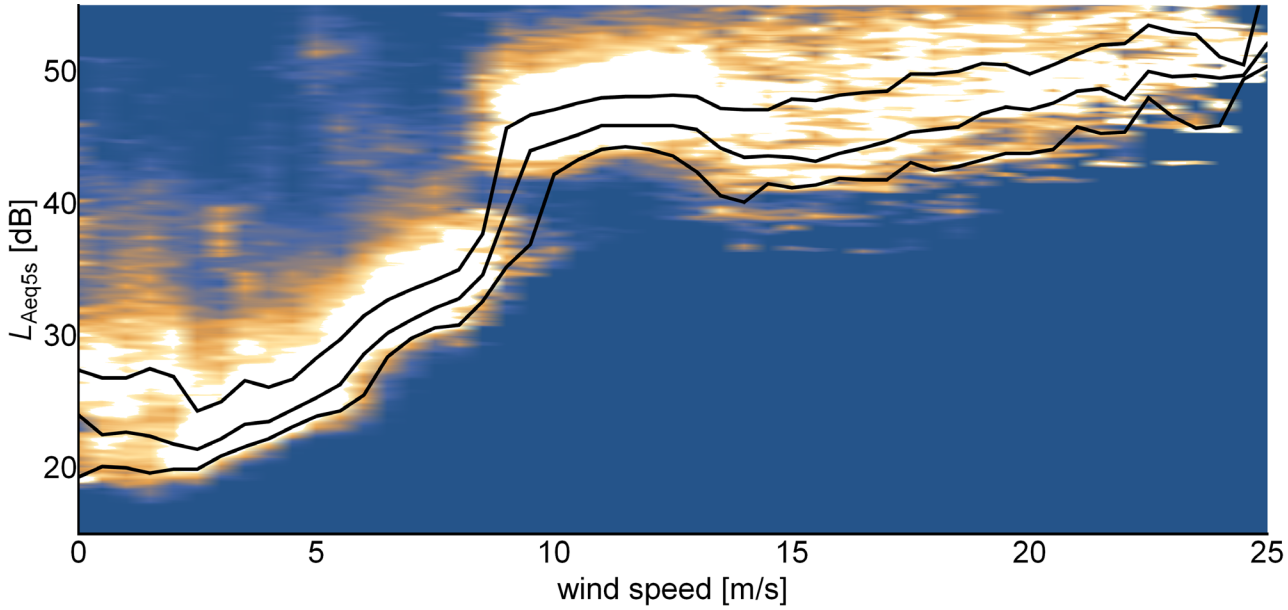

Figure 10 Distribution of 5s-levels for the quiet hours of the night and for favorable wind directions vs wind speed at hub height of WT 1. Black lines show the L95, L80 and L50.

5. Time dependent changes

5.1 Sound pressure levels

The statistical distributions shown in the previous section had width of 8dB or more for the sound pressure levels. A possible reason for the width of the distributions might be found in the levels themselves. The $L_{Aeq,100ms}$ are very sensitive to short time variations which might be of no interest when determining a long-term average. Figure 11 shows a sound pressure level plot for a time with amplitude modulations (AM). If one is interested in finding the AM, the $L_{Aeq,100ms}$ nicely shows how the level goes up and down. For a long-term average, these short-term variations may be considered a distraction. And they can be included with the levels assigned to the wind turbines, since they clearly are caused by the wind turbines.
Increasing the integration time of the sound pressure levels to 5s evens out the AM, as can be seen in the $L_{Aeq,5s}$ shown in Figure 11. The 5s are long enough that the plot does not follow the amplitude of the AM, and short enough to show the slower fluctuations on the scale of 5 to 15

seconds. Choosing an integration time is always a compromise, for the following 5s will be used.

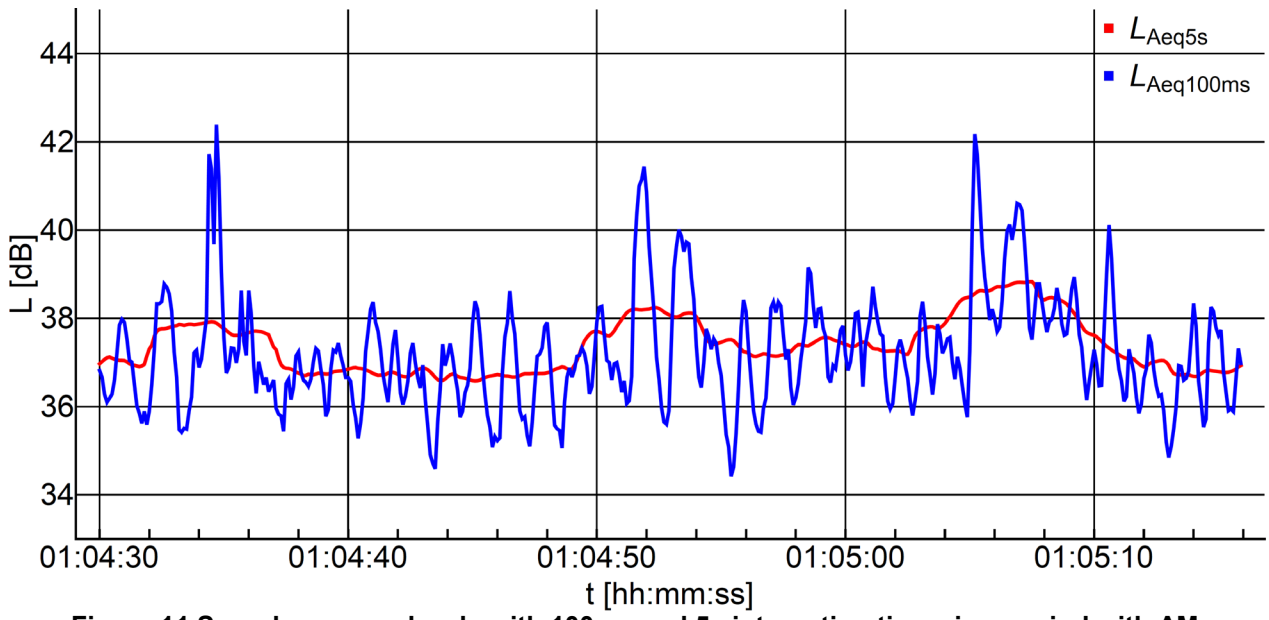

Figure 11 Sound pressure levels with 100ms and 5s integration times in a period with AM

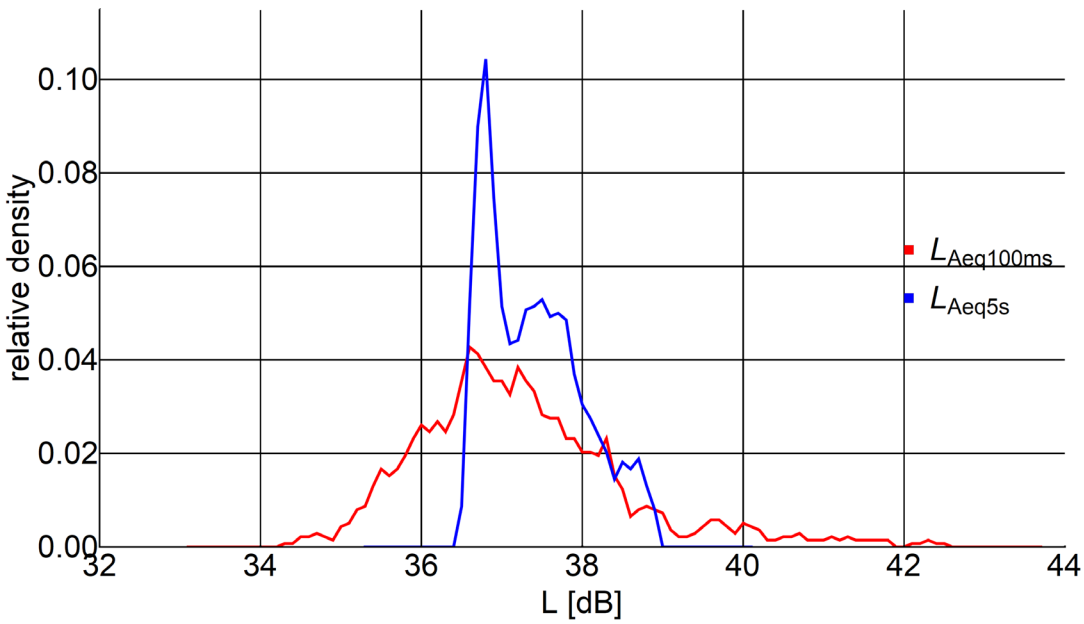

Figure 12 Distribution of sound pressure levels with 100ms and 5s integration times in a period with AM

Figure 12 shows the distribution of sound pressure levels for the same time as shown in Figure 11. As expected, for the $L_{Aeq,5s}$, the distribution is much more narrow than for the $L_{Aeq,100ms}$. But it still reflects that the sound pressure levels fluctuate even when AM are averaged out. Note in Figure 11 and Figure 12 that even within this 50s time-window, the $L_{Aeq,5s}$ varies by over 2dB.

Going back to the sound pressure level distribution vs wind speed, Figure 10 shows the distribution for the $L_{Aeq,5s}$. Comparing Figure 9 and Figure 10, some changes in the details can be seen due to the change from 100ms to 5s integration times in the levels, but overall the difference is small, and the width of the distribution is very similar. There is still a lot of variation in the sound pressure level, even with 5s integration time.

5.2 Wind speed

The discontinuity visible in the level distributions in Figure 7 to Figure 10 is an indication of a classification problem. Wind speeds and the potential influence on the measurement results need to be looked at closer.

Before going into more detailed classifications, the wind speed as hub height as the main parameter needs to be looked at more closely, as the wind speed data shows a lot of very quick fluctuations.
A possible way of quantifying this is shown in Figure 13. It is a standard deviation of the difference between two wind speeds with a time difference of τ in between:

$$\sigma(\tau) = \sqrt{E\left|\left(v_{t_i} - v_{t_i+\tau}\right)^2\right|}$$

(This is directly related to the autocorrelation function, but has the advantage of showing the difference to be expected between two values.)

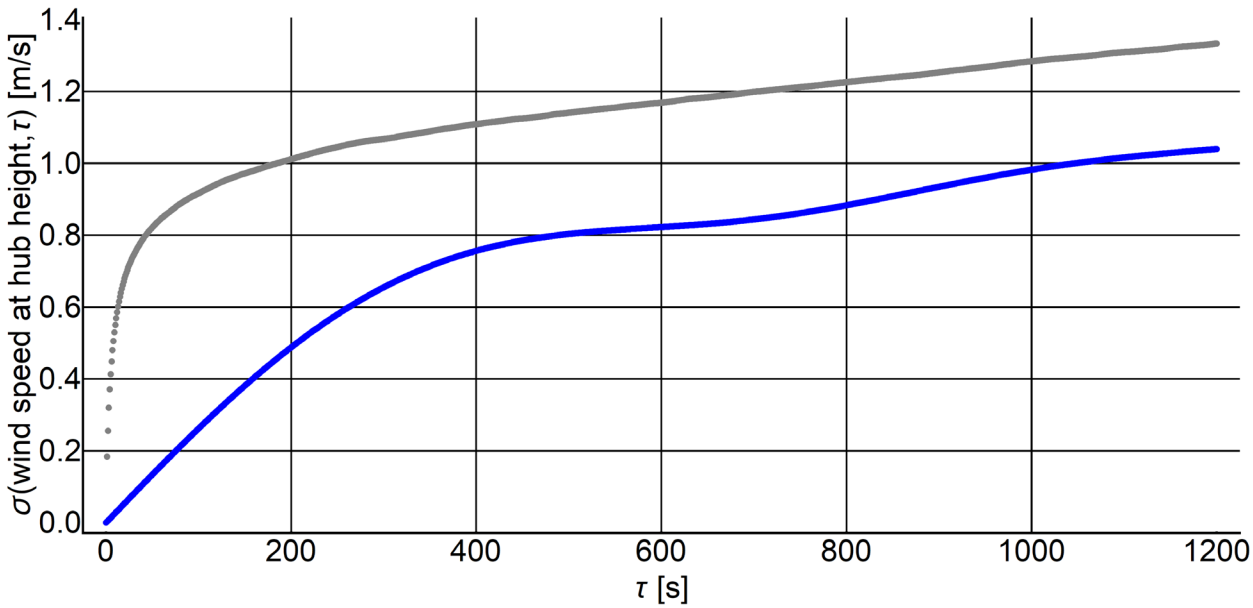

Figure 13 Time dependent standard deviation of the hub-height wind speed. Gray is the measured data, blue is the signal conditioned with a low-pass filter.

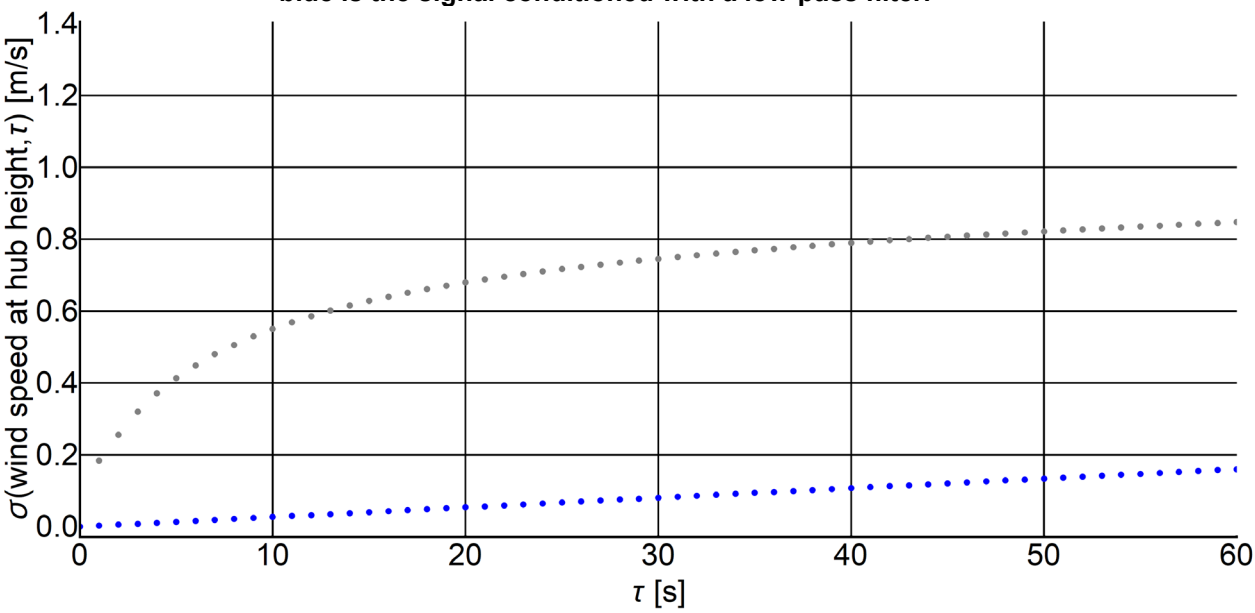

Figure 14 Time dependent standard deviation of the hub-height wind speed. Gray is the measured data, blue is the signal conditioned with a low-pass filter.

Figure 14 shows the standard deviations for small times. After less than 10s, 0.5m/s is exceeded. This indicates that the wind speed as recorded at hub height will usually change by 0.5m/s within less than 10s. The shape of the curve in Figure 13 indicates that these short term fluctuations mask the long-term correlations. They might be noise in the measurement, or they might be actual short-term fluctuations that contain relevant information on the turbulence of the atmosphere. In any case, they overlay the longer-term trend of the hub-height wind speed.

A possible approach to obtaining a more stable quantity is to apply a low pass filter to the wind speed signal, hopefully getting a better classification parameter.

6. Wind induced noise – or not?

A possible cause of increased measured sound pressure levels in the context of wind turbine noise is wind induced noise. As the wind speed at the hub of the wind turbine increases, so does the wind close to the ground. This wind causes noise itself, when blowing over or through vegetation for example, and that noise is not due to the wind turbine. Care has to be taken not to include this wind induced noise with the wind turbine noise.
Even worse, as wind speeds increase, the microphone itself may pick up wind induced noise, and that not be included in a environmental noise at all.

A possible way of checking for wind induced noise is to look a sound pressure levels vs wind speed close to the ground for fixed wind speeds at the hub of the wind turbine. To do this and have a reasonable resolution for effects at different hub height wind speeds, the wind speeds at hub height are conditioned as shown in the previous section.
With the conditioned hub-height wind speed, a classification by ground height wind speed is possible. As examples, three wind speed ranges are set:

- Conditioned hub-height wind speed 7m/s (6.75m/s to 7.25m/s)
- Conditioned hub-height wind speed 10m/s (9.75m/s to 10.25m/s)
- Conditioned hub-height wind speed 13m/s (12.75m/s to 13.25m/s)

As a second classification parameter, the wind speed at 7m height – next to the microphone - is used. Figure 15, Figure 16 and Figure 17 show the distributions of $L_{Aeq,5s}$ for the three hub-height wind speeds vs 7m height wind speed. The width of the distribution is roughly 5dB, and while that may not be narrow enough, it certainly is an improvement.

Figure 18 shows the L80 for the three distributions. Some qualitative information can be gathered:

- The measured sound pressure levels at small 7m height wind speeds is smallest for 7m/s at hub height, and biggest for 13m/s at hub height. So the higher the wind speed at hub height, the higher the levels from the wind turbines – as certainly expected.
- At (roughly) about 4m/s wind speed at 7m height, the levels start increasing. The microphone has been tested not to have any sensitivity to wind up to at least 6m/s wind speed, so at least some of this effect probably is not due to wind noise induced at the microphone itself.
- Up to about 8m/s wind speed at 7m height, the levels for the three different hub-height wind speeds are different. If the rise in levels was only due to wind induced noise, the difference in the L80 should be much smaller for 4 to 8 m/s wind speed at 7m height.
    - The statistics may be too limited, and the results may be an artifact of bad statistics, or
    - There may be a correlation between between wind speed at 7m height and the levels due to the wind turbine for fixed hub-height wind speeds.

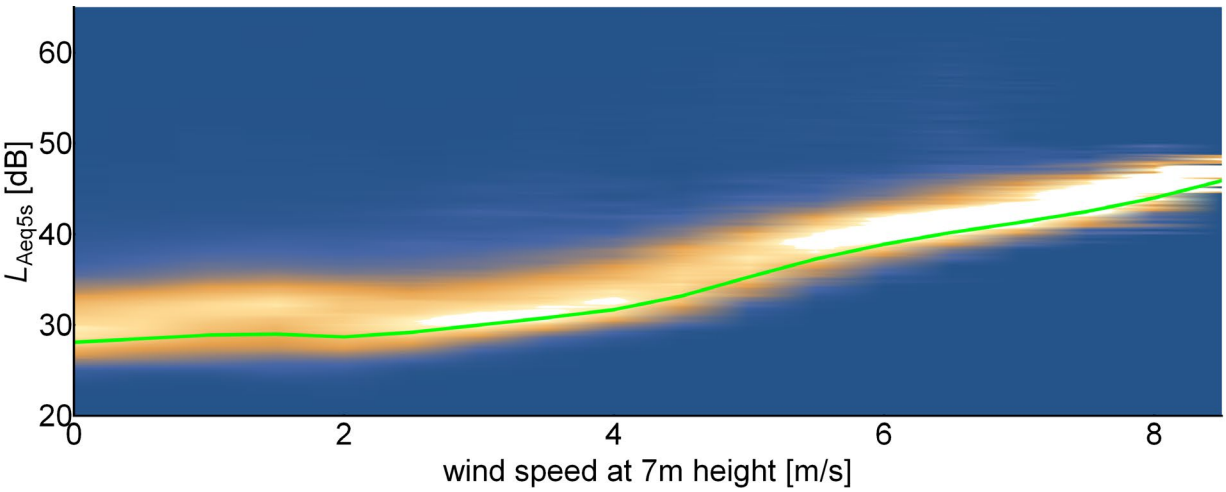

Figure 15 Sound pressure levels vs windspeed at 7m height for 7m/s windspeed at hub height. The green line shows the L80.

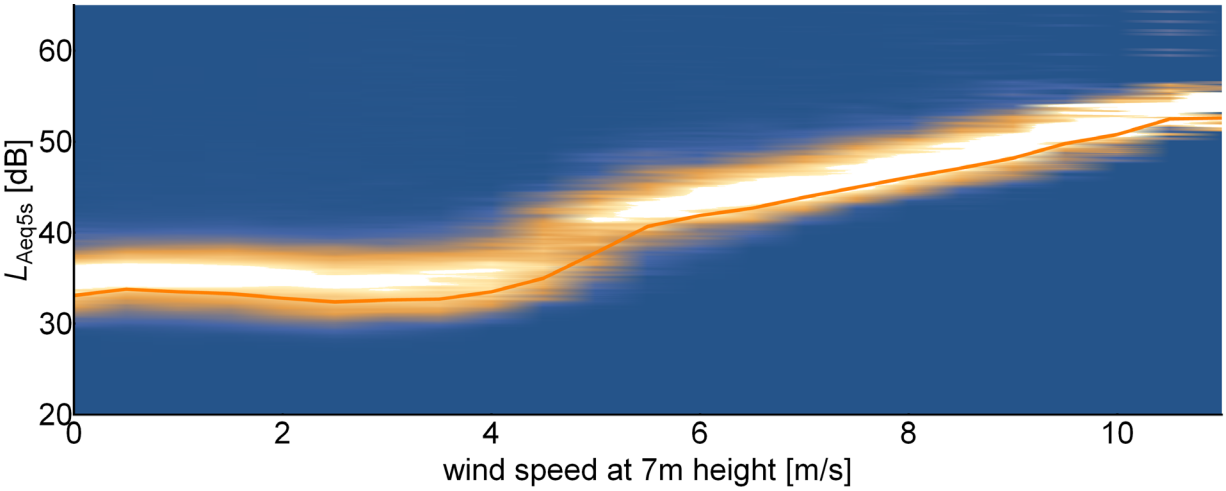

Figure 16 Sound pressure levels vs windspeed at 7m height for 10m/s windspeed at hub height. The orange line shows the L80.

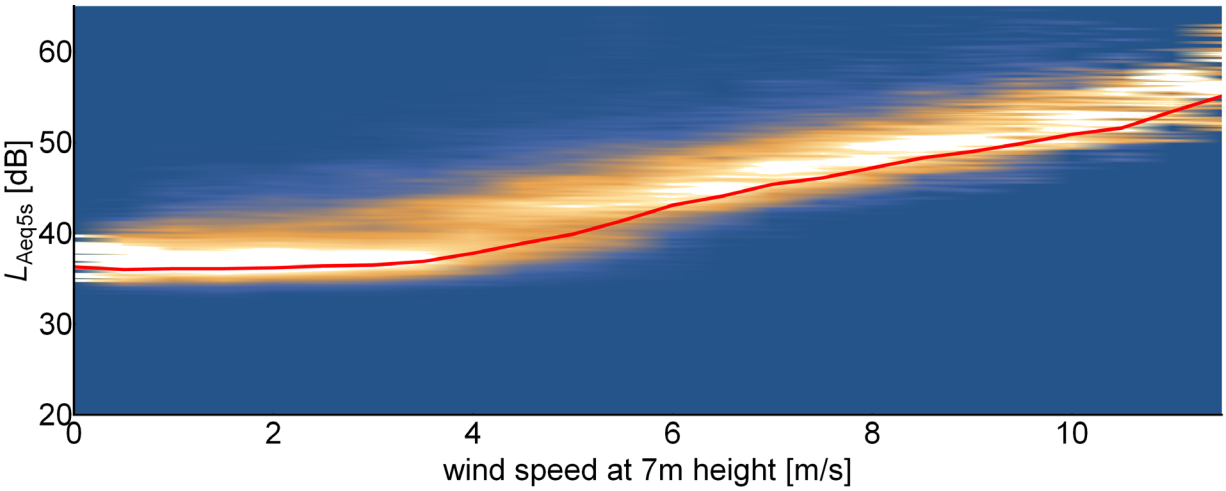

Figure 17 Sound pressure levels vs windspeed at 7m height for 13m/s windspeed at hub height. The red line shows the L80.

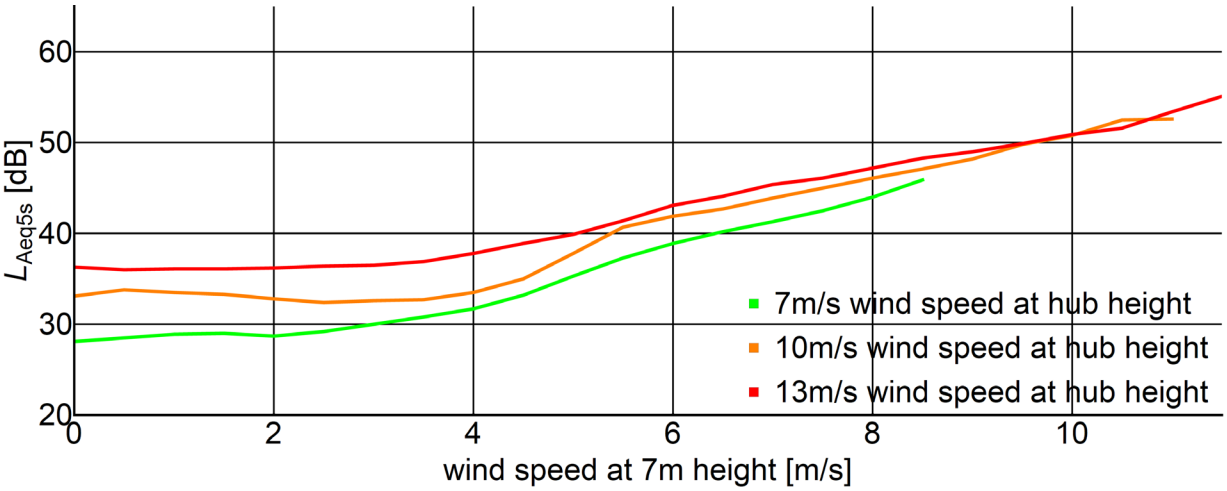

Figure 18 The L80 for 7m/s, 10m/s and 13 m/s wind speeds at hub height, plotted vs the wind speed at 7m height.

The data indicates that the sound pressure levels due to the wind turbines are dependent on the wind speeds at low levels. Data with high wind speeds close to the ground needs to be included in the evaluation of the long term equivalent sound pressure levels due to wind turbines, otherwise the levels would be underestimated.

On the other hand, there most likely is wind induced noise included in the measured sound pressure levels. And this wind induced noise needs to be subtracted to get to sound pressure levels due to the wind turbines. Doing this properly by just looking at A-weighted levels may not be possible, it may not be precise enough – in any case, it is beyond the scope of this paper.

7. More time dependent changes

7.1 Classification

As an example, assume that the conditions where wind turbine 1 is at 2100kW are to be studied. Figure 19 shows the distribution of hub-height wind speeds for 2100kW. The 15 and 85 percentile of this distribution are 11.0 m/s and 12.4m/s. Use these values as limits for the conditioned wind speed at hub height to find time periods that might be in the same class. Within the two month measurement time, 119 such time periods can be found, the longest being 41 minutes long. Figure 20 shows the distribution of length of the time periods, the average is just over 8 minutes.

A basic idea for time dependent classifications might be to take such time periods, take average sound pressure levels for each, and classify them by source and propagation conditions. The following is an illustration why this probably is too limited.

Figure 21 shows sound pressure levels vs time for a time period chosen because the wind speeds close to the microphone were low. On this time scale, even the $L_{Aeq,5s}$show a lot a variation. A smoothed trend line was derived by low-pass filtering the $L_{Aeq,5s}$. A small advantage of the smoothed levels is that they cut off some short noise events that do not belong to the wind turbines. The main purpose is to visualize how the levels change on the scale of several minutes.
Figure 22 shows the distribution of sound pressure levels in the example period. For the whole time, the hub-height wind speed was in a narrow window. The wind direction did not change. And still the level distribution is not narrow.

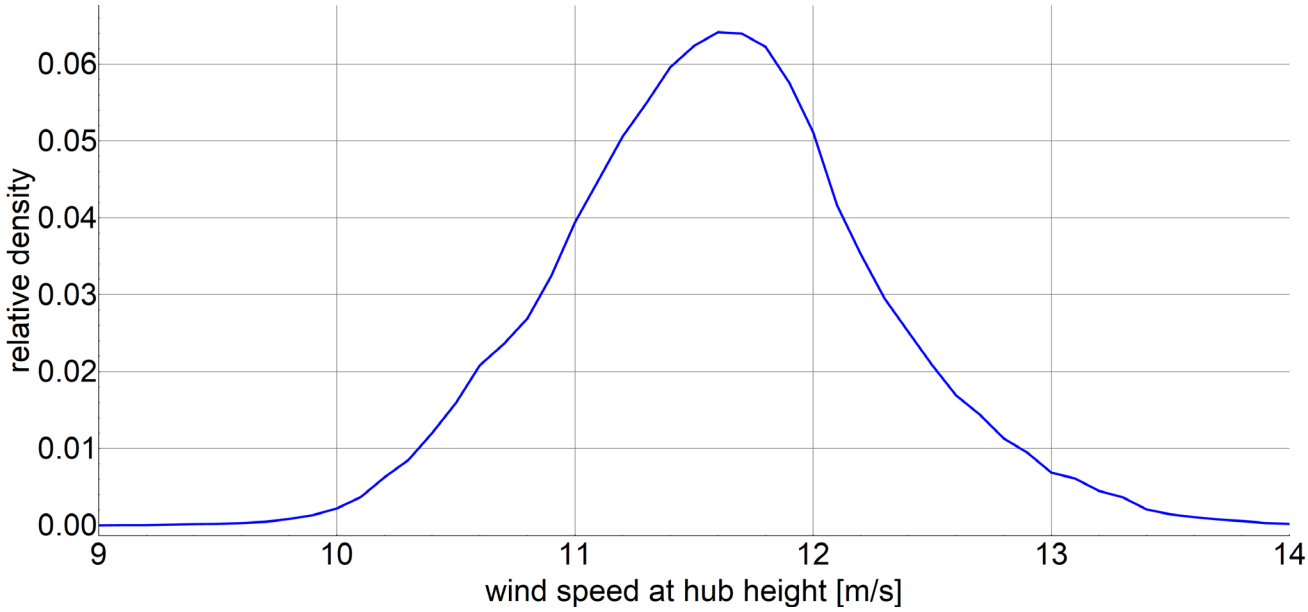

Figure 19 Distribution for wind speeds at hub height for 2100kW power from wind turbine 1

Shorter time intervals will result in narrow level distributions in each interval, if the intervals are chosen properly. At this time, it is not obvious how to choose the best intervals. Since wind speed profiles are very relevant for the sound source as well as the propagation, changing points may be visible in the recorded wind speeds.
Figure 23 shows the wind speeds recorded at different heights during the example period. These are unconditioned signals, and the presentation is not very useful.
Figure 24 shows the same wind data, but conditioned with a low pass filter. “MP1 7m” is at 7m height close to the microphone position, “MP2 4m” is at 4m height in the same position. Both wind speeds are well below 4m/s, so no or very little wind induced noise is expected.
In the level plot (Figure 21), vertical lines are used to mark the maxima in the smoothed levels. The same vertical lines are used in the wind data plots. A correlation between wind speeds and sound pressure levels is not obvious.

Figure 25 shows the variance of the wind speeds around the smoothed values. With wind measurements in non-ideal conditions, the variance of wind speeds might be a more robust indicator for the stability of the atmosphere and the wind speed profiles than the actual wind speed measurements. In the presented example, the correlation of wind speed variance with sound pressure levels is not apparent. More work on this is required.

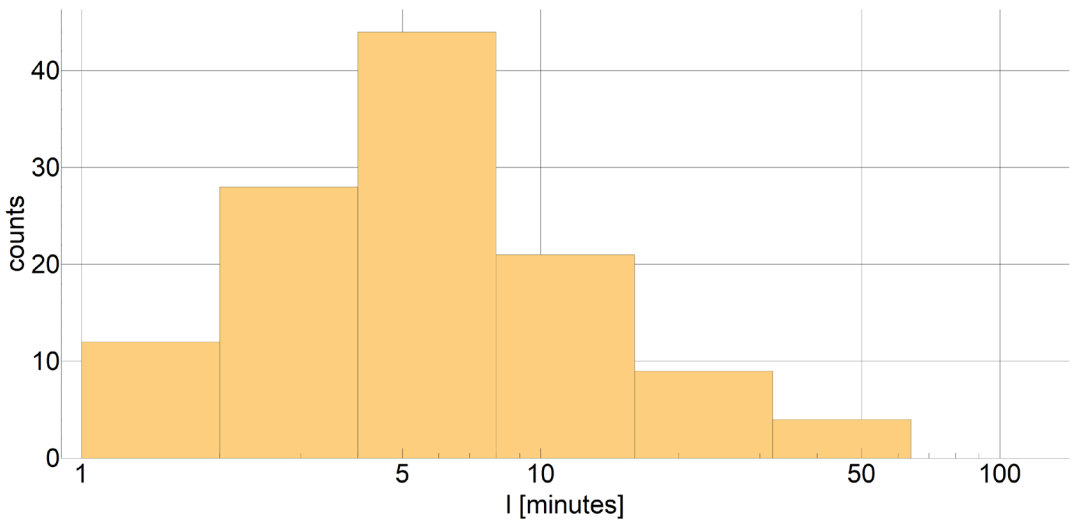

Figure 20 Distribution of lengths for the periods with hub height wind speeds within the limits.

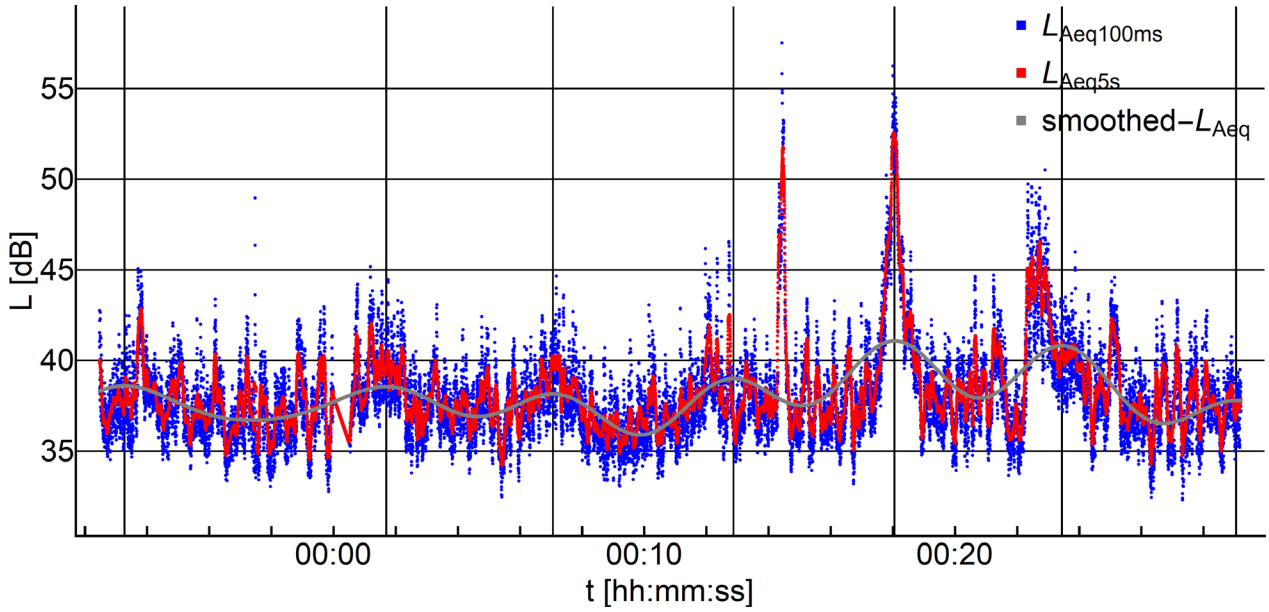

Figure 21 Sound pressure levels for an example period where the wind speed at hub height is within the limits

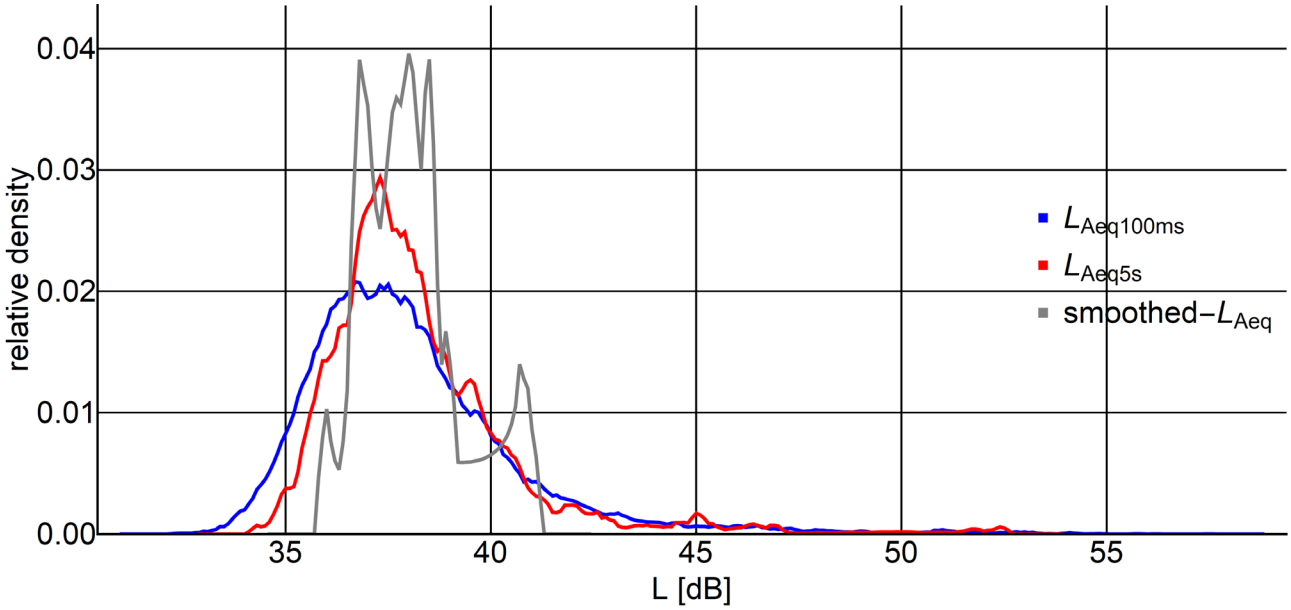

Figure 22 Distribution of the sound pressure levels for the example time period

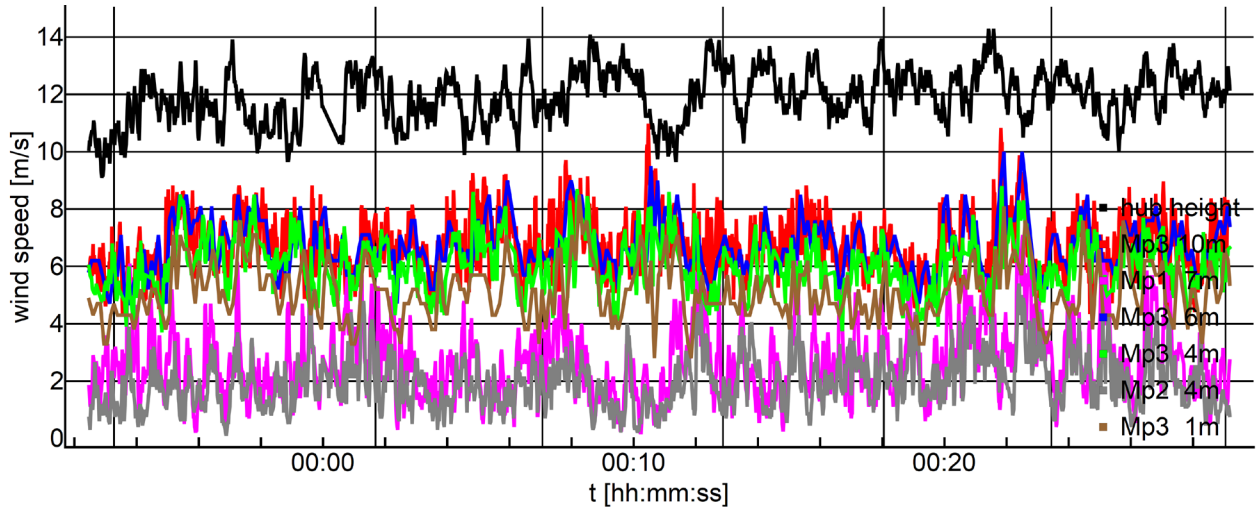

Figure 23 Wind speeds at different heights during the example time period

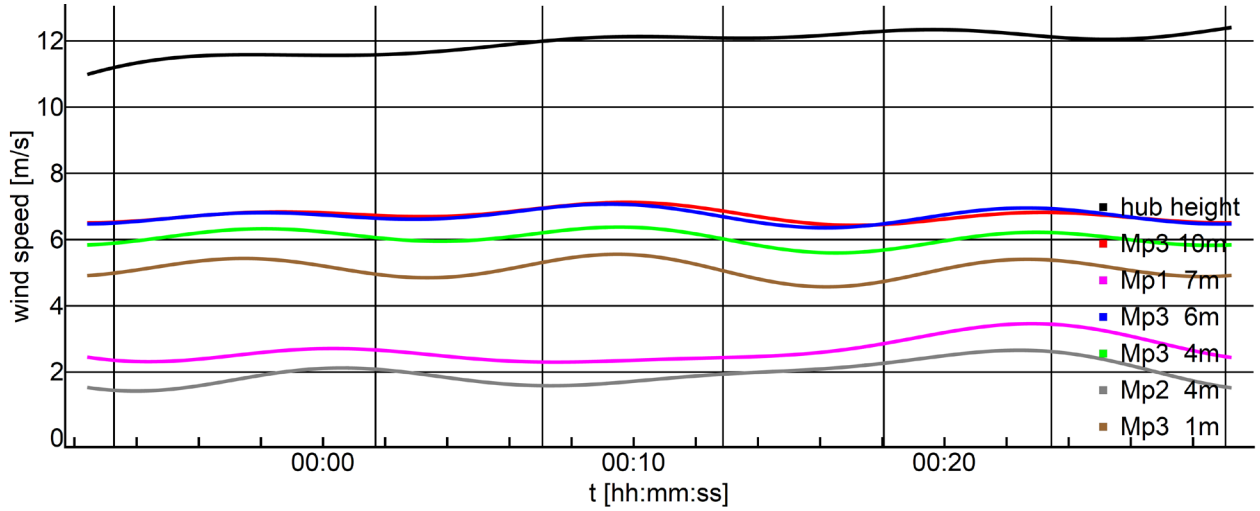

Figure 24 Conditioned wind speeds at different heights during the example time period

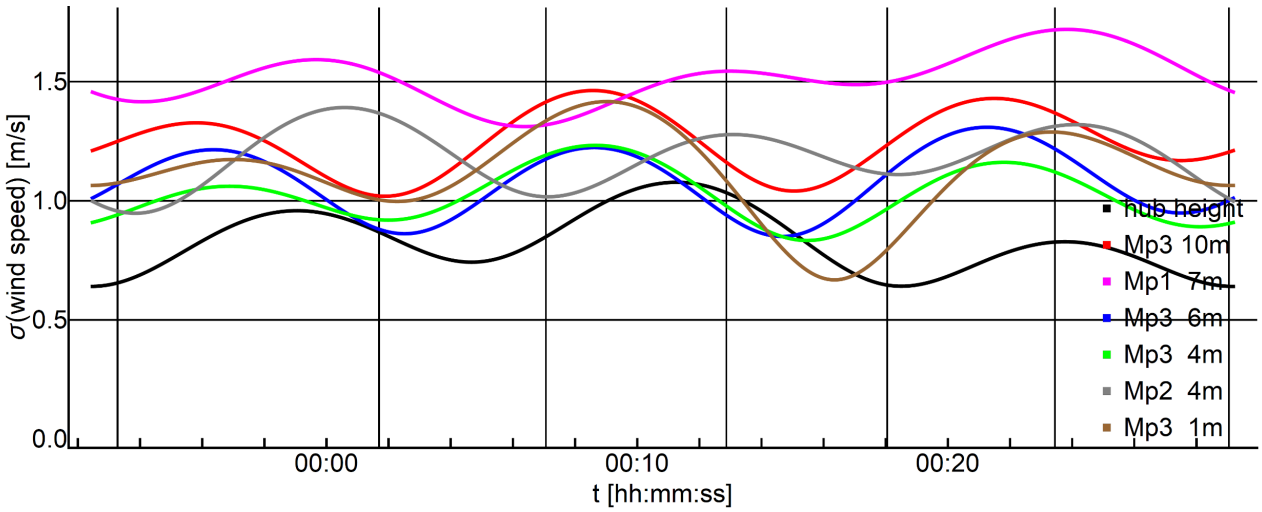

Figure 25 Wind speed variances at different heights during the example time period

8. Conclusions

It is desirable to find classes for source and propagation conditions that result in narrow distributions of the sound pressure levels within the classes. For the determination of equivalent continuous sound pressure levels, ISO 1996-2 actually makes such classes a requirement.

Purely statistical classification of the data may be too limited to find such classes. In the example discussed, the background noise is low enough to clearly see the effects of the wind turbines on the sound pressure levels, but at 1000m distance the distributions in the simple classifications shown are very wide.

Conditioning signals in the time-domain can help in improving the resolution within classes. Examples shown include the wind speed as well as sound pressure levels.

Beyond the statistical classification, a time-dependent detection of changing atmospheric conditions may help in sorting data. At this time, it is not clear why even smoothed sound pressure levels can change by several dB within minutes, and if the reason can be determined by studying the atmospheric conditions.

ACKNOWLEDGEMENTS

With thanks to the German Environment Agency (Umweltbundesamt – UBA) for authorizing the use of data from the project “Geräuschwirkungen bei der Nutzung von Windenergie an Land”.

References

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