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Atmospheric absorption in sound power measurements of wind turbines

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Summary

Attenuation of sound due to atmospheric absorption varies for different meteorological conditions and will cause variability in the measured apparent sound power level for a wind turbine according the IEC 61400-11 standard. But the attenuation is not considered in the measurement method described in latest version of the standard.

This document describes:

- theoretical effect of variations in atmospheric absorption on a measured sound power level 1/3 octave spectrum from a modern wind turbine
- a method to take the atmospheric absorption into account in the sound power measurement method described in IEC 61400-11
- the described method applied on real turbine measurements

The study shows convincing results giving lower variability of measured apparent Sound Power Level after applying the proposed correction for atmospheric absorption.

1. Introduction

Attenuation of sound due to atmospheric absorption varies for different meteorological conditions and is well described and standardized. But attenuation caused by atmospheric absorption is not considered in the wind turbine noise measurement method described in the IEC 61400-11 standard. Within typical northern European weather conditions, mainly cold and dry weather can result in significantly higher attenuation at frequencies in kHz ranges. The influence on the IEC sound power results can be significant on large modern turbines due to increased measurement distances. At Siemens Gamesa Renewable Energy we also observe that the main energy in the noise frequency spectrum has changed in the last decades from approximately 200-500 Hz to 2-3 kHz. Therefore, atmospheric absorption becomes more and more important when calculating the apparent Sound Power Level.

The present study proposes a correction method for atmospheric absorption and shows convincingly that this method gives a lower variability of the measured apparent Sound Power Level.

2. Air absorption effects on measured IEC noise levels

Attenuation of sound due to atmospheric absorption varies for different meteorological conditions and is sensitive to the composition of the air. Air absorption in general will not be discussed in this document, but the following investigations are based on the well described and standardized formulas given in ISO 9613-1:1993 [3].

2.1 Variations of atmospheric absorption

The molar concentration of water vapor in the air varies a lot over time close to ground level. The variation is related to seasonal changes at a specific geographical point and can even vary rapidly within a few hours. Day and night shifts or just rapid changes in weather will affect the molar concentration of water vapor in the air. Based on ISO 9613-1 these changes have a major influence on the atmospheric absorption.

The air absorption can be calculated from equation 3-5 in ISO 9613-1:1993 [3]. Below is equation 5 in the ISO standard given as equation 1 in this document:

α is the pure tone attenuation coefficient, given in dB/m for atmospheric absorption, and is calculated using equation 1 below:

Eq. 1
$$\alpha = 8.686 f^2 \left(\begin{array}{l} \left(1.84 \times 10^{-11} \left(\frac{P_a}{P_r} \right)^{-1} \left(\frac{T}{T_0} \right)^{1/2} \right) \\ + \left(\frac{T}{T_0} \right)^{-5/8} \times \left(\begin{array}{l} 0.01275 \left(\exp\left(\frac{-2239.1}{T} \right) \right) \left(f_{rO} + \left(\frac{f^2}{f_{rO}} \right) \right)^{-1} \\ + 0.1068 \left(\exp\left(\frac{-3352.0}{T} \right) \right) \left(f_{rN} + \left(\frac{f^2}{f_{rN}} \right) \right)^{-1} \end{array} \right) \end{array} \right)$$

Where:

p_a ambient atmospheric pressure [kPa]
p_r reference ambient atmospheric pressure [kPa]
T ambient atmospheric temperature [K]
T_0 reference air temperature [K]
f frequency on sound [Hz]
f_{r0} oxygen relaxation frequency [Hz], can be calculated using equation 2 below
f_{rN} nitrogen relaxation frequency [Hz], can be calculated using equation 3 below

Eq. 2
$$f_{r0} = \frac{p_a}{p_r} \left(24 + 4.404 \times 10^4 h \frac{0.02 + h}{0.391 + h} \right)$$

Eq. 3
$$f_{rN} = \frac{p_a}{p_r} \left(\frac{T}{T_0} \right)^{-1/2} \times \left(9 + 280 h \times \exp\left(-4.170 \left(\frac{T}{T_0} \right)^{-1/3} - 1 \right) \right)$$

Where:

h molar concentration of water vapor, as a percentage (calculated from relative humidity)

Equations 1-3 correspond to the equations 3, 4 and 5 in ISO 9613-1:1993 standard [3]. In the standard it is mentioned that *"these equations are all that is needed to calculate the pure-tone attenuation coefficient for atmospheric absorption for selected values of the variables … Humidity data … are rarely supplied in terms of molar concentration of water vapour. Annex B* ..[in the standard].. *provides information on conversation of humidity, dewpoint and other measures, to corresponding values of molar concentration."*

Temperature, relative humidity (RH) and atmospheric pressure (and frequency and distance) are the variables that change the air absorption levels. Since variation of atmospheric pressure for a given geographical position is relatively small and the atmospheric pressure has minor influence on the air absorption, variations in atmospheric pressure are generally negligible. Therefore, all calculations in this study are based on a fixed atmospheric pressure of 1 ATM.

2.2 Method for normalization of atmospheric absorption

To reduce the variability caused by variation in temperature and relative humidity, it has been considered to correct for the absorption and thereby calculate the "real" apparent sound power level based on pure results from the IEC61400-11 ed. 3.0:2012 [1]. Since the atmospheric absorption is very high at high frequencies, this will result in a dramatic change of the overall sound power level, mainly caused by high frequencies in the spectrum. Since the measured sound power spectrum in the high frequency range often has a large uncertainty due to poor S/N-ratio, the air absorption *correction* will cause an even larger variation in the results due to background noise.

For this reason, a method was developed which *normalizes* the measured sound power level for the effect of atmospheric absorption, i.e. calculating the spectrum that would have been measured under reference conditions.

The *corrected* sound power level, $L_{W,C}$, can be calculated by correcting the measured sound power level spectrum, $L_{W,m}$, for each 1/3 ovate band, i, using equation 4 below:

Eq 4

$$L_{W,m,i} = L_{W,C,i} - R_1 \alpha_{act,i}$$

$$\Updownarrow$$

$$L_{W,C,i} = L_{W,m,i} + R_1 \alpha_{act,i}$$

Where:

$L_{W,m,i}$ is the measured sound power in the 1/3 octave band with center frequency i

R_1 is the slant distance between rotor center and microphone according to IEC 61400-11

$a_{act,i}$ is the atmospheric absorption coefficient at frequency i, at actual atmospheric conditions

The *normalized* sound power in the 1/3 octave band with center frequency i, called $L_{W,N,i}$, at reference conditions is given by equation 5:

Eq 5

$$L_{W,N,i} = L_{W,C,i} + R_1 \alpha_{ref,i}$$

Where:

$L_{W,C,i}$ is the corrected sound power in the 1/3 octave band with center frequency i

Inserting the corrected sound power, $L_{W,C,i}$,from equation 4 in equation 5, the normalized sound power level, $L_{W,N,i}$, is then given by equation 6:

Eq 6 $$L_{W,N,i} = L_{W,m,i} + R_1\left(\alpha_{act,i} - \alpha_{ref,i}\right)$$

Where:

$L_{W,N,i}$ is the measured sound power in the 1/3 octave band with center frequency i

R_1 is the slant distance between rotor center and microphone according to IEC 61400-11

$a_{act,i}$ is the atmospheric absorption coefficient at frequency i, at actual atmospheric conditions

$a_{ref,i}$ is the atmospheric absorption coefficient at frequency i, at reference conditions

It has been decided to use the following reference conditions for this study:

- Atmospheric pressure: 1013.25 hPa corresponding to 1 ATM
- Temperature: 15°C
- Humidity: 80% RH

These reference conditions are chosen because atmospheric pressure and temperature are equal to the reference conditions for the power curve used in the IEC 61400-11 ed. 3.0. A relative humidity of 80%, which correspond to the relative humidity used in the Danish legislation, BEK 135 [4], as standardized value for the propagation calculation. It seems to be a reasonable mean humidity for windy areas in northern Europe.

2.3 Calculated effect of atmospheric absorption for realistic turbine spectra

The possible effect of air absorption on the apparent sound level was calculated for a modern Siemens Gamesa turbine with a 130-m rotor diameter and equipped with the latest serrations and vortex generators. Table 1 shows the normalized overall sound levels for different atmospheric conditions, representative for a north European site.

The reference condition is indicated in red and errors within ±0.5 dB are shown as green text. It is interesting that the sound power level is never overestimated by more than 0.5 dB. However, depending on the conditions the apparent sound level may be underestimated by as much as 2 dB or more.

	Temp [Deg C]								
RH	-15	-10	-5	0	5	10	15	20	25
30	0.90	-0.64	-2.35	-3.04	-2.74	-2.18	-1.64	-1.20	-0.89
35	0.50	-1.19	-2.63	-2.86	-2.39	-1.82	-1.31	-0.92	-0.68
40	0.10	-1.64	-2.72	-2.62	-2.08	-1.52	-1.04	-0.71	-0.52
45	-0.28	-1.96	-2.68	-2.38	-1.81	-1.26	-0.83	-0.53	-0.39
50	-0.63	-2.18	-2.57	-2.15	-1.57	-1.04	-0.65	-0.39	-0.30
55	-0.95	-2.30	-2.43	-1.93	-1.35	-0.86	-0.49	-0.28	-0.22
60	-1.22	-2.34	-2.28	-1.73	-1.16	-0.70	-0.36	-0.18	-0.17
65	-1.44	-2.34	-2.12	-1.55	-1.00	-0.55	-0.25	-0.11	-0.12
70	-1.62	-2.30	-1.97	-1.39	-0.85	-0.43	-0.16	-0.04	-0.09
75	-1.76	-2.23	-1.82	-1.23	-0.71	-0.32	-0.07	0.01	-0.06
80	-1.86	-2.15	-1.68	-1.10	-0.59	-0.22	0.00	0.06	-0.04
85	-1.92	-2.05	-1.55	-0.97	-0.48	-0.13	0.06	0.10	-0.03
90	-1.96	-1.96	-1.42	-0.85	-0.38	-0.05	0.12	0.13	-0.02
95	-1.97	-1.86	-1.30	-0.74	-0.29	0.02	0.17	0.16	-0.01
100	-1.97	-1.76	-1.19	-0.64	-0.21	0.08	0.21	0.18	-0.01

Table 1: Variation in the apparent sound power level under different atmospheric conditions for a modern Siemens Gamesa turbine, assuming the given source spectrum.

In order to show an example on a measured spectrum, the result of a measurement from a cold but wet winter day is shown in figure 1. The measured spectrum is shown as a bold black line.

The thin dashed magenta line shows a spectrum where only the correction has been applied and not the normalization (using only the correction calculated in equation 4). It is noticeable that there is a high correction at maximum level due to the relatively high peak frequency in the spectrum. The background noise level was low at high frequencies during the measurement, but it still results in unrealistic high levels from approximately 5 kHz and up. Due to too low S/N-ratio at the highest frequencies the overall level will probably be predicted wrong and is therefore not shown for the reference spectrum. The background noise levels dominate the levels at the highest frequencies.

Dotted bold curves are spectra normalized to different atmospheric conditions. These curves illustrate that differences up to more than 1 dB can occur in the apparent sound level, depending on the atmospheric conditions. These differences are currently not accounted for in the IEC standard.

Keeping in mind that the purpose of measuring sound power level is to predict sound pressure levels further away from the turbine, the real sound power level is irrelevant for longer distances and thereby for neighbor noise levels, because the air absorption affected frequencies will anyway be damped a lot in the propagation calculations towards the neighbor.

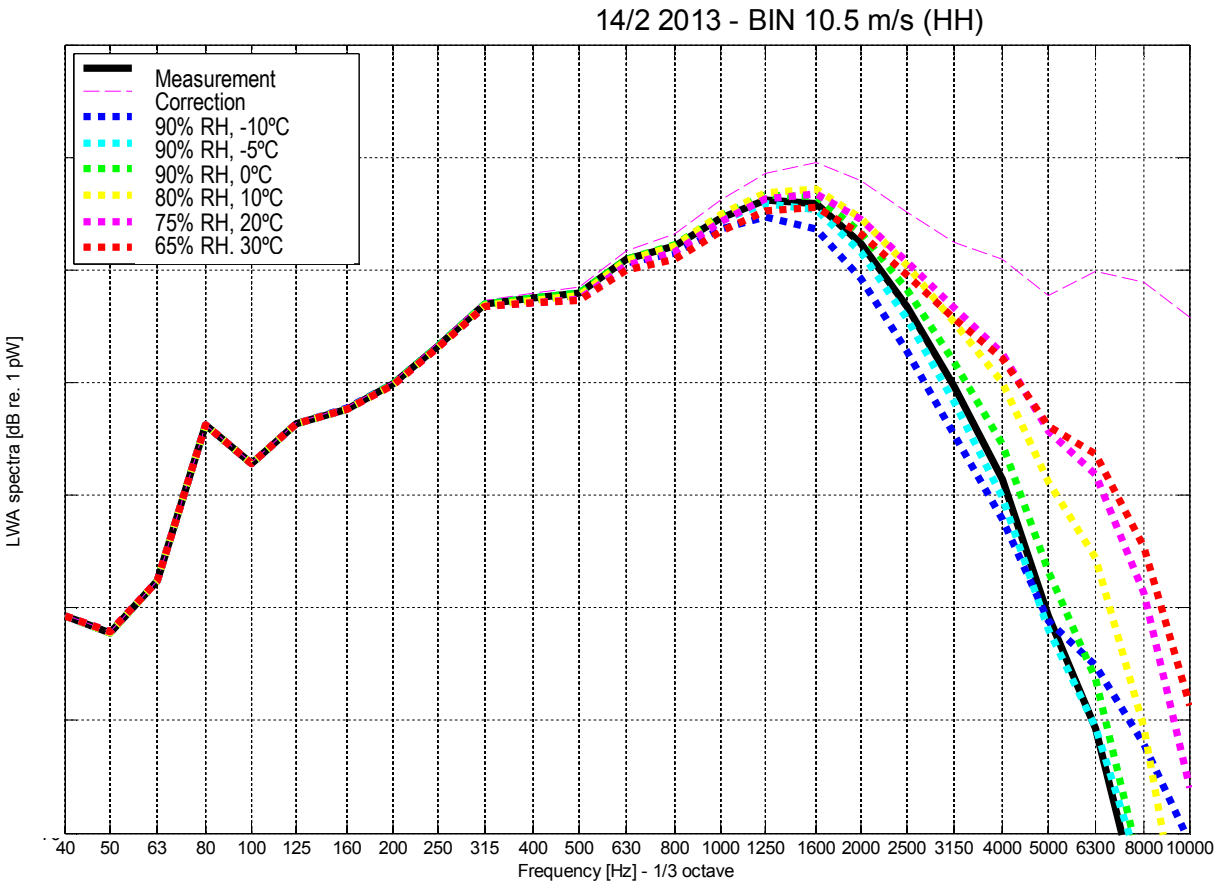

Figure 1: Atmospheric absorption correction and normalization applied to a measured spectrum of a SiemensGamesa 108 m rotor. There is 5 dB between horizontal lines in the plot.

To illustrate this effect on smaller and older turbine types, appendix 1 shows similar results for this and two other measured turbine spectra. The data shows that the influence of atmospheric

absorption is more prominent for large modern turbines due to IEC measurement distance and shape of the sound power spectrum.

2.4 Experimental evidence for atmospheric absorption

Until now we have calculated the potential effects of air absorption by *assuming* the absorption values from the ISO standard. In this section we will show that these effects are real and can be observed in actual field measurements. Figure 2 below shows that normalization of air absorption results in a substantially better reproducibility of the measurement results. The data are results of measured sound power level according to IEC 61400-11 3d 3.0:2012 [1]. The turbine rotor has a diameter of 130-m, and is equipped with the latest serrations and vortex generators.

The red curve was measured on October 8th, 2015 on a day with atmospheric conditions very close to reference conditions (10°C, 90% RH). The red curve spectrum was measured a few months later a winter day, January 22nd, 2016 (-2.7°C,71% RH). The left plot shows measured data according to IEC 61400-11 ed. 3.0 and the right plot shows the same spectra but normalized to reference conditions (15°C, 80% RH).

The normalization shows that the apparent sound power level of the January measurement was underestimated by approximately. 1.2 dB on BIN averages due to atmospheric absorption, compared to reference conditions. 10 sec data points were underestimated by up to 1.8 dB.

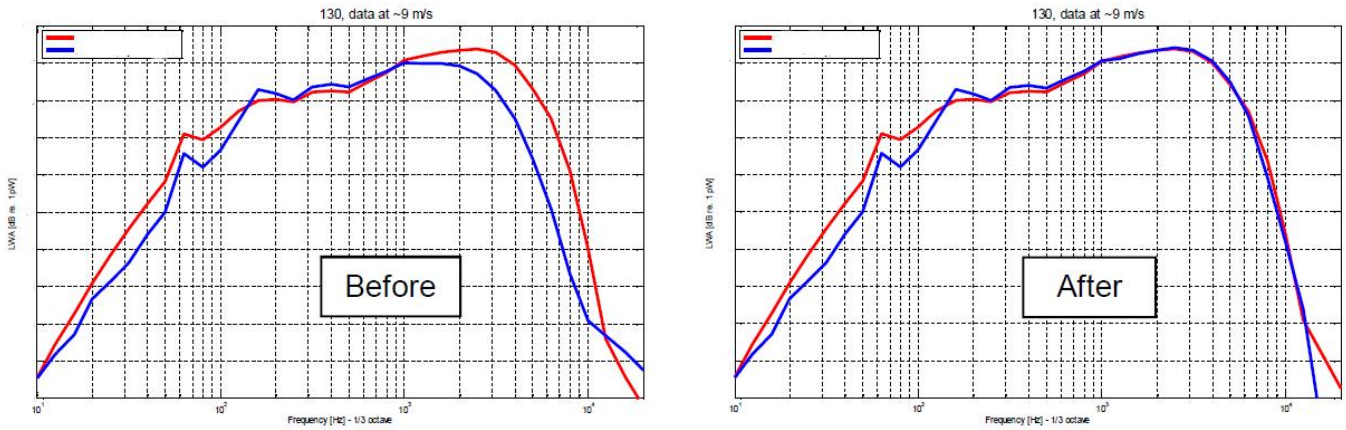

Figure 2: Atmospheric correction and normalization applied to a measured spectrum from two measurements of a SiemensGamesa 130 m rotor. There is 5 dB between horizontal lines in the plot. Left plot shows measured data according to IEC 61400-11, right plot shows results normalized to reference conditions.

Based on the results shown above, variations in atmospheric conditions, namely humidity and temperature, result in a large variation in apparent sound power level measured according to the IEC standard for a modern turbine. The variation is mainly seen in the high frequency range, but since the spectra for a modern turbine have more energy at high frequencies, the atmospheric absorption may cause a significant error in the measured apparent sound power level.

Figure 3 below show the sound power level obtained at three measurements on the same turbine at three different periods. The dashed curves are measured in October with higher air temperature. The blue is measured in January and the red curve is the same but normalized for atmospheric absorption. The normalization allows a higher repeatability. The difference in sound power level up to 9 m/s is due to other factors.

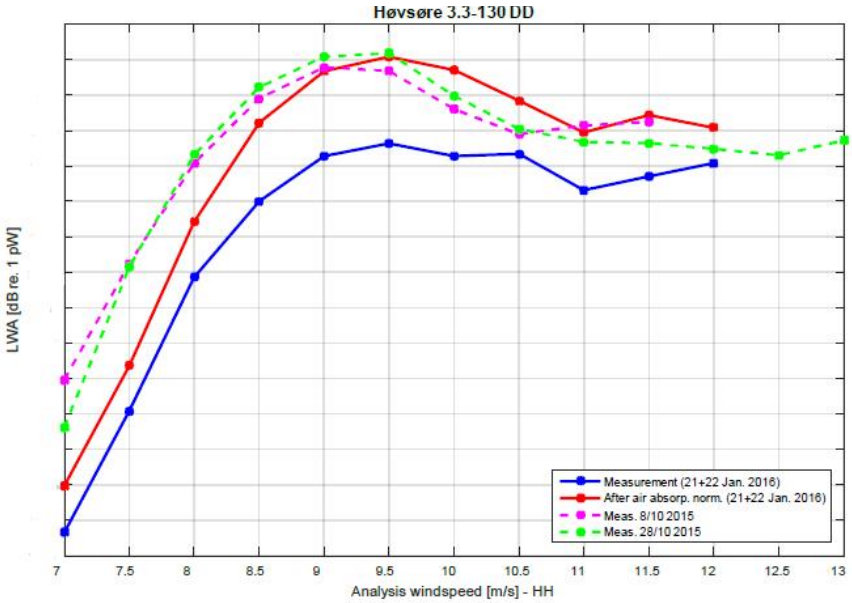

Figure 3: Atmospheric correction and normalization applied to a measured spectrum from three measurements of a SiemensGamesa 130 m rotor. The red curve shows the normalization of the measurement result shown as the blue curve.

There is 0.5 dB between horizontal lines in the plot.

2.5 Variation within one measurement campaign

But what happens if the measurement is carried out over a long period having significant variations in the weather conditions? E.g. a measurement carried out over 24 hours with change in weather conditions due to a front passage or a day/night shift causing temperature drop and change in the relative humidity.

If the 10 sec averaged measurement points are measured for different atmospheric conditions, this will result in large scatter of the points and air absorption normalization cannot be applied to the final bin-averaged noise curve.

According to the IEC 61400-11 ed. 3.0 standard, the spectra are calculated based on a bin analysis of all results. In the amendment from 2018 [2] some directions are given for cases where it is necessary to combine measurement series measured under different conditions. But it can be difficult to divide the measurement into series with equal conditions if the temperature or relative humidity changes slowly during the measurement.

The next chapter describes how this difficulty can be solved by correcting individual 10-s averages for absorption effects.

3. Sound power domain method

As mentioned at the end of the previous section, this chapter describes how 10-s averaged measurement points within one test period can be corrected for atmospheric absorption effects. The methodology in IEC 61400-11 ed. 3.0 is that the measured 10 sec values of background noise are binned in the wind speed domain. The 10 sec averages of total noise collected during turbine operation are binned separately from the background noise results. Background noise correction is carried out by correction bin center values of the total noise using bin center values of background noise.

Since background noise obviously is not affected by air absorption, normalization of uncorrected total noise values will result in significant errors due to the typical poor signal to noise ratio high frequencies.

3.1 Engineering method description

To reduce variability in internal measurements, it has been necessary to develop an engineering method based on the method given in IEC 61400-11 ed. 3.0. The idea is therefore to be able to normalize background corrected 10 sec data points separately.

The methodology deviates from the IEC methodology in the following points:

- Background noise is binned as described in the IEC standard.
- Total noise spectrum is background corrected in 10 sec values in the wind speed domain without binning, using calculated background noise spectrum from the bin analysis corresponding to the exact same wind speed.
- It is crucial that the binned background noise result is representative for the measurement period. This can be simply achieved by using different sets of background noise data, e.g. if microphone position was changed or other conditions changed during the measurement period.
- After background correction of the 10 sec total noise data, it is now possible to calculate sound power levels in terms of 10 sec data points. This opens also the opportunity to normalize for air absorption based on measured atmospheric conditions. Furthermore, any other correction can be added here.
- When data are highly affected by background noise, the air absorption normalization will result in obvious wrong results. To avoid this, we have introduced a requirement of minimum 5 dB S/N-ratio at each frequency to normalize for air absorption. This means that some 1/3 octave bands may not be normalized, but this occurs typically at very low or very high frequencies. For practical reasons we have furthermore decided not to normalize 1/3 octave bands above 8 kHz.
- Finally, the bin analysis is straightforward using the same principle as in the IEC standard, but now for the 10 sec sound power data points.

Because the sound power level data are now given in 10 sec data points, the method opens opportunities to study variability – even between different measurement series, time of the year, weather conditions, distance to turbine etc. An example is given in Section 3.2.

3.2 Example of results based on sound power domain method

A measurement was carried out in a period of approximately 8 hours on January 21st and 22nd. The measurement was done at daytime and night time with a significant shift in meteorological conditions. The temperature dropped from 0ºC to -5ºC during the measurement and the relative humidity changed between almost 100% and 65% RH.

The turbine with 130 m rotor was situated at DTU's prototype site in Høvsøre. Since the measurement was done at this site, there is access to a lot of meteorological data. The data from the meteorological mast was correlated in time with the acoustic data and data from the turbine. Figure 4 below shows temperature, relative humidity, atmospheric pressure during the measurement period.

The last plot in figure 4 shows the corresponding variation of normalization for air absorption calculated for the measured spectrum at each individual 10 sec periods. The air absorption normalizations on the overall noise levels range from approximately +0.5 to +1.8 dB.

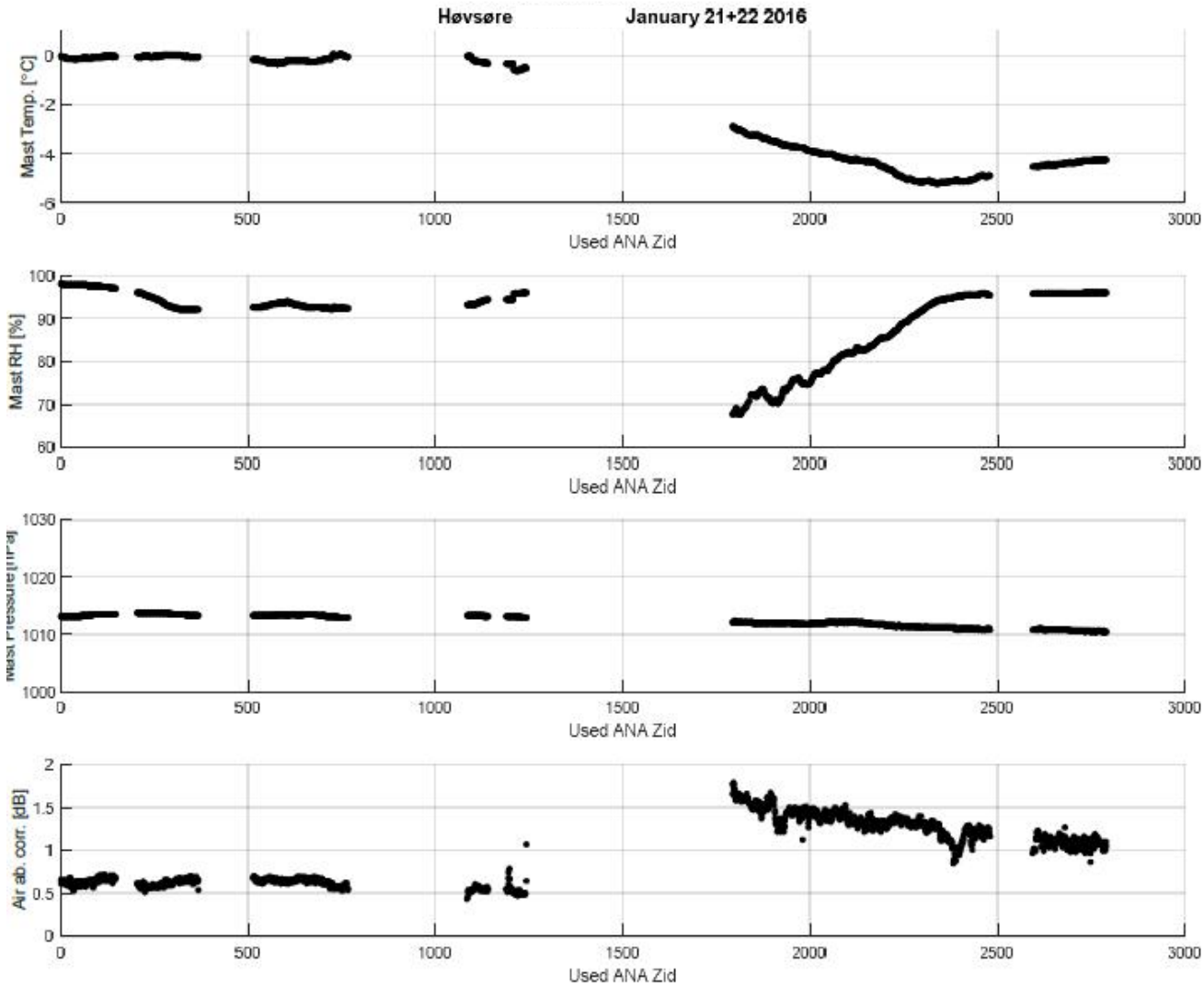

Figure 4: Meteorological data and resulting air absorption nomaization for the measured spectra duing a measurement with significant changses in the metrolodical conditions.

Figure 5 below show 10 sec data points in terms of sound power levels calculated using the methodology described above.

Blue circles are not normalized for air absorption, red dots are normalized. On the left plot measured and normalized data are shown as measured, with and without atmospheric absorption normalization. On the right plot a 1 dB offset is added to the measured data to show the difference in the scatter of the data. It is clear the scatter of the 10 sec sound power level data points has reduced after the data has been normalized for air absorption.

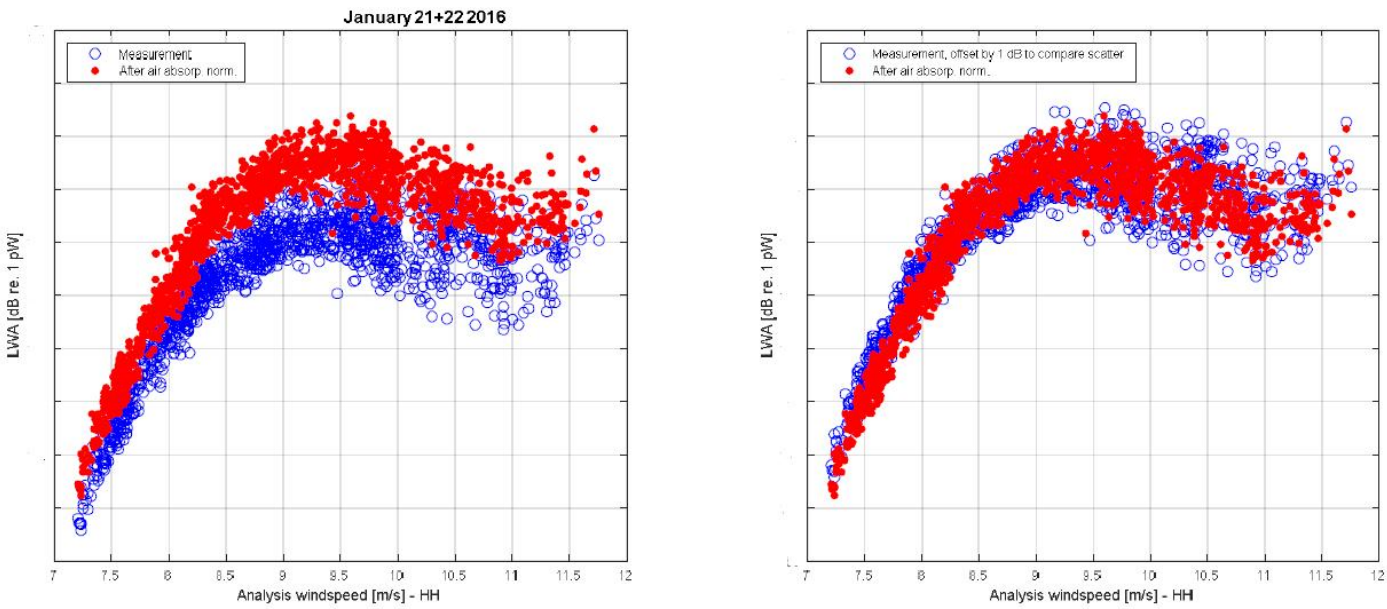

Figure 5: Measured 10 sec sound power data points. Blue circles are the measured data, red dots are data points where air absorption normalization is applied. Left is measured and normalized data points. In the right plot a 1 dB offset has been added to the measured data to show difference in scatter. The distance between horizontal lines is 1 dB.

4. Remarks about the normalization method

This section provides some remarks about the proposed correction method for atmospheric absorption effects.

Atmospheric absorption is given in dB/m. Large underestimation of the apparent sound level happens for spectra with most energy at high frequencies, where the atmospheric absorption is greatest. The suggested underestimation of sound power level from modern turbines at specific meteorological conditions is therefore negligible on predicted neighbor overall sound pressure level, because the atmospheric absorption will be even higher at large distances.

The results underline that it is important to compare noise performance of turbines based on noise propagation calculations using the correct spectra and the frequency dependent atmospheric absorption, and not only based on sound power levels.

There are several benefits of the proposed method.

- The methodology makes it possible to merge several measurement series recorded under different conditions in a consistent way.
- The method makes it possible to correct for other conditions that may vary during the measurement and can influence the results

Obviously, the methodology introduces some uncertainties:

- It is known that the major contributor to the noise from a modern wind turbine is the outer part of the blade. The slant distance used is the distance to the rotor center and not the distance to the primary noise source near the tip. This effect is not expected to be significant.
- Temperature and humidity are measured according to the IEC standard at 2 m height. The meteorological conditions may vary with height, which introduces some uncertainty in the normalization. This has been investigated based on one year of meteorological measurement on DTU's test site in Høvsøre. Atmospheric absorption is calculated at 2 kHz

based on pressure, temperature and humidity measured in 2 and 100 m height, see figure 6 below. Significant sessional variations are seen. But difference in resulting atmospheric absorption based on 2 m and 100 m data is less than 0.5, which is evaluated as an acceptable variation compared to the effort it takes to measure and correct for the error.

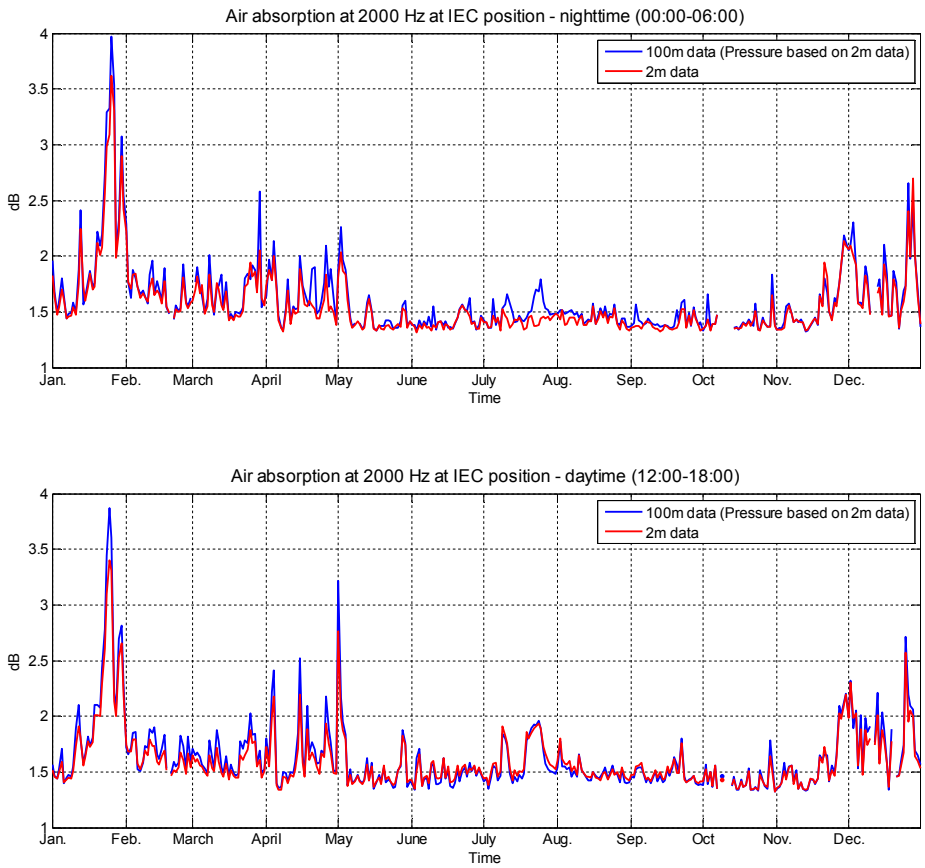

Figure 6: Atmospheric absorption is calculated at 2 kHz based on pressure, temperature and humidity measured in 2 and 100 m height at DTU's test site in Høvsøre. Upper plot is night time data, lower plot is daytime data.

Even though some uncertainties are introduced, this study suggests that the scatter of the data points is significantly reduced by introducing normalization for atmospheric absorption. Therefore, the methodology discussed in this document is proposed to be introduced in the next version of the IEC 61400-11 standard.

5. Conclusions

Studies of variability and repeatability of internal noise measurements according to IEC61400-11 performed by Siemens Gamesa suggest that one of the most important factors influencing variability is the attenuation due to atmospheric absorption. IEC results obtained in cold and dry conditions can be underestimated by up to 1.5 dB or more in overall A-weighted sound levels.

A procedure has been developed to correct measured sound levels for atmospheric absorption effects. The method can provide the sound power spectrum for each 10-sec data point. To minimize large errors introduced by the background noise level at higher frequencies, the developed analysis method is based on normalization to a chosen reference meteorological condition.

The study shows convincing results giving lower variability of measured apparent Sound Power Level after applying the proposed correction for atmospheric absorption.

6. References

[1] IEC 61400-11 ed. 3.0:2012
[2] IEC 61400-11 ed. 3.0 amendment A1:2018
[3] ISO 1996-2:1993
[4] BEK nr 135 af 07/02/2019 (https://www.retsinformation.dk/Forms/R0710.aspx?id=206666)

7. Appendix A

This Appendix presents calculations on three IEC measurements to show the possible influence of air absorption on the measured results. The three spectra have different shapes (energy distributions) to show that it matters for the influence of the air absorption on the overall levels. Results are only shown for hub height wind speeds of 10.5 m/s, which corresponds to the top of the noise curves.

The air absorption normalization is based on the method given in section 3.

Temperature, relative humidity (RH) and atmospheric pressure (and frequency and distance) are the variables that change the air absorption levels. All results shown are calculated with 1 ATM (1013.25 hPa).

The table below shows the three measurements:

Turbine	Rotor size [m]	Date	Hub height [m]	Slant dist. [m]	RH [%]	Temp. [°C]
1	93	7/11 2012	80	148	85	10
2	113	9/10 2014	90	173	88	16
3	130	14/2 2013	100	189	80	-1

Table 2: Data for measurements shown in this appendix

Turbine 1: this spectrum has most energy around 300 Hz
Turbine 2: this spectrum has most energy around 1 kHz, but is relatively flat
Turbine 3: this spectrum has most energy around 1.6 kHz

The three measurements are *corrected* to show a spectrum with “no” air absorption using equation 4, based on the corresponding temperature and relative humidity. Finally, this reference spectrum is recalculated to show the spectrum in different atmospheric conditions (temperature and relative humidity), based on equation 6, by *normalizing* to different atmospheric conditions. The results are shown in figure 6, 7 and 8.

The table below shows the calculated difference in sound power levels, that potentially would be measured in different combinations of temperature and relative humidity. The values are calculated based on equation 6, *normalizing* to different atmospheric conditions.

RH [%]	Temp. [°C]	Turbine 1 [dB]	Turbine 2 [dB]	Turbine 3 [dB]
90	-10	-0.29	-0.79	-0.82
90	-5	-0.16	-0.49	-0.37
90	0	-0.06	-0.22	0
80	10	0	0	0.30
75	20	-0.03	0.00	0.27
65	30	-0.14	-0.24	-0.08
Largest difference (-10°C to 30°C)		0.29	0.79	1.12
Largest difference (0°C to 20°C)		0.06	0.22	0.30

Table 3: Difference in calculated expected measured sound power levels at different atmospheric conditions

The data shows that the influence of atmospheric absorption is more prominent for large modern turbines due to IEC measurement distance and shape of the sound power spectrum.

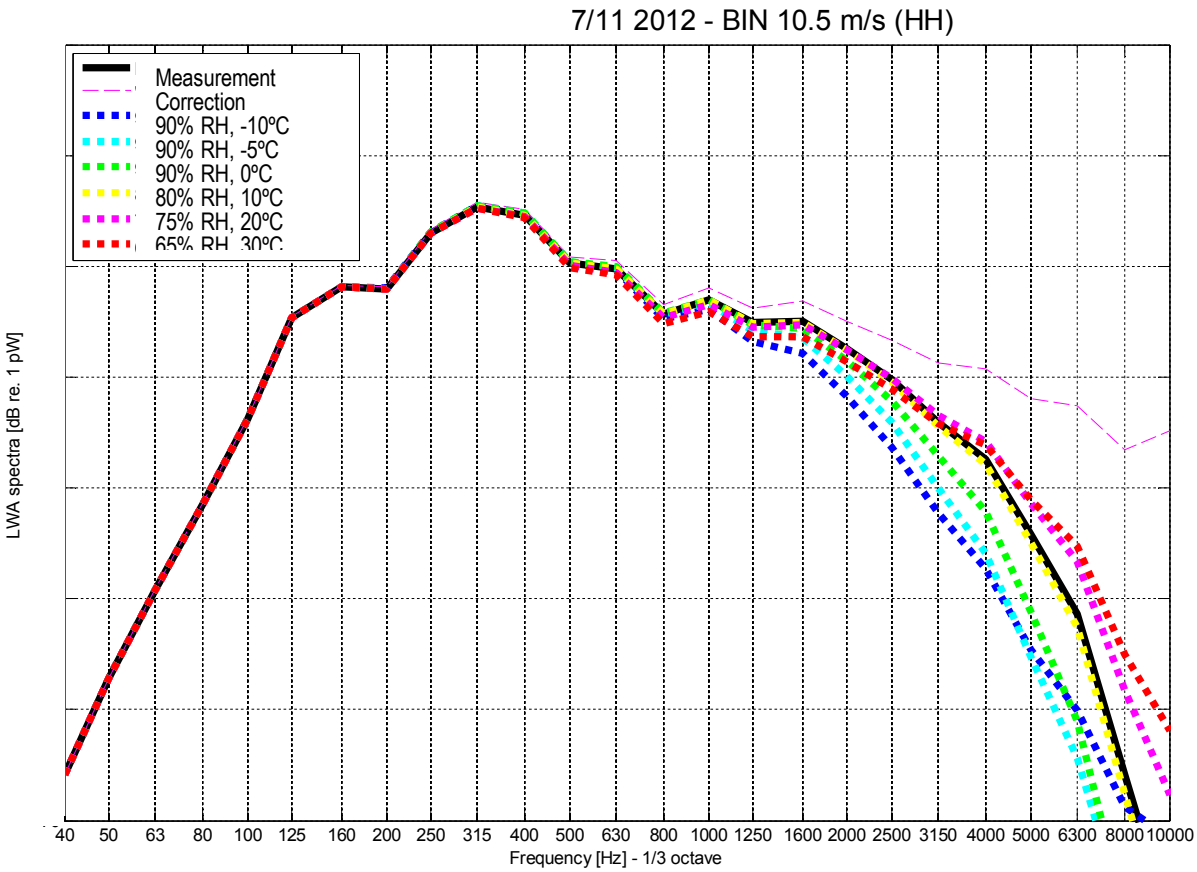

Figure 7: Atmospheric absorption correction and normalization applied to a measured spectrum of a SiemensGamesa 93 m rotor (turbine 1). There is 5 dB between horizontal lines in the plot.

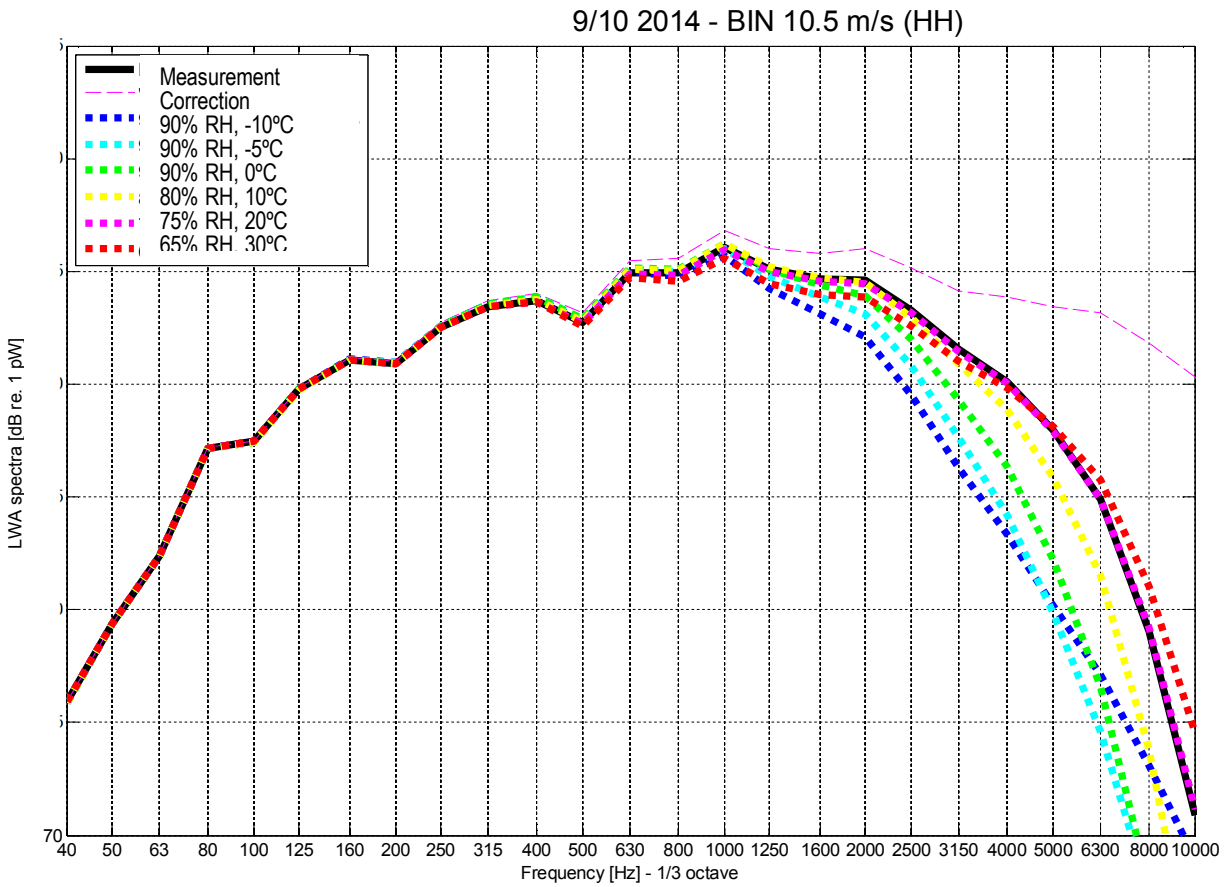

Figure 8: Atmospheric absorption correction and normalization applied to a measured spectrum of a SiemensGamesa 113 m rotor (turbine 2). There is 5 dB between horizontal lines in the plot.

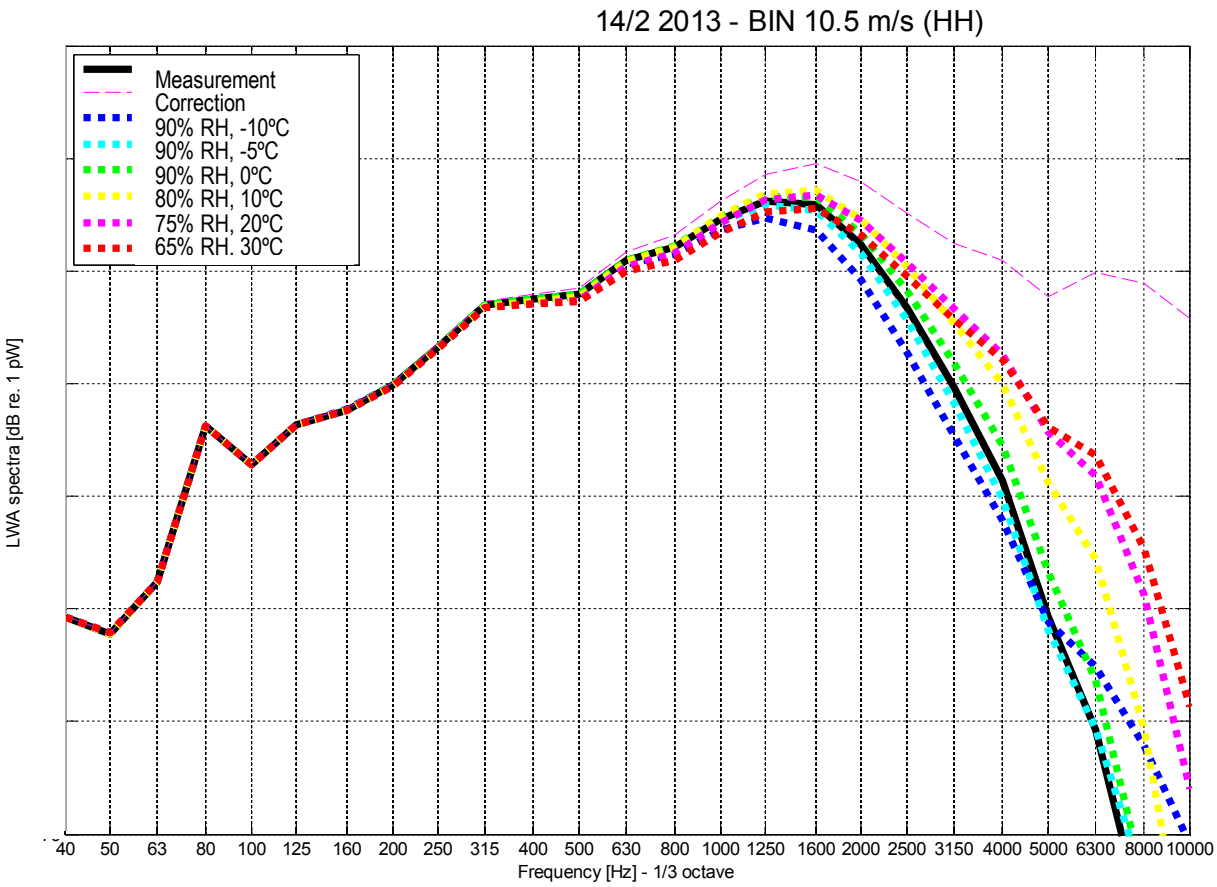

Figure 9: Atmospheric absorption correction and normalization applied to a measured spectrum of a SiemensGamesa 108 m rotor (turbine 3). There is 5 dB between horizontal lines in the plot.