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# SCHALL_KOGE - A PROJECT ON ACOUSTICS OF WIND TURBINE NOISE IN COMPLEX TERRAIN

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## ABSTRACT

In this article we describe the aims and methods of the Schall_KoGe (sound in complex terrain) project and present some important findings from it. Within the project Schall_KoGe data from two measurement campaigns were used to develop an improved sound propagation model that provides robust and realistic noise forecasts. To this end, one campaign was located in a region with simple flat terrain in Harsewinkel, Germany and on the other had difficult flow patterns which occurred in complex terrain in Perdigão, Portugal.

An analysis of long-term measurement data of meteorology and sound is performed, including operational data from wind turbines as well as model data derived from precise flow models at both sites, which were performed over the past years. The measurement data was used partly as input data for the different models e.g. wind field, aeroacoustic and sound propagation model and partly to validate the model results.

The study begins with an analysis of monitoring data e.g. propagation conditions were classified, which make it possible to compare similar measurements with each other. A major result was that the same wind energy plant doesn't produce the same noise at the same wind speeds at hub height, because operating mode, turbulence intensity, external noises, etc. create a variation in the noise levels per wind speed at the hub.

The source parameterization of the wind turbine was extensively examined so that a simplified yet realistic noise forecast is possible. Here we found that the source directivity is more important than the source location within the rotor space. The influence of terrain and flow was studied to explain immission variations of noise. Finally, a scientific model was compared with conventional calculation methods and the differences are presented.

**Keywords:** *wind energy, meteorology, atmospheric sound propagation, ray acoustics*

## 1. INTRODUCTION

To predict the noise level of wind turbines, we find ourselves in a predicament between simple calculation methods that do not require too much input data, but represent less realism, and complicated methods that are computationally intensive and whose results are not easy to interpret. Currently, this task is solved by a relatively simple and well-established method according to DIN ISO 9613-2 [1], but in fact is only valid for simple (flat) terrain. Due to several assumptions in the method, the ISO 9613-2 was developed based on measurements of ground-level sources, and therefore, information on the uncertainty of the method is only provided for source heights up to 30 m and for horizontal distances up to 1,000 m. This prediction method probably could be adapted for complex terrain and updated for larger source heights and distances. Mostly the ISO 9613-2 predicts higher sound pressure levels (SPL) than measured on average and makes it more difficult to expand renewable energies onshore. The good practice guide to the application of ETSU-R-97 for the assessment and rating of wind turbine noise [2] gives also a valuable recommendation of how to deal with WTN measurements and data analysis.

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The effects of the atmosphere on the propagation of sound in this context are well known, as temperature gradients, wind direction and wind gradients cause refraction and change the sound pressure level at a receiver to a large extent. Additionally ground effects may cause shadow zones or influence reflections. In literature many examples can be found: e.g.: Barlas et.al [3] or Heimann et.al. [4] and there is evidence that specific case studies are necessary.

From the analysis of measurement data the following question is raised: What can be done to fairly address wind turbine noise in comparison to other sound sources? Further it was investigated, which parameters and model capabilities are necessary to predict the sound field in any terrain and flow conditions as accurate as possible? For flat terrain the simple concept of ISO 9613-2 might be good enough to protect people, but in complex terrain this method may fail.

## 2. METHODOLOGICAL APPROACH

Within the Schall_KoGe project, measurements and simulations are used to complement each other in such a way that simulations can be started on the basis of the measurements.

**Data Analysis:** Due to the large amount of measurement data, methods need to be developed that allow for automatic filtering according to different criteria. By classifying typical meteorological situations, it is possible to focus on important cases for sound generation and propagation, thereby reducing the amount of data to be considered.

**High-Fidelity Simulations:** One goal is to run simulations with a setup as close to reality as possible. For this purpose high fidelity models are good tools for better understanding the underlying physics. This starts with high resolution flow simulations and ends up in dedicated sound propagation models e.g. our own code ”AKUMET” based on Lagrangian Sound Particles and described in Heimann et.al [4]. The code was redeveloped during the project to ”AKU_KoGe” with a user-friendly input interface. Thus, effects in measurements can also be verified with the help of simulations by switching individual effects in the simulations on and off.

**Validation:** Thus, effects in measurements can also be verified with the help of simulations. Finally, the results need to be related to conventional calculations (ISO 9613-2) to test both of them for usefulness, applicability and reliability. Consequently, the measurement data will also be used to validate the models.

## 3. TERRAIN AND FLOW FIELD CHARACTERISTICS

First flow conditions and sound propagation in simple terrain are studied from measurements in Harsewinkel (Germany), presented in Figure 1. The distance between the sound source and the noise monitoring stations (NMT) is about 500 m and 1000m.

The terrain at Perdigão is characterized by two parallel ridges, 4500 m long, approximately the same height and 1400 m apart. The main wind direction is typically perpendicular to the ridges from the southwest or northeast. On the southwestern ridge there is a wind turbine, of which the sound immission was recorded at several locations as shown in Figure 2. There the microphones are labeled with their serial number to which we refer later in the analysis section and the WT is marked as a blue cross on the top of the SW-ridge.

**Figure 1**: Location in flat terrain of the WT (blue) and the monitoring stations (orange) near Harsewinkel in the northern part of Germany

The acoustic measurements carried out in Perdigão are intended to answer questions of whether the noise measurements can be assigned to the wind turbine (WT) as a dominant sound source and how much the WT noise depends on atmospheric stratification and wind conditions. The measurement setup with the description of topography and the positions of our microphones is described in [5] and in [6].

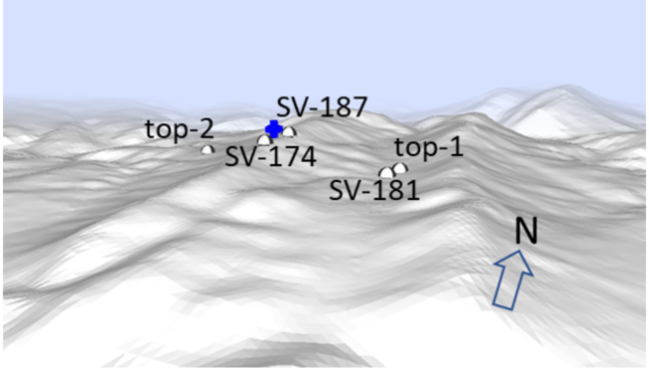

**Figure 2**: Topography of Perdigão with the locations of the wind turbine (blue cross) and the microphones. Distances from WT to microphones vary between 125 to 950m.

Simultaneously at many positions in the field the flow was measured through meteorological wind masts. The density of measurements to capture the complex flow is shown in Figure 3. Here the positions of meteorological wind masts are shown in a perpendicular slice through the valley in the terrain of Perdigão. The flow above and around the hills create different wind regimes in the vicinity of the wind turbine compared to the different microphone locations.

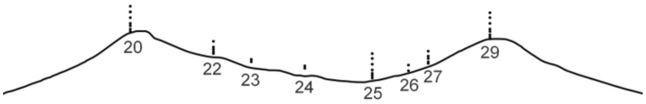

**Figure 3**: Schematic representation of the wind mast positions perpendicular to the valley.

In complex terrain only the combination of dense measurements and flow simulations allow for a complete virtual reconstruction of the atmosphere for the purpose of sound propagation simulations. In [7] a numerical simulation of the given conditions for Perdigão is described which reproduced comparable results to the measurements. Figure 4 highlights the complexity of the wind field in hilly terrain, where for e.g., channeling in the valley can be observed, that means that wind directions according to the axis of the valley are observable more often. In hilly terrain like this, differences in wind speed and direction are very local between the valley and higher located positions. While comparing the model results with measurements one can observe the difference in the valley. The flow simulations then are used for sound propagation models as boundary conditions and represent all the local effects of terrain influence on the flow. These investigations to improve flow simulation and adapt to sound propagation was also an important aspect in the project.

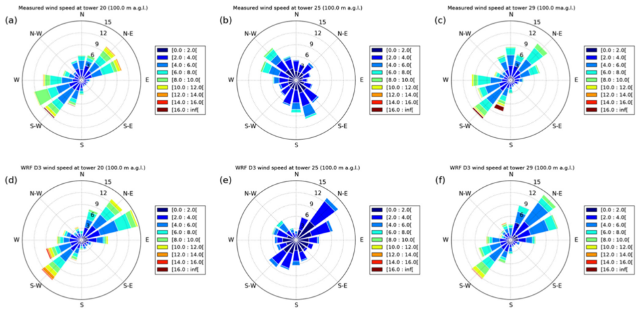

**Figure 4**: Distribution of wind speed and direction at the three 100m masts T20, T25 and T29 on the southwestern hill, in the valley and northeastern hill. Shown are distributions measured a) to c) and simulated d) to f).

## 4. DATA ANALYSIS AND SIMULATIONS

The atmosphere affects the sound source itself. It also affects the subsequent propagation of the sound. In addition, wind produces sound around microphones. This poses several challenges in both data analysis and in simulations.

### 4.1 Analysis of Wind Turbine Sound Characteristics

In the following, we will concentrate on a single aspect of spectral indicators for the WT as a source of sound. Monitoring results will sometimes show a clear signal that can be contributed to the WT and other times this signal will be heavily masked by ambient noise. In addition to the aero-acoustic phenomena, the electromagnetically excited vibration of the generator is the most significant source of noise in direct drive wind turbines. This structure-borne sound, is coupled by its frequency to the rotational speed and thus also to the wind speed as well as to a specific number $N$ for a specific wind turbine according to equa-

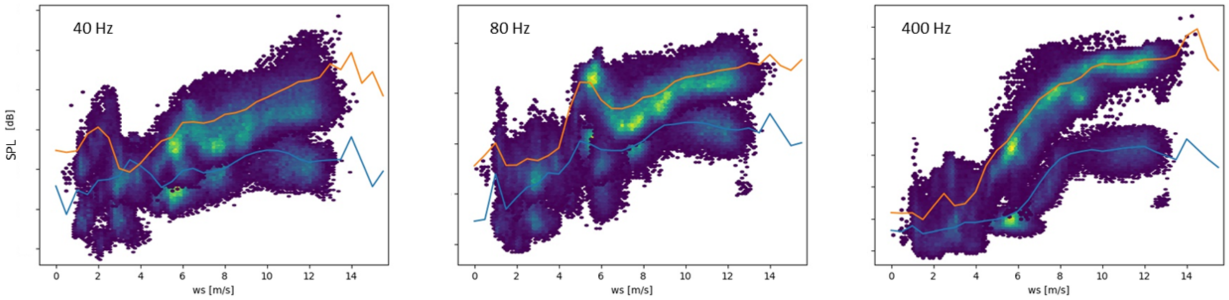

**Figure 5**: Analysis of SPL of specific 1/3-octave-bands at two positions depending on wind speed (red at mic SV-174 in 125m and blue at mic SV-181 in 950m distance from the wind turbine).

tion 1:

$$f_N = \frac{U_{min}}{60} N, \tag{1}$$

Here $U_{min}$ is the rotational speed in rotations per minute and $N$ is the number of gaps inside the rotor.

From analysing measurement data under different aspects (frequency, distance, meteorological conditions) we derived for e.g. in Figure 5, that shows individual one-third-octave band pressure levels as a function of wind speed. Each sub-plot shows at specific frequency the SPL for microphone SV-174 at about 125m distance and for microphone SV-181 at about 950m distance to the WT, as well as the corresponding averaged levels (red=SV-174, blue=SV-181). Looking at the low-frequency one-third octave bands, only a slight correlation between near and far field is recognisable across all wind speeds. The emission sound level increases significantly with increasing wind speed, but the sound level in the far field does not follow to the same extent. Conversely, in the low-frequency range (up to a maximum of approx. 100 Hz) the slot frequency (see equation 1) can be recognised very well, depending on rotation and thus wind speed. In the 40 Hz third-octave band, for example, this peak occurs at a wind speed of 2-3 m/s, or in the 80 Hz third-octave band at 6 m/s, according to the resulting slot frequency. With increasing wind speed, the slot frequency is finally lost in the general wind turbine noise. This applies to the downwind case as well as to upwind. In the 100 Hz frequency bands, there is a very good correlation between the level of near field and far field across all wind speeds.

### 4.2 High-Fidelity Simulations

By simulating isolated physical processes and comparing them with measurement data for most appropriate conditions one might assess individual effects.

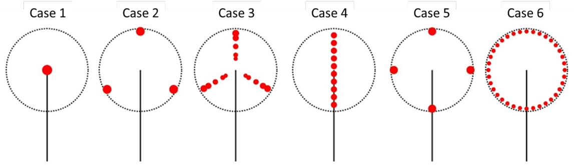

**Figure 6**: Distribution of sound sources within the rotor plane and Δ SPL compared to case 6.

In engineering models the noise of a wind turbine is described by a single substitute source. This surrogate source is an undirected, frequency-dependent point source. Its source strength is determined by the sound power level which is determined with the measurement method of DIN EN 61400-11 [8]. Octave band sound power levels are used as input values in the modified DIN ISO 9613-2 procedure.

A single point source is easy to implement in calculations but may cause different shadow zones due to obstacles or terrain irregularities. Therefore the localization of more than one sound source might be more realistic. In high-fidelity models like AKU_KoGe, the source can be described with a higher degree of freedom, therefore allowing for a better representation of the actual source. Studies on the localization of sound sources on the WT rotor diameter (centre, tip, profile, quarter, circle) were performed as demonstrated in Figure 6. All simulations were performed with third-octave bands.

It is well known that the sound source directivity of the WT is non negligible. Depending on wind direction and the orientation of the turbine directivity there may be large differences in sound pressure level on microphone positions. This was proved in different model implementations by introducing the directivity compared to the influence of source location.

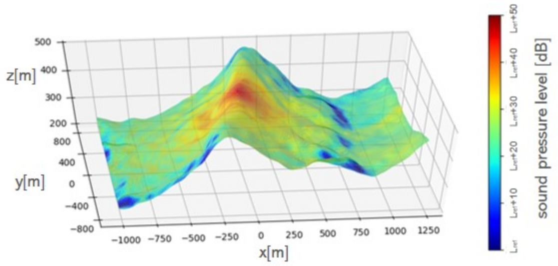

**Figure 7**: Simulated sound pressure level on the ground for Perdigão.

Figure 7 shows the sound pressure level on the ground, simulated with Aku_KoGe under slightly favourable sound propagation conditions in Perdigão. In comparison, figure 8 shows the outcome of an Aku_KoGe simulation for slightly favourable conditions in Harsewinkel.

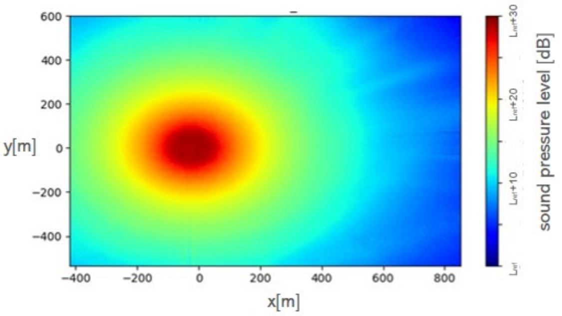

**Figure 8**: Simulated sound pressure level on the ground for Harsewinkel.

## 5. RESULTS AND DISCUSSION

In the following we distinguish between the results achieved in the simple case of Harsewinkel and the results in the complex terrain around Perdigão.

### 5.1 Harsewinkel

Sound prediction with simple methods was performed for flat terrain by our project partner Wobben Research and Development GmbH (WRD) and an attenuation of the SPL was calculated for different distances from the sound source. In those cases the ISO 9613-2 gave sufficiently good results comparable to measurements from Harsewinkel.

Table 1 shows the total sound level of the measurement and the Aku_KoGe simulation as well as the results of the calculations according to the standard for comparison. The simulation was carried out with settings that were as realistic as possible and evaluated at the measurement locations NMT500 and NMT1000 in Harsewinkel. Selected here was an example of conditions, where ISO 9613-2 gave quieter results than measurement. Such cases are rather unlikely and don't appear in longtime averages. In contrast the meteo-sensitive code and appropriate input data in Aku_KoGe predicted higher results than the measurements.

**Table 1**: Difference in sound level between calculated and measured values (i.e. calculation - measurement) at immission locations NMT500 and NMT1000. Positive level: simulation louder than measurement, negative level: simulation quieter than measurement.

| meas.loc. | Aku_KoGe | ISO 9613-2 |
|---|---:|---:|
| NMT_500 | +2.7 | -2.6 |
| NMT_1000 | +0.3 | -4.4 |

### 5.2 Perdigão

The meteorological measurements at the site of Perdigão were used to improve the flow field modelling in the first place. Acoustical measurements were additionally performed, due to the good opportunity to have for later exact boundary conditions for use in sound propagation modelling.

The ISO9613-2 was not adapted to the complex situation in Perdigão, due to the lack of emission data for validation as well as due to remaining uncertainties concerning specific situations with accompanying background noise. However, as was already shown in Figure 4, the complex meteorological situation that can arise in hilly terrain like Perdigão cannot be adressed by standard calculation methods.

Instead of this, an analysis of different influence factors for predicting the sound field were investigated. One was the distribution of sound sources in the rotor plane. But, in the complex terrain the specific location of sound source gave no clear result as seen in Figure 9. From the simulations it can be seen that the influence of the directivity is considerably greater than the influence of the different source geometries. The source geometry produces differences of 0.5 dB on average and max. 2-3 dB, but differences of up to 12 dB in directivity are possible.

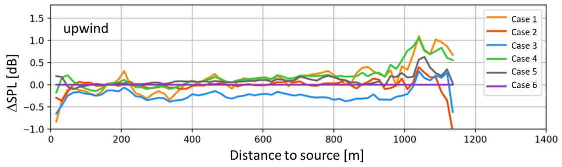

**Figure 9**: Δ SPL compared to case 6 resulting from distribution of sound sources within the rotor plane

Furthermore, the influence of orography and meteorology (flow field as well as stratification), with and without the wake of the WT, were also quantified in simulations. Figure 10 highlights the influence of the Perdigão orography on the sound pressure level at ground level for receivers placed in the line perpendicular to the rotor plane where the rotor plane is assumed to be in line with the ridge. For reference, the thick solid line indicates the elevation of the terrain, given in meters above sea level (masl). The thin dashed line illustrates the sound pressure level simulated for the Perdigão orography whereas the thin solid line shows the simulated sound pressure level for a flat orography. The atmosphere is neutral without any wind field or temperature gradient. Close to the wind turbine, the sound pressure level with orography is slightly lower compared to the sound pressure level with flat terrain. This is caused by the slightly longer distance between source and receiver, as the wind turbine in the case with orography is placed right at the ridge, i.e. the terrain below the WT is lower than it would be in the case of flat terrain. At every bump in the terrain, the sound pressure level exceeds the flat terrain sound pressure level whereas in the valley a shadow zone is forming which leads to lower sound pressure levels compared to the flat terrain. At the left and right end of the domain, the Perdigão terrain is increasing again in height and therefore also the sound pressure level exceeds the flat terrain SPL.

Figures 11 and 12 illustrate the overall influence of topography and meteorology on the sound pressure level field at ground level. In both figures, the black curve illustrates the mean sound pressure level difference between the simulation with and without orography and meteorology, respectively, i.e. positive values indicate the average sound pressure level including the respective influence is higher than without and vice versa. The white curve represents the standard deviation of $1\sigma$ range, i.e. $\mu - \pm 1\sigma$. The colour of the points denotes the frequency with which the sound pressure level difference occurs, i.e. yellow is very frequent whereas dark purple is a single occurrence.

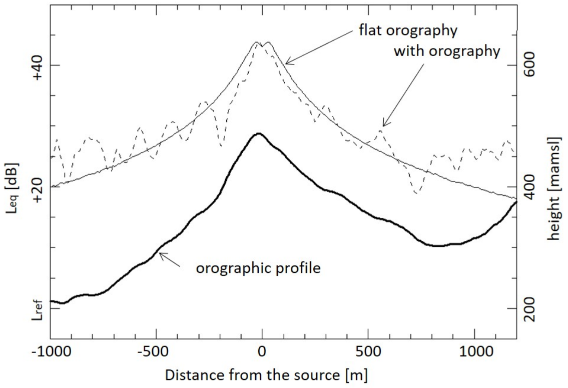

**Figure 10**: Influence of the orography on the sound pressure level curve between source and receiver, in a straight line, upwind and downwind from the source.

In case of the orography (cf. figure 11) we find a similar result as in figure 10 but without the level details, as the bumps and indentations in the terrain are irregular and therefore smoothing out the overall result. However, the influence of the valley (which is approximately uniform in y-direction, i.e. in direction parallel to the ridge) is still significant and the sound pressure level drops nearly 10 dB here. Like in figure 10, the SPL close to the source is lower with terrain and higher in the far field.

The influence of meteorology (see figure 12) is generally lower compared to the orography. It must however be mentioned that the meteorological field that was used in this simulation represented only slightly favourable sound propagation conditions, where the downwind domain is the positive x-axis and correspondingly, the negative x-axis accounts for upwind. The strongest effect can be seen again in the area of the valley at around +800m, where in case of meteorology it is significantly louder than in the remaining domain. This is explained by downward refracted sound rays that now can reach into an area that is characterized by a shadow zone in the simulation without meteorology.

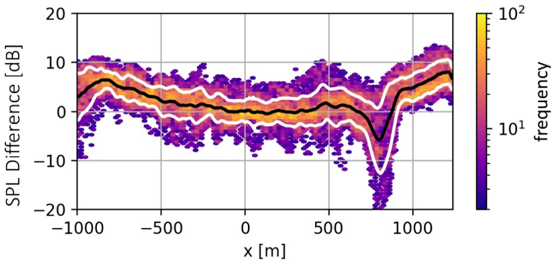

**Figure 11**: Influence of the orography on the sound pressure level (with - without). Black: mean SPL difference $\mu$, white: mean SPL difference - standard deviation $\mu - \pm 1\sigma$

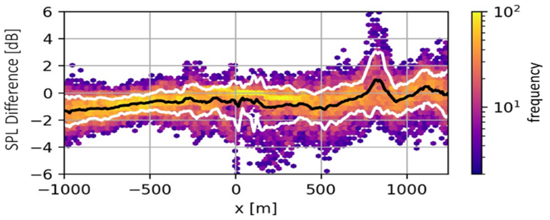

**Figure 12**: Influence of the meteorology on the sound pressure level (with - without). Black: mean SPL difference $\mu$, white: mean SPL difference - standard deviation $\mu - \pm 1\sigma$

## 6. CONCLUSION

From starting with simple terrain data analysis, simple flow configuration or simple source setup we could establish a model chain from sound emission through sound propagation to sound immission. Thereafter the work was extended towards incorporating complex terrain and specific flow and sound propagation cases. A filtering of the data significantly improves the evaluation of the results. The large amount of data sets was reduced in such a way that only relevant cases for a specific question are included in the analysis or evaluation. The combination of a dense meteorological measuring network together with acoustic measurements make the data-set of Perdigão immensely valuable. This data-set is available in [9]. The models for the flow based on this data set have shown that they can generate accurate flow fields to be able to calculate realistic sound propagation with high fidelity methods subsequently.

Results from sound propagation models compared to measured values enabled the project team to evaluate single physical processes like topography or wake effects.

## 7. ACKNOWLEDGMENTS

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