Propagation Modeling Parameters for Wind Power Projects

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Noise modeling of wind turbines can be problematic in that they generate sound over a large area, from a high elevation, and make the most noise in very high wind conditions. For ISO 9613, these factors directly relate to how ground attenuation and meteorology are accounted for.

To study how ground attenuation and wind speed affect the accuracy of propagation modeling for wind turbines, data were gathered at an existing industrial-scale wind farm, and propagation modeling was conducted using Cadna A modeling software by Datakustik, GmbH for the same site under the same operating conditions in which monitoring was carried out. By adjusting the type of ground attenuation used in the model and the meteorological conditions, the best combinations for modeling propagation for wind turbines were determined with comparisons to the monitored data.

Standards Background

ISO 9613-2 (1996)[1,2] provides two methods for calculating ground effect (A_{gr}). The first method, known as spectral ground attenuation, divides the ground area between the source and the receiver into three regions: a source region, a receiver region, and a middle region. The source region extends from the source toward the receiver at a distance equal to 30 times the height of the source. For a tall wind turbine, this can be up to 2 to 3 km. The receiver region extends from the receiver toward the source at a distance equal to 30 times the height of the receiver. If the source and receiver regions do not overlap, the distance between the two regions is defined as the middle region. The ISO standard goes on to define ground attenuation for each octave band utilizing a ground factor (G) for each region depending on how reflective or absorptive it is. For reflective, hard ground, G=0; and porous, absorptive ground suitable for vegetation, G=1. If the ground is a mixture of the two, G equals the fraction of the ground that is absorptive. The ISO standard states that "This method of calculating the ground effect is applicable only to ground that is approximately flat, either horizontally or with a constant slope."

The second method provided in ISO 9613-2, known as nonspectral ground attenuation, is for modeling A-weighted sound pressure level over absorptive or mostly absorptive ground; but the ground does not need to be flat. Using the alternative method also requires an additional factor (D_Ω) be added to the modeled sound power level to account for reflections from the ground near the source.

To show the effect of using spectral vs. nonspectral ground attenuation for a source at a reasonable wind turbine hub height of 80 m, the ground attenuation (A_{gr}) was calculated using both methods for a source height of 80 m and 1 m over a range of distances from 0 to 3.5 km with the ground factor, G, set to zero. In a third scenario, G was set to 1, and an 80-m source height was used. In each example, the receiver height was set at 1 meter. The results for spectral ground attenuation are shown in Figure 1, and nonspectral ground attenuation results are shown in Figure 2.

As shown in the graphs, over soft, porous, spectral ground, attenuation for an 80-meter source is approximately 2 dB less than a 1-meter source. For nonspectral ground attenuation, an 80-m source height actually has negative ground attenuation over the first 750 m due to reflections from the ground.

ISO 9613-2 is only valid for moderate nighttime inversions or downwind conditions. The valid range of wind speeds is 1 to 5 m/s at 3 to 11 m high. For wind turbines, it may be more accurate to consider adjustments such as those presented by CONCAWE[3] or HARMONOISE.[4] These adjustments account for propagation at various wind speed, wind directions, and atmospheric stability. The CONCAWE meteorological adjustments are built into Cadna A and were used in this study.

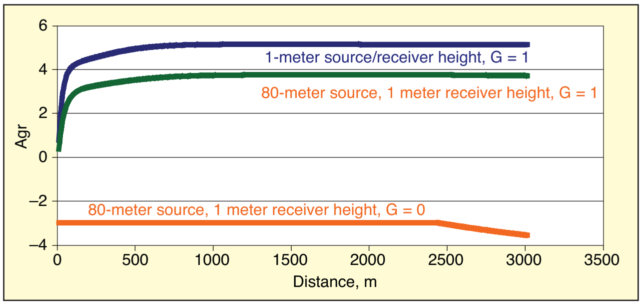

Figure 1. Spectral ground attenuation (A_{gr}) over distance for an 80-m and 1-m-high source; 1-m-high receiver and ground factor set to 1 (soft) and 0 (hard).

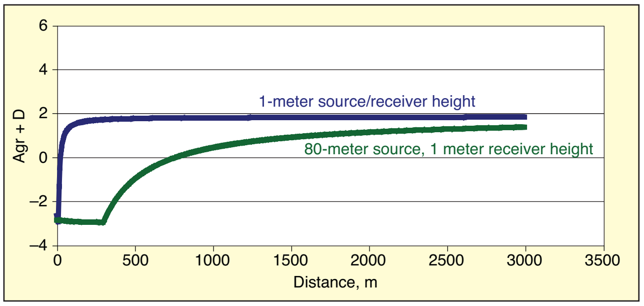

Figure 2. Nonspectral ground attenuation (A_{gr}) over distance for an 80-m and-1 m source and 1-m receiver height. Nonspectral ground attenuation is not a function of ground hardness.

Figure 3. Rural 100-MW wind farm used to study ground attenuation and meteorological modeling factors.

Wind Farm Background

The wind farm in this study is situated on nearly 8 square miles of flat farm land. There are a total of 67 wind turbines that are capable of producing about 100 megawatts of electricity. Each turbine hub is 80 m tall, and the rotation path of the three blades is 80 m in diameter. The turbines are roughly 1,000 ft apart, but there is a wide variation for individual pairs. An image of the terrain and some of the turbines is shown in Figure 3, and Figure 4 shows the layout of the wind farm.

Sound Monitoring

Two sound level meters were set up at 120 m and 610 m from the northern edge of the wind farm. Each sound level meter was an IEC Type I Cesva SC310 fitted with windscreens. The sound level meter at 120 m was placed flat on a 1-m-square ground board,

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Based on a paper presented at Noise-Con 2007, Institute of Noise Control Engineering, Reno, NV, October, 2007.

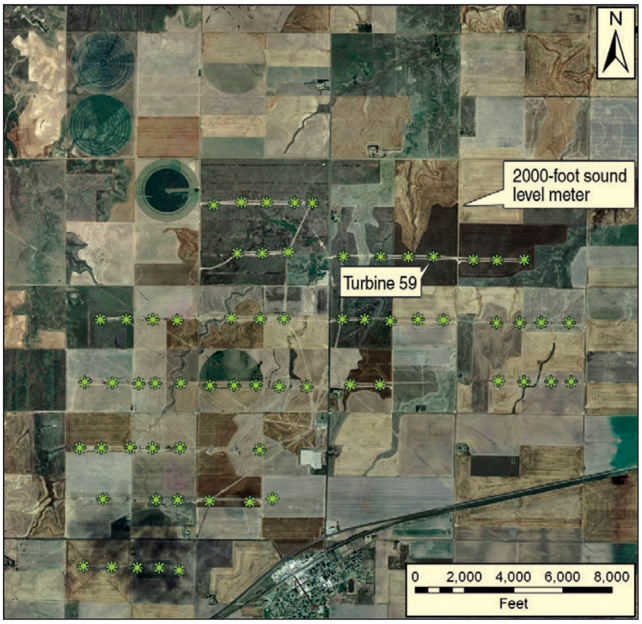

Figure 4. Map of wind farm used for study ; asterisks = wind turbines.

while the meter at 610 m was mounted on a stake at approximately 1 m off the ground.

The measurement period was at night from approximately 10 p.m. to 10 a.m. Each meter logged 1-minute equivalent average sound levels in 1/3-octave bands. In addition, recordings of WAV files were made at certain points.

At the same time, spot measurements of wind speed and direction at hub height, blade rotational frequency, and energy output for each wind turbine were made at 10-minute intervals.

Since we could not obtain background sound levels, we assumed that much of the localized noise from wind passing through the surrounding wheat field would be at and above 2,000 Hz. This was confirmed by listening to and analyzing the WAV file recordings. Therefore, to isolate the wind turbine sound, we created a virtual low-pass filter eliminating sound at frequencies above 2 kHz. In addition, assuming that the wind turbines operated within a narrow range of sound power over any one 10-minute period, we used the 90th-percentile, 1-minute equivalent average sound level for each 10-minute period for comparison to modeled results. This minimized the localized effects of noise from wind gusts.

Sound Monitoring

The Cadna A sound propagation model made by Datakustik GmbH was used to model sound levels from the wind farm. Cadna A can use several standards of modeling, including ISO 9613 with or without CONCAWE meteorological adjustments.

A model run was conducted for every 10-minute period of turbine operation during the monitoring period. This was done by running Cadna A for the following scenarios:

- Standard meteorology with spectral ground attenuation and G=1.
- Standard meteorology with spectral ground attenuation and G=0.
- Standard meteorology with nonspectral ground attenuation.
- Standard meteorology with no ground attenuation.
- CONCAWE adjustments for D/E stability with winds from the south at greater than 3 m/s and spectral ground attenuation, assuming G=1.
- CONCAWE adjustments for D/E stability with winds from the south at greater than 3 m/s and nonspectral ground attenuation.
- CONCAWE adjustments for D/E stability with winds from the south at greater than 3 m/s and no ground attenuation.

For each scenario, a "protocol" was run that listed the ISO 9613-2 attenuation and propagation factors by frequency between each turbine and receivers at 120 m and 610 m from the northern end of the wind farm; that is, the receivers represented by the sound

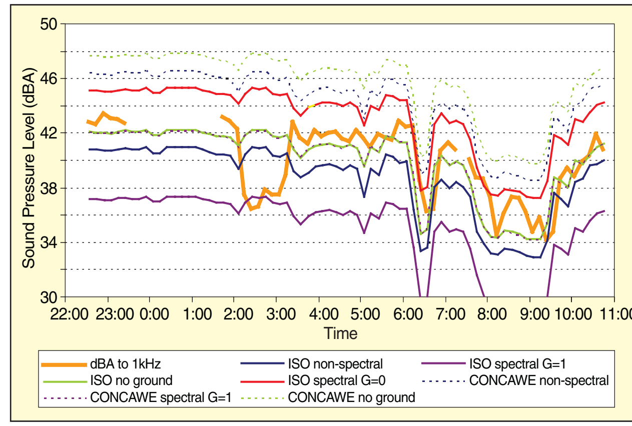

Figure 5. Comparison of monitored sound levels over time at 610 m (shown in orange) with modeled sound levels under various combinations of ground attenuation and meteorological factors.

monitoring locations. These attenuation factors were then put into a spreadsheet model that looked up the manufacturer sound power level for each turbine for each 10-minute period based on actual measured wind speeds at each turbine. The spreadsheet model then calculated the sound level from each turbine by subtracting the attenuation factors from the sound power levels and then combining each turbine to get an overall sound pressure level at the 610-m receiver.

Results

A comparison of the modeled results to monitored sound levels over time is shown in Figure 5. The orange line toward the middle is the actual monitored sound levels. As shown, these monitored levels ranged from about 34 dBA to 43 dBA. Except for the period between 2:00 and 3:00 a.m., the sound levels were highly correlated with wind speed.

We conducted further regression analyses to determine which method achieved the best fit to the modeled data. The results are shown in Figures 6 and 7. Starting with Figure 6a, we found that the CONCAWE meteorology combined with spectral ground attenuation had a coefficient close to 1.0 and, on average, underestimated sound levels by only 1%. The CONCAWE meteorology along with the nonspectral ground attenuation consistently overestimated monitored sound levels. The ISO meteorology with nonspectral ground attenuation yielded a good fit. The coefficient of 0.957 indicates that average modeled levels underestimated monitored levels by about 4%. On the opposite end of the scale, the ISO meteorology along with spectral ground attenuation and G=1 significantly underestimated modeled sound levels by an average of 13%.

Starting with Figure 7a, the CONCAWE meteorology with no ground attenuation overestimated monitored sound levels by approximately 13%, while the ISO meteorology with no ground attenuation provided the best fit of all the runs, with a coefficient of 0.9924. Finally, the ISO meteorology with spectral ground attenuation and G=0 yields moderately accurate results but overestimates by approximately 3%. All trend lines were statistically significant with probabilities greater than 99%.

Discussion and Conclusions

The results of the study indicate the modeling of wind turbines in flat and relatively porous terrain may yield results that underestimate actual sound levels when using the standard ISO 9613-2 algorithms with spectral ground attenuation and G=1. We found that the best fit between modeled and monitored sound levels for this case occurs when using ISO meteorology and no ground attenuation. The second-best model fit was with the CONCAWE adjustments for wind direction and speed along with spectral ground attenuation and G=1. Using the ISO methodology with nonspectral ground attenuation also yielded good results.

While the ISO 9613-2 methodology specifically recommends spectral ground attenuation for flat or constant-slope terrain with G=1, in this case, it underestimated the sound levels. This may be due to the height of the hub (80 m) as compared with typical noise

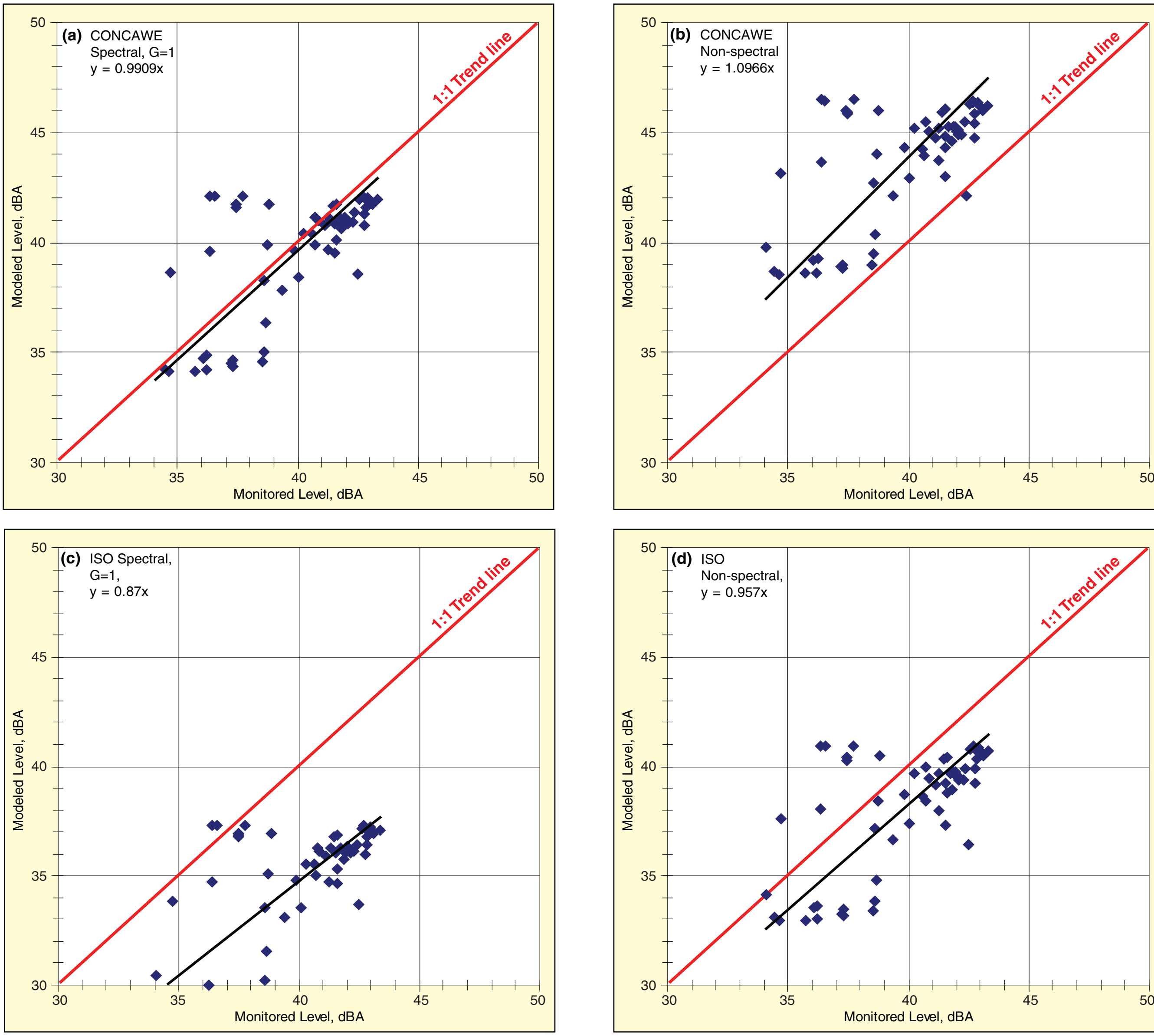

Figure 6a-d. Comparison of modeled and monitored sound levels for four meteorological and ground attenuation combinations. Regression coefficients are shown in the upper left-hand corner. Regression trendline shown in black; 1:1 trendline, indicating a match between monitored and modeled sound levels, is shown in red. N = 60.

sources. That is, the sound waves may not significantly interact with the ground over that distance. It may also be due to the fact that sound from wind turbines comes not from a single point – we assumed a single point at hub height – but is more likely to be similar to a circular area source. Finally, wind turbines often operate with wind speeds that are higher than ISO 9613-2 recommends. The combination of higher wind speeds and an elevated noise source may result in greater downward refraction.

To be more representative, a larger dataset should be obtained. Some improvements to the methodology and study would include:

- Improved accounting for background sound levels.
- Measurements of ground impedance so that the ISO 9613-2 G factor can be better estimated.
- Monitoring over a larger range of wind speeds.
- Using ground boards for the measurement microphone to minimize self-induced wind noise.
- Using larger wind screens.
- Measuring at distances greater than 610 m.
- Applying the methodology to other ground types and terrain.

Care should be taken in applying this methodology in other projects that are not similar. Overall, the ISO 9613-2 methodology is appropriate for propagation modeling of wind turbines, but modeling parameters should be adjusted appropriately to account for this source's unique characteristics.

Acknowledgments

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4. "Harmonized Accurate and Reliable Methods for the EU Directive on the Assessment and Management Of Environmental Noise, Final Technical Report," Information Society and Technology Program, European Commission, February 2005.

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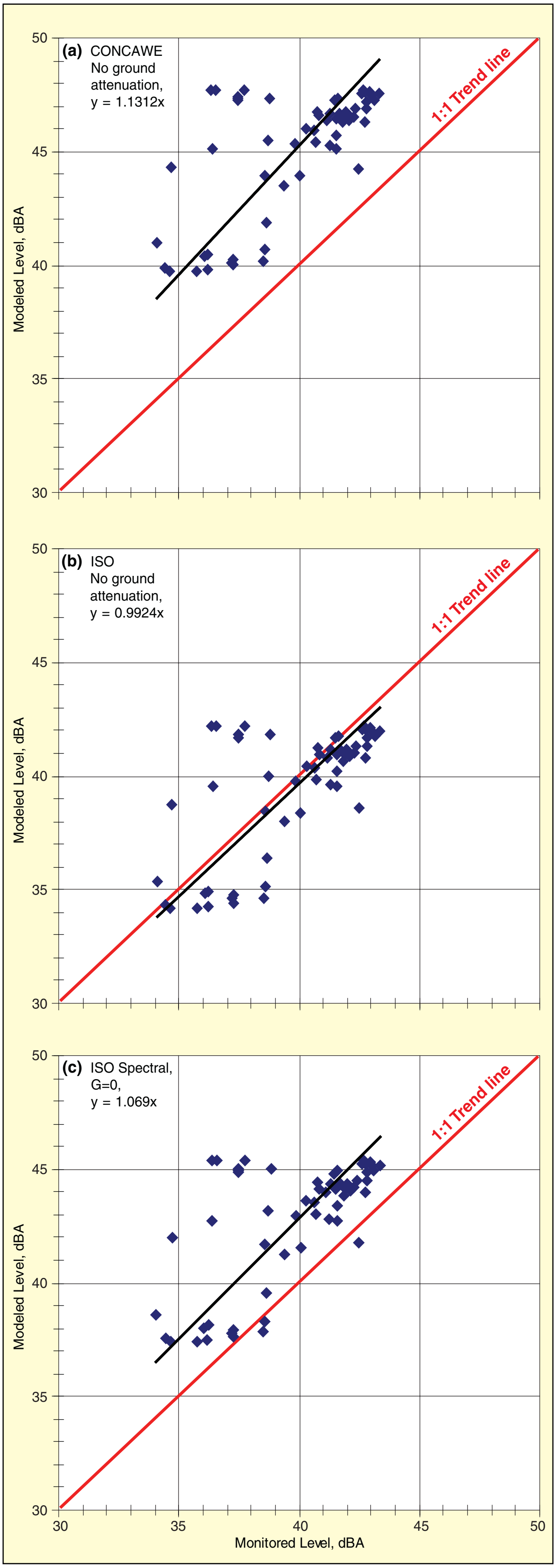

Figure 7a-c. Comparison of modeled and monitored sound levels for three meteorological and ground attenuation combinations. Regression coefficients shown in upper left-hand corner. Regression trend line shown in black; 1:1 trend line, indicating a match between monitored and modeled sound levels, is shown in red. N = 60.