IV LOUD SOUNDS IN WEAK WINDS: effect of the wind profile on turbine sound level

IV.1 The Rhede wind farm

In Germany several wind turbine farms have been and are being established in sparsely populated areas near the Dutch border. One of these is the Rhede wind farm in northwestern Germany (53° 6.2’ latitude, 7° 12.6’ longitude) with seventeen Enercon E-66 1.8 MW turbines of 98 m hub height and with 3-blade propellers of 35 m blade length. The turbines have a variable speed increasing with wind velocity, starting with 10 rpm (revolutions per minute) at a wind velocity of 2.5 m/s at hub height up to 22 rpm at wind velocities of 12 m/s and over.

At the Dutch side of the border is a residential area along the Oude Laan and Veendijk in De Lethe (see figure IV.2): countryside dwellings surrounded by trees and agricultural fields. The dwelling nearest to the wind farm is some 500 m west of the nearest wind turbine (nr. 16). According to a German noise assessment study a maximum immission level of 43 dB(A) was expected, 2 dB below the relevant German noise limit. According to a Dutch consultancy immission levels would comply with Dutch (wind velocity dependent) noise limits.

After the farm was put into operation residents made complaints about the noise, especially at (late) evening and night. The residents, united in a neighbourhood group, could not persuade the German operator into mitigation measures or an investigation of the noise problem and brought the case to court. The Science Shop for Physics had just released a report explaining a possible discrepancy between calculated and real sound immission levels of wind turbines because of changes in wind profile, and was asked to investigate the consequences of this discrepancy by sound measurements. Although at first the operator agreed to supply measurement data from the wind turbines (such as power output, rotation speed, axle direction), this was withdrawn after the measurements had started. All relevant data therefore had to be supplied or deduced from our own measurements.
Figure IV.2: turbines (dots W1….W17) in and measurement locations (crosses A….X) near the Rhede wind farm; Duch – German border indicated by line of +++ (through A); grid lines are 1 km apart, north is at top
IV.2 Noise impact assessment

In the Netherlands and Germany noise impact on dwellings near a wind turbine or wind farm is calculated with a sound propagation model. Wind turbine sound power levels $L_W$ are used as input for the model, based on measured or estimated data. In Germany a single ‘maximum’ sound power level (at 95% of maximum electric power) is used to assess sound impact. In the Netherlands sound power levels related to wind velocities at 10 m height are used; the resulting sound immission levels are compared to wind velocity dependent noise limits (see figure VII.1). Implicitly this assessment is based on measurements in daytime and does not take into account atmospheric conditions affecting the wind profile, especially at night.

In the Netherlands a national calculation model is used [VROM 1999] to assess noise impact, as is the case in Germany [TA-Lärm 1998]. According to Kerkers [Kerkers 1999] there are, at least in the case of these wind turbines, no significant differences between both models.

In both sound propagation models the sound immission level $L_{imm}$ at a specific observation point is a summation over $j$ sound power octave band levels $L_{Wj}$ of $k$ sources (turbines), reduced with attenuation factors $D_{j,k}$:

$$L_{imm} = 10 \cdot \log \left[ \sum_j \sum_k 10^{0.1 \cdot (L_{Wj} - D_{j,k})} \right]$$

(IV.1)
L_{W,j,k} assumed identical for all k turbines, is a function of rotational speed.
D_j is the attenuation due to geometrical spreading (D_{geo}), air absorption (D_{j,air})
and ground absorption (D_{j,ground}): D_{j,k} = D_{geo,k} + D_{j,air,k} + D_{j,ground,k}.
Formula (IV.1) is valid for a downwind situation. For long term assessment purposes a
meteorological correction factor is applied to (IV.1) to account for 'average atmospheric conditions'.
When comparing calculated and measured sound immission levels in this study no such
meteo-correction is applied because measurements were always downwind of a turbine or the wind farm.

IV.3 Wind turbine noise perception
There is a distinct audible difference between the night and daytime wind turbine sound
at some distance from the turbines. On a summer’s day in a moderate or even strong wind the turbines may only be heard within a few
hundred meters and one might wonder why residents should complain of the sound
produced by the wind farm. However, in quiet nights the wind farm can be heard at distances of up to several kilometers when
the turbines rotate at high speed. In these nights, certainly at distances from
500 to 1000 m from the wind farm, one can hear a low pitched thumping sound
with a repetition rate of about once a second (coinciding with the frequency
of blades passing a turbine mast), not unlike distant pile driving,
superimposed on a constant broad band 'noisy' sound. A resident living at 1 km from the nearest turbine says it is the rhythmic character of the sound
that attracts attention: beats are clearly audible for some time, then fade away to come back again a little later. A resident
living at 2.3 km from the wind farm describes the sound as ‘an endless train’. In daytime these pulses are usually not audible and the sound from the wind farm is less intrusive or even inaudible (especially in strong winds because of the then high ambient sound level).
In the wind farm the turbines are audible for most of the (day and night)
time, but the thumping is not evident, although a ‘swishing’ sound –a regular variation in sound level- is readily discernible. Sometimes a rumbling sound can be heard, but it is difficult to assign it, by ear, to a specific turbine or to assess it’s direction.
IV.5 Measurement instruments and method

Sound immission measurements were made over 1435 hours, of which 417 hours at night, within four months on two consecutive locations with an unmanned Sound and Weather Measurement System (SWMS) consisting of a sound level meter (type 1 accuracy) with a microphone at 4.5 m height fitted with a 9 cm diameter foam wind shield, and a wind meter at 10 m as well as at 2 m height. Every second wind velocity and wind direction (at 10 m and at 2 m height) and the A-weighted sound level were measured; the measured data were stored as statistical distributions over 5 minute intervals. From these distributions all necessary wind data and sound levels can be calculated, such as average wind velocity, median wind direction or equivalent sound level and any percentile (steps of 5%) wind velocity, wind direction or sound level, in intervals of 5 minutes or multiples thereof.

Also complementary measurements were done with logging sound level meters (type 1 and 2 accuracy) and a spectrum analyser (type 1) to measure immission sound levels in the residential area over limited periods, and emission levels near wind turbines. Emission levels were measured according to international standards [IEC 1998, Ljunggren 1997], but for practical purposes they could not be adhered to in detail: with respect to the recommended values a smaller reflecting board was used for the microphone (30·44 cm² instead of a 1 m diameter circular board) and a smaller distance to the turbine (equal to tower height instead of tower height + blade length); reasons for this were given in Chapter II. Also it was not possible to do emission measurements with only one turbine in operation.

IV.6 Results: sound emission

Emission levels $L_{eq}$ measured very close to the centre of a horizontal, flat board at a distance $R$ from a turbine hub can be converted to a turbine sound power level $L_W$ [IEC 1998, Ljunggren 1997]:

$$L_W = L_{eq} - 6 + 10 \cdot \log(4\pi R^2/A_o) \quad (IV.2)$$

where $A_o$ is a unit surface (1 m²). From earlier measurements [Kerkers 1999] a wind velocity dependence of $L_W$ was established as given in table
IV.1. As explained above, the wind velocity at 10 m height was not considered a reliable single measure for the turbine sound power, but rotational speed was a better measure.

Emission levels have been measured, typically for 5 minutes per measurement, at nine turbines on seven different days with different wind conditions. The results are plotted in figure IV.3; the sound power level is plotted as a function of rotational speed $N$. $N$ is proportional to wind velocity at hub height and could be determined by counting, typically during one minute, blades passing the turbine mast. This counting procedure is not very accurate (accuracy per measurement is $\leq 2$ counts, corresponding to 2/3 rpm) and is probably the dominant reason for the spread in figure IV.3. The best logarithmic least squares fit to the data points in figure IV.3 is:

$$L_w = 67.1 \cdot \log(N) + 15.4 \text{ dB(A)} \quad (IV.3)$$

with a correlation coefficient of 0.98. The standard deviation of measurement values with respect to this fit is 1.0 dB.

<table>
<thead>
<tr>
<th>wind velocity $V_{10}$ m/s</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>sound power level $L_w$ dB(A)</td>
<td>94</td>
<td>96</td>
<td>98</td>
<td>101</td>
<td>102</td>
<td>103</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>frequency (Hz)</th>
<th>63</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>$L_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>this report dB(A)</td>
<td>82</td>
<td>92</td>
<td>94</td>
<td>98</td>
<td>98</td>
<td>93</td>
<td>88</td>
<td>103</td>
</tr>
<tr>
<td>[Kerkers 1999] dB(A)</td>
<td>85</td>
<td>91</td>
<td>95</td>
<td>98</td>
<td>98</td>
<td>92</td>
<td>83</td>
<td>103</td>
</tr>
</tbody>
</table>
At the specification extremes of 10 rpm and 22 rpm the (individual) wind turbine sound power level $L_W$ is 82.8 dB(A) and 105.7 dB(A), respectively. In table IV.2 earlier measurement results [Kerkers 1999] are given for the octave band sound power spectrum. Also in table IV.2 the results of this study are given: the logarithmic average of four different spectra at different rotational speeds. In all cases spectra are scaled, with formula IV.3, to the same sound power level of 103 dB(A).

To calculate sound immission levels at a specific rotational speed (or vice versa) the sound power level given in formula (IV.3), and the spectral form in table IV.2 (‘this report’) have been used.

IV.7 Results: sound immission

The sound immission level has been measured with the unmanned SWMS on two locations. From May 13 until June 22, 2002 it was placed amidst open fields with barren earth and later low vegetation at 400 meters west of the westernmost row of wind turbines (location A, see figure IV.2). This site was a few meters west of the Dutch-German border, visible as a ditch and a 1.5 to 2 m high dike. From June 22 until September 13, 2002 the SWMS was placed on a lawn near a dwelling at 1500 m west of the westernmost row (location B), with low as well as tall trees in the vicinity. On both locations there were no reflections of turbine sound towards the microphone, except via the ground, and no objects (such as trees) in the line of sight between the turbines and the microphone. Apart from possible wind induced sound in vegetation relevant sound sources are traffic on rather quiet roads, agricultural activities, and birds. As, because of the trees, the correct (potential) wind velocity and direction could not be measured on location B, wind measurement data provided by the KNMI were used from their Nieuw Beerta site 10 km to the north. These data fitted well with the measurements on location A.

At times when the wind turbine sound is dominant, the sound level is relatively constant within 5 minute intervals. In figure IV.4 this is demonstrated for two nights. Thus measurement intervals with dominant turbine sound could be selected with a criterion based on a low variation in sound level: $L_5 - L_{95} \leq 4$ dB, where $L_5$ and $L_{95}$ are the 5 and 95 percentile.
sound level in the measurement interval. In a normal (Gaussian) distribution this would equal $\sigma \leq 1.2$ dB, with $\sigma$ the standard deviation.

![Figure IV.4: 48 hour registration of immission level ($L_5$, $L_{eq}$ and $L_{95}$) per 5 minutes at location A; turbines are considered the dominant sound source if $L_5 - L_{95} \leq 4$ dB](image)

On location A, 400 m from the nearest turbine, the total measurement time was 371 hours. In 25% of this time the wind turbine sound was dominant, predominantly at night (23:00 – 6:00 hours: 72% of all 105 nightly hours) and hardly in daytime (6:00 – 19:00 hours: 4% of 191 hours). See table IV.3.

On location B, 1500 m from the nearest turbine, these percentages are almost halved, but still the turbine sound is dominant for over one third of the time at night (38% of 312 hours). The trend in percentages agree with complaints concerning mostly noise in the (late) evening and at night and their being more strongly expressed by residents closer to the wind farm.
Table IV.3: total measurement time in hours and selected time with dominant wind turbine sound

<table>
<thead>
<tr>
<th>Location</th>
<th>total time (hours and % of total measurement time at location)</th>
<th>Night 23:00-6:00</th>
<th>Evening 19:00-23:00</th>
<th>Day 6:00-19:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: total</td>
<td>371 h 105 75 191</td>
<td>75</td>
<td></td>
<td>191</td>
</tr>
<tr>
<td>A: selected</td>
<td>92 h 25% 76 72%</td>
<td>9 12%</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>B: total</td>
<td>1064 h 312 183 569</td>
<td>312</td>
<td></td>
<td>569</td>
</tr>
<tr>
<td>B: selected</td>
<td>136 h 13% 119 38%</td>
<td>13 7%</td>
<td></td>
<td>4</td>
</tr>
</tbody>
</table>

In figure IV.5 the selected ($L_5-L_{95} \leq 4$ dB) 5 minute equivalent immission sound levels $Leq,5min$ are plotted as a function of wind direction (left) and of wind velocity (right) at 10 m height, for both location A (above) and B (below). The KNMI wind velocity data (used for location B) were given as integer values of the wind velocity.

Also the wind velocity at 10 m and 2 m height on location A are plotted (in IV.5A and IV.5B, respectively), and the local wind velocity (influenced by trees) at 10 m on location B (IV.5C). The immission level data points are separated in two classes where the atmosphere was stable or neutral, according to observations of wind velocity and cloud cover at Eelde. Eelde is the nearest KNMI site for these observations, but it is 40 km to the west, so not all observations will be valid for our area.

In figure IV.5B a grey line is plotted connecting calculated sound levels with sound power levels according to table IV.1 (the lowest value at 2.5 m/s is extrapolated [Van den Berg et al 2002]), implicitly assuming a fixed logarithmic wind profile according to formula (III.2). If this line is compressed in the direction of the abscissa with a factor 2.6, the result is a (black) line coinciding with the maximum one hour values ($Leq,1h$). Apparently for data points on this line the sound emission corresponds to a wind velocity at hub height that is 2.6 times higher than expected. In figure IV.6 this is given for one hour periods: all 5 minute measurement periods
that satisfied the L₅-L₉₅-criterion, with at least 4 periods per hour, were taken together in consecutive hourly periods and the resulting Lₐₐₜ (T = 20 to 60 minutes) was calculated. The resulting 83 Lₐₐₜ-values are plotted against the average wind velocity V₁₀. Also plotted in figure IV.6 are the expected immission levels assuming a logarithmic wind profile calculated from (III.4), with \( f_{\log} = (V_{98}/V_{10})_{\log} = 1.4 \) (for \( f_{xx^2} \): see text above equation III.4); the immission levels assuming a stable wind profile with \( m = 0.41 \), so \( f_{\text{stable}} = 2.5 = 1.8 \cdot f_{\log} \); the maximum immission levels assuming \( f_{\text{max}} = 3.7 \)
= 2.6·f_{\text{log}}, in agreement with a wind profile (III.2) with \( m = 0.57 \). The best fit of all data points (\( L_{eq,T} \)) in figure IV.6 is \( L_{eq} = 32\cdot\log(V_{10}) + 22 \text{ dB} \) (correlation coefficient 0.80) with \( 1 < V_{10} < 5.5 \text{ m/s} \). This agrees within 0.5 dB with the expected level according to the stable wind profile. The best fit of all 5 minute data-points in figure IV.5B yields the same result.

Thus on location A the highest one hour averaged hub height wind velocities at night are 2.6 times the expected values according to the logarithmic wind profile in formula (III.4). As a consequence, sound levels at (in night-time) frequently occurring wind velocities of 3 and 4 m/s are 15 dB higher than expected, 15 dB being the vertical distance between the expected and highest one-hour immission levels at 3- 4 m/s (upper and lower lines in figures 5B and 6).

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**Figure IV.6:** selected measured sound levels \( L_{eq,T} \) (\( T = 20 – 60 \text{ min} \)) at location A with best fit; and expected sound levels according to a logarithmic wind profile \( (v_{98}/v_{10} = f_{\text{log}} = 1.4) \), a stable wind profile \( (v_{98}/v_{10} = 1.8\ f_{\text{log}}) \) and with the maximum wind speed ratio \( (v_{98}/v_{10} = 2.6\ f_{\text{log}}) \).
The same lines as in figure IV.5B, but valid for location B, are plotted in figure IV.5D; immission levels here exceed the calculated levels, even if calculated on the basis of a 2.6 higher wind velocity at hub height. An explanation may be that a lower ambient sound level is necessary compared to location A to allow wind turbine sound to be dominant at location B (as selected with the $L_5 - L_{95}$ -criterion), implying a lower near ground wind velocity and thus a higher stability. It may also be caused by an underestimate of actual sound level in the calculation model for long distances, at least for night conditions (this issue will be addressed in section IV.10).

As is clear from the wind velocity at 2 m height plotted in figure IV.5B, there is only a very light wind near the ground even when the turbines rotate at high power. This implies that in a quiet area with low vegetation the ambient sound level may be very low. The contrast between the turbine sound and the ambient sound is therefore at night higher than in daytime.

Although at most times the wind turbine sound dominates the sound levels in figure IV.5, it is possible that at low sound levels, i.e. at low rotational speeds and low wind velocities, the $L_5$-$L_{95}$-criterion is met while the sound level is not entirely determined by the wind turbines. This is certainly the case at levels close to 20 dB(A), the sound level meter noise floor. The long term night-time ambient background level, expressed as the 95-percentile ($L_{95}$) of all measured night-time sound levels on location B, was 23 dB(A) at 3 m/s ($V_{10}$) and increasing with 3.3 dB/m-s$^{-1}$ up to $V_{10} = 8$ m/s [Van den Berg et al 2002]. Comparing this predominantly non-turbine background level with the sound levels in figure IV.5B and 5D, it is clear that the lowest sound levels may not be determined by the wind turbines, but by other ambient sounds (and instrument noise). This wind velocity dependent, non-turbine background sound level $L_{95}$ is, however, insignificant with respect to the highest measured levels. Thus, the high sound levels do not include a significant amount of ambient sound not coming from the wind turbines. This has also been verified in a number of evenings and nights by personal observation.
IV.8 Comparison of emission and immission sound levels

From the 30 measurements of the equivalent sound level \( L_{\text{eq},T} \) (with \( T \) typically 5 minutes) measured at distance \( R \) from the turbine hub (\( R \) typically \( 100\sqrt{2} \, \text{m} \)), a relation between sound power level \( L_W \) and rotational speed \( N \) of a turbine could be determined: see formula (IV.3). This relation can be compared with the measured immission sound level \( L_{\text{imm},T} \) (\( T = 5 \) minutes) at location A, 400 m from the wind farm (closest turbine), in 22 cases where the rotational speed was known. The best logarithmic fit for the data points of the immission sound level \( L_{\text{imm}} \) as a function of rotational speed \( N \) is:

\[
L_{\text{imm}} = 57.6 \log(N) - 30.6 \, \text{dB(A)} \tag{IV.4}
\]

with a correlation coefficient of 0.92 and a standard deviation of 1.5 dB with respect to the fit. Both relations from formulae (IV.3) and (IV.4) and the datapoints are given in figure IV.7. The difference between both relations is \( L_W - L_{\text{imm}} = 9.5 \log(N) + 46.0 \, \text{dB} \). For the range 14 – 20 rpm, where both series have data points, the average difference is 57.9 dB, the maximum deviation from this average is 0.8 dB (14 rpm: 57.1 dB(A); 20 rpm: 58.6 dB(A); see lower part of figure IV.7). It can be shown by calculation that about half of this deviation can be explained by the variation of sound power spectrum with increasing speed \( N \).

The sound immission level can be calculated with formula (IV.1). For location A, assuming all turbines have the same sound power \( L_W \), this leads to \( L_W - L_{\text{imm}} = 58.0 \, \text{dB} \). This is independent of sound power level or rotational speed, as it is calculated with a constant spectrum averaged over several turbine conditions, \( i.e \) turbine speeds. The measured difference (57.9 dB) matches very closely the calculated difference (58.0 dB).

The variation in sound immission level at a specific wind velocity \( V_{10} \) in figures IV.5B and IV.5D is thus seen to correspond to a variation in rotational speed \( N \), which in turn is related to a variation in wind velocity.
at hub height, not to a variation in \( V_{10} \). At location A, \( N \) can be calculated from the measured immission level with the help of formula (IV.4) or its inverse form: \( N = 3.4 \times 10^{\frac{L_{\text{imm}}}{57.6}} \).

**Figure IV.7:** turbine sound power levels \( L_W \) measured near wind turbines and immission levels \( L_{\text{imm}} \) measured at 400 m from wind farm: averages differ 57.9 dB; (below) increase of difference \( L_W - L_{\text{imm}} \) with rotational speed (\( L_W \) data points taken from figure IV.3)

### IV.9 Atmospheric stability and Pasquill class

In figure IV.5 measurement data have been separated in two sets according to atmospheric stability in Pasquill classes, supplied by KNMI from their measurement site Eelde, 40 km to the west of our measurement site. Although the degree of stability will not always be the same for Eelde and our measurement location, the locations will correlate to a high degree in view of the relatively small distance between them. For night-time conditions ‘stable’ refers to Pasquill classes E and F (lightly to very stable) and corresponds to \( V_{10} \leq 5 \) m/s and cloud coverage \( C \leq 50\% \) or \( V_{10} \leq 3.5 \) m/s and \( C \leq 75\% \), ‘neutral’ (class D) corresponding to all other situations. Although from figure IV.5 it is clear that the very highest sound levels at an easterly wind (\( \approx 80^\circ \)) do indeed occur in stable conditions, it is also
clear that in neutral conditions too the sound level is higher than expected for most of the time, the expected values corresponding to the grey lines in figures IV.5B and D, derived from daytime conditions. According to this study the sound production, and thus wind velocity at 100 m height is at night often higher than expected, in a stable, but also in a neutral atmosphere. On the other hand, even in stable conditions sound levels may be lower than expected (i.e. below the grey lines), although this occurs rarely. It may be concluded from these measurements that a logarithmic wind profile based only on surface roughness does not apply to the nighttime atmosphere in our measurements, not in a stable atmosphere and not always in a neutral atmosphere when determined from Pasquill classes.

**IV.10 Additional measurements**

In several nights in the period that the SMWS was measuring at location A, manual measurements were performed at a number of locations in the area between 0.6 and 2.3 km west of the wind farm. The locations are plotted in figure IV.2. Most locations were close to dwellings, but two (locations U and X) were in open fields. Locations P and Q are close and at the same distance from the western row of turbines and can be considered equal with respect to the turbines (Q was chosen instead of P as P was at the verge of a garden with a loud bird chorus in the early morning). The surface of most of the area is covered with grass and low crops, with trees at some places. For these measurements one or more logging sound level meters (accuracy type 1 or 2) were used simultaneously, storing a broad band A-weighted sound pressure level every second. Before and after measurement the meters were calibrated with a 94.0 dB, 1000 Hz calibration source, and as a result measurement accuracy due to the instruments is within 0.2 dB. On every location the microphone was in a 10 cm spherical foam wind screen approximately 1.2 m above the surface. There were no reflections of the wind turbine sound to the microphone, except via the ground.
**IV.10.1 Measured and calculated immission sound levels**

Figure IV.8 gives a simultaneous registration from just before midnight on May 17, 2002, till noon on May 18, of the equivalent sound pressure levels per 5 minutes at locations A (from the SWMS), P/Q and U (from the manual meters) at distances to the westernmost row of turbines of 400, 750 and 1050 m, respectively. In the night hours the sound of the turbines was dominant at each of these locations, apart from an occasional bird or car. Also plotted in figure IV.8 are the wind velocity at 2 and 10 m heights at location A.

![Figure IV.8: measured sound immission level (Leq,5mn) at locations A, P/Q, and U, and wind velocities at A with an eastnortheasterly wind](image)

A short decrease in wind velocity at around 2:00 is apparently accompanied by a similar decrease in wind velocity at hub height, as the sound level varies much in the same way. However, the registrations show that the sound level increases from 0:30 until 6:00 while the 10-m wind velocity does not show a net increase in this period. In fact the sound level at location A at 3:00 implies a rotational speed of 21 rpm, which is just below maximum (22 rpm), even though the wind velocity at 10 m height is
only 4.5 m/s and at 2 m height is less than 1 m/s. Only occasionally there are other sounds until the dawn chorus of birds just after 4:00 and after that the near-ground wind picks up.

In figure IV.9 the 5-minute equivalent sound levels at P/Q and U relative to the sound level at A are plotted. The advantage of taking the sound level at A as a reference value is that it is not necessary to know the exact sound power level of the turbines themselves. The level differences are 3.5 and 6.5 dB, respectively, with a variation of ±1 dB. The variations must be due to differences in sound propagation mostly, because other disturbances (such as one at 23:55 at P) are rare.

Comparable simultaneous measurements have been made in the night of June 2 - 3 and of June 17 – 18, 2002. In Appendix C the registrations are given, as well as the level differences between the distant locations P through T, V and X and the reference location A. The measured and calculated decrease in sound level with distance, relative to location A, as well as the discrepancy between both, are given in table IV.4 and figure IV.10. In all cases the wind was easterly (60° – 100°), that is: from the
wind farm to the measurement location. Also there was little near-ground wind and low background sound levels from other sources.

The calculated differences have been determined with equation IV.1 and the Dutch national model [VROM 1999]. The measured differences in table IV.4 are the difference in the equivalent sound level at a location minus the same at location A over the given measurement time T; only very few of the $L_{eq,5min}$ values were omitted from this $L_{eq,T}$ because they were apparently disturbed by another sound. To minimize influence of possible disturbing sounds the median of all $L_{eq,5min}$ values can be used, as this value gives the prevailing difference and is thus less sensitive to the influence of disturbances; this, however, yields the same results within 0.5 dB.

The discrepancies between measured and calculated levels are small, especially considering the large distances involved: -0.2 to 1.5 dB. One may conclude that the calculation model is quite satisfactory in this relatively simple situation (a high sound source above flat ground).

<table>
<thead>
<tr>
<th>location</th>
<th>R</th>
<th>P/Q</th>
<th>U</th>
<th>V</th>
<th>S</th>
<th>X</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>distance to western row wind farm (m)</td>
<td>600</td>
<td>750</td>
<td>1000</td>
<td>1100</td>
<td>1250</td>
<td>1900</td>
<td>2250</td>
</tr>
<tr>
<td>date of measurement (in 2002)</td>
<td>June 2/3</td>
<td>May 17/18, June 2/3 +18</td>
<td>May 17/18</td>
<td>June 18</td>
<td>June 2/3</td>
<td>June 18</td>
<td>June 2/3</td>
</tr>
<tr>
<td>measurement time T (min.)</td>
<td>200</td>
<td>295+200+115</td>
<td>120</td>
<td>140</td>
<td>190</td>
<td>85</td>
<td>195</td>
</tr>
<tr>
<td>measured difference</td>
<td>-3.5</td>
<td>-3.8 *</td>
<td>-6.4</td>
<td>-9.1</td>
<td>-8.5</td>
<td>-12.1</td>
<td>-1.3</td>
</tr>
<tr>
<td>calculated difference</td>
<td>-4.5</td>
<td>-4.1</td>
<td>-6.6</td>
<td>-10.6</td>
<td>-8.3</td>
<td>-13.1</td>
<td>-14.2</td>
</tr>
<tr>
<td>discrepancy calculation - measurement</td>
<td>-1.0</td>
<td>-0.3</td>
<td>-0.2</td>
<td>-1.5</td>
<td>0.2</td>
<td>-1.0</td>
<td>-12.9</td>
</tr>
</tbody>
</table>

*: measurement time weighted logarithmic average of resp. 3.5, 3.6 and 4.6 dB
In figure IV.10 a line is plotted corresponding to \(-20\cdot\log(R/R_a)\), where \(R_a\) is the distance from A to the western turbine row. This decrease corresponds to spherical divergence from a point source only, with no attenuation due to absorption. It is clear that, with the exception of location T (see next section), the measured decrease is close to this spherical divergence: the measured values at the locations P/Q, U, S and X are 1.4 to 1.7 dB above the plotted line, at the more northern locations R and V they are 0 to 0.3 dB below the line. Approximately the same is true for the calculated levels: the calculated values at the locations P/Q, U, S and X are 0.4 to 1.6 dB above the plotted line, at the more northern locations R and V they are 1.0 to 1.8 dB below the line.

There are two counteracting causes explaining this apparently ‘almost spherical’ attenuation. The first is that the wind farm cannot be considered a point source. Due to its large dimension (3 km from south to north, see figure IV.2) normal to the shortest distance from location A and locations further west, the geometrical divergence should be between cylindrical and...
spherical divergence, that is: proportional to \(-X \cdot \log(R/R_A)\), with \(10 < X < 20\). Secondly one expects a decrease due to absorption ('excess attenuation') above the decrease due to geometrical divergence: for the Rhede turbines calculation shows that this excess attenuation is expected to be 1.7 dB per km.

**IV.10.2 Immission level increase due to inversion layer?**

In the night of June 2 to 3, 2002, high sound levels were measured at the most distant measurement location T, 2250 m from the wind farm. The immission sound level varied between approximately 40 and 45 dB(A) and was more variable than at the other locations (see Appendix C). The resident close to this measurement location could hear the wind farm well, at 22:30 hours describing it as: “The sound changes from ‘an endless train’ to a more pulsating sound; the sound grows louder en sharper. At the background is a kind of humming, comparable to the sound of a welding transformer”. The sound was audible indoors.

In our research we have not met this phenomenon again. However, mr. Flight living near another wind farm south of the Rhede wind farm observed the same phenomenon: on a location appr. 750 m from the closest turbine, where at night he usually measured an immission level of 42 to 44 dB(A), he measured a level of 50 to 52 dB(A) in the night of September 24, 2002. It was clear that the sound came from the nearest wind farm, but also from a second, more distant wind farm that usually was not audible here. Again, the atmosphere was stable and there was a weak near-ground easterly wind, blowing from the wind farm to the observer.

This may be a result of strong refraction of sound below an inversion layer. This inversion layer must be at or above the rotor to have the highest effect, so at or above 130 m (= hub height + blade length).

Suppose the turbines in the Rhede wind farm each have a sound power level \(L_W\) at a certain wind velocity. If we substitute the entire farm by one single turbine at the site of the turbine closest to location T (nr. 12), it can be calculated that the sound level of that single turbine must be \(L_W + 9.4\) to produce the same immission level at T as the entire wind farm.
Considering only spherical spreading, this immission level is \( L_{\text{imm}} = L_W + 9.4 - 10 \cdot \log(4\pi \cdot 2250^2) = L_W - 68.6 \). Now the sound waves will be refracted downwards at the inversion layer and we assume that all sound propagates below the inversion layer. At large distances (\( \gg \) height inversion layer) this is equivalent to sound spreading cylindrically from a vertical line source. To simulate this we replace the substitute single turbine, which was modelled as a point source at hub height, by a vertical line source from the ground up to the inversion layer height (130 m). If the sound power levels of both point and line source are equal, the line source must have a sound power level of \( L_W' = L_W + 9.4 - 10 \cdot \log(130) = L_W - 11.7 \) dB/m. If again the sound level decreases by geometrical (now: cylindrical) spreading only, the sound immission level at 2250 m from this line source is \( L_{\text{imm}}' = L_W - 11.7 - 10 \cdot \log(2 \cdot 2250) = L_W - 54.6 \) dB. Comparison of the immission level due to a point source \( (L_W - 68.6) \) and a line source \( (L_W - 54.6) \) shows that the line source causes a 14 dB higher immission level. This simple calculation shows that the rise in level caused by a simplified high inversion layer is close to the observed increase (13 dB): the higher level is a result of the sound being 'trapped' below the inversion layer. However, more observations and data are needed to verify this hypothesis.

### IV.11 Conclusion

Sound immission measurements have been made at 400 m (location A) and 1500 m (location B) from the wind farm Rhede with 17 tall (98 m hub height), variable speed wind turbines. It is customary in wind turbine noise assessment to calculate immission sound levels assuming wind velocities based on wind velocities \( V_{10} \) at reference height (10 m) and a logarithmic wind profile. Our study shows that the immission sound level may, at the same wind velocity \( V_{10} \) at 10 m height, be significantly higher in nighttime than in daytime. A 'stable' wind profile predicts a wind velocity \( V_h \) at hub height 1.8 times higher than expected and agrees excellently with the average measured nighttime sound immission levels. Wind velocity at hub height may still be higher: at low wind velocities \( V_{10} \) up to 4 m/s, the wind velocity \( v_h \) is at night up to 2.6 times higher than expected.
Thus, the logarithmic wind profile, depending only on surface roughness and not on atmospheric stability, is not a good predictor for wind profiles at night. Especially for tall wind turbines, estimates of the wind regime at hub height based on the wind velocity distribution at 10 m, will lead to an underestimate of the immission sound level at night: at low wind velocities ($V_{10} < 5$ m/s) the actual sound level will be higher than expected for a significant proportion of time. This is not only the case for a stable atmosphere, but also -to a lesser degree- for a neutral atmosphere.

The change in wind profile at night also results in lower ambient background levels then expected: at night the wind velocity near the ground may be lower than expected from the velocity at 10 m and a logarithmic wind profile, resulting in low levels of wind induced sound from vegetation. The contrast between wind turbine and ambient sound levels is therefore at night more pronounced.

Measured immission sound levels at 400 m from the nearest wind turbine almost perfectly match (average difference: 0.1 dB) sound levels calculated from measured emission levels near the turbines. From this it may be concluded that both the emission and immission sound levels could be determined accurately, even though the emission measurements were not fully in agreement with the standard method. As both levels can be related through a propagation model, it may not be necessary to measure both: the immission measurements can be used to assess immission as well as emission sound levels.

At greater distances the calculated level may underestimate the measured level, but considering the distances involved (up to 2 km) the discrepancy is small: 1.5 dB or less.

In one night the sound level at a distant location (over 2 km from the wind farm) was much higher than expected, perhaps because of an inversion layer adding more downward refracted sound. It apparently is a rare occurrence at the Rhede wind farm, and could be more significant where high inversion layers occur more often.