

**First International Meeting
On
Wind Turbine Noise: Perspectives for Control
Berlin 17th and 18th October 2005**

**The Use of 10 m Wind Speed Measurements in the Assessment
of Wind Farm Developments**

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Summary

Most wind turbine manufacturers provide the sound power level (L_{WA}) of their turbines in accordance with IEC61400-11 [1]. This requires the L_{WA} to be reported against a wind speed at a height of 10 m above ground level (agl). Since the turbine source noise is given at 10 m agl, noise predictions and planning limits are often also undertaken against wind speeds at a height of 10 m agl. This use of a 10 m reference height for wind speed measurements during acoustic measurements of wind turbines seems largely historic and may have been appropriate for the tower heights at the time. Today's wind turbines are generally much taller and the reference height of 10 m is perhaps no longer appropriate.

The relationship between the wind speed at a height of 10 m and that at the hub height of a turbine (the wind speed profile or wind shear) is not constant and is not simply a function of the site surface roughness, Z_0 , as expressed by the logarithmic wind speed profile and used in the IEC 61400-11 standard. The site wind speed profile is dependent on the site topography, wind direction and atmospheric conditions.

This paper examines the wind speed profiles at four sites that have the same surface roughness, based on a physical examination of the site. Two of the sites are in flat terrain in Australia and two in complex terrain in New Zealand. It shows that as the wind speed profiles vary significantly between the four sites and with time of day at a given site, the use of surface roughness to determine wind speeds for wind farm acoustic assessment can lead to errors.

The paper proposes that hub-height wind speeds should be used for the entire acoustic assessment of both wind turbines (sound power level determination) and wind farms (prediction and measurement), and outlines the advantages of this approach.

1. Introduction

The majority of standards and guidelines [1,2,3,4] that set out procedures to determine the sound power level (L_{WA}) of a wind turbine, require that the results be reported against a wind speed at a height of 10 m above ground level (agl). The first version of IEC 61400-11 required that the results be reported at 8 m/s at 10 m agl and this was referred to as the reference conditions. The 2002 version of this same standard requires the results to be reported at wind speeds of 6 to 10 m/s, all referenced to a height of 10 m above ground level.

Since the sound power level of a wind turbine is reported against a wind speed at 10 m agl, this same wind speed measurement height is often used when predicting noise from a proposed wind farm development. In many instances it also becomes a wind speed measurement height against which planning conditions are assessed.

This paper outlines the typical steps in assessing the noise from a wind farm which are influenced by the assumptions made on the wind speed variations with height (wind speed profile). Measured wind speed records have been analysed in order to make a comparison against theoretical wind speed profiles.

2. The typical phases in wind farm noise assessments and the 10 m wind speed reference height

Typically there are three distinct phases required to complete the assessment of the noise from wind farms. These are:

- I. Wind turbine manufacturers measure and provide the sound power level of their turbines. These are typically measured in accordance with IEC 61400-11.
- II. Wind farm developers undertake wind farm noise predictions using the sound power level information provided by the wind turbine manufacturers and a suitable noise propagation model.
- III. Local authorities require that the wind farm developer demonstrates compliance with the limits placed on the wind farm development, through measurements conducted after the wind farm is operational.

As the sound power level of a wind turbine is dependent on its power output, and therefore the hub height wind speed, it is important that the height above ground level of the wind speed measurement, in each of the three phases above, is clearly defined and consistent. Typically most noise predictions and assessments are done relative to a wind speed at 10 m agl, primarily because this is the height of the wind speed required to be reported by IEC 61400-11 [1]. Other guidelines and standards such as AWEA [2] and IEA [3] also require sound power level measurements to be reported against a wind speed at 10 m agl.

At the time that these standards and guidelines were first developed, wind turbine hub heights were significantly lower than they are today. As a consequence, the

uncertainty in determining a hub height wind speed, at 30 m or 40 m, from a 10 m wind speed to was not significant. Hub heights of wind turbines today are significantly greater and turbine hub heights in excess of 70 m are common for megawatt class turbines.

Additionally, measurements taken for wind resource monitoring purposes have shown that the relationship between hub height wind speeds (40 m to 80 m) and the wind speed at 10 m is not constant and dependent on surface roughness alone. Atmospheric stability, wind direction and the topographical changes in the vicinity of a wind turbine will also influence the rate of change in wind speed with height above ground level.

3. The IEC 61400-11 sound power level measurement procedure

During the measurement of a wind turbine's sound power level, as per IEC 61400-11:2002, wind speeds can be derived in one of two ways.

- I. Method 1. Determination of the wind speed from the electric output and the power curve.
- II. Method 2. Determination of the wind speed with an anemometer positioned between 10 m and the wind turbine hub height.

Method 1 is the preferred method and is mandatory for certification and declaration of measurements. It is interesting to note that this method suggests that it is preferable to use a power curve measured in accordance with IEC61400-12 [5] and preferably for the same wind turbine. IEC61400-12 requires a hub height anemometer to be used for the derivation of the power curve and therefore if both preferences of Method 1 of IEC61400-11 are being complied with, it is very likely that a hub height anemometer would be situated nearby.

Irrespective of which method is used to determine the wind speeds in accordance with IEC61400-11, an anemometer is required (of height between 10m and hub height) to determine the wind speeds while the wind turbine is shut-down. The shut-down measurements are used to determine the background noise levels in order to make a correction for the background noise levels while the wind turbine is operating.

Assuming the preferred method of wind speed derivation is used under IEC 61400-11 (Method 1), the hub height wind speeds (derived from the power curve) are then converted to 10 m high wind speeds simply using the reference surface roughness Z_{0ref} of 0.05 m. If wind speed measurements are recorded at any height between 10 m and hub height, they are corrected to hub height using the site roughness length Z_0 and then converted to 10 m wind speeds using the reference surface roughness Z_{0ref} of 0.05m. Note that these 'two' conversions are done together using equation (7) in IEC 61400-11:2002.

In effect, the 10 m reference wind speeds against which the sound power levels are reported are reliant on the relationship between the 10 m and hub height wind

speeds being well defined by the visual assessment of the site surface roughness. This is not always the case as is discussed in Section 6.

4. Shortcomings of the IEC61400-11 methodology

In IEC61400-11, where wind speed measurements are corrected to hub height using the surface roughness, there is a probability that they are not consistent with the wind speed derived from the power curve. Where any wind speed measurements are derived from an anemometer at a height other than at hub height (Method 2) their absolute value may not be entirely correct as the logarithmic extrapolation method is not precise. The logarithmic wind speed profile assumed can have an effect on the reported sound power level, irrespective of which method of wind speed determination is used.

Since the preferred method of wind speed determination in IEC61400-11 is via the wind turbine power curve, it only requires the acoustic assessment of the wind turbine up to a wind speed of 95% of rated power. The correlation between the sound power level of the turbine and the electrical output is low beyond the rated power of the turbine. This is a shortcoming of the Standard as there are some wind turbines which have an increased sound power level when the turbine reaches rated power and starts to limit its power output. If hub height wind speed measurements were mandatory, the wind speed range against which the sound power levels were reported, could be extended.

5. The logarithmic wind speed profiles

The logarithmic wind speed profile that is used to extrapolate wind speeds from one height to another (as in IEC61400-1) is defined as follows:

$$V = V_{\text{ref}} * \ln(Z/Z_0) / \ln (Z_{\text{ref}} / Z_0) \quad \dots\dots\dots\text{equation (1)}$$

Where

V = wind speed at height Z
 V_{ref} = wind speed at height Z_{ref}
 Z = height above ground level
 Z_0 = surface roughness

Clearly this equation describes the relationship between two different height wind speeds as a function of the surface roughness alone. While this function may be appropriate on an average basis (e.g. over a year) it is not as robust when converting 10 m high wind speeds to their hub height equivalents for the purposes of sound power level certification or assessment. This is discussed further in Section 6.

6. Wind profile examination

To investigate the variation of the logarithmic wind speed profile, data for a year at three sites and data for 8 months at a fourth site have been analysed. For all four sites 10-minute wind data records at hub height (50 m to 80 m) have been monitored simultaneously with wind speeds typically at a height of 10 m and in one case 15 m. The sites were situated in both New Zealand and Australia and covered both flat and complex terrain.

The four sites at which data has been monitored and analysed are listed in Table 1.

Site Name	Wind speed measurement heights	Data period	Location	Topography
Site 1	80 m, 10 m	1 year	Australia	Flat site
Site 2	50 m, 10 m	1 year	Australia	Flat site
Site 3	70 m, 15 m	8 months	New Zealand	Complex terrain
Site 4	40 m, 10 m	1 year	New Zealand	Complex terrain

Table 1. Data at which wind speed profiles were examined

For each of the 4 sites, the mean wind speeds at the two heights were used to calculate the theoretical site surface roughness based on equation 1. Using the calculated surface roughness for the site, the logarithmic wind speed profile was drawn for each of the four sites and is shown in Figure 1. The calculation of the site surface roughness was then repeated using only the day time data (06h00 to 22h00) and the night time data (22h10 to 05h50). Each of the logarithmic profiles were added to the charts in Figure 1.

In addition to the calculated logarithmic profiles, the wind speed profiles based on the observed site surface roughness ($Z_0 = 0.03\text{m}$), which were used for wind flow modelling, and the IEC61400-11 reference surface roughness $Z_0 = 0.05\text{m}$ have been plotted. The calculated surface roughness values are listed in Table 2.

Site Name	All time	Day time	Night time	Observed from terrain
Site 1	0.1741	0.0513	0.7834	0.03
Site 2	0.1262	0.0499	0.4752	0.03
Site 3	0.0011	0.0006	0.0029	0.03
Site 4	0.0007	0.0005	0.0014	0.03

Table 2. Calculated surface roughness lengths from site measurements

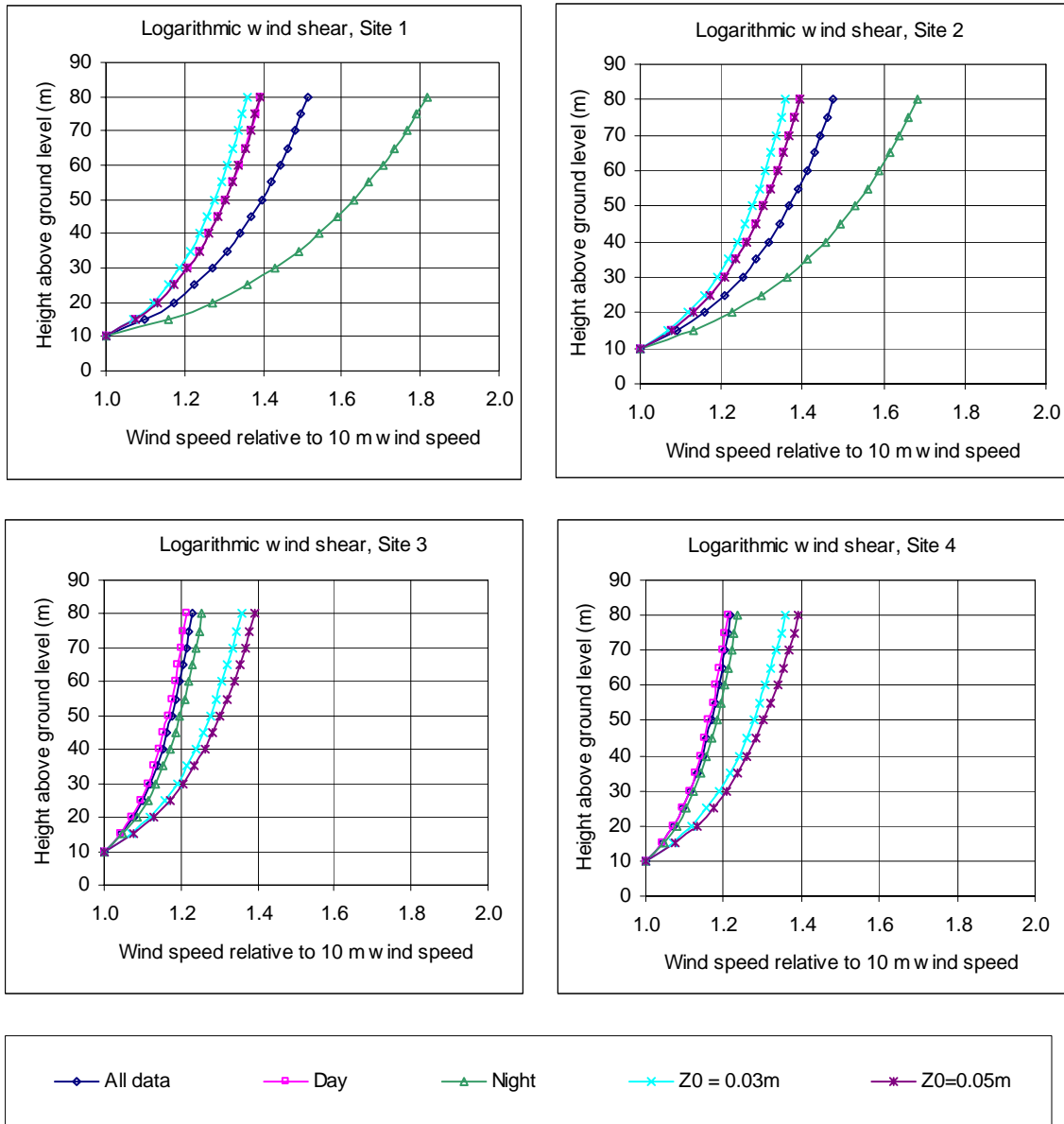


Figure 1. Logarithmic wind speed profiles at 4 different sites.

Some observations that can be made from the results shown in Figure 1 are:

- In all cases the wind speed profile based on the observed site surface roughness is different to the measured “all data” wind profile.
- Using the wind speed profile based on the estimated site surface roughness significantly under-estimates the hub height wind speed at night at the two Australian sites (flat terrain).
- The wind speed profile based on the estimated site surface roughness is similar to the measured day time wind speed profile for the two Australian sites.
- There is a significant difference between the day and night profiles at the two Australian sites.

- The estimated site surface roughness over-estimates the hub height wind speed at both New Zealand sites (complex terrain sites).
- There is very little difference between the day and night wind speed profiles at the two New Zealand sites.
- In all cases, the differences that are identified are greater for higher wind turbine hub heights.

From Figure 1 it is evident that the actual wind speed profile at a particular site is not simply a function of the estimated surface roughness but is dependant on both atmospheric conditions (stability) and the site topography and wind direction.

7. The influence of wind speed height in noise propagation modelling

When noise modelling is undertaken for a potential wind farm site, the wind speed for which the results have been produced needs to be stated. If a developer is undertaking and presenting wind farm noise predictions for a given hub height wind speed, they simply use the L_{WA} of the turbine, provided in accordance with IEC61400-11 and correct the wind speed to hub height using the reference surface roughness $Z_0 = 0.05m$. For example, for a 70 m hub height wind turbine, the IEC61400-11 10 m reported wind speeds translate to those in Table 3. This is in effect the reverse of how the wind speeds were initially derived from the wind turbine power curve.

Reference Wind speed (at 10 m) (m/s)	70m hub height wind speed (m/s)
6	8.2
7	9.6
8	10.9
9	12.3
10	13.7

Table 3. 70 m equivalent wind speeds based on $Z_{0,ref} = 0.05m$

If the developer is calculating and presenting wind farm noise predictions with reference to 10 m high wind speeds, they are required to convert the IEC61400-11 wind speeds to hub height (again using $Z_0 = 0.05m$) and then correct them a second time to a site specific 10 m wind speed value using the site specific surface roughness or the measured wind speed profile. Representing the noise predictions as a function of a 10 m value creates uncertainties where the wind speed profile at the site varies between day and night. One solution would be to provide two sets of predictions, one for each wind speed profile, however this can be eliminated if noise predictions are done for a specific hub height wind speed.

It should be noted that if the wind speeds, at which predictions are made, are converted to 10 m wind speeds, they are only valid for times when the relationship

between wind speed at hub height and 10 m are as per those used in their conversion. As shown in Section 6, the relationship between wind speeds at two different levels is not constant and can vary by time of day, wind direction and site topography.

Clearly there are advantages in presenting wind farm noise predictions as a function of the hub height wind speed as the predictions will always be valid for the stated wind speed. Additionally it doesn't rely on the estimate of the site surface roughness when presenting the results.

There have been two papers [6,7] published that suggest that wind farm noise predictions are inaccurate especially under stable atmospheric conditions, which can occur at some locations more frequently at night. As shown in Figure 1, the wind speed profile often varies between day and night at some sites and furthermore the profile varies between sites which appear to have the same surface roughness. In the Rhede wind farm example referenced in [6,7] it is perhaps not so much that the noise predictions were inaccurate but that the assumptions made on the wind speed profile were inaccurate for the reasons outlined above. If the wind farm was required to meet a planning limit based on a hub height wind speed rather than a 10 m high wind speed this would have required the wind farm to meet the planning noise limit irrespective of the site wind speed profile.

From the analysis completed in Section 6 and shown in Figure 1, for an 80 m hub height wind speed of 15 m/s at night, the error in the hub height wind speed estimate could have been 3.6 m/s. This in turn would have led to an error in the sound power level assumption, the extent to which would have been dependant on the particular turbine type being used.

8. Setting limits based on hub height wind speed rather than 10 m

As has been shown in Section 6 the relationship between the wind speed at 10 m agl and hub height may not be constant at a particular site. Likewise, for sites of the same surface roughness the wind speed profiles can be quite different. It is important also to note that it is the hub height wind speed and not the 10 m wind speed that dictates the sound power level of a wind turbine.

Where noise limits are placed on a wind farm and are assessed against a 10 m wind speed measurement height, the wind farm developer needs to be aware of the actual relationship between the 10 m wind speed and that at hub height for a range of atmospheric conditions to ensure that the noise levels are met under the range of wind speed profiles experienced at the site.

An approach that is used in the UK [8], New Zealand [9], Australia [10] and the Netherlands [11], is to set the wind farm limit as a function of the background noise level that exists prior to the wind farm being installed. This typically requires background levels to be measured prior to the wind farm installation and background plus wind farm levels to be measured once the wind farm is operational. In both cases, the noise levels are plotted against wind speeds recorded simultaneously with

the noise measurements. Ideally these wind speeds measurements should be those at the hub height of the wind turbines, however a height of 10 m is regularly used. Again this height appears to be adopted only since the wind turbine sound power levels are listed against 10 m high wind speeds. These could just as easily be plotted against hub height wind speeds.

In cases where the background noise levels are plotted against hub height wind speed, the noise measurements should include the representative range of wind speed profiles experienced at the site. Typically, best practice is to divide the data (and therefore the compliance limit) into day and night too. Furthermore if the background noise levels are plotted against the site hub height site wind speed, it eliminates the problems that occur at sites where the wind speed profile changes due to atmospheric stability, wind direction and site topography.

9. Conclusions

The historical use of 10 m high wind speed measurements for the acoustic assessment of both wind turbines and wind farms has the ability to create inaccuracies and sometimes confusion around sound power levels, noise predictions and even demonstration of wind farm compliance. The use of 10 m high wind speed measurements appears to be largely historic and there are advantages in using hub height wind speeds throughout the noise assessment process.

In the determination of the sound power level of a wind turbine in accordance with IEC61400-11, the use of the surface roughness to determine the hub height wind speed has the ability to introduce errors into the measurement procedure. Hub height wind speeds should be required and these could be obtained either from the nacelle anemometer or, if possible, a hub height anemometer that was used in the measurement of the power-curve of the wind turbine. Consideration should also be given to determining the sound power level of turbines to beyond their rated power, since some wind turbines increase their sound power level once they start to control their power output.

For wind farm noise compliance measurements the hub height wind speed can be derived from either the power curve of the operational wind turbine, the nacelle anemometer or a wind farm meteorological monitoring mast. Where hub height wind speeds are required prior to the wind farm installation, these are more reliably obtained from coincident measurements at two heights (e.g. 10 m and 50 m) rather than based on surface roughness wind speed corrections.

There are already wind turbine manufacturers that provide their sound power levels as a function of the hub height wind speed and to beyond rated power. There are advantages to developers in having that information and it would be beneficial if this was a mandatory requirement within IEC61400-11.

The continued use of a wind speed reference height of 10 m used in IEC61400-11 appears largely historical and with increasing turbine hub heights there are good reasons why this should now be changed.

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