3D Turbulence

at the Offshore Wind Farm Egmond aan Zee

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Abstract
NoordzeeWind carries out an extensive measurement and evaluation program as part of the Offshore Wind farm Egmond aan Zee (OWEZ) project. The technical part of the measurement and evaluation program considers topics as climate statistics, wind and wave loading, detailed performance monitoring of the wind turbines, etc. The datasets are available in the public domain.

The data considered in this report are taken from sonic anemometers. From measurements the 3D turbulence components are extracted: longitudinal, lateral and normal. In this report the three turbulence components are considered at three different heights. It has been regarded when the meteorological mast is in the wake of the wind farm and when the turbines are producing power or not.

The possibilities to compute coherences are discussed as well.

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List of symbols

σ	Standard deviation of wind speed	m/s
Long	Longitudinal wind speed	m/s
Lat	Lateral wind speed	m/s
Norm	Normal wind speed	m/s
α	Angle between vertical axis and the line through two anemometers	degrees

1. Introduction

NoordzeeWind (NZW) carries out an extensive measurement and evaluation program (NSW-MEP) as part of the OWEZ project. NoordzeeWind contracted Bouwcombinatie Egmond (BCE) to build and operate an offshore meteorological mast at the location of the OWEZ wind farm. BCE contracted Mierij Meteo to deliver and install the instrumentation in the meteorological mast. After the data have been validated, BCE delivers the measured 10-minute statistics data to NoordzeeWind. ECN created a database under assignment of NoordzeeWind and fills the database with the delivered data. NoordzeeWind contracted ECN to report the data.

The technical part of the measurement and evaluation program considers topics as climate statistics, wind and wave loading, detailed performance monitoring of the wind turbines, etc. A 116m high meteorological mast has been installed to measure the wind, water and wave conditions. This mast is in operation since the summer of 2005 and the measurements have been made available by NoordzeeWind. The requirements are specified in the measurement and evaluation program [1]. This report deals with item 1.2.1 Ad 15, which addresses 3D turbulence.

The data used in this report come from the 116m high meteorological mast at the offshore wind farm location OWEZ, for which the instrumentation is described in [2]. More specifically, the wind data are taken by anemometers and vanes, attached to booms of the mast at 116m, 70m (hub height) and 21m above MSL. To determine the turbulence, data from the sonic anemometers on the North-West booms of the mast are used. Data are available from the 1st of May 2007 until the 27th of December 2008. A total of 84853 data points are used.

This report is set up as follows: In section 2 the turbulence components are regarded with respect to the wind speed. Also, distinction is made whether the meteorological mast is in the wake of the turbines or not. Section 3 gives an angular description of the turbulence components. A selection on power producing turbines is made. The possibilities to compute coherences are discussed in section 4 and the main conclusions are summarised in section 5.

2. 3D Turbulence and Wind speed

From the data of the sonic anemometers on the meteorological mast 3 wind speed components are constructed: the longitudinal wind speed, the lateral wind speed and the normal wind speed. These wind speed components are defined as follows: From given 10min time series the mean (3d) wind speed vector is determined. The longitudinal wind speed is defined to be aligned along this mean (3d) wind speed vector and the lateral wind speed is perpendicular to the longitudinal wind speed, lying in the horizontal plane. The remaining normal wind speed is perpendicular to both the longitudinal and the lateral wind speed. We note here that with this definition the longitudinal wind speed need not necessarily lie in the horizontal plane; it is tilted from this plane with the inflow angle. The same applies to the normal wind speed: this wind speed component need not necessary be aligned with the vertical axis, but is tilted from this with the inflow angle. So, with this definition the wind speed components may differ (depending on the inflow angle) from ordinary horizontal and vertical wind speed components. This is illustrated in Figure 2.1. The motivation for this is that, now, the longitudinal wind speed really is along the mean 3d wind speed vector. This definition is also recommended in [3] as far as 3d turbulence is concerned.

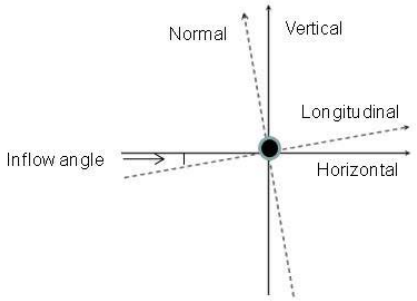


Figure 2.1 *Vector graph of longitudinal and normal wind speed components (dotted arrows) versus horizontal and vertical wind speed components (straight arrows) The former is tilted with respect to the latter with the inflow angle. The black dot in the middle indicates the lateral wind speed component and is pointing inwards the graph*

From the 10min time series of all three wind speed components the mean and the standard deviation is determined. The standard deviations are considered to be measures of the 3D turbulence.

In Figure 2.2 the standard deviations of the three wind speed components are given as function of the mean longitudinal wind speed for all three heights. The left plots show the scatter data and the right plots the binned values. Here, the data have been binned according to the longitudinal wind speed, with bin sizes of 1 m/s.

From the binned data we see that, generally, the standard deviations of the three wind speed components increase with increasing mean longitudinal wind speed and that the standard deviations decrease with increasing height. We also see that the longitudinal standard deviation is larger than the lateral standard deviation, which, on its turn, is larger than the normal standard deviation.

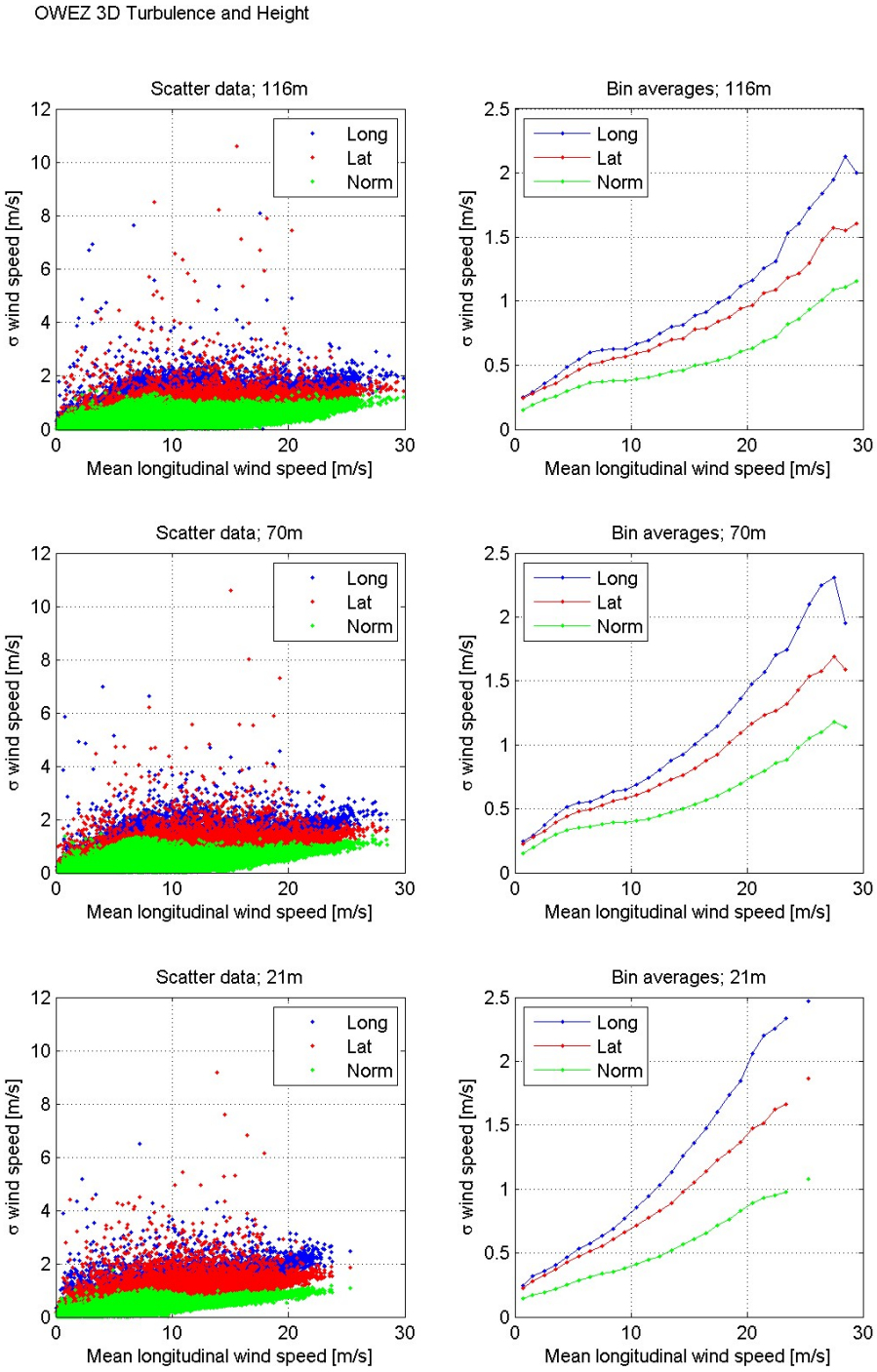


Figure 2.2 *Standard deviation of the longitudinal (blue), lateral (red) and normal (green) wind speed as function of the mean longitudinal wind speed at 116m (upper plots), 70m (middle plots) and 21m (lower plots). The left plots show scatter data and the right plots binned values.*

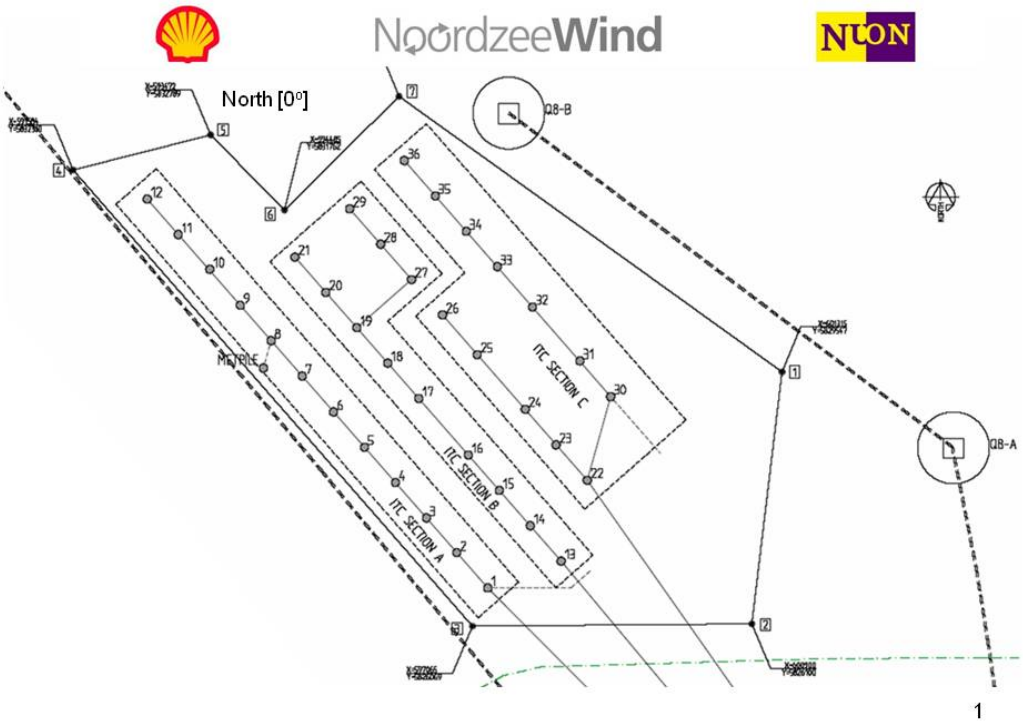


Figure 2.3 *OWEZ wind farm lay-out*

For the data used for Figure 2.2 all wind directions are considered. However, for some wind directions the meteorological mast is in the wake of the wind farm. As can be read in [4] this happens for wind directions between 143 and 316 degrees based on IEC 61400-12-1. The selection of data where the mast is in or out of the wake of the farm has been done based on the wind direction[1] at 70m (hub height). For clarification a lay-out of the OWEZ wind farm is given in Figure 2.3.

In Figure 2.4 the standard deviations of all three wind speed components are again given as function of the mean longitudinal wind speed for all three heights. Binned values are considered, where distinction has been made whether the mast is in the wake of the wind farm or not. We see that the standard deviations are in all cases higher when the mast is in the wake of the farm. Some exceptions occur at higher longitudinal wind speeds.

[1] This wind direction is a constructed signal where mast distortion has been minimized. See [5] and subsequent half year reports for more detail.

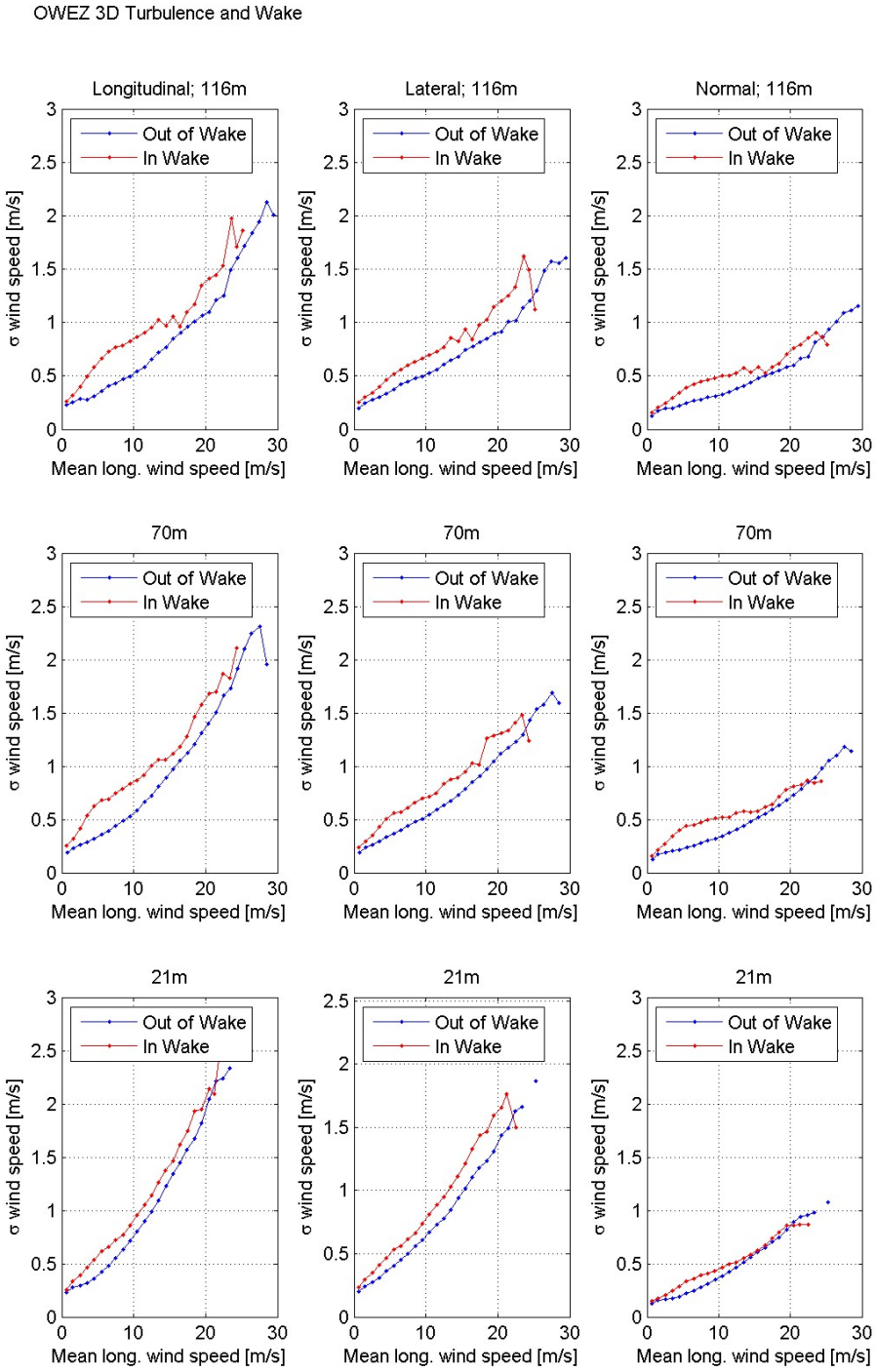


Figure 2.4 *Longitudinal (left plots), lateral (middle plots) and normal (right plots) standard deviation as function of the mean longitudinal wind speed at 116m (upper plots), 70m (middle plots) and 21m (lower plots). Distinction has been made whether the mast is in the wake of the farm (red) or not (blue).*

3. 3D Turbulence and Wind direction

In Figure 3.1 the standard deviations of the three wind speed components are given as function of the wind direction for all three heights. The left plots show the scatter data and the right plots the binned values. Here, the data have been binned according to the wind direction, with bin sizes of 5 degrees.

The plots with the binned values, especially for 70m and 116m, are in shape comparable to the plots presented in [6][2] (and subsequent half year reports) for the average turbulence intensity. (Multiple) Turbine wake effects are supposed to be at 16, 67, 88, 102 and 340 degrees [2]. These can be recognised in Figure 3.1. Here, we also have to note that the sonic anemometers are on the North-West boom, only. Therefore, these anemometers experience the wake of the mast (~90 degrees to ~150 degrees).

3.1 Power producing wind turbines

When the meteorological mast is in the wake of the wind farm it may still matter whether the turbines are in a power producing mode. As can be read in [4], based on IEC 61400-12-1 regulations, only the turbines 5-10 and 18-21 are too close to the meteorological mast and therefore influencing wind measurements. These turbines are considered when distinction is made whether turbines are producing power or not.

In Figure 3.2 the same plots are shown as the right plots in Figure 3.1, but now distinction is made whether the turbines are producing power (right plots) or not (left plots). Turbine wake effects are much better seen in the right plots. We also see that, generally, the turbulence levels are much higher when the turbines are on. Furthermore, we notice a large peak around 200-220 degrees in the left plots, i.e. when the turbines are off. Concerning the last two issues we note that a selection on power producing turbines is to a big extend also a selection on wind speed, namely turbines are only producing power between cut-in (4 m/s) and cut-out (25 m/s) wind speed. The low level of the standard deviations of the wind speed components in the left plots as compared to those in the right plots may (partially) be explained by the presence of a large number of low wind speed (<4 m/s) data points. As Figure 2.2 points out a low wind speed corresponds to a low standard deviation. The peak around 200-220 degrees in the left plots of Figure 3.2 is explained by the presence of high wind speeds (>25 m/s), which have occurred for those wind directions.

As an attempt to account for this implicit wind speed selection Figure 3.3 gives turbulence intensities as function of the wind direction. Here, turbulence intensities are defined as the standard deviations of the longitudinal wind speed (blue), the lateral wind speed (red) and the normal wind speed (green) divided by the mean longitudinal wind speed. We, indeed, notice that the peak around 200-220 degrees has disappeared. Although the differences have become smaller the turbine wake effects are still better seen when the turbines are on. However, contrary to the plots in Figure 3.2 we now notice, especially in the undisturbed sector, that the turbulence intensity levels are lower when the turbines are on. Most probably the implicit wind speed selection still plays a role.

[2] In this reporting period the turbines are fully active over the entire period for the first time [4].

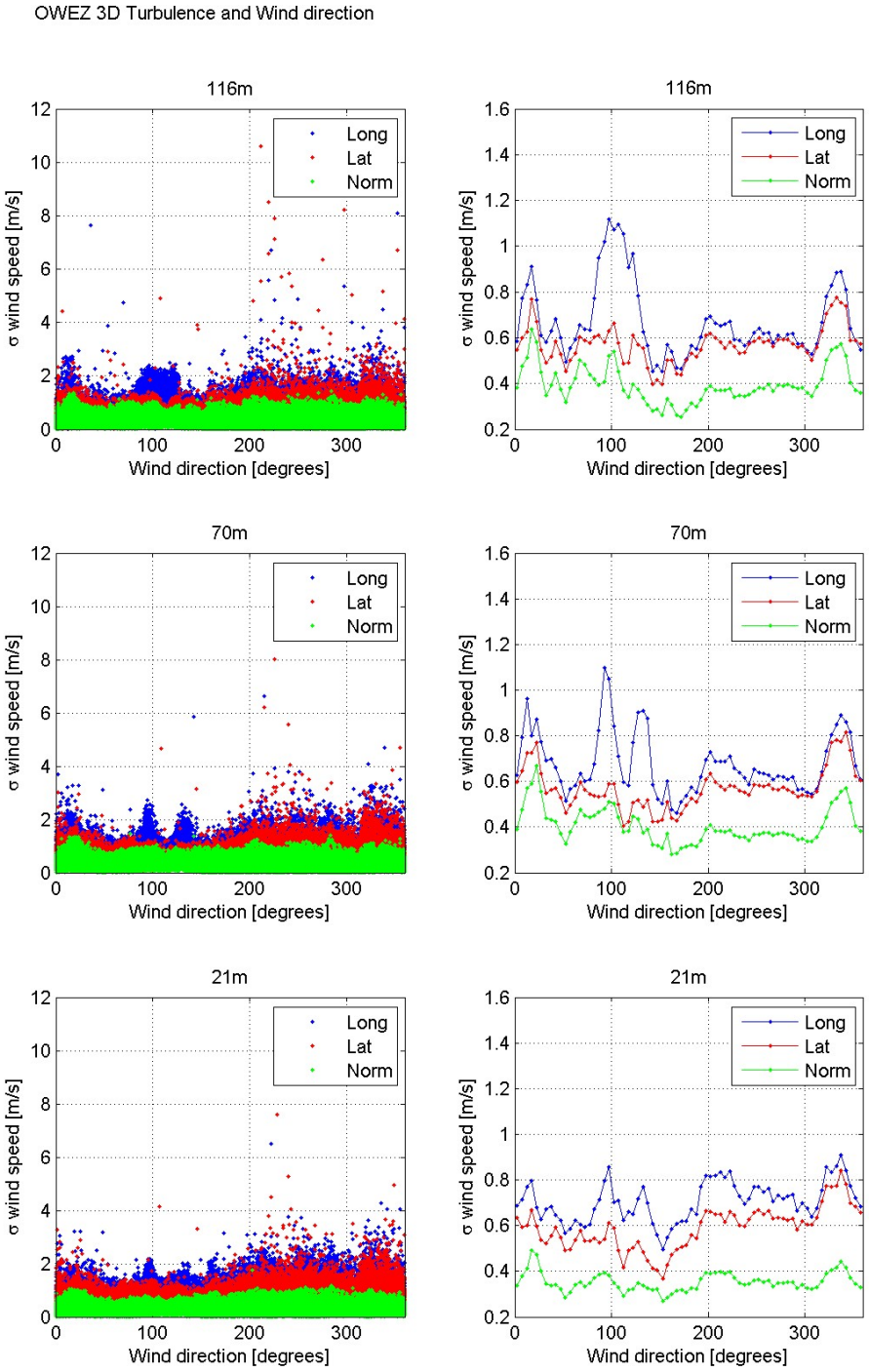


Figure 3.1 *Standard deviation of the longitudinal (blue), lateral (red) and normal (green) wind speed as function of the wind direction at 116m (upper plots), 70m (middle plots) and 21m (lower plots). The left plots show scatter data and the right plots binned values.*

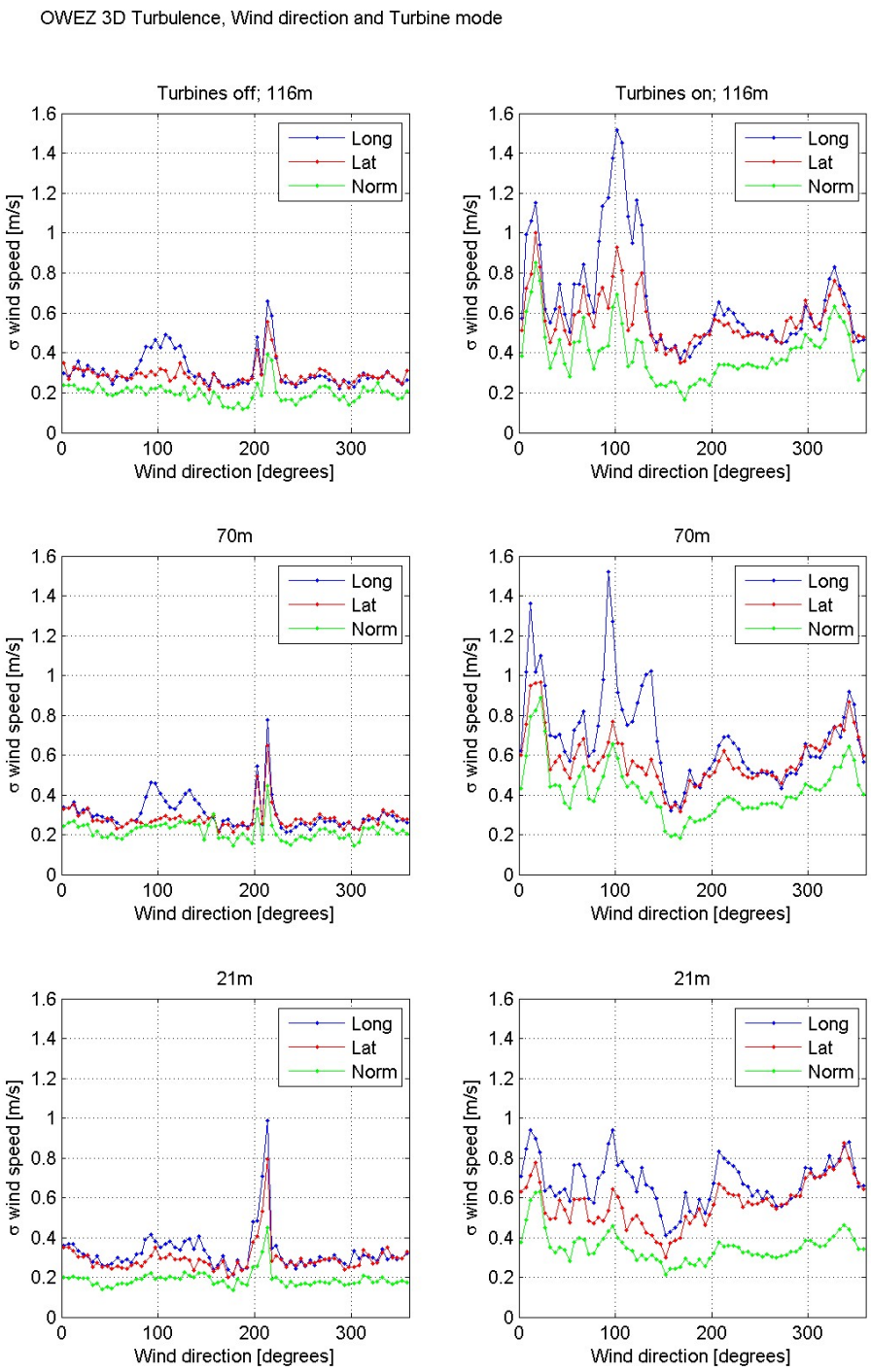


Figure 3.2 *Standard deviation of the longitudinal (blue), lateral (red) and normal (green) wind speed as function of the wind direction at 116m (upper plots), 70m (middle plots) and 21m (lower plots). Distinction has been made whether the turbines are producing power (right plots) or not (left plots).*

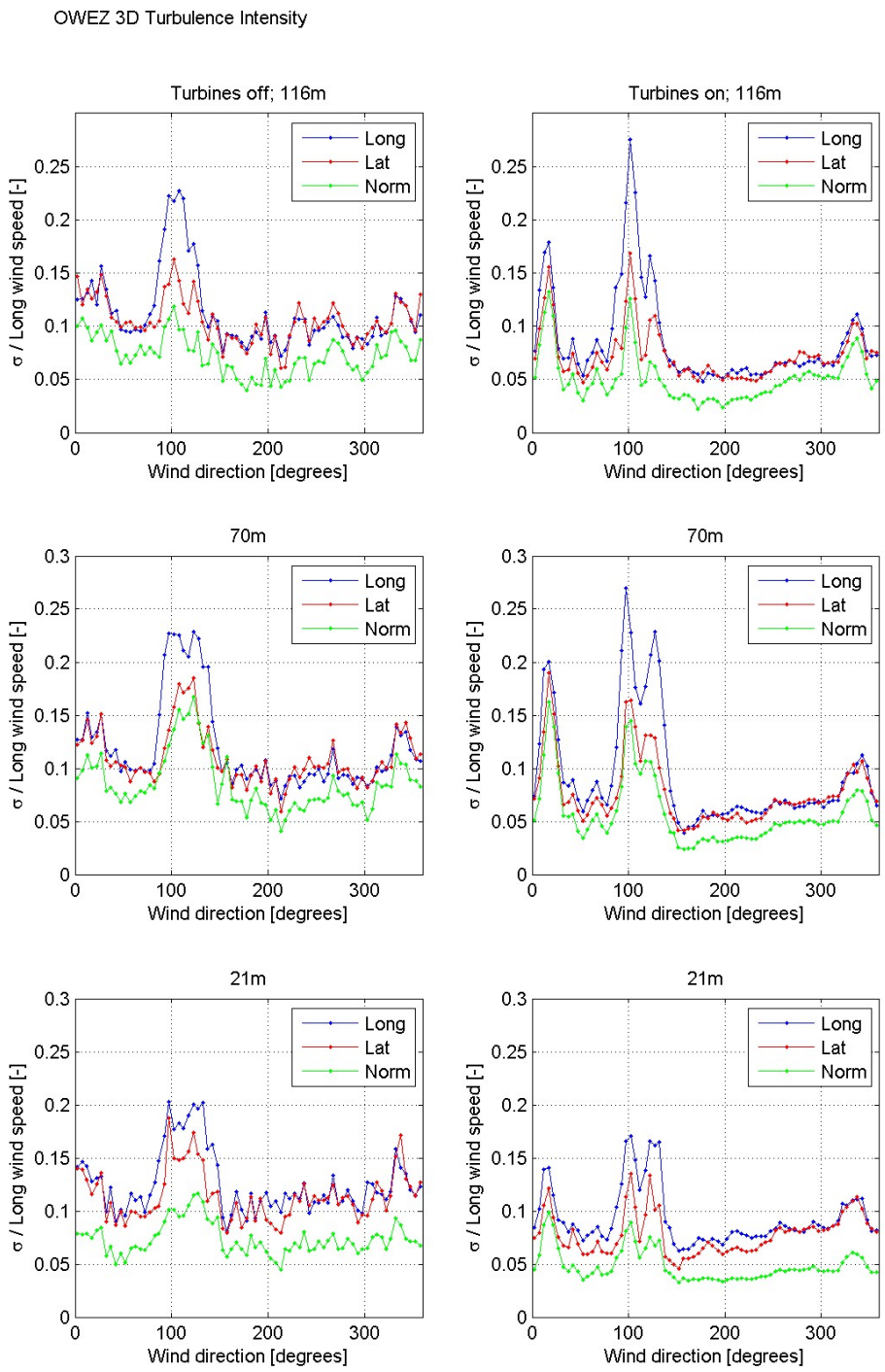


Figure 3.3 *Turbulence Intensities of the longitudinal (blue), lateral (red) and normal (green) wind speed as function of the wind direction at 116m (upper plots), 70m (middle plots) and 21m (lower plots). Distinction has been made whether the turbines are producing power (right plots) or not (left plots).*

3.2 Wind speed selection

The plots in Figure 3.4 show the various turbulence intensities as function of the wind direction in the same way as in Figure 3.3. Here, no distinction is made whether turbines are producing power or not, instead two wind speed classes are considered: wind speeds around 8 m/s (7.5 - 8.5 m/s) and around 12 m/s (11.5 - 12.5 m/s). The wind speed is constructed as follows: for the sector 295 degrees to 45 degrees the nacelle anemometer of turbine 36 is chosen and for the sector 45 degrees to 155 degrees the nacelle anemometer of turbine 30 is chosen. In these ranges the meteorological mast experiences wake effects from the wind farm. For the remaining range (155 degrees to 295 degrees) various anemometers on the mast at 70 m are chosen, such that mast disturbances are minimised (see [5] and subsequent half year reports for more detail). We notice that the plots for both wind speeds are, at least in shape, very much alike.

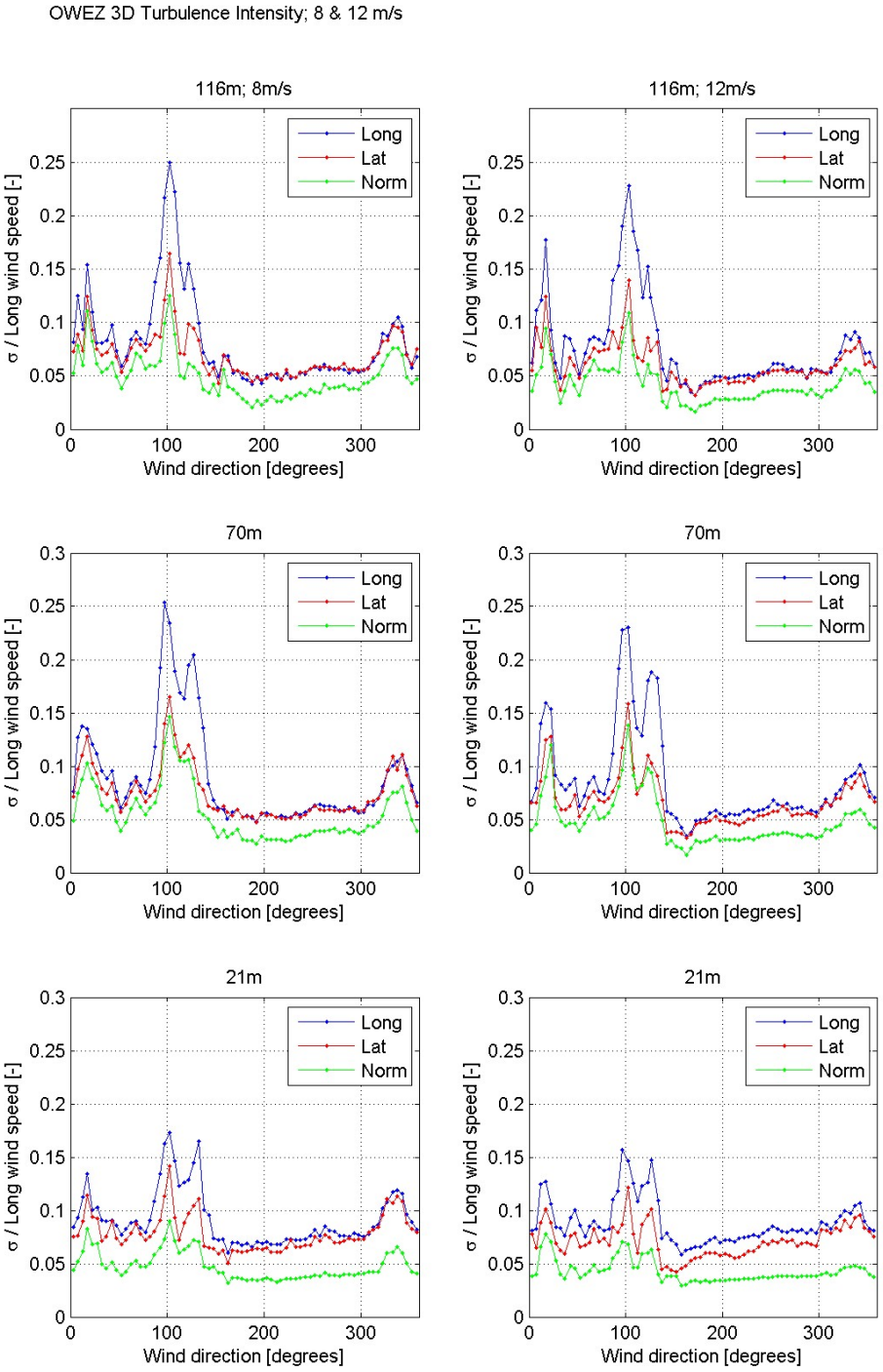
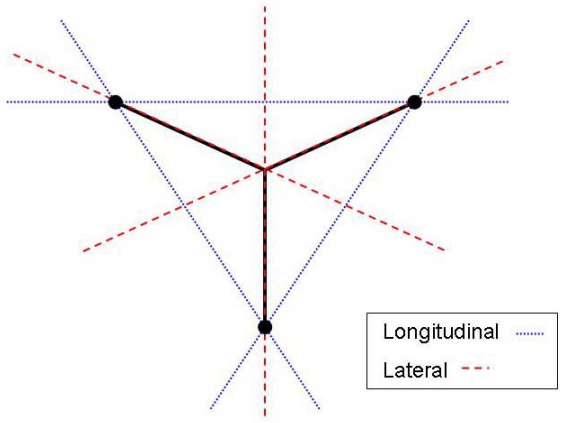


Figure 3.4 *Turbulence Intensities of the longitudinal (blue), lateral (red) and normal (green) wind speed as function of the wind direction at 116m (upper plots), 70m (middle plots) and 21m (lower plots). For the left plots wind speeds of 8m/s and for the right plots wind speeds of 12m/s are selected.*

4. Coherence

The measurements performed at the meteorological mast give the opportunity to compute coherences, although the possibilities are limited. To compute a coherence use can be made of 2 different wind speed sensors separated by a distance *x*. From two (synchronous) time series, extracted by these sensors, a coherence can be determined as function of the frequency, which is the coherence at separation distance *x*. As far as this separation is concerned, 3 types are considered: longitudinal, lateral and vertical separation [7]. In the first case the two anemometers need to be along the wind direction, i.e. behind each other, in the second case the line of the two anemometers is perpendicular to the wind direction and in the horizontal plane. For the coherence for vertical separations the anemometers are obviously vertically separated. In all three cases the wind is considered to be in the horizontal plane. In this section we mention and list the possibilities to compute coherences.

Horizontal separations:
As it is pointed out in [2] there are three levels (21m, 70m and 116m) with booms. The booms at these various levels have similar constructions and differ only in size. There are three cup anemometers at every level, which can be combined in pairs. This gives six opportunities for coherence computations with longitudinal separation, i.e. six wind directions can be selected to compute the coherence with longitudinal separation, and six opportunities for coherence computations with lateral separation. This is indicated in Figure 4.1[3].



Longitudinal separation	Lateral separation
30°	0°
90°	60°
150°	120°
210°	180°
270°	240°
330°	300°

Figure 4.1 *Possibilities in wind direction to compute the coherence with longitudinal separation (blue) and with lateral separation (red) at every level.*

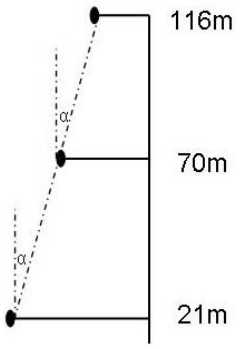
The separation distance at every level (height) is different. At 21m this distance is 24m, at 70m it is 15.6m and at 116m the distance between the cup anemometers is 5.5m.

It is possible to average the time series of two anemometers to estimate the wind speed in the middle of these two. This increases the possibilities to compute coherences. However, since it concerns estimates these possibilities are not further investigated and listed.

[3] Figure 4.1 is a sketch of the situation and may seem asymmetric. Obviously, the meteorological mast is symmetric.

Vertical separations:
Besides the possibilities in the horizontal plane there are also possibilities in the vertical direction. Vertically separated anemometers can be combined to compute coherences.

The anemometers are mounted on booms, which are oriented in tree different directions: 60°, 180° and 300°. It should be noted that per direction the anemometers are not positioned exactly above each other. The possibilities per boom direction are given in Figure 4.2. Also given are the angles between the straight line through the anemometers and the vertical line.



Possibility	Angle [°]
$Cup_{116} - Cup_{70}$	$\alpha = 7.2$
$Cup_{70} - Cup_{21}$	$\alpha = 5.7$
$Cup_{116} - Cup_{21}$	$\alpha = 6.4$

Figure 4.2 *Possibilities to compute the coherences with vertical separation per boom direction, based on cup anemometers.*

Besides the cup anemometers there are also sonic anemometers present. As mentioned before these are located on the North-West booms (300°), only. So, Figure 4.2 also applies for the sonic anemometers, but only for the 300° direction. Both anemometers (cup and sonic) have the same scan rate, namely 4Hz.

There are more combinations possible, especially for vertically displaced anemometers. For instance, the cup anemometer on one boom at one height could be combined with a cup anemometer on a boom with a different direction and at a different height. The added value of the resulting coherence is, however, questionable.

As pointed out in section 2 the meteorological mast is for certain wind directions in the wake of the wind farm, which obviously influences the computation of the coherence. The disturbed sector is 143 – 316 degrees. Because the meteorological mast was installed before the wind turbines, there is a period of data taking where the wind is undisturbed for all wind directions. The meteorological mast was installed in the summer of 2005 and the installation of the turbines started in the summer of 2006 (for more details on this matter we refer to [4] and [5]), which roughly gives one year of undisturbed wind.

Above we have given the possibilities to compute coherences. Although various possibilities are given, in an ideal situation one would like to have the opportunity to compute coherences at more and especially larger separation distances, which unfortunately is not possible.

5. Conclusions

In this section the main conclusions are summarised.

- We have seen that the longitudinal standard deviation is larger than the lateral standard deviation, which, on its turn is larger than the normal one. Generally, the standard deviations of the wind speed components decrease with increasing height. Also, the standard deviations are larger when they are in the wake of the wind farm.

- The standard deviations of the different wind speed components as function of the wind direction are in shape, especially for 70m and 116m height, comparable to standard deviations of the average wind speeds as function of the wind direction reported earlier. (Multiple) Wake effects are clearly recognisable.

- When data are selected where the turbines are producing power, wake effects are much more pronounced.

- The turbulence intensities for two wind speed classes (around 8m/s and around 12m/s) are, at least in shape, very much alike.

- The possibilities to compute coherences with longitudinal, lateral and vertical separation are mentioned, listed and discussed. The possibilities are limited due to the limited variety of separation distances between the anemometers. Ideally, computation of coherences at larger anemometer separation would be desirable, but this unfortunately is not possible.

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