# Turbulence assessment with ground based LiDARs

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# Contents

# Summary

One of the tasks of the LAWINE project concerns the analysis and development of measurement technology and data processing technology to apply ground based LiDARs to wind resource assessments and turbulence assessments. Since turbulence intensity measurement with the ground based LiDAR principle requires special attention, the current study focusses on turbulence assessment with two ground based LiDARs vs a meteorological mast at the ECN Wind turbine Test site Wieringermeer (EWTW).

In general, the results with the LiDARs are in better agreement with the sonic anemometers than with the cups. Especially at lower wind speeds (< 4 m/s), the turbulence intensities measured with cups result in approximately 2-4% lower values compared to sonic anemometers, and 2-6% lower values compared to LiDARs. At higher wind speeds (>5 m/s), the LiDARs measure slightly lower turbulence intensities (<0.5%) compared to sonic anemometers, and higher turbulence intensities (<1%) compared to cups.

In general, turbulence intensities measured with the ground based LiDARs are in between the results measured with cups and sonics, which demonstrates that the accuracy of the LiDAR technique for turbulence measurements is satisfactory. Moreover, the reproducibility of the LiDAR technique turned out to be very good.

# 1 Introduction

Light Detection and Ranging (LIDAR) is a technology that uses the Doppler frequency shift of backscattered light of transmitted laser beams to measure the line-of-sight velocities in order to estimate the three wind vector components. ECN has initiated the project named “Efficiency improvements by LiDAR assistance” or “LAWINE: Lidar Application for WINd farmEfficiency” together with Delft University of Technology, Avent Lidar Technology and XEMC Darwind in the framework of TKI Wind op Zee. The project is built around testing, evaluating and developing LiDAR technology to reduce the Cost of Energy for offshore wind farms.

Work package A of the LAWINE project concerns the analysis and development of measurement technology and data processing technology to apply ground based LiDARs to wind resource assessments and turbulence assessments. Details about the measurement plan for this task can be found in [1]. Turbulence intensity measurement with the ground based LiDAR principle requires special attention. Ground based LiDARs perform averaging over a large measurement volume. For turbulence measurements, this has a similar effect as applying a low pass filter, which reduces the standard deviation of the measured signal (i.e. wind velocities) resulting in reduced values of the turbulence intensity. The opposite effect, i.e. an increase of the standard deviation of the measured velocities with ground based LiDARs, may also occur when the flow is not horizontally homogenous. Non-homogeneous horizontal flow within the measured volume introduces random errors which may increase the standard deviation, resulting in higher values of the turbulence intensity. Although not subject of discussion in this study, these effects are possibly accounted for via applied algorithms in the data processing of the LiDAR system.

This study focusses on turbulence assessment with two ground based LiDARs vs a meteorological mast at the ECN Wind turbine Test site Wieringermeer (EWTW). The main question that needs to be answered is: how do the turbulence measurements with the ground based LiDARs compare with the cup and sonic anemometers installed on the mast? Only 10 minute statistics of the measured signals are considered as these are prescribed in standards for wind turbine design and wind energy resource assessment.

# 2

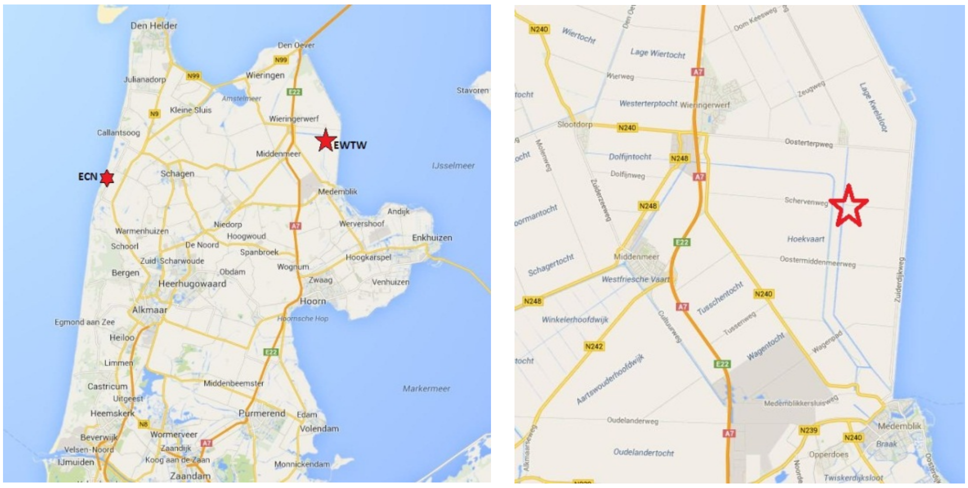
# Test site

This chapter summarizes the most relevant information of the test site EWTW. More detailed information of the test site and the instrumentation of the meteorological mast 3 (MM3) can be found in [2].

## 2.1 Environment

The ECN Wind turbine Test site Wieringermeer (EWTW) is located in the polder Wieringermeer, in the North East of the Province Noord-Holland of the Netherlands, 27 km East of ECN Petten ( see **Figure 1**).

**Figure 1**: Map of the province Noord-Holland (left) and a detailed map of the test site EWTW (right).




The test site and its surroundings are characterised by flat terrain, consisting of mainly agricultural area with single farmhouses and rows of trees. The lake IJsselmeer is located at a distance of 2 km East of meteorological mast 3 (MM3). The location of MM3, the ground based LiDARs and the wind turbines at EWTW are shown in **Figure 2**.

**Figure 2**: Layout of the test site EWTW: the meteorological mast 3 (12) is surrounded by 5 research turbines (5 – 9), 6 prototype wind turbines (1 – 4, 10, 11) and 4 smaller single wind turbines (13 – 16). The location of the 2 ground based LiDARs is denoted by the white square south of the meteorological mast 3.


## 2.2 Meteorological mast 3

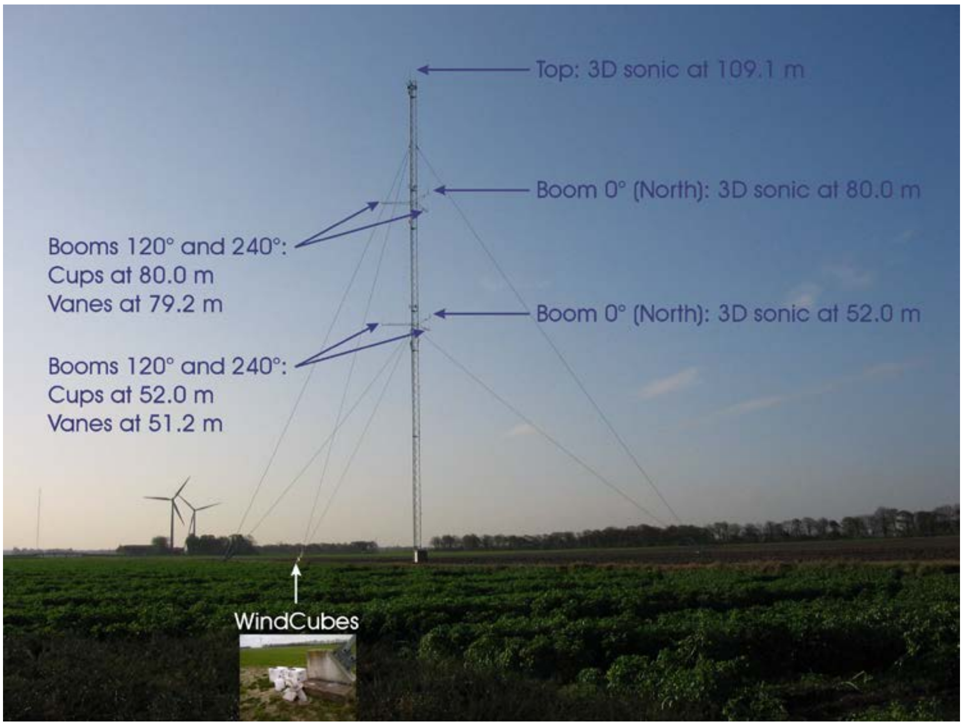
The meteorological mast 3 (MM3) is located approximately 200 m south of a line of 5 Nordex N80 wind turbines, see **Figure 2**. About 1,5 km south of the met mast a line of 5 large prototype wind turbines are located. Within the same distance, also 4 smaller wind turbines are operating.

On two booms pointing north (0°) at 52.0 and 80.0 m height 3D sonic anemometers (Gill) are mounted. Both at 50.4 and 78.4 m height two booms (120° and 240°) are mounted with cup anemometers (52.0 and 80 m height) and wind vanes (51.2 and 79.2 m height).

On top of the mast a sonic anemometer is mounted on the East pillar at 109.1 m height. This anemometer is almost completely undisturbed by the mast except for the wind direction of 210° at which the top anemometer is in the wake of the lightning rod mounted on the South pillar.

The MM3 data is available in the LAWINE database from 14-03-2013.

**Figure 3**: Relevant signals of meteorological mast 3. Photograph taken from the tower base of research turbine 6, see also **Figure 2**.




## 2.3 Ground based LiDARs

The WindCubeV2 is a ground based LiDAR (Light Detection And Ranging) system that sends infrared laser pulses into the atmosphere, using four beams along a 28° cone angle. The wind speed is determined from the Doppler shift of the backscattered light.

Two WindCubeV2 system (WC127 and WC258), are located at the foot of the guy wires south of meteorological mast 3, approximately 60 m from the mast (see **Figure 3**). The WC258 is an upgraded version with Flow Complexity Recognition (FCR). This FCR system uses a fifth vertical beam to measure the vertical wind speed, which enables a reduction of the measurement bias in complex terrain and complex flow [3]. However, since the test site EWTW is considered as fairly simple terrain, the effect of this fifth beam is expected to be insignificant for this study.

Up to 10 different range gates can be measured simultaneously using the laser pulse time, allowing to measure the wind speed at 10 different heights. The WindCubes have been configured to have three of these measurement heights identical to the measurement heights of the met mast (i.e. 52, 80 and 108 meter).

The data from the WC127 is available from 17-03-2013 up to 16-09-2013, and the data from the WC258 is available from 22-11-2012 up to 23-01-2014 in the LAWINE database.

# 3 Data analysis

In this chapter the measured turbulence data of cups, sonics an LiDARs are analysed. The turbulence is evaluated by the turbulence intensity. Based on 10 minute wind speed series, the turbulence intensity $I_v$ (or TI) of a sample is the ratio of the wind speed standard deviation to the average wind speed:

$$I_v = \frac{\sigma_v}{\overline{V}}$$

## 3.1 Data availability

The measured signals of the LiDARs and the meteorological mast are stored in the LAWINE database. **Figure 4** shows the availability for comparison of the supplied data. For the WC127 the period of available data for comparison with the meteorological mast is approximately 6 months. For the WC258, the period of available data for comparison is almost 11 months.

**Figure 4**: Data availability from the LAWINE database for the meteorological mast and the two ground based LiDARs.

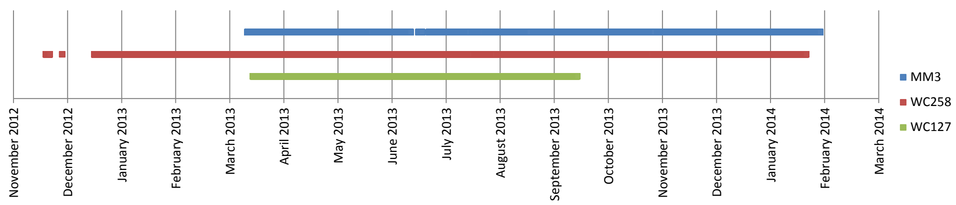



Table 1 lists the relevant signals. Only 10 minute statistics of these signals are used for the comparisons. More details of the instrumentation can be found in [2].

**Table 1**: List of used signals.

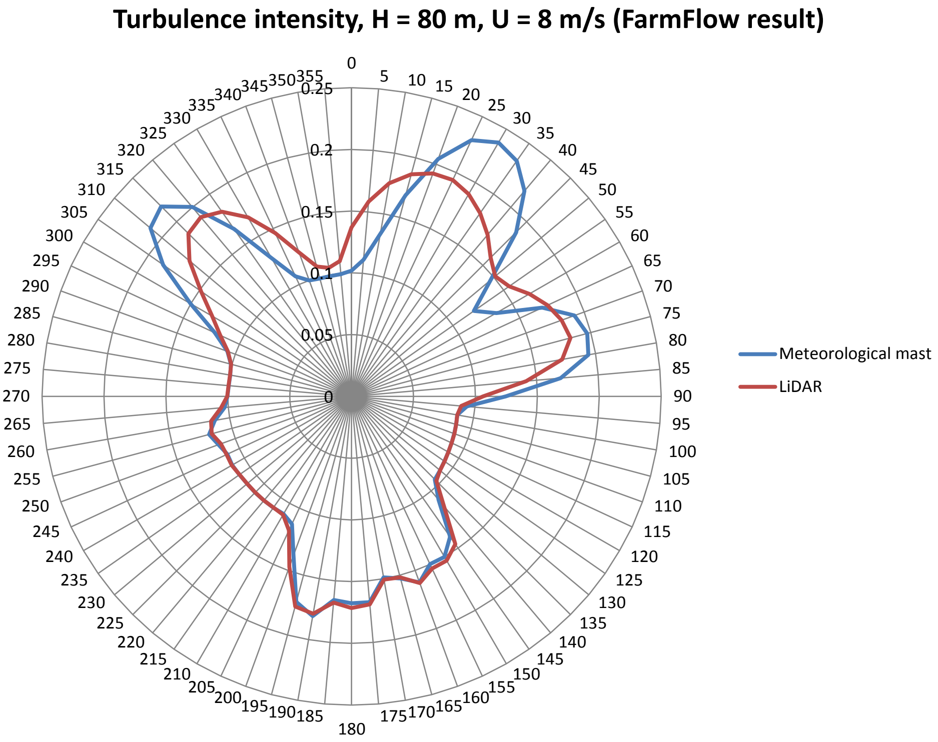
| Signal name | Dimension | Height [m] | Instrument type |
|---|---|---|---|
| MM3_H52_Wd_Q1_avg | deg | 52 | Vanes |
| MM3_H52_Ws_Q1_avg | m/s | 52 | Cups |
| MM3_H52_Ws_Q1_std | m/s | 52 | Cups |
| MM3_H52_WdHorSon_Q5_avg | deg | 52 | 3D sonic |
| MM3_H52_WsHorSon_Q5_avg | m/s | 52 | 3D sonic |
| MM3_H52_WsHorSon_Q5_std | m/s | 52 | 3D sonic |
| WC127-52m Wind Direction | deg | 52 | WindCube |
| WC127-52m Wind Speed | m/s | 52 | WindCube |
| WC127-52m Wind Speed Dispersion | m/s | 52 | WindCube |
| WC258-52m Wind Direction | deg | 52 | WindCube |
| WC258-52m Wind Speed | m/s | 52 | WindCube |
| WC258-52m Wind Speed Dispersion | m/s | 52 | WindCube |
| MM3_H80_Wd_Q1_avg | deg | 80 | Vanes |
| MM3_H80_Ws_Q1_avg | m/s | 80 | Cups |
| MM3_H80_Ws_Q1_std | m/s | 80 | Cups |
| MM3_H80_WdHorSon_Q5_avg | m/s | 80 | 3D sonic |
| MM3_H80_WsHorSon_Q5_avg | m/s | 80 | 3D sonic |
| MM3_H80_WsHorSon_Q5_std | m/s | 80 | 3D sonic |
| WC127-80m Wind Direction | deg | 80 | WindCube |
| WC127-80m Wind Speed | m/s | 80 | WindCube |
| WC127-80m Wind Speed Dispersion | m/s | 80 | WindCube |
| WC258-80m Wind Direction | deg | 80 | WindCube |
| WC258-80m Wind Speed | m/s | 80 | WindCube |
| WC258-80m Wind Speed Dispersion | m/s | 80 | WindCube |
| MM3_H108_WdHorSon_Q5_avg | deg | 108 | 3D sonic |
| MM3_H108_WsHorSon_Q5_avg | m/s | 108 | 3D sonic |
| MM3_H108_WsHorSon_Q5_std | m/s | 108 | 3D sonic |
| WC127-108m Wind Direction | deg | 108 | WindCube |
| WC127-108m Wind Speed | m/s | 108 | WindCube |
| WC127-108m Wind Speed Dispersion | m/s | 108 | WindCube |
| WC258-108m Wind Direction | deg | 108 | WindCube |
| WC258-108m Wind Speed | m/s | 108 | WindCube |
| WC258-108m Wind Speed Dispersion | m/s | 108 | WindCube |

## 3.2 Effect of different location

The view towards the line of Nordex turbines seen from the meteorological mast differs from the view seen at the position of the two LiDARs, which are located approximately 60 m south of the mast. In order to quantify the effect of the different locations, the effect of the environment for both locations have been simulated with FarmFlow [4].

**Figure 5** shows the calculated turbulence rose for both locations. The results for the LiDAR location have been averaged for the four points of the laser beams at 80 m height.

**Figure 5**: Calculated turbulence rose at 80 m height at the location of the meteorological mast and the LiDARs.



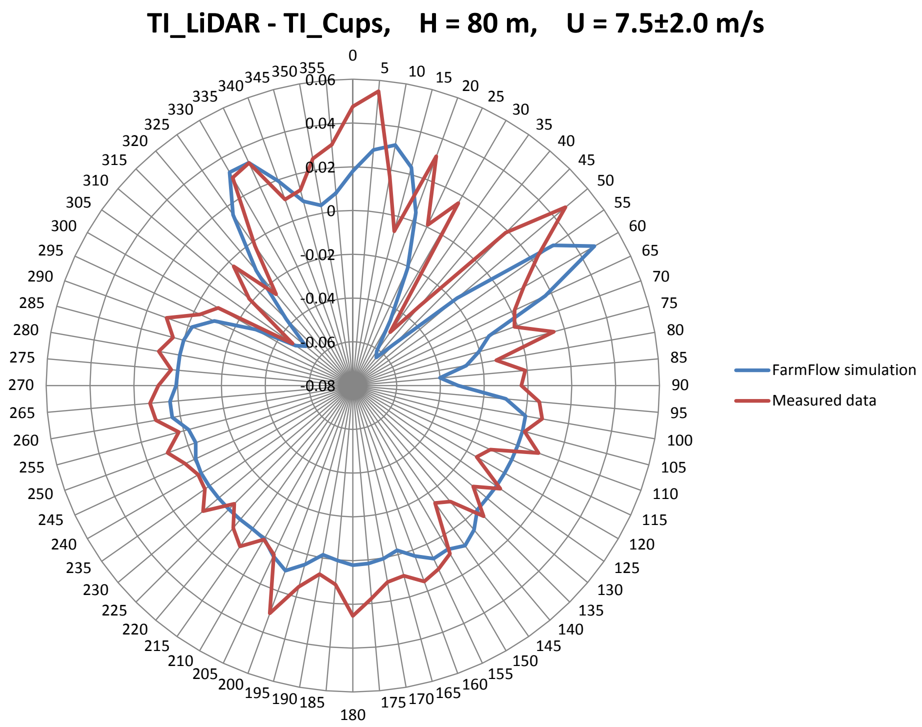

The results show clearly that the meteorological mast experiences higher turbulence levels in the northern sector compared to the LiDARs. The total sector of disturbance is also 15° wider. Obviously, these differences are an effect of the distance towards the line of Nordex turbines, which is approximately 60 m (30%) larger for the LiDARs.

The same effect occurs for the prototype wind turbines for wind direction between 145 and 210°. Fortunately, because of the large distance between these turbines and the meteorological mast, this effect will be hardly noticeable for the southern sectors.

From these results it can be concluded that a fair comparison of the results from the meteorological mast and LiDARs is only possible in the sector 100 – 285°. For that reason it has been decided to use this sector for all comparisons.

In **Figure 6** the difference of the turbulence intensity between LiDAR and meteorological mast is plotted both with results from the FarmFlow simulation shown in **Figure 5** and with measured data. As expected, the FarmFlow simulation (blue line) shows almost no difference in the sector of 100 – 285°. When compared with the measured data (red line) two observations can be made. First, the shape of both roses are quite similar, which gives confidence in the accuracy of both the FarmFlow simulations and the measurements. Second, the LiDAR measurements produce slightly higher turbulence levels in comparison with the cup anemometers for all wind directions with the exception of south-easterly winds.

**Figure 6**: Rose with difference in turbulence intensity from LiDAR measurements with respect to the meteorological mast (cups only).




## 3.3 Comparison LiDAR vs mast

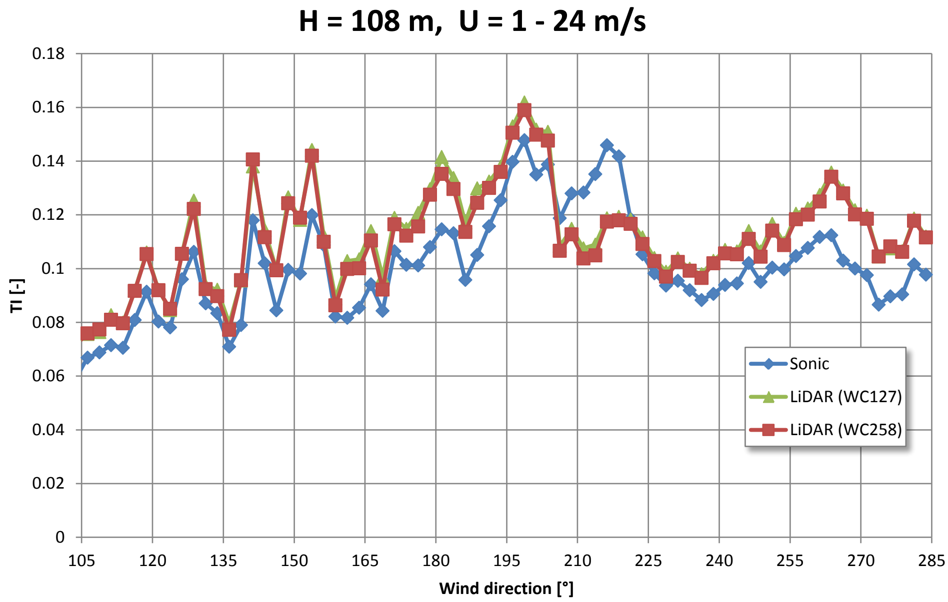
In this section all turbulence intensities are determined from 10 minute statistics (i.e. the ratio of the wind speed standard deviation to the average wind speed). Moreover, for proper comparison, if a sample of one instrument is not valid, the synchronised samples of all other instruments in the same comparison are also rejected. This means that all compared data sets shown in the graphs are still synchronised.

### 3.3.1 Turbulence vs. wind direction

Except for the lightning rod, the 3D sonic anemometer at 109.1 m height has a free view without disturbance of the met mast. Only for wind directions of approximately 210°, the wake of the lightning rod, which is mounted on the South pillar, disturbs the wind at the sonic anemometer, which is mounted on the East pillar.

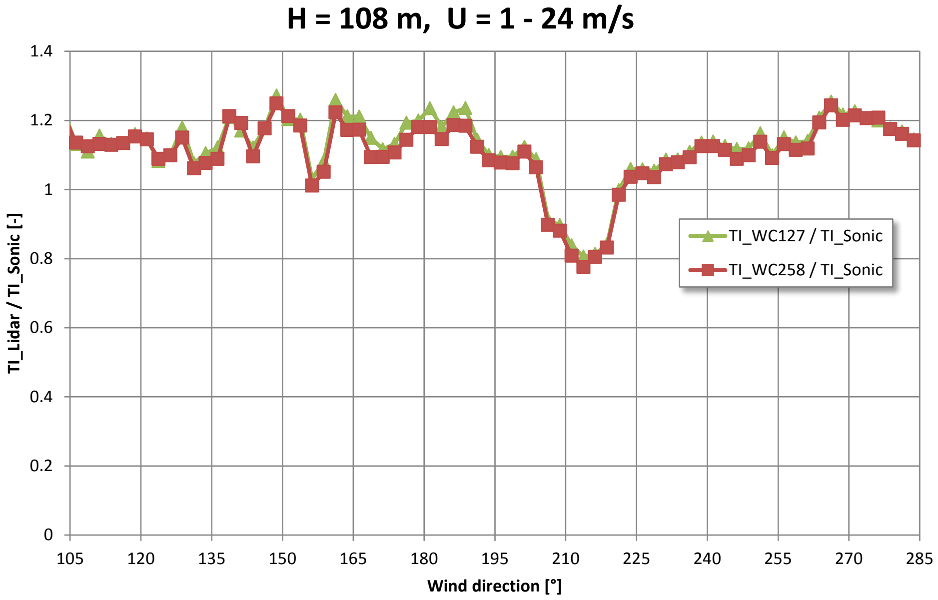
**Figure 9** displays the turbulence intensity at 109.1 m height measured with the sonic anemometer together with the results for 108 m height obtained with the two ground based LiDARs. The turbulence intensities are displayed as a function of wind direction for all wind speeds between 1 and 24 m/s. The results of the two ground base LiDARs are almost identical. The reproducibility of these ground based LiDARs are, at least up to a height of 108 m, very good. Also the shape of the curves are almost identical to the curve measured with the sonic anemometer. A gap with roughly constant distance exists between the curve of the sonic anemometer and the curves of the LiDARs.

**Figure 7**: Comparison of turbulence intensities measured with a 3D sonic anemometer and two ground based LiDARs at 108 m height.




A more clear view on the differences between the results of the ground based LiDARs and the sonic anemometer is given in **Figure 8**. Here, the ratios between the turbulence intensities measured with the ground based LiDARs and with the sonic anemometer is displayed. Excluding the sector 205 – 220°, where the sonic measurements are disturbed by the wake of the lightning rod, the differences show that the turbulence intensities measured with the ground based LiDARs are approximately a factor 1.13 higher than the results measured with the sonic anemometer. There seems to be no influence of the type of environment on these differences: wind from the lake (105 – 120°), wakes from the prototype wind turbines (145 – 205°) as well as wind above normal polder landscape (220 – 285°) show approximately the same differences between both type of instruments. The wiggles between 140 and 160° are probably explained by the different location of LiDARs with respect to the mast. As a result, the ground based LiDARs measure different parts of the wakes from prototype turbines 3 and 4.

Figure 8: Ratio between turbulence intensities measured with ground based LiDARs and with a 3D sonic anemometer at 108 m height.




In general, the measured differences between the ground based LiDARs and the sonic anemometer at 108 m height as a function of wind direction give the impression of a calibration error of the sonic anemometer and/or both the two LiDARs.

### 3.3.2 Turbulence vs. wind speed

In **Figure 9** to **Figure 12** measured turbulence intensities between cups, sonic and the two ground based LiDARs are compared for the sector 100 – 285° at 52 and 80 m height as a function of wind speed. As before, only 10 minute averaged samples are used in each plot on condition that for each time stamp all instruments (cups, sonic and LiDAR) produced valid data. Frequency histograms of the samples are shown below the turbulence graphs.

It should be mentioned that the 3D sonic anemometers on the North booms at 52 and 80 meter height are for a substantial part disturbed by the mast. For wind directions between 170 and 190° the sonic anemometers are in the wake of the lattice frame of the mast, while between 145° and 215° turbulence from the wakes of the southern booms disturb the measurements. Actually, the main purpose of these sonic anemometers is for measuring the wake effects from the Nordex turbines North of the mast.

Between the three methods, measurements from LiDAR and sonic are in best agreement with each other. The measurements with cups show lower and decreasing turbulence levels at low and decreasing wind speeds. An obvious explanation for this is that the response time of the cup anemometer, due to the inertia of the cups, reduces the variance of the measured wind speed.

**Figure 9**: Comparison of turbulence intensities measured with cup and sonic anemometers and a ground based LiDAR (WC127) at 52 m height.

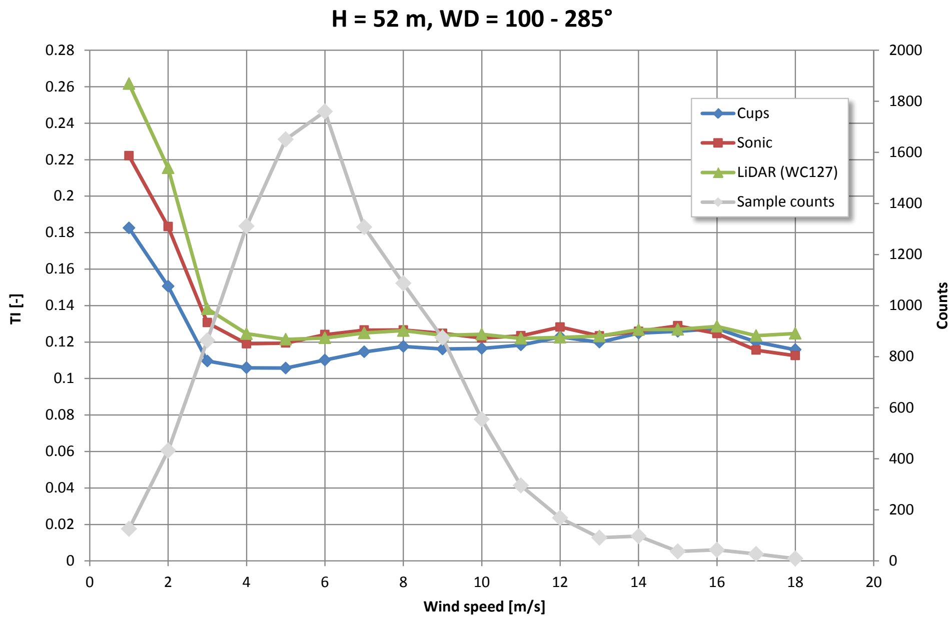



**Figure 10**: Comparison of turbulence intensities measured with cup and sonic anemometers and a ground based LiDAR (WC258) at 52 m height.

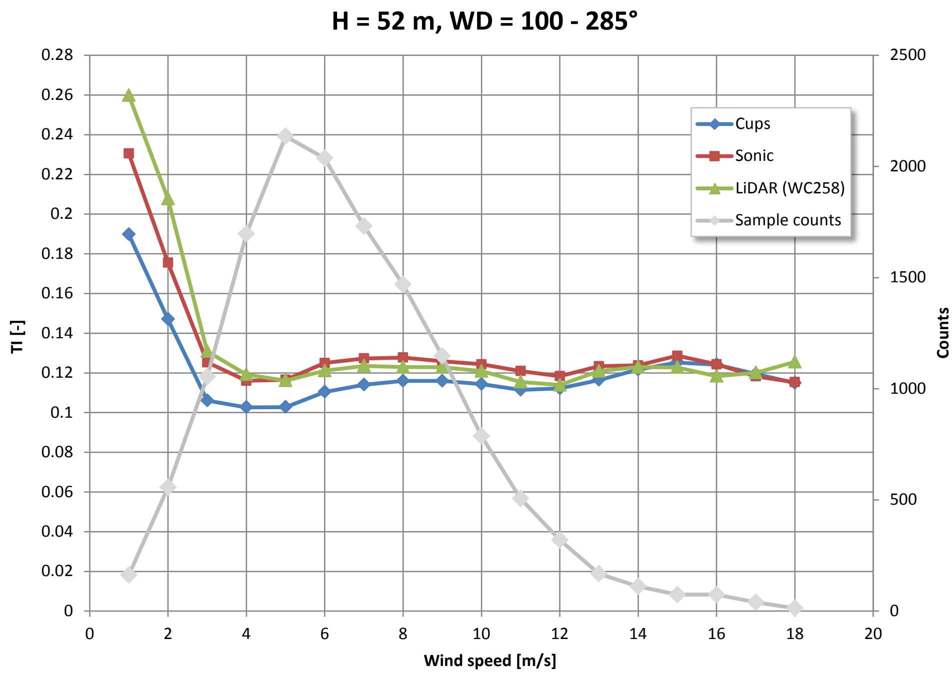


**Figure 11**: Comparison of turbulence intensities measured with cup and sonic anemometers and a ground based LiDAR (WC127) at 80 m height.

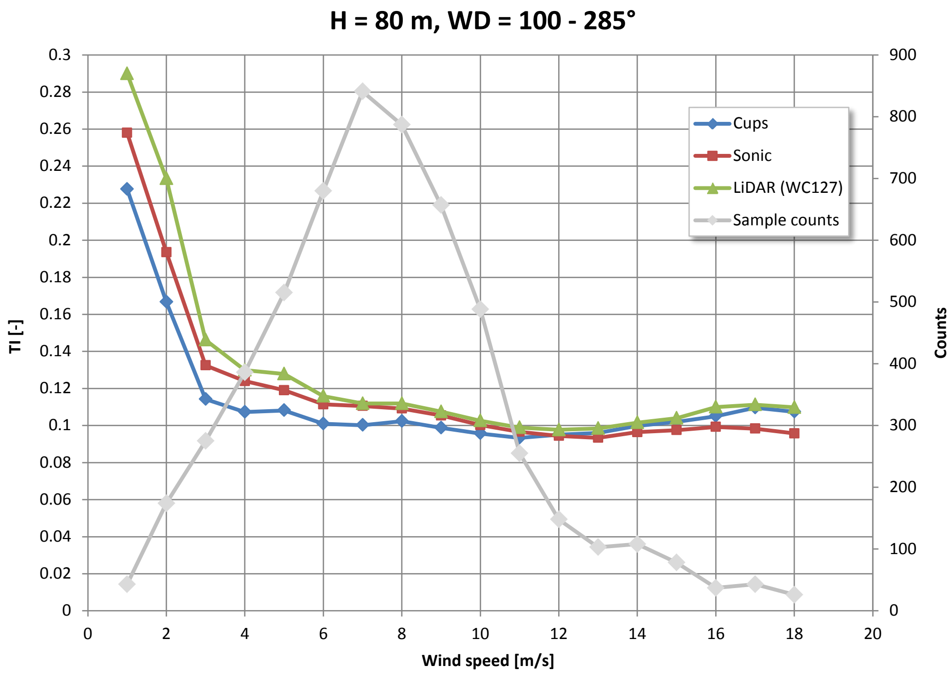
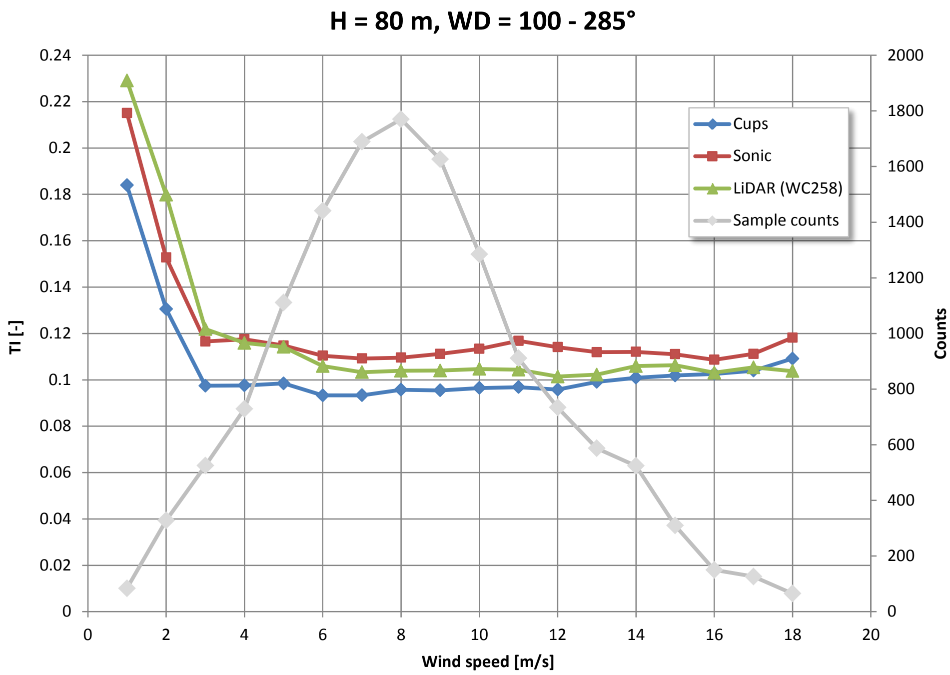


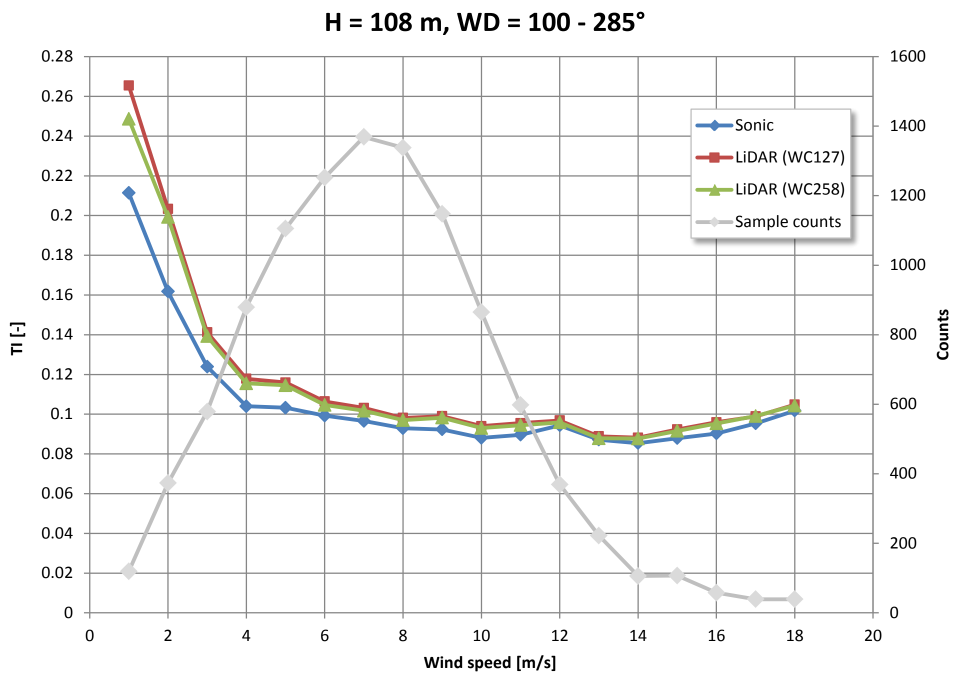

**Figure 12**: Comparison of turbulence intensities measured with cup and sonic anemometers and a ground based LiDAR (WC258) at 80 m height.



The results are in line with an earlier study at the offshore platform FINO1 [4], at which also higher turbulence intensities were found with a WindCube LiDAR system in comparison with cups. In addition, this effect has also been investigated with power spectrum analysis of the velocity fluctuations [5].

**Figure 13** shows a comparison of measured turbulence intensities between both ground based LiDARs and the sonic anemometer at 108 m height. It was expected that the results of the two LiDARs agree better with each other than with the sonic anemometer. Still, it is remarkable how close the lines of the two LiDARs match. In comparison with the turbulence intensity measured with the sonic anemometer, the values from LiDAR are a factor of 1.1 higher for wind speeds below 6 m/s. For larger wind speeds, the factor reduces to almost 1.0 at 13 m/s. This implies that the LiDARs and sonic are in better agreement with respect to the results of section 3.3.1, where an average factor of 1.13 was found with the same data. This difference however is caused by the fact that the larger part of the data is within the wind sector 180 – 270°, which includes the disturbance sector of the lightning rod (see also **Figure 8**). Actually, for fair comparison, the turbulence intensities measured with the sonic anemometer in **Figure 13** need to be corrected by decreasing the values with 0.0027 to account for the lightning rod.

**Figure 13**: Comparison of turbulence intensities measured with a sonic anemometer and two ground based LiDARs (WC127 and WC258) at 108 m height.



# 4

# Conclusions and recommendations

At EWTW turbulence measurements with two ground based LiDARs have been performed and compared with more conventional measurements with cup and sonic anemometers.

The results show that the turbulence intensities measured with the LiDARs are in better agreement with the sonic anemometers than with the cups. Especially at lower wind speeds (< 4 m/s), the turbulence intensities measured with cups result in approximately 2-4% lower values compared to sonic anemometers, and 2-6% lower values compared to LiDARs. An obvious explanation for the lower turbulence intensities measured with the cups is the response time of the cup anemometer, due to the inertia of the cups, which reduces the variance of the measured wind speed. The higher turbulence intensities measured with the LiDARs at low wind speeds are probably due to the assumption of a homogeneous velocity field inside the measuring volume, which is a less valid assumption at lower wind speeds. At higher wind speeds (>5 m/s), the LiDARs measure slightly lower turbulence intensities (<0.5%) compared to sonic anemometers, and higher turbulence intensities (<1%) compared to cups.

In general, turbulence intensities measured with the ground based LiDARs are in between the results measured with cup and sonic anemometers, which demonstrates that the accuracy of the LiDAR technique for turbulence measurements is satisfactory. Moreover, the reproducibility of the LiDAR technique turned out to be very good.

The difference between turbulence intensities measured with the ground based LiDARs and the sonic anemometers give the impression of a calibration error, since the trend of the curve are quite similar. A power spectrum density analysis at different heights is recommended to find a more substantiated explanation of these differences.

# 5

# References


[1] Wagenaar, J.W., Bergman, G., and Boorsma, K., *Measurement plan LAWINE project tasks A and C*, ECN-X--13-059, November 2013.

[2] Berman, G., Wagenaar, J.W., and Boorsma, K., *LAWINE instrumentation report*, ECN-X--14-085.

[3] Press Release, *LEOSPHERE's FCR technology validated by DTU for greater LiDAR wind measurement accuracy in complex terrain*, July 1st 2014.

[4] Bot, E.T.G., *FarmFlow validation against four full scale wind farms*, ECN-E--12-005, December 2012.

[5] Westerhellweg, A. et al, *One year of LiDAR measurements at FINO1-platform: comparison and verification to met-mast data*, DEWEK 2010, Bremen.

[6] Canadillas, B. et al, *Comparison of turbulence spectra derived from LiDAR and sonic measurements at the offshore platform FINO1*, ECN-C--03-034, ECN, 2003.

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