Validation of the ZephIR 300 LiDAR at the ECN LiDAR Calibration Facility for the offshore Europlatform measurement campaign

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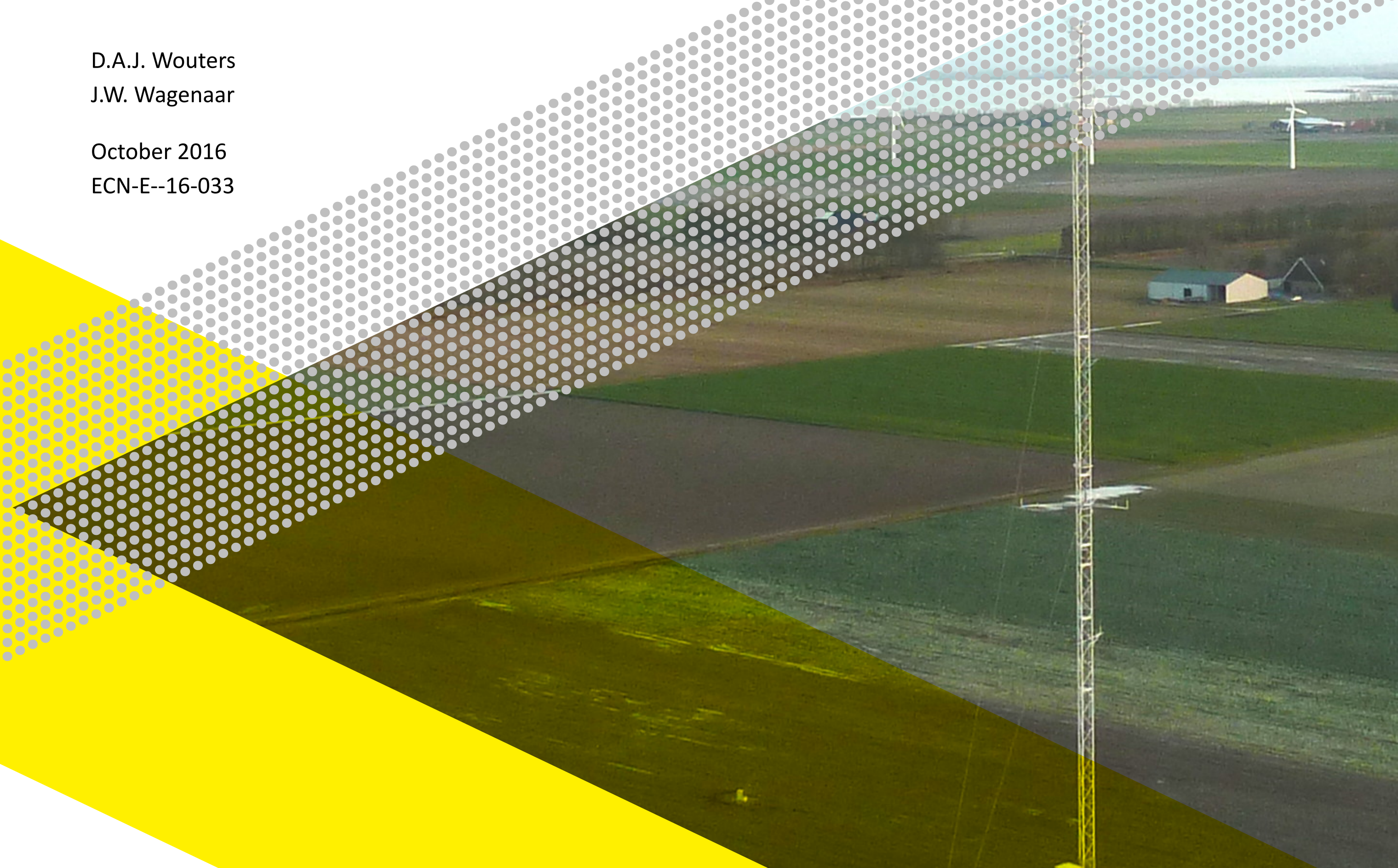


Contents

Executive Summary

As part of the North Sea offshore wind conditions measurement program a ZephIR LiDAR is installed at the so-called Europlatform on May 9, 2016. In order to assure high quality measurements, the LiDAR unit (ZephIR 300, U308) was first validated at the ECN LiDAR Calibration Facility for the period of February 27 till April 27, 2016. The validation is performed by checking Key Performance Indicators (KPIs).

The comparison is performed for five measurement heights: 29 m, 44 m, 59 m, 90 m and 100 m and the KPIs resulting for the validation are listed in table 1. Based on these results ECN qualifies this LiDAR unit as suitable for offshore application at the Europlatform.

The validation method used in this report is intended as a concise check of the LiDAR performance, which can be established in a limited amount of time. The validity of the results is based on the KPIs alone. A detailed, IEC compliant analysis of the same data is presented in another report[10].

Table 1: LiDAR validation Key Performance Indicators results (copy)

KPI	height	result	unit	lower limit	upper limit	status
	m	unit		unit	unit	
$\text{slope}_{\text{WS},1p}$	100	1.002	-	0.98	1.02	pass
	90	1.008	-	0.98	1.02	pass
	59	1.004	-	0.98	1.02	pass
	44	1.003	-	0.98	1.02	pass
	29	1.004	-	0.98	1.02	pass
$R^2_{\text{WS},1p}$	100	1.000	-	0.98	1.00	pass
	90	1.000	-	0.98	1.00	pass
	59	1.000	-	0.98	1.00	pass
	44	1.000	-	0.98	1.00	pass
	29	0.999	-	0.98	1.00	pass
$\text{offset}_{\text{WD,median}}$	100	-2.148	°	-5.00	5.00	pass
	90	-1.655	°	-5.00	5.00	pass
	59	-2.343	°	-5.00	5.00	pass
	44	-1.831	°	-5.00	5.00	pass
	29	-2.955	°	-5.00	5.00	pass
$\Delta_{90_{\text{WD}}}$	100	2.292	%	0.00	3.00	pass
	90	2.324	%	0.00	3.00	pass
	59	1.824	%	0.00	3.00	pass
	44	1.169	%	0.00	3.00	pass
	29	0.506	%	0.00	3.00	pass
system availability		100.0	%	95.00		pass
data availability	100	89.2	%	85.00		pass
	90	89.3	%	85.00		pass
	59	89.3	%	85.00		pass
	44	89.0	%	85.00		pass
	29	88.6	%	85.00		pass

1

Introduction

The Dutch government has ambitious plans for offshore wind energy towards 2020 and beyond. In order to achieve the goals that have been set, various development zones have been defined in the North Sea. The Dutch government creates a level playing field for developers among others to provide them with wind data on which business cases can be build.

To acquire wind data, the Dutch ministry of Economic Affairs has contracted ECN Wind Energy to carry out a measurement campaign on the North Sea. This campaign comprises among others of LiDAR measurements at the so-called 'Europlatform' (EPL). To this end, the ZephIR 300 LiDAR U308 was installed at EPL on May 9, 2016.

High quality measurements will reduce the uncertainty in the measurements creating more favourable finance conditions for developers. Therefore, and to assure the high quality, the LiDAR was first validated at the newly developed ECN LiDAR Calibration Facility (ELCF) located at the ECN Wind turbine Test site Wieringermeer (EWTW). The development of the this calibration facility was part of the LAWINE project [3] in the framework of the Top consortium Knowledge and Innovation (TKI) 'Wind op Zee'.

This report describes the comparison of the LiDAR with Meteorological Mast 4 (MM4) for the period February 27 till April 27, 2016. The measurements at the mast are performed according to IEC 61400-12-1 [5]. Furthermore, the LiDAR is validated, which means that Key Performance Indicators (KPIs) are checked. These KPIs are set-up by ECN based on NORSEWinD criteria [4] and the 'Carbon Trust Offshore Wind Accelerator roadmap for the commercial acceptance of floating LIDAR technology'[7]; they are defined in chapter 4.

The measurement campaign is described in chapter 2 and details the site, the mast and the LiDAR. It focuses on Meteorological Mast 4; a full description of the calibration facility will be done in a separate report. Chapter 3 describes the data preparation steps. The validation of the KPI's is discussed in chapter 4.

2

Measurement campaign

2.1 ECN LiDAR Calibration Facility

The ECN LiDAR Calibration Facility (ELCF) is part of the test site EWTW. The site mainly consists of agricultural land, with single farmhouses and rows of trees as shown in figure 1. It is located in the Wieringermeer, a polder in the North East of the province of North Holland, 3 km North of the village of Medemblik. To the East, the site is 1 km removed from the vast IJsselmeer lake. The altitude is 5 m below sea level. The site is considered sufficiently flat according to [5].

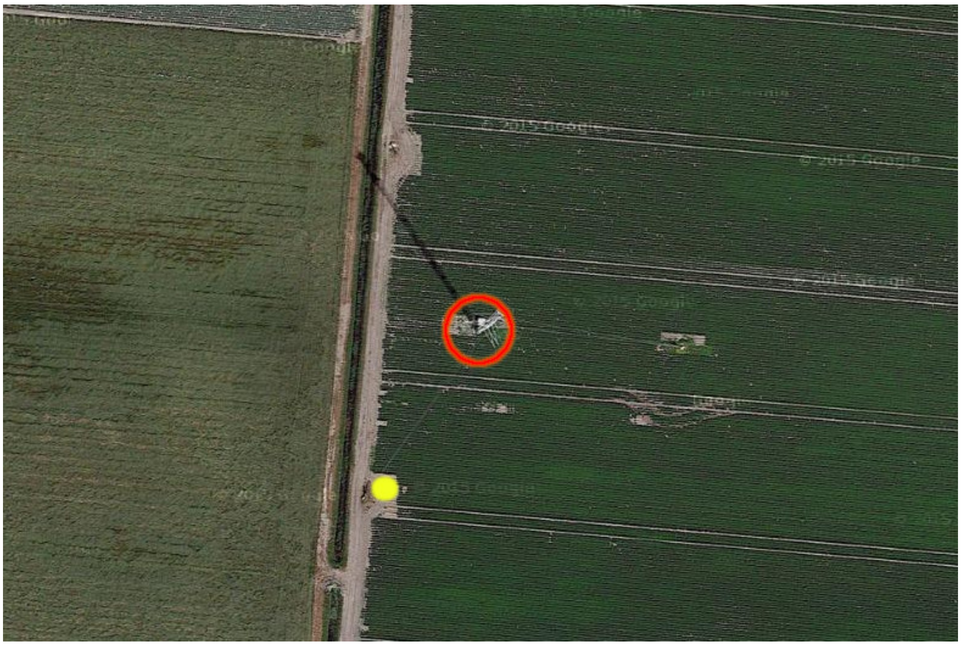
Figure 1: Overview of the ECN test site EWTW, with in red indicated the ECN LiDAR Calibration Facility

Source: Google Maps

2.2 Meteorological mast

The ELCF is detailed in a separate report[9]. The Meteorological Mast 4 is an essential part of the ELCF. It is a lattice tower with a triangular cross section, supported by guy wires at two levels: 41 m and 83 m. The guy wires are fixed to concrete anchors at a radius of 60 m from the tower base at 95°, 215° and 335°. As part of the ELCF a dedicated spot for placing the remote sensor is being created near the anchor of the 215° wires, as shown in figure 2. However, because this is still work in progress, the ZephIR 300 LiDAR U308 was in this particular case placed at the base of MM4 instead.

Figure 2: Overview of the ELCF, indicated in red Meteorological Mast 4 and in yellow the calibration platform



Source: Google Maps

The wind speed is measured at 29 m, 44 m, 59 m, 90 m and 100 m. These are the heights at which the LiDAR measurements are compared to the MM4.

At the heights of 87.5 m and 42 m multiple sensors are installed on two or three booms of MM4. By combining the signals from these sensors, the influence of the mast on the measurements can be minimized. The resulting signal is an example of what is referred to as a 'pseudo signal'. At 87.5 m two booms are installed, which measure the wind speed at 90 m and the wind direction at 88 m. At 42 m three booms are installed, which measure the wind speed at 44 m and the wind direction at 42 m. The layout of MM4 is shown in figure 3.

All wind speed measurements are performed with Thies First Class Advanced cup anemometers. All wind direction measurements use Thies First Class wind vanes.

2.3 Measurement sector

The wind direction sector for which the measurements by the mast and the LiDAR are unaffected by obstacles is referred to as the measurement sector. It is determined based on [5] using Meassector 2.2 [8]. This measurement sector is shown in figure 4 and the total measurement sector is composed of the following sectors:

- 104.5° to 284.1°
- 355.6° to 24.2°

2.4 LiDAR

The LiDAR is a ZephIR 300. This unit has identification number U308. It is configured to perform measurements at ten heights: 28 m, 43 m, 58 m, 89 m, 99 m, 119 m, 139 m, 159 m, 179 m and 199 m above the lens. The lens height is specified as 1 m above ground level (agl). The LiDAR has a cone angle of 30°.

A picture of the ZephIR U308 LiDAR is presented in figure 5. This picture was taken at the former deployment location of the U308: the Offshore Meteorological Mast IJmuiden.

To achieve the highest quality LiDAR measurements, a filter named 'availability' is defined based on two metrics: 'number of points' *npts* and 'number of packets' *npackets*. For a 10-minute averaged sample, *npts* returns the average value of the number of points used for the fits (one fit per wind speed measurement at a certain height) in the 10-minute period. The number of measurements performed in the 10-minute period is expressed by *npackets*. In order to quantify the overall availability of the LiDAR in a 10-minute interval (for a certain height), we calculate the total number of readings used in a 10-minute interval

$$n_{total} = npts \cdot npackets$$

Normalizing to 100 %, we obtain

$$availability = \frac{n_{total}}{\mathsf{max}(npts) \cdot \mathsf{max}(npackets)} \cdot 100\% \tag{2.1}$$

where $\mathsf{max}(npts)$ and $\mathsf{max}(npackets)$ are the maximum values of the *npts* and *npackets* metrics observed in the entire data set.

2.5 Data stream

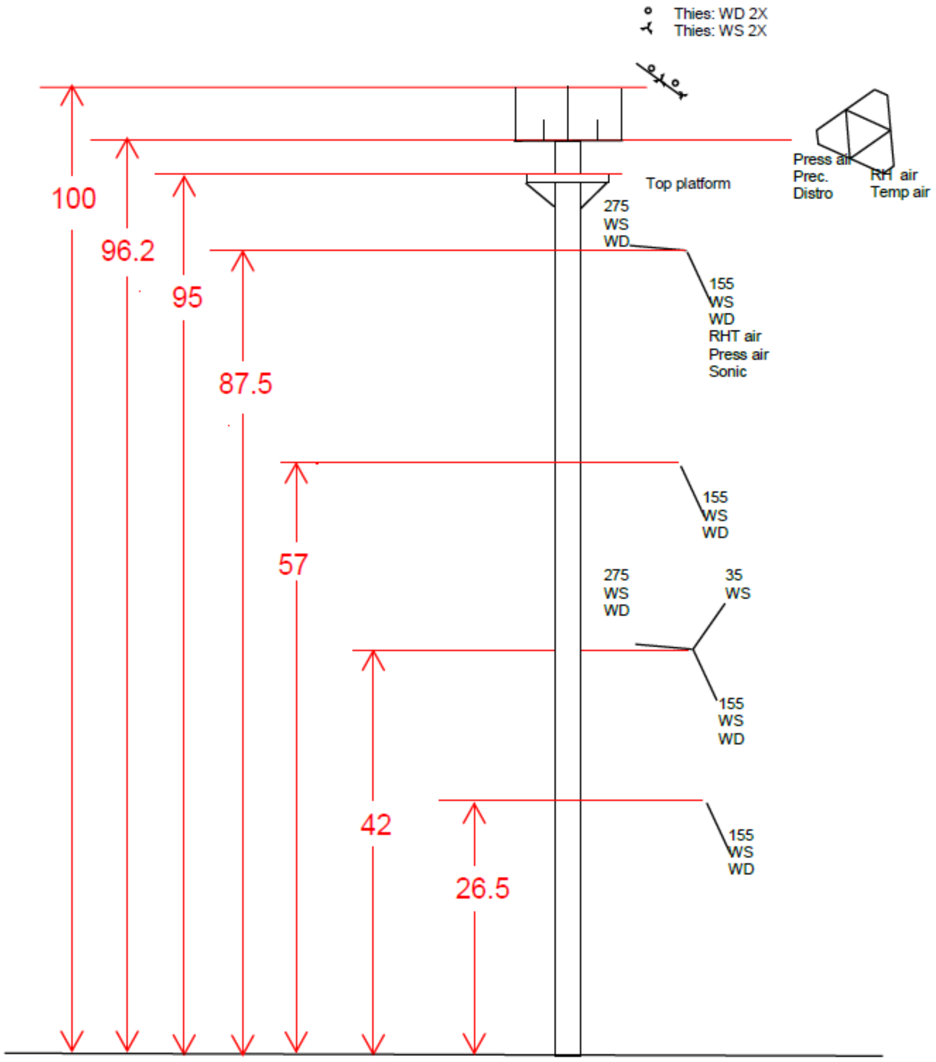
The Meteorological Mast 4 is connected via a glass fibre network to the measurement pavilion on the test site. From here, the data are transported on a daily basis to the offices in Petten, where they are stored in a dedicated Wind Data Management System (WDMS) database [1].

The LiDAR data are accumulated in the LiDAR device itself. The binary data files are transferred directly to the offices in Petten and subsequently converted to ASCII format, using an application[1] supplied by the LiDAR manufacturer. The ASCII files are imported into the WDMS database.

Valid data are gathered for the period of February 27, 2016 00:00 until April 28, 2016 00:00. All times are expressed in UTC.

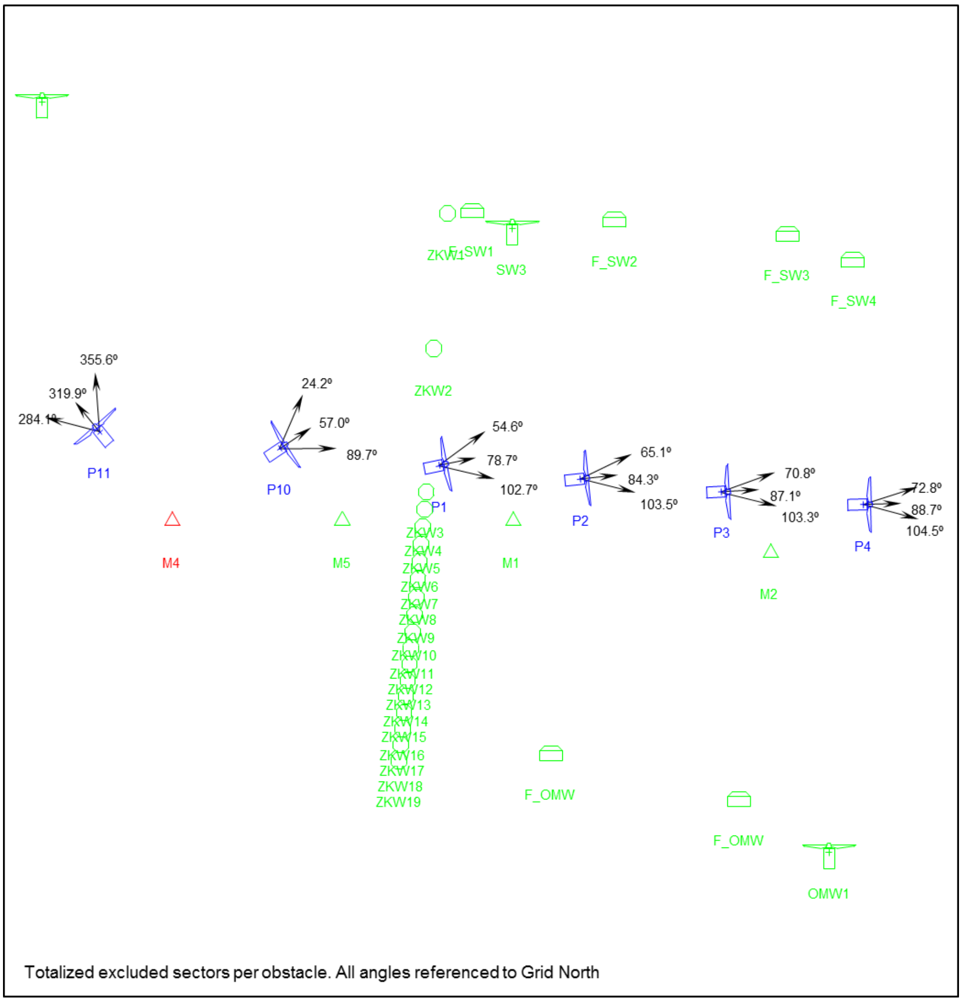
[1] ZephIR® waltz™, Version 4.0, Build 41

Figure 3: Layout of Meteorological Mast 4



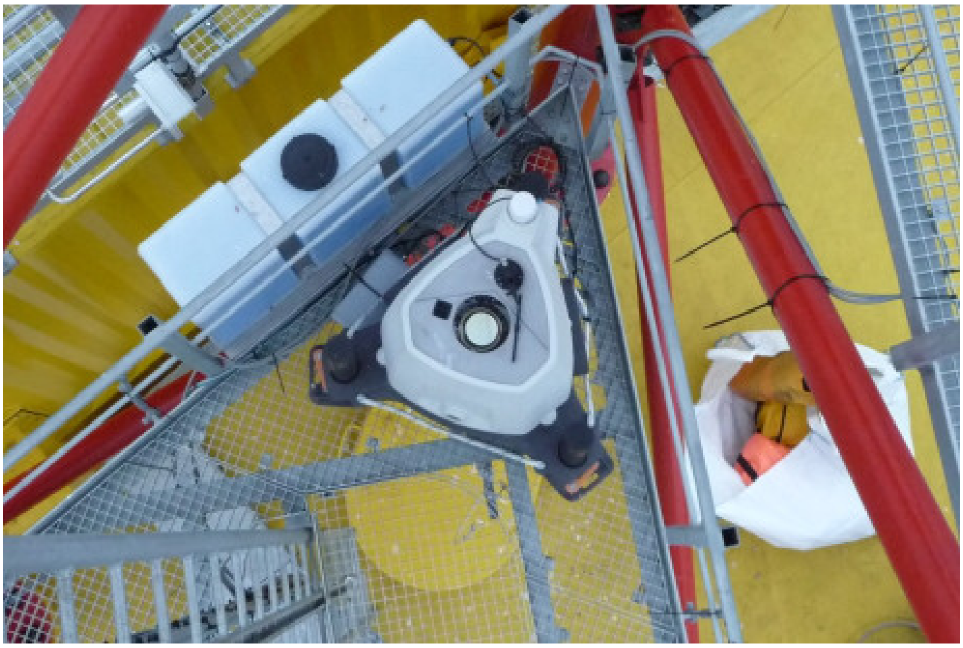
Source: ECN-X--13-087 [2]

Figure 4: Measurement sector



Source: Meassector 2.2

Figure 5: ZephIR U308 LiDAR



Taken at Offshore Meteorological mast IJmuiden

3

Data preparation

The validation is performed using 10 minute average values. The following data filters are applied, in accordance with [6, Annex L.2.2].

1 Mast free of wake from obstacles

The measurement sector is defined in section 2.3 and the filtering is applied to the wind direction measurements at that comparison height h.

$$
\begin{aligned}
104.5° \leq \quad & \text{Wd}(h) \quad \leq 284.1° \qquad \text{or} \\
355.6° \leq \quad & \text{Wd}(h) \quad \leq 24.2°
\end{aligned}
$$

2 LiDAR free of wake from mast

Because the LiDAR is located near the base of MM4, the LiDAR measurements are never completely free from the wake of MM4. At each comparison height, the measurement volume of the LiDAR contains MM4. However, the ratio between the wind speeds measured by MM4 and the LiDAR does not show a strong directional dependency. Therefore, no filtering is applied in this respect.

The LiDAR is located only 5 m from the base of MM4, so the mast interferes with the laser beam at all comparison heights. As a result the LiDAR availability rarely attains 100 %. Investigations proved that an availability range of 90 % to 100 % has little effect on the wind speed deviation.

The investigation of the effect of the wake of MM4 on the wind speed deviation showed that the influence is small. Yet a pattern can be discerned in the directional dependency, which is to be expected due to the extreme proximity.

3 Anemometers free of wake from mast

The influence of the MM4 wake on the reference cup anemometers is mostly mitigated by using multiple cups on booms at different angles at the each measurement height, combined with the pseudo signal equations. At comparison heights 29 m and 59 m only a single boom is present. In these cases the additional sector of 315° to 355° is omitted for the wind speed measurements at these comparison heights. The filtering performed is based on the wind direction measured by the wind vane installed at the comparison height.

4 Cup anemometers free of icing

To eliminate the influence of icing on the wind speed measurements, all data acquired by cup anemometer is disregarded if the air temperature, measured at 96 m drops below 0.5 °C. The temperature is below the threshold value of 0.5 °C for 0.6 % of the time.

5 LiDAR availability

The threshold for the 'availability' defined in equation 2.1 is set to 90 %.

$$\text{availability} \geq 0.9$$

6 Precipitation

As prescribed, no filtering is performed on precipitation.

4

LiDAR Validation KPIs

For each comparison height, the 10-minute averaged wind speed and wind direction measured by the LiDAR are compared to the values obtained with the sensors on the Meteorological Mast 4. We will refer to the LiDAR results as 'rsd' (remote sensing device) and the Meteorological Mast 4 results as 'ref' (reference).

Regression parameters of the wind speed and direction comparisons are identified as Key Performance Indicators (KPIs), which should lay in specified ranges. This is referred to as LiDAR validation and results are presented in this chapter.

4.1 Wind speed comparison

The wind speed plots show the raw data, which are the 10-minute averaged wind speed samples, in blue. The deviation, in red, is the relative difference between the wind speeds measured by the ref, v_{ref}, and the rsd, v_{rsd}. The deviation is defined as

$$\text{deviation} = \frac{v_{\mathrm{rsd}} - v_{\mathrm{ref}}}{v_{\mathrm{ref}}} \cdot 100\,\% \tag{4.1}$$

From the raw data, bin-wise[2] mean values are computed, which are represented by square markers. The bin-wise mean values of bins that do not meet the bin-count threshold of three samples are omitted.

Two regression methods are applied to the data. The two-parameter (2p) method, a linear regression with a slope and offset, is applied to both the raw data and the bin-wise means (binmeans).

$y_{2p} = \text{slope} \cdot x + \text{offset}$

The one-parameter (1p) method, a linear regression with only a slope, is applied to the bin-wise means only.

$y_{1p} = \text{slope} \cdot x$

The results are shown in figures 6-10.

[2] The bin-width equals 0.5 m/s, centred at integer multiples of 0.5 m/s. The first and last bin are only 0.25 m/s wide to fill the 4 m/s to 16 m/s range.

4.2 Wind direction comparison

Performing a regression on the wind direction comparison which features a slope - as was done for the wind speed - makes little physical sense, because the value obtained at 0° should match the one at 360°. Therefore, we only consider the offset. This is best visualised by plotting the difference.

The wind direction comparison plots 11-15 show the difference between the wind direction measured by the ref, wd_{ref}, and the rsd, wd_{rsd}. The difference is defined as

$$\Delta_{wd} = wd_{\text{rsd}} - wd_{\text{ref}} \tag{4.2}$$

From the raw data, bin-wise[3] mean values are computed, which are represented by square markers. The bin-wise mean values of bins that do not meet the bin-count threshold of three samples are omitted.

The regression of the binmeans is in this case simply the mean of the binmeans.

Strong outliers are caused by the heterodyne behaviour of the LiDAR, which causes the LiDAR to sometimes report the wind direction with a 180° error. The percentage of the samples affected are reported as $\Delta_{90_{\text{WD}}} \equiv |\Delta| > 90°$. These outliers strongly influence the binmeans (and standard deviation). To provide an estimate of the offset in the unaffected samples, the median value of Δ_{wd} is shown too.

ECN has defined KPIs on wind speed and wind direction regression parameters in the same fashion as the NORSEWinD criteria [4] and the KPIs defined in the 'Carbon Trust Offshore Wind Accelerator roadmap for the commercial acceptance of floating LIDAR technology' [7]. The KPIs are shown in table 3. It is clear that all criteria have been met.

4.3 Availability

This section presents the LiDAR availability KPIs. We use the KPIs as defined in Offshore Wind Accelerator (OWA) roadmap[7].

The monthly availabilities are reported in table 2 per calendar month. Therefore the first and last month contain the data for a fraction of the month. The monthly system availability (MSA) represents the time that the LiDAR system was recording data. The monthly post-processed data availability (MPDA) represents the time that the LiDAR delivered data that passed our filtering criteria. It should be noted that the MPDA is strongly affected by the lower limit that is chosen for the LiDAR availability metric as defined by equation 2.1. Recall that the lower limit was set as high as 90 % in spite of the fact that the LiDAR is located so close to MM4 that interference of the laser beam is inevitable.

Table 2 also lists the overall system availability and the overall data availability for the whole campaign. Only these overall values are evaluated as a KPI in table 3.

During this campaign, the LiDAR achieved perfect system availability. The data availability meets the requirement at all comparison heights, in spite of the fact that the lower limit for the LiDAR availability metric is rather strict given the obstructed placement of the LiDAR.

[3] The bin-width equals 10°.

Table 2: LiDAR availability KPIs

month	samples	MSA [%]	MPDA [%]				
			29 m	44 m	59 m	90 m	100 m
February	432	100.0	99.5	99.5	99.3	99.3	99.3
March	4464	100.0	87.1	87.1	87.3	87.1	86.8
April	3888	100.0	90.5	90.7	90.6	90.0	89.4
overall		**100.0**	**89.2**	**89.3**	**89.3**	**89.0**	**88.6**

Table 3: LiDAR validation Key Performance Indicators results

KPI	height	result	unit	lower limit	upper limit	status
	m	**unit**		**unit**	**unit**	
$\text{slope}_{\text{WS},1p}$	100	1.002	-	0.98	1.02	pass
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	59	1.004	-	0.98	1.02	pass
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	44	89.0	%	85.00		pass
	29	88.6	%	85.00		pass

Figure 6: Wind speed comparison @29m

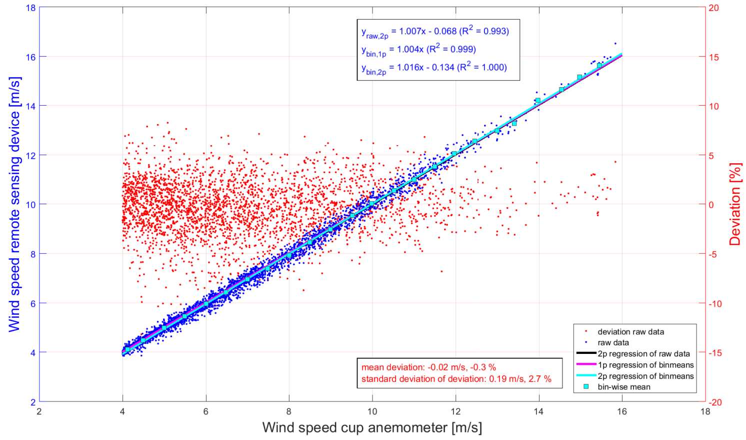


Figure 7: Wind speed comparison @44m

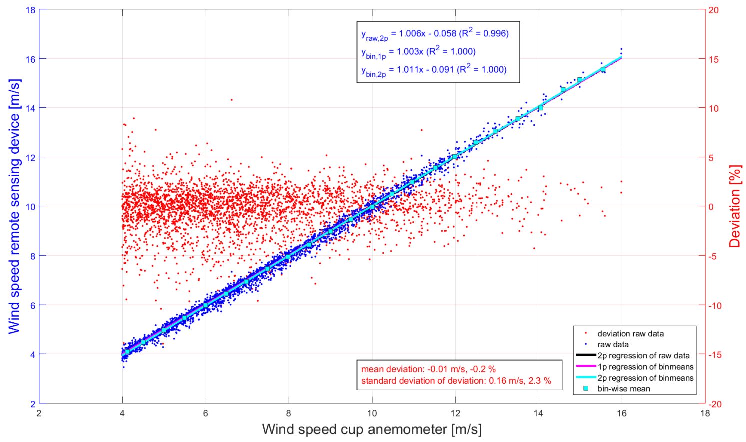


Figure 8: Wind speed comparison @59m

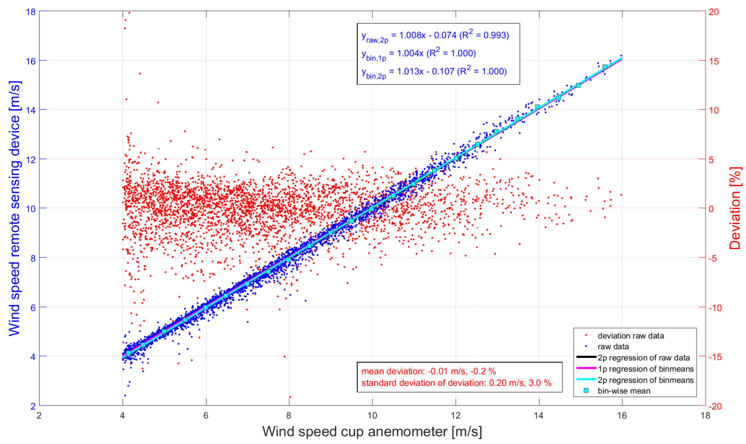


Figure 9: Wind speed comparison @90m

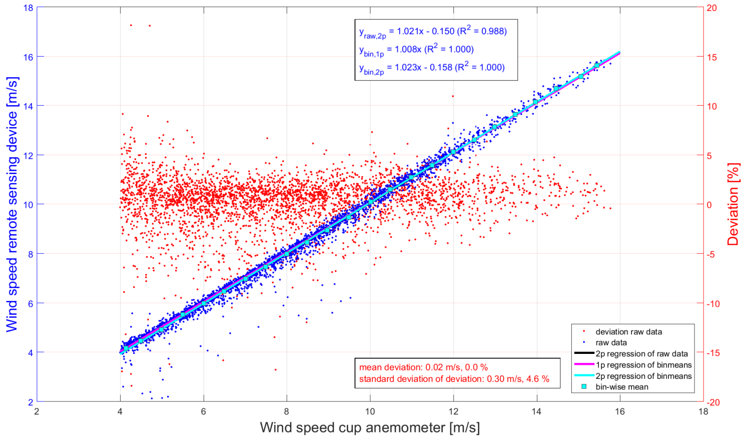


Figure 10: Wind speed comparison @100m

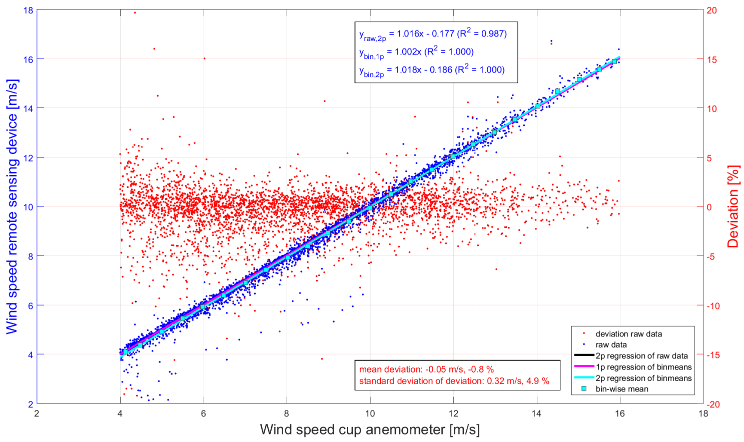


Figure 11: Comparison of 10-minute averages of the wind direction @29m

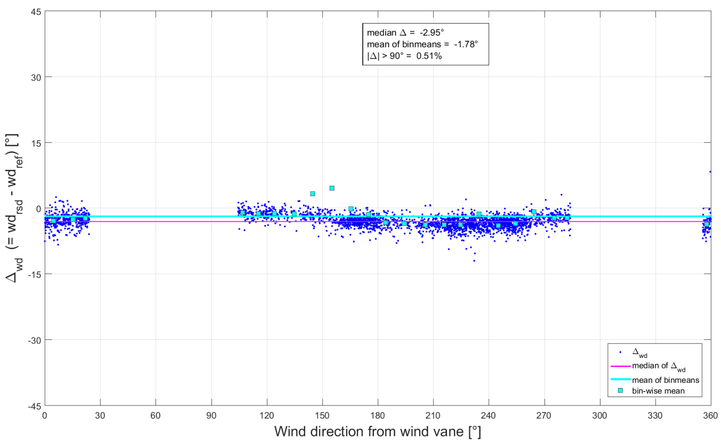


Figure 12: Comparison of 10-minute averages of the wind direction @44m

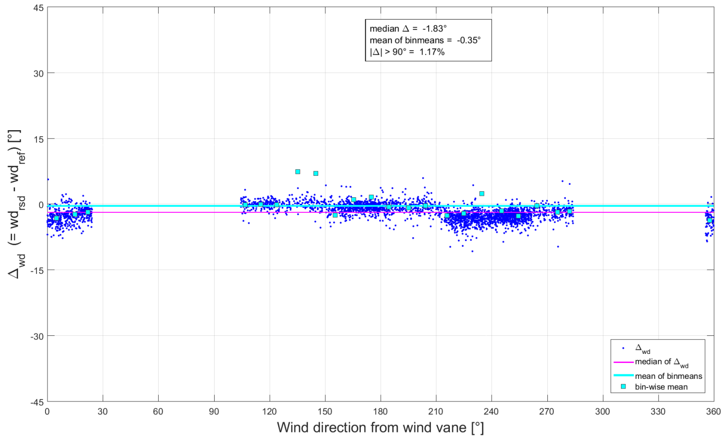


Figure 13: Comparison of 10-minute averages of the wind direction @59m

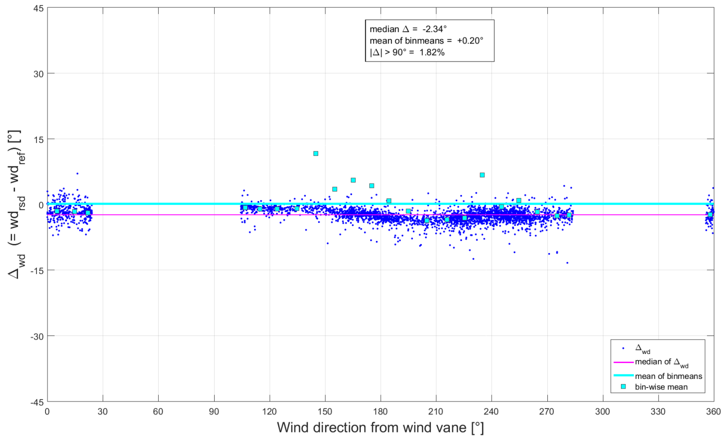


Figure 14: Comparison of 10-minute averages of the wind direction @90m

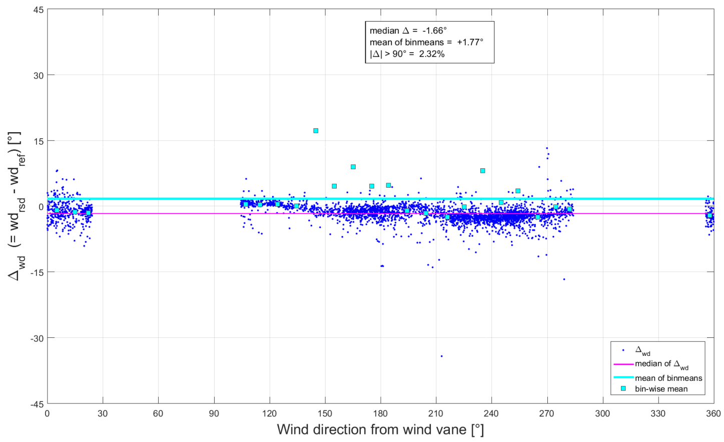
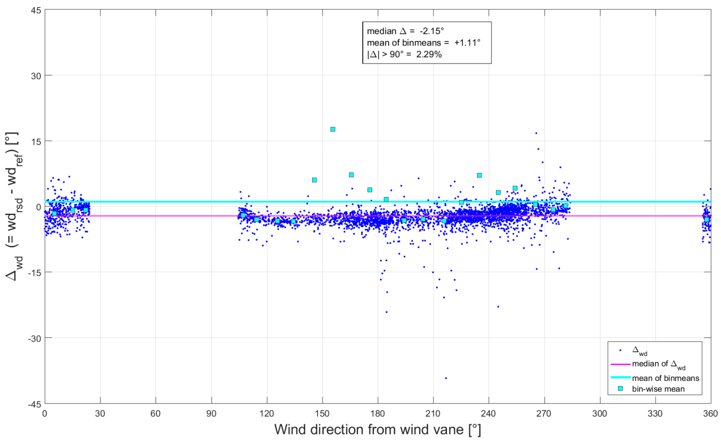


Figure 15: Comparison of 10-minute averages of the wind direction @100m



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