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TNO report

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Verification of LEOSPHERE WINDCUBE V2 unit WLS7-258 at TNO LiDAR Calibration Facility, for offshore measurements at Lichteiland Goeree

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TNO Wind Energy is accredited conform ISO / IEC 17025 and accepted as RETL under IECRE WE-OMC

- Power performance measurements according to IEC 61400-12-1, Measnet Power Performance measurement procedure, FGW TR2, FGW TR5
- NTF/NPC measurements according to IEC61400-12-2
- Mechanical loads measurements according to IEC61400-13
- Meteorological parameters (windspeed, wind direction, temperature, air pressure, relative humidity conform IEC 61400-12-1
- Characterization of Remote Sensing Devices conform IEC 61400-12-1, Appendix L

Results only apply for the tested LiDAR with the settings used during the measurement period.
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Summary

As part of the North Sea offshore wind conditions measurement program a Leosphere LiDAR is installed at Lichteiland Goeree on 24 October 2019. In order to assure high quality measurements, the LiDAR unit (Leosphere Windcube, WLS7-258, firmware 1.1.15) was validated at the TNO LiDAR Calibration Facility (TLCF) for the period of 12 July 2019 until 8 September 2019. The validation is performed by checking Key Performance Indicators (KPIs).

The comparison is performed for three measurement heights: 41.9 m, 81.4 m, and 120.9 m and the KPIs resulting for the validation are listed in table 1. Based on these results TNO qualifies this LiDAR unit as suitable for offshore application at LEG.

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 the validation report [1].

Table 1: LiDAR validation Key Performance Indicators results

KPI	height	result	unit	lower limit	upper limit	status
	m	unit		unit	unit	
$slope_{ws,1p}$	120.9	1.004	-	0.98	1.02	pass
	81.4	1.003	-			pass
	41.9	1.002	-			pass
$R^2_{ws,1p}$	120.9	1.000	-	0.98		pass
	81.4	1.000	-			pass
	41.9	1.000	-			pass
$offset_{,median}$	120.9	-0.170	°	-5	5	pass
	81.4	-0.817	°			pass
	41.9	1.633	°			pass
$\triangle 90_{WD}$	120.9	0.000	%		3	pass
	81.4	0.000	%			pass
	41.9	0.000	%			pass

Contents

1 Introduction

The Dutch government has ambitious plans for offshore wind energy towards 2030 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 and Climate Policy has contracted TNO Energy Transition - Wind Energy to carry out a measurement campaign on the North Sea. This campaign comprises among others of LiDAR measurements at Lichteiland Goeree (LEG). To this end, the Leosphere Windcube LiDAR WLS7-258, firmware 1.1.15 was installed at LEG on 24 October 2019.

High quality measurements will reduce the uncertainty in the measurements creating more favorable finance conditions for developers. Therefore, and to assure the high quality, the LiDAR was first validated at the TNO LiDAR Calibration Facility (TLCF) located at the ECN Wind turbine Test site Wieringermeer (EWTW) [2].

This report describes the comparison of the LiDAR with Meteorological Mast 6 (MM6) for the period of 12 July 2019 until 8 September 2019. The measurements at the mast are performed according to IEC 61400-12-1 (2017) [9] and part of the TNO accreditation on meteorological measurements. Furthermore, the LiDAR is validated, which means that Key Performance Indicators (KPIs) are checked. These KPIs are set-up by TNO based on NORSEWinD criteria [4] and the 'Carbon Trust Offshore Wind Accelerator roadmap for the commercial acceptance of floating LIDAR technology' [5]; 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 6; a full description of the calibration facility can be found in the instrumentation report [6]. Chapter 3 describes the data preparation steps. The validation of the KPI's is discussed in chapter 4.

2 Measurement Campaign

2.1 TNO’s LiDAR Calibration Facility

The TNO’s LiDAR Calibration Facility (TLCF) is currently part of the test site EWTW. EWTW 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 IEC 61400-12-1 (2017) [9].

Figure 1: Detailed map of the ECN Wind Turbine Test Site Wieringermeer (EWTW)

2.2 Meteorological mast

The mast is a un-guyed triangular lattice tower with a height of 118.9 m, see Figure 2. At the bottom the width of the tower is 5.86 m. On the top of the mast a vertical tube is installed with a total height of 1.775 m above the mast top. Including the sensor height of 0.225 m this adds up to a top cup measuring height of 120.9 m.

Figure 2: Meteorological Mast 6 (MM6)

In Figure 3 the location of the calibration platform is given in more detail.

Figure 3: Indicated in red Meteorological Mast 6 and in yellow the calibration platform

A total of 8 booms are mounted on to the mast. Five booms, pointing at 320° in relation to north, support three wind vanes and two cup anemometers. Three booms, pointing at 140° relative to north, support anemometers. At the lower and mid measuring heights two cups are installed in opposite directions. Within the large measurement sector, a single cup measurement would result in large wake effects at specific wind direction. Combined, the influence is minimized. At the lower and mid measuring height the vanes are installed on a separate boom 4 meters below the cup measuring height. The measuring heights of the cup anemometers are 41.9, 81.4, 115.9 and 120.9 m. The measuring heights of the wind vanes are 37.9, 77.4 and 115.9 m. At 111.9 m below the cup anemometer a sonic anemometer is located. The booms can be retracted for maintenance of the sensors. In Figure 4 the layout of Meteorological Mast 6 is given.

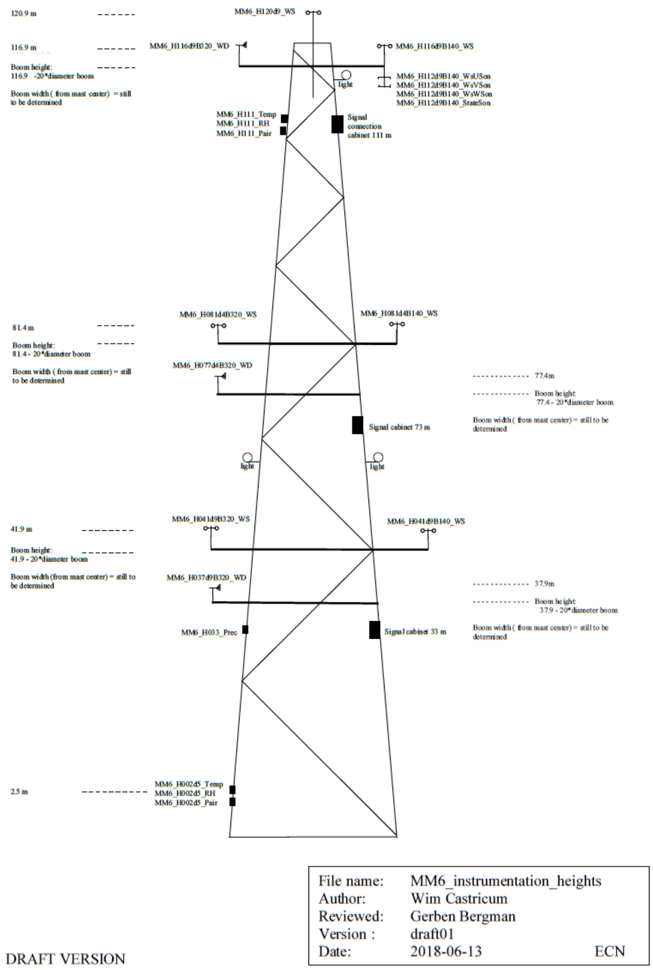

Figure 4: Layout of Meteorological Mast 6

More detail of Meteorological Mast is given in the instrumentation report [6]

2.3 Measurement sector

The "measurement sector" is the wind direction sector for which the met mast measurements and LiDAR measurements are unaffected by obstacles. The measurement sector for this verification project is determined based on IEC 61400-12-1 (2017) [9] using MeasSector version 2.2.1 [7].

The measurement sector during campaign consists of two parts:

- 105.5° to 117.7°
- 196.2° to 359.3°

In Figure 5 the lay-out of the test site EWEF is given with the wind turbines and meteorological mast. This information is used to determine the undisturbed measurement sector.

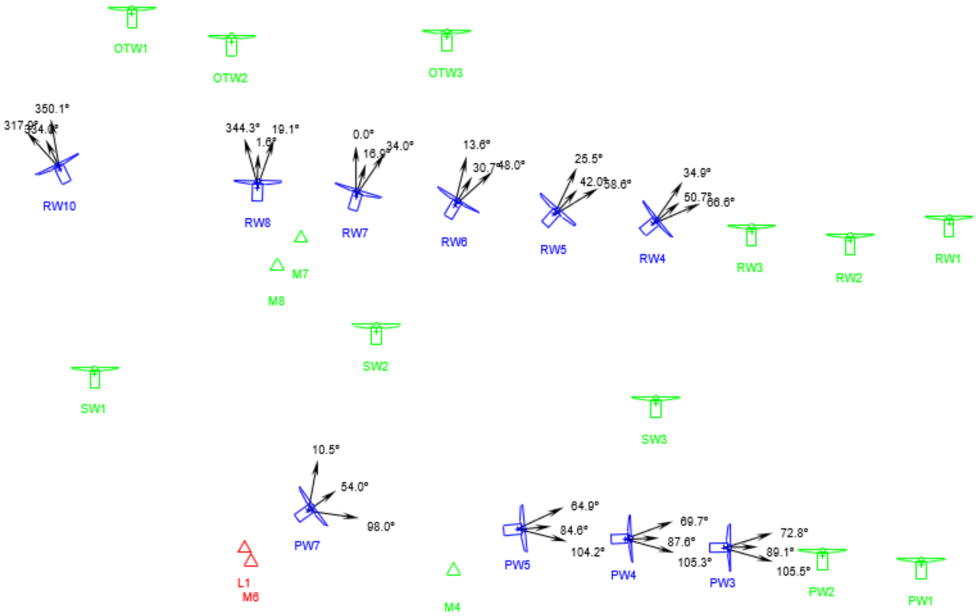

Figure 5: Lay-out test site EWEF used to determine measurement sector.

2.4 LiDAR

The LiDAR is a Leosphere Windcube. This unit has identification number WLS7-258 (firmware 1.1.15) as shown in Figure 6. It is configured to perform measurements at 10 heights: 40 m, 68 m, 93 m, 118 m, 143 m, 168 m, 193 m, 218 m, 243 m and 268 m. The LiDAR has a cone half-angle of 28°.

```
HeaderSize=40
Version=1.1.15
ID System=WLS7-258
ID Client=ECN
Location=N9_east250m
GPS Location=Lat:52.785510N, Long:4.673328E
```

Figure 6: Configuration of WLS7-258

The Windcube LiDAR at the TNO LiDAR Calibration Facility is presented in picture Figure 7.

Figure 7: The Leosphere WLS7-258 LiDAR

2.5 Data stream

The Meteorological Mast 6 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 TNO offices in Petten, where they are stored in a dedicated Wind Data Management System (WDMS) database [8]. The LiDAR data are accumulated in the LiDAR device itself. The data files are transferred directly to the TNO offices in Petten. There the files are imported into the WDMS database. Valid data are gathered for the period of 12 July 2019 00:00 until 8 September 2019 00:00. All times are expressed in UTC.
Please note that for the analysis we use the STA files the LiDAR produces (So we use the 10-minute averaging as performed by the LiDAR itself. Even though we also obtain the ‘fast’ data and have our database compute 10-min averages too.)

3 Data preparation

The validation is performed using 10-minute average values. The following data filters are applied at each comparison height, in accordance with annex L.2.3 [9].

a) Mast free of wake from obstacles
The measurement sector is defined in paragraph 2.3 and the filtering is applied to the wind direction measurements at each comparison height individually.

b) LiDAR free of wake from mast
The LiDAR is located 74.6 m from the base of MM6. At all measurement heights Meteorological Mast 6 is outside the (circular) measurement volume of the LiDAR. Due to the cone angle of the LiDAR, the radius of this circle increases with measurement height. For each comparison height, the wind directions for which MM6 casts a wake on the height-dependent measurement volume, are filtered from the dataset.

The resulting ratio between the wind speeds measured by MM6 and the LiDAR at each comparison height, does not show a strong directional dependency.

c) Anemometers free of wake from mast

For measurement heights below the top cup, the influence of the MM6 wake on the reference cup anemometers is mitigated by combining measurements of two cups on booms at opposite sides of the mast.

d) Cup anemometers free of icing

To eliminate the influence of icing on the wind speed measurements, the MEASNET icing criterion is used. All data acquired by cup anemometer is disregarded if the air temperature, measured at 111 m is lower than 2°C while the relative humidity is higher than 80 %.

e) LiDAR availability

LiDAR data with a carrier-to-noise ratio (CNR) less than -22dB is rejected.
All data with LiDAR availability less than 100 % are filtered from the data set.

f) 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 6. We will refer to the LiDAR results as ‘rsd’ (remote sensing device) and the Meteorological Mast 6 results as ‘ref’ (reference).

Regression parameters of the wind speed and direction comparisons are identified as Key Performance Indicators (KPIs), which should lie 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

$$\text{deviation} = \frac{v_{rsd} - v_{ref}}{v_{ref}} \cdot 100\%$$

From the raw data, bin-wise mean values are computed, which are represented by square markers. The binwidth 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. 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 using a slope and offset, is applied to both the raw data and the bin-wise means (binmeans).
y_{2p} = slope·x + offset
The one-parameter (1p) method, a linear regression using only a slope that passes through the origin, is applied to the bin-wise means only.
y_{1p} = slope·x
The results are shown in figures 8 to 10.

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 in figs. 11 to 13 show the difference between the wind direction measured by the ref, wd_{ref}, and the rsd, wd_{rsd}. The difference is defined as

$$\Delta_{wd} = wd_{rsd} - wd_{ref}$$

From the raw data, bin-wise mean values are computed, which are represented by square markers. The binwidth equals 10°. 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 can be caused by the heterodyne detection 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 $\Delta_{90_{\mathrm{WD}}} \equiv |\Delta| > 90°$. 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. Because of the method employed by the Windcube LiDAR to offset the direction uncertainty resulting from the heterodyne detection, we expect the values of $\Delta_{90_{\mathrm{WD}}}$ to be negligible.

TNO 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' [5]. The KPIs are shown in table 2. It is clear that all criteria have been met.

Table 2: LiDAR validation Key Performance Indicators results

KPI	height	result	unit	lower limit	upper limit	status
	m	unit		unit	unit	
$slope_{ws,1p}$	120.9	1.004	-	0.98	1.02	pass
	81.4	1.003	-			pass
	41.9	1.002	-			pass
$R^2_{ws,1p}$	120.9	1.000	-	0.98		pass
	81.4	1.000	-			pass
	41.9	1.000	-			pass
$offset_{,median}$	120.9	-0.170	°	-5	5	pass
	81.4	-0.817	°			pass
	41.9	1.633	°			pass
$\Delta_{90_{WD}}$	120.9	0.000	%		3	pass
	81.4	0.000	%			pass
	41.9	0.000	%			pass

4.3 Availability

This section presents the LiDAR availability KPIs. We use the KPIs as defined in Offshore Wind Accelerator (OWA) roadmap [5].

The monthly availabilities are reported in table 3 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, which we set to 100 %.

Table 3 also lists the overall system availability and the overall data availability for the whole campaign. Only these overall values are evaluated as a KPI. We require the overall system availability to exceed 90 % and the overall data availability to exceed 85 % at each comparison height. During this campaign, the LiDAR achieved perfect system availability. The data availability also meets the requirement at all comparison heights.

Table 3: LiDAR availability KPIs

Month	samples	MSA	MPDA		
			120.9m	81.4m	41.9m
		%	%	%	%
July	2880	99.9	97.3	97.6	97.4
August	4464	100.0	98.2	98.5	98.3
September	1008	100.0	97.3	97.6	97.3
Overall		**100.0**	**97.8**	**98.1**	**97.8**

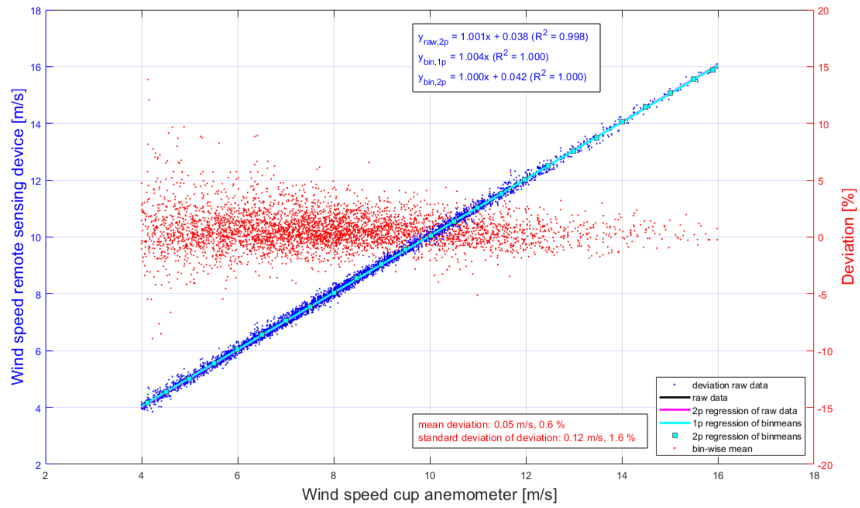

Figure 8: Wind speed comparison @120.9 m

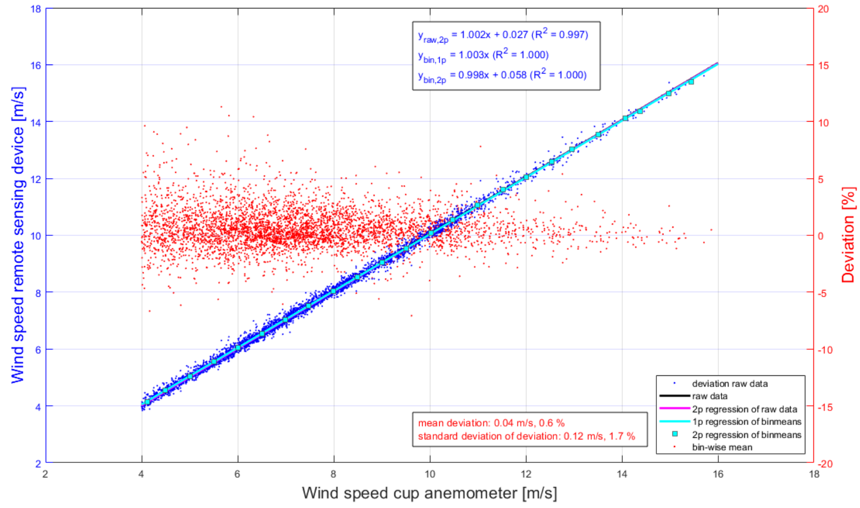

Figure 9: Wind speed comparison @81.4 m

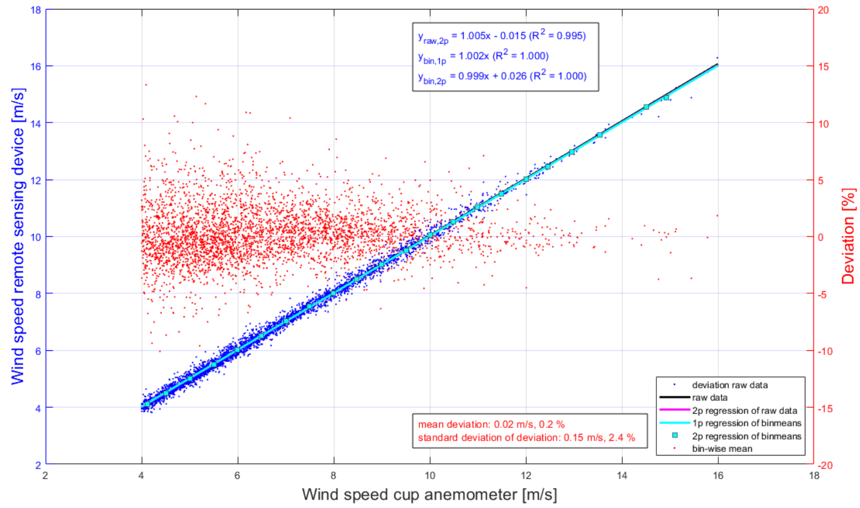

Figure 10: Wind speed comparison @41.9 m

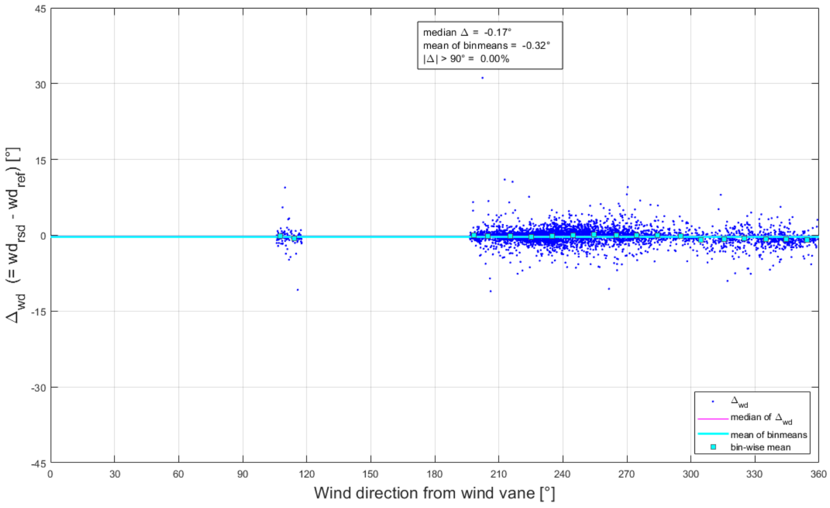

Figure 11: Comparison of 10-minute averages of the wind direction @120.9 m

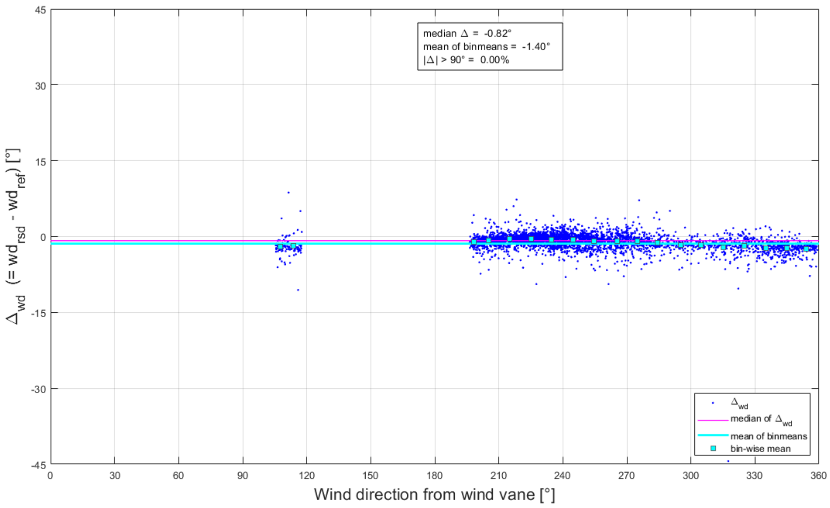

Figure 12: Comparison of 10-minute averages of the wind direction @81.4 m

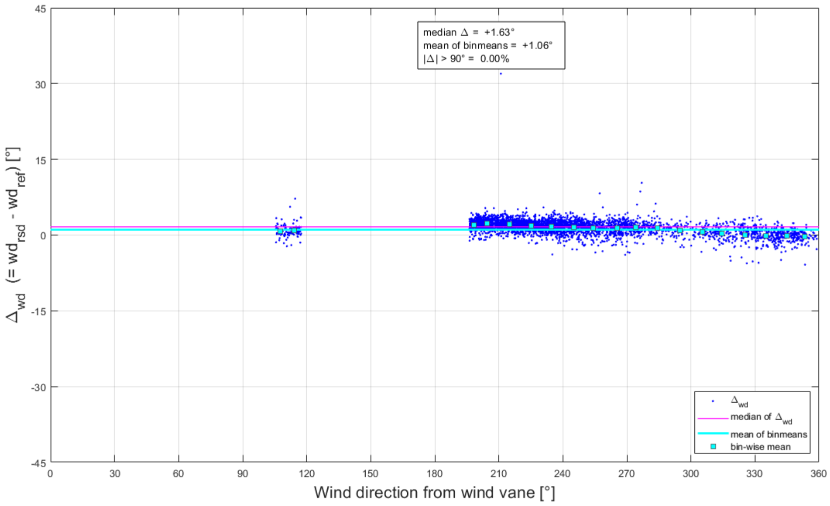

Figure 13: Comparison of 10-minute averages of the wind direction @41.9 m

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