Westerduinweg 3
1755 LE Petten
P.O. Box 15
1755 ZG Petten
The Netherlands

www.tno.nl

T +31 88 866 50 65

TNO report

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

Date	26 March 2020
Author(s)	J.P. Verhoef, D.A.J. Wouters, L. Zhang
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		RvA is participant in the ILAC-MRA.

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 Governmental measurement program a Leosphere Windcube 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 summarized, IEC compliant measurement campaign, analysis of the same data is presented in the verification 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 by providing 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 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]; these KPI’s are defined in chapter 4.

The measurement campaign is described in chapter 2 and gives details of 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, as said, is discussed in chapter 4 while chapter 5 presents the LiDAR verification. Chapter 6 describes the sensitivity and Chapter 7 focusses on the uncertainty of both the reference instrumentation and the Remote Sensing Device (RSD). Finally, chapter 8 concludes with the deviations.

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 town of Medemblik. To the East, the site is 1 km away from the large 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 above the land surface.

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 wake 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 above land surface. 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.

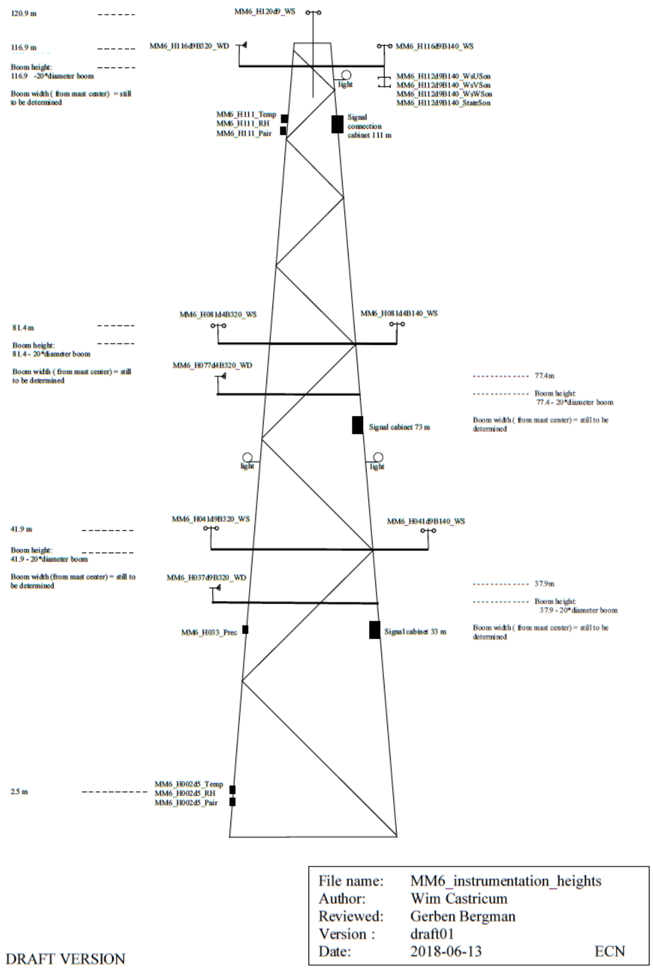

Figure 4: Layout of Meteorological Mast 6

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 is unaffected by obstacles. The measurement sector for this verification project is determined based on IEC 61400-12-1 (2017) [9] using TNO’s software package MeasSector version 2.2.1 [7].

The measurement sector during the 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.

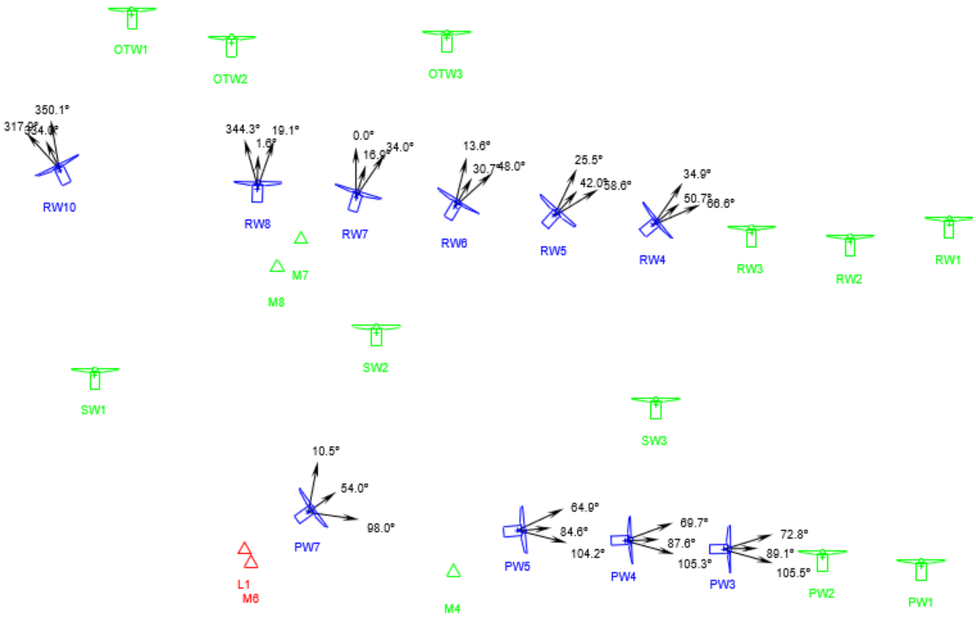

Figure 5: Lay-out test site EWEF used to determine measurement sector.

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 to the measurement pavilion on the test site via a glass fibre network. From here, the data is transmitted on a daily basis to the TNO offices in Petten, where it is stored in a dedicated Wind Data Management System (WDMS) database [8]. The LiDAR data is 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 Windcube 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].

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

2. 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 in the undisturbed sectors, does not show a strong directional dependency.

3. 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 simultaneous measurements of two cups on booms at opposite sides of the mast.

4. 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 %.

5. 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.

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 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, centered 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 11 to 13.

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. 8 to 10 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 per calendar month in table. 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 (near) 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**

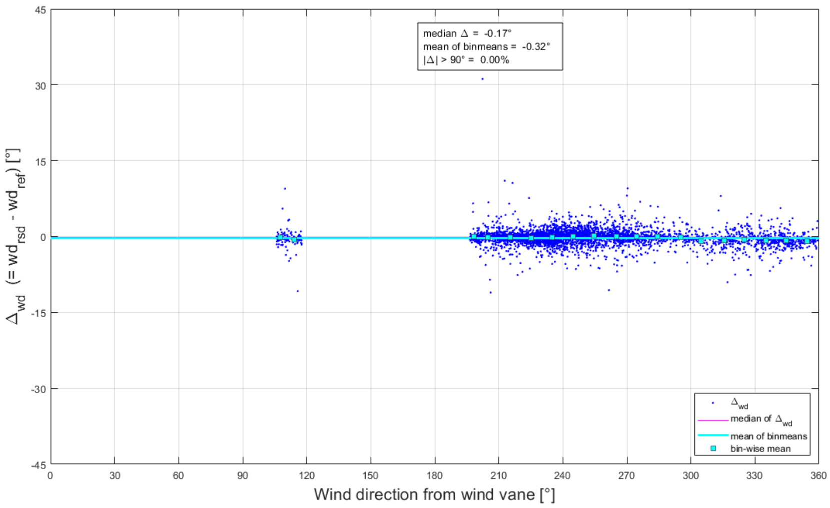

Figure 8: Comparison of 10-minute averages of the wind direction @120.9 m

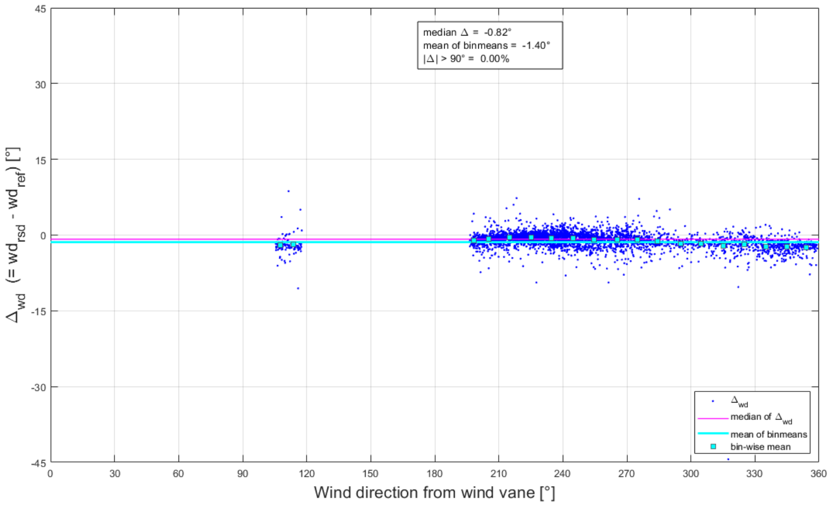

Figure 9: Comparison of 10-minute averages of the wind direction @81.4 m

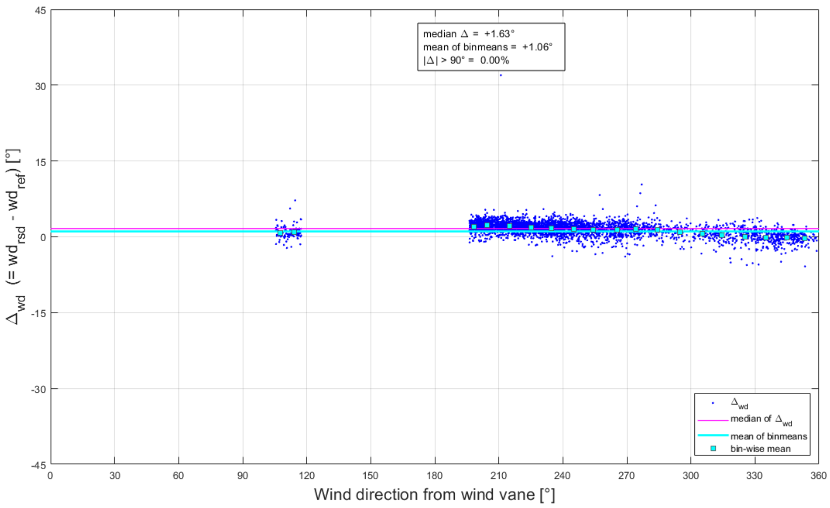

Figure 10: Comparison of 10-minute averages of the wind direction @41.9 m

5 LiDAR verification

This chapter reports the results of the LiDAR verification analysis as defined in annex L.3 [9]. The analysis is performed using the in-house software tool RSDverification version 2.2.1 [7].

5.1 Direct data comparison

A comparison of the horizontal wind speed between the Meteorological Mast 6 devices and the LiDAR for each comparison height is presented in figs. 11 to 13. The format is taken from figure L.5 [9]. Only samples for which the reference wind speed is in the range of 4 m/s to 16 m/s are used according [9].

5.2 Bin-wise data comparison

The bin-wise comparison described in Annex L.3 [5] first requires binning of the reference wind speeds measured on the Meteorological Mast 6. The prescribed bin width is 0.5 m/s centred on integer multiples of 0.5 m/s. Because the range is 4 m/s to 16 m/s, the first and last bin are given half the prescribed width and are centred at 4.125 m/s and 15.875 m/s respectively.

The resulting bin count histograms are presented in fig. 27. Due to the smaller bin width, the first and last bin have a significantly lower bin count.

With the exception of 100 m, all comparison heights have bins in the upper end of the 4 m/s to 16 m/s range that contain less than the minimum of three data sets, specified by data coverage requirement c) [9, L.2.2]. This is a deviation from the standard, reported in chapter 8.

The resulting bin-wise comparisons for each measurement height, are presented in figs. 14 to 16. The results of the regressions are summarised in Table 4. The uncertainty intervals shown in these figures are discussed in section 7.1.

Table 4: LiDAR verification IEC 61400-12-1 (2017) Annex L results

Height	Slope	Offset	R^2
m	-	m/s	-
120.9	1.000	0.042	1.000
81.4	0.998	0.056	1.000
41.9	0.999	0.026	1.000

5.3 Systematic uncertainties

The results of the systematic uncertainty analysis, as described in section 7.2, are presented for each comparison height in tables 4 to 8. The tables are modelled after table L.9 [9]. The total LiDAR uncertainty is reported in column 'V_{rsd}'.

If there are fewer than three data sets in any bin, all statistics (mean and standard deviation) and derived properties are omitted from the table.

5.4 Environmental conditions

The uncertainty computation for the LiDAR as part of a future power performance campaign requires the environmental conditions experienced during the LiDAR verification test [9, annex L.7.1, item i]. For completeness we report the environmental conditions even though this verification test is not linked to a power performance campaign. The conditions at each comparison height are reported in tables 8 to 10. The environmental data is subject to the same filtering steps as the (wind speed) data used for the verification analysis. The environmental data is binned against the reference wind speed[1].[1]

In addition to the tabulated sensitivity results, these environmental variables for which a significant sensitivity is found in Table 14 are also plotted as a function of wind speed along with their distribution in figs. 17 to 25.

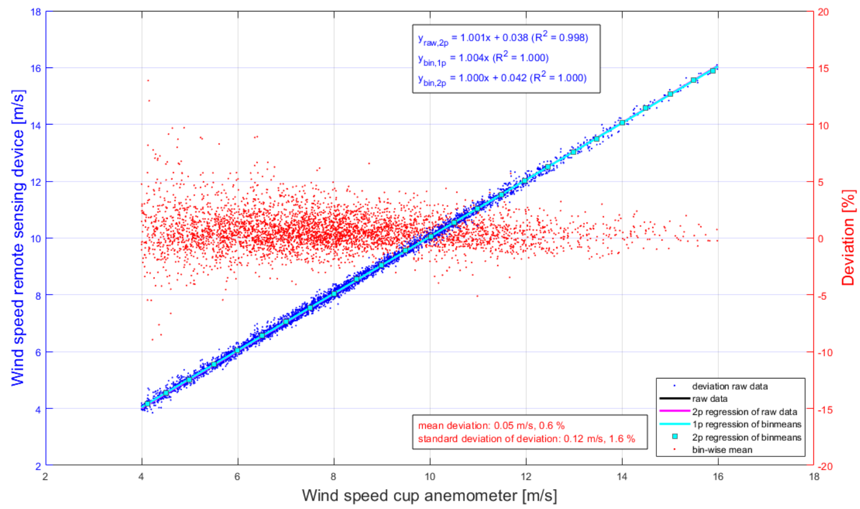

Figure 11: Wind speed comparison @120.9 m

[1] For the reference wind speed the bin center is reported, because each environmental condition may have a slightly difference bin-wise mean wind speed depending on the availability of environmental data.

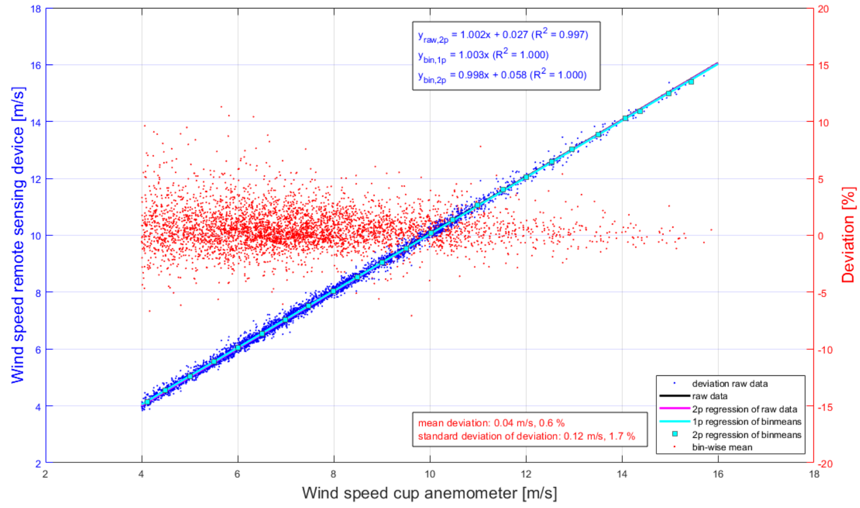

Figure 12: Wind speed comparison @81.4 m

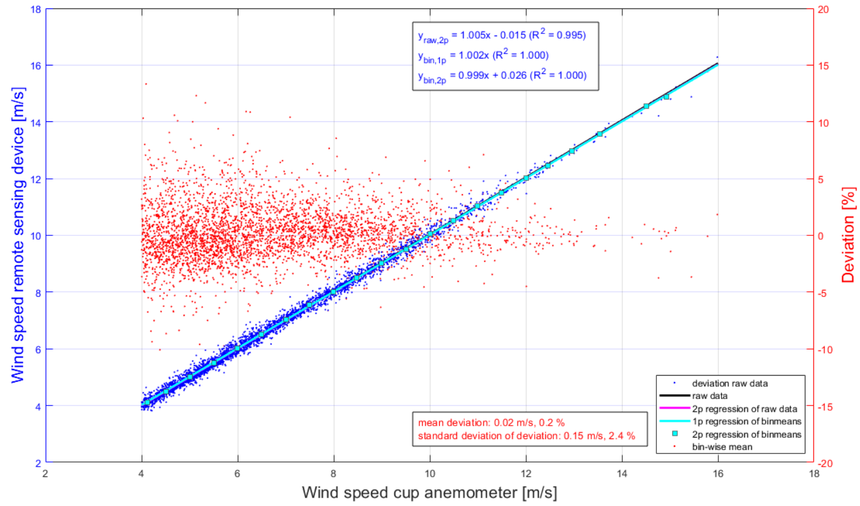

Figure 13: Wind speed comparison @41.9 m

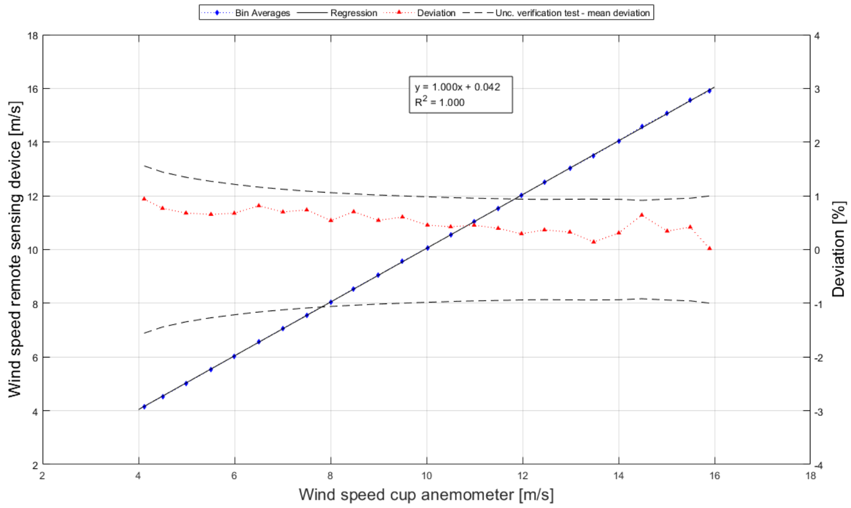

Figure 14: Bin-wise comparison of horizontal wind speed measurements of the WLS7-258 lidar and the Thies First Class advanced cup anemometer at 120.9 m height.

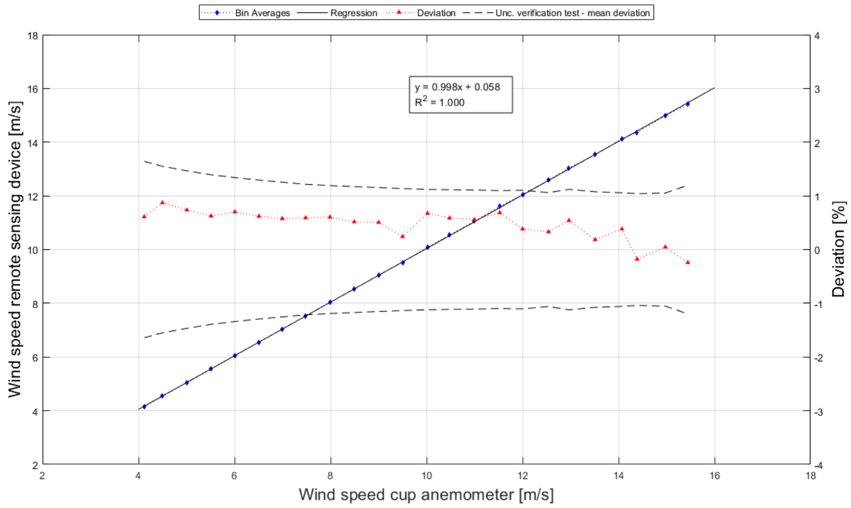

Figure 15: Bin-wise comparison of horizontal wind speed measurements of the WLS7-258 lidar and the Thies First Class advanced cup anemometer at 81.4 m height.

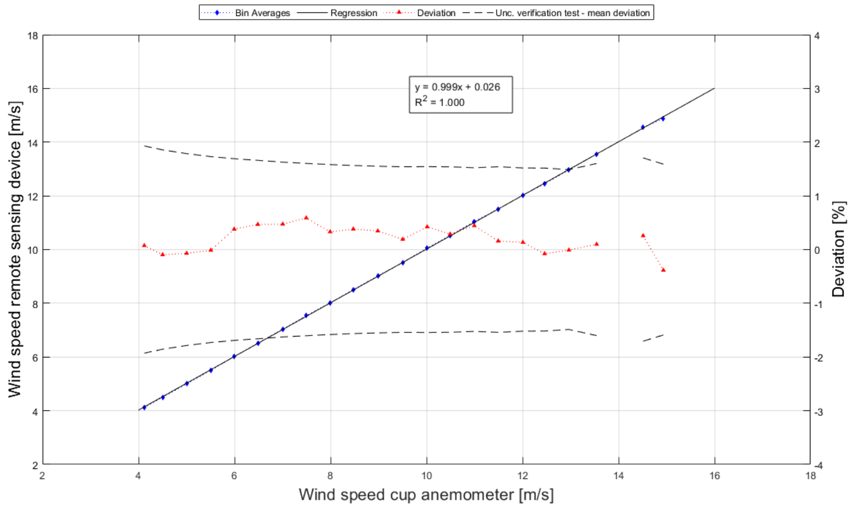

Figure 16: Bin-wise comparison of horizontal wind speed measurements of the WLS7-258 lidar and the Thies First Class advanced cup anemometer at 41.9 m height.

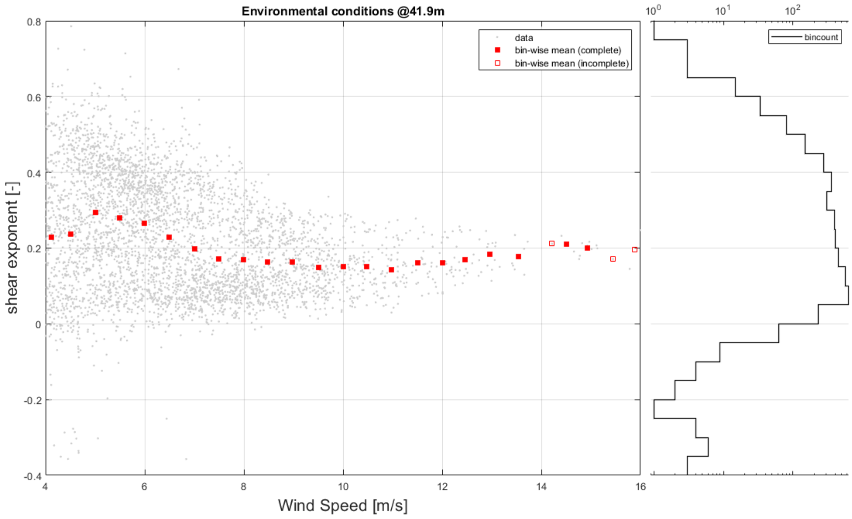

Figure 17: Environmental conditions: shear exponent @ 42 m

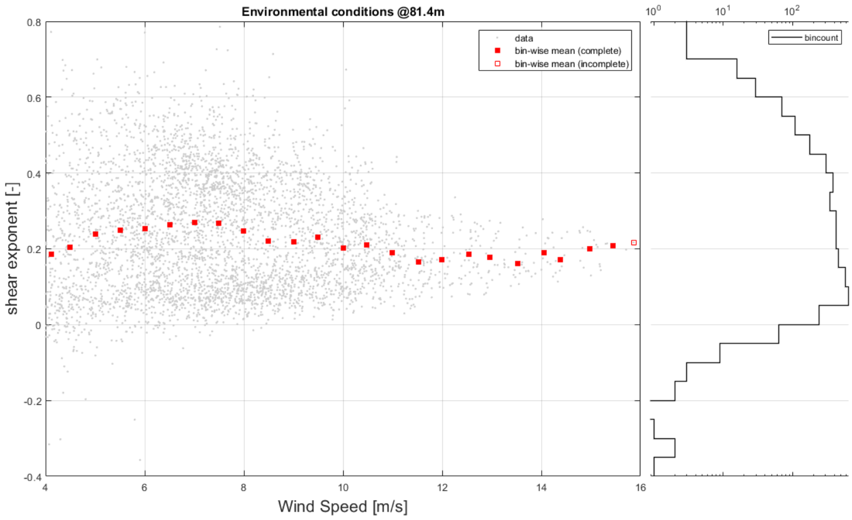

Figure 18: Environmental conditions: shear exponent @ 81.4 m

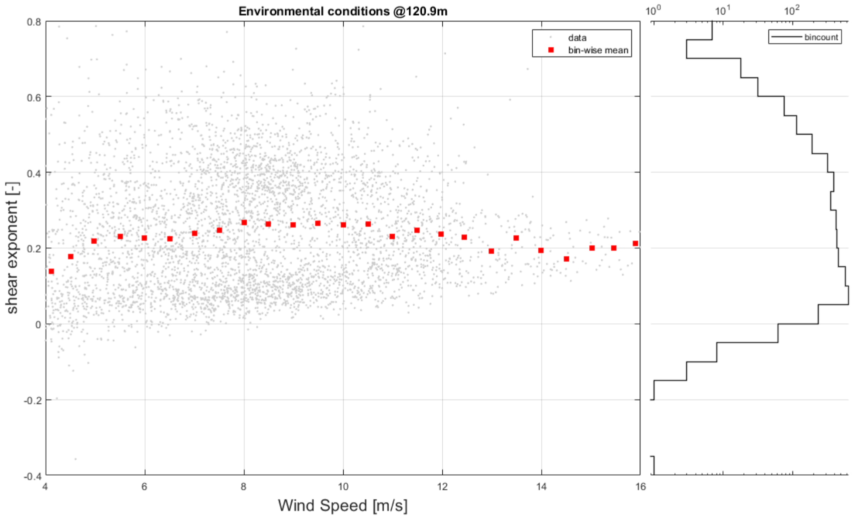

Figure 19: Environmental conditions: shear exponent @ 121 m

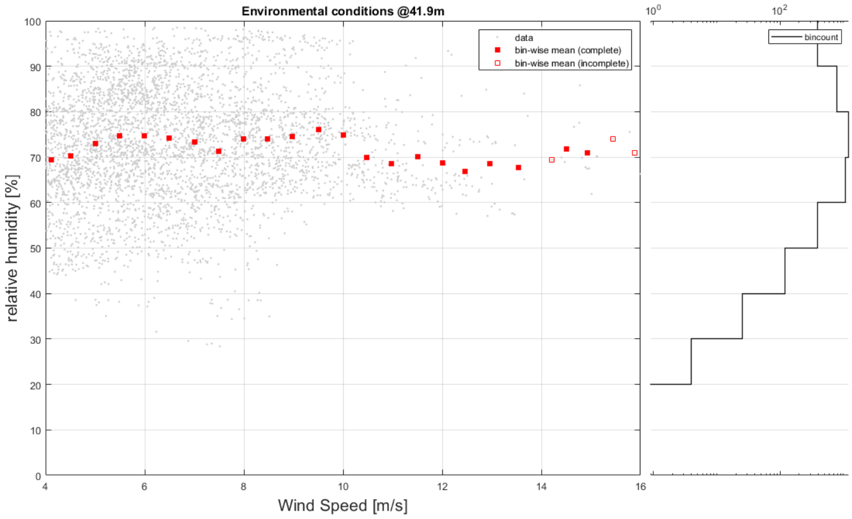

Figure 20: Environmental conditions: relative humidity @ 42 m

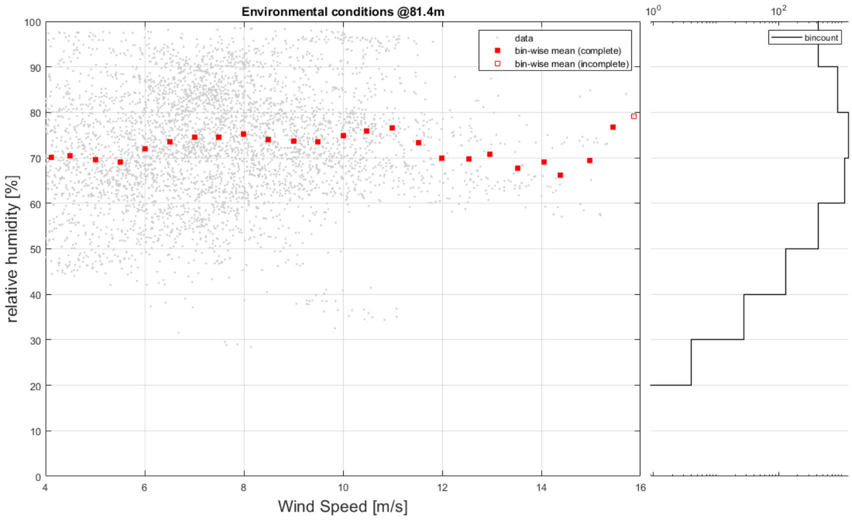

Figure 21: Environmental conditions: relative humidity @ 81.4 m

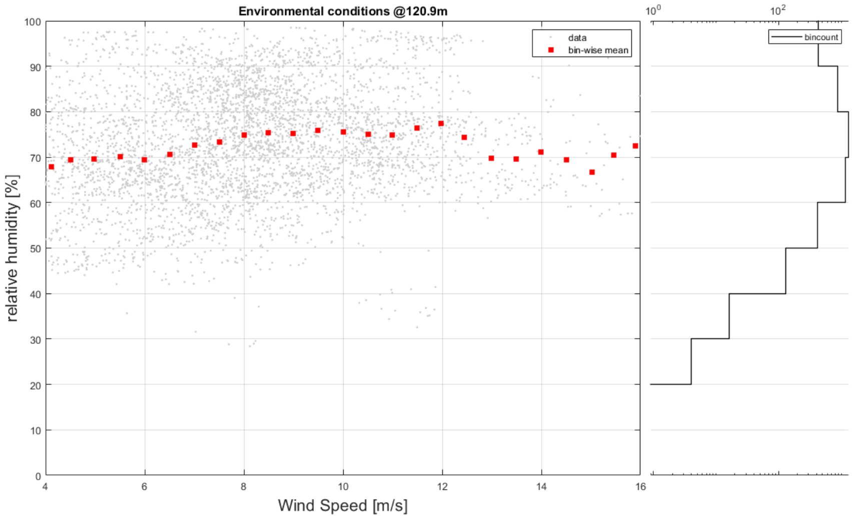

Figure 22: Environmental conditions: relative humidity @ 121 m

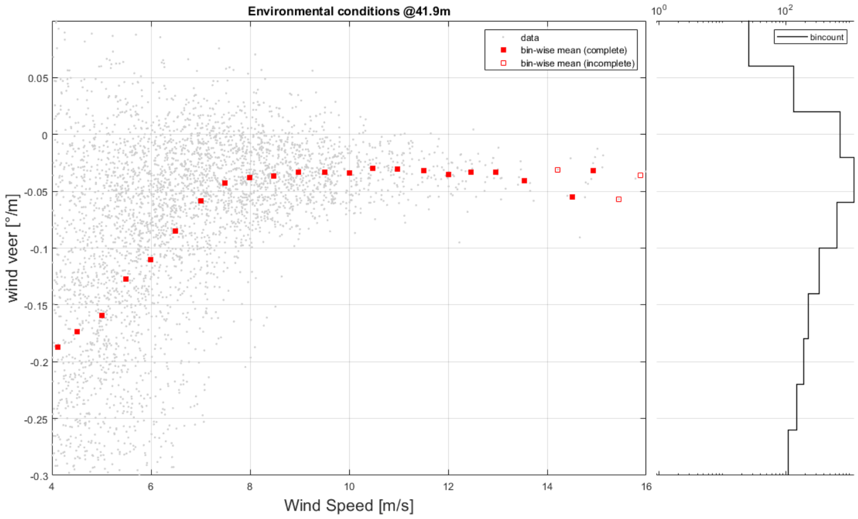

Figure 23: Environmental conditions: wind veer @ 41.9 m

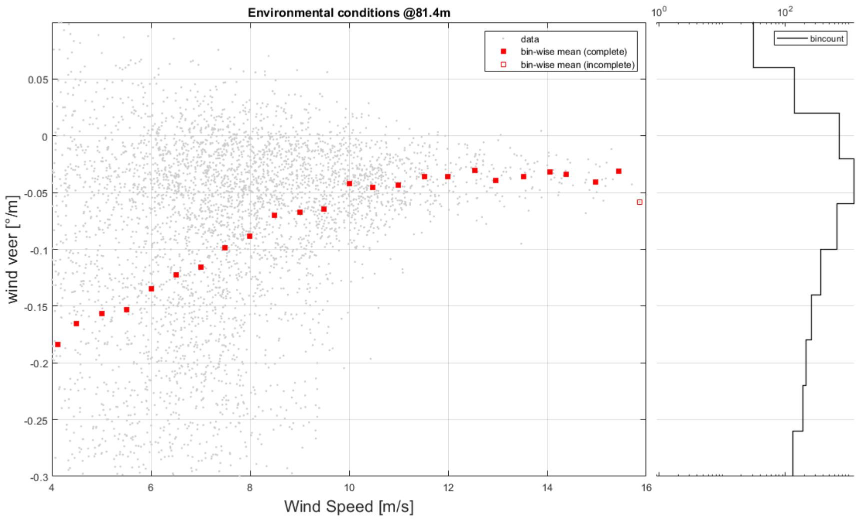

Figure 24: Environmental conditions: relative humidity @ 81.4 m

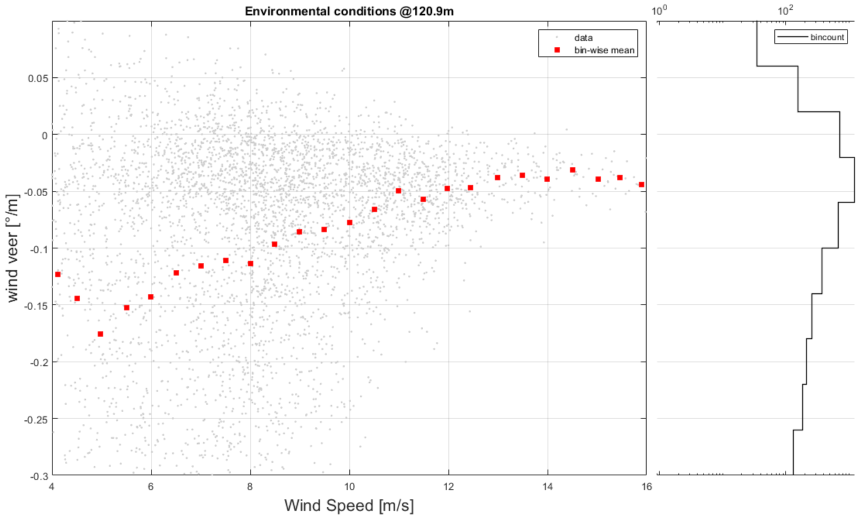

Figure 25: Environmental conditions: wind veer @ 121 m

Table 5: Systematic uncertainties from the verification test of WLS7-258 against meteorological mast 6 at 120.9 m.

V_{cup}	V_{rsd}	Data sets	V_{rsd} max	V_{rsd} min	V_{rsd} std	V_{rsd} std/$\sqrt{n}$	mean dev.	V_{cup} unc.	mount. unc. rsd	separation unc.	V_{rsd} unc.
m/s	m/s	#	m/s	m/s	m/s	m/s	%	%	%	%	%
4.12	4.16	77	4.71	3.85	0.16	0.018	0.939	1.417	0.10	0.42	1.818
4.50	4.53	205	5.12	4.03	0.19	0.013	0.768	1.330	0.10	0.42	1.634
4.99	5.02	245	5.69	4.61	0.17	0.011	0.679	1.239	0.10	0.42	1.507
5.51	5.55	276	6.08	5.13	0.18	0.011	0.654	1.161	0.10	0.42	1.428
5.99	6.03	295	6.45	5.49	0.19	0.011	0.677	1.102	0.10	0.42	1.390
6.51	6.56	337	7.07	6.18	0.17	0.009	0.815	1.050	0.10	0.42	1.419
7.01	7.06	350	7.55	6.58	0.18	0.009	0.700	1.007	0.10	0.42	1.323
7.50	7.56	397	8.18	7.14	0.18	0.009	0.738	0.971	0.10	0.42	1.315
8.01	8.05	396	8.47	7.53	0.18	0.009	0.540	0.939	0.10	0.42	1.189
8.48	8.54	336	9.31	8.13	0.19	0.010	0.704	0.913	0.10	0.42	1.253
9.00	9.05	269	9.46	8.63	0.18	0.011	0.543	0.888	0.10	0.42	1.151
9.50	9.56	222	10.11	9.01	0.19	0.013	0.606	0.867	0.10	0.42	1.168
10.02	10.06	174	10.48	9.57	0.19	0.014	0.455	0.847	0.10	0.42	1.082
10.50	10.55	201	11.10	9.93	0.21	0.015	0.424	0.831	0.10	0.42	1.057
10.99	11.04	157	11.70	10.43	0.20	0.016	0.453	0.816	0.10	0.42	1.058
11.49	11.54	134	12.35	11.08	0.21	0.018	0.395	0.803	0.10	0.42	1.026
11.98	12.01	93	12.45	11.55	0.19	0.020	0.294	0.791	0.10	0.42	0.983
12.46	12.50	72	13.14	12.19	0.20	0.023	0.366	0.780	0.10	0.42	1.001
12.99	13.03	41	13.54	12.64	0.20	0.032	0.325	0.769	0.10	0.42	0.992
13.48	13.50	38	13.99	13.08	0.23	0.037	0.140	0.760	0.10	0.42	0.949
14.00	14.05	29	14.51	13.60	0.22	0.041	0.309	0.751	0.10	0.42	0.985
14.48	14.58	21	14.86	14.32	0.16	0.035	0.640	0.743	0.10	0.42	1.117
15.01	15.07	12	15.38	14.81	0.18	0.051	0.344	0.736	0.10	0.42	1.001
15.49	15.56	10	15.80	15.30	0.19	0.061	0.417	0.729	0.10	0.42	1.042
15.90	15.90	4	16.10	15.76	0.16	0.079	0.017	0.724	0.10	0.42	0.998

Table 6: Systematic uncertainties from the verification test of WLS7-258 against meteorological mast 6 at 81.4 m.

V_{cup}	V_{rsd}	data sets	V_{rsd} max	V_{rsd} min	V_{rsd} std	V_{rsd} std/$\sqrt{n}$	mean dev.	V_{cup} unc.	mount. unc. rsd	separation unc.	V_{rsd} unc.
m/s	m/s	#	m/s	m/s	m/s	m/s	%	%	%	%	%
4.12	4.14	114	4.54	3.84	0.13	0.012	0.610	1.471	0.10	0.62	1.751
4.50	4.54	276	5.04	4.20	0.17	0.010	0.871	1.382	0.10	0.62	1.778
5.01	5.05	272	5.55	4.52	0.18	0.011	0.737	1.290	0.10	0.62	1.641
5.51	5.55	317	6.30	5.17	0.18	0.010	0.625	1.210	0.10	0.62	1.526
6.01	6.05	405	6.61	5.56	0.19	0.010	0.702	1.153	0.10	0.62	1.513
6.51	6.55	426	7.21	6.19	0.18	0.009	0.619	1.102	0.10	0.62	1.434
7.00	7.04	423	7.63	6.52	0.20	0.010	0.576	1.055	0.10	0.62	1.380
7.48	7.53	371	8.05	7.08	0.18	0.010	0.590	1.009	0.10	0.62	1.350
7.99	8.04	322	8.57	7.51	0.18	0.010	0.603	0.981	0.10	0.62	1.335
8.50	8.54	245	9.04	8.04	0.17	0.011	0.517	0.957	0.10	0.62	1.281
9.00	9.05	232	9.60	8.44	0.18	0.012	0.505	0.934	0.10	0.62	1.259
9.50	9.52	191	9.95	8.94	0.20	0.014	0.241	0.909	0.10	0.62	1.161
10.02	10.09	180	10.55	9.52	0.19	0.014	0.674	0.892	0.10	0.62	1.307
10.48	10.54	155	11.08	10.14	0.21	0.017	0.588	0.879	0.10	0.62	1.259
11.00	11.06	98	11.92	10.55	0.21	0.021	0.558	0.866	0.10	0.62	1.241
11.53	11.61	68	12.25	11.18	0.21	0.026	0.686	0.844	0.10	0.62	1.294
12.00	12.05	48	12.57	11.49	0.21	0.030	0.383	0.845	0.10	0.62	1.169
12.54	12.58	38	12.96	12.30	0.15	0.025	0.330	0.802	0.10	0.62	1.110
12.97	13.04	28	13.63	12.46	0.26	0.050	0.540	0.820	0.10	0.62	1.245
13.51	13.54	25	13.92	13.12	0.21	0.042	0.183	0.786	0.10	0.62	1.091
14.07	14.12	15	14.40	13.85	0.16	0.042	0.382	0.768	0.10	0.62	1.124
14.39	14.36	8	14.50	14.14	0.11	0.038	-0.180	0.757	0.10	0.62	1.055
14.98	14.98	15	15.37	14.68	0.19	0.048	0.046	0.750	0.10	0.62	1.054
15.44	15.41	3	15.61	15.29	0.18	0.102	-0.243	0.747	0.10	0.62	1.222
		1	15.94	15.94							

Table 7: Systematic uncertainties from the verification test of WLS7-258 against meteorological mast 6 at 41.9 m.

V_{cup}	V_{rsd}	Data sets	V_{rsd} max	V_{rsd} min	V_{rsd} std	V_{rsd} std/$\sqrt{n}$	mean dev.	V_{cup} unc.	mount. unc. rsd	separation unc.	V_{rsd} unc.
m/s	m/s	#	m/s	m/s	m/s	m/s	%	%	%	%	%
4.12	4.12	187	4.64	3.82	0.14	0.010	0.073	1.461	0.10	1.21	1.930
4.50	4.50	404	5.18	3.94	0.20	0.010	-0.096	1.368	0.10	1.21	1.858
5.00	5.00	419	5.77	4.38	0.19	0.009	-0.070	1.276	0.10	1.21	1.787
5.51	5.51	439	6.12	4.93	0.20	0.009	-0.014	1.201	0.10	1.21	1.730
5.99	6.02	384	6.85	5.59	0.21	0.011	0.380	1.142	0.10	1.21	1.733
6.49	6.52	305	7.01	5.87	0.21	0.012	0.469	1.096	0.10	1.21	1.726
7.01	7.04	280	7.83	6.53	0.20	0.012	0.473	1.046	0.10	1.21	1.695
7.49	7.54	244	8.13	7.11	0.20	0.013	0.589	1.011	0.10	1.21	1.709
7.99	8.02	253	8.74	7.36	0.22	0.014	0.330	0.975	0.10	1.21	1.616
8.47	8.51	200	9.18	7.80	0.22	0.015	0.382	0.945	0.10	1.21	1.611
8.98	9.02	170	9.71	8.41	0.22	0.017	0.346	0.921	0.10	1.21	1.590
9.50	9.52	145	10.18	8.90	0.23	0.019	0.190	0.901	0.10	1.21	1.553
10.01	10.06	87	10.58	9.43	0.25	0.027	0.423	0.887	0.10	1.21	1.601
10.49	10.52	57	11.11	10.06	0.26	0.035	0.288	0.861	0.10	1.21	1.567
11.00	11.04	64	11.91	10.66	0.24	0.029	0.444	0.850	0.10	1.21	1.586
11.49	11.51	34	12.11	10.91	0.26	0.045	0.159	0.837	0.10	1.21	1.550
12.01	12.02	29	12.53	11.47	0.23	0.043	0.134	0.809	0.10	1.21	1.525
12.46	12.45	20	12.81	12.06	0.21	0.046	-0.078	0.799	0.10	1.21	1.519
12.97	12.96	13	13.20	12.80	0.13	0.036	-0.010	0.782	0.10	1.21	1.488
13.54	13.56	7	13.94	13.28	0.24	0.090	0.098	0.774	0.10	1.21	1.605
		1	14.19	14.19							
14.51	14.55	3	14.74	14.30	0.23	0.131	0.257	0.761	0.10	1.21	1.726
14.93	14.88	9	15.23	14.21	0.30	0.099	-0.385	0.755	0.10	1.21	1.636
		1	14.88	14.88							
		2	16.28	15.77							

Table 8: Environmental conditions experienced during verification test of WLS7-258 against MM 6 at 120.9 m.

V_{cup}	V_{rsd}	Data sets	V_{rsd} max	V_{rsd} min	V_{rsd} std	V_{rsd} std/$\sqrt{n}$	mean dev.	V_{cup} unc.	mount. unc. rsd	separation unc.	V_{rsd} unc.
m/s	m/s	#	m/s	m/s	m/s	m/s	%	%	%	%	%
4.12	4.16	77	4.71	3.85	0.16	0.018	0.939	1.417	0.10	0.42	1.818
4.50	4.53	205	5.12	4.03	0.19	0.013	0.768	1.330	0.10	0.42	1.634
4.99	5.02	245	5.69	4.61	0.17	0.011	0.679	1.239	0.10	0.42	1.507
5.51	5.55	276	6.08	5.13	0.18	0.011	0.654	1.161	0.10	0.42	1.428
5.99	6.03	295	6.45	5.49	0.19	0.011	0.677	1.102	0.10	0.42	1.390
6.51	6.56	337	7.07	6.18	0.17	0.009	0.815	1.050	0.10	0.42	1.419
7.01	7.06	350	7.55	6.58	0.18	0.009	0.700	1.007	0.10	0.42	1.323
7.50	7.56	397	8.18	7.14	0.18	0.009	0.738	0.971	0.10	0.42	1.315
8.01	8.05	396	8.47	7.53	0.18	0.009	0.540	0.939	0.10	0.42	1.189
8.48	8.54	336	9.31	8.13	0.19	0.010	0.704	0.913	0.10	0.42	1.253
9.00	9.05	269	9.46	8.63	0.18	0.011	0.543	0.888	0.10	0.42	1.151
9.50	9.56	222	10.11	9.01	0.19	0.013	0.606	0.867	0.10	0.42	1.168
10.02	10.06	174	10.48	9.57	0.19	0.014	0.455	0.847	0.10	0.42	1.082
10.50	10.55	201	11.10	9.93	0.21	0.015	0.424	0.831	0.10	0.42	1.057
10.99	11.04	157	11.70	10.43	0.20	0.016	0.453	0.816	0.10	0.42	1.058
11.49	11.54	134	12.35	11.08	0.21	0.018	0.395	0.803	0.10	0.42	1.026
11.98	12.01	93	12.45	11.55	0.19	0.020	0.294	0.791	0.10	0.42	0.983
12.46	12.50	72	13.14	12.19	0.20	0.023	0.366	0.780	0.10	0.42	1.001
12.99	13.03	41	13.54	12.64	0.20	0.032	0.325	0.769	0.10	0.42	0.992
13.48	13.50	38	13.99	13.08	0.23	0.037	0.140	0.760	0.10	0.42	0.949
14.00	14.05	29	14.51	13.60	0.22	0.041	0.309	0.751	0.10	0.42	0.985
14.48	14.58	21	14.86	14.32	0.16	0.035	0.640	0.743	0.10	0.42	1.117
15.01	15.07	12	15.38	14.81	0.18	0.051	0.344	0.736	0.10	0.42	1.001
15.49	15.56	10	15.80	15.30	0.19	0.061	0.417	0.729	0.10	0.42	1.042
15.90	15.90	4	16.10	15.76	0.16	0.079	0.017	0.724	0.10	0.42	0.998

Table 9: Environmental conditions experienced during verification test of WLS7-258 against MM 6 at 81.4 m.

V_{cup}	V_{rsd}	data sets	V_{rsd} max	V_{rsd} min	V_{rsd} std	V_{rsd} std/$\sqrt{n}$	mean dev.	V_{cup} unc.	mount. unc. rsd	separation unc.	V_{rsd} unc.
m/s	m/s	#	m/s	m/s	m/s	m/s	%	%	%	%	%
4.12	4.14	114	4.54	3.84	0.13	0.012	0.610	1.471	0.10	0.62	1.751
4.50	4.54	276	5.04	4.20	0.17	0.010	0.871	1.382	0.10	0.62	1.778
5.01	5.05	272	5.55	4.52	0.18	0.011	0.737	1.290	0.10	0.62	1.641
5.51	5.55	317	6.30	5.17	0.18	0.010	0.625	1.210	0.10	0.62	1.526
6.01	6.05	405	6.61	5.56	0.19	0.010	0.702	1.153	0.10	0.62	1.513
6.51	6.55	426	7.21	6.19	0.18	0.009	0.619	1.102	0.10	0.62	1.434
7.00	7.04	423	7.63	6.52	0.20	0.010	0.576	1.055	0.10	0.62	1.380
7.48	7.53	371	8.05	7.08	0.18	0.010	0.590	1.009	0.10	0.62	1.350
7.99	8.04	322	8.57	7.51	0.18	0.010	0.603	0.981	0.10	0.62	1.335
8.50	8.54	245	9.04	8.04	0.17	0.011	0.517	0.957	0.10	0.62	1.281
9.00	9.05	232	9.60	8.44	0.18	0.012	0.505	0.934	0.10	0.62	1.259
9.50	9.52	191	9.95	8.94	0.20	0.014	0.241	0.909	0.10	0.62	1.161
10.02	10.09	180	10.55	9.52	0.19	0.014	0.674	0.892	0.10	0.62	1.307
10.48	10.54	155	11.08	10.14	0.21	0.017	0.588	0.879	0.10	0.62	1.259
11.00	11.06	98	11.92	10.55	0.21	0.021	0.558	0.866	0.10	0.62	1.241
11.53	11.61	68	12.25	11.18	0.21	0.026	0.686	0.844	0.10	0.62	1.294
12.00	12.05	48	12.57	11.49	0.21	0.030	0.383	0.845	0.10	0.62	1.169
12.54	12.58	38	12.96	12.30	0.15	0.025	0.330	0.802	0.10	0.62	1.110
12.97	13.04	28	13.63	12.46	0.26	0.050	0.540	0.820	0.10	0.62	1.245
13.51	13.54	25	13.92	13.12	0.21	0.042	0.183	0.786	0.10	0.62	1.091
14.07	14.12	15	14.40	13.85	0.16	0.042	0.382	0.768	0.10	0.62	1.124
14.39	14.36	8	14.50	14.14	0.11	0.038	-0.180	0.757	0.10	0.62	1.055
14.98	14.98	15	15.37	14.68	0.19	0.048	0.046	0.750	0.10	0.62	1.054
15.44	15.41	3	15.61	15.29	0.18	0.102	-0.243	0.747	0.10	0.62	1.222
		1	15.94	15.94							

Table 10: Environmental conditions experienced during verification test of WLS7-258 against MM 6 at 41.9 m.

V_{cup}	V_{rsd}	Data sets	V_{rsd} max	V_{rsd} min	V_{rsd} std	V_{rsd} std/$\sqrt{n}$	mean dev.	V_{cup} unc.	mount. unc. rsd	separation unc.	V_{rsd} unc.
m/s	m/s	#	m/s	m/s	m/s	m/s	%	%	%	%	%
4.12	4.12	187	4.64	3.82	0.14	0.010	0.073	1.461	0.10	1.21	1.930
4.50	4.50	404	5.18	3.94	0.20	0.010	-0.096	1.368	0.10	1.21	1.858
5.00	5.00	419	5.77	4.38	0.19	0.009	-0.070	1.276	0.10	1.21	1.787
5.51	5.51	439	6.12	4.93	0.20	0.009	-0.014	1.201	0.10	1.21	1.730
5.99	6.02	384	6.85	5.59	0.21	0.011	0.380	1.142	0.10	1.21	1.733
6.49	6.52	305	7.01	5.87	0.21	0.012	0.469	1.096	0.10	1.21	1.726
7.01	7.04	280	7.83	6.53	0.20	0.012	0.473	1.046	0.10	1.21	1.695
7.49	7.54	244	8.13	7.11	0.20	0.013	0.589	1.011	0.10	1.21	1.709
7.99	8.02	253	8.74	7.36	0.22	0.014	0.330	0.975	0.10	1.21	1.616
8.47	8.51	200	9.18	7.80	0.22	0.015	0.382	0.945	0.10	1.21	1.611
8.98	9.02	170	9.71	8.41	0.22	0.017	0.346	0.921	0.10	1.21	1.590
9.50	9.52	145	10.18	8.90	0.23	0.019	0.190	0.901	0.10	1.21	1.553
10.01	10.06	87	10.58	9.43	0.25	0.027	0.423	0.887	0.10	1.21	1.601
10.49	10.52	57	11.11	10.06	0.26	0.035	0.288	0.861	0.10	1.21	1.567
11.00	11.04	64	11.91	10.66	0.24	0.029	0.444	0.850	0.10	1.21	1.586
11.49	11.51	34	12.11	10.91	0.26	0.045	0.159	0.837	0.10	1.21	1.550
12.01	12.02	29	12.53	11.47	0.23	0.043	0.134	0.809	0.10	1.21	1.525
12.46	12.45	20	12.81	12.06	0.21	0.046	-0.078	0.799	0.10	1.21	1.519
12.97	12.96	13	13.20	12.80	0.13	0.036	-0.010	0.782	0.10	1.21	1.488
13.54	13.56	7	13.94	13.28	0.24	0.090	0.098	0.774	0.10	1.21	1.605
		1	14.19	14.19							
14.51	14.55	3	14.74	14.30	0.23	0.131	0.257	0.761	0.10	1.21	1.726
14.93	14.88	9	15.23	14.21	0.30	0.099	-0.385	0.755	0.10	1.21	1.636
		1	14.88	14.88							
		2	16.28	15.77							

6 Sensitivities

This chapter investigates the sensitivity of the LiDAR measurement for various environmental variables (EVs). The sensitivity analysis is performed in accordance with the classification analysis specified in annex L.2 [9]. For this analysis we use the same dataset as for the verification analysis. As a result the wind speed range is restricted from 4 m/s to 16 m/s.

6.1 Sensitivity analysis

The basis of this analysis is the deviation between the wind speeds measured by the ref, and the *rsd,* v_{ref} and the *rsd,* v_{rsd}. The deviation is defined in eq.(4.1). Subsequently the sensitivity of this deviation is tested against various EVs. The list of variables is based on table L.2 [9]. The variables considered are described below.

Unless stated otherwise the EVs are height-independent, meaning the same value was used for the sensitivity analysis at each comparison height.

1. **Shear exponent [-]**
   The shear exponent is computed by fitting a power law wind shear model through the v_{ref} measurements at 41.9 m, 81.4 m and 120.9 m. The power law is defined by

$$\frac{vref}{vr} = \left(\frac{\boldsymbol{h}}{\boldsymbol{href}}\right)^{\dot{\alpha}}$$

2. **Reference turbulence intensity [-]**
   The reference turbulence intensity, measured by MM6, is defined by

$$reference\ turbulence\ intensity = \frac{std(vref)}{mean\ (vref)}$$

   This variable is height-dependent.

3. **Precipitation [%]**
   The rain sensor returns a 0% to 100% signal indicating the amount of time precipitation was detected in the 10-minute interval. The precipitation is measured at 81.4 m.

4. **Reference wind direction [°]**
   The wind direction, as measured by MM6, is height-dependent.

5. **Air temperature [°C]**
   The air temperature is measured at 81.4 m.

6. **Relative humidity [%RH]**
   The relative humidity is measured at 81.4 m. (The relative humidity was added to the list of EVs, because it used as in the MEASNET icing criterion in chapter 3.)

7. **Air density [kg/m^3]**

The air density is computed from the air pressure, air temperature and relative humidity, all measured at 81.4 m in accordance with equation (12) IEC 61400-12-1: 2017 [9]

8. **Flow inclination**
   The flow inclination is defined as

$$flow\ inclination = \arctan(\frac{vvert}{vhor})$$

   The horizontal (v_{hor}) and vertical (v_{vert}) wind speed components are measured by a sonic at a height of m.

9. **Wind veer [°/m]**
   The wind veer is computed as the difference between the wind direction measurements by MM6 at 41.9 m and 81.4 m, divided by the height difference. This definition was taken from IEC 61400-12-1: 2017 [9].

$$\boldsymbol{wind\ veer} = \frac{\boldsymbol{vd{,}41.9 - vd{,}81.4}}{\boldsymbol{81.4 - 41.9}} \qquad \textbf{(6.4)}$$

10. **Reference wind speed [m/s]**
    This wind speed, as measured by MM6, is height-dependent.

The sensitivity analysis leads to the results presented in table 16, which is presented in the same format as table L.2 [9]. In this table column ‘m’ represents the slope of the two-parameter regression of the bin-wise averaged data. Column r^2 represents the correlation coefficient of the two-parameter regression of the scatter data.

For the computation of the bin-wise averages, only those bins are included that meet the following bin-count requirement, stipulated by the criterion in eq. (6.5) [9, eq. L.2]. When the reference wind speed is used as the EV, also the criterion in equation (L.3) needs to be applied.

The sensitivity of the LiDAR for an EV is considered as significant if either the sensitivity exceeds a value of 0.5, or the product of sensitivity and r exceeds 0.1. In table 16 the sensitivity criteria that exceed their threshold value are highlighted in red. The regressions associated with these significant sensitivities are presented in fig. 28. In case a significant sensitivity for an EV is observed for at least one comparison height, that EV must be considered as significant for all comparison heights. Table 14 provides an overview of the significant sensitivities.

6.2 Impact on accuracy

Although our interest is not in determining an accuracy class, but rather investigate the sensitivities presented in section 6.1, we would be amiss not to present the impact these sensitivities have on the accuracy.

The basis for the accuracy class is the product of m, as already presented in table 16, and the range of the EV. The EV ranges are largely prescribed by table 17. The results are presented in L.6 [5], which is presented in a similar format as table 16.

The range is a defined quantity, presented in the column `range' of table 17. The IEC 61400-12-1 standard defines the measured range of variation through the ratio of bins that meet the criterion in(6.5). The result is presented in the column `covered range'. The measured range of variation is considered sufficient if the covered range is at least 25%.

Table 14: Overview of significant sensitivities

environmental variable	Comparison height			overall
	120.9 m	81.4 m	41.9 m	
shear exponent	√	√		√
turbulence intensity	√	√	√	√
precipitation				
wind direction				
air temperature				
relative humidity				
air density				
flow inclination				
wind veer				
reference wind speed				

From the results of both sensitivity tests only the mean values of the environmental variables are used to derive the classification uncertainty. The slopes of the significant sensitivities are taken from the Leosphere WindCube classification report by Deutsche WindGuard [10].

The classification report finds four environment variables to be significant. We use the slopes found for the measurement height closest to the measurement height of the reference lidar. For the measurement height of 120.9 m the closest reported slopes are for 120 m:

1. Wind shear: -2.9 %
2. Turbulence intensity: 18.2 %
3. Wind direction: 0.0075 % / °
4. Precipitation: 0.008 % / %

For the measurement height of 81.4 m the closest reported slopes are for 80 m:

1. Wind shear: -0.7 %
2. Turbulence intensity: 16.7 %
3. Wind direction: 0.0044 % / °
4. Precipitation: 0.011 % / %

The contributions to the classification uncertainty from the first three environmental variables is derived using equation (E.17) [9, p.109]. Precipitation is not measured on the off-shore platform. Therefore its contribution is derived by using equation (E.18) [9, p.109]. For the expected precipitation range the worst-case value of 0 - 100 % was used.

The total bin-wise classification uncertainty varies between 0.6 and 1.2 %. It should be noted that:

- The wind shear during the off-shore campaign is measured with a 23 m height offset compared to the on-shore verification.
- For the wind direction the (corrected) wind direction w.r.t. North was used, rather than keeping the inflow direction w.r.t. the lidar orientation constant.

The approach used for the precipitation yields an over-estimation of its contribution.

Table 15: Preliminary accuracy classes

Height	Considering all variables	Considering only significant variables
m	-	-
41.9	7.9	5.7
81.4	7.8	5.8
120.9	9.0	5.9

It should be noted that the results table 15 cannot be used directly to derive the final accuracy class numbers, because the interdependency between the EVs has not been eliminated.

7 Uncertainty

This chapter describes the uncertainty contributions to the horizontal wind speed that were taken into account. These uncertainties are the basis for the LiDAR verification analysis reported in chapter 5. The uncertainty analysis is performed for application in the verification analysis only., therefor the uncertainty is limited to the (horizontal) wind speed measurements.

All uncertainties are reported with a coverage factor of one (*k* = 1). To obtain uncertainties for *k* = 2 the results have to be doubled).

7.1 Reference devices - cup anemometers

The following contributions to the systematic uncertainty of the cup anemometers are taken into account in accordance with Annex L 4.2 [5].

1 **Calibration**: For the top cup anemometer, the calibration certificate of *Thies First Class advanced* cup anemometer (TNO ID 6109) the wind speed uncertainty of the tunnel (0.053 m/s) with a coverage factor of two (*k* = 2) and the standard error of the regression (0.014 m/s) are combined.

$$u_{VS,precal,i} = \sqrt{(0.053/k\ m/s)^2 + (0.014\ m/s)^2} = 0.030\ m/s$$

At the two lower heights, two cups are used at booms on opposite sides of MM6. The calibration uncertainty is determined by taking the maximum uncertainty resulting from the equation above applied to both cups at each height (TNO ID's 2185 and 2180 at 81.4 m and ID's 2182 and 2179 at 41.9 m).

2 **Classification**: The cup anemometer is of class 0.9A. In accordance with equation (I.4) [2, p.182], which is corrected in Corrigendum 1 [15], this results in the following uncertainty.

$$u_{VS,class,i} = (0.05\ m/s + 0.5\ \% \cdot V_i) \cdot 0.9 / \sqrt{3}$$

3 **Mounting effects**: The reference anemometer is a single top-mounted cup. Hence the prescribed uncertainty equals:

$$u_{VS,mnt,i} = 0.5\ \% \cdot V_i$$

4 **Mast correction**: No mast correction is applied for the top cup.

5 **Lightning finial**: The meteorological mast does not have a lightning finial.

6 **Data acquisition**: The cup is connected to a digital pulse counting module. The uncertainty of the module together with the anemometer calibration factors lead to the following uncertainty:

$$u_{dVS,i} = 0.1\ \% \cdot V_i + 0.023\ m/s$$

The total systematic uncertainty of the reference sensor is obtained by adding all contributions in quadrature. As in IEC 61400-12-1 (2017), this is referred to as 'reference type B' uncertainty in figure 26.

7.2 Remote sensing device

The following contributions to the uncertainty of the LiDAR wind speed measurements are taken into account in accordance with annex L.4.3 [5].

1. **Standard uncertainty of the reference sensor**
   This is the total of all uncertainty contributions of the reference sensor listed above, added in quadrature. This is listed in column 'V_{cup} unc.' in Table 5.

2. **Mean deviation** between the reference cup and the lidar. This is shown as 'Deviation' in Figure 14 and listed in column 'mean dev.' in Table 5.

3. **Standard uncertainty of the LiDAR**. This is listed in column 'V_{rsd} std/$\sqrt{n}$' in Table 5.

4. Mounting effects of the lidar. The default magnitude is used [2, Annex E.7.5, p.110]. This is listed in column 'mount. unc. rsd' in Table 5.

$$u_{VR,mnt,i} = 0.1\ \% \cdot V_i$$

5. **Non-homogeneous flow** within the measurement volume: A flow model of the surroundings of the LiDAR location is used to estimate a worst-case uncertainty contribution.

$$u_{VR,flow,i} = 0.2\ \% \cdot V_i$$

6. **Separation distance**. This uncertainty contribution is based on the measurement height and the distance between the base of the meteorological mast and the LiDAR (74.6 m). This is listed in column 'separation unc.' in Table 5.

$$separation\ uncertainty = 1\ \% \cdot V_i \cdot \frac{81.4\ m}{height}$$

   Note that for comparison heights below the top cup, this separation uncertainty is the dominant contribution.

   The total LiDAR uncertainty is obtained by adding in quadrature the contributions above. The results reported in the last column of tables 4 to 8. An overview of the various contributions is presented in figure 26.

   The uncertainty interval shown in figures 16 to 20 is also obtained by adding in quadrature the contribution above, but with the exception of the mean deviation.

8 Deviations

Meteorological Measurements at MM6 have been performed in accordance with the IEC 61400-12-1: 2017 so in this respect no deviations are to be reported.

With respect to the data captures the following three figures represent the coverage per height.

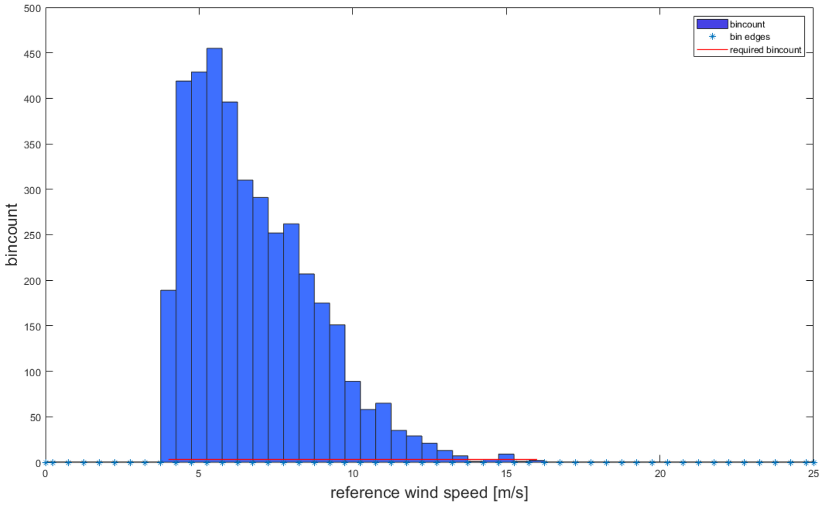

Figure 26: Data coverage 42 m

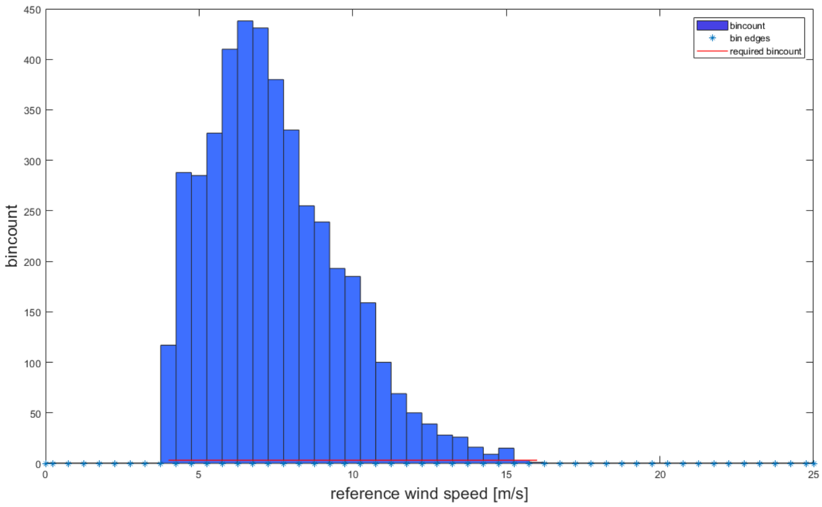

Figure 27: Data coverage 81 m

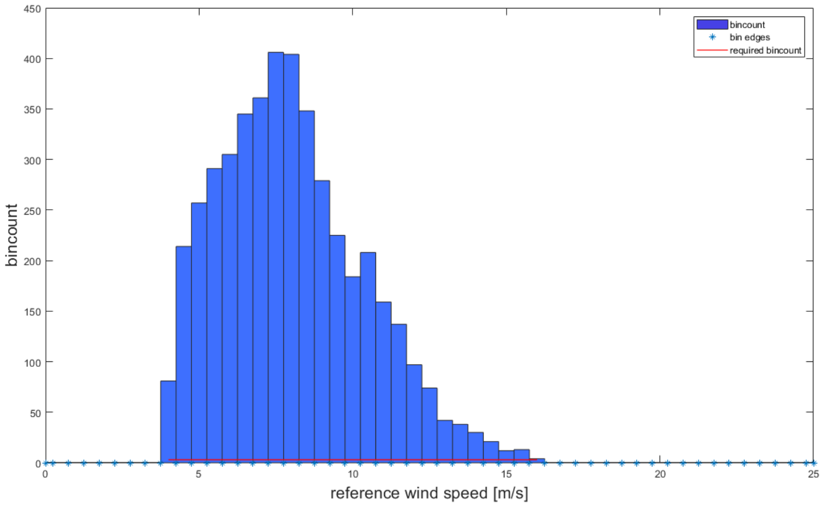

Figure 28: Data coverage 121 m

9 References

[1] D. Wouters and J. Verhoef, “Verification of the WLS7-258 at TNO LiDAR Calibration Facility for LEG campaign,” TNO 2020 R10285, March 2020.

[2] C. A. van Diggelen and J. W. Wagenaar, “Instrumentation LiDAR Calibration Facility at EWTW,” ECN, tech.report ECN-X--16-119, August 2016.

[3] Wind turbines - Part 12-1: Power performance measurements of electricity producing wind turbines, International Electrotechnical Commission Std.IEC61400-12-1:2005, December 2005.

[4] Hasager et al., “Hub height ocean winds over the North Sea observed by the NORSEWinD lidar array: Measuring techniques, quality control and data management”, Remote Sensing,vol.5,pp.4280–4303, 2013.

[5] The Carbon Trust, “Carbon Trust offshore wind accelerator roadmap for the commercial acceptance of floating lidar technology”, The Carbon Trust, tech.report CTC819 Version1.0, November 2013.

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[7] P.A. van der Werff, “User manual Meassector 2.2”, ECN, 2015.

[8] I.A.Alting,“WDMS4 developer reference”, ECN, tech.report ECN-WindMemo-11-023, October 2011.

[9] Wind energy generation systems-Part 12-1: Power performance measurements of electricity producing wind turbines, International Electrotechnical Commission Std.IEC61400-12-1:2017-03, Rev.2.0, Mar. 2017

A IEC visualisations

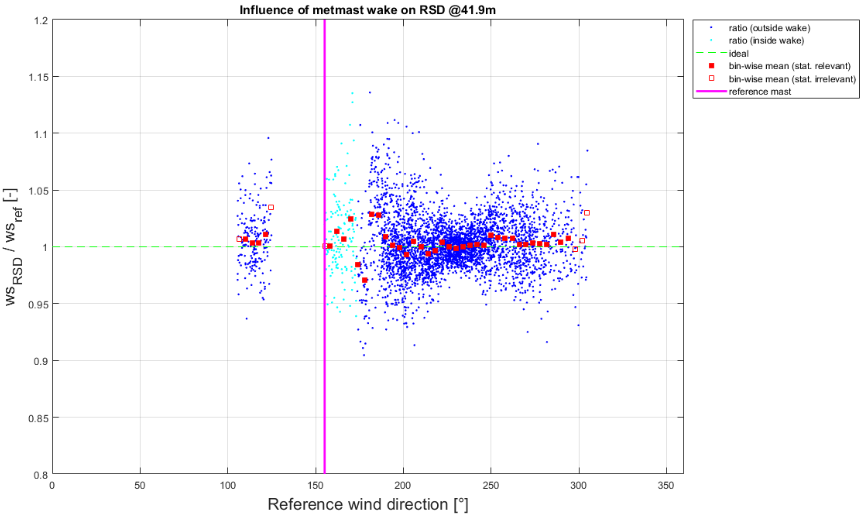


Figure 29: Influence of the wake of MM6 on the LiDAR @41.9 m

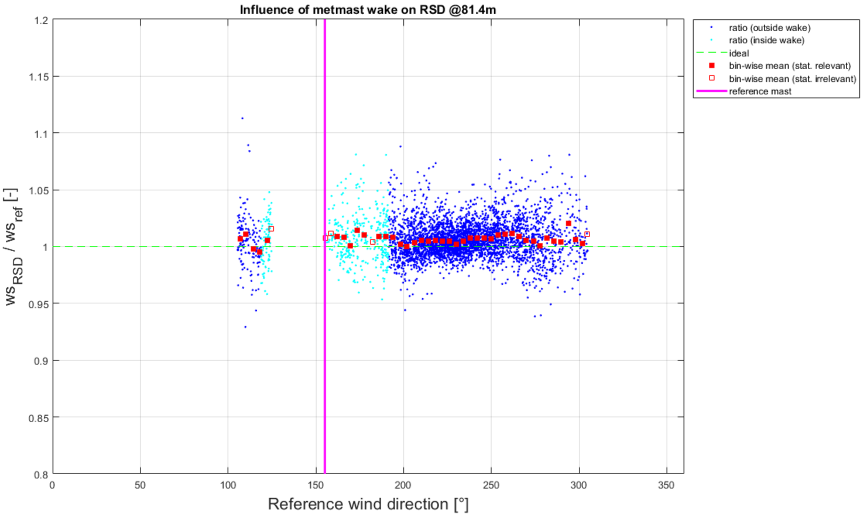


Figure 30: Influence of the wake of MM6 on the LiDAR @81.4 m

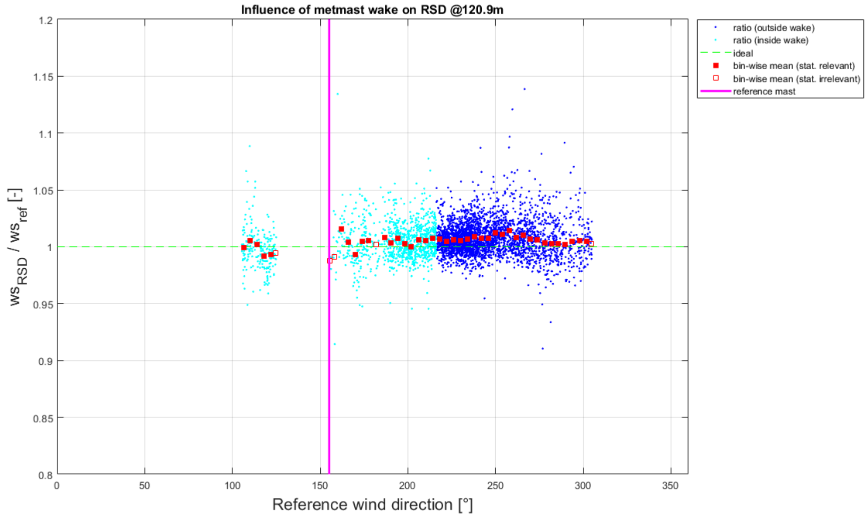
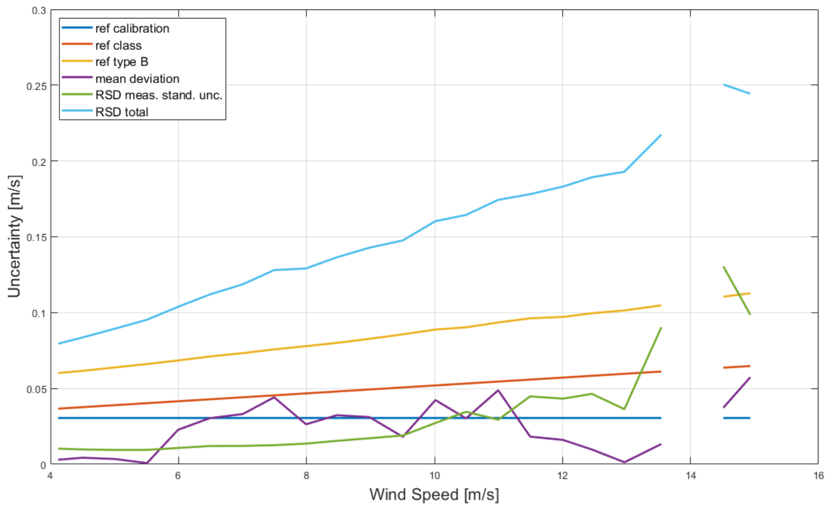
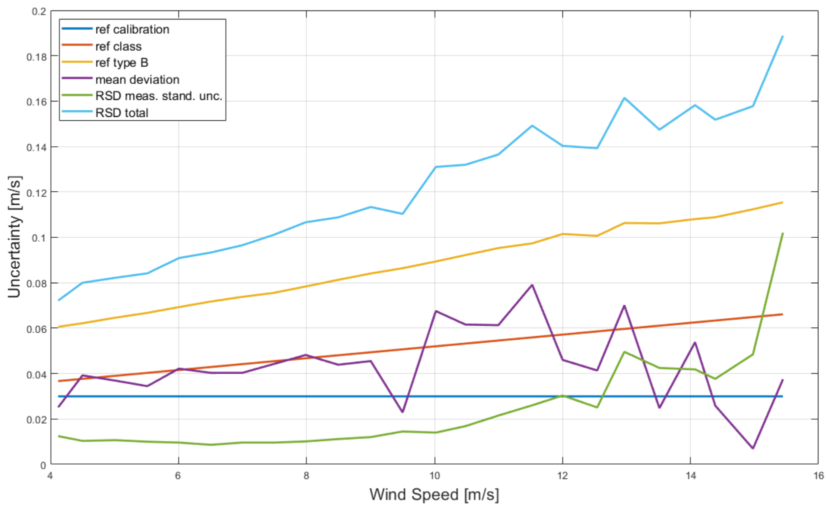
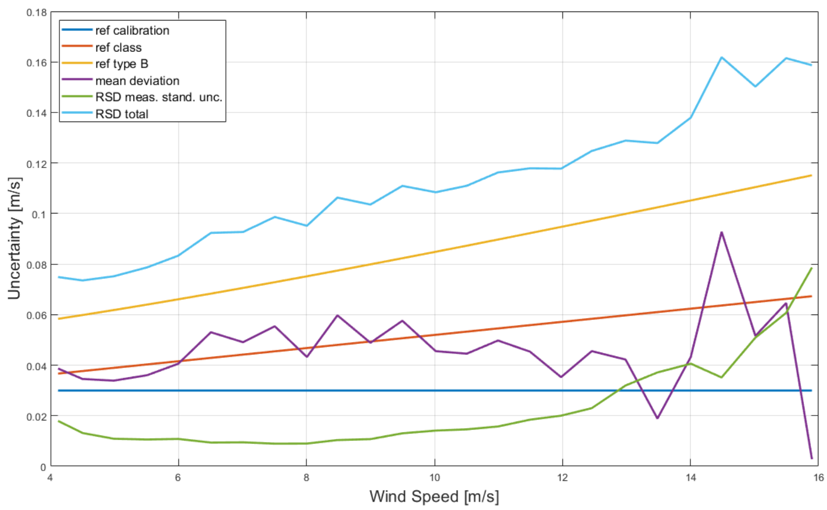


Figure 31: Influence of the wake of MM6 on the LiDAR @ 121 m


ref calibration
ref class
ref type B
mean deviation
RSD meas. stand. unc.
RSD total
Uncertainty [m/s]
Wind Speed [m/s]


ref calibration
ref class
ref type B
mean deviation
RSD meas. stand. unc.
RSD total
Uncertainty [m/s]
Wind Speed [m/s]


ref calibration
ref class
ref type B
mean deviation
RSD meas. stand. unc.
RSD total
Uncertainty [m/s]
Wind Speed [m/s]

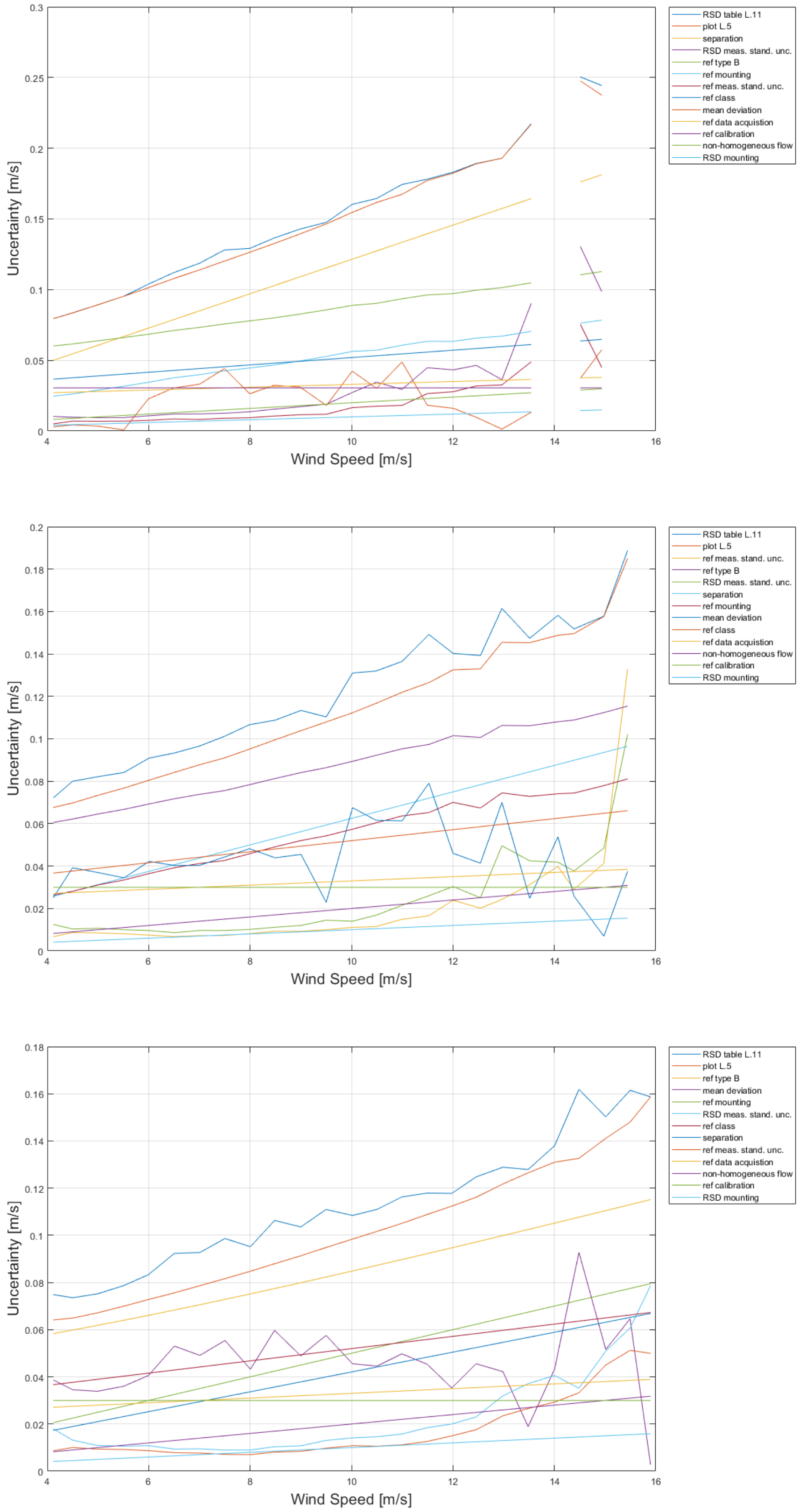
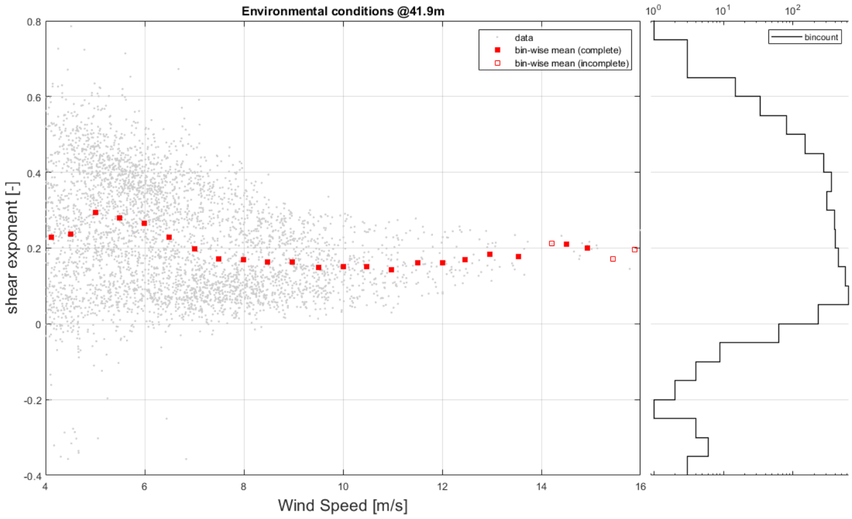
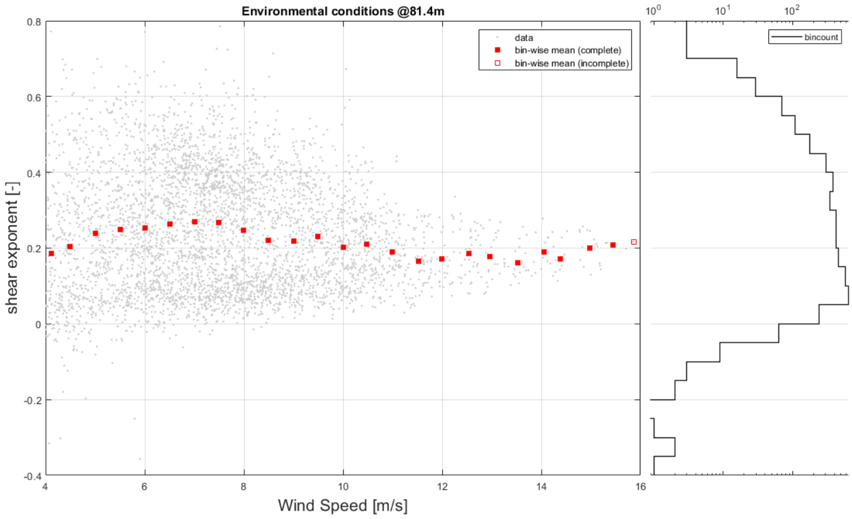
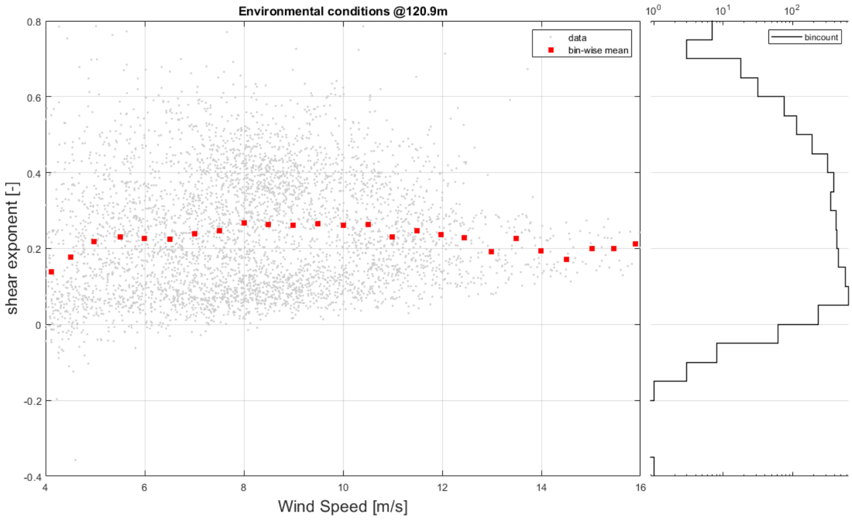
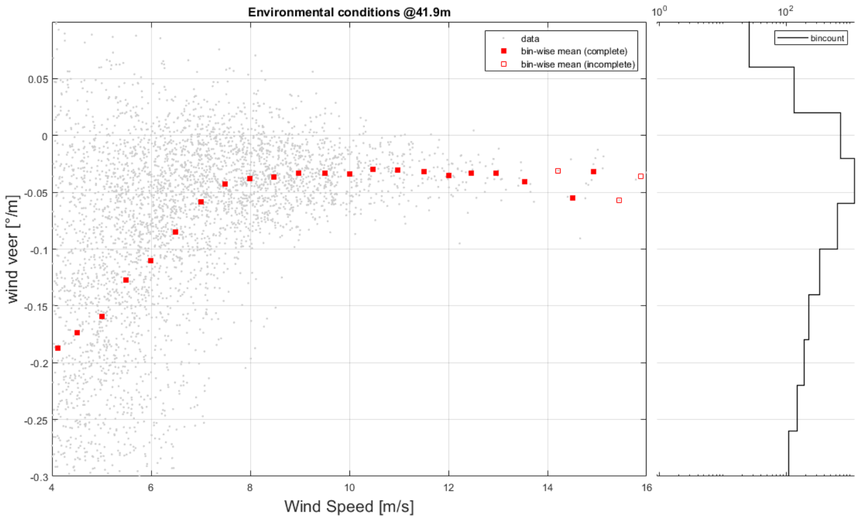


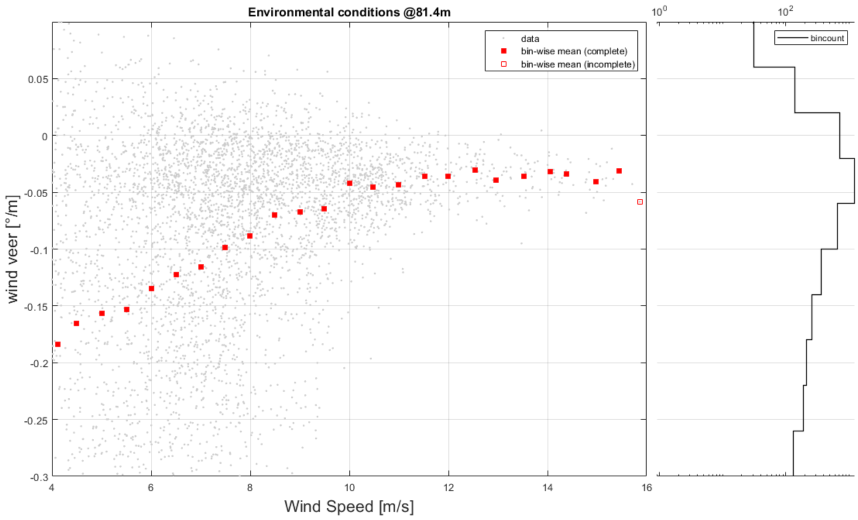
Figure 32: Contributions to the LiDAR uncertainty

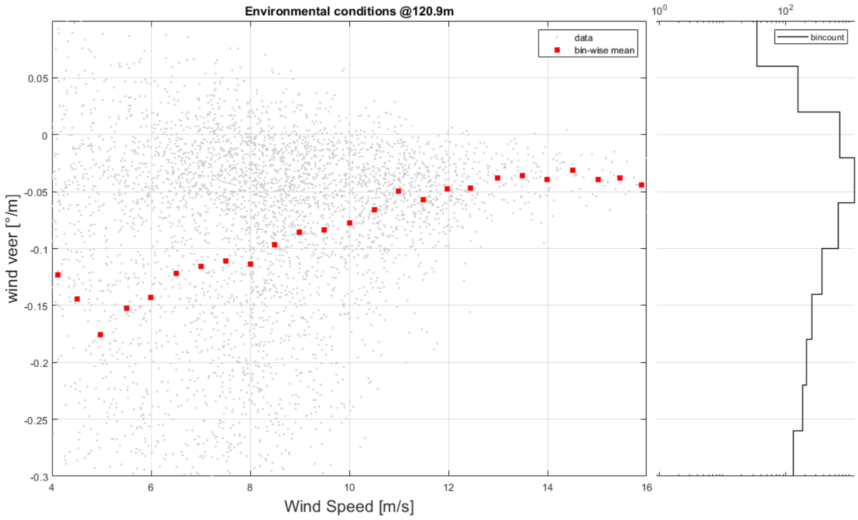

Environmental conditions @41.9m
data
bin-wise mean (complete)
bin-wise mean (incomplete)
bincount
shear exponent [-]
Wind Speed [m/s]

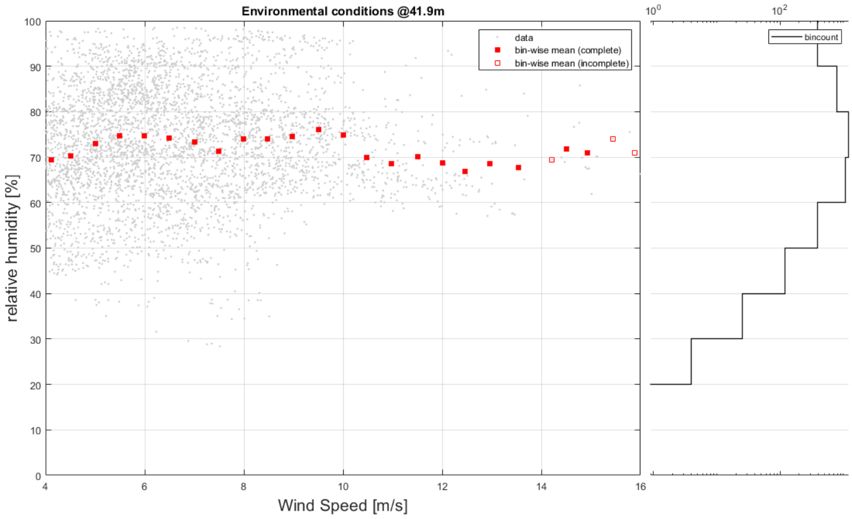

Environmental conditions @81.4m
data
bin-wise mean (complete)
bin-wise mean (incomplete)
bincount
shear exponent [-]
Wind Speed [m/s]

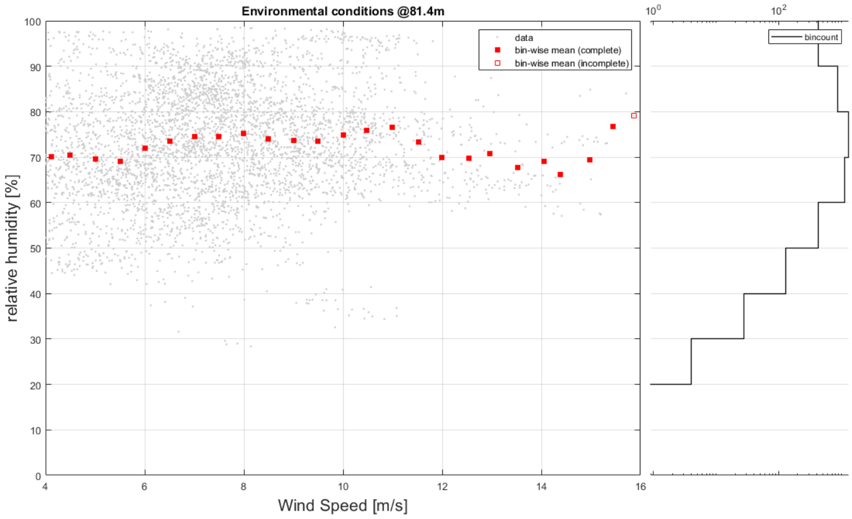

Environmental conditions @120.9m
data
bin-wise mean
bincount
shear exponent [-]
Wind Speed [m/s]

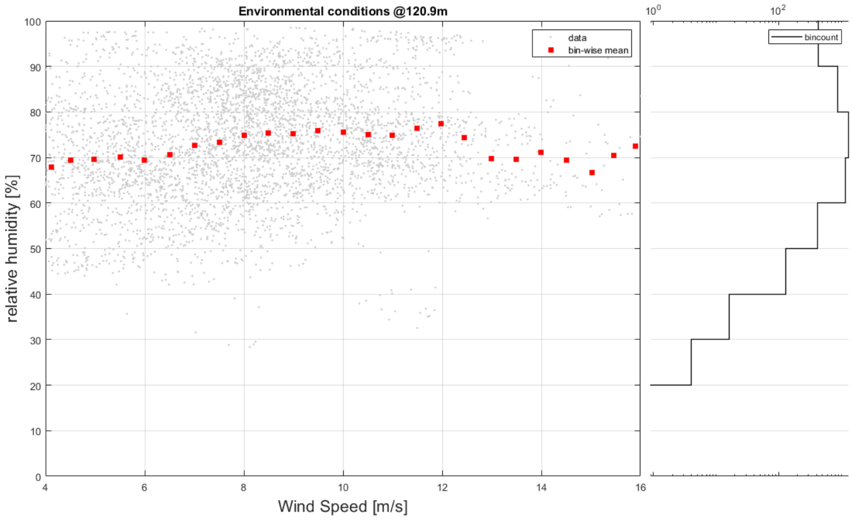

Environmental conditions @41.9m
data
bin-wise mean (complete)
bin-wise mean (incomplete)
bincount
wind veer [°/m]
Wind Speed [m/s]


Environmental conditions @81.4m
data
bin-wise mean (complete)
bin-wise mean (incomplete)
bincount
wind veer [°/m]
Wind Speed [m/s]


Environmental conditions @120.9m
data
bin-wise mean
bincount
wind veer [°/m]
Wind Speed [m/s]

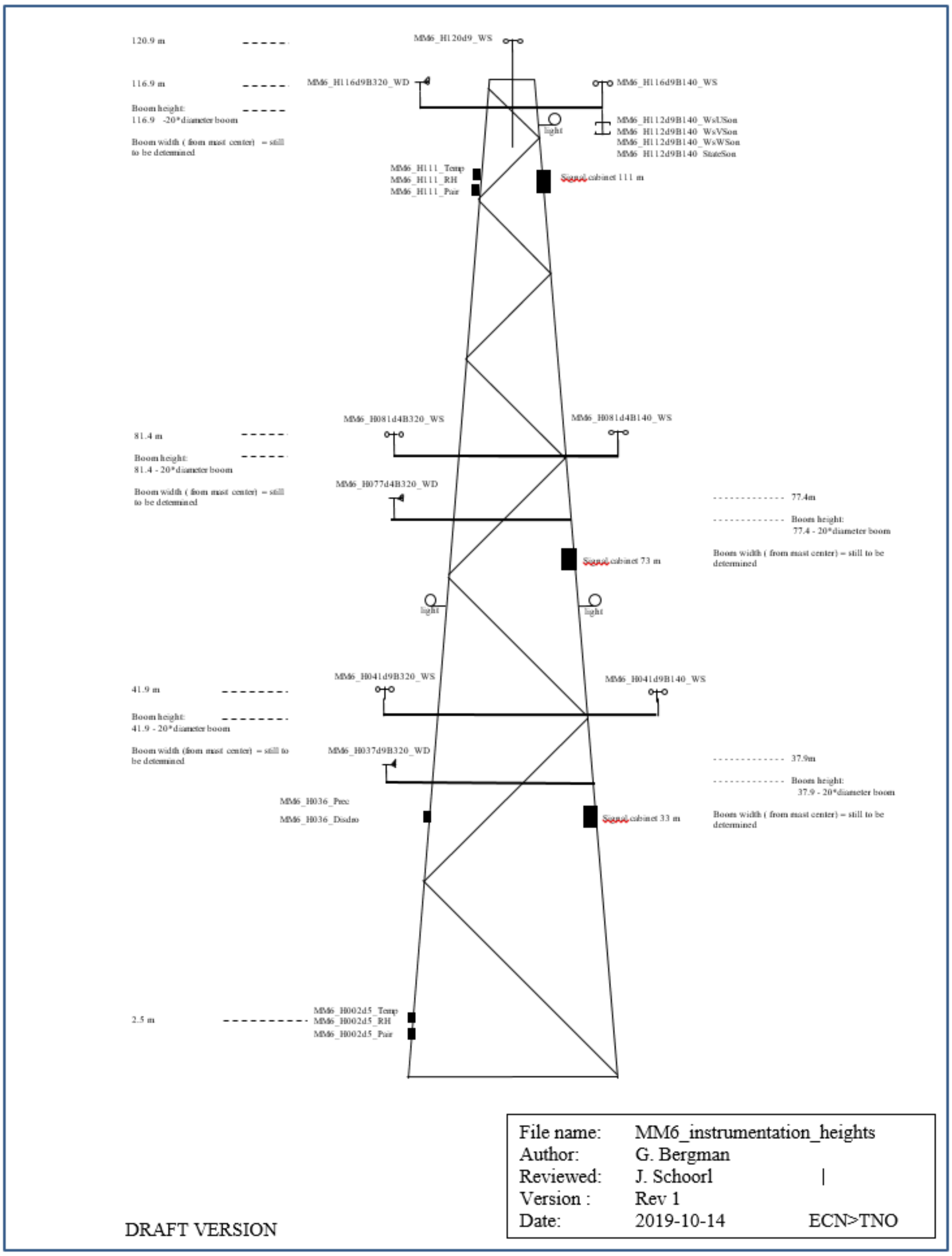

Environmental conditions @41.9m
data
bin-wise mean (complete)
bin-wise mean (incomplete)
bincount
relative humidity [%]
Wind Speed [m/s]


Environmental conditions @81.4m
data
bin-wise mean (complete)
bin-wise mean (incomplete)
bincount
relative humidity [%]
Wind Speed [m/s]


Environmental conditions @120.9m
data
bin-wise mean
bincount
relative humidity [%]
Wind Speed [m/s]

B Instrumentation details

This appendix presents the instrumentation details of Meteorological Mast 6 (including the used calibration sheets)



Name	Location	Short name	Sensor	Unit	Freq (Hz)	IEC status
Metmast Signals						
Wind speed 120.9 meter		MM6_H120d9_Ws_Q1_m	Thies first class advanced	m/s		requirement
Wind speed 120.9 meter pulse counter		MM6_H120d9_Ws_Pcount_Q1_m				
Wind speed 115.9 meter		MM6_H111d9B140_Ws_Q1_m	Thies first class advanced	m/s		requirement
Wind speed U direction, sonic 111.9 meter		MM6_H111d9B140_WsUSon_Q1_m		m/s		recommendation
Wind speed V direction, sonic 111.9 meter		MM6_H111d9B140_WsVSon_Q1_m		m/s		recommendation
Wind speed W direction, sonic 111.9 meter		MM6_H111d9B140_WsWSon_Q1_m	Metek 3D sonic	m/s		recommendation
Temperature (Sonic) 111.9 meter		MM6_H111d9B140_TempSon_Q1_m		deg C		recommendation
Status Sonic 111.9 meter		MM6_H111d9B140_StateSon_Q1_m				
Wind direction 115.9 meter		MM6_H115d9B320_Wd_Q1_m	Thies First class	deg		requirement
Relative humidity 111 meter		MM6_H111_RH_Q1_m	Vaisala HMP155D	%		requirement
Air temperature 111 meter		MM6_H111_Temp_Q1_m		deg C		requirement
Air pressure 111 meter		MM6_H111_Pair_Q1_m	Vaisala PTB210	hPa		requirement
Wind speed 81.4 meter, 140 deg boom		MM6_H81d4B140_Ws_Q1_m	Thies first class advanced	m/s		recommendation
Wind speed 81.4 meter, 320 deg boom		MM6_H81d4B320_Ws_Q1_m	Thies first class advanced	m/s		recommendation
Wind direction 77.4 meter	MM6	MM6_H77d4B320_Wd_Q1_m	Thies First class	deg	4	recommendation
Wind speed 41.9 meter, 140 deg boom		MM6_H41d9B140_Ws_Q1_m	Thies first class advanced	m/s		requirement
Wind speed 41.9 meter, 320 deb boom		MM6_H41d9B320_Ws_Q1_m	Thies first class advanced	m/s		requirement
Wind direction 37.9 meter		MM6_H37d9B320_Wd_Q1_m	Thies First class	deg		recommendation
Relative humidity 2.5 meter		MM6_H2d5_RH_Q1_m	Vaisala HMP155D	%		requirement
Air temperature 2.5 meter		MM6_H2d5_Temp_Q1_m		deg C		recommendation
Air pressure 2.5 meter		MM6_H2d5_Pair_Q1_m	Vaisala PTB210	hPa		recommendation
Precipitation, 100% / 0%		MM6_H40_Prec_Q1_m	Thies 5.4103.10.000	%		requirement
amount of precipitation		MM6_H036_Disdro_Amount_Q5_m		mm		
intensity of precipitation		MM6_H036_Disdro_Intensity_Q5_m		mm/h		
Quality signal 0 ..100%		MM6_H036_Disdro_Quality_Q5_m		%		
Precipitation yes / no (100% / 0%)		MM6_H036_Disdro_Rain_Q5_m	Thies 5.4110.00.300	%		
Status OK signal (1 = cleaning laser required)		MM6_H036_Disdro_StaticOK_Q5_m		#		
SYNOP code according table 4677		MM6_H036_Disdro_SYNOP_Q5_m		#		
Visibility		MM6_H036_Disdro_Visibility_Q5_m		m		

DEWS6109

DEWS 6109

DEUTSCHE WINDGUARD

Deutsche WindGuard
Wind Tunnel Services GmbH

IECRE and MEASNET approved test laboratory

accredited by the / *akkreditiert durch die*

Deutsche Akkreditierungsstelle GmbH

as calibration laboratory in the / *als Kalibrierlaboratorium im*

Deutschen Kalibrierdienst DKD

DAkkS Deutsche Akkreditierungsstelle D-K-15140-01-00

Calibration certificate
Kalibrierschein

Calibration mark
Kalibrierzeichen

1714688
D-K-15140-01-00
11/2017

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.00.000
Serial number *Fabrikat/Serien-Nr.*	04126802
Customer *Auftraggeber*	ECN Wind Energy
Order No. *Auftragsnummer*	ECN4186952/15.09.2017
Project No. *Projektnummer*	VT170913
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	15.11.2017

This calibration certificate documents the traceability to national standards, which realize the units of measurement according to the International System of Units (SI).
The DAkkS is signatory to the multilateral agreements of the European co-operation for Accreditation (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates.
The user is obliged to have the object recalibrated at appropriate intervals.
Dieser Kalibrierschein dokumentiert die Rückführung auf nationale Normale zur Darstellung der Einheiten in Übereinstimmung mit dem Internationalen Einheitensystem (SI).
Die DAkkS ist Unterzeichner der multilateralen Übereinkommen der European co-operation for Accreditation (EA) und der International Laboratory Accreditation Cooperation (ILAC) zur gegenseitigen Anerkennung der Kalibrierscheine.
Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
15.11.2017	D. Westermann Dipl. Phys. Dieter Westermann	H. Jansen Hendrik Jansen, B. Eng.

Calibration object *Kalibriergegenstand*	Cup Anemometer
Calibration procedure *Kalibrierverfahren*	• Deutsche WindGuard Wind Tunnel Services: VA Anemometerkalibrierung Based on following standards: • MEASNET ANEMOMETER CALIBRATION PROCEDURE Version 2 / 2009 • IEC 61400-12-1:2017 Power performance measurements of electricity producing wind turbines • IEC 61400-12-2:2013 Power performance of electricity producing wind turbines based on nacelle anemometry • ISO 3966:2008 Measurement of fluid in closed conduits • ISO 16622:2002 Meteorology - Sonic anemometers/thermometers
Place of calibration *Ort der Kalibrierung*	Wind tunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel

Test conditions *Messbedingungen*

wind tunnel area	10000 cm²
anemometer frontal area	230 cm²
diameter of mounting pipe	34 mm
blockage ratio [1)]	0.023 [-]
software version	7.7

[1)] Due to the special construction of the test section no blockage correction is necessary.

Ambient conditions *Umgebungsbedingungen*

air temperature	21.7 °C ± 0.1 °C
air pressure	1023.1 hPa ± 0.3 hPa
relative air humidity	40.8 % ± 2.0 %

Measurement uncertainty *Messunsicherheit*

The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k=2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%.
The reference flow speed measurement is traceable to the German NMI (Physikalisch-Technische Bundesanstalt) standard for flow speed. It is realized by using a PTB owned and calibrated Laser Doppler Anemometer (Standard Uncertainty 0.2 %, k=2)

Additional remarks *Zusätzliche Anmerkungen*

-

1714688
D-K- 15140-01-00
11/2017

Calibration result
Kalibrierergebnis

Sensor Hz	Tunnel Speed m/s	Uncertainty m/s
81.501	3.987	0.050
123.001	5.891	0.050
166.380	7.885	0.051
209.329	9.897	0.051
254.106	11.918	0.052
295.410	13.839	0.052
338.651	15.804	0.053
316.547	14.812	0.053
275.477	12.910	0.052
230.116	10.869	0.051
187.123	8.872	0.051
144.872	6.924	0.051
102.111	4.953	0.050

File: 1714688

Statistical analysis

Slope	0.04598 (m/s)/(Hz) ±0.00006 (m/s)/(Hz)
Offset	0.2528 m/s ±0.014 m/s
Standard error (Y)	0.014 m/s
Correlation coefficient	0.99999

Remarks

The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard Wind Tunnel measnet Services GmbH

Graphical representation of the result
Grafische Darstellung des Ergebnisses

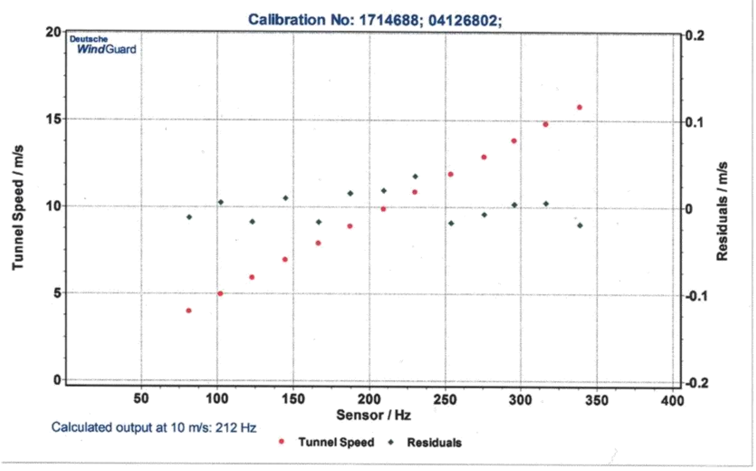
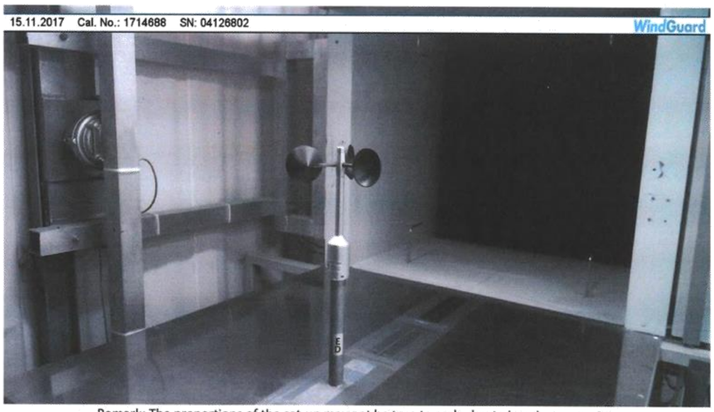


Photo of the measurement setup
Foto des Messaufbaus



Remark: The proportions of the set-up may not be true to scale due to imaging geometry.

DEWS5156

DEWS 5156

DEUTSCHE WINDGUARD

Deutsche WindGuard
Wind Tunnel Services GmbH

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as calibration laboratory in the / *als Kalibrierlaboratorium im*

Deutschen Kalibrierdienst DKD

DAkkS Deutsche Akkreditierungsstelle D-K-15140-01-00

Calibration certificate
Kalibrierschein

Calibration mark
Kalibrierzeichen

1714431
D-K-15140-01-00
10/2017

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.00.000
Serial number *Fabrikat/Serien-Nr.*	06114062 DEWS5156
Customer *Auftraggeber*	ECN Wind Energy
Order No. *Auftragsnummer*	Email 2017-08-31, Alizai
Project No. *Projektnummer*	VT170888
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	27.10.2017

This calibration certificate documents the traceability to national standards, which realize the units of measurement according to the International System of Units (SI).
The DAkkS is signatory to the multilateral agreements of the European co-operation for Accreditation (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates.
The user is obliged to have the object recalibrated at appropriate intervals.
Dieser Kalibrierschein dokumentiert die Rückführung auf nationale Normale zur Darstellung der Einheiten in Übereinstimmung mit dem Internationalen Einheitensystem (SI).
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Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

This calibration certificate may not be reproduced other than in full except with the permission of both the German Accreditation Body and the issuing laboratory. Calibration certificates without signature are not valid. This calibration certificate has been generated electronically.
Dieser Kalibrierschein darf nur vollständig und unverändert weiterverbreitet werden. Auszüge oder Änderungen bedürfen der Genehmigung sowohl der Deutschen Akkreditierungsstelle als auch des ausstellenden Kalibrierlaboratoriums. Kalibrierscheine ohne Unterschrift haben keine Gültigkeit. Dieser Kalibrierschein wurde elektronisch erzeugt.

Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
27.10.2017	D. Westermann Dipl. Phys. Dieter Westermann	H. Jansen Hendrik Jansen, B. Eng.

Calibration object *Kalibriergegenstand*	Cup Anemometer
Calibration procedure *Kalibrierverfahren*	• Deutsche WindGuard Wind Tunnel Services: VA Anemometerkalibrierung Based on following standards: • MEASNET ANEMOMETER CALIBRATION PROCEDURE Version 2 / 2009 • IEC 61400-12-1:2017 Power performance measurements of electricity producing wind turbines • IEC 61400-12-2:2013 Power performance of electricity producing wind turbines based on nacelle anemometry • ISO 3966:2008 Measurement of fluid in closed conduits • ISO 16622:2002 Meteorology - Sonic anemometers/thermometers
Place of calibration *Ort der Kalibrierung*	Wind tunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel

Test conditions
Messbedingungen

wind tunnel area	10000 cm²
anemometer frontal area	230 cm²
diameter of mounting pipe	34 mm
blockage ratio [1)]	0.023 [-]
software version	7.7

1) Due to the special construction of the test section no blockage correction is necessary.

Ambient conditions
Umgebungsbedingungen

air temperature	23.3 °C ± 0.1 °C
air pressure	1019.8 hPa ± 0.3 hPa
relative air humidity	48.6 % ± 2.0 %

Measurement uncertainty
Messunsicherheit

The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k=2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%.
The reference flow speed measurement is traceable to the German NMI (Physikalisch-Technische Bundesanstalt) standard for flow speed. It is realized by using a PTB owned and calibrated Laser Doppler Anemometer (Standard Uncertainty 0.2 %, k=2)

Additional remarks
Zusätzliche Anmerkungen

-

1714431
D-K-15140-01-00
10/2017

Calibration result
Kalibrierergebnis

Sensor Hz	Tunnel Speed m/s	Uncertainty m/s
81.816	3.985	0.050
123.329	5.881	0.050
167.590	7.899	0.051
210.585	9.907	0.051
254.171	11.914	0.051
295.787	13.854	0.052
339.508	15.814	0.053
317.338	14.822	0.052
275.804	12.916	0.052
231.119	10.873	0.052
188.623	8.876	0.051
146.230	6.950	0.051
101.992	4.937	0.050

File: 1714431

Statistical analysis	Slope	0.04601 (m/s)/(Hz) ±0.00007 (m/s)/(Hz)
	Offset	0.2194 m/s ±0.015 m/s
	Standard error (Y)	0.015 m/s
	Correlation coefficient	0.999989

Remarks

The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard Wind Tunnel measnet Services GmbH

Graphical representation of the result
Grafische Darstellung des Ergebnisses

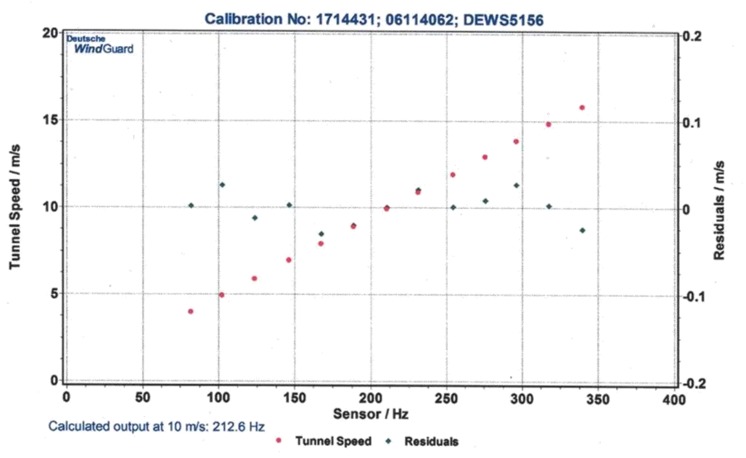
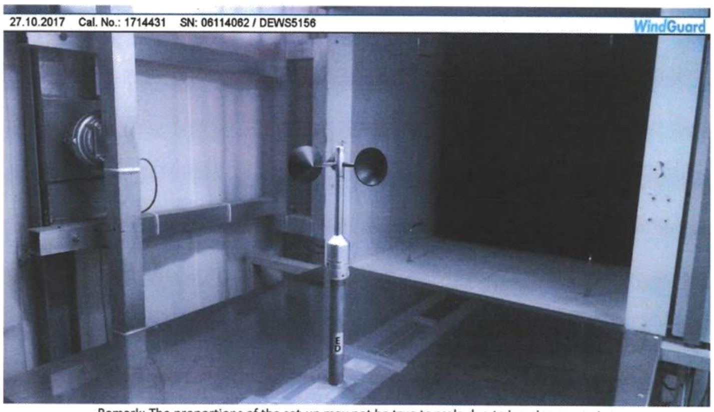


Photo of the measurement setup
Foto des Messaufbaus



Remark: The proportions of the set-up may not be true to scale due to imaging geometry.

DEWS2185

DEWS 2185

DEUTSCHE **WINDGUARD**

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as calibration laboratory in the / *als Kalibrierlaboratorium im*

Deutschen Kalibrierdienst DKD

DAkkS Deutsche Akkreditierungsstelle D-K-15140-01-00

Calibration certificate
Kalibrierschein

Calibration mark
Kalibrierzeichen

1714432
D-K-
15140-01-00
10/2017

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.00.000
Serial number *Fabrikat/Serien-Nr.*	07130387 DEWS2185
Customer *Auftraggeber*	ECN Wind Energy
Order No. *Auftragsnummer*	Email 2017-08-31, Alizai
Project No. *Projektnummer*	VT170888
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	27.10.2017

This calibration certificate documents the traceability to national standards, which realize the units of measurement according to the International System of Units (SI).
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Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
27.10.2017	Dipl. Phys. Dieter Westermann	Hendrik Jansen, B. Eng.

Calibration object
Kalibriergegenstand

Cup Anemometer

Calibration procedure
Kalibrierverfahren

• Deutsche WindGuard Wind Tunnel Services: VA Anemometerkalibrierung
Based on following standards:
• MEASNET ANEMOMETER CALIBRATION PROCEDURE Version 2 / 2009
• IEC 61400-12-1:2017 Power performance measurements of electricity producing wind turbines
• IEC 61400-12-2:2013 Power performance of electricity producing wind turbines based on nacelle anemometry
• ISO 3966:2008 Measurement of fluid in closed conduits
• ISO 16622:2002 Meteorology - Sonic anemometers/thermometers

Place of calibration
Ort der Kalibrierung

Wind tunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel

Test conditions
Messbedingungen

wind tunnel area	10000 cm²
anemometer frontal area	230 cm²
diameter of mounting pipe	34 mm
blockage ratio [1)]	0.023 [-]
software version	7.7

[1)] Due to the special construction of the test section no blockage correction is necessary.

Ambient conditions
Umgebungsbedingungen

air temperature	23.4 °C ± 0.1 °C
air pressure	1020.2 hPa ± 0.3 hPa
relative air humidity	48.2 % ± 2.0 %

Measurement uncertainty
Messunsicherheit

The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k=2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%.
The reference flow speed measurement is traceable to the German NMI (Physikalisch-Technische Bundesanstalt) standard for flow speed. It is realized by using a PTB owned and calibrated Laser Doppler Anemometer (Standard Uncertainty 0.2 %, k=2)

Additional remarks
Zusätzliche Anmerkungen

-

Calibration result
Kalibrierergebnis

Sensor Hz	Tunnel Speed m/s	Uncertainty m/s
81.818	3.975	0.050
123.254	5.881	0.050
166.988	7.874	0.051
210.875	9.903	0.051
254.279	11.912	0.051
296.139	13.848	0.052
339.969	15.822	0.053
317.703	14.822	0.052
275.767	12.904	0.052
230.879	10.850	0.052
187.847	8.876	0.051
146.034	6.943	0.051
102.484	4.936	0.050

File: 1714432

Statistical analysis	Slope	0.04596 (m/s)/(Hz) ±0.00005 (m/s)/(Hz)
	Offset	0.2224 m/s ±0.012 m/s
	Standard error (Y)	0.012 m/s
	Correlation coefficient	0.999993

Remarks

The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard Wind Tunnel Services GmbH measnet

Graphical representation of the result
Grafische Darstellung des Ergebnisses

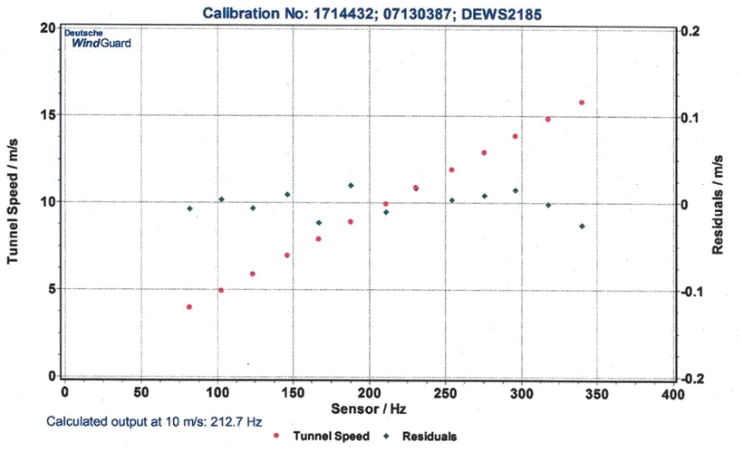
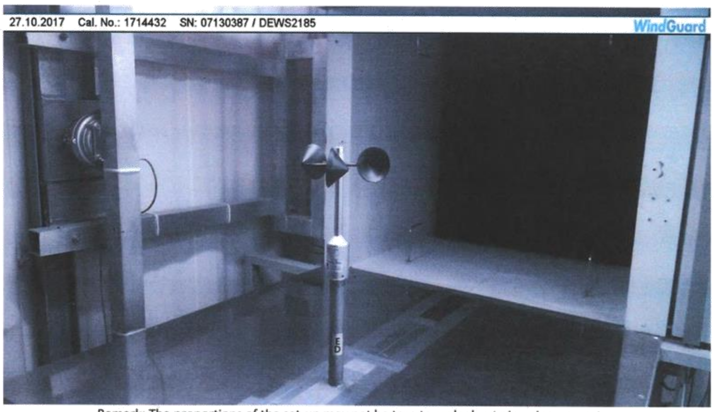


Photo of the measurement setup
Foto des Messaufbaus



Remark: The proportions of the set-up may not be true to scale due to imaging geometry.

DEWS2180

DEWS2180

DEUTSCHE WINDGUARD

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Wind Tunnel Services GmbH

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Deutschen Kalibrierdienst DKD

Deutsche Akkreditierungsstelle D-K-15140-01-00

Calibration certificate
Kalibrierschein

Calibration mark
Kalibrierzeichen

1713714
D-K-15140-01-00
09/2017

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.00.000
Serial number *Fabrikat/Serien-Nr.*	07130388 DEWS2180
Customer *Auftraggeber*	ECN Wind Energy
Order No. *Auftragsnummer*	ECN4195422
Project No. *Projektnummer*	VT170753
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	07.09.2017

This calibration certificate documents the traceability to national standards, which realize the units of measurement according to the International System of Units (SI).
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Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
07.09.2017	D. Westermann Dipl. Phys. Dieter Westermann	D. Henninges Techniker Dirk Henninges

Calibration object *Kalibriergegenstand*	Cup Anemometer
Calibration procedure *Kalibrierverfahren*	• Deutsche WindGuard Wind Tunnel Services: QM-KL-AK-VA Based on following standards: • MEASNET: Anemometer calibration procedure • IEC 61400-12-1: Power performance measurements of electricity producing wind turbines • IEC 61400-12-2: Power performance of electricity producing wind turbines based on nacelle anemometry • ISO 3966: Measurement of fluid in closed conduits • ISO 16622: Meteorology - Sonic anemometers/thermometers
Place of calibration *Ort der Kalibrierung*	Windtunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel

Test conditions *Messbedingungen*	wind tunnel area	10000 cm²
	anemometer frontal area	230 cm²
	diameter of mounting pipe	34 mm
	blockage ratio [1)]	0.023 [-]
	software version	7.7

[1)] Due to the special construction of the test section no blockage correction is necessary.

Ambient conditions *Umgebungsbedingungen*	air temperature	23.3 °C ± 0.1 °C
	air pressure	1011.9 hPa ± 0.3 hPa
	relative air humidity	53.0 % ± 2.0 %

Measurement uncertainty *Messunsicherheit*	The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k=2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%. The reference flow speed measurement is traceable to the German NMI (Physikalisch-Technische Bundesanstalt) standard for flow speed. It is realized by using a PTB owned and calibrated Laser Doppler Anemometer (Standard Uncertainty 0.2 %, k=2)
Additional remarks *Zusätzliche Anmerkungen*	-

Calibration result
Kalibrierergebnis

Sensor Hz	Tunnel Speed m/s	Uncertainty m/s
81.751	3.978	0.050
123.210	5.895	0.051
166.899	7.903	0.051
211.979	9.931	0.051
254.786	11.944	0.052
296.286	13.874	0.052
340.197	15.842	0.053
318.180	14.852	0.053
276.556	12.945	0.052
232.001	10.903	0.052
189.129	8.908	0.051
146.277	6.965	0.051
102.650	4.943	0.050

File: 1713714

Statistical analysis

Slope	0.04597 (m/s)/(Hz) ±0.00006 (m/s)/(Hz)
Offset	0.2262 m/s ±0.014 m/s
Standard error (Y)	0.014 m/s
Correlation coefficient	0.999990

Remarks

The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard Wind Tunnel Services GmbH · measnet

Graphical representation of the result
Grafische Darstellung des Ergebnisses

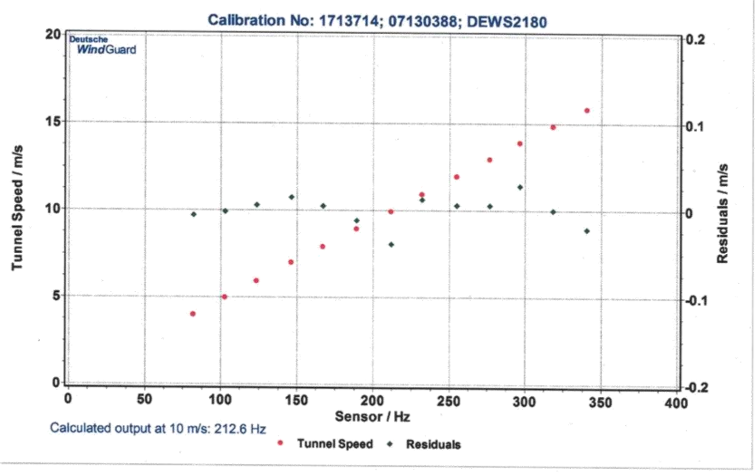
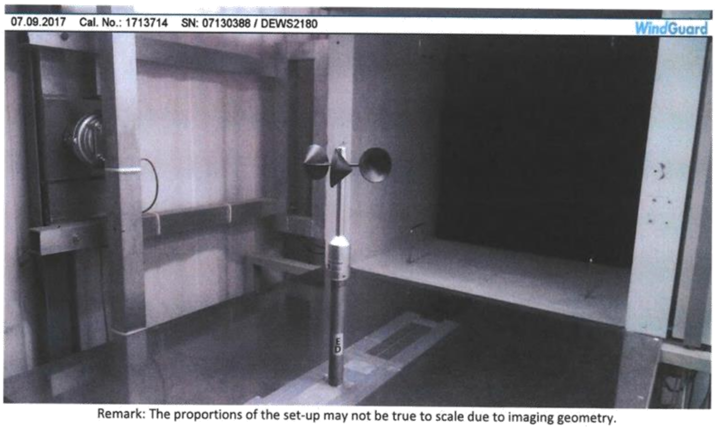


Photo of the measurement setup
Foto des Messaufbaus



Remark: The proportions of the set-up may not be true to scale due to imaging geometry.

DEWS2182

DEWS 2182

DEUTSCHE WINDGUARD

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Wind Tunnel Services GmbH

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as calibration laboratory in the / *als Kalibrierlaboratorium im*

Deutschen Kalibrierdienst DKD

DAkkS Deutsche Akkreditierungsstelle D-K-15140-01-00

Calibration certificate
Kalibrierschein

Calibration mark
Kalibrierzeichen

1713711
D-K-15140-01-00
09/2017

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.00.000
Serial number *Fabrikat/Serien-Nr.*	07130390 DEWS2182
Customer *Auftraggeber*	ECN Wind Energy
Order No. *Auftragsnummer*	ECN4195422
Project No. *Projektnummer*	VT170753
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	07.09.2017

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Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
07.09.2017	D. Westermann Dipl. Phys. Dieter Westermann	D. Henninges Techniker Dirk Henninges

Calibration object *Kalibriergegenstand*	Cup Anemometer	
Calibration procedure *Kalibrierverfahren*	• Deutsche WindGuard Wind Tunnel Services: QM-KL-AK-VA Based on following standards: • MEASNET: Anemometer calibration procedure • IEC 61400-12-1: Power performance measurements of electricity producing wind turbines • IEC 61400-12-2: Power performance of electricity producing wind turbines based on nacelle anemometry • ISO 3966: Measurement of fluid in closed conduits • ISO 16622: Meteorology - Sonic anemometers/thermometers	
Place of calibration *Ort der Kalibrierung*	Windtunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel	
Test conditions *Messbedingungen*	wind tunnel area	10000 cm²
	anemometer frontal area	230 cm²
	diameter of mounting pipe	34 mm
	blockage ratio [1)]	0.023 [-]
	software version	7.7
	[1)] Due to the special construction of the test section no blockage correction is necessary.	
Ambient conditions *Umgebungsbedingungen*	air temperature	22.9 °C ± 0.1 °C
	air pressure	1011.8 hPa ± 0.3 hPa
	relative air humidity	53.9 % ± 2.0 %
Measurement uncertainty *Messunsicherheit*	The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k=2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%. The reference flow speed measurement is traceable to the German NMI (Physikalisch-Technische Bundesanstalt) standard for flow speed. It is realized by using a PTB owned and calibrated Laser Doppler Anemometer (Standard Uncertainty 0.2 %, k=2)	
Additional remarks *Zusätzliche Anmerkungen*	-	

Calibration result
Kalibrierergebnis

Sensor	Tunnel Speed	Uncertainty
Hz	m/s	m/s
81.767	3.982	0.050
123.481	5.907	0.050
166.948	7.914	0.051
211.291	9.945	0.051
255.382	11.952	0.052
296.100	13.882	0.052
339.933	15.852	0.052
318.068	14.861	0.052
276.865	12.954	0.051
232.658	10.904	0.051
188.499	8.911	0.051
146.124	6.964	0.051
101.822	4.946	0.050

File: 1713711

Statistical analysis	Slope	0.04594 (m/s)/(Hz) ±0.00006 (m/s)/(Hz)
	Offset	0.2418 m/s ±0.015 m/s
	Standard error (Y)	0.015 m/s
	Correlation coefficient	0.999989

Remarks

The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard Wind Tunnel Services GmbH measnet

Graphical representation of the result
Grafische Darstellung des Ergebnisses

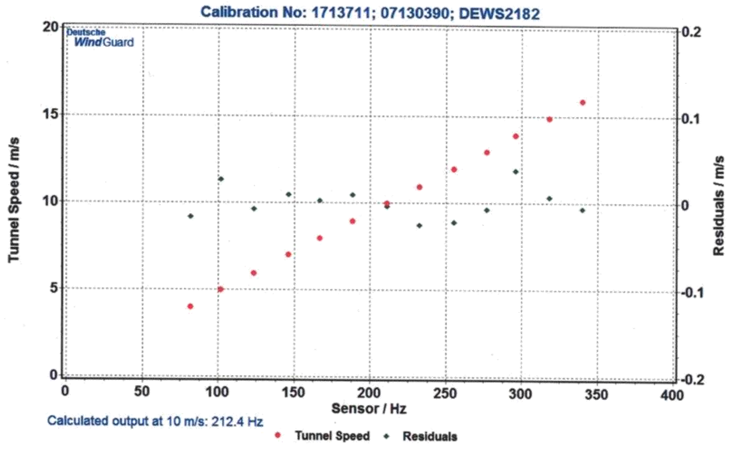
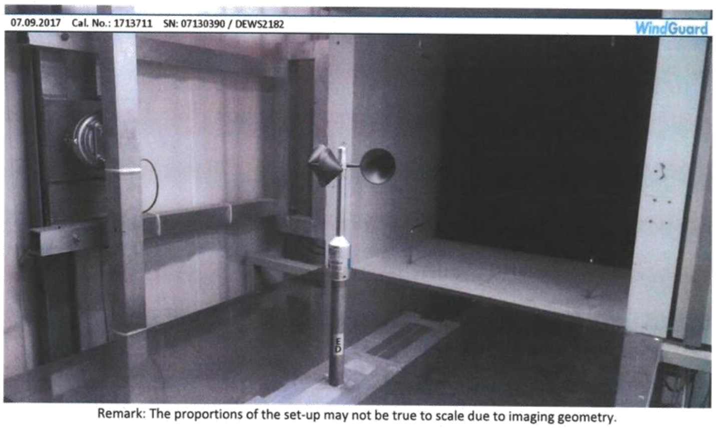


Photo of the measurement setup
Foto des Messaufbaus



Remark: The proportions of the set-up may not be true to scale due to imaging geometry.

DEWS2179

DEWS 2179

DEUTSCHE WINDGUARD

Deutsche WindGuard
Wind Tunnel Services GmbH

IECRE and MEASNET approved test laboratory

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Deutsche Akkreditierungsstelle GmbH

as calibration laboratory in the / *als Kalibrierlaboratorium im*

Deutschen Kalibrierdienst DKD

DAkkS Deutsche Akkreditierungsstelle D-K-15140-01-00

Calibration certificate
Kalibrierschein

Calibration mark
Kalibrierzeichen

1713426
D-K-
15140-01-00
08/2017

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.00.000
Serial number *Fabrikat/Serien-Nr.*	07130386
Customer *Auftraggeber*	ECN Wind Energy
Order No. *Auftragsnummer*	ECN4185425
Project No. *Projektnummer*	VT170772
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	22.08.2017

This calibration certificate documents the traceability to national standards, which realize the units of measurement according to the International System of Units (SI).
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Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
22.08.2017	Dipl. Phys. Dieter Westermann	Hendrik Jansen, B. Eng.

Calibration object *Kalibriergegenstand*	Cup Anemometer
Calibration procedure *Kalibrierverfahren*	• Deutsche WindGuard Wind Tunnel Services: QM-KL-AK-VA Based on following standards: • MEASNET: Anemometer calibration procedure • IEC 61400-12-1: Power performance measurements of electricity producing wind turbines • IEC 61400-12-2: Power performance of electricity producing wind turbines based on nacelle anemometry • ISO 3966: Measurement of fluid in closed conduits • ISO 16622: Meteorology - Sonic anemometers/thermometers
Place of calibration *Ort der Kalibrierung*	Windtunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel

Test conditions *Messbedingungen*	wind tunnel area	10000 cm²
	anemometer frontal area	230 cm²
	diameter of mounting pipe	34 mm
	blockage ratio [1)]	0.023 [-]
	software version	7.7

[1)] Due to the special construction of the test section no blockage correction is necessary.

Ambient conditions *Umgebungsbedingungen*	air temperature	25.8 °C ± 0.1 °C
	air pressure	1020.8 hPa ± 0.3 hPa
	relative air humidity	47.7 % ± 2.0 %

Measurement uncertainty
Messunsicherheit

The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k=2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%.
The reference flow speed measurement is traceable to the German NMI (Physikalisch-Technische Bundesanstalt) standard for flow speed. It is realized by using a PTB owned and calibrated Laser Doppler Anemometer (Standard Uncertainty 0.2 %, k=2)

Additional remarks
Zusätzliche Anmerkungen

-

1713426
D-K- 15140-01-00
08/2017

Calibration result
Kalibrierergebnis

Sensor Hz	Tunnel Speed m/s	Uncertainty m/s
81.290	3.968	0.050
123.222	5.892	0.051
166.769	7.901	0.051
209.763	9.928	0.051
254.570	11.944	0.052
295.248	13.865	0.052
339.185	15.879	0.052
317.247	14.852	0.052
276.071	12.939	0.052
231.410	10.932	0.051
187.308	8.882	0.051
144.951	6.931	0.051
101.875	4.932	0.050

File: 1713426

Statistical analysis	Slope	0.04614 (m/s)/(Hz) ±0.00007 (m/s)/(Hz)
	Offset	0.2264 m/s ±0.016 m/s
	Standard error (Y)	0.016 m/s
	Correlation coefficient	0.999987

Remarks

The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard Wind Tunnel Services GmbH · measnet

Graphical representation of the result
Grafische Darstellung des Ergebnisses

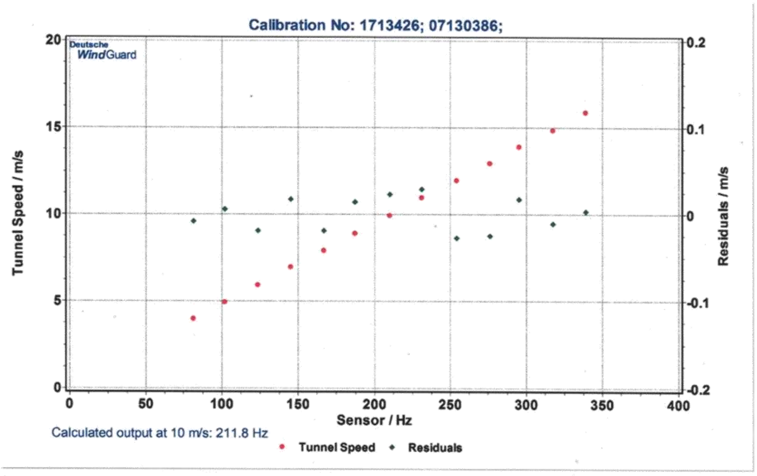
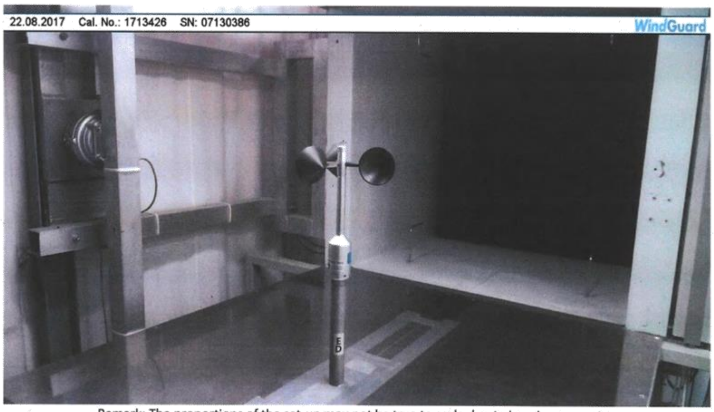


Photo of the measurement setup
Foto des Messaufbaus



Remark: The proportions of the set-up may not be true to scale due to imaging geometry.

DEWR6071

DEWR6071

DEUTSCHE WINDGUARD

Deutsche WindGuard
Wind Tunnel Services GmbH

IECRE and MEASNET approved test laboratory

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Deutsche Akkreditierungsstelle GmbH

as calibration laboratory in the / *als Kalibrierlaboratorium im*

Deutschen Kalibrierdienst DKD

DAkkS Deutsche Akkreditierungsstelle D-K-15140-01-00

Calibration certificate
Kalibrierschein

Calibration mark
Kalibrierzeichen

1723026
D-K-15140-01-00
11/2017

Object *Gegenstand*	Wind Vane
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3150.00.400
Serial number *Fabrikat/Serien-Nr.*	08110047 DEWR6071
Customer *Auftraggeber*	ECN Wind Energy
Order No. *Auftragsnummer*	ECN4186952/15.09.2017
Project No. *Projektnummer*	VT170913
Number of pages *Anzahl der Seiten*	6
Date of Calibration *Datum der Kalibrierung*	14.11.2017

This calibration certificate documents the traceability to national standards, which realize the units of measurement according to the International System of Units (SI).
The DAkkS is signatory to the multilateral agreements of the European co-operation for Accreditation (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates.
The user is obliged to have the object recalibrated at appropriate intervals.
Dieser Kalibrierschein dokumentiert die Rückführung auf nationale Normale zur Darstellung der Einheiten in Übereinstimmung mit dem Internationalen Einheitensystem (SI).
Die DAkkS ist Unterzeichner der multilateralen Übereinkommen der European co-operation for Accreditation (EA) und der International Laboratory Accreditation Cooperation (ILAC) zur gegenseitigen Anerkennung der Kalibrierscheine.
Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
14.11.2017	Dipl. Phys. Dieter Westermann	Heiko Westermann, B. Sc.

Calibration object *Kalibriergegenstand*	Wind Vane
Calibration procedure *Kalibrierverfahren*	• Deutsche WindGuard Wind Tunnel Services: VA Kalibrierung von Windrichtungssensoren Based on following standards: • IEC 61400-12-1:2017 Power performance measurements of electricity producing wind turbines • IEC 61400-12-2:2013 Power performance of electricity producing wind turbines based on nacelle anemometry • ISO 16622:2002 Meteorology - Sonic anemometers/thermometers • ASTM 5366-96: Standard Test Method of Measuring the Dynamic Performance of Wind Vanes
Place of calibration *Ort der Kalibrierung*	Wind tunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel

Test conditions *Messbedingungen*

wind tunnel area	10000 cm²
anemometer frontal area	200 cm²
diameter of mounting pipe	34 mm
blockage ratio [1)]	0.020 [-]
software version	7.7

[1)] Due to the special construction of the test section no blockage correction is necessary.

Ambient conditions *Umgebungsbedingungen*

air temperature	21.5 °C ± 0.1 °C
air pressure	1018.2 hPa ± 0.3 hPa
relative air humidity	43.1 % ± 2.0 %

Measurement uncertainty *Messunsicherheit*

The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k=2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%.
The reference flow speed measurement is traceable to the German NMI (Physikalisch-Technische Bundesanstalt) standard for flow speed. It is realized by using a PTB owned and calibrated Laser Doppler Anemometer (Standard Uncertainty 0.2 %, k=2)

Additional remarks *Zusätzliche Anmerkungen*

-

Calibration result (1/3)
Kalibrierergebnis (1/3)

Azimuth	UNC	Sensor out	Azimuth-Sensor out	Flow speed	UNC	Flow dir
deg	deg	deg	deg	m/s	m/s	deg
4.99	0.8	5.28	-0.29	7.84	0.5	-0.17
9.94	0.8	10.22	-0.28	7.83	0.5	-0.16
14.99	0.8	15.25	-0.26	7.84	0.5	-0.16
20.00	0.8	20.32	-0.32	7.84	0.5	-0.18
25.05	0.8	25.47	-0.42	7.84	0.5	-0.17
30.01	0.8	30.53	-0.52	7.84	0.5	-0.18
34.98	0.8	35.55	-0.58	7.84	0.5	-0.14
40.00	0.8	40.53	-0.53	7.84	0.5	-0.15
45.03	0.8	45.65	-0.62	7.84	0.5	-0.24
49.99	0.8	50.54	-0.54	7.84	0.5	-0.20
54.97	0.8	55.51	-0.54	7.84	0.5	-0.18
60.02	0.8	60.59	-0.58	7.83	0.5	-0.20
64.98	0.8	65.53	-0.55	7.84	0.5	-0.20
69.96	0.8	70.57	-0.60	7.84	0.5	-0.15
74.98	0.8	75.67	-0.69	7.84	0.5	-0.14
80.00	0.8	80.62	-0.62	7.84	0.5	-0.18
84.96	0.8	85.53	-0.57	7.84	0.5	-0.15
89.99	0.8	90.40	-0.42	7.84	0.5	-0.10
95.02	0.8	95.28	-0.26	7.84	0.5	-0.20
100.04	0.8	100.30	-0.26	7.84	0.5	-0.19
105.04	0.8	105.35	-0.32	7.84	0.5	-0.16
110.06	0.8	110.50	-0.43	7.83	0.5	-0.15
115.02	0.8	115.57	-0.55	7.84	0.5	-0.17
119.99	0.8	120.69	-0.69	7.84	0.5	-0.14
124.99	0.8	125.73	-0.74	7.84	0.5	-0.14
130.06	0.8	130.82	-0.76	7.84	0.5	-0.12
135.08	0.8	135.81	-0.73	7.84	0.5	-0.21
140.06	0.8	140.75	-0.69	7.84	0.5	-0.16
145.10	0.8	145.81	-0.71	7.84	0.5	-0.14
150.10	0.8	150.89	-0.79	7.84	0.5	-0.21

Calibration result (2/3)
Kalibrierergebnis (2/3)

Azimuth	UNC	Sensor out	Azimuth-Sensor out	Flow speed	UNC	Flow dir
deg	deg	deg	deg	m/s	m/s	deg
155.12	0.8	156.14	-1.02	7.84	0.5	-0.18
160.02	0.8	161.14	-1.13	7.84	0.5	-0.17
164.99	0.8	166.19	-1.20	7.84	0.5	-0.12
170.03	0.8	171.23	-1.21	7.84	0.5	-0.15
175.02	0.8	176.04	-1.03	7.84	0.5	-0.23
179.99	0.8	180.74	-0.75	7.84	0.5	-0.22
185.01	0.8	185.66	-0.64	7.84	0.5	-0.15
190.01	0.8	190.57	-0.57	7.84	0.5	-0.15
194.95	0.8	195.59	-0.64	7.84	0.5	-0.23
199.99	0.8	200.79	-0.80	7.84	0.5	-0.17
204.98	0.8	206.05	-1.07	7.84	0.5	-0.13
209.95	0.8	211.13	-1.19	7.84	0.5	-0.18
214.98	0.8	216.17	-1.19	7.84	0.5	-0.14
219.97	0.8	221.17	-1.21	7.84	0.5	-0.14
225.03	0.8	226.16	-1.13	7.84	0.5	-0.13
230.01	0.8	231.12	-1.11	7.84	0.5	-0.19
234.97	0.8	236.05	-1.08	7.83	0.5	-0.16
239.98	0.8	241.10	-1.12	7.84	0.5	-0.18
245.03	0.8	246.28	-1.24	7.84	0.5	-0.15
249.99	0.8	251.34	-1.34	7.84	0.5	-0.18
255.20	0.8	256.14	-0.94	7.84	0.5	-0.17
260.04	0.8	260.83	-0.79	7.84	0.5	-0.19
265.06	0.8	265.85	-0.78	7.84	0.5	-0.22
270.13	0.8	270.66	-0.53	7.84	0.5	-0.23
275.08	0.8	275.51	-0.42	7.84	0.5	-0.15
280.05	0.8	280.46	-0.41	7.84	0.5	-0.14
285.06	0.8	285.52	-0.46	7.84	0.5	-0.13
290.06	0.8	290.57	-0.51	7.84	0.5	-0.12
295.02	0.8	295.62	-0.61	7.83	0.5	-0.15
300.03	0.8	300.68	-0.65	7.84	0.5	-0.16
304.94	0.8	305.68	-0.73	7.84	0.5	-0.16
309.93	0.8	310.57	-0.64	7.84	0.5	-0.17

Calibration result (3/3)
Kalibrierergebnis (3/3)

Azimuth deg	UNC deg	Sensor out deg	Azimuth-Sensor out deg	Flow speed m/s	UNC m/s	Flow dir deg
314.97	0.8	315.62	-0.65	7.84	0.5	-0.14
319.99	0.8	320.58	-0.59	7.84	0.5	-0.18
325.02	0.8	325.62	-0.60	7.83	0.5	-0.16
329.97	0.8	330.64	-0.67	7.84	0.5	-0.15
334.97	0.8	335.80	-0.83	7.84	0.5	-0.19
339.97	0.8	340.91	-0.94	7.84	0.5	-0.10
344.99	0.8	345.94	-0.95	7.84	0.5	-0.17
349.98	0.8	350.88	-0.90	7.84	0.5	-0.26
354.96	0.8	355.67	-0.71	7.84	0.5	-0.16

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Statistical analysis Average offset -0.72 deg

Graphical representation of the result
Grafische Darstellung des Ergebnisses

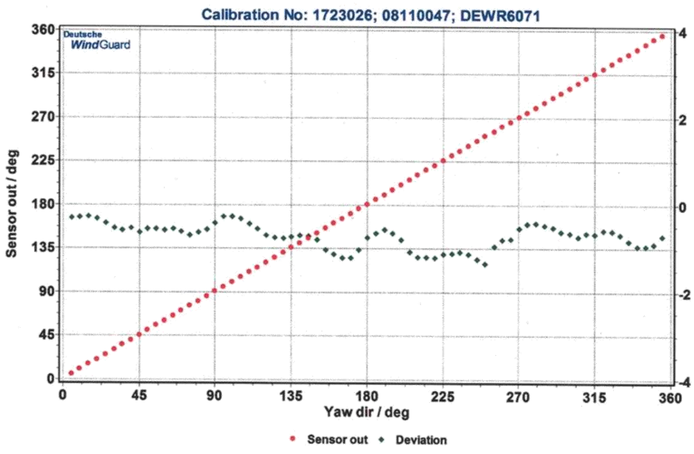
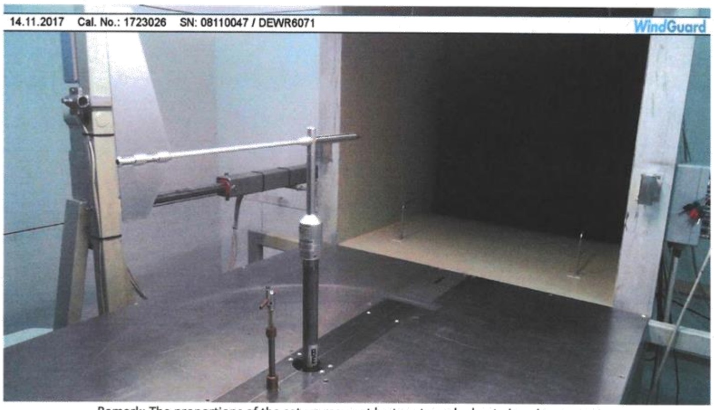


Photo of the measurement setup
Foto des Messaufbaus



Remark: The proportions of the set-up may not be true to scale due to imaging geometry.

DEWR5212

DEWR 5212

DEUTSCHE WINDGUARD

Deutsche WindGuard
Wind Tunnel Services GmbH

IECRE and MEASNET approved test laboratory

accredited by the / *akkreditiert durch die*

Deutsche Akkreditierungsstelle GmbH

as calibration laboratory in the / *als Kalibrierlaboratorium im*

Deutschen Kalibrierdienst DKD

DAkkS Deutsche Akkreditierungsstelle D-K-15140-01-00

Calibration certificate
Kalibrierschein

Calibration mark
Kalibrierzeichen

1723343
D-K- 15140-01-00
12/2017

Object *Gegenstand*	Wind Vane
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3150.00.400
Serial number *Fabrikat/Serien-Nr.*	04120059 DEWR5212
Customer *Auftraggeber*	ECN Wind Energy
Order No. *Auftragsnummer*	ECN4188417
Project No. *Projektnummer*	VT171087
Number of pages *Anzahl der Seiten*	6
Date of Calibration *Datum der Kalibrierung*	27.12.2017

This calibration certificate documents the traceability to national standards, which realize the units of measurement according to the International System of Units (SI).
The DAkkS is signatory to the multilateral agreements of the European co-operation for Accreditation (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates.
The user is obliged to have the object recalibrated at appropriate intervals.
Dieser Kalibrierschein dokumentiert die Rückführung auf nationale Normale zur Darstellung der Einheiten in Übereinstimmung mit dem Internationalen Einheitensystem (SI).
Die DAkkS ist Unterzeichner der multilateralen Übereinkommen der European co-operation for Accreditation (EA) und der International Laboratory Accreditation Cooperation (ILAC) zur gegenseitigen Anerkennung der Kalibrierscheine.
Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

This calibration certificate may not be reproduced other than in full except with the permission of both the German Accreditation Body and the issuing laboratory. Calibration certificates without signature are not valid. This calibration certificate has been generated electronically.
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Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
27.12.2017	Dipl. Phys. Dieter Westermann	Kai Schuster, B. Eng.

Calibration object
Kalibriergegenstand

Wind Vane

Calibration procedure
Kalibrierverfahren

• Deutsche WindGuard Wind Tunnel Services: VA Kalibrierung von Windrichtungssensoren
Based on following standards:
• IEC 61400-12-1:2017 Power performance measurements of electricity producing wind turbines
• IEC 61400-12-2:2013 Power performance of electricity producing wind turbines based on nacelle anemometry
• ISO 16622:2002 Meteorology - Sonic anemometers/thermometers
• ASTM 5366-96: Standard Test Method of Measuring the Dynamic Performance of Wind Vanes

Place of calibration
Ort der Kalibrierung

Wind tunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel

Test conditions
Messbedingungen

wind tunnel area	10000 cm²
anemometer frontal area	200 cm²
diameter of mounting pipe	34 mm
blockage ratio [1)]	0.020 [-]
software version	7.7

[1)] Due to the special construction of the test section no blockage correction is necessary.

Ambient conditions
Umgebungsbedingungen

air temperature	20.0 °C ± 0.1 °C
air pressure	983.9 hPa ± 0.3 hPa
relative air humidity	43.5 % ± 2.0 %

Measurement uncertainty
Messunsicherheit

The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k=2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%.
The reference flow speed measurement is traceable to the German NMI (Physikalisch-Technische Bundesanstalt) standard for flow speed. It is realized by using a PTB owned and calibrated Laser Doppler Anemometer (Standard Uncertainty 0.2 %, k=2)

Additional remarks
Zusätzliche Anmerkungen

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Seite

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12/2017

Calibration result (1/3)
Kalibrierergebnis (1/3)

Azimuth	UNC	Sensor out	Azimuth-Sensor out	Flow speed	UNC	Flow dir
deg	deg	deg	deg	m/s	m/s	deg
4.98	0.8	5.09	-0.10	7.91	0.5	-0.11
10.00	0.8	10.00	-0.00	7.90	0.5	-0.21
14.97	0.8	14.96	0.01	7.90	0.5	-0.20
19.97	0.8	19.92	0.05	7.91	0.5	-0.22
24.92	0.8	24.84	0.09	7.90	0.5	-0.14
29.96	0.8	29.96	0.00	7.90	0.5	-0.20
34.76	0.8	34.81	-0.05	7.90	0.5	-0.22
40.01	0.8	40.18	-0.17	7.90	0.5	-0.11
45.02	0.8	45.18	-0.16	7.90	0.5	-0.19
50.05	0.8	50.15	-0.10	7.90	0.5	-0.17
54.99	0.8	55.11	-0.12	7.90	0.5	-0.23
59.95	0.8	60.18	-0.24	7.90	0.5	-0.18
64.99	0.8	65.25	-0.26	7.90	0.5	-0.26
70.01	0.8	70.31	-0.31	7.91	0.5	-0.16
75.01	0.8	75.31	-0.30	7.91	0.5	-0.23
80.02	0.8	80.33	-0.31	7.91	0.5	-0.12
85.00	0.8	85.29	-0.29	7.90	0.5	-0.20
89.95	0.8	90.13	-0.19	7.91	0.5	-0.20
94.99	0.8	95.04	-0.05	7.91	0.5	-0.21
100.05	0.8	100.03	0.02	7.91	0.5	-0.15
105.03	0.8	105.00	0.04	7.91	0.5	-0.17
109.93	0.8	109.96	-0.03	7.91	0.5	-0.20
114.94	0.8	115.01	-0.07	7.90	0.5	-0.16
120.03	0.8	120.20	-0.17	7.91	0.5	-0.15
125.04	0.8	125.20	-0.16	7.91	0.5	-0.18
129.94	0.8	130.14	-0.20	7.91	0.5	-0.19
135.00	0.8	135.25	-0.25	7.91	0.5	-0.18
140.07	0.8	140.40	-0.33	7.91	0.5	-0.14
145.00	0.8	145.33	-0.32	7.91	0.5	-0.22
149.99	0.8	150.35	-0.37	7.91	0.5	-0.20

Calibration result (2/3)
Kalibrierergebnis (2/3)

Azimuth	UNC	Sensor out	Azimuth-Sensor out	Flow speed	UNC	Flow dir
deg	deg	deg	deg	m/s	m/s	deg
155.03	0.8	155.56	-0.53	7.90	0.5	-0.18
160.09	0.8	160.75	-0.66	7.91	0.5	-0.17
165.02	0.8	165.76	-0.74	7.91	0.5	-0.11
170.02	0.8	170.84	-0.82	7.91	0.5	-0.20
175.05	0.8	175.80	-0.75	7.91	0.5	-0.16
180.04	0.8	180.71	-0.67	7.91	0.5	-0.14
185.02	0.8	185.63	-0.61	7.91	0.5	-0.19
190.05	0.8	190.47	-0.43	7.90	0.5	-0.16
194.95	0.8	195.35	-0.40	7.91	0.5	-0.20
199.91	0.8	200.34	-0.43	7.91	0.5	-0.20
204.86	0.8	205.43	-0.58	7.91	0.5	-0.21
209.97	0.8	210.62	-0.65	7.91	0.5	-0.14
215.04	0.8	215.69	-0.65	7.91	0.5	-0.22
220.02	0.8	220.75	-0.73	7.90	0.5	-0.27
224.96	0.8	225.72	-0.76	7.91	0.5	-0.18
229.95	0.8	230.69	-0.75	7.91	0.5	-0.21
235.00	0.8	235.74	-0.74	7.91	0.5	-0.22
240.02	0.8	240.79	-0.77	7.91	0.5	-0.21
244.96	0.8	245.90	-0.94	7.91	0.5	-0.15
250.02	0.8	251.05	-1.03	7.91	0.5	-0.15
255.04	0.8	256.12	-1.08	7.91	0.5	-0.22
260.02	0.8	261.02	-1.00	7.90	0.5	-0.14
264.96	0.8	265.86	-0.89	7.90	0.5	-0.19
270.01	0.8	270.75	-0.74	7.91	0.5	-0.15
275.03	0.8	275.56	-0.53	7.90	0.5	-0.15
280.16	0.8	280.32	-0.16	7.91	0.5	-0.13
285.00	0.8	285.01	-0.01	7.91	0.5	-0.17
289.97	0.8	290.09	-0.12	7.91	0.5	-0.17
294.99	0.8	295.13	-0.14	7.91	0.5	-0.16
300.02	0.8	300.13	-0.11	7.91	0.5	-0.22
305.12	0.8	305.31	-0.19	7.91	0.5	-0.13
310.07	0.8	310.35	-0.27	7.90	0.5	-0.16

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Calibration result (3/3)
Kalibrierergebnis (3/3)

Azimuth	UNC	Sensor out	Azimuth-Sensor out	Flow speed	UNC	Flow dir
deg	deg	deg	deg	m/s	m/s	deg
315.06	0.8	315.36	-0.30	7.91	0.5	-0.19
320.10	0.8	320.31	-0.21	7.90	0.5	-0.18
325.06	0.8	325.27	-0.22	7.90	0.5	-0.21
330.10	0.8	330.41	-0.31	7.90	0.5	-0.18
335.10	0.8	335.55	-0.44	7.91	0.5	-0.18
340.04	0.8	340.49	-0.45	7.90	0.5	-0.11
344.98	0.8	345.40	-0.42	7.90	0.5	-0.20
349.97	0.8	350.38	-0.41	7.91	0.5	-0.16
354.97	0.8	355.37	-0.40	7.91	0.5	-0.09

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Statistical analysis Average offset -0.37 deg

Graphical representation of the result
Grafische Darstellung des Ergebnisses

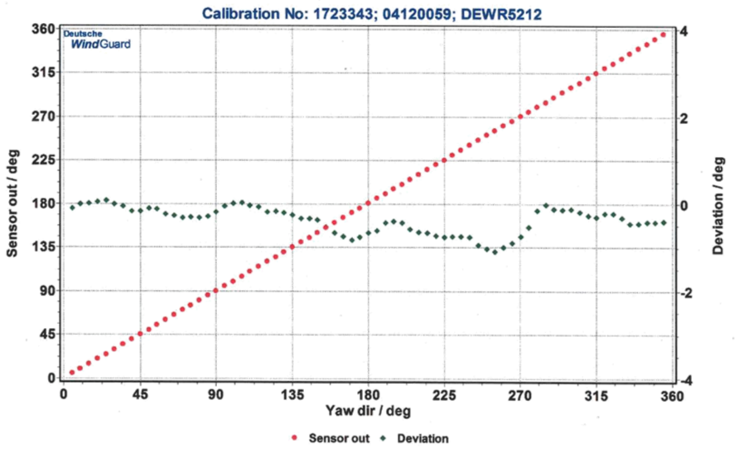
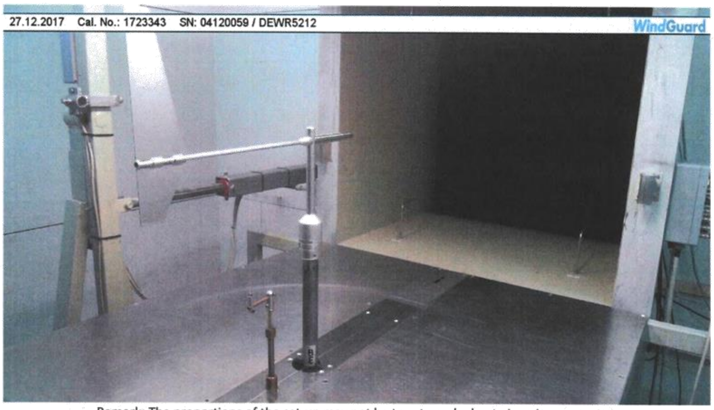


Photo of the measurement setup
Foto des Messaufbaus



Remark: The proportions of the set-up may not be true to scale due to imaging geometry.

DEWR6091

DEWR 6091

DEUTSCHE WINDGUARD

Deutsche WindGuard
Wind Tunnel Services GmbH

IECRE and MEASNET approved test laboratory

accredited by the / *akkreditiert durch die*

Deutsche Akkreditierungsstelle GmbH

as calibration laboratory in the / *als Kalibrierlaboratorium im*

Deutschen Kalibrierdienst DKD

DAkkS Deutsche Akkreditierungsstelle D-K-15140-01-00

Calibration certificate
Kalibrierschein

Calibration mark
Kalibrierzeichen

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Object *Gegenstand*	Wind Vane
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3150.00.400
Serial number *Fabrikat/Serien-Nr.*	04120069 DEWR6091
Customer *Auftraggeber*	ECN Wind Energy
Order No. *Auftragsnummer*	ECN4188417
Project No. *Projektnummer*	VT171087
Number of pages *Anzahl der Seiten*	6
Date of Calibration *Datum der Kalibrierung*	27.12.2017

This calibration certificate documents the traceability to national standards, which realize the units of measurement according to the International System of Units (SI).
The DAkkS is signatory to the multilateral agreements of the European co-operation for Accreditation (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates.
The user is obliged to have the object recalibrated at appropriate intervals.
Dieser Kalibrierschein dokumentiert die Rückführung auf nationale Normale zur Darstellung der Einheiten in Übereinstimmung mit dem Internationalen Einheitensystem (SI).
Die DAkkS ist Unterzeichner der multilateralen Übereinkommen der European co-operation for Accreditation (EA) und der International Laboratory Accreditation Cooperation (ILAC) zur gegenseitigen Anerkennung der Kalibrierscheine.
Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

This calibration certificate may not be reproduced other than in full except with the permission of both the German Accreditation Body and the issuing laboratory. Calibration certificates without signature are not valid. This calibration certificate has been generated electronically.
Dieser Kalibrierschein darf nur vollständig und unverändert weiterverbreitet werden. Auszüge oder Änderungen bedürfen der Genehmigung sowohl der Deutschen Akkreditierungsstelle als auch des ausstellenden Kalibrierlaboratoriums. Kalibrierscheine ohne Unterschrift haben keine Gültigkeit. Dieser Kalibrierschein wurde elektronisch erzeugt.

Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
27.12.2017	Dipl. Phys. Dieter Westermann	Kai Schuster, B. Eng.

Calibration object *Kalibriergegenstand*	Wind Vane
Calibration procedure *Kalibrierverfahren*	• Deutsche WindGuard Wind Tunnel Services: VA Kalibrierung von Windrichtungssensoren Based on following standards: • IEC 61400-12-1:2017 Power performance measurements of electricity producing wind turbines • IEC 61400-12-2:2013 Power performance of electricity producing wind turbines based on nacelle anemometry • ISO 16622:2002 Meteorology - Sonic anemometers/thermometers • ASTM 5366-96: Standard Test Method of Measuring the Dynamic Performance of Wind Vanes
Place of calibration *Ort der Kalibrierung*	Wind tunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel

Test conditions
Messbedingungen

wind tunnel area	10000 cm²
anemometer frontal area	200 cm²
diameter of mounting pipe	34 mm
blockage ratio [1)]	0.020 [-]
software version	7.7

[1)] Due to the special construction of the test section no blockage correction is necessary.

Ambient conditions
Umgebungsbedingungen

air temperature	19.8 °C ± 0.1 °C
air pressure	984.0 hPa ± 0.3 hPa
relative air humidity	43.7 % ± 2.0 %

Measurement uncertainty
Messunsicherheit

The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k=2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%.
The reference flow speed measurement is traceable to the German NMI (Physikalisch-Technische Bundesanstalt) standard for flow speed. It is realized by using a PTB owned and calibrated Laser Doppler Anemometer (Standard Uncertainty 0.2 %, k=2)

Additional remarks
Zusätzliche Anmerkungen

-

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Calibration result (1/3)
Kalibrierergebnis (1/3)

Azimuth	UNC	Sensor out	Azimuth-Sensor out	Flow speed	UNC	Flow dir
deg	deg	deg	deg	m/s	m/s	deg
5.03	0.8	4.60	0.42	7.91	0.5	-0.18
10.00	0.8	9.51	0.49	7.91	0.5	-0.18
15.03	0.8	14.48	0.55	7.91	0.5	-0.18
20.09	0.8	19.46	0.63	7.91	0.5	-0.13
25.08	0.8	24.45	0.63	7.91	0.5	-0.20
29.64	0.8	29.05	0.59	7.91	0.5	-0.15
35.06	0.8	34.55	0.52	7.91	0.5	-0.17
40.13	0.8	39.72	0.41	7.91	0.5	-0.24
45.04	0.8	44.64	0.40	7.91	0.5	-0.23
50.02	0.8	49.70	0.32	7.91	0.5	-0.19
55.04	0.8	54.70	0.34	7.90	0.5	-0.19
60.01	0.8	59.73	0.28	7.91	0.5	-0.22
65.00	0.8	64.74	0.27	7.91	0.5	-0.17
69.98	0.8	69.83	0.15	7.91	0.5	-0.25
74.98	0.8	74.81	0.17	7.91	0.5	-0.22
79.98	0.8	79.81	0.17	7.91	0.5	-0.22
84.95	0.8	84.75	0.20	7.91	0.5	-0.17
89.94	0.8	89.68	0.26	7.91	0.5	-0.10
94.98	0.8	94.63	0.35	7.91	0.5	-0.17
99.95	0.8	99.39	0.55	7.91	0.5	-0.21
104.92	0.8	104.35	0.58	7.90	0.5	-0.20
109.96	0.8	109.45	0.52	7.91	0.5	-0.17
114.96	0.8	114.52	0.44	7.91	0.5	-0.11
119.93	0.8	119.53	0.39	7.91	0.5	-0.19
124.97	0.8	124.62	0.35	7.91	0.5	-0.15
129.94	0.8	129.66	0.28	7.91	0.5	-0.19
134.96	0.8	134.66	0.29	7.90	0.5	-0.17
139.91	0.8	139.63	0.27	7.91	0.5	-0.16
144.92	0.8	144.71	0.21	7.90	0.5	-0.14
149.97	0.8	149.83	0.14	7.91	0.5	-0.28

Calibration result (2/3)
Kalibrierergebnis (2/3)

Azimuth	UNC	Sensor out	Azimuth-Sensor out	Flow speed	UNC	Flow dir
deg	deg	deg	deg	m/s	m/s	deg
154.90	0.8	154.91	-0.01	7.91	0.5	-0.19
159.91	0.8	160.03	-0.12	7.91	0.5	-0.17
164.98	0.8	165.27	-0.29	7.91	0.5	-0.18
169.98	0.8	170.33	-0.35	7.91	0.5	-0.15
174.94	0.8	175.25	-0.32	7.91	0.5	-0.16
179.93	0.8	180.15	-0.22	7.91	0.5	-0.20
184.95	0.8	185.00	-0.05	7.91	0.5	-0.21
190.04	0.8	189.96	0.08	7.91	0.5	-0.15
195.00	0.8	194.92	0.08	7.91	0.5	-0.22
200.04	0.8	200.02	0.02	7.91	0.5	-0.21
205.09	0.8	205.17	-0.08	7.91	0.5	-0.23
210.03	0.8	210.15	-0.11	7.91	0.5	-0.25
214.94	0.8	215.12	-0.19	7.91	0.5	-0.21
219.99	0.8	220.14	-0.15	7.91	0.5	-0.19
225.06	0.8	225.29	-0.23	7.91	0.5	-0.16
230.06	0.8	230.30	-0.24	7.91	0.5	-0.16
235.02	0.8	235.25	-0.22	7.91	0.5	-0.16
240.01	0.8	240.26	-0.25	7.91	0.5	-0.11
245.03	0.8	245.33	-0.29	7.91	0.5	-0.20
250.02	0.8	250.40	-0.38	7.91	0.5	-0.21
255.04	0.8	255.44	-0.40	7.91	0.5	-0.20
260.12	0.8	260.56	-0.43	7.91	0.5	-0.14
265.08	0.8	265.39	-0.31	7.91	0.5	-0.17
270.02	0.8	270.20	-0.18	7.91	0.5	-0.17
275.02	0.8	275.03	-0.01	7.91	0.5	-0.17
279.90	0.8	279.62	0.28	7.91	0.5	-0.15
284.89	0.8	284.29	0.60	7.91	0.5	-0.19
289.93	0.8	289.36	0.58	7.91	0.5	-0.18
295.01	0.8	294.54	0.48	7.91	0.5	-0.22
300.05	0.8	299.65	0.40	7.91	0.5	-0.16
305.08	0.8	304.74	0.35	7.91	0.5	-0.20
310.02	0.8	309.71	0.31	7.91	0.5	-0.18

Calibration result (3/3)
Kalibrierergebnis (3/3)

Azimuth	UNC	Sensor out	Azimuth-Sensor out	Flow speed	UNC	Flow dir
deg	deg	deg	deg	m/s	m/s	deg
314.98	0.8	314.68	0.30	7.91	0.5	-0.16
320.01	0.8	319.67	0.34	7.91	0.5	-0.17
325.06	0.8	324.73	0.33	7.91	0.5	-0.19
330.04	0.8	329.80	0.24	7.91	0.5	-0.18
335.05	0.8	334.87	0.18	7.91	0.5	-0.19
340.04	0.8	339.93	0.10	7.91	0.5	-0.18
344.99	0.8	344.90	0.09	7.91	0.5	-0.20
349.99	0.8	349.89	0.11	7.91	0.5	-0.16
355.06	0.8	354.83	0.23	7.91	0.5	-0.13

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Statistical analysis Average offset 0.16 deg

Graphical representation of the result
Grafische Darstellung des Ergebnisses

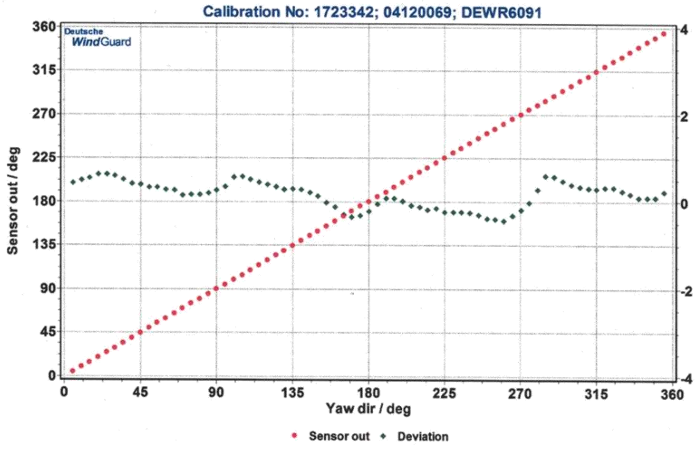
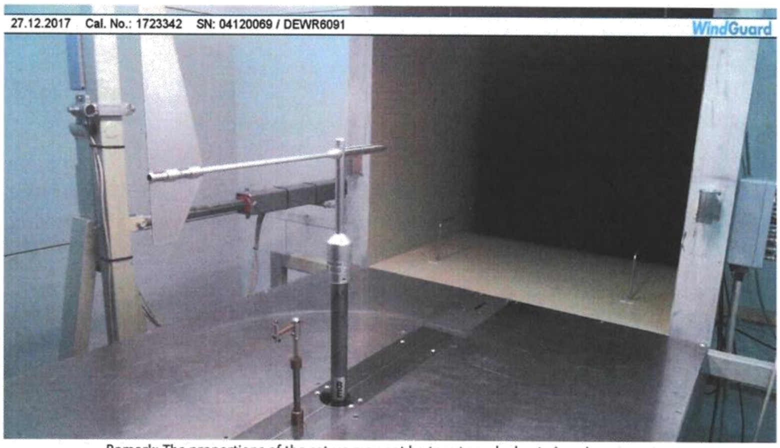


Photo of the measurement setup
Foto des Messaufbaus



Remark: The proportions of the set-up may not be true to scale due to imaging geometry.

C Manufacturer Verification Certificate – WINDCUBE

LEOSPHERE

Manufacturer Verification Certificate - WINDCUBE® v2

System	*WLS7-258*
Test date	*01-2016*

Reference system

System measurement has been compared to LEOSPHERE's reference WINDCUBE v2 lidar unit: **WLS7-341**
This Lidar was certified by the Danish Technical University (DTU) in March 2014 at the Høvsøre test site in Denmark.
The reference Lidar's measurements were compared to a 116m reference mast with a test process approved by DANAK.

Data analysis

Data used for comparison are averaged 10 minutes data.
Wind speed and direction data are compared using regression curves applying the model ***y=ax+b***, where ***y*** is the lidar wind speed, ***x*** the reference wind speed, ***a*** the regression slope and ***b*** the regression offset. ***R²*** is the coefficient of determination.
Wind speed mean deviation presented in this report is the mean of wind speed difference between the reference and the tested system during the validation period. The mean deviation and its standard deviation are given in m/s.

Results

Horizontal Wind speed regression:

Altitude	*Criteria*	*Value*	*Passed*
40m	Wind speed regression gain is 1±0.02	1.002	yes
	Wind speed regression offset is 0±0.2 m/s	-0.022	yes
	Coefficient of determination R^2 is greater than 0.99	0.997	yes
80m	Wind speed regression gain is 1±0.015	0.999	yes
	Wind speed regression offset is 0±0.2 m/s	0.004	yes
	Coefficient of determination R^2 is greater than 0.99	0.999	yes
120m	Wind speed regression gain is 1±0.015	0.998	yes
	Wind speed regression offset is 0±0.2 m/s	0.017	yes
	Coefficient of determination R^2 is greater than 0.99	0.999	yes
160m	Wind speed regression gain is 1±0.015	0.998	yes
	Wind speed regression offset is 0±0.2 m/s	0.008	yes
	Coefficient of determination R^2 is greater than 0.99	0.999	yes

Wind direction regression:

Altitude	*Criteria*	*Value*	*Passed*
100m	Wind direction regression gain is 1±0.01	1.000	yes
	Wind direction regression offset is 0±2°	0.763	yes
	Coefficient of determination R^2 is greater than 0.99	0.999	yes

Horizontal Wind speed Deviation and Standard deviation of deviation:

Altitude	*Criteria*	*Value*	*Passed*
40m	Wind speed deviation is 0±0.1m/s	-0.011	yes
	Wind speed std deviation of deviation is 0±0.2 m/s	0.086	yes
80m	Wind speed deviation is 0±0.1m/s	-0.004	yes
	Wind speed std deviation of deviation is 0±0.2 m/s	0.068	yes
120m	Wind speed deviation is 0±0.1m/s	-0.003	yes
	Wind speed std deviation of deviation is 0±0.2 m/s	0.070	yes
160m	Wind speed deviation is 0±0.1m/s	-0.018	yes
	Wind speed std deviation of deviation is 0±0.2 m/s	0.084	yes

Validation Service agreement

System **WLS7-258** has passed LEOSPHERE acceptance tests.

Marion REMY

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The present document is provided solely for information purposes.

D Nomenclature

EV	Environmental variable
IEC	International Electrotechnical Commission
LEG	Lichteiland Goeree
OWA	Offshore Wind Accelerator
rsd	Remote Sensing Device
RvA	Raad voor Accreditatie / Dutch Accreditation Council
Std	standard deviation
TLCF	TNO LiDAR Calibration Facility
UTC	Coordinated Universal Time
WDMS	Wind Data Management System