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TNO report

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Validation of the TNO ZX300 LiDAR system unit 308 at the TNO RSD Verification Facility

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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.

- Power performance measurements conform to IEC 61400-12-1, MEASNET Power Performance measurement procedure, FGW TR2, FGW TR5
- NTF/NPC measurements conform to IEC 61400-12-2
- Mechanical loads measurements conform to IEC 61400-13
- Meteorological measurements (wind speed, wind direction, temperature, air pressure and relative humidity) conform to IEC 61400-12-1
- Verification of ground-based or nacelle-mounted Remote Sensing Devices conform to IEC 61400-12-1, Appendix L
- Verification of Floating LiDAR conform to IEC 61400-12-1, Appendix L and IEA Recommended Practices 18

Results only apply for the tested floating LiDAR system with the settings used during the measurement period.
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Management summary

As part of the 2021 Windconditions@northsea project a ZX Lidars ZX300 with serial number 308 was installed at the TNO RSD Verification Facility on 11 July 2019. The LiDAR was validated before using it for wind field measurements at Europlatform.

The official measurement campaign started on 15 July 2019 14:40 UTC and lasted until 8 September 2019 00:00 UTC, covering 54 days. The LiDAR validation was successful.

The primary results of this validation are based on the IEC 61400-12-1:2017.

All meteorological measurements are carried out under ISO 17025 accreditation. TNO Wind Energy is an IECRE approved test lab.

1 Introduction

The activities that TNO performs under the independent ISO 17025 accreditation and IECRE approval are:

- Power performance
- Mechanical loads
- Meteorological measurements
- Remote sensing device verification
- Floating LiDAR verification

Remote Sensing Devices have emerged in the last years as a promising alternative to anemometers in masts, since they are typically quicker and easier to deploy, avoiding the drawn-out planning consent process to construct a tall meteorological mast. LiDARs/RSD also have the potential to reduce costs and time taken for turbine type certification and site assessment within onshore and offshore projects. Therefore, the high quality verification of the LiDARs/RSD is critical for excellent performance. To that end, TNO developed the TNO RSD Verification Facility at ECN Wind Turbine test site in Wieringermeer (EWTW) near the meteorological mast number 6 (MM6).

A ZX Lidars ZX300 with serial number 308 was installed at the TNO RSD Verification Facility (TRVF) at the EWTW test site near MM6 on 11 July 2019. The LiDAR was validated before using it for wind field measurements at Europlatform (EPL) in the 2021 Windconditions@northsea project. This report describes the validation results.

After verifying correct operation of the LiDAR, the measurement campaign was started on 15 July 2019 14:40 UTC and lasted until 8 September 2019 00:00 UTC.

The results of this validation are based on the IEC 61400-12-1:2017 [1] standard.

2 Measurement campaign

2.1 TNO RSD Verification Facility

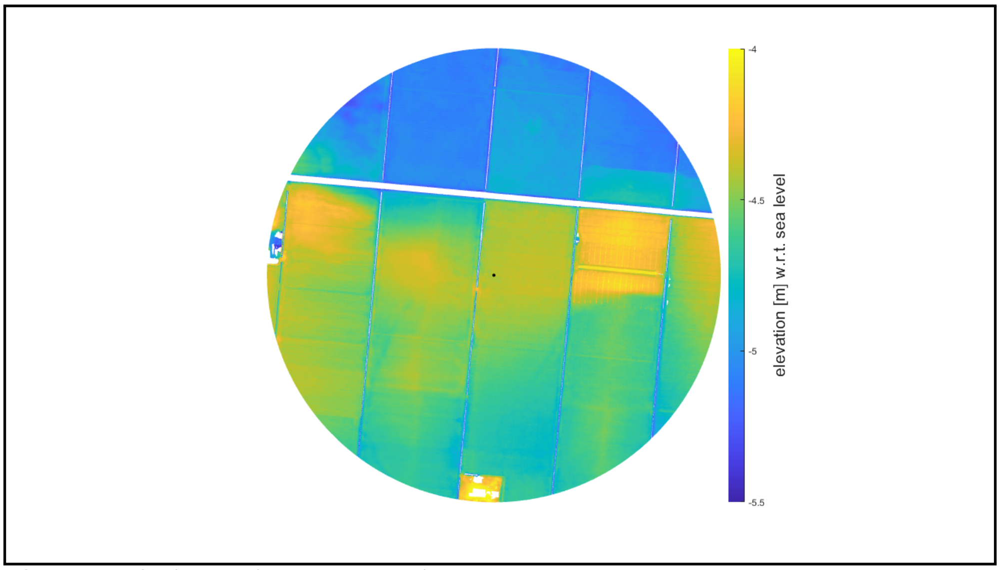
The TNO RSD Verification Facility (TRVF) [2] is located at the ECN Wind Turbine test site Wieringermeer (EWTW). The terrain at the EWTW test site consists mainly of agricultural land, with single farmhouses and rows of trees as shown in fig. 1. It is located in the Wieringermeer, a polder in the north east of the province of North Holland, 3 km North of the village Medemblik. To the East, the site is 1 km removed from the vast IJsselmeer lake. The altitude is 5 m below sea level. The site is considered sufficiently flat according to IEC 61400-12-1:2017 as demonstrated by the laser altimetry in fig. 2.

Source: Google Maps

Figure 1: Detailed overview of the south EWTW locations and corresponding meteo mast locations as well as the nearby obstacles

MM6 is an un-guyed triangular lattice tower with a height of 118.9 m, see fig. 3. At the bottom the width of the tower is 5.86 m. On 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.

A total of 8 booms are mounted on to the mast, as is presented in the layout drawing in fig. 7. Five booms, pointing at 320 ° in relative to North, support three wind vanes and two cup anemometers. Three booms, pointing at 140 ° relative to North, support anemometers. At the lower and mid measuring heights two cups are installed in opposite directions. Within the large measurement sector a single cup measurement would result in large wake effects at specific wind direction. Combined, the influence is minimized. At the lower and mid measuring height the vanes are installed on a separate boom 4 m below the cup measuring height. The measuring heights of the cup anemometers are 41.9 m, 81.4 m, 115.9 m and 120.9 m. The measuring heights of the wind vanes are 37.9 m, 77.4 m and 115.9 m. At 111.9 m, 4 m below the cup anemometer, a sonic anemometer is located. The booms can be retracted for maintenance of the sensors.



Source: PDOK / AHN-3 (0.5 m raster DTM)

Figure 2: Ground level elevation map of the LiDAR's surroundings (radius = 5×120.9 m)

Figure 3: Meteorological Mast 6

In table 1 the coordinates of the meteorological mast and LiDAR locations are summarized. In fig. 4 the location of the verification platform is shown in more detail.

Table 1: Coordinates of the reference mast as well as the LiDAR platform

location	RD	WGS 84
MM6	132 384 m, 536 649 m	52°48.598′N, 5°3.63′E
LiDAR platform	132 343 m, 536 623 m	52°48.589′N, 5°3.41′E

RD Rijksdriehoeksmeting (Dutch geodetic datum)
WGS 84 world geodetic system 1984

Source: Google Maps

Figure 4: Position of the LiDAR at 49 m from the meteorological mast; indicated in green is the meteorological mast and in yellow the verification platform

2.2 Measurement sector

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

The measurement sector consists of two parts:
- 104.0° to 119.4°
- 191.3° to 0.0°

In fig. 5 the lay-out of the EWTW test site is given with the excluded sectors of all the relevant obstacles. This information is used to determine the undisturbed measurement sector.

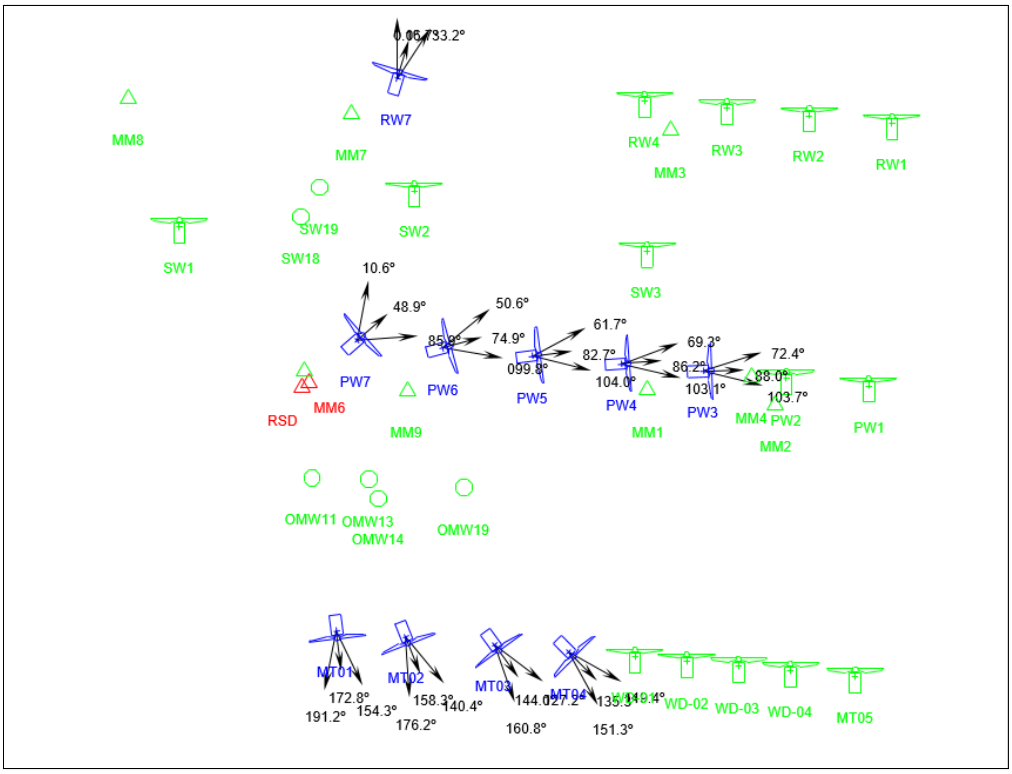


Figure 5: Layout of the EWTW test site used to determine the measurement sector

2.3 Remote Sensing Device

The Remote Sensing Device (RSD) is a ZX Lidars ZX300 LiDAR. This unit has identification number 308 (software version 2.208). It is configured to perform measurements at 10 heights: 23 m, 43 m, 63 m, 82 m, 102 m, 122 m, 142 m, 162 m, 182 m and 202 m. The LiDAR has a cone half-angle of 30 °. Note that the LiDAR measurement heights are 1 m above the reference heights as the lens height was not accounted for in the LiDAR height configuration. The comparison heights are specified in table 2.

Table 2: Measurement heigths for verification

Comparison height	MM6 height	LiDAR height
m	m	m
120.9	120.9	122
81.4	81.4	82
41.9	41.9	43

The ZX300 LiDAR at the TNO RSD Verification Facility is presented in fig. 6.

2.4 Data stream

The Meteorological Mast 6 is connected via a glass fibre network to the measurement office at the EWTW test site. From here, the data are transported on a daily basis to the TNO offices in Petten, where they are stored on a server and imported in a dedicated Wind Data Management System (WDMS) database [3]. The LiDAR data are accumulated in the LiDAR device itself.
Please note that for the analysis we use the Wind10 files the LiDAR produces. (So we use the 10-minute averaging as performed by the LiDAR itself.)

Figure 6: ZX300 308 at the TNO RSD Verification Facility

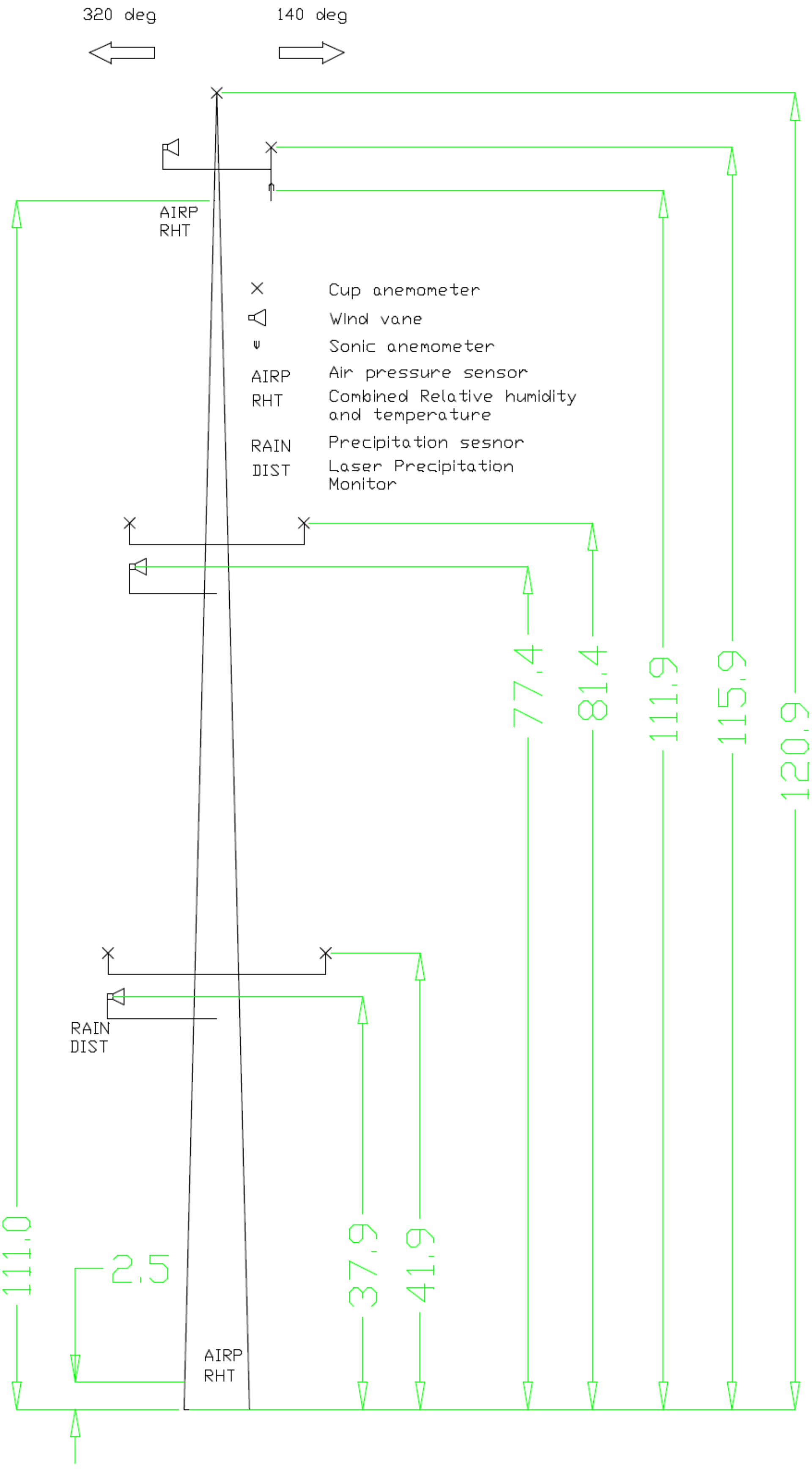


Figure 7: Layout of the meteorological mast MM6

3 Data selection

The LiDAR measurement campaign officially starts on 15 July 2019 14:40 UTC and ends on 8 September 2019 00:00 UTC. Figures 8 and 9 show the time series for the wind speed and wind direction measured by the reference meteorological mast and the LiDAR, prior to filtering. Note that due to a power outage no MM6 data is available from 23 August 2019 until 01 September 2019.

Figure 8: Unfiltered wind speed time series for the comparison heights by the reference meteorological mast at the TNO RSD Verification Facility (top) and the LiDAR (bottom)

3.1 Filter criteria

The data is filtered in accordance with IEC requirements [1, Annex L.2.3, p.204]:

a) *Reference meteorological mast free of wakes*
The measurement sector is defined in paragraph 2.3 and the filtering is applied to the wind direction measurements at each comparison height individually.

b) *LiDAR free of wakes*
The LiDAR is located 49 m from the base of MM6. At 120.9 m MM6 is inside the (circular) measurement volume of the LiDAR. Due to the cone angle of the LiDAR, the radius of this circle increases with measurement height.

The resulting ratio between the wind speeds measured by MM6 and the LiDAR at each comparison height and within the measurement sector, does not show a strong directional dependency, see fig. 18.

c) *Anemometers free of mast wake*
For measurement heights below the top cup, the influence of the MM6 wake on the reference cup anemometers is mitigated by combining measurements of

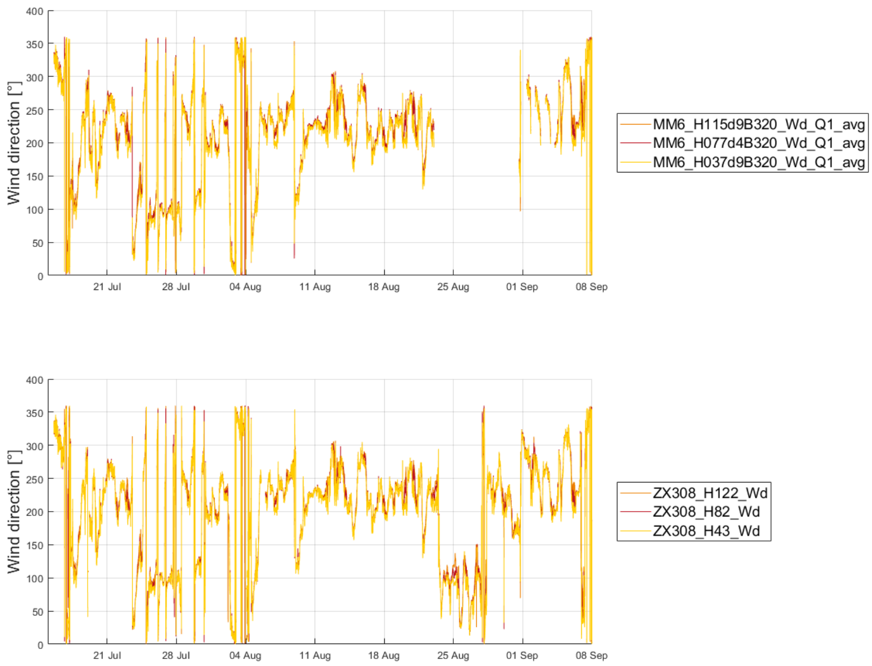


Figure 9: Unfiltered wind direction time series for various heights by the reference meteorological mast at the TNO RSD Verification Facility (top) and the LiDAR (bottom)

two cups on booms at opposite sides of the mast.

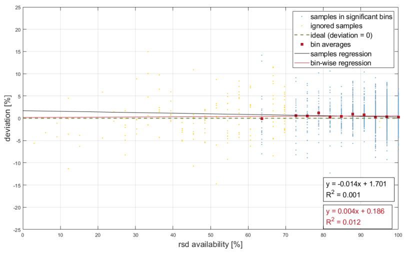
d) *Icing*
The MEASNET [4] icing criterion is applied, which eliminates data if the temperature is below 2 °C while the relative humidity is over 80 %. The impact of this criterion is shown in fig. 11.

e) *Data availability*
No filtering is applied on the data availability to improve the quality of the LiDAR data. The LiDAR gives a status code 9999 when no wind field data is available, during analysis the status code is replaced by NaN. For analysis of the influence of the availability on the quality of the data first a signal named ‘availability’ is defined based on the number of packets logged for each 10-minute averaged sample. In order to quantify the overall availability of the LiDAR in a 10-minute interval (for a certain height), we normalize the number of packets in a 10-minute interval to 100 % using

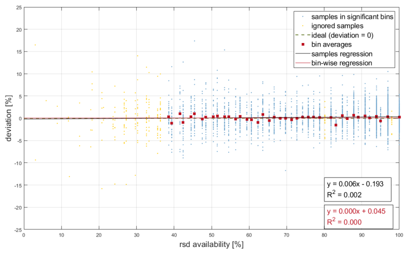
$$\text{availability} = \frac{n_{\text{packets}} \cdot n_{\text{points}}}{\max(n_{\text{packets}}) \cdot \max(n_{\text{points}})} \cdot 100\,\% \tag{3.1}$$

where $\max(n_{\text{packets}})$ is the maximum value for the number of packets metric observed in the entire data set. Figure 10 does not show a clear relation between the LiDAR availability and the deviation.

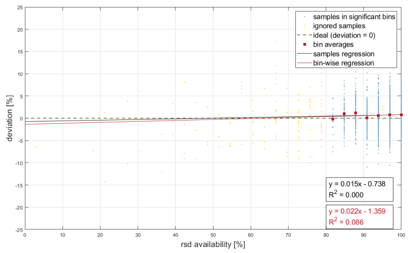
f) *Precipitation*
No filtering on precipitation was undertaken. The IEC 61400-12-1:2017 describes that in general no filtering on precipitation should be applied unless specifically described by the manufacturers guidelines.



(a) 120.9 m



(b) 81.4 m



(c) 41.9 m

Figure 10: Sensitivity plots for the LiDAR availability

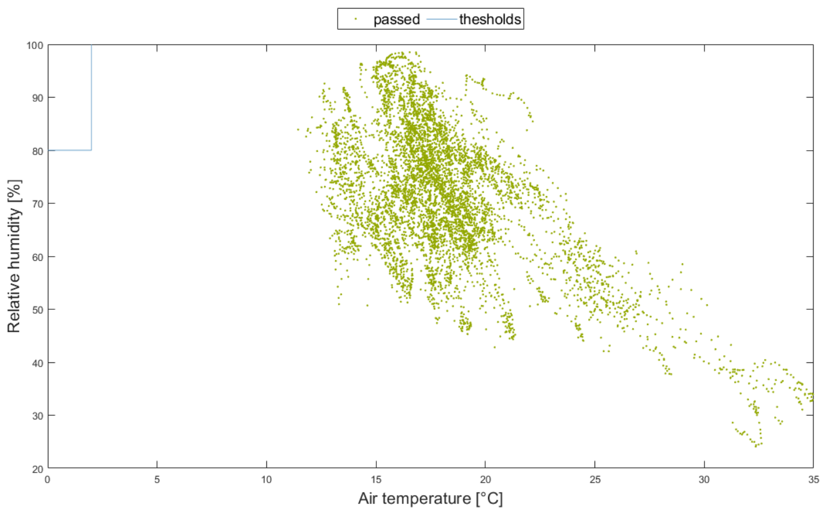


Figure 11: Filter: MEASNET icing criterion

4 LiDAR verification

This chapter reports the results of the LiDAR verification analysis as defined in annex L.3 [1]. The analysis is performed using the in-house software tool *RSDverification* version 1.3.1.

4.1 Direct data comparison

A comparison of the horizontal wind speed between the meteorological mast devices and the LiDAR for each comparison height is presented in figs. 12 to 14. The format is taken from figure L.5 [1]. Only samples for which the reference wind speed is in the range of 4 m/s to 16 m/s are used.

4.2 Bin-wise data comparison

The bin-wise comparison described in Annex L.3 [1] first requires binning of the reference wind speeds measured on the meteorological mast. 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. 20. Due to the smaller bin width, the first and last bin have a significantly lower bin count.

The resulting bin-wise comparisons for each measurement height, are presented in figs. 15 to 17. The results of the regressions are summarised in table 3. The uncertainty intervals shown in these figures are discussed in section 6.2.

Table 3: LiDAR verification IEC 61400-12-1:2017 Annex L results

height	slope	offset	R^2
m	**-**	**m/s**	**-**
120.9	1.010	-0.044	1.000
81.4	1.001	0.018	1.000
41.9	1.004	0.014	1.000

4.3 Systematic uncertainties

The results of the systematic uncertainty analysis, as described in section 6.2, are presented for each comparison height in tables 4 to 6. The tables are modelled after table L.9 [1]. The total LiDAR uncertainty is reported in column 'V_{rsd} uncertainty'.

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.

4.4 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 [1, annex L.7.1, item i]. The conditions at each comparison height are defined in chapter 5 and reported in tables 7 to 9. 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] For the reference wind speed the bin centre is reported, because each environmental condition may have a slightly different bin-wise mean wind speed depending on the availability of environmental data.

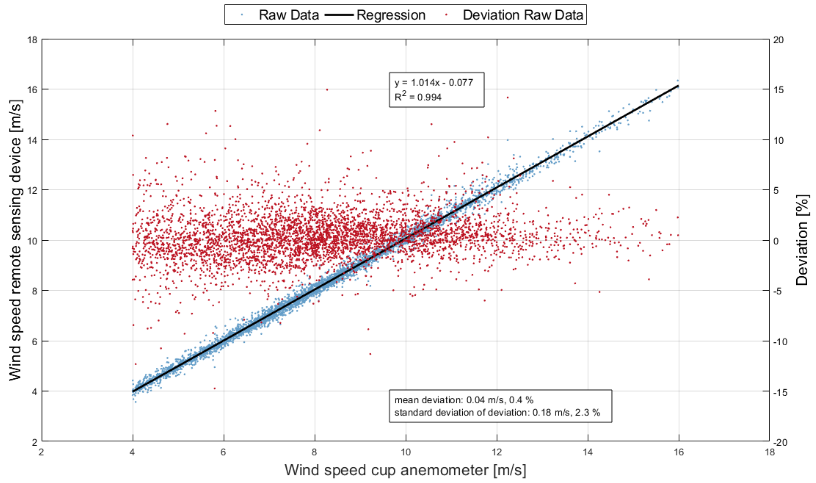


Figure 12: Wind speed comparison @120.9 m

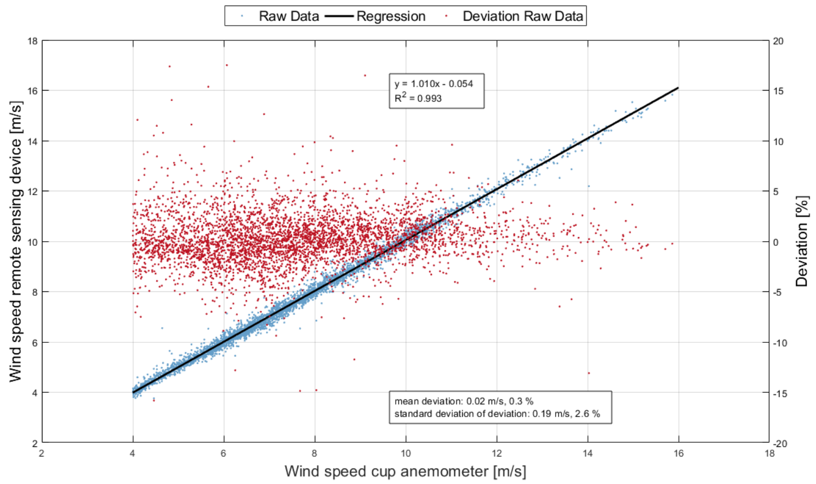


Figure 13: Wind speed comparison @81.4 m

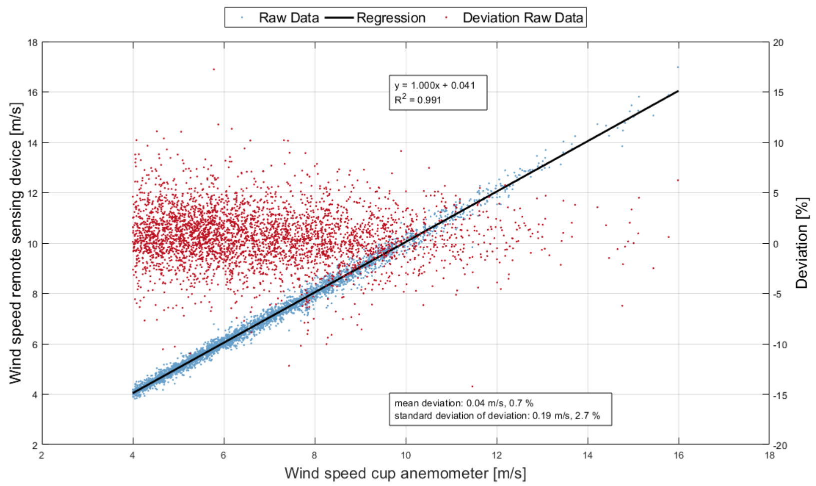


Figure 14: Wind speed comparison @41.9 m

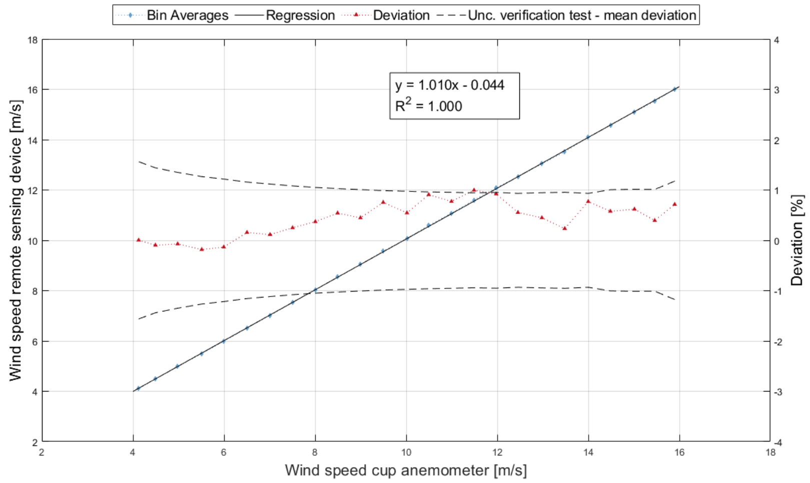


Figure 15: Bin-wise wind speed comparison @120.9 m

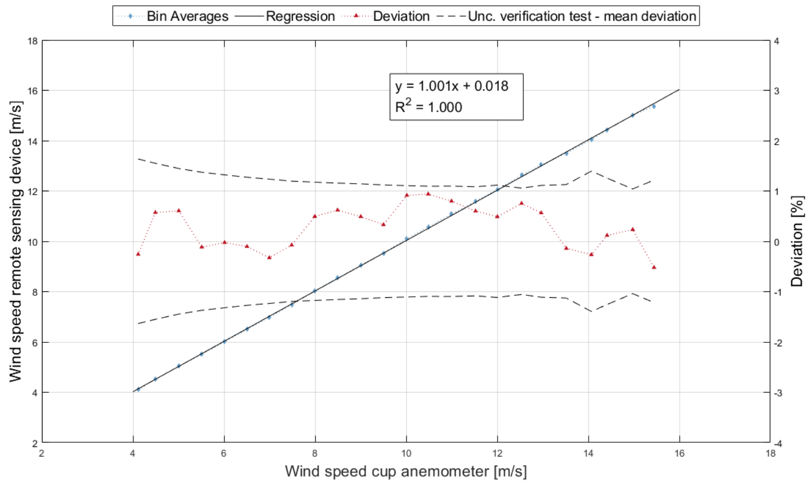


Figure 16: Bin-wise wind speed comparison @81.4 m

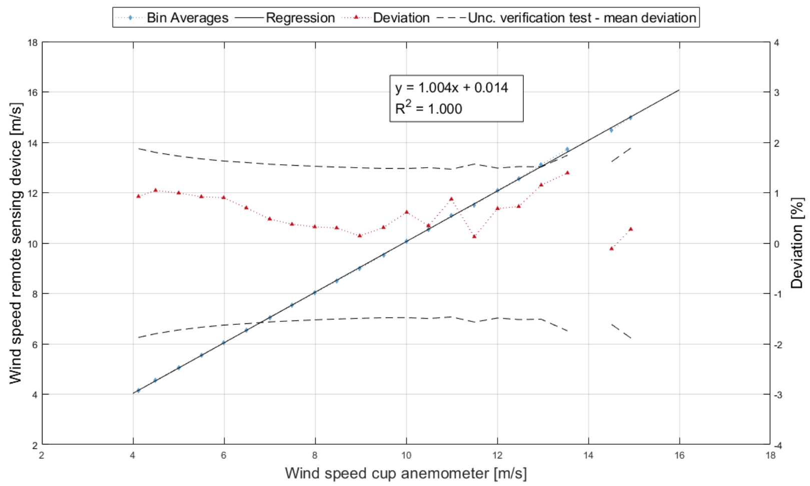


Figure 17: Bin-wise wind speed comparison @41.9 m

Table 4: Uncertainty calculations arising from performance verification of the rsd @120.9 m in terms of systematic uncertainties.

V_{ref}	V_{rsd}	data sets	V_{rsd} max	V_{rsd} min	V_{rsd} std	$V_{\mathrm{rsd}} \frac{\mathrm{std}}{\sqrt{n}}$	mean deviation	V_{ref} uncertainty	mounting unc. rsd	separation unc.	V_{rsd} uncertainty
m/s	m/s	#	m/s	m/s	m/s	m/s	%	%	%	%	%
4.13	4.13	73	4.47	3.57	0.171	0.020	0.004	1.415	0.10	0.39	1.562
4.49	4.49	185	5.00	3.95	0.193	0.014	-0.098	1.331	0.10	0.39	1.443
4.98	4.98	211	5.64	4.56	0.204	0.014	-0.072	1.240	0.10	0.39	1.351
5.51	5.50	240	6.21	4.92	0.195	0.013	-0.183	1.161	0.10	0.39	1.279
5.99	5.99	244	6.84	4.95	0.237	0.015	-0.134	1.102	0.10	0.39	1.224
6.51	6.52	275	7.11	5.94	0.195	0.012	0.156	1.050	0.10	0.39	1.167
7.01	7.02	314	7.68	6.27	0.227	0.013	0.113	1.007	0.10	0.39	1.123
7.51	7.52	355	8.31	6.86	0.219	0.012	0.250	0.970	0.10	0.39	1.110
8.01	8.04	382	9.00	7.47	0.214	0.011	0.369	0.939	0.10	0.39	1.113
8.49	8.54	341	9.51	8.00	0.232	0.013	0.541	0.912	0.10	0.39	1.162
9.00	9.04	294	10.05	8.18	0.236	0.014	0.447	0.888	0.10	0.39	1.102
9.50	9.57	234	10.21	9.09	0.216	0.014	0.754	0.867	0.10	0.39	1.243
10.02	10.07	191	10.64	9.49	0.232	0.017	0.546	0.847	0.10	0.39	1.116
10.50	10.59	217	11.79	9.88	0.272	0.018	0.907	0.831	0.10	0.39	1.322
11.00	11.08	163	12.15	10.43	0.281	0.022	0.773	0.816	0.10	0.39	1.227
11.49	11.61	147	12.58	10.87	0.283	0.023	0.996	0.803	0.10	0.39	1.371
11.98	12.09	98	13.98	11.45	0.331	0.033	0.921	0.791	0.10	0.39	1.324
12.45	12.52	75	13.38	12.01	0.261	0.030	0.552	0.780	0.10	0.39	1.084
12.98	13.04	42	14.01	12.54	0.266	0.041	0.447	0.769	0.10	0.39	1.046
13.48	13.51	38	14.33	13.04	0.300	0.049	0.233	0.760	0.10	0.39	0.982
14.00	14.11	30	14.54	13.67	0.246	0.045	0.769	0.751	0.10	0.39	1.209
14.48	14.57	21	15.12	13.53	0.335	0.073	0.576	0.743	0.10	0.39	1.159
15.01	15.11	12	15.50	14.59	0.276	0.080	0.619	0.736	0.10	0.39	1.187
15.46	15.52	13	15.97	14.75	0.298	0.083	0.394	0.730	0.10	0.39	1.084
15.90	16.01	4	16.34	15.73	0.258	0.129	0.713	0.724	0.10	0.39	1.376

Table 5: Uncertainty calculations arising from performance verification of the rsd @81.4 m in terms of systematic uncertainties.

V_{ref}	V_{rsd}	data sets	V_{rsd} max	V_{rsd} min	V_{rsd} std	$V_{\mathrm{rsd}}\ \frac{\mathrm{std}}{\sqrt{n}}$	mean deviation	V_{ref} uncertainty	mounting unc. rsd	separation unc.	V_{rsd} uncertainty
m/s	m/s	#	m/s	m/s	m/s	m/s	%	%	%	%	%
4.12	4.10	98	4.61	3.77	0.146	0.015	-0.258	1.468	0.10	0.58	1.654
4.49	4.52	228	6.55	3.76	0.232	0.015	0.572	1.378	0.10	0.58	1.652
5.01	5.04	233	5.65	4.65	0.195	0.013	0.605	1.281	0.10	0.58	1.568
5.51	5.50	275	6.53	5.09	0.195	0.012	-0.116	1.203	0.10	0.58	1.376
6.01	6.01	354	7.13	5.42	0.237	0.013	-0.025	1.146	0.10	0.58	1.321
6.51	6.50	373	7.18	5.45	0.218	0.011	-0.104	1.096	0.10	0.58	1.276
7.00	6.97	395	7.76	6.34	0.249	0.013	-0.327	1.052	0.10	0.58	1.277
7.49	7.48	365	8.47	6.54	0.230	0.012	-0.074	1.008	0.10	0.58	1.197
7.99	8.03	339	8.78	6.85	0.247	0.013	0.492	0.982	0.10	0.58	1.274
8.49	8.55	272	9.26	7.97	0.234	0.014	0.619	0.960	0.10	0.58	1.312
9.00	9.05	244	10.61	7.83	0.264	0.017	0.491	0.938	0.10	0.58	1.242
9.50	9.53	194	10.38	8.90	0.242	0.017	0.330	0.912	0.10	0.58	1.167
10.02	10.11	193	10.77	9.28	0.248	0.018	0.914	0.897	0.10	0.58	1.435
10.48	10.58	161	11.27	10.09	0.226	0.018	0.938	0.885	0.10	0.58	1.442
11.00	11.08	101	12.08	10.43	0.280	0.028	0.798	0.868	0.10	0.58	1.357
11.52	11.59	68	12.31	11.14	0.261	0.032	0.601	0.845	0.10	0.58	1.240
12.00	12.06	49	12.70	11.41	0.314	0.045	0.488	0.848	0.10	0.58	1.218
12.53	12.63	39	13.23	12.25	0.228	0.037	0.753	0.803	0.10	0.58	1.297
12.97	13.04	28	13.62	12.24	0.286	0.054	0.564	0.820	0.10	0.58	1.246
13.52	13.50	26	14.05	12.52	0.352	0.069	-0.140	0.789	0.10	0.58	1.136
14.07	14.03	16	14.60	12.19	0.554	0.138	-0.266	0.768	0.10	0.58	1.420
14.41	14.43	9	15.18	13.91	0.335	0.112	0.118	0.767	0.10	0.58	1.261
14.98	15.01	15	15.53	14.73	0.210	0.054	0.232	0.750	0.10	0.58	1.065
15.44	15.36	3	15.59	15.23	0.196	0.113	-0.520	0.747	0.10	0.58	1.323
		1	15.83	15.83							

Table 6: Uncertainty calculations arising from performance verification of the rsd @41.9 m in terms of systematic uncertainties.

V_{ref}	V_{rsd}	data sets	V_{rsd} max	V_{rsd} min	V_{rsd} std	V_{rsd} $\frac{\text{std}}{\sqrt{n}}$	mean deviation	V_{ref} uncertainty	mounting unc. rsd	separation unc.	V_{rsd} uncertainty
m/s	m/s	#	m/s	m/s	m/s	m/s	%	%	%	%	%
4.12	4.16	157	4.52	3.82	0.143	0.011	0.925	1.454	0.10	1.13	2.090
4.50	4.54	384	5.17	3.93	0.191	0.010	1.045	1.367	0.10	1.13	2.080
5.00	5.05	385	5.62	4.42	0.187	0.010	0.993	1.272	0.10	1.13	1.991
5.50	5.55	434	6.16	4.69	0.206	0.010	0.920	1.199	0.10	1.13	1.907
5.99	6.05	365	6.88	5.59	0.203	0.011	0.901	1.140	0.10	1.13	1.861
6.49	6.54	302	7.26	5.82	0.233	0.013	0.696	1.092	0.10	1.13	1.744
7.00	7.04	288	7.60	6.44	0.222	0.013	0.476	1.045	0.10	1.13	1.636
7.49	7.52	246	8.28	6.53	0.244	0.016	0.373	1.010	0.10	1.13	1.588
7.99	8.02	263	8.70	7.13	0.285	0.018	0.322	0.976	0.10	1.13	1.558
8.47	8.50	205	9.16	7.43	0.288	0.020	0.301	0.948	0.10	1.13	1.538
8.98	8.99	178	9.75	8.16	0.293	0.022	0.142	0.923	0.10	1.13	1.501
9.50	9.53	153	10.37	8.70	0.277	0.022	0.308	0.904	0.10	1.13	1.513
10.01	10.07	88	10.80	9.36	0.264	0.028	0.610	0.889	0.10	1.13	1.601
10.49	10.53	58	11.30	9.75	0.340	0.045	0.342	0.861	0.10	1.13	1.536
10.99	11.09	63	11.68	10.45	0.280	0.035	0.872	0.852	0.10	1.13	1.706
11.50	11.51	35	12.27	9.84	0.447	0.076	0.124	0.839	0.10	1.13	1.573
12.01	12.09	29	12.89	11.54	0.315	0.059	0.684	0.809	0.10	1.13	1.638
12.47	12.56	21	12.95	11.83	0.333	0.073	0.726	0.802	0.10	1.13	1.683
12.97	13.12	13	13.70	12.63	0.278	0.077	1.150	0.782	0.10	1.13	1.900
13.54	13.73	7	14.25	13.12	0.379	0.143	1.392	0.774	0.10	1.13	2.230
		1	14.72	14.72							
14.51	14.50	3	14.66	14.26	0.212	0.122	-0.114	0.761	0.10	1.13	1.620
14.93	14.97	9	15.81	13.84	0.577	0.192	0.273	0.755	0.10	1.13	1.904
		1	15.06	15.06							
		2	16.98	15.88							

Table 7: Environmental conditions experienced during verification test for LiDAR measurements @120.9 m.

wind speed	shear exponent	turbulence intensity	precipitation	wind direction	air temperature	relative humidity	air density	flow inclination	wind veer
m/s	-	%	%	°	°C	%	kg/m³	°	°/m
4.125	0.1432	12.74	3.10	258.2	17.55	68.86	1.197	0.202	-0.1221
4.500	0.1666	9.85	0.89	259.5	17.14	70.95	1.200	-0.009	-0.1320
5.000	0.2208	8.81	4.16	244.5	17.28	69.34	1.199	0.249	-0.1625
5.500	0.2250	8.62	4.33	247.1	17.29	70.96	1.198	0.221	-0.1398
6.000	0.2131	8.91	3.50	240.0	17.81	69.18	1.195	0.180	-0.1290
6.500	0.2142	8.72	2.46	244.2	17.49	70.60	1.195	0.164	-0.1134
7.000	0.2353	9.13	5.63	243.9	17.39	72.47	1.194	0.102	-0.1098
7.500	0.2448	8.48	6.95	245.8	17.11	73.17	1.196	0.079	-0.1120
8.000	0.2680	8.18	7.33	238.2	17.14	74.69	1.195	0.066	-0.1148
8.500	0.2562	8.51	7.68	238.4	17.29	75.30	1.193	0.087	-0.0957
9.000	0.2516	8.60	7.52	233.2	17.28	75.06	1.193	0.020	-0.0822
9.500	0.2392	8.92	10.06	236.0	17.15	75.87	1.193	0.150	-0.0718
10.000	0.2477	8.76	7.74	232.9	17.32	74.70	1.193	0.089	-0.0698
10.500	0.2553	8.49	7.17	227.2	17.68	73.87	1.190	0.147	-0.0629
11.000	0.2184	9.74	13.15	234.5	17.52	73.86	1.191	0.098	-0.0433
11.500	0.2374	8.92	11.96	225.5	17.49	75.28	1.189	0.188	-0.0517
12.000	0.2315	9.10	14.79	224.5	17.46	75.07	1.189	0.275	-0.0432
12.500	0.2249	9.40	10.49	240.9	17.22	72.61	1.191	0.115	-0.0398
13.000	0.2011	9.21	8.55	246.4	17.36	68.86	1.193	-0.111	-0.0237
13.500	0.2260	8.99	9.26	244.5	16.38	69.75	1.197	-0.041	-0.0350
14.000	0.1904	9.53	15.80	240.0	16.98	71.03	1.192	0.007	-0.0387
14.500	0.1830	10.34	17.46	248.0	16.09	70.51	1.199	0.053	-0.0303
15.000	0.2032	9.59	13.36	246.2	15.79	67.11	1.202	0.115	-0.0388
15.500	0.1993	9.82	18.57	240.5	16.24	70.73	1.198	-0.013	-0.0395
15.875	0.2123	10.07	4.86	228.0	17.20	72.55	1.191	0.088	-0.0442

Table 8: Environmental conditions experienced during verification test for LiDAR measurements @81.4 m.

wind speed	shear exponent	turbulence intensity	precipitation	wind direction	air temperature	relative humidity	air density	flow inclination	wind veer
m/s	**-**	**%**	**%**	**°**	**°C**	**%**	**kg/m³**	**°**	**°/m**
4.125	0.1933	10.86	3.06	255.1	17.17	70.89	1.200	-0.248	-0.1598
4.500	0.1918	9.50	2.83	249.4	17.05	71.06	1.200	0.151	-0.1490
5.000	0.2350	10.15	3.98	244.7	17.18	69.78	1.198	0.217	-0.1453
5.500	0.2426	9.63	2.21	239.4	17.42	69.51	1.196	0.331	-0.1429
6.000	0.2469	9.78	3.92	236.9	17.57	72.08	1.194	0.188	-0.1300
6.500	0.2623	9.56	6.52	239.9	17.38	73.09	1.195	0.165	-0.1168
7.000	0.2572	9.31	8.55	239.1	17.22	74.27	1.194	0.129	-0.1140
7.500	0.2485	9.90	8.72	234.1	17.30	74.98	1.193	0.124	-0.0922
8.000	0.2311	9.88	6.74	229.9	17.23	74.82	1.194	0.087	-0.0810
8.500	0.2098	10.87	5.81	233.4	17.32	73.15	1.195	0.047	-0.0641
9.000	0.2041	10.66	7.92	236.9	17.59	73.03	1.193	0.073	-0.0609
9.500	0.2231	10.76	8.03	229.6	17.82	72.65	1.190	0.171	-0.0572
10.000	0.1987	11.54	9.77	235.4	17.82	73.99	1.188	-0.056	-0.0369
10.500	0.2075	11.35	11.30	232.4	17.65	74.57	1.189	0.037	-0.0375
11.000	0.1891	11.47	17.07	235.4	17.29	75.15	1.191	0.138	-0.0394
11.500	0.1604	11.79	6.51	238.0	17.01	72.77	1.192	0.038	-0.0363
12.000	0.1654	12.21	12.82	255.9	16.26	69.89	1.198	-0.147	-0.0305
12.500	0.1893	11.30	6.16	233.9	17.36	69.98	1.191	-0.045	-0.0297
13.000	0.1824	11.19	18.25	249.4	16.42	71.14	1.196	-0.041	-0.0374
13.500	0.1637	11.69	15.84	239.6	17.02	67.98	1.195	-0.023	-0.0361
14.000	0.1896	11.88	17.13	233.5	16.79	69.44	1.196	-0.013	-0.0332
14.500	0.1804	11.73	6.46	237.8	16.41	67.54	1.200	0.202	-0.0348
15.000	0.1991	11.27	2.25	228.5	16.95	69.36	1.195	0.160	-0.0405
15.500	0.2085	12.83	30.27	224.8	17.76	76.69	1.185	0.370	-0.0309
15.875									

Table 9: Environmental conditions experienced during verification test for LiDAR measurements @41.9 m.

wind speed	shear exponent	turbulence intensity	precipitation	wind direction	air temperature	relative humidity	air density	flow inclination	wind veer
m/s	**-**	**%**	**%**	**°**	**°C**	**%**	**kg/m³**	**°**	**°/m**
4.125	0.2165	11.51	2.51	231.7	17.20	69.43	1.199	0.180	-0.1683
4.500	0.2251	10.69	2.64	230.7	17.11	70.36	1.198	0.274	-0.1635
5.000	0.2837	11.05	7.65	230.6	17.27	73.83	1.194	0.244	-0.1525
5.500	0.2611	11.67	8.08	229.4	17.36	74.64	1.193	0.292	-0.1168
6.000	0.2447	11.82	5.59	225.8	17.35	73.15	1.194	0.262	-0.1066
6.500	0.2023	12.91	7.08	231.0	17.25	71.42	1.195	0.167	-0.0814
7.000	0.1698	13.21	6.43	236.3	17.49	71.63	1.193	0.037	-0.0496
7.500	0.1695	13.18	6.10	235.8	18.39	69.62	1.190	0.048	-0.0367
8.000	0.1622	13.78	6.65	238.8	17.98	72.60	1.190	-0.100	-0.0340
8.500	0.1601	13.88	10.62	234.7	17.84	72.20	1.191	-0.029	-0.0335
9.000	0.1604	13.93	9.09	238.3	17.45	73.20	1.191	-0.078	-0.0301
9.500	0.1472	14.15	11.32	239.3	17.31	75.11	1.191	-0.159	-0.0312
10.000	0.1521	13.83	10.19	242.0	17.08	73.99	1.192	-0.167	-0.0336
10.500	0.1501	14.28	4.16	241.5	17.17	69.83	1.192	0.100	-0.0297
11.000	0.1406	14.21	7.27	245.3	17.01	68.75	1.194	-0.140	-0.0285
11.500	0.1625	13.96	19.02	249.1	16.63	70.07	1.196	-0.235	-0.0303
12.000	0.1629	14.35	12.67	229.8	17.24	68.78	1.193	-0.008	-0.0362
12.500	0.1736	13.76	10.16	237.5	16.64	67.92	1.198	-0.030	-0.0353
13.000	0.1830	14.40	1.10	225.6	17.04	68.52	1.195	0.248	-0.0330
13.500	0.1765	15.21	12.97	223.2	16.70	67.64	1.197	0.045	-0.0410
14.000									
14.500	0.2107	14.63	0.00	220.5	18.24	71.86	1.183	0.420	-0.0552
15.000	0.1993	15.75	14.01	220.4	18.35	70.92	1.183	0.589	-0.0317
15.500									
15.875									

5 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 [1]. However, for this analysis we use the same dataset as for the verification analysis. As a result the wind speed range is restricted to 4 m/s to 16 m/s.

5.1 Sensitivity analysis

The basis of this analysis is the deviation between the wind speeds measured by the ref, v_{ref}, and the rsd, v_{rsd}. The deviation is defined in eq. (5.1). Subsequently the sensitivity of this deviation is tested against various EVs. The list of variables is based on table L.2 [1]. The variables considered are described below.

$$deviation = \frac{v_{\text{ref}} - v_{\text{rsd}}}{v_{\text{rsd}}} \tag{5.1}$$

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, α, 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
   $$\frac{v_{\text{ref}}}{v_r} = \left(\frac{h}{h_r}\right)^{\alpha} \tag{5.2}$$

2. **Reference turbulence intensity [-]**
   The reference turbulence intensity, measured by meteorological mast, is defined by
   $$\text{reference turbulence intensity} = \frac{\text{std}(v_{\text{ref}})}{\text{mean}(v_{\text{ref}})} \cdot 100\,\% \tag{5.3}$$
   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 40 m.

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

5. **Air temperature [°C]**
   The air temperature is measured at 111 m.

6. **Relative humidity [%RH]**
   The relative humidity is measured at 111 m. (The relative humidity was added to the list of EVs, because it is used 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 111 m, in accordance with equation (12) of IEC 61400-12-1:2017.

8. **Flow inclination [°]**
   The flow inclination is defined as

$$\text{flow inclination} = \text{arctan}\left(\frac{v_{\text{vert}}}{v_{\text{hor}}}\right) \tag{5.4}$$

   The horizontal (v_{hor}) and vertical (v_{vert}) wind speed components are measured by a sonic anemometer at a height of 111.9 m.

9. **Wind veer [°/m]**
   The wind veer is computed as the difference between the wind direction measurements by meteorological mast at 41.9 m and 115.9 m, divided by the height difference. This definition was taken from IEC 61400-12-1:2017.

$$\text{wind veer} = \frac{w_{d,41.9} - w_{d,115.9}}{115.9 - 41.9} \tag{5.5}$$

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

The sensitivity analysis leads to the results presented in table 11, which is presented in the same format as table L.2 [1]. 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. (5.6) [1, eq. L.2]. When the reference wind speed is used as the EV, also the criterion in equation (L.3) needs to be applied.

$$n_i > \frac{N}{2 \cdot n_b} \tag{5.6}$$

The sensitivity, presented in column 'sens.', is defined by

$$\text{sensitivity} = m \cdot \text{std} \tag{5.7}$$

where 'std' is the standard deviation of the EV data.

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 11, the sensitivity criteria that exceed their threshold value are highlighted in red. 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 10 provides an overview of the significant sensitivities, empty in case the sensitivity to the environmental variable is found to be not significant.

5.2 Impact on accuracy

The basis for the accuracy class is the product of m, as already presented in table 11, and the range of the EV. Although out interest is not in determining the accuracy class, we are interested in the effect of the significant sensitivities presented in section 5.1. The EV ranges are largely prescribed by table L.3 [1]. The results are presented in table 12, which is presented in a similar format as table L.6 [1].

Table 10: 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				
rsd availability				

The range is a defined quantity, presented in the column ‘range’ of table 12. The IEC 61400-12-1:2017 standard defines the measured range of variation through the ratio of bins that meet the criterion in eq. (5.6). 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 %.

For the relative humidity no range is prescribed; we used 0 % to 100 %.

The EVs precipitation, air density, reference wind speed and LiDAR availability do not meet the range requirement. For the precipitation this is caused by our choice of the metric: the amount of time precipitation is registered in a 10-minute interval. This causes most samples to fall in either the 0 % or the 100 % bin. For the air density this is caused by the limited variation of air density at the site with respect to the prescribed range. For the reference wind speed at 41.9 m and 81.4 m some of the higher wind speeds bins do not meet the minimum requirement of three data sets per bin.

The last column of table 12 represents the contribution to the preliminary accuracy class for each EV. From this we can draw the conclusion that at 120.9 m the wind shear and turbulence intensity have the highest influence on the accuracy.

Table 11: Sensitivity to environmental variables for the LiDAR

variable	unit	height	avg	std	m	sens.	R^2	sens.$\times R$
		m	unit	unit	%/unit	%		%
shear exponent		42	0.21	0.13	4.403	0.554	0.049	0.123
		81	0.22	0.14	-1.941	-0.263	0.011	-0.027
		121	0.23	0.14	-2.804	-0.383	0.020	-0.054
turbulence intensity	%	42	12.30	2.87	-0.016	-0.047	0.001	-0.001
		81	9.83	3.25	0.211	0.686	0.086	0.201
		121	8.61	3.07	0.170	0.521	0.062	0.130
precipitation	%	42	0.06	0.65			0.000	
		81	0.06	0.64			0.000	
		121	0.06	0.67			0.001	
wind direction	°	42	229.96	39.60	-0.002	-0.090	0.014	-0.011
		81	234.96	39.25	0.008	0.323	0.021	0.046
		121	237.45	39.10	0.005	0.186	0.007	0.016
air temperature	°C	42	17.03	1.84	-0.020	-0.038	0.002	-0.002
		81	17.00	1.86	-0.102	-0.189	0.008	-0.017
		121	16.97	1.87	-0.068	-0.127	0.007	-0.010
relative humidity	%	42	73.20	10.50	0.025	0.260	0.012	0.028
		81	73.68	10.64	0.005	0.055	0.000	0.000
		121	73.80	10.68	0.020	0.213	0.005	0.015
air density	kg/m^3	42	1.19	0.01	-6.674	-0.091	0.000	-0.001
		81	1.19	0.01	6.259	0.085	0.001	0.002
		121	1.20	0.01	0.288	0.004	0.000	0.000
flow inclination	°	42	0.05	0.69	0.356	0.247	0.019	0.034
		81	0.00	0.62	-0.184	-0.115	0.005	-0.008
		121	0.03	0.64	0.112	0.072	0.001	0.002
wind veer	°/m	42	-0.05	0.04	-8.804	-0.388	0.028	-0.064
		81	-0.05	0.05	4.223	0.190	0.003	0.011
		121	-0.05	0.05	5.138	0.234	0.005	0.016
reference wind speed	m/s	42	6.55	1.66	-0.143	-0.238	0.011	-0.025
		81	7.41	1.90	0.095	0.180	0.006	0.014
		121	7.91	2.07	0.123	0.256	0.018	0.035
rsd availability	%	42	95.69	3.46	0.022	0.075	0.000	0.002
		81	83.66	17.44	0.000	0.008	0.002	0.000
		121	95.15	5.16	0.004	0.018	0.001	0.001

Notes for table 11:

- The sensitivity, computed as $m \times$ std, is reported in column ‘sens.’.
- The values for ‘avg’, ‘std’ and R^2 are derived from a regression of the 10-minute data contained in the bins that have a statistically significant bin-count, while m is the slope derived from a regression of the bin-wise mean values [1, p.207-208]. (As a result, no slope - and by extension no sensitivity - can be computed for variables that only yield a single bin with a significant bin-count.)

Table 12: Maximum influence of environmental variables on the LiDAR wind speed

variable	unit	min	max	bin	range	height	covered	$m\times$ range
		unit	unit	unit	unit	m	%	%
shear exponent		-0.4	0.8	0.05	1.2	42	42	5.284
						81	46	-2.330
						121	46	-3.365
turbulence intensity	%	3	24	1	21	42	62	-0.343
						81	62	4.436
						121	57	3.568
precipitation	%	0	100	10	100	42	10	
						81	10	
						121	10	
wind direction	°	0	360	5	180	42	40	-0.407
						81	43	1.481
						121	43	0.855
air temperature	°C	0	40	2	40	42	25	-0.820
						81	25	-4.062
						121	25	-2.708
relative humidity	%	0	100	10	100	42	50	2.475
						81	50	0.515
						121	50	1.993
air density	kg/m^3	0.9	1.35	0.05	0.45	42	22	-3.003
						81	22	2.816
						121	22	0.130
flow inclination	°	-3	3	0.2	6	42	53	2.135
						81	47	-1.107
						121	50	0.674
wind veer	°/m	-0.3	0.1	0.04	0.4	42	50	-3.522
						81	50	1.689
						121	50	2.055
reference wind speed	m/s	0	30	0.5	25	42	22	-3.580
						81	27	2.367
						121	28	3.085
rsd availability	%	0	100	1	20	42	7	0.434
						81	40	0.009
						121	11	0.071

Notes for table 12:

- The columns 'min', 'max' and 'bin' report the minimum and maximum value of the binning interval [1, Table L.3, p.211], and the bin width [1, Table L.1, p.208], used for the regression. The 'range' columns reports the expected natural range of variation for each environmental variable.
- The column 'covered' reports the percentage of the range that was covered by bins that meet the bin-count criteria of equations (L.2) and (L.3) [1, p.208]. If the covered range is less than 25 %, the sensitivity results for this environmental variable are considered unrepresentative. Unrepresentative covered ranges are highlighted in red, otherwise they are green.
- The product of m, the slope of the regression reported in table 11, and the full range of variation, reported in the ultimate column, represents the maximum influence an environmental variable can have on the uncertainty of the horizontal wind speed. Note that this result is highly dependent on the chosen range value, which may be far greater than the variations actually observed during the campaign.

6 Uncertainty

This chapter describes the uncertainty contributions to the horizontal wind speed measurement that were taken into account. These uncertainties are the basis for the LiDAR verification analysis reported in chapter 4. The uncertainty analysis is performed for application in the verification analysis only, therefore the uncertainty analysis 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.

6.1 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 [1].

1. **Wind tunnel calibration**
   The uncertainty associated with wind tunnel calibration is computed by adding in quadrature the reported (maximum) uncertainty in the wind tunnel speed and the uncertainty due to linearisation.

   The calibration certificates of the Thies First Class Advanced cup anemometers (see section B.1) are used to estimate the uncertainty used for the cup anemometers. For the top cup the maximum uncertainty in the wind tunnel speed is 0.053 m/s with a coverage factor of two ($k = 2$). The standard error of the regression is 0.014 m/s. The total standard uncertainty therefore is

   $$u_{\text{VS,precal},i} = \sqrt{\left(\frac{0.053\,\text{m/s}}{2}\right)^2 + (0.014\,\text{m/s})^2} = 0.030\,\text{m/s}.$$

2. **Effects according to anemometer classification**
   The classification of the Thies First Class Advanced cup anemometer is 0.9A (for flat terrain). The uncertainty in the wind speed due to operational characteristics therefore is

   $$u_{\text{VS,class},i} = [0.5\,\% + 0.053\,\text{m/s}] \cdot \frac{0.9}{\sqrt{3}}$$

3. **Mounting effects**
   The default values for the uncertainty associated with the mounting of the anemometer on mast are specified in Annex E.6.3.5 [1]. At the height of 120.9 m a top mounted anemometers is used, for which the default uncertainty is

   $$u_{\text{VS,mnt},i} = 0.5\,\%.$$

   At all other comparison heights, side-mounted anemometers are used. Normally this results in a 1.5 % mounting uncertainty, however for the verification the 'true wind speed' pseudo signals are used which make use of mast flow corrected wind speed signals. For flow corrected wind speed signals the uncertainty is determined by the root-sum-square of half the mean correction applied to the wind speed signal and 0,5% of the measured signal. Wake sectors are excluded. So the minimum uncertainty is 0,5%.

   $$u_{\text{VS,mnt},i} \geq 0.5\,\%.$$

4. **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. $u_f = 0.1\,\% \cdot F + 0.5\,\text{Hz}$. Table 15 shows that the gains of all Thies cup anemometers are close to 0.046 m/s/Hz. This results in an uncertainty of the wind speed of

$$u_{\text{d,VS},i} = 0.1\,\% + 0.023\,\text{m/s}.$$

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 fig. 19.

6.2 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 [1].

1. **Systematic uncertainty of the reference sensor**
   This is the systematic uncertainty of the cup anemometer as defined in section 6.1.

2. **Mean deviation**
   No correction of the LiDAR wind speed measurement is performed. Therefore, this contribution is defined as the bin-wise average deviation between the reference sensor and the LiDAR.

3. **Standard uncertainty of the LiDAR measurements**
   The standard uncertainty is defined by eq. (6.1).

   $$\text{standard uncertainty}_i = \frac{\sigma_{v_i}}{\sqrt{n_i}} \tag{6.1}$$

   Where σ_{v_i} is the standard deviation of 10-minute average measurements in wind speed bin i and n_i is the bincount.

4. **Mounting effects of the LiDAR**
   We are using the default magnitude stated in clause E.7.5 [1, p.110].

   $$u_{\text{VR,mnt},i} = 0.01\,\%$$

   The mounting uncertainty is reported in tables 4 to 6.

5. **Non-homogeneous flow**
   The uncertainty due to non-homogeneous flow in the measurement volume of the LiDAR is estimated from a terrain flow assessment [5] based on the terrain information shown in fig. 2.

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

6. **Separation**
   The uncertainty due to the separation between the LiDAR and meteorological mast is prescribed as

   $$u_{\text{VR,sep},i} = 1\,\% \cdot \frac{d_{\text{sep}}}{h}$$

   where d_{sep} is the separation distance between, equal to 49 m, and h is the measurement height of the (reference) wind speed for that comparison height. The uncertainty due to the separation distance is reported in the penultimate column of tables 4 to 6.

The total LiDAR uncertainty is obtained by adding in quadrature the contributions above. The result is reported in the last column of tables 4 to 6. An overview of the various uncertainty contributions is presented in fig. 19.

The uncertainty interval shown in figs. 15 to 17 is also obtained by adding in quadrature the contributions above, but with the exception of the mean deviation.

7 Deviations

The LiDAR verification as presented in chapter 4 is performed in accordance with IEC 61400-12-1:2017 Annex L. However the Thies cup anemometers used during the verification campaign are classified according the IEC 61400-12-1:2005 standard.

8 Conclusions

The TNO LiDAR ZX300 308 is successfully validated against reference meteorological mast MM6 at the TNO RSD Verification Facility at the EWTW test site in the Wieringermeer. In this campaign the LiDAR is validated at three measurement heights ranging from 41.9 m to 120.9 m. The wind speed range covered during the verification campaign for the measurement height 41.9 m and 81.4 m was incomplete for some of the higher wind speed bins.

During the measurement campaign that ran from 15 July 2019 14:40 UTC until 8 September 2019 00:00 UTC, spanning 54 days, all data coverage requirements of the IEC 61400-12-1:2017 Annex L are met. The LiDAR system wind speed deviates from the reference wind speed between −1 % and 1.5 %.

Two significant sensitivities were identified for the LiDAR system, shear and turbulence intensity. For the precipitation, air density, reference wind speed and LiDAR availability sensitivity analysis the range covered was insufficient.

9 Bibliography

[1] IEC 61400-12-1:2017-03. *Wind energy generation systems – Part 12-1: Power performance measurements of electricity producing wind turbines*. Mar. 2017.

[2] G. Bergman and J. P. Verhoef. *TNO Ground Based RSD Verification Facility*. TNO 2020 R10781. TNO, July 2020.

[3] I. A. Alting. *WDMS4 Developer reference*. ECN-Wind Memo-11-023. ECN, Oct. 2011.

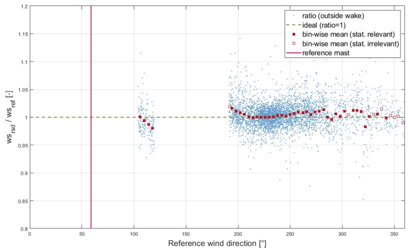
[4] *Power performance measurement procedure - Version 5*. MEASNET, Dec. 2009.

[5] D. A. J. Wouters. *Non-homogeneous flow within a lidar measurement volume at EWTW*. TNO 2019 M10109. ECN part of TNO, Jan. 2019.

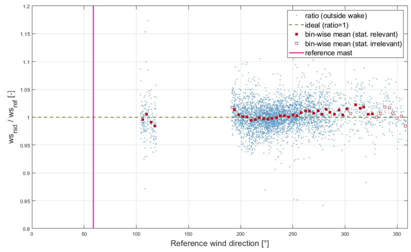
[6] G. Bergman. *Meteorological Mast 6 (lowered), Instrumentation Report*. TNO 2018 R11336. ECN part of TNO, Nov. 2018.

A IEC visualisations

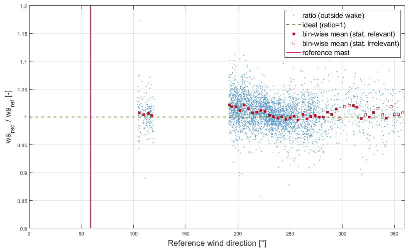
This appendix contains visualizations associated with the IEC analysis reported in chapters 4 and 5 that are not a reporting requirement.



(a) 120.9 m

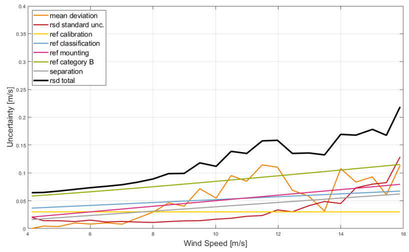


(b) 81.4 m

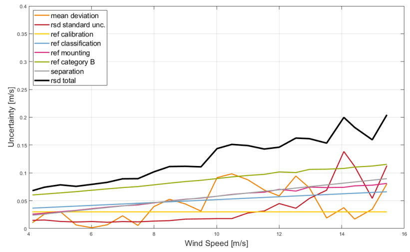


(c) 41.9 m

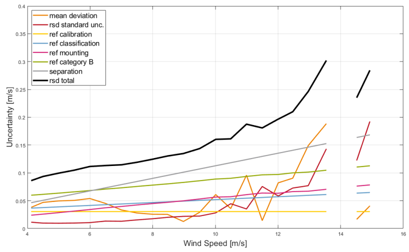
Figure 18: Influence of the wake of meteorological mast on the LiDAR. The ratio of the wind speed measured by the LiDAR (rsd) and the reference meteorological mast 6 (ref) is plotted against the wind direction measured by the reference meteorological mast. The magenta line marks the direction for which the wind flows over the reference meteorological mast 6 towards the LiDAR. The red squares are the bin-wise average wind speed ratios; these are solid only if the respective bin contains a statistically significant number of data points.



(a) 120.9 m

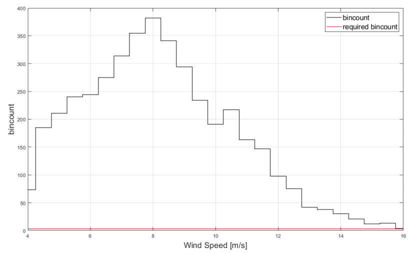


(b) 81.4 m

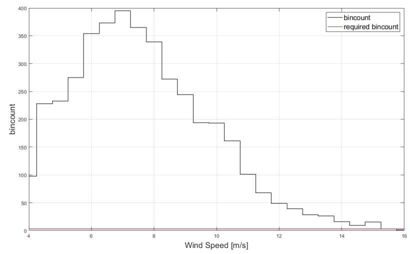


(c) 41.9 m

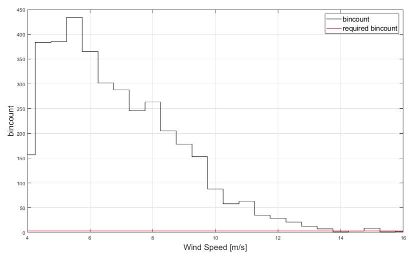
Figure 19: Contributions to the LiDAR uncertainty



(a) 120.9 m



(b) 81.4 m



(c) 41.9 m

Figure 20: Histograms for bin-wise wind speed comparison

B Instrumentation details

This appendix presents detailed information about the meteorological mast signals and sensors used. More detailed information about meteorological mast MM6 can be found in the meteorological mast instrumentation report [6].

At the meteorological mast measurement heights, as seen in fig. 7, the meteorological mast measurements are compared to the LiDAR measurements. Table 13 lists these comparison heights and the wind speed and wind direction signals used from both the meteorological mast and the LiDAR. All of these signals are 10-minute average statistics.

Some of the statistics are directly derived from measured signals, presented in table 14. Other statistics are based on pseudo signals, presented in table 16, which are calculated signals.

The sensors used to measure these signals and the data acquisition modules they are attached to are listed in table 15. This table also presents installation and calibration due dates.

Table 13: Signals used for each comparison height

height	metmast	LiDAR
m		
	wind speed	
120.9	MM6_H120d9_Ws_Q1_avg	Horizontal Wind Speed (m/s) at 121m
81.4	MM6_H081d4_Ws_True_Q1_avg	Horizontal Wind Speed (m/s) at 81m
41.9	MM6_H041d9_Ws_True_Q1_avg	Horizontal Wind Speed (m/s) at 41m
	wind direction	
120.9	MM6_H115d9B320_Wd_Q1_avg	Wind Direction (deg) at 116m
81.4	MM6_H077d4B320_Wd_Q1_avg	Wind Direction (deg) at 77m
41.9	MM6_H037d9B320_Wd_Q1_avg	Wind Direction (deg) at 38m

Table 14: List of measured signals

name	location	short name	sensor	unit	installed	rate	ISO
						Hz	
wind speed, 120.9 m, centre	MM6	MM6_H120d9_Ws_Q1_m	Thies First Class Advanced 4.3352.00.000	m/s	TNO	4	*
wind speed, 81.4 m, 140°	MM6	MM6_H081d4B140_Ws_Q1_m	Thies First Class Advanced 4.3352.00.000	m/s	TNO	4	*
wind speed, 81.4 m, 320°	MM6	MM6_H081d4B320_Ws_Q1_m	Thies First Class Advanced 4.3352.00.000	m/s	TNO	4	*
wind speed, 41.9 m, 140°	MM6	MM6_H041d9B140_Ws_Q1_m	Thies First Class Advanced 4.3352.00.000	m/s	TNO	4	*
wind speed, 41.9 m, 320°	MM6	MM6_H041d9B320_Ws_Q1_m	Thies First Class Advanced 4.3352.00.000	m/s	TNO	4	*
wind direction, 115.9 m, 320°	MM6	MM6_H115d9B320_Wd_Q1_m	Thies First Class 4.3150.00.400	°	TNO	4	*
wind direction, 77.4 m, 320°	MM6	MM6_H077d4B320_Wd_Q1_m	Thies First Class 4.3150.00.400	°	TNO	4	*
wind direction, 37.9 m, 320°	MM6	MM6_H037d9B320_Wd_Q1_m	Thies First Class 4.3150.00.400	°	TNO	4	*
air temperature, 111 m	MM6	MM6_H111_Temp_Q1_m	Vaisala RHT probe HMP155D	°C	TNO	4	*
relative humidity, 111 m	MM6	MM6_H111_RH_Q1_m	Vaisala RHT probe HMP155D	%	TNO	4	*
air pressure, 111 m	MM6	MM6_H111_Pair_Q1_m	Vaisala digital barometer PTB210	hPa	TNO	4	*
precipitation, 40 m	MM6	MM6_H040_Prec_Q1_m	Thies precipitation sensor 5.4103.10.000	%	TNO	4	*
precipitation, distro, 36 m	MM6	MM6_H036_Prec_Disdro_Q1_m	Thies LPM 5.4110.00.300	%	TNO	4	*
wind speed, sonic u, 111.9 m, 140°	MM6	MM6_H111d9B140_S_U_Q5_m		m/s	TNO	4	*
wind speed, sonic v, 111.9 m, 140°	MM6	MM6_H111d9B140_S_V_Q5_m	Metek 3D ultrasonic anemometer	m/s	TNO	4	*
wind speed, sonic w, 111.9 m, 140°	MM6	MM6_H111d9B140_S_W_Q5_m		m/s	TNO	4	*

Table 15: List of equipment used per signal

Signal	Sensor						Modue				
short name	brand / type	ID	gain	offset[a]	cal. due date[b]	inst. date	type	ID	gain	offset	cal. due date
MM6_H121_Ws_Q1_m	Thies 4.3352.00.000	6109	4.598e-2	2.528e-1	2019-08-21	2018-08-21	NI 9423 digital input	2000	1.000e+0	0.000e+0	2021-12-11
MM6_H081d4B140_Ws_Q1_m	Thies 4.3352.00.000	2185	4.591e-2	2.190e-1	2019-09-05	2018-09-05	NI 9423 digital input	2000	1.000e+0	0.000e+0	2021-12-11
MM6_H081d4B320_Ws_Q1_m	Thies 4.3352.00.000	2180	4.582e-2	2.324e-1	2019-09-05	2018-09-05	NI 9423 digital input	2000	1.000e+0	0.000e+0	2021-12-11
MM6_H041d9B140_Ws_Q1_m	Thies 4.3352.00.000	2182	4.586e-2	2.224e-1	2019-09-05	2018-09-05	NI 9423 digital input	2000	1.000e+0	0.000e+0	2021-12-11
MM6_H041d9B320_Ws_Q1_m	Thies 4.3352.00.000	2179	4.591e-2	2.203e-1	2019-09-05	2018-09-05	NI 9423 digital input	2000	1.000e+0	0.000e+0	2021-12-11
MM6_H115d9B320_Wd_Q1_m	Thies 4.3150.00.400	6071	1.000e-1	-1.070e+2	2019-08-21	2018-08-21	NI 9871 RS485	2398	1.000e+0	0.000e+0	2022-12-11
MM6_H077d4B320_Wd_Q1_m	Thies 4.3150.00.400	5212	1.000e-1	-2.630e+1	2019-09-05	2018-09-05	NI 9871 RS485	2398	1.000e+0	0.000e+0	2022-12-11
MM6_H037d9d9B320_Wd_Q1_m	Thies 4.3150.00.400	6091	1.000e-1	-5.305e+1	2019-09-05	2018-09-05	NI 9871 RS485	2398	1.000e+0	0.000e+0	2022-12-11
MM6_H111_Temp_Q1_m MM6_H111_RH_Q1_m	Vaisala RHT HMP155	2455	1.000e-1	0.000e+0	2019-08-21	2018-08-21	NI 9871 RS485	2340	1.000e+0	0.000e+0	2021-12-11
MM6_H111_Pair_Q1_m	Vaisala digital barometer PTB210	5140	1.000e-2	0.000e+0	2019-08-21	2018-08-21	NI 9871 RS485	2398	1.000e+0	0.000e+0	2022-12-11
MM6_H040_Prec_Q1_m	Thies precipitation sensor 5.4103.10.000	5139	1.000e+0	0.000e+0	2023-08-21	2018-08-21	NI 9423 digital input	2000	1.000e+0	0.000e+0	2021-12-11
MM6_H111d9B140_WsUS_Q1_m MM6_H111d9B140_WsVS_Q1_m MM6_H111d9B140_WsWS_Q1_m	Metek 3D ultrasonic	6084	1.000e-2	0.000e+0	2021-04-27	2018-08-21	NI 9871 RS485	2340	1.000e+0	0.000e+0	2021-12-11

a]For wind vanes the offset is governed by the North alignment of the vane w.r.t. its mounting orientation. Hence it does not reflect the offset reported on the calibration certificate.
b]For cup anemometers and wind vanes the (annual) calibration due date is based on the installation date (not the wind tunnel calibration date).
c]The measurement period of the sensors exceeded the 12 month limit however the re-calibration or re-verification afterwards was successful for all sensors.

Table 16: List of calculated (pseudo) signals

name	short name	unit	rate	ISO	constituents/derivation	
			Hz			
wind speed, 81.4 m	MM6_H081d4_Ws_True_Q1	m/s	4	*	MM6_H077d4B320_Wd_Q1 MM6_H081d4B140_Ws_Q1_m MM6_H081d4B320_Ws_Q1_m	B.1
wind speed, 41.9 m	MM6_H041d9_Ws_True_Q1	m/s	4	*	MM6_H037d9_Wd_Q1 MM6_H041d9B140_Ws_Q1_m MM6_H041d9B320_Ws_Q1_m	B.2
horizontal wind speed, sonic, 111.9 m	MM6_H111d9B140_WsHor_Q1	m/s	4	*	MM6_H111d9B140_WsUSon_Q1_m MM6_H111d9B140_WsVSon_Q1_m	B.3

$$f(\#1, \#2, \#3) = \begin{cases} \#2, & \text{if } 50.45^\circ < \#1 \leq 230.45^\circ \\ \#3, & \text{otherwise} \end{cases} \tag{B.1}$$

$$f(\#1, \#2, \#3) = \begin{cases} \#2, & \text{if } 49.84^\circ \leq \#1 < 229.84^\circ \\ \#3, & \text{otherwise} \end{cases} \tag{B.2}$$

$$f(\#1, \#2) = \sqrt{\#1^2 + \#2^2} \tag{B.3}$$

B.1 Calibration sheets

B.1.1 Cup anemometer

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

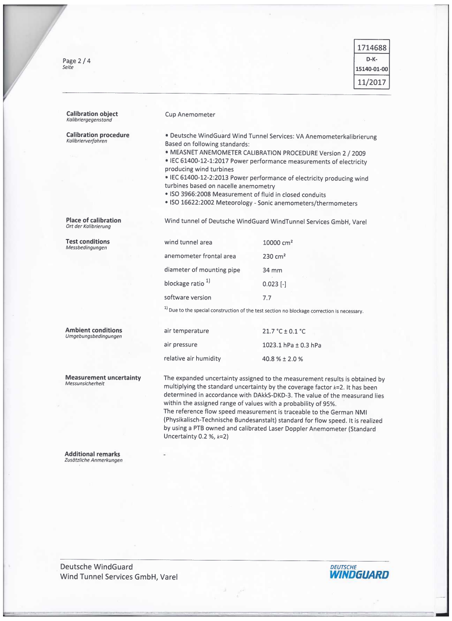
Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.00.000
Serial number *Fabrikat/Serien-Nr.*	04126802
Customer *Auftraggeber*	ECN Wind Energy
Order No. *Auftragsnummer*	ECN4186952/15.09.2017
Project No. *Projektnummer*	VT170913
Number of pages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

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*
15.11.2017	Dipl. Phys. Dieter Westermann	Hendrik Jansen, B. Eng.

(a) Cup anemometer 6109, page 1/4



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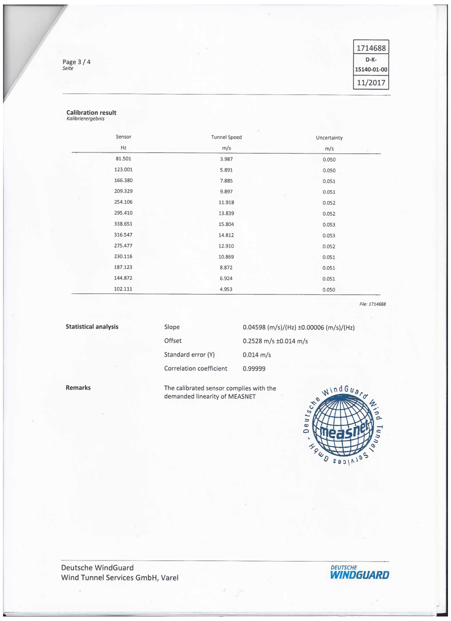
1714688 | D-K-15140-01-00 | 11/2017

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*	-	

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

(b) Cup anemometer 6109, page 2/4



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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

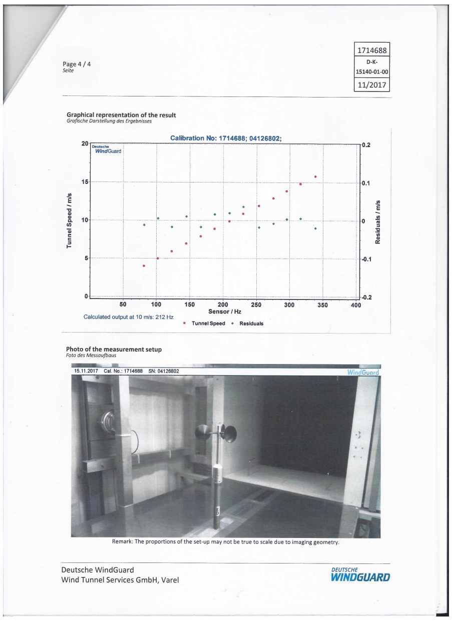
Statistical analysis	Slope	0.04598 (m/s)/(Hz) ±0.00006 (m/s)/(Hz)
	Offset	0.2528 m/s ±0.014 m/s
	Standard error (Y)	0.014 m/s
	Correlation coefficient	0.99999
Remarks	The calibrated sensor complies with the demanded linearity of MEASNET	

Deutsche WindGuard Wind Tunnel Services GmbH measnet

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

(c) Cup anemometer 6109, page 3/4



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

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.

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

(d) Cup anemometer 6109, page 4/4

DEWS 2185

DEUTSCHE WINDGUARD

Deutsche WindGuard
Wind Tunnel Services GmbH

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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

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).
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.

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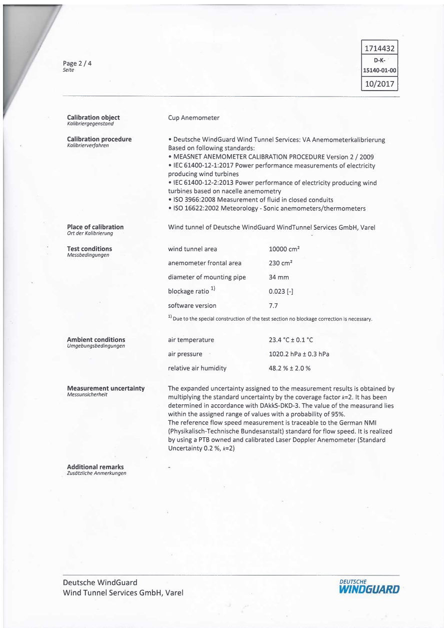
Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
27.10.2017	Dipl. Phys. Dieter Westermann	Hendrik Jansen, B. Eng.

(e) Cup anemometer 2185, page 1/4



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

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*: -

Deutsche WindGuard
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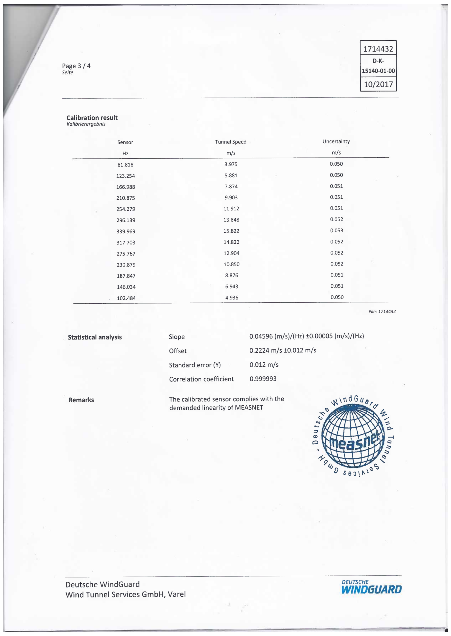
(f) Cup anemometer 2185, page 2/4



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

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

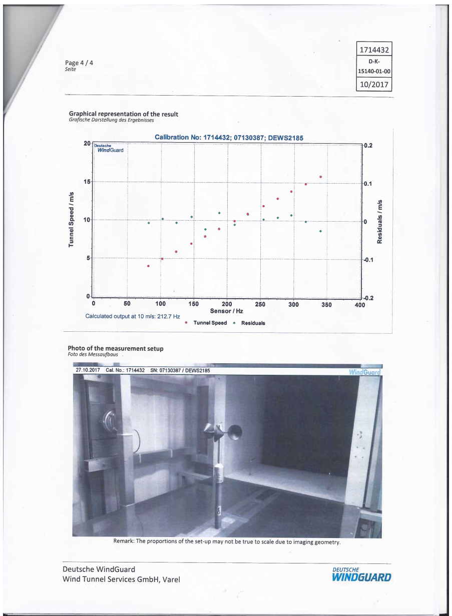
Slope	0.04596 (m/s)/(Hz) ±0.00005 (m/s)/(Hz)
Offset	0.2224 m/s ±0.012 m/s
Standard error (Y)	0.012 m/s
Correlation coefficient	0.999993

Remarks: The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard Wind Tunnel Services GmbH measnet

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

(g) Cup anemometer 2185, page 3/4



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

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.

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

(h) Cup anemometer 2185, page 4/4

DEWS 2180

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

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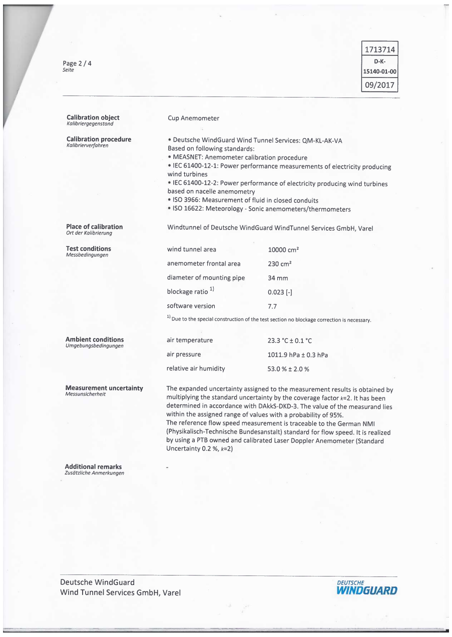
Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
07.09.2017	Dipl. Phys. Dieter Westermann	Techniker Dirk Henninges

(i) Cup anemometer 2180, page 1/4



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

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
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*	-	

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

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel
DEUTSCHE WINDGUARD

(j) Cup anemometer 2180, page 2/4

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

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

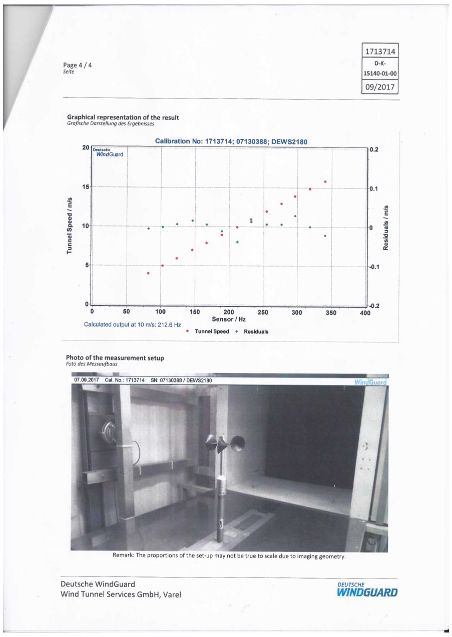
File: 1713714

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

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel
DEUTSCHE WINDGUARD

(k) Cup anemometer 2180, page 3/4



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

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.

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel
DEUTSCHE WINDGUARD

(l) Cup anemometer 2180, page 4/4

DEWS 2182

DEUTSCHE WINDGUARD

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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

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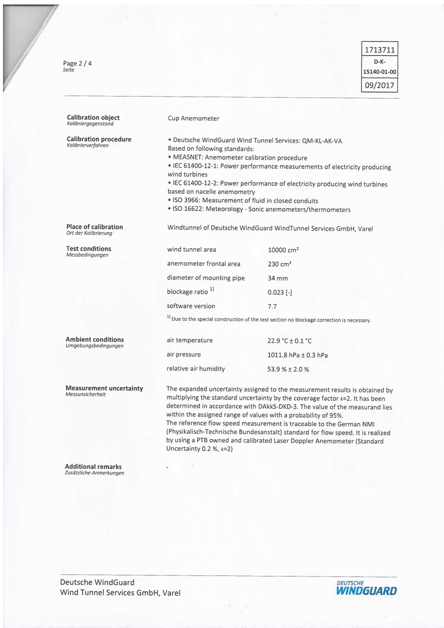
Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
07.09.2017	Dipl. Phys. Dieter Westermann	Techniker Dirk Henninges

(m) Cup anemometer 2182, page 1/4



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

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 %

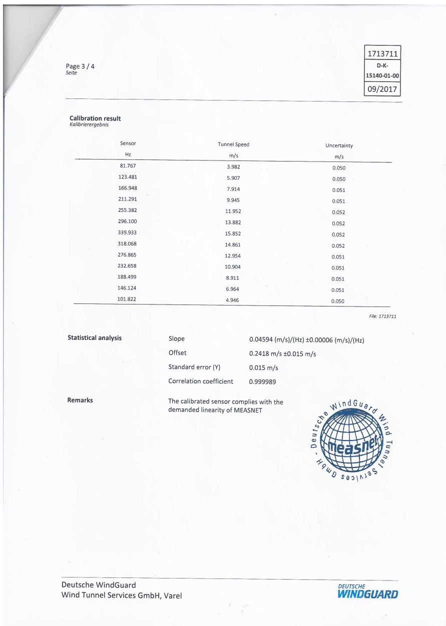
Measurement uncertainty *Messunsicherheit*: The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k=2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of 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*: -

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

(n) Cup anemometer 2182, page 2/4



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

Calibration result
Kalibrierergebnis

Sensor Hz	Tunnel Speed m/s	Uncertainty 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

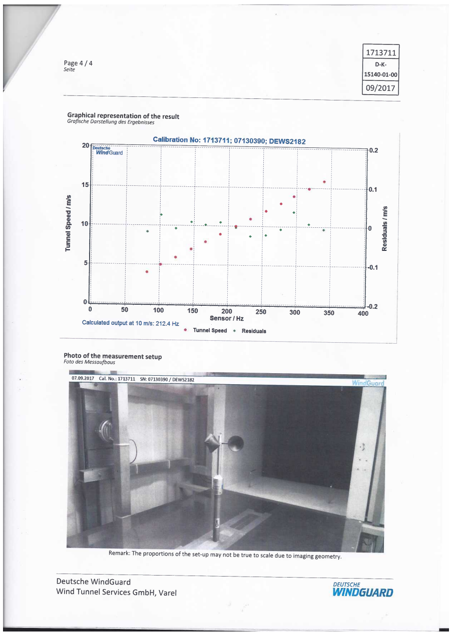
Remarks: The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard Wind Tunnel Services GmbH measnet

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

(o) Cup anemometer 2182, page 3/4



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

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.

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

(p) Cup anemometer 2182, page 4/4

DEWS 2179

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*: 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).
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.

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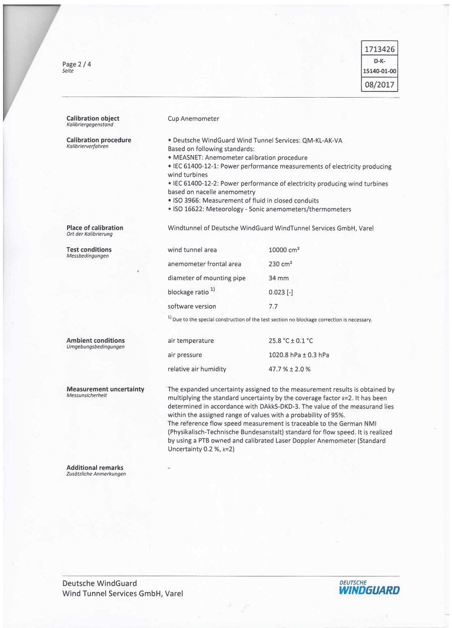
Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
22.08.2017	Dipl. Phys. Dieter Westermann	Hendrik Jansen, B. Eng.

(q) Cup anemometer 2179, page 1/4



Page 2 / 4 *Seite*

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

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* -

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

(r) Cup anemometer 2179, page 2/4

Page 3 / 4 *Seite*

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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

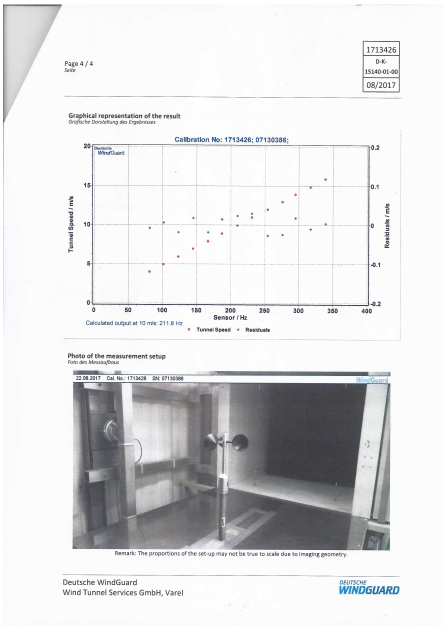
Slope	0.04614 (m/s)/(Hz) ±0.00007 (m/s)/(Hz)
Offset	0.2264 m/s ±0.016 m/s
Standard error (Y)	0.016 m/s
Correlation coefficient	0.999987

Remarks The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard Wind Tunnel Services GmbH measnet

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

(s) Cup anemometer 2179, page 3/4



Page 4 / 4 *Seite*

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

Graphical representation of the result *Grafische Darstellung des Ergebnisses*

Photo of the measurement setup *Foto des Messaufbaus*

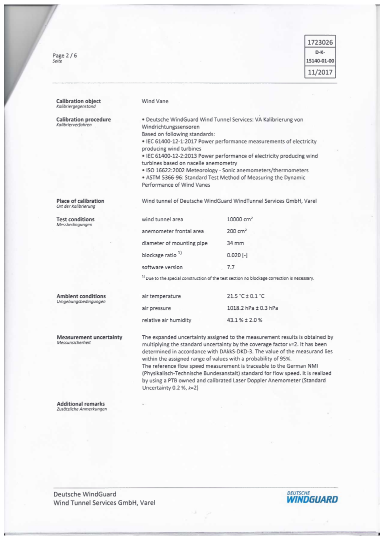
Remark: The proportions of the set-up may not be true to scale due to imaging geometry.

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

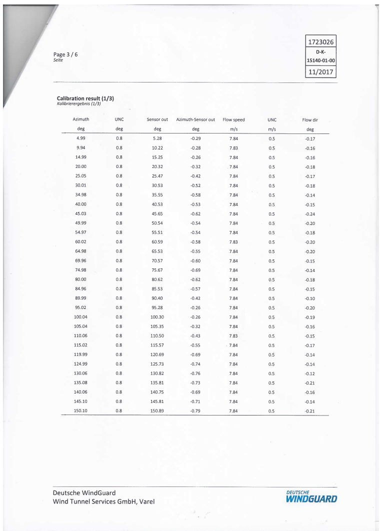
(t) Cup anemometer 2179, page 4/4

B.1.2 Wind vane

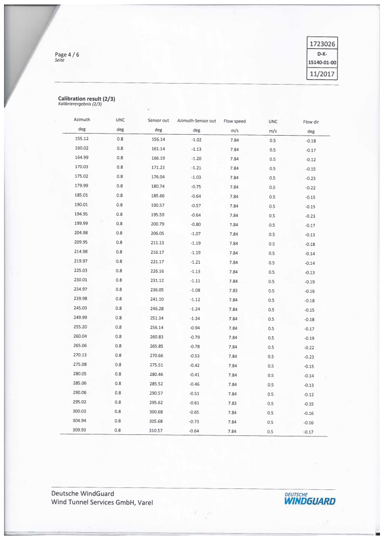
(a) Wind vane 6071, page 1/6



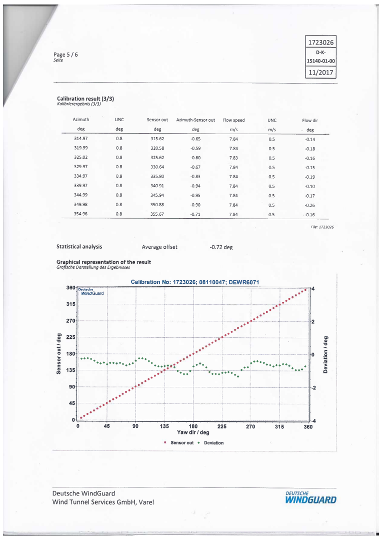
(b) Wind vane 6071, page 2/6



(c) Wind vane 6071, page 3/6



(d) Wind vane 6071, page 4/6



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Seite

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

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

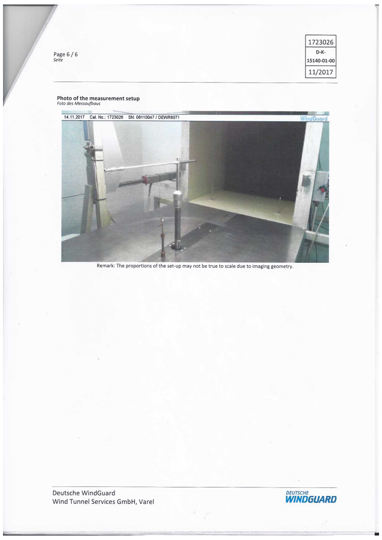
File: 1723026

Statistical analysis Average offset -0.72 deg

Graphical representation of the result
Grafische Darstellung des Ergebnisses

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

(e) Wind vane 6071, page 5/6



Page 6 / 6
Seite

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

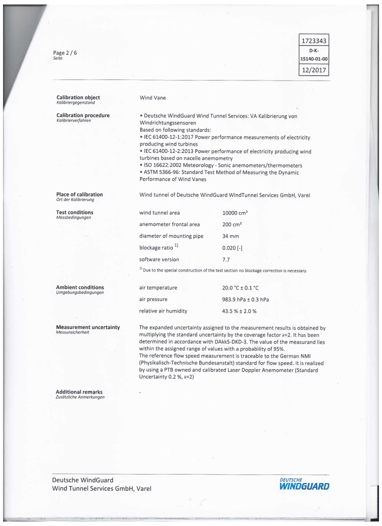
Photo of the measurement setup
Foto des Messaufbaus

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

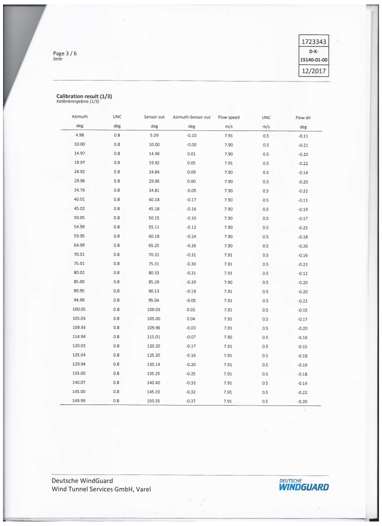
Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

(f) Wind vane 6071, page 6/6

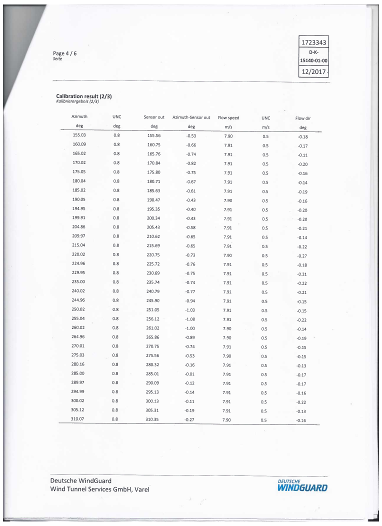
(g) Wind vane 5212, page 1/6



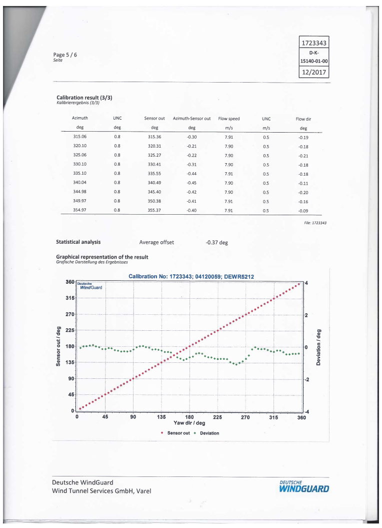
(h) Wind vane 5212, page 2/6



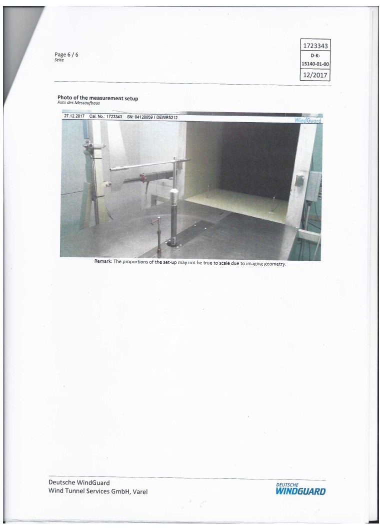
(i) Wind vane 5212, page 3/6



(j) Wind vane 5212, page 4/6

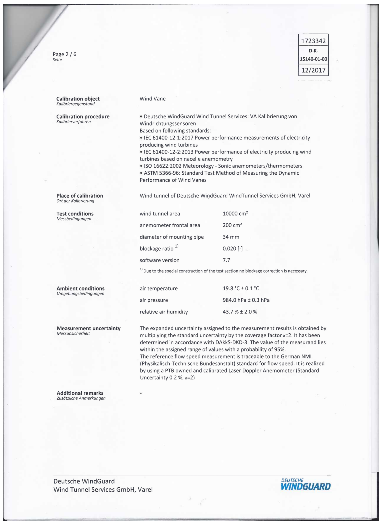


(k) Wind vane 5212, page 5/6

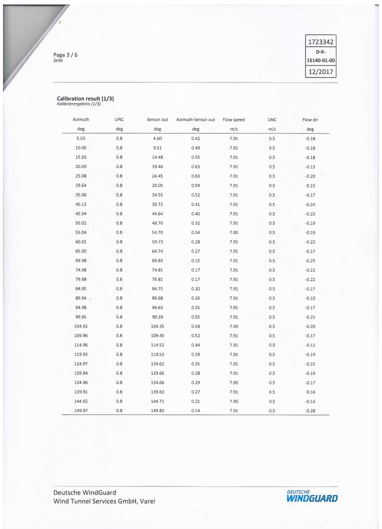


(l) Wind vane 5212, page 6/6

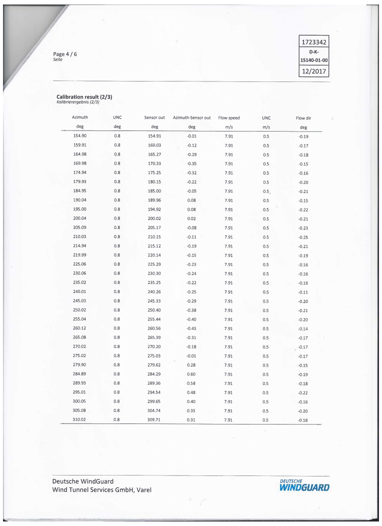
(m) Wind vane 6091, page 1/6



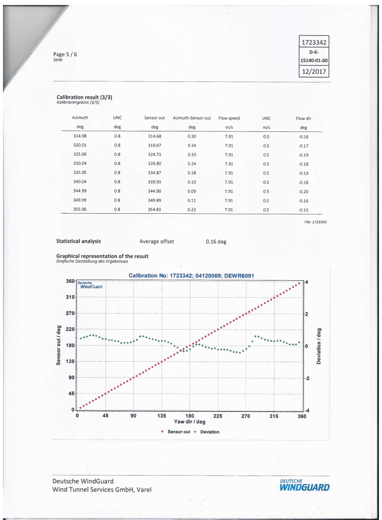
(n) Wind vane 6091, page 2/6



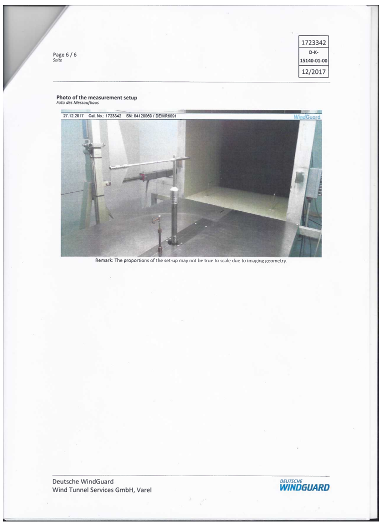
(o) Wind vane 6091, page 3/6



(p) Wind vane 6091, page 4/6



(q) Wind vane 6091, page 5/6



(r) Wind vane 6091, page 6/6

B.1.3 Relative humidity and temperature


DERH 2455

caliz calibration

CALIBRATION RvA K 152

Certificaat 18-13000-2-1
blad 1 van 2

Aanvrager: TNO - Locatie ECN Petten
Westerduinweg 3
1755 LE PETTEN

Aangeboden: Thermohygrotransmitter
aantal: 1
De identificatiegegevens zijn gegeven bij resultaat.

Wijze van onderzoek: De hygrometer is gekalibreerd in een geklimatiseerde ruimte door vergelijking van de geïndiceerde waarde met de werkelijke luchtvochtigheid, gemeten met een standaard thermometer en een standaard dauwpuntsmeter.
De thermometer is gekalibreerd door vergelijking van de geïndiceerde waarde met de werkelijke temperatuur, gemeten met een standaard thermometer.
De gegeven resultaten zijn met behulp van een statistische rekenmethode afgeleid uit de werkelijk gemeten waarden.
De omgevingstemperatuur staat vermeld op de vervolgbladen.

Datum van onderzoek: 4 juli 2018

Resultaat: De meetresultaten zijn gegeven op het volgblad.
De gerapporteerde onzekerheid is gebaseerd op een standaardonzekerheid, vermenigvuldigd met een dekkingsfactor k = 2, welke overeenkomt met een dekkingswaarschijnlijkheid van ongeveer 95 %.
De standaardonzekerheid is bepaald volgens EA-4/02M.

Herleidbaarheid: De metingen zijn uitgevoerd met standaarden waarvan de herleidbaarheid naar (inter)nationale standaarden, ten overstaan van de Raad voor Accreditatie, is aangetoond.

Berlicum, 5 juli 2018

V.J.M. Bomers
Kalibratiemedewerker

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E-mail: info@caliz.nl
Website: www.caliz.nl

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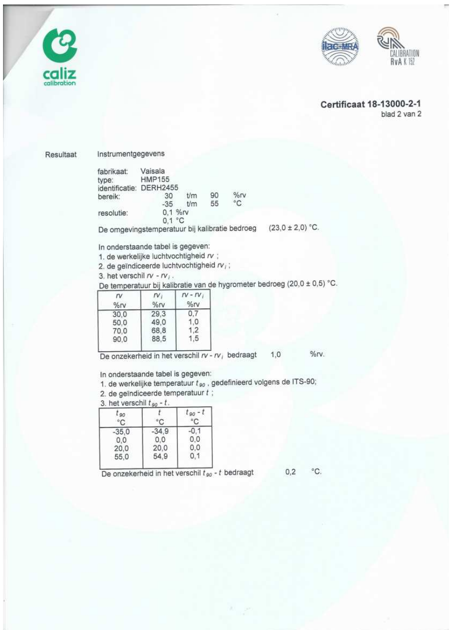
(a) RHT 2455, page 1/2


caliz calibration

CALIBRATION RvA K 152

Certificaat 18-13000-2-1
blad 2 van 2

Resultaat: Instrumentgegevens

fabrikaat: Vaisala
type: HMP155
identificatie: DERH2455
bereik: 30 t/m 90 %rv
-35 t/m 55 °C
resolutie: 0,1 %rv
0,1 °C
De omgevingstemperatuur bij kalibratie bedroeg (23,0 ± 2,0) °C.

In onderstaande tabel is gegeven:
1. de werkelijke luchtvochtigheid rv ;
2. de geïndiceerde luchtvochtigheid rv_i ;
3. het verschil rv - rv_i .
De temperatuur bij kalibratie van de hygrometer bedroeg (20,0 ± 0,5) °C.

rv %rv	rv_i %rv	$rv - rv_i$ %rv
30,0	29,3	0,7
50,0	49,0	1,0
70,0	68,8	1,2
90,0	88,5	1,5

De onzekerheid in het verschil rv - rv_i bedraagt 1,0 %rv.

In onderstaande tabel is gegeven:
1. de werkelijke temperatuur t_{90} , gedefinieerd volgens de ITS-90;
2. de geïndiceerde temperatuur t ;
3. het verschil t_{90} - t.

t_{90} °C	t °C	$t_{90} - t$ °C
-35,0	-34,9	-0,1
0,0	0,0	0,0
20,0	20,0	0,0
55,0	54,9	0,1

De onzekerheid in het verschil t_{90} - t bedraagt 0,2 °C.

(b) RHT 2455, page 2/2

B.1.4 Air pressure


DELD 5140

caliz calibration

CALIBRATION RvA K 152

Certificaat 18-13000-2-7
blad 1 van 2

Aanvrager: TNO - Locatie ECN Petten
Westerduinweg 3
1755 LE PETTEN

Aangeboden: Barometer
aantal: 1
De identificatiegegevens zijn gegeven bij resultaat.

Wijze van onderzoek: De drukmeter is gekalibreerd door vergelijking van de geïndiceerde waarde met de referentie druk, gemeten met een standaard drukmeter.
Daarbij is een cyclus van toenemende en afnemende druk doorlopen.
De omgevingstemperatuur bedroeg (20,0 ± 1,0) °C.

Datum van onderzoek: 5 juli 2018

Resultaat: De meetresultaten zijn gegeven op het volgblad.
De gerapporteerde onzekerheid is gebaseerd op een standaardonzekerheid, vermenigvuldigd met een dekkingsfactor k = 2, welke overeenkomt met een dekkingswaarschijnlijkheid van ongeveer 95 %.
De standaardonzekerheid is bepaald volgens EA-4/02M.

Herleidbaarheid: De metingen zijn uitgevoerd met standaarden waarvan de herleidbaarheid naar (inter)nationale standaarden, ten overstaan van de Raad voor Accreditatie, is aangetoond.

Berlicum, 5 juli 2018

E. R. Cornelissen
Kalibratiemedewerker

CALIZ B.V.
Nederhof 3
5258 CB BERLICUM
Tel.: +31 73 503 20 02
E-mail: info@caliz.nl
Website: www.caliz.nl

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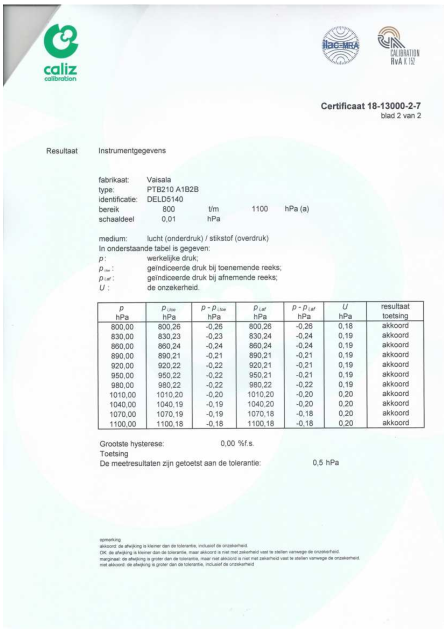
(a) Air pressure 5140, page 1/2


caliz calibration

CALIBRATION RvA K 152

Certificaat 18-13000-2-7
blad 2 van 2

Resultaat: Instrumentgegevens

fabrikaat: Vaisala
type: PTB210 A1B2B
identificatie: DELD5140
bereik 800 t/m 1100 hPa (a)
schaaldeel 0,01 hPa

medium: lucht (onderdruk) / stikstof (overdruk)
In onderstaande tabel is gegeven:
p: werkelijke druk;
$p_{i,toe}$: geïndiceerde druk bij toenemende reeks;
$p_{i,af}$: geïndiceerde druk bij afnemende reeks;
U: de onzekerheid.

p hPa	$p_{i,toe}$ hPa	$p - p_{i,toe}$ hPa	$p_{i,af}$ hPa	$p - p_{i,af}$ hPa	U hPa	resultaat toetsing
800,00	800,26	-0,26	800,26	-0,26	0,18	akkoord
830,00	830,23	-0,23	830,24	-0,24	0,19	akkoord
860,00	860,24	-0,24	860,24	-0,24	0,19	akkoord
890,00	890,21	-0,21	890,21	-0,21	0,19	akkoord
920,00	920,22	-0,22	920,21	-0,21	0,19	akkoord
950,00	950,22	-0,22	950,21	-0,21	0,19	akkoord
980,00	980,22	-0,22	980,22	-0,22	0,19	akkoord
1010,00	1010,20	-0,20	1010,20	-0,20	0,20	akkoord
1040,00	1040,19	-0,19	1040,20	-0,20	0,20	akkoord
1070,00	1070,19	-0,19	1070,18	-0,18	0,20	akkoord
1100,00	1100,18	-0,18	1100,18	-0,18	0,20	akkoord

Grootste hysterese: 0,00 %f.s.
Toetsing
De meetresultaten zijn getoetst aan de tolerantie: 0,5 hPa

opmerking
akkoord: de afwijking is kleiner dan de tolerantie, inclusief de onzekerheid.
OK: de afwijking is kleiner dan de tolerantie, maar akkoord is niet met zekerheid vast te stellen vanwege de onzekerheid.
marginaal: de afwijking is groter dan de tolerantie, maar niet akkoord is niet met zekerheid vast te stellen vanwege de onzekerheid.
niet akkoord: de afwijking is groter dan de tolerantie, inclusief de onzekerheid

(b) Air pressure 5140, page 2/2

B.1.5 Sonic 3D

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

accredited by the / *akkreditiert durch die*

Deutsche Akkreditierungsstelle GmbH

as calibration laboratory in the / *als Kalibrierlaboratorium im*

Deutschen Kalibrierdienst

Deutsche Akkreditierungsstelle D-K-15140-01-00

Calibration certificate / *Kalibrierschein*

Calibration mark / *Kalibrierzeichen*: 1621277 D-K-15140-01-00 04/2016

Object *Gegenstand*	3D Sonic Anemometer
Manufacturer *Hersteller*	METEK GmbH D-25337 Elmshorn
Type *Typ*	uSonic-3 Sci Basic
Serial number *Fabrikat/Serien-Nr.*	0105033455 DEWS6084
Customer *Auftraggeber*	ECN Wind Energy
Order No. *Auftragsnummer*	-
Project No. *Projektnummer*	VT160431
Number of pages *Anzahl der Seiten*	5
Date of Calibration *Datum der Kalibrierung*	27.04.2016

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.
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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.

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Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
27.04.2016	Dipl. Phys. Dieter Westermann	Dipl.-Ing. (FH) Catharina Herold

(a) Sonic 3D 6084, page 1/5

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Seite

1621277 D-K-15140-01-00 04/2016

Calibration object *Kalibriergegenstand*	3D Sonic 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: 370 cm² diameter of mounting pipe: 43 mm blockage ratio [1)]: 0.037 [-] software version: 7.64 1) Due to the special construction of the test section no blockage correction is necessary.
Ambient conditions *Umgebungsbedingungen*	air temperature: 20.8 °C ± 0.1 °C air pressure: 1003.5 hPa ± 0.3 hPa relative air humidity: 46.9 % ± 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*	Orientation: 0°

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Calibration result
Kalibrierergebnis

Bin	Tunnel speed	Sensor x	Sensor y	Sensor z	Unc
-	m/s	cm/s	cm/s	cm/s	m/s
2	3.97	-399.356	-8.156	2.225	0.05
3	5.97	-599.075	-9.287	-0.875	0.05
4	7.97	-797.025	-9.825	-6.869	0.05
5	10.02	-1000.681	-9.900	-13.694	0.05
6	12.00	-1197.612	-8.331	-22.869	0.05
7	14.00	-1398.737	-7.331	-32.819	0.05
8	15.99	-1596.481	-2.413	-40.837	0.05
9	15.02	-1501.519	-5.313	-37.813	0.05
10	13.01	-1300.350	-8.625	-27.225	0.05
11	10.98	-1094.856	-13.106	-16.525	0.05
12	8.99	-894.644	-13.006	-8.356	0.05
13	7.03	-700.600	-12.400	-2.837	0.05
14	4.93	-492.419	-9.875	0.381	0.05

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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.

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Nomenclature

α	exponent of the power law wind shear model, see equation (5.2)
AHN	Actueel Hoogtebestand Nederland (Dutch laser altimetry map)
DTM	Digital Terrain Model
EV	environmental variable
EWTW	ECN Wind Turbine test site Wieringermeer
h	measurement height, see equation (5.2)
h_r	reference height for shear profile, see equation (5.2)
IEC	International Electrotechnical Commission
IECRE WE	IEC system for certification to standards relating to equipment for use in Renewable Energy applications - Wind Energy
ILAC MRA	International Laboratory Accreditation Cooperation Mutual Recognition Arrangement
N	number of 10-minute samples, see equation (5.6)
n_b	number of bins, see equation (5.6)
n_i	bin-count for bin i, see equation (5.6)
OWA	Offshore Wind Accelerator
PDOK	Publieke Dienstvoorziening Op de Kaart
RD	Rijksdriehoekscoördinaten (Dutch geodetic datum)
RETL	Renewable Energy Testing Laboratory
RvA	Raad voor Accreditatie / Dutch Accreditation Council
std	standard deviation
TRVF	TNO RSD Verification Facility
UTC	Coordinated Universal Time
v_{hor}	horizontal wind speed, see equation (5.4)
v_r	wind speed of shear profile at h_r, see equation (5.2)
v_{vert}	vertical wind speed, see equation (5.4)
v_d	wind direction, see equation (5.5)
WDMS	Wind Data Management System
WGS 84	world geodetic system 1984