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Period: 22 November 2024 to 7 January 2025

Verification of the Wind@Sea Lidar ZX1524 at the EWTW test site near meteorological mast MM6

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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 Systems conform to IEC 61400-12-1, Appendix L and IEA Recommended Practices 18

Adaptation of scope for remote sensing verification to IEC 61400-50-2 by RvA is currently pending.

Results only apply for the tested lidar with the settings used during the measurement period.
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Abbreviations

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)
PDOK	Publieke Dienstvoorziening Op de Kaart
RD	Rijksdriehoekscoördinaten (Dutch geodetic datum)
RETL	Renewable Energy Testing Laboratory
RSD	Remote Sensing Device
RvA	Raad voor Accreditatie (Dutch Accreditation Council)
std	standard deviation
TNO	Nederlandse Organisatie voor toegepast-natuurwetenschappelijk onderzoek (Netherlands Organisation for applied scientific research)
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

Management summary

As part of the Wind@Sea project a ZX Lidars ZX 300M with serial number ZX1524 was installed at the EWTW test site near meteorological mast MM6 on 21 November 2024. The lidar was verified after being deployed for wind field measurements at offshore platform K13-A.

The official measurement campaign started on 22 November 2024 00:00 UTC and lasted until 7 January 2025 00:00 UTC, covering 46 days. The comparison of the lidar against meteorological mast MM6 is performed for 3 measurement heights, 42 m, 81 m and 118 m.

For all comparison heights the regression slope is close to 1.00 and the offset is up to 0.12 m/s with an R^2 close to 1. The maximum deviation observed is 1.5 %. The sensitivity analysis did not result in any significant sensitivities for the lidar.

The results of this verification are based on IEC 61400-50-2:2022 (formerly Annex L of the IEC 61400-12-1:2017) standard and the TNO *Work instructions for verification RSD* (v.4).

TNO Wind Energy is ISO 17025 accredited for ground based remote sensing device verification.

1 Introduction

A ZX Lidars ZX 300M with serial number ZX1524 was installed at the EWTW test site near MM6 on 21 November 2024. The lidar was verified after being deployed for wind field measurements at offshore platform K13-A in the Wind@Sea project [1]. This report presents the verification results.

After verifying correct operation of the lidar, the measurement campaign was started on 22 November 2024 00:00 UTC and lasted until 7 January 2025 00:00 UTC.

The results of this verification are based on the IEC 61400-50-2:2022 [2] (formerly Annex L of the IEC 61400-12-1:2017) standard and the TNO *Work instructions for verification RSD* (v.4).

2 Measurement campaign

2.1 RSD verification location

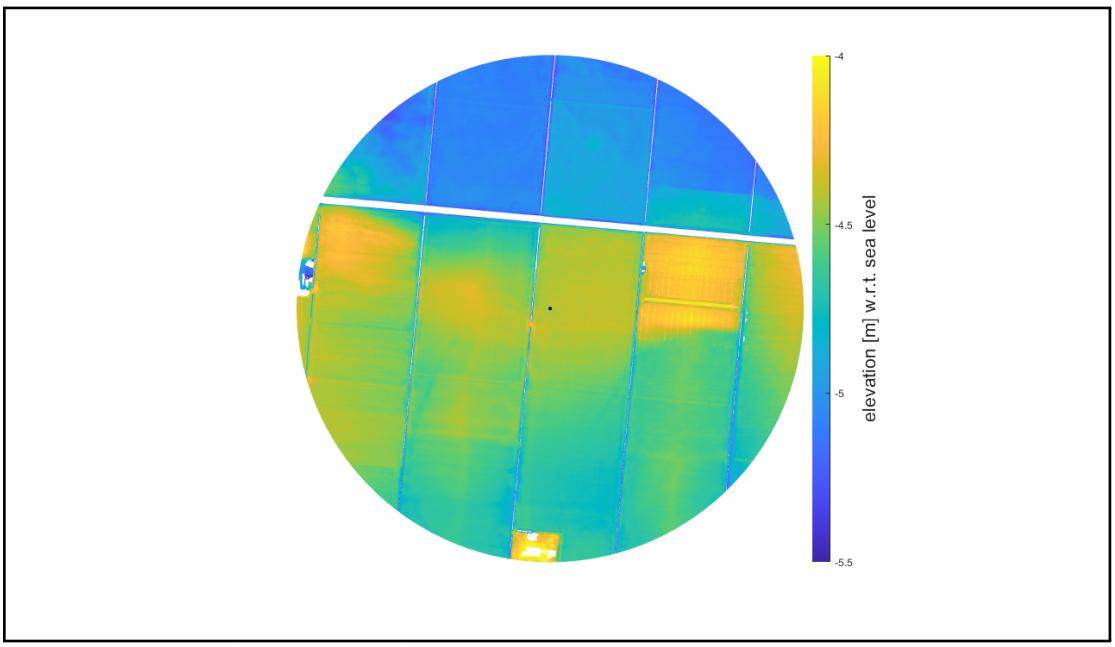
The Lidar is verified near meteorological mast MM6 at the EWTW test site [3]. The terrain at the EWTW test site consists mainly of agricultural land, with single farmhouses and rows of trees as shown in fig. 2.1. It is located in the Wieringermeer, a polder in the north east of the province of North Holland, 3 km North of the village Medemblik and 1 km West from the vast IJsselmeer lake. The altitude is 5 m below sea level. The site is considered sufficiently flat according to IEC 61400-12-5:2022 [4] as demonstrated by the laser altimetry in fig. 2.2.

Source: Google Earth

Figure 2.1: Detailed overview of the south EWTW locations and corresponding meteo mast locations as well as the nearby obstacles. Meteorological mast MM6 is highlighted by the green circle

The mast is an un-guyed triangular lattice tower with a height of 115.5 m, see fig. 2.3. At the bottom the width of the tower is 5.86 m. On the top of the mast a vertical tube is installed with a total height of 1.775 m above the mast top. Including the sensor height of 0.225 m this adds up to a top cup measuring height of 117.5 m.

A total of eight booms are mounted on to the mast, as is presented in the layout drawing in fig. 2.7. 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 reduced. At the lower and mid measuring heights the vanes are installed on a separate boom 4 m below the cup measuring height. The measuring



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

Figure 2.2: Ground level elevation map of the lidar's surroundings (radius = 5×117.5 m)

Figure 2.3: Meteorological Mast MM6

heights of the cup anemometers are 41.9 m, 81.4 m, 112.5 m and 117.5 m. The measuring heights of the wind vanes are 37.9 m, 77.4 m and 112.5 m. At 108.5 m, 4 m below the cup anemometer, a sonic anemometer is located. The booms can be retracted for maintenance of the sensors.

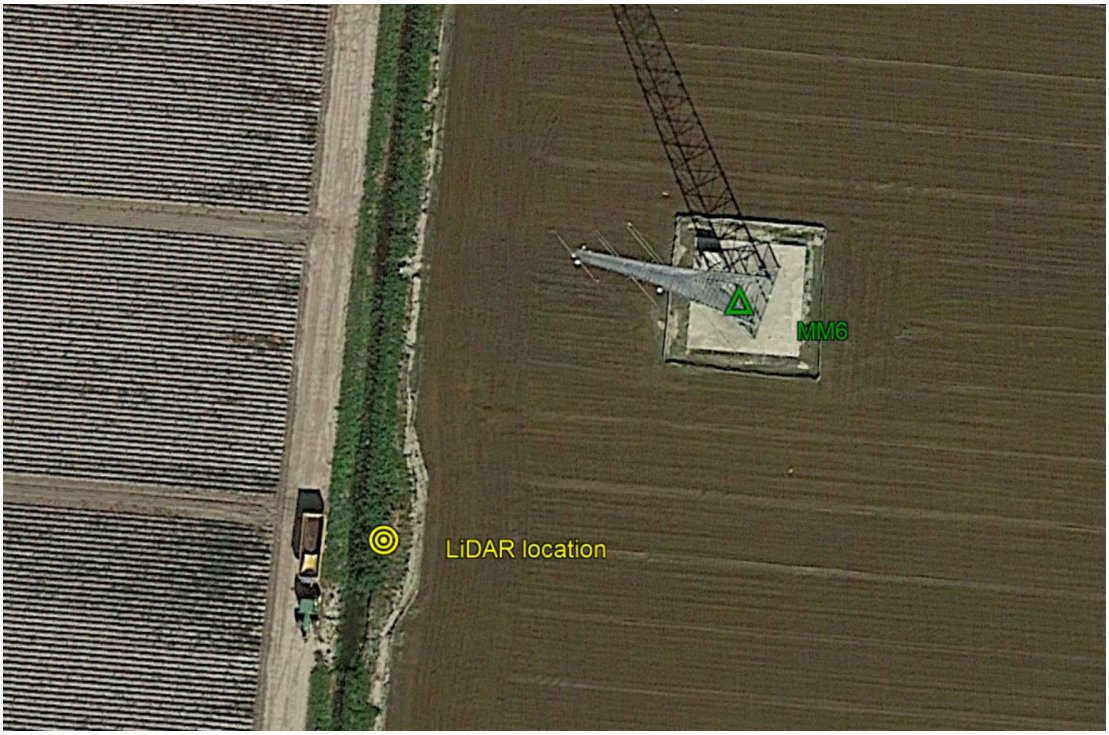
In table 2.1 the coordinates of the meteorological mast and lidar locations are summarized.

Table 2.1: Coordinates of the reference mast as well as the lidar

location	RD	WGS 84
MM6	132 384 m, 536 649 m	52°48.997′N, 5°3.105′E
lidar	132 344 m, 536 622 m	52°48.982′N, 5°3.069′E

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

In fig. 2.4 the location of the verification platform is shown in more detail.



Source: Google Maps

Figure 2.4: 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 61400-12-5:2022 [4] using MeasSector version 2.2.1. In fig. 2.5 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.

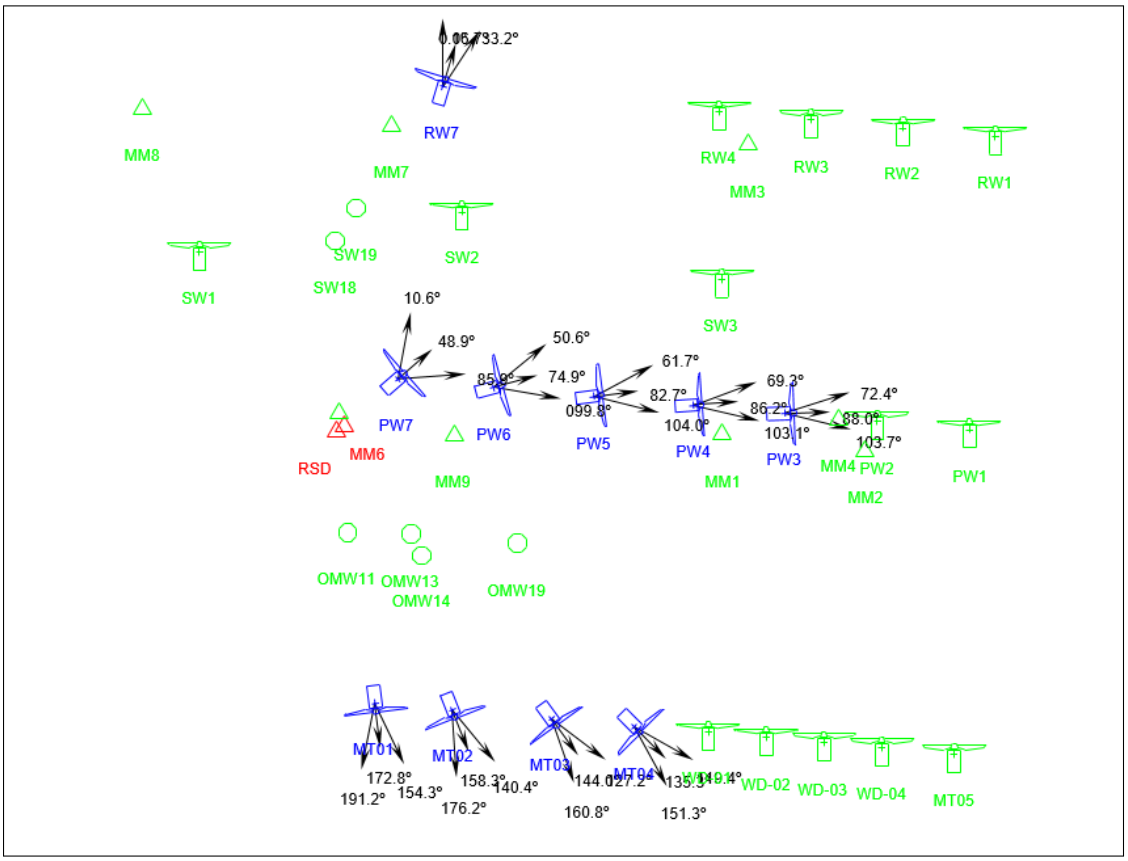


Figure 2.5: Layout of the EWTW test site used to determine the measurement sector

The measurement sector is height dependent as for the boom mounted measuring heights an extra sector is excluded where the wind direction is in line with the boom orientation, 320°±10°, see table 2.2.

Table 2.2: Excluded sectors per measuring height.

Excluded sector	comparison height		
	117.5m	81.4m	41.9m
0.1° to 104.0°	x	x	x
119.4° to 191.2°	x	x	x
310° to 330°		x	x

2.3 Remote Sensing Device

The Remote Sensing Device (RSD) is a ZX 300M lidar. This unit has identification number ZX1524 (software version 3.2003). It is configured to perform measurements at 10 heights: 21 m, 42 m, 61 m, 81 m, 101 m, 113 m, 118 m, 141 m, 161 m and 181 m. The lidar has a cone half-angle of 30°. The comparison heights are specified in table 2.3. During the verification test the lidar was oriented 5° w.r.t. North.

The ZX 300M lidar at the RSD verification location is presented in fig. 2.6.

Table 2.3: Measurement heights for verification

comparison height	MM6 height	lidar measuring height	lidar configured height
m	m	m	
117.5	117.5	118	117
81.4	81.4	81	80
41.9	41.9	42	41

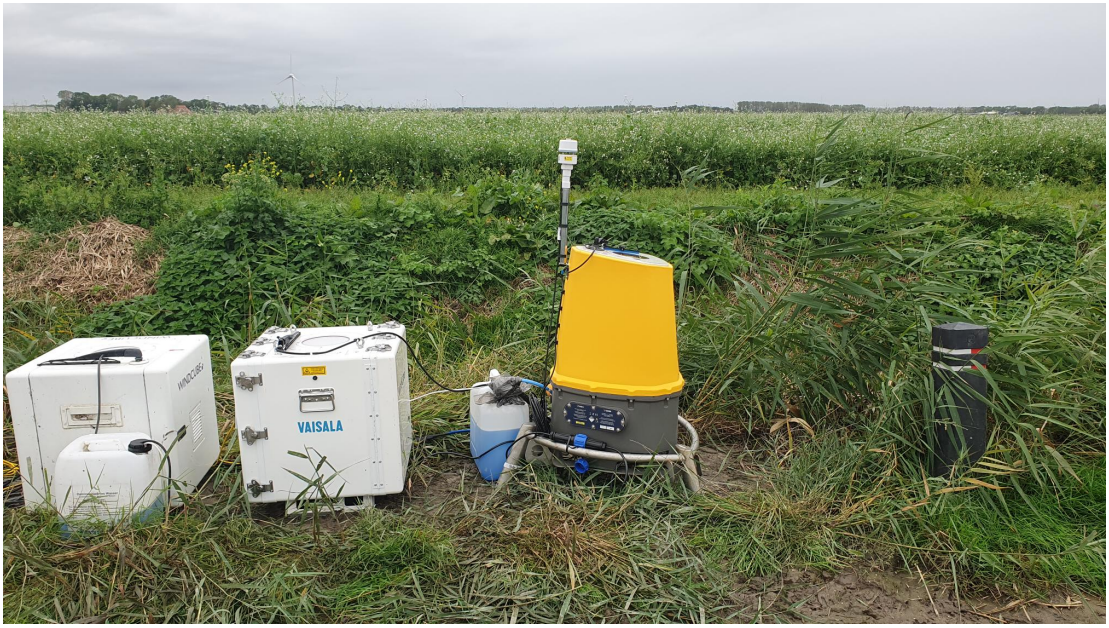


Figure 2.6: ZX 300M ZX1524 (right lidar in yellow) at the RSD verification location.

2.4 Data stream

The Meteorological Mast MM6 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. The lidar data are accumulated in the lidar device itself.

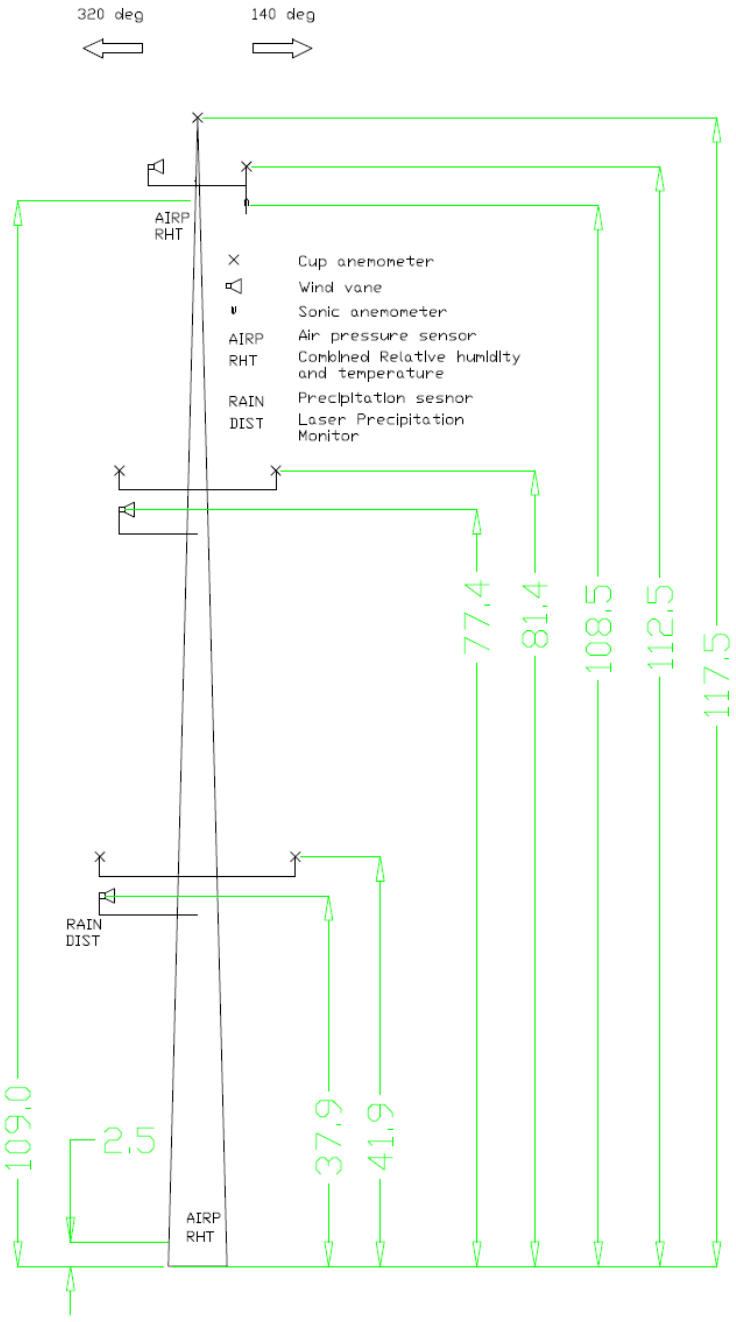


Figure 2.7: Layout of the meteorological mast MM6

3 Data selection

The lidar measurement campaign officially starts on 22 November 2024 00:00 and ends on 7 January 2025 00:00 UTC. Figures 3.1 and 3.2 show the time series for the wind speed and wind direction measured by the reference meteorological mast and the lidar, prior to filtering.

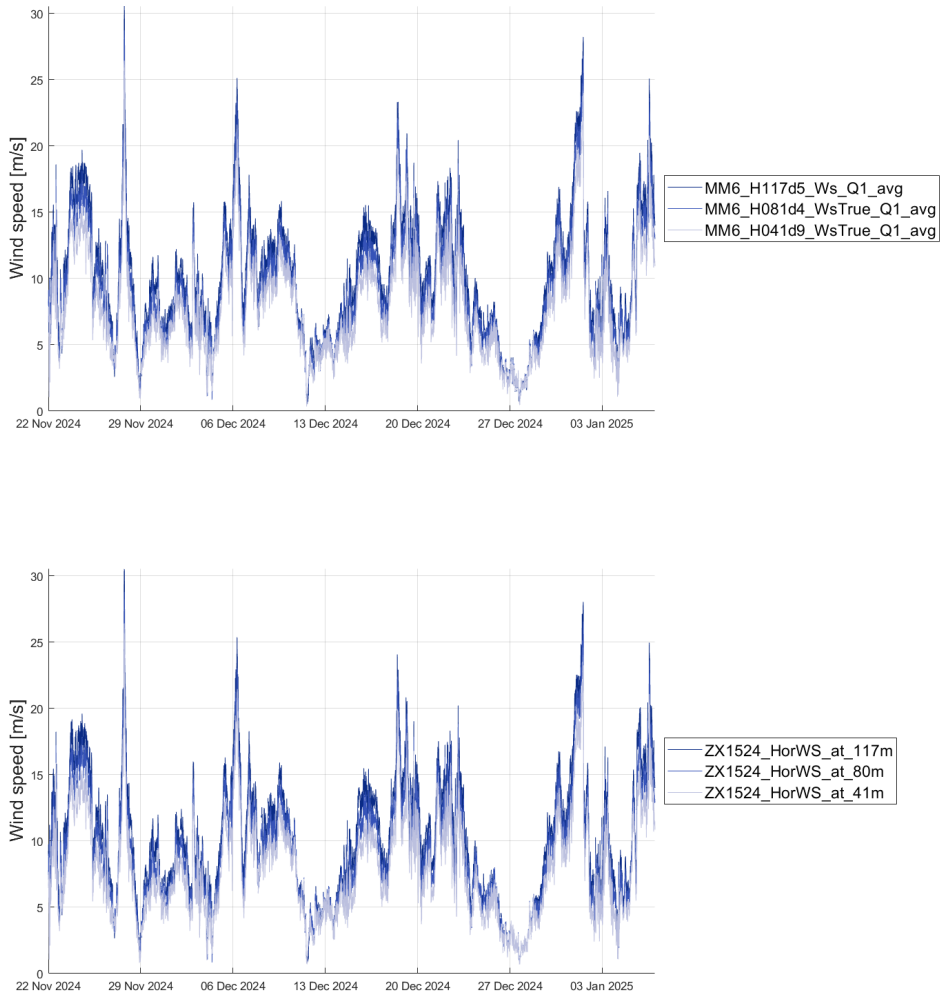


Figure 3.1: Unfiltered wind speed time series for the comparison heights by the reference meteorological mast at the RSD verification location (top) and the lidar (bottom)

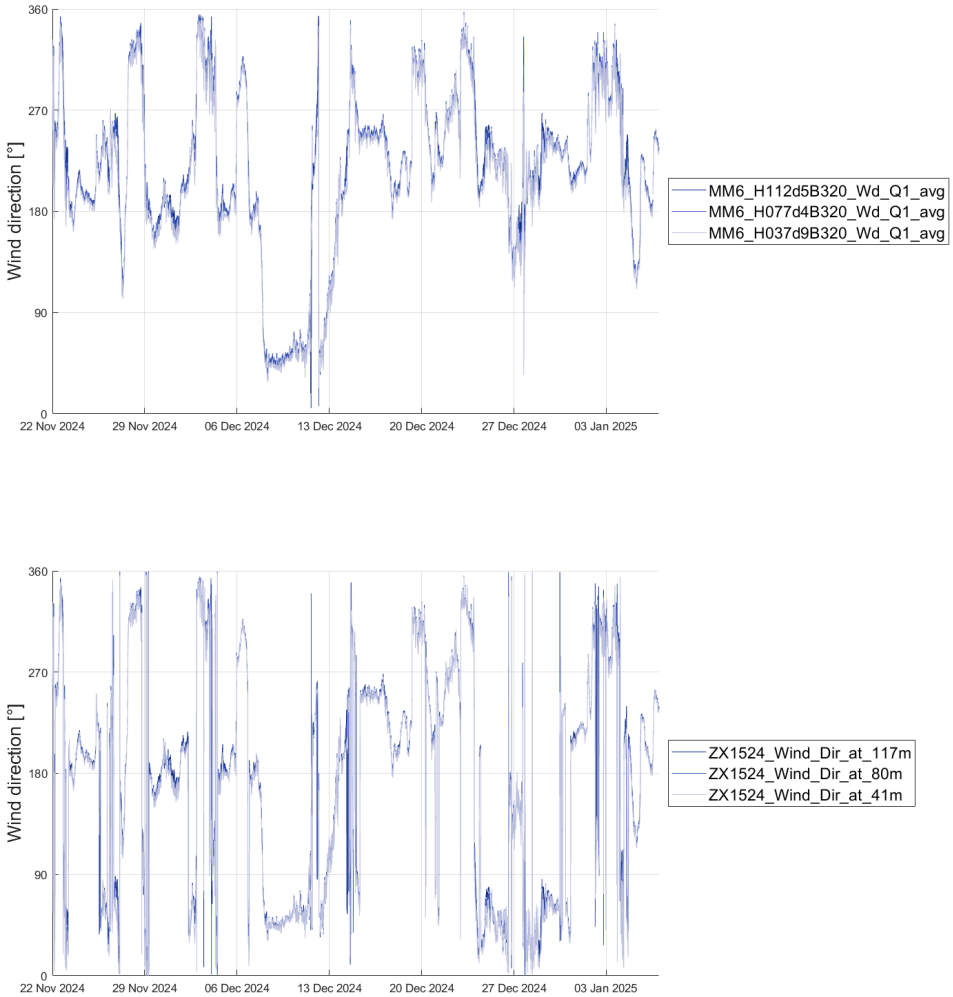


Figure 3.2: Unfiltered wind direction time series for various heights by the reference meteorological mast at the RSD verification location (top) and the lidar (bottom)

3.1 Filter criteria

The data is filtered in accordance with IEC 61400-50-2:2022 [2, clause 6.3, p.15]:

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 117.5 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. A.1.

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 two cups on booms at opposite sides of the mast.

d) *Icing*
The MEASNET [5] 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. 3.3.

e) *Data availability*
For the LiDAR system no availability filtering is applied, other than the data that is being rejected by the LiDAR system itself.

f) *Precipitation*
The lidar performance might be affected by precipitation however no filtering on precipitation was undertaken. The IEC 61400-50-2:2022 describes that in general no filtering on precipitation should be applied unless specifically described by the manufacturers guidelines.

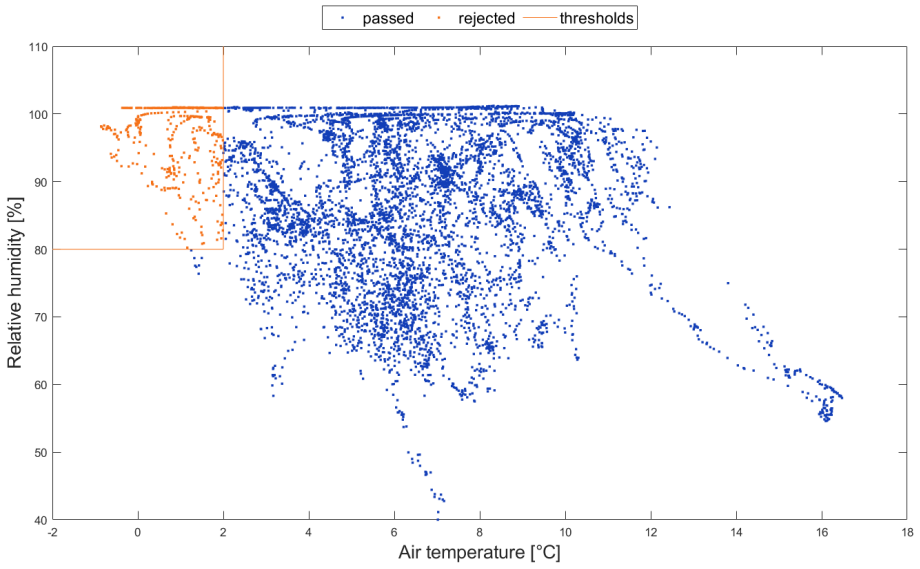


Figure 3.3: Filter: MEASNET icing criterion

4 lidar verification

This chapter reports the results of the lidar verification analysis as defined in clause 7 [2]. The analysis is performed using the in-house software tool *RSDverification* version 2.0.21.

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. 4.1 to 4.3. The format is taken from figure 6 [2]. 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 clause 7 [2] 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. A.3. 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. 4.4 to 4.6. The results of the regressions are summarised in table 4.1. The uncertainty intervals shown in these figures are discussed in section 6.2.

Table 4.1: lidar verification IEC 61400-50-2 results

height	slope	offset	R^2
m	–	m/s	–
117.5	1.013	-0.121	1.000
81.4	1.001	-0.049	1.000
41.9	0.991	0.038	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 4.2 to 4.4. The tables are modelled after table 11 [2]. 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 campaign requires the environmental conditions experienced during the lidar verification test [2, clause 11.1, item i].

The conditions at each comparison height are defined in chapter 5 and reported in tables 4.5 to 4.7. These tables covers all the measured environmental variables. However, the DNV-GL classification report [6] for the ZX300 lidar names seven significant environmental variables in the conclusion, among which 'temperature gradient' is not measured in this verification.

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.

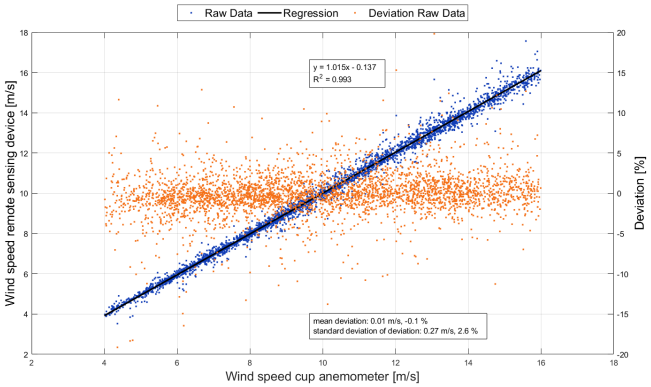


Figure 4.1: Wind speed comparison @117.5 m

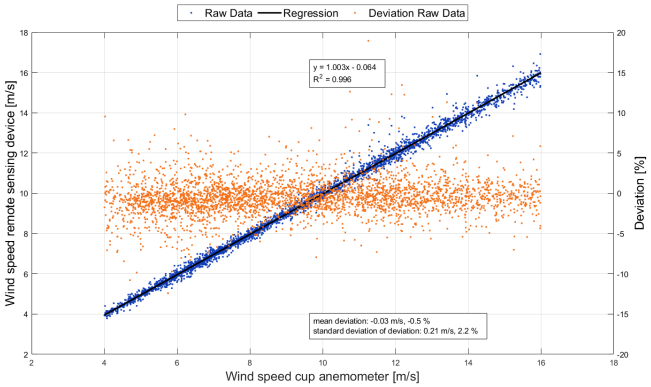


Figure 4.2: Wind speed comparison @81.4 m

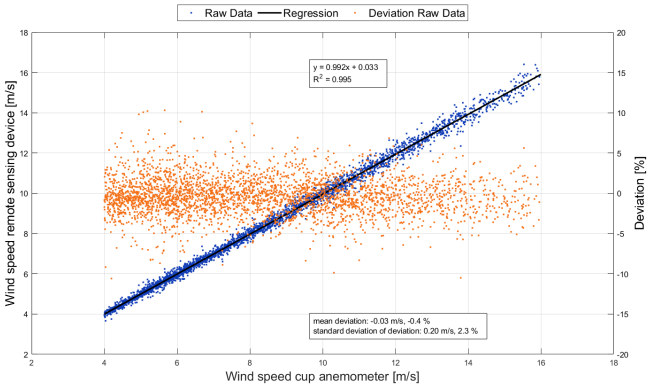


Figure 4.3: Wind speed comparison @41.9 m

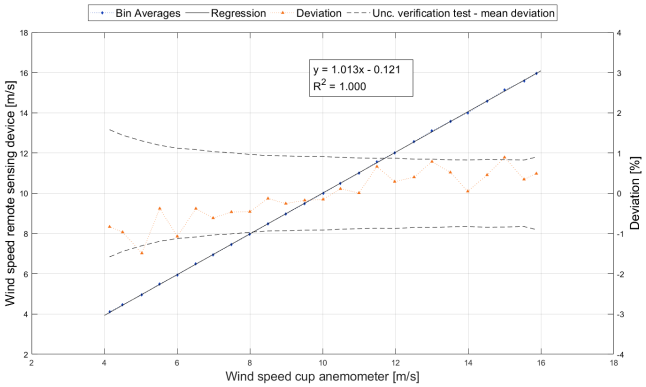


Figure 4.4: Bin-wise wind speed comparison @117.5 m

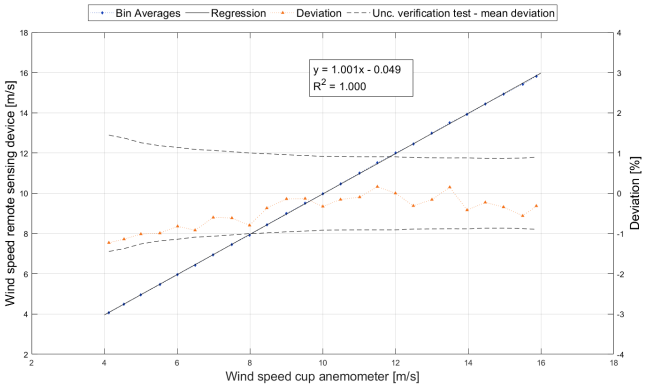


Figure 4.5: Bin-wise wind speed comparison @81.4 m

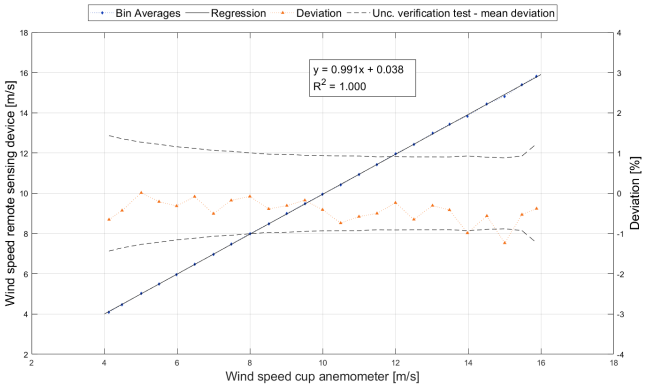


Figure 4.6: Bin-wise wind speed comparison @41.9 m

Table 4.2: Uncertainty calculations of the lidar @117.5 m

V_{ref}	V_{rsd}	data sets	V_{rsd} max	V_{rsd} min	V_{rsd} std	$V_{rsd}\frac{std}{\sqrt{n}}$	mean deviation	V_{ref} unc.	mounting unc. rsd	V_{rsd} unc.
m/s	m/s	#	m/s	m/s	m/s	m/s	%	%	%	%
4.14	4.11	24	4.41	3.89	0.159	0.033	-0.832	1.353	0.10	1.786
4.50	4.46	64	4.91	3.52	0.228	0.029	-0.966	1.278	0.10	1.737
5.03	4.96	86	5.36	3.91	0.227	0.024	-1.488	1.188	0.10	1.977
5.52	5.50	118	6.06	5.00	0.206	0.019	-0.379	1.120	0.10	1.251
6.00	5.94	170	6.51	5.17	0.213	0.016	-1.072	1.066	0.10	1.552
6.52	6.49	168	7.54	5.49	0.253	0.020	-0.380	1.019	0.10	1.150
6.99	6.95	187	7.53	6.32	0.224	0.016	-0.615	0.983	0.10	1.204
7.49	7.46	151	8.37	6.72	0.237	0.019	-0.464	0.948	0.10	1.110
8.00	7.96	190	8.62	6.84	0.224	0.016	-0.456	0.918	0.10	1.069
8.50	8.49	207	9.11	7.76	0.209	0.015	-0.129	0.893	0.10	0.945
8.99	8.96	187	9.64	7.78	0.287	0.021	-0.255	0.871	0.10	0.963
9.51	9.49	174	10.48	8.29	0.301	0.023	-0.174	0.855	0.10	0.932
10.01	10.00	129	11.11	8.74	0.316	0.028	-0.151	0.841	0.10	0.926
10.49	10.50	153	11.31	9.40	0.315	0.025	0.112	0.829	0.10	0.900
11.00	11.00	165	11.92	9.80	0.322	0.025	0.008	0.818	0.10	0.878
11.49	11.57	160	13.01	10.45	0.330	0.026	0.663	0.809	0.10	1.094
11.98	12.01	124	13.86	10.59	0.360	0.032	0.289	0.801	0.10	0.921
12.52	12.57	171	13.76	11.52	0.336	0.026	0.402	0.793	0.10	0.939
13.01	13.11	174	15.66	11.82	0.391	0.030	0.787	0.786	0.10	1.157
13.51	13.58	165	15.14	12.99	0.333	0.026	0.520	0.779	0.10	0.982
13.99	14.00	130	15.21	13.04	0.311	0.027	0.050	0.773	0.10	0.829
14.52	14.59	107	16.22	13.08	0.402	0.039	0.456	0.766	0.10	0.957
15.00	15.13	111	16.59	14.17	0.424	0.040	0.893	0.761	0.10	1.224
15.54	15.59	95	17.57	14.44	0.376	0.039	0.346	0.756	0.10	0.896
15.88	15.95	30	17.05	15.35	0.383	0.070	0.490	0.753	0.10	1.025

Table 4.3: Uncertainty calculations of the lidar @81.4 m

V_{ref}	V_{rsd}	data sets	V_{rsd} max	V_{rsd} min	V_{rsd} std	$V_{rsd}\frac{std}{\sqrt{n}}$	mean deviation	V_{ref} unc.	mounting unc. rsd	V_{rsd} unc.
m/s	m/s	#	m/s	m/s	m/s	m/s	%	%	%	%
4.12	4.07	43	4.40	3.79	0.130	0.020	-1.228	1.343	0.10	1.896
4.54	4.49	89	4.97	4.03	0.204	0.022	-1.139	1.270	0.10	1.785
5.00	4.95	156	5.52	4.41	0.184	0.015	-1.013	1.202	0.10	1.615
5.53	5.47	181	6.00	5.04	0.176	0.013	-0.991	1.135	0.10	1.542
6.01	5.96	197	6.84	5.29	0.217	0.015	-0.820	1.090	0.10	1.406
6.49	6.43	211	6.99	5.83	0.212	0.015	-0.917	1.042	0.10	1.424
6.99	6.95	218	7.36	6.33	0.224	0.015	-0.600	1.020	0.10	1.224
7.51	7.46	204	8.08	6.85	0.207	0.014	-0.614	0.990	0.10	1.202
7.99	7.93	187	8.43	7.52	0.180	0.013	-0.796	0.962	0.10	1.279
8.47	8.43	148	9.13	7.78	0.221	0.018	-0.368	0.934	0.10	1.051
9.01	8.99	140	9.63	8.50	0.226	0.019	-0.140	0.906	0.10	0.967
9.52	9.51	158	10.48	8.94	0.248	0.020	-0.131	0.888	0.10	0.948
10.01	9.97	149	10.56	9.04	0.238	0.019	-0.327	0.867	0.10	0.973
10.49	10.48	150	11.50	9.88	0.269	0.022	-0.155	0.858	0.10	0.924
11.02	11.01	134	12.11	10.26	0.269	0.023	-0.094	0.855	0.10	0.913
11.50	11.52	181	13.39	10.65	0.332	0.025	0.164	0.853	0.10	0.922
12.00	12.00	159	13.82	11.13	0.365	0.029	0.002	0.846	0.10	0.908
12.49	12.45	127	13.28	11.74	0.248	0.022	-0.310	0.841	0.10	0.941
13.01	12.99	109	14.26	12.18	0.313	0.030	-0.157	0.824	0.10	0.898
13.49	13.51	104	14.94	12.84	0.316	0.031	0.152	0.820	0.10	0.893
13.97	13.91	91	15.85	13.10	0.341	0.036	-0.416	0.814	0.10	0.976
14.47	14.44	85	15.23	13.78	0.266	0.029	-0.227	0.813	0.10	0.895
14.97	14.92	74	16.32	14.27	0.336	0.039	-0.342	0.793	0.10	0.930
15.50	15.41	71	16.07	14.19	0.341	0.040	-0.561	0.807	0.10	1.041
15.87	15.82	37	16.92	15.26	0.337	0.055	-0.315	0.792	0.10	0.948

Table 4.4: Uncertainty calculations of the lidar @41.9 m

V_{ref}	V_{rsd}	data sets	V_{rsd} max	V_{rsd} min	V_{rsd} std	$V_{rsd}\frac{std}{\sqrt{n}}$	mean deviation	V_{ref} unc.	mounting unc. rsd	V_{rsd} unc.
m/s	m/s	#	m/s	m/s	m/s	m/s	%	%	%	%
4.13	4.10	97	4.35	3.66	0.120	0.012	-0.653	1.385	0.10	1.576
4.49	4.47	218	5.04	4.04	0.176	0.012	-0.427	1.310	0.10	1.421
5.01	5.01	227	5.71	4.51	0.210	0.014	0.012	1.218	0.10	1.269
5.50	5.49	225	6.24	4.83	0.222	0.015	-0.208	1.165	0.10	1.234
5.99	5.97	243	6.63	5.53	0.209	0.013	-0.315	1.112	0.10	1.198
6.48	6.47	187	7.36	5.92	0.223	0.016	-0.082	1.065	0.10	1.120
7.00	6.96	188	7.45	6.46	0.197	0.014	-0.507	1.022	0.10	1.180
7.49	7.47	151	8.22	6.92	0.231	0.019	-0.176	0.988	0.10	1.058
8.00	7.99	174	8.77	7.35	0.235	0.018	-0.078	0.953	0.10	1.007
8.52	8.48	167	9.10	7.92	0.217	0.017	-0.388	0.926	0.10	1.047
9.02	8.99	149	9.77	8.34	0.263	0.022	-0.306	0.911	0.10	1.015
9.51	9.49	155	10.01	8.73	0.242	0.019	-0.173	0.895	0.10	0.960
10.00	9.96	163	10.68	9.31	0.266	0.021	-0.409	0.882	0.10	1.019
10.50	10.42	166	11.38	9.29	0.278	0.022	-0.739	0.878	0.10	1.187
11.00	10.94	130	11.76	10.09	0.315	0.028	-0.579	0.864	0.10	1.093
11.49	11.44	129	12.00	10.84	0.265	0.023	-0.500	0.854	0.10	1.035
12.00	11.97	109	12.64	11.31	0.310	0.030	-0.236	0.848	0.10	0.941
12.51	12.43	90	13.48	11.74	0.286	0.030	-0.650	0.843	0.10	1.114
13.02	12.98	71	13.80	12.10	0.299	0.035	-0.305	0.834	0.10	0.955
13.49	13.43	77	14.39	12.76	0.357	0.041	-0.414	0.822	0.10	0.994
13.98	13.84	59	14.71	12.35	0.388	0.051	-0.988	0.826	0.10	1.356
14.51	14.43	45	15.03	13.54	0.313	0.047	-0.562	0.807	0.10	1.059
15.01	14.82	32	15.56	14.37	0.254	0.045	-1.235	0.798	0.10	1.517
15.48	15.40	38	16.41	14.55	0.393	0.064	-0.530	0.798	0.10	1.067
15.88	15.82	8	16.39	15.15	0.407	0.144	-0.380	0.801	0.10	1.288

Table 4.5: Environmental conditions @117.5 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	0.2654	8.89	0.00	262.9	5.78	83.10	1.263	1.377	-0.1956
4.500	0.2631	8.01	0.51	261.7	5.62	81.80	1.262	1.719	-0.2389
5.000	0.2775	6.82	0.65	250.8	5.50	83.37	1.263	1.447	-0.2253
5.500	0.2690	7.35	1.50	253.4	5.72	88.62	1.260	1.440	-0.1962
6.000	0.2600	6.98	2.54	250.7	6.27	86.83	1.255	1.390	-0.1896
6.500	0.2863	7.54	4.39	261.4	6.50	85.63	1.254	1.495	-0.1479
7.000	0.3212	7.20	6.36	258.1	5.94	83.79	1.254	1.615	-0.1651
7.500	0.2975	7.85	6.68	258.6	6.30	85.23	1.250	1.569	-0.1260
8.000	0.2973	8.11	5.28	265.2	6.29	82.51	1.248	1.609	-0.1090
8.500	0.2903	8.33	7.01	259.1	6.63	84.15	1.248	1.528	-0.0928
9.000	0.2903	8.73	9.69	259.8	6.50	85.17	1.248	1.557	-0.0848
9.500	0.2718	9.13	14.89	257.8	6.86	84.44	1.244	1.598	-0.0763
10.000	0.2576	9.04	13.77	247.4	7.01	83.59	1.241	1.500	-0.0724
10.500	0.2563	8.76	17.07	239.0	6.97	86.28	1.242	1.352	-0.0684
11.000	0.2561	8.94	12.56	247.8	6.93	84.96	1.243	1.507	-0.0626
11.500	0.2488	8.84	11.21	247.6	7.25	86.32	1.241	1.429	-0.0578
12.000	0.2334	10.02	12.77	263.7	6.92	83.27	1.240	1.658	-0.0542
12.500	0.2363	9.75	13.03	254.9	7.43	85.51	1.238	1.492	-0.0478
13.000	0.2334	9.91	10.57	252.4	7.64	85.37	1.237	1.506	-0.0482
13.500	0.2292	10.16	13.57	256.6	7.60	84.27	1.235	1.568	-0.0457
14.000	0.2213	9.66	17.05	253.5	7.82	83.89	1.233	1.487	-0.0419
14.500	0.2207	9.76	23.44	252.7	7.73	85.53	1.230	1.473	-0.0460
15.000	0.2130	9.89	27.42	240.3	8.16	85.57	1.226	1.457	-0.0461
15.500	0.2163	9.69	32.09	241.8	8.16	86.93	1.223	1.486	-0.0481
15.875	0.2180	9.53	30.48	227.2	8.93	85.21	1.214	1.364	-0.0468

Table 4.6: Environmental conditions @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	0.2313	8.51	0.16	244.6	5.55	84.33	1.265	1.450	-0.1794
4.500	0.2515	7.66	0.07	242.3	5.89	84.28	1.261	1.534	-0.2200
5.000	0.2852	8.02	1.05	243.9	5.74	86.47	1.259	1.423	-0.2063
5.500	0.2846	7.99	2.61	249.7	6.35	87.58	1.254	1.359	-0.1896
6.000	0.2994	7.84	3.18	252.3	6.55	85.00	1.253	1.514	-0.1554
6.500	0.2724	8.56	8.43	240.8	6.22	87.33	1.253	1.300	-0.1462
7.000	0.2868	9.12	5.15	250.5	6.50	85.41	1.249	1.435	-0.1155
7.500	0.2895	9.58	7.16	252.5	6.68	85.09	1.248	1.443	-0.0992
8.000	0.2732	9.11	7.87	246.1	6.45	85.88	1.247	1.370	-0.0962
8.500	0.2654	10.18	9.99	249.0	7.09	84.14	1.243	1.338	-0.0758
9.000	0.2483	10.11	17.97	235.5	7.35	86.71	1.240	1.279	-0.0730
9.500	0.2480	10.05	18.10	232.4	7.13	86.46	1.240	1.171	-0.0681
10.000	0.2519	9.94	15.33	238.6	7.08	86.51	1.241	1.288	-0.0638
10.500	0.2388	10.33	8.76	238.6	7.11	88.13	1.241	1.321	-0.0580
11.000	0.2377	10.67	9.96	243.8	7.53	87.03	1.240	1.353	-0.0559
11.500	0.2339	11.38	12.64	245.4	7.65	87.19	1.237	1.326	-0.0479
12.000	0.2294	10.97	13.45	244.6	7.58	86.44	1.238	1.381	-0.0443
12.500	0.2189	11.59	13.53	250.1	7.71	84.54	1.235	1.384	-0.0425
13.000	0.2178	11.26	24.57	243.8	7.76	86.12	1.231	1.338	-0.0451
13.500	0.2213	10.80	22.37	231.5	8.35	86.54	1.227	1.386	-0.0482
14.000	0.2132	11.08	31.87	233.9	8.07	86.23	1.224	1.338	-0.0469
14.500	0.2144	10.96	25.44	231.6	8.64	84.70	1.219	1.377	-0.0481
15.000	0.2034	10.54	26.77	228.7	8.58	85.35	1.220	1.336	-0.0475
15.500	0.2106	10.74	30.72	220.8	9.36	82.79	1.214	1.339	-0.0443
15.875	0.2100	10.70	27.78	222.9	10.05	84.14	1.210	1.385	-0.0388

Table 4.7: Environmental conditions @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	0.3128	9.15	2.03	247.1	6.07	83.14	1.255	1.720	-0.2275
4.500	0.2862	8.76	3.15	239.4	5.98	84.54	1.254	1.610	-0.2201
5.000	0.2846	9.93	6.54	238.8	6.66	86.98	1.251	1.468	-0.1569
5.500	0.2818	10.92	8.42	244.3	6.14	85.38	1.252	1.518	-0.1256
6.000	0.2726	11.36	4.54	240.7	6.38	86.71	1.251	1.373	-0.1045
6.500	0.2523	11.63	5.43	240.8	6.72	86.50	1.248	1.293	-0.0905
7.000	0.2495	11.67	7.72	242.0	7.00	84.98	1.243	1.333	-0.0847
7.500	0.2551	11.81	12.31	239.6	7.20	82.90	1.241	1.283	-0.0779
8.000	0.2472	11.86	18.48	231.0	7.32	86.71	1.240	1.214	-0.0638
8.500	0.2444	12.12	14.36	231.0	7.17	87.83	1.241	1.287	-0.0641
9.000	0.2369	12.48	12.98	238.4	7.14	88.17	1.239	1.377	-0.0583
9.500	0.2356	12.42	8.77	242.3	7.51	87.47	1.241	1.413	-0.0514
10.000	0.2352	12.54	10.70	243.6	7.63	86.38	1.240	1.368	-0.0477
10.500	0.2199	12.92	11.66	243.6	7.60	86.58	1.239	1.401	-0.0445
11.000	0.2165	12.81	16.45	242.0	7.59	85.82	1.235	1.353	-0.0429
11.500	0.2166	12.75	22.35	236.3	8.16	85.62	1.229	1.416	-0.0456
12.000	0.2143	12.73	30.24	228.3	7.89	88.20	1.229	1.346	-0.0486
12.500	0.2101	13.07	28.47	229.8	8.31	85.99	1.224	1.337	-0.0478
13.000	0.2054	12.97	20.25	232.9	8.30	83.44	1.219	1.404	-0.0458
13.500	0.2107	12.63	28.99	218.9	9.21	84.62	1.215	1.365	-0.0445
14.000	0.2031	13.40	24.48	226.2	9.91	80.36	1.219	1.325	-0.0436
14.500	0.1978	13.17	22.40	225.0	9.74	84.58	1.210	1.316	-0.0437
15.000	0.1896	13.40	28.84	234.3	9.17	86.05	1.213	1.272	-0.0404
15.500	0.1824	13.51	34.36	237.1	9.52	87.65	1.211	1.339	-0.0431
15.875	0.1857	13.22	14.35	244.6	9.09	85.13	1.209	1.436	-0.0389

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 clause 6 [2]. 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 4 [2]. The variables considered are described below.

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

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 117.5 m. For the wind shear, the top cup measurement is combined with the mast flow distortion corrected [7] signals for the boom mounted cup measuring heights 41.9 m and 81.4 m. This way the measurements at all heights are effectively undisturbed. 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 on the 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 on the meteorological mast, is height-dependent.

5. **Air temperature [°C]**
   The air temperature is measured at 109 m.

6. **Relative humidity [%RH]**
   The relative humidity is measured at 109 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 109 m, in accordance with equation (12) of IEC 61400-12-1:2022.

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

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

   The horizontal (v_{hor}) and vertical (v_{vert}) wind speed components are measured by a sonic anemometer at a height of 108.5 m.

9. **Wind veer [°/m]**
   The wind veer is computed as the difference between the wind direction measurements by meteorological mast at 37.9 m and 112.5 m, divided by the height difference. This definition was taken from IEC 61400-12-1:2022.

$$\text{wind veer} = \frac{w_{d,37.9} - w_{d,112.5}}{112.5 - 37.9} \tag{5.5}$$

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

The sensitivity analysis leads to the results presented in table 5.2, which is presented in the same format as table 4 [2]. 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) [2, eq. 3]. When the reference wind speed is used as the EV, also the criterion in equation (4) 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 5.2, 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 5.1 shows that none of the environmental variables result in a significant sensitivity. The distribution of the environmental variables is shown in table 5.4.

5.2 Impact on accuracy

The basis for the accuracy class is the product of m, as already presented in table 5.2, and the range of the EV. Although our interest is not in determining the accuracy class, we are

Table 5.1: Overview of significant sensitivities, '-' means the environmental variable is not significant.

environmental variable	comparison height			overall
	117.5m	81.4m	41.9m	
shear exponent	-	-	-	-
turbulence intensity	-	-	-	-
precipitation	-	-	-	-
wind direction	-	-	-	-
air temperature	-	-	-	-
relative humidity	-	-	-	-
air density	-	-	-	-
flow inclination	-	-	-	-
wind veer	-	-	-	-
reference wind speed	-	-	-	-

interested in the effect of the significant sensitivities. However, as presented in section 5.1, no significant sensitivities are found. The EV ranges are largely prescribed by table 5 [2]. The results are presented in table 5.3, which is presented in a similar format as table 8 [2].

The range is a defined quantity, presented in the column 'range' of table 5.3. The IEC 61400-50-2 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 EV air density, for all heights, does not meet the range requirement. This is caused by the limited variation of air density at the site with respect to the prescribed range.

The last column of table 5.3 represents the contribution to the preliminary accuracy class for each EV. From this we can draw the conclusion that shear has the highest influence on the accuracy.

Table 5.2: 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		41.9	0.25	0.07	2.117	0.145	0.008	0.013
		81.4	0.26	0.08	−1.918	−0.149	0.004	−0.010
		117.5	0.26	0.08	−3.478	−0.275	0.015	−0.034
turbulence intensity	%	41.9	11.59	2.42	0.069	0.167	0.004	0.011
		81.4	9.50	2.67	0.063	0.168	0.007	0.014
		117.5	8.45	2.49	0.068	0.169	0.009	0.016
precipitation†	%	41.9	12.61	29.69	0.000	−0.009	0.000	0.000
		81.4	11.84	29.09	0.007	0.203	0.015	0.024
		117.5	11.34	28.16	0.002	0.065	0.004	0.004
wind direction	°	41.9	238.60	36.67	−0.001	−0.045	0.001	−0.001
		81.4	242.79	37.31	−0.005	−0.198	0.016	−0.025
		117.5	256.03	43.45	−0.010	−0.426	0.023	−0.064
air temperature	°C	41.9	7.13	2.24	0.050	0.112	0.002	0.005
		81.4	7.01	2.21	0.100	0.220	0.005	0.015
		117.5	6.82	2.13	0.227	0.484	0.025	0.076
relative humidity	%	41.9	85.06	10.65	0.001	0.010	0.000	0.000
		81.4	84.83	10.83	0.004	0.041	0.002	0.002
		117.5	83.22	10.90	0.024	0.258	0.026	0.042
air density	kg/m^3	41.9	1.24	0.02	−2.585	−0.042	0.002	−0.002
		81.4	1.24	0.02	−14.000	−0.228	0.021	−0.033
		117.5	1.24	0.02	−26.370	−0.405	0.023	−0.061
flow inclination	°	41.9	1.36	0.45	−0.092	−0.041	0.000	0.000
		81.4	1.37	0.46	0.192	0.088	0.001	0.003
		117.5	1.48	0.55	−0.176	−0.097	0.002	−0.004
wind veer	°/m	41.9	−0.06	0.03	0.759	0.022	0.000	0.000
		81.4	−0.06	0.04	−0.534	−0.020	0.000	0.000
		117.5	−0.06	0.04	3.741	0.144	0.003	0.007
reference wind speed	m/s	41.9	8.02	2.60	−0.034	−0.088	0.001	−0.003
		81.4	8.93	2.82	0.110	0.311	0.022	0.046
		117.5	9.68	2.63	0.162	0.426	0.030	0.073

› 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 [2, p.18-19]. (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.)

› An environmental variable is considered significant if either the sensitivity exceeds the value of 0.5 %, or the product of the sensitivity and the correlation coefficient of the regression (sensitity $\times$ R), reported in the ultimate column, exceeds the value of 0.1 % [2, Clause 6.5]. The numbers in these columns are highlighted in orange if they cause the variable to be considered significant, otherwise they are blue.

† These variables employ a modified bin-count criterion [2, eq. 3, p.18]. In order to allow for a sensitivity analysis, the number of data points (N) is reduced to those data points that have a non-zero value.

Table 5.3: 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	41.9	29	2.540
						81.4	33	−2.302
						117.5	33	−4.174
turbulence intensity	%	3	24	1	21	41.9	57	1.455
						81.4	57	1.323
						117.5	52	1.420
precipitation	%	0	100	10	100	41.9	100	−0.031
						81.4	100	0.697
						117.5	100	0.231
wind direction	°	0	360	5	180	41.9	38	−0.219
						81.4	38	−0.958
						117.5	44	−1.766
air temperature	°C	0	40	2	40	41.9	25	2.000
						81.4	25	3.996
						117.5	25	9.098
relative humidity	%	0	100	10	100	41.9	40	0.098
						81.4	40	0.376
						117.5	40	2.364
air density	kg/m^3	0.9	1.35	0.05	0.45	41.9	22	−1.163
						81.4	22	−6.300
						117.5	22	−11.867
flow inclination	°	-3	3	0.2	6	41.9	37	−0.550
						81.4	37	1.153
						117.5	43	−1.057
wind veer	°/m	-0.3	0.1	0.04	0.4	41.9	40	0.304
						81.4	50	−0.213
						117.5	50	1.496
reference wind speed	m/s	4	16	0.5	12	41.9	79	−0.406
						81.4	88	1.321
						117.5	79	1.945

- The columns 'min', 'max' and 'bin' report the minimum and maximum value of the binning interval [2, Table 5, p.21], and the bin width [2, Table 3, p.18], 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 (3) and (4) [2, p.18-19]. If the covered range is less than 25 %, the sensitivity results for this environmental variable are considered unrepresentative. Unrepresentative covered ranges are highlighted in orange, otherwise they are blue.
- The product of m, the slope of the regression reported in table 5.2, 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.

Table 5.4: Distribution of environmental variables used in the lidar sensitivity study

variable	unit	height	min	Q1	median	Q3	max
		m	*unit*	*unit*	*unit*	*unit*	*unit*
shear exponent		41.9	−0.91	0.16	0.22	0.28	1.04
		81.4	−0.91	0.16	0.22	0.28	1.04
		117.5	−0.91	0.16	0.22	0.28	1.04
turbulence intensity	%	41.9	2.21	10.26	11.86	13.37	39.36
		81.4	1.89	7.94	9.90	11.64	36.65
		117.5	1.77	6.64	8.60	10.45	34.39
precipitation	%	41.9	0.00	0.00	0.00	0.00	100.00
		81.4	0.00	0.00	0.00	0.00	100.00
		117.5	0.00	0.00	0.00	0.00	100.00
air temperature	°C	41.9	−0.86	4.54	6.19	8.01	16.47
		81.4	−0.86	4.54	6.19	8.01	16.47
		117.5	−0.86	4.54	6.19	8.01	16.47
relative humidity	%	41.9	40.01	77.60	87.93	96.43	101.20
		81.4	40.01	77.60	87.93	96.43	101.20
		117.5	40.01	77.60	87.93	96.43	101.20
air density	kg/m^3	41.9	1.17	1.24	1.25	1.26	1.30
		81.4	1.17	1.24	1.25	1.26	1.30
		117.5	1.17	1.24	1.25	1.26	1.30
flow inclination	°	41.9	−12.76	0.72	1.24	1.73	21.47
		81.4	−12.76	0.72	1.24	1.73	21.47
		117.5	−12.76	0.72	1.24	1.73	21.47
wind veer	°/m	41.9	−1.19	−0.10	−0.06	−0.04	2.07
		81.4	−1.19	−0.10	−0.06	−0.04	2.07
		117.5	−1.19	−0.10	−0.06	−0.04	2.07
reference wind speed	m/s	41.9	4.00	5.86	8.09	10.63	15.96
		81.4	4.00	6.68	8.98	11.76	15.99
		117.5	4.01	7.14	9.50	12.51	16.00

- The lower and upper quartiles are indicated by Q1 and Q3. The minimum, median and maximum values represent Q0, Q2 and Q4. These quartiles indicate below what value 0 %, 25 %, 50 %, 75 % and 100 % of the data is found.
- The filters described in section 3.1 are only applied to the wind-related variables: rsd availability, reference wind speed, wind direction and - by extension - shear exponent, wind veer and turbulence intensity. All other variables are not filtered.
- All wind-related variables data is discarded when the wind speed is less than 2 m/s. At very low wind speeds, differences in the measured wind speed between the lidar and the reference meteorological mast lead to high percentage deviations that could skew the sensitivity regression. This filtering also causes the reference wind speed variable to not contain values below 2 m/s.
- Wind direction is omitted from this table, because it is a directional quantity.

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 Clause 8.2 [2].

1. Wind tunnel calibration
   The wind tunnel uncertainty, with a coverage factor of two ($k = 2$), is found in the wind tunnel calibration reports, see section B.1. The standard uncertainty ($k = 1$) is therefore the reported uncertainty divided by two.

2. Effects according to anemometer classification
   The classification of the Thies First Class Advanced cup anemometer is 0.9S (heating on), see section B.2 for the classification results according the IEC 61400-50-1:2022 [8]. The uncertainty in the wind speed due to operational characteristics therefore is

$$u_{\text{VS,class},i} = [0.5\,\% + 0.05\,\text{m/s}] \cdot \frac{0.9}{\sqrt{3}}$$

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 [9]. At the height of 117.5 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 uncertainty is at least 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.

$$u_{\text{f}} = 0.1\,\% \cdot F + 0.5\,\text{Hz}.$$

Table B.3 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

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

The total systematic uncertainty of the reference sensor is obtained by adding all contributions in quadrature. As in IEC 61400-50-2, this is referred to as 'reference type B' uncertainty in fig. A.2.

6.2 Remote sensing device

The following contributions to the uncertainty of the lidar wind speed measurements are taken into account in accordance with clause 8.3 [2].

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 [9, p.74].

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

   The mounting uncertainty is reported in tables 4.2 to 4.4.
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 [10] based on the terrain information shown in fig. 2.2.

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

As the separation distance does not compromise the criteria as stated in clause 6.2, item d [2, p.14], no additional uncertainty contribution is taken into account.

The total lidar uncertainty is obtained by adding in quadrature the contributions above. The result is reported in the last column of tables 4.2 to 4.4. An overview of the various uncertainty contributions is presented in fig. A.2.

The uncertainty interval shown in figs. 4.4 to 4.6 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 61400-50-2:2022. No deviations are to be reported in this respect.

8 Conclusions

The Wind@Sea lidar ZX 300M ZX1524 is validated against reference meteorological mast MM6 at the RSD verification location at the EWTW test site in the Wieringermeer. In this campaign the lidar is validated at three measurement heights ranging from 42 m to 118 m.

During the measurement campaign that ran from 22 November 2024 00:00 UTC until 7 January 2025 00:00, spanning 46 days, all data coverage requirements of the IEC 61400-50-2:2022 are met.

For all comparison heights the regression slope is close to 1.00 and the offset is up to 0.12 m/s with an R^2 close to 1. The maximum deviation observed is 1.5 %. The sensitivity analysis did not result in any significant sensitivities for the lidar. For the air density at all comparison heights the range covered was insufficient.

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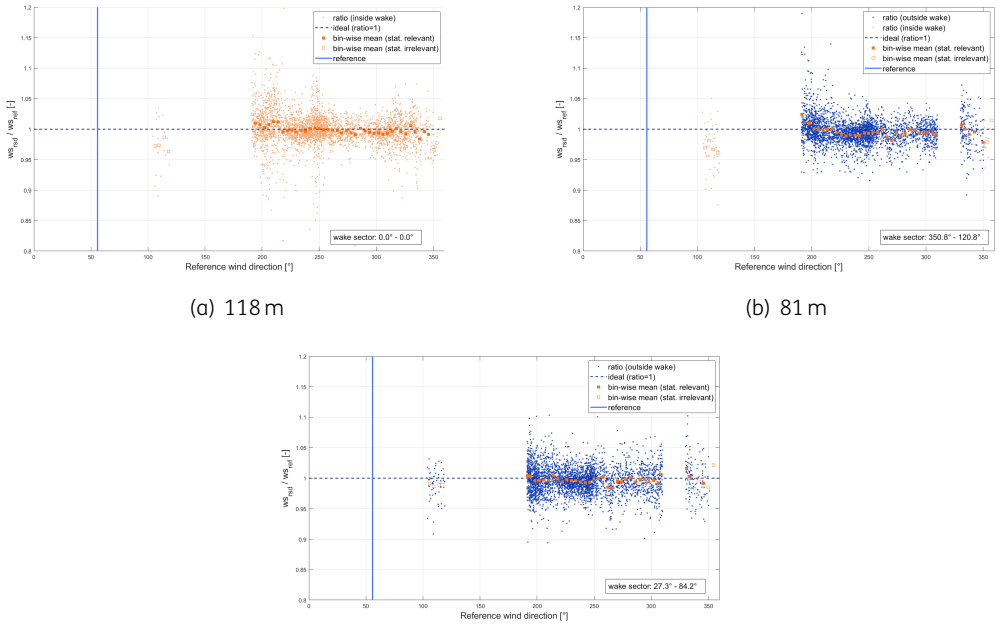
Signature

	Date: January 2025	**Report number:** TNO 2025 R10084
Title	Verification of the Wind@Sea Lidar ZX1524 at the EWTW test site near meteorological mast MM6 Period: 22 November 2024 to 7 January 2025	
Author(s)	G. Bergman	
Principal(s)	Ministry of Economic Affairs and Climate (EZK)	
Project number **Programme(s)**	060.63173 Wind Energy	
Abstract As part of a lidar verification campaign a ZX Lidars lidar with serial number ZX1524 was deployed near MM6 at the EWTW test site in the Wieringermeer. This report describes the verification campaign for the lidar.		
Keywords	Wind@Sea, ZX 300M, ECN Wind Turbine test site Wieringermeer, K13-A, lidar, verification	

Task	Name	Role	Signature
Author	G. Bergman	Data analyst	ValidSigned by Gerben Bergman on 2025-01-28 09:04:18
Expert review	D.A.J. Wouters	Data analyst	ValidSigned by Dennis Wouters on 2025-01-28 09:35:57
Generic review	J.P. Verhoef	Project manager	ValidSigned by Hans Verhoef on 2025-01-29 09:04:01
Approval	R.H.M. Giepman	Deputy research manager	ValidSigned by Rogier Giepman on 2025-01-29 13:15:36
Authorization	E.D. Nennie	Research manager	ValidSigned by Rogier Giepman on 2025-01-29 13:15:37

Appendix A
IEC visualisations

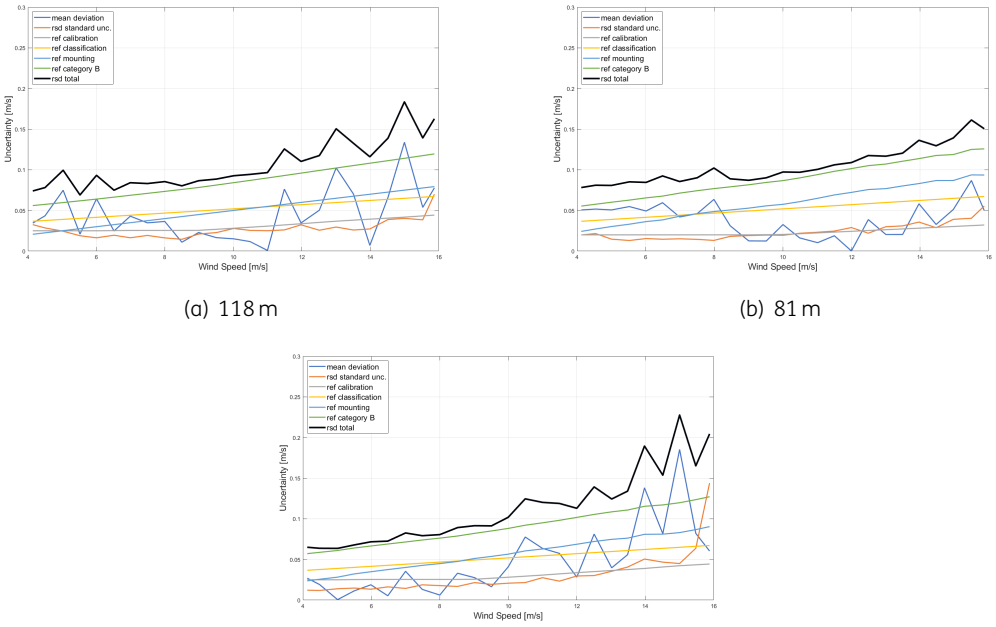
This appendix contains visualizations associated with the IEC analysis reported in chapters 4 and 5 that are not a reporting requirement.



(a) 118 m (b) 81 m

(c) 42 m

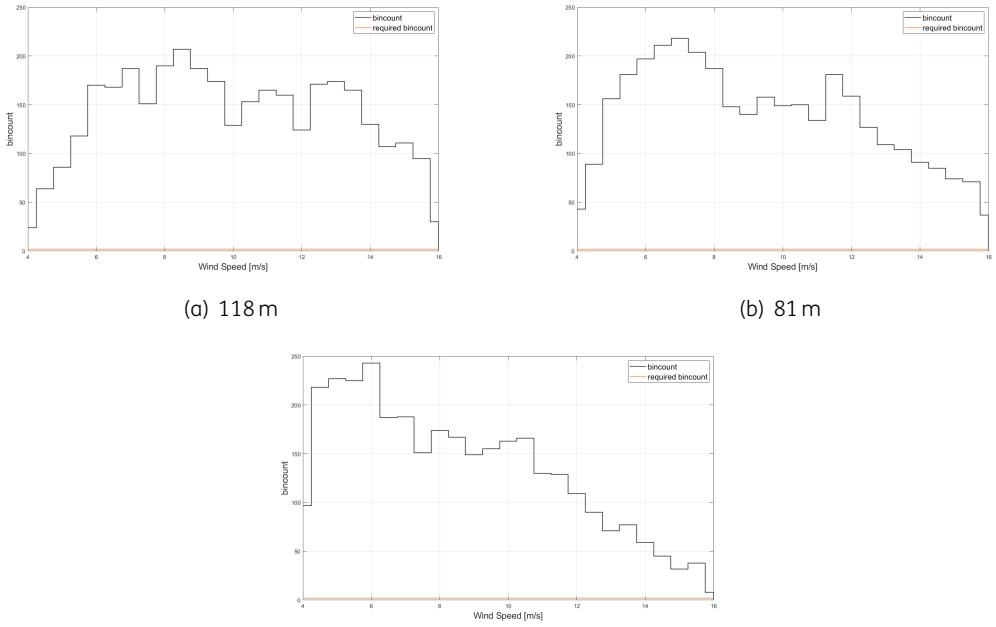
Figure A.1: Influence of the wake of meteorological mast on the lidar. The ratio of the wind speed measured by the lidar (rsd) and the reference meteorological mast MM6 (ref) is plotted against the wind direction measured by the reference meteorological mast. The blue line marks the direction for which the wind flows over the reference meteorological mast MM6 towards the lidar. The orange 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) 118 m (b) 81 m

(c) 42 m

Figure A.2: Contributions to the lidar uncertainty



(a) 118 m (b) 81 m

(c) 42 m

Figure A.3: Histograms for bin-wise wind speed comparison

Appendix 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 [11].

At the meteorological mast measurement heights, as seen in fig. 2.7, the meteorological mast measurements are compared to the lidar measurements. Table B.1 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 B.2. Other statistics are based on pseudo signals, presented in table B.4, which are calculated signals.

The sensors used to measure these signals and the data acquisition modules they are attached to are listed in table B.3. This table also presents installation and calibration due dates.

Table B.1: Signals used for each comparison height

height (m)	met mast	lidar
	wind speed	
117.5	MM6_H117d5_Ws_Q1_avg	Horizontal Wind Speed (m/s) at 118m
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 42m
	wind direction	
117.5	MM6_H112d5B320_Wd_Q1_avg	Wind Direction (deg) at 118m
81.4	MM6_H077d4B320_Wd_Q1_avg	Wind Direction (deg) at 81m
41.9	MM6_H037d9B320_Wd_Q1_avg	Wind Direction (deg) at 42m

Table B.2: List of measured signals

name	location	short name	sensor	unit	installed	rate	ISO
						Hz	
wind speed, 117.5 m, centre	MM6	MM6_H117d5_Ws_Q1_m	Thies First Class Advanced 4.3352.00.000	m/s	TNO	4	*
wind speed, 112.5 m, 140°	MM6	MM6_H112d5B140_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, 112.5 m, 320°	MM6	MM6_H112d5B320_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, 109 m	MM6	MM6_H109_Temp_Q1_m	Vaisala RHT probe HMP155D	°C	TNO	4	*
relative humidity, 109 m	MM6	MM6_H109_RH_Q1_m	Vaisala RHT probe HMP155D	%	TNO	4	*
air pressure, 109 m	MM6	MM6_H109_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	*
wind speed, sonic u, 108.5 m, 140°	MM6	MM6_H108d5B140_S_U_Q5_m	Metek 3D ultrasonic anemometer	m/s	TNO	4	*
wind speed, sonic v, 108.5 m, 140°	MM6	MM6_H108d5B140_S_V_Q5_m	Metek 3D ultrasonic anemometer	m/s	TNO	4	*
wind speed, sonic w, 108.5 m, 140°	MM6	MM6_H108d5B140_S_W_Q5_m	Metek 3D ultrasonic anemometer	m/s	TNO	4	*

Table B.3: List of equipment used per signal

Signal	Sensor						Module				
short name	brand / type	ID	gain	offset†	cal. due date‡	inst. date	type	ID	gain	off-set	cal. due date
MM6_H117d5_Ws_Q1_m	Thies 4.3352.00.000	94025518	4.579e-2	2.2051e-1	2025-06-25	2024-06-25	NI 9423	94011863	1.000	0.000	2026-12-11
MM6_H112d5B140_Ws_Q1_m	Thies 4.3352.00.000	94025509	4.586e-2	1.9731e-1	2025-06-25	2024-06-25	NI 9423	94011863	1.000	0.000	2026-12-11
MM6_H081d4B140_Ws_Q1_m	Thies 4.3352.00.000	94028566	4.587e-2	2.1863e-1	2025-06-25	2024-06-25	NI 9423	94011863	1.000	0.000	2026-12-11
MM6_H081d4B320_Ws_Q1_m	Thies 4.3352.00.000	94025507	4.5769e-2	2.229e-1	2025-06-25	2024-06-25	NI 9423	94011863	1.000	0.000	2026-12-11
MM6_H041d9B140_Ws_Q1_m	Thies 4.3352.00.000	94028568	4.582e-2	2.0849e-1	2025-06-25	2024-06-25	NI 9423	94011863	1.000	0.000	2026-12-11
MM6_H041d9B320_Ws_Q1_m	Thies 4.3352.00.000	94025516	4.579e-2	2.0694e-1	2025-06-25	2024-06-25	NI 9423	94011863	1.000	0.000	2026-12-11
MM6_H112d5B320_Wd_Q1_m	Thies 4.3150.00.400	94012496	1.000e-1	-2.54e+1	2025-06-25	2024-06-25	NI 9871	94012138	1.000	0.000	N/A
MM6_H077d4B320_Wd_Q1_m	Thies 4.3150.00.400	94012006	1.000e-1	-3.91e+1	2025-06-25	2024-06-25	NI 9871	94012138	1.000	0.000	N/A
MM6_H037d9d9B320_Wd_Q1_m	Thies 4.3150.00.400	94012544	1.000e-1	2.892e+2	2025-06-25	2024-06-25	NI 9871	94012138	1.000	0.000	N/A
MM6_H109_Temp_Q1_m	Vaisala HMP155	94012135	1.000e-2	0.000	2025-06-25	2024-06-25	NI 9871	94012165	1.000	0.000	N/A
MM6_H109_RH_Q1_m	Vaisala HMP155	94012135	1.000e-2	0.000	2025-06-25	2024-06-25	NI 9871	94012165	1.000	0.000	N/A
MM6_H109_Pair_Q1_m	Vaisala PTB210	94012574	1.000e-2	0.000	2025-06-25	2024-06-25	NI 9871	94012138	1.000	0.000	N/A
MM6_H040_Prec_Q1_m	Thies 5.4103.10.000	94012476	1.000	0.000	2025-06-25	2024-06-25	NI 9423	94011863	1.000	0.000	N/A
MM6_H108d5B140_WsUS_Q1_m	Metek 3D ultrasonic	94012345	1.000e-2	0.000	2025-03-30	2029-05-22	NI 9871	94012165	1.000	0.000	N/A
MM6_H108d5B140_WsVS_Q1_m	Metek 3D ultrasonic	94012345	1.000e-2	0.000	2025-03-30	2029-05-22	NI 9871	94012165	1.000	0.000	N/A
MM6_H108d5B140_WsWS_Q1_m	Metek 3D ultrasonic	94012345	1.000e-2	0.000	2025-03-30	2029-05-22	NI 9871	94012165	1.000	0.000	N/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.

‡ For cup anemometers and wind vanes the (annual) calibration due date is based on the installation date (not the wind tunnel calibration date).

Table B.4: 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_MFDC_Q1_m MM6_H081d4B320_Ws_MFDC_Q1_m	B.1
wind speed, 41.9 m	MM6_H041d9_Ws_True_Q1	m/s	4	*	MM6_H037d9_Wd_Q1 MM6_H041d9B140_Ws_MFDC_Q1_m MM6_H041d9B320_Ws_MFDC_Q1_m	B.2
horizontal wind speed, sonic, 108.5 m	MM6_H108d5B140_WsHor_Q1	m/s	4	*	MM6_H108d5B140_WsUSon_Q1_m MM6_H108d5B140_WsVSon_Q1_m	B.3

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

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

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

B.1 Calibration sheets

B.1.1 Cup anemometer

DEUTSCHE WINDGUARD

IECRE and MEASNET approved test laboratory

Calibration Certificate / *Kalibrierschein*

issued by the calibration laboratory / *erstellt durch das Kalibrierlaboratorium*

Deutsche WindGuard Wind Tunnel Services GmbH

Member of / *Mitglied im*
Deutschen Kalibrierdienst

accredited to / *akkreditiert nach*
DIN EN ISO/IEC 17025:2018

Calibration mark / *Kalibrierzeichen*: 2411412 | D-K-15140-01-00 | 05/2024

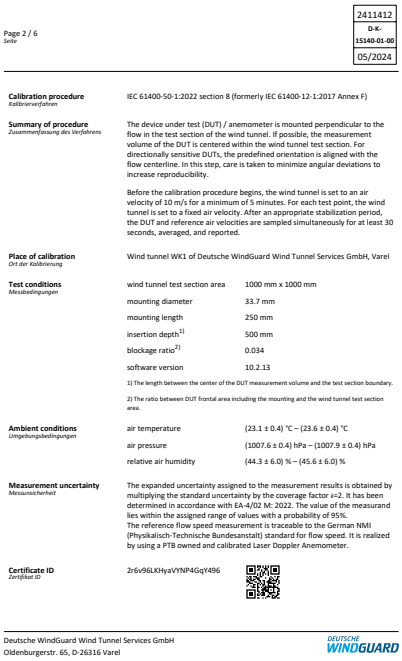
Device under test (DUT) *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies CLIMA
Type *Typ*	4.3352.00.000
Serial number *Fabrikat/Serien-Nr.*	04201562 94025518
Customer *Auftraggeber*	TNO NL - 1755 LE Petten
Order No. *Auftragsnummer*	3100409804
Project No. *Projektnummer*	VT240267
Number of pages *Anzahl der Seiten*	6
Date of Calibration *Datum der Kalibrierung*	2024-05-17

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 presented results relate only to the calibrated object. 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. Die dargestellten Ergebnisse beziehen sich nur auf den kalibrierten Gegenstand. 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 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 des ausstellenden Kalibrierlaboratoriums. Kalibrierscheine ohne Unterschrift haben keine Gültigkeit. Dieser Kalibrierschein wurde elektronisch erzeugt.

Date / *Datum*	Freigegeben durch / *Approval by* Head of the calibration laboratory	Person in charge / *Bearbeiter*
2024-05-17	Heiko Westermann	Janika Bachmann

(a) Cup anemometer 94025518, page 1/4



2411412 | D-K-15140-01-00 | 05/2024

Calibration procedure *Kalibrierverfahren*: IEC 61400-50-1:2022 section 8 (formerly IEC 61400-12-1:2017 Annex F)

Summary of procedure *Zusammenfassung des Verfahrens*

The device under test (DUT) / anemometer is mounted perpendicular to the flow in the test section of the wind tunnel. If possible, the measurement volume of the DUT is centered within the wind tunnel test section. For directionally sensitive DUTs, the predefined orientation is aligned with the flow centerline. In this step, care is taken to minimize angular deviations to increase reproducibility.

Before the calibration procedure begins, the wind tunnel is set to an air velocity of 10 m/s for a minimum of 5 minutes. For each test point, the wind tunnel is set to a fixed air velocity. After an appropriate stabilization period, the DUT and reference air velocities are sampled simultaneously for at least 30 seconds, averaged, and reported.

Place of calibration *Ort der Kalibrierung*: Wind tunnel WK1 of Deutsche WindGuard Wind Tunnel Services GmbH, Varel

Test conditions *Messbedingungen*

wind tunnel test section area	1000 mm x 1000 mm
mounting diameter	33.7 mm
mounting length	250 mm
insertion depth[1]	500 mm
blockage ratio[2]	0.034
software version	10.2.13

1) The length between the center of the DUT measurement volume and the test section boundary.

2) The ratio between DUT frontal area including the mounting and the wind tunnel test section area.

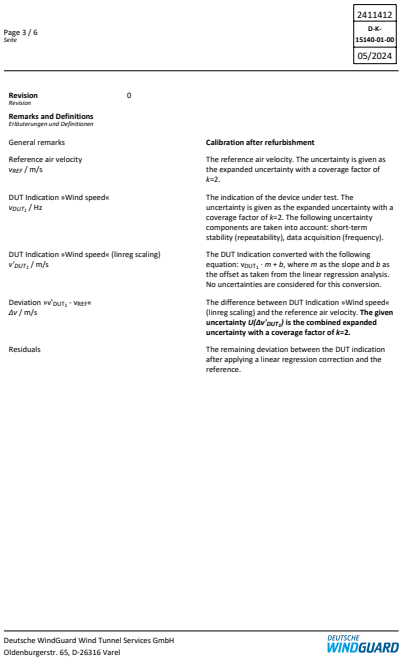
Ambient conditions *Umgebungsbedingungen*

air temperature	(23.1 ± 0.4) °C – (23.6 ± 0.4) °C
air pressure	(1007.6 ± 0.4) hPa – (1007.9 ± 0.4) hPa
relative air humidity	(44.3 ± 6.0) % – (45.6 ± 6.0) %

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 EA-4/02 M: 2022. 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.

Certificate ID *Zertifikat ID*: 2r6v96LKHyaVYNP4GqY496

(b) Cup anemometer 94025518, page 2/4



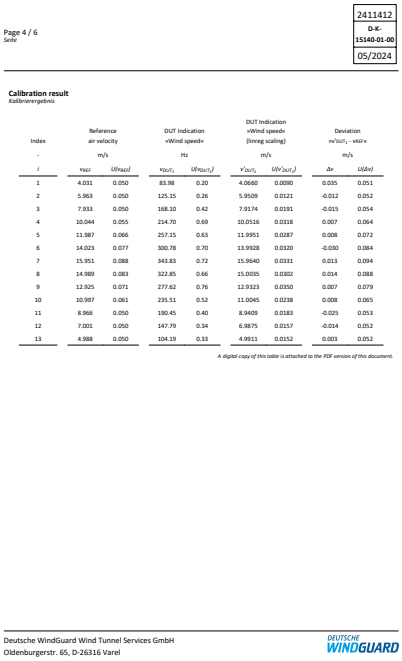
2411412 | D-K-15140-01-00 | 05/2024

Revision *Revision*: 0

Remarks and Definitions *Erläuterungen und Definitionen*

General remarks	**Calibration after refurbishment**
Reference air velocity v_{REF} / m/s	The reference air velocity. The uncertainty is given as the expanded uncertainty with a coverage factor of *k*=2.
DUT Indication »Wind speed« v_{DUT_i} / Hz	The indication of the device under test. The uncertainty is given as the expanded uncertainty with a coverage factor of *k*=2. The following uncertainty components are taken into account: short-term stability (repeatability), data acquisition (frequency).
DUT Indication »Wind speed« (linreg scaling) v'_{DUT_i} / m/s	The DUT Indication converted with the following equation: $v_{DUT_i} \cdot m + b$, where *m* as the slope and *b* as the offset as taken from the linear regression analysis. No uncertainties are considered for this conversion.
Deviation »v'_{DUT_i} - v_{REF}« Δv / m/s	The difference between DUT Indication »Wind speed« (linreg scaling) and the reference air velocity. **The given uncertainty $U(\Delta v'_{DUT_i})$ is the combined expanded uncertainty with a coverage factor of *k*=2.**
Residuals	The remaining deviation between the DUT indication after applying a linear regression correction and the reference.

(c) Cup anemometer 94025518, page 3/4



2411412 | D-K-15140-01-00 | 05/2024

Calibration result *Kalibrierergebnis*

Index	Reference air velocity		DUT Indication »Wind speed«		DUT Indication »Wind speed« (linreg scaling)		Deviation »v'_{DUT_i} - v_{REF}«
-	m/s		Hz		m/s		m/s
i	v_{REF}	$U(v_{REF})$	v_{DUT_i}	$U(v_{DUT_i})$	v'_{DUT_i}	$U(v'_{DUT_i})$	Δv $U(\Delta v)$
1	4.031	0.050	83.98	0.20	4.0660	0.0090	0.035 0.051
2	5.963	0.050	125.15	0.26	5.9509	0.0121	-0.012 0.052
3	7.933	0.050	168.10	0.42	7.9174	0.0191	-0.015 0.054
4	10.044	0.055	214.70	0.69	10.0516	0.0318	0.007 0.064
5	11.987	0.066	257.15	0.63	11.9951	0.0287	0.008 0.072
6	14.023	0.077	300.78	0.70	13.9928	0.0320	-0.030 0.084
7	15.951	0.088	343.83	0.72	15.9640	0.0331	0.013 0.094
8	14.989	0.083	322.85	0.66	15.0035	0.0302	0.014 0.088
9	12.925	0.071	277.62	0.76	12.9323	0.0350	0.007 0.079
10	10.997	0.061	235.51	0.52	11.0045	0.0238	0.008 0.065
11	8.966	0.050	190.45	0.40	8.9409	0.0183	-0.025 0.053
12	7.001	0.050	147.79	0.34	6.9875	0.0157	-0.014 0.052
13	4.988	0.050	104.19	0.33	4.9911	0.0152	0.003 0.052

A digital copy of this table is attached to the PDF version of this document.

(d) Cup anemometer 94025518, page 4/4

DEUTSCHE WINDGUARD

IECRE and MEASNET approved test laboratory

Calibration Certificate / *Kalibrierschein*

issued by the calibration laboratory / *erstellt durch das Kalibrierlaboratorium*

Deutsche WindGuard
Wind Tunnel Services GmbH

Member of / *Mitglied im*
Deutschen Kalibrierdienst

accredited to / *akkreditiert nach*
DIN EN ISO/IEC 17025:2018

DKD

Calibration mark
Kalibrierzeichen

2411411
D-K-15140-01-00
05/2024

Device under test (DUT) *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies CLIMA
Type *Typ*	4.3352.00.000
Serial number *Fabrikat/Serien-Nr.*	04201559 94025509
Customer *Auftraggeber*	TNO NL - 1755 LE Petten
Order No. *Auftragsnummer*	3100409804
Project No. *Projektnummer*	VT240267
Number of pages *Anzahl der Seiten*	6
Date of Calibration *Datum der Kalibrierung*	2024-05-17

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 presented results relate only to the calibrated object. 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. Die dargestellten Ergebnisse beziehen sich nur auf den kalibrierten Gegenstand. Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

Date *Datum*	Freigegeben durch / *Approval by* Head of the calibration laboratory	Person in charge *Bearbeiter*
2024-05-17	Heiko Westermann	Janika Bachmann

(e) Cup anemometer 94025509, page 1/4

Calibration procedure
Kalibrierverfahren
IEC 61400-50-1:2022 section 8 (formerly IEC 61400-12-1:2017 Annex F)

Summary of procedure
Zusammenfassung des Verfahrens
The device under test (DUT) / anemometer is mounted perpendicular to the flow in the test section of the wind tunnel. If possible, the measurement volume of the DUT is centered within the wind tunnel test section. For directionally sensitive DUTs, the predefined orientation is aligned with the flow centerline. In this step, care is taken to minimize angular deviations to increase reproducibility.

Before the calibration procedure begins, the wind tunnel is set to an air velocity of 10 m/s for a minimum of 5 minutes. For each test point, the wind tunnel is set to a fixed air velocity. After an appropriate stabilization period, the DUT and reference air velocities are sampled simultaneously for at least 30 seconds, averaged, and reported.

Place of calibration
Ort der Kalibrierung
Wind tunnel WK1 of Deutsche WindGuard Wind Tunnel Services GmbH, Varel

Test conditions
Messbedingungen

wind tunnel test section area	1000 mm x 1000 mm
mounting diameter	33.7 mm
mounting length	250 mm
insertion depth[1)]	500 mm
blockage ratio[2)]	0.034
software version	10.2.13

1) The length between the center of the DUT measurement volume and the test section boundary.

2) The ratio between DUT frontal area including the mounting and the wind tunnel test section area.

Ambient conditions
Umgebungsbedingungen

air temperature	(22.9 ± 0.4) °C – (23.5 ± 0.4) °C
air pressure	(1007.6 ± 0.4) hPa – (1008.0 ± 0.4) hPa
relative air humidity	(44.4 ± 6.0) % – (46.4 ± 6.0) %

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 EA-4/02 M: 2022. 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.

Certificate ID
Zertifikat ID
FSQRBTqzEN9j4zbiUfGk2y

(f) Cup anemometer 94025509, page 2/4

Revision 0
Revision

Remarks and Definitions
Erläuterungen und Definitionen

General remarks

Calibration after refurbishment

Reference air velocity
v_{REF} / m/s

The reference air velocity. The uncertainty is given as the expanded uncertainty with a coverage factor of *k*=2.

DUT Indication »Wind speed«
v_{DUT_1} / Hz

The indication of the device under test. The uncertainty is given as the expanded uncertainty with a coverage factor of *k*=2. The following uncertainty components are taken into account: short-term stability (repeatability), data acquisition (frequency).

DUT Indication »Wind speed« (linreg scaling)
v'_{DUT_1} / m/s

The DUT indication converted with the following equation: $v_{DUT_1} \cdot m + b$, where *m* as the slope and *b* as the offset as taken from the linear regression analysis. No uncertainties are considered for this conversion.

Deviation $v'_{DUT_1} - v_{REF}$
Δv / m/s

The difference between DUT Indication »Wind speed« (linreg scaling) and the reference air velocity. **The given uncertainty $U(\Delta v'_{DUT_1})$ is the combined expanded uncertainty with a coverage factor of *k*=2.**

Residuals

The remaining deviation between the DUT indication after applying a linear regression correction and the reference.

(g) Cup anemometer 94025509, page 3/4

Calibration result
Kalibrierergebnis

Index	Reference air velocity		DUT Indication »Wind speed«		DUT Indication »Wind speed« (linreg scaling)		Deviation $v'_{DUT_1} - v_{REF}$	
-	m/s		Hz		m/s		m/s	
i	v_{REF}	$U(v_{REF})$	v_{DUT_1}	$U(v_{DUT_1})$	v'_{DUT_1}	$U(v'_{DUT_1})$	Δv	$U(\Delta v)$
1	4.044	0.050	83.94	0.20	4.0469	0.0091	0.003	0.051
2	5.948	0.050	125.48	0.30	5.9522	0.0136	0.004	0.052
3	7.946	0.050	168.26	0.37	7.9142	0.0170	-0.032	0.053
4	10.048	0.055	214.06	0.48	10.0148	0.0220	-0.033	0.060
5	11.978	0.066	257.43	0.61	12.0036	0.0278	0.025	0.072
6	14.017	0.077	301.23	0.69	14.0127	0.0316	-0.004	0.083
7	15.956	0.088	343.41	0.74	15.9472	0.0339	-0.009	0.094
8	14.983	0.083	322.15	0.69	14.9720	0.0317	-0.011	0.088
9	12.928	0.071	278.00	0.60	12.9471	0.0274	0.019	0.076
10	11.095	0.061	237.70	0.53	11.0989	0.0242	0.004	0.066
11	8.974	0.050	192.32	0.43	9.0178	0.0199	0.044	0.054
12	6.904	0.050	145.93	0.37	6.8900	0.0170	-0.014	0.053
13	5.012	0.050	105.06	0.32	5.0157	0.0145	0.003	0.052

A digital copy of this table is attached to the PDF version of this document.

(h) Cup anemometer 94025509, page 4/4

DEUTSCHE WINDGUARD

IECRE and MEASNET approved test laboratory

Calibration Certificate / *Kalibrierschein*

issued by the calibration laboratory / *erstellt durch das Kalibrierlaboratorium*

Deutsche WindGuard
Wind Tunnel Services GmbH

Member of / *Mitglied im*
Deutschen Kalibrierdienst

accredited to / *akkreditiert nach*
DIN EN ISO/IEC 17025:2018

Calibration mark
Kalibrierzeichen

2411416
D-K-15140-01-00
05/2024

Device under test (DUT) *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies CLIMA
Type *Typ*	4.3352.00.000
Serial number *Fabrikat/Serien-Nr.*	10191176 94028566
Customer *Auftraggeber*	TNO NL - 1755 LE Petten
Order No. *Auftragsnummer*	3100409804
Project No. *Projektnummer*	VT240267
Number of pages *Anzahl der Seiten*	6
Date of Calibration *Datum der Kalibrierung*	2024-05-17

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 presented results relate only to the calibrated object. The user is obliged to have the object recalibrated at appropriate intervals.
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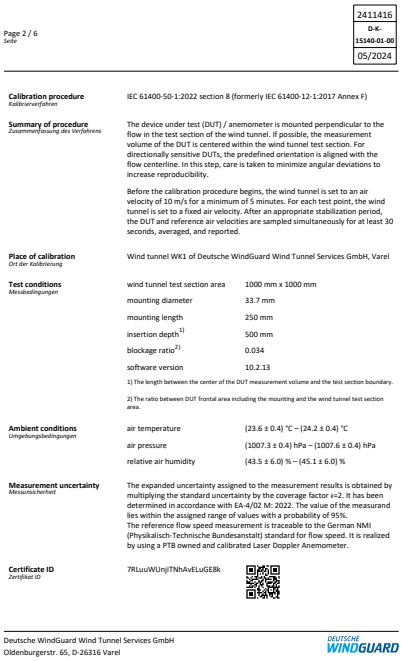
Die DAkkS ist Unterzeichner der multilateralen Übereinkommen der European co-operation for Accreditation (EA) und der International Laboratory Accreditation Cooperation (ILAC) zur gegenseitigen Anerkennung der Kalibrierscheine. Die dargestellten Ergebnisse beziehen sich nur auf den kalibrierten Gegenstand. Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

Date *Datum*	Freigegeben durch / *Approval by* Head of the calibration laboratory	Person in charge *Bearbeiter*
2024-05-17	Heiko Westermann	Janika Bachmann

(i) Cup anemometer 94028566, page 1/4



Calibration procedure *Kalibrierverfahren*
IEC 61400-50-1:2022 section 8 (formerly IEC 61400-12-1:2017 Annex F)

Summary of procedure *Zusammenfassung des Verfahrens*
The device under test (DUT) / anemometer is mounted perpendicular to the flow in the test section of the wind tunnel. If possible, the measurement volume of the DUT is centered within the wind tunnel test section. For directionally sensitive DUTs, the predefined orientation is aligned with the flow centerline. In this step, care is taken to minimize angular deviations to increase reproducibility.

Before the calibration procedure begins, the wind tunnel is set to an air velocity of 10 m/s for a minimum of 5 minutes. For each test point, the wind tunnel is set to a fixed air velocity. After an appropriate stabilization period, the DUT and reference air velocities are sampled simultaneously for at least 30 seconds, averaged, and reported.

Place of calibration *Ort der Kalibrierung*
Wind tunnel WK1 of Deutsche WindGuard Wind Tunnel Services GmbH, Varel

Test conditions *Messbedingungen*

wind tunnel test section area	1000 mm x 1000 mm
mounting diameter	33.7 mm
mounting length	250 mm
insertion depth [1]	500 mm
blockage ratio [2]	0.034
software version	10.2.13

1) The length between the center of the DUT measurement volume and the test section boundary.

2) The ratio between DUT frontal area including the mounting and the wind tunnel test section area.

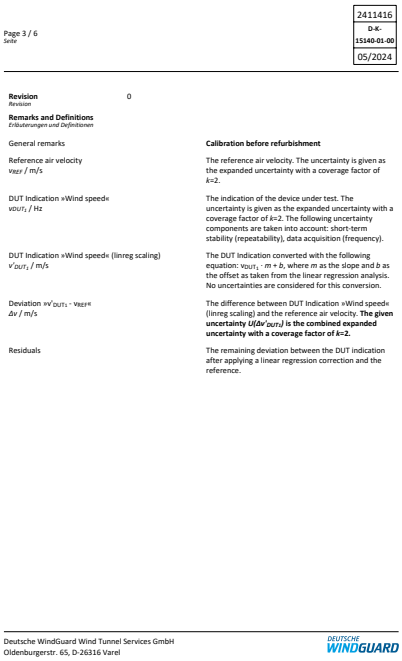
Ambient conditions *Umgebungsbedingungen*

air temperature	(23.6 ± 0.4) °C – (24.2 ± 0.4) °C
air pressure	(1007.3 ± 0.4) hPa – (1007.6 ± 0.4) hPa
relative air humidity	(43.5 ± 6.0) % – (45.1 ± 6.0) %

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 EA-4/02 M: 2022. 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.

Certificate ID *Zertifikat ID*
7RLuuWUnjiTNhAvELuGE8k

(j) Cup anemometer 94028566, page 2/4



Revision 0

Remarks and Definitions
Erläuterungen und Definitionen

General remarks

Calibration before refurbishment

Reference air velocity
v_{REF} / m/s
The reference air velocity. The uncertainty is given as the expanded uncertainty with a coverage factor of *k*=2.

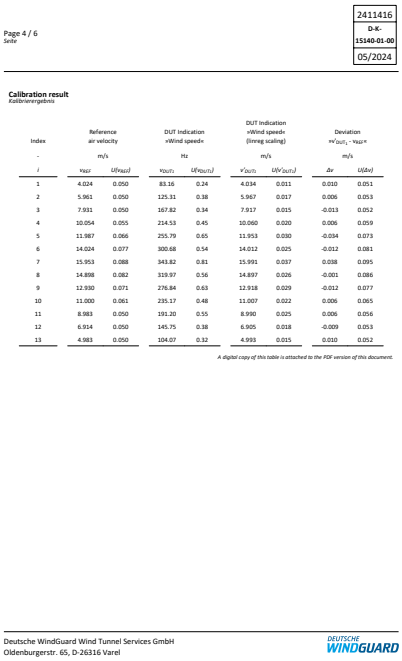
DUT Indication »Wind speed«
v_{DUT_i} / Hz
The indication of the device under test. The uncertainty is given as the expanded uncertainty with a coverage factor of *k*=2. The following uncertainty components are taken into account: short-term stability (repeatability), data acquisition (frequency).

DUT Indication »Wind speed« (linreg scaling)
v'_{DUT_i} / m/s
The DUT indication converted with the following equation: $v_{DUT_i} \cdot m + b$, where *m* as the slope and *b* as the offset as taken from the linear regression analysis. No uncertainties are considered for this conversion.

Deviation $v'_{DUT_i} - v_{REF_i}$
Δv / m/s
The difference between DUT Indication »Wind speed« (linreg scaling) and the reference air velocity. **The given uncertainty $U(\Delta v'_{DUT_i})$ is the combined expanded uncertainty with a coverage factor of *k*=2.**

Residuals
The remaining deviation between the DUT indication after applying a linear regression correction and the reference.

(k) Cup anemometer 94028566, page 3/4



Calibration result
Kalibrierergebnis

Index	Reference air velocity		DUT Indication »Wind speed«		DUT Indication »Wind speed« (linreg scaling)		Deviation $v'_{DUT_i} - v_{REF}$	
-	m/s		Hz		m/s		m/s	
i	v_{REF}	$U(v_{REF})$	v_{DUT_i}	$U(v_{DUT_i})$	v'_{DUT_i}	$U(v'_{DUT_i})$	Δv	$U(\Delta v)$
1	4.024	0.050	83.16	0.24	4.034	0.011	0.010	0.051
2	5.961	0.050	125.31	0.38	5.967	0.017	0.006	0.053
3	7.931	0.050	167.82	0.34	7.917	0.015	-0.013	0.052
4	10.054	0.055	214.53	0.45	10.060	0.020	0.006	0.059
5	11.987	0.066	255.79	0.65	11.953	0.030	-0.034	0.073
6	14.024	0.077	300.68	0.54	14.012	0.025	-0.012	0.081
7	15.953	0.088	343.82	0.81	15.991	0.037	0.038	0.095
8	14.898	0.082	319.97	0.56	14.897	0.026	-0.001	0.086
9	12.930	0.071	276.84	0.63	12.918	0.029	-0.012	0.077
10	11.000	0.061	235.17	0.48	11.007	0.022	0.006	0.065
11	8.983	0.050	191.20	0.55	8.990	0.025	0.006	0.056
12	6.914	0.050	145.75	0.38	6.905	0.018	-0.009	0.053
13	4.983	0.050	104.07	0.32	4.993	0.015	0.010	0.052

A digital copy of this table is attached to the PDF version of this document.

(l) Cup anemometer 94028566, page 4/4

DEUTSCHE WINDGUARD

IECRE and MEASNET approved test laboratory

Calibration Certificate / *Kalibrierschein*

issued by the calibration laboratory / *erstellt durch das Kalibrierlaboratorium*

Deutsche WindGuard
Wind Turbine Services GmbH

Member of / *Mitglied im*
Deutschen Kalibrierdienst

accredited to / *akkreditiert nach*
DIN EN ISO/IEC 17025:2018

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

DKD

Calibration mark
Kalibrierzeichen

2411408
D-K-15140-01-00
05/2024

Device under test (DUT) *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies CLIMA
Type *Typ*	4.3352.00.000
Serial number *Fabrikat/Serien-Nr.*	04201554 94025507
Customer *Auftraggeber*	TNO NL - 1755 LE Petten
Order No. *Auftragsnummer*	3100409804
Project No. *Projektnummer*	VT240267
Number of pages *Anzahl der Seiten*	6
Date of Calibration *Datum der Kalibrierung*	2024-05-17

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 presented results relate only to the calibrated object. 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. Die dargestellten Ergebnisse beziehen sich nur auf den kalibrierten Gegenstand. Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

Date *Datum*	Freigegeben durch / *Approval by* Head of the calibration laboratory	Person in charge *Bearbeiter*
2024-05-17	Heiko Westermann	Janika Bachmann

(m) Cup anemometer 94025507, page 1/4

2411408
D-K-15140-01-00
05/2024

Calibration procedure *Kalibrierverfahren*	IEC 61400-50-1:2022 section 8 (formerly IEC 61400-12-1:2017 Annex F)	
Summary of procedure *Zusammenfassung des Verfahrens*	The device under test (DUT) / anemometer is mounted perpendicular to the flow in the test section of the wind tunnel. If possible, the measurement volume of the DUT is centered within the wind tunnel test section. For directionally sensitive DUTs, the predefined orientation is aligned with the flow centerline. In this step, care is taken to minimize angular deviations to increase reproducibility. Before the calibration procedure begins, the wind tunnel is set to an air velocity of 10 m/s for a minimum of 5 minutes. For each test point, the wind tunnel is set to a fixed air velocity. After an appropriate stabilization period, the DUT and reference air velocities are sampled simultaneously for at least 30 seconds, averaged, and reported.	
Place of calibration *Ort der Kalibrierung*	Wind tunnel WK1 of Deutsche WindGuard Wind Turbine Services GmbH, Varel	
Test conditions *Messbedingungen*	wind tunnel test section area	1000 mm x 1000 mm
	mounting diameter	33.7 mm
	mounting length	250 mm
	insertion depth[1]	500 mm
	blockage ratio[2]	0.034
	software version	10.2.13
Ambient conditions *Umgebungsbedingungen*	air temperature	(22.7 ± 0.4) °C – (23.2 ± 0.4) °C
	air pressure	(1007.5 ± 0.4) hPa – (1007.8 ± 0.4) hPa
	relative air humidity	(44.5 ± 6.0) % – (46.5 ± 6.0) %
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 EA-4/02 M: 2022. 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.	
Certificate ID *Zertifikat ID*	dSjHLbhQadRUv9LyhmrNDV	

1) The length between the center of the DUT measurement volume and the test section boundary.

2) The ratio between DUT frontal area including the mounting and the wind tunnel test section area.

(n) Cup anemometer 94025507, page 2/4

2411408
D-K-15140-01-00
05/2024

Revision 0
Revision

Remarks and Definitions
Erläuterungen und Definitionen

General remarks

Calibration after refurbishment

Reference air velocity
v_{REF} / m/s

The reference air velocity. The uncertainty is given as the expanded uncertainty with a coverage factor of *k*=2.

DUT Indication »Wind speed«
v_{DUT_i} / Hz

The indication of the device under test. The uncertainty is given as the expanded uncertainty with a coverage factor of *k*=2. The following uncertainty components are taken into account: short-term stability (repeatability), data acquisition (frequency).

DUT Indication »Wind speed« (linreg scaling)
v'_{DUT_i} / m/s

The DUT indication converted with the following equation: $v_{DUT_i} \cdot m + b$, where *m* as the slope and *b* as the offset as taken from the linear regression analysis. No uncertainties are considered for this conversion.

Deviation $v'_{DUT_i} - v_{REF}$
Δv / m/s

The difference between DUT Indication »Wind speed« (linreg scaling) and the reference air velocity. **The given uncertainty $U(\Delta v'_{DUT_i})$ is the combined expanded uncertainty with a coverage factor of *k*=2.**

Residuals

The remaining deviation between the DUT indication after applying a linear regression correction and the reference.

(o) Cup anemometer 94025507, page 3/4

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05/2024

Calibration result
Kalibrierergebnis

Index	Reference air velocity		DUT Indication »Wind speed«		DUT Indication »Wind speed« (linreg scaling)		Deviation $v'_{DUT_i} - v_{REF}$	
-	m/s		Hz		m/s		m/s	
i	v_{REF}	$U(v_{REF})$	v_{DUT_i}	$U(v_{DUT_i})$	v'_{DUT_i}	$U(v'_{DUT_i})$	Δv	$U(\Delta v)$
1	4.022	0.050	83.21	0.25	4.031	0.012	0.009	0.051
2	5.957	0.050	125.38	0.32	5.960	0.015	0.004	0.052
3	7.950	0.050	168.70	0.43	7.943	0.020	-0.007	0.054
4	10.054	0.055	214.76	0.52	10.051	0.024	-0.003	0.060
5	11.986	0.066	256.95	0.60	11.981	0.027	-0.004	0.072
6	14.018	0.077	300.73	0.70	13.985	0.032	-0.033	0.084
7	15.963	0.088	344.85	0.69	16.004	0.032	0.041	0.093
8	14.901	0.082	320.72	0.72	14.899	0.033	-0.001	0.088
9	12.925	0.071	277.83	0.64	12.937	0.029	0.012	0.077
10	11.051	0.061	236.47	0.53	11.044	0.024	-0.007	0.066
11	8.979	0.050	190.88	0.42	8.958	0.019	-0.021	0.054
12	6.907	0.050	145.85	0.38	6.897	0.017	-0.010	0.053
13	5.015	0.050	105.25	0.27	5.039	0.012	0.024	0.052

A digital copy of this table is attached to the PDF version of this document.

(p) Cup anemometer 94025507, page 4/4

DEUTSCHE WINDGUARD

IECRE and MEASNET approved test laboratory

Calibration Certificate / *Kalibrierschein*

issued by the calibration laboratory / *erstellt durch das Kalibrierlaboratorium*

Deutsche WindGuard
Wind Turnel Services GmbH

Member of / *Mitglied im*
Deutschen Kalibrierdienst

accredited to / *akkreditiert nach*
DIN EN ISO/IEC 17025:2018

Calibration mark
Kalibrierzeichen

2411414
D-K-15140-01-00
05/2024

Device under test (DUT) *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies CLIMA
Type *Typ*	4.3352.00.000
Serial number *Fabrikat/Serien-Nr.*	04201567 94028568
Customer *Auftraggeber*	TNO NL - 1755 LE Petten
Order No. *Auftragsnummer*	3100409804
Project No. *Projektnummer*	VT240267
Number of pages *Anzahl der Seiten*	6
Date of Calibration *Datum der Kalibrierung*	2024-05-17

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 presented results relate only to the calibrated object. The user is obliged to have the object recalibrated at appropriate intervals.
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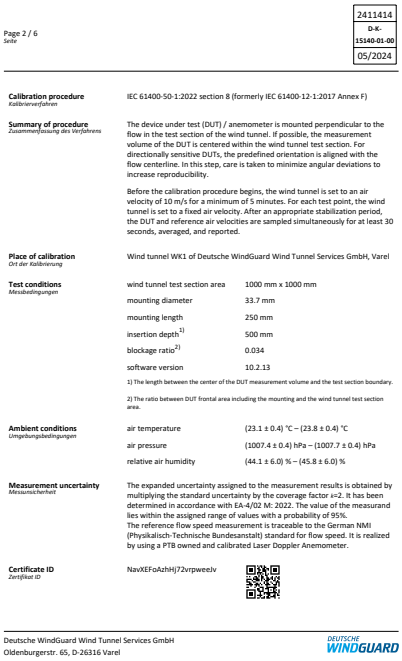
Date *Datum*	Freigegeben durch / *Approval by* Head of the calibration laboratory	Person in charge *Bearbeiter*
2024-05-17	Heiko Westermann	Janika Bachmann

(q) Cup anemometer 94028568, page 1/4



2411414
D-K-15140-01-00
05/2024

Calibration procedure *Kalibrierverfahren*: IEC 61400-50-1:2022 section 8 (formerly IEC 61400-12-1:2017 Annex F)

Summary of procedure *Zusammenfassung des Verfahrens*: The device under test (DUT) / anemometer is mounted perpendicular to the flow in the test section of the wind tunnel. If possible, the measurement volume of the DUT is centered within the wind tunnel test section. For directionally sensitive DUTs, the predefined orientation is aligned with the flow centerline. In this step, care is taken to minimize angular deviations to increase reproducibility.

Before the calibration procedure begins, the wind tunnel is set to an air velocity of 10 m/s for a minimum of 5 minutes. For each test point, the wind tunnel is set to a fixed air velocity. After an appropriate stabilization period, the DUT and reference air velocities are sampled simultaneously for at least 30 seconds, averaged, and reported.

Place of calibration *Ort der Kalibrierung*: Wind tunnel WK1 of Deutsche WindGuard Wind Turnel Services GmbH, Varel

Test conditions *Messbedingungen*

wind tunnel test section area	1000 mm x 1000 mm
mounting diameter	33.7 mm
mounting length	250 mm
insertion depth [1]	500 mm
blockage ratio [2]	0.034
software version	10.2.13

1) The length between the center of the DUT measurement volume and the test section boundary.

2) The ratio between DUT frontal area including the mounting and the wind tunnel test section area.

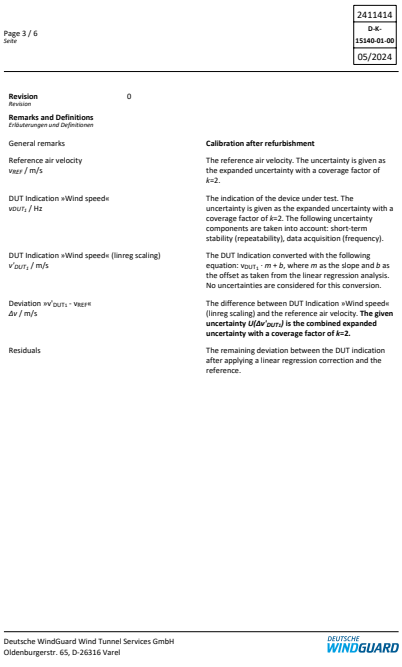
Ambient conditions *Umgebungsbedingungen*

air temperature	(23.1 ± 0.4) °C – (23.8 ± 0.4) °C
air pressure	(1007.4 ± 0.4) hPa – (1007.7 ± 0.4) hPa
relative air humidity	(44.1 ± 6.0) % – (45.8 ± 6.0) %

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 EA-4/02 M: 2022. 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.

Certificate ID *Zertifikat ID*: NavXEFoAzhHj72vrpweeJv

(r) Cup anemometer 94028568, page 2/4



2411414
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05/2024

Revision *Revision*: 0

Remarks and Definitions *Erläuterungen und Definitionen*

General remarks

Reference air velocity
v_{REF} / m/s

DUT Indication »Wind speed«
v_{DUT_i} / Hz

DUT Indication »Wind speed« (linreg scaling)
v'_{DUT_i} / m/s

Deviation $v'_{DUT_i} - v_{REF}$
Δv / m/s

Residuals

Calibration after refurbishment

The reference air velocity. The uncertainty is given as the expanded uncertainty with a coverage factor of *k*=2.

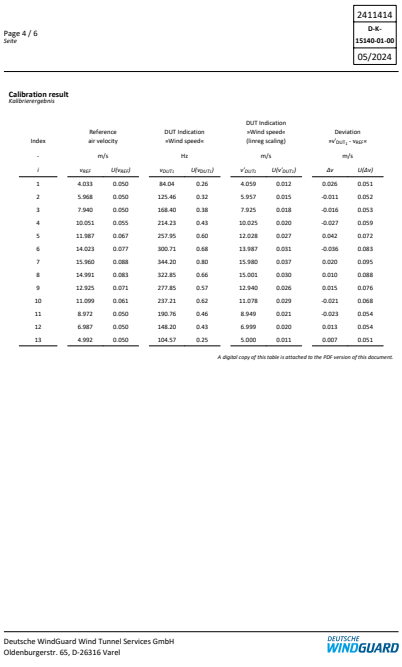
The indication of the device under test. The uncertainty is given as the expanded uncertainty with a coverage factor of *k*=2. The following uncertainty components are taken into account: short-term stability (repeatability), data acquisition (frequency).

The DUT indication converted with the following equation: $v_{DUT_i} \cdot m + b$, where *m* as the slope and *b* as the offset as taken from the linear regression analysis. No uncertainties are considered for this conversion.

The difference between DUT Indication »Wind speed« (linreg scaling) and the reference air velocity. **The given uncertainty $U(\Delta v'_{DUT_i})$ is the combined expanded uncertainty with a coverage factor of *k*=2.**

The remaining deviation between the DUT indication after applying a linear regression correction and the reference.

(s) Cup anemometer 94028568, page 3/4



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Calibration result *Kalibrierergebnis*

Index	Reference air velocity		DUT Indication »Wind speed«		DUT Indication »Wind speed« (linreg scaling)		Deviation $v'_{DUT_i} - v_{REF}$	
-	m/s		Hz		m/s		m/s	
i	v_{REF}	$U(v_{REF})$	v_{DUT_i}	$U(v_{DUT_i})$	v'_{DUT_i}	$U(v'_{DUT_i})$	Δv	$U(\Delta v)$
1	4.033	0.050	84.04	0.26	4.059	0.012	0.026	0.051
2	5.968	0.050	125.46	0.32	5.957	0.015	-0.011	0.052
3	7.940	0.050	168.40	0.38	7.925	0.018	-0.016	0.053
4	10.051	0.055	214.23	0.43	10.025	0.020	-0.027	0.059
5	11.987	0.067	257.95	0.60	12.028	0.027	0.042	0.072
6	14.023	0.077	300.71	0.68	13.987	0.031	-0.036	0.083
7	15.960	0.088	344.20	0.80	15.980	0.037	0.020	0.095
8	14.991	0.083	322.85	0.66	15.001	0.030	0.010	0.088
9	12.925	0.071	277.85	0.57	12.940	0.026	0.015	0.076
10	11.099	0.061	237.21	0.62	11.078	0.029	-0.021	0.068
11	8.972	0.050	190.76	0.46	8.949	0.021	-0.023	0.054
12	6.987	0.050	148.20	0.43	6.999	0.020	0.013	0.054
13	4.992	0.050	104.57	0.25	5.000	0.011	0.007	0.051

A digital copy of this table is attached to the PDF version of this document.

(t) Cup anemometer 94028568, page 4/4

DEUTSCHE WINDGUARD

IECRE and MEASNET approved test laboratory

Calibration Certificate / *Kalibrierschein*

issued by the calibration laboratory / *erstellt durch das Kalibrierlaboratorium*

Deutsche WindGuard
Wind Tunnel Services GmbH

Member of / *Mitglied im*
Deutschen Kalibrierdienst

accredited to / *akkreditiert nach*
DIN EN ISO/IEC 17025:2018

Calibration mark
Kalibrierzeichen

2411413
D-K-
15140-01-00
05/2024

Device under test (DUT) *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies CLIMA
Type *Typ*	4.3352.00.000
Serial number *Fabrikat/Serien-Nr.*	04201565 94025516
Customer *Auftraggeber*	TNO NL - 1755 LE Petten
Order No. *Auftragsnummer*	3100409804
Project No. *Projektnummer*	VT240267
Number of pages *Anzahl der Seiten*	6
Date of Calibration *Datum der Kalibrierung*	2024-05-17

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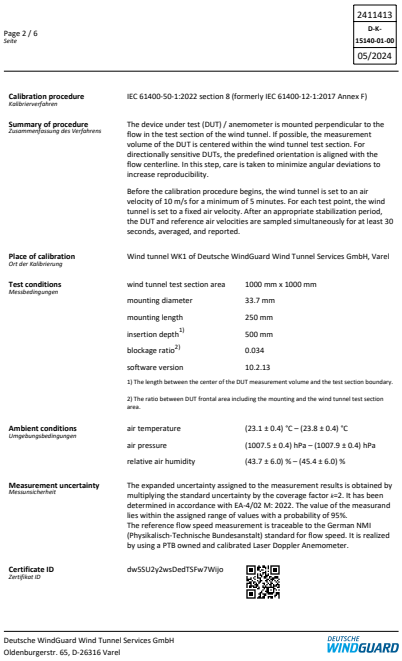
Date *Datum*	Freigegeben durch / *Approval by* Head of the calibration laboratory	Person in charge *Bearbeiter*
2024-05-17	Heiko Westermann	Janika Bachmann

(u) Cup anemometer 94025516, page 1/4



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D-K-
15140-01-00
05/2024

Calibration procedure
Kalibrierverfahren
IEC 61400-50-1:2022 section 8 (formerly IEC 61400-12-1:2017 Annex F)

Summary of procedure
Zusammenfassung des Verfahrens
The device under test (DUT) / anemometer is mounted perpendicular to the flow in the test section of the wind tunnel. If possible, the measurement volume of the DUT is centered within the wind tunnel test section. For directionally sensitive DUTs, the predefined orientation is aligned with the flow centerline. In this step, care is taken to minimize angular deviations to increase reproducibility.

Before the calibration procedure begins, the wind tunnel is set to an air velocity of 10 m/s for a minimum of 5 minutes. For each test point, the wind tunnel is set to a fixed air velocity. After an appropriate stabilization period, the DUT and reference air velocities are sampled simultaneously for at least 30 seconds, averaged, and reported.

Place of calibration
Ort der Kalibrierung
Wind tunnel WK1 of Deutsche WindGuard Wind Tunnel Services GmbH, Varel

Test conditions
Messbedingungen

wind tunnel test section area	1000 mm x 1000 mm
mounting diameter	33.7 mm
mounting length	250 mm
insertion depth[1)]	500 mm
blockage ratio[2)]	0.034
software version	10.2.13

1) The length between the center of the DUT measurement volume and the test section boundary.

2) The ratio between DUT frontal area including the mounting and the wind tunnel test section area.

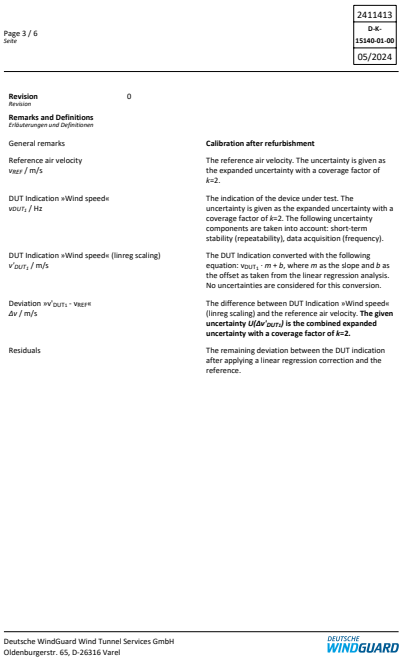
Ambient conditions
Umgebungsbedingungen

air temperature	(23.1 ± 0.4) °C – (23.8 ± 0.4) °C
air pressure	(1007.5 ± 0.4) hPa – (1007.9 ± 0.4) hPa
relative air humidity	(43.7 ± 6.0) % – (45.4 ± 6.0) %

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 EA-4/02 M: 2022. 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.

Certificate ID
Zertifikat ID
dw5SU2y2wsDedTSFw7Wijo

(v) Cup anemometer 94025516, page 2/4



2411413
D-K-
15140-01-00
05/2024

Revision 0
Revision

Remarks and Definitions
Erläuterungen und Definitionen

General remarks

Calibration after refurbishment

Reference air velocity
v_{REF} / m/s
The reference air velocity. The uncertainty is given as the expanded uncertainty with a coverage factor of *k*=2.

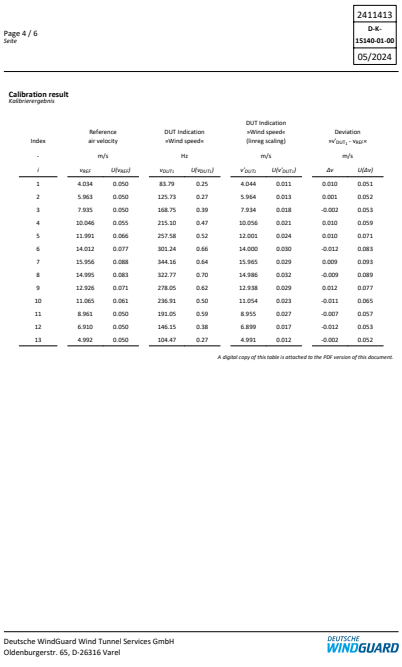
DUT Indication »Wind speed«
v_{DUT_1} / Hz
The indication of the device under test. The uncertainty is given as the expanded uncertainty with a coverage factor of *k*=2. The following uncertainty components are taken into account: short-term stability (repeatability), data acquisition (frequency).

DUT Indication »Wind speed« (linreg scaling)
v'_{DUT_1} / m/s
The DUT indication converted with the following equation: $v_{DUT_1} \cdot m + b$, where *m* as the slope and *b* as the offset as taken from the linear regression analysis. No uncertainties are considered for this conversion.

Deviation v'_{DUT_1} - v_{REF}
Δv / m/s
The difference between DUT Indication »Wind speed« (linreg scaling) and the reference air velocity. **The given uncertainty $U(\Delta v'_{DUT_1})$ is the combined expanded uncertainty with a coverage factor of *k*=2.**

Residuals
The remaining deviation between the DUT indication after applying a linear regression correction and the reference.

(w) Cup anemometer 94025516, page 3/4



2411413
D-K-
15140-01-00
05/2024

Calibration result
Kalibrierergebnis

Index	Reference air velocity		DUT Indication »Wind speed«		DUT Indication »Wind speed« (linreg scaling)		Deviation v'_{DUT_1} - v_{REF}	
-	m/s		Hz		m/s		m/s	
i	v_{REF}	$U(v_{REF})$	v_{DUT_1}	$U(v_{DUT_1})$	v'_{DUT_1}	$U(v'_{DUT_1})$	Δv	$U(\Delta v)$
1	4.034	0.050	83.79	0.25	4.044	0.011	0.010	0.051
2	5.963	0.050	125.73	0.27	5.964	0.013	0.001	0.052
3	7.935	0.050	168.75	0.39	7.934	0.018	-0.002	0.053
4	10.046	0.055	215.10	0.47	10.056	0.021	0.010	0.059
5	11.991	0.066	257.58	0.52	12.001	0.024	0.010	0.071
6	14.012	0.077	301.24	0.66	14.000	0.030	-0.012	0.083
7	15.956	0.088	344.16	0.64	15.965	0.029	0.009	0.093
8	14.995	0.083	322.77	0.70	14.986	0.032	-0.009	0.089
9	12.926	0.071	278.05	0.62	12.938	0.029	0.012	0.077
10	11.065	0.061	236.91	0.50	11.054	0.023	-0.011	0.065
11	8.961	0.050	191.05	0.59	8.955	0.027	-0.007	0.057
12	6.910	0.050	146.15	0.38	6.899	0.017	-0.012	0.053
13	4.992	0.050	104.47	0.27	4.991	0.012	-0.002	0.052

A digital copy of this table is attached to the PDF version of this document.

(x) Cup anemometer 94025516, page 4/4

B.1.2 Wind vane

DEUTSCHE WINDGUARD

IECRE and MEASNET approved test laboratory

Calibration Certificate / *Kalibrierschein*

issued by the calibration laboratory / *erstellt durch das Kalibrierlaboratorium*

Deutsche WindGuard
Wind Tunnel Services GmbH

Member of / *Mitglied im*
Deutschen Kalibrierdienst

accredited to / *akkreditiert nach*
DIN EN ISO/IEC 17025:2018

Calibration mark
Kalibrierzeichen

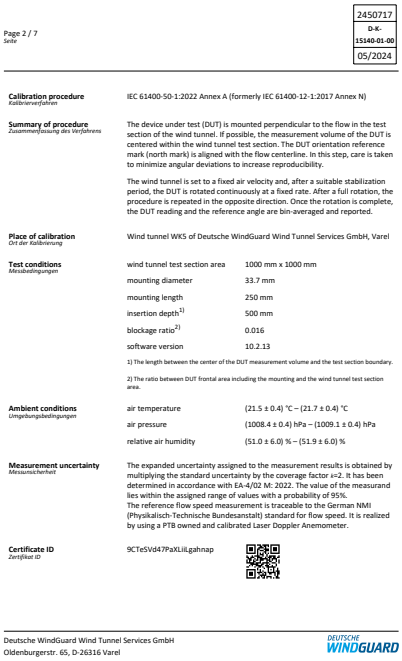
2450717
D-K-15140-01-00
05/2024

Device under test (DUT) *Gegenstand*	Wind Vane
Manufacturer *Hersteller*	Thies CLIMA
Type *Typ*	4.3150.00.400
Serial number *Fabrikat/Serien-Nr.*	06110043
Customer *Auftraggeber*	TNO NL - 1755 LE Petten
Order No. *Auftragsnummer*	3100409804
Project No. *Projektnummer*	VT240267
Number of pages *Anzahl der Seiten*	7
Date of Calibration *Datum der Kalibrierung*	2024-05-21

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 presented results relate only to the calibrated object. 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. Die dargestellten Ergebnisse beziehen sich nur auf den kalibrierten Gegenstand. Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

Date *Datum*	Freigegeben durch / *Approval by* Head of the calibration laboratory	Person in charge *Bearbeiter*
2024-05-21	Heiko Westermann	Chd Krüger

(a) Wind vane 94012496, page 1/6



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D-K-15140-01-00
05/2024

Calibration procedure *Kalibrierverfahren*: IEC 61400-50-1:2022 Annex A (formerly IEC 61400-12-1:2017 Annex N)

Summary of procedure *Zusammenfassung des Verfahrens*:
The device under test (DUT) is mounted perpendicular to the flow in the test section of the wind tunnel. If possible, the measurement volume of the DUT is centered within the wind tunnel test section. The DUT orientation reference mark (north mark) is aligned with the flow centerline. In this step, care is taken to minimize angular deviations to increase reproducibility.

The wind tunnel is set to a fixed air velocity and, after a suitable stabilization period, the DUT is rotated continuously at a fixed rate. After a full rotation, the procedure is repeated in the opposite direction. Once the rotation is complete, the DUT reading and the reference angle are bin-averaged and reported.

Place of calibration *Ort der Kalibrierung*: Wind tunnel WKS of Deutsche WindGuard Wind Tunnel Services GmbH, Varel

Test conditions *Messbedingungen*

wind tunnel test section area	1000 mm x 1000 mm
mounting diameter	33.7 mm
mounting length	250 mm
insertion depth[1)]	500 mm
blockage ratio[2)]	0.016
software version	10.2.13

1) The length between the center of the DUT measurement volume and the test section boundary.

2) The ratio between DUT frontal area including the mounting and the wind tunnel test section area.

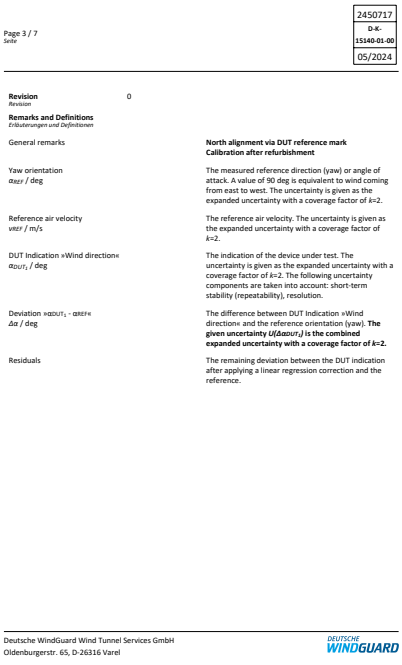
Ambient conditions *Umgebungsbedingungen*

air temperature	(21.5 ± 0.4) °C – (21.7 ± 0.4) °C
air pressure	(1008.4 ± 0.4) hPa – (1009.1 ± 0.4) hPa
relative air humidity	(51.0 ± 6.0) % – (51.9 ± 6.0) %

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 EA-4/02 M: 2022. 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.

Certificate ID *Zertifikat ID*: 9CTeSVd47PaXLiiLgahnap

(b) Wind vane 94012496, page 2/6



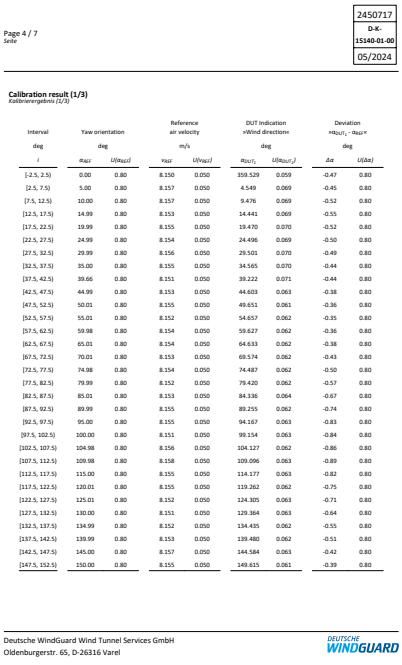
2450717
D-K-15140-01-00
05/2024

Revision *Revision*: 0

Remarks and Definitions *Erläuterungen und Definitionen*

General remarks	**North alignment via DUT reference mark** **Calibration after refurbishment**
Yaw orientation α_{REF} / deg	The measured reference direction (yaw) or angle of attack. A value of 90 deg is equivalent to wind coming from east to west. The uncertainty is given as the expanded uncertainty with a coverage factor of k=2.
Reference air velocity v_{REF} / m/s	The reference air velocity. The uncertainty is given as the expanded uncertainty with a coverage factor of k=2.
DUT Indication »Wind direction« α_{DUT_i} / deg	The indication of the device under test. The uncertainty is given as the expanded uncertainty with a coverage factor of k=2. The following uncertainty components are taken into account: short-term stability (repeatability), resolution.
Deviation $\alpha_{DUT_i} - \alpha_{REF}$ $\Delta\alpha$ / deg	The difference between DUT Indication »Wind direction« and the reference orientation (yaw). **The given uncertainty $U(\Delta\alpha_{DUT_i})$ is the combined expanded uncertainty with a coverage factor of k=2.**
Residuals	The remaining deviation between the DUT indication after applying a linear regression correction and the reference.

(c) Wind vane 94012496, page 3/6



2450717
D-K-15140-01-00
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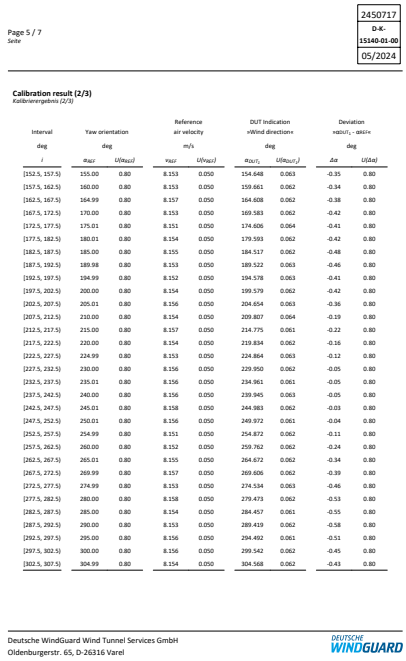
Calibration result (1/3)
Kalibrierergebnis (1/3)

Interval	Yaw orientation		Reference air velocity		DUT Indication »Wind direction«		Deviation $\alpha_{DUT_i} - \alpha_{REF}$
deg	deg		m/s		deg		deg
i	α_{REF}	$U(\alpha_{REF})$	v_{REF}	$U(v_{REF})$	α_{DUT_i}	$U(\alpha_{DUT_i})$	$\Delta\alpha$	$U(\Delta\alpha)$
[-2.5, 2.5)	0.00	0.80	8.150	0.050	359.529	0.059	-0.47	0.80
[2.5, 7.5)	5.00	0.80	8.157	0.050	4.549	0.069	-0.45	0.80
[7.5, 12.5)	10.00	0.80	8.157	0.050	9.476	0.069	-0.52	0.80
[12.5, 17.5)	14.99	0.80	8.153	0.050	14.441	0.069	-0.55	0.80
[17.5, 22.5)	19.99	0.80	8.155	0.050	19.470	0.070	-0.52	0.80
[22.5, 27.5)	24.99	0.80	8.154	0.050	24.496	0.069	-0.50	0.80
[27.5, 32.5)	29.99	0.80	8.156	0.050	29.501	0.070	-0.49	0.80
[32.5, 37.5)	35.00	0.80	8.155	0.050	34.565	0.070	-0.44	0.80
[37.5, 42.5)	39.66	0.80	8.151	0.050	39.222	0.071	-0.44	0.80
[42.5, 47.5)	44.99	0.80	8.153	0.050	44.603	0.063	-0.38	0.80
[47.5, 52.5)	50.01	0.80	8.155	0.050	49.651	0.061	-0.36	0.80
[52.5, 57.5)	55.01	0.80	8.152	0.050	54.657	0.062	-0.35	0.80
[57.5, 62.5)	59.98	0.80	8.154	0.050	59.627	0.062	-0.36	0.80
[62.5, 67.5)	65.01	0.80	8.154	0.050	64.633	0.062	-0.38	0.80
[67.5, 72.5)	70.01	0.80	8.153	0.050	69.574	0.062	-0.43	0.80
[72.5, 77.5)	74.98	0.80	8.154	0.050	74.487	0.062	-0.50	0.80
[77.5, 82.5)	79.99	0.80	8.152	0.050	79.420	0.062	-0.57	0.80
[82.5, 87.5)	85.01	0.80	8.153	0.050	84.336	0.064	-0.67	0.80
[87.5, 92.5)	89.99	0.80	8.155	0.050	89.255	0.062	-0.74	0.80
[92.5, 97.5)	95.00	0.80	8.155	0.050	94.167	0.063	-0.83	0.80
[97.5, 102.5)	100.00	0.80	8.151	0.050	99.154	0.063	-0.84	0.80
[102.5, 107.5)	104.98	0.80	8.156	0.050	104.127	0.062	-0.86	0.80
[107.5, 112.5)	109.98	0.80	8.158	0.050	109.096	0.063	-0.89	0.80
[112.5, 117.5)	115.00	0.80	8.155	0.050	114.177	0.063	-0.82	0.80
[117.5, 122.5)	120.01	0.80	8.155	0.050	119.262	0.062	-0.75	0.80
[122.5, 127.5)	125.01	0.80	8.152	0.050	124.305	0.063	-0.71	0.80
[127.5, 132.5)	130.00	0.80	8.151	0.050	129.364	0.063	-0.64	0.80
[132.5, 137.5)	134.99	0.80	8.152	0.050	134.435	0.062	-0.55	0.80
[137.5, 142.5)	139.99	0.80	8.153	0.050	139.480	0.062	-0.51	0.80
[142.5, 147.5)	145.00	0.80	8.157	0.050	144.584	0.063	-0.42	0.80
[147.5, 152.5)	150.00	0.80	8.155	0.050	149.615	0.061	-0.39	0.80

(d) Wind vane 94012496, page 4/6



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05/2024

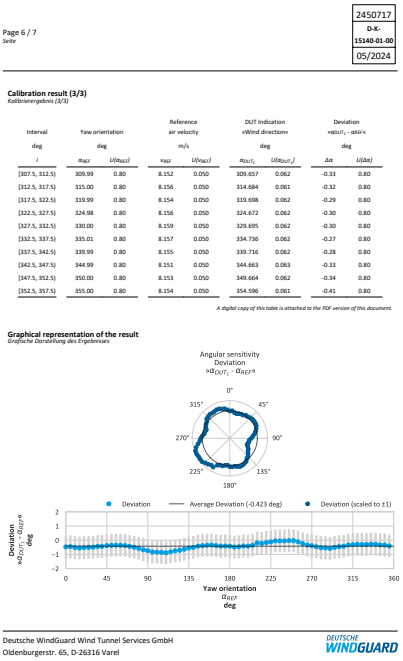
Calibration result (2/3)
Kalibrierergebnis (2/3)

Interval	Yaw orientation		Reference air velocity		DUT Indication «Wind direction»		Deviation «α_DUT_i − α_REF»
deg	deg		m/s		deg		deg
i	α_{REF}	$U(\alpha_{REF})$	v_{REF}	$U(v_{REF})$	α_{DUT_i}	$U(\alpha_{DUT_i})$	$\Delta\alpha$	$U(\Delta\alpha)$
[152.5, 157.5)	155.00	0.80	8.153	0.050	154.648	0.063	-0.35	0.80
[157.5, 162.5)	160.00	0.80	8.153	0.050	159.661	0.062	-0.34	0.80
[162.5, 167.5)	164.99	0.80	8.157	0.050	164.608	0.062	-0.38	0.80
[167.5, 172.5)	170.00	0.80	8.153	0.050	169.583	0.062	-0.42	0.80
[172.5, 177.5)	175.01	0.80	8.151	0.050	174.606	0.064	-0.41	0.80
[177.5, 182.5)	180.01	0.80	8.154	0.050	179.593	0.062	-0.42	0.80
[182.5, 187.5)	185.00	0.80	8.155	0.050	184.517	0.062	-0.48	0.80
[187.5, 192.5)	189.98	0.80	8.153	0.050	189.522	0.063	-0.46	0.80
[192.5, 197.5)	194.99	0.80	8.152	0.050	194.578	0.063	-0.41	0.80
[197.5, 202.5)	200.00	0.80	8.154	0.050	199.579	0.062	-0.42	0.80
[202.5, 207.5)	205.01	0.80	8.156	0.050	204.654	0.063	-0.36	0.80
[207.5, 212.5)	210.00	0.80	8.154	0.050	209.807	0.064	-0.19	0.80
[212.5, 217.5)	215.00	0.80	8.157	0.050	214.775	0.061	-0.22	0.80
[217.5, 222.5)	220.00	0.80	8.154	0.050	219.834	0.062	-0.16	0.80
[222.5, 227.5)	224.99	0.80	8.153	0.050	224.864	0.063	-0.12	0.80
[227.5, 232.5)	230.00	0.80	8.156	0.050	229.950	0.062	-0.05	0.80
[232.5, 237.5)	235.01	0.80	8.156	0.050	234.961	0.061	-0.05	0.80
[237.5, 242.5)	240.00	0.80	8.156	0.050	239.945	0.063	-0.05	0.80
[242.5, 247.5)	245.01	0.80	8.158	0.050	244.983	0.062	-0.03	0.80
[247.5, 252.5)	250.01	0.80	8.156	0.050	249.972	0.061	-0.04	0.80
[252.5, 257.5)	254.99	0.80	8.151	0.050	254.872	0.062	-0.11	0.80
[257.5, 262.5)	260.00	0.80	8.152	0.050	259.762	0.062	-0.24	0.80
[262.5, 267.5)	265.01	0.80	8.155	0.050	264.672	0.062	-0.34	0.80
[267.5, 272.5)	269.99	0.80	8.157	0.050	269.606	0.062	-0.39	0.80
[272.5, 277.5)	274.99	0.80	8.153	0.050	274.534	0.063	-0.46	0.80
[277.5, 282.5)	280.00	0.80	8.158	0.050	279.473	0.062	-0.53	0.80
[282.5, 287.5)	285.00	0.80	8.154	0.050	284.457	0.061	-0.55	0.80
[287.5, 292.5)	290.00	0.80	8.153	0.050	289.419	0.062	-0.58	0.80
[292.5, 297.5)	295.00	0.80	8.156	0.050	294.492	0.061	-0.51	0.80
[297.5, 302.5)	300.00	0.80	8.156	0.050	299.542	0.062	-0.45	0.80
[302.5, 307.5)	304.99	0.80	8.154	0.050	304.568	0.062	-0.43	0.80

Deutsche WindGuard Wind Tunnel Services GmbH
Oldenburgerstr. 65, D-26316 Varel

DEUTSCHE WINDGUARD

(e) Wind vane 94012496, page 5/6



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

Interval	Yaw orientation		Reference air velocity		DUT Indication «Wind direction»		Deviation «α_DUT_i − α_REF»
deg	deg		m/s		deg		deg
i	α_{REF}	$U(\alpha_{REF})$	v_{REF}	$U(v_{REF})$	α_{DUT_i}	$U(\alpha_{DUT_i})$	$\Delta\alpha$	$U(\Delta\alpha)$
[307.5, 312.5)	309.99	0.80	8.152	0.050	309.657	0.062	-0.33	0.80
[312.5, 317.5)	315.00	0.80	8.156	0.050	314.684	0.061	-0.32	0.80
[317.5, 322.5)	319.99	0.80	8.154	0.050	319.698	0.062	-0.29	0.80
[322.5, 327.5)	324.98	0.80	8.156	0.050	324.672	0.062	-0.30	0.80
[327.5, 332.5)	330.00	0.80	8.159	0.050	329.695	0.062	-0.30	0.80
[332.5, 337.5)	335.01	0.80	8.157	0.050	334.736	0.062	-0.27	0.80
[337.5, 342.5)	339.99	0.80	8.155	0.050	339.716	0.062	-0.28	0.80
[342.5, 347.5)	344.99	0.80	8.151	0.050	344.663	0.063	-0.33	0.80
[347.5, 352.5)	350.00	0.80	8.153	0.050	349.664	0.062	-0.34	0.80
[352.5, 357.5)	355.00	0.80	8.154	0.050	354.596	0.061	-0.41	0.80

A digital copy of this table is attached to the PDF version of this document.

Graphical representation of the result
Grafische Darstellung des Ergebnisses

Deutsche WindGuard Wind Tunnel Services GmbH
Oldenburgerstr. 65, D-26316 Varel

DEUTSCHE WINDGUARD

(f) Wind vane 94012496, page 6/6

DEUTSCHE WINDGUARD

IECRE and MEASNET approved test laboratory

Calibration Certificate / *Kalibrierschein*

issued by the calibration laboratory / *erstellt durch das Kalibrierlaboratorium*

Deutsche WindGuard
Wind Tunnel Services GmbH

Member of / *Mitglied im*
Deutschen Kalibrierdienst

accredited to / *akkreditiert nach*
DIN EN ISO/IEC 17025:2018

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

2450713
D-K-
15140-01-00
05/2024

Calibration mark
Kalibrierzeichen

Device under test (DUT) *Gegenstand*	Wind Vane
Manufacturer *Hersteller*	Thies CLIMA
Type *Typ*	4.3150.00.400
Serial number *Fabrikat/Serien-Nr.*	07130078
Customer *Auftraggeber*	TNO NL - 1755 LE Petten
Order No. *Auftragsnummer*	3100409804
Project No. *Projektnummer*	VT240267
Number of pages *Anzahl der Seiten*	7
Date of Calibration *Datum der Kalibrierung*	2024-05-21

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 presented results relate only to the calibrated object. 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. Die dargestellten Ergebnisse beziehen sich nur auf den kalibrierten Gegenstand. Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

Date *Datum*	Freigegeben durch / *Approval by* Head of the calibration laboratory	Person in charge *Bearbeiter*
2024-05-21	Heiko Westermann	Chd Krüger

(g) Wind vane 94012006, page 1/6

Calibration procedure *Kalibrierverfahren*	IEC 61400-50-1:2022 Annex A (formerly IEC 61400-12-1:2017 Annex N)
Summary of procedure *Zusammenfassung des Verfahrens*	The device under test (DUT) is mounted perpendicular to the flow in the test section of the wind tunnel. If possible, the measurement volume of the DUT is centered within the wind tunnel test section. The DUT orientation reference mark (north mark) is aligned with the flow centerline. In this step, care is taken to minimize angular deviations to increase reproducibility. The wind tunnel is set to a fixed air velocity and, after a suitable stabilization period, the DUT is rotated continuously at a fixed rate. After a full rotation, the procedure is repeated in the opposite direction. Once the rotation is complete, the DUT reading and the reference angle are bin-averaged and reported.
Place of calibration *Ort der Kalibrierung*	Wind tunnel WK5 of Deutsche WindGuard Wind Tunnel Services GmbH, Varel
Test conditions *Messbedingungen*	wind tunnel test section area: 1000 mm x 1000 mm mounting diameter: 33.7 mm mounting length: 250 mm insertion depth[1]: 500 mm blockage ratio[2]: 0.016 software version: 10.2.13 1) The length between the center of the DUT measurement volume and the test section boundary. 2) The ratio between DUT frontal area including the mounting and the wind tunnel test section area.
Ambient conditions *Umgebungsbedingungen*	air temperature: (21.0 ± 0.4) °C – (21.3 ± 0.4) °C air pressure: (1010.3 ± 0.4) hPa – (1010.8 ± 0.4) hPa relative air humidity: (51.5 ± 6.0) % – (52.9 ± 6.0) %
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 EA-4/02 M: 2022. 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.
Certificate ID *Zertifikat ID*	dpf8EJfWgoWK7CkszGjcmV

(h) Wind vane 94012006, page 2/6

Revision *Revision*	0

Remarks and Definitions
Erläuterungen und Definitionen

General remarks	**North alignment via DUT reference mark** **Calibration after refurbishment**
Yaw orientation α_{REF} / deg	The measured reference direction (yaw) or angle of attack. A value of 90 deg is equivalent to wind coming from east to west. The uncertainty is given as the expanded uncertainty with a coverage factor of *k*=2.
Reference air velocity v_{REF} / m/s	The reference air velocity. The uncertainty is given as the expanded uncertainty with a coverage factor of *k*=2.
DUT Indication »Wind direction« α_{DUT_i} / deg	The indication of the device under test. The uncertainty is given as the expanded uncertainty with a coverage factor of *k*=2. The following uncertainty components are taken into account: short-term stability (repeatability), resolution.
Deviation »α_{DUT_i} - α_{REF}« $\Delta\alpha$ / deg	The difference between DUT Indication »Wind direction« and the reference orientation (yaw). **The given uncertainty ($U(\Delta\alpha_{DUT_i})$ is the combined expanded uncertainty with a coverage factor of *k*=2.**
Residuals	The remaining deviation between the DUT indication after applying a linear regression correction and the reference.

(i) Wind vane 94012006, page 3/6

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

Interval	Yaw orientation		Reference air velocity		DUT Indication »Wind direction«		Deviation »α_{DUT_i} - α_{REF}«	
deg	deg		m/s		deg		deg	
i	α_{REF}	$U(\alpha_{REF})$	v_{REF}	$U(v_{REF})$	α_{DUT_i}	$U(\alpha_{DUT_i})$	$\Delta\alpha$	$U(\Delta\alpha)$
[-2.5, 2.5)	0.00	0.80	8.178	0.050	359.736	0.059	-0.26	0.80
[2.5, 7.5)	5.00	0.80	8.183	0.050	4.703	0.069	-0.30	0.80
[7.5, 12.5)	10.00	0.80	8.183	0.050	9.539	0.069	-0.46	0.80
[12.5, 17.5)	15.00	0.80	8.184	0.050	14.480	0.069	-0.53	0.80
[17.5, 22.5)	19.99	0.80	8.184	0.050	19.439	0.070	-0.56	0.80
[22.5, 27.5)	24.99	0.80	8.182	0.050	24.420	0.069	-0.57	0.80
[27.5, 32.5)	29.99	0.80	8.181	0.050	29.476	0.070	-0.51	0.80
[32.5, 37.5)	34.99	0.80	8.181	0.050	34.515	0.070	-0.48	0.80
[37.5, 42.5)	39.65	0.80	8.185	0.050	39.215	0.071	-0.43	0.80
[42.5, 47.5)	45.00	0.80	8.182	0.050	44.649	0.062	-0.35	0.80
[47.5, 52.5)	49.99	0.80	8.183	0.050	49.689	0.063	-0.30	0.80
[52.5, 57.5)	55.01	0.80	8.180	0.050	54.766	0.062	-0.24	0.80
[57.5, 62.5)	60.01	0.80	8.181	0.050	59.766	0.062	-0.25	0.80
[62.5, 67.5)	65.01	0.80	8.183	0.050	64.770	0.063	-0.24	0.80
[67.5, 72.5)	69.99	0.80	8.180	0.050	69.747	0.063	-0.24	0.80
[72.5, 77.5)	74.99	0.80	8.186	0.050	74.695	0.061	-0.30	0.80
[77.5, 82.5)	79.99	0.80	8.182	0.050	79.648	0.061	-0.34	0.80
[82.5, 87.5)	84.99	0.80	8.181	0.050	84.633	0.064	-0.36	0.80
[87.5, 92.5)	90.01	0.80	8.184	0.050	89.571	0.063	-0.44	0.80
[92.5, 97.5)	95.00	0.80	8.182	0.050	94.498	0.062	-0.51	0.80
[97.5, 102.5)	99.99	0.80	8.184	0.050	99.410	0.062	-0.58	0.80
[102.5, 107.5)	105.00	0.80	8.183	0.050	104.406	0.062	-0.60	0.80
[107.5, 112.5)	110.00	0.80	8.184	0.050	109.398	0.064	-0.60	0.80
[112.5, 117.5)	115.00	0.80	8.181	0.050	114.364	0.063	-0.64	0.80
[117.5, 122.5)	120.00	0.80	8.179	0.050	119.480	0.062	-0.51	0.80
[122.5, 127.5)	124.99	0.80	8.180	0.050	124.548	0.062	-0.45	0.80
[127.5, 132.5)	129.98	0.80	8.187	0.050	129.573	0.064	-0.41	0.80
[132.5, 137.5)	135.00	0.80	8.185	0.050	134.708	0.063	-0.29	0.80
[137.5, 142.5)	139.99	0.80	8.186	0.050	139.709	0.061	-0.29	0.80
[142.5, 147.5)	145.00	0.80	8.183	0.050	144.778	0.063	-0.22	0.80
[147.5, 152.5)	149.99	0.80	8.185	0.050	149.805	0.062	-0.19	0.80

(j) Wind vane 94012006, page 4/6

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

Interval	Yaw orientation		Reference air velocity		DUT Indication »Wind direction«		Deviation »α$_{DUT_i}$ - α$_{REF}$«
deg	deg		m/s		deg		deg
i	α_{REF}	$U(\alpha_{REF})$	v_{REF}	$U(v_{REF})$	α_{DUT_i}	$U(\alpha_{DUT_i})$	$\Delta\alpha$	$U(\Delta\alpha)$
[152.5, 157.5)	154.99	0.80	8.182	0.050	154.787	0.064	-0.20	0.80
[157.5, 162.5)	159.99	0.80	8.183	0.050	159.792	0.062	-0.20	0.80
[162.5, 167.5)	165.01	0.80	8.182	0.050	164.801	0.063	-0.21	0.80
[167.5, 172.5)	169.99	0.80	8.182	0.050	169.726	0.063	-0.27	0.80
[172.5, 177.5)	175.00	0.80	8.183	0.050	174.696	0.063	-0.30	0.80
[177.5, 182.5)	179.99	0.80	8.185	0.050	179.654	0.063	-0.34	0.80
[182.5, 187.5)	184.98	0.80	8.182	0.050	184.591	0.061	-0.39	0.80
[187.5, 192.5)	189.98	0.80	8.182	0.050	189.588	0.062	-0.39	0.80
[192.5, 197.5)	194.99	0.80	8.183	0.050	194.613	0.063	-0.37	0.80
[197.5, 202.5)	199.98	0.80	8.188	0.050	199.595	0.062	-0.38	0.80
[202.5, 207.5)	204.98	0.80	8.183	0.050	204.651	0.062	-0.33	0.80
[207.5, 212.5)	210.00	0.80	8.185	0.050	209.753	0.062	-0.25	0.80
[212.5, 217.5)	215.01	0.80	8.182	0.050	214.854	0.064	-0.15	0.80
[217.5, 222.5)	219.99	0.80	8.186	0.050	219.882	0.062	-0.11	0.80
[222.5, 227.5)	225.01	0.80	8.183	0.050	224.978	0.063	-0.03	0.80
[227.5, 232.5)	229.99	0.80	8.185	0.050	229.999	0.062	0.01	0.80
[232.5, 237.5)	235.00	0.80	8.187	0.050	235.074	0.062	0.08	0.80
[237.5, 242.5)	240.02	0.80	8.185	0.050	240.117	0.062	0.10	0.80
[242.5, 247.5)	245.01	0.80	8.184	0.050	245.113	0.063	0.10	0.80
[247.5, 252.5)	249.99	0.80	8.185	0.050	250.101	0.063	0.11	0.80
[252.5, 257.5)	255.01	0.80	8.183	0.050	255.070	0.063	0.06	0.80
[257.5, 262.5)	259.99	0.80	8.184	0.050	259.996	0.062	0.00	0.80
[262.5, 267.5)	264.98	0.80	8.182	0.050	264.915	0.062	-0.07	0.80
[267.5, 272.5)	269.98	0.80	8.181	0.050	269.815	0.062	-0.17	0.80
[272.5, 277.5)	274.99	0.80	8.188	0.050	274.755	0.062	-0.24	0.80
[277.5, 282.5)	279.99	0.80	8.182	0.050	279.736	0.063	-0.25	0.80
[282.5, 287.5)	284.98	0.80	8.183	0.050	284.721	0.064	-0.26	0.80
[287.5, 292.5)	290.00	0.80	8.181	0.050	289.743	0.062	-0.25	0.80
[292.5, 297.5)	295.00	0.80	8.184	0.050	294.770	0.062	-0.23	0.80
[297.5, 302.5)	299.98	0.80	8.186	0.050	299.788	0.061	-0.20	0.80
[302.5, 307.5)	305.01	0.80	8.186	0.050	304.881	0.063	-0.13	0.80

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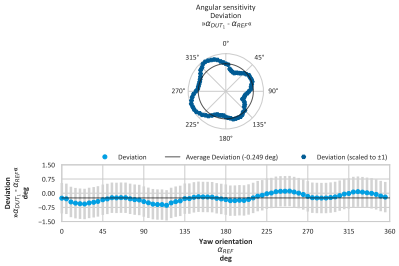
Calibration result (3/3)
Kalibrierergebnis (3/3)

Interval	Yaw orientation		Reference air velocity		DUT Indication »Wind direction«		Deviation »α$_{DUT_i}$ - α$_{REF}$«
deg	deg		m/s		deg		deg
i	α_{REF}	$U(\alpha_{REF})$	v_{REF}	$U(v_{REF})$	α_{DUT_i}	$U(\alpha_{DUT_i})$	$\Delta\alpha$	$U(\Delta\alpha)$
[307.5, 312.5)	309.99	0.80	8.185	0.050	309.945	0.062	-0.05	0.80
[312.5, 317.5)	314.97	0.80	8.185	0.050	314.953	0.062	-0.01	0.80
[317.5, 322.5)	319.97	0.80	8.186	0.050	320.039	0.061	0.06	0.80
[322.5, 327.5)	325.00	0.80	8.182	0.050	325.083	0.062	0.08	0.80
[327.5, 332.5)	330.00	0.80	8.184	0.050	330.054	0.063	0.06	0.80
[332.5, 337.5)	335.00	0.80	8.181	0.050	335.019	0.063	0.02	0.80
[337.5, 342.5)	340.00	0.80	8.186	0.050	339.996	0.063	-0.01	0.80
[342.5, 347.5)	345.01	0.80	8.185	0.050	344.943	0.061	-0.06	0.80
[347.5, 352.5)	350.00	0.80	8.183	0.050	349.848	0.063	-0.15	0.80
[352.5, 357.5)	355.00	0.80	8.184	0.050	354.797	0.062	-0.21	0.80

A digital copy of this table is attached to the PDF version of this document.

Graphical representation of the result
Grafische Darstellung des Ergebnisses



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DEUTSCHE WINDGUARD

IECRE and MEASNET approved test laboratory

Calibration Certificate / *Kalibrierschein*

issued by the calibration laboratory / *erstellt durch das Kalibrierlaboratorium*

Deutsche WindGuard
Wind Tunnel Services GmbH

Member of / *Mitglied im*
Deutschen Kalibrierdienst

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

2023244
D-K-15140-01-00
10/2020

Calibration certificate
Kalibrierschein

Calibration mark
Kalibrierzeichen

Object *Gegenstand*	Wind Vane
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3150.00.400
Serial number *Fabrikat/Serien-Nr.*	04120057 DEWR5211
Customer *Auftraggeber*	TNO 2509 JE The Hague - The Netherlands
Order No. *Auftragsnummer*	3100287001
Project No. *Projektnummer*	VT200850
Number of pages *Anzahl der Seiten*	6
Date of Calibration *Datum der Kalibrierung*	19.10.2020

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 presented results relate only to the calibrated object. 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. Die dargestellten Ergebnisse beziehen sich nur auf den kalibrierten Gegenstand. Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

Date *Datum*	Head of the calibration laboratory *Leitej des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
19.10.2020	Dipl. Phys. Dieter Westermann	Techniker Andre Krummen

(m) Wind vane 94012544, page 1/6

Calibration object *Kalibriergegenstand*	Wind Vane	
Calibration procedure *Kalibrierverfahren*	IEC 61400-12-1:2017	
Place of calibration *Ort der Kalibrierung*	Wind tunnel 2 of Deutsche WindGuard Wind Tunnel Services GmbH, Varel	
Test conditions *Messbedingungen*	wind tunnel area	10000 cm²
	anemometer frontal area	200 cm²
	diameter of mounting pipe	33.7 mm
	blockage ratio [1]	0.020 [-]
	software version	9.0.1
Ambient conditions *Umgebungsbedingungen*	air temperature	(20.7 ± 0.2) °C – (20.8 ± 0.2) °C
	air pressure	(1020.0 ± 0.3) hPa – (1020.4 ± 0.3) hPa
	relative air humidity	(40.1 ± 2.0) % – (40.3 ± 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 EA-4/02 M: 2013. 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*	Bent fin	
Revision *Revision*	0	

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

(n) Wind vane 94012544, page 2/6

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

Reference Air velocity	Reference Unc	Reference Yaw angle	Reference Unc	Test item Direction	Test item Deviation
m/s	m/s	deg	deg	deg	deg
7.94	0.05	0.85	0.80	1.01	0.16
7.95	0.05	5.04	0.80	5.04	0.00
7.95	0.05	9.96	0.80	10.09	0.13
7.95	0.05	14.96	0.80	15.22	0.26
7.94	0.05	19.53	0.80	20.06	0.53
7.95	0.05	24.96	0.80	25.72	0.76
7.94	0.05	29.98	0.80	30.89	0.92
7.95	0.05	35.00	0.80	35.99	0.99
7.95	0.05	40.01	0.80	40.92	0.91
7.95	0.05	45.01	0.80	45.66	0.65
7.94	0.05	50.03	0.80	50.64	0.61
7.94	0.05	54.98	0.80	55.53	0.55
7.94	0.05	59.84	0.80	60.51	0.67
7.94	0.05	65.13	0.80	65.83	0.70
7.94	0.05	70.08	0.80	70.77	0.69
7.94	0.05	75.09	0.80	76.00	0.92
7.94	0.05	80.05	0.80	81.08	1.03
7.94	0.05	84.95	0.80	85.91	0.96
7.95	0.05	89.93	0.80	90.81	0.87
7.95	0.05	94.96	0.80	95.67	0.71
7.95	0.05	99.99	0.80	100.57	0.58
7.95	0.05	104.91	0.80	105.58	0.66
7.94	0.05	109.89	0.80	110.67	0.78
7.95	0.05	114.91	0.80	115.80	0.89
7.94	0.05	119.92	0.80	120.98	1.06
7.94	0.05	124.95	0.80	126.07	1.12
7.94	0.05	129.98	0.80	131.07	1.09
7.94	0.05	134.97	0.80	135.88	0.92
7.95	0.05	139.96	0.80	140.92	0.97
7.94	0.05	145.00	0.80	145.77	0.77
7.95	0.05	150.01	0.80	150.59	0.59

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

Reference Air velocity	Reference Unc	Reference Yaw angle	Reference Unc	Test item Direction	Test item Deviation
m/s	m/s	deg	deg	deg	deg
7.95	0.05	155.00	0.80	155.71	0.71
7.94	0.05	160.01	0.80	160.85	0.84
7.94	0.05	164.97	0.80	165.78	0.81
7.95	0.05	169.92	0.80	170.72	0.79
7.95	0.05	174.95	0.80	175.51	0.56
7.95	0.05	179.98	0.80	180.36	0.38
7.95	0.05	184.94	0.80	185.23	0.29
7.95	0.05	189.93	0.80	190.13	0.21
7.95	0.05	194.97	0.80	195.29	0.33
7.95	0.05	199.99	0.80	200.54	0.55
7.95	0.05	205.03	0.80	205.69	0.67
7.94	0.05	210.02	0.80	210.85	0.82
7.94	0.05	215.02	0.80	215.87	0.85
7.94	0.05	220.01	0.80	220.77	0.76
7.95	0.05	224.98	0.80	225.67	0.69
7.95	0.05	230.00	0.80	230.33	0.33
7.95	0.05	235.05	0.80	235.30	0.24
7.94	0.05	240.06	0.80	240.33	0.27
7.95	0.05	245.01	0.80	245.41	0.39
7.94	0.05	250.02	0.80	250.71	0.69
7.95	0.05	255.06	0.80	255.82	0.76
7.95	0.05	260.07	0.80	260.90	0.83
7.94	0.05	265.07	0.80	265.94	0.87
7.94	0.05	270.09	0.80	270.79	0.70
7.95	0.05	275.11	0.80	275.78	0.66
7.95	0.05	280.10	0.80	280.61	0.51
7.94	0.05	285.09	0.80	285.53	0.45
7.94	0.05	290.03	0.80	290.57	0.54
7.94	0.05	295.02	0.80	295.61	0.58
7.95	0.05	299.99	0.80	300.62	0.63
7.95	0.05	305.03	0.80	305.72	0.69

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

Reference Air velocity	Reference Unc	Reference Yaw angle	Reference Unc	Test item Direction	Test item Deviation
m/s	m/s	deg	deg	deg	deg
7.94	0.05	310.03	0.80	310.53	0.50
7.94	0.05	315.00	0.80	315.42	0.42
7.94	0.05	319.95	0.80	320.26	0.31
7.95	0.05	324.93	0.80	325.15	0.23
7.95	0.05	329.92	0.80	330.37	0.45
7.95	0.05	334.96	0.80	335.48	0.51
7.95	0.05	339.98	0.80	340.70	0.72
7.95	0.05	345.00	0.80	345.73	0.73
7.95	0.05	349.99	0.80	350.55	0.55
7.94	0.05	354.97	0.80	355.43	0.47
7.94	0.05	358.64	0.80	358.92	0.28

Statistical analysis Average offset 0.63 deg

Graphical representation of the result
Grafische Darstellung des Ergebnisses

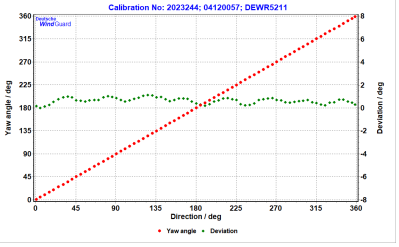

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Photo of the measurement setup
Foto des Messaufbaus

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

- End of document / Ende des Dokuments -

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B.1.3 Relative humidity and temperature

VAISALA

Vaisala is ISO 9001 and ISO 14001 certified company.
MEASUREMENT STANDARDS LABORATORY
ACCREDITED CALIBRATION LABORATORY

FINAS Finnish Accreditation Service
K008 (EN ISO/IEC 17025)

CERTIFICATE OF CALIBRATION no K008-H01321

Customer	TNO Wind Energy Westerduinweg 3 1755 LE Petten The Netherlands
Instrument	Humidity and Temperature Probe
Manufacturer	Vaisala Oyj
Model	HMP155E
Serial number	M1141113
Instrument number	94012135
Calibration date	On March 09, 2024
Calibration due date	May 09, 2025
Issue date	March 09, 2024
Signature	Sergei Fedorov Calibration Engineer
Page 1 (4)	
Documents attached	-
NOTES	The instrument was adjusted during calibration.
Conditions when received	Reported in Service Report.

Vaisala Oyj, PO Box 26, FI-00421 Helsinki, Finland
Telephone + 358 9 894 91 • Fax + 358 9 8949 2227
Email helpdesk@vaisala.com • www.vaisala.com
Domicile Vantaa, Finland • VAT FI01244162 • Business ID 0124416-2

(a) RHT 94012135, page 1/2

VAISALA

DESCRIPTION
The measurement results were obtained from the measured values or the results were calculated from the measured values by using adjustment coefficients.
The instrument's configuration, settings and coefficients were read from the instrument's memory.
Before measurements the instrument was allowed to stabilize to the conditions of the laboratory for at least 1 hour with 24,0 VDC ± 0,3 VDC power supply on.
The instrument was configured to use pressure 1013,25 hPa settings for the time of the calibration if there is a pressure compensation setting in the instrument.

REFERENCES USED DURING TEMPERATURE CALIBRATION
PTU30T Pressure and Temperature Transmitter, serial number U1020819, due date 2024-May-31

REFERENCES USED DURING HUMIDITY CALIBRATION
PTU30T Pressure and Temperature Transmitter, serial number U1020819, due date 2024-May-31
Thunder 2500 Humidity Generator, serial number 9711111, due date 2024-May-31
PTB330 Digital Barometer, serial number U1320322, due date 2024-May-31

TRACEABILITY
The measurement results are traceable to the international system of units (SI) through national metrology institutes (NIST in USA or equivalent) or accredited calibration laboratories.

CALIBRATION PROCEDURE
DOC233127 temperature. DOC230528 humidity.

UNCERTAINTY
The reported expanded uncertainty of measurement is stated as the standard uncertainty of measurement multiplied by the coverage factor k = 2, which for a normal distribution corresponds to a coverage probability of approximately 95 %. The standard uncertainty of measurement has been determined in accordance with EA Publication EA-4/02.
The measurement uncertainty represents the situation at the time and conditions of calibration. When using the UUC at different conditions and at different time the effect of the conditions and stability of the UUC shall be evaluated separately.
The measurement results and uncertainty are representing the measured instrument and measurement points only.
The calibration uncertainty includes known uncertainty components related to the instrument under calibration.
The instrument-dependent calibration uncertainty of the calibration point has not been defined entirely when the calibration uncertainty is marked with the text ** due to a large instrument reading error, due to the possibility of digital or analog output freezing to output a constant reading near the upper or lower limit of the output range or due to equivalent instrument-related reason. In the case of marking **, the calibration uncertainty is given without considering the effect of above-mentioned not exactly known reasons on the calibration results.

STATEMENT OF CONFORMITY
The calibration results and the statement of conformity with specification relate only to the calibrated instrument and the calibration points.
The statement of conformity is based on simple acceptance, whether the calibration result is within or outside the manufacturer's specification. The calibration uncertainty is not taken into account in the statement of conformity.
The probability of accepting a non-conforming result or rejecting a conforming result can be as large as 50 % with this acceptance rule when the calibration result is close to the specification limit.
Pass = The calibration result is equal or within the manufacturer's specification.
Fail = The calibration result is outside the manufacturer's specification.
There is no specified specification when the specification is marked with 'None'.

AMBIENT CONDITIONS

Temperature	23 °C ± 3 °C
Humidity	35 %rh ± 32 %rh

(b) RHT 94012135, page 2/2

B.1.4 Air pressure

VAISALA

Vaisala is ISO 9001 and ISO 14001 certified company.
MEASUREMENT STANDARDS LABORATORY
ACCREDITED CALIBRATION LABORATORY

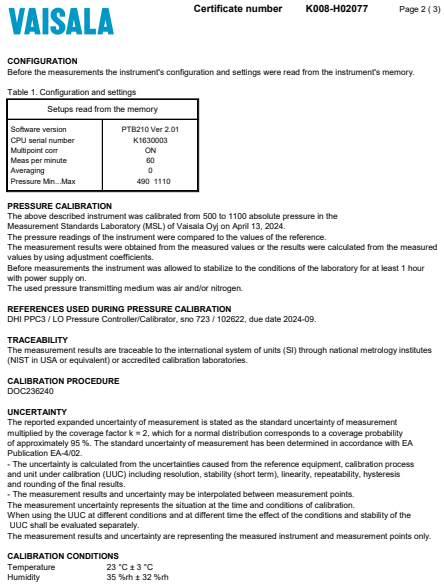
ilac-MRA FINAS Finnish Accreditation Service
K008 (EN ISO/IEC 17025)

CERTIFICATE OF CALIBRATION no K008-H02077

Customer	TNO Wind Energy Westerduinweg 3 1755 LE Petten The Netherlands
Instrument	Pressure Transmitter
Manufacturer	Vaisala Oyj
Model	PTB210A
Serial number	K1630003
Instrument number	94012574
Calibration date	On April 13, 2024
Calibration due date	June 13, 2025
Issue date	April 13, 2024
Signature	Sergei Fedorov Calibration Engineer
Page 1 (3)	
Documents attached	-
NOTES	Adjusted.
Conditions when received	Reported in Service Report.

Vaisala Oyj, PO Box 26, FI-00421 Helsinki, Finland
Telephone + 358 9 894 91 • Fax • 358 9 8949 2227
Email helpdesk@vaisala.com • www.vaisala.com
Domicile Vantaa, Finland • VAT FI01244162 • Business ID 0124416-2

(a) Air pressure sensor 94012574, page 1/2



VAISALA

Certificate number **K008-H02077** Page 2 (3)

CONFIGURATION
Before the measurements the instrument's configuration and settings were read from the instrument's memory.

Table 1. Configuration and settings

Setups read from the memory	
Software version	PTB210 Ver 2.01
CPU serial number	K1630003
Multipoint corr	ON
Meas per minute	60
Averaging	0
Pressure Min...Max	490 1110

PRESSURE CALIBRATION
The above described instrument was calibrated from 500 to 1100 absolute pressure in the Measurement Standards Laboratory (MSL) of Vaisala Oyj on April 13, 2024.
The pressure readings of the instrument were compared to the values of the reference.
The measurement results were obtained from the measured values or the results were calculated from the measured values by using adjustment coefficients.
Before measurements the instrument was allowed to stabilize to the conditions of the laboratory for at least 1 hour with power supply on.
The used pressure transmitting medium was air and/or nitrogen.

REFERENCES USED DURING PRESSURE CALIBRATION
DH PPC3 / LO Pressure Controller/Calibrator, sno 723 / 102622, due date 2024-09.

TRACEABILITY
The measurement results are traceable to the international system of units (SI) through national metrology institutes (NIST in USA or equivalent) or accredited calibration laboratories.

CALIBRATION PROCEDURE
DOC236240

UNCERTAINTY
The reported expanded uncertainty of measurement is stated as the standard uncertainty of measurement multiplied by the coverage factor k = 2, which for a normal distribution corresponds to a coverage probability of approximately 95 %. The standard uncertainty of measurement has been determined in accordance with EA Publication EA-4/02.
- The uncertainty is calculated from the uncertainties caused from the reference equipment, calibration process and unit under calibration (UUC) including resolution, stability (short term), linearity, repeatability, hysteresis and rounding of the final results.
- The measurement results and uncertainty may be interpolated between measurement points.
The measurement uncertainty represents the situation at the time and conditions of calibration.
When using the UUC at different conditions and at different time the effect of the conditions and stability of the UUC shall be evaluated separately.
The measurement results and uncertainty are representing the measured instrument and measurement points only.

CALIBRATION CONDITIONS

Temperature	23 °C ± 3 °C
Humidity	35 %rh ± 32 %rh

(b) Air pressure sensor 94012574, page 2/2

B.1.5 Sonic 3D

DEUTSCHE WINDGUARD

IECRE and MEASNET approved test laboratory

Calibration Certificate / *Kalibrierschein*

issued by the calibration laboratory / *erstellt durch das Kalibrierlaboratorium*

Deutsche WindGuard
Wind Tunnel Services GmbH

Member of / *Mitglied im*
Deutschen Kalibrierdienst

accredited to / *akkreditiert nach*
DIN EN ISO/IEC 17025:2018

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

DKD

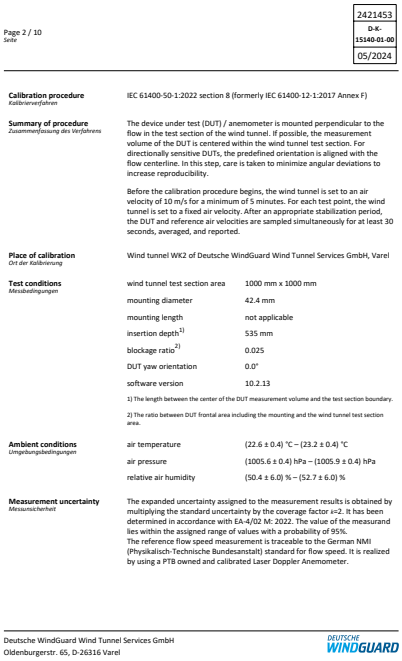
Calibration mark / *Kalibrierzeichen*: 2421453 | D-K-15140-01-00 | 05/2024

Device under test (DUT) *Gegenstand*	Ultrasonic Anemometer
Manufacturer *Hersteller*	METEK
Type *Typ*	uSonic-3 Sci
Serial number *Fabrikat/Serien-Nr.*	0111107372
Customer *Auftraggeber*	TNO NL - 1755 LE Petten
Order No. *Auftragsnummer*	3100409804
Project No. *Projektnummer*	VT240267
Number of pages *Anzahl der Seiten*	10
Date of Calibration *Datum der Kalibrierung*	2024-05-22

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 presented results relate only to the calibrated object. 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.
Die dargestellten Ergebnisse beziehen sich nur auf den kalibrierten Gegenstand. Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

Date / *Datum*	Freigegeben durch / *Approval by* Head of the calibration laboratory	Person in charge / *Bearbeiter*
2024-05-24	Heiko Westermann	Alina Roß

(a) Sonic 3D 94012345, page 1/6



2421453 | D-K-15140-01-00 | 05/2024

Calibration procedure *Kalibrierverfahren*	IEC 61400-50-1:2022 section 8 (formerly IEC 61400-12-1:2017 Annex F)
Summary of procedure *Zusammenfassung des Verfahrens*	The device under test (DUT) / anemometer is mounted perpendicular to the flow in the test section of the wind tunnel. If possible, the measurement volume of the DUT is centered within the wind tunnel test section. For directionally sensitive DUTs, the predefined orientation is aligned with the flow centerline. In this step, care is taken to minimize angular deviations to increase reproducibility. Before the calibration procedure begins, the wind tunnel is set to an air velocity of 10 m/s for a minimum of 5 minutes. For each test point, the wind tunnel is set to a fixed air velocity. After an appropriate stabilization period, the DUT and reference air velocities are sampled simultaneously for at least 30 seconds, averaged, and reported.
Place of calibration *Ort der Kalibrierung*	Wind tunnel WK2 of Deutsche WindGuard Wind Tunnel Services GmbH, Varel
Test conditions *Messbedingungen*	wind tunnel test section area: 1000 mm x 1000 mm mounting diameter: 42.4 mm mounting length: not applicable insertion depth[1]: 535 mm blockage ratio[2]: 0.025 DUT yaw orientation: 0.0° software version: 10.2.13 1) The length between the center of the DUT measurement volume and the test section boundary. 2) The ratio between DUT frontal area including the mounting and the wind tunnel test section area.
Ambient conditions *Umgebungsbedingungen*	air temperature: (22.6 ± 0.4) °C – (23.2 ± 0.4) °C air pressure: (1005.6 ± 0.4) hPa – (1005.9 ± 0.4) hPa relative air humidity: (50.4 ± 6.0) % – (52.7 ± 6.0) %
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 EA-4/02 M: 2022. 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.

(b) Sonic 3D 94012345, page 2/6

2421453 | D-K-15140-01-00 | 05/2024

Certificate ID *Zertifikat ID*	mmAzoPc4kQMq6vLbmZwzBp

(c) Sonic 3D 94012345, page 3/6

2421453 | D-K-15140-01-00 | 05/2024

Revision *Revision*	0

Remarks and Definitions *Erläuterungen und Definitionen*

General remarks	**North alignment via DUT geometry**
Reference air velocity v_{REF} / m/s	The reference air velocity. The uncertainty is given as the expanded uncertainty with a coverage factor of *k*=2.
DUT Indication ⌀$v_{DUT_{UV}}$⌀ $v_{DUT_{UV}}$ / m/s	The indication of the device under test converted to the horizontal wind speed $v_{DUT_{UV}}$ with vectorial averaging according to ISO 16622:2002 from DUT Indication ⌀xx (calculated) and DUT Indication ⌀y⌀ (calculated). The expanded uncertainty is given with a coverage factor of *k*=2.
Deviation ⌀$v_{DUT_{UV}}$ - v_{REF}⌀ Δv / m/s	The difference between DUT Indication ⌀$v_{DUT_{UV}}$⌀ and the reference air velocity. **The given uncertainty $U(\Delta v_{DUT_{UV}})$ is the combined expanded uncertainty with a coverage factor of *k*=2.**
DUT Indication x⌀x v_{DUT_1} / cm/s	The indication of the device under test. The uncertainty is given as the expanded uncertainty with a coverage factor of *k*=2. The following uncertainty components are taken into account: short-term stability (repeatability), resolution.
DUT Indication x⌀x (calculated) v'_{DUT_1} / m/s	The DUT Indication converted to the reference unit with the following equation: $v_{DUT_1} \cdot 0.01$. No uncertainties are considered for this conversion.
DUT Indication y⌀y v_{DUT_2} / cm/s	The indication of the device under test. The uncertainty is given as the expanded uncertainty with a coverage factor of *k*=2. The following uncertainty components are taken into account: short-term stability (repeatability), resolution.
DUT Indication y⌀y (calculated) v'_{DUT_2} / m/s	The DUT Indication converted to the reference unit with the following equation: $v_{DUT_2} \cdot 0.01$. No uncertainties are considered for this conversion.
DUT Indication z⌀z v_{DUT_3} / cm/s	The indication of the device under test. The uncertainty is given as the expanded uncertainty with a coverage factor of *k*=2. The following uncertainty components are taken into account: short-term stability (repeatability), resolution.
DUT Indication z⌀z (calculated) v'_{DUT_3} / m/s	The DUT Indication converted to the reference unit with the following equation: $v_{DUT_3} \cdot 0.01$. No uncertainties are considered for this conversion.

(d) Sonic 3D 94012345, page 4/6

DUT Indication $v_{\alpha DUT_{UV}\alpha}$
$\alpha_{DUT_{UV}}$ / deg

The indication of the device under test converted to the yaw orientation $\alpha_{DUT_{UV}}$ with vectorial averaging according to ISO 16622:2002 from "DUT Indication $v_{X\alpha}$ (calculated)" and "DUT Indication $v_{Y\alpha}$ (calculated)". The expanded uncertainty is given with a coverage factor of k=2.

Residuals

The remaining deviation between the DUT indication after applying a linear regression correction and the reference.

(e) Sonic 3D 94012345, page 5/6

Calibration result
Kalibrierergebnis

Index	Reference air velocity		DUT Indication $v_{\alpha DUT_{UV}\alpha}$		Deviation $v_{\alpha DUT_{UV}\alpha} - v_{REF\alpha}$	
-	m/s		m/s		m/s	
i	v_{REF}	$U(v_{REF})$	$v_{DUT_{UV}}$	$U(v_{DUT_{UV}})$	Δv	$U(\Delta v)$
1	3.955	0.040	4.0206	0.0060	0.066	0.040
2	6.014	0.040	6.0698	0.0060	0.056	0.040
3	7.903	0.040	7.9350	0.0061	0.032	0.040
4	9.998	0.040	10.0351	0.0061	0.037	0.041
5	11.980	0.048	12.0188	0.0063	0.038	0.048
6	14.048	0.056	14.1136	0.0066	0.065	0.057
7	15.974	0.064	16.0584	0.0065	0.084	0.064
8	15.024	0.060	15.0935	0.0065	0.070	0.061
9	13.023	0.052	13.0738	0.0063	0.051	0.053
10	11.003	0.044	11.0476	0.0062	0.045	0.044
11	8.968	0.040	9.0068	0.0062	0.038	0.041
12	6.942	0.040	7.0017	0.0060	0.060	0.040
13	4.979	0.040	5.0621	0.0061	0.083	0.041

A digital copy of this table is attached to the PDF version of this document.

(f) Sonic 3D 94012345, page 6/6

B.2 Thies cup classification sheet

Summary report of cup anemometer classification

DEUTSCHE WINDGUARD

Class S Classification

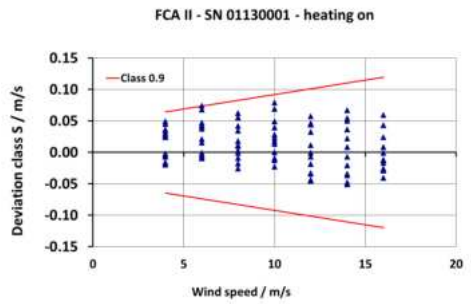
Reference:

IEC 61400-12-1 Edition 2.0
Wind Turbine Power Performance Testing
2017-03

Result:
Figure showing the calculated total deviation of the Thies First Class Advanced anemometer type 4.3352.00.000 taking into account all influencing parameters according to Class S definition.

Internal shaft heating ON

Classification index: S 0.9
(average of five sensors)



Class S Classification

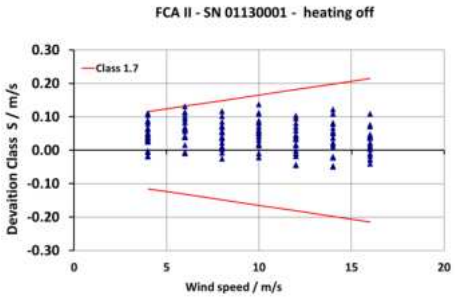
Reference:

IEC 61400-12-1 Edition 2.0
Wind Turbine Power Performance Testing
2017-03

Result:
Figure showing the calculated total deviation of the Thies First Class Advanced anemometer type 4.3352.00.000 taking into account all influencing parameters according to Class S definition.

Internal shaft heating OFF

Classification index: S 1.7
(average of five sensors)



(a) Thies cup 4.3352 classification report, page 10/11

Energy & Materials Transition

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www.tno.nl

TNO innovation for life