DNV·GL

PA-0

Independent analysis and reporting of PA-0 SODAR performance verification executed by DNV GL at Janneby test site

REMTECH

Report No.: 10118786-R-1, Rev. A
Date: 2019-09-20

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Project name:	PA-0	DNV GL - Energy
Report title:	Independent analysis and reporting of PA-0 SODAR performance verification executed by DNV GL at Janneby test site	Renewables Measurements Germany Loads & Power Performance
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Date of issue:	2019-09-20	
Project No.:	10118786	
Report No.:	10118786-R-1, Rev. A	

Task and objective:
Independent analysis and reporting of PA-0 SODAR performance verification executed by DNV GL at Janneby test site

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Keywords:
REMTECH, SODAR, performance verification

Reference to part of this report which may lead to misinterpretation is not permissible.

Rev. No.	Date	Reason for Issue	Prepared by	Verified by	Approved by
A	2019-09-20	Final report (electronic version, only)	Fied	BScm	BScm

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1 INTRODUCTION

GL Garrad Hassan Deutschland GmbH ("GH-D"), a member of the DNV GL Group ("DNV GL"), has been assigned on 2018-08-03 by REMTECH to prepare an independent analysis and report of a REMTECH SODAR performance verification on DNV GL test site at Janneby, Germany. In this analysis and report the REMTECH SODAR with the serial number PA-0 will be discussed. The verification measurements for this device were performed next to a 100 m meteorological mast (met. mast) located at the DNV GL test site in Janneby, Germany, from 2018-09-28 to 2018-10-30 divided in two trials at slightly different locations at the Jenneby site from:

1. Trial: 2018-09-28 to 2018-10-18
2. Trial: 2018-10-18 to 2018-10-30

The met tower was equipped with classical anemometry components (cup anemometers, wind vanes etc.) serving as the verification reference for the SODAR wind speed and wind direction comparisons. Those comparisons were performed based on a Remote Sensing (RS) best practice verification approach as developed within the EU-FP7-Projekt NORSEWInD [1] against corresponding Key Performance Indicators (KPIs) (compare APPENDIX A).

It is noted that the wind speed ranges 0 – 30 m/s and 3 – 15 m/s chosen in this analysis deviates from wind speed ranges of the performance verification approach according to NORSEWInD KPIs [1]. Thus, the defined Acceptance Criteria (see APPENDIX A) is not using for a best practice approach in this analysis.

DNV GL is accredited according to ISO 17025 for measurements on wind turbines and for wind resource measurements and energy assessments. DNV GL is also a full member of the network of measurement institutes in Europe 'MEASNET' and in the FGW (Fördergesellschaft Windenergie und anderer Erneuerbaren Energien).

The work has been conducted in compliance with all relevant health and safety legislation. GL Garrad Hassan Deutschland GmbH operates an Occupational Health and Safety Management System certified according to the OHSAS 18001:2007.

2 DESCRIPTION OF THE TEST SITE

2.1 The test site

The SODAR validation measurement campaign test site is located in the Northern German county Schleswig-Flensburg, approximately 30 km inland from the North Sea coast and some 20 km to the South West of a town called Flensburg. It belongs to the Northern German federal state of Schleswig-Holstein.

Due to its benign and flat terrain the site has good conditions for the purposes of verification trials of remote sensing (RS) devices like SODAR systems. Figure 1 provides an overview map of the very flat region between Flensburg and the North Sea, where the marked test site is located.

The site has a good exposure to largely undisturbed wind condition, i.e. undisturbed winds from almost all sectors. The elevation of the site is only a few meters above mean sea level. The surface roughness is low due to a mainly agricultural land use.

Figure 1: Map of test site location at Janneby, Germany.

Details of the test site can be taken from Figure 2. It has to be noted that there are two wind turbines in the proximity of the meteorological mast. Namely the turbine WT N100 located in 80° and 170 m distance and the turbine WT N117 located at 150° and 560m distance from the reference mast and test pad have to be taken into account, as it requires a filtering of the wind direction data for turbine wake influenced sectors. This is to assure the usage of unbiased wind data for the actual comparison between SODAR and cup anemometers as mounted to the reference mast.

Two test pads are provided for the setup of remote sensing devices, one to the North of the mast, the other one to the South West. The second test pad (Pad 2) has been used for the REMTECH trial at hand.

Figure 2: Inlet map of test site location at Janneby, Germany

2.2 Measuring equipment

In the following sections, the technical details and specifications of the measuring equipment are described. This description covers the meteorological reference mast (met mast) including its sensors and data acquisition system as well as the tested SODAR.

2.2.1 Meteorological mast: layout, sensors distribution and data acquisition

The met mast is a 3-fold guyed 100 m lattice tower with a constant face width of 0.4 m over its entire extension. Eight (8) MEASNET calibrated [4] cup anemometers (cups) of type Thies First Class Advanced (No. 4.3351), and a 3D sonic anemometer are mounted to the mast. As can be seen in Figure 3 at 29m, 57 m and 75 m above ground every 2 cups are mounted on booms pointing towards 150° and 330°, and the 2 top-mounted cups at 100 m above ground are installed in a Goal-Post-arrangement with a central boom pointing towards 330°/150°. The Sonic's position at 97 m is pointing towards 150°.

For the top mounting Goal-Post-arrangement of cups, the horizontal distance between the cups is 1.5 m, see Figure 3. All mounting arrangements are consistent with the currently valid IEC and IEA recommendations [3] for the use of cup anemometry at meteorological masts. The wind sensor setup also includes a temperature and humidity sensor and a pressures sensor near the mast top. A precipitation watch is installed approx. 10 m above ground.

Wind vanes of type Friedrichs are present at 97 m and 54 m height above ground, as well mounted on side booms. Table 1 gives the offset of each wind vane's death band relative to true North as applied in the logger configuration or during post-processing.

A Campbell Scientific CR1000 data logger is utilized as the met mast data acquisition system to record 10-minute averaged wind and other meteorological data such as temperature, humidity and air pressure and precipitation (watch: yes/no) throughout the measurement campaign. This logger was programmed to sample data at a rate of 1 Hz and store data as ten-minute averages with statistics.

The following transfer functions were applied in the logger configuration to the output signal from the anemometers:

Adjusted wind speed [m/s] = Slope x recorded wind speed [Hz] + Offset [m/s]

The slope and offset parameters are taken from wind tunnel calibrations according to the high-quality standards MEASNET [4]. Further details on the met mast can be seen in APPENDIX B, Figure 3, Table 2 and Table 3 that illustrates the sensor configuration at/near the top of the mast and the boom mounting at 57 m for cup anemometers and 54 m for the wind vane, respectively.

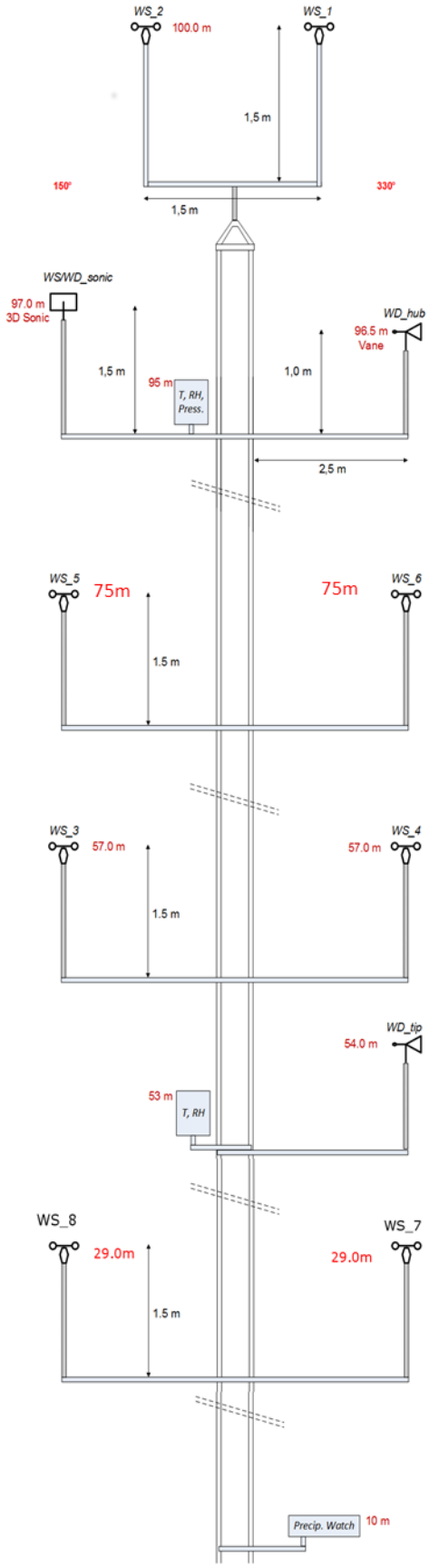


Figure 3: Mast configuration for top and boom mounted wind sensors.

Wind Vane Height	Offset Applied to Wind Vane
97 m	90°
54 m	90°

Table 1: Wind vane correction values

Label	Height [m]	Orientation - Mast to Instrument [°]	Instrument Type	Instrument Model	Cup to Boom Centre Height [mm]	Instrument to Mast Centre Length [mm]
WS_1	100	150	Cup Anemometer	Thies First Class Advanced 4.3351.00.000	1500	750
WS_2	100	330	Cup Anemometer	Thies First Class Advanced 4.3351.00.000	1500	750
WS/WD_sonic	97	150	Ultrasonic Anemometer / Vane	Gill WindMaster (Part 1590-PK-020)	1500	2500
WD_hub	96.5	330	Wind Vane	Theodor Friedrichs 4444.0004	1000	2500
T	95	150	Termometer	Thies Hygro-Thermo compact 1.1005.54.241	-	-
RH	95	150	Hygrometer	Thies Hygro-Thermo compact 1.1005.54.241	-	-
Press	95	150	Barometer	Vaisala PTB100A	-	-
WS_6	75	330	Cup Anemometer	Thies First Class Advanced 4.3351.00.000	1500	2500
WS_5	75	150	Cup Anemometer	Thies First Class Advanced 4.3351.00.000	1500	2500
WS_4	57	330	Cup Anemometer	Thies First Class Advanced 4.3351.00.000	1500	2500
WS_3	57	150	Cup Anemometer	Thies First Class Advanced 4.3351.00.000	1500	2500
WD_tip	54	330	Wind Vane	Theodor Friedrichs 4444.0004	1000	2500
T (lower level)	53	150	Termometer	Thies Hygro-Thermo compact 1.1005.54.241	-	-
RH (lower level)	53	150	Hygrometer	Thies Hygro-Thermo compact 1.1005.54.241	-	-
WS_8	29	150	Cup Anemometer	Thies First Class Advanced 4.3351.00.000	1500	2500
WS_7	29	330	Cup Anemometer	Thies First Class Advanced 4.3351.00.000	1500	2500
Precip. Watch	10	330	Watch (Yes/No)	Thies Precipitation Monitor 5.4103.10.000	-	-

Table 2: List of meteorological sensors and individual anemometers installed at the mast during verification campaign.

Label		WS_1	WS_2	WS_5	WS_6	WS_3	WS_4	WS_8	WS_7
Model		Thies First Class Advanced	Thies First Class Advanced	Thies First Class Advanced	Thies First Class Advanced	Thies First Class Advanced	Thies First Class Advanced	Thies First Class Advanced	Thies First Class Advanced
S/N		8154593	9143536	8165654	8165655	310565	10115031	8165657	8165656
Height [m]		100	100	75	75	57	57	30	30
Orientation - Mast to		150	330	150	330	150	330	150	330
DWG*	Calibration date	02.03.2017	02.03.2017	23.08.2016	23.08.2016	02.03.2017	02.03.2017	23.08.2016	23.08.2016
	Slope	0.04605	0.04601	0.04600	0.04597	0.04585	0.04595	0.04601	0.04603
	Offset	0.2482	0.2472	0.2187	0.2400	0.2518	0.2449	0.2153	0.2427
Applied	Slope	0.04605	0.04601	0.0460	0.04597	0.04585	0.04595	0.04601	0.04603
	Offset	0.2482	0.2472	0.2187	0.2400	0.2518	0.2449	0.2153	0.2427

Table 3: List of calibration factors for cup anemometers. The valid calibration certificates are attached to this report in APPENDIX E.

*Deutsche WindGuard

2.2.2 The REMTECH SODAR

The SODAR of type PA-0 is a Doppler SODAR that is specifically designed to measure wind speeds at heights in the boundary layer of the atmosphere. During the measurement campaign, the SODAR PA-0 was configured to record wind speed measurements at discrete heights between 40 m and 200 m in 5 m steps, see Table 4.

The installation and configuration were carried out by the customer. Figure 4 shows the SODAR unit being located approximately 142 m to the Northwest at the second verification trial and approx. 53 m to the Northwest at the first trial of the base of the mast. The system was configured at an offset angle of -42° (318°) degrees from true North.

Further all data provided by the SODAR has been validated internally and therefore no post filtering has been applied.

Figure 4: Installation setup of the SODAR next to the reference mast at Janneby test site.

			Height Settings (relative to ground level)								
SODAR – PA-0 [m]			40	45	..	**55**	**75**	**100**	..	195	200
Mast/WS-Cup Level [m]						**57**	**75**	**100**			
Mast/WD-Vane Level [m]						**54**		**97**			

Table 4: Selected height settings of SODAR and reference mast. Levels for wind speed and wind direction comparisons are highlighted in bold letters.

3 SODAR PERFORMANCE VERIFICATION (SPV) APPROACH

3.1 Common test conditions and data filtering

In the process of the SPV trial the following test conditions and filters are applied

- All comparisons are based on 10-minute average wind values returned from wind vanes and MEASNET calibrated cup anemometers installed on the reference mast (primary reference) and concurrent wind direction and wind speed data from the SODAR under test.
- All data collected during periods of possible icing at cup anemometers, i.e. temperatures below 0.5 °C.
- All other reported data (particularly wind speed) within undisturbed free-stream wind direction sector relative to the reference mast as well to the SODAR are used in the comparison analysis.
- For the validation of SODAR wind speeds against the mast, the wind speeds from TFCA cup anemometers at 57 m, 75 m and 100 m are used. It is noted that the wind speed at height 55 m at the SODAR was extrapolated to the reference height of 57 m. The SODAR data are selected according to the sector screening of the cup data prior to comparison, see following section.
- No SODAR specific quality filters are applied to the measured SODAR data prior to the analysis conducted.

3.2 Sector filtering

A sector filtering of wind data for wind directions based on the mast wind vane data needs to be performed in order to account for downwind flow distortions caused by

a) the neighbouring wind turbines.

b) the Goal post side-by-side mounting of the two top anemometers, mutually

c) the mast lattice structure of the two side mounted cups at 57 m and 75 m.

For case (a) within a sector between 50° and in 170° is clipped to account for the turbines wake. Compare hatched sector in Figure 5.

In cases (b) and (c), i.e. at all the comparison levels (30 m, 57 m, 75 m and 100 m) the orientation of one of the cup carrying goal posts or booms is to the North West (330°) on one side and to the South East (150°) on the other side. Hence, wind speed data need to be screened at wind directions between 130° and 170° for the cups on the Northwest side and between 310° and 350° for cups on the Southeast side of the mast, i.e. assuming a sufficiently wide screening sector of 40° (+/- 20°). This means that within these two disturbed sectors wind speed data from the single cup mounted on the upwind directed boom is considered valid, only.

For wind directions where cup data from both boom directions is available, i.e. for wind directions out of the two disturbed sectors (and excluding the turbine wake sectors), the wind speed average of the two oppositely mounted instruments is used as reference for the comparison with the SODAR wind speed. In this case the data is further screened if the wind speed difference between both cups exceeds 0.3 m/s.

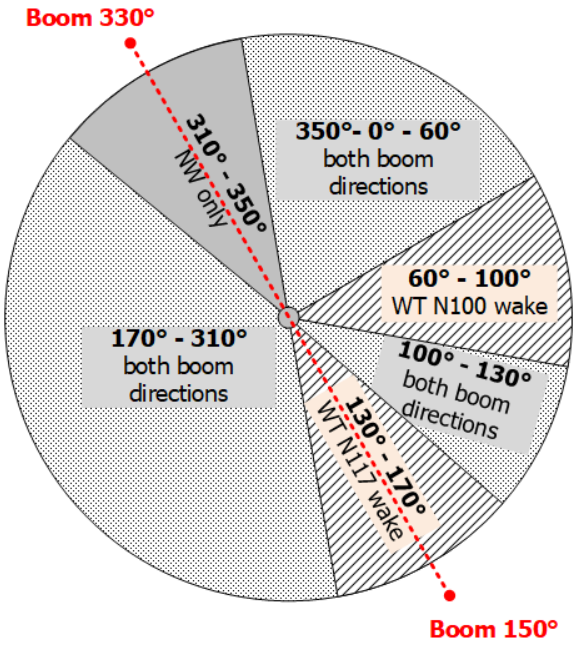


Figure 5: Wind direction sectors used to select undisturbed wind speed data from oppositely arranged cup carrying booms for comparison.

3.3 Data coverage requirements for accuracy assessment

The following data coverage definitions are prescribed for the SPV:

- The overall minimum number of 10 minute data points after filtering (according to sections 3.1 and 3.2) for the WS ranges [all > 0 m/s] and [3 to 15 m/s] should not be lower than 600.

Those data coverage requirements are regarded as achievable for a typical test period of 4 weeks.

3.4 SPV evaluation

The performance of the SODAR under test is evaluated for its system and data availability as well as for its wind data accuracy, based on a number of Key Performance Indicators (KPI).

The evaluation approach in terms of the applicable KPIs is outlined in APPENDIX A, where KPIs for system and data availability are listed in Table 16 those for wind data quality in Table 17.

The performance assessment of the given KPIs regarding Availability and Accuracy is executed at each reference level present, in this case at each of the three (3) met tower's 1st Class reference anemometry levels which are 57 m, 75 m and 100 m a.g.l. and for both verification periods.

4 RESULTS

For the treated SODAR Performance Verification (SPV) campaign data were provided for the 2 trials, 2018-09-28 until 2018-10-18 and 2018-10-18 until 2018-10-30. So the campaign was completed after 19.7 days for the first period and after 12.2 days for the second period. The verification trials covered wind speeds up to 18.2 m/s at the upper level (100 m) and up to 16.2 m/s at the lower level (57 m) for the whole campaign. The data coverage per wind speed range, as defined in section 3.3, can be seen in Table 5 and 6 for both periods.

	# of Data points		
WS-range	**57**	**75**	**100**
All >= 0 m/s	1859	1695	1615
3 - 15 m/s	1711	1604	1551

Table 5: Number of 10 minute data points after filtering used for WS comparison at each of the three (3) levels for 1. Trial.

	# of Data points		
WS-range	**57**	**75**	**100**
All > 0 m/s	1237	1224	1209
4 - 16 m/s	1153	1147	1118

Table 6: Number of 10 minute data points after filtering used for WS comparison at each of the three (3) levels for 2. Trial.

4.1 System availability

The system availability as applied to the SODAR device is defined by a percentage of the maximum possible number of ten-minute periods within campaign duration of 19.7 days for 1. Period, which represents 2834 concurrent data points for the 1.Period. As 2834 SODAR ten-minute data entries were present (regardless of the data validity), the SODAR device achieved a system availability of 100 %, see Table 7.

	SODAR Availability Assessment		
Height / m	**57**	**75**	**100**
Max. # of 10-min points in period	2834	2834	2834
After accounting power outages	2834	2834	2834
Data present	2834	2834	2834
System availability (**KPI SA_{CA}**)	100.0%	100.0%	100.0%
Total # of 10-minute valid data	2393	2395	2287
Data availability (**KPI DA_{CA}**)	84.4%	84.5%	80.7%
# after external filtering	1859	1695	1615
Data availability for comparison	65.6%	59.8%	57.0%

Table 7: Summary of system and data availabilities, 1. Trial

The system availability as applied to the SODAR device for the 2.Trial is within a duration of 12.2 days, which represents 1749 concurrent data points. However, periods of power outage should be taken into account. Therefore, after accounting the total number of missed data points due to power outages (Table 8), the maximum possible number of data points is reduced to 1484. Which represents a net campaign duration of 10.3 days. As 1484 SODAR ten-minute data entries were present (regardless of the data validity), the SODAR device achieved a system availability of 100 %, see Table 9.

Power Outage Period		
Start	**End**	**Missed Data points**
2018-Oct-26 17:00:00	2018-Oct-26 17:00:00	1
2018-Oct-26 20:10:00	2018-Oct-27 06:30:00	63
2018-Oct-27 20:10:00	2018-Oct-28 07:20:00	68
2018-Oct-28 20:10:00	2018-Oct-29 07:10:00	67
2018-Oct-29 21:10:00	2018-Oct-30 08:00:00	66
	Total missed data	265

Table 8 power outages description, 2. Trial.

	SODAR Availability Assessment		
Height / m	**57**	**75**	**100**
Max. # of 10-min points in period	1749	1749	1749
After accounting power outages	1484	1484	1484
Data present	1484	1484	1484
System availability (**KPI SA_{CA}**)	100.0%	100.0%	100.0%
Total # of 10-minute valid data	1314	1328	1309
Data availability (**KPI DA_{CA}**)	88.5%	89.5%	88.2%
# after external filtering	1237	1224	1209
Data availability for comparison	83.4%	82.5%	81.5%

Table 9: Summary of system and data availabilities, 2. Trial.

4.2 Data availability

Table 7 and Table 9 summarize the period of overlap between met-mast and SODAR system during the measurement campaign with the system availability as stated in the previous section.

Data for individual heights were treated as available when they show a numeric value in contrast to a value being flagged as -9999. The difference in number of available data between the rows "system" and "data availability" Table 7 and Table 9 reflect the reduction of valid data according to internal system filtering.

This can be seen in Figure 6 and Figure 7 showing the SODAR system availability and in particular the data recovery rate at each of the verification heights. The already mentioned system availability is – by definition – the same for all heights (white bars). The total data availability (blue bars) between the 57 m height and 100 m measurement level is above 80 % for the 1. Trial and above 85 % for the 2. Trial.

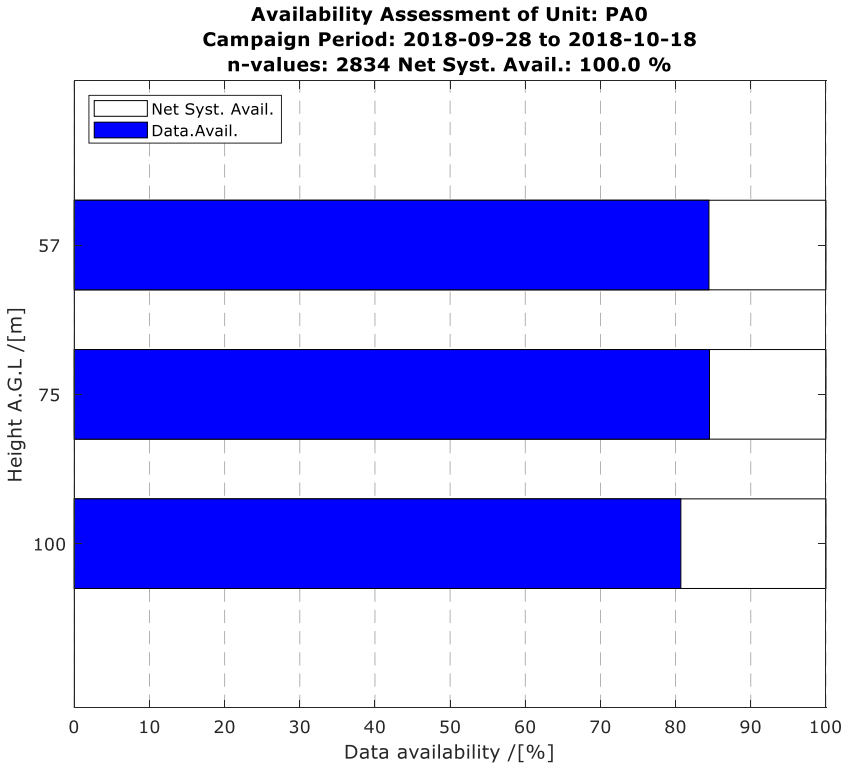


Figure 6: SODAR system and data availabilities for measurement levels, 1. Trial.

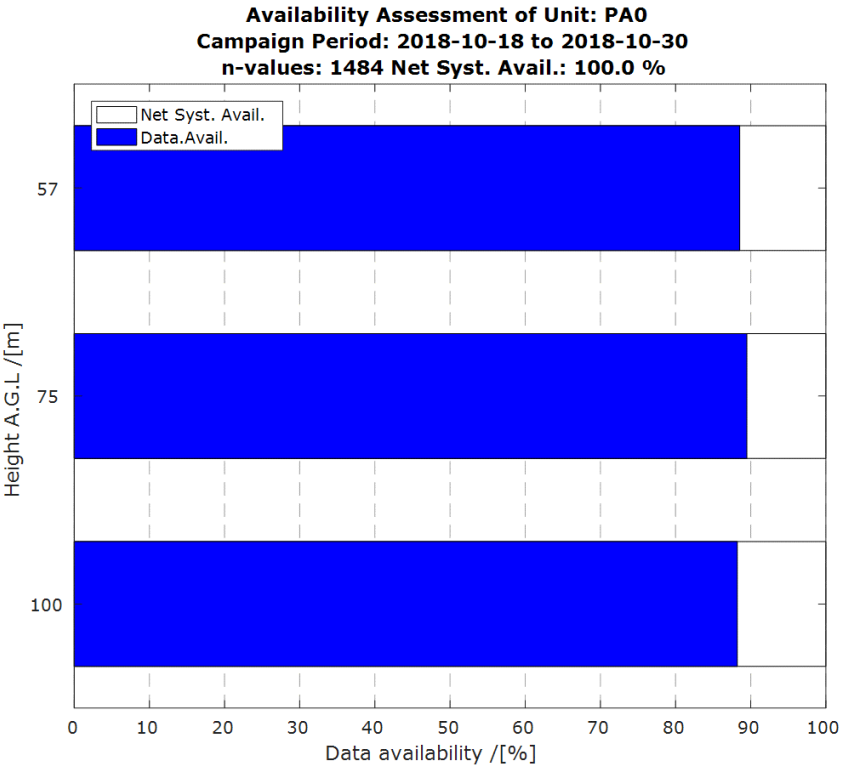


Figure 7: SODAR system and data availabilities for measurement levels, 2. Trial.

4.3 Data filtering

The data from both the SODAR and the mast were filtered for external parameters:

- wind direction to avoid non-valid wind speed sectors being influenced by e.g. mast wake effects, compare section 3.2 and
- Temperature < 0.5°C (Temperature sensor at 95 m was used as reference)

After the application of those filters the number of ten-minute data points remaining to be processed was reduced to a percentage between 65.6 % at 57 m and 57.0 % at 100 m for 1. Trial and 83.4 % at 57 m and 81.5 % at 100 m for 2. Trial (compare Table 7 and Table 9).

4.4 Wind speed comparison

Cup anemometers are regarded as the current industry standard for wind speed measurements at wind farm sites. Measurements with cup anemometers must therefore be considered the standard reference against which any new measurement device needs to be judged.

Wind speed as treated in this SPV process are assessed by means of Linear Regressions through the origin of the form

$$y = m\,x + b \text{ and } \quad b=:0$$

between SODAR (y-axis) wind speeds and cup (x-axis) wind speeds for the three mentioned height levels were derived from the comparison of data from the following wind speed ranges

a) all above 0 m/s

b) 3 to 15 m/s

according to the following KPIs

1) slope (m) (**KPI** X_{mws}) WS ranges a) and b)
2) R^2 (**KPI** R^2_{mws}) for all WS ranges a) and b)

as prescribed in and Appendix A.

This campaign represents a series performance test of a technology proven Remote Sensing device. As the test campaign was limited in WS coverage for natural reasons, the core verification concentrates on a subset of statistically meaningful performance criteria (in terms of amount of available representative data) being treated relevant for acceptance.

Results of wind speed comparisons

The time series of wind speeds measured by the SODAR (for all 3 pre-set heights) covering 19.7 days for 1. Trial and 12.2 days for 2. Trial are overlapped by the met mast own measurements. Two comparison heights (57 m and 100 m) for both Trials are shown in APPENDIX C.

Table 10 and Table 11 summarize the wind speed regression results for all three (3) comparison heights showing that the REMTECH SODAR at hand achieves a suitable level of accuracy compared to the respective cups in terms of regression slopes (m) and good regression coefficient R^2 (**KPI** R^2_{mws}). Figure 8 and Figure 9 show the corresponding regression plots for the wind speed range >= 0 m/s (upper row out of 4).

The mean SODAR wind speeds as averaged over all used values (**KPI** C_{mwsd}) resemble those of the cups closely (see columns 5 and 6 of Table 10 and Table 11), yielding a good relative Campaign Mean WS

Differences (**KPI** C_{mwsd}) at all assessed measurement heights for both WS ranges with respect to the SODAR technology.

57 m level	# values	slope	R^2	WS-avg Cup	WS-avg SODAR	mean diff.	rel. mean difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		**KPI X_{mws}**	**KPI R^2_{mws}**				**KPI C_{mwsd}**
0 - 30 m/s	1859	1.020	0.952	5.54	5.65	0.110	1.99%
3 - 15 m/s	1711	1.020	0.944	5.80	5.92	0.122	2.10%

75 m level	# values	slope	R^2	WS-avg Cup	WS-avg SODAR	mean diff.	rel. mean difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		**KPI X_{mws}**	**KPI R^2_{mws}**				**KPI C_{mwsd}**
0 - 30 m/s	1695	1.000	0.962	6.09	6.09	0.005	0.08%
3 - 15 m/s	1604	1.000	0.956	6.29	6.29	0.007	0.12%

100 m level	# values	slope	R^2	WS-avg Cup	WS-avg SODAR	mean diff.	rel. mean difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		**KPI X_{mws}**	**KPI R^2_{mws}**				**KPI C_{mwsd}**
0 - 30 m/s	1615	1.008	0.973	6.64	6.71	0.070	1.06%
3 - 15 m/s	1551	1.008	0.969	6.82	6.89	0.072	1.05%

Table 10: Regression results for comparison, 1. Trial.

57 m level	# values	slope	R^2	WS-avg Cup	WS-avg SODAR	mean diff.	rel. mean difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		**KPI X_{mws}**	**KPI R^2_{mws}**				**KPI C_{mwsd}**
0 - 30 m/s	1237	1.007	0.976	6.77	6.86	0.092	1.36%
3 - 15 m/s	1153	1.008	0.974	6.99	7.09	0.104	1.49%

75 m level	# values	slope	R^2	WS-avg Cup	WS-avg SODAR	mean diff.	rel. mean difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		**KPI X_{mws}**	**KPI R^2_{mws}**				**KPI C_{mwsd}**
0 - 30 m/s	1224	1.002	0.982	7.31	7.37	0.063	0.86%
3 - 15 m/s	1147	1.009	0.980	7.29	7.38	0.092	1.26%

100 m level	# values	slope	R^2	WS-avg Cup	WS-avg SODAR	mean diff.	rel. mean difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		**KPI X_{mws}**	**KPI R^2_{mws}**				**KPI C_{mwsd}**
0 - 30 m/s	1209	1.002	0.985	7.84	7.90	0.060	0.76%
3 - 15 m/s	1118	1.011	0.983	7.64	7.74	0.096	1.26%

Table 11: Regression results for comparison, 2. Trial.

Table 12 and Table 13 reflect the results according to the absolute wind speed error criterion.

Criterion for abs WS error	> 0.5 m/s for 0 to 30 m/s KPI A_{wsd}		
Height Level	total #	identified #	fraction
57 m	1859	348	18.72%
75 m	1695	302	17.82%
100 m	1615	220	13.62%

Table 12: Summary of absolute wind speed differences between cups and SODAR, 1. Trial

Criterion for abs WS error	> 0.5 m/s for 0 to 30 m/s KPI A_{wsd}		
Height Level	total #	identified #	fraction
57 m	1237	272	21.99%
75 m	1224	222	18.14%
100 m	1209	183	15.14%

Table 13: Summary of absolute wind speed differences between cups and SODAR, 2. Trial

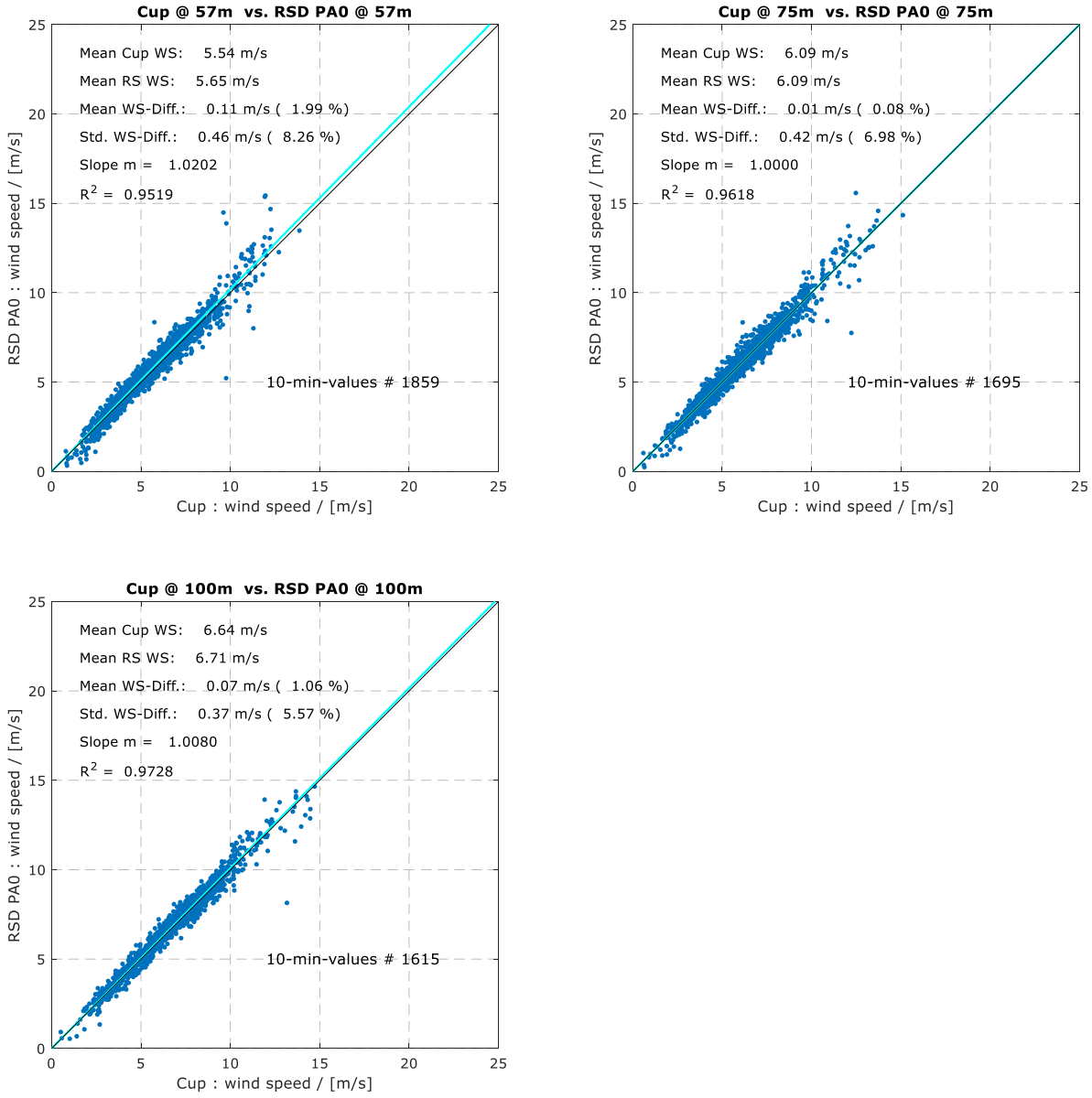


Figure 8: Plots of linear wind speed regression results for 100 m, 75 m and 57 m, 1. Trial.

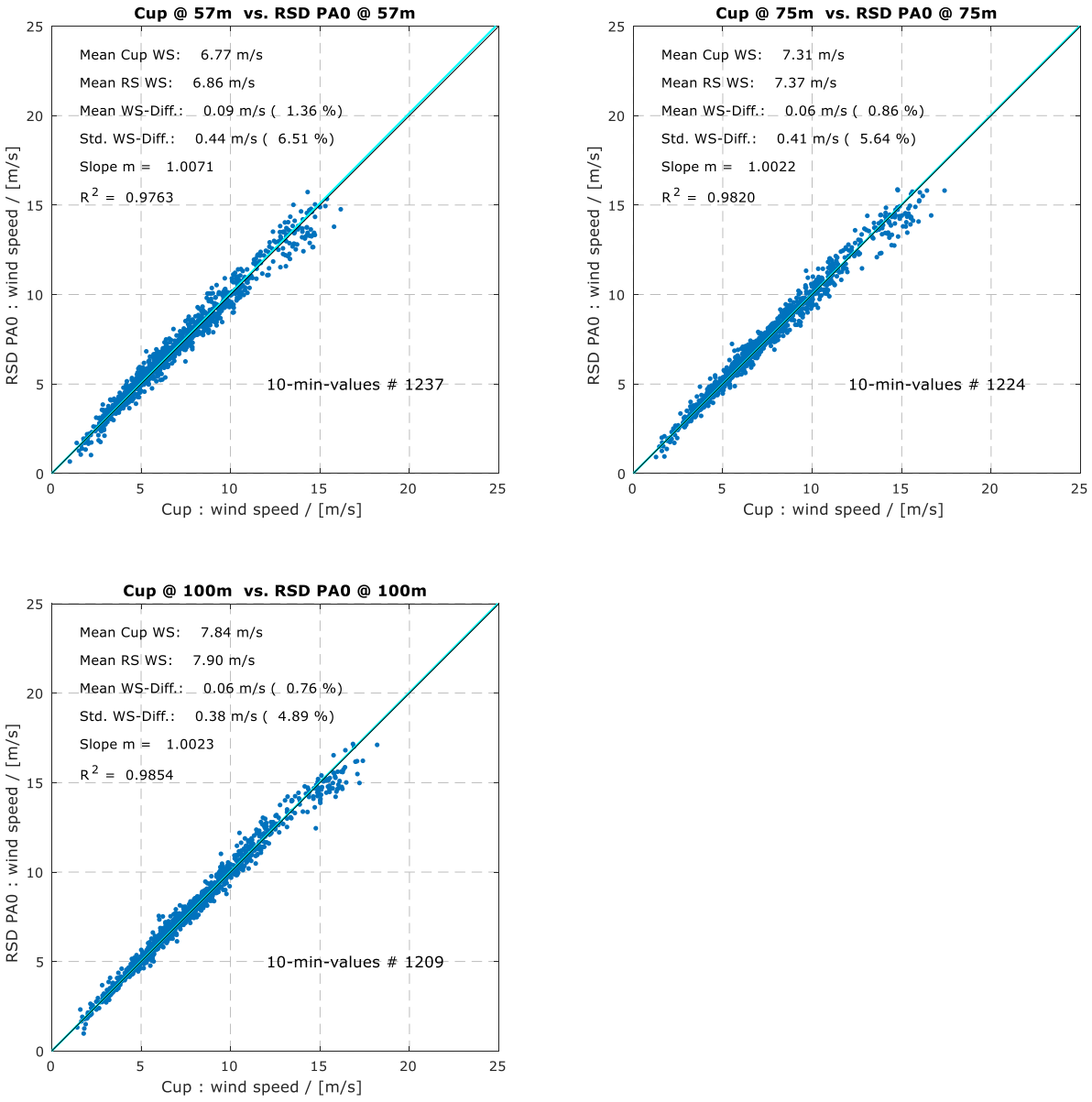


Figure 9: Plots of linear wind speed regression results for 100 m, 75 m and 57 m, 2. Trial.

4.5 Wind direction comparison

By comparing the wind direction as measured by the SODAR device at its 57 and 100 m level with the mast mounted wind vane at 54 and 97 m A.G.L., it is possible to see how well correlated the measures are, providing confidence in that the SODAR is 'seeing' the same wind direction as the vane. In order to validate this comparison quantitatively a two variant regression solving for the slope m and the interception of the best-fit line with the y-axis *b* (according to y = m x + b) was performed, compare APPENDIX A.

The results of such regression are shown in the x-y-plots in Figure 10 and Figure 11 with the vane wind direction at 97 and 54 m on the x-axis and the SODAR direction at 100 and 57 m on the y-axis.

Time series of wind direction present during the course of the campaign together with raw data correlations and WD distribution statistics can be found in APPENDIX D.

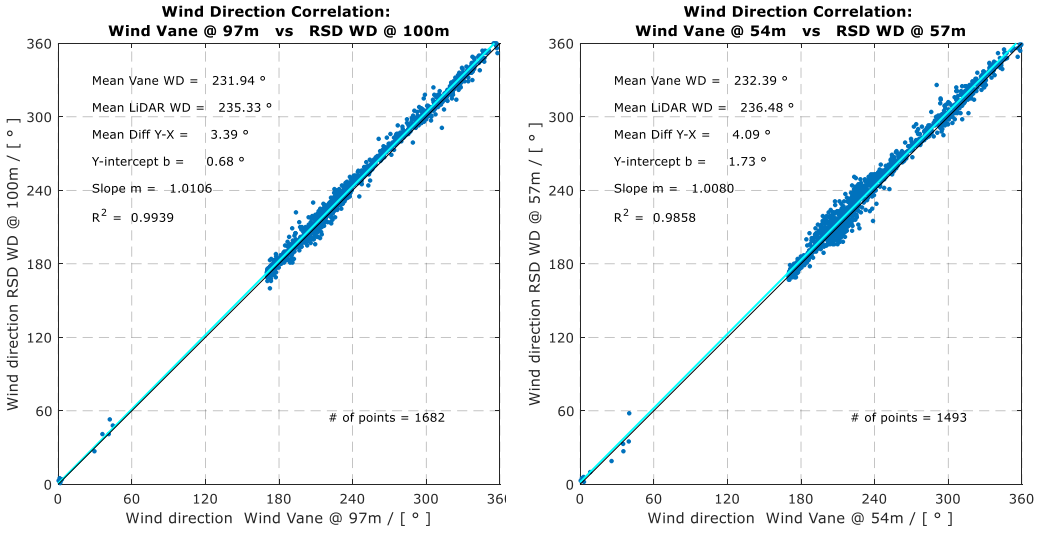


Figure 10: Regression plot of wind direction comparisons at 97 m (left) and 54 m (right panel), 1. Trial.

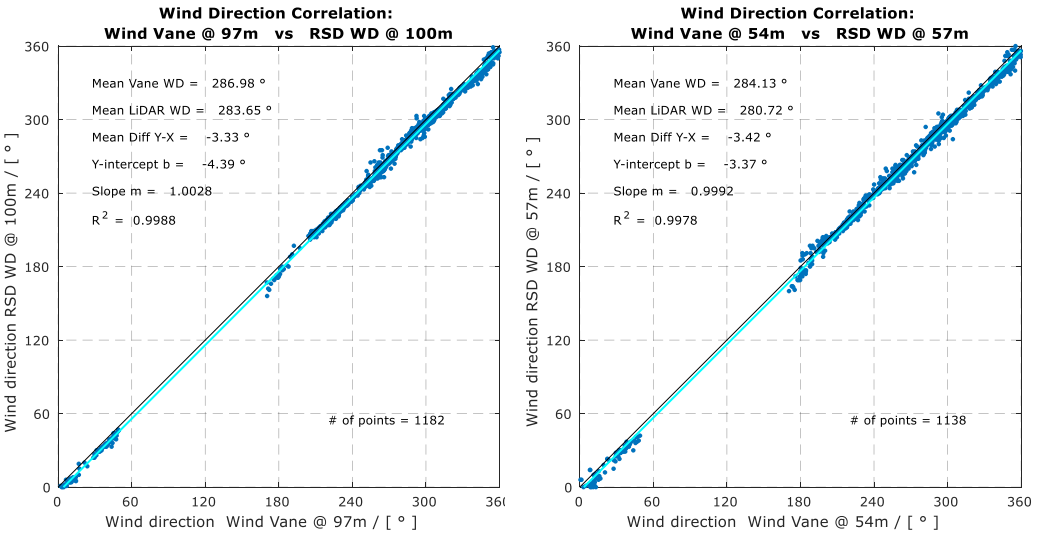


Figure 11: Regression plot of wind direction comparisons at 97 m (left) and 54 m (right panel), 2. Trial.

The regression plots in Figure 10 and Figure 11 reveal a close resemblance between SODAR and wind vane wind direction measures for both heights at 100 m and 57 m with an offset of max. 4.1° at 1. Trial and -3.4° ant 2. Trial which is within typical directional setup uncertainties for wind vanes and remotes sensing devices. Table 14 summarizes the WD comparison results for relevant WD comparison levels, showing an equally good resemblance slope.

WS filtering for WS > 0 m/s				
Height level	**# values**	**slope**	**offset [°]**	**R^2**
[m]	[-]	**KPI X_{mwd}**	**KPI OFF_{mwd}**	**KPI R^2_{mwd}**
97	1682	1.011	3.387	0.994
54	1493	1.008	4.086	0.986

Table 14: Summary of WD comparison results for both comparison levels, 1. Trial

WS filtering for WS > 0 m/s				
Height level	**# values**	**slope**	**offset [°]**	**R^2**
[m]	[-]	**KPI X_{mwd}**	**KPI OFF_{mwd}**	**KPI R^2_{mwd}**
97	1182	1.003	-3.333	0.999
54	1138	0.999	-3.418	0.998

Table 15: Summary of WD comparison results for both comparison levels, 2. Trial

5 IMPORTANT REMARKS AND LIMITATIONS

Independently performed SODAR Performance Verifications (SPV) of individual SODAR devices as reported in this document present a reasonable means to assure overall system integrity of the SODAR unit after manufacturing, and are meant to give an indication of the quality of wind data produced by the SODAR.

Any statement given in the context of system integrity and data quality related results within this report are limited to the given test site conditions, to the prevailing atmospheric (in particular wind) conditions and to the specific SODAR configuration as selected for this SPV campaign.

6 CONCLUSION

Concurrent REMTECH SODAR and cup anemometer wind measurements were carried out at the Janneby test site to validate SODAR wind data quality against a well-known high quality standard cup anemometer. Measurement heights of 57 m, 75 m and 100 m were available for wind speed correlations (54/97m for wind direction correlation) between a proximate met mast and a REMTECH SODAR with the serial number PA-0. The whole duration of the validation was 31.9 days, divided in two trials, 19.7 days and 12.2 days. The wind data coverage is considered sufficient for the purpose of characterizing the wind data performance of the REMTECH SODAR in the context of a SODAR Performance Verification.

For the treated SPV campaign data were provided for the 2 periods, 2018-09-28 until 2018-10-18 and 2018-10-18 until 2018-10-30. So, the campaign was completed after 19.7 days for the first Trial and after 12.2 days for the second Trial.

Wind speed (and direction) correlations were carried out for each of the three WS measurement heights (two for WD) mentioned above. The wind speeds of both techniques at all treated heights correlated suitable, showing a acceptable level of scatter and an good resemblance of SODAR wind speeds to those of cups, in terms of linear regression slopes and correlation coefficient with respect to SODAR technology.

7 REFERENCES

1. DNV GL, " *Best Practice Test and Verification Procedure for Wind LiDARs on the Høvsøre Test Site",* GL GH-D Report WT 6960/09 for EU-Project NORSEWInD, Deliv. 1.1, June 2009

2. International Standard: IEC 61400-12-1: Wind turbines – Part 12-1: Power performance measurements of electricity producing wind turbines. Ed. 2., Apr. 2017

3. IEA EXPERT GROUP STUDY ON RECOMMENDED PRACTICES FOR WIND TURBINE TESTING AND EVALUATION 11. WIND SPEED MEASUREMENT AND USE OF CUP ANEMOMETRY, 1. EDITION 1999

4. MEASNET: "Cup Anemometer Calibration Procedure". Version 1, September 1997

8 GLOSSARY

The following table lists abbreviations and acronyms used in this report.

Abbreviation Acronym	Meaning
AC	Acceptance Criterion
a.g.l.	Above ground level
DNV GL	New company name, successor of legacy GL GH
IEC	International Electro-technical Commission
IEA	International Energy Agency
GH-D	GL Garrad Hassan Deutschland GmbH
KPI	Key Performance Indicator
MM	Meteorological Mast
PAR	Performance Assessment Requirement
SPV	SODAR Performance Verification
TFCA	Thies First Class Advanced (cup anemometer)
TI	Turbulence Intensity
WD	Wind direction
WS	Wind speed

APPENDIX A KEY PERFORMANCE INDICATORS AND ACCEPTANCE CRITERIA [2]

Table 16: List of KPIs and ACs relevant for System and Data Availability assessment

KPI	Definition / Rationale	Acceptance Criteria[1]
SA_{CA}	**System Availability** The LIDAR system is ready to function according to specifications and to deliver data, taking into account all time stamped data entries in the output data files including flagged data (e.g. by NaNs or 9999s) for the pre-defined total campaign length. The System Availability is the number of these time stamped data entries relative to the maximum possible number of data entries (for 10 minute intervals) within the pre-defined total campaign period. (Any conditions affecting the test's data availability outside of the LIDAR system's control is not to be included in this calculation. Such as: power outages, acts of nature causing system damage, communication outages, maintenance, etc.)	≥95%
DA_{CA}	**Data Availability** The Data Availability is defined as the number of valid data points returned by the LIDAR unit as compared to maximum number of possible points that can be acquired during the test (Any conditions affecting the test's data availability outside of the LIDAR system's control is not to be included in this calculation. Such as: power outages, acts of nature causing system damage, communication outages, maintenance, etc.)	≥90%

1 Requirements of KPIs and Acceptance Criteria in grey are not considered.

Table 17: List of KPIs and ACs relevant for Wind Data Accuracy assessment

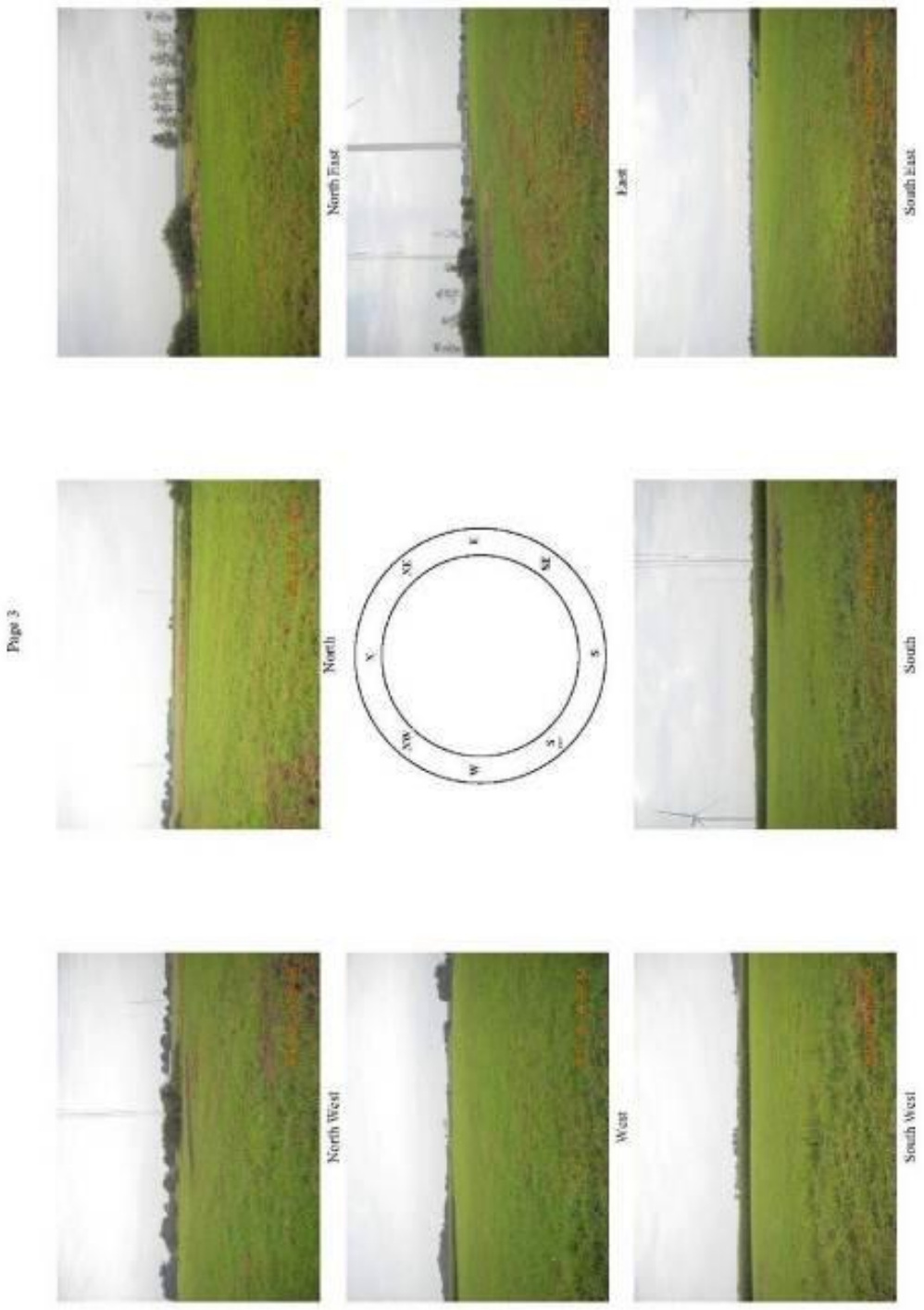
KPI	Definition / Rationale	Acceptance Criteria[1]	
		Best Practice	Minimum
C_{mwsd}	**Campaign Mean Wind Speed – Difference** Absolute difference of mean wind speeds between LIDAR and reference as measured over the whole verification campaign duration, expressed as percentage relative to the Campaign Mean Wind Speed A threshold is imposed on the Difference. Analysis shall be applied to wind speed ranges a) all above 3 m/s b) 4 to 16 m/s given achieved data coverage requirements	< 1 %	1 – 1.5 %
A_{wsd}	**Absolute Wind Speed Differences** Absolute 10 minute mean wind speed differences between LIDAR and reference for all data points treated after filtering. A threshold is imposed on the Difference. Analysis shall be applied to wind speed ranges a) 3 to 16 m/s given achieved data coverage requirements.	a) > 0.5 m/s Not more than 10% of data to exceed the criteria above.	
X_{mws}	**Mean Wind Speed – Slope** Slope returned from single variant regression with the regression analysis constrained to pass through the origin. A tolerance is imposed on the Slope value. Analysis shall be applied to wind speed ranges a) all above 3 m/s b) 4 to 16 m/s given achieved data coverage requirements.	0.98 – 1.02	0.97 – 1.03
R^2_{mws}	**Mean Wind Speed – Coefficient of Determination** Correlation Co-efficient returned from single variant regression A threshold is imposed on the Correlation Co-efficient value. Analysis shall be applied to wind speed ranges a) all above 3 m/s b) 4 to 16 m/s given achieved data coverage requirements.	>0.98	>0.97

KPI	Definition / Rationale	Acceptance Criteria[1]	
		Best Practice	Minimum
X_{mwd}	**Mean Wind Direction – Slope** Slope returned from a two-variant regression. A tolerance is imposed on the Slope value. Analysis shall be applied to a) all wind speeds above 3 m/s regardless of coverage requirements.	0.98– 1.02	0.97 – 1.03
OFF_{mwd}	**Mean Wind Direction – Offset (absolute value)** (same as for M_{mwd})	< 5°	< 7.5°
R^2_{mwd}	**Mean Wind Direction – Coefficient of Determination** (same as for M_{mwd})	> 0.97	> 0.95

1 Requirements of KPIs and Acceptance Criteria in grey are not considered.

APPENDIX B JANNEBY MET MAST DETAILS

360° Panorama Photos, taken on 2015-09-01, see inspection report [6]:



Met Mast Photo:

Photo 1: Close-up of mast top towards East

Photo 2: Mast and Wind turbine to the East

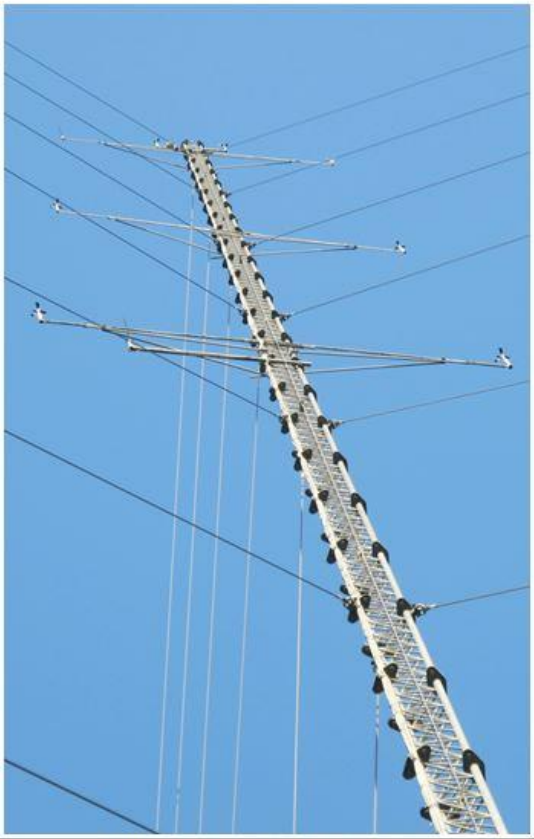
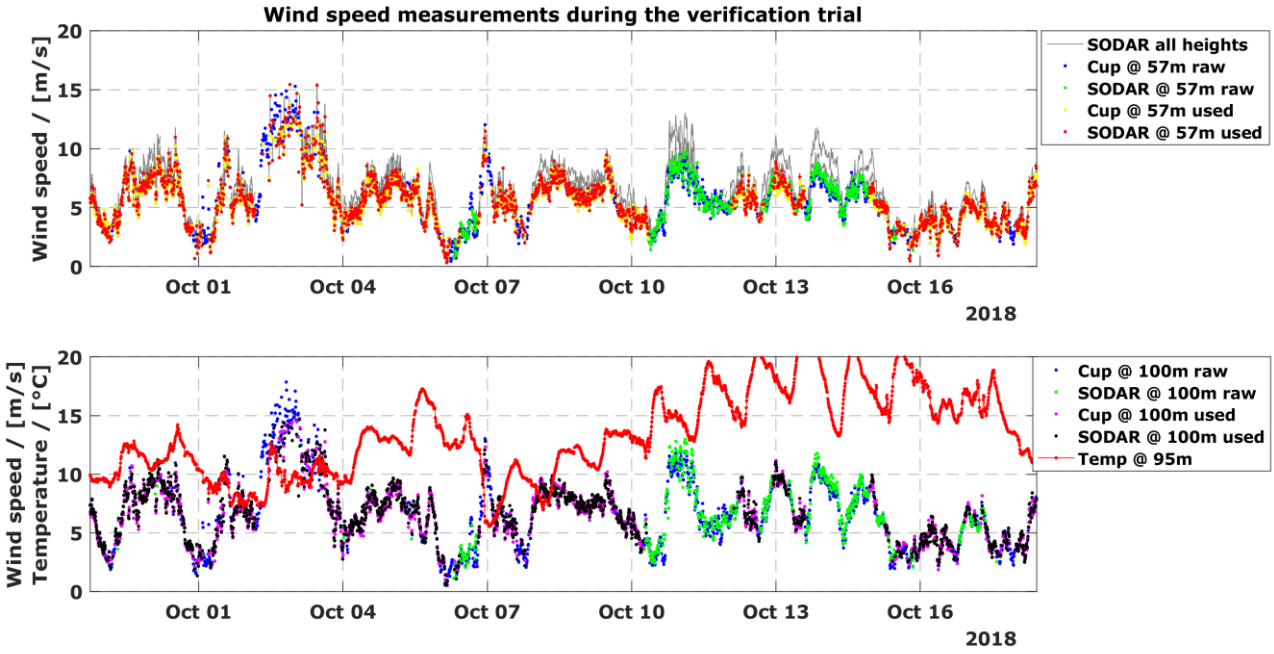


Photo 3: Mast measurement levels

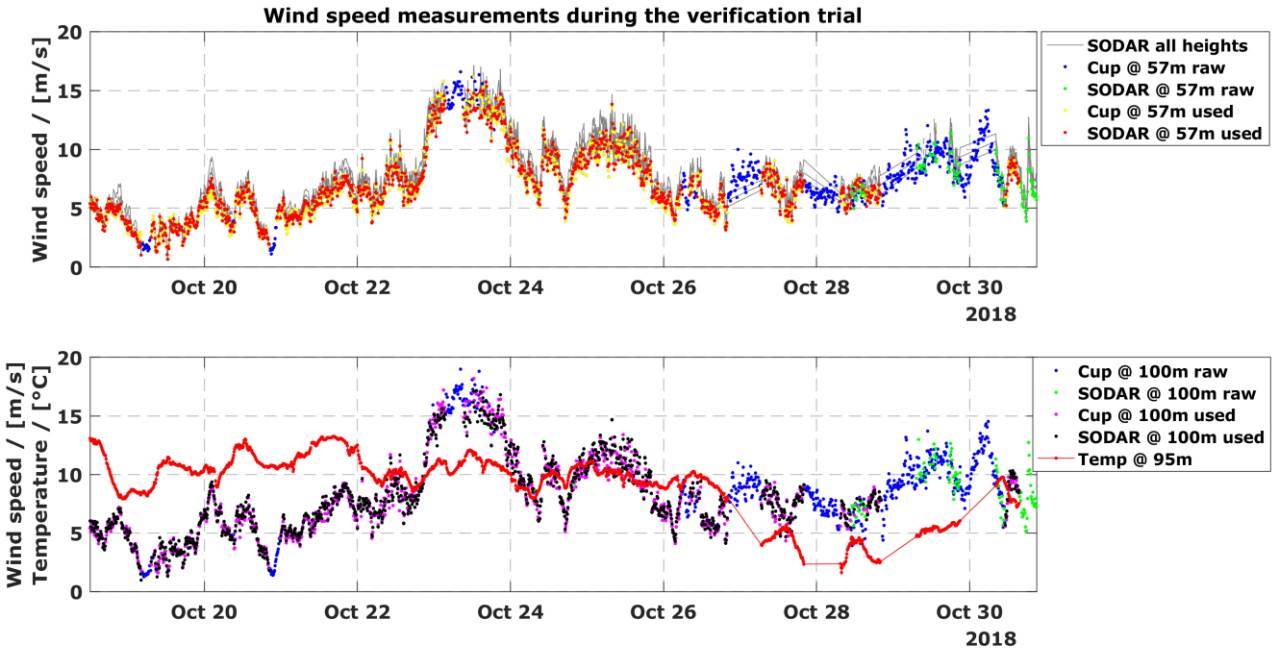
APPENDIX C TIME SERIES OF WIND SPEED

Wind Speed time series for upper and lower level with temperature at bottom plot.

1.Trial

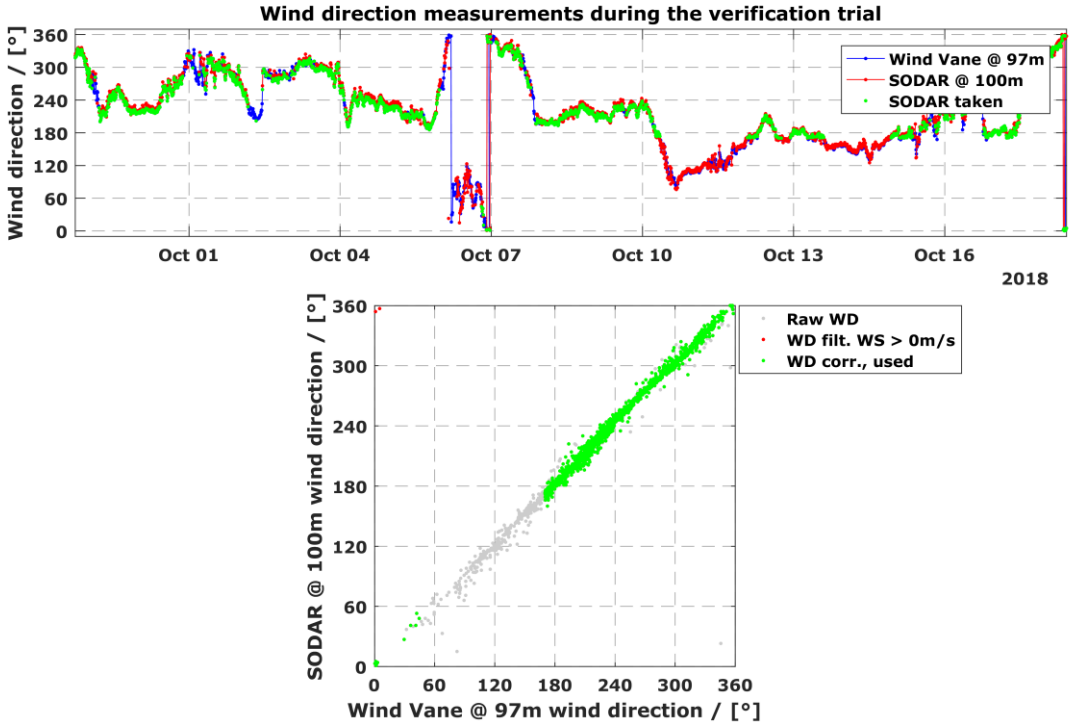


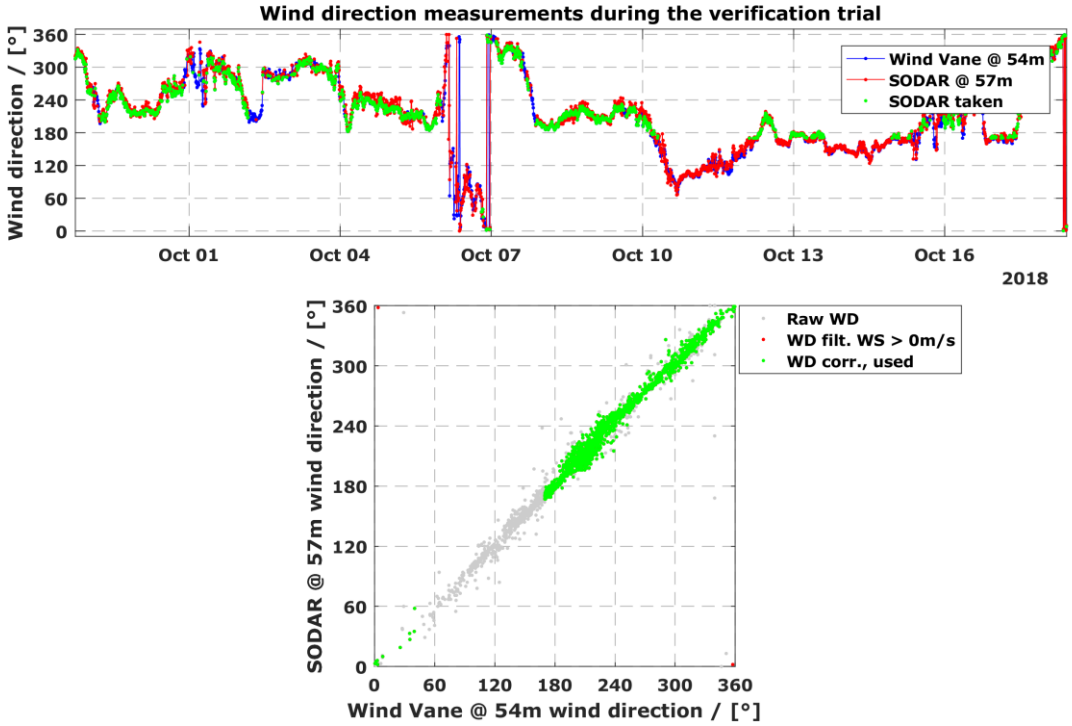
2. Trial



APPENDIX D WIND DIRECTION

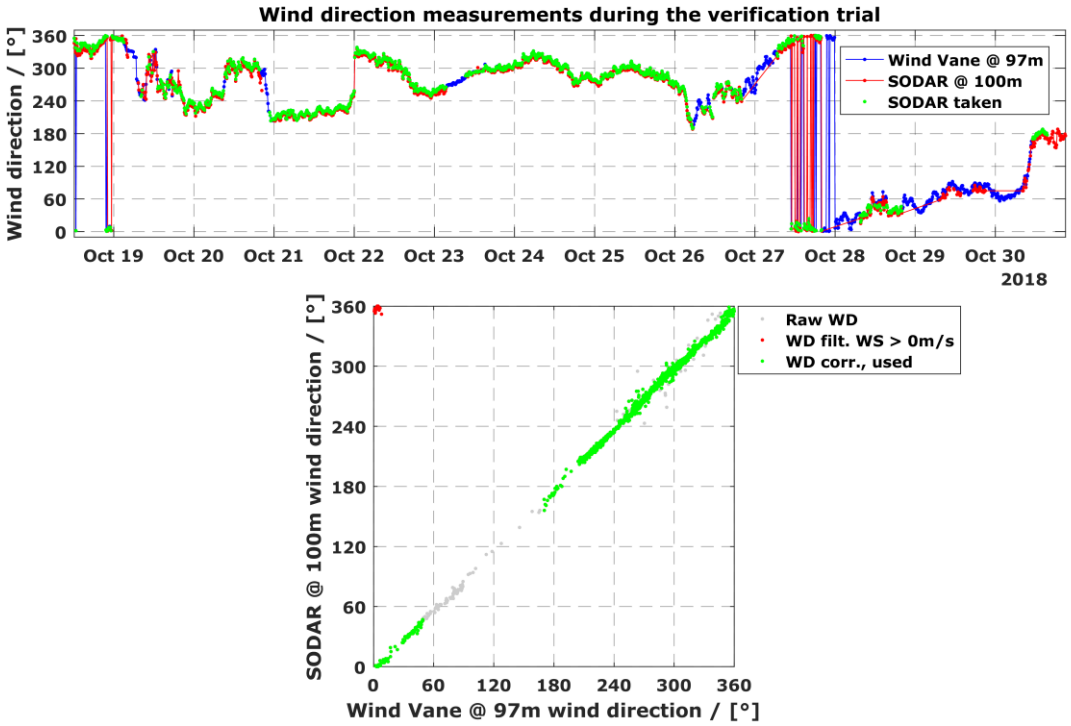
WD time series of both wind vane levels, 1. Trial:

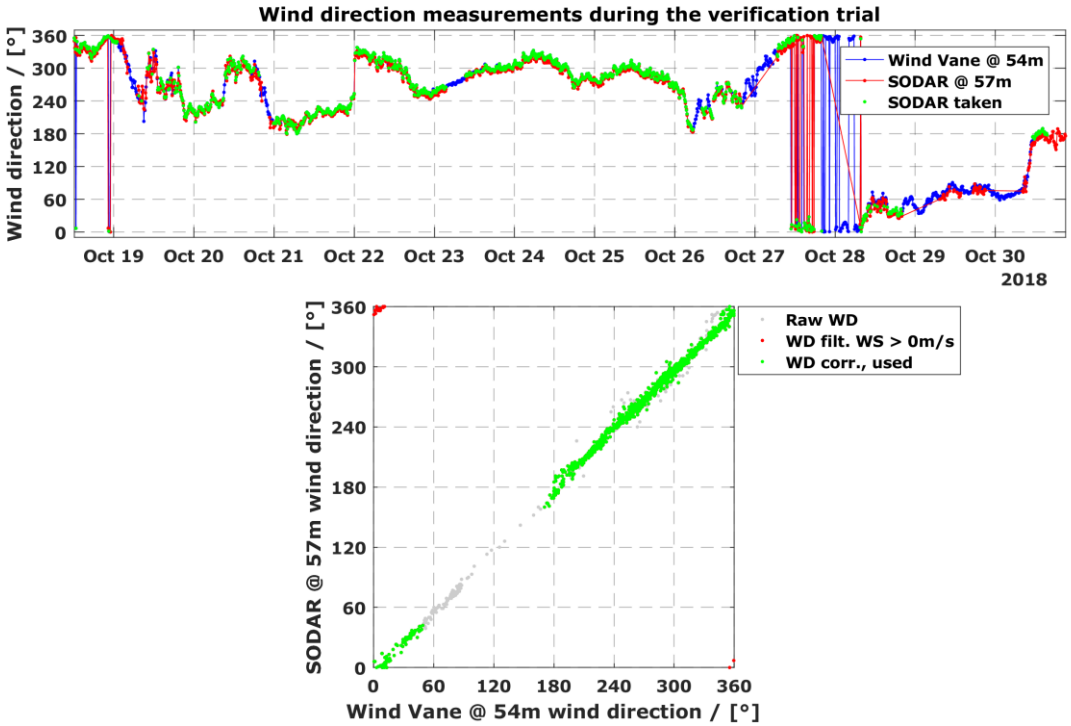




X-Y-plot of wind direction data for WS > 0 m/s (red dots) and 180° ambiguity corrected data (green dots) between wind vane and SODAR measures

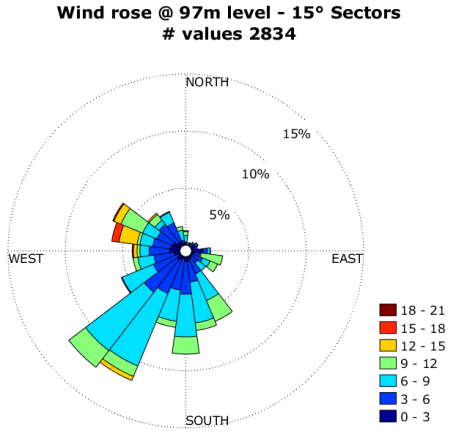
WD time series of both wind vane levels, 2. Trial:

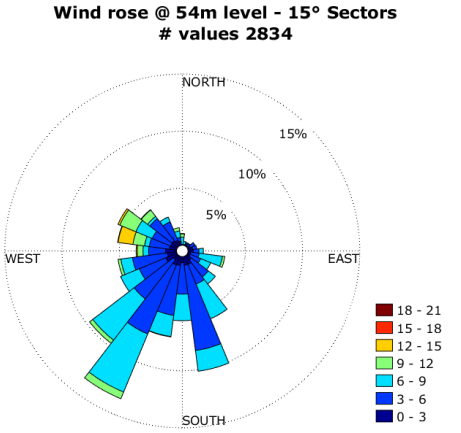




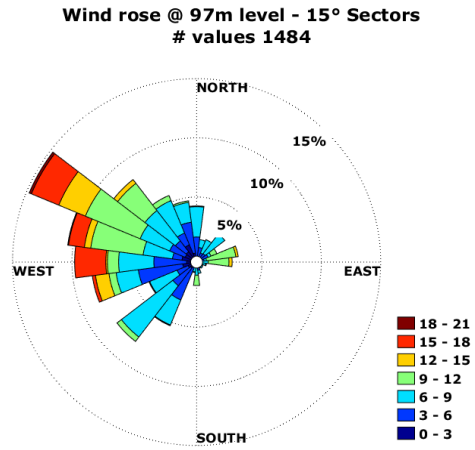
X-Y-plot of wind direction data for WS > 0 m/s (red dots) and 180° ambiguity corrected data (green dots) between wind vane and SODAR measures

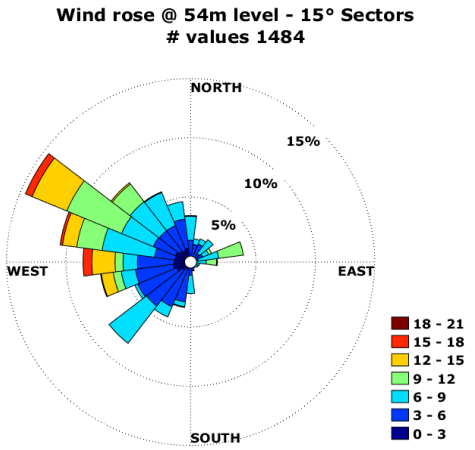
Wind rose, 1. Trial:





Wind rose, 2. Trial:





APPENDIX E CUP CALIBRATION CERTIFICATES

WS_1-Thies First Class Cup Anemometer at 100 m, 150° orientation:

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

accredited by the / *akkreditiert durch die*

Deutsche Akkreditierungsstelle GmbH

as calibration laboratory in the / *als Kalibrierlaboratorium im*

Deutschen Kalibrierdienst DKD

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

Calibration certificate *Kalibrierschein*	1731095
Calibration mark *Kalibrierzeichen*	D-K-15140-01-00 03/2017

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.00.000
Serial number *Fabrikat/Serien-Nr.*	08154593
Customer *Auftraggeber*	GL Garrad Hassan D-25709 Kaiser-Wilhelm-Koog
Order No. *Auftragsnummer*	18527/17
Project No. *Projektnummer*	VT170301
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	02.03.2017

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

Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
02.03.2017	Dipl. Phys. Dieter Westermann	Techniker Andre Krummen

1731095
D-K-15140-01-00
03/2017

Calibration object
Kalibriergegenstand

Cup Anemometer

Calibration procedure
Kalibrierverfahren

- Deutsche WindGuard Wind Tunnel Services: QM-KL-AK-VA

Based on following standards:

- MEASNET: Anemometer calibration procedure
- IEC 61400-12-1: Power performance measurements of electricity producing wind turbines
- IEC 61400-12-2: Power performance of electricity producing wind turbines based on nacelle anemometry
- ISO 3966: Measurement of fluid in closed conduits
- ISO 16622: Meteorology - Sonic anemometers/thermometers

Place of calibration
Ort der Kalibrierung

Windtunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel

Test conditions
Messbedingungen

wind tunnel area	10000 cm²
anemometer frontal area	230 cm²
diameter of mounting pipe	34 mm
blockage ratio [1)]	0.023 [-]
software version	7.64

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

Ambient conditions
Umgebungsbedingungen

air temperature	22.4 °C ± 0.1 °C
air pressure	1001.2 hPa ± 0.3 hPa
relative air humidity	33.7 % ± 2.0 %

Measurement uncertainty
Messunsicherheit

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

Additional remarks
Zusätzliche Anmerkungen

-

1731095
D-K-15140-01-00
03/2017

Calibration result
Kalibrierergebnis

Sensor out	Tunnel speed	Uncertainty (k=2)
Hz	m/s	m/s
80.599	3.958	0.050
123.244	5.919	0.050
166.938	7.950	0.050
209.995	9.912	0.051
252.995	11.891	0.051
296.545	13.910	0.051
336.869	15.775	0.051
316.186	14.812	0.051
275.175	12.906	0.051
231.613	10.908	0.050
189.117	8.938	0.051
145.265	6.955	0.050
102.388	4.968	0.050

File: 1731095

Statistical analysis	Slope	0.04605 (m/s)/(Hz) ±0.00004 (m/s)/(Hz)
	Offset	0.2482 m/s ±0.009 m/s
	Standard error (Y)	0.006 m/s
	Correlation coefficient	0.999996
Remarks	The calibrated sensor complies with the demanded linearity of MEASNET	

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

Graphical representation of the result
Grafische Darstellung des Ergebnisses

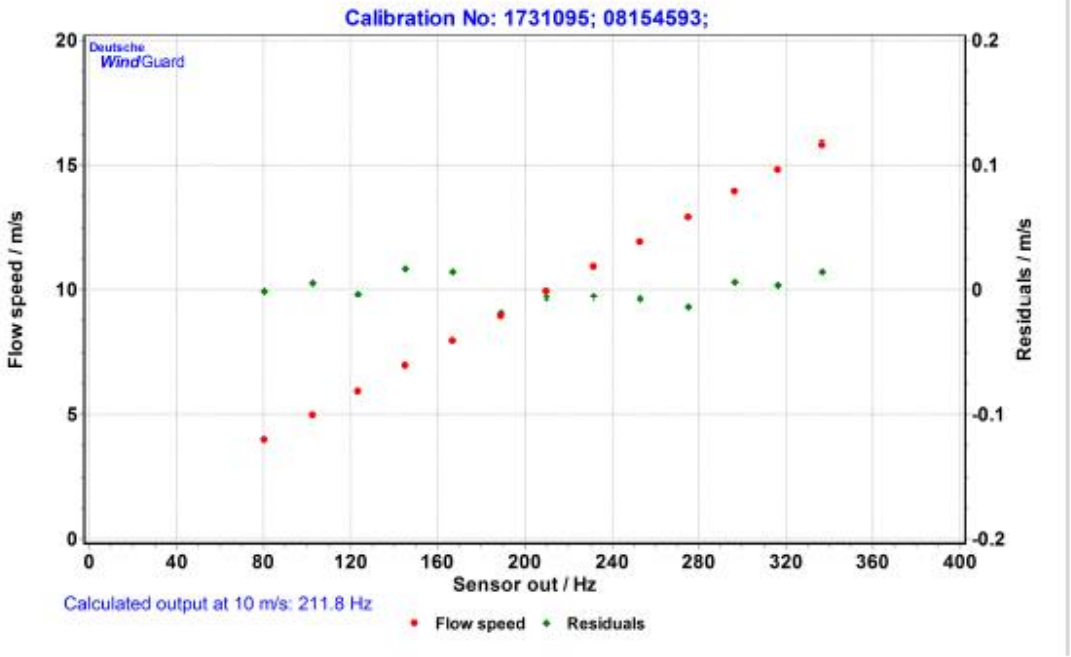


Photo of the measurement setup
Foto des Messaufbaus

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

WS_2-Thies First Class Cup Anemometer at 100 m, 330° orientation

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

accredited by the / *akkreditiert durch die*

Deutsche Akkreditierungsstelle GmbH

as calibration laboratory in the / *als Kalibrierlaboratorium im*

Deutschen Kalibrierdienst

DKD

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

Calibration certificate *Kalibrierschein*	1731097
Calibration mark *Kalibrierzeichen*	D-K-15140-01-00 03/2017

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.00.000
Serial number *Fabrikat/Serien-Nr.*	09143536
Customer *Auftraggeber*	GL Garrad Hassan D-25709 Kaiser-Wilhelm-Koog
Order No. *Auftragsnummer*	18527/17
Project No. *Projektnummer*	VT170301
Number of pages *Anzahl der Seiten*	4
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This calibration certificate documents the traceability to national standards, which realize the units of measurement according to the International System of Units (SI).
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The user is obliged to have the object recalibrated at appropriate intervals.
Dieser Kalibrierschein dokumentiert die Rückführung auf nationale Normale zur Darstellung der Einheiten in Übereinstimmung mit dem Internationalen Einheitensystem (SI).
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Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
02.03.2017	Dipl. Phys. Dieter Westermann	Techniker Andre Krummen

1731097
D-K-15140-01-00
03/2017

Calibration object
Kalibriergegenstand

Cup Anemometer

Calibration procedure
Kalibrierverfahren

- Deutsche WindGuard Wind Tunnel Services: QM-KL-AK-VA

Based on following standards:

- MEASNET: Anemometer calibration procedure
- IEC 61400-12-1: Power performance measurements of electricity producing wind turbines
- IEC 61400-12-2: Power performance of electricity producing wind turbines based on nacelle anemometry
- ISO 3966: Measurement of fluid in closed conduits
- ISO 16622: Meteorology - Sonic anemometers/thermometers

Place of calibration
Ort der Kalibrierung

Windtunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel

Test conditions
Messbedingungen

wind tunnel area	10000 cm²
anemometer frontal area	230 cm²
diameter of mounting pipe	34 mm
blockage ratio [1)]	0.023 [-]
software version	7.64

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

Ambient conditions
Umgebungsbedingungen

air temperature	22.4 °C ± 0.1 °C
air pressure	1002.0 hPa ± 0.3 hPa
relative air humidity	33.8 % ± 2.0 %

Measurement uncertainty
Messunsicherheit

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

Additional remarks
Zusätzliche Anmerkungen

-

1731097
D-K-15140-01-00
03/2017

Calibration result
Kalibrierergebnis

Sensor out	Tunnel speed	Uncertainty (k=2)
Hz	m/s	m/s
80.614	3.955	0.050
123.479	5.917	0.050
167.327	7.947	0.050
209.570	9.913	0.051
253.174	11.890	0.051
296.671	13.908	0.051
337.509	15.773	0.052
316.954	14.808	0.051
275.031	12.906	0.051
231.273	10.902	0.051
189.193	8.940	0.050
145.739	6.950	0.050
102.533	4.966	0.050

File: 1731097

Statistical analysis	Slope	0.04601 (m/s)/(Hz) ±0.00004 (m/s)/(Hz)
	Offset	0.2472 m/s ±0.010 m/s
	Standard error (Y)	0.008 m/s
	Correlation coefficient	0.999995

Remarks The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

Graphical representation of the result
Grafische Darstellung des Ergebnisses

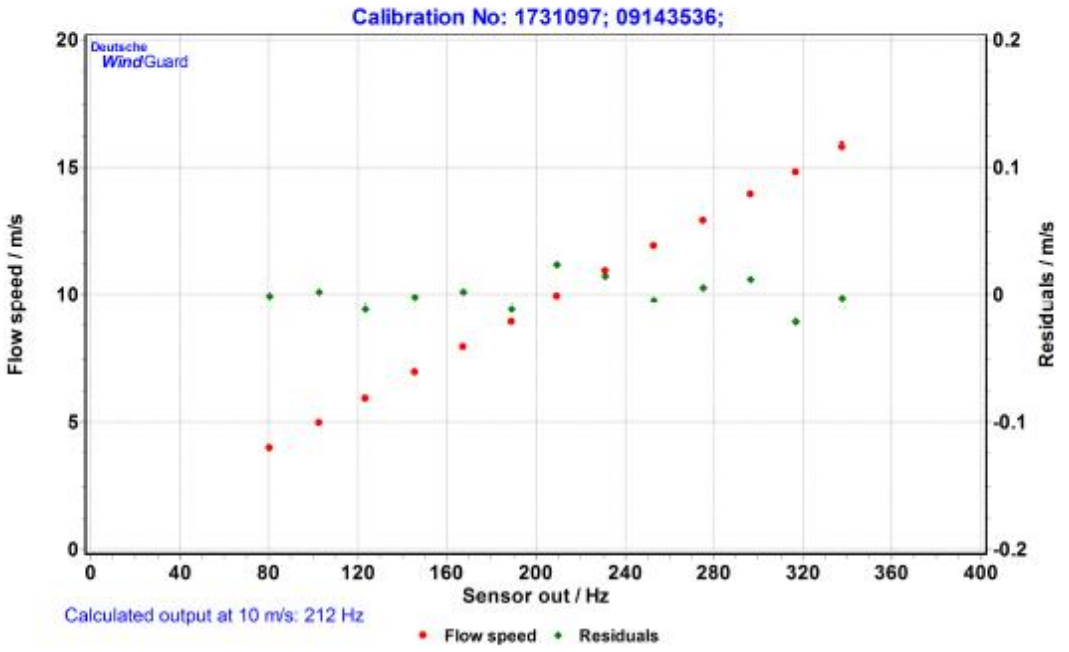

Photo of the measurement setup
Foto des Messaufbaus

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

WS_3-Thies First Class Cup Anemometer at 57 m, 150° orientation

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

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Deutsche Akkreditierungsstelle GmbH

as calibration laboratory in the / *als Kalibrierlaboratorium im*

Deutschen Kalibrierdienst

DKD

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

Calibration certificate *Kalibrierschein*	Calibration mark *Kalibrierzeichen*
	1731094
	D-K-15140-01-00
	03/2017

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.00.000
Serial number *Fabrikat/Serien-Nr.*	0310565
Customer *Auftraggeber*	GL Garrad Hassan D-25709 Kaiser-Wilhelm-Koog
Order No. *Auftragsnummer*	18527/17
Project No. *Projektnummer*	VT170301
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	02.03.2017

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

Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
02.03.2017	Dipl. Phys. Dieter Westermann	Techniker Andre Krummen

Calibration object *Kalibriergegenstand*	Cup Anemometer	
Calibration procedure *Kalibrierverfahren*	• Deutsche WindGuard Wind Tunnel Services: QM-KL-AK-VA Based on following standards: • MEASNET: Anemometer calibration procedure • IEC 61400-12-1: Power performance measurements of electricity producing wind turbines • IEC 61400-12-2: Power performance of electricity producing wind turbines based on nacelle anemometry • ISO 3966: Measurement of fluid in closed conduits • ISO 16622: Meteorology - Sonic anemometers/thermometers	
Place of calibration *Ort der Kalibrierung*	Windtunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel	
Test conditions *Messbedingungen*	wind tunnel area	10000 cm²
	anemometer frontal area	230 cm²
	diameter of mounting pipe	34 mm
	blockage ratio [1)]	0.023 [-]
	software version	7.64
	[1)] Due to the special construction of the test section no blockage correction is necessary.	
Ambient conditions *Umgebungsbedingungen*	air temperature	22.3 °C ± 0.1 °C
	air pressure	1000.7 hPa ± 0.3 hPa
	relative air humidity	33.7 % ± 2.0 %
Measurement uncertainty *Messunsicherheit*	The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by the coverage factor k = 2. It has been determined in accordance with DAkkS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%. The reference flow speed measurement is traceable to the German NMI (Physikalisch-Technische Bundesanstalt) standard for flow speed. It is realized by using a PTB owned and calibrated Laser Doppler Anemometer (Standard Uncertainty 0.2 %, k=2)	
Additional remarks *Zusätzliche Anmerkungen*	-	

1731094
D-K-15140-01-00
03/2017

Calibration result
Kalibrierergebnis

Sensor out	Tunnel speed	Uncertainty (k=2)
Hz	m/s	m/s
81.245	3.957	0.050
123.523	5.919	0.050
167.437	7.946	0.050
210.488	9.908	0.051
254.010	11.898	0.051
298.312	13.913	0.051
338.418	15.777	0.051
317.524	14.814	0.051
276.413	12.908	0.051
232.399	10.907	0.051
189.085	8.942	0.050
146.190	6.956	0.050
102.923	4.968	0.050

File: 1731094

Statistical analysis	Slope	0.04585 (m/s)/(Hz) ±0.00004 (m/s)/(Hz)
	Offset	0.2518 m/s ±0.010 m/s
	Standard error (Y)	0.009 m/s
	Correlation coefficient	0.999995

Remarks The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

Graphical representation of the result
Grafische Darstellung des Ergebnisses

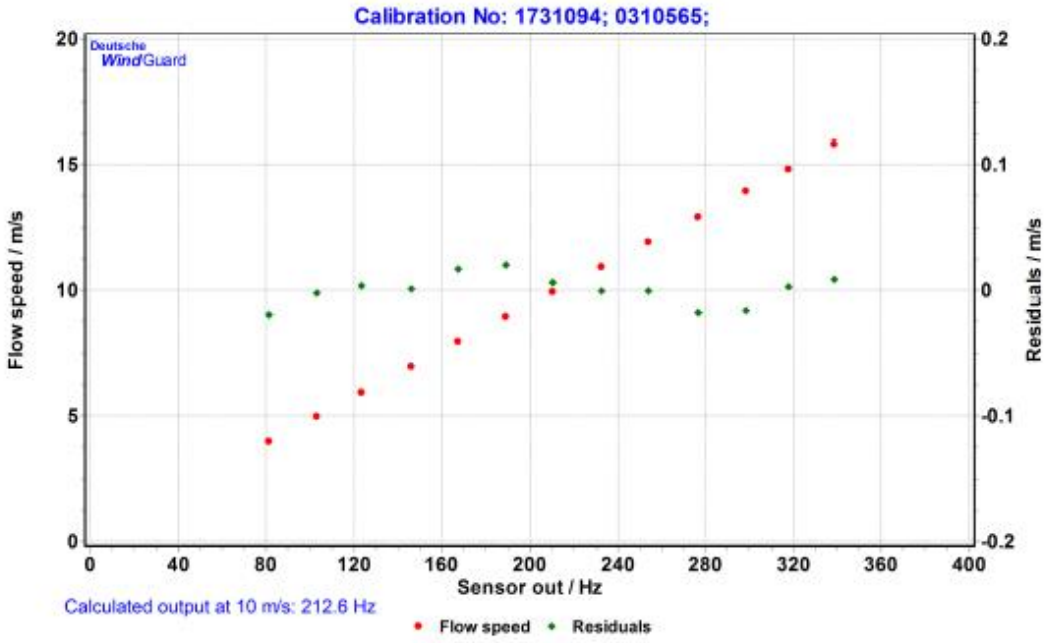

Photo of the measurement setup
Foto des Messaufbaus

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

WS_4-Thies First Class Cup Anemometer at 57 m, 330° orientation

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

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as calibration laboratory in the / *als Kalibrierlaboratorium im*

Deutschen Kalibrierdienst

DKD

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1731101
D-K-15140-01-00
03/2017

Calibration certificate
Kalibrierschein

Calibration mark
Kalibrierzeichen

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.00.000
Serial number *Fabrikat/Serien-Nr.*	10115031
Customer *Auftraggeber*	GL Garrad Hassan D-25709 Kaiser-Wilhelm-Koog
Order No. *Auftragsnummer*	18527/17
Project No. *Projektnummer*	VT170301
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	02.03.2017

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

Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
02.03.2017	Dipl. Phys. Dieter Westermann	Techniker Andre Krummen

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D-K-15140-01-00
03/2017

Calibration object
Kalibriergegenstand

Cup Anemometer

Calibration procedure
Kalibrierverfahren

- Deutsche WindGuard Wind Tunnel Services: QM-KL-AK-VA

Based on following standards:

- MEASNET: Anemometer calibration procedure
- IEC 61400-12-1: Power performance measurements of electricity producing wind turbines
- IEC 61400-12-2: Power performance of electricity producing wind turbines based on nacelle anemometry
- ISO 3966: Measurement of fluid in closed conduits
- ISO 16622: Meteorology - Sonic anemometers/thermometers

Place of calibration
Ort der Kalibrierung

Windtunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel

Test conditions
Messbedingungen

wind tunnel area	10000 cm²
anemometer frontal area	230 cm²
diameter of mounting pipe	34 mm
blockage ratio [1)]	0.023 [-]
software version	7.64

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

Ambient conditions
Umgebungsbedingungen

air temperature	22.4 °C ± 0.1 °C
air pressure	1003.7 hPa ± 0.3 hPa
relative air humidity	33.9 % ± 2.0 %

Measurement uncertainty
Messunsicherheit

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

Additional remarks
Zusätzliche Anmerkungen

-

1731101
D-K-15140-01-00
03/2017

Calibration result
Kalibrierergebnis

Sensor out	Tunnel speed	Uncertainty (k=2)
Hz	m/s	m/s
81.370	3.957	0.050
123.138	5.925	0.050
167.507	7.947	0.050
210.493	9.912	0.051
253.619	11.896	0.051
297.148	13.912	0.051
338.160	15.778	0.051
317.017	14.810	0.051
275.923	12.902	0.051
232.186	10.910	0.051
188.661	8.941	0.050
146.055	6.957	0.050
102.969	4.972	0.050

File: 1731101

Statistical analysis	Slope	0.04595 (m/s)/(Hz) ±0.00005 (m/s)/(Hz)
	Offset	0.2449 m/s ±0.012 m/s
	Standard error (Y)	0.013 m/s
	Correlation coefficient	0.999992

Remarks The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

Graphical representation of the result
Grafische Darstellung des Ergebnisses

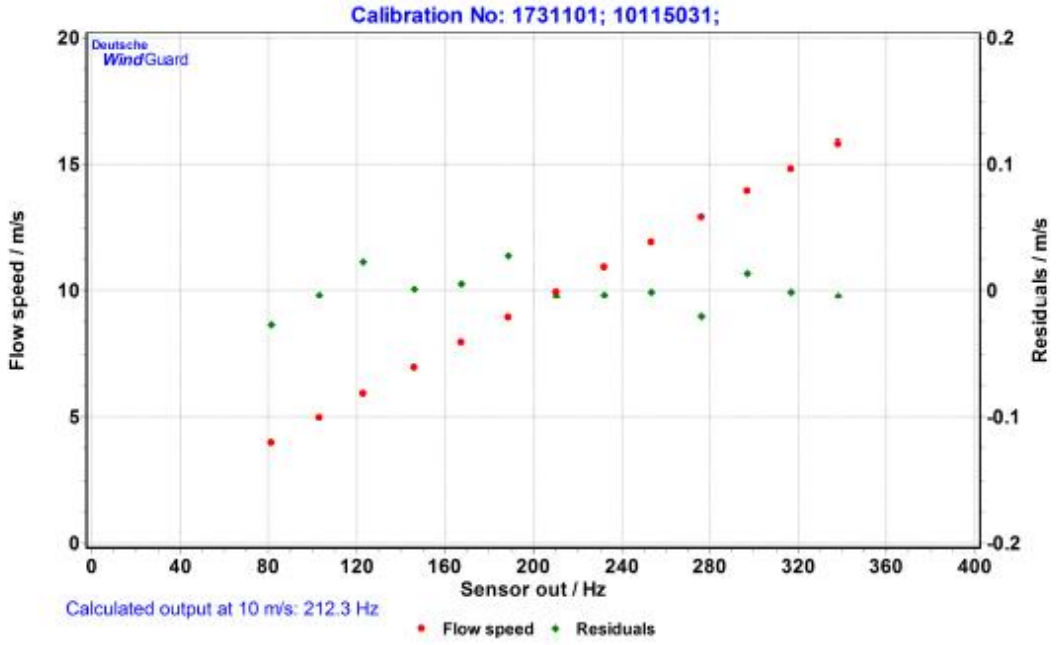

Photo of the measurement setup
Foto des Messaufbaus

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

WS_5-Thies First Class Cup Anemometer at 75 m, 150° (SE) orientation

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

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Deutschen Kalibrierdienst

DKD

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1614385
D-K-15140-01-00
08/2016

Calibration certificate
Kalibrierschein

Calibration mark
Kalibrierzeichen

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.00.000
Serial number *Fabrikat/Serien-Nr.*	08165654
Customer *Auftraggeber*	GL Garrad Hassan D-25709 Kaiser-Wilhelm-Koog
Order No. *Auftragsnummer*	18190/16
Project No. *Projektnummer*	VT160827
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	23.08.2016

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

Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
23.08.2016	Dipl. Phys. Dieter Westermann	Techniker Dirk Henninges

1614385
D-K-15140-01-00
08/2016

Calibration object
Kalibriergegenstand

Cup Anemometer

Calibration procedure
Kalibrierverfahren

• Deutsche WindGuard Wind Tunnel Services: QM-KL-AK-VA
Based on following standards:
• MEASNET: Anemometer calibration procedure
• IEC 61400-12-1: Power performance measurements of electricity producing wind turbines
• IEC 61400-12-2: Power performance of electricity producing wind turbines based on nacelle anemometry
• ISO 3966: Measurement of fluid in closed conduits
• ISO 16622: Meteorology - Sonic anemometers/thermometers

Place of calibration
Ort der Kalibrierung

Windtunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel

Test conditions
Messbedingungen

wind tunnel area	10000 cm²
anemometer frontal area	230 cm²
diameter of mounting pipe	34 mm
blockage ratio [1)]	0.023 [-]
software version	7.64

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

Ambient conditions
Umgebungsbedingungen

air temperature	24.2 °C ± 0.1 °C
air pressure	1026.1 hPa ± 0.3 hPa
relative air humidity	56.5 % ± 2.0 %

Measurement uncertainty
Messunsicherheit

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

Additional remarks
Zusätzliche Anmerkungen

-

1614385
D-K-15140-01-00
08/2016

Calibration result
Kalibrierergebnis

Sensor out Hz	Tunnel speed m/s	Uncertainty (k=2) m/s
83.032	4.015	0.050
124.332	5.931	0.050
168.242	7.949	0.051
212.619	9.986	0.051
256.787	12.009	0.052
297.771	13.942	0.052
342.562	15.947	0.053
319.735	14.928	0.053
277.923	13.012	0.051
233.336	10.976	0.051
189.508	8.940	0.051
146.418	6.987	0.051
103.618	4.990	0.050

File: 1614385

Statistical analysis	Slope	0.04600 (m/s)/(Hz) ±0.00007 (m/s)/(Hz)
	Offset	0.2187 m/s ±0.016 m/s
	Standard error (Y)	0.016 m/s
	Correlation coefficient	0.999987

Remarks The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

Graphical representation of the result
Grafische Darstellung des Ergebnisses

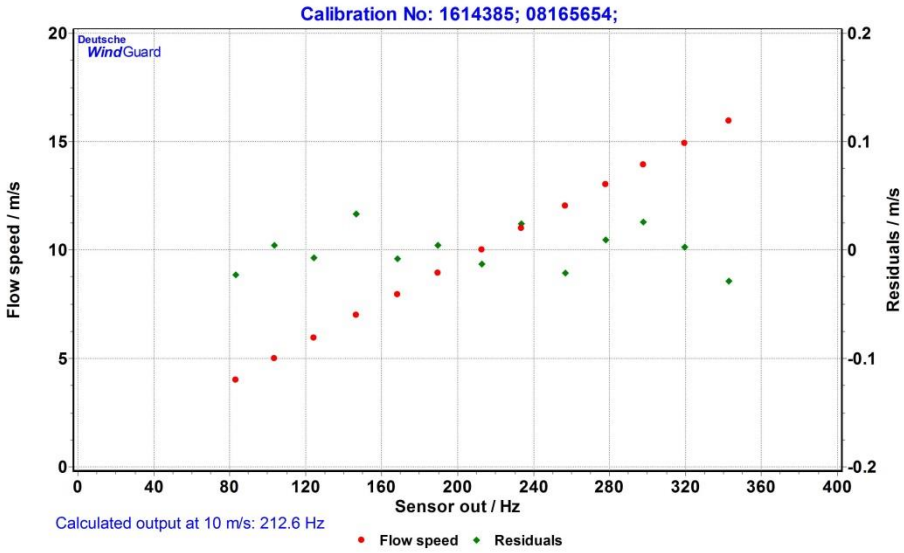
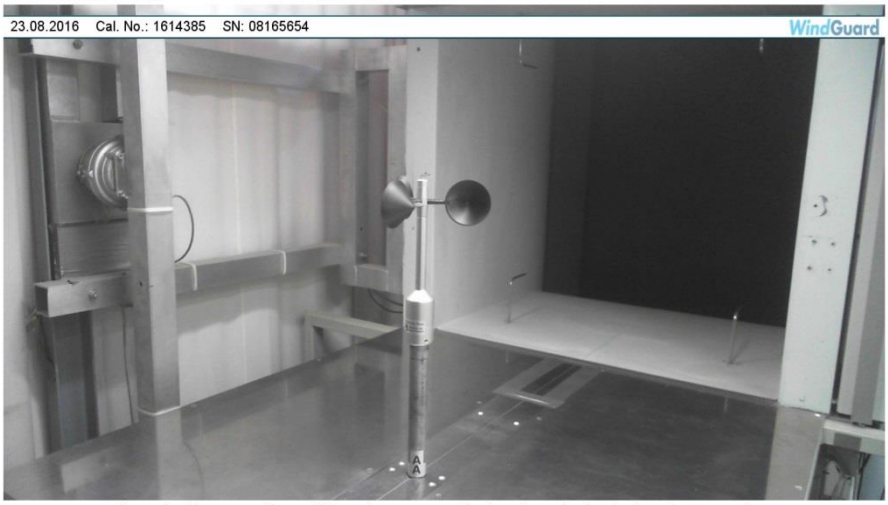


Photo of the measurement setup
Foto des Messaufbaus



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

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

WS_6-Thies First Class Cup Anemometer at 57 m, 330° (NW) orientation

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

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Deutsche Akkreditierungsstelle GmbH

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

as calibration laboratory in the / *als Kalibrierlaboratorium im*

Deutschen Kalibrierdienst DKD

Calibration certificate *Kalibrierschein*	Calibration mark *Kalibrierzeichen*
	1614386
	D-K-15140-01-00
	08/2016

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.00.000
Serial number *Fabrikat/Serien-Nr.*	08165655
Customer *Auftraggeber*	GL Garrad Hassan D-25709 Kaiser-Wilhelm-Koog
Order No. *Auftragsnummer*	18190/16
Project No. *Projektnummer*	VT160827
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	23.08.2016

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

Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
23.08.2016	Dipl. Phys. Dieter Westermann	Techniker Dirk Henninges

1614386
D-K-15140-01-00
08/2016

Calibration object
Kalibriergegenstand

Cup Anemometer

Calibration procedure
Kalibrierverfahren

- Deutsche WindGuard Wind Tunnel Services: QM-KL-AK-VA

Based on following standards:

- MEASNET: Anemometer calibration procedure
- IEC 61400-12-1: Power performance measurements of electricity producing wind turbines
- IEC 61400-12-2: Power performance of electricity producing wind turbines based on nacelle anemometry
- ISO 3966: Measurement of fluid in closed conduits
- ISO 16622: Meteorology - Sonic anemometers/thermometers

Place of calibration
Ort der Kalibrierung

Windtunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel

Test conditions
Messbedingungen

wind tunnel area	10000 cm²
anemometer frontal area	230 cm²
diameter of mounting pipe	34 mm
blockage ratio [1)]	0.023 [-]
software version	7.64

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

Ambient conditions
Umgebungsbedingungen

air temperature	24.4 °C ± 0.1 °C
air pressure	1026.0 hPa ± 0.3 hPa
relative air humidity	56.2 % ± 2.0 %

Measurement uncertainty
Messunsicherheit

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

Additional remarks
Zusätzliche Anmerkungen

-

1614386
D-K- 15140-01-00
08/2016

Calibration result
Kalibrierergebnis

Sensor out Hz	Tunnel speed m/s	Uncertainty (k=2) m/s
82.470	4.012	0.050
124.082	5.927	0.051
167.542	7.937	0.051
212.076	9.988	0.051
255.774	12.012	0.052
298.226	13.947	0.052
342.359	15.953	0.054
319.802	14.945	0.052
277.681	13.016	0.052
233.549	10.977	0.052
188.681	8.944	0.051
146.441	6.992	0.051
102.589	4.956	0.050

File: 1614386

Statistical analysis	Slope	0.04597 (m/s)/(Hz) ±0.00006 (m/s)/(Hz)
	Offset	0.2400 m/s ±0.013 m/s
	Standard error (Y)	0.013 m/s
	Correlation coefficient	0.999992

Remarks The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

Graphical representation of the result
Grafische Darstellung des Ergebnisses

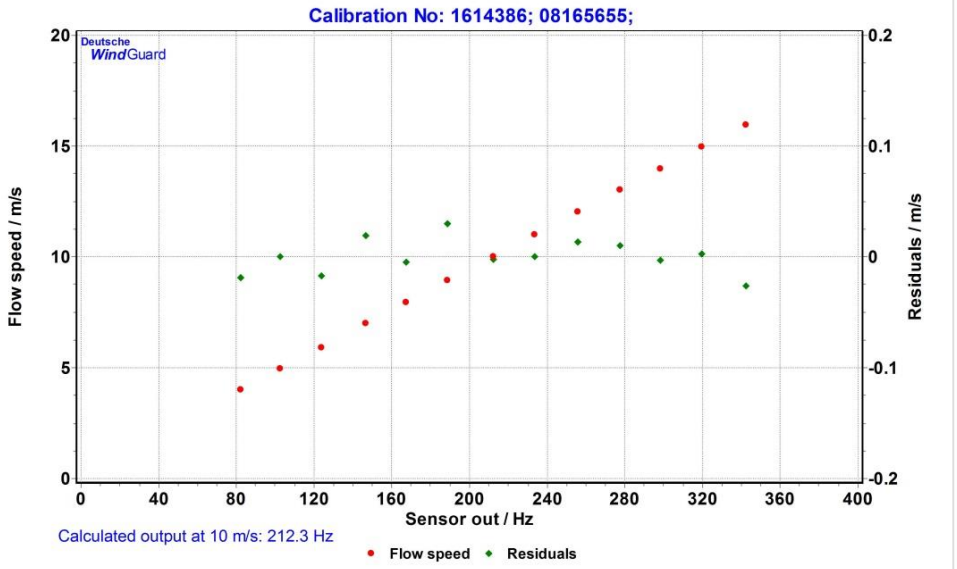

Photo of the measurement setup
Foto des Messaufbaus

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

WS_7-Thies First Class Cup Anemometer at 29m, 330° (NW) orientation

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

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as calibration laboratory in the / *als Kalibrierlaboratorium im*

Deutschen Kalibrierdienst DKD

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

Calibration certificate *Kalibrierschein*	Calibration mark *Kalibrierzeichen*
	1614387
	D-K-15140-01-00
	08/2016

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.00.000
Serial number *Fabrikat/Serien-Nr.*	08165656
Customer *Auftraggeber*	GL Garrad Hassan D-25709 Kaiser-Wilhelm-Koog
Order No. *Auftragsnummer*	18190/16
Project No. *Projektnummer*	VT160827
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	23.08.2016

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

Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
23.08.2016	Dipl. Phys. Dieter Westermann	Techniker Dirk Henninges

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Calibration object
Kalibriergegenstand

Cup Anemometer

Calibration procedure
Kalibrierverfahren

• Deutsche WindGuard Wind Tunnel Services: QM-KL-AK-VA
Based on following standards:
• MEASNET: Anemometer calibration procedure
• IEC 61400-12-1: Power performance measurements of electricity producing wind turbines
• IEC 61400-12-2: Power performance of electricity producing wind turbines based on nacelle anemometry
• ISO 3966: Measurement of fluid in closed conduits
• ISO 16622: Meteorology - Sonic anemometers/thermometers

Place of calibration
Ort der Kalibrierung

Windtunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel

Test conditions
Messbedingungen

wind tunnel area	10000 cm^2
anemometer frontal area	230 cm^2
diameter of mounting pipe	34 mm
blockage ratio [1)]	0.023 [-]
software version	7.64

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

Ambient conditions
Umgebungsbedingungen

air temperature	24.5 °C ± 0.1 °C
air pressure	1026.0 hPa ± 0.3 hPa
relative air humidity	55.9 % ± 2.0 %

Measurement uncertainty
Messunsicherheit

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

Additional remarks
Zusätzliche Anmerkungen

-

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Calibration result
Kalibrierergebnis

Sensor out	Tunnel speed	Uncertainty (k=2)
Hz	m/s	m/s
81.999	4.013	0.050
124.037	5.940	0.050
167.858	7.961	0.051
211.883	9.974	0.052
255.689	12.001	0.052
297.472	13.943	0.052
341.736	15.959	0.054
318.961	14.934	0.053
277.375	13.009	0.052
232.948	10.984	0.051
188.873	8.943	0.051
146.429	6.984	0.051
102.656	4.984	0.050

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Statistical analysis	Slope	0.04603 (m/s)/(Hz) ±0.00004 (m/s)/(Hz)
	Offset	0.2427 m/s ±0.010 m/s
	Standard error (Y)	0.010 m/s
	Correlation coefficient	0.999995

Remarks The calibrated sensor complies with the demanded linearity of MEASNET

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Wind Tunnel Services GmbH, Varel

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Graphical representation of the result
Grafische Darstellung des Ergebnisses

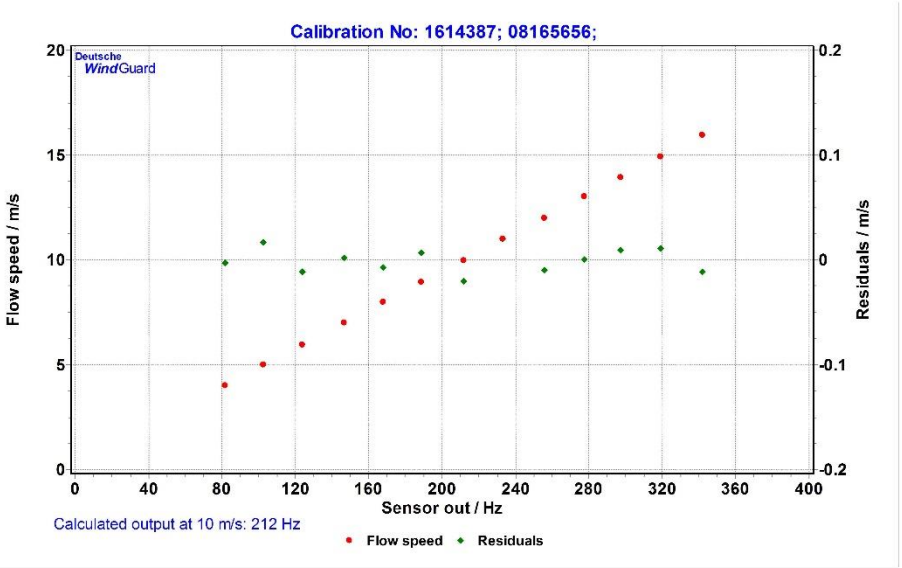
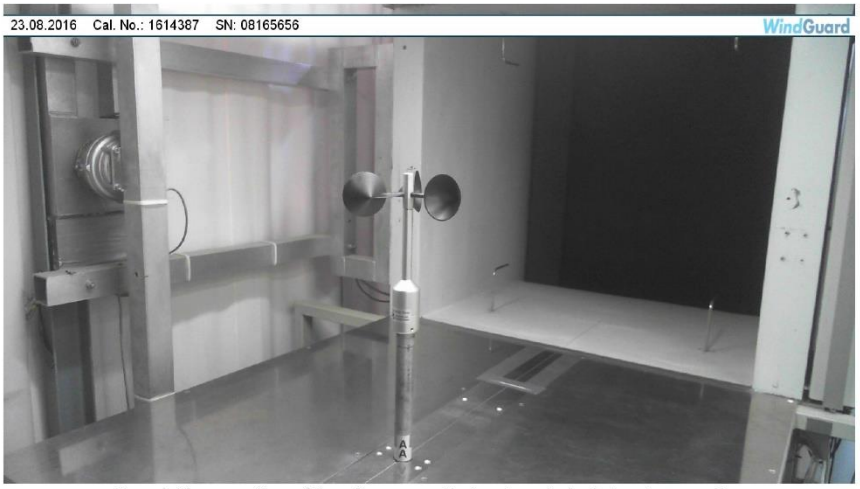


Photo of the measurement setup
Foto des Messaufbaus



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

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

WS_8-Thies First Class Cup Anemometer at 29m, 150° (SE) orientation

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

accredited by the / *akkreditiert durch die*

Deutsche Akkreditierungsstelle GmbH

as calibration laboratory in the / *als Kalibrierlaboratorium im*

Deutschen Kalibrierdienst

DKD

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

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Calibration certificate
Kalibrierschein

Calibration mark
Kalibrierzeichen

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.00.000
Serial number *Fabrikat/Serien-Nr.*	08165657
Customer *Auftraggeber*	GL Garrad Hassan D-25709 Kaiser-Wilhelm-Koog
Order No. *Auftragsnummer*	18190/16
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23.08.2016	Dipl. Phys. Dieter Westermann	Techniker Dirk Henninges

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Place of calibration
Ort der Kalibrierung

Windtunnel of Deutsche WindGuard WindTunnel Services GmbH, Varel

Test conditions
Messbedingungen

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anemometer frontal area	230 cm^2
diameter of mounting pipe	34 mm
blockage ratio [1)]	0.023 [-]
software version	7.64

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

Ambient conditions
Umgebungsbedingungen

air temperature	24.7 °C ± 0.1 °C
air pressure	1025.9 hPa ± 0.3 hPa
relative air humidity	55.6 % ± 2.0 %

Measurement uncertainty
Messunsicherheit

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

Additional remarks
Zusätzliche Anmerkungen

-

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

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Calibration result
Kalibrierergebnis

Sensor out	Tunnel speed	Uncertainty (k=2)
Hz	m/s	m/s
82.750	4.015	0.050
124.450	5.944	0.051
168.832	7.957	0.051
212.038	9.976	0.051
256.232	12.006	0.052
298.279	13.951	0.053
341.935	15.959	0.052
320.108	14.927	0.052
278.249	13.009	0.052
233.526	10.964	0.051
189.812	8.950	0.051
146.783	6.997	0.051
103.120	4.959	0.050

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Statistical analysis	Slope	0.04601 (m/s)/(Hz) ±0.00005 (m/s)/(Hz)
	Offset	0.2153 m/s ±0.011 m/s
	Standard error (Y)	0.011 m/s
	Correlation coefficient	0.999994

Remarks The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

Graphical representation of the result
Grafische Darstellung des Ergebnisses

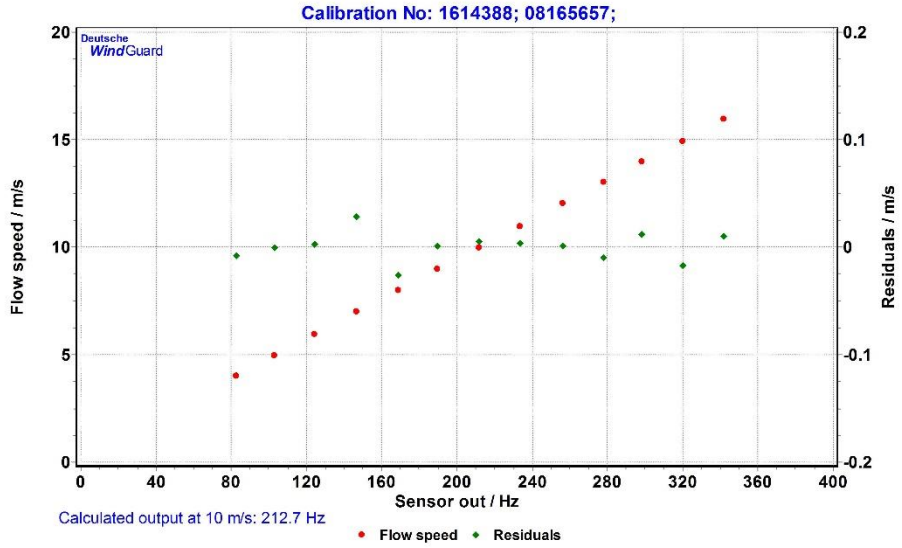
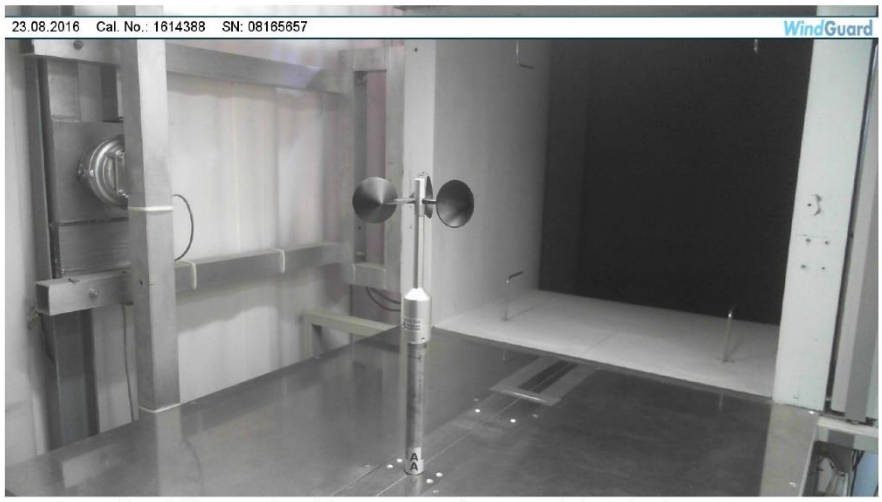


Photo of the measurement setup
Foto des Messaufbaus



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

About DNV GL

Driven by our purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification and technical assurance along with software and independent expert advisory services to the maritime, oil and gas, and energy industries. We also provide certification services to customers across a wide range of industries. Operating in more than 100 countries, our 12,000 professionals are dedicated to helping our customers make the world safer, smarter and greener.