ZP 598

Independent analysis and reporting of ZephIR Lidar performance verification executed by ZephIR Ltd. at Pershore test site, including IEC compliant validation analysis

ZephIR Ltd

Report No.: GLGH-4270 16 13713 258-R-0023, Rev. A
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Task and objective:
Independent analysis and reporting of ZephIR Lidar performance verification executed by ZephIR Ltd. at Pershore test site, including IEC compliant validation analysis

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

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A	2017-05-23	Final report (electronic version, only)	DanHell	Bscm	Koeh

Table of contents

Appendices

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

GL Garrad Hassan Deutschland GmbH ("GH-D"), a member of the DNV GL Group ("DNV GL"), has been assigned on 2017-02-27 by ZephIR Ltd. ("ZephIR") to prepare an independent analysis and report of a ZephIR Lidar performance verification. In this analysis and report the ZephIR Lidar with the serial number ZP 598 will be discussed. The verification measurements for this device were performed by ZephIR Ltd. at their test site in Pershore, UK between 2017-01-04 and 2017-02-05.

The met tower was equipped with classical anemometry components (cup anemometers, wind vanes etc.) serving as the verification reference for the Lidar wind speed and wind direction comparisons. Those comparisons were performed in line with a Remote Sensing (RS) best practice verification approach as developed within the EU-FP7-Projekt NORSEWInD [2] against corresponding Key Performance Indicators (KPIs) and Acceptance Criteria (ACs; compare Appendix A).

In addition, a performance verification and uncertainty calculation is carried out in accordance with the second edition of the reviewed IEC 61400-12-1 standard, Annex L [4].

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).

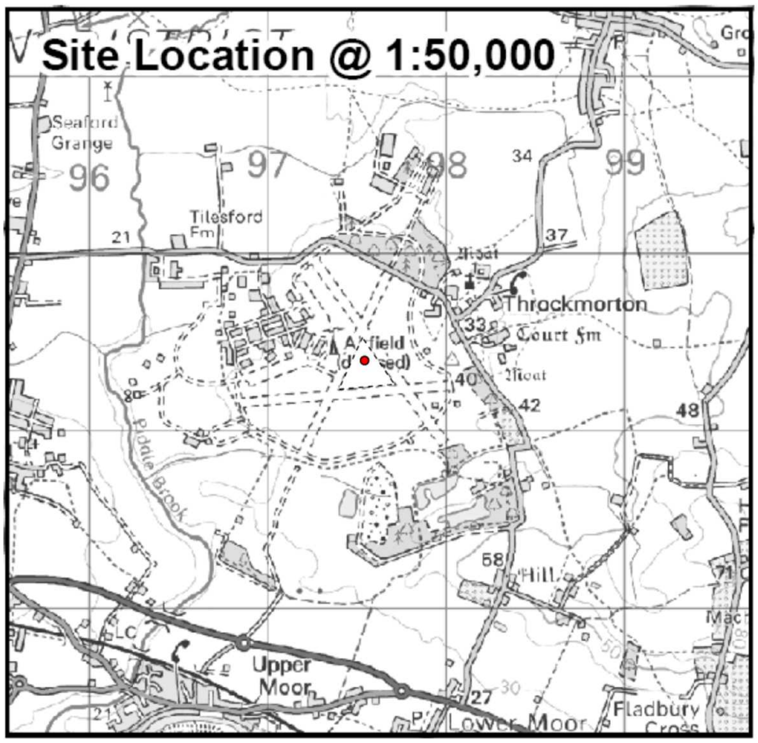
The work has been conducted in compliance with all relevant health and safety legislation. GL Garrad Hassan Deutschland GmbH operates an Occupational Health and Safety Management System certified according to the OHSAS 18001:2007.

2 DESCRIPTION OF THE TEST SITE

2.1 The test site

The following description and figures of the Pershore test site, which is a disused air field, are taken from a technical report by ZephIR Ltd. [1]:

The terrain in the vicinity of the mast is flat and covered with sparse low growing vegetation. A freestanding lattice tower of approximately 40 m in height exists on a bearing of 270° at 230m from the mast. A number of hangars and outbuildings exist in sectors between 260° and 317° at distances between 300m and 700m from the mast. These buildings are estimated not to exceed 14m in height. Approximately 500 m to the North-East lies the small village of Throckmorton which consists of a few scattered farms and houses. 700 m to the South-West of the mast between 190° and 240° lies an area of spoil heaps and filtration pools associated with a mining operation. On a wider scale the site is surrounded by flat arable land that is devoid of any dense closed canopy forest. The larger conurbations of Pershore and Evesham lie at distances of 5km and 9km to the South West and South East respectively.



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● Test Mast 397557E 249426 N BNG

Figure 1: Map of the Pershore test site near Throckmorton, UK. The position of the reference mast is marked by a red dot.

The site specifications given in the above description have been verified during a site visit by a DNV GL expert on 2015-09-01, see [7]. Further details on the site are given in [1], a 360° photo round is shown in Appendix B.

2.2 Measuring equipment

In the following sections 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 Lidar.

The following items regarding the meteorological measurement systems have been verified during the above mentioned site visit:

- Site suitability and exact positions of mast and Lidar test stand
- Mast height, measurement levels and boom orientations
- Distribution and mounting of sensors at the mast
- Validity of MEASNET [6] calibrations of cups and correct application of calibration factors and offsets
- Wind vane offsets
- Data acquisition components, logger configuration
- Data storage and data provision

2.2.1 Meteorological mast: layout, sensors distribution and data acquisition

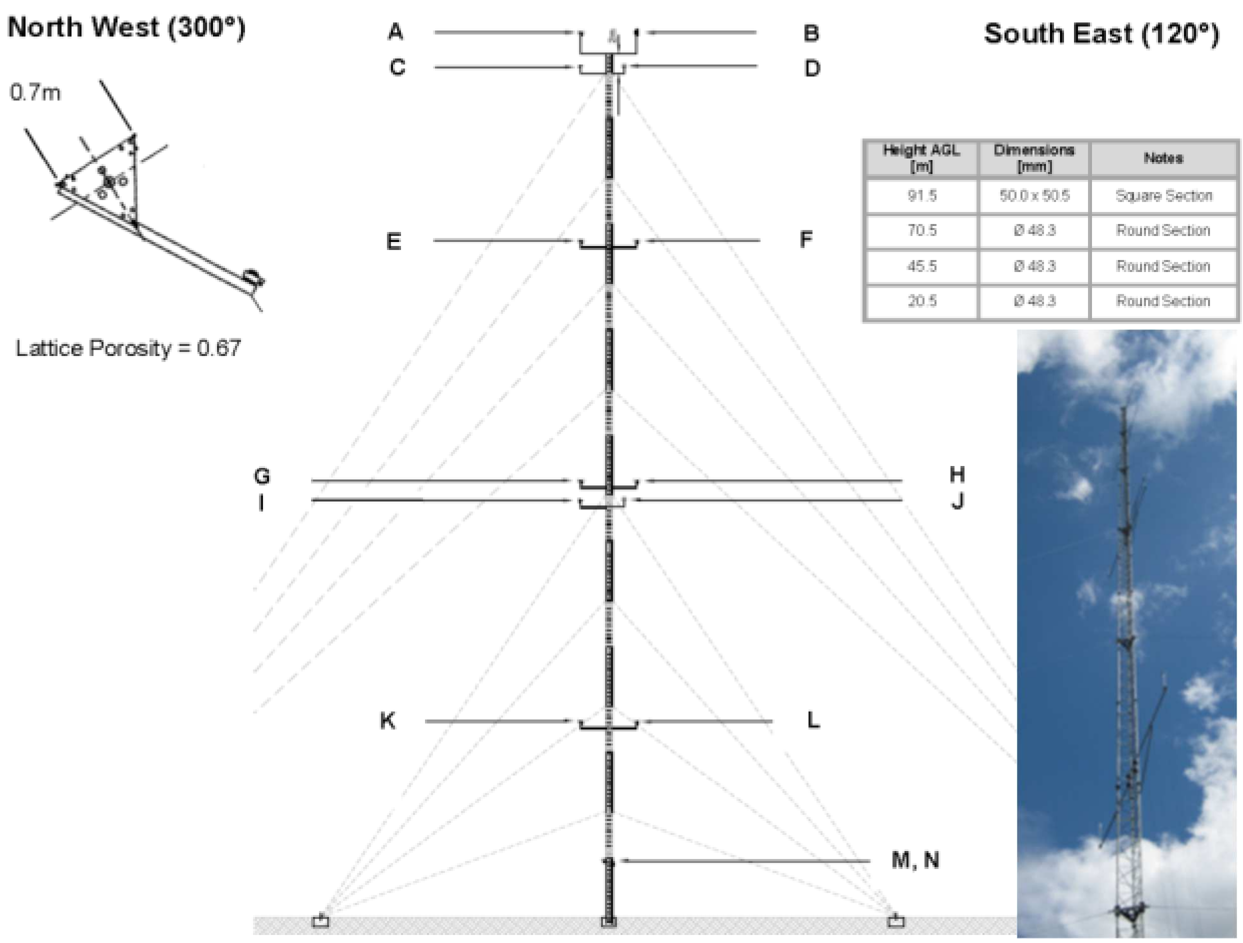
The following description is taken from [1]:

The mast has been constructed to be fully compliant with the current edition of IEC 61400-12-1 [3] and the terrain of the test site falls within requirements for testing without a site calibration. All cup anemometers installed on the reference mast are class 1A instruments as defined by [3] and have undergone individual rotor specific MEASNET [6] calibration at a MEASNET certified wind tunnel.

All boom and upright dimensions have been determined using the lattice porosity and mast dimensions provided by the manufacturer and in compliance with [3] to operate within a maximum flow distortion of 0.5% at the wind measurement locations. The directional vanes are installed with their North markings aligned along the booms towards the mast. The boom orientation is compensated for in the data logger.

The main mast installation documents (as presented in [1]) are included for reference in Appendix B and the instrument calibration certificates are included in Appendix E. Those calibrations belong to the most recently changed anemometers, hence being valid for the wind speed sensors of the met tower during this verification campaign.

The met mast is a guyed 90.5 m triangular lattice tower with a face width of 0.7 m. The MEASNET calibrated [6] cup anemometers (cups) of type Thies Frist Class Advanced (TFCA) are mounted on booms aside the mast at heights of 20.5 m, 45.5 m and 70.5 m and in a top mounting position at 90.5 m A.G.L., see Figure 2. Those mounting arrangements are consistent with the IEA [5] and IEC [3] recommendations for the use of cup anemometry at masts.



Height AGL [m]	Dimensions [mm]	Notes
91.5	50.0 x 50.5	Square Section
70.5	Ø 48.3	Round Section
45.5	Ø 48.3	Round Section
20.5	Ø 48.3	Round Section

Figure 2: Schematic of the sensor level and boom distribution at the 90.5 m mast, as taken from [1].

Table 1 shows the technical specifications of the mast. Table 2 lists the different sensors and serial numbers. Respective calibration certificates for each sensor are given in Appendix E. The photo in the right box of Figure 2 shows mast anemometry levels between 20 and 90.5 m AGL.

The position of the test stand (Lidar / met mast) in terms of the WGS84 standard is:

- **Lat** N 52° 08' 35"
- **Lon** W 002° 02' 14"

Label	Height (m)	Orientation – Mast to Instrument (°)	Instrument Type	Instrument Model	Cup to Boom Centre Height (mm)	Instrument to Mast Centre Length (mm)
A	91.5	300	Cup Anemometer	Thies First Class Advanced	1520	1025
B	91.5	120	Cup Anemometer	Thies First Class Advanced	1500	1025
C	88	300	Direction Vane	Vector W200P	920	3700
D	88	120	Temperature / Humidity	Campbell Scientific CS215	-	-
E	70.5	300	Cup Anemometer	Thies First Class Advanced	960	3700
F	70.5	120	Cup Anemometer	Thies First Class Advanced	915	3700
G	45.5	300	Cup Anemometer	Thies First Class Advanced	955	3700
H	45.5	120	Cup Anemometer	Thies First Class Advanced	1160	3700
I	43.5	300	Direction Vane	Vector W200P	920	3700
J	43.5	120	Temperature / Humidity	Campbell Scientific CS215	-	-
K	20.5	300	Cup Anemometer	Thies First Class Advanced	960	3700
L	20.5	12	Cup Anemometer	Thies First Class Advanced	930	3700
M	-	-	Pressure	Campbell Scientific CS100	-	-
N	-	-	Data Logger	Campbell Scientific CR 1000	-	-

Table 1: List of meteorological sensors and individual anemometers installed at the mast during verification campaign, as of Appendix B.

Label		A	B	E	F	G	H	K	L
Channel		WS_2R	WS_1M	WS_4R	WS_3V	WS_6R	WS_5V	WS_8R	WS_7V
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		09164177	10164580	10164581	08157941	08157939	10164582	10164583	08157940
Height		91.5	91.5	70.5	70.5	45.5	45.5	20.5	20.5
Orientation – Mast to Instrument (°)		300	120	300	120	300	120	300	120
DWG*	Calibration Date	17/08/2016	22/11/2016	22/11/2016	17/08/2015	17/08/2015	22/11/2016	22/11/2016	17/08/2015
	Slope	0.04596	0.04589	0.04610	0.04600	0.04618	0.04592	0.04601	0.04603
	Offset	0.2519	0.2519	0.2530	0.2568	0.2164	0.2872	0.2802	0.2482
SOH*	Calibration Date	N/A	N/A	N/A	06/10/2015	06/10/2015	N/A	N/A	06/10/2015
	Slope	N/A	N/A	N/A	0.04688	0.04677	N/A	N/A	0.04687
	Offset	N/A	N/A	N/A	0.17228	0.18630	N/A	N/A	0.18083
Applied	Slope	0.04596	0.04589	0.04610	0.4644	0.04648	0.04592	0.04601	0.04645
	Offset	0.2519	0.2519	0.2530	0.2145	0.2014	0.2872	0.2802	0.2145

Table 2: List of calibration factors for cup anemometers. The valid calibration certificates are attached to this report in Appendix E.

2.2.2 The ZephIR Lidar

The Lidar under test is a ZephIR of type Z 300 Doppler Wind Lidar, employing a CW laser (continuous wave laser) that has specifically been designed to measure wind speeds at heights in the boundary layer of the atmosphere. The serial number of this individual device is ZP 598. During the measurement campaign the Lidar system was configured to record wind speed measurements at 8 different levels between 10 and 200 m. The actual Lidar measurement heights were 10, 20, 45, 70, 91, 120, 149 and 200 m above ground. The four heights at 20, 45, 70 and 91 m were used for the comparison to the cup/mast reference measurements.

Figure 3 shows an array of ZephIR Lidars under test being typically located to the East of the base of the met mast, and Table 3 lists wind speed and wind direction measurement and comparison levels as given and selected for the performance verification.

Figure 3: Typical setup of ZephIR Lidars next to the reference mast at Pershore.

Height Settings (relative to ground level)								
ZP300 Meas. Levels [m]	10	**20**	**45**	**70**	**91**	120	149	200
Mast/WS-Cup Levels [m]		**20**	**45**	**70**	**91**			
Mast/WD-Vane Levels [m]			**44**		**88**			

1 Standard height in ZephIR ZP300 devises (automatically recorded)

Table 3: Height settings of ZP300 Lidar and reference mast. Levels for wind speed and wind direction comparisons are highlighted in bold letters.

3 LIDAR PERFORMANCE VERIFICATION (LPV) APPROACH

3.1 Common test conditions and data filtering

In the process of the LPV 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 Lidar under test.
- All data collected during periods of possible icing at cup anemometers, i.e. with temperatures below 0.2 °C near mast top height are excluded.
- All other reported data (particularly wind speed) within undisturbed free-stream wind direction sector relative to the reference mast as well to the Lidar are used in the comparison analysis.
- For the validation of Lidar wind speeds against the mast the wind speeds from TFCA cup anemometers at 20 m, 45 m, 70 m and 91 m are used. The Lidar data are selected according to the sector screening of the cup data prior to comparison, see following section.
- No Lidar specific quality filters are applied to the measured Lidar data prior to the analysis conducted.

3.2 Sector filtering

The orientation of cup carrying booms at the mast is to the North West at one side and to the South East on the other side. Hence, wind speed data need to be screened at wind directions between 85° and 155° for cups on the Northwest side of the mast and between 265° and 335° for cups on the Southeast side of the mast. This sector screening of 70° per boom directions accounts for downwind mast wake effects on the boom mounted instruments, see sector sketch in Figure 4.

If cup data from both boom directions is available (i.e. for wind directions out of the remaining two sectors), the wind speed average of the two oppositely mounted instruments is used as reference for the comparison with the Lidar wind speeds. In this case data are further screened for the wind speed difference between both cups to exceed 0.3 m/s. Within the two disturbance sectors wind speed data from a single cup, i.e. from the one mounted on the upwind directed boom is considered valid, only.

Cup data at the 90.5 m and 70.5 m levels are screened against wind direction data from vane at 88.0 m. Instruments at the 45.5 m and 20.5 m are screened against wind direction data from the vane at 43.5 m.

For the validation of ZephIR wind speeds against the mast, only wind speeds from the cup anemometers are used as reference.

For this validation only cup data at 91.5 m height at the 300° orientation was available.

No Lidar specific filters were applied to the measured Lidar data prior to the analysis conducted.

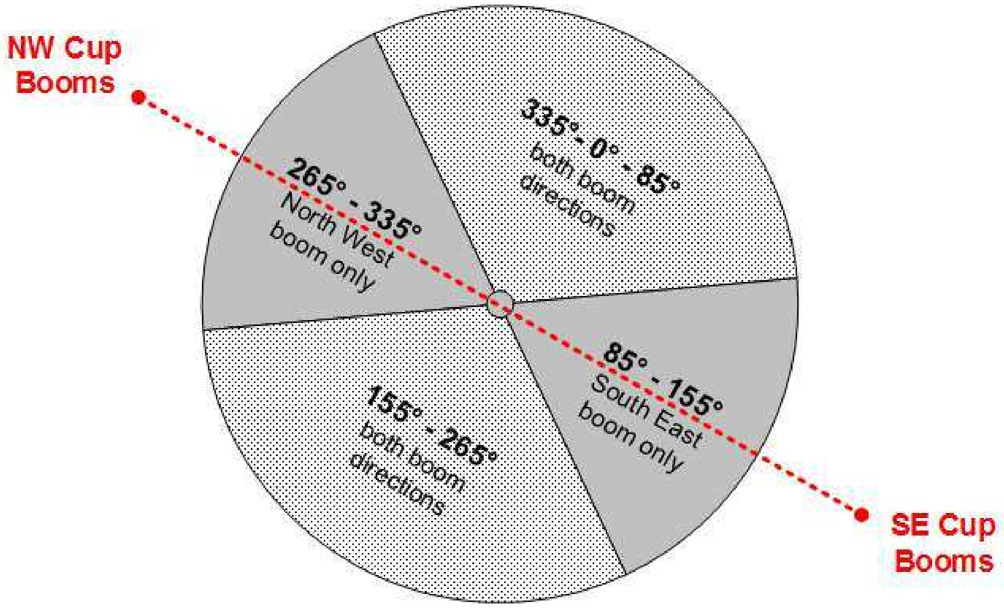


Figure 4: Wind direction sectors used to select undisturbed wind speed data from oppositely arranged cup carrying booms for comparison.

3.3 Data coverage requirements for accuracy assessment

The following data coverage definitions are prescribed for the LPV:

- The overall minimum number of 10 minute data points after filtering (according to sections 3.1 and 3.2) for the WS ranges [all > 3 m/s] and [4 to 16 m/s] should not be lower than 600.
- At least 200 10-minute data points should to be in the WS range between 4 and 8 m/s and 200 data points between 8 and 12 m/s.

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

3.4 LPV evaluation

The performance of the LIDAR 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) and according Acceptance Criteria (AC).

The evaluation approach in terms of the applicable KPIs and according ACs is outlined in Appendix A, where KPIs and ACs for system and data availability are listed in Table 14 those for wind data quality in Table 15.

The performance assessment of the given KPIs and respective Acceptance Criteria regarding Availability and Accuracy is executed at each reference level present, in this case at each of the four (4) met tower's 1st Class reference anemometry levels which are 20 m, 45 m, 70 m and 91 m a.g.l.

4 RESULTS

For the treated Lidar Performance Verification (LPV) campaign data were provided for the period 2017-01-04, 14:00 until 2017-02-05, 23:40. So the campaign was completed after 32.4 days. The wind speed ranges covered and used for comparison are 3 to 18.0 m/s at the upper level (91 m) and 3 to 14.0 m/s at the lower level (20 m).

WS-range	# of Data Points per Height Level			
	91	70	45	20
All >= 3 m/s	2798	3253	2954	2399
4 - 8 m/s	1608	2059	1893	1516
8 - 12 m/s	702	610	410	262
4 - 16 m/s	2578	2953	2534	1935

Table 4: Number of 10 minute data points after filtering used for WS comparison at each of the four (4) levels.

The completeness requirements as of section 3.3 are fulfilled for all WS ranges.

4.1 System availability

The system availability as applied to the Lidar device is defined by a percentage of the maximum possible number of ten-minute periods within the above mentioned total campaign duration of 32.4 days, which is 4667. As 4667 Lidar ten-minute data entries were present (regardless of the data validity) the Lidar device achieved a system availability of 100.0 % see table below.

- ✓ The Acceptance Criterion for Data Availability (**KPI** SA_{CA}) to be ≥95 % is successfully met.

Period from	04/01/2017 14:00	to	05/02/2017 23:40	
Test Height / m	**91**	**70**	**45**	**20**
Max. # of 10-min points in period	4667	4667	4667	4667
Data present	4667	4667	4667	4667
System availabiltiy	100.0%	100.0%	100.0%	100.0%
Total # of 10-minute valid data	4464	4499	4508	4527
Data availabiltiy	95.7%	96.4%	96.6%	97.0%
# after ext filtering for T, WD, WS	2798	3253	2954	2399
Data availabiltiy for comparison	60.0%	69.7%	63.3%	51.4%

Table 5: Summary of system and data availabilities

4.2 Data availability

Table 5 above summarizes the period of overlap between the met mast and the Lidar system during the measurement campaign with the system availability of 100.0 % as stated in the previous section. It shows a data availability for the treated comparison measurement levels between 91 m and 20 m A.G.L. – regardless of the relevance for wind data comparisons – between 95.7 % and 97.0 % relative to the maximum possible number of ten-minute periods.

- ✓ The Acceptance Criterion for Data Availability (**KPI** DA_{CA}) to be ≥90 % is successfully met for all measurement levels.

Data for individual heights were treated as available when they show a numeric value in contrast to a value being flagged as NaN (not a number). The difference in number of available data between the rows "system" and "data availability"
Table **5** reflect the reduction of valid data according to internal system filtering.

This can be seen in Figure 5 showing the Lidar system availability and in particular the data recovery rate at each of the eight (8) measurement heights. The already mentioned system availability of 100.0 % is – by definition – the same for all heights (yellow bars). The total data availability (blue bars) between the lowest (10 m) and the highest (200 m) measurement level is well above 90 %.

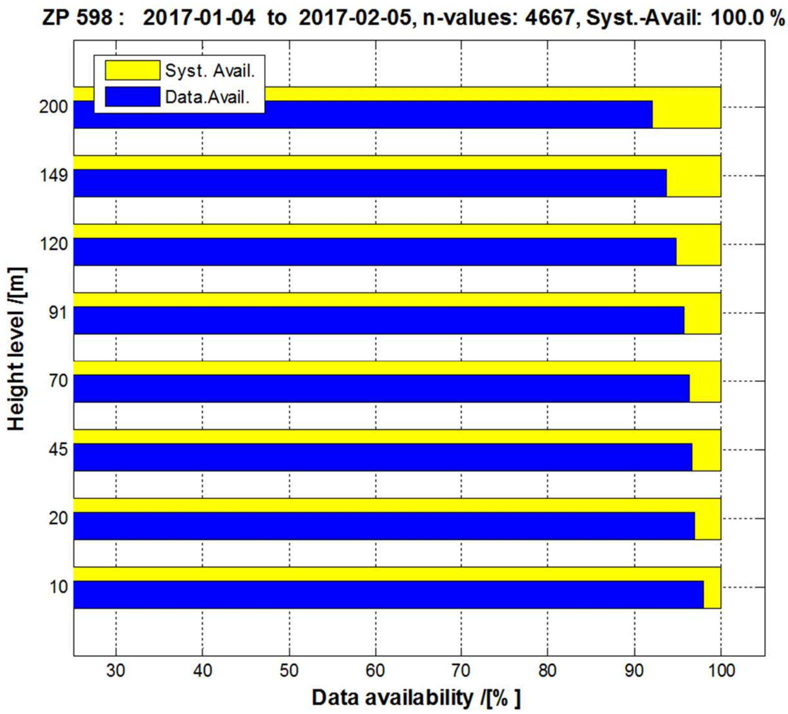


Figure 5: Lidar system and data availabilities for all measurement levels.

4.3 Data filtering

The data from both the Lidar 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
- wind speed, clipping wind speeds below 3 m/s
- air temperature from the ZP-own sensor, to avoid data possibly contaminated from icing at cup anemometers

After the application of those filters the number of ten-minute data points remaining to be processed was reduced to a percentage between 51.4 % at 20 m and 69.7 % at 70 m, compare
Table **5**.

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 LPV process are assessed by means of Linear Regressions through the origin of the form

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

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

a) 4 to 16 m/s [1]

b) all above 3 m/s

according to the following acceptance criteria

1) slope (m) (**KPI** X_{mws}) between 0.98 and 1.02 for all WS ranges a) and b)
2) $R^2 > 0.97$ (**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.

[1] In consistency with the IEC bin selection criteria the actual range spans from 3.75 to 16.25 since 4 m/s and 16 m/s are the central points of the corresponding 0.5 m/s wide bins.

Results of wind speed comparisons

The time series of wind speeds as recorded by the Lidar (for all 8 pre-set heights) covering 32.4 days is overlapped by that of the met mast system. Two comparison heights (70m and 91m) are shown in Appendix C.

Table 6 summarizes the wind speed regression results for all four (4) comparison heights showing that the ZephIR Lidar at hand achieves a high level of accuracy compared to the respective cups in terms of regression slopes (m) which are close to unity and good regression coefficient R^2 (**KPI** R^2_{mws}). Figure 6 shows the corresponding regression plots for the wind speed range >= 3 m/s (upper row out of 4).

The mean Lidar wind speeds as averaged over all used values (**KPI** C_{mwsd}) resemble those of the cups very closely (see columns 5 and 6 of Table 6), yielding a good relative Campaign Mean WS Differences (**KPI** C_{mwsd}) at measurement heights between 20 and 91 m and for both WS ranges.

Table 7 reflects the results according to the absolute wind speed error criterion. It shows that for the wind speed range 3 to 16 m/s at all height levels between 20 to 91 m and for wind speeds above 16 m/s at all treated measurement heights a fraction of 0.9 to 3.8 % of concurrent ten-minute data points exceed the prescribed wind speed difference threshold of 0.5 m/s which is below the allowed upper limit of 10 %.

With respect to the linear WS regressions the following KPI's Acceptance Criteria are passed

- ✓ Regression slope (**KPI** X_{mws}) between 0.98 and 1.02 at all treated levels and for all WS ranges; meeting the Acceptance Criteria.
- ✓ R^2 (**KPI** R^2_{mws}) > 0.97 at all treated levels for both the WS ranges a) [all > 3 m/s] and b) [4 to 16 m/s]; meeting the Acceptance Criteria.
- ✓ The Acceptance Criterion for the relative Campaign Mean Wind Speed Difference (**KPI** C_{mwsd}) (see Table 6, column 7) is successfully passed at the two lower assessment levels (20 m and 45 m) in both WS ranges.

Furthermore, the following wind speed related Acceptance Criteria were met:

- ✓ Absolute Wind Speed Difference (**KPI** A_{wsd}) at all comparison levels and for all analysed wind speed data between 3 and 16 m/s and above 16 m/s, see Table 7.

The following deviation from applicable test conditions and performance criteria are reported.

- o The Acceptance Criterion for the relative Campaign Mean Wind Speed Difference (**KPI** C_{mwsd}) is missed at the two higher comparison levels (70 m and 91 m) in both WS ranges.

91 m level	# values	slope	R^2	WS-avg Cup	WS-avg LiDAR	mean diff.	rel. mean difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{mws}				KPI C_{mwsd}
All >= 3 m/s	2798	0.986	0.993	7.19	7.08	0.12	1.62%
4 - 16 m/s	2578	0.986	0.992	7.44	7.32	0.12	1.67%

70 m level	# values	slope	R^2	WS-avg Cup	WS-avg LiDAR	mean diff.	rel. Mean difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{mws}				KPI C_{mwsd}
All >= 3 m/s	3253	0.989	0.994	6.61	6.53	0.08	1.26%
4 - 16 m/s	2953	0.989	0.993	6.90	6.81	0.09	1.29%

45 m level	# values	slope	R^2	WS-avg Cup	WS-avg LiDAR	mean diff.	rel. Mean difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{mws}				KPI C_{mwsd}
All >= 3 m/s	2954	0.993	0.994	6.02	5.98	0.04	0.73%
4 - 16 m/s	2534	0.993	0.994	6.46	6.40	0.05	0.81%

20 m level	# values	slope	R^2	WS-avg Cup	WS-avg LiDAR	mean diff.	rel. Mean difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{mws}				KPI C_{mwsd}
All >= 3 m/s	2399	0.995	0.994	5.46	5.43	0.03	0.54%
4 - 16 m/s	1935	0.995	0.993	5.96	5.92	0.03	0.59%

Table 6: Regression results for comparison; acceptance relevant results are colour shaded.

Criterion for abs WS error	> 0.5 m/s for 3 to 16 m/s			> 5% above 16 m/s		
	KPI A_{wsd}					
Height Level	total #	identified #	fraction	total #	identified #	fraction
90 m	2780	150	5.4%	18	0	0.0%
70 m	3241	111	3.4%	12	0	0.0%
45 m	2953	57	1.9%	1	0	0.0%
20 m	2399	21	0.9%	0	0	

Table 7: Summary of absolute wind speed differences between cups and Lidar

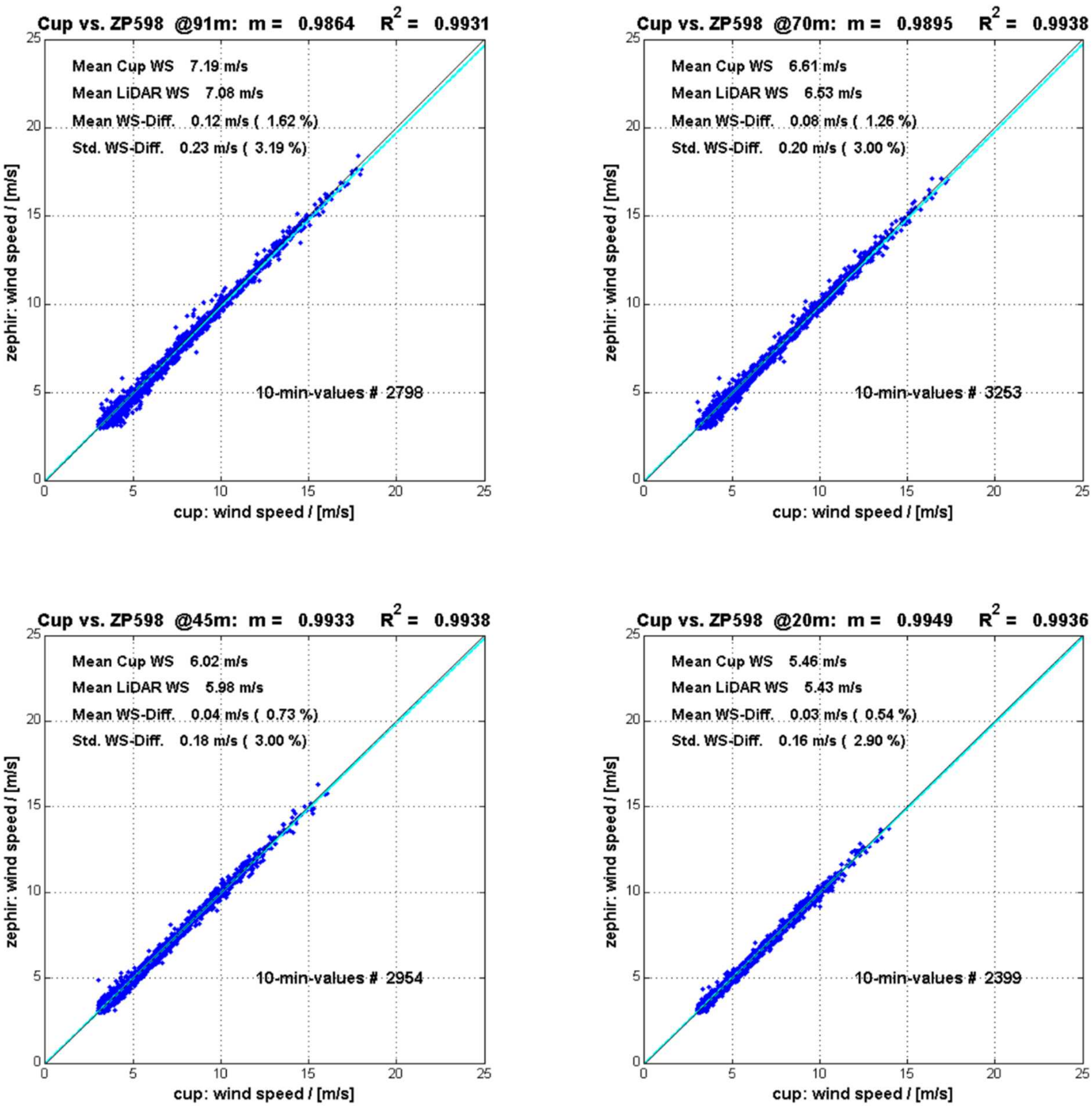


Figure 6: Plots of linear wind speed regression results for 20, 45, 70 and 91 m

4.5 Wind direction comparison

By comparing the wind direction as measured by the Lidar device at its 91 m level with the mast mounted wind vane at 88 m A.G.L., it is possible to see how well correlated the measures are, providing confidence in that the Lidar 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 7 with the vane wind direction at 88 and 44 m on the x-axis and the Lidar direction at 91 and 45 m on the y-axis. For this analysis the data were again filtered for Lidar and the cup wind speeds at 91 m, i.e. for WS >=3 m/s (to avoid false readings from the vane at low wind speeds), but not for possibly disturbed wind directions sectors.

Note that a few 180° wind direction ambiguities were observed, when ZephIR Lidar data were correlated to the wind vane readings at 88 and 44 m (see Appendix D). These ambiguities were solved using mast vane wind directions at the same heights as reference for correction. This mast based correction is justified by the assumption, that the few 180° misreading occurrences are related to lower wind speed in combination with near ground site induced turbulences. 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.

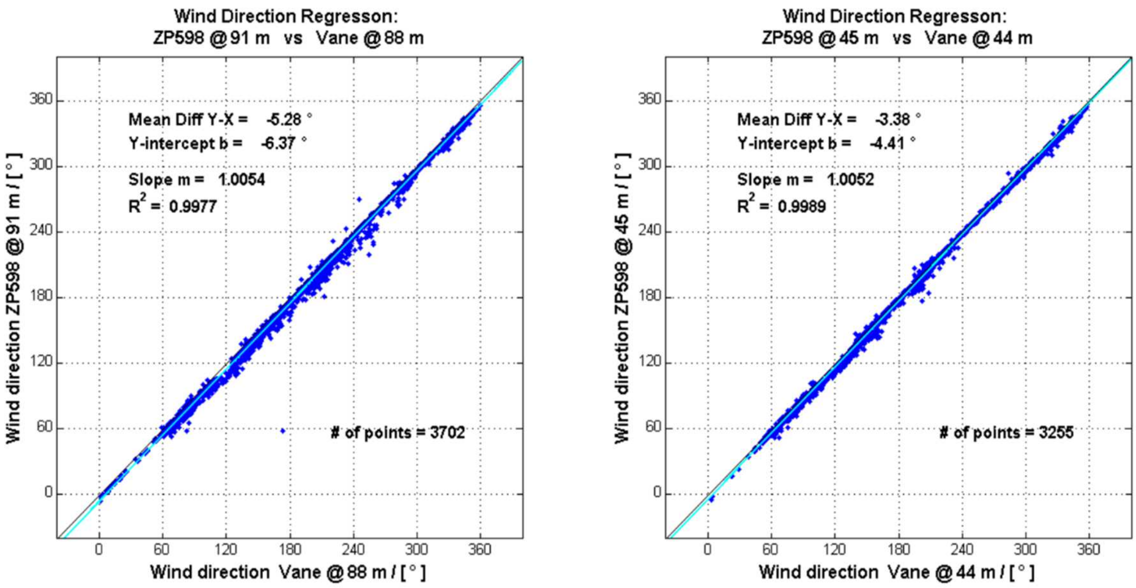


Figure 7: Regression plot of wind direction comparisons at 88 m (left) and 44 m (right panel)

The regression plots in Figure 7 reveal a close resemblance between Lidar and wind vane wind direction measures at 44 m with an offset (in terms of a mean difference) of -3.4° which is well within typical directional setup uncertainties for wind vanes and remotes sensing devices. For the height of 88 m, however, the offset is -5.3° which is slightly above the typical wind vane uncertainty of 5°.

Table 8 summarizes the WD comparison results for the acceptance relevant WD comparison levels at 91 and 45 m, showing an equally good resemblance slope.

Height level	# values	slope	offset [°]	R^2
	-	KPI X_{mwd}	KPI OFF_{mwd}	KPI R^2_{mwd}
91 m	3702	1.005	-5.281	0.998
45 m	3255	1.005	-3.378	0.999

Table 8: Summary of WD comparison results for both comparison levels

✓ The Acceptance Criteria for the respective KPIs for wind direction assessment (**KPIs** for X_{mwd} and $R2_{mwd}$) are successfully passed for both comparison levels. The Criteria for the **KPI** OFF_{mwd} for the wind direction assessment is passed at the lower level

o The Criterion for the **KPI** OFF_{mwd} for the wind direction assessment is just missed at the 88 m level.

4.6 Performance verification according to revised IEC standard, Annex L

This subsection represents as a supplement to the standard Lidar DNV GL / NORSEWInD performance verification test with respect to a Remote Sensing Devices (RSD) validation approach as described in the latest edition of the IEC standard for power performance tests [4]. This approach is based on a wind speed bin averaged procedure in order to compare the horizontal wind speed measurements acquired by the RSD and the reference sensors at the mast. The objective of the IEC approach is to calculate the bin-wise deviation of the two sources and report the associated uncertainty.

The bin averaging procedure was performed using 0.5 m/s wide wind speed bins centred on integers of from 4 to 16 m/s. In order to achieve statistic relevance this IEC approach requires

- a minimum of three (3) 10-minunte values available within each wind speed bin and
- a total amount of 180 hours of valid data (corresponding to a number of 1080 10-min values)

Figures 8 to 11 show scatter plots of the wind speed comparison based on 10 min averages between the data pairs of the Lidar and the cups at 20 m, 45 m, 70 m and 91 m, respectively. In addition the 10 minute averaged deviation for each data point of the two data sets is plotted (red dots).

Furthermore, the correlation coefficient, mean deviation and standard deviation of the deviations are shown in Table 9. The relative deviation of the data pairs was calculated in relation to the cup wind speeds as reference.

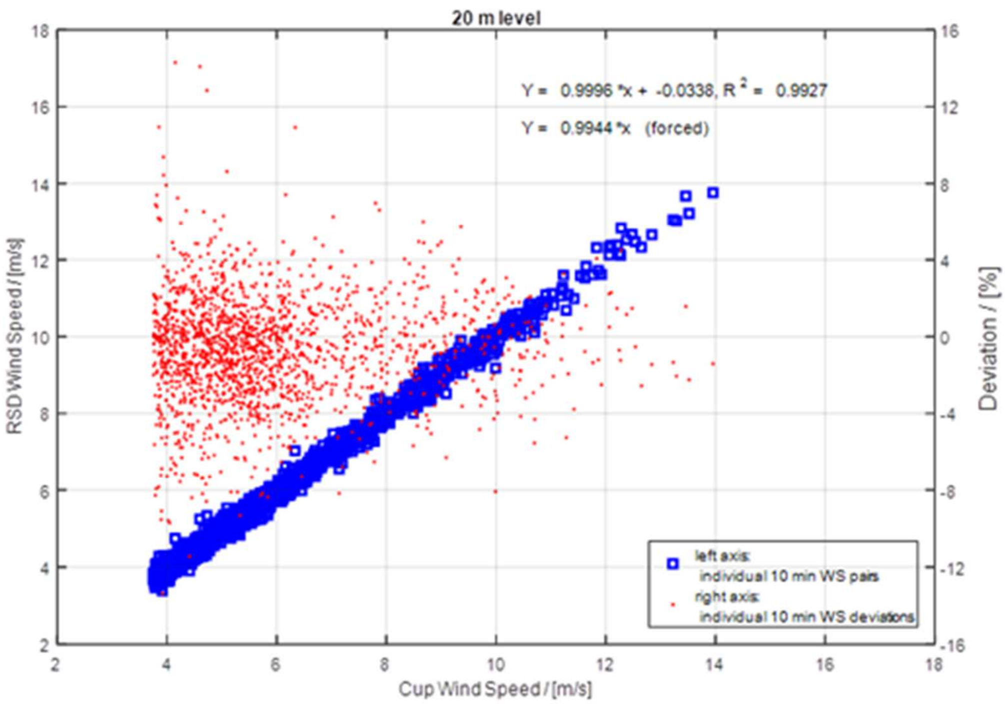


Figure 8: Comparison of the horizontal wind speed component at 20 m

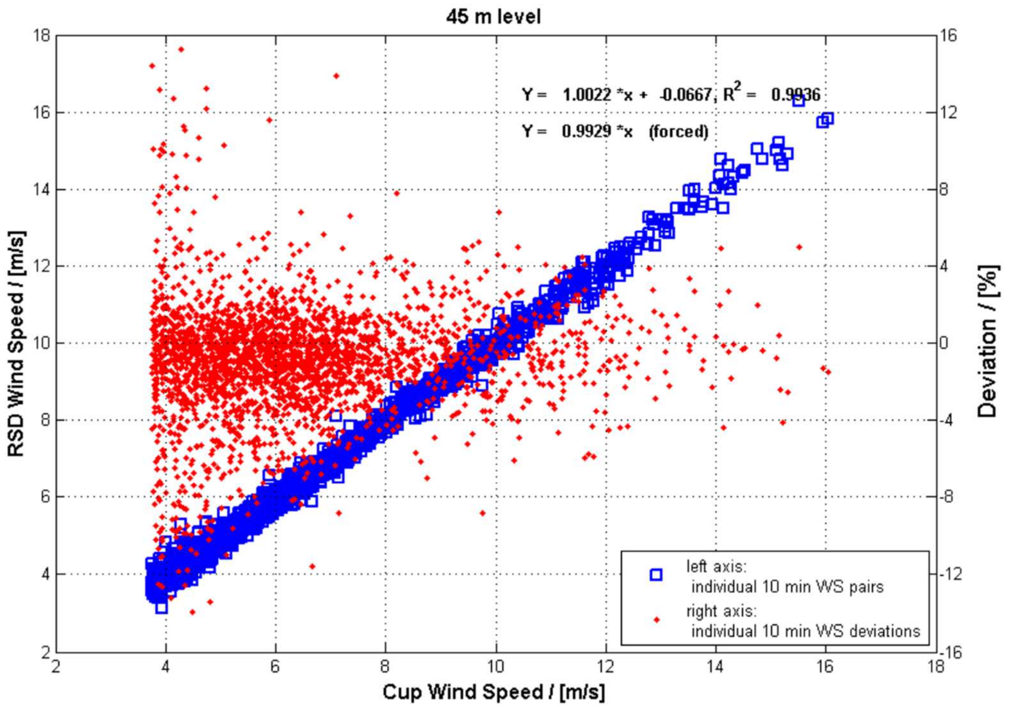


Figure 9: Comparison of the horizontal wind speed component at 45 m

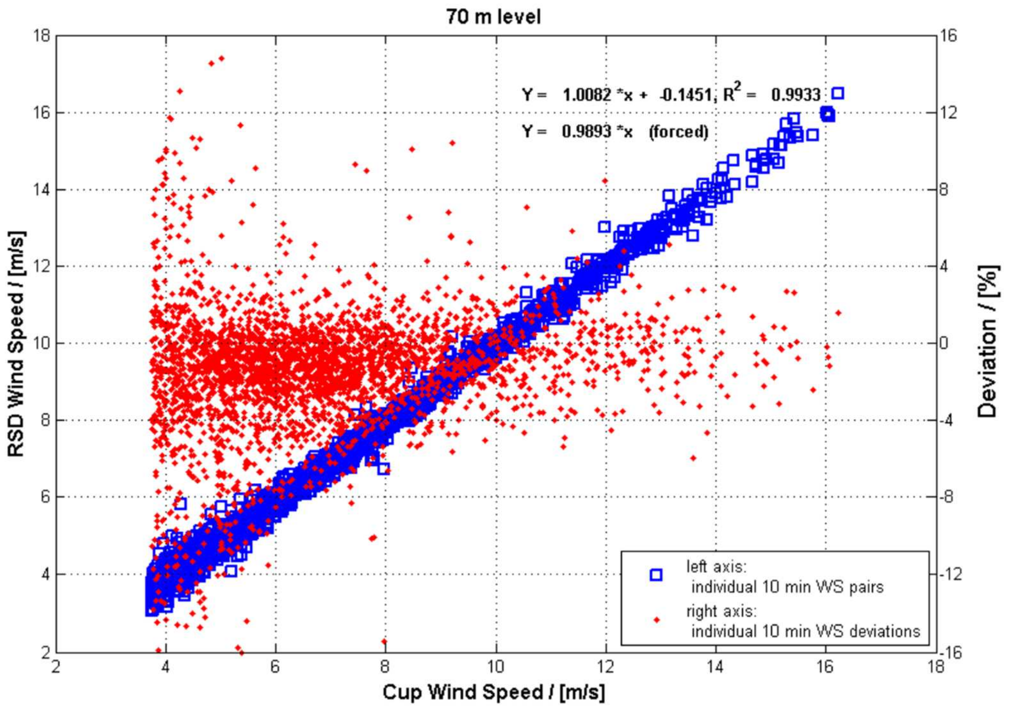


Figure 10: Comparison of the horizontal wind speed component at 70 m

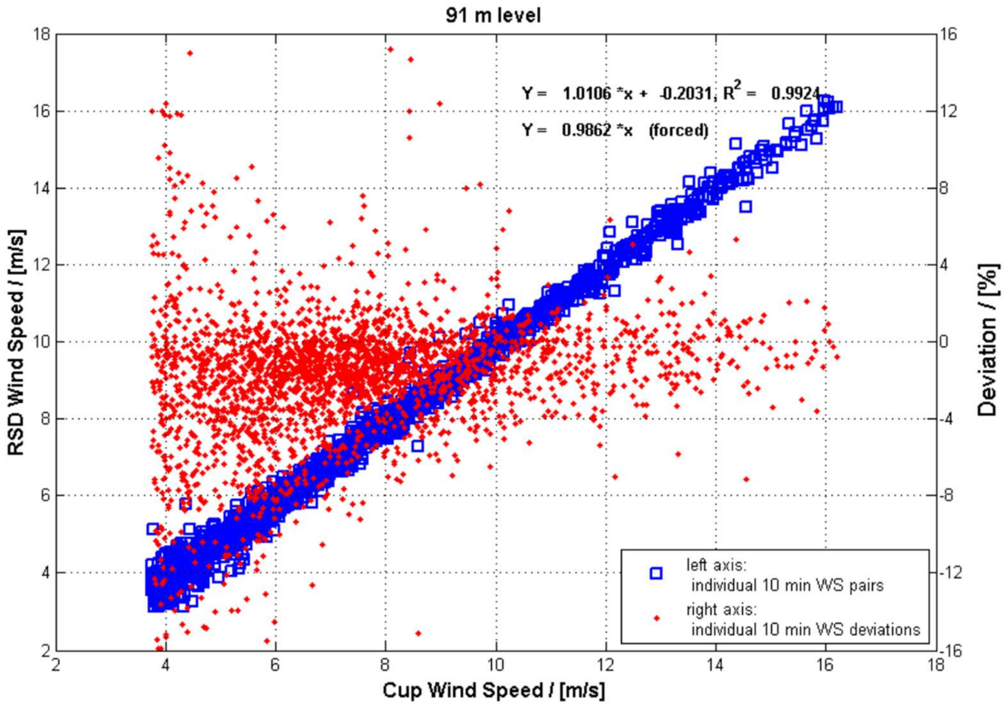


Figure 11: Comparison of the horizontal wind speed component at 91 m

Height level	Coefficient of Determination	Mean Deviation		STD of Deviations	Data Points
[m]	(R^2)	[m/s]	[%]	[%]	#
20	0.9927	0.123	2.11%	1.87%	1935
45	0.9936	0.132	2.16%	2.32%	2534
70	0.9933	0.155	2.51%	2.88%	2953
91	0.9924	0.186	2.88%	3.36%	2578

Table 9: Statistical parameters of wind speed deviation

4.6.1 Performance verification uncertainty

Bin-averaged wind speeds of the RSD and the reference measurements are shown in Figures 12 to 15. The bin-averaged deviation (solid red line in the graphs) can be compared to the standard uncertainty of the cup anemometers combined with the statistical uncertainty of the comparison for each of the WS bins.

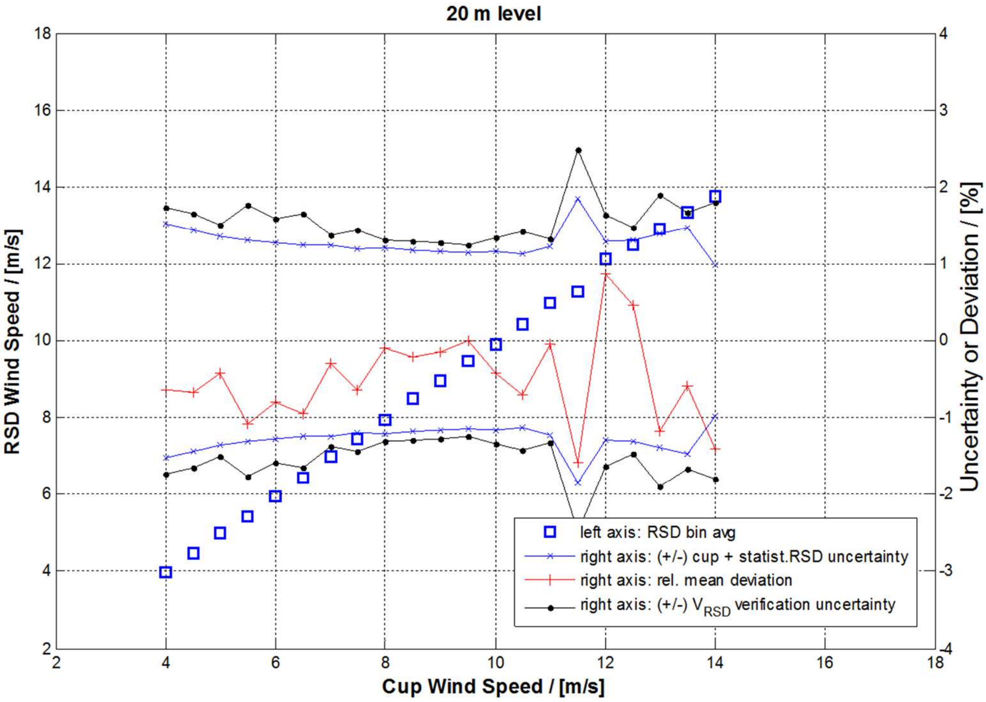


Figure 12: Bin-wise comparison of the horizontal wind speed component at 20 m

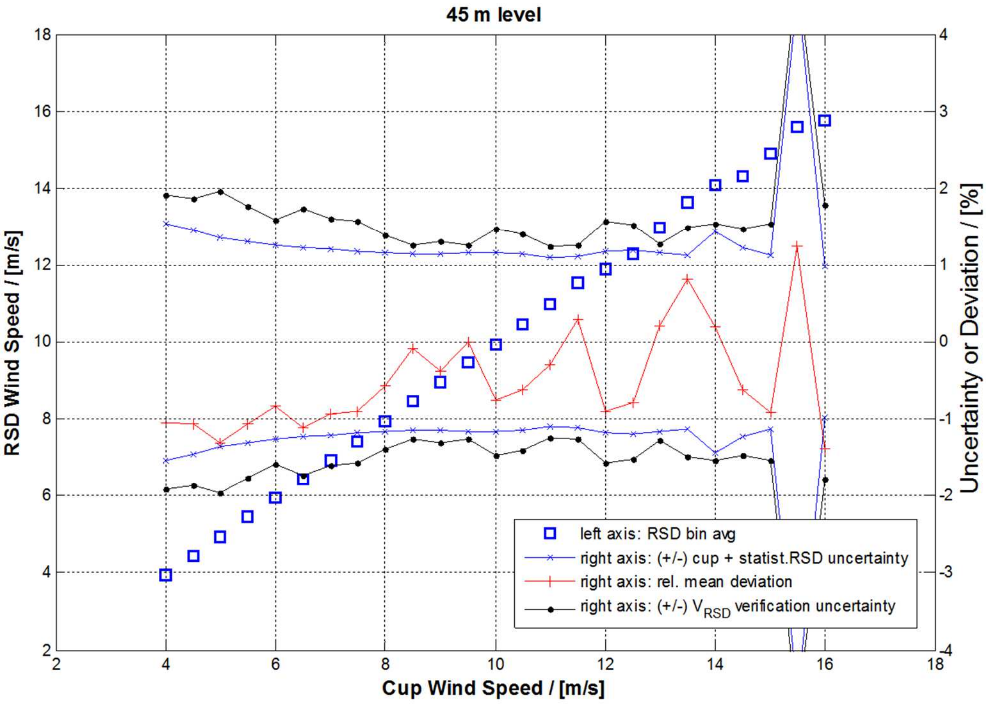


Figure 13: Bin-wise comparison of the horizontal wind speed component at 45 m

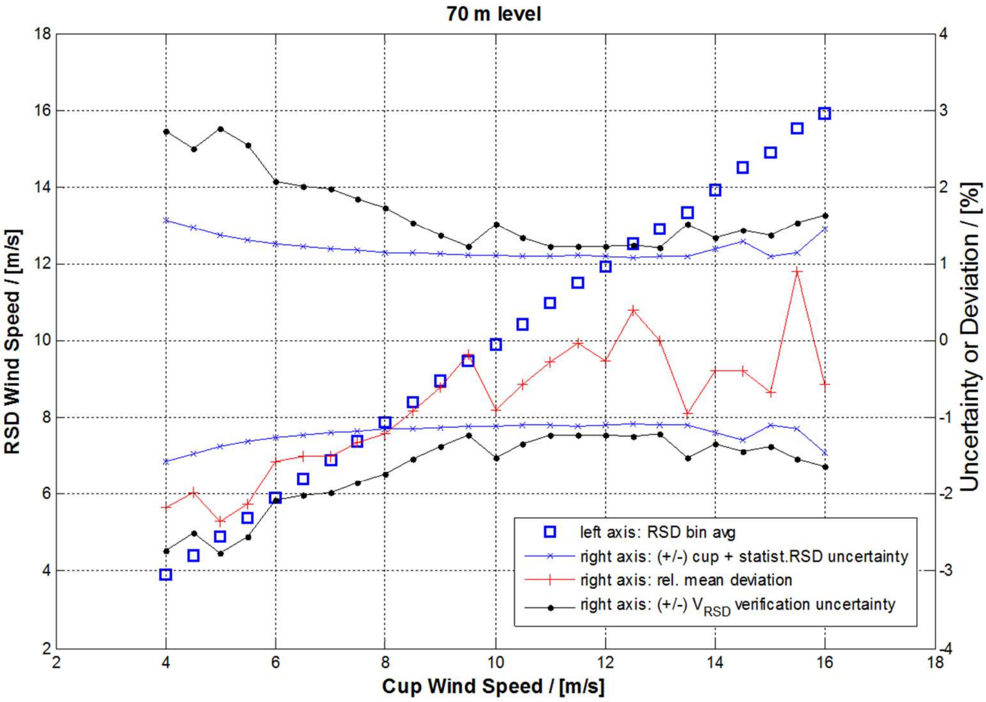


Figure 14: Bin-wise comparison of the horizontal wind speed component at 70 m

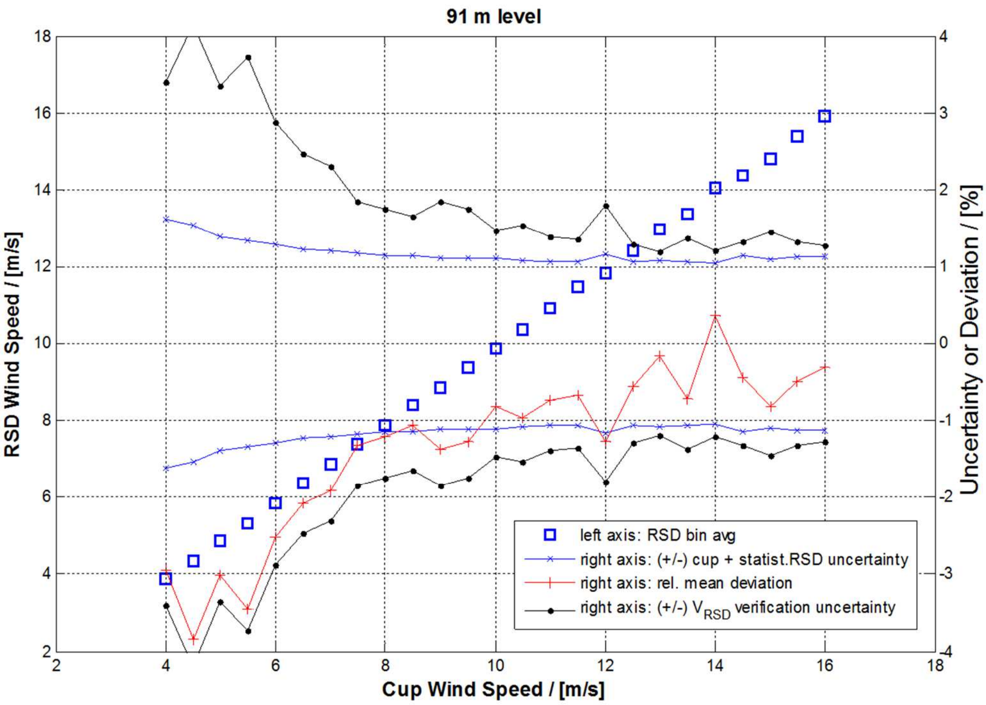


Figure 15: Bin-wise comparison of the horizontal wind speed component at 91 m

According to the IEC standard the verification uncertainty consists of five independent uncertainty components, which are summarized below:

1. Reference / anemometer uncertainty
2. Mean deviation of the remote sensor measurements and the reference measurements
3. Standard uncertainty of the measurement of the remote sensing device
4. Mounting uncertainty of the remote sensor at the verification test
5. Uncertainty due to non-homogenous flow

The different uncertainty components are added in quadrature for each wind speed bin. The uncertainty due to non-homogenous flow between the measurement volume of the Lidar and at the met mast is assumed to be negligible due to the proximity of the Lidar to the mast and the benign terrain conditions at the Pershore test site. Details on the calculation of the separate uncertainty components are described in Appendix F.

The results of the uncertainty calculation for the IEC compliant verification of the Lidar device at every comparison level are plotted in Figures 12 to 15. The finally combined uncertainties of the remote sensing RSD (V_{RSD}) for the different WS bins and comparison levels show results values well below 2 % within most of the bins.

For the current Lidar verification campaign the completeness requirement to yield 180 hours of valid and useable concurrent data (which translates into 7.5 days of data) in the WS range 4 and 16 m/s between the RSD and the reference cup is met for each comparison level.

The additional requirement of yielding a minimum of 3 data pairs in each 0.5 m/s wind speed bin in the same WS range is fulfilled for most of the WS bins and comparison levels, however, with exceptions at bin centre WS greater than 14.0 m/s at the 20 m and greater 15.5 m/s at the 45 m level.

In Appendix G the environmental Parameters - present during the performance verification test - are shown.

		mean WS lid	nbin	mean WS Cup	max WS Lidar	min WS Lidar	std WS Lidar	statiistical uncert. Lidar	mean deviation Lidar - Cup	mounting uncertainty Lidar	RSD to reference separation uncertainty	total cup uncertainty	**overall Lidar trial uncertainty**
BIN lower [m/s]	BIN lower [m/s]	V_{rsd} [m/s]	# of 10 min data sets	V_{mm} [m/s]	V_{maxrsd} [m/s]	V_{minrsd} [m/s]	Std_{Vrsd} [m/s]	$Std_{Vrsd}/\sqrt{n}$ [m/s]	Mean deviation [%]	Mounting uncertainty RSD [%]	Separation uncertainty [%]	V_{cup} Uncertainty [%]	**V_{RSD} Uncertainty [%]**
3.75	4.25	3.97	268	3.99	4.74	3.39	0.20	0.012	-0.63%	0.50%	0.00%	1.50%	**1.73%**
4.25	4.75	4.47	312	4.50	5.33	3.90	0.21	0.012	-0.66%	0.50%	0.00%	1.41%	**1.66%**
4.75	5.25	4.99	296	5.01	5.53	4.43	0.19	0.011	-0.42%	0.50%	0.00%	1.34%	**1.51%**
5.25	5.75	5.44	266	5.49	5.92	4.83	0.18	0.011	-1.08%	0.50%	0.00%	1.29%	**1.77%**
5.75	6.25	5.95	198	5.99	6.62	5.35	0.21	0.015	-0.81%	0.50%	0.00%	1.25%	**1.59%**
6.25	6.75	6.43	128	6.49	7.04	5.88	0.22	0.020	-0.95%	0.50%	0.00%	1.21%	**1.65%**
6.75	7.25	6.98	68	7.00	7.50	6.40	0.24	0.029	-0.30%	0.50%	0.00%	1.18%	**1.38%**
7.25	7.75	7.44	82	7.49	8.03	6.99	0.21	0.024	-0.64%	0.50%	0.00%	1.15%	**1.45%**
7.75	8.25	7.95	53	7.96	8.41	7.27	0.23	0.032	-0.09%	0.50%	0.00%	1.14%	**1.31%**
8.25	8.75	8.50	60	8.52	9.19	8.01	0.27	0.035	-0.21%	0.50%	0.00%	1.11%	**1.30%**
8.75	9.25	8.95	49	8.97	9.55	8.37	0.25	0.036	-0.15%	0.50%	0.00%	1.10%	**1.28%**
9.25	9.75	9.48	40	9.48	9.90	9.04	0.23	0.036	0.00%	0.50%	0.00%	1.08%	**1.25%**
9.75	10.25	9.92	40	9.96	10.50	9.18	0.29	0.046	-0.43%	0.50%	0.00%	1.06%	**1.33%**
10.25	10.75	10.43	30	10.50	10.88	10.02	0.24	0.043	-0.70%	0.50%	0.00%	1.05%	**1.42%**
10.75	11.25	10.98	14	10.99	11.60	10.57	0.27	0.071	-0.06%	0.50%	0.00%	1.04%	**1.32%**
11.25	11.75	11.29	6	11.47	11.83	10.69	0.43	0.176	-1.59%	0.50%	0.00%	1.03%	**2.49%**
11.75	12.25	12.12	11	12.01	12.47	11.61	0.32	0.096	0.87%	0.50%	0.00%	1.01%	**1.64%**
12.25	12.75	12.49	6	12.43	12.83	12.12	0.25	0.102	0.45%	0.50%	0.00%	1.01%	**1.47%**
12.75	13.25	12.91	3	13.06	13.05	12.65	0.22	0.128	-1.18%	0.50%	0.00%	0.99%	**1.89%**
13.25	13.75	13.35	4	13.43	13.67	13.02	0.29	0.146	-0.59%	0.50%	0.00%	1.00%	**1.66%**
13.75	14.25	13.76	1	13.96	13.76	13.76	0.00	0.000	-1.41%	0.50%	0.00%	0.99%	**1.79%**
14.25	14.75		0										
14.75	15.25		0										
15.25	15.75		0										
15.75	16.25		0										

Table 10: Uncertainty calculation for 20 m level

		mean WS lid	nbin	mean WS Cup	max WS Lidar	min WS Lidar	std WS Lidar	statiistical uncert. Lidar	mean deviation Lidar - Cup	mounting uncertainty Lidar	RSD to reference separation uncertainty	total cup uncertainty	**overall Lidar trial uncertainty**
BIN lower [m/s]	BIN lower [m/s]	V_{rsd} [m/s]	# of 10 min data sets	V_{mm} [m/s]	V_{maxrsd} [m/s]	V_{minrsd} [m/s]	Std_{Vrsd} [m/s]	$Std_{Vrsd}/\sqrt{n}$ [m/s]	Mean deviation [%]	Mounting uncertainty RSD [%]	Separation uncertainty [%]	V_{cup} Uncertainty [%]	**V_{RSD} Uncertainty [%]**
3.75	4.25	3.96	304	4.00	4.82	3.13	0.24	0.014	-1.04%	0.50%	0.00%	1.50%	**1.92%**
4.25	4.75	4.44	279	4.49	5.36	3.80	0.24	0.014	-1.06%	0.50%	0.00%	1.42%	**1.86%**
4.75	5.25	4.94	288	5.01	5.57	4.16	0.21	0.012	-1.31%	0.50%	0.00%	1.34%	**1.96%**
5.25	5.75	5.45	270	5.51	5.91	4.92	0.20	0.012	-1.07%	0.50%	0.00%	1.29%	**1.76%**
5.75	6.25	5.96	271	6.01	6.56	5.35	0.19	0.012	-0.83%	0.50%	0.00%	1.25%	**1.59%**
6.25	6.75	6.42	269	6.49	6.91	5.79	0.21	0.013	-1.11%	0.50%	0.00%	1.21%	**1.73%**
6.75	7.25	6.93	193	6.99	8.09	6.36	0.22	0.016	-0.93%	0.50%	0.00%	1.18%	**1.60%**
7.25	7.75	7.43	134	7.50	7.84	6.91	0.20	0.017	-0.91%	0.50%	0.00%	1.15%	**1.57%**
7.75	8.25	7.94	93	7.99	8.85	7.53	0.23	0.024	-0.57%	0.50%	0.00%	1.13%	**1.39%**
8.25	8.75	8.47	68	8.47	8.86	8.05	0.20	0.024	-0.08%	0.50%	0.00%	1.11%	**1.25%**
8.75	9.25	8.96	68	8.99	9.52	8.14	0.25	0.030	-0.37%	0.50%	0.00%	1.09%	**1.30%**
9.25	9.75	9.48	52	9.48	10.20	8.93	0.30	0.041	0.00%	0.50%	0.00%	1.08%	**1.27%**
9.75	10.25	9.92	54	10.00	10.74	8.90	0.33	0.045	-0.75%	0.50%	0.00%	1.06%	**1.47%**
10.25	10.75	10.44	36	10.51	10.92	9.69	0.30	0.051	-0.62%	0.50%	0.00%	1.05%	**1.40%**
10.75	11.25	10.98	45	11.01	11.68	10.57	0.27	0.041	-0.29%	0.50%	0.00%	1.03%	**1.24%**
11.25	11.75	11.55	29	11.52	12.08	10.92	0.27	0.051	0.30%	0.50%	0.00%	1.02%	**1.26%**
11.75	12.25	11.88	24	11.99	12.46	11.09	0.36	0.073	-0.90%	0.50%	0.00%	1.02%	**1.57%**
12.25	12.75	12.30	14	12.40	12.75	11.73	0.29	0.078	-0.78%	0.50%	0.00%	1.01%	**1.51%**
12.75	13.25	12.98	12	12.96	13.29	12.53	0.26	0.075	0.21%	0.50%	0.00%	1.00%	**1.27%**
13.25	13.75	13.64	8	13.53	13.98	13.47	0.21	0.074	0.82%	0.50%	0.00%	0.99%	**1.48%**
13.75	14.25	14.09	9	14.06	14.78	13.52	0.45	0.149	0.19%	0.50%	0.00%	0.98%	**1.54%**
14.25	14.75	14.31	4	14.40	14.48	14.00	0.21	0.107	-0.63%	0.50%	0.00%	0.98%	**1.47%**
14.75	15.25	14.90	6	15.04	15.19	14.60	0.21	0.087	-0.91%	0.50%	0.00%	0.97%	**1.53%**
15.25	15.75	15.60	2	15.41	16.29	14.91	0.97	0.689	1.25%	0.50%	0.00%	0.97%	**4.77%**
15.75	16.25	15.77	2	16.00	15.81	15.74	0.05	0.037	-1.40%	0.50%	0.00%	0.96%	**1.78%**

Table 11: Uncertainty calculation for 45 m level

		mean WS lid	nbin	mean WS Cup	max WS Lidar	min WS Lidar	std WS Lidar	statiistical uncert. Lidar	mean deviation Lidar - Cup	mounting uncertainty Lidar	RSD to reference separation uncertainty	total cup uncertainty	**overall Lidar trial uncertainty**
BIN lower [m/s]	BIN lower [m/s]	V_{rsd} [m/s]	# of 10 min data sets	V_{mm} [m/s]	V_{maxrsd} [m/s]	V_{minrsd} [m/s]	Std_{Vrsd} [m/s]	$Std_{Vrsd}/\sqrt{n}$ [m/s]	Mean deviation [%]	Mounting uncertainty RSD [%]	Separation uncertainty [%]	V_{cup} Uncertainty [%]	**V_{RSD} Uncertainty [%]**
3.75	4.25	3.90	276	3.99	5.01	3.08	0.30	0.018	-2.18%	0.50%	0.00%	1.50%	**2.73%**
4.25	4.75	4.40	266	4.49	5.81	3.47	0.28	0.017	-1.97%	0.50%	0.00%	1.42%	**2.51%**
4.75	5.25	4.90	288	5.01	5.75	4.08	0.22	0.013	-2.35%	0.50%	0.00%	1.34%	**2.77%**
5.25	5.75	5.40	274	5.52	6.16	4.47	0.25	0.015	-2.12%	0.50%	0.00%	1.29%	**2.55%**
5.75	6.25	5.91	284	6.01	6.58	5.19	0.21	0.012	-1.57%	0.50%	0.00%	1.25%	**2.08%**
6.25	6.75	6.42	219	6.51	7.04	5.77	0.21	0.014	-1.51%	0.50%	0.00%	1.21%	**2.01%**
6.75	7.25	6.88	283	6.99	7.46	6.31	0.19	0.011	-1.50%	0.50%	0.00%	1.18%	**1.98%**
7.25	7.75	7.39	213	7.49	8.35	6.77	0.23	0.016	-1.33%	0.50%	0.00%	1.15%	**1.84%**
7.75	8.25	7.88	187	7.97	8.38	6.74	0.22	0.016	-1.21%	0.50%	0.00%	1.13%	**1.74%**
8.25	8.75	8.41	122	8.48	9.34	7.98	0.23	0.021	-0.92%	0.50%	0.00%	1.11%	**1.55%**
8.75	9.25	8.94	103	9.00	10.17	8.39	0.28	0.027	-0.61%	0.50%	0.00%	1.09%	**1.38%**
9.25	9.75	9.49	82	9.51	10.07	8.83	0.24	0.027	-0.19%	0.50%	0.00%	1.07%	**1.23%**
9.75	10.25	9.91	63	10.00	10.54	9.31	0.25	0.032	-0.91%	0.50%	0.00%	1.06%	**1.52%**
10.25	10.75	10.42	55	10.48	11.31	9.85	0.26	0.035	-0.58%	0.50%	0.00%	1.05%	**1.34%**
10.75	11.25	10.98	47	11.01	11.55	10.41	0.26	0.038	-0.28%	0.50%	0.00%	1.03%	**1.23%**
11.25	11.75	11.49	37	11.50	12.14	10.86	0.31	0.051	-0.03%	0.50%	0.00%	1.03%	**1.22%**
11.75	12.25	11.94	37	11.97	13.00	11.42	0.30	0.049	-0.27%	0.50%	0.00%	1.02%	**1.23%**
12.25	12.75	12.53	29	12.48	12.97	11.88	0.26	0.047	0.39%	0.50%	0.00%	1.01%	**1.25%**
12.75	13.25	12.92	27	12.92	13.83	12.45	0.31	0.059	0.00%	0.50%	0.00%	1.00%	**1.21%**
13.25	13.75	13.35	21	13.47	13.86	12.77	0.28	0.061	-0.94%	0.50%	0.00%	0.99%	**1.52%**
13.75	14.25	13.92	13	13.98	14.55	13.20	0.33	0.093	-0.39%	0.50%	0.00%	0.98%	**1.35%**
14.25	14.75	14.52	6	14.58	14.86	14.11	0.31	0.125	-0.40%	0.50%	0.00%	0.97%	**1.44%**
14.75	15.25	14.92	11	15.02	15.36	14.55	0.25	0.076	-0.68%	0.50%	0.00%	0.97%	**1.38%**
15.25	15.75	15.54	5	15.40	15.82	15.34	0.21	0.094	0.89%	0.50%	0.00%	0.97%	**1.54%**
15.75	16.25	15.93	5	16.02	16.48	15.38	0.39	0.175	-0.57%	0.50%	0.00%	0.96%	**1.64%**

Table 12: Uncertainty calculation for 70 m level

		mean WS lid	nbin	mean WS Cup	max WS Lidar	min WS Lidar	std WS Lidar	statiistical uncert. Lidar	mean deviation Lidar - Cup	mounting uncertainty Lidar	RSD to reference separation uncertainty	total cup uncertainty	**overall Lidar trial uncertainty**
BIN lower [m/s]	BIN lower [m/s]	V_{rsd} [m/s]	# of 10 min data sets	V_{mm} [m/s]	V_{maxrsd} [m/s]	V_{minrsd} [m/s]	Std_{Vrsd} [m/s]	$Std_{Vrsd}/\sqrt{n}$ [m/s]	Mean deviation [%]	Mounting uncertainty RSD [%]	Separation uncertainty [%]	V_{cup} Uncertainty [%]	**V_{RSD} Uncertainty [%]**
3.75	4.25	3.89	195	4.00	5.11	3.12	0.34	0.024	-2.95%	0.50%	0.00%	1.49%	**3.40%**
4.25	4.75	4.34	162	4.51	5.78	3.14	0.35	0.028	-3.85%	0.50%	0.00%	1.41%	**4.18%**
4.75	5.25	4.86	158	5.01	5.46	3.87	0.25	0.020	-3.02%	0.50%	0.00%	1.34%	**3.36%**
5.25	5.75	5.33	217	5.52	6.09	4.11	0.29	0.020	-3.45%	0.50%	0.00%	1.29%	**3.73%**
5.75	6.25	5.85	210	6.00	6.51	4.93	0.27	0.018	-2.52%	0.50%	0.00%	1.25%	**2.87%**
6.25	6.75	6.38	224	6.52	6.94	5.77	0.23	0.015	-2.07%	0.50%	0.00%	1.21%	**2.46%**
6.75	7.25	6.86	201	6.99	7.46	6.12	0.23	0.016	-1.91%	0.50%	0.00%	1.18%	**2.31%**
7.25	7.75	7.40	227	7.50	8.67	6.68	0.25	0.017	-1.33%	0.50%	0.00%	1.15%	**1.84%**
7.75	8.25	7.88	189	7.98	9.31	7.33	0.22	0.016	-1.21%	0.50%	0.00%	1.13%	**1.75%**
8.25	8.75	8.41	147	8.50	9.70	7.30	0.29	0.024	-1.07%	0.50%	0.00%	1.11%	**1.64%**
8.75	9.25	8.87	124	8.99	10.10	8.27	0.25	0.022	-1.38%	0.50%	0.00%	1.09%	**1.85%**
9.25	9.75	9.37	94	9.49	10.51	8.71	0.25	0.026	-1.27%	0.50%	0.00%	1.08%	**1.76%**
9.75	10.25	9.88	85	9.96	10.94	9.26	0.30	0.032	-0.81%	0.50%	0.00%	1.06%	**1.47%**
10.25	10.75	10.37	59	10.48	10.73	9.91	0.22	0.028	-0.96%	0.50%	0.00%	1.05%	**1.53%**
10.75	11.25	10.93	60	11.01	11.33	10.47	0.21	0.027	-0.74%	0.50%	0.00%	1.03%	**1.39%**
11.25	11.75	11.46	36	11.54	11.88	11.05	0.22	0.037	-0.67%	0.50%	0.00%	1.02%	**1.36%**
11.75	12.25	11.82	33	11.98	12.84	11.26	0.39	0.069	-1.28%	0.50%	0.00%	1.02%	**1.81%**
12.25	12.75	12.43	30	12.50	13.12	12.05	0.22	0.040	-0.56%	0.50%	0.00%	1.01%	**1.30%**
12.75	13.25	12.98	31	13.01	13.55	12.33	0.29	0.051	-0.16%	0.50%	0.00%	1.00%	**1.19%**
13.25	13.75	13.37	32	13.47	14.16	12.53	0.30	0.053	-0.71%	0.50%	0.00%	0.99%	**1.38%**
13.75	14.25	14.06	18	14.02	14.37	13.69	0.21	0.050	0.36%	0.50%	0.00%	0.98%	**1.21%**
14.25	14.75	14.40	17	14.46	15.13	13.50	0.36	0.088	-0.45%	0.50%	0.00%	0.98%	**1.33%**
14.75	15.25	14.82	9	14.94	15.07	14.40	0.23	0.076	-0.82%	0.50%	0.00%	0.97%	**1.46%**
15.25	15.75	15.41	10	15.48	15.98	15.09	0.29	0.091	-0.49%	0.50%	0.00%	0.97%	**1.33%**
15.75	16.25	15.92	10	15.97	16.24	15.26	0.30	0.095	-0.31%	0.50%	0.00%	0.96%	**1.27%**

Table 13: Uncertainty calculation for 91 m level

5 IMPORTANT REMARKS AND LIMITATIONS

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

Furthermore, the IEC compliant bin-wise uncertainty implementation may serve as a traceable means to judge the uncertainty of the RSD as determined from a well-defined verification process.

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 Lidar configuration as selected for this LPV campaign.

6 CONCLUSION

Concurrent ZephIR 300 Lidar and cup anemometer wind measurements were carried out at the Pershore UK Remote Sensing Test Site to validate Lidar wind data quality against a well-known high quality standard cup anemometer. Measurement heights of 20 m, 45 m, 70 m and 91 m were available for wind speed correlations (88/44 m for wind direction correlation) between a proximate met mast and a ZephIR 300 Lidar with the serial number ZP 598.

The duration of the verification campaign is 32.4 days. The test period and wind data coverage is considered sufficient for the purpose of characterizing the wind data performance of the ZephIR Lidar in the context of a Lidar Performance Verification.

The overall system availability for the mentioned total campaign duration of 32.4 days was 100.0 %. The data availabilities at the selected Lidar measurement levels 20 m, 45 m, 70 m and 91 m was in the range of 95.7 to 97.0 %. These data coverage figures are relative to the number of maximum possible ten-minute data points for the total duration of the campaign.

Wind speed (and direction) correlations were carried out for each of the four WS measurement heights (one for WD) mentioned above. The wind speeds of both techniques at all treated heights correlated very well, showing a very low level of scatter and an excellent resemblance of Lidar wind speeds to those of cups, in terms of linear regression slopes.

In summary the following KPI related Acceptance Criteria are met.

- ✓ The Acceptance Criterion for System Availability (**KPI** SA_{CA}) to be ≥95 % is successfully passed.
- ✓ The Acceptance Criterion for Data Availability (**KPI** DA_{CA}) to be ≥90 % is successfully met at all assessment levels.
- ✓ Regression slope (**KPI** X_{mws}) between 0.98 and 1.02 at all treated levels and for all WS ranges, meeting the Acceptance Criteria.
- ✓ R^2 (**KPI** R^2_{mws}) > 0.97 at all treated levels for the WS ranges a) [all WS > 3 m/s]and b) [4 to 16 m/s], meeting the Acceptance Criteria.
- ✓ The Acceptance Criterion for the relative Campaign Mean Wind Speed Difference (**KPI** C_{mwsd}) (see Table 6, column 7) is successfully passed at assessment levels 20 m and 45 m for both WS ranges.
- ✓ Absolute Wind Speed Difference (**KPI** A_{wsd}) at all comparison levels and for all analysed wind speed data between 3 and 16 m/s and above 16 m/s.
- ✓ The Acceptance Criteria for the respective KPIs for wind direction assessment (**KPIs** for X_{mwd} and R^2_{mwd}) are successfully passed at both comparison levels. The Criterion for the **KPI** OFF_{mwd} for the wind direction assessment is passed at the 45 m level.

The following KPI related Acceptance Criteria are not met.

- o The Acceptance Criterion for the relative Campaign Mean Wind Speed Difference (**KPI** C_{mwsd}) is missed at the 70 m and the 91 m comparison level in both WS ranges.
- o The Criterion for the **KPI** OFF_{mwd} for the wind direction assessment is missed at the 91 m level.

The performance verification and uncertainty calculation has been carried out in accordance with the IEC standard yielding a traceable uncertainty measure. The following deviations from applicable IEC test conditions are reported:

- o During the verification campaign the bins greater 14.0 m/s at the 20 m and greater 15.5 m/s at 45 m the height do not have enough data. Hence, no uncertainty was calculated for these bins.

In summary, this Pershore validation campaign indicates that the ZephIR 300 Lidar with the serial number ZP 598 is able to reproduce cup anemometer wind speeds and wind vane directions at an accurate and acceptable level. DNV GL considers that the ZephIR 300 Lidar device under test (with the S/N ZP 598) can be used for formal wind potential and long-term wind resource assessments. Specifically, DNV GL concludes that this Lidar may be employed as a standalone measurement system – replacing a conventional met mast – given the following criteria are met:

(1) The Lidar is deployed in relatively simple terrain.

(2) The long term data accuracy stability is assured by either

- recording data for a period sufficient to obtain an adequate in-situ correlation to an onsite reference (e.g. a short met. mast)

- or – in case of lack of a suitable in-situ reference – by performing a post deployment performance verification campaign, provided a continuous system operation during the preceding deployment period.

Finally DNV GL recommends, that care needs to be taken with respect to the formal use of Lidar turbulence and extreme wind speed measures, not treated in this report but known to be different from classical anemometry measures. DNV GL likes to point out that good measurement and data collection practices need to be maintained for all wind speed measurements, be they Lidar or more conventional anemometry. Therefore, special care needs to be exercised in the transportation, installation and on-going maintenance of the Lidar as it may be exposed to a wide range of environmental conditions at different sites over time.

A key element of any formal wind study is the traceability of the wind speed data uncertainty. Hence, a strict uncertainty assessment (which is not part of this report) should be employed. Furthermore it is recommended that thorough practices of documenting the salient features of Lidar installation and maintenance are instigated from the outset.

7 REFERENCES

1. Ellis, G., Muhammad, M. and Wylie S, "*UK Remote Sensing Test Site: 91 m Mast Specification* ", by ZephIR Ltd., issued: 22/02/2017.

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3. International Standard: IEC 61400-12-1: Wind turbines – Part 12-1: Power Performance Measurements of Grid Connected Wind Turbines. Ed. 1. International Electronic Commission. 3, rue de Varembé Geneva. Switzerland, Dec. 2005.

4. International Standard: IEC 61400-12-1: Wind turbines – Part 12-1: Power performance measurements of electricity producing wind turbines. Ed. 2. CD. International Electronic Commission.3, June. 2013.

5. 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

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

7. Stein, D. "*Technical Note of Inspection of ZephIR's Reference Met Mast and Lidar Test Site (exec. 2015-09-01) at Pershore/Throckmorton, UK*" DNV GL Report, No. GLGH-4257 15 13307 267 T-0001, Rev. B, 2016-05-02

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
LPV	Lidar 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, IN LINE WITH [2]**

Table 14: List of KPIs and ACs relevant for System and Data Availability assessment

KPI	**Definition / Rationale**	**Acceptance Criteria across total campaign duration**
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%
MV	**Number of Maintenance Visits** Number of Visits to the Lidar system by either the manufacturer or an authorized third party to maintain and service the system. This is to be documented and reported.	N/A
UO	**Number of Unscheduled Outages** Number Unscheduled Outages of the Lidar system in addition to scheduled service outages. Each outage needs to be documented regarding possible cause of outage, exact time / duration and action performed to overcome the Unscheduled outage. This is to be reported.	N/A
CU	**Uptime of Communication System** To be documented and reported by the manufacturer.	N/A

In the above table, during periods of maintenance; the system is deemed unavailable.

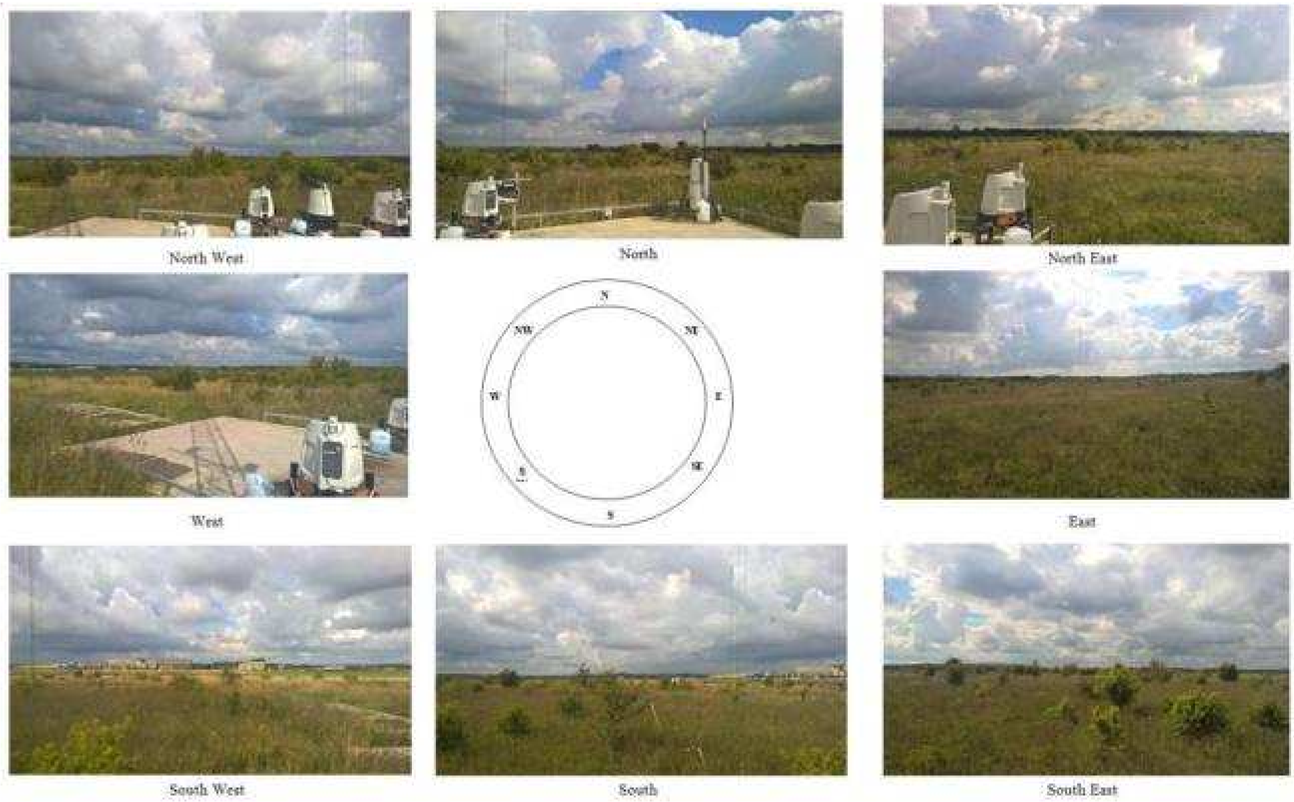
* *Undisturbed sectors: this* means sectors with no significant flow distortion e.g. by wake effects of nearby wind turbines

Table 15: List of KPIs and ACs relevant for Wind Data Accuracy assessment

KPI	Definition / Rationale	Acceptance Criteria
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) 4 to 16 m/s b) all above 3 m/s given achieved data coverage requirements.	< 1 %
Awsd	**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 b) all above 16 m/s given achieved data coverage requirements.	a) < 0.5 m/s b) within 5% 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 > 3 m/s b) 4 to 16 m/s given achieved data coverage requirements.	0.98 – 1.02
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 > 3m/s b) 4 to 16 m/s given achieved data coverage requirements.	>0.97
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.	0.97 – 1.03
OFF_{mwd}	**Mean Wind Direction – Offset (absolute value)** In terms of the campaign mean difference in wind direction (same as for M_{mwd})	< 5°
R^2_{mwd}	**Mean Wind Direction – Coefficient of Determination** (same as for M_{mwd})	> 0.97

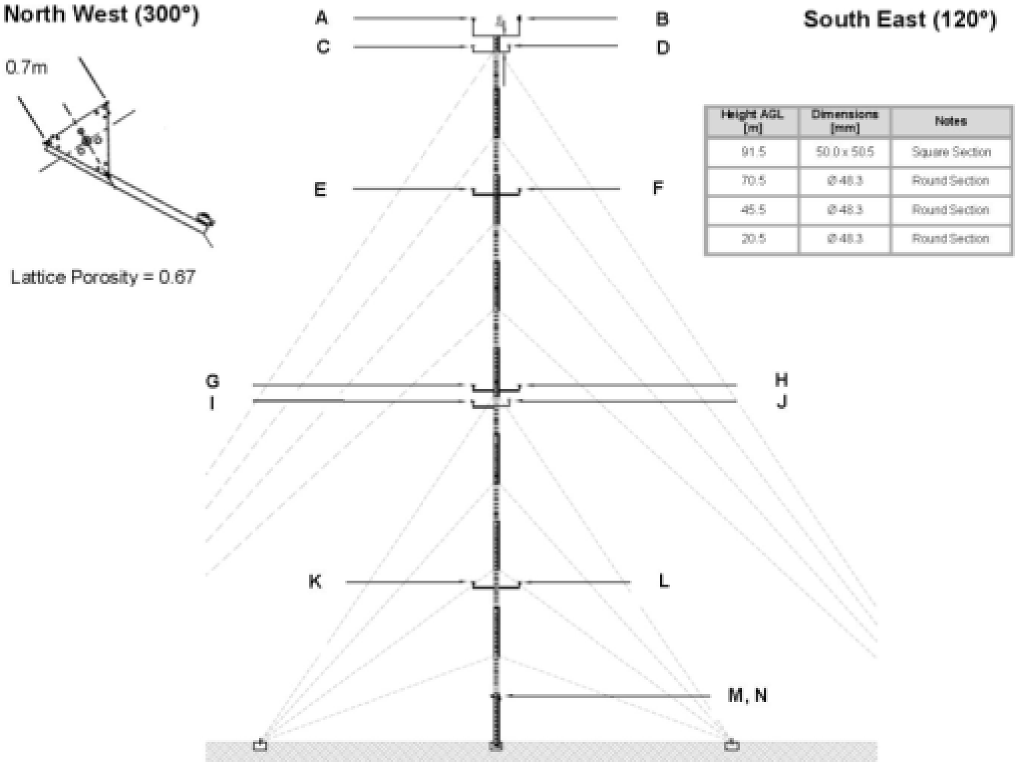
APPENDIX B: **PERSHORE/THROCKMORTON MET MAST DETAILS**

360° Panorama Photos, taken on 2015-09-01, see inspection report [8]:



Met Mast Photo:

Met. Mast Sketch:



Met. Mast Sensor Distribution Table 1:

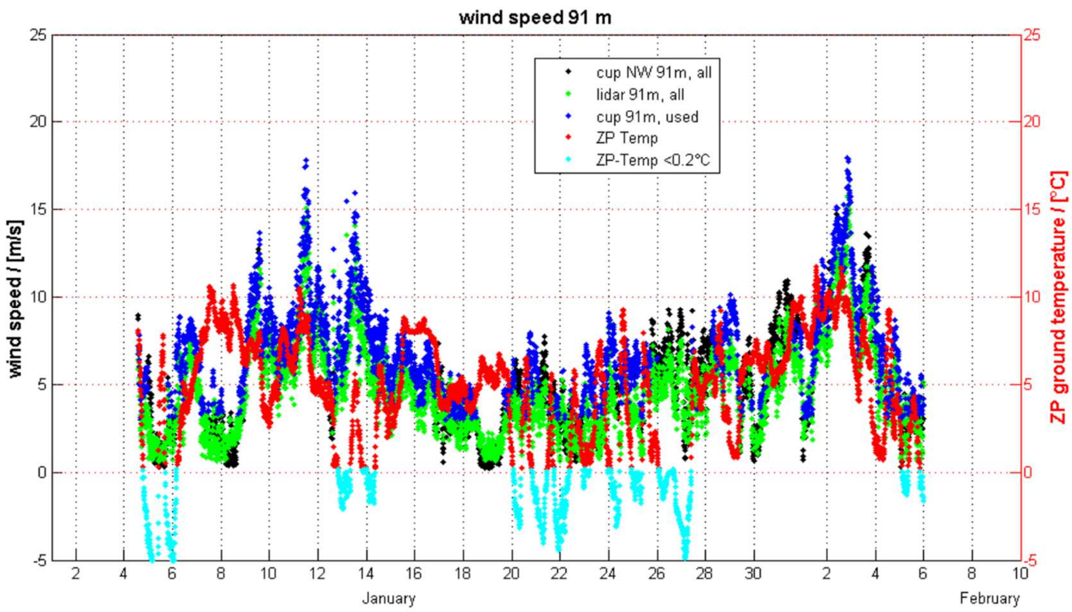
Label	Height (m)	Orientation – Mast to Instrument (°)	Instrument Type	Instrument Model	Cup to Boom Centre Height (mm)	Instrument to Mast Centre Length (mm)
A	91.5	300	Cup Anemometer	Thies First Class Advanced	1520	1025
B	91.5	120	Cup Anemometer	Thies First Class Advanced	1500	1025
C	88	300	Direction Vane	Vector W200P	920	3700
D	88	120	Temperature / Humidity	Campbell Scientific CS215	-	-
E	70.5	300	Cup Anemometer	Thies First Class Advanced	960	3700
F	70.5	120	Cup Anemometer	Thies First Class Advanced	915	3700
G	45.5	300	Cup Anemometer	Thies First Class Advanced	955	3700
H	45.5	120	Cup Anemometer	Thies First Class Advanced'	1160	3700
I	43.5	300	Direction Vane	Vector W200P	920	3700
J	43.5	120	Temperature / Humidity	Campbell Scientific CS215	-	-
K	20.5	300	Cup Anemometer	Thies First Class Advanced	960	3700
L	20.5	12	Cup Anemometer	Thies First Class Advanced	930	3700
M	-	-	Pressure	Campbell Scientific CS100	-	-
N	-	-	Data Logger	Campbell Scientific CR 1000	-	-

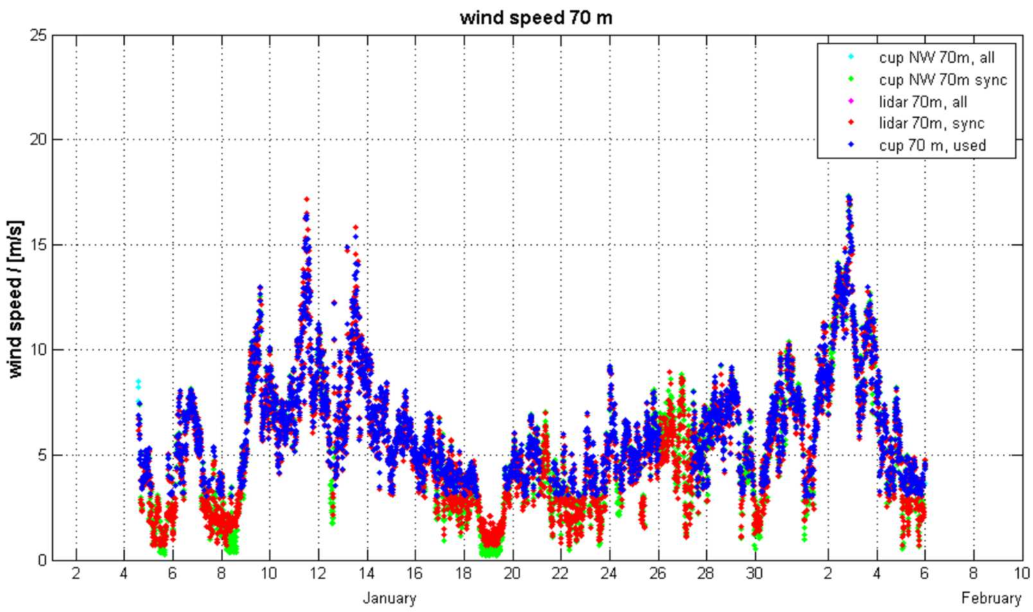
Met. Mast Sensor Distribution Table 2:

Label		A	B	E	F	G	H	K	L
Channel		WS_2R	WS_1M	WS_4R	WS_3V	WS_6R	WS_5V	WS_8R	WS_7V
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		09164177	10164580	10164581	08157941	08157939	10164582	10164583	08157940
Height		91.5	91.5	70.5	70.5	45.5	45.5	20.5	20.5
Orientation – Mast to Instrument (°)		300	120	300	120	300	120	300	120
DWG*	Calibration Date	17/08/2016	22/11/2016	22/11/2016	17/08/2015	17/08/2015	22/11/2016	22/11/2016	17/08/2015
	Slope	0.04596	0.04589	0.04610	0.04600	0.04618	0.04592	0.04601	0.04603
	Offset	0.2519	0.2519	0.2530	0.2568	0.2164	0.2872	0.2802	0.2482
SOH*	Calibration Date	N/A	N/A	N/A	06/10/2015	06/10/2015	N/A	N/A	06/10/2015
	Slope	N/A	N/A	N/A	0.04688	0.04677	N/A	N/A	0.04687
	Offset	N/A	N/A	N/A	0.17228	0.18630	N/A	N/A	0.18083
Applied	Slope	0.04596	0.04589	0.04610	0.4644	0.04648	0.04592	0.04601	0.04645
	Offset	0.2519	0.2519	0.2530	0.2145	0.2014	0.2872	0.2802	0.2145

APPENDIX C: TIME SERIES OF WIND SPEED

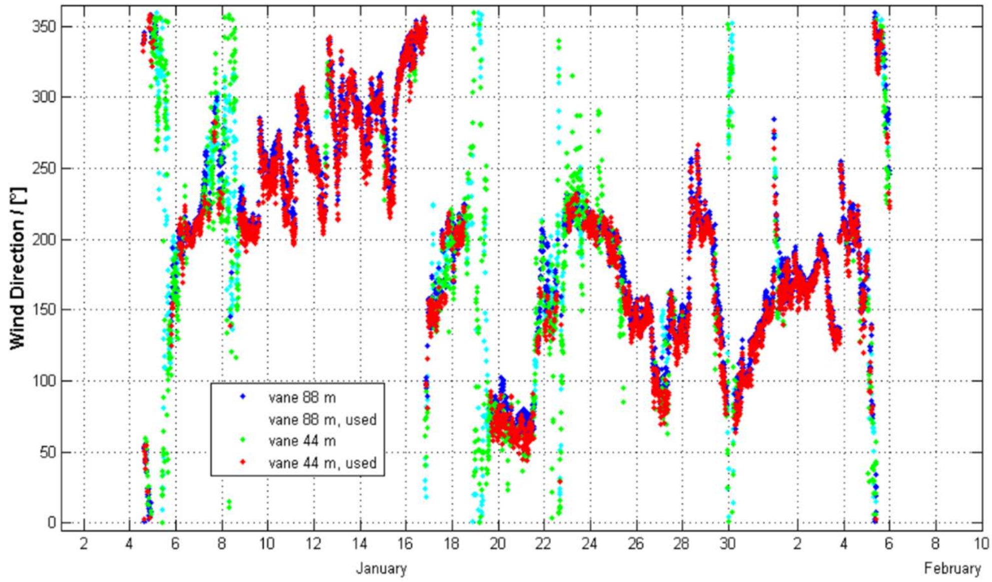
Wind Speed time series for 91 m (upper panel) and 70 m (lower panel). Upper graphic includes temperature time series (red) from ZP-own sensor.



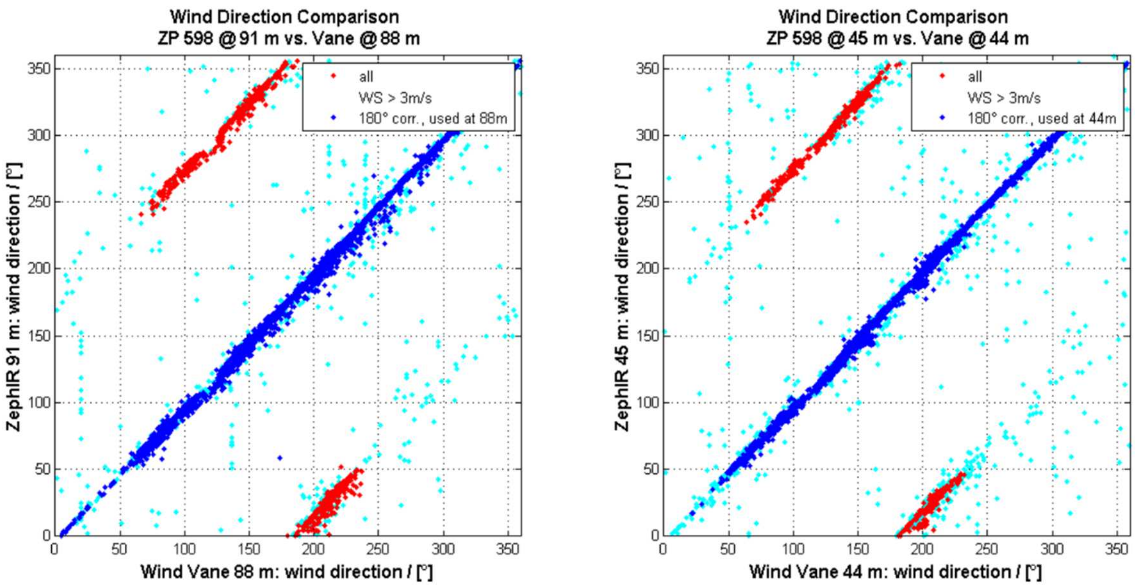


APPENDIX D: WIND DIRECTION

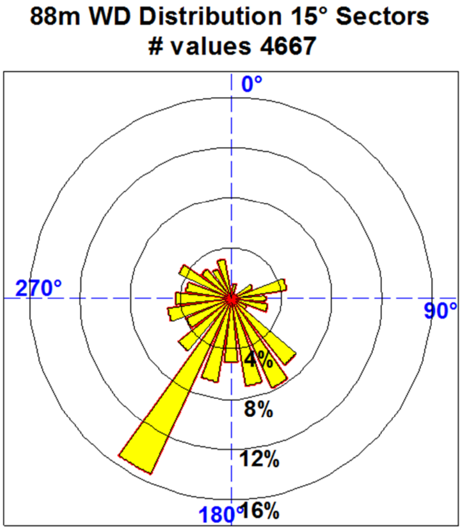
WD time series at 88 m and 44 m wind vane levels:

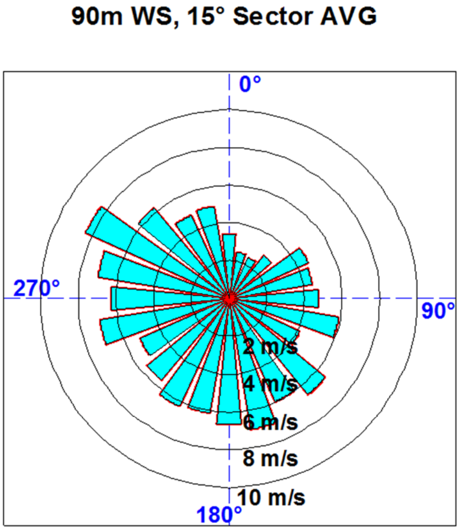


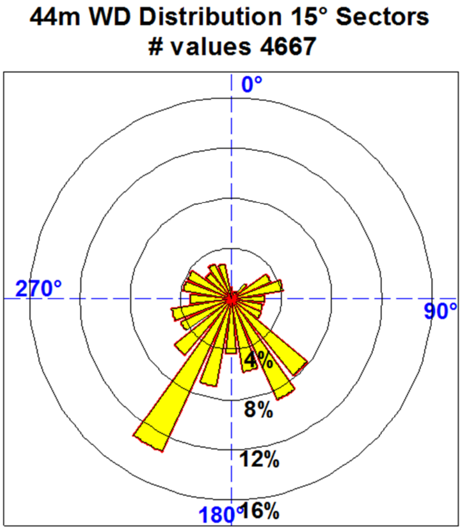
X-Y-plot of wind direction data for WS > 3 m/s (red dots) and 180° ambiguity corrected data (blue dots) between wind vane and Lidar measures; left panel - @88m, right panel - @ 44m:

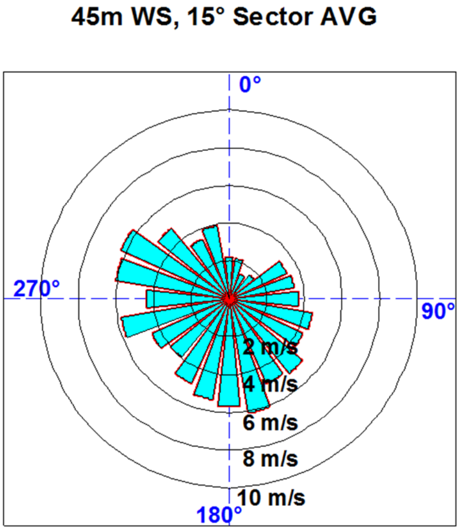


Wind direction related polar plots for wind direction frequency (left panel) and sector averaged WS distribution (right panel) for 88/90m and 44/45m:









APPENDIX E: **CUP CALIBRATION CERTIFICATES**

TFCA Cup S/N 09164177 at 91.5 m, 300° orientation (Deutsche WindGuard Calibration)

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

Calibration mark
Kalibrierzeichen

1615321
D-K-15140-01-00
10/2016

Object *Gegenstand*	L24048
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.10.000
Serial number *Fabrikat/Serien-Nr.*	09164177
Customer *Auftraggeber*	Ammonit Measurement GmbH D-10997 Berlin
Order No. *Auftragsnummer*	L24048
Project No. *Projektnummer*	VT160662
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	14.10.2016

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*
14.10.2016	Dipl. Phys. Dieter Westermann	Techniker Andre Krummen

1615321
D-K-
15140-01-00
10/2016

Calibration object *Kalibriergegenstand*	L24048
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	22.2 °C ± 0.1 °C
air pressure	1011.2 hPa ± 0.3 hPa
relative air humidity	41.9 % ± 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

-

1615321
D-K-
15140-01-00
10/2016

Calibration result
Kalibrierergebnis

Sensor out	Tunnel speed	Uncertainty (k=2)
Hz	m/s	m/s
82.265	4.000	0.050
123.333	5.922	0.050
166.986	7.921	0.051
211.170	9.956	0.051
254.817	11.973	0.052
297.851	13.919	0.052
340.629	15.882	0.053
318.022	14.888	0.053
277.104	12.982	0.052
231.960	10.940	0.052
188.913	8.936	0.051
145.684	6.967	0.051
102.549	4.972	0.050

File: 1615321

Statistical analysis	Slope	0.04596 (m/s)/(Hz) ±0.00007 (m/s)/(Hz)
	Offset	0.2519 m/s ±0.015 m/s
	Standard error (Y)	0.015 m/s
	Correlation coefficient	0.999989

Remarks The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard Wind Tunnel Services GmbH · measnet

Graphical representation of the result
Grafische Darstellung des Ergebnisses

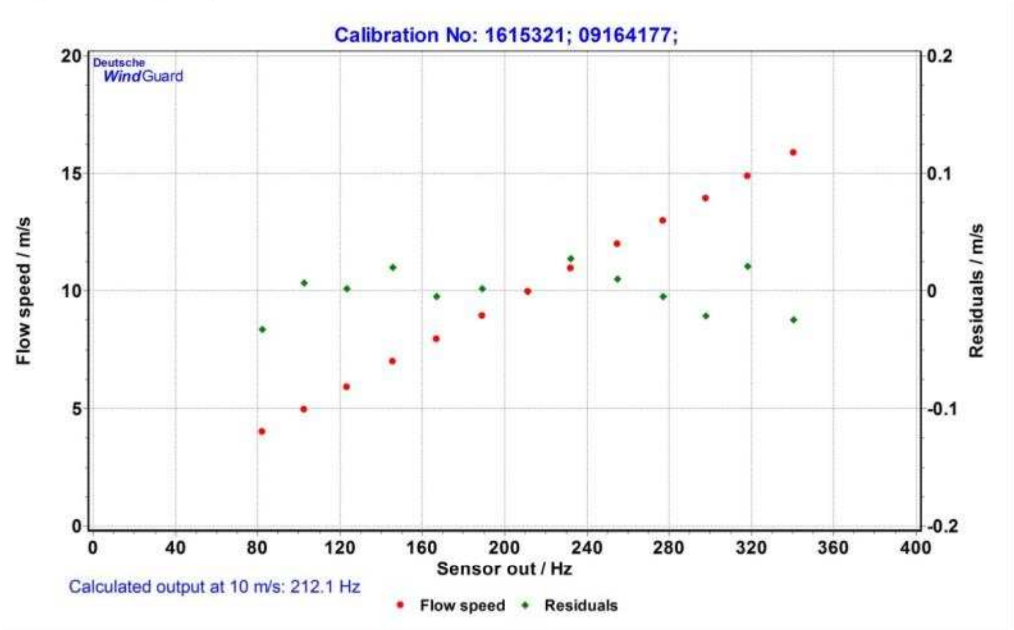


Photo of the measurement setup
Foto des Messaufbaus

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

TFCA Cup S/N 10164580 at 91.5 m, 120° orientation (Deutsche WindGuard Calibration)

ZEPHIR : THROCKMORTON WS - 1M 91.5m SE (B) (TOP)

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

Calibration mark
Kalibrierzeichen

1615854
D-K- 15140-01-00
11/2016

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.10.000
Serial number *Fabrikat/Serien-Nr.*	10164580
Customer *Auftraggeber*	Ammonit Measurement GmbH D-10997 Berlin
Order No. *Auftragsnummer*	L24199
Project No. *Projektnummer*	VT161016
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	22.11.2016

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*
22.11.2016	D. Westermann	D. Henninges
	Dipl. Phys. Dieter Westermann	Techniker Dirk Henninges

Page 2 / 4
Seite

1615854
D-K-15140-01-00
11/2016

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	20.5 °C ± 0.1 °C
air pressure	1008.7 hPa ± 0.3 hPa
relative air humidity	43.1 % ± 2.0 %

Measurement uncertainty *Messunsicherheit*

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

Additional remarks *Zusätzliche Anmerkungen*

-

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

1615854
D-K-15140-01-00
11/2016

Calibration result
Kalibrierergebnis

Sensor out Hz	Tunnel speed m/s	Uncertainty (k=2) m/s
81.749	4.003	0.050
123.380	5.924	0.050
167.453	7.938	0.051
211.193	9.962	0.051
255.657	11.989	0.052
297.259	13.906	0.053
340.409	15.894	0.053
318.978	14.893	0.053
277.463	12.985	0.053
232.804	10.958	0.051
188.551	8.927	0.051
145.821	6.988	0.051
102.503	4.962	0.050

File: 1615854

Statistical analysis	Slope	0.04589 (m/s)/(Hz) ±0.00005 (m/s)/(Hz)
	Offset	0.2653 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

Deutsche WindGuard Wind Tunnel Services GmbH · measnet

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

1615854
D-K-15140-01-00
11/2016

Graphical representation of the result
Grafische Darstellung des Ergebnisses

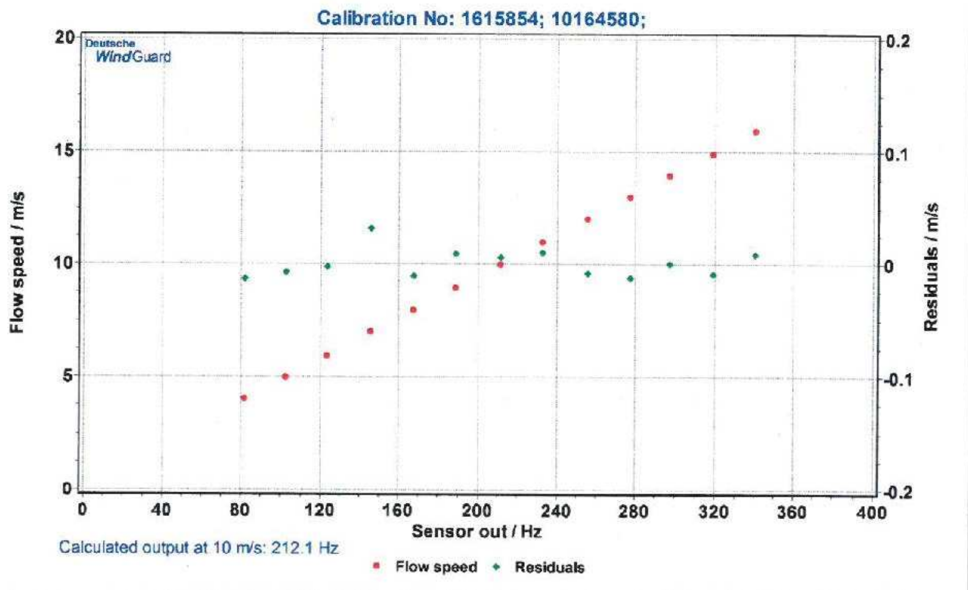


Photo of the measurement setup
Foto des Messaufbaus

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

TFCA Cup S/N 10164581 at 70.5 m, 300° orientation (Deutsche WindGuard Calibration)

ZEPHIR: THROCKMORTON WS-4R 70.5m (N.W.) (E)

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

1615853
D-K-15140-01-00
11/2016

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.10.000
Serial number *Fabrikat/Serien-Nr.*	10164581
Customer *Auftraggeber*	Ammonit Measurement GmbH D-10997 Berlin
Order No. *Auftragsnummer*	L24199
Project No. *Projektnummer*	VT161016
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	22.11.2016

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.

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

Date *Datum*	Head of the calibration laboratory *Leiter des Kalibrierlaboratoriums*	Person in charge *Bearbeiter*
22.11.2016	D. Westermann	D. Henninges
	Dipl. Phys. Dieter Westermann	Techniker Dirk Henninges

1615853
D-K-15140-01-00
11/2016

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	25 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	20.4 °C ± 0.1 °C
air pressure	1008.4 hPa ± 0.3 hPa
relative air humidity	43.1 % ± 2.0 %

Measurement uncertainty
Messunsicherheit

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

Additional remarks
Zusätzliche Anmerkungen

Calibrated with customised specific mount

1615853
D-K- 15140-01-00
11/2016

Calibration result
Kalibrierergebnis

Sensor out	Tunnel speed	Uncertainty (k=2)
Hz	m/s	m/s
82.158	4.009	0.050
123.716	5.926	0.050
167.105	7.931	0.051
210.287	9.963	0.051
254.406	11.987	0.051
296.736	13.922	0.052
340.090	15.896	0.052
317.727	14.903	0.052
276.139	12.973	0.051
230.979	10.949	0.051
187.535	8.933	0.051
146.021	6.986	0.051
101.842	4.973	0.050

File: 1615853

Statistical analysis

Slope	0.04610 (m/s)/(Hz) ±0.00010 (m/s)/(Hz)
Offset	0.2530 m/s ±0.021 m/s
Standard error (Y)	0.022 m/s
Correlation coefficient	0.999976

Remarks

The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard - Wind Tunnel Services GmbH measnet

Page 4 / 4
Seite

1615853
D-K-15140-01-00
11/2016

Graphical representation of the result
Grafische Darstellung des Ergebnisses

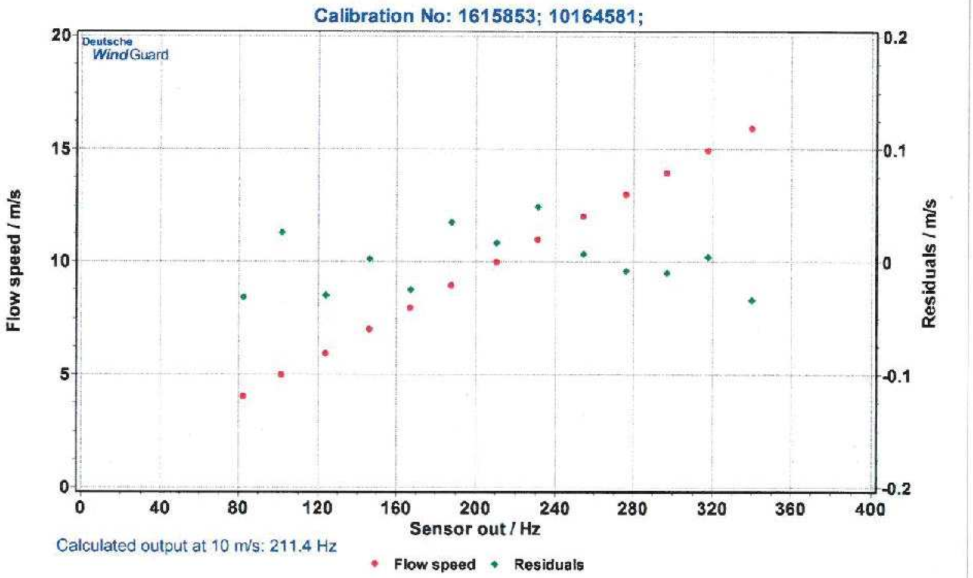
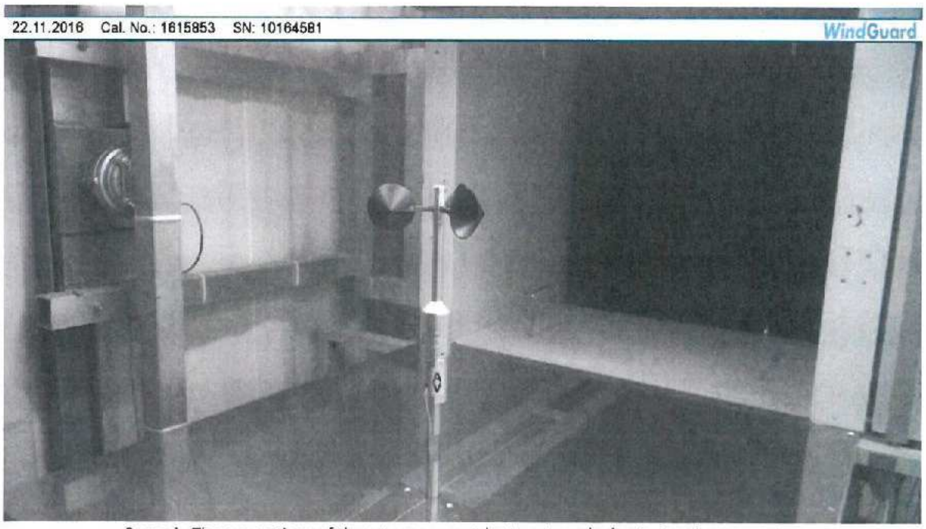


Photo of the measurement setup
Foto des Messaufbaus



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

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

TFCA Cup S/N 08157941 at 70.5 m, 120° orientation (Deutsche WindGuard Calibration)

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

1514069
D-K-15140-01-00
08/2015

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.10.000
Serial number *Fabrikat/Serien-Nr.*	08157941
Customer *Auftraggeber*	Ammonit Measurement GmbH D-10997 Berlin
Order No. *Auftragsnummer*	L23504
Project No. *Projektnummer*	VT150640
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	17.08.2015

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*
17.08.2015	Dipl. Phys. Dieter Westermann	Techniker Dirk Henninges

1514069
D-K-15140-01-00
08/2015

Calibration object *Kalibriergegenstand*	Cup Anemometer
Calibration procedure *Kalibrierverfahren*	• Deutsche WindGuard Wind Tunnel Services: Calibration of anemometers; Version 1.0 (2014) 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 Servies 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	24.8 °C ± 0.1 °C
air pressure	1009.4 hPa ± 0.3 hPa
relative air humidity	57.9 % ± 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)

Latest accreditation
Letzte Akkreditierung

04/2014

Additional remarks
Zusätzliche Anmerkungen

-

1514069
D-K- 15140-01-00
08/2015

Calibration result
Kalibrierergebnis

Sensor out Hz	Tunnel speed m/s	Uncertainty (k=2) m/s
82.469	4.032	0.050
127.044	6.095	0.051
173.907	8.253	0.051
218.777	10.324	0.052
263.517	12.358	0.051
306.557	14.339	0.053
348.762	16.291	0.050
326.565	15.314	0.052
282.431	13.248	0.052
239.957	11.293	0.052
194.276	9.201	0.051
150.515	7.203	0.050
106.305	5.158	0.050

File: 1514069

Linear regression analysis

Slope	0.04600 (m/s)/(Hz) ±0.00006 (m/s)/(Hz)
Offset	0.2568 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 · measnet

Page 4 / 4
Seite

1514069
D-K- 15140-01-00
08/2015

Graphical representation of the result
Grafische Darstellung des Ergebnises

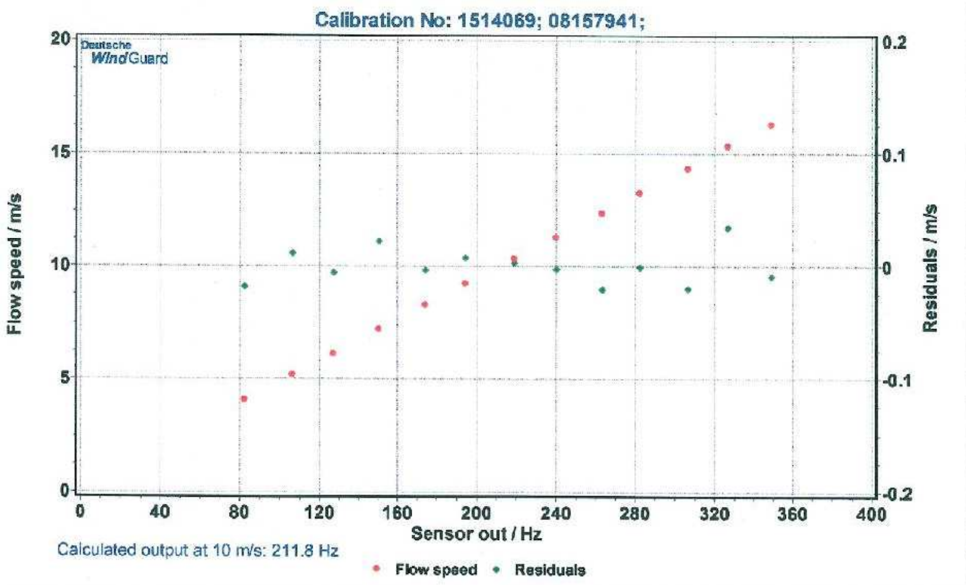
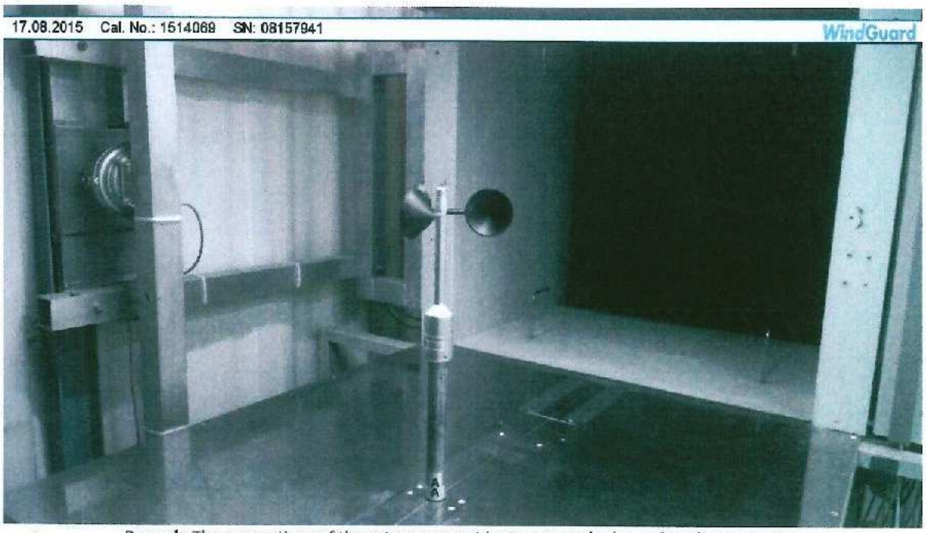


Photo of the measurement setup
Foto des Messaufbaus



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

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

TFCA Cup S/N 08157941 at 70.5 m, 120° orientation (Svend-Ole-Hansen Calibration)

Svend Ole Hansen ApS

SCT. JØRGENS ALLÉ 5C · DK-1615 KØBENHAVN V · DENMARK
TEL: (+45) 33 25 38 38 · WWW.SOHANSEN.DK

WIND ENGINEERING FLUID DYNAMICS

CERTIFICATE FOR CALIBRATION OF CUP ANEMOMETER

Certificate number: 15.02.05824 — **Date of issue:** October 6, 2015

Type: Thies 4.3351.10.000 — **Serial number:** 08157941

Manufacturer: ADOLF THIES GmbH & Co.KG, Hauptstrasse 76, 37083 Göttingen, Germany

Client: WindSensor, Nyvang 6, DK-4000 Roskilde, Denmark

Anemometer received: October 2, 2015 — **Anemometer calibrated:** October 5, 2015

Calibrated by: mmm — **Procedure:** MEASNET, referring to IEC 61400-12-1

Certificate prepared by: cea — **Approved by:** Calibration engineer, rgs

Calibration equation obtained: v [m/s] = 0.04688 · f [Hz] + 0.17228

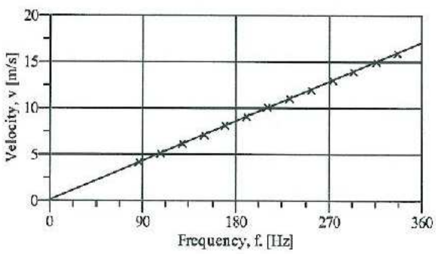
Standard uncertainty, slope: 0.00102 — **Standard uncertainty, offset:** 0.06252

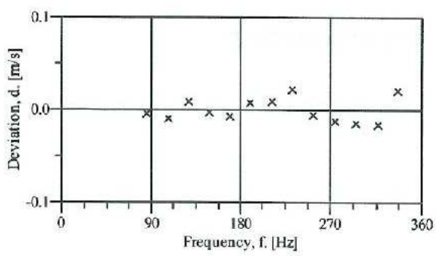
Covariance: -0.0000005 (m/s)²/Hz — **Coefficient of correlation:** $\rho = 0.999994$

Absolute maximum deviation: 0.023 m/s at 11.079 m/s

Barometric pressure: 1016.1 hPa — **Relative humidity:** 32.9%

Succession	Velocity pressure, q. [Pa]	Temperature in wind tunnel [°C]	Temperature in control room [°C]	Wind velocity, v. [m/s]	Frequency, f. [Hz]	Deviation, d. [m/s]	Uncertainty u_c (k=2) [m/s]
2	10.29	29.7	24.4	4.208	86.1557	-0.003	0.021
4	15.59	29.6	24.4	5.177	106.9409	-0.009	0.025
6	22.14	29.4	24.4	6.168	127.6966	0.009	0.029
8	29.83	29.3	24.4	7.158	149.0674	-0.003	0.033
10	38.25	29.2	24.4	8.105	169.3460	-0.007	0.038
12	48.21	29.2	24.4	9.098	190.2206	0.008	0.042
13-last	59.21	29.1	24.4	10.082	211.1694	0.010	0.047
11	71.49	29.2	24.4	11.079	232.1694	0.023	0.051
9	84.18	29.3	24.4	12.024	252.9200	-0.005	0.055
7	98.79	29.4	24.4	13.028	274.4832	-0.012	0.060
5	113.59	29.5	24.4	13.972	294.6672	-0.015	0.064
3	130.65	29.6	24.4	14.988	316.3803	-0.016	0.069
1-first	148.07	29.9	24.4	15.964	336.3975	0.021	0.074





Accreditation to ISO 17025 — DANAK CAL Reg.nr. 452

TFCA Cup S/N 08157939 at 45.5 m, 300° orientation (Deutsche WindGuard Calibration)

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

Calibration mark
Kalibrierzeichen

1514071
D-K-15140-01-00
08/2015

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.10.000
Serial number *Fabrikat/Serien-Nr.*	08157939
Customer *Auftraggeber*	Ammonit Measurement GmbH D-10997 Berlin
Order No. *Auftragsnummer*	L23504
Project No. *Projektnummer*	VT150640
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	17.08.2015

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*
17.08.2015	Dipl. Phys. Dieter Westermann	Techniker Leonid Weise

1514071
D-K-15140-01-00
08/2015

Calibration object *Kalibriergegenstand*	Cup Anemometer
Calibration procedure *Kalibrierverfahren*	• Deutsche WindGuard Wind Tunnel Services: Calibration of anemometers; Version 1.0 (2014) 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 Servies 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	24.9 °C ± 0.1 °C
air pressure	1009.1 hPa ± 0.3 hPa
relative air humidity	58.1 % ± 2.0 %

Measurement uncertainty *Messunsicherheit*

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

Latest accreditation *Letzte Akkreditierung* 04/2014

Additional remarks *Zusätzliche Anmerkungen* -

1514071
D-K- 15140-01-00
08/2015

Calibration result
Kalibrierergebnis

Sensor out Hz	Tunnel speed m/s	Uncertainty (k=2) m/s
82.902	4.031	0.050
126.786	6.068	0.050
174.203	8.254	0.051
219.249	10.315	0.051
262.945	12.362	0.052
305.386	14.341	0.052
348.583	16.301	0.050
326.721	15.317	0.053
282.519	13.250	0.051
239.786	11.284	0.052
194.424	9.190	0.051
151.199	7.215	0.051
106.649	5.165	0.050

File: 1514071

Linear regression analysis

Slope	0.04618 (m/s)/(Hz) ±0.00005 (m/s)/(Hz)
Offset	0.2164 m/s ±0.012 m/s
Standard error (Y)	0.013 m/s
Correlation coefficient	0.999993

Remarks

The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard Wind Tunnel Services GmbH · measnet

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

1514071
D-K- 15140-01-00
08/2015

Graphical representation of the result
Grafische Darstellung des Ergebnises

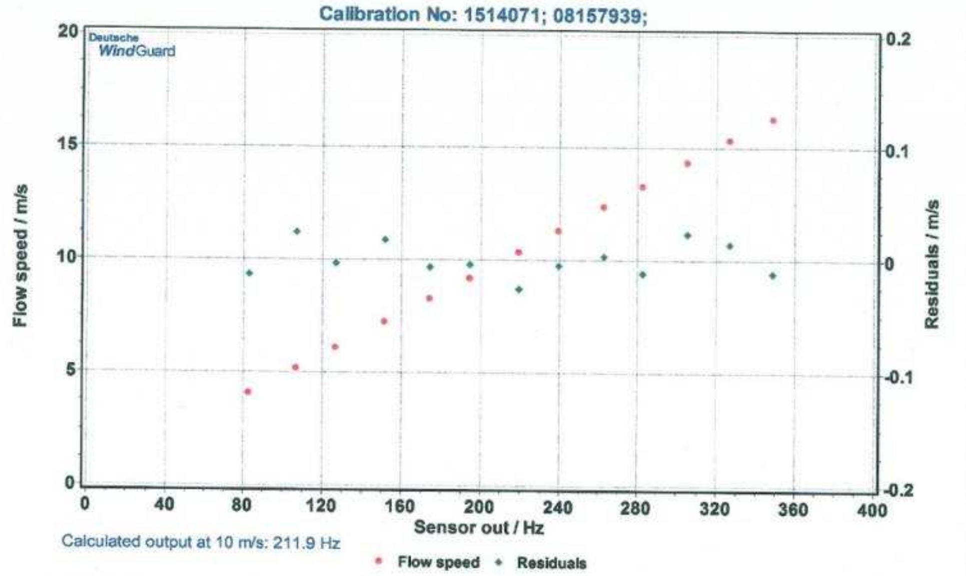
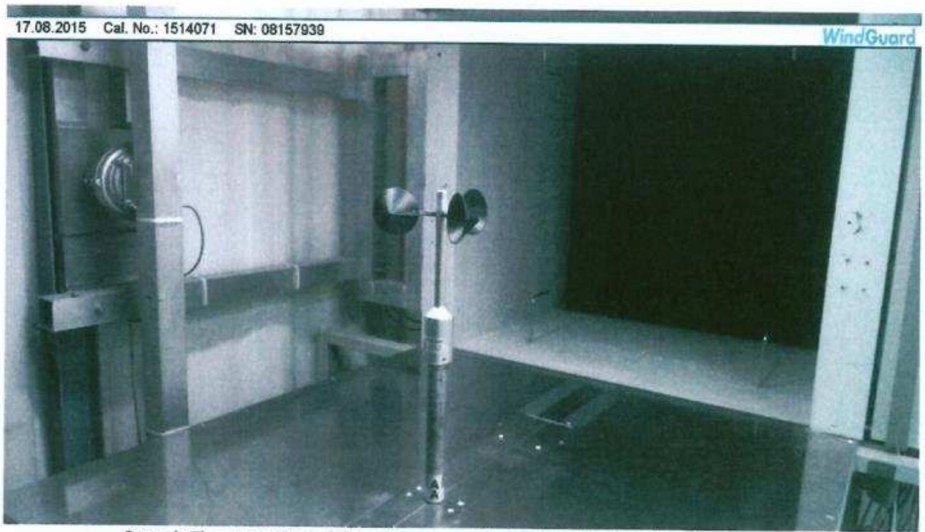


Photo of the measurement setup
Foto des Messaufbaus



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

TFCA Cup S/N 08157939 at 45.5 m, 300° orientation (Svend-Ole-Hansen Calibration)

Svend Ole Hansen ApS

SCT. JØRGENS ALLÉ 5C · DK-1615 KØBENHAVN V · DENMARK
TEL: (+45) 33 25 38 38 · WWW.SOHANSEN.DK

WIND ENGINEERING FLUID DYNAMICS

CERTIFICATE FOR CALIBRATION OF CUP ANEMOMETER

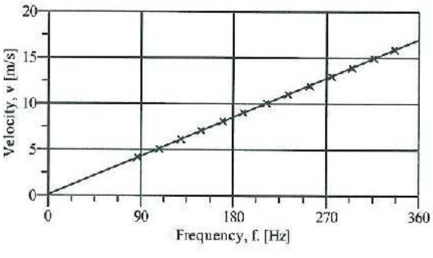
Certificate number: 15.02.05823
Date of issue: October 6, 2015
Type: Thies 4.3351.10.000
Serial number: 08157939
Manufacturer: ADOLF THIES GmbH & Co.KG, Hauptstrasse 76, 37083 Göttingen, Germany
Client: WindSensor, Nyvang 6, DK-4000 Roskilde, Denmark

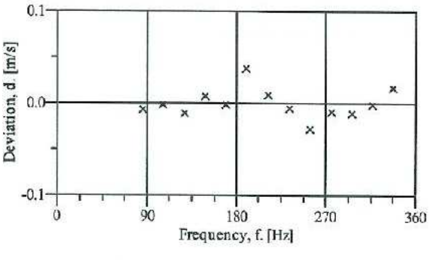
Anemometer received: October 2, 2015
Anemometer calibrated: October 5, 2015
Calibrated by: mmm
Procedure: MEASNET, referring to IEC 61400-12-1
Certificate prepared by: cea
Approved by: Calibration engineer, rgs

Calibration equation obtained: v [m/s] = 0.04677 · f [Hz] + 0.18630
Standard uncertainty, slope: 0.00125
Standard uncertainty, offset: 0.07102
Covariance: -0.0000007 (m/s)²/Hz
Coefficient of correlation: ρ = 0.999991
Absolute maximum deviation: 0.038 m/s at 9.108 m/s

Barometric pressure: 1016.0 hPa
Relative humidity: 33.0%

Succession	Velocity pressure, q. [Pa]	Temperature in wind tunnel [°C]	Temperature in control room [°C]	Wind velocity, v. [m/s]	Frequency, f. [Hz]	Deviation, d. [m/s]	Uncertainty u_c (k=2) [m/s]
2	10.27	29.6	24.4	4.202	86.0002	-0.007	0.021
4	15.62	29.4	24.4	5.181	106.8062	-0.001	0.025
6	22.12	29.3	24.4	6.164	128.0176	-0.010	0.029
8	29.80	29.2	24.4	7.153	148.7729	0.008	0.033
10	38.20	29.1	24.3	8.098	169.1906	-0.002	0.038
12	48.34	29.1	24.3	9.108	189.9349	0.038	0.042
13-last	59.17	29.0	24.3	10.077	211.2457	0.010	0.047
11	71.27	29.1	24.3	11.061	232.5861	-0.005	0.051
9	84.29	29.2	24.4	12.030	253.7971	-0.027	0.055
7	98.92	29.3	24.4	13.034	274.8763	-0.009	0.060
5	114.03	29.4	24.4	13.997	295.4864	-0.011	0.065
3	130.46	29.5	24.4	14.974	316.1671	-0.001	0.069
1-first	148.08	29.8	24.4	15.961	336.8905	0.017	0.074





Accreditation to ISO 17025

DANAK CAL Reg.nr. 452

Page 1 of 2

TFCA Cup S/N 10164582 at 45.5 m, 120° orientation (Deutsche WindGuard Calibration)

ZEPHIR : THROCKMORTON WS_SV 45.5m (S.E) (H)

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

Calibration mark
Kalibrierzeichen

1615852
D-K-15140-01-00
11/2016

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.10.000
Serial number *Fabrikat/Serien-Nr.*	10164582
Customer *Auftraggeber*	Ammonit Measurement GmbH D-10997 Berlin
Order No. *Auftragsnummer*	L24199
Project No. *Projektnummer*	VT161016
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	22.11.2016

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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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*
22.11.2016	D. Westermann	D. Henninges
	Dipl. Phys. Dieter Westermann	Techniker Dirk Henninges

1615852
D-K- 15140-01-00
11/2016

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	25 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	20.2 °C ± 0.1 °C
air pressure	1008.0 hPa ± 0.3 hPa
relative air humidity	43.3 % ± 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 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

Calibrated with customised specific mount

1615852
D-K-15140-01-00
11/2016

Calibration result
Kalibrierergebnis

Sensor out Hz	Tunnel speed m/s	Uncertainty (k=2) m/s
81.568	4.006	0.050
122.954	5.918	0.050
166.840	7.929	0.051
210.821	9.964	0.051
255.031	11.989	0.052
297.170	13.931	0.051
339.513	15.899	0.053
319.244	14.898	0.053
276.657	12.985	0.052
231.053	10.946	0.051
187.793	8.943	0.051
145.739	6.986	0.051
101.672	4.975	0.050

File: 1615852

Statistical analysis

Slope	0.04592 (m/s)/(Hz) ±0.00009 (m/s)/(Hz)
Offset	0.2872 m/s ±0.021 m/s
Standard error (Y)	0.021 m/s
Correlation coefficient	0.999977

Remarks

The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard Wind Tunnel Services GmbH - measnet

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

1615852
D-K-15140-01-00
11/2016

Graphical representation of the result
Grafische Darstellung des Ergebnisses

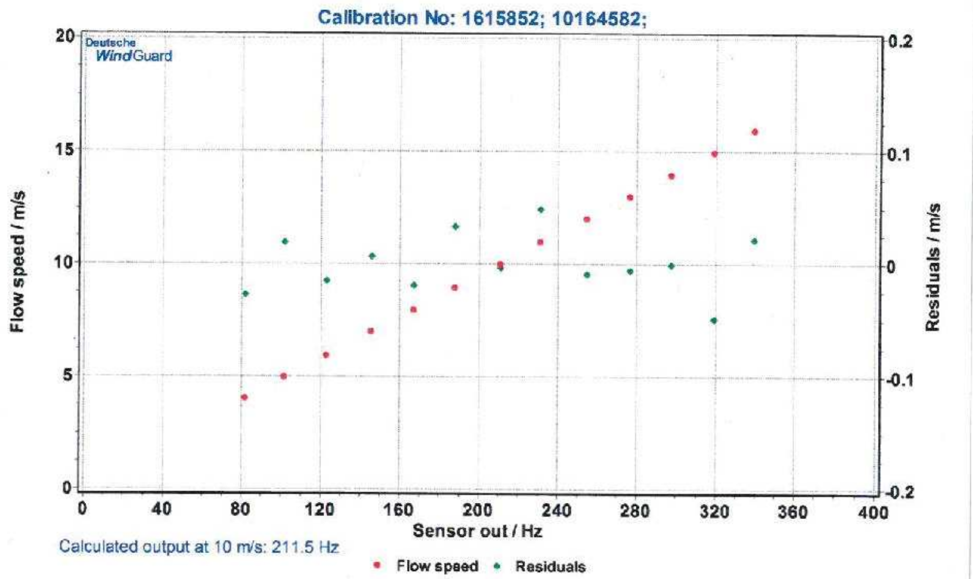
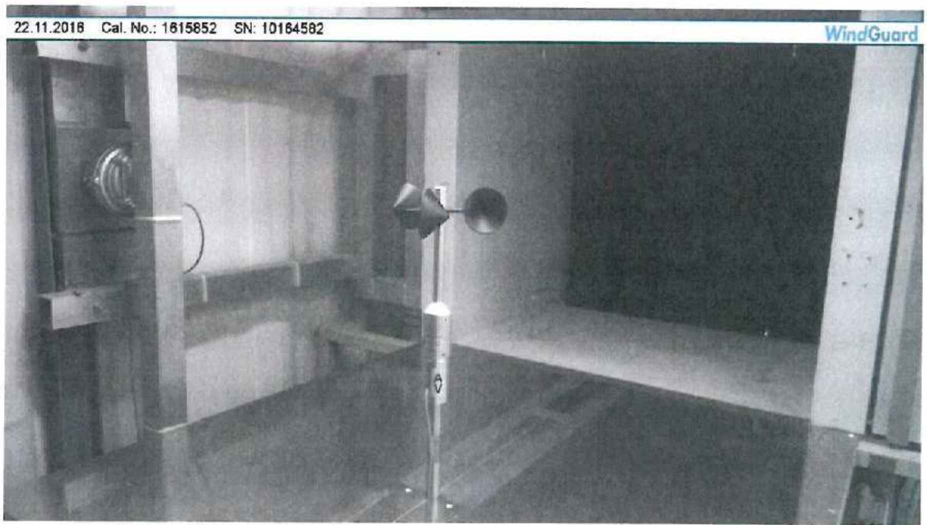


Photo of the measurement setup
Foto des Messaufbaus



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

TFCA Cup S/N 10164583 at 20.5 m, 300° orientation (Deutsche WindGuard Calibration)

ZEPHIR : THROCKMORTON WS - 8R 20.5 m (N.W.) (K)

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

Calibration mark
Kalibrierzeichen

1615851
D-K-
15140-01-00
11/2016

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.10.000
Serial number *Fabrikat/Serien-Nr.*	10164583
Customer *Auftraggeber*	Ammonit Measurement GmbH D-10997 Berlin
Order No. *Auftragsnummer*	L24199
Project No. *Projektnummer*	VT161016
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	22.11.2016

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*
22.11.2016	D. Westermann Dipl. Phys. Dieter Westermann	D. Henninges Techniker Dirk Henninges

1615851
D-K-15140-01-00
11/2016

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	25 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	20.1 °C ± 0.1 °C
air pressure	1007.8 hPa ± 0.3 hPa
relative air humidity	43.6 % ± 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

Calibrated with customised specific mount

1615851
D-K- 15140-01-00
11/2016

Calibration result
Kalibrierergebnis

Sensor out Hz	Tunnel speed m/s	Uncertainty (k=2) m/s
81.737	4.013	0.050
123.199	5.935	0.051
166.642	7.943	0.051
210.778	9.971	0.051
254.564	11.994	0.051
296.816	13.922	0.052
339.365	15.891	0.052
318.274	14.905	0.052
275.587	12.980	0.052
230.972	10.943	0.051
188.429	8.945	0.051
145.134	6.994	0.050
102.050	4.984	0.050

File: 1615851

Statistical analysis

Slope	0.04601 (m/s)/(Hz) ±0.00007 (m/s)/(Hz)
Offset	0.2802 m/s ±0.016 m/s
Standard error (Y)	0.016 m/s
Correlation coefficient	0.999987

Remarks

The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard - Wind Tunnel Services GmbH measnet

1615851
D-K-15140-01-00
11/2016

Graphical representation of the result
Grafische Darstellung des Ergebnisses

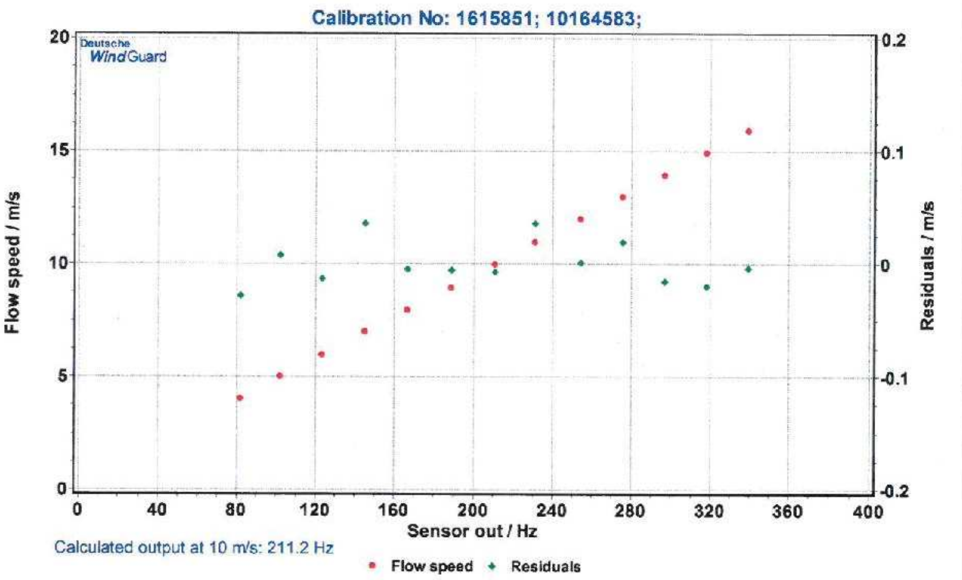
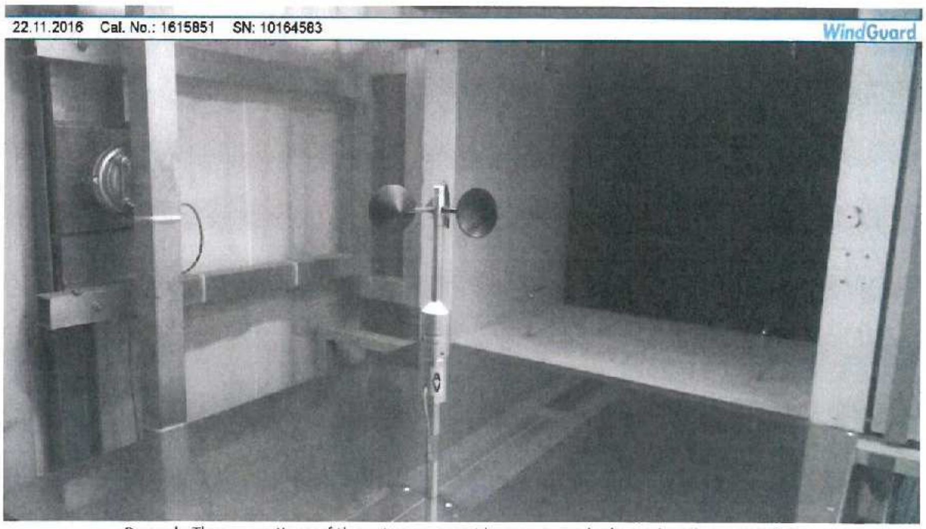


Photo of the measurement setup
Foto des Messaufbaus



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

TFCA Cup S/N 08157940 at 20.5 m, 120° orientation (Deutsche WindGuard Calibration)

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

Calibration mark
Kalibrierzeichen

1514070
D-K-15140-01-00
08/2015

Object *Gegenstand*	Cup Anemometer
Manufacturer *Hersteller*	Thies Clima D-37083 Göttingen
Type *Typ*	4.3351.10.000
Serial number *Fabrikat/Serien-Nr.*	08157940
Customer *Auftraggeber*	Ammonit Measurement GmbH D-10997 Berlin
Order No. *Auftragsnummer*	L23504
Project No. *Projektnummer*	VT150640
Number of pages *Anzahl der Seiten*	4
Date of Calibration *Datum der Kalibrierung*	17.08.2015

This calibration certificate documents the traceability to national standards, which realize the units of measurement according to the International System of Units (SI).
The DAkkS is signatory to the multilateral agreements of the European co-operation for Accreditation (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates.
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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*
17.08.2015	D. Westermann Dipl. Phys. Dieter Westermann	D. Henninges Techniker Dirk Henninges

Calibration object *Kalibriergegenstand*	Cup Anemometer
Calibration procedure *Kalibrierverfahren*	• Deutsche WindGuard Wind Tunnel Services: Calibration of anemometers; Version 1.0 (2014) 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 Servies 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	24.9 °C ± 0.1 °C
air pressure	1009.2 hPa ± 0.3 hPa
relative air humidity	58.0 % ± 2.0 %

Measurement uncertainty
Messunsicherheit

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

Latest accreditation
Letzte Akkreditierung

04/2014

Additional remarks
Zusätzliche Anmerkungen

-

1514070
D-K-
15140-01-00
08/2015

Calibration result
Kalibrierergebnis

Sensor out Hz	Tunnel speed m/s	Uncertainty (k=2) m/s
82.455	4.032	0.050
126.935	6.069	0.050
173.895	8.257	0.051
219.153	10.319	0.051
262.780	12.357	0.052
306.432	14.345	0.052
348.767	16.285	0.050
327.331	15.314	0.053
282.488	13.266	0.052
240.124	11.286	0.052
193.787	9.204	0.051
151.000	7.202	0.051
106.608	5.163	0.050

File: 1514070

Linear regression analysis		
	Slope	0.04603 (m/s)/(Hz) ±0.00006 (m/s)/(Hz)
	Offset	0.2482 m/s ±0.013 m/s
	Standard error (Y)	0.013 m/s
	Correlation coefficient	0.999991

Remarks

The calibrated sensor complies with the demanded linearity of MEASNET

Deutsche WindGuard Wind Tunnel Services GmbH - measnet

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

DEUTSCHE WINDGUARD

1514070
D-K-15140-01-00
08/2015

Graphical representation of the result
Grafische Darstellung des Ergebnises

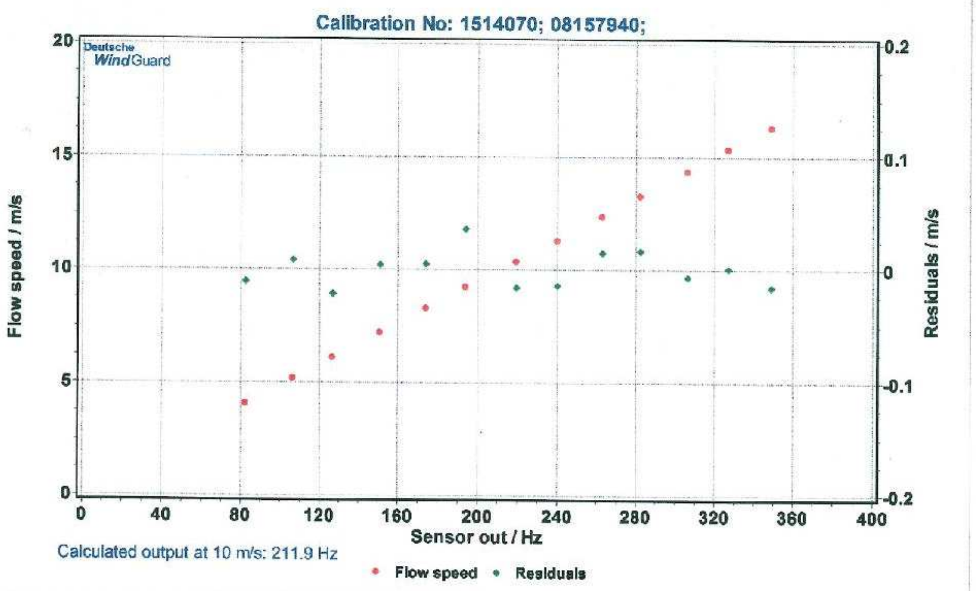
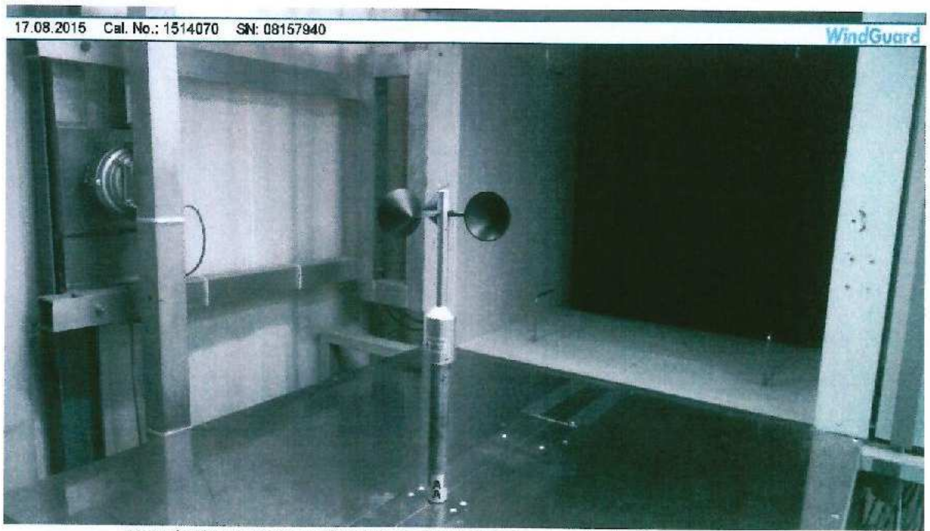


Photo of the measurement setup
Foto des Messaufbaus



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

TFCA Cup S/N 08157940 at 20.5 m, 120° orientation (Svend-Ole-Hansen Calibration)

Svend Ole Hansen ApS

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WIND
ENGINEERING
FLUID
DYNAMICS

CERTIFICATE FOR CALIBRATION OF CUP ANEMOMETER

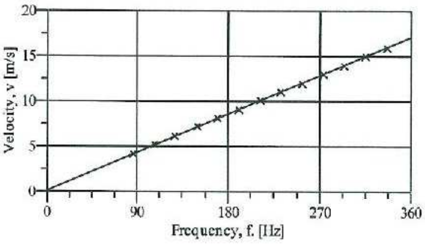
Certificate number: 15.02.05822
Date of issue: October 6, 2015
Type: Thies 4.3351.10.000
Serial number: 08157940
Manufacturer: ADOLF THIES GmbH & Co.KG, Hauptstrasse 76, 37083 Göttingen, Germany
Client: WindSensor, Nyvang 6, DK-4000 Roskilde, Denmark

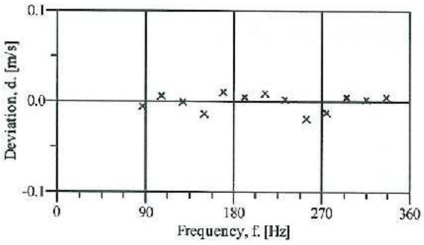
Anemometer received: October 2, 2015
Anemometer calibrated: October 5, 2015
Calibrated by: mmm
Procedure: MEASNET, referring to IEC 61400-12-1
Certificate prepared by: cea
Approved by: Calibration engineer, rgs

Calibration equation obtained: v [m/s] = 0.04687 · f [Hz] + 0.18083
Standard uncertainty, slope: 0.00074
Standard uncertainty, offset: 0.04304
Covariance: -0.0000003 (m/s)²/Hz
Coefficient of correlation: $\rho = 0.999997$
Absolute maximum deviation: -0.018 m/s at 12.038 m/s

Barometric pressure: 1016.2 hPa
Relative humidity: 33.1%

Succession	Velocity pressure, q. [Pa]	Temperature in wind tunnel [°C]	Temperature in control room [°C]	Wind velocity, v. [m/s]	Frequency, f. [Hz]	Deviation, d. [m/s]	Uncertainty u_c (k=2) [m/s]
2	10.40	29.5	24.4	4.227	86.4430	-0.005	0.021
4	15.73	29.3	24.4	5.198	106.8931	0.007	0.025
6	22.08	29.2	24.4	6.156	127.5030	0.000	0.029
8	30.04	29.1	24.4	7.180	149.6298	-0.014	0.033
10	38.52	29.0	24.3	8.129	169.3683	0.010	0.038
12	48.50	28.9	24.3	9.121	190.6334	0.006	0.042
13-last	59.44	28.9	24.3	10.096	211.3694	0.010	0.047
11	71.24	28.9	24.3	11.054	231.9527	0.003	0.051
9	84.46	29.0	24.4	12.038	253.3992	-0.018	0.056
7	98.48	29.1	24.4	13.000	273.7872	-0.012	0.060
5	113.90	29.2	24.4	13.983	294.4054	0.005	0.064
3	130.63	29.4	24.4	14.978	315.6825	0.003	0.069
1-first	147.87	29.6	24.4	15.944	336.2377	0.005	0.073





Accreditation to ISO 17025

DANAK
CAL Reg.nr. 452

Page 1 of 2

APPENDIX F: IEC ANNEX L UNCERTAINTY ANALYSES

1. Reference / anemometer uncertainty

The anemometer uncertainty of the specific reference heights is calculated based on the wind tunnel calibration of the individual anemometer, the anemometer classification and the mounting effect at the met tower.

2. Mean deviation of the remote sensor measurements and the reference measurements

This is the relative deviation between the bin averages of the RSD and the mast reference measurement divided by with the reference measurement.

3. Standard uncertainty of the measurement of the remote sensing device

The standard deviation of the measurements was divided by the square root of the number of data records per bin. The relative uncertainty was calculated by dividing the value by the bin average wind speed of the mast (reference) measurement.

4. Mounting uncertainty of the remote sensor at the verification test

The uncertainty of the remote sensing device due to non-ideal levelling was estimated to be 0.5 %.

5. Uncertainty due to non-homogenous flow

The Lidar device is located in close proximity of the met tower just a few m to the East of the tower base. As a result the uncertainty due to non-homogenous flow within the measurement volume is considered to be negligible.

ENVIRONMENTAL PARAMETERS ACCORDING TO IEC ANNEX L, DURING THE CAMPAIGN, REF. 70 M LEVEL

BIN lower	BIN upper	nbin	Vmm	shear expontent alpha 90 m - 45 m		Turbulence Intensity at 70 m		# PiA Quality Factor at 70 m		Wind direction at 88 m		Air Temperature at 43 m		air density at 43 m		wind veer 88m - 43m	
[m/s]	[m/s]	#	average [m/s]	average [-]	Std [-]	average [-]	Std [-]	average #	Std #	average [°]	Std [°]	average [°C]	Std [°C]	average [kg/m^3]	Std [kg/m^3]	average [°]	Std [°]
3.75	4.25	276	3.99	0.14	0.07	0.09	0.04	34.6	1.3	168.8	82.0	4.4	2.3	1.270	0.021	-1.59	43.23
4.25	4.75	266	4.49	0.21	0.08	0.08	0.04	34.4	1.4	182.0	88.7	4.5	2.3	1.269	0.020	-5.25	23.29
4.75	5.25	288	5.01	0.26	0.09	0.09	0.04	34.2	1.3	210.4	88.0	5.0	2.5	1.265	0.020	-0.58	46.92
5.25	5.75	274	5.52	0.28	0.11	0.09	0.04	34.3	1.5	203.8	76.9	5.1	2.3	1.263	0.019	-5.92	5.77
5.75	6.25	284	6.01	0.30	0.11	0.08	0.04	34.3	1.5	214.1	67.1	5.3	2.4	1.258	0.017	-6.27	5.51
6.25	6.75	219	6.51	0.28	0.11	0.09	0.04	33.9	1.7	218.1	67.9	5.8	2.3	1.253	0.017	-5.55	4.10
6.75	7.25	283	6.99	0.29	0.11	0.09	0.04	34.1	1.6	212.3	57.7	5.6	2.3	1.252	0.018	-5.89	3.97
7.25	7.75	213	7.49	0.28	0.09	0.09	0.04	34.3	1.5	213.6	52.1	6.1	2.5	1.248	0.018	-5.39	3.43
7.75	8.25	187	7.97	0.29	0.09	0.09	0.03	34.7	1.3	221.5	52.6	5.8	2.7	1.248	0.019	-5.35	3.04
8.25	8.75	122	8.48	0.28	0.08	0.09	0.03	34.6	1.3	223.8	52.6	6.1	3.2	1.243	0.022	-5.03	2.85
8.75	9.25	103	9.00	0.27	0.08	0.09	0.03	34.8	1.0	226.8	52.1	6.1	3.1	1.245	0.021	-4.39	1.97
9.25	9.75	82	9.51	0.24	0.07	0.10	0.04	34.5	1.3	215.8	62.8	5.9	2.7	1.242	0.020	-3.72	1.99
9.75	10.25	63	10.00	0.23	0.07	0.10	0.03	34.5	1.3	227.7	50.9	6.5	2.8	1.240	0.020	-4.00	1.78
10.25	10.75	55	10.48	0.21	0.05	0.12	0.03	34.2	1.6	226.3	63.3	6.9	2.9	1.234	0.022	-2.85	1.46
10.75	11.25	47	11.01	0.21	0.05	0.13	0.03	34.2	1.4	204.5	60.4	8.0	2.3	1.226	0.020	-3.16	1.85
11.25	11.75	37	11.50	0.19	0.04	0.14	0.02	34.1	1.6	206.6	61.3	8.4	2.4	1.220	0.019	-2.25	1.49
11.75	12.25	37	11.97	0.20	0.05	0.14	0.03	34.3	1.4	214.8	72.3	7.9	2.8	1.224	0.022	-1.85	1.21
12.25	12.75	29	12.48	0.20	0.03	0.14	0.02	34.3	1.6	221.0	63.1	9.0	2.6	1.220	0.024	-2.22	1.10
12.75	13.25	27	12.92	0.19	0.04	0.14	0.03	34.8	1.0	193.1	59.8	9.9	1.5	1.211	0.018	-2.41	1.04
13.25	13.75	21	13.47	0.22	0.03	0.13	0.03	34.9	0.9	208.7	65.2	9.6	2.2	1.215	0.022	-2.17	1.06
13.75	14.25	13	13.98	0.20	0.03	0.13	0.03	34.8	1.0	195.4	65.1	9.4	2.4	1.214	0.024	-2.53	1.09
14.25	14.75	6	14.58	0.20	0.02	0.13	0.01	34.8	0.8	214.4	59.8	10.1	1.4	1.211	0.020	-2.18	0.84
14.75	15.25	11	15.02	0.19	0.03	0.13	0.02	34.8	1.5	256.4	57.3	8.8	2.6	1.222	0.021	-1.59	1.14
15.25	15.75	5	15.40	0.18	0.02	0.13	0.02	35.0	0.0	226.5	64.9	9.2	2.5	1.218	0.025	-2.10	1.49
15.75	16.25	5	16.02	0.18	0.06	0.11	0.01	35.0	0.7	207.4	48.7	10.2	0.8	1.207	0.015	-2.36	0.79

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 16,000 professionals are dedicated to helping our customers make the world safer, smarter and greener.