Calibration of Whirlwind

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Project No.: VC14424
Report No.: PP17048.A0
Report Date: 2017-09-28

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Project No.:	VC14424
Report No.:	PP17048.A0
Date of Report:	2017-09-28
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Revision History

Revision No.	Date	Status	Amendment
A0	2017-09-28	Final Report	

Note: The last revision replaces all previous versions of the report.

Contents

This report covers 39 pages.

1 Executive Summary

A wind LiDAR (LIght Detection And Ranging) of type Whirlwind by the manufacturer OpticSense GmbH was calibrated on behalf of the manufacturer at the remote sensing test station of Deutsche WindGuard Consulting GmbH (DWG) at Georgsfeld in Lower Saxony, Germany. The radial wind speed measured by the instrument was calibrated against a met mast equipped with traceably calibrated cup anemometers and wind vanes.

The LiDAR was mounted on a container 350 m distance of the mast and targeting the 60 m measurement height of the met mast resulting in a measurement distance of 354 m and a tilt of approx. 9°. The impact of the tilted geometry was fully included in the uncertainty budget.

The calibration was performed by projecting the cup anemometer wind speed into the line-of-sight of the beam of the LiDAR.

Following the measurements the manufacturer enhanced his post processing software based on preliminary evaluations made by DWG. Mast data was not available to the manufacturer. This report evaluated the final submitted data set.

The calibration was based on rejecting LiDAR data with a signal-to-noise ratio below 20 before calculating 10-minute statistics. Only 10-minute intervals with at least 480 valid values were used in the calibration. The wind direction was only allowed to deviate by ±40° from the horizontal beam direction. The calibration is limited to wind speeds above 4 m/s.

The calibration resulted in the following results:

- A mean deviation to the met mast based radial wind speeds of -2.1 % (-0.12 m/s) and a standard deviation of deviations of 3.4 % (0.18 m/s) was observed.
- At radial wind speeds between 4 m/s and 6 m/s deviates from linearity. At 4 m/s and 6 m/s the instrument overestimates, while at 5 m/s it systematically underestimates the wind speed.
- A correlation coefficient of R^2=0.996 was observed, which is moderate for a line-of-sight calibration.
- Bin wise deviations on 0.5 m/s wide wind speed bins vary in wind speed bins above 5.75 m/s between -1.74 % and +0.2 % and lie within the reference uncertainty combined with statistical uncertainty. In the bins between 4.25 m/s and 5.75 m/s the instrument underestimates the wind speed by 5.7 %.
- From the bin wise analysis a combined standard uncertainty (k=1) of the radial wind speed for the application of the instrument between 1.6 % and 6.0 % was derived.

2 Objective

The objective of the measurements presented in this report is the calibration of a nacelle based LiDAR (LIght Detection And Ranging) of type Whirlwind by the manufacturer OpticSense GmbH.

The international vocabulary of metrology (VIM) defines a calibration as an *operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication* [1]. A calibration is therefore a necessary step to relate the output of a measurement instrument to the physical quantity measured.

In the context of the Whirlwind, this translates to the question how to get from the instrument's output (indication) to the values of radial wind speed including the uncertainty thereof.

The radial wind speed measured by the instrument is calibrated against a conventional meteorological met mast equipped with cup anemometers and wind vanes.

3 Calibrated Object

The calibrated object is a prototype LiDAR to be mounted on the nacelle or inside the spinner of a wind turbine. It has a single beam in fixed direction from the instrument. Table 1 summarises the key data of the instrument.

The measurement data of the LiDAR was collected from the instrument by the manufacturer. Radial wind speeds were derived from backscatter data stored by the instrument in post processing by the manufacturer. Based on intermittent data evaluations the manufacturer enhanced his post processing software, mast data was not provided to the manufacturer. Enhancements known to DWG are

- Definition of a measure of signal quality.
- Detection of a software based problem, where for a measurement the range gates were wrongly allocated. Correction of this gate mismatch was indicated by a status signal.

This report covers the last delivered dataset with filename `so12_aurich_24_01_wind_intensity_time_nNaN_on.txt`, which was submitted on 2016-09-06. The submitted dataset contained the following data of Gate 24:

- Status if range gate mismatch was detected
- Radial wind speed (RWS)
- Signal-to-noise ratio (SNR)
- Date
- Time

The date information was affected by a software bug that had the consequence that the change of day happened several minutes after midnight. This could be corrected by DWG before further evaluation of the data.

The LiDAR data is given in irregular time steps with approximate 1.02 s between successive data points.

The manufacturer did not specify an acceptance criterion on the signal quality. To derive such a criterion, mast data was interpolated to the time steps as given in the LiDAR data and projected into the line-of-sight of the beam (see chapter 6.1.2). The comparison of radial wind speeds of LiDAR and mast is shown in Figure 1. A significantly higher deviation between mast and LiDAR can be observed with a SNR below 20.

Property	Value
Manufacturer	OpticSense GmbH
Type	Whirlwind
Serial Number	Not Available
Synchronisation	Not on regular basis
Measurement Ranges	Gate Centres at $d = (n \cdot 15\ \text{m}) - 6.45\ \text{m}$, n=3,...,37
Full Probe Volume Length	30 m
Full Opening Angle	Not Applicable
Number of Beams	1
Software Version	Not given, post processing by manufacturer

Table 1 Key features of the calibrated RSD.

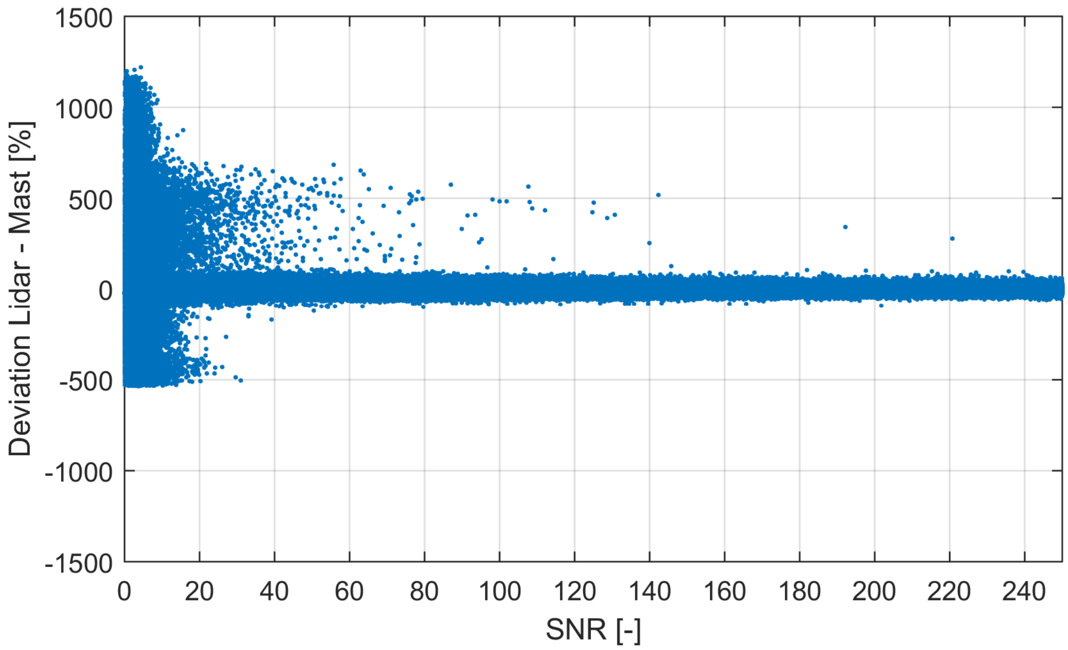

Figure 1 Deviation between radial wind speed of the RSD and the projected mast wind speed as function of the signal to noise ratio as given in the data set. Mast data was linearly interpolated to the irregular time steps of the LiDAR.

4 Measurement Site and Met Mast

The measurement is located near the village Georgsfeld, approximately 5 km north-west of Aurich, in the region Eastern Frisia, which is in the north west of the German state of Lower Saxony. The distance to the North Sea is approximately 20 km.

The area around the met mast position is characterised by flat terrain. The terrain height at the met mast location is about 6 m above sea level. The best fit of a plane to the terrain up to 5km distance going through the bottom of the mast has no significant slope. The maximum deviation of the terrain to this plane is 11 m.

The landscape is characterised by farmland with closed appearance. The land development in the environment mainly consists of small villages, with tree rows along roads and field borders. Noteworthy are the town of Aurich (40 000 inhabitants) 5 km to the South East and a forest 1 km to the North West. In a distance 70 m to the mast an earth dike with low trees runs from South West to North East.

The coordinates of the met mast the neighbouring turbines and the RSD can be found in Table 2. A map of the measurement site is given in Figure 2. Photos of the met mast and a panoramic view of the site are shown in Figure 3 and Figure 4.

The met mast is a 130 m high lattice tower supported by guy wires (see Figure 3). The met mast fulfils the requirements of IEC 61400-12-1, Ed. 2 [2]. It has seven measurement levels, approximately every 20 m of height. At each level, at least two anemometers (cup or sonic) and a wind vane are installed. The mast is also equipped with four temperature, two humidity and two pressure sensors at different heights to measure environmental conditions.

The met mast is an essential part of DWG's accreditation according to DIN EN ISO/IEC 17025:2005 as calibration laboratory for ground based remote sensing devices (RSD). In the calibration described in this report, only the measurement height at approximately 60 m is of relevance and only that will be described here in detail. A full description of the met mast is given in reference [3].

A cup anemometer is installed at 60.4 m on a boom facing in direction 225°, a 3D sonic anemometer is mounted at 60.5 m on a boom facing in direction 45°. At 58.2 m, a wind vane is mounted on a boom in direction 225°.

The cup anemometers are all of type Thies First Class Advanced*.* This type of anemometer was classified as class 0.9A and class 3.0B anemometer according to reference [4]. The terrain is consistent with the limits of Annex A of IEC 61400-12-1 [2], therefore class 0.9A can be applied for the cup anemometers.

The ultrasonic anemometer was of type Thies Ultrasonic 3D. This type of anemometer has not been classified according to references [2] or [4].

All anemometers were calibrated before the measurements by Deutsche WindGuard Wind Tunnel Services according to terms of IEC 61400-12-1, Ed. 1 [4], MEASNET [5] and DKD (for calibration certificates see appendix 10.1).

The wind vanes are of type Thies First Class 4.3150.00.141. Northing of the vanes was performed via compass during installation according to Deutsche WindGuard's quality management system. The angle of magnetic declination of 1.55°E has been taken into account for the data evaluation.

The wind vane and the wind direction of the sonic anemometer were calibrated by Deutsche WindGuard Wind Tunnel Services (see appendix 10.1)

The data acquisition system of the met mast is a data logger of type Campbell 1000. The signals from the sensors are sampled with a sampling rate of 1 Hz. Stored are both the 1 Hz sampled data and 10-minute statistics. The clock of the data logger is synchronised to UTC+1 via the NTP protocol.

Object	Position		Rotor diameter	Distance from	Direction from	Met Mast in Wake		RSD in Wake	
	X	Y	D	met mast	met mast	from	to	from	to
	[m]	[m]	[m]	[m]	[deg]	[deg]	[deg]	[deg]	[deg]
Met mast	2595735	5931491	---	---	---	**29**	61	---	---
RSD	2596085	5931473	---	350	93	---	---	---	---
E-126 E2	2596091	5931472	127	357	93	58	128	57	**129**
E-126-1	2595429	5930971	127	603	210	183	237	**182**	239
E-126-2	2594786	5930479	127	1387	223	205	242	204	**242**
Valid Measurement Sectors:			**242° - 29°** **129° - 182°**						

Table 2 Position of met mast, RSD and neighbouring turbines. All coordinates are given in Gauß-Krüger coordinates (Bessel-Ellipsoid). The exclusion sectors of the RSD are based on the two end points of the two 30 m long probe volumes. The position was derived from the measurement of distance and the verification of direction presented in section 7.1.

Figure 2: Map of the measurement site. The met mast is depicted by the black square and the black circles show the anchor points of the guy wires. The position of the RSD is marked by the circle with black dot in the centre. The direction of the beam is indicated by the dashed line. The RSD was located 350 m East of the met mast. The maximum measurement sectors for the test are 242° to 29° and 129° to 182°.

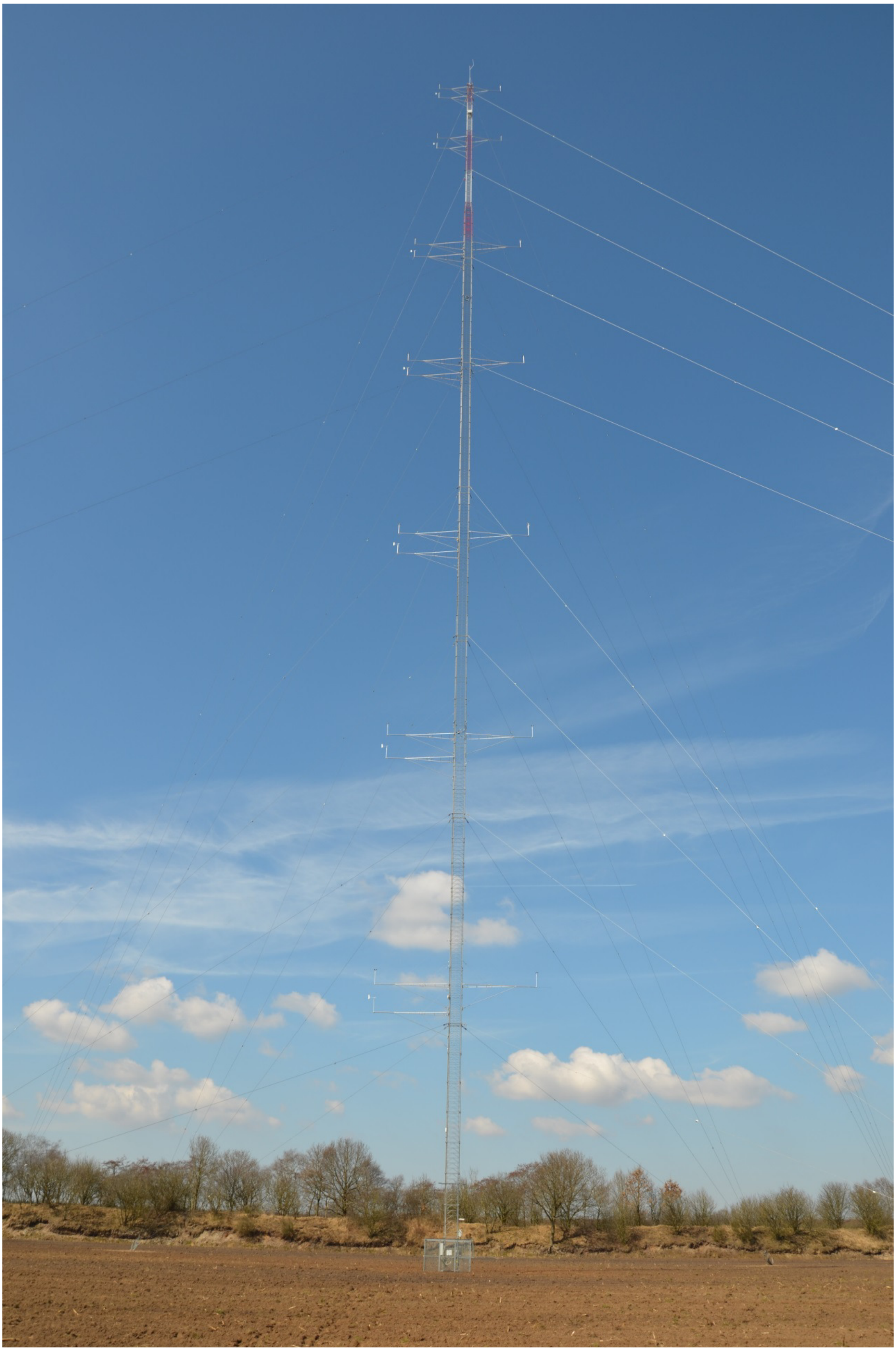
Figure 3: Photo of the 130 m high met mast near Georgsfeld, looking in direction northwest.

N=0° E=90°

E=90° S=180°

Figure 4: Panoramic view of the measurement site taken 13 m from the bottom of the met mast (continued).

S=180° W=270°

W=270° N=360°

Figure 4: Panoramic view of the measurement site taken 13 m from the bottom of the met mast (end).

5 Measurement Setup

The LiDAR was installed together with the manufacturer on 2015-30-01 on a container positioned at the base of turbine E126 E2, approx. 350 m east of the met mast (see Figure 2, Figure 5 and Figure 6). The reference cup anemometer is oriented on a boom at 6.05 m from the centre of the mast. The total horizontal distance between LiDAR and anemometer was measured by laser distance meter to be (350.0±0.5) m. The height difference between mast foundation and LiDAR was verified by the use of tape measure and a rotating laser which can transfer the height levels horizontally over the measurement site. Mast measurement heights were measured by a surveillance engineer. The total height difference between cup anemometer and the LiDAR was (56.4±0.1) m. Using these values a line of sight distance is (354.5±0.5) m and an angle of (9.15±0.02)° to the horizontal plane are calculated.

The manufacturer of the LiDAR determined after the measurements, that the centres of the range gates are given by

$$d_n = n \cdot 15\,m - 6.45\,m\,, \qquad n = 1, \dots, 37 \tag{1}$$

Figure 5 shows the measurement geometry of the LiDAR and the positions of the gates.

The pointing of the LiDAR was performed in the following way: A corner reflector was mounted on the mast at the height of the cup anemometer. A pointing laser emitting visible light was mounted by the manufacturer onto the LiDAR with an offset in such way that the measurement beam passes close to the cup anemometer. The alignment of pointing laser and measurement laser was not tested by DWG.

The system clock was set by the manufacturer at installation. No regular synchronisation with a time reference like GPS or NTP was performed. On some site visits the manufacturer noted differences of the system clock to the time given by a GPS device.

Shortly after the installation of the instrument, the sensors on the met mast were exchanged with newly calibrated sensors. Measurement data only after the change was used. Table 3 summarises the important events during the measurement campaign.

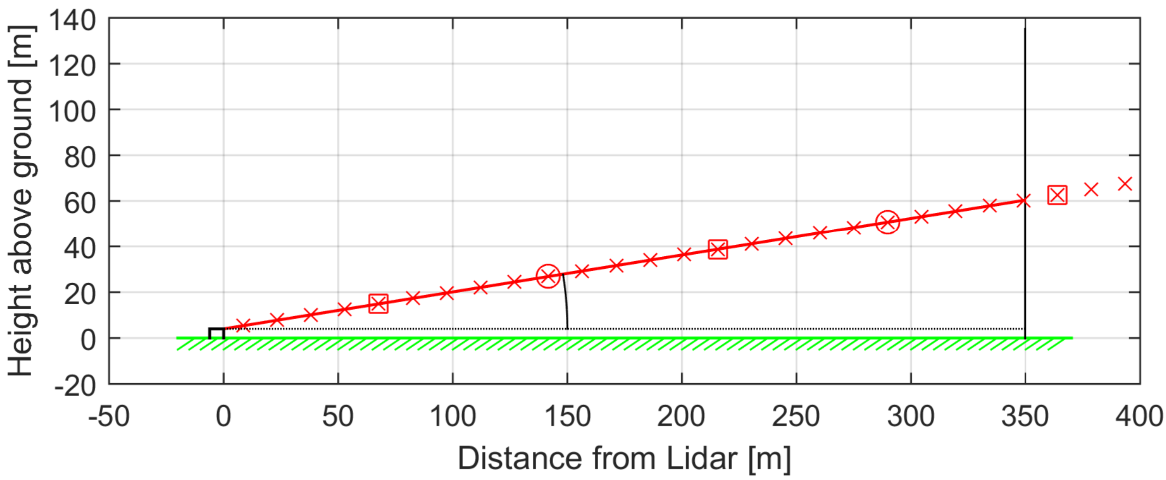

Figure 5 Measurement geometry of the LiDAR. The LiDAR (origin of red line) is positioned on the container (black square). The red crosses mark the gate centres determined with equation (1), red squares mark the gates 5, 15 and 25 and the red circles mark the gates 10 and 20. Gate 24 at the mast is the one evaluated in this report.

Figure 6: The RSD under test installed next to the turbine E126 E2 pointing at the 60 m measurement height of the met mast. The left picture shows the view from the mast towards the instrument; the left shows the mounting of the instrument on container.

From	To	Event
	2015-01-30	Installation
2015-02-03	2015-02-05	Exchange of Sensors on met mast
2015-02-05 15:00		**Start of measurements**
2015-02-13		Observed time difference LiDAR to GPS: +17 s
2015-02-26		Observed time difference LiDAR to GPS: +4 s
2015-03-19		Observed time difference LiDAR to GPS: +5 s
	2015-05-06	**End of measurement**
	2015-05-12	Dismantlement of LiDAR by manufacturer
	2016-09-16	Delivery of Final Dataset

Table 3 Logbook of the measurement period

6 Procedure

6.1 Theoretical Formulation

6.1.1 Vector Averaging of Mast Data

The industry standard for averaging is a 10 minute time interval. Usually wind speed as measured by a cup anemometer is directly averaged. This results in a scalar averaged wind speed. For the projection used in section 6.1.2 the vector nature of the wind vector has to be considered. A vector average of mast data is achieved in the following: way:

For every measurement sample define vector components by combining the output of the cup anemometer with that of a wind vane at approximately the same height:

$$U_{mast} = V_{cup} \cos(\theta_{vane}) \tag{2}$$

$$V_{mast} = V_{cup} \sin(\theta_{vane}) \tag{3}$$

Average these components and derive the vector average for the mast

$$\langle V_h \rangle_{vec} = \sqrt{\langle U_{mast} \rangle^2 + \langle V_{mast} \rangle^2} \tag{4}$$

$$\langle \theta_N \rangle_{vec} = \text{atan2}(\langle U_{mast} \rangle; \langle V_{mast} \rangle) \tag{5}$$

The subscript N denotes that the direction is with regard to geographic north. Please note that $\langle \theta_N \rangle_{vec}$ in equation (5) is different from 10-minute wind directions usually given by logger software which does not consider the wind speed.

Vector averaging has the advantage that projecting the wind vector to another coordinate system and the averaging process are interchangeable as long as the angles between coordinate systems are approximately constant during a 10 minute interval. One example for this kind of coordinate transformation is the projection of the wind vector measured on the mast to the line of sight (LOS) of the beam directions (see chapter 6.1.2).

The topic of scalar vs vector averaging is important to consider for LiDARs with more than one beam. This is not the case for the one beam LiDAR under test here in a fixed measurement position. Dependent on the application of the LiDAR, this topic may become important.

6.1.2 Projection of Mast Data on Line-Of-Sight

The beam of the instrument is oriented close to the reference cup anemometer. The wind speed measured by the cup anemometer is projected to the line of sight of the LiDAR beam in question. Thus a reference radial wind speed is constructed. Based on vector averages $\langle V_h \rangle_{vec}$ and $\langle \theta_N \rangle_{vec}$ according to equations (4), (5) the projected wind speed of the cup is defined as follows:

$$V_{i,ref} = \langle V_h \rangle_{vec} \cdot \cos(\psi) \cdot \cos(\langle \theta_N \rangle_{vec} - \theta_{LOS}) \tag{6}$$

Here, ψ is the vertical angle between beam and the horizontal plane and θ_{LOS} is the horizontal line of sight direction. Strictly speaking this equation should be applied before averaging. However, under the assumption that the beam tilt from the horizontal ψ and the horizontal line-of-sight direction θ_{LOS} are constant over a 10 minute interval, equation (6) holds on the vector averaged wind speed and wind direction. Also neglected is the vertical wind speed W. It could be added by the term

$$\langle W \rangle \cdot \sin(\psi) \tag{7}$$

but this term is usually insignificant compared to the horizontal wind speed, especially with small tilt angles ψ.

6.2 Correction of Mast Effects

At wind directions, where the boom mounted anemometers are located downwind of the met mast, the anemometers are strongly influenced by the wake of the met mast. Wake effects on the anemometer by the met mast are filtered out by the directional filtering.

Furthermore, a small decrease of wind speeds caused by the mast blockage occurs at the boom mounted anemometers at maximum at the wind direction opposite to the boom orientation. The blockage effect caused by the met mast was corrected by assuming that the effect vanishes at wind directions about perpendicular to the boom orientation. For the directions between the maximum blockage and zero blockage a linear increase of the flow effect caused by the mast was assumed. The flow distortion of the mast causes a small flow acceleration at the position of the boom mounted anemometers if the angle between the wind direction and the boom orientation is larger than 90° and if the anemometers are not positioned in the wake of the mast. This flow acceleration effect is assumed to be at its maximum at the border of the wake sector. The maximum flow acceleration effect is assumed to be of equal size than the maximum blockage effect. For wind directions between the direction of maximum flow acceleration and wind directions perpendicular to the boom orientation a linear decrease of the flow acceleration effect caused by the mast was assumed.

The applied correction factors are listed in appendix 10.1.4.

6.3 Verification of Horizontal Centreline Direction θ_{LOC}

The relative horizontal wind direction $\langle\theta\rangle_{vec} = \langle\theta_N\rangle_{vec} - \theta_{LOC}$ is essential in the construction of the reference radial wind speed V_{ref} in equation (6). The orientation of the wind vane with regard to north has only a moderate accuracy in the order of 1° to 2°. This can lead to significant errors in the reference radial wind speed V_{ref}. To get a better estimation of θ_{LOC}, DTU proposed the following two step procedure [6] for a LOS calibration:

1. Determine preliminary value for θ_{LOS} by fitting a cosine function.
    a. Normalise the radial wind speed as measured by the LiDAR $V_{i,meas}$ with the horizontal wind speed and the tilt angle of the beam:

    $$V_{i,norm} = \frac{\langle V_{meas} \rangle}{\langle V_h \rangle_{vec} \cdot \cos(\psi)} \tag{8}$$

    b. Fit a cosine function to this value:

    $$f_{fit} = a_1 \cdot \cos(\langle\theta_N\rangle_{vec} - \theta_0) + a_2 \tag{9}$$

    The parameters a_1 and a_2 should be approx. 1 and 0, respectively. θ_0 gives a preliminary estimation of θ_{LOS}.
2. Get a more precise estimation of θ_{LOS} by analysing the linear relation between measured and projected radial wind speed.

a. Define the projection angle θ_{proj} in a range of ±1° around the first estimate θ_0 with a step size of 0.1°.
b. For each θ_{proj} perform a linear ordinary least squares regression between the measured radial wind speed $\langle V_{meas} \rangle$ and the cup anemometer projected with

$$V_{ref} = \langle V_h \rangle_{vec} \cdot \cos(\psi) \cdot \cos(\langle \theta_N \rangle_{vec} - \theta_{LOS}) \qquad (10)$$

assuming θ_{proj} as value for θ_{LOS}.
c. The sum of squared residuals SS_{res} is plotted as a function of θ_{proj}.
d. Fit a 2nd order polynomial to the function $SS_{res}\ (\theta_{proj})$
e. The minimum of the polynomial is the best estimate for θ_{LOS}.

6.4 Data Processing

The LiDAR data was processed in the following way:

1. The erroneous date stamp was corrected to derive the correct time information
2. Each sample with SNR below 20 was discarded
3. The data was separated into 10-minute intervals and average, maximum, minimum and standard deviation was calculated for each interval

The mast data was processed in the following way:

1. Based on the 1 Hz data the vector components were calculated according to equations (2) and (3).
2. The data was separated into 10-minute intervals and average, maximum, minimum and standard deviation of all channels was calculated for each interval.
3. Cup anemometer data and the corresponding vector components were corrected for blockage and acceleration effects according to section 6.2 and appendix 10.1.4.
4. The line-of-sight wind speed was calculated from the vector averaged wind speed by equation (6).

Then the data sets were combined to a common data set by matching the time stamps. The resulting data set was filtered to the following rules:

- *Valid Reference Measurement*: Any 10-minute interval where the reference sensors show signs of degradation (like icing) or failure is rejected.
- *Measurement Sector*: All wind directions where the reference sensors or probe volumes are in the wake of wind turbines or significant obstacles are excluded, see Table 2.
- *Relative Wind Direction*: The LiDAR will be pointing directly into the wind when applied on top of a nacelle during the power curve measurements. Therefore the calibration is performed with relative wind directions $|\langle \theta_N \rangle_{vec} - \theta_{LOC}| \leq 40°$.
- *Wind Speed*: The horizontal wind speed as measured by the cup anemometer should be greater than 4 m/s due to the following reasons:
    - The wind tunnel calibration of the cup anemometer has been performed in the wind speed range 4-16 m/s according to MEASNET [5]. Despite the limitation of the wind tunnel calibrations to 16 m/s, the wind speed was

not limited for testing the RSD in order to gain indications for the accuracy at higher wind speeds.
  - At low wind speeds, the cup anemometer measurements are linked to higher uncertainties.
  - Lower wind speeds are less relevant as hardly any energy is produced by wind turbines below 4 m/s.
- *Availability within 10-minute interval*: All 10-minute intervals with less than 480 scans were rejected.

7 Results

7.1 Verification of Centre Line Direction

Figure 7 and Figure 8 show the results of the procedure described in section 6.2. The centreline direction results in **θ_{LOC} = 273.0°±0.1°**. The uncertainty estimate of 0.1° is taken from [6].

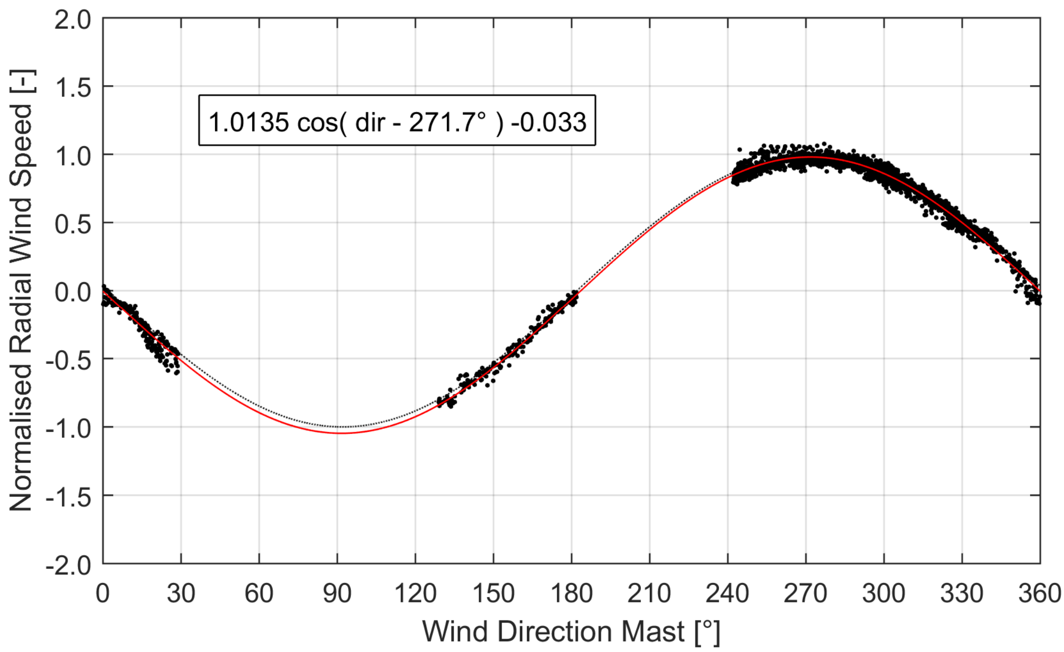

Figure 7 Normalised radial wind speed as function of wind direction. Black dots are 10-minute values, the red line is the best fit cosine function given by the formula in the inset. The dotted line denote the expected cosine function of the beam.

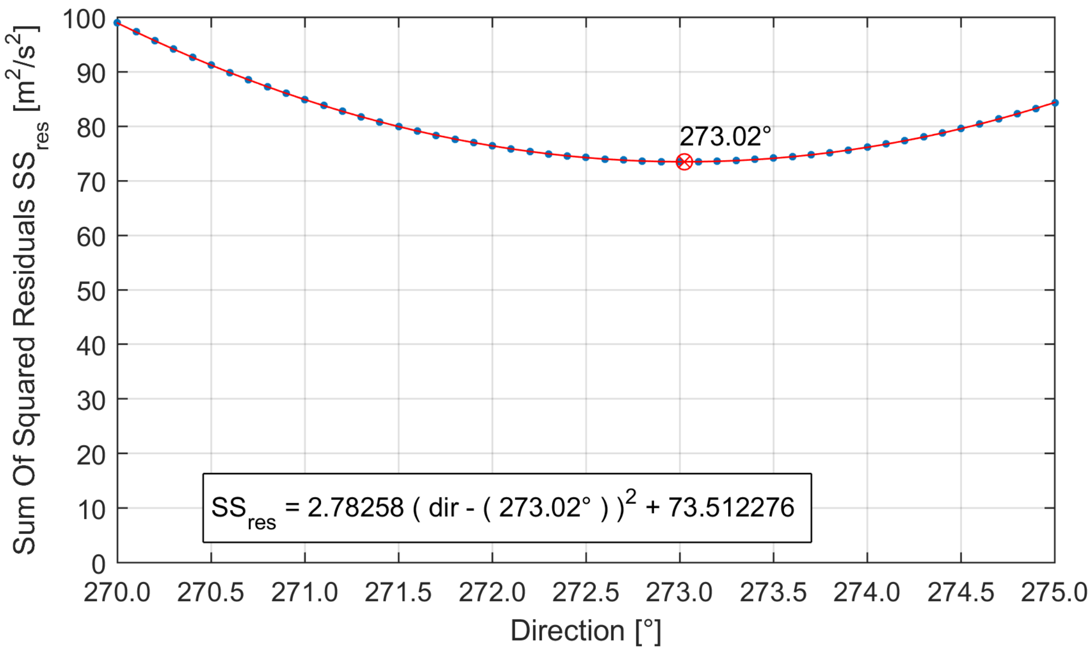

Figure 8 Sum of Squares of a linear regression between measured and projected radial wind speed. The Formula gives the best fit parabola to the blue dots (red line). The red cross in a circle marks the minimum of the parabola.

7.2 Uncorrected Wind Speed Calibration Results

The radial wind speed as measured by the instrument is compared to the projected wind speed of the met mast. Data filtering according to chapter 6.4 was performed, resulting in 1612 data sets available for the evaluation. IEC 61400-12-1, Ed. 2 [2] requires 1080 data sets or 180 hours of data covering all wind speeds between 4 m/s and 16 m/s. The highest full wind speed bin was at 19.4 m/s. Therefore the database is complete.

Figure 9 shows a scatter plot of the wind speed of the RSD as function of the projected wind speed of the cup anemometer. On average the LiDAR underestimates the wind speed with -2.1 % (-0.12 m/s). A fair amount of scatter is present with the standard deviation of deviations being 3.4 % (0.18 m/s). A systematic under estimation of wind speed is present at about 5 m/s. A correlation coefficient of R^2=0.996 was observed, which is moderate for a line-of-sight calibration.

In accordance to IEC 61400-12-1, Ed. 2 [2] further evaluations should be based on the bin averages. These are summarised in Figure 10 and Table 4. For wind speed bins above 5.75 m/s the deviations are between -1.74 % and +0.2 % and lie within the reference uncertainty combined with statistical uncertainty. In the bins between 4.25 m/s and 5.75 m/s the instrument underestimates the wind speed by 5.7 %. This is significantly outside the calibration uncertainty given by the black lines in Figure 10.

From these results a total uncertainty per wind speed bin, which has to be applied during measurements with this instrument, is derived by cumulating every uncertainty component given in chapter 8 including the deviations observed between anemometer and mast. This is given in the two rightmost columns of Table 4 and ranges between 1.6 % and 6.0 %.

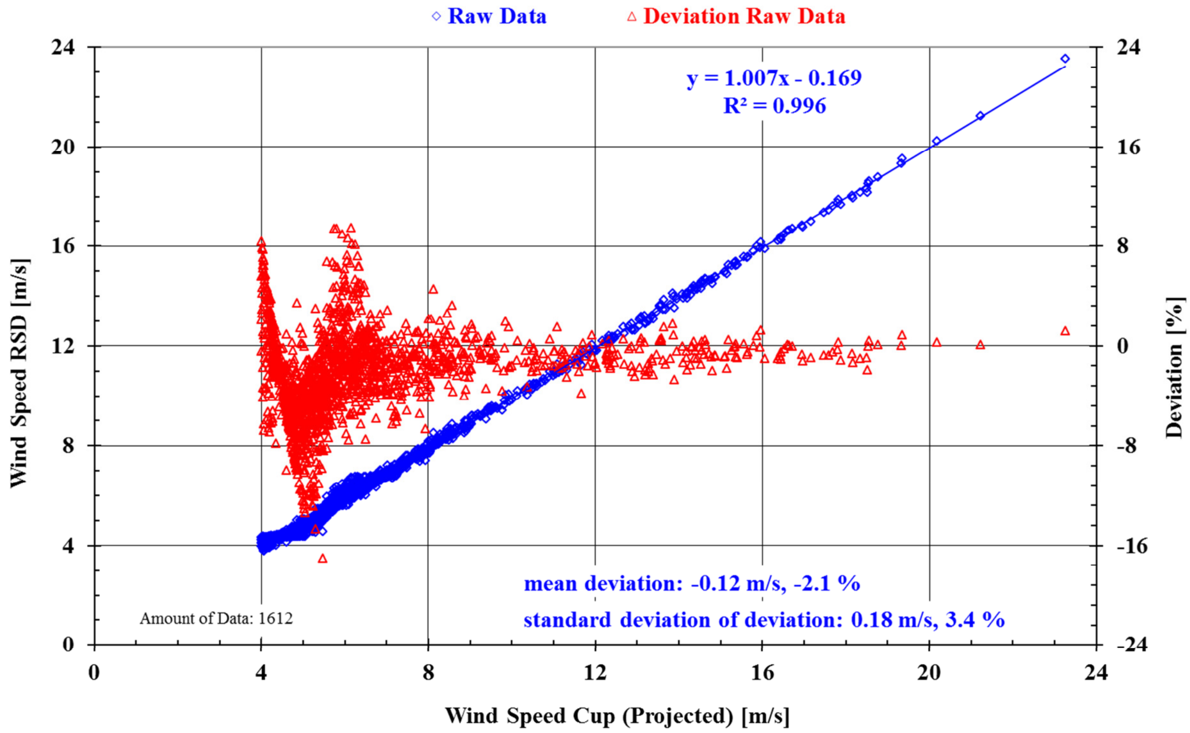

Figure 9 Scatter Plot of resulting wind speed derived from the radial wind speeds against the projected wind speed of the cup anemometer (blue) and the deviation between both values in percent of the projected cup anemometer wind speed (red). Each point represents a 10-minute average.

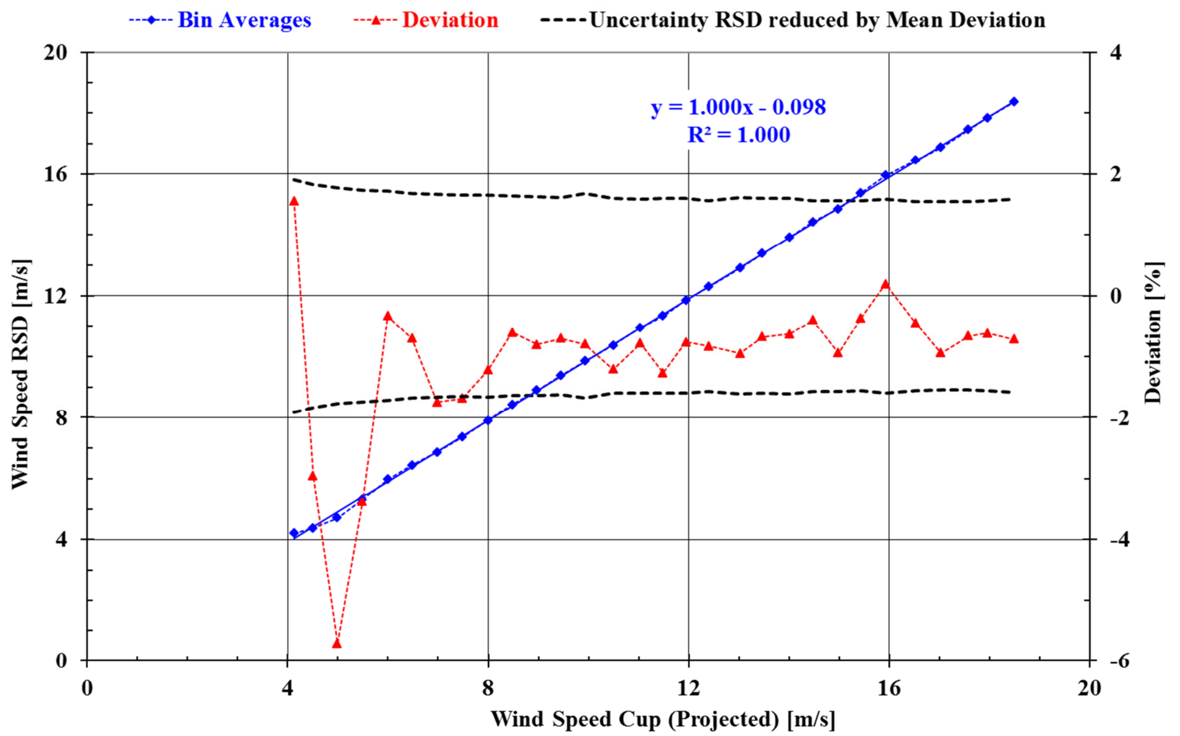

Figure 10 Bin analysis of 10-minute averages of resulting wind speed derived from the radial wind speeds v(RSD) against the projected wind speed of the cup anemometer v(Reference). Only data within 10° of the centreline direction of the LiDAR is used. A positive sign of the deviations v(RSD)-v(Reference) represents overestimation of wind speed by the LiDAR.

v (Reference)	v (RSD)	number of data sets	v (RSD) max	v (RSD) min	v (RSD) std	v (RSD) std/sqrt(n)	v (RSD) - v (Reference)	uncertainty (k=1) (calibration)		uncertainty (k=1) v (RSD)	
[m/s]	[m/s]	[-]	[m/s]	[m/s]	[m/s]	[m/s]	[m/s]	[%]	[m/s]	[%]	[m/s]
4.130	4.194	95	4.405	3.794	0.153	0.016	0.064	1.9	0.08	2.5	0.10
4.506	4.372	241	4.746	4.020	0.093	0.006	-0.133	1.8	0.08	3.5	0.16
4.993	4.708	252	5.142	4.358	0.208	0.013	-0.285	1.8	0.09	6.0	0.30
5.489	5.304	245	6.287	4.522	0.274	0.017	-0.185	1.7	0.10	3.8	0.21
5.999	5.979	181	6.754	5.535	0.257	0.019	-0.020	1.7	0.10	1.8	0.11
6.483	6.438	154	6.783	5.978	0.195	0.016	-0.045	1.7	0.11	1.8	0.12
6.982	6.860	78	7.260	6.532	0.153	0.017	-0.122	1.7	0.12	2.4	0.17
7.478	7.352	51	7.786	6.846	0.204	0.029	-0.126	1.7	0.12	2.4	0.18
7.997	7.899	55	8.498	7.376	0.240	0.032	-0.098	1.7	0.13	2.1	0.16
8.482	8.430	38	8.861	8.099	0.166	0.027	-0.051	1.6	0.14	1.7	0.15
8.968	8.896	25	9.263	8.510	0.217	0.043	-0.072	1.6	0.15	1.8	0.16
9.457	9.390	17	9.588	9.063	0.153	0.037	-0.067	1.6	0.15	1.8	0.17
9.933	9.853	10	10.182	9.415	0.229	0.072	-0.079	1.7	0.17	1.9	0.18
10.495	10.368	14	10.545	10.024	0.147	0.039	-0.127	1.6	0.17	2.0	0.21
11.033	10.947	14	11.253	10.622	0.185	0.049	-0.087	1.6	0.18	1.8	0.20
11.487	11.341	13	11.737	11.046	0.206	0.057	-0.146	1.6	0.18	2.0	0.23
11.947	11.855	9	12.189	11.643	0.165	0.055	-0.092	1.6	0.19	1.8	0.21
12.397	12.294	17	12.749	12.137	0.166	0.040	-0.103	1.6	0.19	1.8	0.22
13.023	12.900	12	13.218	12.629	0.206	0.060	-0.123	1.6	0.21	1.9	0.24
13.472	13.381	14	13.855	12.997	0.274	0.073	-0.091	1.6	0.21	1.7	0.23
14.014	13.926	10	14.120	13.522	0.198	0.063	-0.088	1.6	0.22	1.7	0.24
14.479	14.421	15	14.707	14.062	0.181	0.047	-0.058	1.6	0.23	1.6	0.23
14.987	14.846	8	15.264	14.515	0.230	0.081	-0.141	1.6	0.23	1.8	0.27
15.436	15.380	9	15.581	15.218	0.147	0.049	-0.056	1.6	0.24	1.6	0.25
15.926	15.956	5	16.162	15.795	0.137	0.061	0.030	1.6	0.25	1.6	0.25
16.523	16.450	8	16.713	16.205	0.193	0.068	-0.074	1.6	0.26	1.6	0.27
17.032	16.872	3	17.003	16.768	0.120	0.069	-0.160	1.5	0.26	1.8	0.31
17.581	17.464	3	17.597	17.342	0.128	0.074	-0.117	1.5	0.27	1.7	0.30
17.962	17.850	5	18.038	17.676	0.143	0.064	-0.111	1.6	0.28	1.7	0.30
18.490	18.358	5	18.621	18.156	0.214	0.096	-0.132	1.6	0.29	1.7	0.32

Table 4 Bin analysis of 10-minute averages of resulting wind speed derived from the radial wind speeds v(RSD) against the projected wind speed of the cup anemometer v(Reference). Only data within 10° of the centreline direction of the LiDAR is used. A positive sign of the deviations v(RSD)-v(Reference) represents overestimation of wind speed by the LiDAR. Uncertainties are given as standard uncertainty (k=1)

7.3 Environmental Conditions

The results derived during a calibration are valid for the conditions present at the site during the measurements. These conditions are summarised in Table 5. If the instrument is applied under different conditions than these, an evaluation of the impact on the instrument's performance should be made. With cup anemometers and ground based LiDARs this is covered by classifications according to Annexes I and L.2 of [2], respectively. At the moment of writing, DWG is not aware that such an analysis exists for the RSD.

It has been observed a couple of times by DWG that the uncertainty due to the sensitivity of ground based LiDARs is in the range of the standard deviation of deviations of the LiDAR measurements and reference measurements observed at calibrations. This measure is very similar to the standard deviation of the LiDAR measurements per wind speed bin as included in calibration reports. Hence, the standard deviation of the LiDAR measurements per wind speed bin as reported in Table 4 could be assumed to represent the standard uncertainty due to the sensitivity of the LiDAR measurements on environmental variables, as long as no special investigation of the sensitivities is available.

Height 60.4 m	Depen-dency [-]	Shear Exponent 82.2m-60.4m		Turbulence Intensity TI		Number of Scans per 10-min Interval		Wind Direction		Air Temperature T at 131 m		T Difference 131m-18m		Air Density		Flow Inclination Angle	
Bin-No.	Windspeed [m/s]	avg [-]	std [-]	avg [-]	std [-]	avg [-]	std [-]	avg [deg]	std [deg]	avg [°C]	std [°C]	avg [°C]	std [°C]	avg [kg/m3]	std [kg/m3]	avg [deg]	std [deg]
9	4.13	0.39	0.22	0.114	0.060	579	24	-1.5	23.4	4.6	2.3	-0.50	0.96	1.258	0.016	-0.32	0.95
10	4.51	0.41	0.20	0.109	0.059	579	23	0.6	25.8	4.2	1.9	-0.41	0.96	1.261	0.015	-0.41	0.80
11	4.99	0.38	0.19	0.116	0.055	579	22	-4.0	25.9	4.8	2.5	-0.45	0.91	1.260	0.017	-0.20	0.99
12	5.49	0.35	0.20	0.119	0.068	580	21	4.7	25.7	4.7	2.2	-0.24	1.23	1.262	0.016	-0.37	0.81
13	6.00	0.35	0.17	0.129	0.056	578	26	5.4	25.4	4.7	2.0	-0.51	1.00	1.259	0.016	-0.48	0.80
14	6.48	0.31	0.15	0.147	0.050	576	27	3.9	27.2	4.7	2.3	-0.77	0.80	1.256	0.016	-0.48	0.76
15	6.98	0.26	0.13	0.150	0.052	581	20	4.2	24.4	4.9	2.2	-0.91	0.63	1.253	0.015	-0.27	0.83
16	7.48	0.20	0.11	0.164	0.034	574	26	4.7	22.7	5.0	2.4	-1.19	0.28	1.250	0.015	-0.44	0.83
17	8.00	0.22	0.11	0.149	0.033	566	32	-0.3	18.9	5.6	2.8	-1.16	0.31	1.247	0.015	-0.36	1.02
18	8.48	0.23	0.10	0.157	0.029	565	30	-0.6	18.8	4.8	2.3	-1.07	0.29	1.244	0.013	-0.21	0.67
19	8.97	0.24	0.07	0.168	0.041	561	35	7.4	18.7	4.5	1.9	-1.14	0.29	1.244	0.013	-0.26	1.13
20	9.46	0.18	0.07	0.175	0.036	563	36	6.6	17.7	4.7	1.8	-1.32	0.21	1.242	0.011	-0.55	1.04
21	9.93	0.19	0.04	0.175	0.026	567	32	6.9	17.6	3.9	0.5	-1.25	0.18	1.244	0.008	-0.14	0.67
22	10.49	0.16	0.05	0.177	0.028	561	41	10.3	16.7	4.3	0.9	-1.38	0.14	1.240	0.009	-0.57	1.20
23	11.03	0.18	0.05	0.169	0.021	579	23	6.6	17.3	4.2	0.5	-1.35	0.16	1.239	0.007	-0.15	0.80
24	11.49	0.16	0.03	0.170	0.034	582	27	7.3	12.4	4.1	0.5	-1.40	0.14	1.241	0.007	-0.42	0.94
25	11.95	0.14	0.02	0.155	0.033	571	24	5.2	13.1	4.0	0.4	-1.42	0.13	1.240	0.008	-0.20	0.47
26	12.40	0.16	0.04	0.180	0.024	572	30	10.9	10.6	4.6	0.5	-1.46	0.12	1.237	0.008	-0.01	0.68
27	13.02	0.17	0.05	0.174	0.021	582	23	7.3	14.2	4.6	0.5	-1.42	0.15	1.235	0.009	-0.27	0.90
28	13.47	0.14	0.05	0.165	0.027	575	32	4.2	14.0	4.7	0.5	-1.41	0.17	1.236	0.011	-0.02	0.76
29	14.01	0.17	0.07	0.171	0.026	573	30	3.5	13.3	4.9	0.7	-1.31	0.23	1.235	0.018	-0.09	0.61
30	14.48	0.15	0.05	0.151	0.023	579	22	6.2	13.6	4.6	0.4	-1.43	0.12	1.236	0.011	-0.69	0.55
31	14.99	0.15	0.04	0.162	0.025	586	10	0.1	11.1	5.6	2.0	-1.25	0.21	1.228	0.015	-0.06	0.63
32	15.44	0.19	0.04	0.158	0.023	585	11	4.0	10.8	5.9	1.0	-1.19	0.21	1.213	0.016	-0.11	0.62
33	15.93	0.17	0.05	0.189	0.023	583	15	8.0	9.7	6.3	1.6	-1.23	0.12	1.220	0.013	0.04	0.37
34	16.52	0.16	0.02	0.148	0.025	582	20	-3.2	9.8	6.2	0.7	-1.15	0.09	1.204	0.009	0.05	0.38
35	17.03	0.15	0.04	0.144	0.009	590	0	-9.3	1.2	6.7	0.3	-1.13	0.04	1.199	0.001	0.25	0.18
36	17.58	0.17	0.02	0.149	0.021	563	44	-2.7	6.3	5.7	0.8	-1.23	0.04	1.205	0.004	0.17	0.51
37	17.96	0.16	0.07	0.172	0.025	574	32	2.5	13.2	5.9	0.9	-1.21	0.09	1.209	0.010	0.16	1.09
38	18.49	0.15	0.03	0.164	0.026	563	32	-1.0	8.6	5.8	0.6	-1.19	0.11	1.206	0.007	-0.11	0.68
	Total	0.32	0.18	0.132	0.057	577	25	2.2	24.1	4.7	2.1	-0.66	0.94	1.255	0.018	-0.34	0.86

Table 5 Environmental conditions during the calibration results presented in this report.

8 Measurement Uncertainty

To assess the measurement uncertainty, a comprehensive study of potential uncertainty components has to be performed. The measurement uncertainty calculations are based on [7] and [2] and the work of DTU detailed in [2] and [6]. In the course of this uncertainty assessment a few errors in the reviewed documents were found and corrected.

Table 6 summarises the relevant uncertainty components. In the following subsections each uncertainty component is presented in more detail, the section number corresponding to the number in Table 6.

The uncertainties are with regard to the calibrated radial wind speed.

No.	Source	Unc. Category	Assumed Value
	Reference Anemometer		
1	Calibration Uncertainty	B	From Calibration Certificate
2	Calibration Residuals	B	From Calibration Certificate
3	Operational Characteristics	B	Class 0.9A
4	Mounting	B	0.5%
5	Data Acquisition	B	0.001 m/s
	Relative Wind Direction		
6	Reference Wind Vane	B	From Calibration Certificate
7	Determination of Line of Centre	B	0.1°
	Probe Length of LiDAR		
8	Site Effects	B	Equation (11)
9	Wind Shear	B	Equation (14)
	Height Error		
10	Installation	B	0.5 m
11	Range Error	B	2.2 m
12	Pre-tilt by Wind Load	B	0.02°
13	Variation of Tilt	B	From Measurement
	Projection Error		
14	Installation	B	0.08°
15	Pre-tilt by Wind Load	B	0.02°
16	Flow Inclination	B	From Measurement
	Calibration Measurements		
17	Mean Deviation to Reference	B	From Measurement
18	Statistical Uncertainty	A	From Measurement

Table 6 Uncertainty components to be considered in the calibration. The numbering is in line with the subsection numbering in this section. Uncertainty category A or B of each component is defined according to [7].

8.1.1 Reference Anemometer Calibration Uncertainty

The calibration uncertainty of the reference cup anemometer used for calibrating the LiDAR is given for each wind speed bin covered by the wind tunnel calibrations. The uncertainty is linearly interpolated to the referring bin averages of the measured wind speed finally used for the evaluation in the wind speed range covered by the wind tunnel calibration. For the wind speed range not covered by the wind tunnel calibration, the uncertainty of the nearest wind speed of the wind tunnel calibration shall be applied.

The wind speed measured by the cup anemometer is projected before used as reference wind speed. For each bin of the calibration analysis, the sensitivity of the projected wind speed on the cup anemometer wind speed can be calculated as the ratio of the bin averages of the two wind speeds.

8.1.2 Reference Anemometer Calibration Residuals

The wind tunnel calibration uncertainty of the reference cup anemometer (see section 8.1.1) as given in the calibration report does not include the uncertainty of the regression line due to the residuals of the regression. As the regression line is applied to convert the anemometer output frequency to wind speeds, the uncertainty due to the residuals is relevant.

This uncertainty is first calculated for each bin of the wind tunnel calibration. It is then linearly interpolated to the bin averages of the wind speed measured with the cup anemometer. For wind speeds higher than the highest wind speed covered by the wind tunnel calibration, the residual of the highest covered wind speed bin is scaled by the ratio of the bin average of the wind speed measured at the LiDAR calibration and the highest wind speed covered by the wind tunnel calibration. For wind speeds lower than the lowest wind speed covered by the wind tunnel calibration, it can be assumed that the uncertainty increases linearly with decreasing wind speed from the residual of the lowest covered wind speed bin to the calibration offset of the wind tunnel calibration. As low wind speeds are filtered out, this is not of relevance at this point.

8.1.3 Reference Anemometer Operational Characteristics

The reference anemometer has to be classified according to IEC 61400-12-1, ed.1 [4]. As the terrain at the site is within the limits set in Annex B of both [2] and [4], the Class A of the instrument shall be used, i.e. Class 0.9A for the used anemometer of type Thies First Class Advanced.

8.1.4 Reference Anemometer Mounting Uncertainty

The mounting uncertainty of the reference anemometer includes impacts of deviations from vertical mounting as well as flow disturbances at the anemometer position by the mast and if applicable the horizontal boom. This uncertainty was estimated according to Annex G of [2].

8.1.5 Reference Anemometer Data Acquisition System

The Campbell CR1000 data logger has an accuracy of 1 Hz. Assuming a rectangle distribution and independence between subsequent 1 s sampling periods an uncertainty of 0.001 m/s is derived.

8.1.6 Reference Wind Vane Uncertainty

Due to the procedure of verifying the direction of the line of centre (section 6.2) all systematic measurement uncertainties of the vane that are independent of the wind direction are removed. The wind directional uncertainty of the vane can be derived from the residuals observed during the calibration (see Appendix 10.1.3). Half the range between maximum and minimum residual divided by √3 is taken as the standard uncertainty of the wind vane measurement.

8.1.7 Uncertainty of Line-of-Centre Direction

The origin of relative wind direction measurements θ_{LOC} is determined by maximising the correlation between the measurements of the LiDAR and the met mast (section 6.2). DTU estimates this uncertainty to be 0.1° [6].

8.1.8 Uncertainty due to Flow Distortion along Probe Volume

The probe volume of the Whirlwind has a length of P = 30 m. The wind flow can variate over this length, especially at low calibration heights. The following way was chosen estimating this error:

Assuming a linear wind gradient of 1%/measurement height h along the probe volume estimated from the suggested uncertainty of 2% (3%) for flow distortion in simple terrain power curve tests in case of a distance of the wind turbine and the wind measurement of 2 rotor diameters and 3 rotor diameters according to reference [2], assuming that the rotor diameter is similar to the hub height. The flow variation considering only one half of the probe volume, starting at the one end of the probe volume and ending at the reference met mast, is half the probe length multiplied by the gradient. The weighted flow variation error over half the probe volume is half the total variation over that range. The flow variation error may be considered as being independent between the two halves of the probe volume. Under consideration that both halves of the probe volume are weighted equally the flow variation error over the complete probe volume is the flow variation error over on half of the probe volume divided by √2. For a beam tilted by the angle ψ from the horizontal, this error has to be projected into the line of sight of the beams. In the black box calibration this error propagates through equations (2), (3), and (4) under the assumption of full correlation between the beams.

In summary:

$$u_8 = \frac{1}{\sqrt{2}} \cdot \frac{1}{2} \cdot \frac{P}{2} \cdot \frac{1\%}{h} \cos\psi \tag{11}$$

8.1.9 Uncertainty due to Vertical Wind Shear in a Tilted Probe Volume

When the instrument is installed in a tilted measurement geometry, the probe volume spans a range of heights. In the presence of vertical wind shear the instruments averages over different wind speeds. This leads to a systematic error with regard to the wind speed at the height of the reference instrument. Given an arbitrary wind profile $V(h)$ the error due to the variation of wind speed with height over the probe volume is derived from averaging the deviation from the wind speed at reference height:

$$u_9 = \frac{1}{h_{max} - h_{min}} \int_{h_{min}}^{h_{max}} \left(V(h) - V\left(h_{ref}\right)\right) dh \tag{12}$$

Here h_{max} and h_{min} are the maximum and minimum heights covered by the probe volume, h_{ref} is the measurement height of the reference anemometer. Note that the version of this formula given in [6] erroneously divides the integral by the reference height h_{ref} and not by the length of the integration interval $\Delta h = h_{max} - h_{min}$ as is required.

Assuming a power law wind profile with an exponent a

$$V(h) = V(h_{ref})\left(\frac{h}{h_{ref}}\right)^{a} \tag{13}$$

equation (12) can be analytically solved:

$$u_9 = V(h_{ref})\left(\frac{h_{max}^{a+1} - h_{min}^{a+1}}{\Delta h(a+1)h_{ref}^{a}} - 1\right) \tag{14}$$

With equation (14) the influence of wind shear on a tilted LiDAR beam can be analysed. Here it can be advisable to divide by $v(h_{ref})$; thus a wind speed independent relative uncertainty is derived. With a probe length P the vertical limits of the probe volume is defined by:

$$h_{min} = h_{ref} - \frac{P}{2}\sin\psi \tag{15}$$

$$h_{max} = h_{ref} + \frac{P}{2}\sin\psi \tag{16}$$

$$\Delta h = P\sin\psi \tag{17}$$

Equation (14) is evaluated for every wind speed bin on the bin averages of the wind shear measured at the mast as estimated with the following equation:

$$a = \frac{\ln\frac{V_{cup}(60.4\,m)}{V_{cup}(82.2\,m)}}{\ln\frac{60.4\,m}{82.2\,m}} \tag{18}$$

8.1.10 Uncertainty due Height Error from Installation

In a wind flow with wind shear, the uncertainty in measurement height in the installation of the laser beam results in an uncertainty in wind speed measurement. This can be estimated with equation (13), which is evaluated for every wind speed bin on the bin averages of the wind shear measured at the mast as estimated with equation (18).

The height error of the installation was estimated to be 0.5 m.

8.1.11 Uncertainty due to Range Error

The position of the probe volume along the beam can be erroneous. The uncertainty due to the height error is sensitive to horizontal wind gradients and in a tilted measurement configuration to vertical wind shear. Therefore the displacement along the beam is decomposed into a horizontal component (range error times cos(ψ)) and a vertical one (range error times sin(ψ)). It is assumed that the horizontal effects are independent from the vertical ones.

As in section 8.1.8 a horizontal wind gradient of 1%/measurement height is assumed.

The uncertainty of the range gate error due the vertical displacement in a tilted geometry is analysed according to section 8.1.9. For low measurement heights and large tilt angles the effect of a positive range error (measurement is performed higher than expected) and a negative one is different. Therefore the standard uncertainty is taken to be the average of the uncertainty due to a positive and a negative range error.

The manufacturer performed a direct detection of the range gate error by blocking the beams, leading to the offset in equation (1). DWG was not present at that measurement; therefore a conservative estimation of uncertainty as a third of the detected offset was taken as range gate uncertainty.

8.1.12 Uncertainty due to Height Error from Wind Load

Especially if the LiDAR is mounted on a platform, wind load can induce wind dependent change in the tilt angle of the instrument. This influences both the measurement height close to the reference sensor (this section) and the projection angle (section 8.1.15). Since the instrument does not feature an inclinometer, the size is estimated from the wind load induced tilt measured by an instrument with inclinometer that was mounted in the same position as the Whirlwind during a later measurement. As a conservative estimation the maximum bin average deviation from the overall average (0.02°) is taken to be the tilt due to wind load.

The height error in wind speed is derived by transferring the error in tilt into an error in measurement height, which then is analysed according to section 8.1.10.

As the instrument is mounted on the ground and tilted to the height of the reference sensor the relative error in LOS wind speed is calculated as

$$u_{12} = \left(\frac{\sin(\psi + \Delta\tau)}{\sin(\psi)}\right)^{a} - 1 \tag{19}$$

In the equations ψ is the tilt angle of the beam and $\Delta\tau$ is the systematic tilt error due to wind load and a is the wind shear exponent.

8.1.13 Height Error from Variation in Tilt

In addition to the tilt error from wind load, which is constant, the instrument will also be subject to vibrations and oscillations. Therefore, the tilt angle will be variate within a ten minute averaging interval. During calibration these can be minimised by a solid mounting. During the later measurements on a turbine, the swaying turbine will introduce a much higher variability.

If the measured standard deviation of the tilt is std(τ), for simplicity it is assumed that the tilt is distributed uniformly over the interval [τ - std(τ)√3 , τ + std(τ)√3]. The measurement uncertainty in LOS wind speed is derived from the integral of equation (12) over this interval.

Again this component could not be measured for the Whirlwind, but was derived from a measurement with an instrument mounted in the same position. The maximum standard deviation observed in tilt was less than 0.01° which is used here as conservative estimation.

8.1.14 Uncertainty due to Projection Error from Installation

A misalignment of the LiDAR with regard to the reference sensor does not only result in a measurement in a different height, but also introduces a discrepancy between the physical tilt angle and the tilt angle used in to project the reference wind speed into the measurement geometry of the LiDAR. An error in the tilt angle ψ used in equation (6) transfers to an error in the projected reference wind speed $V_{h,ref}$.

Error propagation through equation (10) gives the relative uncertainty in V_{ref} to

$$u_{14} = \tan(\psi) \cdot u_{\tau} \qquad (20)$$

where u_{τ} is the uncertainty in tilt angle in radians. If u_{τ} is expressed in degrees, it has to be multiplied by the factor π/180°.

The tilt error is calculated from the height error of section 8.1.10 to be 0.08°.

8.1.15 Uncertainty due to Projection Error from Wind Load

The error due to an introduced tilt by wind load on the projection can be treated in the same way as in section 8.1.14. The size of the tilt error is estimated as in chapter 8.1.12.

8.1.16 Uncertainty due to Projection Error from Flow Inclination

In the projection of equation (6) the flow inclination to the horizontal plane is neglected due to the smaller magnitude of the vertical wind speed. The effect of neglecting the flow inclination in the projection is mathematically the same as an error in the tilt as analysed in section 8.1.14. The bin averaged flow inclination as measured by the 3D ultrasonic anemometer at 60.4 m is used as standard uncertainty u_{τ} in equation (20).

8.1.17 Uncertainty due to Deviations of LiDAR and Reference Measurements

The full mean deviation of the measurement of the LiDAR and the reference measurement per wind speed bin is included as standard uncertainty in the total uncertainty of the RSD.

8.1.18 Statistical Uncertainty

The statistical uncertainty is calculated as the standard deviation of the wind speed in each bin divided by the square root of the number of data sets in the bin.

9 References

[1] International vocabulary of metrology — Basic and general concepts and associated terms (VIM), JCGM 200:2008

[2] IEC 61400-12-1, Edition 2, Wind energy generation systems - Part 12-1: Power performance measurements of electricity producing wind turbines, 2017-03-03

[3] Martin, K., Franke, K.: Overview Report RSV15009.A0, 2015-07-14

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[5] MEASNET; Cup Anemometer Calibration Procedure, Version 2, October 2009

[6] Borraccino, A., Courtney, M., & Wagner, R.: Generic methodology for calibrating profiling nacelle LiDARs, DTU Wind Energy. (DTU Wind Energy E; No. 0086), 2015

[7] ISO/IEC Guide 98-3:2008, Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)

10 Appendix:

10.1 Calibration Certificates of Selected Sensors

10.1.1 Calibration Certificate Cup Anemometer at 60.4 m (SW)

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

akkreditiert durch die / *accredited by the*

Deutsche Akkreditierungsstelle GmbH

als Kalibrierlaboratorium im / *as calibration laboratory in the*

Deutschen Kalibrierdienst

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

Kalibrierschein
Calibration certificate

Calibration mark 1422664 D-K-15140-01-00 06/2014

Gegenstand *Object*	Cup Anemometer
Hersteller *Manufacturer*	Thies Clima D-37083 Göttingen
Typ *Type*	4.3351.00.000
Fabrikat/Serien-Nr. *Serial number*	03126298
Auftraggeber *Customer*	Deutsche WindGuard Consulting GmbH D 26316 Varel
Auftragsnummer *Order No.*	VT140670
Anzahl der Seiten des Kalibrierscheines *Number of pages of the certificate*	3
Datum der Kalibrierung *Date of calibration*	26.06.2014

Dieser Kalibrierschein dokumentiert die Rückführung auf nationale Normale zur Darstellung der Einheiten in Übereinstimmung mit dem Internationalen Einheitensystem (SI).
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Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

This calibration certificate 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 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.
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.

Datum *Date*	Leiter des Kalibrierlaboratoriums *Head of the calibration laboratory*	Bearbeiter *Person in charge*
26.06.2014	Dipl. Phys. D. Westermann	Technikerin Sonja Krüger

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Page

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Kalibriergegenstand *Object*	Cup Anemometer		
Kalibrierverfahren *Calibration procedure*	IEC 61400-12-1 – Power performance measurements of electricity producing wind turbines – 2005-12 ISO 3966 – Measurement of fluid in closed conduits – 2008-07		
Ort der Kalibrierung *Place of calibration*	Windtunnel of Deutsche WindGuard, Varel		
Messbedingungen *Test Conditions*	wind tunnel area [1]	10000 cm²	
	anemometer frontal area [2]	230 cm²	
	diameter of mounting pipe [3]	34 mm	
	blockage ratio [4]	0.023 [-]	
	blockage correction [5]	1.000 [-]	
Umgebungsbedingungen *Test conditions*	air temperature	23.6 °C	± 0.1 K
	air pressure	1015.9 hPa	± 0.3 hPa
	relative air humidity	52.8 %	± 2.0 %
Akkreditierung *Accreditation*	01/2013		
Anmerkungen *Remarks*	-		
Auswertesoftware *Software version*	7.62		

[1] Querschnittsfläche der Auslassdüse des Windkanals
[2] Vereinfachte Querschnittsfläche (Schattenwurf) des Prüflings inkl. Montagerohr
[3] Durchmesser des Montagerohrs
[4] Verhältnis von 2) zu 1)
[5] Korrekturfaktor durch die Verdrängung der Strömung durch den Prüfling
Anmerkung: Aufgrund der speziellen Konstruktion der Messstrecke ist keine Korrektur nötig.
Remark: Due to the special construction of the test section no blockage correction is necessary

Dieser Kalibrierschein wurde elektronisch erzeugt
This calibration certificate has been generated electronically

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

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Page

1422664 D-K-15140-01-00 06/2014

Kalibrierergebnis:
Result:

File:	1422664	
Test Item	Tunnel Speed	Uncertainty (k=2)
Hz	m/s	m/s
82.256	3.983	0.050
124.243	5.934	0.050
168.176	7.962	0.050
211.371	9.935	0.051
255.256	11.958	0.051
298.337	13.908	0.051
339.964	15.887	0.051
319.903	14.940	0.051
275.815	12.941	0.051
232.534	10.914	0.051
189.667	8.963	0.050
146.992	6.969	0.050
102.392	4.931	0.050

Angegeben ist die erweiterte Messunsicherheit, die sich aus der Standardmessunsicherheit durch Multiplikation mit dem Erweiterungsfaktor k=2 ergibt. Sie wurde gemäß DAkkS-DKD-3 ermittelt. Der Wert der Messgröße liegt mit einer Wahrscheinlichkeit von 95 % im zugeordneten Wertintervall.

Die Deutsche Akkreditierungsstelle GmbH ist Unterzeichnerin der multilateralen Übereinkommen der European co-operation for Accreditation (EA) und der International Laboratory Accreditation Cooperation (ILAC) zur gegenseitigen Anerkennung der Kalibrierscheine. Die weiteren Unterzeichner innerhalb und außerhalb Europas sind den Internetseiten von EA (www.european-accreditation.org) und ILAC (www.ilac.org) zu entnehmen.

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 DAkkS is signatory to the multilateral agree-ments of the European co-operation for Accredita-tion (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates.

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

Anhang
Annex

1422664

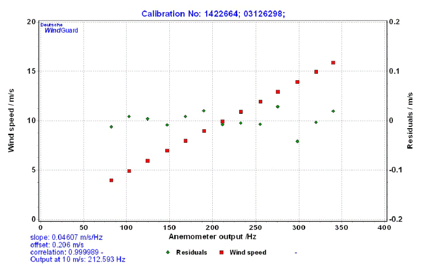
1 Detailed Calibration Results

DKD calibration no.	1422664
Body no.	03126298
Cup no.	
Date	26.06.2014
Air temperature	23.6 °C
Air pressure	1015.9 hPa
Humidity	52.8 %

Deutsche WindGuard Wind Tunnel Services GmbH measnet

Linear regression analysis

Slope	0.04607 (m/s)/(Hz) ±0.00006 (m/s)/(Hz)
Offset	0.2063 m/s ±0.015 m/s
St.err(Y)	0.018 m/s
Correlation coefficient	0.999989
Remarks	no



Deutsche WindGuard Wind Tunnel Services is accredited by MEASNET and by the Deutsche Akkreditierungsdienst – DAkkS (German Accreditation Service). Registration: D-K-15140-01-00

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

Anhang
Annex

1422664

2 Instrumentation

Pos.	Sensor	Manufa.	Type	Range
1	Pitot static tube	Airflow	NPL 8 mm	-
2	Pitot static tube	Airflow	NPL 8 mm	-
3	Pitot static tube	Airflow	NPL 8 mm	-
4	Pitot static tube	Airflow	NPL 8 mm	-
5	Pressure transducer	Setra	C 239	250 Pa
6	Pressure transducer	Setra	C 239	250 Pa
7	Pressure transducer	Setra	C 239	250 Pa
8	Pressure transducer	Setra	C 239	250 Pa
9	El. Barometer	Vaisala	3.11.57.10.000	800hPa -1200 hPa
10	El. Thermometer	Galltec	KPK 1/6-ME	10° C - 40° C
11	El. Humidity sensor	Galltec	KPK 1/6-ME	0-100 %
12	Wind tunnel control	-	-	-
13	CAN-BUS / PC	esd	24 x 16 bit	

Table 1 Description of the data acquisition system
Remark: Last Re-accreditation see page 2

3 Photo of the calibration set-up

Calibration set-up of the anemometer calibration in the wind tunnel of Deutsche WindGuard, Varel. The anemometer and orientation shown may differ from the calibrated one. Remark: The proportion of the set-up is not true to scale due to imaging geometry.

4 Deviation to IEC procedure

The calibration procedure is in all aspects in accordance with the IEC 61400-12-1 Procedure

5 References

[1] D. Westermann, 2009 – Verfahrensanweisung DKD-Kalibrierung von Windgeschwindigkeitssensoren
[2] IEC 61400-12-1 12/2005 – Power performance measurements of electricity producing wind turbines
[3] ISO 3966 2008 – Measurement of fluid flow in closed conduits

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

10.1.2 Calibration Certificate Sonic Anemometer at 60.5 m (NE)

10.1.2.1 Wind Speed

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Wind Tunnel Services GmbH, Varel

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Deutsche Akkreditierungsstelle GmbH

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

als Kalibrierlaboratorium im / *as calibration laboratory in the*

Deutschen Kalibrierdienst DKD

Kalibrierschein
Calibration certificate

Calibration mark 1421533 | D-K-15140-01-00 | 03/2014

Gegenstand *Object*	Sonic Anemometer
Hersteller *Manufacturer*	Thies Clima D-37083 Göttingen
Typ *Type*	4.3830.21.400
Fabrikat/Serien-Nr. *Serial number*	02120013
Auftraggeber *Customer*	Deutsche WindGuard Consulting GmbH D 26316 Varel
Auftragsnummer *Order No.*	VT140354
Anzahl der Seiten des Kalibrierscheines *Number of pages of the certificate*	3
Datum der Kalibrierung *Date of calibration*	13.03.2014

Dieser Kalibrierschein dokumentiert die Rückführung auf nationale Normale zur Darstellung der Einheiten in Übereinstimmung mit dem Internationalen Einheitensystem (SI).
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Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.
This calibration certificate 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.

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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.

Datum *Date*	Leiter des Kalibrierlaboratoriums *Head of the calibration laboratory*	Bearbeiter *Person in charge*
13.03.2014	Dipl. Phys. D. Westermann	Heiko Westermann, B. Sc.

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Page

1421533 | D-K-15140-01-00 | 03/2014

Kalibriergegenstand *Object*	Sonic Anemometer		
Kalibrierverfahren *Calibration procedure*	IEC 61400-12-1 – Power performance measurements of electricity producing wind turbines – 2005-12 ISO 3966 – Measurement of fluid in closed conduits – 2008-07		
Ort der Kalibrierung *Place of calibration*	Windtunnel of Deutsche WindGuard, Varel		
Messbedingungen *Test Conditions*	wind tunnel area [1)]	10000 cm²	
	anemometer frontal area [2)]	270 cm²	
	diameter of mounting pipe [3)]	48 mm	
	blockage ratio [4)]	0.027 [-]	
	blockage correction [5)]	1.000 [-]	
Umgebungsbedingungen *Test conditions*	air temperature	20.7 °C	± 0.1 K
	air pressure	1028.3 hPa	± 0.3 hPa
	relative air humidity	42.0 %	± 2.0 %
Akkreditierung *Accreditation*	01/2013		
Anmerkungen *Remarks*	Calibrated with north ring Orientation: 0 deg, north ring reference		
Auswertesoftware *Software version*	7.61		

1) Querschnittsfläche der Auslassdüse des Windkanals
2) Vereinfachte Querschnittsfläche (Schattenwurf) des Prüflings inkl. Montagerohr
3) Durchmesser des Montagerohrs
4) Verhältnis von 2) zu 1)
5) Korrekturfaktor durch die Verdrängung der Strömung durch den Prüfling
Anmerkung: Aufgrund der speziellen Konstruktion der Messstrecke ist keine Korrektur nötig.
Remark: Due to the special construction of the test section no blockage correction is necessary

Dieser Kalibrierschein wurde elektronisch erzeugt
This calibration certificate has been generated electronically

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

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Page

1421533 | D-K-15140-01-00 | 03/2014

Kalibrierergebnis:
Result:

File:	1421533		
Test Item (m/s)	Test Item (deg)	Tunnel Speed (m/s)	Uncertainty (k=2) (m/s)
4.080	358.571	4.068	0.050
6.076	358.541	6.060	0.050
8.199	358.538	8.172	0.050
10.237	358.558	10.204	0.050
12.337	358.477	12.300	0.050
14.295	358.507	14.258	0.050
16.343	358.423	16.311	0.100
15.365	358.464	15.331	0.050
13.337	358.454	13.304	0.050
11.243	358.507	11.219	0.050
9.223	358.533	9.204	0.050
7.194	358.535	7.184	0.050
5.041	358.568	5.043	0.050

Angegeben ist die erweiterte Messunsicherheit, die sich aus der Standardmessunsicherheit durch Multiplikation mit dem Erweiterungsfaktor k=2 ergibt. Sie wurde gemäß DAkkS-DKD-3 ermittelt. Der Wert der Messgröße liegt mit einer Wahrscheinlichkeit von 95 % im zugeordneten Wertintervall.

Die Deutsche Akkreditierungsstelle GmbH ist Unterzeichnerin der multilateralen Übereinkommen der European co-operation for Accreditation (EA) und der International Laboratory Accreditation Cooperation (ILAC) zur gegenseitigen Anerkennung der Kalibrierscheine. Die weiteren Unterzeichner innerhalb und außerhalb Europas sind den Internetseiten von EA (www.european-accreditation.org) und ILAC (www.ilac.org) zu entnehmen.

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 DAkkS is signatory to the multilateral agree-ments of the European co-operation for Accredita-tion (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates.

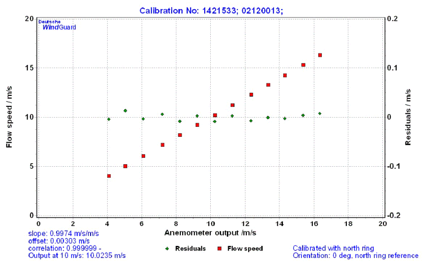
Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

Anhang
Annex 1421533

1 Detailed Calibration Results

DKD calibration no.	1421533
Body no.	02120013
Cup no.	
Date	13.03.2014
Air temperature	20.7 °C
Air pressure	1028.3 hPa
Humidity	42.0 %
Linear regression analysis	
Slope	0.99735 (m/s)/(m/s) ±0.00050 (m/s)/(m/s)
Offset	0.0030 m/s ±0.005 m/s
St.err(Y)	0.007 m/s
Correlation coefficient	0.999999
Remarks	no

Deutsche WindGuard Wind Tunnel Services GmbH - measnet



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Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

Anhang
Annex

1421533

2 Instrumentation

Pos.	Sensor	Manufa.	Type	Range
1	Pitot static tube	Airflow	NPL 8 mm	-
2	Pitot static tube	Airflow	NPL 8 mm	-
3	Pitot static tube	Airflow	NPL 8 mm	-
4	Pitot static tube	Airflow	NPL 8 mm	-
5	Pressure transducer	Setra	C 239	250 Pa
6	Pressure transducer	Setra	C 239	250 Pa
7	Pressure transducer	Setra	C 239	250 Pa
8	Pressure transducer	Setra	C 239	250 Pa
9	El. Barometer	Vaisala	3.11.57.10.000	800hPa -1200 hPa
10	El. Thermometer	Galltec	KPK 1/6-ME	10° C - 40° C
11	El. Humidity sensor	Galltec	KPK 1/6-ME	0-100 %
12	Wind tunnel control	-	-	-
13	CAN-BUS / PC	esd	24 x 16 bit	

Table 1 Description of the data acquisition system
Remark: Last Re-accreditation see page 2

3 Photo of the calibration set-up

Calibration set-up of the anemometer calibration in the wind tunnel of Deutsche WindGuard, Varel. The anemometer and orientation shown may differ from the calibrated one. Remark: The proportion of the set-up is not true to scale due to imaging geometry.

4 Deviation to IEC procedure
The calibration procedure is in all aspects in accordance with the IEC 61400-12-1 Procedure

5 References
[1] D. Westermann, 2009 – Verfahrensanweisung DKD-Kalibrierung von Windgeschwindigkeitssensoren
[2] IEC 61400-12-1 12/2005 – Power performance measurements of electricity producing wind turbines
[3] ISO 3966 2008 – Measurement of fluid flow in closed conduits

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

10.1.2.2 Wind Direction

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

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Deutsche Akkreditierungsstelle GmbH

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

als Kalibrierlaboratorium im / *as calibration laboratory in the*

Deutschen Kalibrierdienst DKD

Kalibrierschein
Calibration certificate

Calibration mark 1421535 / **D-K-15140-01-00** / 03/2014

Gegenstand *Object*: Sonic Anemometer

Hersteller *Manufacturer*: Thies Clima, D-37083 Göttingen

Typ *Type*: 4.3830.21.400

Fabrikat/Serien-Nr. *Serial number*: 02120013

Auftraggeber *Customer*: Deutsche WindGuard Consulting GmbH, D 26316 Varel

Auftragsnummer *Order No.*: VT140354

Anzahl der Seiten des Kalibrierscheines *Number of pages of the certificate*: 4

Datum der Kalibrierung *Date of calibration*: 13.03.2014

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 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.

Datum *Date*	Leiter des Kalibrierlaboratoriums *Head of the calibration laboratory*	Bearbeiter *Person in charge*
13.03.2014	Dipl. Phys. D. Westermann	Heiko Westermann, B. Sc.

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Page

1421535 / **D-K-15140-01-00** / 03/2014

Kalibriergegenstand *Object*: Sonic Anemometer

Ort der Kalibrierung *Place of calibration*: Windtunnel of Deutsche WindGuard, Varel

Kalibrierverfahren *Calibration procedure*: ASTM 5366-96 Standard Test Method of Measuring the Dynamic Performance of Wind Vanes - 2002
Deutsche WindGuard Verfahrensanweisung Kalibrierung von Windrichtungssensoren

Die messtechnische Bestimmung der angezeigten Windrichtung eines Windrichtungssensors zur Strömungsrichtung im Windkanal erfolgt mit Hilfe einer Dreheinrichtung unterhalb der Messstrecke des Windkanals. Während der Messung wird der Windrichtungssensor kontinuierlich von 0 Grad bis 360 Grad und zurück nach 0 Grad bei konstanter Strömungsgeschwindigkeit gedreht. Die Mittelwertbildung erfolgt in Klassen (Klassenbreite siehe Seite 3).

The measurement of the indicated direction of a wind vane to statically yawed air flow is done with the help of an automatic yaw device installed below the wind tunnel test section. During the measurements, the wind vane is yawed continuously from 0 to 360 degrees and back to 0 degree at constant flow speed. The data are bin-averaged in classes (see page 3).

Umgebungsbedingungen: *Test conditions*

air temperature:	21.1 °C	± 0.2 K
air pressure:	1028.1 hPa	± 0.4 hPa
relative air humidity:	42.1 %	± 2 %

Kommentar: *Comment*: Calibrated with north ring

Akkreditierung: *Accreditation*: 01/2013

Dieser Kalibrierschein wurde elektronisch erzeugt
This calibration certificate has been generated electronically

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

File:	1421535					
Bin	Flow Dir	dir	v_hor	v_vert	Unc	Flow speed
-	deg	deg	m/s	m/s	deg	m/s
1	22.47	20.403	8.026	0.017	0.8	7.959
2	44.95	43.179	7.970	0.070	0.8	7.958
3	66.01	64.719	7.938	0.027	0.8	7.958
4	89.94	88.631	7.983	0.015	0.8	7.957
5	112.52	110.670	8.008	0.012	0.8	7.958
6	134.97	132.819	8.016	0.012	0.8	7.957
7	157.46	155.307	7.972	0.058	0.8	7.958
8	179.96	178.422	7.900	0.096	0.8	7.959
9	202.50	201.287	7.935	0.091	0.8	7.960
10	225.06	223.631	7.989	0.088	0.8	7.961
11	247.50	245.784	8.018	0.068	0.8	7.960
12	269.97	267.782	8.017	0.068	0.8	7.961
13	292.44	290.658	7.927	0.144	0.8	7.957
14	314.72	313.159	7.912	0.046	0.8	7.958
15	337.43	336.266	7.980	0.085	0.8	7.960

Angegeben ist die erweiterte Messunsicherheit, die sich aus der Standardmessunsicherheit durch Multiplikation mit dem Erweiterungsfaktor k=2 ergibt. Sie wurde gemäß DAkkS-DKD-3 ermittelt. Der Wert der Messgröße liegt mit einer Wahrscheinlichkeit von 95 % im zugeordneten Wertintervall.

Die Deutsche Akkreditierungsstelle GmbH ist Unterzeichnerin der multilateralen Übereinkommen der European co-operation for Accreditation (EA) und der International Laboratory Accreditation Cooperation (ILAC) zur gegenseitigen Anerkennung der Kalibrierscheine. Die weiteren Unterzeichner innerhalb und außerhalb Europas sind den Internetseiten von EA (www.european-accreditation.org) und ILAC (www.ilac.org) zu entnehmen.

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 DAkkS is signatory to the multilateral agree-ments of the European co-operation for Accredita-tion (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates

Kalibrierergebnisse:
Results

Slope (linear regression): 1.00085deg/deg
Offset (linear regression): -1.8189 deg

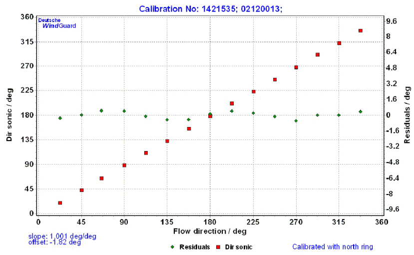

Image 1: Calibration set-up of flow direction test in the wind tunnel of Deutsche WindGuard, Varel. The sensor shown may differ from the calibrated one. Remark: The proportion of the set-up is not true to scale due to imaging geometry.

Sensor config during calibration
Sensorkonfiguration während der Kalibrierung

!02AA00003
!02AB00003
!02AC00003
!02AG00000
!02AM00000
!02AN00001
!02AR00060
!02AU00050
!02AV00001
!02AY00000
!02AZ00000
!02BL00308
!02BH00000
!02BP00100
!02BR00006
!02BS00100
!02BT00000
!02BX00006
!02BY00000
!02BZ00000
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!02CO00000
!02CY00000
!02CZ00000
!02DE00000
!02DM00000
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!02DV19899
!02DW19939
!02EI00002
!02FB00000
!02GU00000
!02HC00010
!02HL00275
!02HH00280
!02HT00001
!02ID00002
!02MA00013
!02MD00005
!02NC00000
!02OR00100
!02OS00000
!02PC00007
!02PR00046
!02PT00048
!02RC00565
!02RD00005
!02RF00060
!02SC00000
!02SH00613
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!02SM00000
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!02UM00000
!02UN00002
!02VC01088
!02VM00000
!02VN00001
!02VT00001
!02WM00000
!02WN00004
!02XI00000

10.1.3 Calibration Certificate Wind Vane at 58.2 m height

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

akkreditiert durch die / *accredited by the*

Deutsche Akkreditierungsstelle GmbH

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

als Kalibrierlaboratorium im / *as calibration laboratory in the*

Deutschen Kalibrierdienst DKD

Kalibrierschein
Calibration certificate

Calibration mark 1422707 D-K-15140-01-00 06/2014

Gegenstand *Object*	Wind Vane
Hersteller *Manufacturer*	Thies Clima D-37083 Göttingen
Typ *Type*	4.3150.00.140
Fabrikat/Serien-Nr. *Serial number*	0209036
Auftraggeber *Customer*	Deutsche WindGuard Consulting GmbH D 26316 Varel
Auftragsnummer *Order No.*	VT140670
Anzahl der Seiten des Kalibrierscheines *Number of pages of the certificate*	4
Datum der Kalibrierung *Date of calibration*	30.06.2014

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Datum *Date*	Leiter des Kalibrierlaboratoriums *Head of the calibration laboratory*	Bearbeiter *Person in charge*
30.06.2014	Dipl. Phys. D. Westermann	Dipl.-Ing. (FH) Catharina Herold

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Kalibriergegenstand *Object*: Wind Vane

Ort der Kalibrierung *Place of calibration*: Windtunnel of Deutsche WindGuard, Varel

Defintion *Definition*

Referenz Richtung (deg): Ist die vom Sensor angezeigte Richtung wenn der Sensor entlang der Mittellinie des Windkanals ausgerichtet ist (Strömungsgeschwindigkeit =0 m/s).
Dynamische Fehlstellung (deg): Ist die Differenz zwischen der Mittellinie des Windkanals und die vom Sensor angezeigte Richtung (Strömungsgeschwindigkeit>0)

Reference Direction (deg): Is the indicated angular position of the vane when aligned along the center line of the wind tunnel.
Dynamic Vane Bias (deg): Is the displacement of the vane from the wind tunnel center line at the flow speed during calibration

Kalibrierverfahren *Calibration procedure*

ASTM 5366-96 Standard Test Method of Measuring the Dynamic Performance of Wind Vanes - 2002
Deutsche WindGuard Verfahrensanweisung Kalibrierung von Windrichtungssensoren

Die messtechnische Bestimmung der angezeigten Windrichtung eines Windrichtungssensors zur Strömungsrichtung im Windkanal erfolgt mit Hilfe einer Dreheinrichtung unterhalb der Messstrecke des Windkanals. Während der Messung wird der Windrichtungssensor kontinuierlich von 0 Grad bis 360 Grad und zurück nach 0 Grad bei konstanter Strömungsgeschwindigkeit gedreht. Die Mittelwertbildung erfolgt in Klassen (Klassenbreite siehe Seite 3).

The measurement of the indicated direction of a wind vane to statically yawed air flow is done with the help of an automatic yaw device installed below the wind tunnel test section. During the measurements, the wind vane is yawed continuously from 0 to 360 degrees and back to 0 degree at constant flow speed. The data are bin-averaged in classes (see page 3).

Umgebungsbedingungen: *Test conditions*

air temperature:	23.8 °C	± 0.2 K
air pressure:	1014.5 hPa	± 0.4 hPa
relative air humidity:	52.8 %	± 2 %

Kommentar: *Comment*: -

Akkreditierung: *Accreditation*: 01/2013

Dieser Kalibrierschein wurde elektronisch erzeugt
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Bin	Flow Direction	Sensor Reading	Calculated Output	Uncertainty	Flow Speed
-	deg	mA	deg	deg	m/s
1	22.58	1.22	22.34	0.8	8.036
2	45.09	2.48	44.96	0.8	8.036
3	67.47	3.74	67.49	0.8	8.036
4	88.14	4.89	88.00	0.8	8.035
5	112.50	6.25	112.48	0.8	8.037
6	134.90	7.52	135.13	0.8	8.037
7	157.49	8.78	157.81	0.8	8.036
8	180.04	10.02	180.03	0.8	8.034
9	202.43	11.28	202.45	0.8	8.038
10	224.88	12.54	225.12	0.8	8.036
11	247.53	13.81	247.80	0.8	8.036
12	270.01	15.05	270.02	0.8	8.035
13	292.63	16.30	292.44	0.8	8.034
14	314.99	17.55	314.81	0.8	8.034
15	337.42	18.80	337.22	0.8	8.034

Angegeben ist die erweiterte Messunsicherheit, die sich aus der Standardmessunsicherheit durch Multiplikation mit dem Erweiterungsfaktor k=2 ergibt. Sie wurde gemäß DAkkS-DKD-3 ermittelt. Der Wert der Messgröße liegt mit einer Wahrscheinlichkeit von 95 % im zugeordneten Wertintervall.

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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 DAkkS is signatory to the multilateral agree-ments of the European co-operation for Accredita-tion (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates

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Anhang
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Kalibrierergebnisse: *Results*

Total resistance:	- Ohm
Slope (linear regression):	0.05584mA/deg
Offset (linear regression):	-0.0281 mA
Reference Direction:	-
Dynamic Vane Bias:	-

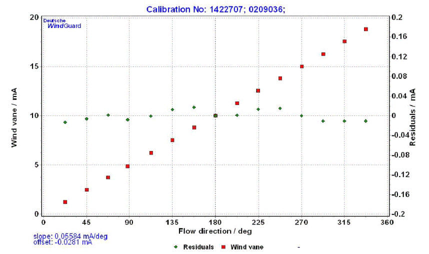

Image 1: Calibration set-up of flow direction test in the wind tunnel of Deutsche WindGuard, Varel. The windvane shown may differ from the calibrated one. Remark: The proportion of the set-up is not true to scale due to imaging geometry.

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Wind Tunnel Services GmbH, Varel

10.1.4 Correction Factors Cup Anemometer at 60.4 m (SW)

wind direction	correction factor wind speed	correction factor turbulence intensity
[°]	[-]	[-]
0	0.998	1.000
5	0.998	1.000
10	0.997	1.000
15	0.997	1.000
20	0.997	1.000
25	0.997	1.000
30	1.001	0.947
35	1.012	0.911
40	1.065	0.723
45	1.128	0.833
50	1.109	0.762
55	1.046	0.794
60	1.011	0.932
65	1.000	1.000
70	0.997	1.000
75	0.997	1.000
80	0.997	1.000
85	0.998	1.000
90	0.998	1.000
95	0.998	1.000
100	0.998	1.000
105	0.999	1.000
110	0.999	1.000
115	0.999	1.000
120	0.999	1.000
125	1.000	1.000
130	1.000	1.000
135	1.000	1.000
140	1.000	1.000
145	1.000	1.000
150	1.001	1.000
155	1.001	1.000
160	1.001	1.000
165	1.001	1.000
170	1.001	1.000
175	1.001	1.000
180	1.002	1.000
185	1.002	1.000
190	1.002	1.000
195	1.002	1.000
200	1.002	1.000
205	1.003	1.000
210	1.003	1.000
215	1.003	1.000
220	1.003	1.000
225	1.003	1.000
230	1.003	1.000
235	1.003	1.000
240	1.003	1.000
245	1.003	1.000
250	1.002	1.000
255	1.002	1.000
260	1.002	1.000
265	1.002	1.000
270	1.002	1.000
275	1.001	1.000
280	1.001	1.000
285	1.001	1.000
290	1.001	1.000
295	1.001	1.000
300	1.001	1.000
305	1.000	1.000
310	1.000	1.000
315	1.000	1.000
320	1.000	1.000
325	1.000	1.000
330	0.999	1.000
335	0.999	1.000
340	0.999	1.000
345	0.999	1.000
350	0.998	1.000
355	0.998	1.000
360	0.998	1.000