Wind Iris nacelle LiDAR calibration at ECN test site

J.W. Wagenaar
G. Bedon
E.J. Werkhoven
C van Diggelen

September 2016
ECN-X--16-116

Acknowledgement

The LAWINE project is partially funded by the Dutch government in the framework of TKI Wind op Zee

TKI reference number: TKIWO1006

ECN project number: 5.2241

The calibration is performed with a Wind Iris nacelle LiDAR provided by Avent Lidar Technology.

Revisions

Rev.	Date	Description
0.1	August 2016	First draft for approval
0.2	September 2016	Second draft for approval
1.0	September 2016	Final version

Archiving

\\ECN\Groups\g_lawine\Reports\ECN-X-16-116 Wind Iris nacelle LiDAR calidation.pdf

TESTING RvA L 324 ilac-MRA	ECN is ISO / IEC 17025 accredited for meteorological measurements.

Distribution

TKI Wind op Zee	(pdf)
Avent Lidar Technology	(pdf)
A. van der Pal	(pdf)
M. van Roermund	(pdf)
J.W. Wagenaar	(pdf)
G. Bedon	(pdf)
E.J. Werkhoven	(pdf)
K. Boorsma	(pdf)
ECN Wind Energy archive	(pdf)

Results only apply for the tested nacelle LiDAR with the settings used during the measurement period.
In case copies of this report are made, only integral copying is allowed.

Contents

Executive summary

A Wind Iris 2-beam nacelle LiDAR has been calibrated using the white box and black box approach from the ground. The tests have been carried out at the ECN Wind turbine Test site Wieringermeer with particular reference to meteorological mast 2. Measurements have been taken from the 19th of May 2016 until the 17th of August 2016.

Tilt and Roll calibration

In addition tilt and roll calibrations have been performed and the following values are found:

Tilt: a=1.0678, b=-0.2517 degrees, R^2=0.9993

Roll: a=1.0180, b=0.1295 degrees, R^2=0.9987

In addition, the opening angle of the two beams has been determined to be 29.96 degrees.

Wind speed calibration; white box

In the white box approach each beam has separately been oriented towards a calibrated sonic anemometer mounted in a meteorological mast at a height of 23m and at a distance of 205m. The results of the comparisons show that the measured mast wind speeds and LiDAR wind speeds compare very well. The regression parameters on the binned values are:

Beam 1: a=0.99196, b=0.09430m/s, R^2=0.99994

Beam 2: a=0.99502, b=0.06477m/s, R^2=0.99996

In addition, the deviations, i.e. the binned differences between the nacelle LiDAR wind speed and sonic wind speed data, do not exceed the set uncertainty limits.

The results of the uncertainty analysis reveal that uncertainty of the calibrated LiDAR is at most 0.16m/s (at 8.35m/s) for beam 1 and 0.18m/s (at 10.44m/s) for beam 0. It is also seen that the calibration has a lowering effect on the uncertainty and that a large part of the nacelle LiDAR wind speed uncertainty is due to the reference sonic wind speed uncertainty itself. On average, the uncertainty of the nacelle LiDAR wind speed is about

11% (beam 0) and 15% (beam 1) higher than the uncertainty of the reference sonic wind speed.

With this calibration the wind speed measurements of the Wind Iris nacelle LiDAR with serial number C400114 are traced back to standard units and its uncertainties have been quantified both according to ISO 17025.

Wind speed calibration; black box

In the black box approach the nacelle LiDAR's central line is oriented towards the mast, in other words, the beams are on either side of the mast. It is concluded that the comparison shows more scatter and outliers than what is found for the white box calibration. No clear indications or obvious errors causing the observed behavior could be found in the individual steps of the approach. Also, malfunctioning of the LiDAR is excluded as the LiDAR has shown good performance in the white box calibration. Therefore, it is assumed that the implicit wind field homogeneity assumption of the system is to a lesser extent valid in this case. Here, the two measurement points are separated by a horizontal distance of about 100m at 23m height. Most probably turbulence generated at the surface causes that the wind is less homogeneous at 23m than it is for instance at hub height (80m). Therefore, the black box approach apparently is less suitable at this height.

1 Introduction

Although nacelle LiDARs have great interest from and are being used by the industry, currently no standards exist for calibrating such devices. Status is that several individual parties have gained experience and/or have developed (own) procedures, whereas international alignment is still under discussion. The most common examples are the founding of the new MEASNET expert group on remote sensing calibration and the IEA Wind task 32 on LiDAR.

Two methodologies for calibrating (nacelle) LiDARs were identified among others from the “Glasgow” progress meeting of the IEA task 32 on LiDAR in November 2014: the “black box” approach and the “white box” approach. In the black box approach, the output of a (nacelle) LiDAR is considered and compared to a known reference. In the white box approach, every individual step of the LiDAR related to a wind speed measurement is assessed. A procedure for the white box calibration of nacelle LiDARs was developed by DTU [1].

In the framework of the Lawine project (task H) this report describes the calibration of the Wind Iris nacelle LiDAR C400121. Avent/Leosphere uses this system as internal reference in their manufacturing process. In the framework of task C and as a separate assignment to Avent Lidar Technology, ECN has already tested and applied the black box approach [2,3]. In this report the black box and the white box approach from the ground is applied.

The calibration test is carried out at the ECN test site. ECN Wind Energy Systems is ISO 17025 accredited for meteorological measurements. The meteorological measurements as part of this project are carried out under this accreditation.

The remainder of this report is organized as follows:

- Chapter 2 presents background information concerning test conditions;
- Chapter 3 describes the measurement procedure and the white box method;
- Chapter 4 describes the obtained results;
- Chapter 5 describes the uncertainty analysis;
- Chapter 6 presents the conclusions.

2

Test Conditions

The test conditions and the measurement set-up are among others described in great detail in [4], also available to Avent. The main aspects are treated in the sections below.

2.1 Test site

The test site and its surroundings (see **Figure 1**) are characterized as flat terrain, consisting of mainly agriculture area, with single farm houses and rows of trees. Further details about the site and about the surroundings (obstacles etc.) can be found in [4].

The LiDAR is installed on a platform placed next to the private road on the EWTW test site, between prototype turbines Wt03 and Wt04 (see **Figure 2** and **Figure 3**). From that position, the LiDAR is oriented towards a sonic anemometer in meteorological mast 2 (MM2).

Figure 1: Layout of the test site with the position of the Wind Iris (yellow pin) and MM2 (white star).

Figure 2: Location of Wt03 (left), Wt04 (right), MM2, and LiDAR (red dot).

Figure 3: Position of the LiDAR (red dot) with respect to the MM2.

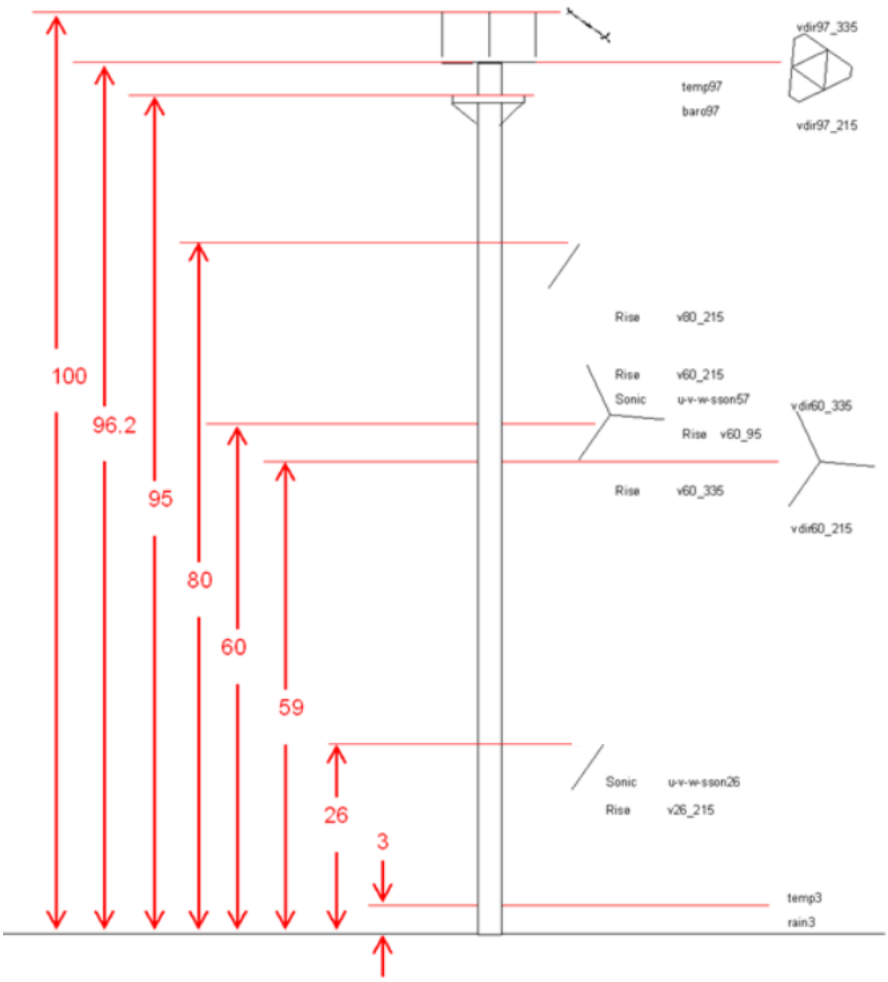
2.2 Meteorological Mast 2

MM2 is a lattice tower with a height of 100 meter. A calibrated sonic anemometer of brand Metek USA-1 (standard configuration) is mounted on the 215 degree boom, at a height of 26 meter, upside down. The anemometer is aligned to measure correct wind direction. At a height of 60m two Thies Clima wind vanes are installed on the 215 degree and 335 degree boom. They are combined to minimize mast effects in the wind direction measurements. For details reference is made to section 3.2.2. A list of the used instrumentation installed in the MM2 is reported in **Table 1** whereas a scheme with the sensors is shown in **Figure 4**.

Table 1: Used instrumentation installed in the MM2

Sensor name	ID	Signal names	Calibration date	Due date
Ultra sonic Metek USA-1 4 (standard configuration)	DEWS 6085	MM2_H23B215_Sson_Q1 MM2_H23B215_Uson_Q1 MM2_H23B215_Vson_Q1 MM2_H23B215_Wson_Q1	04-16-2016	04-16-2017
Wind vane Thies Clima	DEWR 6054	MM2_H60B215_Wd_Q1	15-02-2016	28-06-2017
Wind vane Thies Clima	DEWR 5113	MM2_H60B335_Wd_Q1	15-02-2016	28-06-2017
Module name	**ID**	**Sensor**	**Calibration date**	**Due date**
Dante Module digital	DEWS 6062	Metek USA-1 4	04-08-2011 01-08-2016	04-08-2016 01-08-2021
Dante Module digital	DEMO 5221	Thies Clima (215 boom)	11-05-2012	11-05-2017
Dante Module digital	DEMO 5222	Thies Clima (335 boom)	11-05-2012	11-05-2017

Figure 4: Layout of meteorological mast 2. The sonic anemometer used for the test is mounted on the boom at 26m.



2.3 LiDAR

The Wind Iris LiDAR of Avent, serial number C400114, is a 2-beam pulsed LiDAR measuring in the horizontal plane with a separation angle of 30 degrees. It is configured such that it measures the line of sight (LOS) wind speed at distances of 80m to 400m in front of the LiDAR in 10 steps. Further specifications are given in Appendix B.

The Wind Iris is placed on the ground on a tripod (see photos in **Figure 5**); the data acquisition system is placed in a nearby box.

Figure 5: Position of the LiDAR on the ground.

The distance considered in this report is the 4th measurement of the LiDAR, i.e. 200 m, as this coincides with the distance from the LiDAR to the mast.

Just above the LiDAR a theodolite is mounted to be able to measure the angles that the LiDAR laser beams make with respect to the horizontal plane. Theodolite sits on 56.25 cm above the lasers of the LiDAR. During this calibration two gun sights are mounted on top of the LiDAR to be able to determine the position of the laser beams in the next steps. For the white box calibration, the theodolite is exactly pointing at the sonic anemometer as can be seen in **Figure 6**, therefore minimizing the mounting error on the wind speed measurement.

Figure 6: Theodolite pointing at the sonic anemometer during white box calibration.

3

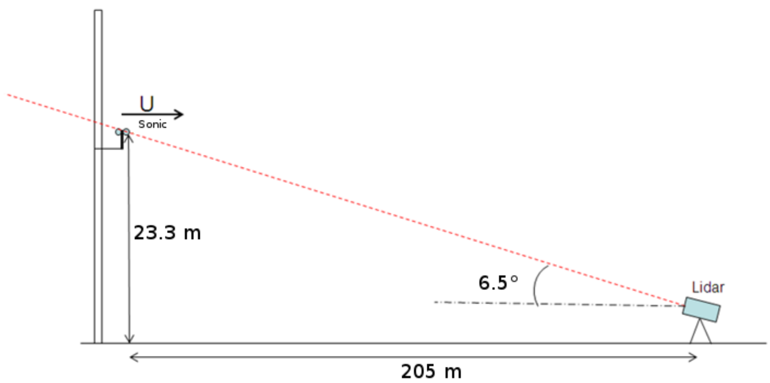
Measurement Procedure

3.1 Calibration procedure

Two methodologies have been identified for calibrating nacelle LiDARs: the black box and the white box approach [1]. ECN has tested a black box approach where the LiDAR was placed atop a 2.5 MW ECN research turbine and reference was made to the nearby IEC compliant meteorological mast 3 with cup anemometer measurements at hub height [2,3]. The advantage is that at a height of 80m the wind field in this flat terrain is assumed to be sufficiently homogeneous considering the beam separation. A disadvantage may be the movement of the turbine, which is affecting the comparison.

In this analysis both the white box approach and the black box approach from the ground are considered. The LiDAR is installed on the ground with the beam tilted upward (see **Figure 7**). With a laser distance measurement device the distance from the LiDAR to the mast is determined to be 205m and the height of the sonic measurement device 23.3m. The tilting angle is therefore determined to be 6.5 degrees.

Figure 7: Testing from the ground with an inclined beam (side view).



The angle between the LiDAR and the sonic anemometer is determined to be 56 degrees using a compass. The North marking of the sonic was determined to be 33.4

degrees by comparing the sonic wind direction measurement with the wind vane at 60m (215 degrees boom). Therefore, the projection angle is determined to be 22.6 degrees.

3.1.1 White box calibration

In the white box approach each individual step is assessed in the calibration of the system. For this approach the guidelines by DTU [1] are followed to the maximum extent possible. Therefore, the nacelle LiDAR calibration consists roughly of two parts:

- The calibration of non-wind speed measurement sensors;
- The calibration of the wind speed measurement.

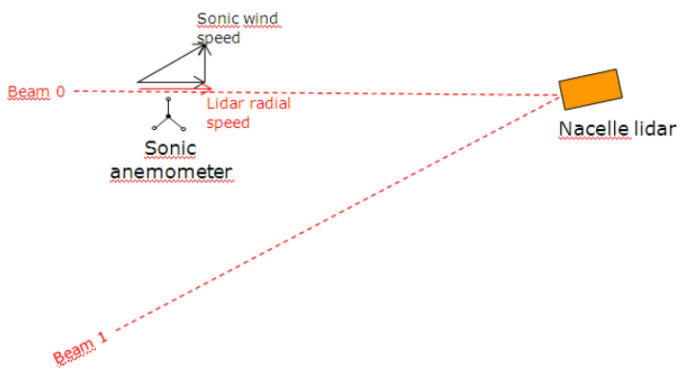
The calibration of non-wind speed sensors needs to be performed by first determining the exact position of the laser beams and estimation:

- The opening angle between the two laser beams.
- The gain & offset of the tilt and roll sensors in the LiDAR

The calibration of non-wind speed measurement sensors is conducted by considering various tilt (from -0.25° to 1° degrees in steps of 0.25°) and roll angles (from -0.75° to 0.75° in steps of 0.25°). The position of the laser beams is found at a distance of approximately 80 meters from the LiDAR by using a boards with a movable hole (2 cm x 2 cm). The hole is meant to intercept the beam and provide its position. Using the theodolite, the angle of the beams with respect to the horizontal plane is measured and compared with the output of the LiDAR itself. From these measurements, gain and offset values for the roll and tilt sensors in the LiDAR are determined. Using the position of the beams, it is also possible to calculate the opening angle.

The calibration of the wind speed measurement is conducted by tilting the LiDAR so that one of the laser beams points close to the sonic anemometer on 26 meter height in MM2 (see **Figure 8**). The meteorological mast and the LiDAR data are recorded until enough information was gathered. After the first beam, the same is done for the second beam. The analysis is performed as much as possible according to Annex L of [5].

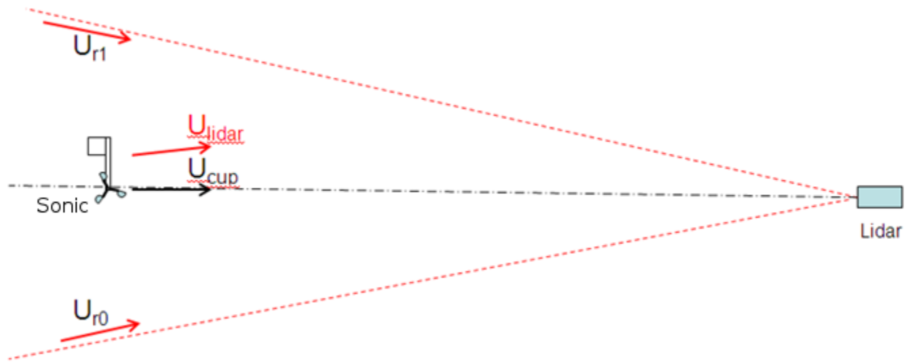
Figure 8: Line of Sight calibration method (top view)



3.1.2 Black box calibration

For the black box approach there is no need to determine the opening angle of the LiDAR and to calibrate tilt and roll angles. This, because it is the wind speed delivered by the machine as it is that is compared against the mast. Hereto, the LiDAR is placed such that the two beams are oriented on either side of a reference anemometer in a meteorological mast (see **Figure 9**).

Figure 9: Testing from the ground with an inclined beam (top view).



3.2 Data collection and selection

3.2.1 Signals

The measurement systems, the data collection in the database and all the details are described in [4]. The measurements from MM2 are directly stored in a dedicated database. The measurements from the LiDAR are stored locally and retrieved from the system itself. 10 minute averages have been considered for the analysis for the period 19th of May 2016 until 17th of August 2016. The signals used for the analysis are:

- MM2_H23_Vradial_WindIris_avg — mast projected wind speed at 23m height
- MM2_H60_Wd_Q1_avg — mast wind direction at 60m height
- RWS0m — nacelle LiDAR radial wind speed 0 at distance 4 (200m)
- RWS0_availability — nacelle LiDAR radial wind speed 0 status signal at distance 4 (200m)
- RWS1m — nacelle LiDAR radial wind speed 1 at distance 4 (200m)
- RWS1 availability — nacelle LiDAR radial wind speed 1 status signal at distance 4 (200m)
- HWSm — nacelle LiDAR horizontal wind speed at distance 4 (200m)
- HWS availability — nacelle LiDAR horizontal wind speed status

signal at distance 4 (200m)

3.2.2 Pseudo signals

In the above paragraph the mast project wind speed is introduced as a pseudo signal. This signal is defined as

MM2_H23_Vradial_WindIris = cos(ϕ)*(cos(θ)*U-sin(θ)*V)+sin(ϕ)*W, where

ϕ = elevation angle of LiDAR from the ground. In section 3.1 an angle of 6.5 degrees was found. In the database an angle of 6.2 degrees was erroneously entered. It is assumed that the difference of 0.3 degrees has a negligible effect on the analysis.
θ = horizontal angle between sonic anemometer and LiDAR, corrected for North marking of sonic anemometer (22.6 degrees, see 3.1).
U = MM2_H23B215_Uson_Q1: measured u-component wind speed
V = MM2_H23B215_Vson_Q1: measured v-component wind speed
W = MM2_H23B215_Wson_Q1: measured w-component wind speed

Also introduced is the combined wind direction signal, which is defined as
IF ((95 < MM2_H60B215_Wd < 200) OR (275 < MM2_H60B215_Wd _215 < 350))
MM2_H60_Wd = MM2_H60B215_Wd
ELSE
MM2_H60_Wd = MM2_H60B335_Wd, where
MM2_H60B215_Wd_Q1: measured wind direction at 60m height on boom 215 degrees
MM2_H60B335_Wd_Q1: measured wind direction at 60m height on boom 335 degrees

3.2.3 Data filtering

The sonic data are filtered for availability. For a good comparison the LiDAR should be well aligned to the wind, therefore a wind direction window (based on the MM2_H60_Wd_Q1_avg signal) is adopted between 191º to 281º.

The data are also filtered on the availability of the nacelle LiDAR wind speed measurements, radial wind speeds above 0m/s and the status should be at least 0.5.

Time frames are selected depending on executed tests specified below:

White box beam 1:	19-05-2016 15:10 UTC until 07-06-2016 05:00 UTC
White box beam 0:	07-06-2016 06:00 UTC until 01-07-2016 00:00 UTC
Black box:	05-07-2016 19:20 UTC until 17-08-2016 23:50 UTC

4

Calibration Results

In this chapter, the results from the white and black box calibration activities are reported.

4.1 White box calibration

The non-wind speed calibration measurements have been performed on the 18th of April 2016.

4.1.1 Non-wind speed measurement sensors

Following the approach described in section 3.1.1 the analysis provides the angle of the beams with respect to the horizon:

- horizontal: 29.96°
- vertical: 0.08°

The total angles between the two beams can be therefore calculated by vector summing the two angles. The angle between the beams therefore results to be **29.96**°.

The LiDAR is tilted from the zero position with steps of 0.25°. The right and left beam tilt angles are determined considering the different beam positions in the intercepting holes. The measured tilt angle is plotted against the LiDAR tilt angle along with a linear regression. The charts are reported in **Figure 10** and **Figure 11**.

Figure 10: Left beam tilt angle against measured tilt angle.

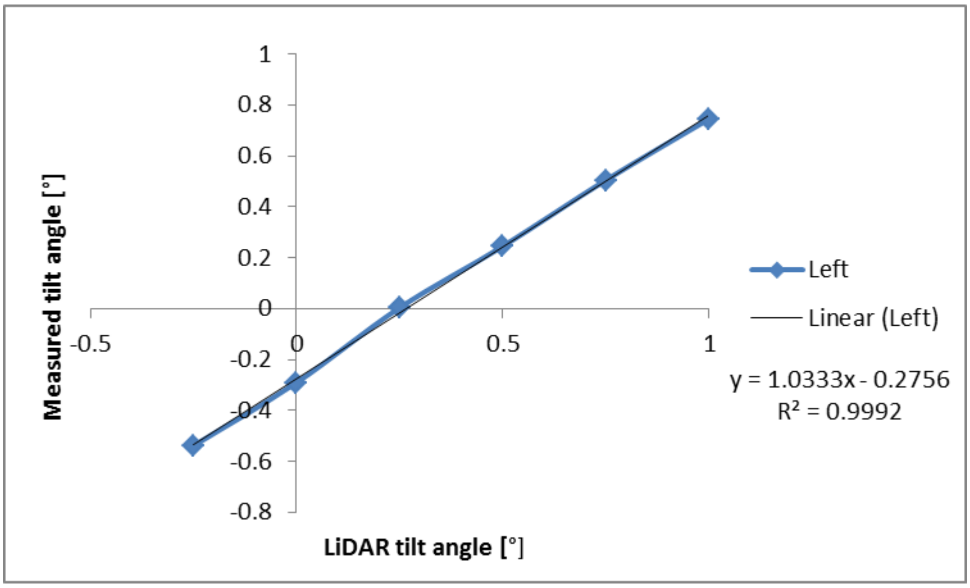
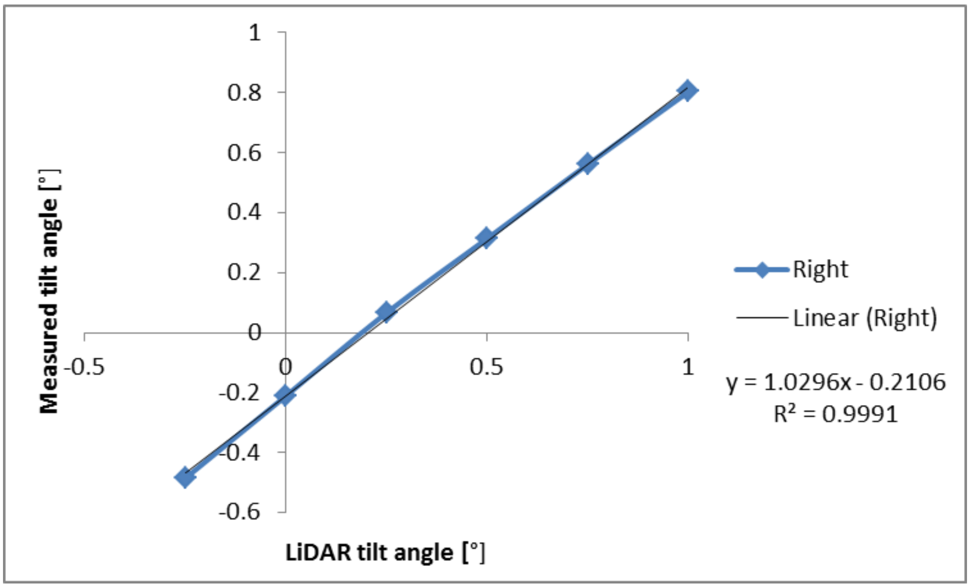


Figure 11: Right beam tilt angle against measured tilt angle.



The same procedure is applied to the roll angle of the LiDAR. The measurements are reported in **Figure 12** and **Figure 13** and a 2-parameter linear fit is made on the data.

Figure 12: Left beam roll angle against measured roll angle.

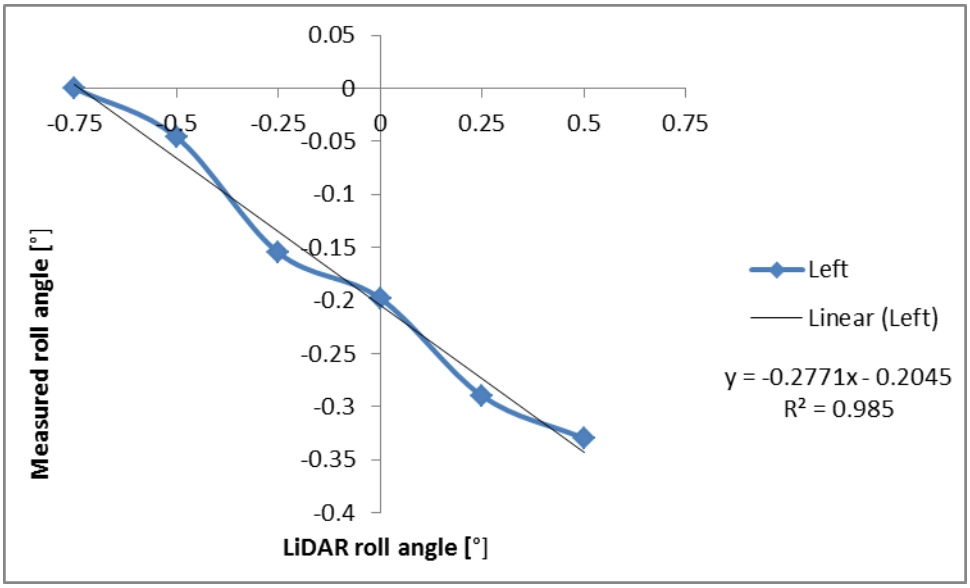
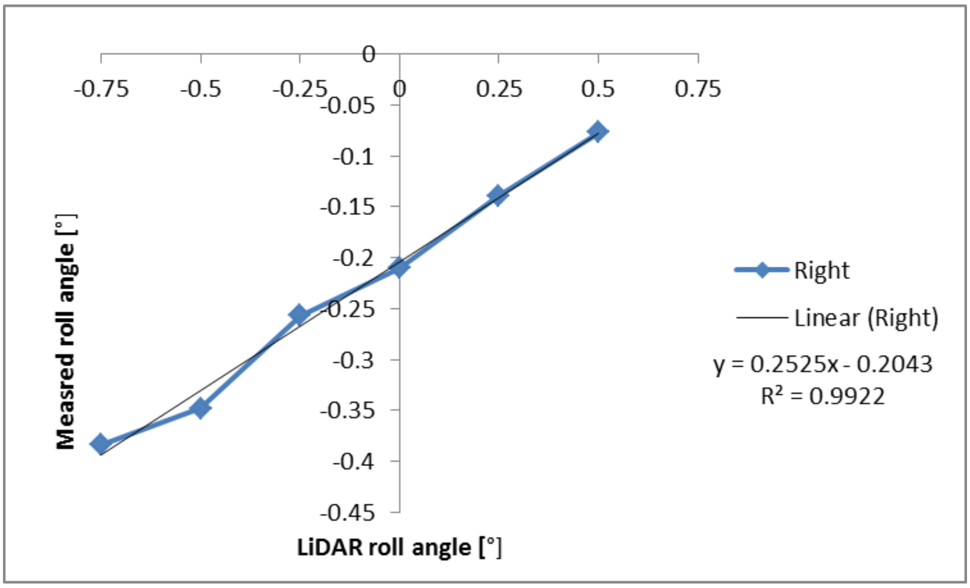


Figure 13: : Right beam roll angle against measured roll angle.

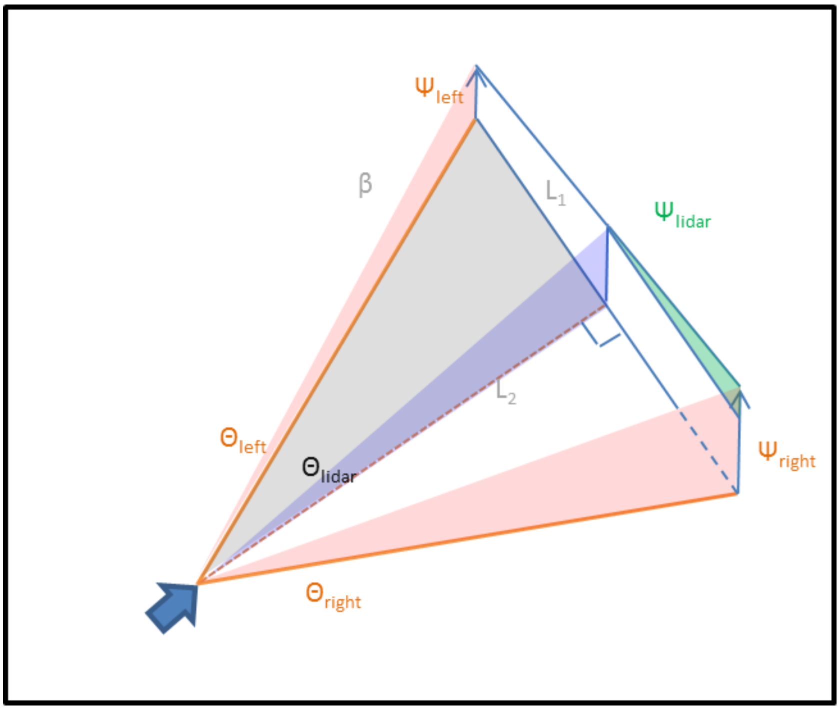


The tilt and roll angles for the two beams can be combined to obtain the LiDAR (nominal) tilt and roll angles. In fact, considering **Figure 14**, the following formulas apply:

$$\Theta_{lidar} = \operatorname{atan}\left(\frac{\tan(\Theta_{right}) + \tan(\Theta_{left})}{2\cos(\beta)}\right)$$

$$\Psi_{lidar} = \operatorname{atan}\left(\frac{\tan(\Psi_{right}) - \tan(\Psi_{left})}{2\sin(\beta)}\right)$$

Figure 14: Geometry scheme to refer single beam roll and tilt angles with lidar roll and tilt angles.



The comparisons between the measured and nominal roll and tilt angles, along with their linear fit, are reported in **Figure 15** and **Figure 16**.

Figure 15: Measured vs Nominal LiDAR tilt angle.

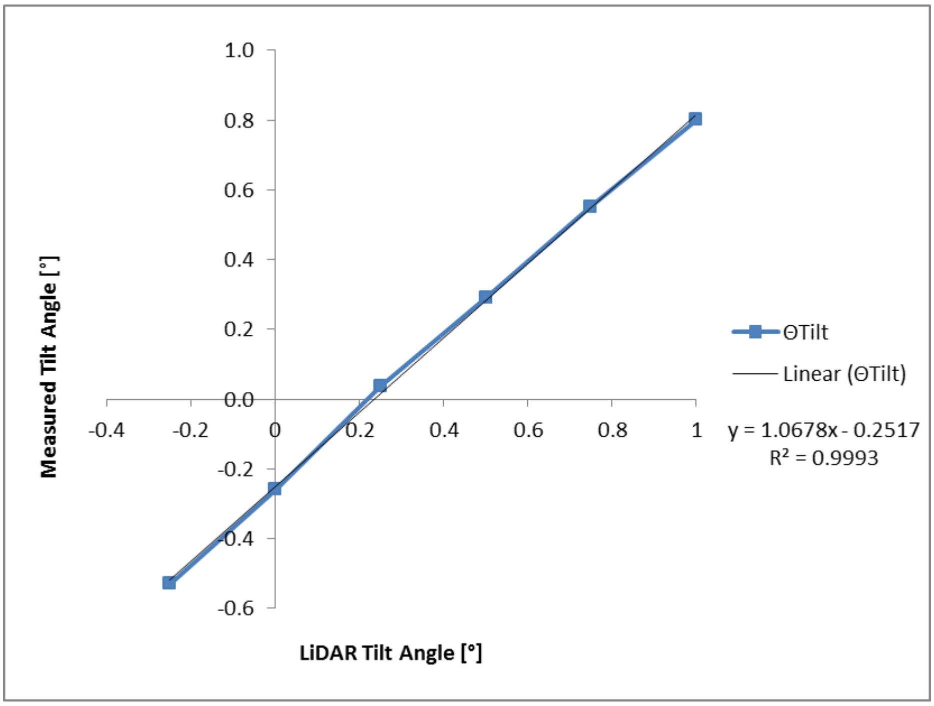
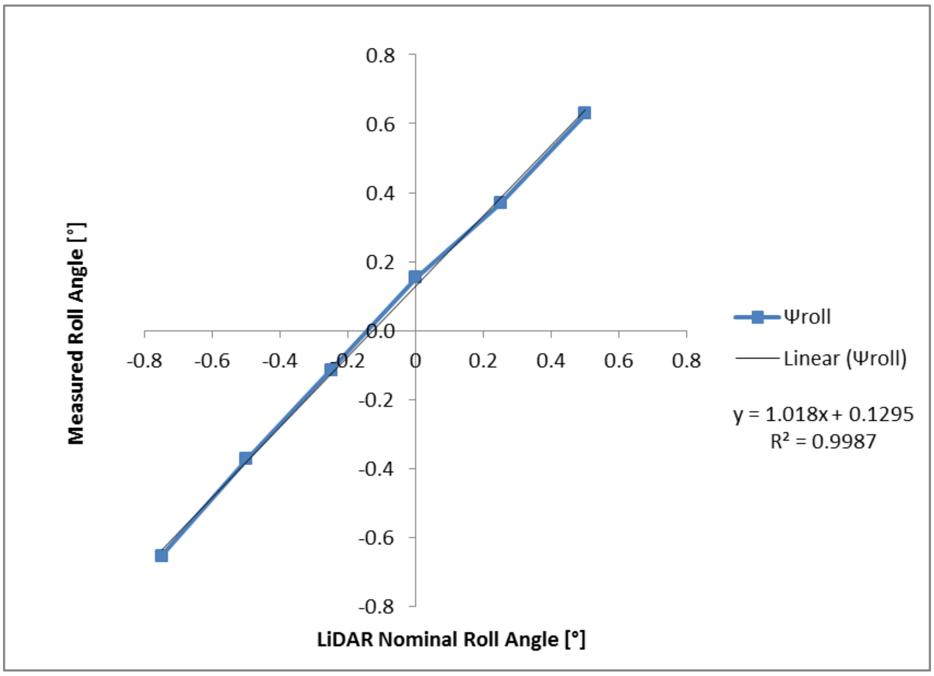


Figure 16: Measured vs Nominal LiDAR roll angle.



It is concluded that the LiDAR underestimates the tilt angle and overestimates the roll angle. The results are presented as follows:

Tilt: a=1.0678, b=-0.2517 degrees, R^2=0.9993

Roll: a=1.0180, b=0.1295 degrees, R^2=0.9987

4.1.2 Wind speed measurement sensors

The LiDAR measurement for each single beam is compared to the wind speed as measured with the sonic anemometer on the MM2 as much as possible according to [5]. Given the tilt angle for the measurement between the LiDAR and the sonic anemometer, the wind speed measurement from the mast is projected along the LiDAR direction. The total data set is respectively 3418 and 2210 data points for the two beams, where a data point is a 10 minute averaged value. Besides the direct comparison, the data are also binned in bins of 0.5m/s according to the mast measurements with bin centers at every half integer wind speed. A bin is taken into account if it contains at least 3 data points. The results are reported in **Figure 17** and **Figure 18**.

A linear fit is made on the scatter data as well as on the binned data. The results of the comparisons and the fitting are also included in **Figure 17** and **Figure 18** and show that the two measured wind speeds compare very well: the fit parameters for the linear coefficients and the offsets are very close to 1 and 0m/s, respectively, the R^2 values are above 0.99. The regression parameters on the binned values are:

Beam 1: a=0.99196, b=0.09430m/s, R^2=0.99994

Beam 2: a=0.99502, b=0.06477m/s, R^2=0.99996

Figure 17: Wind speed comparison between the first beam (1) of the LiDAR and the sonic anemometer.

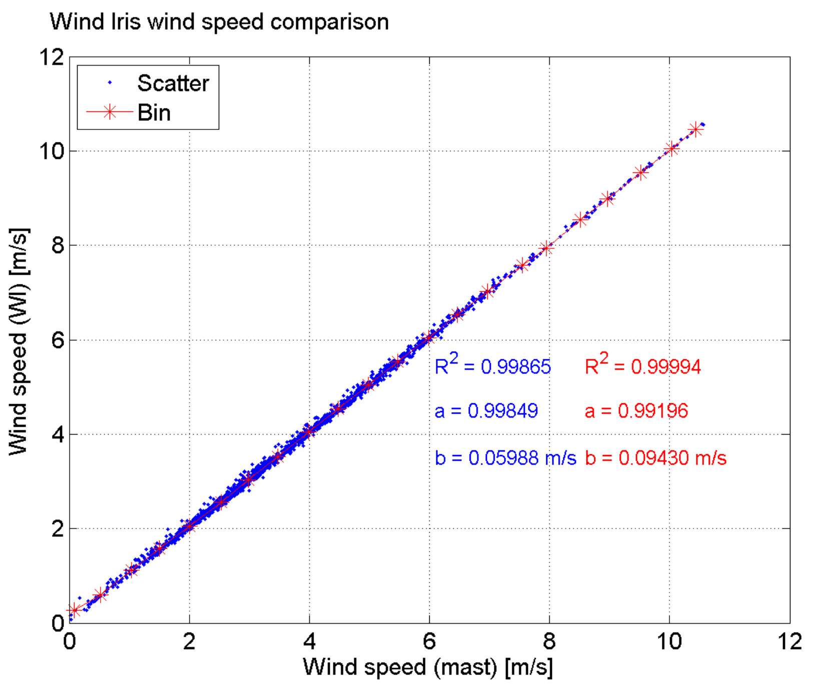
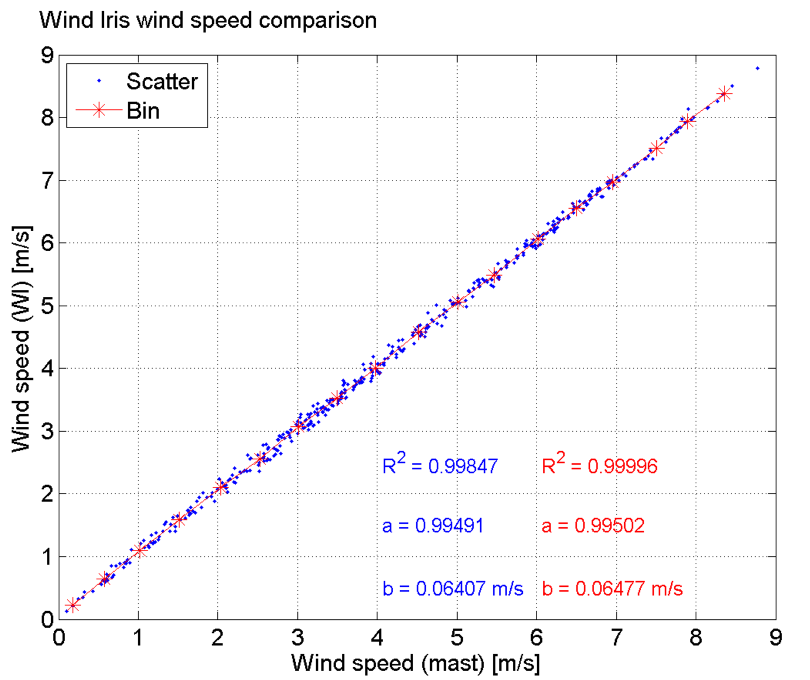


Figure 18: Wind speed comparison between the second beam (0) of the LiDAR and the sonic anemometer.



The deviation is defined as the nacelle LiDAR wind speed minus the mast wind speed. This deviation is shown in **Figure 19** and **Figure 20** as function of the (mast) wind speed respectively for the first and second beam.

The black lines indicate the uncertainty of the reference sensor added by the statistical uncertainty of each bin. The uncertainty of the reference sensor is determined in Chapter 5. The binned deviations are within these uncertainty limits.

Figure 19: Wind speed deviation between LIDAR and sonic anemometer measurements with respect to the sonic wind speed measurement, first beam (1).

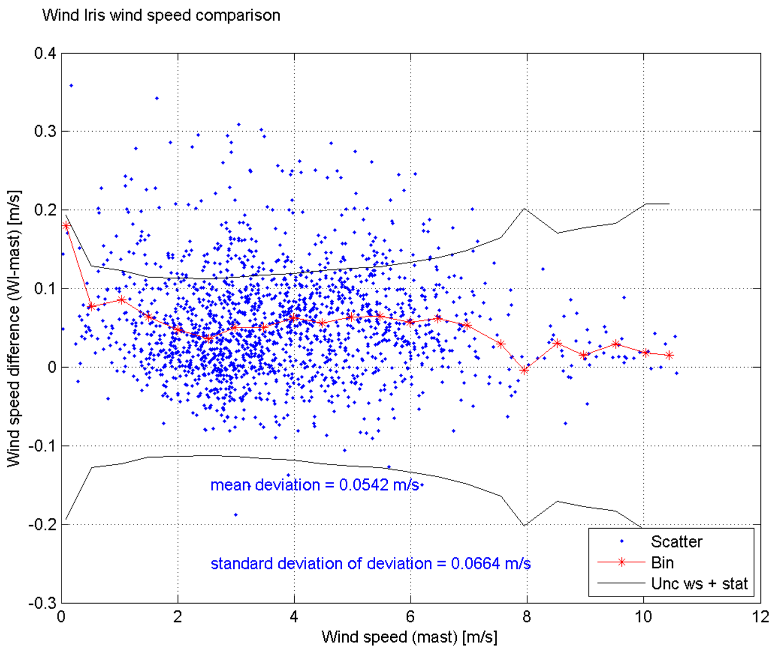
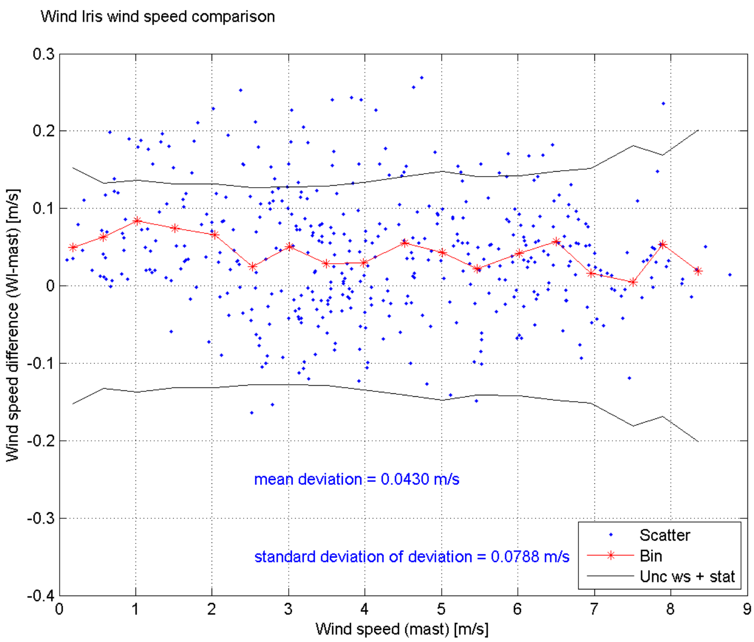


Figure 20: Wind speed deviation between LIDAR and sonic anemometer measurements with respect to the sonic wind speed measurement, second beam (0).



4.1.3 LiDAR uncertainty

The uncertainty of the calibrated LiDAR needs to be assessed. In order to do so, the regression parameters resulting from the linear fit on the binned wind speed values are used to calibrate the nacelle LiDAR and the wind speed comparison is performed again. This procedure is allowed according to [5].

The considered uncertainty contributions are the following:

- The uncertainty of the reference sonic anemometer (see Chapter 5).
- The binned average deviation.
- The standard deviation of the binned deviation.
- The mounting uncertainty
    - One part is the uncertainty in the mounting of the gun sight on the machine leading to an uncertainty in the orientation of the beam. However, because the beam should be pointed 'close to' the sonic anemometer it is save to neglect this contribution.
    - A second part is the uncertainty in the definition of the sonic wind speed projection (although one might also argue to consider this is as a reference anemometer uncertainty contribution). In this definition (see section 3.2.2) several angles are determined based on laser distance measurements. The uncertainties in those measurements have not been quantified. Instead an overall sonic wind speed project uncertainty of 0.5% of the wind speed is assumed.

The wind vanes at 60m are used to measure the wind direction based on which the sector selection for the wind speed comparison is done. A sector of 90 degrees is chosen which is a trade-off between accuracy, i.e. better alignment of the wind and the LiDAR beam, on the one hand and number of data points on the other hand. Therefore, the uncertainty in the wind direction, typically a few degrees, is reflected in the statistical uncertainty of the comparison (standard deviation of the binned deviation). In this respect the wind direction uncertainty is not further treated and specified as it is assumed to be incorporated already.

The system combines the two beams to come to an overall horizontal wind speed. In doing so an assumption is made on the homogeneity of the wind field over the beam separation. Although the beam separation angle can be taken into account in the uncertainty budget – [1] has shown that this contribution is negligible – the wind field homogeneity assumption effect will differ from site to site. This effect is not taken into account in this analysis.

The uncertainty contributions for the two beams are respectively listed in **Table 2** and **Table 3**.

Table 2: Wind speed bin means, uncertainty contributions and total WI wind speed uncertainty, first beam (1).

Wind speed [m/s]	Reference sensor uncertainty [m/s]	Mean deviation [m/s]	Statistical uncertainty [m/s]	Mounting uncertainty [m/s]	Total uncertainty [m/s]	Total uncertainty [%]
0.16	0.050	-0.015	0.057	0.001	0.078	48.19
0.58	0.051	0.001	0.037	0.003	0.063	10.85
1.04	0.052	0.024	0.040	0.005	0.070	6.76
1.53	0.055	0.017	0.034	0.008	0.067	4.39
2.05	0.058	0.012	0.032	0.010	0.068	3.31
2.50	0.062	-0.028	0.026	0.012	0.074	2.94
3.02	0.066	0.001	0.025	0.015	0.073	2.40
3.48	0.071	-0.018	0.024	0.017	0.079	2.27
3.96	0.076	-0.016	0.027	0.020	0.085	2.14
4.53	0.082	0.013	0.032	0.023	0.092	2.04
5.02	0.088	0.003	0.037	0.025	0.099	1.97
5.45	0.093	-0.016	0.027	0.027	0.102	1.88
6.03	0.100	0.007	0.026	0.030	0.108	1.80
6.53	0.107	0.025	0.029	0.033	0.118	1.81
6.94	0.112	-0.014	0.030	0.035	0.122	1.76
7.48	0.119	-0.022	0.057	0.037	0.139	1.86
7.92	0.125	0.028	0.042	0.040	0.141	1.78
8.35	0.131	-0.004	0.072	0.042	0.155	1.86

Table 3: Wind speed bin means, uncertainty contributions and total WI wind speed uncertainty, second beam (0).

Wind speed [m/s]	Reference sensor uncertainty [m/s]	Mean deviation [m/s]	Statistical uncertainty [m/s]	Mounting uncertainty [m/s]	Total uncertainty [m/s]	Total uncertainty [%]
0.17	0.050	0.087	0.099	0.001	0.141	81.79
0.51	0.051	-0.013	0.033	0.003	0.062	12.11
1.03	0.052	0.000	0.027	0.005	0.059	5.69
1.49	0.054	-0.018	0.016	0.007	0.060	4.04
1.98	0.058	-0.031	0.014	0.010	0.067	3.41
2.49	0.062	-0.038	0.011	0.012	0.074	2.99
2.97	0.066	-0.020	0.011	0.015	0.071	2.40
3.46	0.071	-0.016	0.012	0.017	0.075	2.18
3.99	0.076	0.000	0.012	0.020	0.080	2.00
4.48	0.082	-0.002	0.014	0.022	0.086	1.92
4.99	0.088	0.010	0.014	0.025	0.093	1.86
5.49	0.094	0.014	0.014	0.027	0.100	1.82
6.00	0.100	0.011	0.017	0.030	0.106	1.77
6.48	0.106	0.020	0.020	0.032	0.115	1.77
6.98	0.113	0.016	0.027	0.035	0.122	1.75
7.54	0.120	-0.004	0.040	0.038	0.132	1.75
7.91	0.125	-0.035	0.076	0.040	0.156	1.97
8.52	0.133	0.005	0.041	0.043	0.146	1.71
8.96	0.139	-0.007	0.045	0.045	0.153	1.70
9.52	0.147	0.011	0.047	0.048	0.161	1.70
10.04	0.154	0.005	0.069	0.050	0.176	1.75
10.44	0.159	0.005	0.066	0.052	0.180	1.72

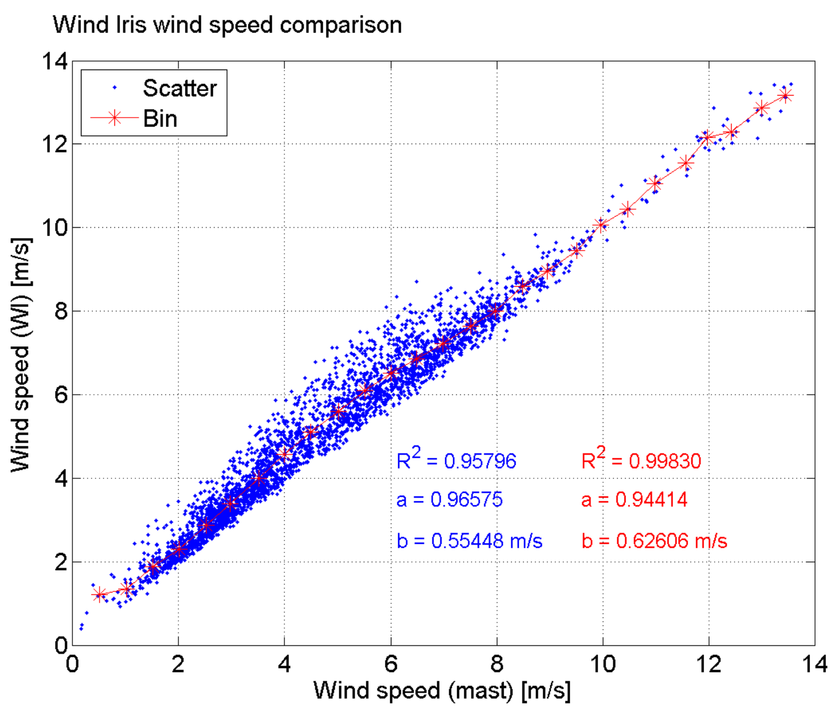
The results of the uncertainty analysis reveal that uncertainty of the calibrated LiDAR is at most 0.16m/s (at 8.35m/s) for beam 1 and 0.18m/s (at 10.44m/s) for beam 0. It is also seen that the calibration has a lowering effect on the uncertainty and that a large part of the nacelle LiDAR wind speed uncertainty is due to the reference sonic wind speed uncertainty itself. On average, the uncertainty of the nacelle LiDAR wind speed is about 11% (beam 0) and 15% (beam 1) higher than the uncertainty of the reference sonic sonic speed.

4.2 Black box calibration

In this paragraph, the results from the black box calibration is reported. The LiDAR measurement for the wind speed is compared with the wind speed as measured with the sonic anemometer on the MM2. Given the tilt angle for the measurement between the LiDAR and the sonic anemometer, the wind speed measurement from the mast is projected along the LiDAR central direction, in other words, the beams are on either side of the mast. The total data set is 6034 data points, where a data point is a 10 minute averaged value. Besides the direct comparison, the data are also binned in bins of 0.5m/s according to the mast measurements with bin centers at every half integer wind speed. The results are reported in **Figure 21**.

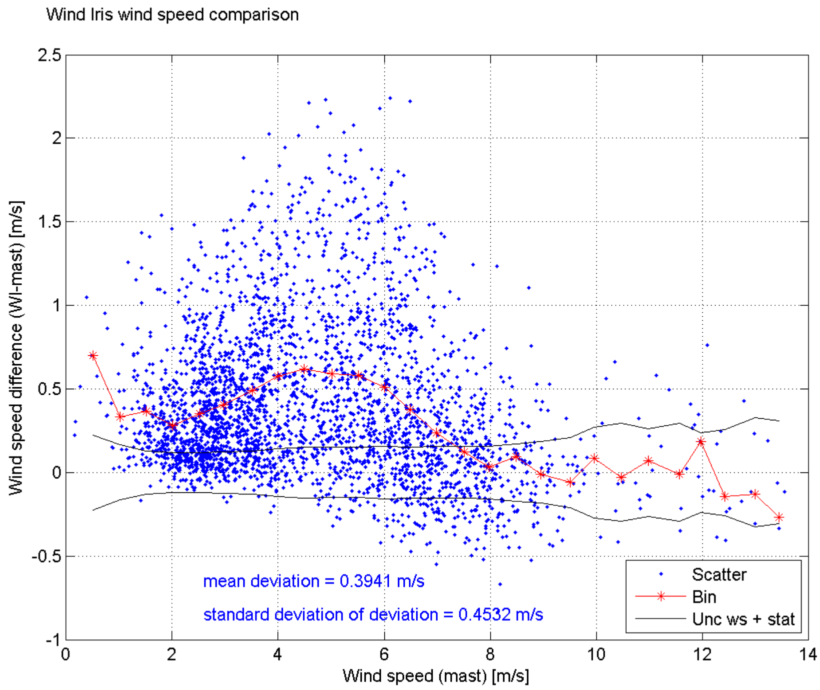
A linear fit is made on the scatter data (10 minute averages) as well as on the binned data. The results of the comparisons and the fitting are also included in **Figure 21**.

Figure 21: Wind speed comparison between the LiDAR and the sonic anemometer.



The deviation is defined as the nacelle LiDAR wind speed minus the mast wind speed. This deviation is shown in **Figure 22** as function of the (mast) wind speed. The black lines indicate the uncertainty of the reference sensor added by the statistical uncertainty of each bin. The uncertainty of the reference sensor is determined in Chapter 5.

Figure 22: Wind speed deviation between LIDAR and sonic anemometer measurements with respect to the sonic wind speed measurement.



From both **Figure 21** and **Figure 22** it can be concluded that the comparison is less than what is found in section 4.1 and in [2,3]. Therefore, a detailed uncertainty analysis is omitted, here.

No clear indications for or obvious errors causing the observed behavior could be found in the individual steps of the black box approach from the ground. It is assumed that the implicit wind field homogeneity assumption of the system is to a lesser extent valid in this case. Here, the two measurement points are separated by a horizontal distance of about 100m at 23m height.

5

Uncertainty Analysis Reference

Uncertainties are calculated following international standards and regulations [5]. In this chapter the uncertainties of the reference wind speed measurements on the mast are quantified.

Following the recommendations in [5], five sources of uncertainty in the wind speed measurements are identified:

- Uncertainty due to calibration $u_{V1,i}$
- Uncertainty due to operational characteristics $u_{V2,i}$
- Uncertainty due to mounting effects $u_{V3,i}$
- Uncertainty due to terrain effects $u_{V4,i}$
- Uncertainty due to of the sensor according the specifications $u_{V5,i}$

Uncertainty due to calibration:

The sonic anemometer is calibrated in a MEASNET wind tunnel. The uncertainty in the wind speed is assumed to 0.05m/s.

$u_{V1,i}$ = 0.05 m/s.

Uncertainty due to operational characteristics:

The anemometer is a digital sonic anemometer and therefore this uncertainty is null.

$u_{V2,i}$ = 0 m/s.

Uncertainty due to mounting:

The sonic anemometer is a boom mounted anemometer. Following the guidelines in [5] the uncertainty due to flow around the boom is estimated to be less than 0.5 %.

$U_{V3\ boom,i} = 0.5\% * U$

Here, U is the wind speed.

According [5] the flow distortion around the mast should be less than 1.0%. In the given sector the anemometer never is the wake of the mast and only blockage effects need to be taken into account. It's assumed that the resulting uncertainty for flow effects around the mast is 0.5%.

$U_{V3\ mast,i} = 0.5\% * U$

The sonic anemometer itself also has structures influencing the flow. In line with [1] and considering a 90 degrees sector, this uncertainty contribution is assumed to be 0.5%
$U_{V3\ sonic,i} = 0.5\% * U$

It’s also assumed that these effects are independent so the resulting uncertainty for mounting effects is:
$u_{V3,i} = \sqrt{(U_{V3\ boom,i}{}^2 + U_{V3\ mast,i}{}^2 + U_{V3\ sonic,i}{}^2)} = \sqrt{(0.5\%^2 + 0.5\%^2 + 0.5\%^2)} * U = 0.87\% * U$
$u_{V3,i} = 0.87\% * U$.

Uncertainty due to terrain:
It is estimated that horizontal difference in the locations of the wind speed measurements (mast and nacelle LiDAR), possibly influenced by the terrain, are negligible.
$u_{V4,i} = 0$.

Uncertainty of the sensor according the specifications
The uncertainty in the wind speed of the instrument (Metek) is:
$u_{V5,i} = 0.02 * U/\sqrt{3}$.

6

Conclusions and Discussion

6.1 Conclusions on calibration

In this section the main conclusions are drawn.

Tilt and Roll calibration

A tilt and roll calibration has been performed and the following values are found:
Tilt: a=1.0678, b=-0.2517 degrees, R^2=0.9993
Roll: a=1.018, b=0.1295 degrees, R^2=0.9987
In addition, the opening angle of the two beams has been determined to be 29.96 degrees.

Wind speed calibration; white box

In the white box approach each beam has separately been oriented towards a calibrated sonic anemometer mounted in a meteorological mast at a height of 23m and at a distance of 205m. The results of the comparisons show that the measured mast wind speeds and LiDAR wind speeds compare very well. The regression parameters on the binned values are:
Beam 1: a=0.99196, b=0.09430m/s, R^2=0.99994
Beam 2: a=0.99502, b=0.06477m/s, R^2=0.99996
In addition, the deviations, i.e. the binned differences between the nacelle LiDAR wind speed and sonic wind speed data, do not exceed the set uncertainty limits.

The results of the uncertainty analysis reveal that uncertainty of the calibrated LiDAR is at most 0.16m/s (at 8.35m/s) for beam 1 and 0.18m/s (at 10.44m/s) for beam 0. It is also seen that the calibration has a lowering effect on the uncertainty and that a large part of the nacelle LiDAR wind speed uncertainty is due to the reference sonic wind speed uncertainty itself. On average, the uncertainty of the nacelle LiDAR wind speed is about 11% (beam 0) and 15% (beam 1) higher than the uncertainty of the reference sonic wind speed.

With this calibration the wind speed measurements of the Wind Iris nacelle LiDAR with serial number C400114 are traced back to standard units and its uncertainties have been quantified both according to ISO 17025.

Wind speed calibration; black box

In the black box approach the nacelle LiDAR's central line is oriented towards the mast, in other words, the beams are on either side of the mast. It is concluded that the comparison shows more scatter and outliers than what is found for the white box calibration. No clear indications or obvious errors causing the observed behavior could be found in the individual steps of the approach. Also, malfunctioning of the LiDAR is excluded as the LiDAR has shown good performance in the white box calibration. Therefore, it is assumed that the implicit wind field homogeneity assumption of the system is to a lesser extent valid in this case. Here, the two measurement points are separated by a horizontal distance of about 100m at 23m height. Most probably turbulence generated at the surface causes that the wind is less homogeneous at 23m than it is for instance at hub height (80m). Therefore, the black box approach apparently is less suitable at this height.

6.2 Discussion on White box vs Black box

In this report both the white box and the black box approach from the ground have been considered. In an earlier report the black box approach from a nacelle of a wind turbine had been considered. Here, we compare these approaches.

It is already clear from this report that the black box approach from the ground was less successful than the white box approach. Most likely this is due to the inhomogeneity of the wind field over 100m horizontal separation at a height of 23m, caused by turbulence at the surface. For comparison, the black box approach from the nacelle, with a horizontal beam separation of 100m at 80m height, did show good results. It is therefore advised to apply the black box approach at sufficient height, where the wind field is sufficiently homogeneous, say for instance hub height.

Considering the white box from the ground and the black box from the nacelle it is seen that both the regression results and the uncertainty values are much alike. So, the difference is not so much in the results, but in the approach.

In the black box approach from the turbine the dynamics of the turbine and the wind field variation over the measurement sector is incorporated in the comparison. Therefore, this approach is more dependent on local conditions and settings as compared to the white box approach.

Practically speaking it is anticipated that the black box approach will be used as a validation step prior to for instance a power performance campaign on a wind turbine and with a meteorological mast present at site.

It is concluded that the white box approach from the ground is less sensitive to local conditions and less dependent on the application of the system. This is considered as a great advantage.

Costs aspects have not been considered in great detail. However, it is noted that both white box approach and the black box approach from the nacelle have a labour intensive component, namely, the beam detection and the installation/dismantling, respectively. The wind speed measurements themselves are matter of data taking. In this respect it is acknowledged that the more beams a system has the longer the white box calibration takes.

Bibliography

[1] M. Courtney, Calibrating Nacelle Lidars, Roskilde, Denmark, 2013.

[2] J.W. Wagenaar, S. Davoust, A. Medawar, G. Coubard-Millet, K. Boorsma, in:, EWEA 2014 Conf., European Wind Energy Association, Barcelona, Spain, 2014.

[3] J.W. Wagenaar, G. Bergman, Wind Iris Nacelle LiDAR Validation against Meteorological Mast 3 at the ECN Test Site, Petten, the Netherlands, 2015.

[4] E.J. Werkhoven, J.W. Wagenaar, Calibration of Avent Wind Iris nacelle LiDAR system, measurement plan, ECN-WIND-2016-099, 2016.
C. van Diggelen, LiDAR Calibration Facility at EWTW, instrumentation report, ECN-X-16-119, 2016

[5] FDIS IEC 61400-12-1 Wind turbines - Part 12-1 Power performance measurements of electricity producing wind turbines, IEC, 2016.

Appendix A. Calibration certificate

DEWS6085

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

Deutsche WindGuard

akkreditiert durch die / *accredited by the*

Deutsche Akkreditierungsstelle GmbH

als Kalibrierlaboratorium im / *as calibration laboratory in the*

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

Deutschen Kalibrierdienst DKD

Kalibrierschein
Calibration certificate

Calibration mark 22183 / D-K-15140-01-00 / 04/2012

Gegenstand *Object*	Sonic Anemometer
Hersteller *Manufacturer*	METEK GmbH D-25337 Elmshorn
Typ *Type*	uSonic-3 Sci Basic
Fabrikat/Serien-Nr. *Serial number*	0105033458
Auftraggeber *Customer*	METEK GmbH D-25337 Elmshorn
Auftragsnummer *Order No.*	VT120524
Anzahl der Seiten des Kalibrierscheines *Number of pages of the certificate*	3
Datum der Kalibrierung *Date of calibration*	16.04.2012

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.

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*
26.04.2012	Dipl. Phys. D. Westermann	Dipl.-Ing. (FH) Catharina Herold

Seite 2
Page

22183
D-K-15140-01-00
04/2012

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]	220 cm²	
	diameter of mounting pipe [3]	50 mm	
	blockage ratio [4]	0.022 [-]	
	blockage correction [5]	1.000 [-]	
Umgebungsbedingungen *Test conditions*	air temperature	20.6 °C	± 0.1 K
	air pressure	1019.0 hPa	± 0.3 hPa
	relative air humidity	39.2 %	± 2.0 %
Akkreditierung *Accreditation*	05/2011		
Anmerkungen *Remarks*	Orientation: 180 deg		
Auswertesoftware *Software version*	7.0		

[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

Kalibrierergebnis:
Result:

File:	22183				
Bin	Tunnel Speed	U	V	W	Unc
-	m/s	cm/s	cm/s	cm/s	m/s
1	3.82	391.608	16.848	-6.848	0.05
2	6.05	616.248	20.866	-9.701	0.05
3	8.18	829.611	16.611	-15.051	0.05
4	10.21	1031.443	9.475	-19.848	0.05
5	12.19	1225.070	-0.310	-24.051	0.05
6	14.18	1421.747	-4.487	-26.949	0.05
7	15.94	1596.905	-5.810	-25.165	0.05
8	14.96	1498.886	-5.639	-25.354	0.05
9	13.18	1322.038	-2.196	-23.025	0.05
10	11.23	1128.089	5.297	-18.570	0.05
11	9.21	927.121	13.726	-13.471	0.05
12	7.18	725.937	20.772	-9.285	0.05
13	4.94	499.829	20.892	-6.310	0.05

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.

Appendix B. Wind Iris specifications

Wind iris

Technical specifications

Functional

	Accurate performance monitoring mode	High frequency turbulence and control mode
Range	80 to 400 meters	40 to 200 meters
Probed length	60 meters	30 meters
Data sampling rate	1 - 2,5Hz	1 - 8Hz
Laser source	Fiber pulsed laser 1,54µm	
Number of measuring distances	10	
Speed accuracy	0.1m/s	
Speed range	-10 to +40m/s	
Direction accuracy	+/- 0,5°	
Scanning angle	15°, 30° half angle (custom angles upon request)	
Leveling accuracy	+/- 0,05°	
Window cleaning device	Patented non-mechanical wiper	

Operational

Optical Head	L81cm, W54cm, H33cm	30kg
Processing unit	L71cm, W33cm, H59cm	37kg
Tripod	Hmin 68cm, Hmax 82cm	15kg
Cable length	7 meters	
Temperature range	-30°C to +60°C	
Operation humidity	0 to 100% (splash water and marine environment resistant)	
Power supply	120 - 240VAC (50/60Hz)	
Power consumption	350 Watts	
Communication ports	CAN Bus, RJ45	
Communication protocol	TCP/IP, CAN / CAN Open available	
Data storage	> 6 months (128 GB SSD) MySQL database access	

Contact us to discuss which configuration is best for you!

Options

3G Iris
Remote access to the Wind Iris from any location

CAN Bus / CAN Open
Customization and other interfaces upon request

Warranty extensions
Up to 3 years for peace of mind

Longer cable
10m to provide additional flexibility for larger turbines

Mounting bracket
Ideal for mounting the processing unit to optimize space

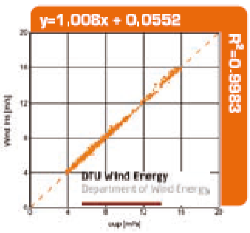
Quality commitment

We have implemented a Quality System that documents our R&D, Manufacturing and Customer Service practices. This ensures our customers and partners that our products and services comply with international regulatory certifications and consistently meet our standards of excellence.

Certifications

Laser classification	Class 1
Eye safety	IEC 60825-1
Housing	IEC 60529, IP65 (optical head), IP64 (processing unit)
Shocks & vibrations	IEC 60068-2
EMC & Lightning	IEC 61326-1, IEC 62311, IEC 61000-4, FCC part 15
Electrical safety	IEC 61010-1
Other tests completed	Wind tunnel test, cold temperatures, snow, freezing rain

Download full studies and find out more at aventlidartechnology.com



Validation of the Wind Iris against IEC 61400-12-1 met mast[1]

[1] Nacelle Lidar power performance measurement in the context of the IEC 61400-12-1 standard, R. Wagner et al. EWEA Offshore 2011.

	Date: September 2016	Number of report: ECN-X--16-116
Title	Wind Iris nacelle LiDAR calibration at the ECN test site	
Author(s)	J.W. Wagenaar, G. Bedon, E.J. Werkhoven and C. van Diggelen	
Principal(s) TKI Wind op Zee		
ECN project number **Principals' order number**	5.2241 TKIWO1006	
Programme(s)	Facilities and Experiments	

Abstract

A tilt and roll calibration has been performed and the following values are found:

Tilt: a=1.0678, b=-0.2517 degrees, R^2=0.9993

Roll: a=1.0180, b=0.1295 degrees, R^2=0.9987

In addition, the opening and the opening angle of the two beams has been determined to be 29.96 degrees.

The results for the white box approach show that the measured mast wind speeds and LiDAR wind speeds compare very well. The regression parameters on the binned values are:

Beam 1: a=0.99196, b=0.09430m/s, R^2=0.99994

Beam 2: a=0.99502, b=0.06477m/s, R^2=0.99996

In addition, the deviations, i.e. the binned differences between the nacelle LiDAR wind speed and sonic wind speed data, do not exceed the set uncertainty limits.

The results for the black box approach are not as good as compared to the white box approach. Most probably this is due to wind field inhomogeneity at the considered height.

Key words: Wind Iris, nacelle LiDAR calibration, Avent Lidar Technology, White box Black box, ECN test site EWTW, meteorological mast 2

Authorization	Name		Signature	Date
Checked	K. Boorsma	Project manager	i.o. [signature]	22-9-2016
Approved	M. van Roermund	Group manager	[signature]	22-9-2016
Authorized	A. van der Pal	Unit director	[signature]	22/9/2016

ECN

Westerduinweg 3
1755 LE Petten
The Netherlands

P.O. Box 1
1755 LG Petten
The Netherlands

T +31 88 515 4949
F +31 88 515 8338
info@ ecn.nl
www.ecn.nl