DTU Wind Energy LC I-167 (EN)

Calibration of ground-based lidar instrument: WLS866-26

Østerild Test Site

Denmark

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Abstract

This report presents the result of the lidar calibration performed for the Windcube WLS866-26 at DTU's test site for large wind turbine at Østerild, Denmark. Calibration is here understood as the establishment of a relation between the reference wind speed measurements with measurement uncertainties provided by measurement standard and corresponding lidar wind speed indications with associated measurement uncertainties. The lidar calibration concerns the 10 minute mean wind speed measurements. The comparison of the lidar measurements of the wind direction with that from wind vanes measurements are given for information only.

The evaluated data cover the measurement period from 17-12-2019 18:00 to 28-01-2020 00:00.

The tested lidar is of the type Windcube v2 Offshore 8.66, and the data used in this report is the not motion-compensated data.

Total number of pages: 27

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1. Test site and instrumentation

1.1 Location of test site

The calibration was performed at the Danish National Test Station for Large Wind Turbines, located at Østerild in Northern Jutland. The location of the Østerild test site is shown in the map in Figure 1. The test site consists of seven test pads and associated meteorological masts, as well as two 245m light masts, one at the north end and another at the south end. The row of wind turbine stands is aligned in the North-South direction. The distance between the wind turbine test pads is 600m and the distance between the meteorological masts and test pads ranges from 380m to 500m.

Figure 1 Location of Østerild test site in Northern Jutland.

Figure 2 Photograph of the Østerild test station, taken from light mast south, towards North, with stand 6 on the foreground, and stand 1 on the background (year 2012).

1.2 Terrain description

The test site at Østerild is a close to flat site with grasslands, and forests in the southern half of the test site, with canopy heights between 10m and 20m. The terrain variations in the majority of the area are less than 5m, with slightly higher variations (in the order of magnitude of 10m) towards the north end. From the north end of the test station, the North Sea coast is at a distance of 3.9km. From the south end of the test station, Limfjord is at a distance of 6km.

The only relevant obstacles in the area are a row of eight wind turbines 2.8km west from test pad 6, another row of four wind turbines 2.3km east from test pad 4, some buildings in the vicinity of test pad 3, and a building 1.8km west from test pad 7.

1.3 Location of tested lidar

The lidar was placed 14 m west of the light mast north. The distance and lidar offset were selected in order to maximize the correlation between lidar and reference measurements while avoiding the laser beams to hit the mast and its wires for any azimuth position.

A sketch of the placement of the tested lidar relative to the met mast is shown in Figure 3. The distance to the closest turbine is illustrated in Figure 4.

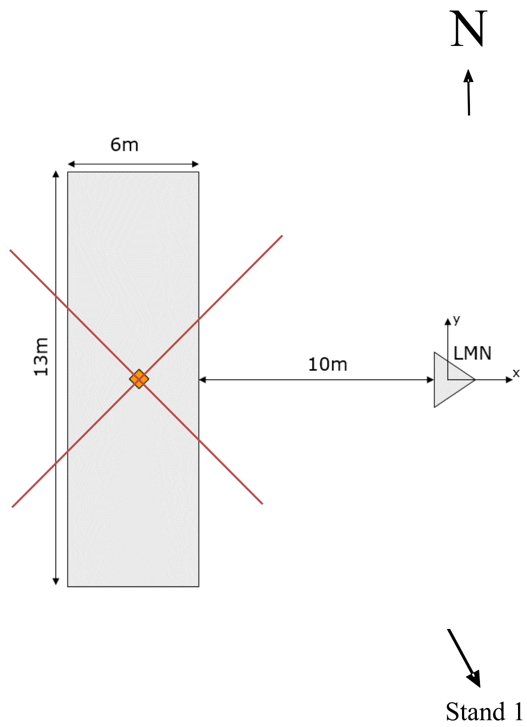


Figure 3 Sketch of lidar position (and the laser line-of-sights) relative to the met. mast. The lidars are located ~14 m to the west from the mast center. Beam directions are offset by about 45˚ relative to north-south.

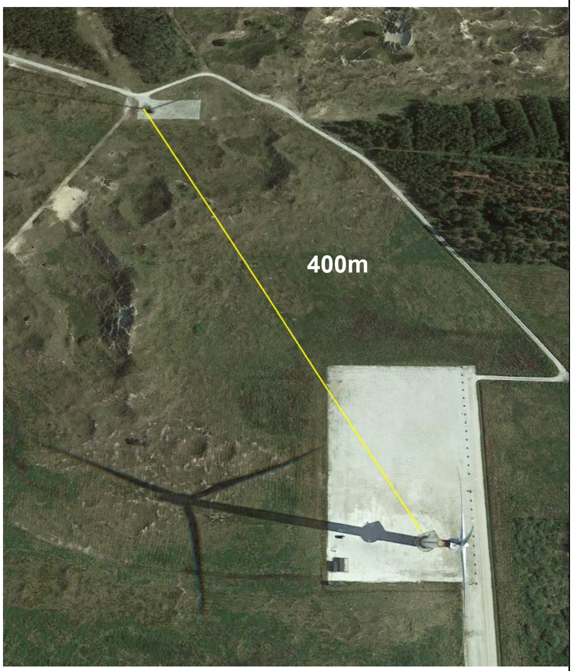


Figure 4 Distance between light. mast north and wind turbine at test stand 1 (picture from Google Earth).

The lidar was leveled in order to be horizontal by adjusting the lengths of the four lidar legs. The position and mounting (as given in the data files for the corresponding days) are as given in the following table.

Table 1 Installation parameters at three different times during the measurement campaign

Date	*Position N [°]*	*Position E [°]*	*Pitch [°]*	*Roll [°]*	*Direction offset [°]*	*Software version*
20/12/2019	57.087055	8.880480	-	-	45	2.1.9
05/01/2020	57.087050	8.880478	-	-	45	2.1.9
22/01/2020	57.087100	8.880545	-	-	45	2.1.9

Pitch and roll are not reported on the statistical files of a WLS866, the gyroscope files were not inspected. At installation and during the measurements the pitch and roll are controlled to be below 0.3°.

1.4 Instrumentation of reference mast

The lidar measurements are compared with reference wind speeds and wind directions that are measured at the met. mast, i.e. the reference mast. The purpose of this mast has been to supplement the wind measurements at the turbine test stands, providing additional information about the climatology at Østerild as well as meteorological data for boundary layer research. Due to the high quality of the instrumentation, maintenance and quality control, the data from this mast are well suited for the calibration of lidars.

Sensors used as references are the four cup anemometers, placed at 40 m, 106 m, 178 m, and 244 m height, two sonic anemometers at 103 m and 175 m, and two wind vanes at 40 m and 244 m. The cups at 10 m, 40 m, 70 m, 106 m, 140 m, 178 m, 210 m, and 244 m are used to calculate the wind shear and obtain the sensing height error from the three parametric fit.

The wind speed and direction measurements are complemented by temperature (temperature sensors at 37 m, 103 m, 175 m and 241 m) used for filtering the data (see details in section 2).

The entire instrumentation of the met mast is shown in a sketch in Figure 5.

Installation procedures and location of instruments on masts are covered by the quality manual procedure for power curve measurements and application instructions for anemometers and for wind vanes. The description for the system set-up of all the reference instruments is covered by the other accreditation areas (QI 7.4.3, QI 7.4.4, QP 8.12 and QP8.1).

1.5 Measurement sector

The valid measurement sector for the calibration test results as follows. Wind data from the southern sector (±45 deg) are excluded from the analysis due to wakes from the turbines south of the met. mast, affecting both the lidar and the mast measurements. Since the reference sensors are mounted on the north side of the mast, excluding the southern sector also removes the data for which the reference measurements are affected by the mast shadow.

Additionally, wind directions are excluded where the mast wake enters at least one of the beam directions of the lidar. For a Windcube™ with a cone angle of about 30˚, set up at the pre-defined lidar test stand, the resulting combined measurement sector is given by the west sector 240˚-300˚.

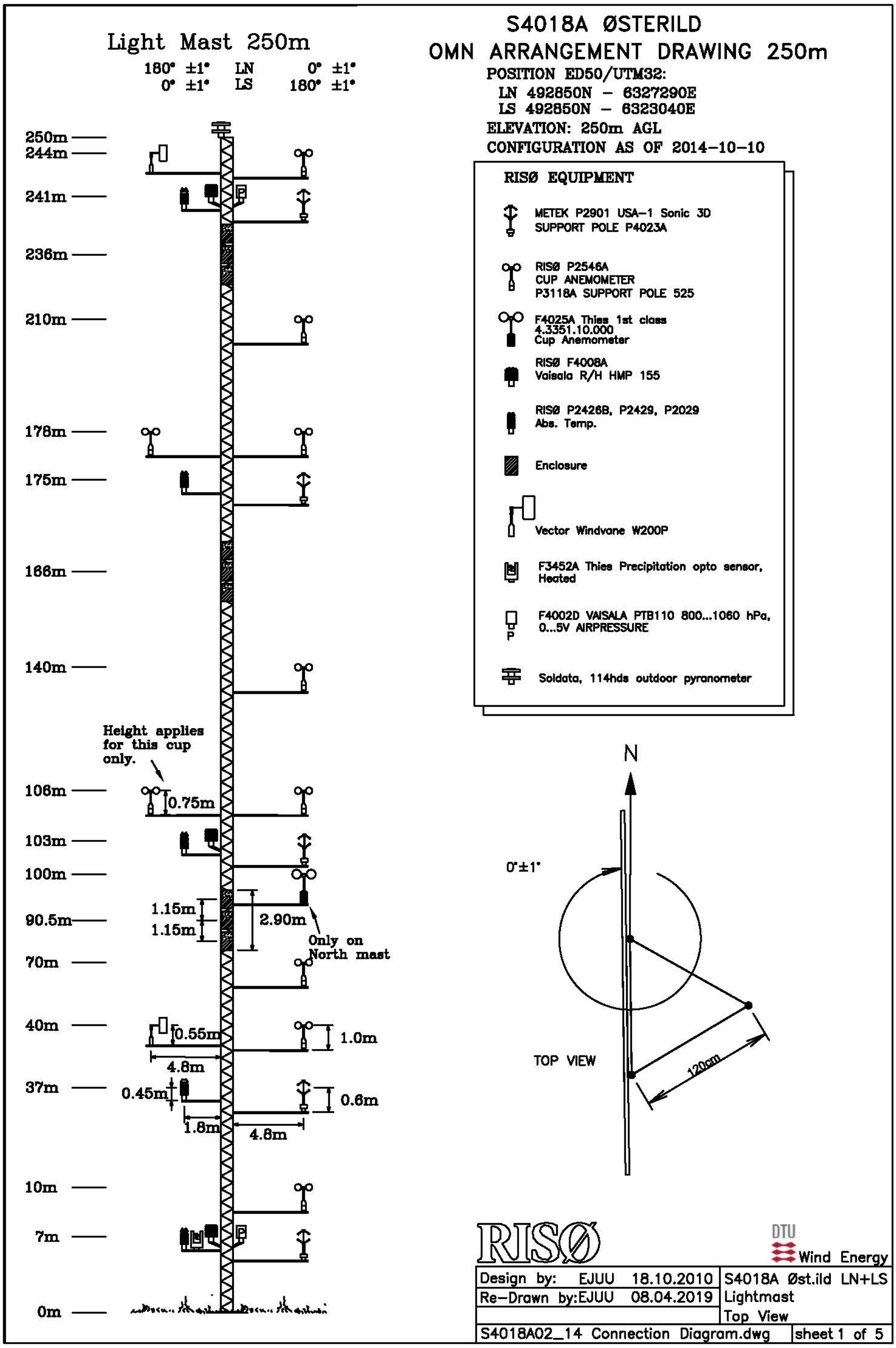


Figure 5 Sketch specifying the instrumentation of the met. mast.

1.6 Specifications of reference sensors

For the reference wind speed measurements, WindSensor P2546a cup anemometers are used. They are all classified as class 1A instruments and calibrated according to the respective MEASNET standard (see http://www.cupanemometer.com/products.htm for more details). Specifications of all used reference sensors are given in Table 2.

Table 2 Specifications of reference sensors used in the lidar calibration

Parameter	Position	Sensor	Date installed	Date calibrated	Calibration place	Calibration check
wind speed	Light mast north **10 m** height	cup anemometer PFV reg. 2184	11/04/2019	18/01/2019	Deutsche WindGuard*	Yes
wind speed	Light mast north **40 m** height	cup anemometer PFV reg. 2338	11/04/2019	13/04/2018	Deutsche WindGuard*	Yes
wind speed	Light mast north **70 m** height	cup anemometer PFV reg. 2354	10/04/2019	13/04/2018	Deutsche WindGuard *	Yes
wind speed	Light mast north **106 m** height	cup anemometer PFV reg. 2362	10/04/2019	21/01/2019	Deutsche WindGuard *	Yes
wind speed	Light mast north **140 m** height	cup anemometer PFV reg. 2365	10/04/2019	21/01/2019	Deutsche WindGuard *	Yes
wind speed	Light mast north **178 m** height	cup anemometer PFV reg. 2460	10/04/2019	21/01/2019	Deutsche WindGuard *	Yes
wind speed	Light mast north **210 m** height	cup anemometer PFV reg. 2516	10/04/2019	21/01/2019	Deutsche WindGuard *	Yes
wind speed	Light mast north **244 m** height	cup anemometer PFV reg. 2640	10/04/2019	18-01-2019	Deutsche WindGuard *	Yes
wind direction	Light mast north **40 m** height	Wind vane PFV reg. 3203	10/05/2016			N/A
wind direction	Light mast north **103 m** height	Sonic anemometer PFV reg. 3231	10/05/2016			N/A
wind direction	Light mast north **175 m** height	Sonic anemometer PFV reg. 3232	10/05/2016			N/A
wind direction	Light mast north **244 m** height	Wind vane PFV reg. 3204	10/05/2016			N/A
Temperature	Light mast north **37 m** height	Temp. Sensor PFV reg. 3017	12/02/2019	22/12/2017	DTU*	Yes
Temperature	Light mast north **103 m** height	Temp. Sensor PFV reg. 3018	12/02/2019	22/12/2017	DTU*	Yes
Temperature	Light mast north **175 m** height	Temp. Sensor PFV reg. 3721	12/02/2019	11/09/2018	DTU*	Yes
Temperature	Light mast north **241 m** height	Temp. Sensor PFV reg. 3724	12/02/2019	11/09/2018	DTU*	Yes

*Accredited calibration laboratory

1.7 Time synchronization

The lidar and reference instruments data acquisition are synchronized to the same time server at least every hour. Possible time deviations are less than 10 s.

2. Procedure of calibration

The calibration is done according to procedure QP 8.15 “Calibration of ground based lidar”, and it is compliant with Annex L of IEC 6140012-1 Ed. 2 [1] with the following observations: the database completion criteria is reduced to 100hrs based on the site characteristics and our knowledge of the wind conditions based on nearly 10 years of meteorological measurements at the site and of the lidars being tested.

2.1 General concept

The lidar data (10 minute averages, data is not motion-compensated) are compared with the reference data from the cup anemometers at 40 m, 106 m, 178 m and 244 m for the wind speed analysis, and with the sonic anemometers at 103 m and 175 m and the wind vanes at 40 m and 244 m for the wind direction analysis. To maximise the comparability of the test data and the repeatability of the test, the sampled data are filtered before evaluation according to different criteria (described in section 2.2). Lidar and reference data – for mean wind speed and wind direction – are compared in terms of different types of regression approaches. In addition, an analysis of the lidar deviation, defined as the difference between the wind speed measured by the lidar and the reference sensor, is performed. The applied techniques of analysis are described in more detail in section 2.3.

2.2 Data filtering

To maximize comparability between the lidar and the reference measurements and repeatability between different instances of the test, the sampled data are filtered before evaluation according to the following set of well-defined filtering criteria.

A. Wind speed
Only 10 minute mean (reference) wind speeds within the interval 4-16 m/s are considered to be valid. This corresponds to the range of a standard cup anemometer calibration.

B. Wind direction
The wind sector 240 to 300 degrees was selected for all comparison heights as the reference cup anemometers as well as the lidar beams are free of any obstacle wakes. The data were selected according to the measurements of the wind vane at 40m for the comparison at 40m, the direction measurements of the sonic anemometer at 103m for the comparison at 106m, the direction measurements of the sonic anemometer at 175m for the comparison at 178m and the direction measurements of the wind vane at 244m for the comparison at 244m.

C. Icing of cup anemometers
All data with an absolute temperature below 2 ˚C are discarded in order to make sure the reference cup anemometers are not affected by any icing. The data were selected according to the measurements of the temperature sensor at 37m for the comparison at 40m, the measurements of the temperature sensor at 103m for the comparison at 106m, the measurements of the temperature sensor at 175m for the comparison at 178m and the measurements of the temperature sensor at 241m for the comparison at 244m.

D. Lidar availability
The availability parameter of the Windcube^{TM} has to give a value equal to or greater than 90% for each valid 10 minute period. This parameter indicates

- For a windcube V1 and a standard windcube V2: the availability shows how many samples in a 10-min period have passed a pre-defined threshold value of the signal strength (i.e. CNR: Carrier to Noise Ratio).
- For a buoy lidar: the availability shows how many samples in a 10-min period have passed a pre-defined CNR threshold value and have a valid measurement of the pitch and roll angles.

Additionally the following period were removed from the analysis:
- Acquisition failure: 21/Jan/2020 13:20 – 13:50

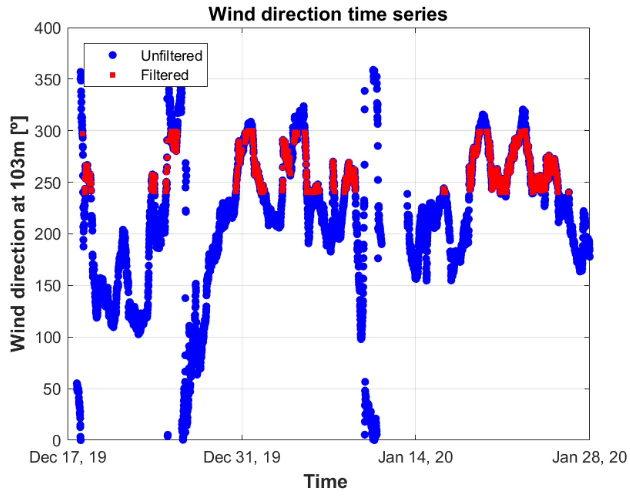


Figure 6 Wind direction (sonic anemometer) at 103m: all records (blue) and direction within the wind sector considered for the test (red).

Table 3 Absolute (and relative) number of samples remaining after the various filtering steps

Height	***Total***	***A***	***+B***	***+C***	***+D***
40m	5638	4989	1588	1588	1585
	100%	88%	28%	28%	28%
106m	5636	5128	1574	1574	1562
	100%	91%	28%	28%	28%
178m	5547	4767	1491	1491	1429
	100%	86%	27%	27%	26%
244m	5303	4125	1486	1486	1284
	100%	78%	28%	28%	24%

According to the internal procedure QP 8.15, the test is completed when 600 valid data points have been obtained at each height. It is furthermore required that there are at least 150 points in the range 4-8 m/s for the 106m level, and 150 points in the range 8-16 m/s for the 40m level. The demand for total valid data points is fulfilled at all heights. The demand for 150 points at low wind speeds at 106m and 150 points at high wind speeds at 40m was met as well. The properties of the filtered database obtained in this test are summarized in Table 4.

Table 4 Database properties

Parameter	***Requirement***	***Database***
Minimum number of data per height	600	1284
Number of data between 8-16m/s at 40m	150	770
Number of data between 4-8m/s at 106m	150	213

2.3 Data analysis (data evaluation and model of errors)

- Linear regression analysis for horizontal mean wind speeds (lidar wind speed vs. reference wind speed) with and without non-zero offset, i.e. applying the models $y = C + kx$ and $y = mx$ (with y lidar wind speed, x reference wind speed), gives estimates for the offset (C), the two regression slopes (k and m) and respective coefficients of determination (two different values for R^2).

- Calculation of the deviation between the lidar wind speed measurement and the reference wind speed measurement, for each 10 min data. Distribution of the deviation, calculation of the mean value and the standard deviation. For each wind speed bin of 0.5 m/s, calculation of the mean value of the deviation and the uncertainty term: $\pm 2u_{lidar}^{(2)}$. The definition of the lidar uncertainty is given in section 5. This uncertainty budget is used as an indication regarding the bias; it is considered large when the mean lidar deviation lies outside $\pm 2u_{lidar}^{(2)}$ (see figures 11c to 15c).

- Three-parametric regression analysis applying the model $y = D + k_u u + k_g g + k_{\sigma w} \sigma_w$, with y lidar wind speed, u reference wind speed, g wind gradient and σ_w the standard deviation of the vertical wind speed, gives estimates for the offset (D), the three slopes (k_u, k_g *and* $k_{\sigma w}$) and the respective coefficient of determination (R^2). It enables us to estimate the dependency of the lidar error on these three parameters, independently of each other.

  The local wind speed gradient is determined as the derivative of the vertical wind speed profile at the considered height, and it is derived on the basis of the cup anemometers wind speed measurements. The profiles measured are fitted to the following function: $wsp(z) = a + bz + cz^2 + dz^3 + e \ln(z)$ where z is the height. The wind gradient at the measurement height z_0 is then given by $g(z=z_0) = b + 2cz_0 + 3dz_0^2 + e/z_0$.

  The standard deviation of the vertical component of the wind speed is measured by the lidar.

  For information, the lidar error versus the local gradient on one hand and the vertical turbulence intensity on the other hand are displayed in two plots.

- Linear regression analysis for mean wind directions (lidar wind direction vs. reference wind direction) applying the model $y = C + kx$ (with y lidar wind direction and x reference wind direction), gives estimates for the offset (C), the regression slope (k) and the corresponding coefficient of determination (R^2).

3. Wind speed

3.1 Wind speed distributions:

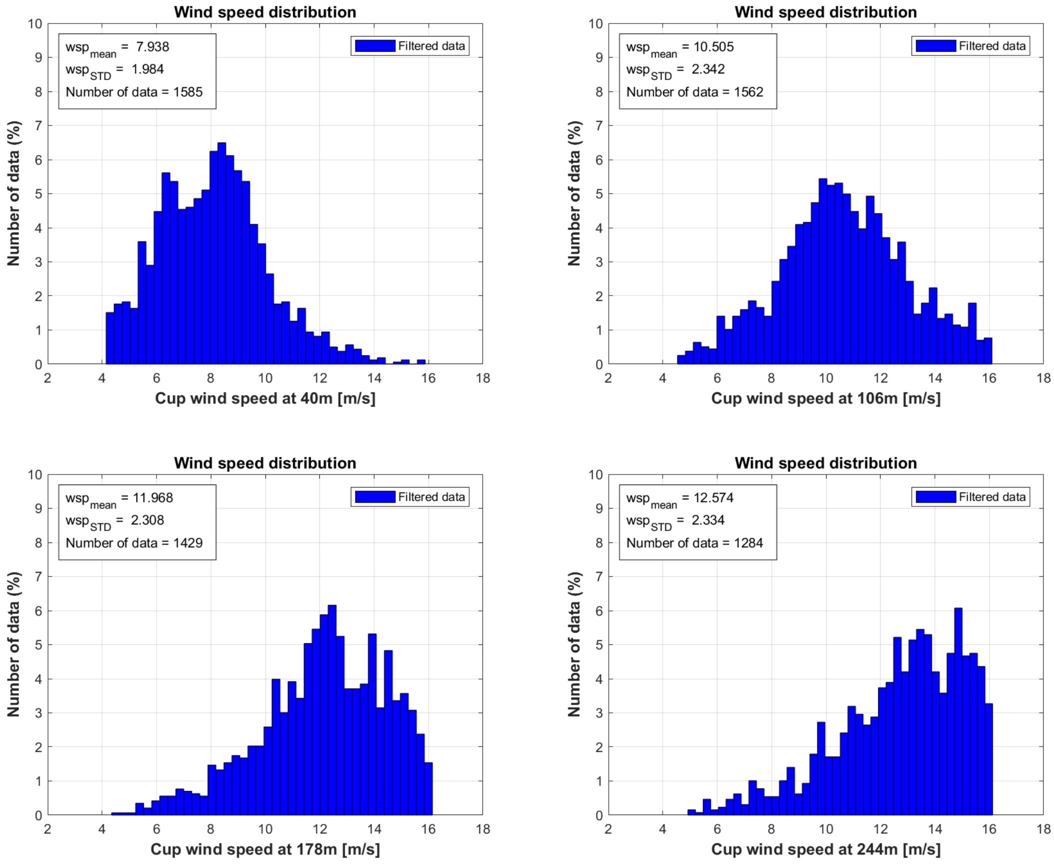


Figure 7 Distribution of the wind speed measured by the cup anemometer at each height.

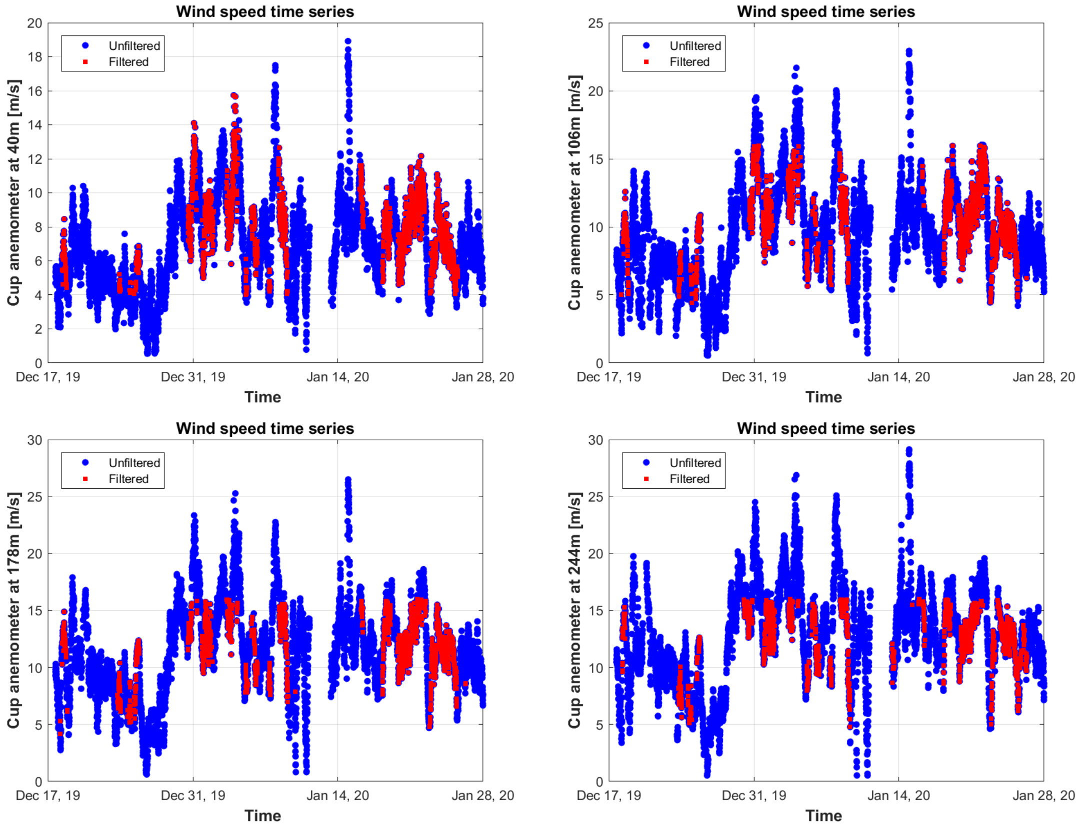


Figure 8 Time series of the wind speed measured by the cup anemometer at each height; all data (blue), and data remaining after complete filtering (red).

3.2 Ten minute mean wind speed at 40 m:

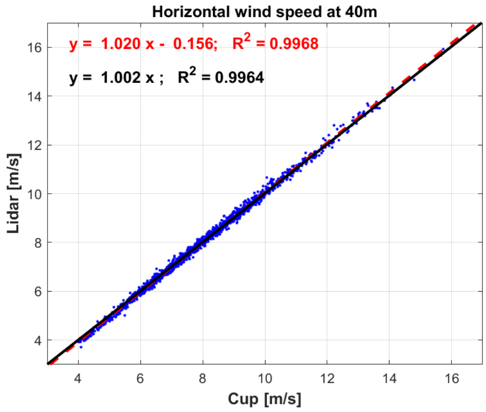


Figure 9.a 1-parametric regression between the 10 minute mean wind speed measurements from the Windcube at 40m and the cup anemometer at 40m.

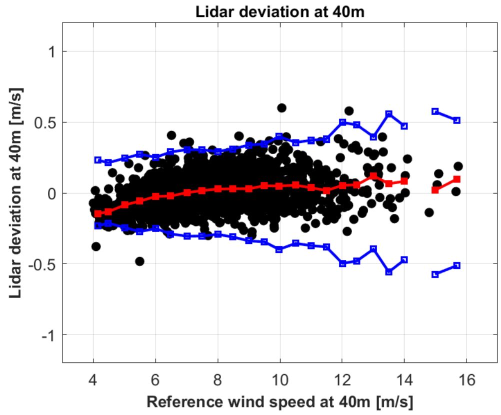


Figure 9.c Deviation at 40m versus reference wind speed. Each black dot represents a 10 min value; the red dots are the wind speed bin averages and the blue squares show $\pm 2u_{lidar}^{(2)}$*. The lines result from linear interpolation.*

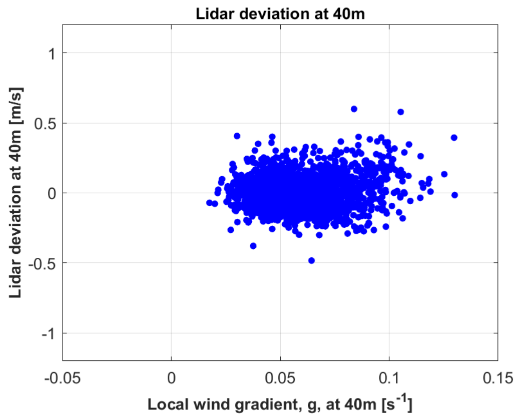


Figure 9.d Deviation at 40m versus local gradient at 40m

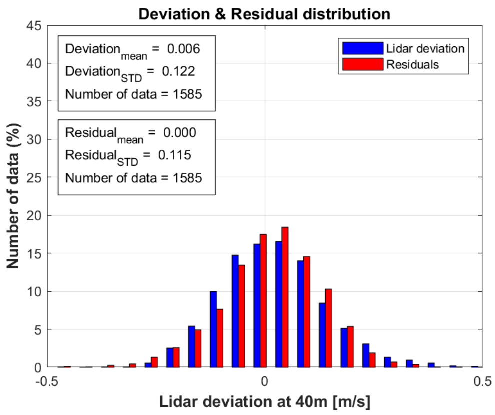


Figure 9.b Distribution of the deviation (blue) and the residuals in the 3-parametric regression (red); data after complete filtering

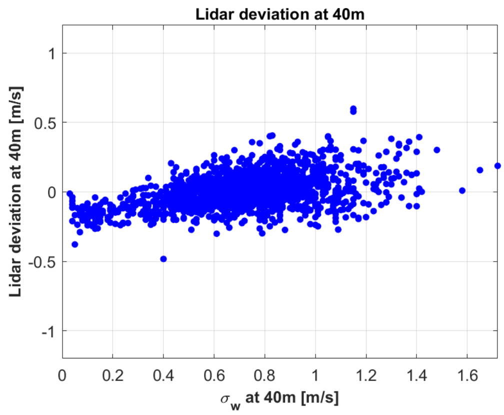


Figure 9.e Deviation at 40m versus standard deviation of vertical wind speed at 40m

Result of the 3-parametric regression:
$y = -0.071 + 0.974u + 0.050g + 0.386\sigma_w$
$R^2 = 0.9972$

3.3 Ten minute mean wind speed at 106:

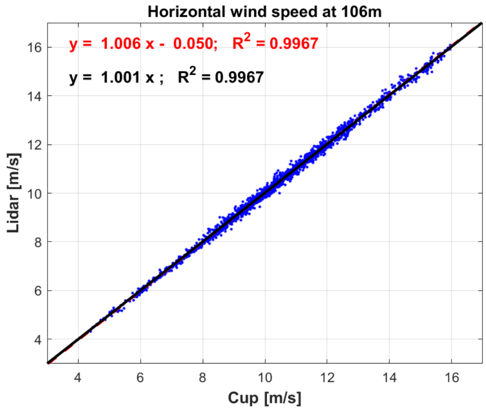


Figure 10.a 1-parametric regression between the 10 minute mean wind speed measurements from the Windcube at 106m and the cup anemometer at 106m.

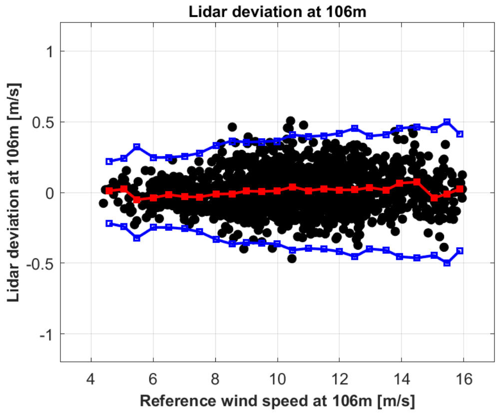


Figure 10.c Deviation at 106m versus reference wind speed. Each black dot represents a 10 min value; the red dots are the wind speed bin averages and the blue squares show $\pm 2u_{lidar}^{(2)}$*.The lines result from linear interpolation.*

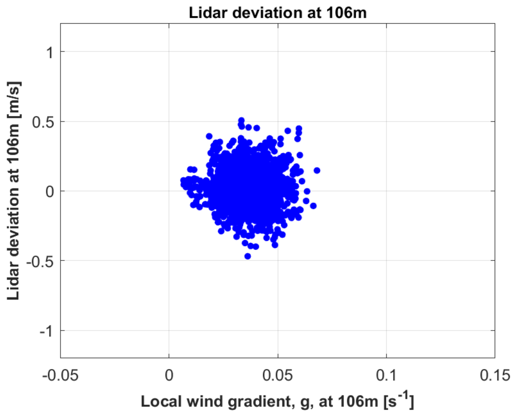


Figure 10.d Deviation at 106m versus local gradient at 106m

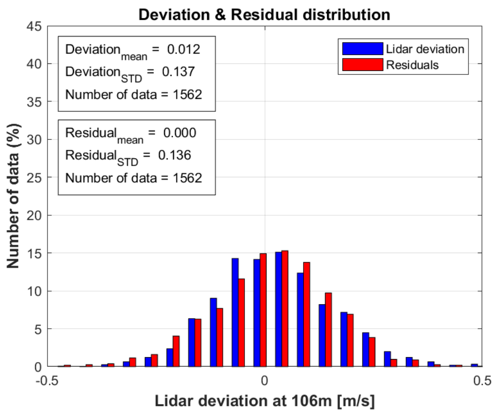


Figure 10.b Distribution of the deviation (blue) and the residuals in the 3-parametric regression (red); data after complete filtering

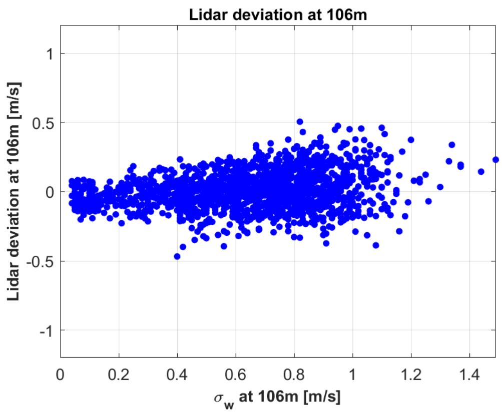


Figure 10.e Deviation at 106m versus standard deviation of vertical wind speed at 106m

Result of the 3-parametric regression:
$y = -0.001 + 0.99u - 0.229g + 0.196\sigma_w$
$R^2 = 0.9969$

3.4 Ten minute mean wind speed at 178 m:

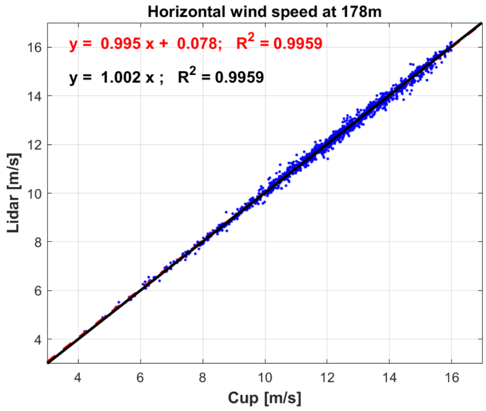


Figure 11.a 1-parametric regression between the 10 minute mean wind speed measurements from the Windcube at 178m and the cup anemometer at 178m.

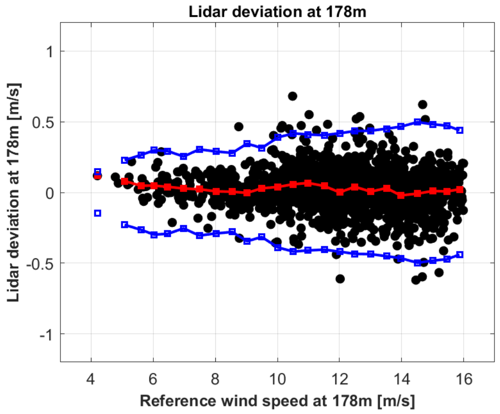


Figure 11.c Deviation at 178m versus reference wind speed. Each black dot represents a 10 min value; the red dots are the wind speed bin averages and the blue squares show $\pm 2u_{lidar}^{(2)}$*. The lines result from linear interpolation.*

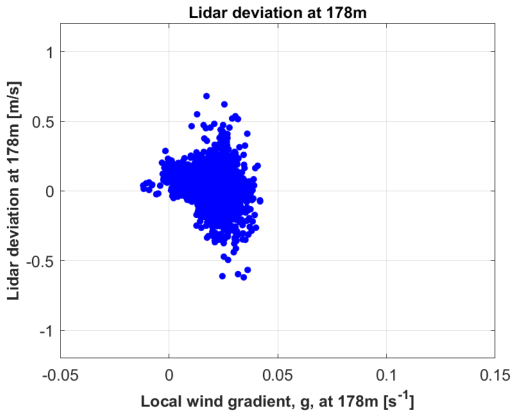


Figure 11.d Deviation at 178m versus local gradient at 178m

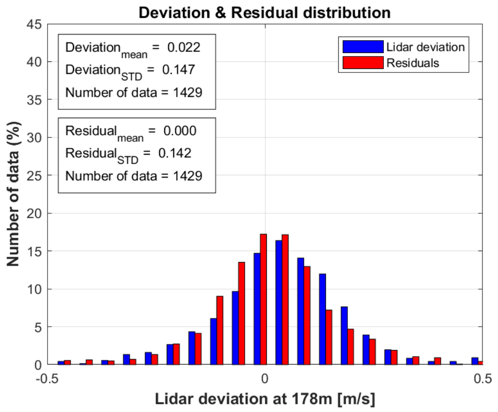


Figure 11.b Distribution of the deviation (blue) and the residuals in the 3-parametric regression (red); data after complete filtering

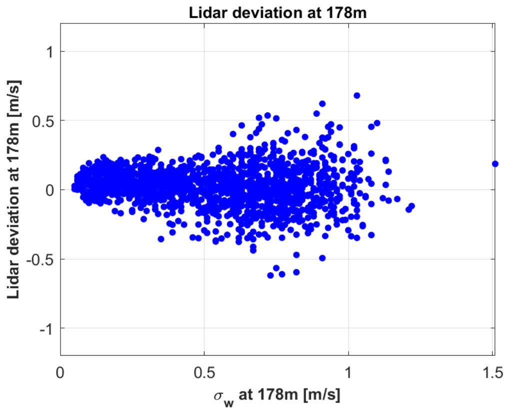


Figure 11.e Deviation at 178m versus standard deviation of vertical wind speed at 178m

Result of the 3-parametric regression:
$y = 0.079 + 1.002u - 5.166g + 0.040\sigma_w$
$R^2 = 0.9962$

3.5 Ten minute mean wind speed at 244 m:

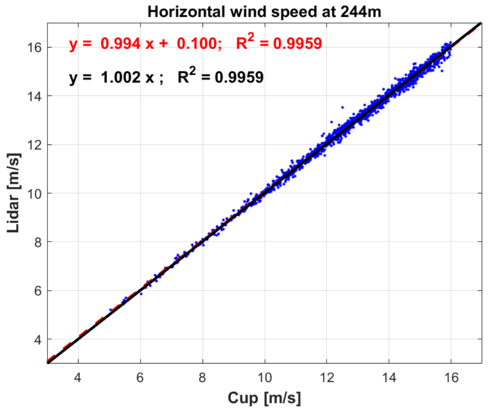


Figure 12.a 1-parametric regression between the 10 minute mean wind speed measurements from the Windcube at 244m and the cup anemometer at 244m.

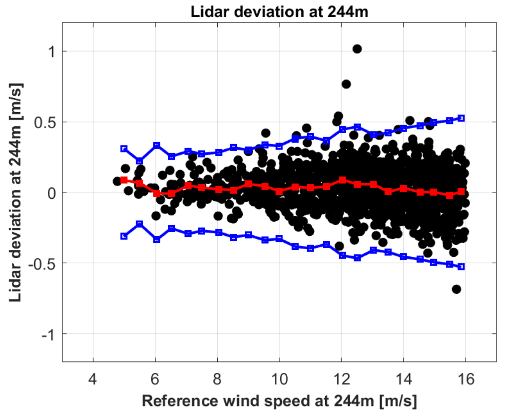


Figure 12.c Deviation at 244m versus reference wind speed. Each black dot represents a 10 min value; the red dots are the wind speed bin averages and the blue squares show $\pm 2u_{lidar}^{(2)}$*. The lines result from linear interpolation.*

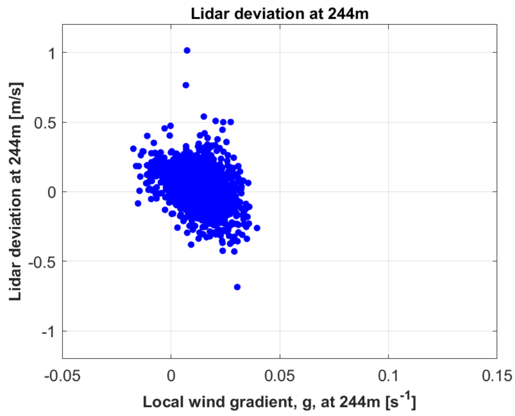


Figure 12.d Deviation at 244m versus local gradient at 244m

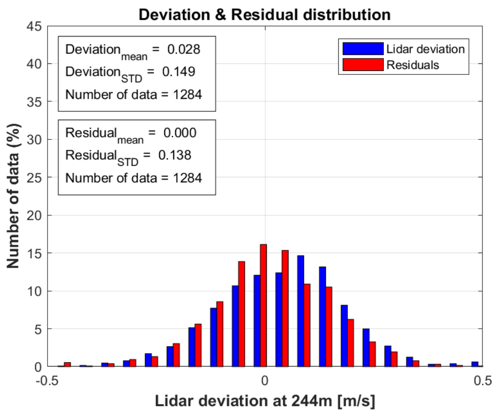


Figure 12.b Distribution of the deviation (blue) and the residuals in the 3-parametric regression (red); data after complete filtering

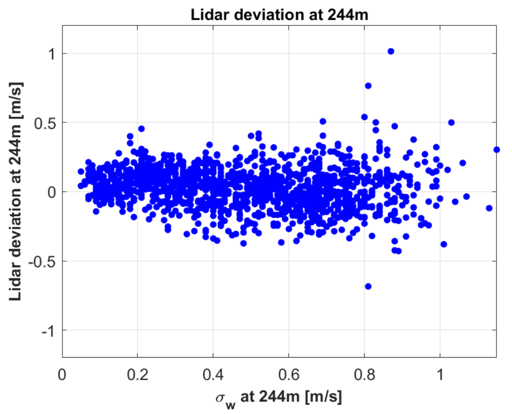


Figure 12.e Deviation at 244m versus standard deviation of vertical wind speed at 244m

Result of the 3-parametric regression:
$y = 0.084 + 1.001u - 5.957g + 0.017\sigma_w$
$R^2 = 0.9965$

Table 5 Results for one-parametric regression analysis for mean wind speed, with and without offset in the model

Height [m]	*C [m/s]*		*k [-]*		*R^2*	*m [-]*		*R^2*
40	-0.156	±0.023	1.020	±0.003	0.9968	1.002	±0.001	0.9964
106	-0.050	±0.031	1.006	±0.003	0.9967	1.001	±0.001	0.9967
178	0.078	±0.040	0.995	±0.003	0.9959	1.002	±0.001	0.9959
244	0.100	±0.044	0.994	±0.003	0.9959	1.002	±0.001	0.9959

Table 6 Statistics of lidar error and wind speed residuals (for 3-parameter regression)

	deviation		*Residuals*	
Height [m]	average [m/s]	s.d. [m/s]	average [m/s]	s.d. [m/s]
40	0.006	0.122	0.000	0.107
106	0.012	0.137	0.000	0.130
178	0.022	0.147	0.000	0.142
244	0.028	0.149	0.000	0.138

Table 7 Results for three-parametric regression analysis for mean wind speed

Height [m]	*D [m/s]*		*k_u[-]*		*k_g[m]*		*$k_{\sigma w}$[-]*		*R^2*
40	-0.071	±0.026	0.974	±0.006	0.050	±0.304	0.386	±0.048	0.9972
106	-0.001	±0.031	0.990	±0.005	-0.229	±0.885	0.196	±0.036	0.9969
178	0.079	±0.040	1.002	±0.004	-5.166	±1.059	0.040	±0.036	0.9962
244	0.084	±0.042	1.001	±0.004	-5.957	±0.878	0.017	±0.040	0.9965

4. Wind direction

The comparison of the 10 minute mean wind direction measured by the lidar to the sonic anemometer/vane measurements at the same height are shown here as complementary/indicative information and is not covered by the accreditation.

4.1 10 minute mean wind direction at 40m:

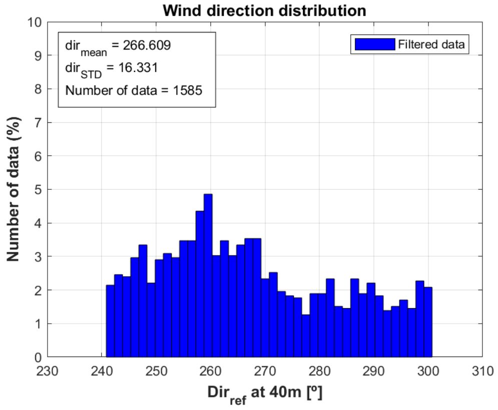


Figure 13.a Distribution of the wind direction measured by the vane at 40m.

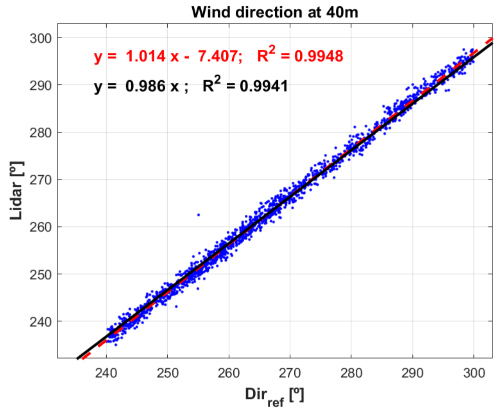


Figure 13.b 1-parametric regression between the 10 minute mean wind direction measurements at 40m.

4.2 10 minute mean wind direction at 103m:

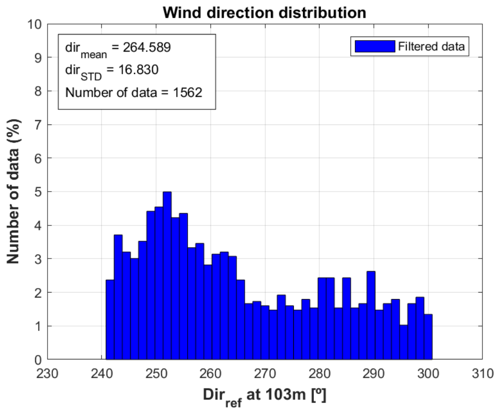


Figure 14.a Distribution of the wind direction measured by the sonic anemometer at 103m.

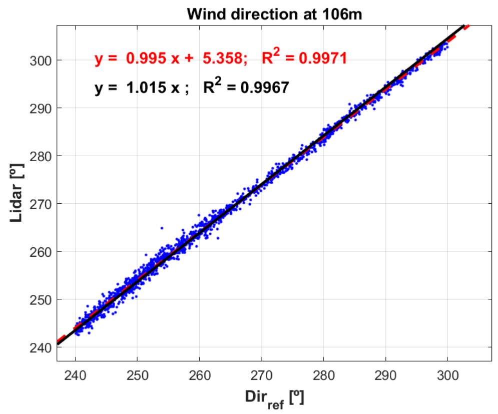
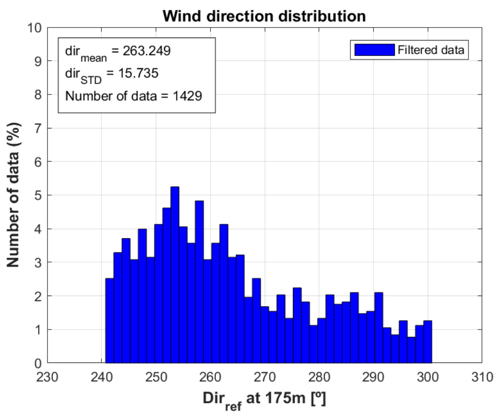


Figure 14.b 1-parametric regression between the 10 minute mean wind direction measurements at103m.

4.3 10 minute mean wind direction at 175m:



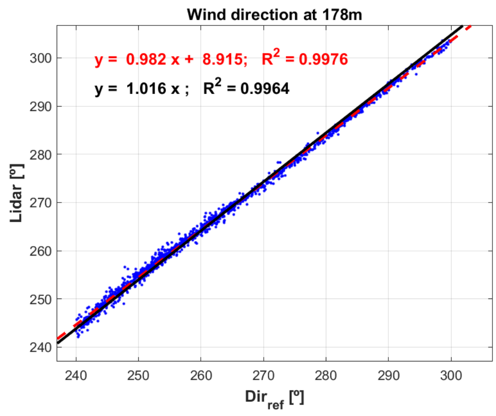
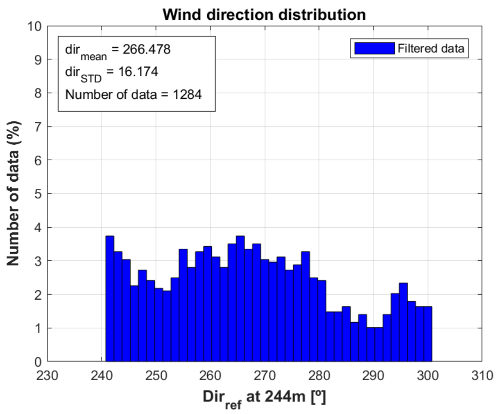


Figure 15.a Distribution of the wind direction measured by the sonic anemometer at 175m.

Figure 15.b 1-parametric regression between the 10 minute mean wind direction measurements at 175m.

4.4 10 minute mean wind direction at 244m:



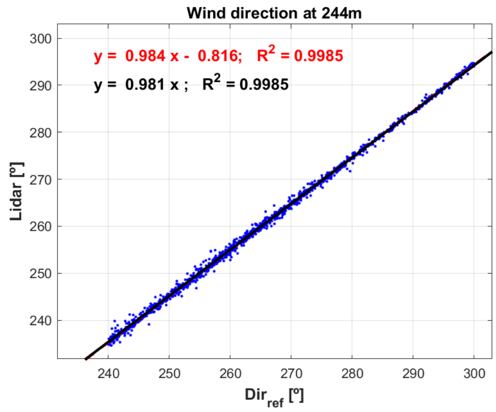


Figure 16.a Distribution of the wind direction measured by the vane at 244m.

Figure 16.b 1-parametric regression between the 10 minute mean wind direction measurements at 244m.

Table 8 Results for one-parametric regression for mean direction

Height [m]	*C [deg.]*		*k[-]*		*R^2*
40	-7.407	0.961	1.014	0.004	0.995
103	5.358	0.708	0.995	0.003	0.997
175	8.915	0.663	0.982	0.003	0.998
244	-0.816	0.564	0.984	0.002	0.998

Note: the offset (C) at every height results from both the uncertainty in the mounting of the vanes and sonics on the booms and the uncertainty in the lidar orientation.

5. Uncertainty

The uncertainty of the wind speed measurements by the lidar is evaluated as the combination of terms, evaluated at each height, for each wind speed bin of 0.5 m/s centered on multiple integers of 0.5m/s, within the range m/s, following the requirements in [1]:

i) u_{ref}: the standard uncertainty of the reference sensor and the relevant instructions for use of instruments and measurement system (the site effect is neglected as the lidar is located only 14m away from the mast):

$$u_{ref} = \sqrt{u_{cal1}^2 + u_{cal2}^2 + u_{ope}^2 + u_{mast}^2}$$

where:

- The calibration uncertainties due to wind tunnel calibration and traceability, are considered as two separated components:

  u_{cal1} is the wind tunnel calibration standard uncertainty (k=1). In this case equals 0.025 m/s.

  u_{cal2} is the traceability from a Measnet accredited wind tunnel, assuming a rectangular distribution of uncertainty. Measnet states that the tunnels are within ±1% [2]. Consequently $u_{cal2} = 0.01/\sqrt{3} * v_i$

- u_{ope} is the operational uncertainty:

$$u_{ope} = \frac{k}{\sqrt{3}}(0.05\ m/s\ + 0.005 \cdot v_i)$$

  the class number for the Windsensor cup anemometers used is k = 1.31 [3].

- The uncertainty due to mounting is:

  u_{mast} = 0.8% for all cup anemometers.

The uncertainty contributions of the reference sensor are all stated with a coverage factor of 1. The term v_i refers to the average of the reference wind speed in bin “i”.

ii) Δv: the mean lidar deviation, i.e. the bin average of the difference between the lidar and the cup anemometer measurement;

iii) $\sigma_{lidar}/\sqrt{n}$: the uncertainty of the lidar mean, where σ_{lidar} is the standard deviation of the lidar measurements and n the number of data in the bin;

iv) σ_{dev}: the statistical uncertainty of the lidar measurements, where σ_{dev} is the standard deviation of the lidar deviations.

The lidar mounting effects uncertainty is considered negligible, since the lidar pitch and roll angles were minimized and monitored during the campaign. Moreover, the terrain is flat with a slope variation smaller than 0.05%; therefore the flow variations within the lidar measurement volume are considered as negligible.

The different uncertainty components are assumed to be independent from each other and are added in quadrature for each wind speed bin:

$$u_{lidar}^{(1)} = \sqrt{u_{ref}^2 + \Delta v^2 + \frac{\sigma_{lidar}^2}{n} + \sigma_{dev}^2}$$

Note that this uncertainty budget includes the mean lidar deviation. If the mean lidar deviation is large, it implies a bias in the lidar measurements. The lidar measurements may then be corrected based on the results of the 1-parametric regression with the reference cup anemometer. If the lidar measurements are corrected, the mean lidar deviation should not be taken into account and the uncertainty budget should be:

$$u_{lidar}^{(2)} = \sqrt{u_{ref}^2 + \frac{\sigma_{lidar}^2}{n} + \sigma_{dev}^2}$$

The total uncertainty of lidar wind speed measurement is based on a coverage factor of 2, in order to have a 95%-coverage according to the EA 4/02. Therefore the uncertainty is either $2u_{lidar}^{(1)}$ or $2u_{lidar}^{(2)}$. An indication of a large bias is when the mean lidar deviation lies outside $\pm 2\, u_{lidar}^{(2)}$ (see figures 10c to 16c).

Table 9 Wind speed measurement comparison including the uncertainty budget at 40m for every wind speed bin

V_{cup} [m/s]	u_{ref} [m/s]	V_{lidar} [m/s]	Δv [m/s]	σ_{lidar} [m/s]	n	$\frac{\sigma_{lidar}}{\sqrt{n}}$ [m/s]	σ_{dev} [m/s]	$2u_{lidar}^{(1)}$ [m/s]	$2u_{lidar}^{(2)}$ [m/s]
4.15	0.07	4.00	-0.15	0.09	19	0.02	0.09	0.37	0.23
4.47	0.07	4.34	-0.13	0.16	46	0.02	0.07	0.34	0.21
5.02	0.08	4.94	-0.08	0.19	57	0.02	0.09	0.30	0.24
5.49	0.08	5.43	-0.06	0.19	84	0.02	0.11	0.30	0.27
6.01	0.09	5.99	-0.02	0.17	131	0.01	0.09	0.26	0.25
6.49	0.09	6.46	-0.02	0.19	148	0.02	0.11	0.29	0.29
7.01	0.10	7.01	0.00	0.18	122	0.02	0.12	0.31	0.30
7.50	0.10	7.52	0.02	0.18	129	0.02	0.11	0.31	0.30
8.00	0.11	8.03	0.03	0.17	173	0.01	0.10	0.30	0.29
8.49	0.11	8.52	0.03	0.18	167	0.01	0.11	0.32	0.31
9.01	0.12	9.04	0.03	0.18	155	0.01	0.12	0.34	0.34
9.50	0.12	9.55	0.05	0.19	98	0.02	0.12	0.36	0.35
9.97	0.13	10.02	0.05	0.24	75	0.03	0.15	0.41	0.40
10.50	0.13	10.56	0.05	0.20	48	0.03	0.12	0.37	0.36
11.00	0.14	11.04	0.04	0.20	37	0.03	0.12	0.38	0.37
11.49	0.14	11.51	0.02	0.15	31	0.03	0.12	0.38	0.38
12.01	0.15	12.06	0.05	0.23	22	0.05	0.19	0.51	0.50
12.47	0.15	12.53	0.06	0.19	12	0.06	0.18	0.49	0.48
13.01	0.16	13.13	0.12	0.19	15	0.05	0.11	0.46	0.40
13.50	0.16	13.56	0.06	0.13	7	0.05	0.22	0.57	0.56
14.00	0.17	14.08	0.08	0.22	4	0.11	0.12	0.50	0.47
					*				
14.99	0.18	15.00	0.02	0.30	3	0.18	0.14	0.57	0.57
15.70	0.18	15.80	0.10	0.18	2*	0.13	0.13	0.55	0.51
					*				

** Bin 15.70 is incomplete (contains less than 3 data points), and therefore the obtained calibration results in this bin may not be representative. The bins at 14.5m/s and 16m/s are missing.*

Table 10 Wind speed measurement comparison including the uncertainty budget at 106m for every wind speed bin

V_{cup} [m/s]	u_{ref} [m/s]	V_{lidar} [m/s]	Δv [m/s]	σ_{lidar} [m/s]	n	$\frac{\sigma_{lidar}}{\sqrt{n}}$ [m/s]	σ_{dev} [m/s]	$2u_{lidar}^{(1)}$ [m/s]	$2u_{lidar}^{(2)}$ [m/s]
					*				
4.59	0.08	4.60	0.01	0.17	7	0.06	0.05	0.22	0.22
5.05	0.08	5.08	0.02	0.15	13	0.04	0.08	0.25	0.24
5.47	0.08	5.42	-0.05	0.23	11	0.07	0.12	0.34	0.32
6.01	0.09	5.98	-0.04	0.16	34	0.03	0.08	0.26	0.25
6.50	0.09	6.49	-0.02	0.15	31	0.03	0.08	0.25	0.25
7.01	0.10	6.98	-0.03	0.17	50	0.02	0.08	0.26	0.26
7.48	0.10	7.45	-0.03	0.18	40	0.03	0.09	0.29	0.28
8.02	0.11	8.01	-0.01	0.20	64	0.03	0.12	0.33	0.33
8.54	0.11	8.53	-0.01	0.22	92	0.02	0.14	0.37	0.36
9.00	0.12	9.01	0.01	0.20	108	0.02	0.13	0.36	0.36
9.50	0.12	9.51	0.01	0.20	132	0.02	0.13	0.36	0.36
10.00	0.13	10.01	0.01	0.18	145	0.02	0.13	0.37	0.36
10.49	0.13	10.53	0.04	0.21	139	0.02	0.15	0.42	0.41
10.99	0.14	11.01	0.01	0.20	117	0.02	0.14	0.40	0.40
11.50	0.14	11.53	0.03	0.19	122	0.02	0.14	0.40	0.40
11.99	0.15	12.00	0.02	0.20	102	0.02	0.15	0.42	0.42
12.49	0.15	12.51	0.02	0.21	93	0.02	0.17	0.46	0.45
12.97	0.16	13.00	0.03	0.19	63	0.02	0.12	0.40	0.40
13.50	0.16	13.52	0.02	0.17	45	0.02	0.12	0.41	0.41
13.94	0.17	14.01	0.07	0.20	45	0.03	0.15	0.47	0.45
14.50	0.17	14.57	0.07	0.17	39	0.03	0.15	0.49	0.46
15.04	0.18	15.00	-0.04	0.20	37	0.03	0.13	0.45	0.44
15.47	0.18	15.46	-0.01	0.20	24	0.04	0.17	0.50	0.50
15.88	0.19	15.90	0.02	0.12	9	0.04	0.08	0.41	0.41

** The bin at 4 m/s is missing.*

Table 11 Wind speed measurement comparison including the uncertainty budget at 178m for every wind speed bin

V_{cup} [m/s]	u_{ref} [m/s]	V_{lidar} [m/s]	Δv [m/s]	σ_{lidar} [m/s]	n	$\frac{\sigma_{lidar}}{\sqrt{n}}$ [m/s]	σ_{dev} [m/s]	$2u_{lidar}^{(1)}$ [m/s]	$2u_{lidar}^{(2)}$ [m/s]
4.20	0.07	4.32	0.12	0.00	1*	0.00	0.00	0.28	0.14
					*				
5.08	0.08	5.16	0.08	0.19	6	0.08	0.02	0.28	0.23
5.61	0.08	5.65	0.05	0.10	7	0.04	0.09	0.28	0.26
6.03	0.09	6.08	0.05	0.22	9	0.07	0.10	0.31	0.30
6.47	0.09	6.51	0.04	0.15	15	0.04	0.11	0.30	0.29
6.98	0.10	7.00	0.03	0.15	20	0.03	0.07	0.26	0.25
7.48	0.10	7.51	0.02	0.18	13	0.05	0.10	0.31	0.30
8.03	0.11	8.04	0.01	0.17	37	0.03	0.09	0.29	0.29
8.55	0.11	8.55	0.00	0.15	39	0.02	0.08	0.28	0.28
9.02	0.12	9.02	0.00	0.20	39	0.03	0.12	0.35	0.35
9.50	0.12	9.53	0.03	0.16	47	0.02	0.10	0.32	0.32
10.02	0.13	10.06	0.04	0.21	77	0.02	0.15	0.40	0.39
10.51	0.13	10.57	0.06	0.23	82	0.03	0.16	0.43	0.42
10.98	0.14	11.05	0.07	0.20	86	0.02	0.15	0.43	0.41
11.51	0.14	11.56	0.05	0.22	125	0.02	0.14	0.41	0.40
12.00	0.15	12.00	0.00	0.20	138	0.02	0.15	0.42	0.42
12.50	0.15	12.54	0.04	0.22	138	0.02	0.15	0.44	0.43
13.00	0.16	13.00	0.01	0.22	89	0.02	0.15	0.44	0.44
13.51	0.16	13.54	0.03	0.20	97	0.02	0.16	0.45	0.45
13.97	0.17	13.95	-0.02	0.20	109	0.02	0.16	0.47	0.46
14.52	0.17	14.51	-0.01	0.22	94	0.02	0.18	0.50	0.50
15.00	0.18	15.01	0.01	0.20	84	0.02	0.16	0.48	0.48
15.46	0.18	15.47	0.01	0.21	56	0.03	0.15	0.47	0.47
15.86	0.19	15.89	0.02	0.16	21	0.03	0.11	0.44	0.44

**Bin 4.20 is incomplete (contains less than 3 data points), and therefore the obtained calibration results in this bin may not be representative. The bin at 4.5m/s is missing.*

Table 12 Wind speed measurement comparison including the uncertainty budget at 244m for every wind speed bin

V_{cup} [m/s]	u_{ref} [m/s]	V_{lidar} [m/s]	Δv [m/s]	σ_{lidar} [m/s]	n	$\frac{\sigma_{lidar}}{\sqrt{n}}$ [m/s]	σ_{dev} [m/s]	$2u_{lidar}^{(1)}$ [m/s]	$2u_{lidar}^{(2)}$ [m/s]
					*				
					*				
4.99	0.08	5.07	0.09	0.19	3	0.11	0.08	0.36	0.31
5.50	0.08	5.56	0.07	0.09	7	0.03	0.07	0.26	0.22
6.05	0.09	6.05	-0.01	0.20	5	0.09	0.11	0.33	0.33
6.51	0.09	6.51	-0.01	0.15	13	0.04	0.08	0.25	0.25
7.07	0.10	7.11	0.05	0.19	15	0.05	0.10	0.31	0.29
7.50	0.10	7.53	0.03	0.16	17	0.04	0.08	0.28	0.27
8.04	0.11	8.07	0.02	0.16	15	0.04	0.08	0.29	0.28
8.51	0.11	8.53	0.02	0.16	26	0.03	0.11	0.32	0.32
9.00	0.12	9.05	0.06	0.15	18	0.03	0.09	0.32	0.30
9.53	0.12	9.58	0.05	0.18	53	0.02	0.11	0.35	0.34
9.99	0.13	10.00	0.01	0.18	38	0.03	0.10	0.33	0.33
10.51	0.13	10.55	0.04	0.19	55	0.03	0.14	0.39	0.38
10.99	0.14	11.03	0.03	0.21	70	0.02	0.14	0.40	0.39
11.52	0.14	11.56	0.04	0.18	68	0.02	0.11	0.38	0.37
12.03	0.15	12.12	0.09	0.23	86	0.02	0.17	0.48	0.45
12.51	0.15	12.57	0.06	0.22	107	0.02	0.17	0.48	0.46
13.03	0.16	13.09	0.06	0.17	111	0.02	0.13	0.42	0.41
13.50	0.16	13.51	0.00	0.20	119	0.02	0.13	0.42	0.42
13.99	0.17	14.02	0.03	0.23	94	0.02	0.15	0.46	0.46
14.53	0.17	14.53	0.00	0.20	116	0.02	0.16	0.47	0.47
14.98	0.18	14.98	0.00	0.22	110	0.02	0.17	0.49	0.49
15.48	0.18	15.46	-0.02	0.22	105	0.02	0.18	0.51	0.51
15.86	0.19	15.86	0.01	0.19	33	0.03	0.18	0.53	0.53

The bins at 4.0 and 4.5m/s are missing.

6. References

1. IEC 61400-12-1, ed. 2, March 2017
2. Measnet anemometer calibration procedure. Version 2. October 2009.
3. http://www.windsensor.dk/products.htm
4. Windcube user guide V.1, Leosphere, October 2018.