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Verification test for three WindCube WLS7 LiDARs at the Høvsøre test site

Gottschall, Julia; Courtney, Michael

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Verification test for three WindCube^{TM} WLS7 LiDARs at the Høvsøre test site

Risø-R-Report

Julia Gottschall, Michael Courtney
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Authors: Julia Gottschall, Michael Courtney
Title: Verification test for three WindCube™ WLS7 LiDARs at the Høvsøre test site
Division: Wind Energy Division

Abstract:
The report describes the procedure of testing ground-based WindCube™ lidars (manufactured by the French company Leosphere) at the Høvsøre test site in comparison to reference sensors mounted at a meteorological mast. Results are presented for three tested units – in detail for unit WLS7-0062, and in a summary for units WLS7-0064 and WLS7-0066. The verification test covers the evaluation of measured mean wind speeds, wind directions and wind speed standard deviations. The data analysis is basically performed in terms of different kinds of regression analyses.

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Information Service Department
Risø National Laboratory for Sustainable Energy
Technical University of Denmark
P.O.Box 49
DK-4000 Roskilde
Denmark
Telephone +45 46774005
bibl@risoe.dtu.dk
Fax +45 46774013
www.risoe.dtu.dk

Contents

1 Introduction

The report describes the procedure of testing a commercial ground-based lidar profiler in comparison to a reference mast equipped with cup anemometers and wind vanes as reference sensors. Results are presented for three WindCube™ lidars manufactured by the French company Leosphere. For a description of this type of lidar and details about its measurement principle see e.g. [1].

For the reference measurements a tall meteorological mast, located at the Danish National Test Station for Large Wind Turbines at Høvsøre, is used with reference sensors at up to five heights. Cup anemometers for the measurement of the horizontal wind speed are available at five heights (40 m, 60 m, 80 m, 100 m, 116 m)[1], wind vanes for wind direction measurements at two heights (60 m, 100 m).

The measurement performance of the lidar is evaluated on the basis of 10-min mean values of the measured quantities. The verification of the instrument is performed in terms of different regression approaches and a detailed analysis of the lidar error that is defined by the difference between the simultaneous measurements by the lidar and the reference sensor.

This introduction is followed by a more detailed description of the test site and the instrumentation in section 2. In section 3, the procedure of testing and the models for the data evaluation are itemized. Detailed verification results for one of the three tested WindCube™ units are given in sections 4 and 5. A summary of the results for the two other units is presented in section 6. The report is completed by a discussion of the results and a short conclusions section in section 7 and 8, resp.

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1 The top verification height is defined as 116 m although the reference cup anemometer is mounted at a height of 116.5 m, i.e. 0.5 m higher. A finer resolution (< 1 m in height) seems with respect to the measuring volume of the lidar not to be reasonable.

2 Test site and instrumentation

2.1 Location of test site

The tests were performed at the Danish National Test Station for Large Wind Turbines, located at Høvsøre in Western Jutland, Denmark, about 30 km west-northwest of Holstebro.

The facility comprises a line of five test stands for MW-class wind turbines, oriented north-south parallel to the coast (slightly, about 3 deg, tilted to the east), and each stand has its dedicated upstream measuring mast for performance tests to the west. The lidar tests are performed at the southern end of the turbine row and 200 m from the closest wind turbine, next to an intensively instrumented meteorological mast (met. mast) – see Figures 2-1 and 2-2.

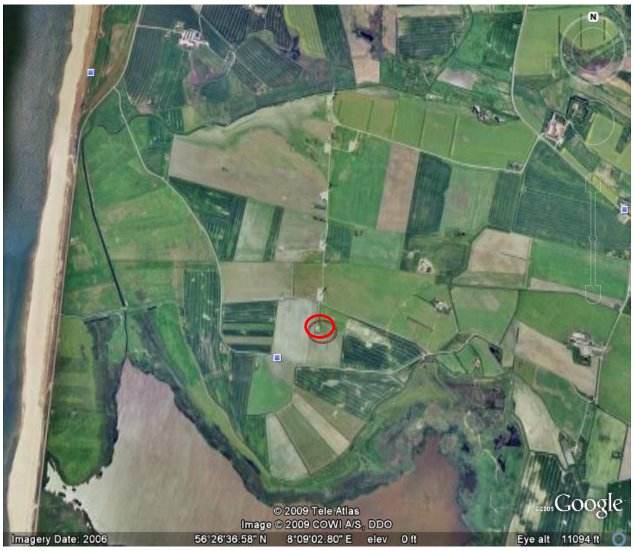


Figure 2-1 Outline of Høvsøre test site (picture from Google Earth). The met. mast used for the reference measurements is marked by the red circle.

Figure 2-2 The row of wind turbines at the Høvsøre test site with the tall met. mast in the front.

2.2 Terrain description

The test site at Høvsøre is a flat site, mainly consisting of grasslands, with maximum height variations less than 5 m. To the south is a lagoon, at the closest point 900 m from the met. mast, and about 1.8 km to the west the North Sea, separated from the land by a strip of sand dunes about 10 m high – see Figure 2-3. The land behind the dike lies about 1-5 m above sea level. The most homogeneous fetch is represented by the easterly directions with mostly open farmland.

Figure 2-3 Høvsøre test site seen from the coastline in the west.

2.3 Location of tested lidar

Since there is no problem with backscatter from the mast structure for the lidar (unlike fixed-echo problems for sodar testing), it is possible and indeed advantageous to place the lidar instruments close to or directly next to the reference mast and thus maximize the correlation between lidar and reference measurements. A sketch of the placement of the tested WindCube^{TM} units relative to the met. mast is shown in Figure 2-4. The distance to the closest turbine is illustrated in Figure 2-5.

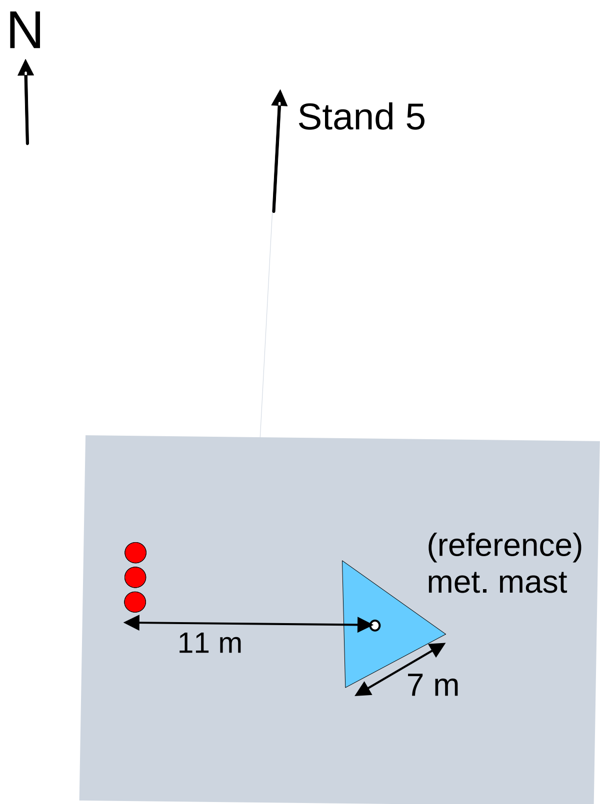


Figure 2-4 Sketch of lidar placement relative to met. mast. The lidars have been located 11 m to the west and 1-2 m to the north from the mast center. Beam directions are offset by 45 deg relative to north-south.

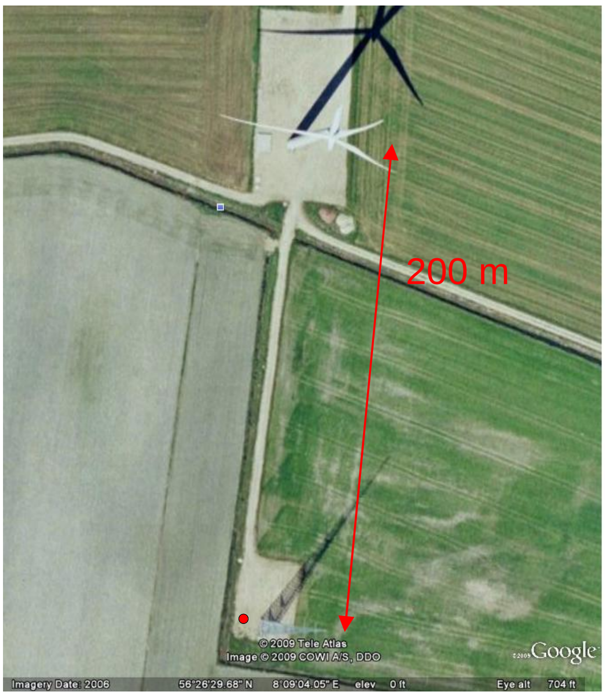


Figure 2-5 Distance between met. mast and wind turbine at test stand 5 (picture from Google Earth). The location of the tested lidars is indicated by the red dot.

2.4 Measurement sector

The valid measurement sector for the verification test results as follows. Wind data from the northerly sector (±45 deg) are excluded from the analysis due to wakes from the turbines north of the met. mast, affecting both the lidar and the mast measurements. Since the reference sensors are mounted on the south side of the mast, excluding the northerly sector also removes the data for that 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^{TM} with a cone angle of about 30 deg, set up at the pre-defined lidar test stand, the resulting combined measurement sector is given by the two sectors 150-180 deg (south-east sector) and 230-300 deg (west sector) – cf. [2].

2.5 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 Høvsøre 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 lidar verification tests.

Sensors used as direct reference sensors are the five cup anemometers, placed at 40 m, 60 m, 80 m, 100 m and 116.5 m height, and two wind vanes at 60 m and 100 m. The cup anemometer at 116.5 m measurement height is top-mounted, all other reference sensors are mounted on booms pointing towards the south. To minimize the uncertainty in mounting, the cup anemometer measurements at the four lower heights are corrected for boom and mast effects – for a description of the correction approach see [2].

The wind speed and direction measurements are complemented by rain (Vaisala rain sensor at stand 5) and temperature (temperature sensor at 100 m) measurements as well as a wind speed measurement at 114 m height, not used for a direct comparison with the lidar measurements but for a filtering of the data (details in section 3).

The entire instrumentation of the met. mast is shown in a sketch in Figure 2-6.

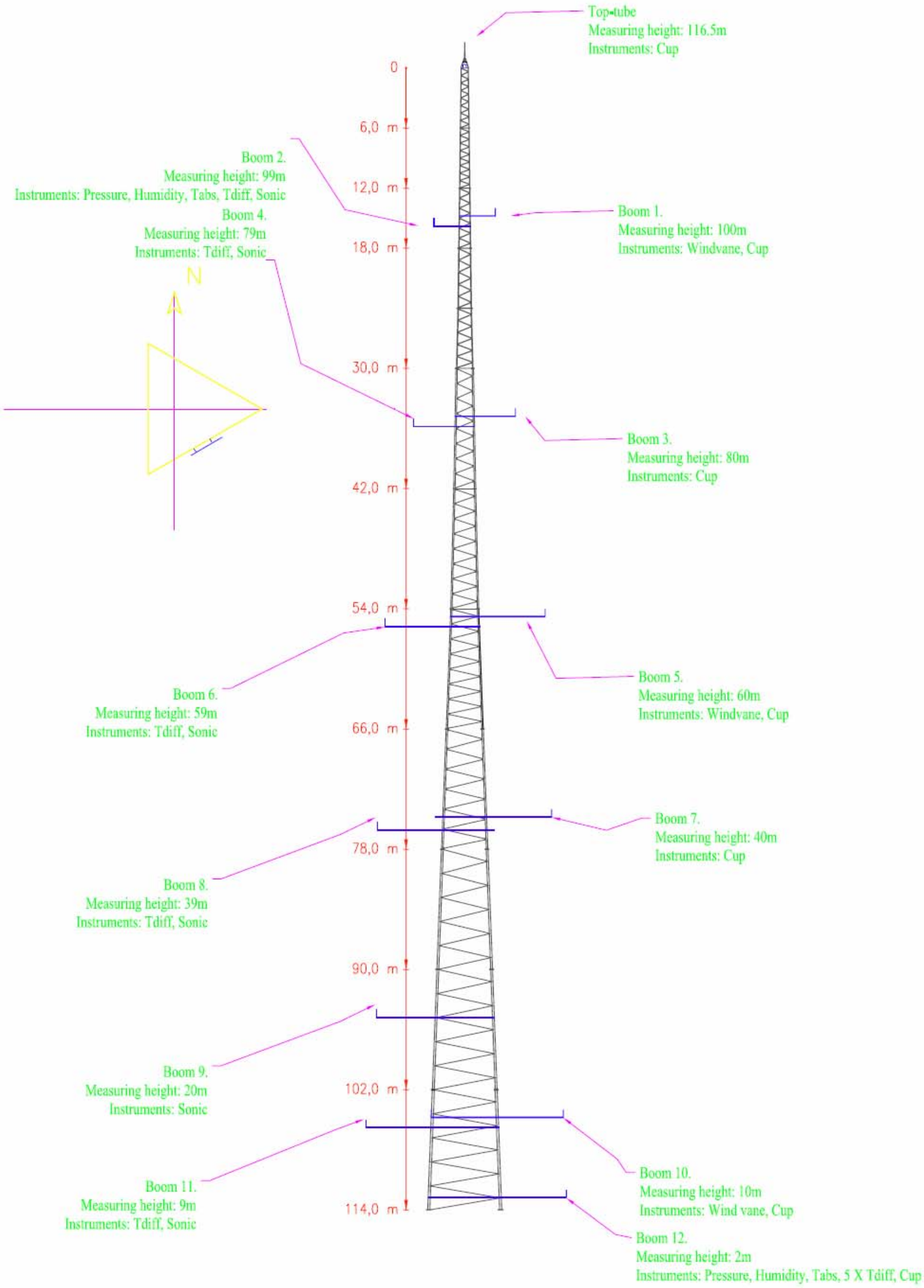


Figure 2-6 Sketch specifying the instrumentation of the met. mast.

2.6 Specifications of reference sensors

For the reference wind speed measurements Risø 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). Specification of all used reference sensors are given in Table 2-1.

Table 2-1 Specifications of used sensors.

Parameter	Position	Sensor
wind speed	met. mast (stand 6) 40 m height	cup anemometer 2546a serial number 6542 PFV 1109 reg. 2353
wind speed	met. mast (stand 6) 60 m height	cup anemometer 2546a serial number 5835 PFV 1109 reg. 2340
wind speed	met. mast (stand 6) 80 m height	cup anemometer 2546a serial number 6548 PFV 1109 reg. 2359
wind speed	met. mast (stand 6) 100 m height	cup anemometer 2546a serial number 6549 PFV 1109 reg. 2360
wind speed	met. mast (stand 6) 116.5 m height	cup anemometer 2546a serial number 6551 PFV 1109 reg. 2362
wind speed	met. mast (stand 6) 114 m height	cup anemometer 2546a serial number 6550 PFV 1109 reg. 2361
wind direction	met. mast (stand 6) 60 m height	vane P2633a serial number 54 PFV 1214 reg. 0113
wind direction	met. mast (stand 6) 100 m height	vane P2633a serial number 107 PFV 1214 reg. 0861
Rain	met. mast (stand 5) 60 m height	Nedbørmåler (Thies) F3452a Type 5.4103.10.000 (ser. no. 0904066) PFV 1516 reg. 2018
Temperature	met. mast (stand 6) 100 m height	PFV 1310 reg. 1376

2.7 Time synchronization

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

3 Procedure of testing (verification test)

3.1 General concept

The lidar data are compared with the reference data from the cup anemometers and the wind vanes at each of the five considered measurement heights (40 m, 60 m, 80 m, 100, 116 m; however, only 60 m and 100 m for wind direction data) on the basis of 10-min averages.

To maximise the comparability of the test data and the repeatability of the test, the sampled data are filtered before evaluation according to different filtering criteria that are listed in section 3.3. Pre-tests might be necessary to define the filtering criteria in an adequate way and consider possible specific conditions (e.g. cold periods where cup anemometer icing might be observed but is not in a simple relation to measured air temperature – results of data analysis in section 4).

Lidar and reference data – for mean wind speed, wind direction and wind speed standard deviation – are compared in terms of different types of regression approaches. In addition, a detailed analysis of the lidar error, defined by the difference between the wind speeds measured by the lidar and the reference sensors, is performed. The applied techniques of analysis are described in more detail in section 3.4.

As a final step, the results for the different measurement heights are summarized and related to each other in the discussion.

3.2 Data preparation

Extrapolation of wind directions

As mentioned earlier, reference wind direction measurements are only available at 60 m and 100 m measurement height. To account for this, the wind direction measurements of the lidar are to be verified only at these two heights. For correction and data filtering purposes, however, an approximate wind direction measurement is needed for each verification height. Wind direction values for heights lacking a reference wind direction sensor are extrapolated according to the following scheme: The approximated wind direction at 40 m is taken as the wind direction measured at 60 m. The approximated wind direction at 116.5 m (as well as at 114 m) is taken as the wind direction measured at 100 m. The approximated wind direction at 80 m is interpolated from the two reference measurements at 60 m and 100 m according to the formula *dir(80 m):= dir(100 m)-[dir(100 m)-dir(60 m)]/2* (ensuring that the absolute difference between the two measured directions is not larger than 180 deg by adding or subtracting 360 deg).

Derivation of measure for wind direction shear

A measure for wind direction shear is defined as the difference between the two measured wind directions, i.e. *dir(100 m)-dir(60 m)*. As a filtering parameter, we use the absolute value of this quantity.

Derivation of wind gradient (as local wind speed shear measure)

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 (corrected) reference wind speed measurements. The profile is obtained in terms of a polynomial function forced through the single data points. For the case of five measurement points (referring to the five measurement heights in our test), the fitting function $wsp(z) = a + bz + cz^2 + e \log(z)$ is applied where z is the measurement height. The wind gradient is then given as the quantity $g(z=z_0) = b + 2cz_0 + 3dz_0^2 + e/z_0$.

3.3 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 direction**
According to the measurement sector determined in section 2.4, valid wind directions are only those coming from the sectors 150-180 deg, i.e. a small south-east sector, and 230-300 deg, i.e. the west sector.

B. **Wind speed**
Only mean (reference) wind speeds within the interval 4-16 m/s are considered to be valid. This corresponds to the range a standard cup anemometer calibration is performed in.

C. **(Adjacent) precipitation**
Filtering on precipitation is done for the rain sensor indicating precipitation (regardless of its strength) in a 10-min period. In addition to the period itself also the 10-min period before and after the indication are filtered out.

D. **Wind direction shear**
10-min periods with an absolute wind direction shear value (according to the definition above) larger than 5 deg are filtered out.

E. **Lidar availability**
The availability parameter of the WindCube™ has to give a value of 100 % for each valid 10-min period. This parameter indicates 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).

F. **Icing of cup anemometers**
Respective filtering is either based on a temperature measurement or done by comparing the performance of the top-mounted cup anemometer (at 116.5 m) with another reference cup anemometer that is mounted at 114 m height. The relative deviation after correction then has to lie within the open interval]0.990, 1.010[− i.e. within ± 1% of wind speed deviation. (Note that the applied correction for mast and boom effects at 114 m includes a correction of the average wind speed deviation due to shear.)

3.4 Data analysis (data evaluation and model of errors)

The following steps of data analysis are performed.

For 40 m, 60 m, 80 m, 100 m and 116 m measurement height:

- 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).

- Two-parametric regression analysis applying the model $y = D + k_u x + k_g g$ (with y lidar wind speed, x reference wind speed and g wind gradient, see definition above) gives estimates for the offset (D), the two slopes (k_u and k_g) and the respective coefficient of determination (R^2).

- Derivation of mean value and standard deviation of the lidar error, defined as lidar wind speed minus reference wind speed, and standard deviation of the model residuals (measured lidar wind speed y minus modelled lidar wind speed, i.e. mx, $C + kx$ or $D + k_u x + k_g g$, resp.)

- Linear regression analysis for wind speed standard deviations (lidar wind speed s.d. vs. reference wind speed s.d.) with non-zero offset, i.e. applying the model $y = C + kx$ (with y lidar wind speed s.d., x reference wind speed s.d.), gives estimates for the offset (C), the two regression slope (k) and the respective coefficient of determination (R^2).

For 60 m and 100 m measurement height:

- 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).

Estimated regression parameters are stated together with the corresponding standard uncertainties.

Further, more specific parts of the data analysis are described in section 4 together with the results.

4 Detailed results (WindCube^{TM} unit WLS7-0062)

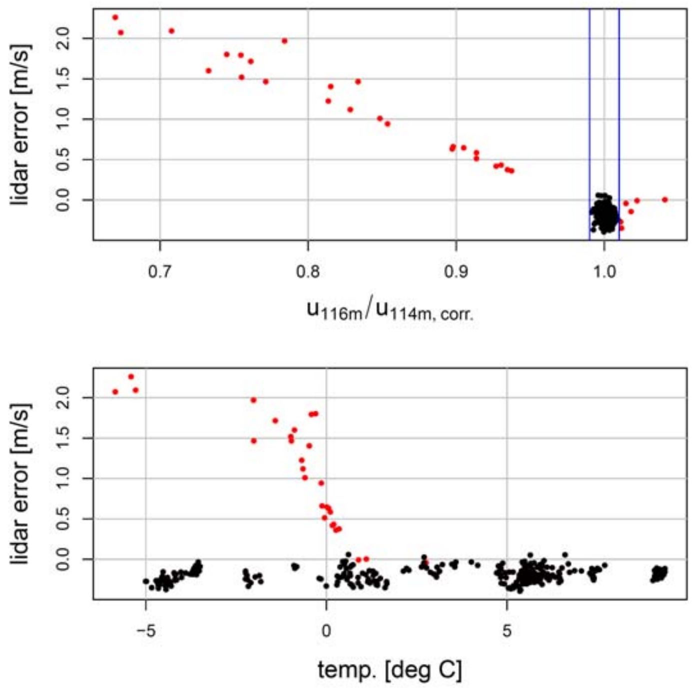
4.1 Evaluated data sets

The evaluated data cover the measurement period from 04 December, 2009 (13:20) to 26 January, 2010 (09:50). For each of the five measurement heights, a total number of 7117 data samples were recorded – each data sample with one value, respectively, for all the mentioned quantities measured by the lidar and the reference sensors.

The data sets were then reduced according to the data filtering procedure described in 3.3. A critical filtering criterion for the covered time period has been item F (i.e. icing of cup anemometers). The cup anemometer at 116.5 m height turned out to have not been working properly during the measurement period. Therefore, a comparison with the control anemometer at 114 m did not serve as a reliable test on icing for the cup anemometers at the lower heights. A filtering solely based on a temperature measurement (e.g. with a temperature limit defined as +2 deg C –for this, we used a temperature sensor at 100 m), on the other hand, deletes in the winter period too many data samples, and especially also samples that are not at all affected by icing.

In order to determine which filtering criterion should be applied, a critical investigation of the observed lidar error versus the temperature as well as the ratio between the readings of the cup anemometers at 114 m and 116.5 m was performed – see Figure 4-1. Applying the filtering on the defined reference ratio, we sort out data where the anemometer at 116.5 m seems not to work properly – so, it is a very useful filtering criterion for the measurement data at 116.5 m (even when it works here as a quality control and is not directly related to icing). Furthermore, extreme lidar errors at 100 m and 80 m are filtered out. At 60 m and 40 m measurement height, however, the filtering only removes unremarkable data points, i.e. data points that otherwise do not seem to be wrong in any way. In a similar way, a filtering solely based on the temperature measurement does not have the wanted effect on the extreme lidar errors – some extreme values are removed but also too many data points that seem to be valid otherwise.

Based on this investigation, we decided to apply the filtering on the defined reference ratio at 116 m, 100 m and 80 m measurement height but to consider no filtering on icing for the two lower heights, i.e. for 60 m and 40 m.



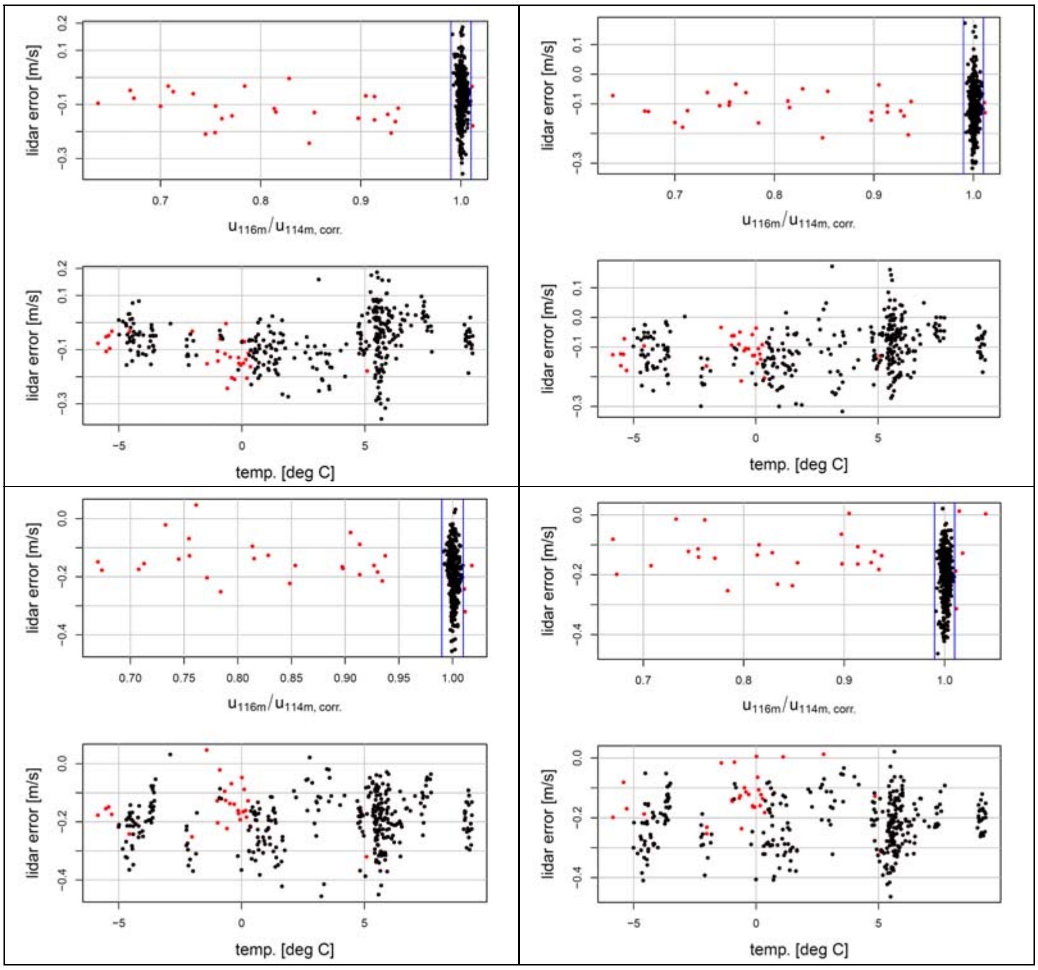


Figure 4-1 Lidar error versus reference ratio (*wsp(116 m)/wsp(114 m)*; see 3.3 F) and temperature, resp. – for 116 m (top), 40 m and 60 m (middle), 80 m and 100 m (bottom). Points filtered out according to criterion F are shown in red. The vertical blue lines define the range of tolerance defined by the filtering criterion F.

Table 4-1 gives an overview about the number of data samples remaining after the complete filtering procedure. The particular filtering steps are further itemized in Table 4-2, where it is differentiated between the filtering on wind direction, wind speed, precipitation, wind direction shear, lidar availability and cup anemometer icing (the last being only applied for the measurements at 80 m, 100 m and 116 m height) – cf. filtering criteria A-F in 3.3.
The largest amount of the original data is filtered out due to the restrictions in wind direction. The filtering on precipitation and wind direction shear is the same for all considered measurement heights, the filtering on wind direction is the same for the two upper and the two lower heights, respectively, due to the extrapolation of the wind direction measurements.

Table 4-1 Number of data samples before and after filtering.

Height [m]	Total	after filtering	[%]
40	7117	358	5.0
60	7117	361	5.1
80	7117	332	4.7
100	7117	336	4.7
116	7117	333	4.7

Table 4-2 Number of data samples remaining after the single filtering steps A-F (see 3.3) or A-E, resp. For the columns B-F the combined filtering criterion is considered, including the preceding criteria in the columns to the left. The individual impact on the non-filtered data set is given in the parentheses.

Height [m]	A	+B	+C	+D	+E	+F
40	867	687	506	358	**358**	329
		(6011)	(6049)	(5536)	(6549)	(4110)
60	867	705	515	361	**361**	332
		(6182)	(6049)	(5536)	(6476)	(4110)
80	881	710	515	360	360	**332**
		(5751)	(6049)	(5536)	(6447)	(4110)
100	894	725	533	366	366	**336**
		(6267)	(6049)	(5536)	(6409)	(4110)
116	894	736	532	365	364	**333**
		(6026)	(6049)	(5536)	(6379)	(4110)

Figure 4-2 shows the time series of the measured reference wind speeds before and after filtering. Corresponding histograms of the data, here only for 40 m and 116 m measurement height, are shown in Figure 4-3.

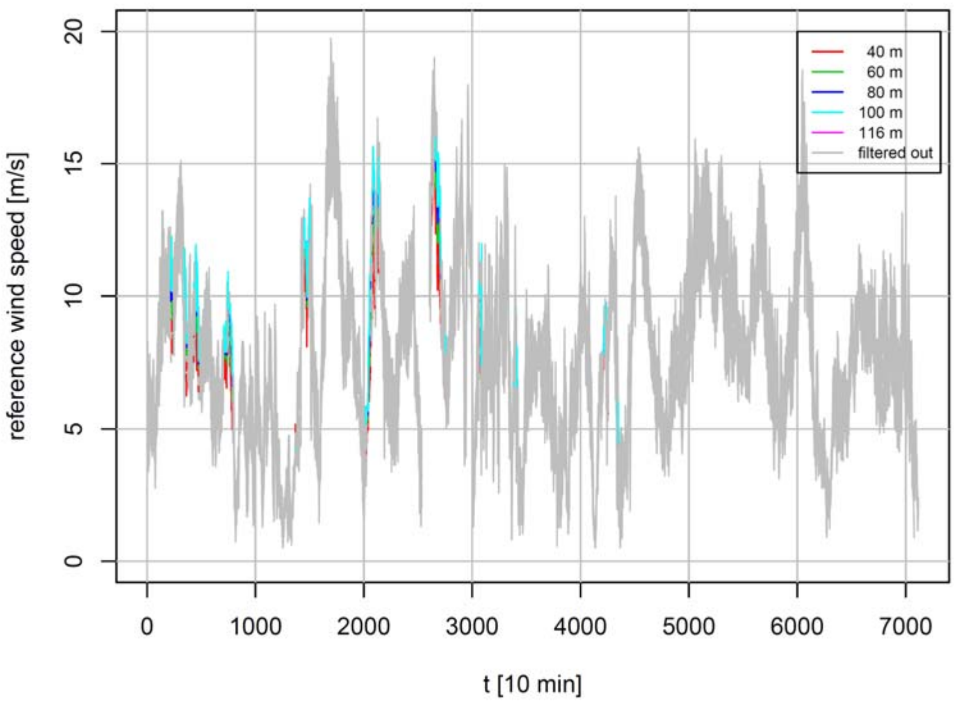


Figure 4-2 Time series plot of filtered and non-filtered reference mean wind speeds at different heights – for details see legend.

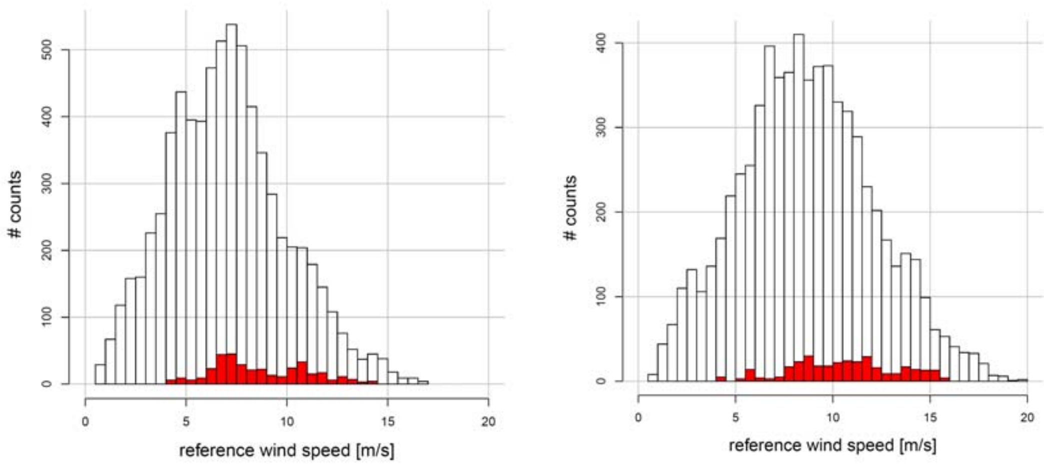


Figure 4-3 Histograms of reference mean wind speed data for 40 m (left) and 116 m measurement height (right). The filtered data is shown in red in comparison to the data before filtering.

4.2 One-parametric regression for mean wind speeds

To compare the horizontal mean wind speeds measured by the lidar and the reference cup anemometers, respectively, in a standard way, a one-parametric regression analysis is performed. Two linear models are applied – defined by the equations $y = C + kx$ and $y = mx$ where y is the mean wind speed measured by the lidar and x the reference wind speed measured by the respective reference cup anemometer at the considered measurement height. The results, estimated parameters and the coefficients of determination (R^2) for the two models, are given in Table 4-3. The corresponding regression plots are shown in Figure 4-4.

Table 4-3 Results for one-parametric regression analysis for mean wind speeds (with and without offset in model).

Height [m]	C [m/s]	k [-]	R^2	m [-]	R^2
40	0.01 (.02)	0.990 (.002)	0.9986	0.9920 (.0005)	0.9986
60	0.02 (.02)	0.987 (.002)	0.9991	0.9890 (.0004)	0.9991
80	0.00 (.02)	0.980 (.002)	0.9992	0.9805 (.0004)	0.9992
100	-0.05 (.02)	0.984 (.002)	0.9992	0.9790 (.0004)	0.9992
116	-0.02 (.02)	0.983 (.001)	0.9993	0.9821 (.0004)	0.9993

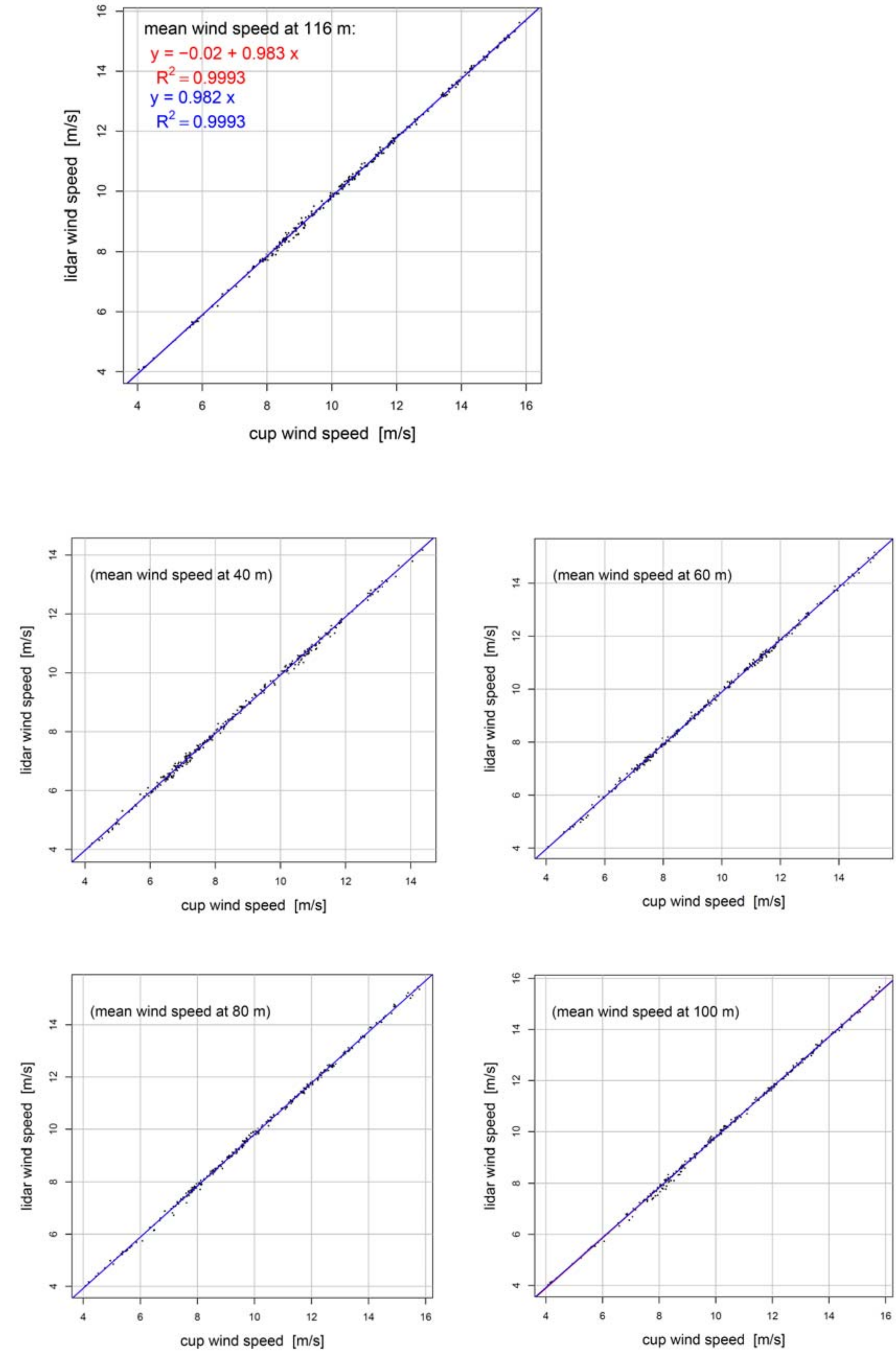


Figure 4-4 Illustration of one-parametric regression for mean wind speeds. The results for the regression model with offset are shown as red line, here hidden by the results for the model without offset (shown as blue line).

4.3 Two-parametric regression analysis

As extension of the one-parametric regression analysis for the mean wind speeds (presented in 4.2), we performed a two-parametric regression analysis with the shear gradient as second independent variable. The applied linear model reads $y = D + k_u x + k_g g$ where y is the mean wind speed measured by the lidar, x the reference wind speed measured by the respective reference cup anemometer and g the derived shear gradient at the considered measurement height. The results, estimated parameters and the coefficient of determination (R^2), are given in Table 4-4. The corresponding regression plots are shown in Figure 4-5.

In [3] the two-parametric regression analysis was performed with the lidar error (instead of the lidar wind speed, as used here) as dependent variable. This alternative definition has the disadvantage that the obtained values for R^2 are very small and especially directly dependent on the "gain errors", i.e. a bias between the mean lidar wind speed and the reference found as non-unity regression slopes in the standard regression analysis. Performing the two-parametric regression analysis in the way it is done in this report, gives results that can be compared more easily with the results of the respective one-parametric regression analysis.

Table 4-4 Results for two-parametric regression analysis.

Height [m]	D [m/s]	k_u [-]	k_g [m]	R^2
40	-0.01 (.02)	0.990 (.002)	0.0 (.2)	0.9986
60	0.01 (.01)	0.984 (.002)	1.1 (.2)	0.9992
80	0.00 (.02)	0.981 (.002)	-0.4 (.3)	0.9992
100	-0.05 (.02)	0.985 (.002)	-0.8 (.3)	0.9992
116	-0.02 (.02)	0.987 (.001)	-1.6 (.3)	0.9993

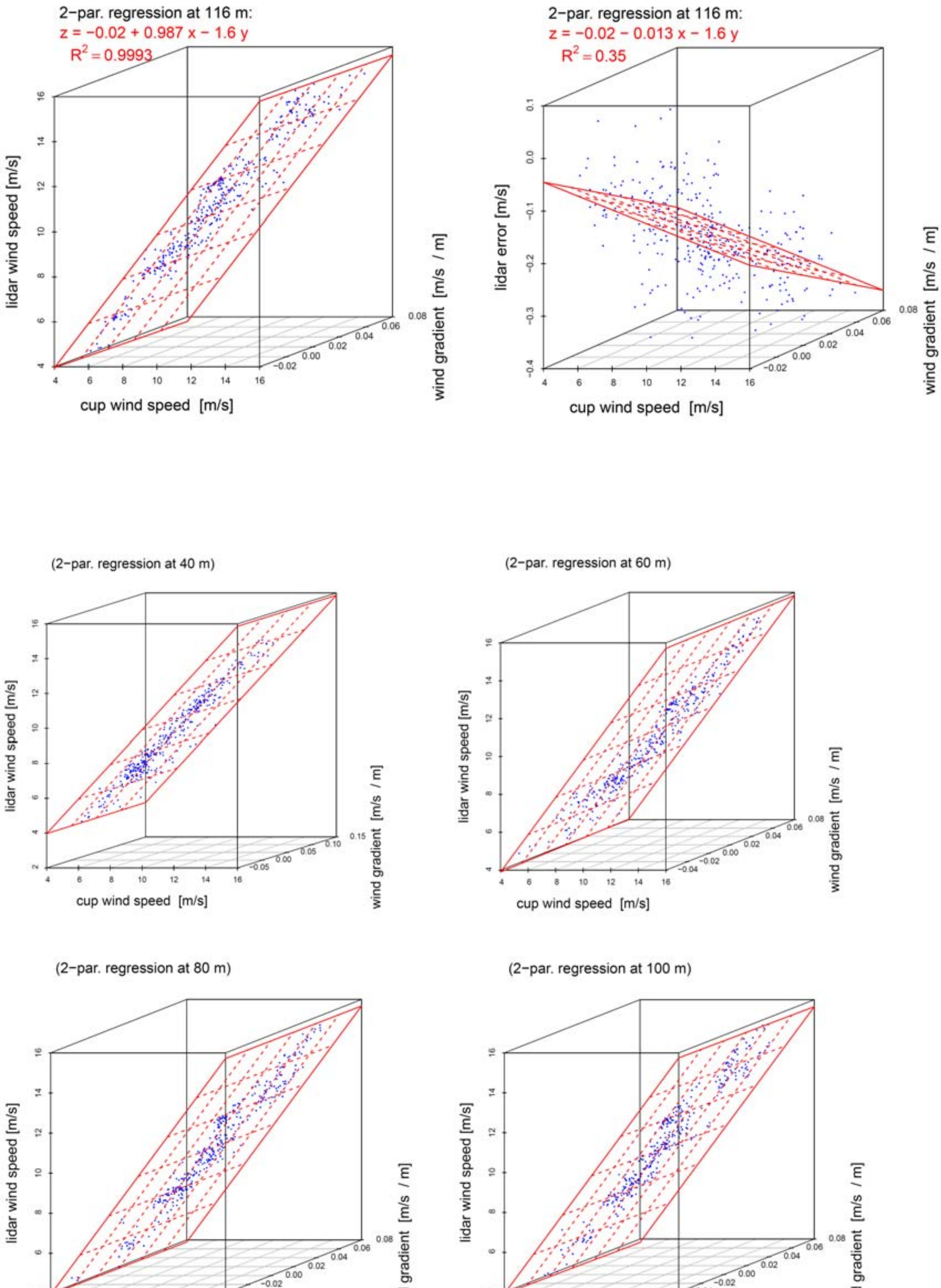


Figure 4-5 Illustration of two-parametric regression. The regression result is shown as red plane. For the data at 116 m two different approaches are shown – with the measured lidar wind speed and the lidar error, resp., as dependent variable.

4.4 Statistics of lidar error and wind speed residuals

The lidar error is defined as the wind speed measured by the lidar minus the reference wind speed measured by the corresponding reference cup anemometer. In Table 4-5 and Figure 4-6, the statistics of the lidar error, given by its mean value and standard deviation, is compared with the standard deviations of the residuals for the three regression models introduced in 4.2 and 4.3. The deviation between the standard deviations of the model residuals and the standard deviation of the lidar error is an indication for how much the"scatter" associated to the lidar measurements (with respect to the reference measurements) can be reduced by applying a calibration based on the respective regression model.

Table 4-5 Statistics of lidar error and wind speed residuals.

Height [m]	mean (lidar error) [m/s]	sd (lidar error) [m/s]	sd (res1a)	sd (res1b)	sd (res2)
40	-0.069	0.089	0.086	0.086	0.086
60	-0.106	0.078	0.072	0.072	0.070
80	-0.196	0.087	0.071	0.071	0.071
100	-0.220	0.085	0.073	0.074	0.073
116	-0.191	0.084	0.072	0.072	0.068

Sd: standard deviation
Res1a: residuals for model $y = C + k x$
Res1b: residuals for model $y = m x$
Res2: residuals for model $y = D + k_u x + k_g g$

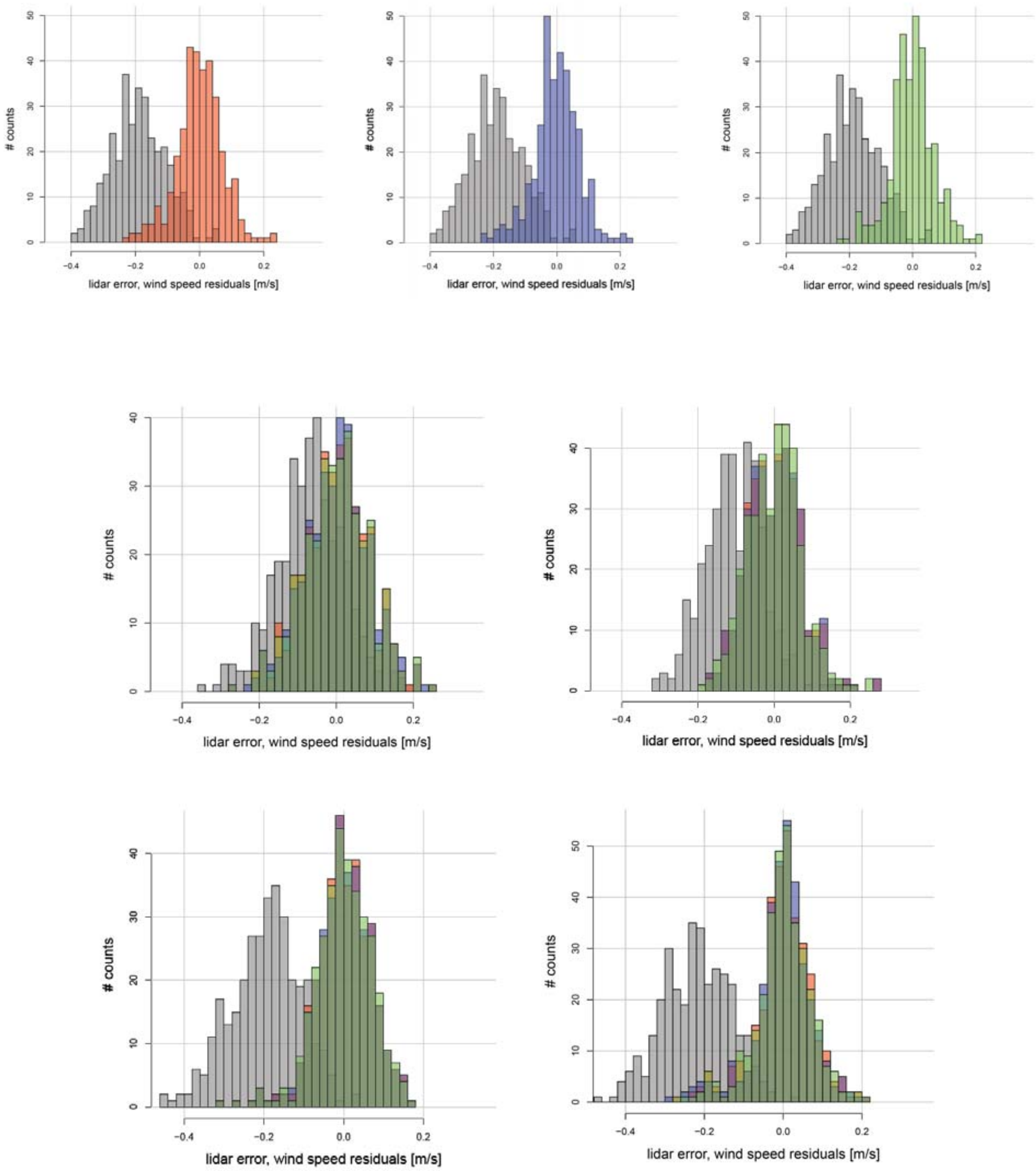


Figure 4-6 Histograms of lidar error (grey) and wind speed residuals – for 116 m (top), 40 m and 60 m (middle), 80 m and 100 m measurement height (bottom). Red for res1a (residuals for model $y = C + kx$), blue for res1b (residuals for model $y = mx$) and green for res2 (residuals for model $y = D + k_u x + k_g g$).

4.5 Detailed investigation of lidar error

Figure 4-7 shows a plot of the lidar error versus the reference wind speed for the five different measurement heights between 40 m and 116 m. The negative trend is due to the regression slopes found to be smaller than one (see results in 4.2 and 4.3). However, no indication of a nonlinear relationship is observed.

As further quality checks, the lidar error is plotted versus mean values for CNR (Carrier to Noise Ratio) and vdis (a measure for the spectral broadening), see Figure 4-8 and Figure 4-9. Again no abnormalities are observed.

In Figure 4-10, the lidar error is plotted versus the reference direction and the valid measurement sector (cf. 2.4) is marked. The plots confirm the made decision regarding the chosen valid wind directions.

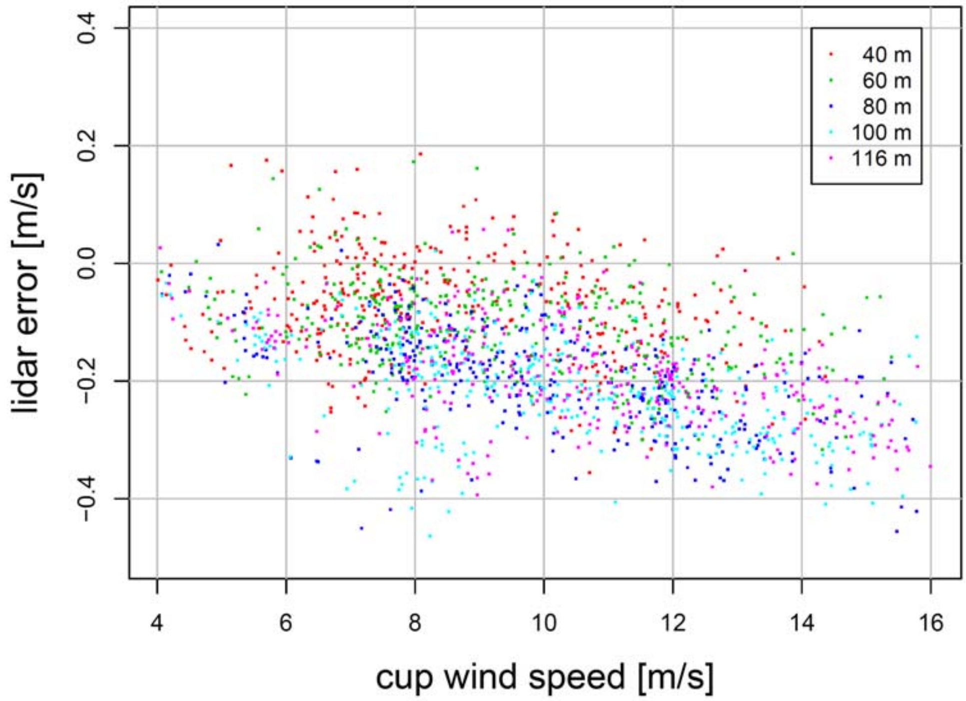


Figure 4-7 Lidar error versus reference wind speed for the five different measurement heights (see legend).

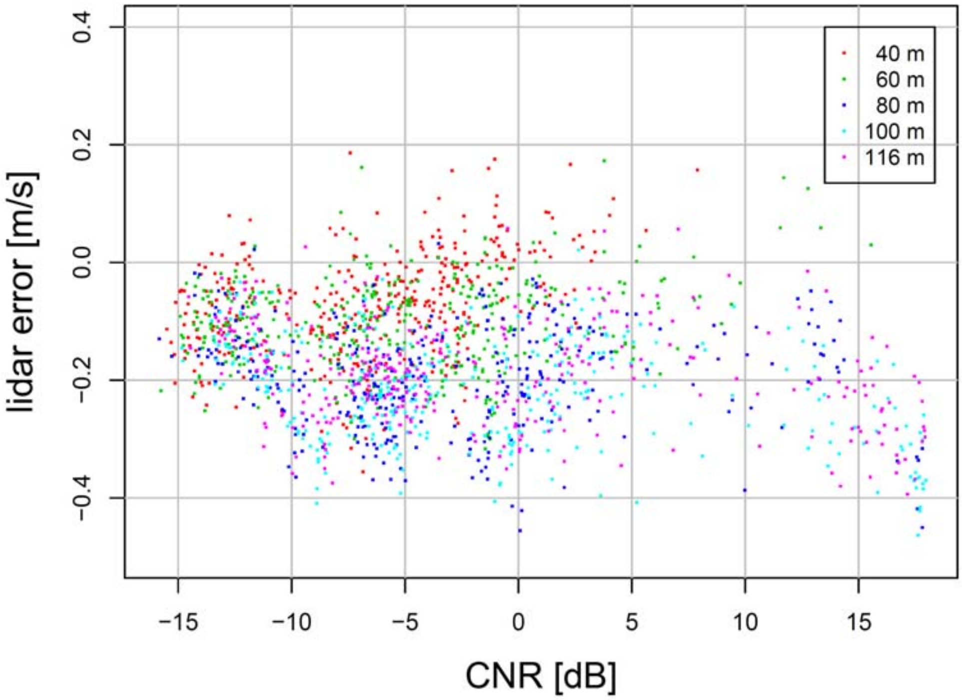


Figure 4-8 Lidar error versus mean CNR (Carrier to Noise Ratio) for the five different measurement heights (see legend).

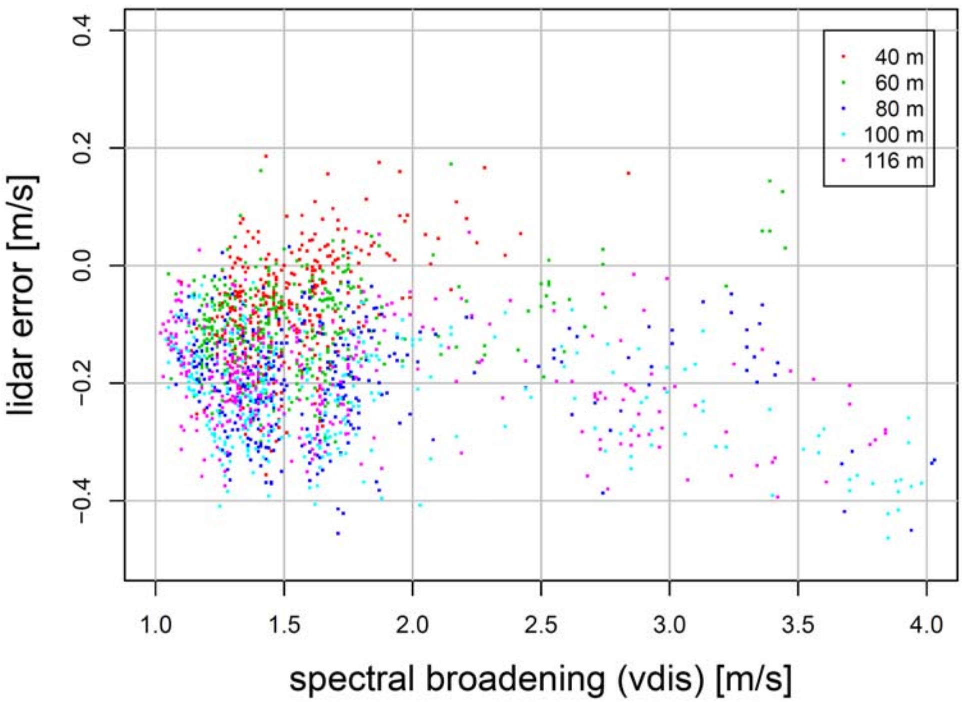


Figure 4-9 Lidar error versus mean value for vdis (spectral broadening) for the five different measurement heights (see legend).

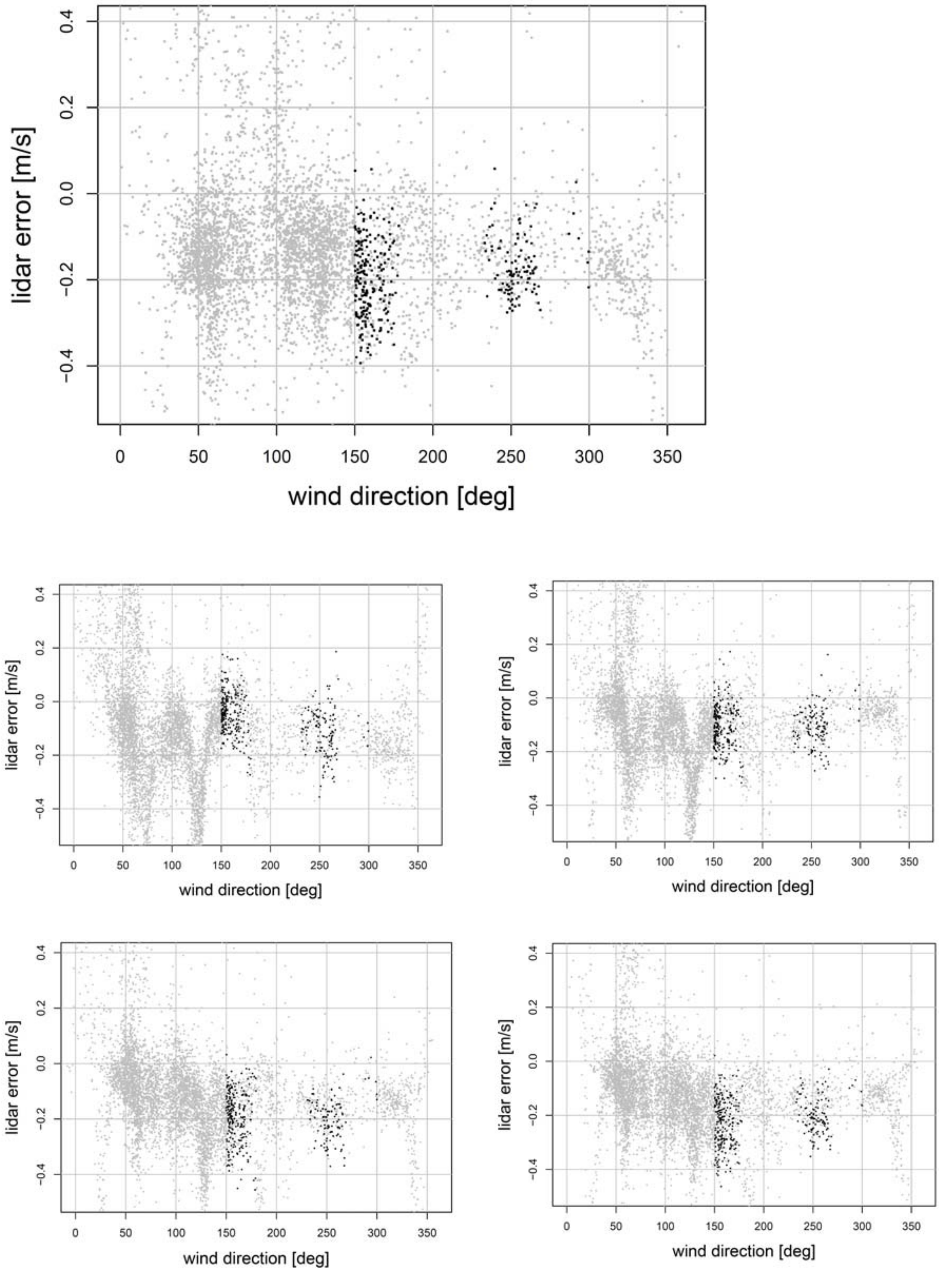


Figure 4-10 Lidar error versus reference wind direction – for 116 m (top), 40 m and 60 m (middle), 80 m and 100 m measurement height (bottom). The filtered (i.e. valid) data points are shown in black, the unfiltered data points in grey.

4.6 One-parametric regression analysis for mean wind directions

In the same way as for the mean wind speeds (see 4.2), a one-parametric regression analysis is applied to the wind directions measured by the lidar and the reference wind vanes. In this case, however, only the standard model with offset parameter is considered – defined by the equation $y = C + kx$ where y is the mean wind direction measured by the lidar and x the reference wind direction measured by the respective reference wind vane at the considered measurement height. (As mentioned before, reference wind vanes were only available at 100 m and 60 m measurement height.)
The results, estimated parameters and the coefficient of determination (R^2), are given in Table 4-6. The corresponding regression plots are presented in Figure 4-11 (left).
The regression was only performed for the partial data set. The first third of the data set is affected by an offset, the data were initially not corrected for. This is seen in Figure 4-11 (right) more clearly.

Table 4-6 Results for one-parametric regression analysis for mean wind directions.

Height [m]	C [deg]	k [-]	R^2
40	--	--	--
60	0.0 (.2)	0.973 (.001)	0.9998
80	--	--	--
100	0.6 (.2)	0.973 (.001)	0.9998
116	--	--	--

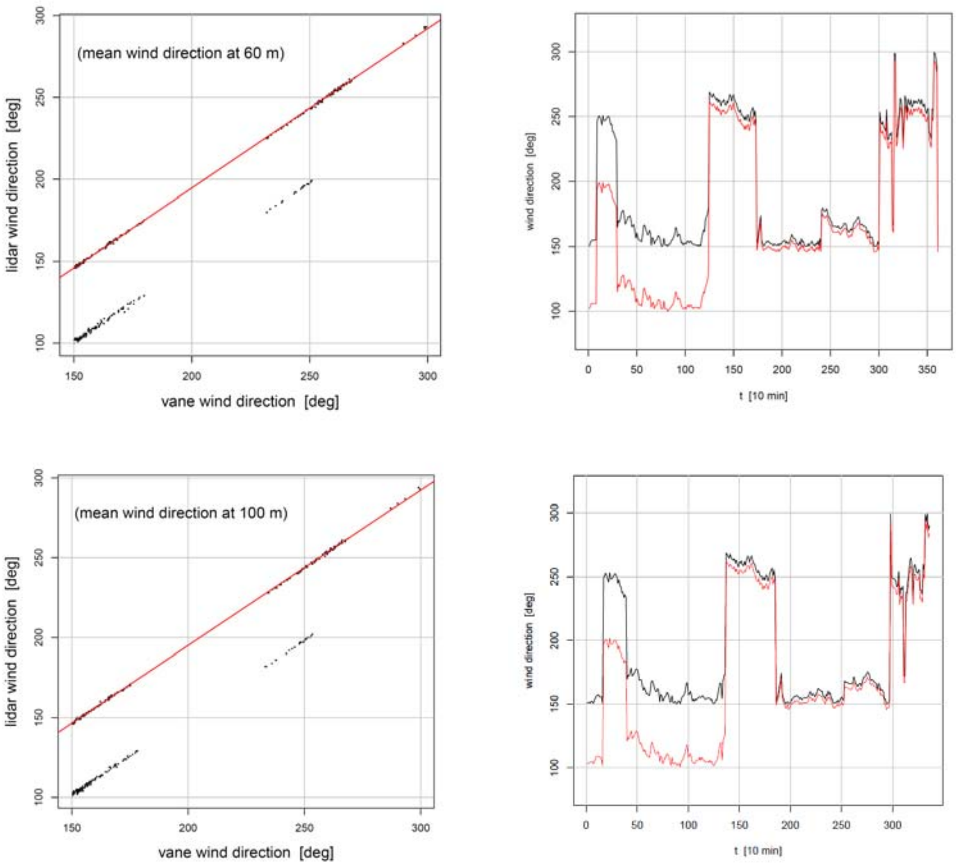


Figure 4-11 Illustration of one-parametric regression for mean wind directions (left) – the results of the regression for the reduced data set are shown as red line. (Right:) Time series of lidar wind direction (red) in comparison to reference wind direction (black).

4.7 One-parametric regression analysis for wind speed standard deviations

To compare the wind speed standard deviations, as measure for horizontal turbulence, measured by the lidar and by the respective reference cup anemometers, again the linear model $y = C + kx$ is applied – where y is in this case the lidar standard deviation and x the standard deviation derived from the cup anemometer measurements. The averaging time is, as for the mean values, 10 min.
The results, estimated parameters and the coefficient of determination (R^2), are given in Table 4-7. The corresponding regression plots are presented in Figure 4-12.

Table 4-7 Results for one-parametric regression analysis for wind speed standard deviations.

Height [m]	C [m/s]	k [-]	R^2
40	0.00 (.01)	0.90 (.01)	0.93
60	0.01 (.01)	0.94 (.01)	0.93
80	0.01 (.01)	0.94 (.01)	0.93
100	0.03 (.01)	0.92 (.01)	0.92
116	0.04 (.01)	0.91 (.02)	0.90

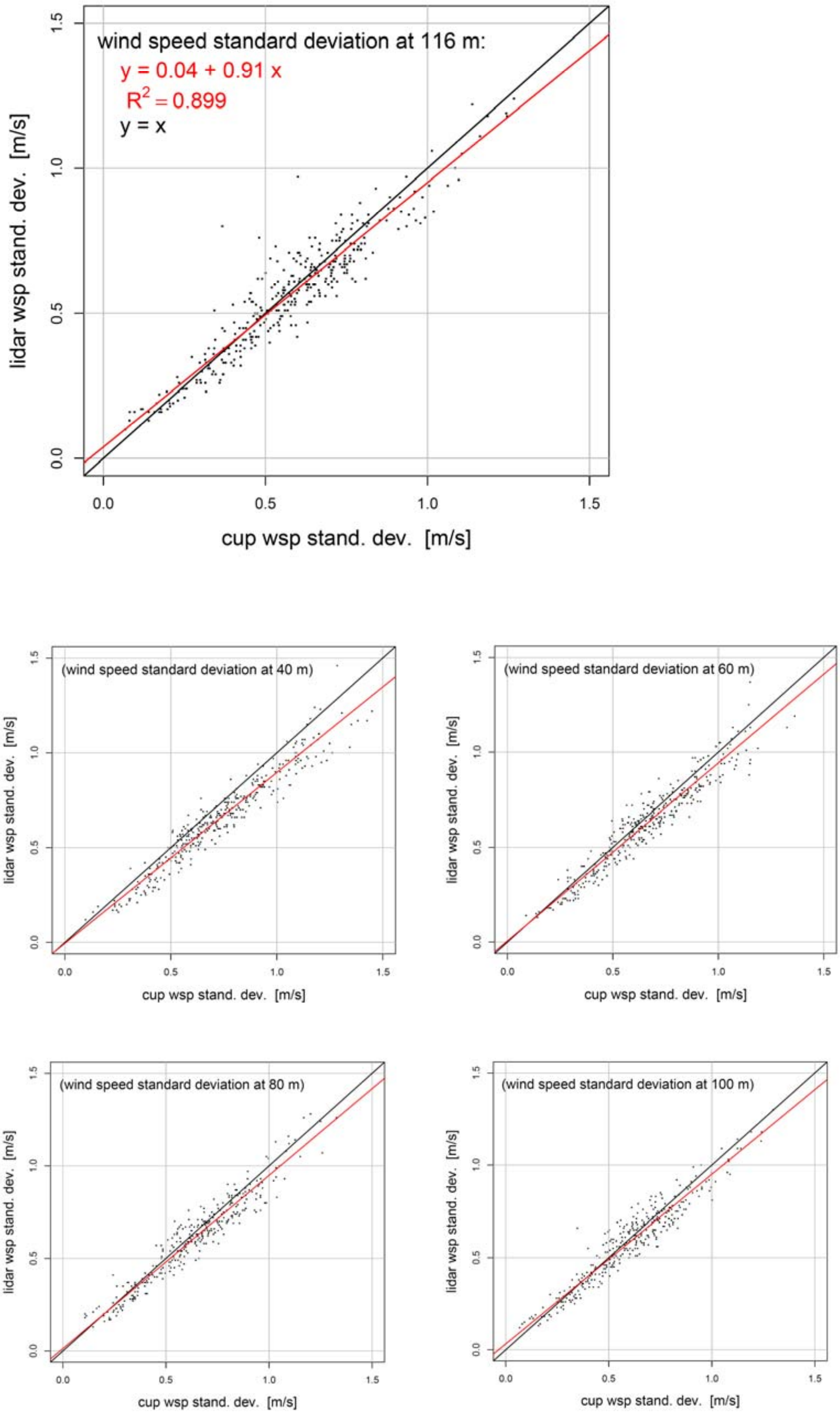


Figure 4-12 Illustration of one-parametric regression for wind speed standard deviations. The results of the regression are shown as red lines. The black lines indicate the relation $y = x$.

5 Comparison of results and further analyses

In Figure 5-1, some of the derived quantities are compared versus the different heights – the three different regression slopes describing the wind speed dependence, i.e. k and m (cf. 4.2) and k_u from the two-parametric regression (see 4.3), the parameter k_g from the two-parametric regression also referred to as altitude error and the mean lidar error (cf. 4.4) as bias between the lidar and the reference wind speed measurements.

Systematic variations of these quantities with height are assumed to be due to vertical wind shear. The wind speed profile over the probe length of the lidar is not constant or linear, and the extent of the nonlinearity changes with the measurement height.

In Figure 5-2, time series of the local wind gradient (derivation see 3.2) for the different measurement heights are presented, showing the expected deviations due to the nonlinear vertical wind profile. Note that the time series for the gradients at 40 m and 116 m show larger variations because the extrapolation of the profile from the five measurement points is here less stable – there are no neighbouring points below or above, respectively.

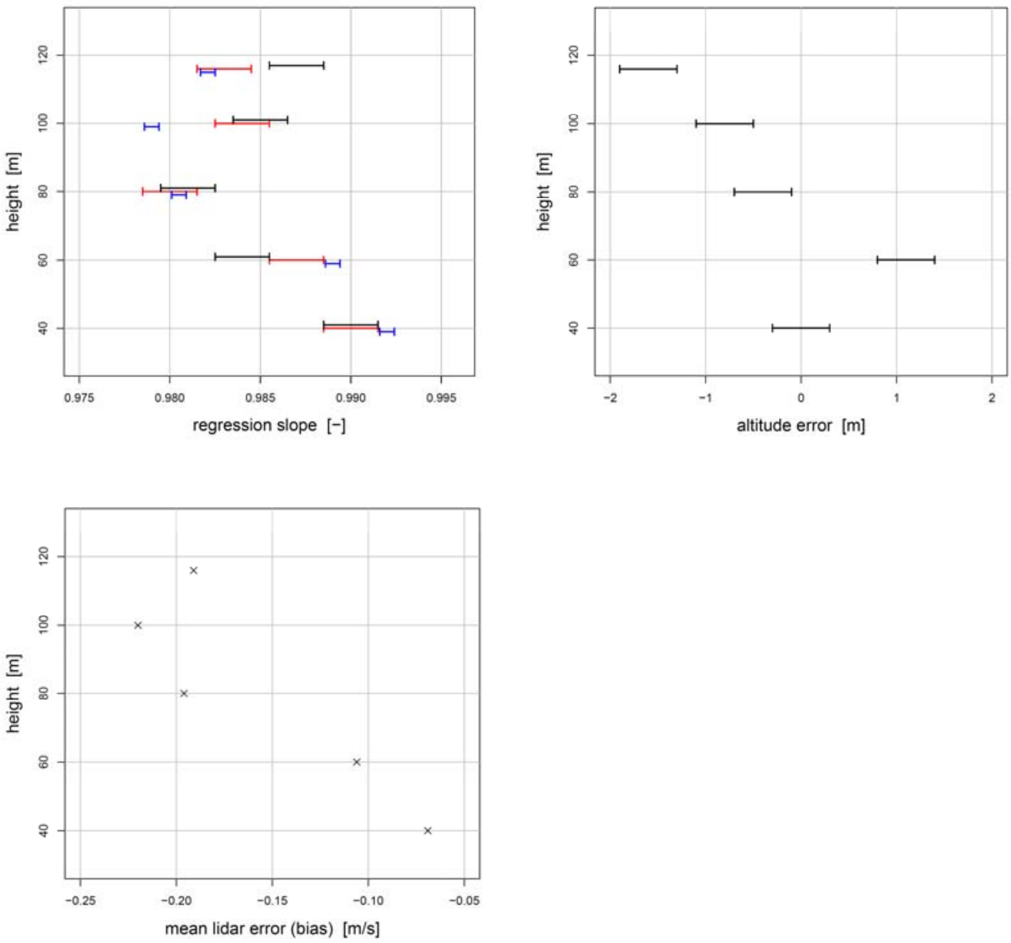


Figure 5-1 Comparison of (top left) regression slopes – k, m and k_u, resp., (top right) the estimated altitude error – parameter k_g in two-parametric regression, and (bottom) mean lidar error for the five measurement heights.

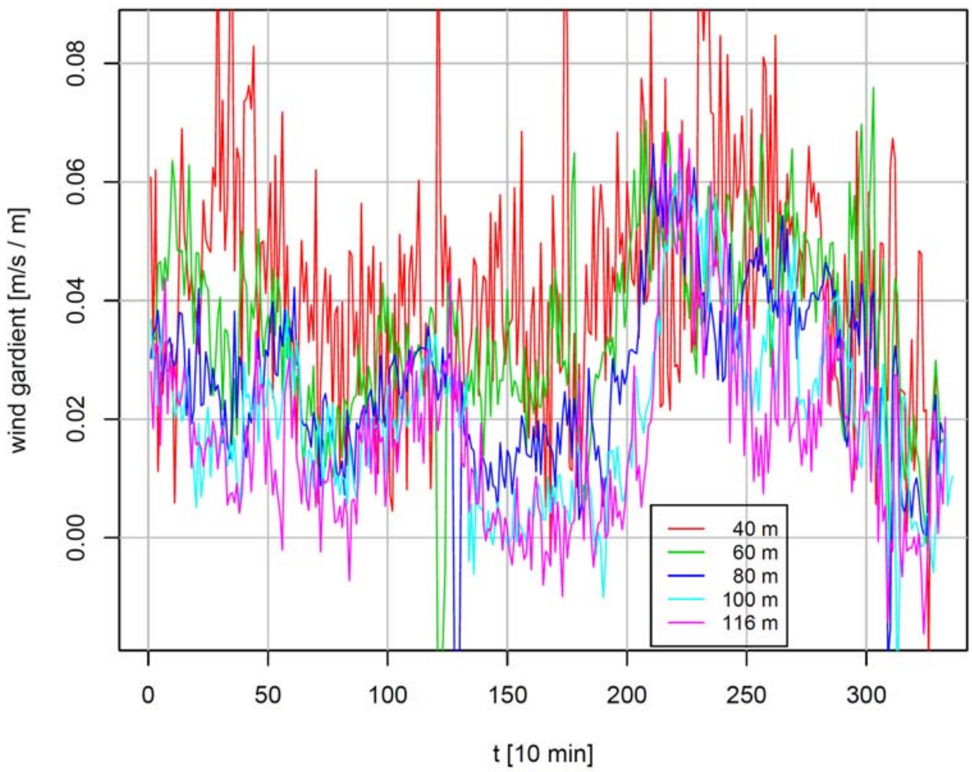


Figure 5-2 Time series of local wind gradient for different measurement heights (see legend).

Variations in the vertical wind shear may also cause systematic differences between the results for different measurement sectors. The valid measurement sector according to 2.4 consists of two smaller sectors, the south-east sector for wind directions in the interval 150-180 deg and the west sector for wind directions between 230 and 300 deg. Due to the different terrain types representative for these two sectors (cf. 2.2), different shear patterns are observed affecting again the verification results.

Table 5-1 to 5-4 show the results for the different verification results, regression parameters and statistics of lidar error and wind speed residuals, separately for the two partial measurement sectors. For clarity of presentation, this analysis was only performed for the data at 40 m and 116 m measurement height.

The estimated numbers differ significantly for the two measurement sectors. The numbers for the total measurement sector are clearly averages between the two more extreme results.

Table 5-1 Number of data samples – for south-east sector (red) and for west sector (blue).

Height [m]	Total	after filtering	[%]
40	7117	358	5.0
		230	3.2
		128	1.8
60	7117	361	5.1
80	7117	332	4.7
100	7117	336	4.7
116	7117	333	4.7
		224	3.1
		109	1.5

Table 5-2 Results for one-parametric regression analysis for mean wind speeds (with and without offset in model) – for south-east sector (red) and for west sector (blue).

Height [m]	C [m/s]	k [-]	R^2	m [-]	R^2
40	0.01(.02)	0.990 (.002)	0.9986	0.9920 (.0005)	0.9986
	0.07 (.02)	0.988 (.002)	0.9991	0.9946 (.0005)	0.9991
	-0.07 (.03)	0.995 (.004)	0.9980	0.9868 (.0009)	0.9980
60	0.02 (.02)	0.987 (.002)	0.9991	0.9890 (.0004)	0.9991
80	0.00 (.02)	0.980 (.002)	0.9992	0.9805 (.0004)	0.9992
100	-0.05 (.02)	0.984 (.002)	0.9992	0.9790 (.0004)	0.9992
116	-0.02 (.02)	0.983 (.001)	0.9993	0.9821 (.0004)	0.9993
	-0.04 (.02)	0.985 (.002)	0.9993	0.9814 (.0005)	0.9993
	0.05 (.03)	0.978 (.002)	0.9994	0.9836 (.0005)	0.9993

Table 5-3 Results for two-parametric regression analysis – for south-east sector (red) and for west sector (blue).

Height [m]	D [m/s]	k_u [-]	k_g [m]	R^2
40	-0.01 (.02)	0.990 (.002)	0.0 (.2)	0.9986
	0.07 (.02)	0.988 (.002)	-0.2 (.2)	0.9991
	-0.08 (.04)	0.995 (.004)	0.1 (.4)	0.9980
60	0.01 (.01)	0.984 (.002)	1.1 (.2)	0.9992
80	0.00 (.02)	0.981 (.002)	-0.4 (.3)	0.9992
100	-0.05 (.02)	0.985 (.002)	-0.8 (.3)	0.9992
116	-0.02 (.02)	0.987 (.001)	-1.6 (.3)	0.9993
	-0.05 (.02)	0.989 (.002)	-1.5 (.4)	0.9993
	0.08 (.02)	0.977 (.002)	-2.5 (.5)	0.9995

Table 5-4 Statistics of lidar error and wind speed residuals – for south-east sector (red) and for west sector (blue).

Height [m]	mean (lidar error) [m/s]	sd (lidar error) [m/s]
40	-0.069	0.089
	-0.043	0.078
	-0.116	0.088
60	-0.106	0.078
80	-0.196	0.087
100	-0.220	0.085
116	-0.191	0.084
	-0.202	0.089
	-0.167	0.068

sd (res1a)	sd (res1b)	sd (res2)
0.086	0.086	0.086
0.072	0.074	0.072
0.087	0.089	0.087
0.072	0.072	0.070
0.071	0.071	0.071
0.073	0.074	0.073
0.072	0.072	0.068
0.077	0.078	0.075
0.051	0.052	0.045

Sd: standard deviation
Res1a: residuals for model $y = C + k\,x$
Res1b: residuals for model $y = m\,x$
Res2: residuals for model $y = D + k_u\,x + k_g\,g$

6 Results for WindCube^{TM} units WLS7-0064 and WLS7-0066

In this section the main verification results for the two WindCube^{TM} units WLS7-0064 and WLS7-0066 are presented. For details about the procedures of analysis see section 4.

Evaluated data sets

Table 6-1 Number of data samples before and after filtering for unit WLS7-0064.

Height [m]	Total	after filtering	[%]
40	7220	360	5.0
60	7220	363	5.0
80	7220	334	4.6
100	7215	338	4.7
116	7220	335	4.6

Table 6-2 Number of data samples before and after filtering for unit WLS7-0066.

Height [m]	Total	after filtering	[%]
40	7212	358	5.0
60	7212	360	5.0
80	7212	332	4.6
100	7212	336	4.7
116	7212	333	4.6

One-parametric regression for mean wind speeds

Table 6-3 Results for one-parametric regression analysis for mean wind speeds (with and without offset parameter in model) for unit WLS7-0064.

Height [m]	C [m/s]	k [-]	R^2	m [-]	R^2
40	0.02 (.02)	0.993 (.002)	0.9986	0.9954 (.0005)	0.9986
60	0.02 (.01)	0.990 (.001)	0.9992	0.9919 (.0004)	0.9992
80	0.05 (.01)	0.978 (.001)	0.9994	0.9831 (.0003)	0.9993
100	0.03 (.01)	0.979 (.001)	0.9994	0.9814 (.0003)	0.9994
116	0.03 (.02)	0.982 (.001)	0.9993	0.9846 (.0003)	0.9993

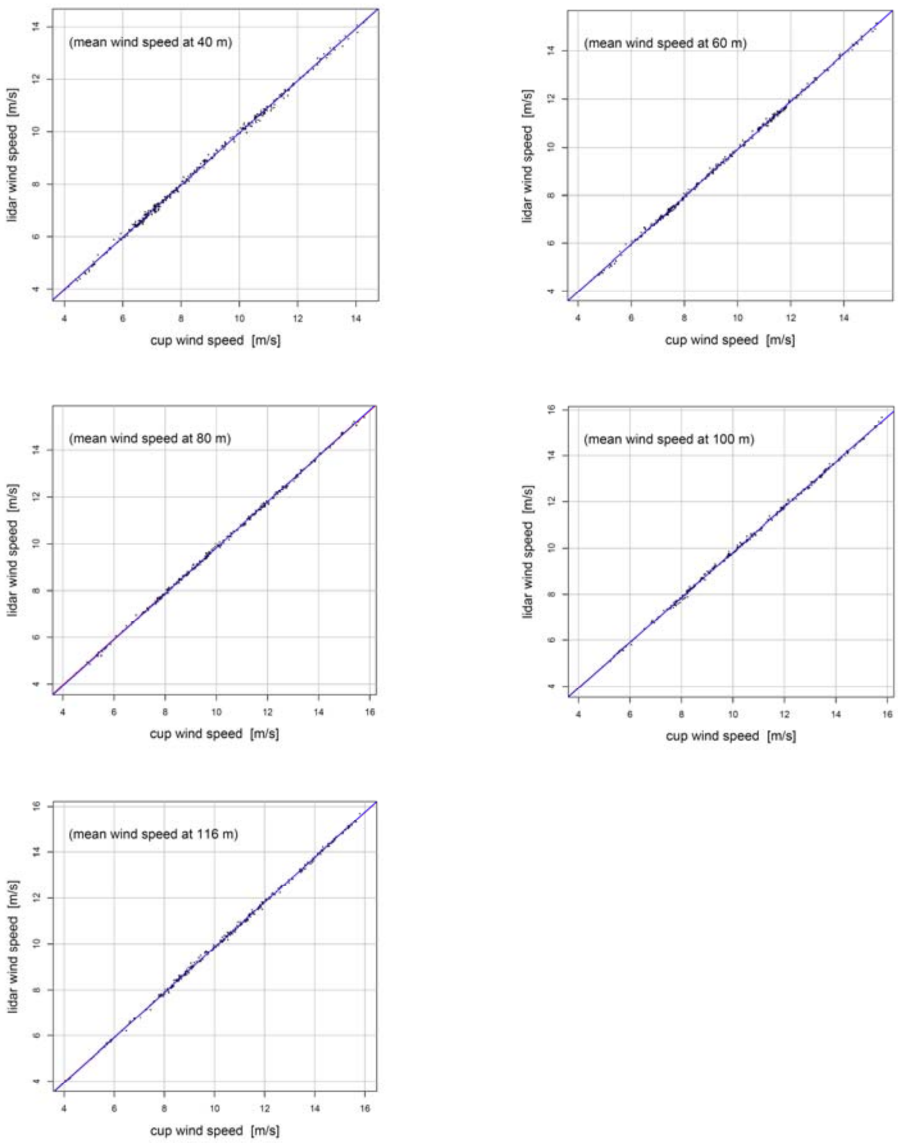


Figure 6-1 Illustration of one-parametric regression for mean wind speeds for unit WLS7-0064.

Table 6-4 Results for one-parametric regression analysis for mean wind speeds (with and without offset parameter in model) for unit WLS7-0066.

Height [m]	C [m/s]	k [-]	R^2	m [-]	R^2
40	0.04 (.02)	0.989 (.002)	0.9983	0.9931 (.0006)	0.9983
60	0.01 (.02)	0.987 (.002)	0.9991	0.9876 (.0004)	0.9991
80	-0.06 (.03)	0.986 (.003)	0.9978	0.9797 (.0006)	0.9978
100	-0.10 (.03)	0.987 (.003)	0.9974	0.9781 (.0007)	0.9973
116	0.01 (.02)	0.982 (.002)	0.9986	0.9823 (.0005)	0.9986

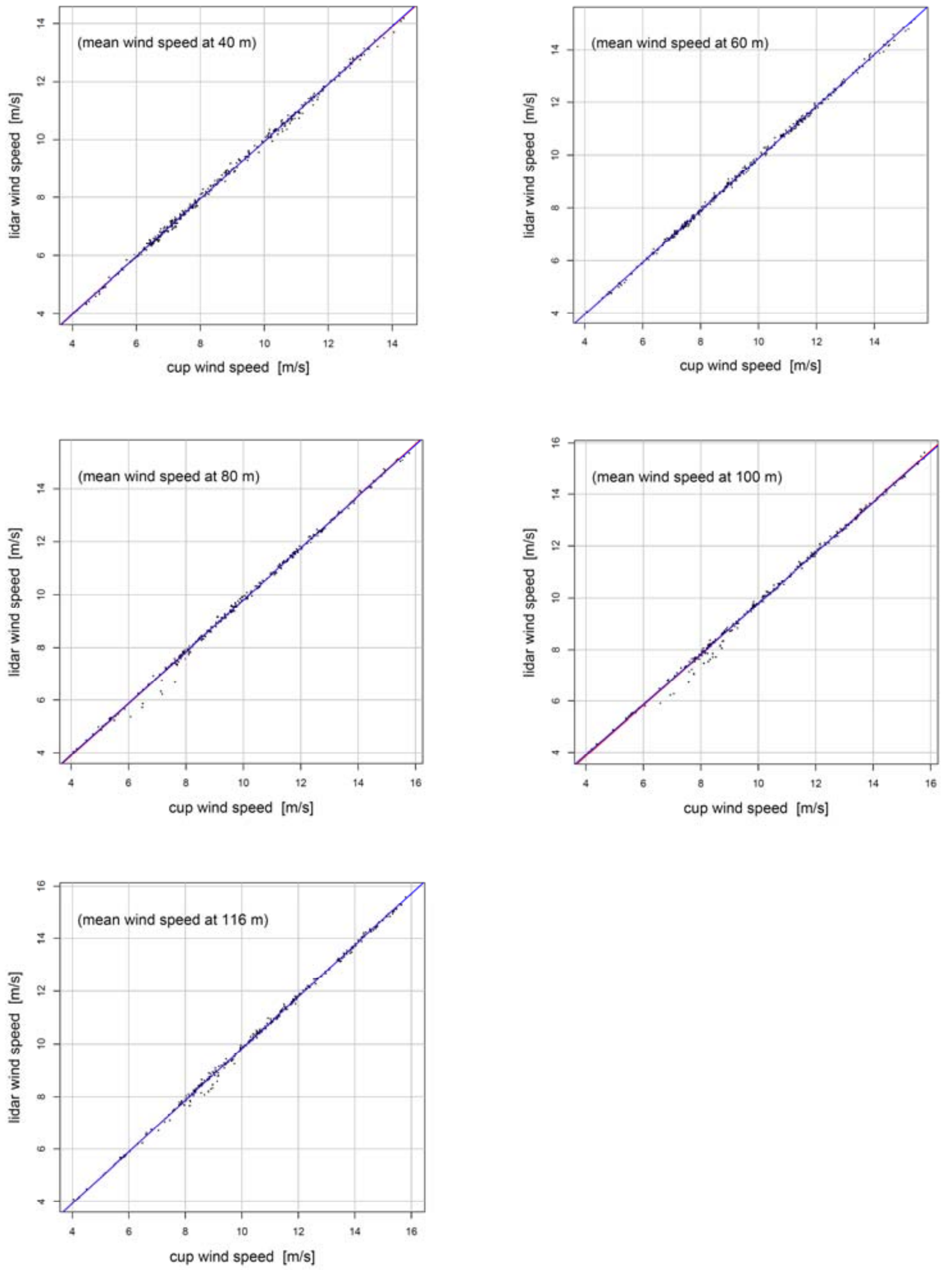


Figure 6-2 Illustration of one-paramteric regression for mean wind speeds for unit WLS7-0066.

Two-parametric regression analysis

Table 6-5 Results for two-parametric regression analysis for unit WLS7-0064.

Height [m]	c [m/s]	k_u [-]	k_g [m]	R^2
40	0.02 (.02)	0.993 (.002)	0.0 (.2)	0.9986
60	0.02 (.01)	0.986 (.002)	0.9 (.2)	0.9992
80	0.05 (.01)	0.979 (.002)	-0.2 (.3)	0.9994
100	0.02 (.01)	0.981 (.001)	-0.9 (.2)	0.9994
116	0.02 (.01)	0.986 (.001)	-2.2 (.2)	0.9995

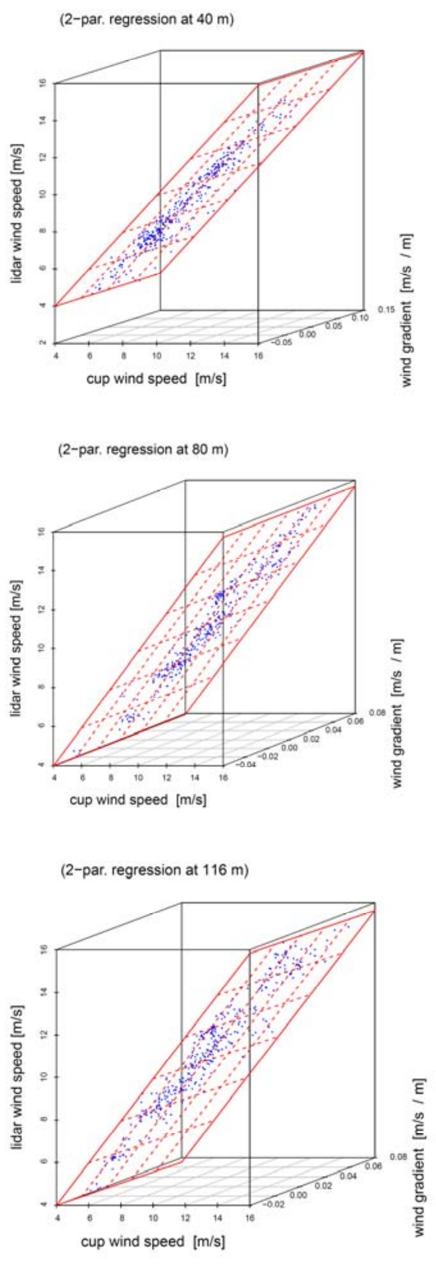


Figure 6-3 Illustration of two-parametric regression for unit WLS7-0064.

Table 6-6 Results for two-parametric regression analysis for unit WLS7-0066.

Height [m]	c [m/s]	k_u [-]	k_g [m]	R^2
40	0.03 (.02)	0.989 (.002)	0.2 (.2)	0.9983
60	0.01 (.02)	0.986 (.002)	0.4 (.3)	0.9991
80	-0.06 (.03)	0.989 (.003)	-1.2 (.5)	0.9979
100	-0.11 (.03)	0.993 (.003)	-2.4 (.5)	0.9975
116	0.00 (.02)	0.987 (.002)	-2.4 (.4)	0.9988

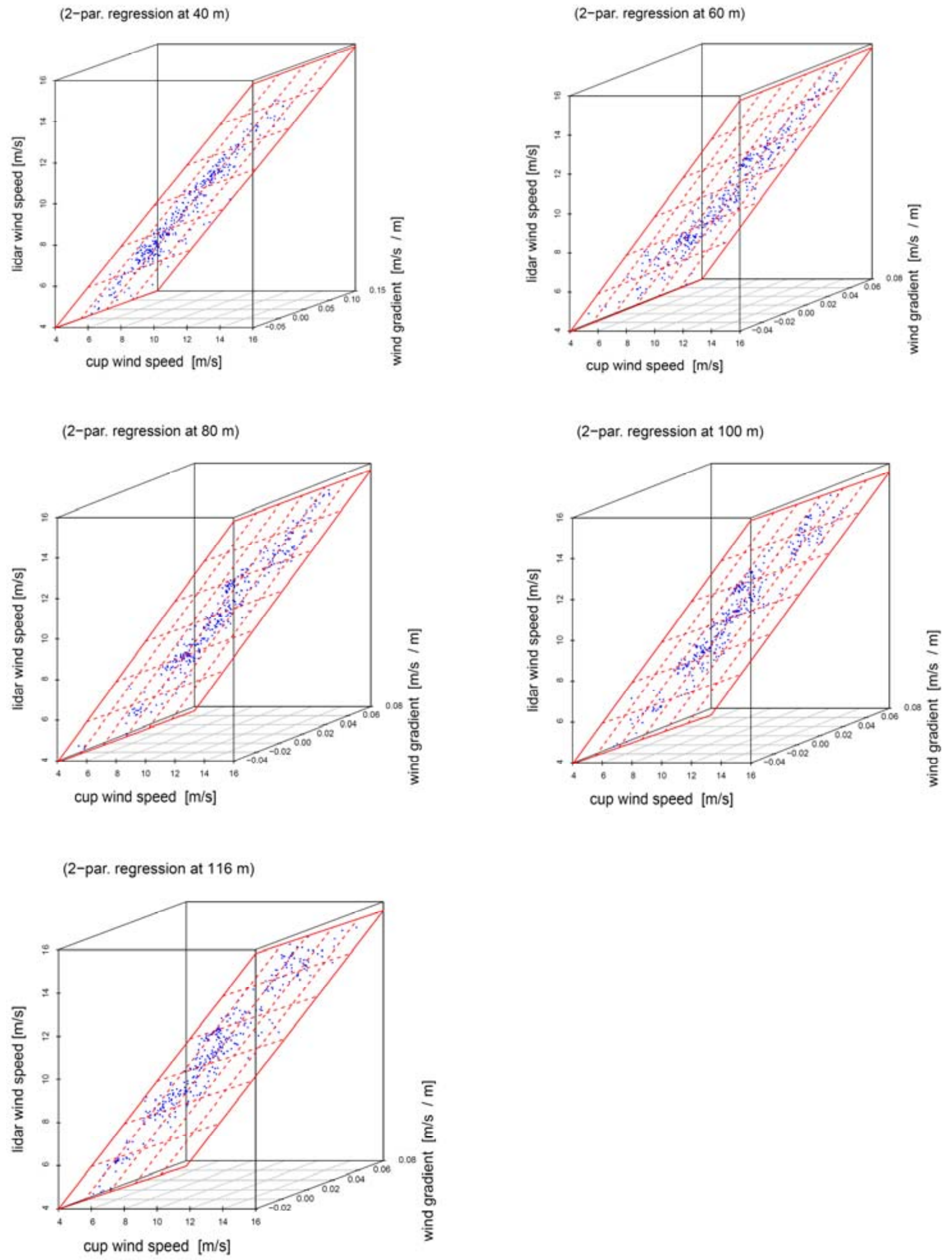


Figure 6-4 Illustration of two-parametric regression for unit WLS7-0066.

Statistics of lidar error and wind speed residuals

Table 6-7 Statistics of lidar error and wind speed residuals for unit WLS7-0064.

Height [m]	mean (lidar error) [m/s]	sd (lidar error) [m/s]	sd (res1a)	sd (res1b)	sd (res2)
40	-0.039	0.088	0.086	0.087	0.086
60	-0.075	0.075	0.070	0.071	0.069
80	-0.167	0.084	0.063	0.065	0.063
100	-0.190	0.083	0.062	0.063	0.061
116	-0.161	0.085	0.069	0.069	0.062

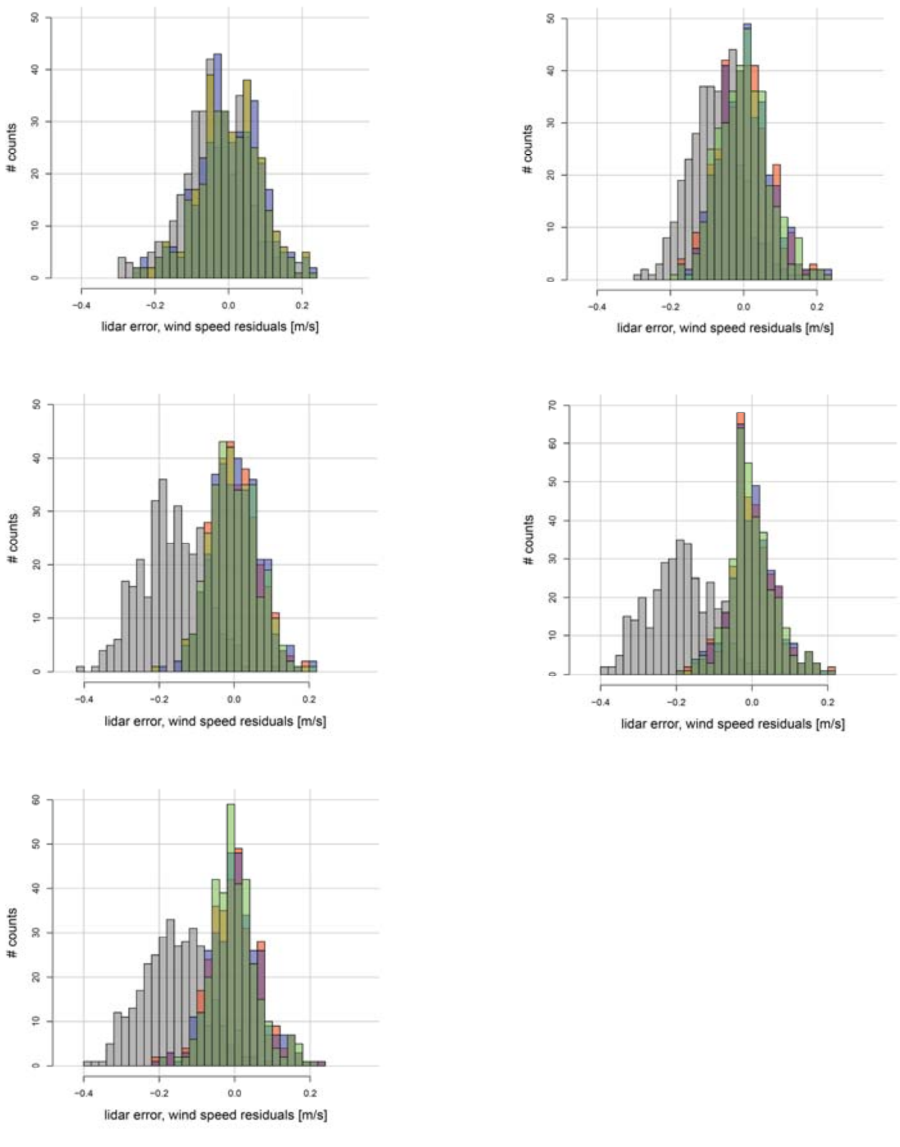


Figure 6-5 Histograms of lidar error (grey) and wind speed residuals for unit WLS7-0064.

Table 6-8 Statistics of lidar error and wind speed residuals for unit WLS7-0066.

Height [m]	mean (lidar error) [m/s]	sd (lidar error) [m/s]	sd (res1a)	sd (res1b)	sd (res2)
40	-0.057	0.097	0.093	0.094	0.093
60	-0.116	0.082	0.076	0.076	0.076
80	-0.208	0.123	0.117	0.118	0.116
100	-0.233	0.136	0.132	0.134	0.128
116	-0.187	0.110	0.099	0.099	0.093

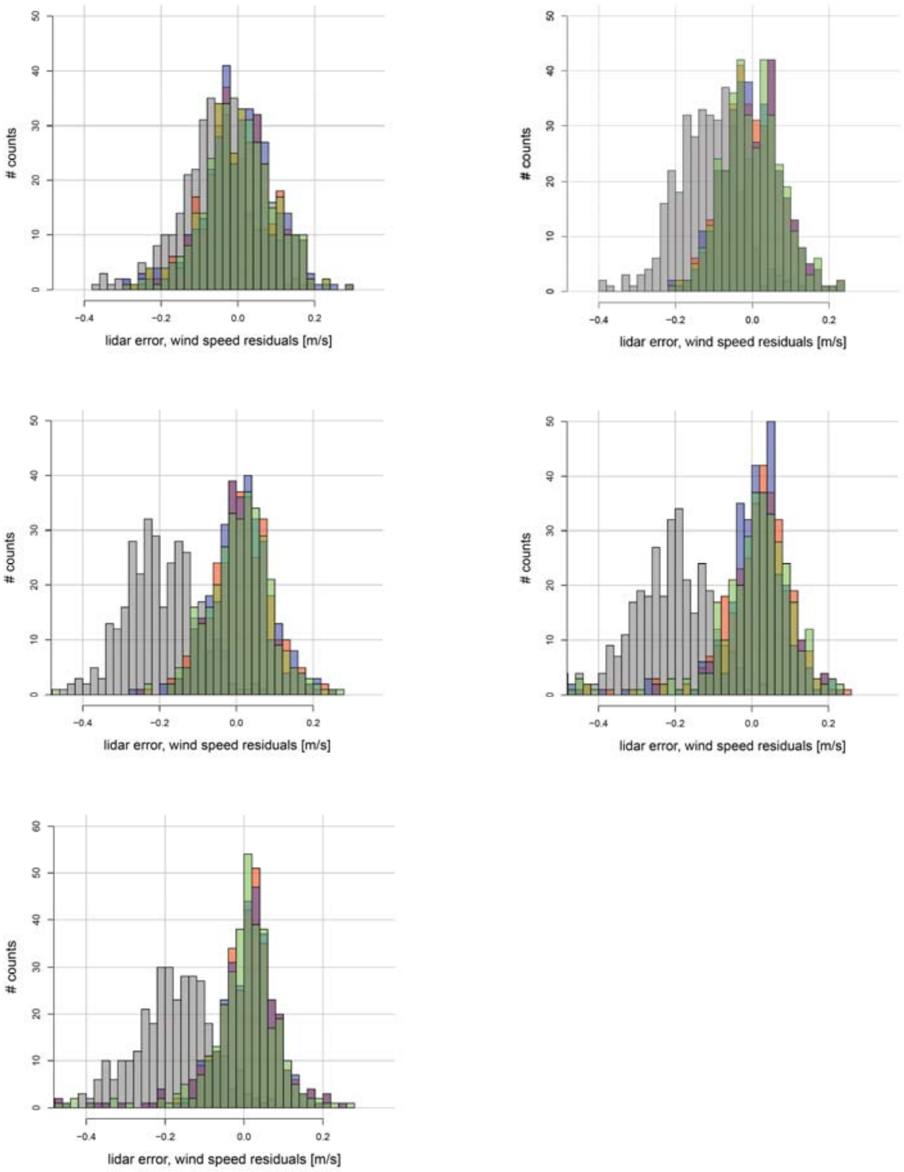


Figure 6-6 Histograms of lidar error (grey) and wind speed residuals for unit WLS7-0066.

7 Discussion

The test period, referred to in this report, has been a quite difficult period in the sense that only a small number of data samples were obtained from the valid measurement sectors, i.e. the sectors that are not affected by the different wake constellations. In addition, the tests were performed in the winter period where especially the reference wind speed measurements may typically be affected by icing. We adjusted the filtering on icing-effected reference measurements and combined two smaller measurement sectors in the way that we could obtain a maximum of valid data samples. The resulting number was then between 330 and 360 data samples for the different measurement heights. This number still lies significantly below the recommended number of at least 600 data samples for a valid verification test.

On the other hand, the verification results look already for this small number of data samples quite satisfactorily. Coefficients of determination (i.e. values for R^2) above 0.9990 and values for the standard deviations of the lidar error as well as the model residuals significantly below 0.10 m/s indicate a good performance of the lidar in terms of a good correlation to the reference wind speed measurements. For WindCube^{TM} unit WLS7-0062, poorer results were only obtained for the measurements at 40 m heights, which is however assumed to be due to the reference cup anemometer and not due to the lidar itself.[2]

We introduced three different regression models for the measured mean wind speeds – differing in the number of free parameters from one to three. As to be expected, the model with the largest number of free parameters (here: the two-parametric regression) shows the best performance in terms of the highest values for R^2 and the lowest values for the standard deviation of the corresponding model residuals. The deviation to the two other models are however rather marginal.
The results of all three models could be used as calibration functions to be applied to the data measured by the lidar. The complexity of the model is then to be weighted up with a reduction in uncertainty achieved by the calibration. For a more detailed discussion see [4]. The estimation of the uncertainty associated to the lidar measurements is not an issue of this report.

In addition to the measured mean wind speeds, also the wind speed standard deviations and the mean wind directions were analysed in terms of a one-parametric regression analysis. The results are rather of informative nature.
The comparison of the wind direction measurements showed an offset in the lidar data for about the first third of the data set. The measured data should be normally corrected for such an offset before the verification test is performed.
The comparison of the wind speed standard deviations is affected by significantly more scatter than the comparison of the mean values. This lower correlation is due to the extremely different measurement principles of the two compared instruments, resulting in very different measuring volumes but also different sampling rates of the raw data, and is generally not to be interpreted as a poor performance of the tested lidar.

Definitely a distinctive feature of the reported verification test has been that three lidars, identical in type and version, were tested at the same location and at the same time. This makes so to say a further dimension of comparison possible.

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2 The boom dimensions at 40 m are different from those at the other heights. The applied correction algorithm for boom and mast effects (cf. 2.5) is optimized with respect to the measurements at 80 m and therefore not performing in an optimal way for the measurements at 40 m.

The verification results for WindCube^{TM} unit WLS7-0064 are very similar to those of unit WLS7-0062 that has been analysed in detail before. For unit WLS7-0066 a poorer performance was observed for the measurements at 80 m and 100 m height whereas the results at the other heights are more or less at the same level as the results for the two other lidar units. There is no obvious explanation for this poorer performance.

8 Conclusions

The three WindCube^{TM} units WLS7-0062, WLS7-0064 and WLS7-0066 were tested at the Danish National Test Station for Large Wind Turbines at Høvsøre by comparing simultaneous lidar and reference measurements at five distinct measurement heights. The data – mean wind speeds, wind speed standard deviations and mean wind directions – were recorded over a period of about eight weeks from 04 December 2009 to 26 January 2010, but only about 5% of the data could be evaluated in the verification test mainly due to unsuitable wind directions.

The data evaluation was performed in terms of different types of regression analyses. The verification results confirm that the tested WindCube^{TM} units do not show any severe abnormal behaviour for the test period and may be considered as satisfactorily performing systems.

The results are however only valid in flat terrain with truly homogeneous flow, and they cannot be applied to measurements in conditions significantly differing from that such as complex terrain.

Acknowledgements

The authors would like to thank the permanent staff at the Høvsøre test site, Bjarne Sønderskov and Anders Ramsing Vestergaard, for their untiring and highly professional support, as well as Steen Sørensen at Risø DTU for managing the database.

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Risø DTU
National Laboratory for Sustainable Energy
Technical University of Denmark

Frederiksborgvej 399
PO Box 49
DK-4000 Roskilde
Denmark
Phone +45 4677 4677
Fax +45 4677 5688

www.risoe.dtu.dk