Executive summary of key test results for SgurrEnergy Galion

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1 Setup of test and data processing

The SgurrEnergy Galion was tested at the Danish National Test Station for Large Wind Turbines, located at Høvsøre in flat terrain in Western Jutland, Denmark, and operated by Risø DTU. Testing of lidars is performed next to an intensively instrumented meteorological mast. As reference sensors cup anemometers at five different measurement heights between 40 m and 116.5 m are used. All cup anemometers are classified as class 1A cups and calibrated according to the Measnet standard. Wind vanes at 60 m and 100m are used for the comparison of wind direction measurements.
The considered measurement period spans about four weeks from 19 May (12:00) till 15 June (00:00). For the data evaluation 10-minute mean values and standard deviations are considered.
For each considered height a total number of 3754 sets of measurement values were sampled. The data were then screened on wind direction (ie. excluding wind directions that are affected by turbine or mast wakes), wind speed (> 4 m/s), wind direction shear (deviation between wind direction at 60 m and at 100 m < 5 degrees) and adjacent rain. The screening results in a reduction of the data sets as given in table 1.

Table 1: Number of data samples remaining after screening for five considered measurement heights.

height [m]	# data samples after screening
40	558
60	559
80	576
100	601
116	601

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2 Results of data evaluation

2.1 Standard regression analysis for horizontal wind speed

Two linear models are applied – $y = C + k \cdot x$ and $y = m \cdot x$ where y is the wind speed measured by the lidar and x the reference wind speed measured by the respective cup anemometer at the considered measurement height. The results, estimated parameters and the coefficient of determination (R^2), are given in table 2 and illustrated by figure 1.

Table 2: Results of standard regression analysis (with and without offset) for horizontal wind speed.

height [m]	C [m/s]	k [-]	R^2	m [-]	R^2
40	-0.14 (±.04)	0.998 (±.005)	0.9872	0.983 (±.002)	0.9870
60	0.02 (±.02)	0.991 (±.003)	0.9960	0.993 (±.001)	0.9960
80	0.07 (±.02)	0.983 (±.002)	0.9972	0.991 (±.001)	0.9971
100	0.12 (±.02)	0.976 (±.002)	0.9975	0.988 (±.001)	0.9973
116	0.07 (±.02)	0.981 (±.002)	0.9969	0.988 (±.001)	0.9969

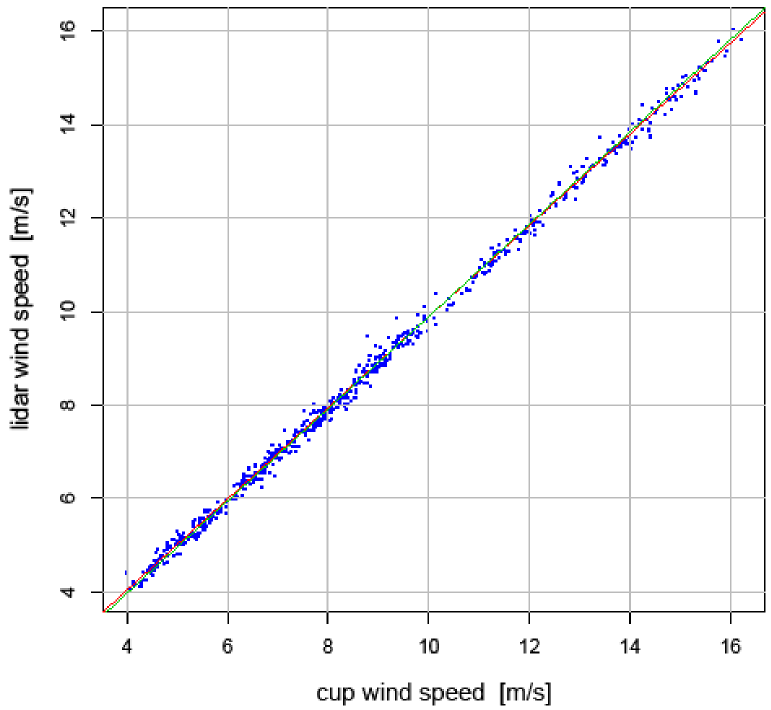

Figure 1: Illustration of standard regression analysis for horizontal wind speed at 100 m measurement height. Blue dots denote 10-minute average values, the red line gives the fitted linear model with offset, the green line is for the model without offset.

2.2 Statistics of lidar error

The lidar error is defined as the wind speed measured by the lidar minus the reference wind speed measured by the corresponding cup anemometer. Table 3 summarizes mean values and standard deviations as basic statistical quantities of the lidar error at each measurement height. Figure 2 shows an example of the corresponding histogram of data (here for 100 m measurement height).

Table 3: Mean value and standard deviation of lidar error for considered measurement heights.

height [m]	mean value [m/s]	standard deviation [m/s]
40	-0.16	0.31
60	-0.05	0.18
80	-0.07	0.16
100	-0.09	0.17
116	-0.10	0.18

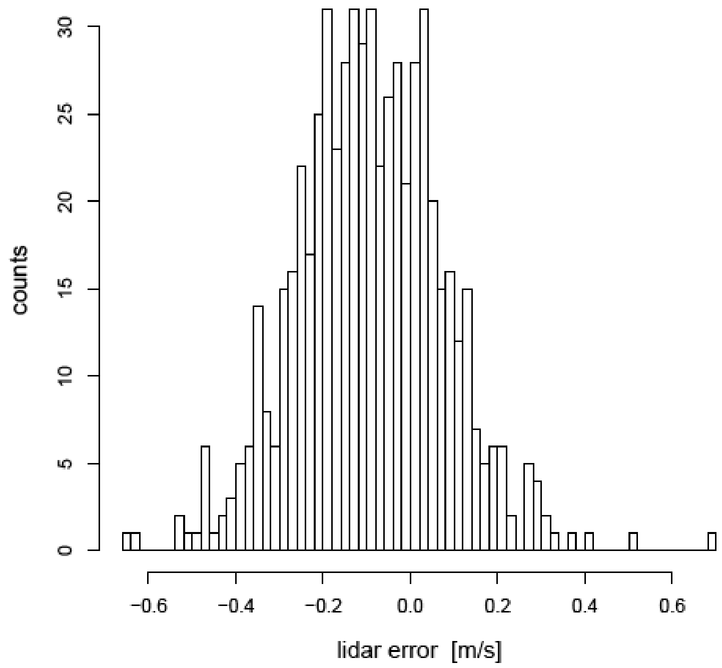

Figure 2: Histogram of lidar error (lidar wind speed minus cup wind speed) for 100 m measurement height – mean value and standard deviation are -0.09 m/s and 0.17 m/s, respectively.

2.3 Two-parametric regression analysis

In a two-parametric regression the lidar error is analysed as function of wind speed and wind shear. Independent variables are the reference wind speed measured by the cup anemometers and a wind gradient that is derived as local shear measure on the basis of the five considered simultaneous cup measurements. The wind speed dependence of the lidar error gives a gain value (k_u). The dependence on the wind gradient results in an approximate altitude error (k_g). The corresponding linear model reads $z = k_u \cdot x + k_g \cdot y$ where z is the lidar error, x the reference wind speed and y the estimated wind gradient. Results of the two-parametric regression analysis for the Galion data in the above mentioned measurement period are given in table 4 and illustrated in figure 3.

Table 4: Results of of two-parametric regression – offset (C) of linear model, gain (k_u) and altitude error (k_g).

height [m]	C [m/s]	k_u [-]	k_g [m]	R^2
40	-0.14 (±.04)	-0.002 (±.005)	0.1 (±.9)	0.0003
60	0.02 (±.02)	-0.008 (±.003)	-0.1 (±1.0)	0.0181
80	0.07 (±.02)	-0.017 (±.002)	-0.5 (±1.0)	0.0945
100	0.12 (±.02)	-0.024 (±.002)	0.9 (±1.1)	0.1939
116	0.05 (±.02)	-0.015 (±.002)	-3.3 (±.9)	0.1231

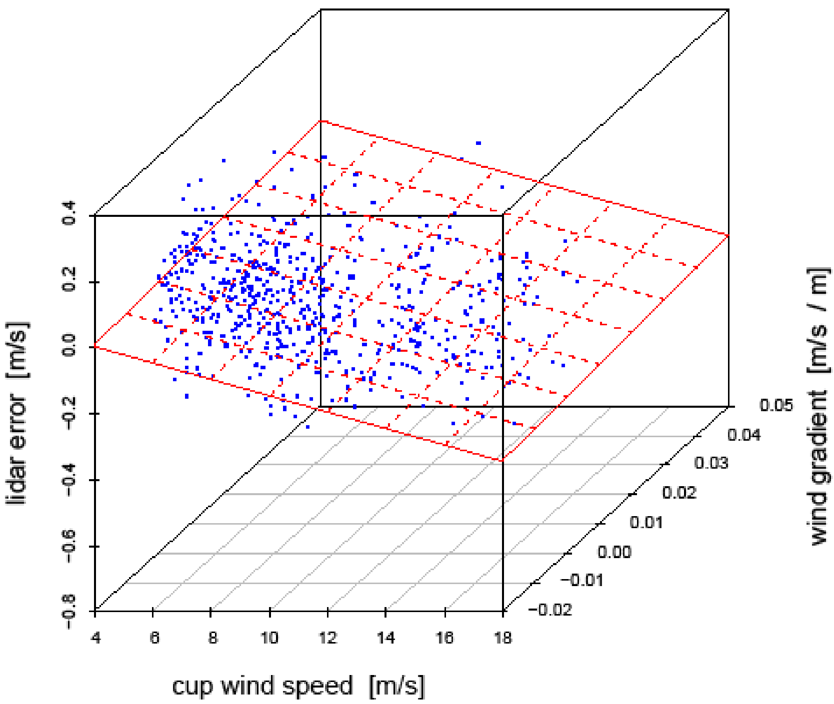

Figure 3: Illustration of two-parametric regression, here for 100 m measurement height.

2.4 Standard regression analysis for wind direction

In the same way as for the mean wind speed comparison (see 2.1), two linear models are applied for the measured wind directions – y = C + k·x and y = m·x where y is the wind direction measured by the lidar and x the reference wind direction measured by the respective wind vane (at 60 m and at 100 m measurement height where vane measurements are availabe) or an extra-/interpolated wind direction. The results, estimated parameters and the respective coefficient of determination (R^2) are given in table 5 and illustrated by figure 4.

Table 5: Results of standard regression analysis (with and without offset) for wind direction. Note that wind vane measurements are only available at 60 m and 100 measurement height. The reference wind directions at 40 m and 116 m are extrapolated simply assuming the closest available measurement, the wind direction at 80 m is interpolated from the measurements above and below.

height [m]	C [deg]	k [-]	R^2	m [-]	R^2
40	5.3 (±.6)	0.960 (±.002)	0.9970	0.980 (±.000)	0.9965
60	10.1 (±.5)	0.944 (±.002)	0.9977	0.984 (±.000)	0.9959
80	6.4 (±.4)	0.962 (±.002)	0.9980	0.988 (±.000)	0.9975
100	2.5 (±.4)	0.982 (±.002)	0.9983	0.991 (±.000)	0.9982
116	3.5 (±.4)	0.978 (±.002)	0.9983	0.992 (±.000)	0.9981

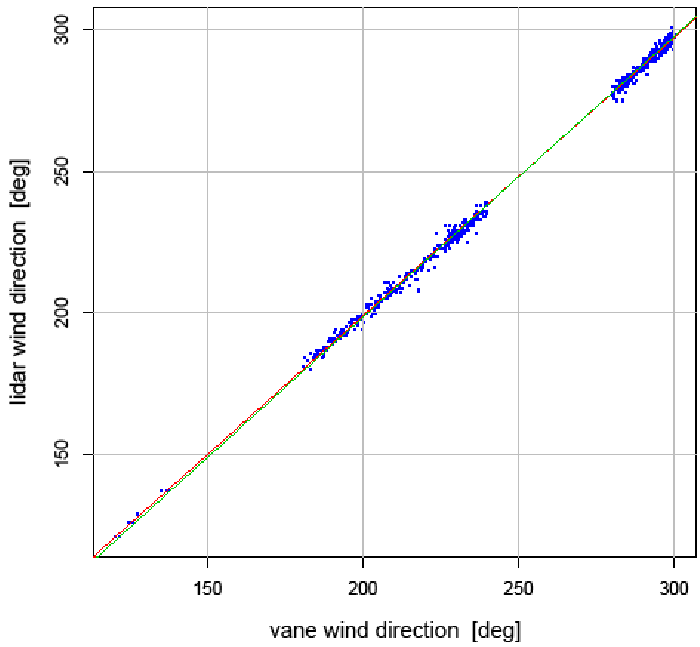

Figure 4: Illustration of standard regression analysis for wind direction at 100 m measurement height. Blue dots denote 10-minute average values (after screening on valid wind sectors), the red line gives the fitted linear model with offset, the green line is for the model without offset.

2.5 Standard regression analysis for wind speed standard deviation

To compare the wind speed standard deviation as measure for turbulence measured by the lidar and by the cup anemometers as reference sensors, again a linear model y = C + k·x is applied where y is in this case the lidar standard deviation and x the standard deviation derived from the cup measurements. Since the estimated values for the offset (C) are significantly larger than zero and respective gain values (k) smaller than one, a second model without offset (as in 2.1 for the wind speed mean values and in 2.4 for the wind direction) is not considered here. Results for the model with offset are given in table 6 and illustrated in figure 5.

Table 6: Results of regression analysis for standard deviation horizontal wind speed (as measure for turbulence).

height [m]	C [m/s]	k [-]	R^2
40	0.36 (±.02)	0.68 (±.03)	0.5538
60	0.22 (±.01)	0.84 (±.02)	0.7713
80	0.18 (±.01)	0.89 (±.02)	0.7932
100	0.18 (±.01)	0.91 (±.02)	0.7681
116	0.23 (±.02)	0.84 (±.02)	0.6925

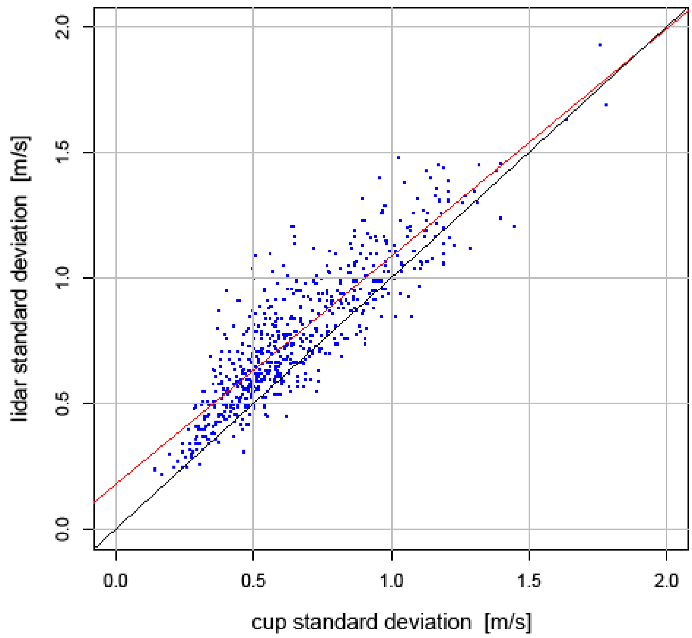

Figure 5: lustration of standard regression analysis for standard deviation of horizontal wind speed at 100 m measurement height. Blue dots denote 10-minute average values, the red line gives the fitted linear model and the black line corresponds to the relation y = x (ie lidar standard deviation equals cup standard deviation).

3 Short summary and discussion of results

The results of the analyses show an acceptable traceability of the Galion measurements to the respective reference data (sampled by the cup anemometers at the five considered measurement heights and the wind vane at two heights).The lidar error, defined as lidar wind speed minus cup wind speed, lies between -0.05 m/s and -0.10 m/s with a standard deviation of 0.18 m/s and 0.16 m/s, respectively, ignoring the measurement at 40 m for which greater scatter is observed.

A standard (one-parametric) regression analysis for a comparison of lidar and reference wind speed data and a two-parametric regression analysis for the lidar error, including in addition to the wind speed dependence also the wind gradient as local measure for shear and as second independent variable, indicate nearly the same values of wind speed offset and regression slope (gain) for the wind speed comparison. Ignoring again the 40 m measurement, wind speed offsets lie between 0.02 m/s and 0.12 m/s, gain values between -0.8 % and -2.4 %. The comparison at 40 m gives as only measurement a coefficient of determination (R^2) below 0.99 – for all other heights R^2 is larger than 0.996.

The two-parametric regression analysis furthermore gives estimates for possible altitude errors that are however negligible with values between -3.3 m and 0.9 m and lie within the uncertainty assumed for the applied model (that is significantly larger than the derived standard errors).

Also the comparison of wind direction measurements shows an acceptable traceability even although the reference directions at 40 m, 80 m and 100 m were only extra- or interpolated but not measured directly.

The comparison of wind speed standard deviations (as measure for turbulence) shows much larger scatter than for the mean values which is a typical outcome of lidar-cup standard deviation comparisons. This results partly from the fact that the lidar standard deviation is attenuated due to the volume averaging and partly that the lidar standard deviation is 'contanimated' by varying amounts of the vertical turbulence.

For the analysed Galion data, the lidar mainly overestimates the degree of turbulent fluctuations (due to an offset significantly larger than zero but with an estimated slope between 0.7 and 0.9). The large scatter however gives rise to correspondingly low values for R^2.