Vindicator LiDAR – S/N 3007 PERFORMANCE VERIFICATIONS AT DNV GL TEST SITE IN JANNEBY, GERMANY

AXYS Technologies Inc.

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Table of contents

Appendices

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

GL Garrad Hassan Deutschland GmbH (“GH-D”) has been contracted by AXYS Technologies Inc. (“AXYS”) on 2014-04-14 to execute a Lidar performance verification of a Vindicator type Lidar on the DNV GL test site at Janneby, Germany. In this report the Vindicator Lidar with the serial number 3007 is treated.

The verification measurements for this unit were performed next to a 100 m meteorological mast (met. mast) located at the DNV GL test site in Janneby, Germany from 2014-04-16 until 2014-05-22 (according to deployment log in [2]).

The met tower was equipped with classical anemometry components (cup anemometers, wind vanes etc.) serving as the verificatioin reference for the Lidar wind speed and wind direction comparisons. Those comparisons were performed in line with a Remote Sensing (RS) best practice verification approach as developed within the EU-FP7-Projekt NORSEWInD [2] against corresponding Key Performance Indicators (KPIs) and Acceptance Criteria (ACs). The KPIs and ACs were discussed with the client and defined in order to be applicabble for the system specific requierements (compare Appendix A).

GH-D is accredited according to ISO 17025 for measurements on wind turbines and for wind resource measurements and energy assessments. GH-D is also a full member of the network of measurement institutes in Europe ‘MEASNET’ and in the FGW (Fördergesellschaft Windenergie und anderer Erneuerbaren Energien).

The work has been conducted in compliance with all relevant health and safety legislation. GL Garrad Hassan Deutschland GmbH operates an Occupational Health and Safety Management System certified according to the OHSAS 18001:2007.

2 DESCRIPTION OF THE TEST SITE

2.1 The test site

The LiDAR validation measurement campaign test site is located in the Northern German county Schleswig-Flensburg, approximately 30 km inland from the North Sea coast and some 20 km to the South West of a town called Flensburg. It belongs to the Northern German federal state of Schleswig-Holstein.

Due to its benign and flat terrain the site has good conditions for the purposes of verification trials of remote sensing (RS) devices like LiDAR systems. Figure 1 provides an overview map of the very flat region between Flensburg and the North Sea, where the marked test site is located.

The site has a good exposure to rather undisturbed wind condition, i.e. undisturbed winds from almost all sectors. The elevation of the site is only a few meters above mean sea level. The surface roughness is low due to a mainly agricultural land use.

Figure 1: Map of test site location at Janneby, Germany

Details of the test site can be taken from Figure 2. It has to be noted that there are two wind turbines in the proximity of the meteorological mast. Namely the turbine located in 80° and 210 m distance from the reference mast and test pad has to be taken into account, as it requires a filtering of the wind direction data for a turbine wake influenced sector. This is to assure the usage of unbiased wind data for the actual comparison between LiDAR and cup anemometers as mounted to the reference mast.

Two test pads are provided for the setup of remote sensing devices, one to the North of the mast, the other one to the South West. The latter has been used for Vindicator trial at hand. See Figure 3 for details, showing a bird's view drawing of the mast and test pad arrangement, including mast boom orientations.

Figure 2: Inlet map of test site location at Janneby, Germany

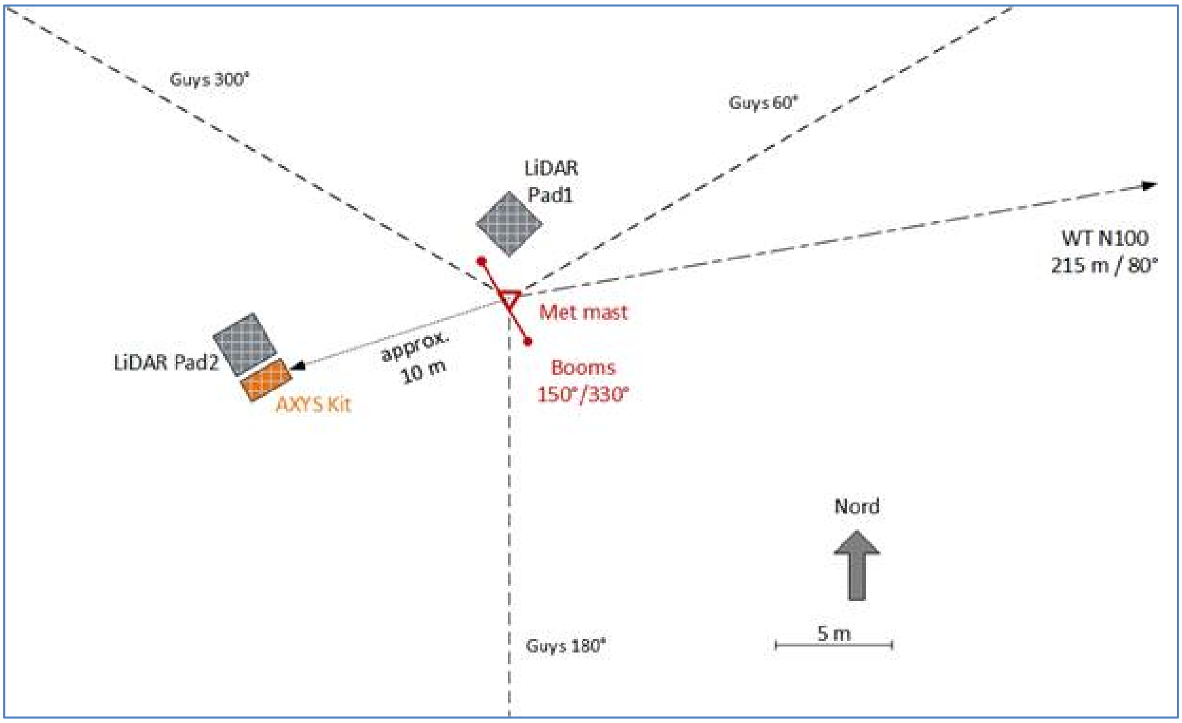


Figure 3: Bird's view schematic of met mast and test site layout with Lidar test pads, including planned position for AXYS Vindicator Kit.

2.2 Measuring equipment

In the following sections technical details and specs of the measuring equipment like the meteorological mast (met mast) with its sensors and logger measuring equipment as well as of the RS device under test are given.

2.2.1 Meteorological mast, sensors and logger

The met mast is a 3-fold guyed 100 m lattice tower with a constant face width of 0.4 m over its entire height. Four (4) MEASNET calibrated [6] cup anemometers (cups) of type Thies First Class Advanced (No. 4.3351, and a sonic anemometer are mounted to the mast. As can be seen in Figure 4 the lower 2 cups are mounted at 57 m above ground on booms pointing towards 150° and 330°, and the two (2) top mounted cups at 100 m above ground are installed in a Goal-Post-arrangement with a central boom pointing towards 330°/150°. The Sonic's position at 97m is pointing towards 150°.

For the top mounting Goal-Post-arrangement of cups the horizontal distance between the cups is 1.5 m, see Figure 4. All mounting arrangements are consistent with the currently valid IEC [4] recommendations for the use of cup anemometry at meteorological masts. The wind sensor setup also includes a temperature and humidity sensor and a pressures sensor near the mast top. A precipitation watch is installed approx. 10 m above ground.

Wind vanes of type Friedrichs are present at 97 m and 54 m height above ground, as well mounted on side booms. Table 1 gives the offset of each wind vane's death band relative to true North as applied in the logger configuration or during post processing.

A Campbell Scientific CR1000 data logger is utilized as the met mast data acquisition system to record 10 minute averaged wind and other meteorological data such as temperature, humidity and air pressure and precipitation (watch: yes/no) throughout the measurement campaign. This logger was programmed to sample data at a rate of 1 Hz and store data as ten-minute averages with statistics.

The following transfer functions were applied in the logger configuration to the output signal from the anemometers:

Adjusted wind speed [m/s] = Slope x recorded wind speed [Hz] + Offset [m/s]

The slope and offset parameters are taken from wind tunnel calibrations according to the high quality standards MEASNET [6]. Further details on the met mast can be seen in Appendix C and Figure 4 that illustrates the sensor configuration at/near the top of the mast and the boom mounting of the 57m.

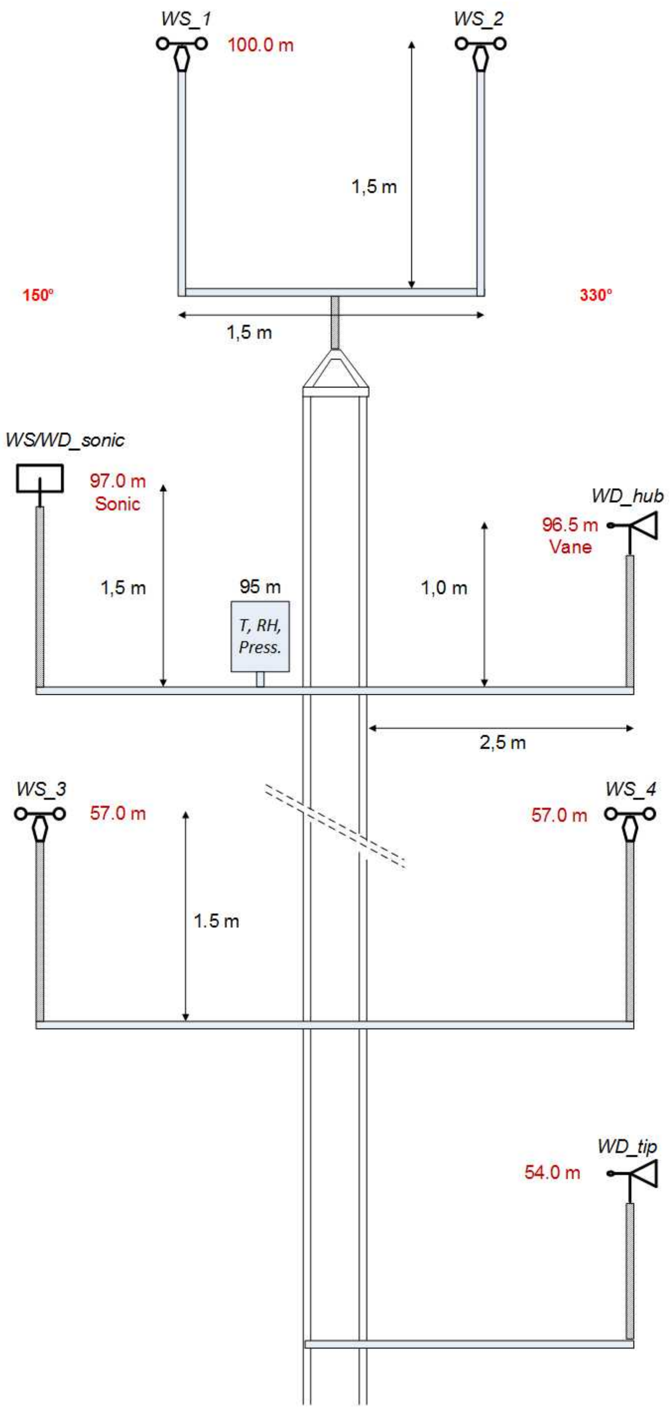


Figure 4: Mast configuration for top and boom mounted wind sensors

Wind Vane Height	Offset Applied to Wind Vane
97 m	90°
54 m	90°

Table 1: Wind vane correction values

2.2.2 The Lidar device

Figure 5 shows a Vindicator Lidar being placed at the Lidar pad (compare Figure 5) approximately 10 meters to the Southwest of the base of the mast. The system was intentionally positioned such as to avoid beam interactions with mast guy wires and lattice structure that could block individual laser beams and hence contaminate wind data.

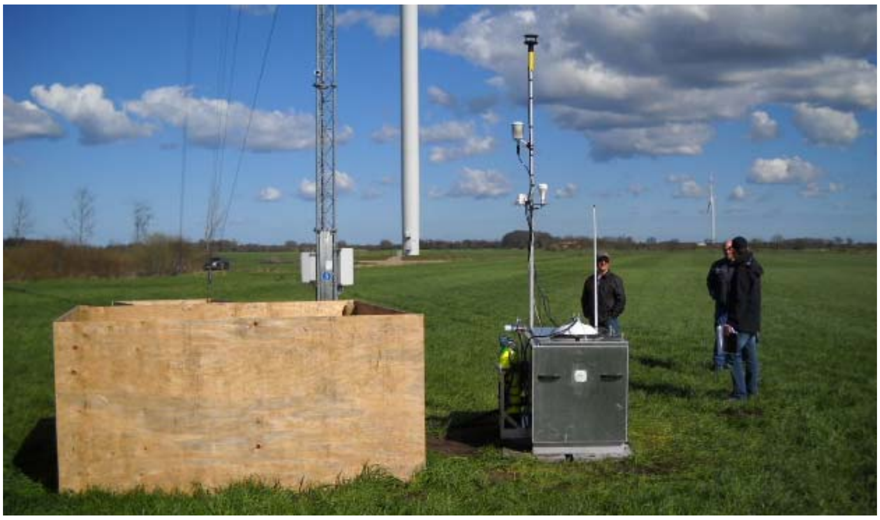


Figure 5: GL GH Janneby test site with met tower base and Lidar test pads, with a Vindicator unit deployed.

Table 2 lists wind speed and wind direction measurement and comparison levels as given and selected for the performance verification.

Height Settings (relative to ground level)						
Vindicator Meas. Levels	**57 m**	66 m	81 m	**101 m**	121 m	151 m
Mast/WS-Cup Levels	**57 m**			**100 m**		
Mast/WD-Vane Levels	**54 m**			**97 m**		

Table 2: Height settings Vindicator and reference mast for wind speed and wind directions measurements and comparisons

3 LIDAR PERFORMANCE VERIFICATION (LPV) APPROACH

3.1 Common test conditions and data filtering

In the process of the LPV trial the following test conditions and filters are applied

- All comparisons are based on 10-minute average wind values returned from wind vanes and MEASNET calibrated cup anemometers installed on the reference mast (primary reference) and concurrent wind direction and wind speed data from the Lidar under test.
- All data collected during periods of possible icing at cup anemometers, i.e. with temperatures below 0.5 °C near mast top height is excluded.
- All data collected during periods of precipitation (i.e. when precipitation is detected by the watch sensor with a ten minute averaged period) are excluded.
- All other reported data (particularly wind speed) within undisturbed free-stream wind direction sector relative to the reference mast as well to the Lidar are used in the comparison analysis.
- For the validation of Lidar wind speeds against the mast the wind speeds from the Thies First Class cup anemometers at 57 m and 100 m are used. The Lidar data are selected according to the sector screening of the cup data prior to comparison, see following section.
- No Lidar specific filters are applied to the measured Lidar data prior to the analysis conducted.

3.2 Sector filtering

A sector filtering of wind data for wind directions based on the mast wind vane data needs to be performed in order to account for downwind flow distortions first of caused by

a) the neighbouring wind turbine.

b) the Goal post side-by-side mounting of the two top anemometers, mutually

c) the mast lattice structure of the two side mounted cups at 57 m.

For case (a) a sector of +/- 20° centred about 80° is clipped to account for the turbine wake. Compare hatched sector in Fig. 6.

For cases (b) and (c), i.e. at both the comparison levels (57 m and 100 m) the orientation of one of the cup carrying Goal post or boom is to the North West (330°) on one side and to the South East (150°) on the other side. Hence, wind speed data need to be screened at wind directions between 130° and 170° for the cups on the Northwest side and between 310° and 350° for cups on the Southeast side of the mast assuming a sufficiently wide screening sector of 40° (+/- 20°).

In addition, if cup data from both boom directions is available, i.e. for wind directions out of the remaining two sectors (excluding the turbine wake sector), the wind speed average of the two oppositely mounted instruments is used to form the reference for the comparison with the Lidar wind speeds. In this case the data are further screened if the wind speed difference between both cups exceeds 0.3 m/s.

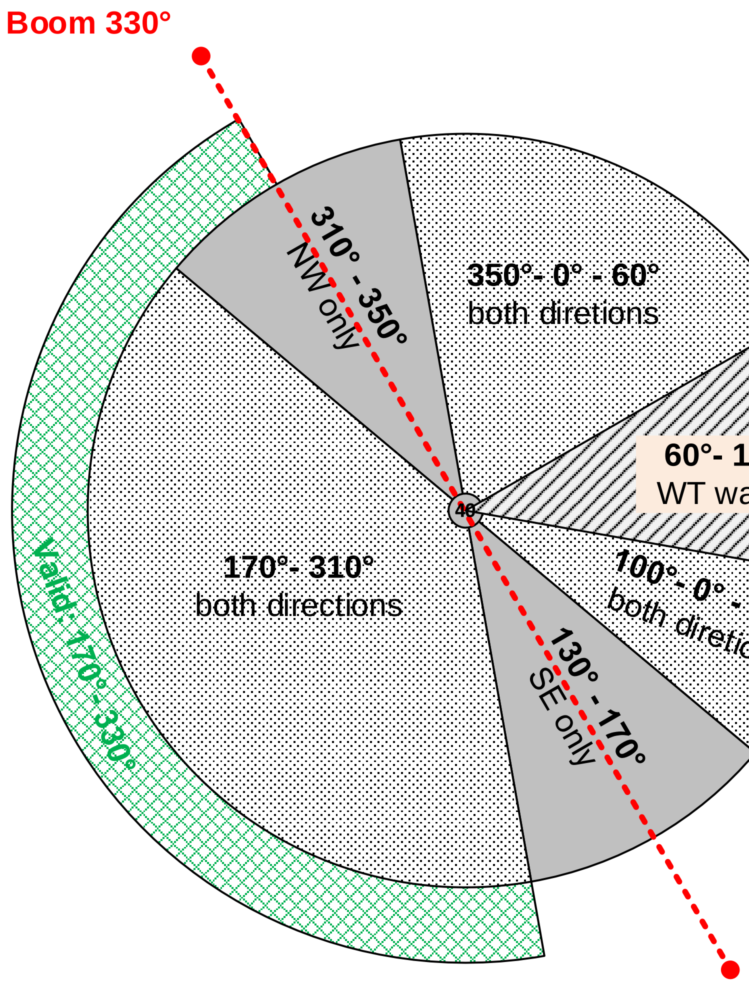


Figure 6: Wind direction sectors used to select undisturbed wind speed data for comparison. Hatched Easterly sector represents exclusion sector for wind turbine downwind wake effects. For Vindicator analysis green squared sector 170°-330° used for valid data analysis.

Additional sector filtering was implemented due to potential mast induced wake effects and hence flow disturbances towards the Lidar beam's probe volumes (for the Lidar being installed approx. 10 m to the Southwest from the mast, compare Fig. 3). For this reason the valid data analysis was restricted to the sector 170° to 330°, see Figure 6.

3.3 Data coverage requirements for accuracy assessment

The following data coverage definitions are prescribed for the LPV:

- The overall minimum number of 10 minute data points after filtering (according to sections 3.1 and 3.2) for the WS ranges [all > 2 m/s] and [4 to 16 m/s] should not be lower than 600.

- At least 200 10-minute data points should to be present in the WS range between 4 and 8 m/s and 200 data points between 8 and 12 m/s.

Those data coverage requirements are regarded as achievable for a typical test period of 4 weeks.

3.4 LPV evaluation

The performance of the LIDAR under test is evaluated for its system and data availability as well as for its wind data accuracy, based on a number of Key Performance Indicators (KPI) and according Acceptance Criteria (AC).

The evaluation approach in terms of the applicable KPIs and according ACs is outlined in Appendix A, where KPIs and ACs for system and data availability are listed in Table 7 those for wind data quality in Table 8.

The performance assessment of the given KPIs and respective Acceptance Criteria regarding Availability and Accuracy is executed at each reference level present, in this case at each of the two (2) met tower's 1st Class reference anemometry levels which are 57 m, 100 m a.g.l.

4 RESULTS

For the treated Lidar performance verification campaign data were collected for the period 2014-04-16, 10:30 until 2014-05-22, 04:50. So the campaign was completed after 35.8 days.

The wind speed ranges covered and used for comparison are 2 to 16.4 m/s at the upper level (100 m) and 2 to 14.4 m/s at the lower level (57 m).

The data coverage requirements as formulated in section 3.3 are fulfilled for all treated WS ranges and for both comparison heights, for details see the following Table 3.

4.1 System availability

The system availability as applied to the Lidar device as defined by a percentage of the maximum possible number of ten-minute data entries within the above mentioned total campaign duration of 35.8 days, which is 5151. As 5151 Lidar ten-minute data entries were present (regardless of the data validity) the Lidar device achieved a system availability of 100 % see Table 3 below.

- ✓ The Acceptance Criterion for Overall System Availability (**KPI** SA_{CA}) to be ≥95% is successfully passed.

Period: Date from	16.04.2014 10:30	to	22.05.2014 04:50	
Height	**57 m**		**100 m**	
External filter	Temp @ 97m >0.5°C, Precip. NO, WS > 2 m/s, WD sector -->			
Max. # of 10-min points	5151	100,0%	5151	100,0%
Data incl. NaN / system availability	5151	100,0%	5151	100,0%
Total # of 10-minute valid data	5125	99,5%	5120	99,4%
# after external filtering	1803	35,0%	1850	35,9%

Table 3: Summary of system and data availabilities

4.2 Data availability

Table 3 above summarizes the period of overlap between the met mast and the Lidar system during the measurement campaign, starting with the system availability in the 2nd yellow shaded row yielding 100% (compare previous section).

For the data availability assessment data at individual heights are treated as valid when they show a numeric value in contrast to a value being flagged as NaN (not a number flag for invalid data).

Table 3 shows in the 3rd row titled "Total # of 10-minute valid data" an availability of valid data for 57 m of 99.5 % and for 100 m of 99.4 % relative to the maximum possible number of ten-minute periods (represented in Figure 7 as blue bars).

- ✓ The Acceptance Criterion for Data Availability (**KPI** DA_{CA}) to be ≥90 % is successfully met at both relevant assessment levels.

The difference in number of available data between the rows "system" and "data availability" in Table 3 reflects the reduction of valid data according to internal system filtering.

For information Figure 5 shows the Lidar system availability (yellow bars) by which definition is the same for all heights, and in particular the data recovery rate (blue bars) for every set measurement height, i.e. between 57 and 151 m a.g.l. It is observed that the availability of valid data recorded by the Lidar shows a slight decrease with height. It ranges from 99.5 % at 57 m to 98.1 % at the level of 151 m.

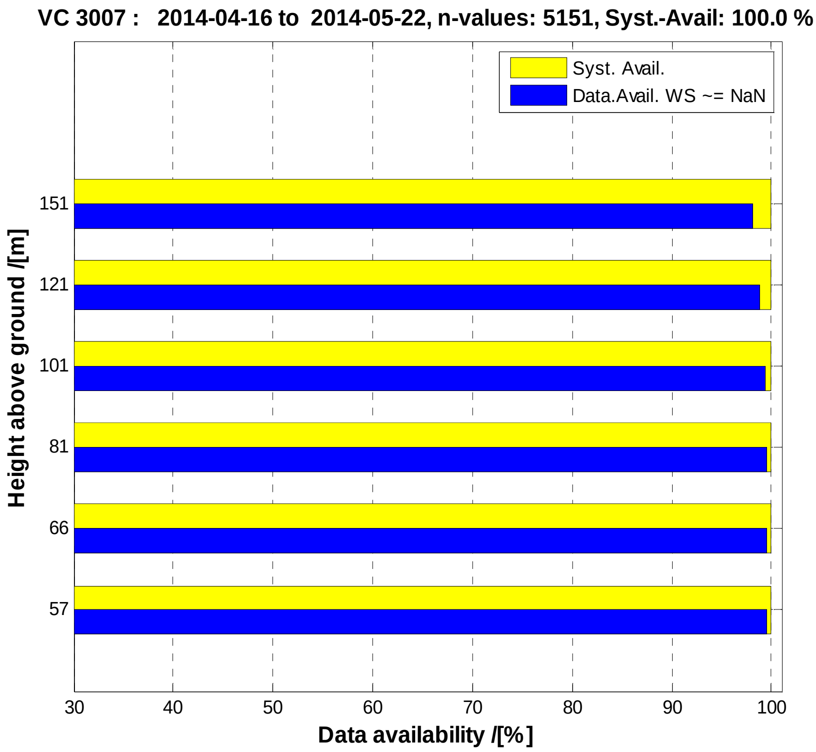


Figure 7: Lidar system and data availabilities for all measurement levels.

4.3 Applied data filtering

The data from both the Lidar and the mast were filtered for external parameters:

- wind direction to avoid non-valid wind speed sectors being influenced by e.g. mast wake effects, compare section 3.2
- wind speed, clipping data below 2 m/s
- air temperature as taken from the near top mounted sensor, to avoid data possibly contaminated from icing at cup anemometers
- precipitation

After the application of those filters the number of ten-minute data points remaining to be processed was reduced to a percentage of 35.0 % at 57 m and 35.9 % at 100 m, compare Table 3.

4.4 Wind speed comparison

Cup anemometers are regarded as the current industry standard for wind speed measurements at wind farm sites. Measurements with cup anemometers must therefore be considered the standard reference against which any new measurement device needs to be judged.

Wind speed as treated in this LPV process are assessed by means of Linear Regressions through the origin of the form

$$y = m\,x + b \text{ and } \quad b =: 0$$

between Lidar (y-axis) and cup wind speeds (x-axis) for the two comparison levels at 57 and 100 m, applying Acceptance Criteria to the KPIs

- slope (**KPI** X_{mws}) between 0.98 and 1.02
- correlation coefficient (**KPI** R^2_{mws}) $R^2 > 0.98$

for wind speed ranges

a) all > 2 m/s

b) 4 to 8 m/s

c) 8 to 12 m/s

d) 4 to 16 m/s

as prescribed in and Appendix A.

As this campaign represents a series performance test of a technology proven Remote Sensing device the test campaign was limited in duration (to about 36 days) – compared to prototype testings typically lasting several months – for practical reasons. In consequence the core verification concentrates on a subset of statistically meaningful performance criteria (in terms of amount of available representative data) being treated relevant for acceptance.

4.4.1 Results of wind speed comparisons

The time series of wind speeds as recorded by the Lidar is overlapped by that of the met mast system covering 35.8 days. Time series of WS as recorded by the Lidar and the cups for the two comparison heights are shown in Appendix C.

Table 4 summarizes the wind speed regression results for the two comparison heights showing that the Lidar at hand achieves a high level of accuracy compared to the respective cups in terms of regression slopes (**KPI** X_{mws}) which are very close to unity at both levels, and regression coefficient R^2(**KPI** R^2_{mws}) between 0.98 and 0.99. Figure 8 shows the corresponding regression plots for the wind speed range >= 2 m/s (upper row).

Table 5 reflects the results according to the absolute wind speed error criterion. It shows that for the wind speed range 2 to 16 m/s at for comparison levels between 2.2 and 5.7 % of concurrent ten-minute data points exceed the prescribed wind speed difference threshold of 0.5 m/s, which is below the allowed upper limit of 10 %. For wind speeds above 16 m/s almost no data are available, which precludes a statistically meaningful assessment regarding the absolute wind speed error criterion for this WS range.

With respect to the linear WS regressions the following KPI’s Acceptance Criteria are passed

- ✓ Regression slope (**KPI** X_{mws}) between 0.98 and 1.02 at both treated levels and for all WS ranges, meeting the Acceptance Criteria.
- ✓ R^2 (**KPI** R^2_{mws}) > 0.98 at the 57 m and 100 m comparison levels for the WS ranges a) [all WS > 2 m/s] and b) [4 to 16 m/s], meeting the Acceptance Criteria.

The mean Lidar wind speeds as averaged over all used values resemble those of the cups closely (see as well columns 4 and 5 of Table 4) yielding the relative Campaign Mean WS Differences (**KPI** C_{mwsd}) of 0.01 % at 100 m and 0.1 % at 57 m.

✓ The Acceptance Criterion for the relative Campaign Mean Wind Speed Difference (**KPI** C_{mwsd}) (see Table 4, column 6) is successfully passed at both relevant assessment levels and WS ranges.

Furthermore, the following wind speed related Acceptance Criteria were met

✓ Absolute Wind Speed Difference (**KPI** A_{wsd}) at both comparison levels and for all analysed wind speed data between 2 and 16 m/s, see Table 5.

✓ Variation in slope between the WS ranges b) and c) (as part of **KPI** X_{mws}) not to be higher than 0.015 at both WS comparison levels.

The following deviations from applied test conditions and performance criteria are reported:

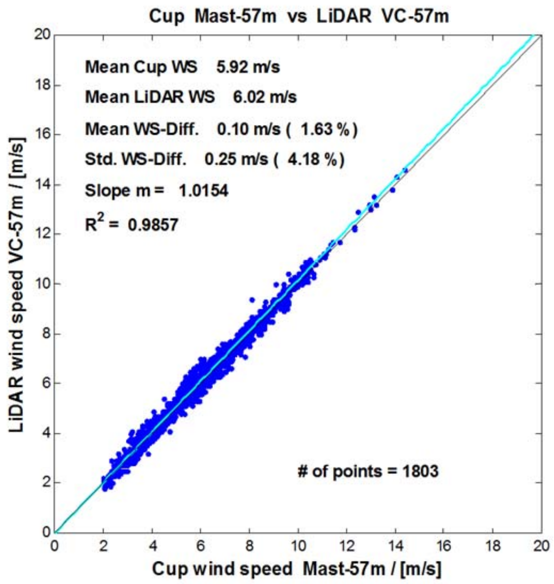
o For both levels in the wind speed sub ranges 4 to 8 m/s and 8 to 12 m/s the R2-values are below the threshold value of 0.98 (see Table 4, column 2). This is considered to be partially due to a generally low data coverage but more important due to an uneven distribution of data in these sub ranges being skewed towards lower wind speeds and hence lowering the correlation coefficient, artificially. See Appendix B for further explanations of this mathematical feature. In conclusion these deviations are regarded as Lidar non-unit-related and hence insignificant.

57 m level	**# Values**	**Slope**	**R^2**	**WS-avg Cup**	**WS-avg LiDAR**	**Mean diff.**
WS-range	-	-	-	[m/s]	[m/s]	[m/s]
All > 2 m/s	1803	1,015	0,998	5,92	6,02	0,10
4 - 8 m/s	1200	1,018	0,949	5,86	5,97	0,11
8 - 12 m/s	271	1,011	0,916	9,18	9,28	0,10
4 - 16 m/s	1481	1,016	0,980	6,51	6,62	0,11
100 m level	**# Values**	**Slope**	**R^2**	**WS-avg Cup**	**WS-avg LiDAR**	**Mean diff.**
WS-range	-	-	-	[m/s]	[m/s]	[m/s]
All > 2 m/s	1850	0,998	0,999	6,72	6,71	0,01
4 - 8 m/s	1072	0,999	0,974	6,14	6,14	0,01
8 - 12 m/s	476	0,998	0,953	9,44	9,42	0,02
4 - 16 m/s	1585	0,998	0,992	7,31	7,30	0,01

Table 4: Regression results for Lidar to cup wind speed comparison; acceptance relevant results are colour shaded.

Height Level	**57m**			**100m**		
Criterion for abs WS error	total #	identified #	percent	total #	identified #	percent
0.5 m/s for 2 to 16 m/s	1803	102	5,7%	1849	40	2,2%
5% above 16 m/s	0	0		1	0	0,0%

Table 5: Absolute wind speed error results



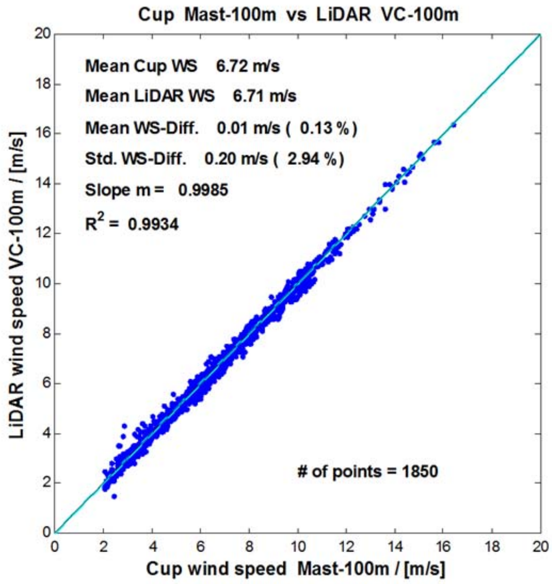


Figure 8: Plots of linear wind speed regression results for 60, 80 and 100 m

4.5 Wind direction comparison

By comparing the wind direction as measured by the Lidar device at its 97 m and 57 m levels with the mast mounted wind vanes at 97 m and 54 m a.g.l., it is possible to see how well correlated the measures are, providing confidence in that the Lidar is ‘seeing’ the same wind direction as the vane.

In order to validate this comparison quantitatively a two variant regression solving for the slope *m* and the interception of the best-fit line with the y-axis *b* (according to $y = m\ x + b$) was performed, compare Appendix A.

The results of such regressions are shown in Table 6 and by the x-y-plot in Figure 9 with the 97 m vane wind direction on the x-axis and the Lidar direction on the y-axis. For this analysis the data were again filtered for Lidar and the cup wind speeds at 100 m to exceed in this case WS >=3 m/s (to avoid false readings from the vane at low wind speeds), and for the nearby wind turbine wake disturbed wind directions sectors.

The time series of wind directions present during the course of the campaign can be found in Appendix E.

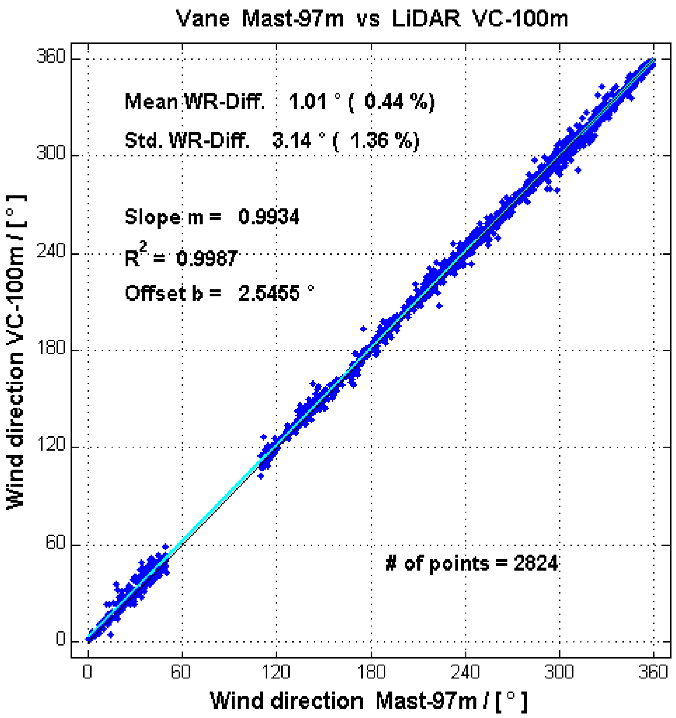


Figure 9: Regression plot of wind direction comparison

The regression plot in Figure 9 reveals a very close resemblance between both wind direction measures with a slight offset of less than 3° which is well within typical directional setup uncertainties for wind vanes and remotes sensing devices.

Table 6 summarizes the WD comparison results for the both acceptance relevant WD comparison levels at 54 and 97 m, showing an equally good resemblance.

WS filtering for WS > 3 m/s				
Height level	# Values	Slope	Offset [°]	R^2
[m]	-	(X_{mwd})	(OFF_{mwd})	(R^2_{mwd})
54	2596	0,991	2,810	0,998
97	2824	0,993	2,546	0,999

Table 6: Summary of WD comparison results for both comparison levels

✓ The Acceptance Criteria for the respective KPIs for wind direction assessment (**KPIs** for X_{mwd}, OFF_{mwd}, and $R2_{mwd}$) are successfully passed at both comparison levels.

5 IMPORTANT REMARKS AND LIMITATIONS

Independently performed Lidar Performance Verifications (LPV) of individual Lidar devices as reported in this document present a reasonable means to assure overall system integrity of the Lidar unit after manufacturing, and are meant to give an indication of the quality of wind data produced by the Lidar.

Any statement given in the context of system integrity and data quality related results within this report are limited to the given test site conditions, to the prevailing atmospheric in particular wind conditions and to the specific Lidar configuration as selected for this LPV campaign.

A LPV is not thought to replace the requirement for an on-site verification of a Lidar in real field campaigns, typically performed in close proximity to an on-site mast over a reasonable period. This is particularly important for sites with non-benign terrain and conditions.

LPVs will not automatically warrant quantitative use of Lidar data in a formal energy assessment of a prospected site. They may help reduce uncertainties and are a good step forward to help build a body of evidence to increase confidence in this type of Remote Sensing device.

6 CONCLUSION

Concurrent Vindicator Lidar and cup anemometer wind measurements were carried out at the DNV GL Janneby test site to Vindicator Lidar wind data quality against well-known high quality mast based cup and vane anemometry. Measurement heights of 57 m 100 m a.g.l. were available for wind speed correlations (54 and 97 m for wind direction correlations) between a proximate met mast and a Vindicator Lidar with the serial number S/N 3007. The duration of the validation was 35.8 days. While additional measurements would have enabled a more extensive assessment of the Lidar system, in particular for wind speeds above 16 m/s, the test period and wind data coverage is considered sufficient for the purpose of characterizing the wind data performance of the Vindicator Lidar in the context of a Lidar Performance Verification.

The total system availability for the mentioned 35.8 days assessment period was 100 %. The gross data availability for the selected Lidar measurement levels at 57 m and 100 m was 99.5 % and 99.4 %, respectively, i.e. well above 95 %. This data availability figure is relative to the number of maximum possible ten-minute data points for the total duration of the campaign.

Wind speed (and direction) correlations were carried out for each of the two (2) wind measurement levels mentioned above. The wind speeds of both techniques at those heights correlated well, showing a low level of scatter and a very good resemblance of Lidar wind speeds to those of cups, in terms of mean campaign WS differences and WS linear regression slopes.

In summary the following KPI related Acceptance Criteria are met.

- ✓ The Acceptance Criterion for System Availability (**KPI** SA_{CA}) to be ≥95% is successfully passed.
- ✓ The Acceptance Criterion for Data Availability (**KPI** DA_{CA}) to be ≥90 % is successfully met at both relevant assessment levels.
- ✓ The Acceptance Criterion for the relative Campaign Mean Wind Speed Difference (**KPI** C_{mwsd}) is successfully passed at both relevant assessment levels and WS ranges.
- ✓ Regression slope (**KPI** X_{mws}) between 0.98 and 1.02 at both treated levels and for all WS ranges, meeting the Acceptance Criteria.
- ✓ R^2 (**KPI** R^2_{mws}) > 0.98 at the 57 m and 100 m comparison levels for the WS ranges a) [all WS > 2 m/s] and b) [4 to 16 m/s], meeting the Acceptance Criteria.
- ✓ The Acceptance Criterion for the relative Campaign Mean Wind Speed Difference (**KPI** C_{mwsd}) (see Table 4, column 6) is successfully passed at both relevant assessment levels and WS ranges.
- ✓ Absolute Wind Speed Difference (**KPI** A_{wsd}) at both comparison levels and for all analysed wind speed data between 2 and 16 m/s.
- ✓ Variation in slope between the WS ranges b) and c) (as part of **KPI** X_{mws}) no higher than 0.015 at both WS comparison levels.
- ✓ The Acceptance Criteria for the respective KPIs for wind direction assessment (**KPIs** for X_{mwd}, OFF_{mwd}, and R^2_{mwd}) are successfully passed at both comparison levels.

The following deviations from applied test conditions and performance criteria are reported:

- o For both WS comparison levels in the wind speed sub ranges b) [4 to 8 m/s] and c) [8 to 12 m/s] the R^2-values are below the threshold value of 0.98. However, this is regarded as Lidar non-unit-related and hence insignificant.

To conclude, the Janneby LPV campaign indicates that the Vindicator Lidar with the serial number S/N 3007 is able to reproduce cup anemometer wind speeds and wind vane directions at an acceptably accurate level.

GH-D considers that for relatively simple (so-called benign or low complex) terrain sites data from this Lidar unit may be used in a quantitative sense with reasonable error bars for the purpose of the assessment of the wind regime at a potential wind farm site given the following criteria are met:

- The long term data accuracy stability of the Lidar is verified by recording data for a period sufficient to obtain an adequate in-situ correlation to an onsite reference (e.g. a short met. mast)

- Such verifications against a suitable onsite reference include WS frequency distribution comparisons, even for short periods of concurrent data, yielding a reasonable resemblance.

However, depending on the specific characteristics of the wind farm site under evaluation, there may be concerns that this LPV – as performed in relatively simple terrain – may not be representative of what may be expected at potential wind farm site. In such situations the Lidar data recorded at this potential site would be used in a qualitative sense only but may well still add value to an analysis.

Furthermore, care needs to be taken with respect to the formal use of Lidar turbulence and extreme wind speed measures (not treated in this report), known to be different from classical anemometry measures.

GH-D likes to point out that good measurement and data collection practices need to be maintained for all wind speed measurements, be they Lidar or more conventional anemometry. Therefore, special care needs to be exercised in the transportation, installation and on-going maintenance of the Lidar as it may be exposed to a wide range of environmental conditions at different sites over time. A key element of any formal wind study is the traceability of the wind speed data uncertainty.

Hence, a strict uncertainty assessment (which is not part of this report) should be executed. Furthermore it is recommended that thorough practices of documenting the salient features of Lidar installation and maintenance are instigated from the outset.

7 REFERENCES

1. GL GH Report: "TEST PLAN FOR LIDAR PERFORMANCE VERIFICATIONS AT DNV GL TEST SITE IN JANNEBY, GERMANY", Report-No. GLGH-4257 14 11747 267-R-0001-B, April 2014

2. GL GH Technical Note: Vindicator LiDAR – S/N 3007: "Installation for performance verification on the DNV GL test site at Janneby, Germany on 2014-04-15", Report-No. GLGH-4257 14 11747 267-T-0002-A, May 2014

3. Kindler, D., "*Best Practice Test and Verification Procedure for Wind LiDARs on the Høvsøre Test Site",* GL GH-D Report WT 6960/09 for EU-Project NORSEWInD, Deliv. 1.1, June 2009

4. International Standard: IEC 61400-12-1: Wind turbines – Part 121: Power Performance Measurements of Grid Connected Wind Turbines. Ed. 1. International Electronic Commission.3, rue de Varembé Geneva. Switzerland, Dec. 2005.

5. IEA EXPERT GROUP STUDY ON RECOMMENDED PRACTICES FOR WIND TURBINE TESTING AND EVALUATION 11. WIND SPEED MEASUREMENT AND USE OF CUP ANEMOMETRY, 1. EDITION 1999

6. MEASNET: "Cup Anemometer Calibration Procedure". Version 1, September 1997

8 GLOSSARY

The following table lists abbreviations and acronyms used in this report.

Abbreviation Acronym	**Meaning**
AC	Acceptance Criterion
a.g.l.	Above ground level
DNV GL	New company name, successor of legacy GL GH
IEC	International Electro-technical Commission
IEA	International Energy Agency
GH-D	GL Garrad Hassan Deutschland GmbH
KPI	Key Performance Indicator
MM	Meteorological Mast
PAR	Performance Assessment Requirement
LPV	Lidar Performance Verification
TI	Turbulence Intensity
WD	Wind direction
WS	Wind speed

APPENDIX A: *KEY PERFORMANCE INDICATORS AND ACCEPTANCE CRITERIA*

Table 7: List of KPIs and ACs relevant for System and Data Availability assessment

KPI	Definition / Rationale	Acceptance Criteria across total campaign duration
SA_{CA}	System Availability The Lidar system is ready to function according to specifications and to deliver data, taking into account all time stamped data entries in the output data files including flagged data (e.g. by NaNs or 9999s) for the pre-defined total campaign length. The System Availability is the number of these time stamped data entries relative to the maximum possible number of data entries (for 10 minute intervals) within the pre-defined total campaign period. (Any conditions affecting the test's data availability outside of the LIDAR system's control is not to be included in this calculation. Such as: power outages, acts of nature causing system damage, communication outages, maintenance, etc.)	≥95%
DA_{CA}	Data Availability The Data Availability is defined as the number of valid data points returned by the Lidar unit as compared to maximum number of possible points that can be acquired during the test (Any conditions affecting the test's data availability outside of the LIDAR system's control is not to be included in this calculation. Such as: power outages, acts of nature causing system damage, communication outages, maintenance, etc.)	≥90%
MV	Number of Maintenance Visits Number of Visits to the Lidar system by either the manufacturer or an authorized third party to maintain and service the system. This is to be documented and reported.	N/A
UO	Number of Unscheduled Outages Number Unscheduled Outages of the Lidar system in addition to scheduled service outages. Each outage needs to be documented regarding possible cause of outage, exact time / duration and action performed to overcome the Unscheduled outage. This is to be reported.	N/A
CU	Uptime of Communication System To be documented and reported by the manufacturer.	N/A

In the above table, during periods of maintenance; the system is deemed unavailable.

* *Undisturbed sectors: this* means sectors with no significant flow distortion e.g. by wake effects of nearby wind turbines

Table 8: List of KPIs and ACs relevant for Wind Data Accuracy assessment

KPI	Definition / Rationale	Acceptance Criteria
C_{mwsd}	Campaign Mean Wind Speed – Difference Absolute difference of mean wind speeds between Lidar and reference as measured over the whole verification campaign duration, expressed as percentage relative to the Campaign Mean Wind Speed A threshold is imposed on the Difference. Analysis shall be applied to wind speed ranges a) 4 to 16 m/s b) all above 2 m/s given achieved data coverage requirements.	< 1 %
Awsd	Absolute Wind Speed Differences Absolute 10 minute mean wind speed differences between Lidar and reference for all data points treated after filtering. A threshold is imposed on the Difference. Analysis shall be applied to wind speed ranges a) 4 to 16 m/s b) all above 16 m/s given achieved data coverage requirements.	a) < 0.5 m/s b) within 5% Not more than 10% of data to exceed the criteria above.
X_{mws}	Mean Wind Speed – Slope Slope returned from single variant regression with the regression analysis constrained to pass through the origin. A tolerance is imposed on the Slope value. Analysis shall be applied to wind speed ranges a) 4 to 16 m/s b) 4 to 8 m/s c) 8 to 12 m/s given achieved data coverage requirements.	0.98 – 1.02 and variation in slope between WS ranges b) and c) < 0.015
R^2_{mws}	Mean Wind Speed – Coefficient of Determination Correlation Co-efficient returned from single variant regression A threshold is imposed on the Correlation Co-efficient value. Analysis shall be applied to wind speed ranges a) 4 to 16 m/s b) 4 to 8 m/s c) 8 to 12 m/s given achieved data coverage requirements.	>0.98

KPI	Definition / Rationale	Acceptance Criteria
X_{mwd}	Mean Wind Direction – Slope Slope returned from a two-variant regression. A tolerance is imposed on the Slope value. Analysis shall be applied to a) all wind directions b) all wind speeds above 2 m/s regardless of coverage requirements.	0.97 – 1.03
OFF_{mwd}	Mean Wind Direction – Offset (absolute value) (same as for M_{mwd})	< 5°
R^2_{mwd}	Mean Wind Direction – Coefficient of Determination (same as for M_{mwd})	> 0.97

APPENDIX B: *CONSIDERATIONS ON LINEAR REGRESSION COEFFICIENTS (R^2) FOR WS SUB-RANGES*

Within a given WS range an overall lower wind speed coverage (data density) in conjunction with a significantly skewed data distribution towards lower WS leads to a reduction of R^2 values, compared to an even distribution, in general. This is in particular the case for the two WS ranges ([4 to 8 m/s] and [8 to 12 m/s]) treated as sub-ranges in the LPV regression analysis, when the campaign duration is as short as a few weeks.

Such a reduction becomes less significant the more data are available within the ranges and the more even the data distribution. From our experiences this is true for longer campaign duration of 3 to 4 months. For that reason it is recommend not to look at the sub-ranges with respect to R^2 values in such standard series verifications, when treating campaign durations shorter than 2 months or so.

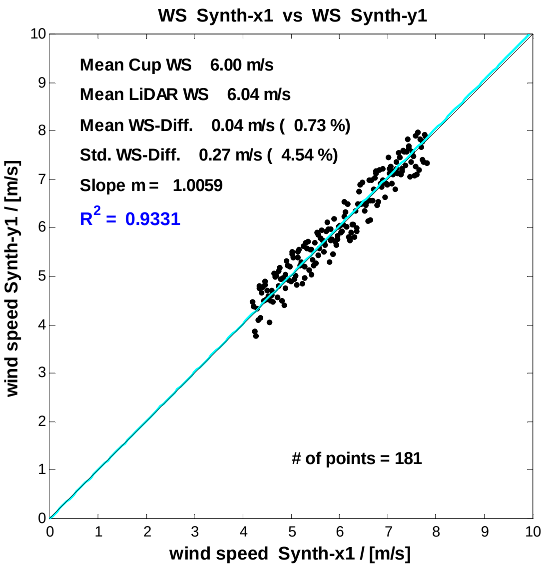
It is shown for the following two theoretical cases how R^2 is reduced due to a skewed data distribution.

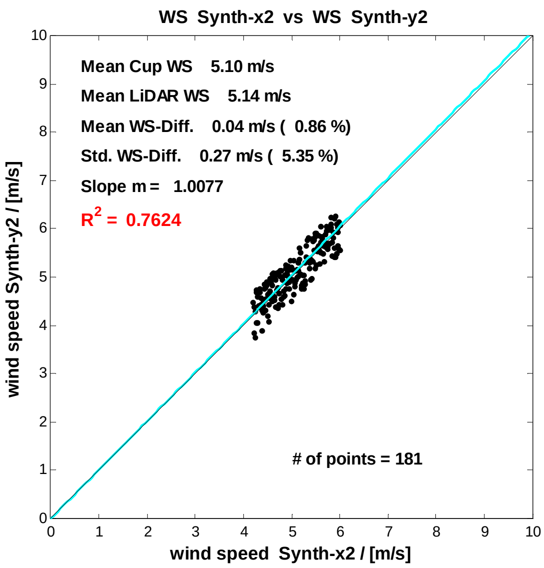
Simple theoretical study:

Results from two theoretical cases based on two synthetized wind speed x/y data sets are shown being evenly distributed over the 4 to 8 m/s range (case 1) and skewed to the range 4 to 6 m/s, with both the same number of values and the same random data scatter, in terms of the standard deviation of differences between x and y.

Case 1:
- WS range 4 to 8 m/s, Overall mean of x-wind speed: 6 m/s
- # of data points: 181
- **STD of difference between x and y: 0.27 m/s**
- **R^2 = 0.9331**

Case 2:
- WS range 4 to 6 m/s, Overall mean of x-wind speed: 5.1 m/s
- # of data points: 181
- **STD of difference between x and y: 0.27 m/s**
- **R^2 = 0.7624**





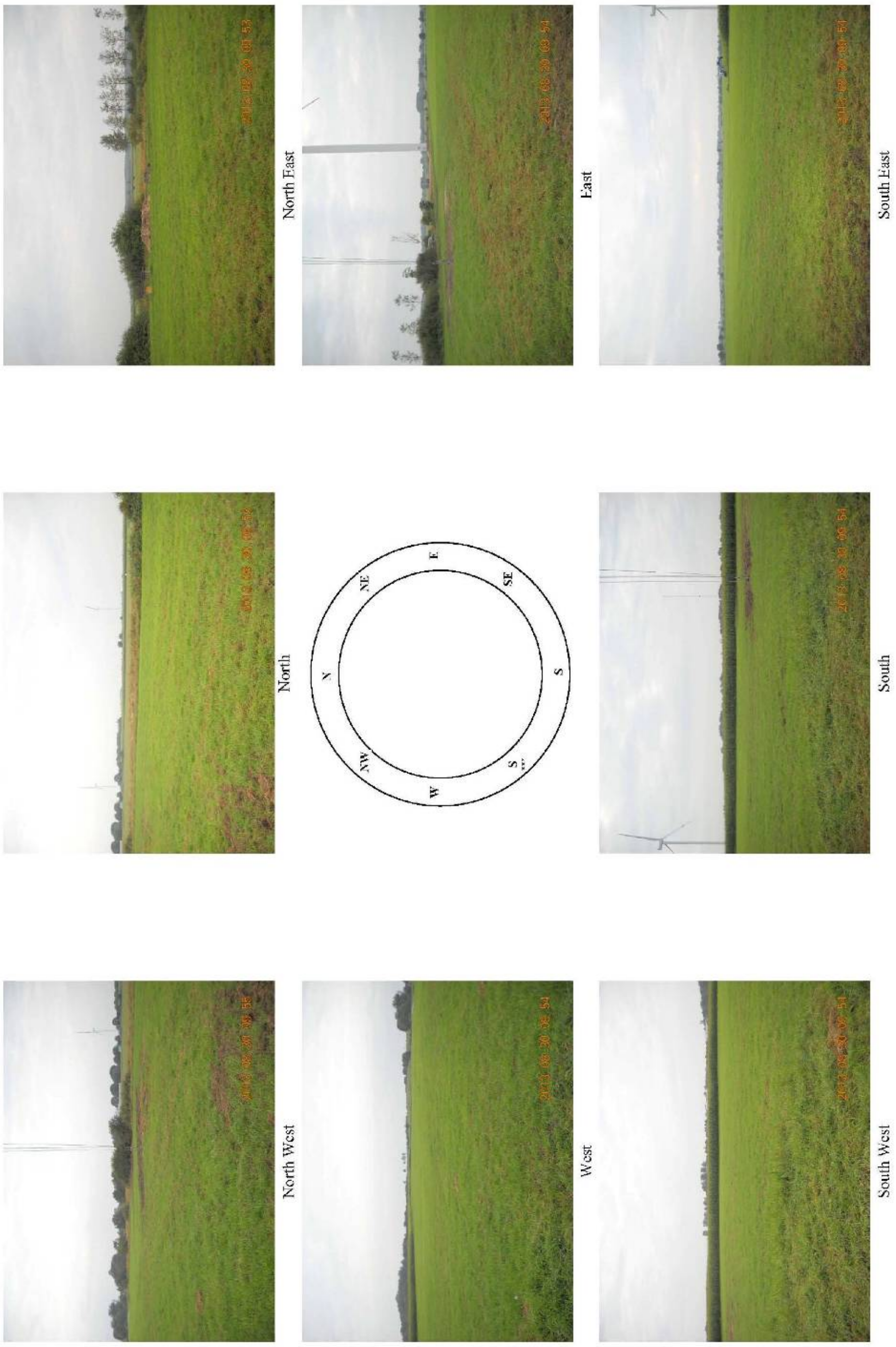
APPENDIX C: *PHOTOS OF TEST SITE AND REF. MAST*

Photo 1: Close-up of mast top towards East

Photo 2: Mast and Wind turbine to the East

Photo 3: Mast measurement levels 54/57 m and 97/100 m

Page 3


North West
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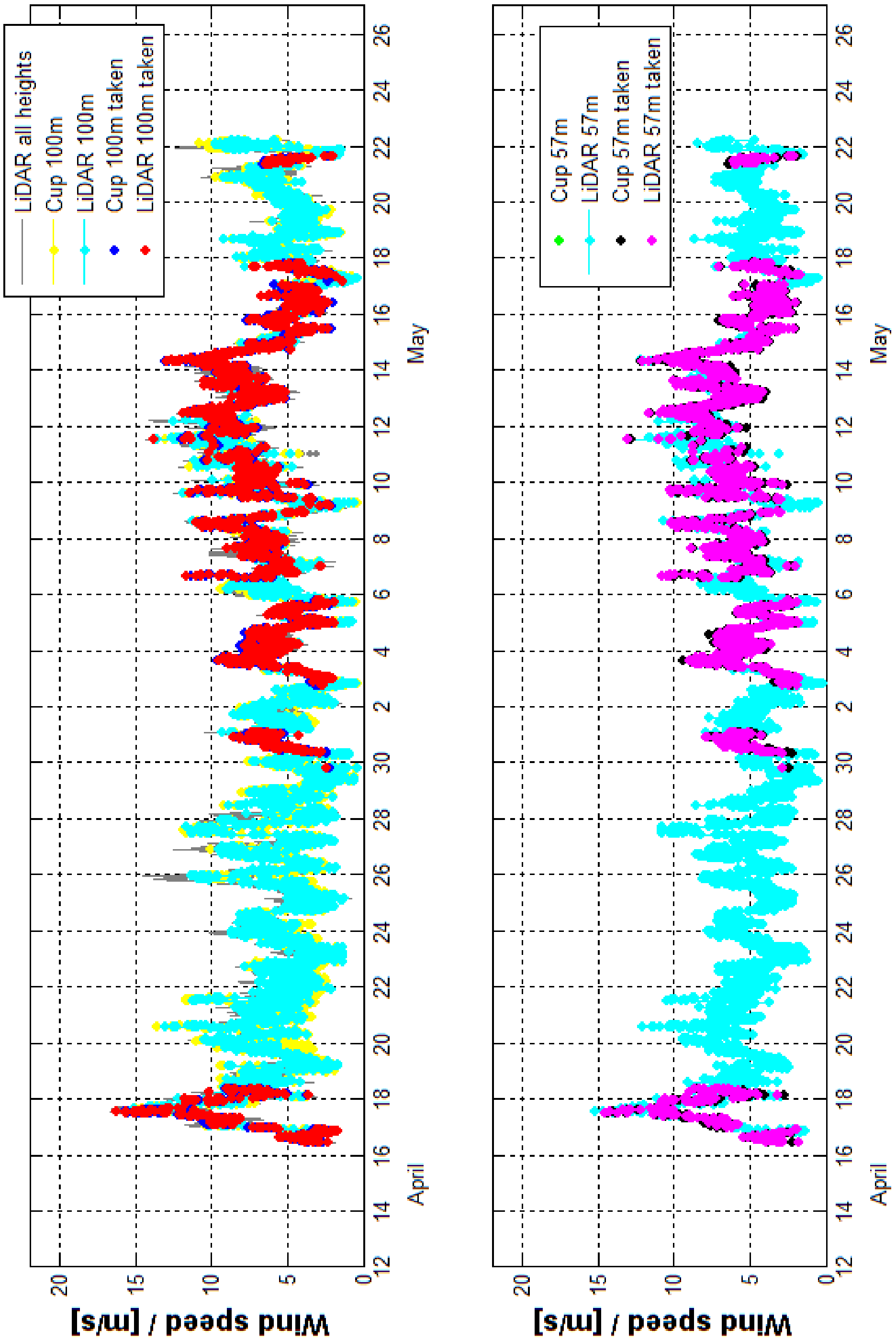
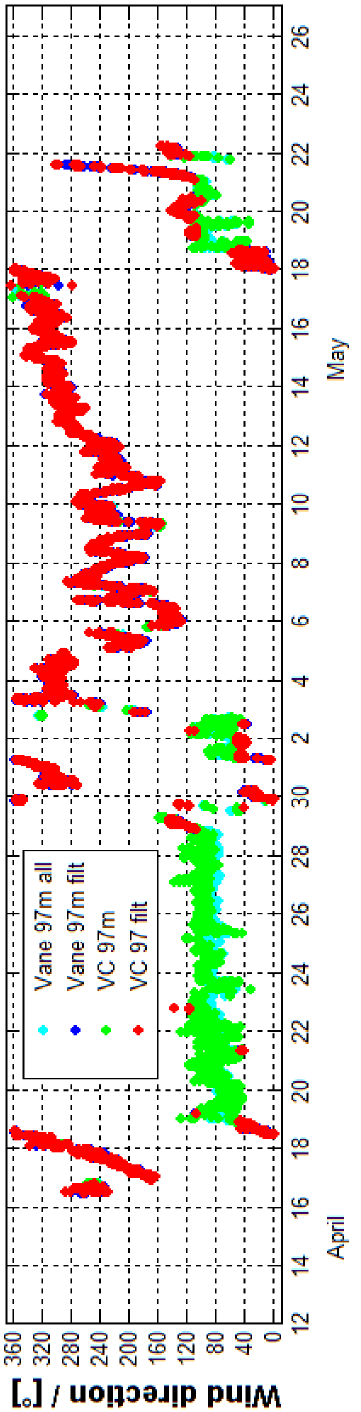
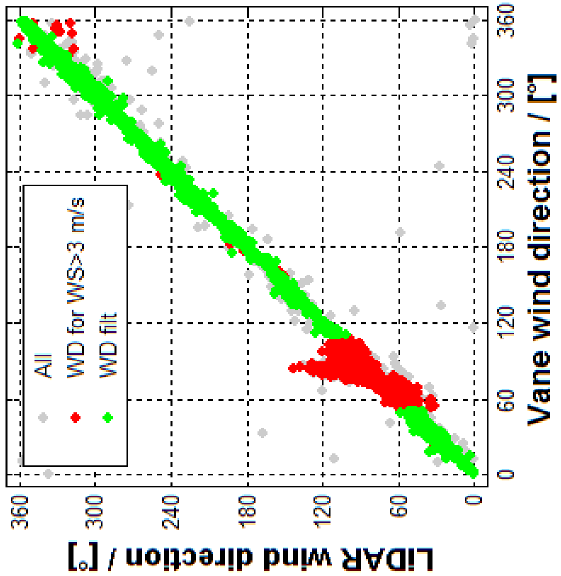
APPENDIX D: *TIME SERIES OF WIND SPEED*



APPENDIX E: ***TIME SERIES OF WIND DIRECTION***





APPENDIX F: *CUP CALIBRATION CERTIFICATES*

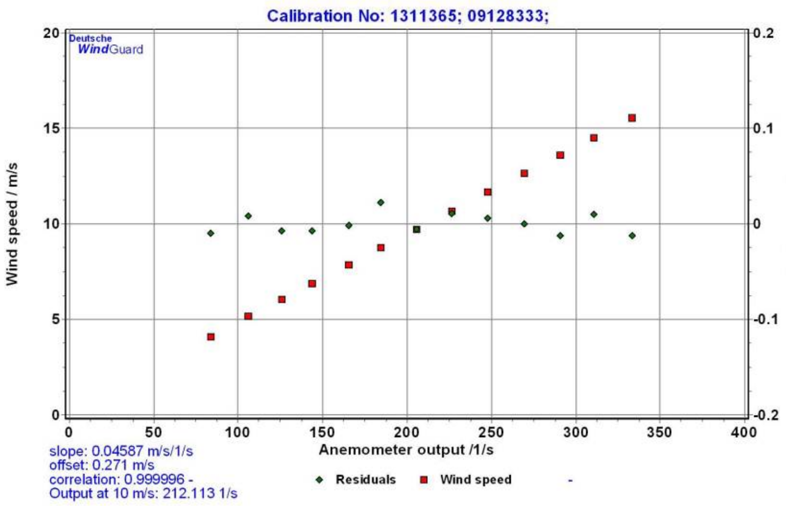
WS_1-Thies First Class Cup Anemometer at 100 m, 150° orientation:

Anhang
Annex

1311365

1 Detailed Calibration Results

DKD calibration no.	1311365
Serial no. 1	09128333
Serial no. 2	
Date	26.03.2013
Air temperature	20.5 °C
Air pressure	1018.8 hPa
Humidity	25.1 %
Linear regression analysis	
Slope	0.04587 (m/s)/(1/s) ±0.00004 (m/s)/(1/s)
Offset	0.2707 m/s ±0.009 m/s
St.err(Y)	0.009 m/s
Correlation coefficient	0.999996
Remarks	no



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Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

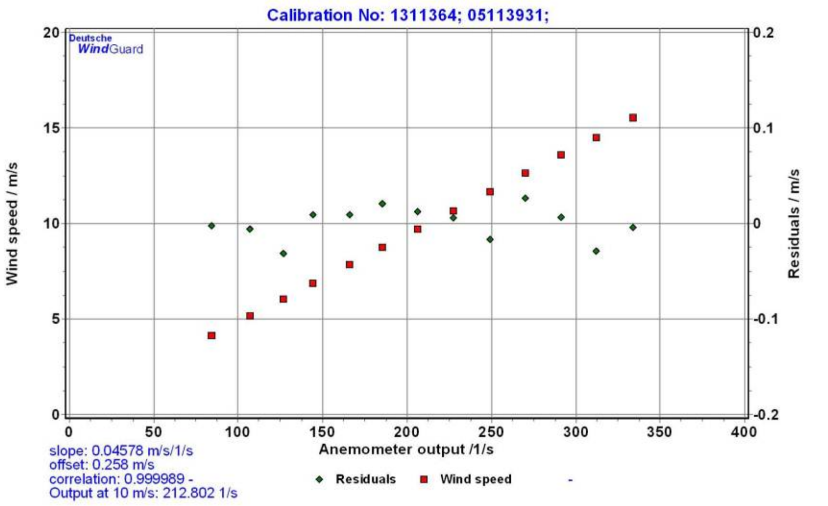
WS_2-Thies First Class Cup Anemometer at 100 m, 330° orientation

1 Detailed Calibration Results

DKD calibration no.	1311364
Serial no. 1	05113931
Serial no. 2	
Date	26.03.2013
Air temperature	20.4 °C
Air pressure	1018.9 hPa
Humidity	25.2 %

Linear regression analysis

Slope	0.04578 (m/s)/(1/s) ±0.00007 (m/s)/(1/s)
Offset	0.2575 m/s ±0.015 m/s
St.err(Y)	0.015 m/s
Correlation coefficient	0.999989
Remarks	no



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Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

WS_3-Thies First Class Cup Anemometer at 57 m, 150° orientation

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WIND ENGINEERING FLUID DYNAMICS

CERTIFICATE FOR CALIBRATION OF CUP ANEMOMETER

Certificate number: 12.02.0213 **Date of issue:** January 10, 2012
Type: Thies 4.3351.00.000 **Serial number:** 12103038
Manufacturer: ADOLF THIES GmbH & Co.KG, Hauptstrasse 76, 37083 Göttingen, Germany
Client: GL Garrad Hassan Deutschland GmbH, Sommerdeich 14b, 25709 Kaiser-Wilhelm-Koog, Germany

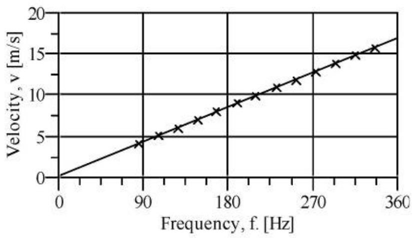
Anemometer received: November 29, 2011 **Anemometer calibrated:** January 9, 2012
Calibrated by: ke **Calibration procedure:** IEC 61400-12-1, MEASNET
Certificate prepared by: jsa **Approved by:** Calibration engineer, soh

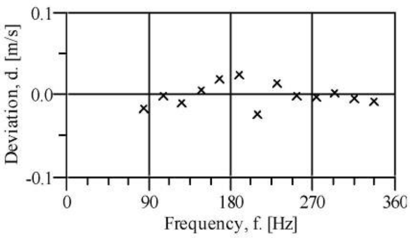
Svend Ole Hansen

Calibration equation obtained: v [m/s] = 0.04625 · f [Hz] + 0.22559
Standard uncertainty, slope: 0.00108 **Standard uncertainty, offset:** 0.04985
Covariance: -0.0000005 (m/s)²/Hz **Coefficient of correlation:** $\rho = 0.999994$
Absolute maximum deviation: 0.025 m/s at 8.997 m/s

Barometric pressure: 1011.3 hPa **Relative humidity:** 19.6%

Succession	Velocity pressure, q. [Pa]	Temperature in wind tunnel [°C]	Temperature in control room [°C]	Wind velocity, v. [m/s]	Frequency, f. [Hz]	Deviation, d. [m/s]	Uncertainty u_c (k=2) [m/s]
2	9.93	29.6	25.7	4.137	84.9191	-0.015	0.021
4	15.20	29.4	25.7	5.117	105.7812	-0.001	0.025
6	21.33	29.3	25.7	6.060	126.3782	-0.010	0.029
8	28.86	29.2	25.6	7.048	147.4141	0.005	0.033
10	37.27	29.1	25.6	8.010	167.8912	0.020	0.037
12	47.04	29.1	25.5	8.997	189.1348	0.025	0.042
13-last	57.05	29.0	25.5	9.907	209.8534	-0.023	0.046
11	69.45	29.1	25.5	10.932	231.1939	0.015	0.051
9	81.99	29.2	25.6	11.880	252.0273	-0.001	0.055
7	96.29	29.2	25.6	12.876	273.5963	-0.003	0.060
5	111.22	29.3	25.7	13.839	294.3289	0.002	0.064
3	127.56	29.5	25.7	14.824	315.7772	-0.005	0.069
1-first	144.39	29.7	25.8	15.779	336.4628	-0.007	0.073





Page 1 of 2

ilac-MRA DANAK
CAL Reg.nr. 452
Accreditation to ISO 17025

WS_4-Thies First Class Cup Anemometer at 57 m, 330° orientation

Anhang
Annex

1314130

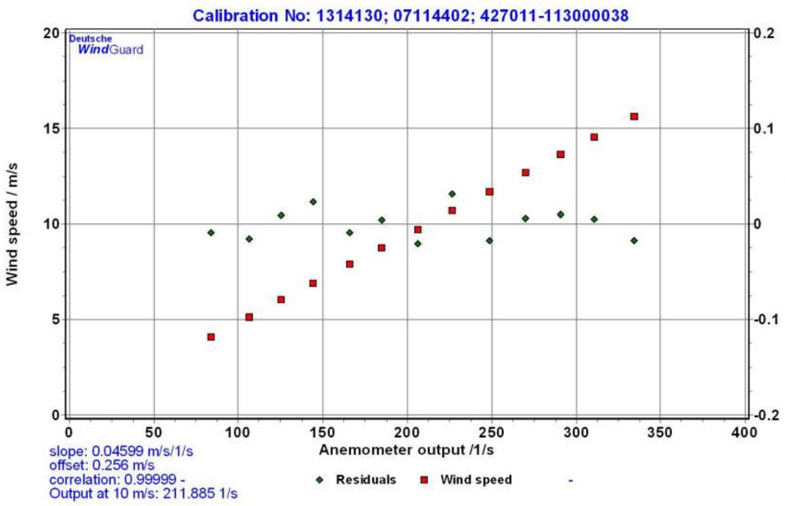
1 Detailed Calibration Results

DKD calibration no.	1314130
Serial no. 1	07114402
Serial no. 2	427011-113000038
Date	20.08.2013
Air temperature	24.9 °C
Air pressure	1027.6 hPa
Humidity	49.7 %

Linear regression analysis

Slope	0.04599 (m/s)/(1/s) ±0.00006 (m/s)/(1/s)
Offset	0.2557 m/s ±0.014 m/s
St.err(Y)	0.014 m/s
Correlation coefficient	0.999990

Remarks no



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