AQ510

Independent Performance Verification of an AQ510 SODAR at Fimmerstad

AQ System Stockholm AB

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1 INTRODUCTION

GL Garrad Hassan Deutschland GmbH (member of DNV GL – hereinafter referred to as “GH-D”) has been assigned on 2014-07-02 by AQ System Stockholm AB (AQS) to prepare an official independent report of an AQ510 SoDAR performance verification. In this analysis and report the AQ510 SoDAR with the serial number AQ510001 will be treated. The verification measurements for this device were performed by AQS at their test site in Fimmerstad, Sweden between 2014-04-02 and 2014-05-05.

The objective of this report is to document comprehensively the Performance Verification (PPV) of this SoDAR unit, independently. As such it is an independently review of the Performance Verification of an individual SoDAR unit with the goal (a) to assure the overall system integrity after manufacturing and prior to delivery, and (b) to give an informative indication of the quality of wind data to be expected from this SoDAR unit.

Furthermore, a PPV is not meant to replace the requirement for an on-site verification of a SoDAR in real field campaigns, typically performed in close proximity to an on-site mast over a reasonable period. This is particularly important for sites in non-benign conditions and for certain atmospheric conditions where SoDAR performance may vary from site to site.

The site for the validation test is a disused air field in Southern Sweden. The SoDAR validation is done versus a “classically” equipped meteorological mast (met mast). The site and in particular the met mast setup had independently been assessed by GH-D for its compliance to suitable standards (like IEC, see [4, 5]) on 2013-04-17, see [1]. In comparison to the instrumentation given in [1] the mast has experienced some modifications. The two wind vanes originally installed at 59.1 and 79.1 m (both at 317°) have been shifted to 54.1 and 74.1 m respectively (both at 137°). In return 2 additional Cup anemometer have been installed at 59.1 and 79.1 m (both at 137°). GH-D recommends to perform a second assessment to proof whether the mast is still IEC compliant after modification.

This independent analysis of an AQ510 SoDAR Performance Verification (PPV) is performed according to Fimmerstad specific SoDAR PPV process [2] as developed by GH-D for AQS.

GH-D has a wide range of experience in validation and testing of SoDAR remote sensing devices not least by participating in the EU-FP7 Project NORSEWInD [7].

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. GH-D 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 location

The following description and figures of the Fimmerstad AQS test site, which is a disused air field, are taken from [2]:

The AQS test facility at Fimmerstad is located in Southern Sweden between the two large Swedish lakes named Vänern and Vättern. The test site consists in the mentioned reference met mast with a top height of 103 m and two (2) dedicated test pads; it is located to the North of a disused air field, see Figure 1. The terrain of the surroundings at the test site can be characterized as little to moderately complex. The proximate surrounding of the disused airfield is flat terrain, open in particular to the Southwest and Northeast. It is mainly used for agricultural purposes. This flat agricultural area is limited by forests in distances to the met mast of 400m to 800 m to the Northwest and to the Southeast.

Figure 1: Satellite map of the Fimmerstad test site in Southern Sweden. The position of the reference mast is marked by a yellow pin.

The site specifications given in the above description have been verified during a site visit by a GH-D expert on 2013-04-21. Further details on the site are given in [1], a 360° photo round is shown in Appendix 2.

2.2 Reference Meteorological Mast

The Meteorological Mast (met mast) on the test site is a lattice tower of type K-Systems K600 with a four legged base. The height of the mast in terms of top most mounted instruments is 103.5 m above ground level. Side booms for wind sensors are attached to the mast pointing in opposite directions of 137 and 317°.
The layout of the wind measurement system at the mast as listed in Table 1 provides in total seven (7) cup anemometers at four (4) different heights (60, 80, 100.9 and 103.8 m, one for each boom direction) and three wind vanes at three (3) different heights (55, 75 and 97 m) .

The met mast setup had independently been assessed by GH-D for its compliance to suitable standards [1] with a focus on wind sensor selection and mounting. As a result the whole mast setup and sensor mounting was found fully compliant to applicable industry best practice standards. In contrast to the assessed original sensor mounting setup the mast has experienced some modifications. The two wind vanes originally installed at 60 and 80 m (both at 317°) have been shifted to 55 and 75 m respectively (both at 137°). In return 2 additional Cup anemometer have been installed at 60 and 80 m (both at 137°). Table 1 shows the updated sensor distribution at the met mast.

Table 1: Wind sensor distribution at met mast

Level	Height a.g.l. [m]	Sensor	Boom orientation [°]
1	103.8	Top Sonic Anemometer	137
2	103.8	Top Cup (heated)	317
3	100.9	Cup Thies 1st Class	137
4	100.9	Cup Thies 1st Class	317
5	97.0	Wind Vane	137
6	80.0	Cup Thies 1st Class	137
7	80.0	Cup Thies 1st Class	317
8	75.0	Wind Vane	137
9	60.0	Cup Thies 1st Class	137
10	60.0	Cup Thies 1st Class	317
11	55.0	Wind Vane	137

The cup anemometry levels at 100.9 m, 80 m and 60 m are selected as relevant comparison levels (i.e. levels 3/4, 6/7 and 9/10 in Table 1) as reference to the SoDAR wind speeds. As the top sensors are of non-1st–Class type they are omitted.

For SoDAR wind direction comparisons the wind vanes at the 97 m 75 m and 55 m (levels 5, 8 and 11 are used.

Table 2: List of individual anemometers as mounted to the mast (see Table 1) during PPV campaign, including serial number and installation date as given in [6]. The valid calibration certificates are attached to this report in Appendix 8.

Cup Type	Height [m]	Boom Direction	Serial Number	Installation Date
Thies 1st Cl	100,9	317°	01142028	2014-03-19
Thies 1st Cl	100,9	137°	01142027	2014-03-19
Thies 1st Cl	80	317°	01142025	2014-03-19
Thies 1st Cl	80	137°	01142026	2014-03-19
Thies 1st Cl	60	317°	01142023	2014-03-19
Thies 1st Cl	60	137°	01142024	2014-03-19

2.3 Test pad for the SoDAR device

The test pad where the AQ510001 has been installed for the performance verification is located east from the met mast in a direction of approx. 104° and at a distance of some 100 m (see Appendix 2). The respective GPS coordinates are given in Appendix 2.

Such distances to the mast are considered necessary in order to avoid any fixed echo contamination of the SoDAR reception caused by the proximate fixed mast lattice structure. In the context of comparability between a SoDAR and the mast those rather large distances present a natural and SoDAR independent limit to the achievable quality of statistical correlations (here linear regressions) between both wind data sets in the course of verification process.

2.4 The AQ510 SoDAR under test

The SoDAR under test is a Doppler wind SoDAR of type AQS AQ510. The AQ510 measures the 3D wind vector, i.e. two perpendicular-horizontal and one vertical component, by transmitting sound into the atmosphere and analysing the echo. AQ510 is based on a mono-static setup, meaning that the speaker that emits the sound pulses also acts as a microphone receiving the signal refracted by the atmosphere. In order to calculate the wind's three components, AQ510 is equipped with three separate speaker/microphone units that emit sound in three directions. The sound that AQ510 emits spreads in a 17° cone-shaped volume. The serial number of this individual device is AQ510001.

During the measurement campaign the AQ510 SoDAR system was configured to record wind speed measurements on 33 different levels between 40 and 200 m a.g.l., employing a spacing of 5 m. Out of those 31 SoDAR levels three heights at 60, 80, 100 m were used for the comparison to the mast wind speed and direction measurements. A detailed installation report of the SoDAR can be found in Appendix 9.

Figure 2 shows the AQ510 SoDAR kit as part of a trailer located some 100 m to the east of the base of the met mast.

Figure 2: Typical setup of AQ510 SoDARs at the Fimmerstad test site.

3 PERFORMANCE VERIFICATION (PPV) APPROACH

3.1 Common test conditions and data filtering

In the process of the PPV 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 SoDAR under test.
- All data collected during periods of possible icing at cup anemometers, i.e. with temperatures below 0.5 °C are excluded.
- All other reported data (particularly wind speed) within undisturbed free-stream wind direction sector of the reference mast are used in the comparison analysis.
- The SoDAR recorded 10 minute vector mean wind speeds are convert to scalar mean wind speeds based and dependent on campaign individual 10-min turbulence intensities measured from the SoDAR itself. The conversion method is described in the AQ510 User Guide [6].
- Scalar mean wind speeds of the SoDAR and the recorded cup wind speeds at the respective relevant comparison heights with a wind speed value > 3 m/s are then used in the comparison analysis.

A sector filtering of wind directions from the mast wind vane data needs to be performed in order to account for downwind flow distortions of side mounted cups induced from the mast lattice structure. The sector filtering was applied as described below (see also Figure 3):

- At the 60, 80 and 100 m level the orientation of both cup carrying booms at the mast is to the North West (317°) at one side and to the South East (117°) on the other side. Hence, wind speed data need to be screened at wind directions between 117° and 157° for the cup on the Northwest side and between 297° and 337° 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, the wind speed average of the two instruments is used to form the reference for the comparison with the SoDAR wind speeds. In this case the data are further screened if the wind speed difference between both cups exceeds 0.3 m/s.

The cup anemometers at the 100 m level are screened against wind direction data from the vane at 97 m. Instruments at the 80 m and 60 m are screened against wind direction data from the vanes at 75 m and 55 m respectively.

For the validation of SoDAR wind speeds against the mast, only wind speeds from the Thies First Class cup anemometers are used. The SoDAR data are selected according to the sector screening of the cup data prior to comparison. No SoDAR specific filters are applied to the measured SoDAR data prior to the analysis conducted.

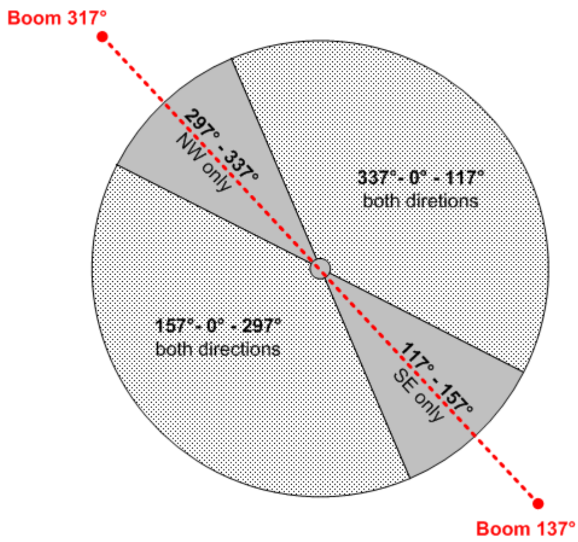

Figure 3: Wind direction sectors used to select undisturbed wind speed data for comparison at 100.9 m, 80 m and 60 m cup levels.

3.2 Data coverage requirements for accuracy assessment

The following data coverage definitions are prescribed for this PPV process in [2]:

a) Minimum number of 20 data points required in each 1 m/s bin wide reference wind speed bin centered between 3.5 m/s and 11.5 m/s, i.e. covering a range between 3 and 12 m/s.

b) Minimum number of 20 data points required in each 2 m/s bin wide reference wind speed bin centered on 13 m/s and 15 m/s, i.e. covering a range 12 m/s and 16 m/s.

c) Minimum number of 20 data points in each 2 m/s bin wide reference wind speed bin centered on 17 m/s and above, i.e. covering a range above 16 m/s only if such number of data is available. This is not mandatory.

Those data coverage requirements are regarded as achievable for the planned 4 weeks deployment period.

3.3 PPV evaluation

The performance of the SODAR 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 together with the selected KPIs and according ACs is outlined in Appendix 1. KPIs and ACs for system and data availability are listed in Table 3, those for wind data quality in Table 4. Detailed definitions and explanations to all KPIs are listed in Appendix 1.

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 met tower's 1st class reference anemometry levels which are 60 m, 80 m and 100.9 m a.g.l.

KPI	Definition / Rationale	Acceptance Criteria across total of four (4) weeks data
OSA_{CA}	Overall System Availability – Campaign Average .	≥95%
$OPDA_{CA}$	Overall Post-processed Data Availability	≥85%
MV	Number of Maintenance Visits	N/A
UO	Number of Unscheduled Outages	N/A
CU	Uptime of Communication System	N/A

Table 3: List KPIs and ACs relevant for System and Data Availability

KPI	Definition / Rationale	Acceptance Criteria	
		RS Best Practice	Minimum
C_{mwsd}	Campaign Mean Wind Speed – Difference	< 1 %	< 2%
X_{mws}	Mean Wind Speed – Slope	0.98 – 1.02	0.97 – 1.03
R^2_{mws}	Mean Wind Speed – Coefficient of Determination	>0.97	>0.93
X_{mwd}	Mean Wind Direction – Slope	0.97 – 1.03	0.95 – 1.05
OFF_{mwd}	Mean Wind Direction – Offset	< 5°	< 10°
R^2_{mwd}	Mean Wind Direction – Coefficient of Determination	> 0.97	> 0.95
FD_{WS}	Frequency Distribution of Wind Speed	N/A	N/A
X_{TI}	Turbulence Intensity – Slope	N/A	N/A
R^2_{TI}	Turbulence Intensity – Correlation Co-efficient	N/A	N/A
A	Wind Speed Shear	N/A	N/A

Table 4: List of KPIs and ACs relevant for Wind Data Accuracy

4 RESULTS

For the SoDAR performance verification campaign data were provided for the period 2014-04-02, 12:10 until 2014-05-05, 14:30. So the campaign was completed after a total campaign duration of 33 days.

The wind speed ranges covered and used for comparison are 3 to 16.7 m/s at the upper level (100.9 m) and 3 to 15.9 m/s at the lower level (60 m).

Table 5 shows that at the 100 m level all mandatory requirements with regards to data coverage are met. At the 60 and 80 m level the numbers of data points were just under the minimum of 20 data points in the 15 m/s bin.

	Center of WS bin / m/s											
	3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5	13	15	17
# values at 60 m	831	837	756	554	357	197	121	67	46	39	10	0
# values at 80 m	653	770	716	705	399	278	143	89	51	51	15	1
# values at 100 m	476	640	546	702	560	331	221	101	70	71	20	4

Table 5: Bin-wise data coverage of data used for PPV analysis

4.1 System availability

The system availability as applied to the SoDAR device is defined by a percentage of the maximum possible number of ten-minute periods within the above mentioned total campaign duration of 33 days, which is 4767. As 4729 SoDAR ten-minute data entries were present (regardless of the data validity) the SoDAR device achieved a system availability of 99.2 %, see table below.

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

Period: Date	02.04.2014 12:10 to 2014-05-05 14:30					
Height	60 m		80 m		100 m	
Internal QC filter for Signal-to-Noise ratio (S/N)	> 21 dB					
External filter for QC	filter for Signal-to-Noise ratio (SN)					
External filter for WD, WS, Temp	filtering for certain WD sections, WS > 3 m/s and temperature					
Max. # of 10-min points	4767		4767		4767	
# of 10-minute data incl. NaN	4729		4729		4729	
Overall System Availibility (OSA_{CA})		99,2%		99,2%		99,2%
# of 10-minute valid data	4606		4528		4374	
Overall Post-processed Data Availibility ($OPDA_{CA}$)		96,6%		95,0%		91,8%
# after ext filtering for WD, WS	3815		3871		3742	
Data Availibility after ext filtering for WS, WD, Temp		80,0%		81,2%		78,5%

Table 6: Summary of system and data availabilities

4.2 Data availability

Table 6 above summarizes the period of overlap between the met mast and the SoDAR system during the measurement campaign with the system availability of 99.2 % as stated in the previous section. It shows a data availability for the treated comparison measurement levels between 60 and 100.9 m A.G.L. – regardless of the relevance for wind data comparisons – between 96.6 and 91.8 % relative to the maximum possible number of ten-minute periods. It has to be mentioned that the SoDAR device under consideration had been operated at 40 % of the default output power during the verification test, only, in order to avoid potential signal contamination of neighboring SoDAR units under test. This in general might have had a lowering influence on the data availability.

Data for individual heights were treated as available when they show a numeric value in contrast to a value being flagged as NaN (Not a Number). The difference in number of available data between the rows "Overall System" and "Overall Post-processed" data availability" in Table 6 reflects the reduction of valid data according to internal system filtering.

For information Figure 4 shows the SoDAR system availability and in particular the data recovery rate for every second out of in total 33 measurement heights, i.e. between 40 and 200 m. It is observed that the availability of valid data recorded by the SoDAR shows a clear decrease with height.

The already mentioned system availability of 99.2 % is – by definition – the same for all heights (yellow bars). The overall data availability (blue bars) stays above 95 % up to 100 m dropping to about 90% at 120m and further to less than 55 % at the uppermost SoDAR level of 200m.

- ✓ The Acceptance Criterion for Overall Post-processed Data Availability (**KPI** $OPDA_{CA}$) to be ≥85% is successfully passed at all relevant assessment levels.

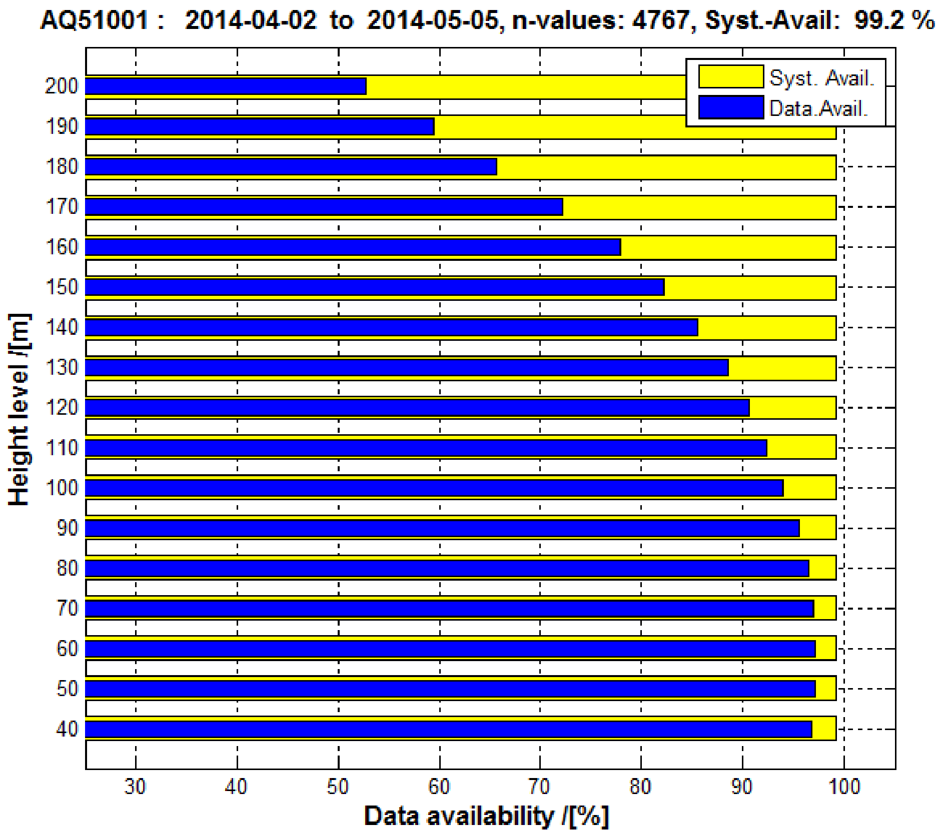

Figure 4: SoDAR system and data availabilities for all measurement levels.

4.3 Applied data filtering

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

- Wind direction to avoid non-valid wind speed sectors being influenced by e.g. mast wake effects, compare section 3.1 and
- Wind speed by clipping data below 3 m/s.

After the application of those two filters the number of ten-minute data points remaining to be processed was reduced to a percentage between 78.5 % and 81.2 %, compare Table 6.

.

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.

As this campaign represents a series PPV of a technology proven Remote Sensing device the test campaign is limited in duration, for practical reasons. In consequence the core verification concentrates on a subset of statistically meaningful KPIs criteria (in terms of amount of available representative data) being treated relevant for acceptance.

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

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

between SoDAR (y-axis) and cup wind speeds (x-axis) for all relevant comparison, applying best practice Acceptance Criteria to the KPIs

- slope (**KPI** X_{mws}) between 0.98 and 1.02
- correlation coefficient (**KPI** R^2_{mws}) $R^2 > 0.97$

for wind speed ranges [all WS > 3 m/s] and [4 < WS < 16 m/s] prescribed in Table 4 and Appendix 1.

4.4.1 Results of wind speed comparisons

The time series of wind speeds as recorded by the SoDAR is overlapped by that of the met mast system covering 33 days. Time series of WS as recorded by the SoDAR and the cups for all comparison heights (60 m, 80 m and 100.9m) are shown in Appendix 2.

Table 7 summarizes the wind speed regression results for all three (3) comparison heights showing that the AQ510 SoDAR at hand achieves a high level of accuracy compared to the respective cups in terms of regression slopes (KPI X_{mws}) which are above 0.98 for all levels, and regression coefficient R^2 (KPI R^2_{mws}) between 0.977 and 0.982
Figure 5 shows the corresponding regression plots for the wind speed range >= 3 m/s (upper row).

The mean SoDAR wind speeds as averaged over all used values resemble those of the cups closely (see as well columns 5 and 6 of Table 7) yielding the mean relative WS differences (KPI C_{mwsd}) for the relevant heights between 0.09 % at 100 m and 0.79 % at 60 m.

- ✓ The Acceptance Criterion for the relative Campaign Mean Wind Speed Difference (KPI C_{mwsd}) (see
- ✓ Table 7, column 8) is successfully passed at all relevant assessment levels, meeting Best Practice criterion at all assessment relevant heights.

60 m level	# values	Slope (Xmws)	R^2_{mws}	WS-avg Cup	WS-avg SoDAR	Mean diff.	rel. Mean diff.	Standard dev. of diff.	
WS-range	-	-	-	[m/s]	[m/s]	[m/s]	[%]	[m/s]	[%]
WS >= 3 m/s, no outlier, WD-avr	3815	1,007	0,977	5,71	5,76	0,05	0,79%	0,31	5,47%
4 - 16 m/s	2905	1,008	0,972	6,37	6,42	0,06	0,87%	0,32	5,07%
80 m level	**# values**	**Slope (Xmws)**	**R^2_{mws}**	**WS-avg Cup**	**WS-avg SoDAR**	**Mean diff.**	**rel. Mean diff.**	**Standard dev. of diff.**	
WS-range	-	-	-	[m/s]	[m/s]	[m/s]	[%]	[m/s]	[%]
WS >= 3 m/s, no outlier, WD-avr	3871	1,009	0,980	6,04	6,10	0,06	0,96%	0,31	5,06%
4 - 16 m/s	3143	1,009	0,975	6,59	6,65	0,07	0,99%	0,32	4,78%
100 m level	**# values**	**Slope (Xmws)**	**R^2_{mws}**	**WS-avg Cup**	**WS-avg SoDAR**	**Mean diff.**	**rel. Mean diff.**	**Standard dev. of diff.**	
WS-range	-	-	-	[m/s]	[m/s]	[m/s]	[%]	[m/s]	[%]
WS >= 3 m/s, no outlier, WD-avr	3742	1,000	0,982	6,50	6,51	0,01	0,09%	0,30	4,63%
4 - 16 m/s	3192	1,000	0,978	6,97	6,98	0,00	0,07%	0,30	4,35%

Table 7: Regression results for comparison; acceptance relevant results are colour shaded.

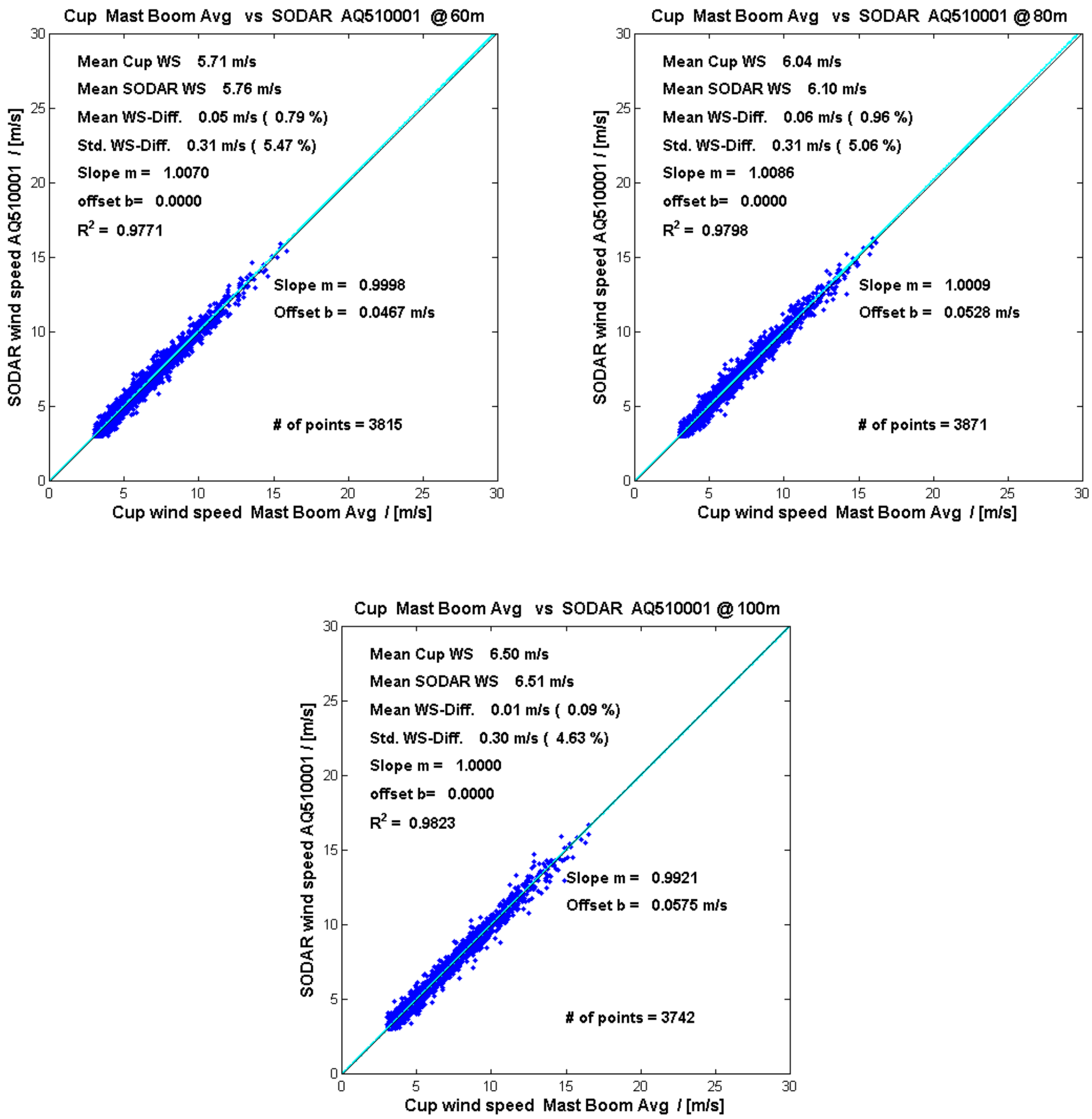

Figure 5: Plots of linear wind speed regression results for 60, 80 and 100 m

4.4.2 Wind speed comparison results according to Acceptance Criteria

In conclusion the following KPI's Acceptance Criteria are passed

- ✓ Regression slope (**KPI** X_{mws}) between 0.98 and 1.02 (Best Practice AC) at all treated levels and for both WS ranges, meeting the Best Practice criterion.
- ✓ R^2 (**KPI** R^2_{mws}) > 0.97 (Best practice AC) at all treated levels and for both WS ranges, meeting Best Practice criterion.

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

- o The data coverage requirements (see section 3.2) are not fulfilled for WS bins above 15 m/s for 60 and 80 m levels. However these coverage ratios are considered to be not mandatory (see above)..

4.5 Wind direction comparison

By comparing the wind direction as measured by the SoDAR device at its 100 m level with the mast mounted wind vane at 97 m A.G.L., it is possible to see how well correlated the measures are, providing confidence in that the SoDAR 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 1.

The results of such regression are shown in the x-y-plots in Figure 6 with the vane wind direction at 97 m on the x-axis and the SoDAR direction at 100 m on the y-axis. For this analysis the data were again filtered for SoDAR and the cup wind speeds at 100.9 m, i.e. for WS >=3 m/s, but not for possibly disturbed wind directions sectors.

The time series of wind directions present during the course of the campaign can be found in Appendix 4.

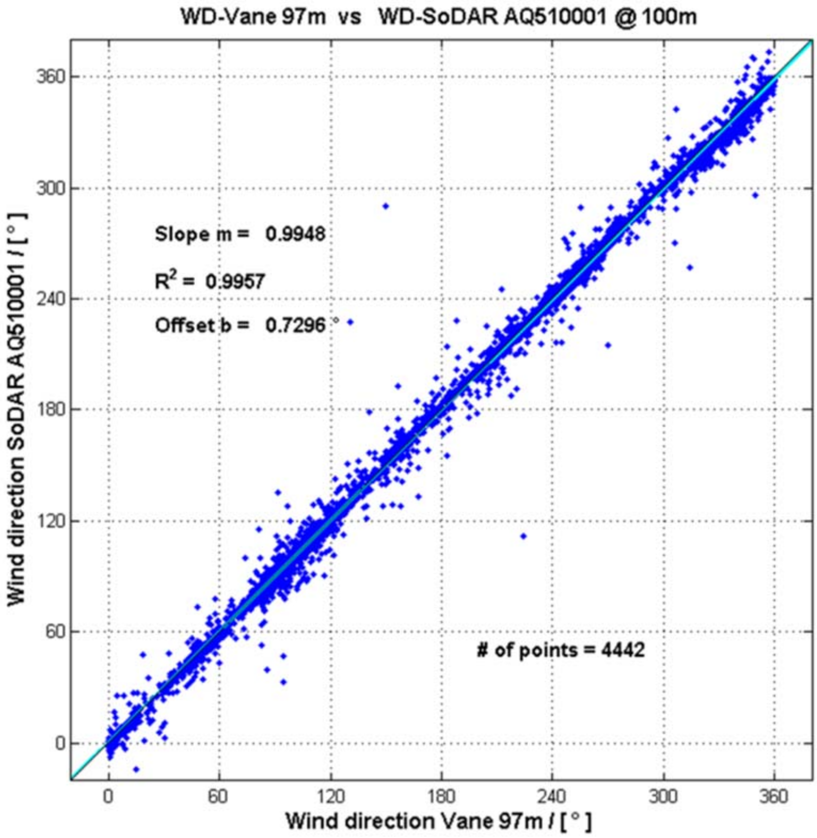

Figure 6: Regression plot of wind direction comparison

The regression plot in Figure 6 reveals a very close resemblance between both wind direction measures with a slight offset of less than 1° which is within typical directional setup uncertainties for wind vanes and remotes sensing devices.

Table 8 summarizes the WD comparison results as well for the other two relevant levels. As the wind vane at 75 m was faulty in the considered period the SoDAR wind direction measurements were compared with the wind vane records at 97 m. At both additional levels (55 and 75 m) the AQ510001 SoDAR device showed as well good results for the WD comparison.

WS filtering for WS > 3 m/s				
Height level	# Values	Slope	Offset [°]	R^2
[m]	-	(X_{mwd})	(OFF_{mwd})	(R^2_{mwd})
55	4594	0,992	2,770	0,994
75	4571	0,994	-1,136	0,993
100	4440	0,995	0,730	0,996

Table 8: Summary of WD comparison results for all three comparison levels

- ✓ The Acceptance Criteria for the respective Key Performance Indicators for wind direction assessment (**KPIs** for X_{mwd}, OFF_{mwd}, and $R2_{mwd}$) have successfully been passed at all comparison levels, meeting Best Practice criteria.

4.6 KPIs of secondary importance

The SoDAR performance for KPIs of secondary importance such as Frequency Distribution of Wind Speed (KPI FD_{ws}), Wind Speed Shear (KPI A) and Turbulence Intensity (KPIs X_{TI} and R^2_{TI}) is assessed without the application of Acceptance Criteria, hence in a poorly informative manner.

The respective results are attached to this report in

- Appendix 5 for Frequency Distribution of Wind Speed
- Appendix 6 for Turbulence Intensity
- Appendix 7 for Wind Speed Shear

5 IMPORTANT REMARKS AND LIMITATIONS

Independently performed (or independently reviewed) Performance Verifications (PPV) of individual SoDAR devices as reported on in this document present a reasonable means to assure overall system integrity of the SoDAR unit after manufacturing, and to give an informative indication of the quality of wind data produced by the SoDAR.

Any statement given in the context of system integrity and data quality related results of within this report are limited to the given test site conditions, to the prevailing atmospheric conditions and to the specific SoDAR configuration as selected during the PPV campaign, only.

A PPV is not thought to replace the requirement for an on-site verification of a SoDAR in real field campaigns, typically performed in close proximity to an on-site mast over a reasonable period. This is particularly important for sites in non-benign conditions and for certain atmospheric conditions where SoDAR performance may vary from site to site.

PPVs will not automatically warrant quantitative use of AQ510 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.

6 CONCLUSION

Concurrent AQ510 SoDAR and cup anemometer wind measurements were carried out at the AQS Fimmerstad test site to verify SoDAR wind data quality against well-known high quality mast based cup and vane anemometry. Measurement heights of 60 m, 80 m, 100.9 m a.g.l. were available for wind speed correlations (55, 75 and 97 m for wind direction correlation) between a proximate met mast and an AQ510 SoDAR with the serial number AQ510001. The duration of the validation was 33 days. While additional measurements – in particular for higher wind speeds – would have enabled a more extensive assessment of the SoDAR system, the test period and wind data coverage is considered sufficient for the purpose of characterizing the wind data performance of the AQ510 SoDAR S/N AQ510001 in the context of a Performance Verification.

The total system availability for the mentioned 33 days assessment period was 99.2 %. The data coverage at the selected SoDAR measurement levels 60 m, 80 m, 100 m was above 90 %. The data coverage figures are 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 three (3) wind measurement heights mentioned above. The wind speeds of both techniques at all treated heights correlated well, showing a reasonable level of scatter and a good resemblance of SoDAR wind speeds to those of cups, in terms of mean campaign WS differences and WS linear regression slopes.

In summary the following Acceptance Criteria for respective KPIs were met.

- ✓ The Acceptance Criterion for Overall System Availability (**KPI** OSA_{CA}) to be ≥95% is successfully passed.
- ✓ The Acceptance Criterion for Overall Post-processed Data Availability (**KPI** $OPDA_{CA}$) to be ≥85% is successfully passed at all relevant assessment levels.
- ✓ The Acceptance Criterion for Campaign Mean Wind Speed Difference (**KPI** C_{mwsd}) is successfully passed at all relevant assessment levels, meeting Best Practice criterion at 100, 80 m and 60 m.
- ✓ Regression slope (**KPI** X_{mws}) between 0.98 and 1.02 (Best Practice AC) at all treated levels and for both WS ranges, meeting the Best Practice criterion.
- ✓ R^2 (**KPI** R^2_{mws}) > 0.97 at all treated levels and for both WS ranges, meeting the Best Practice criterion.
- ✓ The Acceptance Criteria for the respective Key Performance Indicators for wind direction assessment (**KPIs** for X_{mwd}, OFF_{mwd}, and R^2_{mwd}) have successfully been passed at all comparison levels, meeting Best Practice criteria.

To conclude, the Fimmerstad/Throckmorton validation campaign indicates that the AQ510 SoDAR with the serial number AQ510001 is able to reproduce cup anemometer wind speeds and wind vane directions at a reasonably accurate level.

GH-D considers that for relatively simple terrain sites data from the AQ510 device 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 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 PPV – as performed in relatively simple terrain – may not be representative of what may be expected at potential wind farm site. In such situations the AQ510 data recorded at a 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 SoDAR turbulence and extreme wind speed measures, not treated in this report but 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 SoDAR or more conventional anemometry. Therefore, special care needs to be exercised in the transportation, installation and on-going maintenance of the SoDAR 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 employed. Furthermore it is recommended that thorough practices of documenting the salient features of SoDAR installation and maintenance are instigated from the outset.

7 REFERENCES

[1] Stein, D., "TECHNICAL CONFORMANCE OF AQS MET MAST AND TEST SITE IN FIMMERSTAD, SWEDEN", GLGH Report GLGH-4257 12 10162 267-R-0001, Issue B, dated 17th May 2013.

[2] Stein, D., "SODAR PERFORMANCE VERIFICATION PROCESS FOR AQS FIMMERSTAD TEST SITE, SWEDEN", GLGH Report GLGH-4257 12 10162 267-R-0002, Issue B, dated March 2014.

[3] Hansson, J., "Description of the Fimmerstad met mast and surroundings", AQS Report No. 121101-22, Revision 9, dated 19th March 2014

[4] IEC 61400-12-1, "Wind turbines - Part 12-1: Power performance measurements of electricity producing wind turbines", 2005.

[5] Draft CDV IEC 61400-12-1, "Wind turbines - Part 12-1: Power performance measurements of electricity producing wind turbines, Annex L", July 2013

[6] AQSystems, "AQ 500 Windfinder User Guide", Version 3, 2013-12-13, Third Edition

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

[8] 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
AQS	AQ Systems Stockholm AB
CDV	Committee Draft for Voting
DNV GL	New company name, successor of 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
PPV	Pre-Delivery Performance Verification
TI	Turbulence Intensity
WD	Wind direction
WS	Wind speed

APPENDIX 1: SODAR PERFORMANCE VERIFICATION

List of KPIs and ACs relevant for System and Data Availability assessment

KPI	Definition / Rationale	Acceptance Criteria across total of four (4) weeks data
OSA_{CA}	Overall System Availability – Campaign Average The SoDAR 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 Overall System Availability is the number of those time stamped data entries relative to the maximum possible number of (here 10 minute) data entries including periods of maintenance (regarded as 100%) within the pre-defined total campaign period.	≥95%
$OPDA_{CA}$	Overall Post-processed Data Availability The Overall Post-processed Data availability is the number of those data entries remaining • after system internal (unseen) filtering (e.g. S/N 20 for AQ510), i.e. excluding (NaN or 999) flagged data entries • and after application of quality filters based on system own parameters, to be defined and applied in a post processing step on the basis of SoDAR manufacturer guidelines relative to the maximum possible number of (here 10 minute) data entries (regarded as 100%) within the pre-defined total campaign period regardless of the environmental conditions within this period.	≥85%
MV	Number of Maintenance Visits Number of Visits to the SoDAR system by either the manufacturer or an authorized third party to maintain and service the system. This is to be documented and reported by the manufacturer.	N/A
UO	Number of Unscheduled Outages Number Unscheduled Outages of the SoDAR 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 by the manufacturer.	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.

List of KPIs and ACs relevant for Wind Data Accuracy assessment

KPI	Definition / Rationale	Acceptance Criteria	
		RS Best Practice	Minimum
C_{mwsd}	Campaign Mean Wind Speed – Difference Absolute difference of mean wind speeds between SoDAR 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 3 m/s given achieved data coverage requirements.	< 1 %	< 2%
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 c) 4 to 16 m/s d) all above 3 m/s given achieved data coverage requirements.	0.98 – 1.02	0.97 – 1.03
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) all above 3 m/s given achieved data coverage requirements.	>0.97	>0.93
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 3 m/s regardless of coverage requirements.	0.97 – 1.03	0.95 – 1.05
OFF_{mwd}	Mean Wind Direction – Offset (absolute value) (same as for M_{mwd})	< 5°	< 10°

KPI	Definition / Rationale	Acceptance Criteria	
		RS Best Practice	Minimum
R^2_{mwd}	Mean Wind Direction – Coefficient of Determination (same as for M_{mwd})	> 0.97	> 0.95
FD_{WS}	Frequency Distribution of Wind Speed Frequency of occurrence of WS (after filtering) from SoDAR to be compared to cups at relevant heights, presented as bar plots over 1 m/s wide wind speed bins. Analysis shall be applied to all wind speeds available.	N/A	N/A
X_{TI}	Turbulence Intensity – Slope Slope returned from single variant regression with the regression analysis constrained to pass through the origin.	N/A	N/A
R^2_{TI}	Turbulence Intensity – Correlation Co-efficient Correlation Co-efficient returned from single variant regression with the regression analysis constrained to pass through the origin.	N/A	N/A
A	Wind Speed Shear – Shear Exponent Alpha related to Hellman's power law. Alpha to be calculated using reference anemometry heights at 60 m and 100 m Mean Alpha values to be compared for different wind speed ranges such as a) 4 to 8 m/s b) 8 to 12 m/s c) 12 to 16 m/s d) all wind speeds above 2 m/s	N/A	N/A

APPENDIX 2: FIMMERSTAD TEST SIDE LOCATION AND MET MAST

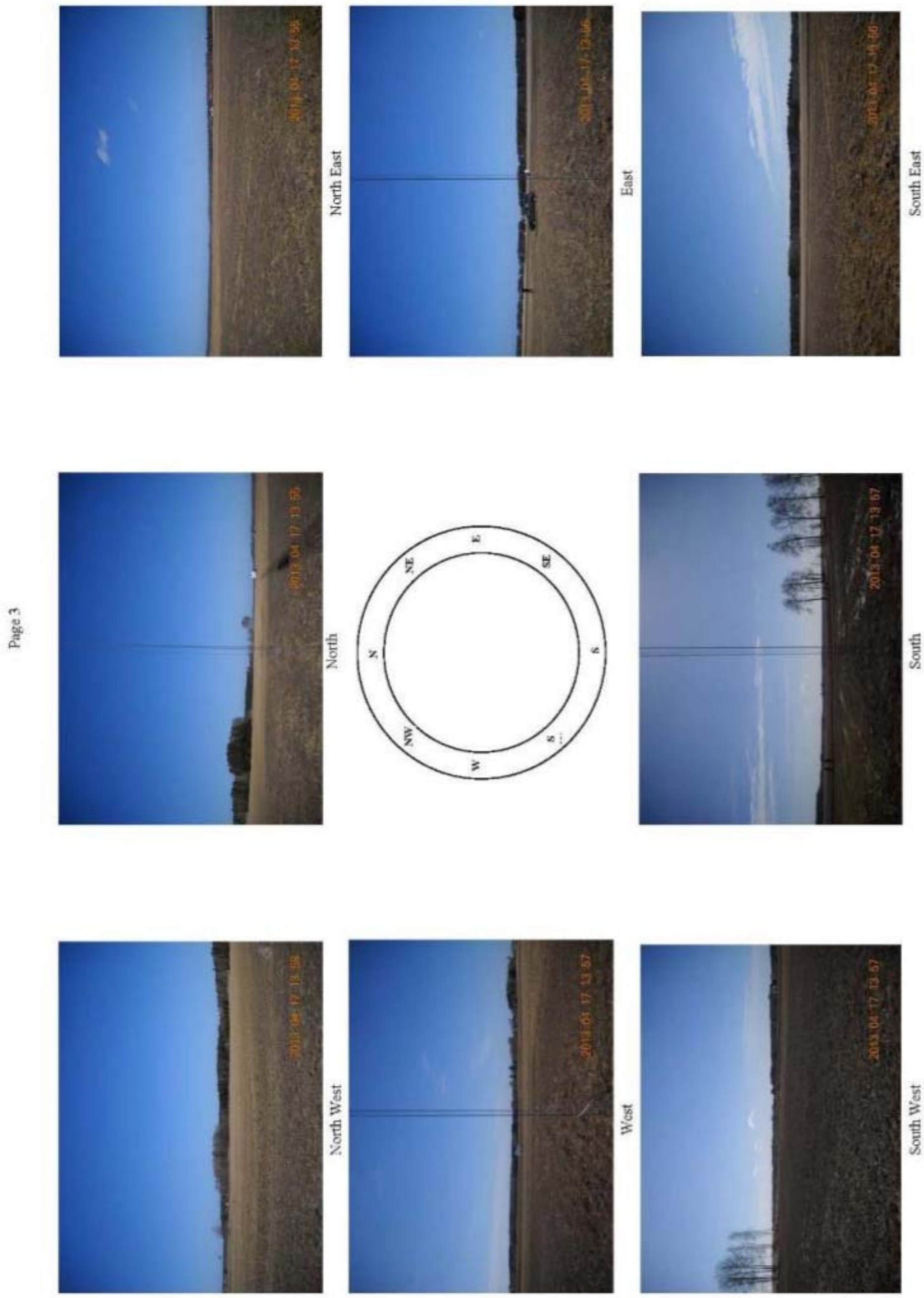

Figure A.1: Photo circle of eight clock wise selected sectors at Fimmerstad met mast surroundings

Name	Position		Distance to Mast	Direction to Pad
	Latitude	Longitude	[m]	[°]
Met Mast	58° 36' 20.26" N	14° 6' 35.55" E	-	-
Test Pad	58° 36' 19.5" N	14° 6' 41.7" E	103	104

Figure A.2: map of AQS Fimmerstad test site, indicating locations for met mast (yellow) and test pad (cyano), together with positions

Photo 1: Close-up of mast top pointing North

Photo 2: Close-up of mast foot pointing E

Photo 3: Forrest to the NW of mast

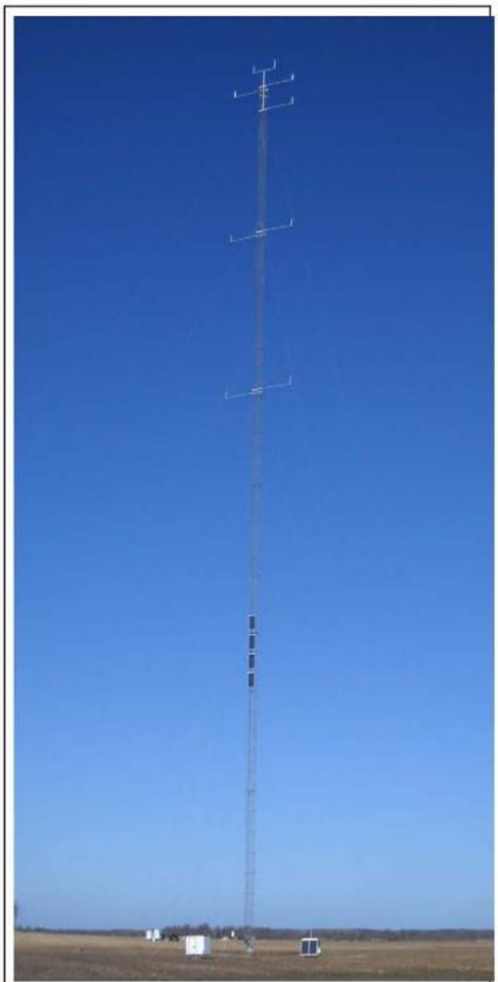

Photo 4: Mast overview pointing NNW

Figure A.3: Photo of upper part of met mast (1), mast foot (2), forest to NW of mast (3) and complete met mast (3) – original set-up as assessed by GH-D.

APPENDIX 3: TIME SERIES PLOTS OF WIND SPEED

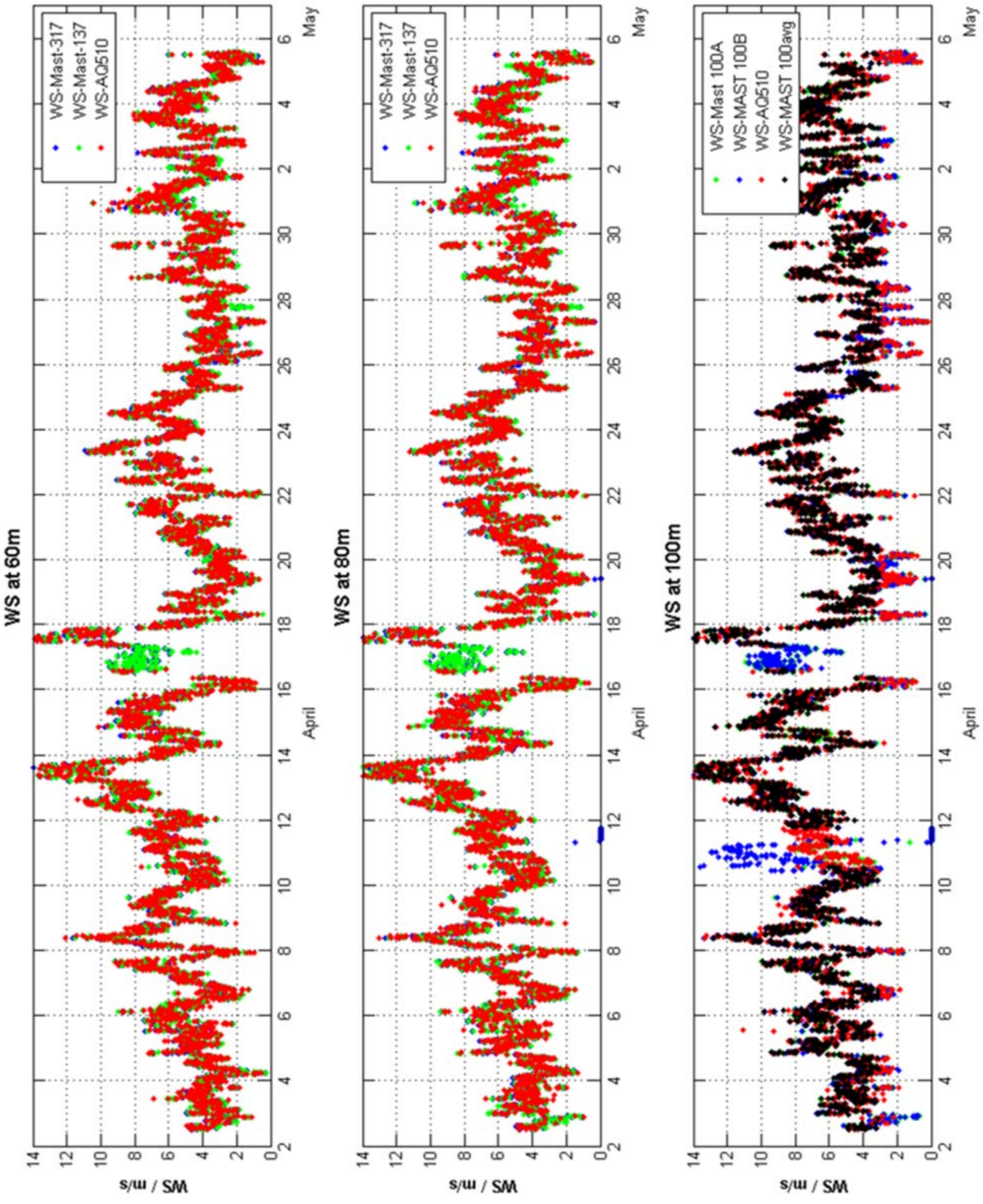

Figure A.4: Wind Speed time series plots for comparison levels 60 m, 80 m and 100 m a.g.l.

APPENDIX 4: TIME SERIES OF WIND DIRECTION

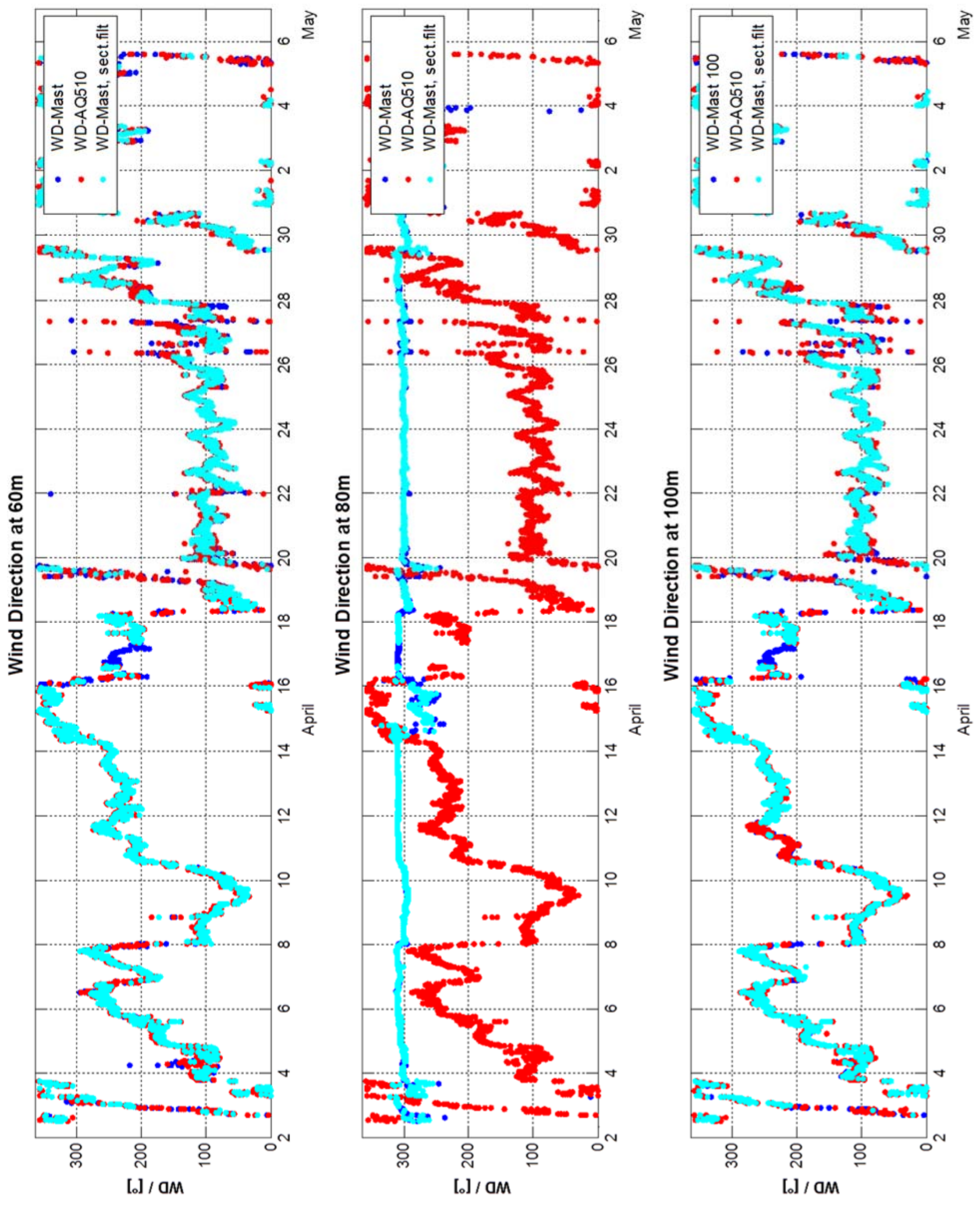

Figure A.5: Wind direction time series plots for comparison levels 60 m, 80 m and 100 m a.g.l

APPENDIX 5 ASSESSMENT OF FREQUENCY DISTRIBUTION OF WIND SPEED

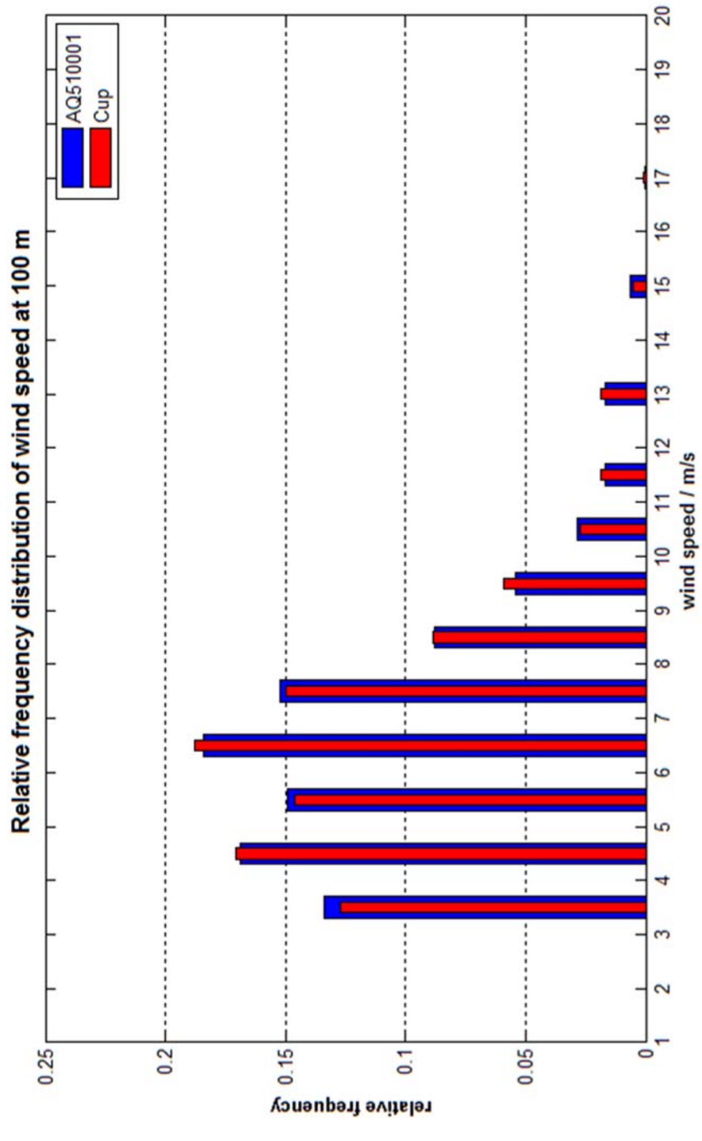

Figure A.6: Wind Speed Frequency Distribution for SoDAR and cup data at 100 m comparison level.

APPENDIX 6 ASSESSMENT OF TURBULENCE INTENSITY

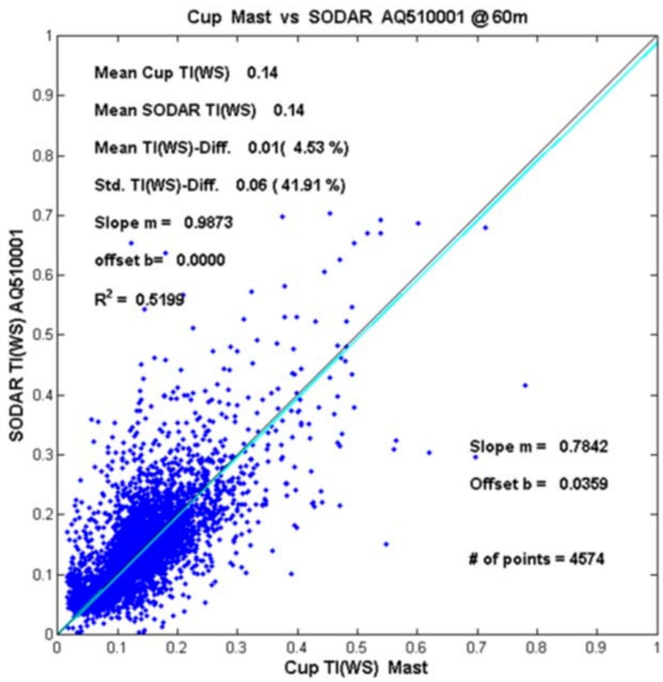

Figure A.7: Linear regression for Turbulence Intensity (TI) from Cup and SoDAR at 60 m

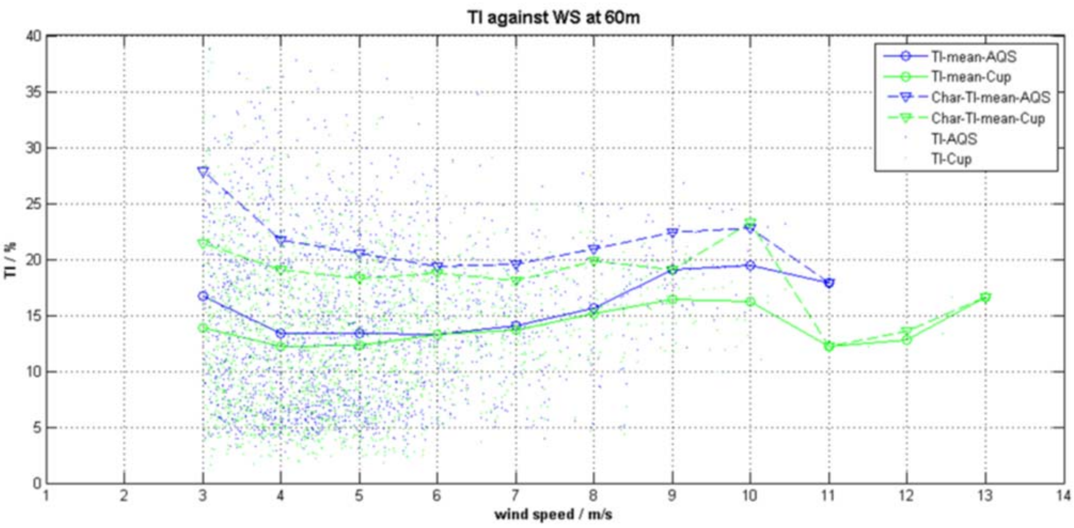

Figure A.8: Turbulence Intensity (TI) from Cup and SoDAR at 60 m plotted against cup WS.

APPENDIX 7: ASSESSMENT OF WIND SPEED SHEAR

WS ranges	Hellmann co-efficient (A)			
	Cup (60m - 100m)		AQ510001 (60m-100m)	
	n	value	n	value
4 - 8 m/s	1718	0,2697	1718	0,2712
8 - 12 m/s	349	0,1548	349	0,1521
12 - 16 m/s	41	0,1292	41	0,1558
3 - end m/s	3308	0,2984	3308	0,2690

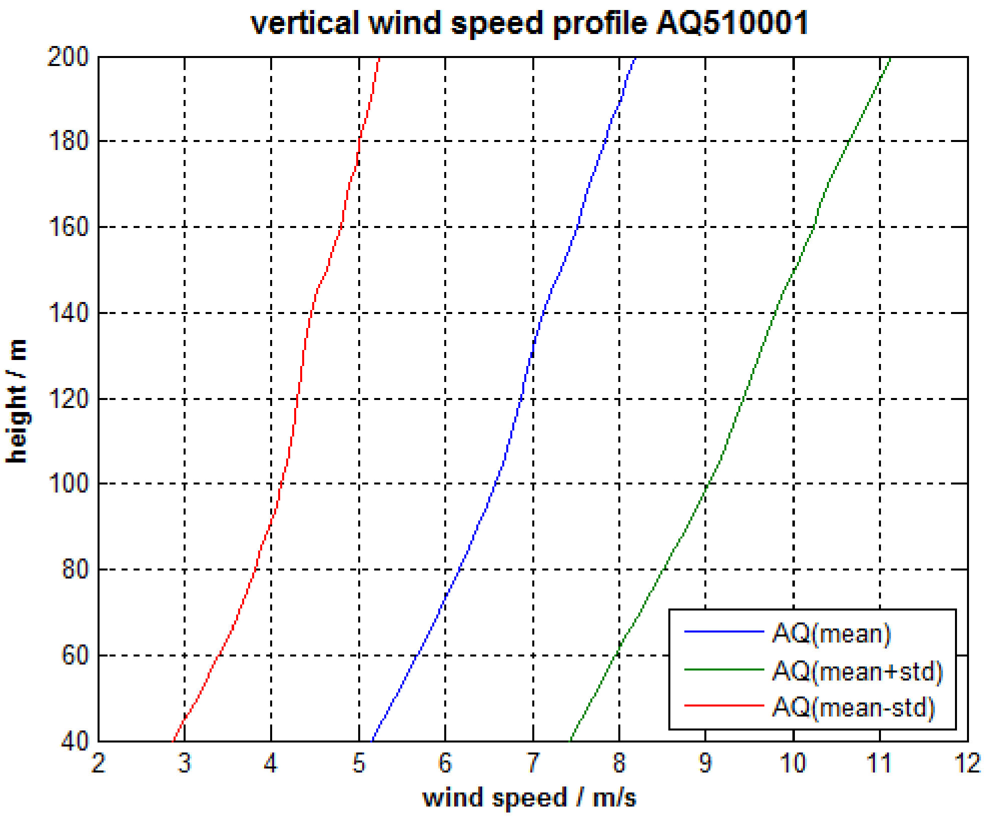

Figure A.9: Vertical Wind Speed profile measured by the SoDAR device AQ510001

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APPENDIX 8: CUP CALIBRATION CERTIFICATES

Thies First Class Cup Anemometer at 100.9 m, 317° orientation

Anhang
Annex

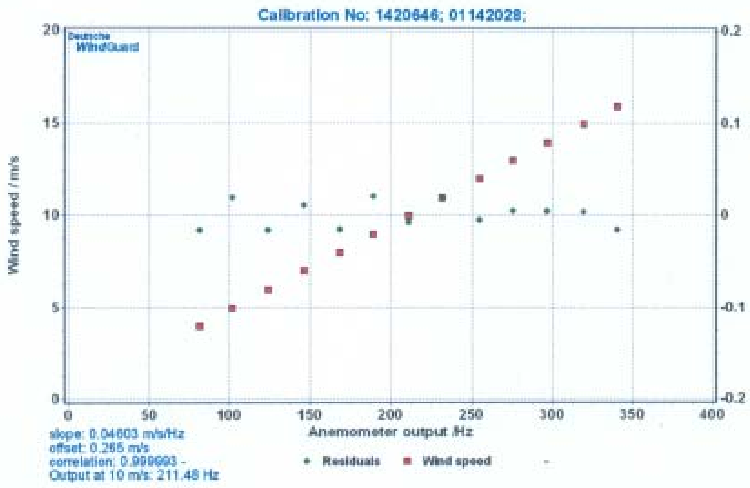
1420646

1 Detailed Calibration Results

DKD calibration no.	1420646
Body no.	01142028
Cup no.	
Date	01.02.2014
Air temperature	20.2 °C
Air pressure	994.4 hPa
Humidity	37.5 %

Linear regression analysis

Slope	0.04603 (m/s)/(Hz) ±0.00005 (m/s)/(Hz)
Offset	0.2649 m/s ±0.011 m/s
St.err(Y)	0.012 m/s
Correlation coefficient	0.999993
Remarks	no



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Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

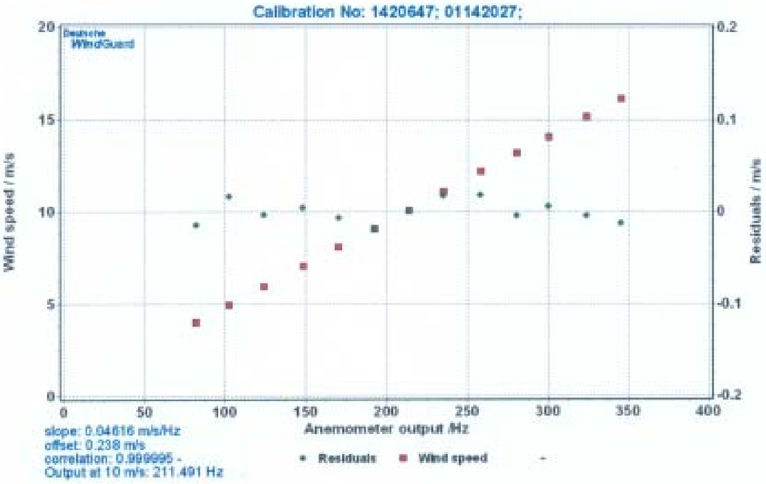
Thies First Class Cup Anemometer at 100.9 m, 137° orientation

Anhang
Annex

1420647

1 Detailed Calibration Results

DKD calibration no.	1420647
Body no.	01142027
Cup no.	
Date	01.02.2014
Air temperature	20.5 °C
Air pressure	994.1 hPa
Humidity	37.3 %
Linear regression analysis	
Slope	0.04616 (m/s)/(Hz) ±0.00004 (m/s)/(Hz)
Offset	0.2383 m/s ±0.010 m/s
St.err(Y)	0.009 m/s
Correlation coefficient	0.999995
Remarks	no



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Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

Deutsche WindGuard

Thies First Class Cup Anemometer at 80 m, 317° orientation

Anhang
Annex

1420649

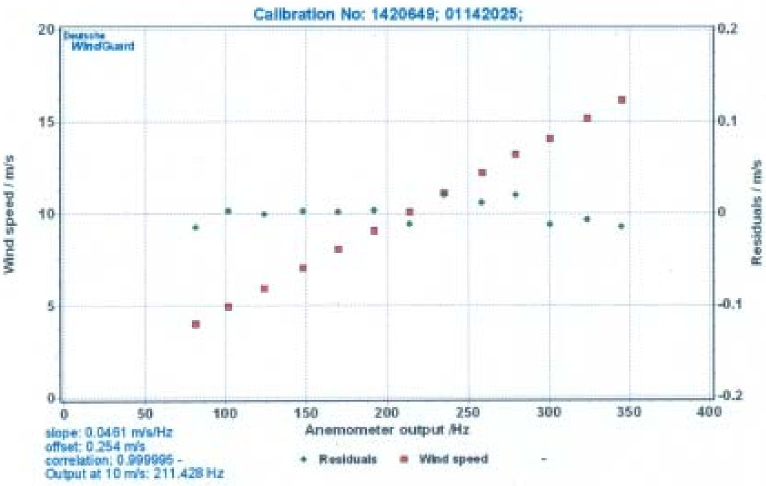
1 Detailed Calibration Results

DKD calibration no.	1420649
Body no.	01142025
Cup no.	
Date	01.02.2014
Air temperature	20.8 °C
Air pressure	994.0 hPa
Humidity	37.2 %

Linear regression analysis

Slope	0.04610 (m/s)/(Hz) ±0.00004 (m/s)/(Hz)
Offset	0.2541 m/s ±0.010 m/s
St.err(Y)	0.008 m/s
Correlation coefficient	0.999995

Remarks no



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Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

Thies First Class Cup Anemometer at 80 m, 137° orientation

Anhang
Annex

1420648

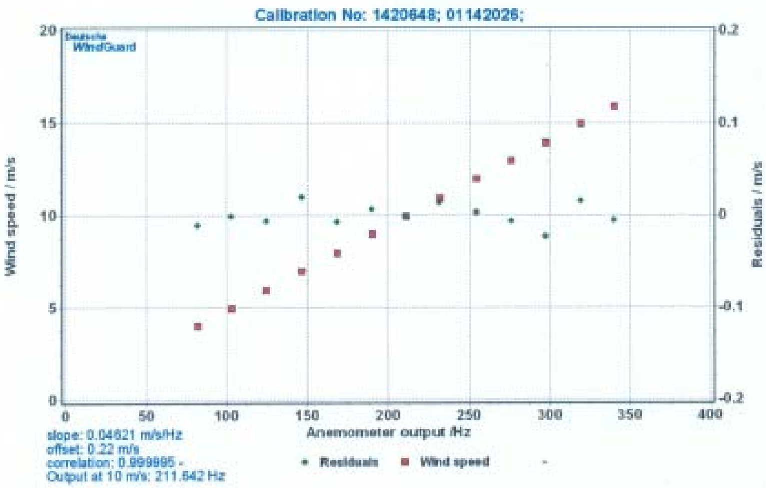
1 Detailed Calibration Results

DKD calibration no.	1420648
Body no.	01142026
Cup no.	
Date	01.02.2014
Air temperature	20.6 °C
Air pressure	993.9 hPa
Humidity	37.2 %

Linear regression analysis

Slope	0.04621 (m/s)/(Hz) ±0.00004 (m/s)/(Hz)
Offset	0.2201 m/s ±0.009 m/s
St.err(Y)	0.010 m/s
Correlation coefficient	0.999995

Remarks no



Deutsche WindGuard Wind Tunnel Services is accredited by MEASNET and by the Deutsche Akkreditierungsdienst – DAkkS (German Accreditation Service). Registration: D-K-15140-01-00

Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

Thies First Class Cup Anemometer at 60 m, 317° orientation

Anhang
Annex

1420651

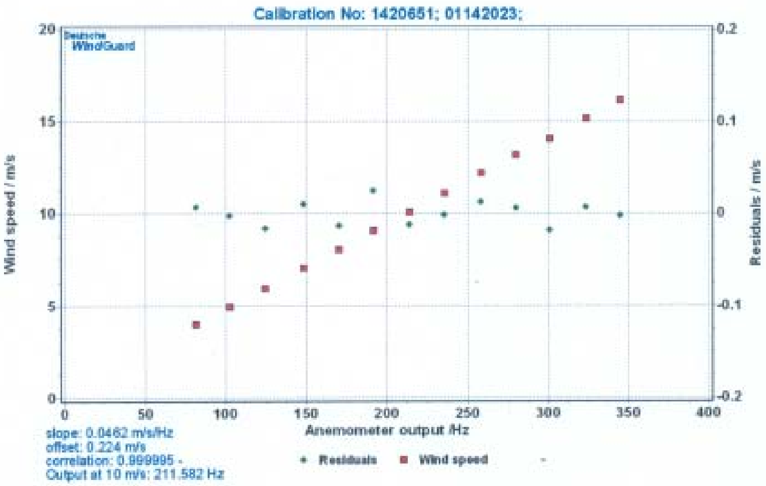
1 Detailed Calibration Results

DKD calibration no.	1420651
Body no.	01142023
Cup no.	
Date	01.02.2014
Air temperature	21.1 °C
Air pressure	994.1 hPa
Humidity	37.0 %

Linear regression analysis

Slope	0.04620 (m/s)/(Hz) ±0.00004 (m/s)/(Hz)
Offset	0.2239 m/s ±0.010 m/s
St.err(Y)	0.011 m/s
Correlation coefficient	0.999995

Remarks no



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Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

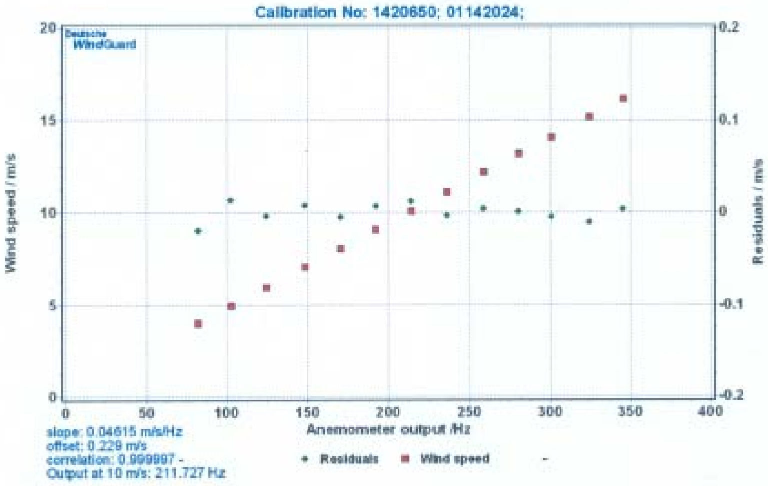
Thies First Class Cup Anemometer at 60 m, 137° orientation

Anhang
Annex

1420650

1 Detailed Calibration Results

DKD calibration no.	1420650
Body no.	01142024
Cup no.	
Date	01.02.2014
Air temperature	21.0 °C
Air pressure	993.9 hPa
Humidity	37.0 %
Linear regression analysis	
Slope	0.04615 (m/s)/(Hz) ±0.00003 (m/s)/(Hz)
Offset	0.2290 m/s ±0.007 m/s
St.err(Y)	0.004 m/s
Correlation coefficient	0.999997
Remarks	no



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Deutsche WindGuard
Wind Tunnel Services GmbH, Varel

APPENDIX 9: SODAR INSTALLATION REPORT

DEPLOYMENT DETAILS

Installation engineer	*Esko Lehtevä*
Installation date	*2014-04-02*
Report date	*2014-04-02*
Position	*LAT 58°36'19.5"N LON 14°6'41.7"E*
Reason if deviation from installation order	*N/A*
Coordinate system	*RT90*
System orientation (degrees)	*102°*

SYSTEM DETAILS

System serial number	*AQ510001*
Client identification number	*AQT1*
Trailer registration number	*N/A*
Sodar phone number	*WEB*
Control unit phone number	*WEB*
Alarm number / e-mail 1	*N/A*
Alarm number / e-mail 2	*N/A*
Alarm number / e-mail 3	*N/A*
Alarm number / e-mail 4	*N/A*
Measurement height	*40-200m*
Sodar software version	*1.00A*
Control unit software version	*N/A*

ON-SITE SYSTEM CHECKS

Temp and humidity sensor installed	OK
Solar panels installed	OK
System leveled	OK
Rise OMNI antenna	OK
Power on system	OK
Generator manual start	N/A
Generator fan start	N/A
Sodar startup	OK
Control unit SIM network register (N/A if WEB)	N/A
Sodar SIM network register	OK
System orientation updated to	*102°*
System name updated to	N/A
System date and time set to	*UTC*
Reasonable temperature readings	OK
Data check initial 30min @ 100W	OK
Spectrum check	OK
Update system output power to 250W	OK
Data check 20min @ 250W	OK

SITE INFORMATION

Type of site	*AQSystem test site*
Terrain type	*Non-complex*
Vehicle requirements	*N/A*

LANDSCAPE OVERVIEW AND INSTALLATION PICTURES

Toward System, Direction N

From System, Direction N
Distance to treeline: 30 m

Toward System, Direction E

From System, Direction E
Distance to treeline: 40 m

Toward System, Direction S

From System, Direction S
Distance to treeline: 10 m

Toward System, Direction W

From System, Direction W
Distance to treeline: 20 m

About DNV GL

Driven by our purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification and technical assurance along with software and independent expert advisory services to the maritime, oil and gas, and energy industries. We also provide certification services to customers across a wide range of industries. Operating in more than 100 countries, our 16,000 professionals are dedicated to helping our customers make the world safer, smarter and greener.