

VERIFICATION REPORT

Verification of the remote sensing device: AQ510 003

at the verification site

Fimmerstad

Västergötland / Sweden

prepared by

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1 INTRODUCTION

BBB Umwelttechnik GmbH was contracted by AQ System Stockholm AB to verify the performance of the Sodar AQ510 003 (RSD) at the site:

Fimmerstad, Västergötland, Sweden.

The comparative verification measurement has been performed during a 15 days campaign, from 05.09.2014 until 20.09.2014, next to a meteorological mast with a height of 103.8 m above ground level (a.g.l.). The reference meteorological mast (Ref) was manufactured by Cue Dee and commissioned by Triventus Consulting and is equipped with all necessary sensors like cup anemometers and wind vanes.

BBB Umwelttechnik erneuerbare Energien GmbH, Albert-Einstein-Straße 5, 92637 Weiden is accredited and has the competence according to DIN EN ISO/IEC 17025:2005 to define,

install, and operate wind measurements as well as to elaborate investigations, reports and certificates in the sector of evaluation of wind resource and energy production of wind turbines according to the following procedures: IEC61400-12-1, FGW TR Part 6 2007-09, BBB-PrV-01_2010-06, BBB-PrV-02_2010-06.



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2 SITE DESCRIPTION

2.1 General

The test site is located between the lakes Viken and the Ymsen in the northeast of the Västergötland province in Sweden. The site for the verification is situated approx. 1.7 km west of Ekeskog, approx. 2.5 km north-east of Bällefors, and approx. 4 km east of Moholm. The test site position and coordinates of the reference meteorological mast (Ref) and the remote sensing device (RSD) are shown in Fig. 1 and Fig. 2 as well as in Tab. 1.



Fig. 1: Location of the test site and position of the reference meteorological mast (blue) and the tested remote sensing device (red) (Origin aerial photo: Google).



	Position (WGS 84, Zone	Elevation	
	Ν	E	in m
Meteorological mast	58.60566°	14.10991°	90 * ¹
Sodar AQ510 003	58.605417°	14.111583°	9 0 *1

 Tab. 1:
 Position and elevation of met mast and remote sensing device.

 $^{\ast 1}$ based on GPS

The test site and its surroundings are characterized by agriculture and forests.

2.2 Description of the test site

The test site is characterized generally by flat terrain with only very small, rather inconspicuous elevations with maximum height variations of less than 3 m within a radius of 300 m and variations of 40 m within a radius of 5 km.

Due to the mainly agricultural use of the area next to the mast, the low forests to the northwest and south-east and the low variation in terrain elevation, one can expect an undisturbed wind flow at least for the upper measurement heights.

The RSD was installed at a distance of approximately 102 m east to the reference mast inside a small trailer.



Fig. 2: Picture of the remote sensing device and the met mast taken from the east [2].



3 INSTRUMENTATION AND DATA AQUISITION

3.1 Reference mast (Ref)

The reference mast was manufactured by Cue Dee and was commissioned by Triventus Consulting in November 2011. It is a guyed lattice tower with a total height of 103.8 m above ground level with high quality MEASNET calibrated cup anemometers and wind vanes. All signals were logged as 10 minute intervals with a Campbell Scientific CR1000 logger.

The description given in this report is based on the information provided by the client as well as on the site visit to the Fimmerstad test site performed by BBB on 17.06.2014.

3.1.1 Description of the met mast

For the acquisition of the wind speed six Thies First Class cup anemometers have been mounted on booms at a distance of 3.7 m to the mast. Further at 3.8 m above the mast structure a Thies Ultrasonic 3D and a Vaisala WAA252 heated cup anemometer were mounted in a side-by-side configuration. The two top anemometers are separated by at least 2.5 m. The wind direction was measured at three heights with Thies First Class wind vanes. The installation of the sensors complies with the requirements of the IEC 61400-12 [3] and [4].

The calibration reports for the sensors were provided by AQ Systems and crosschecked with the programming of the logger. Also a service log book for the met mast was available. Further information about the mast as demanded by [5] can be found in [6] and [7]. Besides the anemometers no further sensors were calibrated. The subsequent tables and figures show the configuration of the sensors at the reference mast.

Sensor	Installation height (a.g.l.)	Boom orientation	Sensor type	Serial no.	Slope m s ⁻¹ Hz ⁻¹	Offset m s ⁻¹
A1	103.8 m	317°	Vaisala WAA252	G15403	0.10295	0.2485
A1b *1	103.8 m	137°	Thies Ultrasonic 3D	05120023	0.99426	0.0063
A2	100.9 m	317°	Thies First Class	01142028	0.04603	0.2649
A2b	100.9 m	137°	Thies First Class	01142027	0.04616	0.2383
A3	80.1 m	317°	Thies First Class	011042025	0.04610	0.2541
A3b	80.1 m	137°	Thies First Class	011042026	0.04621	0.2201
A4	60.1 m	317°	Thies First Class	011042023	0.04620	0.2239
A4b	60.1 m	137°	Thies First Class	011042024	0.04615	0.2290

Tab. 2: Specification of the mounted reference anemometers.

^{*1} not used for the verification



Sensor	Installation height a.g.l.	Sensor type	Serial no.	Sensor orientation	Boom orientation
D1	97.1 m	Thies 43150	08110633	137°	317°
D2	75.1 m	Thies 43150	08110630	137°	317°
D3	55.1 m	Thies 43150	06110600	137°	317°
Temperature 1	99.9 m	Campbell Sc	ientific 107B	-	-

Tab. 3: Specification of the mounted reference wind vanes and the used temperature sensor.





Fig. 3: Mast overview pointing towards NE (photo taken 17.06.2014).



3.2 Remote Sensing Device (RSD)

The Sodar system verified here is the AQ510 003. It was placed in a distance of approximately 102 m east to the reference mast in order to avoid any fixed echo contamination of the signal reception caused by the proximate fixed mast structure (see Fig. 2). The verification measurement lasted for 15 days starting with the 05.09.2014 until 20.09.2014.



Fig. 4: Picture of the trailer containing the RSD next to the reference met mast [2].

3.2.1 Description of the RSD installation

The RSD was configured to measure at 33 different heights in 5 m steps between 40 m and 200 m above ground level. Like the met mast the RSD has been configured to log all measured values at 10-minute intervals. The time synchronisation of this device occurred against a GPS signal every 10 minutes.

Because of the installation of the RSD inside a trailer the real measurement heights above ground are 0.7 m above the configured heights, as shown in the next table.



Configured height in m	Measurement height in m a. g. l.	Configured height in m	Measurement height in m a. g. l.
200	200.7		
195	195.7	60	60.7
190	190.7	55	55.7
185	185.7	50	50.7
180	180.7	45	45.7
		40	40.7

Tab. 4: RSD configuration and resulting measurement heights.

The installation and dismantling procedure of the RSD has been documented by AQ System [2]. No maintenance or other modifications have been done during the verification period. The RSD has been leveled by a digital inclination sensor in order to be horizontal. Pitch and roll were equal or below $\pm 0.5^{\circ}$ at installation and dismantling of the RSD.

Tab. 5: Inclination and direction offset at installation and dismantling of the RSD.

	Date	North	East	Pitch	Roll	Azimuth to
		Geogr,	WGS 84			true north
Installation	05.09.2014	58.605417°	14.111583°	≤ ±0.5°	≤ ±0.5°	38°
Dismantling	20.09.2014	58.605417°	14.111583°	≤ ±0.5°	≤ ±0.5°	38°

Further information about the installation of the RSD can be found in [2].



4 VERIFICATION PROCEDURE

To verify the performance of the RSD the 10 min average wind data of the RSD has been compared to the reference measurement. Both data sets are filtered before evaluation according to several criteria. Based on this data deviations and different regression approaches have been calculated to compare the remote sensing device (RSD) with the reference mast (Ref).

Data analysis

The analysis of the data was performed with Windographer and R [8]. All analyses comply with the recommendations of the IEA guideline [1] about the verification of ground-based remote sensing devices.

At the met mast at all heights, except for the top, two collocated cup anemometers were installed. Therefore to reduce the effect of tower shading the used cup anemometer was depended on the wind direction. For wind directions between 47° and 227° data from the cup anemometers on the south-eastern boom were taken and vice versa. For the top measurement just the Vaisala sensor (A1) was used.



Fig. 5: Wind direction and chosen cup anemometer.

4.1 System availability

The system availability of the remote sensing device is defined as the quotient of available 10-minute data sets to the maximum possible number of 10-minute data sets within the verification campaign. No data filtering regarding the data quality has been performed up to this point.



	Measurement height (in m a. g. l.)				
	Unit	60.7	80.7	100.7	105.7
Max. possible data sets	counts	2175	2175	2175	2175
Data sets excl. NAN (≙ Not a number)	counts	2122	2104	2073	2048
System availability	%	97.6	96.7	95.3	94.2

Tab. 6: Summary of the RSD system availability.

4.2 Data filtering

After a manual/visual data check several steps of data filtering were performed on the measurement data to ensure that representative/valid data is used and to enhance the repeatability of the verification process.

Data Quality

To ensure a good data quality of the RSD measurement an internal RSD data flag for filtering has been used.

• Individual for each height the measurement data has been filtered for data quality values lower than 21. Only values where the quality signal at the corresponding heights are equal or higher than this value have been considered.

The following figures show the effect of the quality value threshold on the relative difference between the wind speed measured by the reference mast and the wind speed measured by the RSD.



Fig. 6: Relative difference of the measured wind speed between Ref and RSD according to the quality value threshold of the RSD. (V1)





Fig. 7: Relative difference of the measured wind speed between Ref and RSD according to the quality value threshold of the RSD. (V2 - V4)



Icing

The reference mast data has been filtered for icing of the anemometers and wind vanes. First a filtering for obvious icing was done by hand, removing obviously invalid data sets from the met mast. Further the data sets gathered at an air temperature of 2° C or less have been omitted.

Wind speed

Corresponding with the calibration range of standard cup anemometers only wind speeds within the interval 3.75 m/s - 16.25 m/s were considered.

Wind direction

Based on aerial photographs the test site has been analysed for obstacles that could affect the wind measurement as defined in [3].

Tab. 7:	Mast effects and obstacles in the surroundings of the test site Fimmerstad and discarded wind
	direction sectors.

					Measureme	nt height (a. g.	l.)
Obstacle/Cause	Start of sector	End of sector	Distance to Ref in m	60.1 m	80.1 m	100.9 m	103.8
Forest	47°	170°	680	disturbed	disturbed	undisturbed	undisturbed
North gap	135°	150°	-	omitted	omitted	omitted	omitted
Forest	212°	360°	750	disturbed	disturbed	undisturbed	undisturbed

The measurements at the height of 60.1 m a. g. l. and 80.1 m a. g. l. are influenced by the forests to the northwest and southeast. Applying this filter on the lower measurement heights would result in following data size.

Tab. 8: Available data sets if the disturbed sectors at 60.1 m and 80.1 m a. g. l. would be removed.

Measurement	Number of data sets				
height (a.g.l.)	Total	Wind speed 4 – 8 m/s	Wind speed 8 – 16 m/s		
60.1 m	109	103	6		
80.1 m	150	144	6		

Removing the affected sectors would reduce the available data at the lower measurement heights below the minimum necessary for verification. Therefore these wind directions sectors were not omitted. An analysis of the data shows that the effect of the forest is small, but still this fact needs to be considered in the calculation of the uncertainties for the verification of the lower measurement heights.

Following figure shows the direction filter used within this verification for all measurement heights.





Fig. 8: Visualisation of the excluded (red) and included (white) wind direction sectors for the verification of the RSD.

4.3 Data availability

Applying all filter steps described above, the amount of valid data sets was reduced according to the table below:

	Unit	105.7 m	100.7 m	80.7 m	60.7 m
Max. possible data sets	counts	2175	2175	2175	2175
Data sets excl. NAN (≙ Not a	counts	2048	2073	2104	2122
number)	%	94.2	95.3	96.7	97.6
Data sets after RSD data-	counts	2031	2055	2099	2121
quality filtering	%	93.4	94.5	96.5	97.5
Data sats after filtering icing	counts	2031	2055	2099	2121
Data sets after lineling icing	%	93.4	94.5	96.5	97.5
Data sets after direction	counts	2026	2050	2092	2116
filtering	%	93.1	94.3	96.2	97.3
Data sets after wind speed	counts	1465	1456	1400	1156
filtering	%	67.4	66.9	64.4	53.1

Tab. 9: Number of data samples remaining after applying all filter steps for the measurement data from the RSD.

The data sets which are omitted for NAN (not a number) in the first step include data sets that were excluded because of obvious icing at the met mast.

Regarding the data availability, following requirements for the acceptance of the verification need to be fulfilled:

- For each verification height at least 600 valid data sets have to be obtained.
- For each verification height for the wind speed range 4 8 m/s at least 150 valid data sets have to be obtained



• For each verification height for the wind speed range 8 – 16 m/s at least 150 valid data sets have to be obtained

Following table shows the results of the data availability analysis:

Tab. 10: Acceptance criteria for the total amount of valid points of RSD datasets.

		Measurement height (a.g.l.)				
Acceptance criteria	Requirement	105.7	100.7	80.7	60.7	
		m	m	m	m	
Valid data sets per height	600	1465	1456	1400	1156	
Valid data sets at U_{RSD} with $U_{Ref} \ge 4$ m/s and <8 m/s	150	1408	1406	1374	1145	
Valid data sets at U_{RSD} with $U_{\text{ref}} \geq\!\! 8$ m/s and <16 m/s	150	57	50	26	11	

The duration of the 15 days measurement campaign supported by the very good system and data availability of the AQ510 produced enough data to have more than 600 data sets for each height. Also the second data criterion with at least 150 data sets within the 4 m/s to 8 m/s interval could be successfully completed. Unfortunately the measurement period was characterized with low wind speeds. Therefore the third data criterion needing 150 data sets within the 8 m/s to 16 m/s interval could not be successfully completed.

4.4 Data acquisition time synchronisation

The RSD is synchronized against a GPS signal every 10 minutes while the data logger of the met mast is synchronized on a daily basis.

The two data sets showed a good correlation and no time shift could be detected (see figure below).







Therefore we can assume a time synchronic operation of both systems.

The following figure demonstrates the synchronic operation of both measurement systems.





4.5 Exceptions and deviations from the applied standards

Following exceptions from the applied standards must be mentioned within this report:

- As demanded by [1] the measurement should continue until all bins between 4 m/s and 16 m/s contain at least one hour of data. Because of the low wind situation during the measurement period the number of wind speed measurements with more than 9 m/s did not comply with this requirement.
- For the same reason also the data criterion with at least 150 data sets within the 8 m/s to 16 m/s interval could not be successfully completed.
- At the measurement heights 60.1 m and 80.1 m the direction sectors which might be affected by forests to the northwest and southeast were not excluded from the verification.

BBB categorizes this deviation as minor deviation not further relevant for the verification process.



5 RESULTS

In this chapter the results of this verification campaign are presented. After a description of the wind characteristics during the measurement period the results of the comparison between remote sensing device (RSD) and reference mast (Ref) are given. Further, the performance of the RSD is verified against several acceptance criteria to confirm the valid operation of the RSD for wind resource assessments.

The verification was done for the four cup anemometer heights. Following table defines the congruent measurement heights and sensors compared within this verification procedure:

Verified	Reference mas	t (Ref) sensors	Remote Sensing device (RSD)			
Height	Wind speed	Wind direction	Measurement height			
V1	A1 (103.8 m)	D1 (97.1 m)	105.7 m			
V2	A2 & A2b (100.9 m)	D1 (97.1 m)	100.7 m			
V3	A3 & A3b (80.1 m)	D2 (75.1 m)	75.7 m			
V4	A4 & A4b (60.1 m)	D3 (55.1 m)	55.7 m			

Tab. 11: Congruent measurement heights and sensors.



5.1 Wind speed distribution

The following figures show the distribution of the filtered reference wind speed data for all compared heights.



Fig. 11: Frequency of wind speed bins in m/s and the cumulative distribution function (green line) for the reference data. (V1, V2)





Fig. 12: Frequency of wind speed bins in m/s and the cumulative distribution function (green line) for the reference data. (V3, V4)





Fig. 13: Diurnal distribution of 10-minute data sets of the reference mast. (V1, V2)





Fig. 14: Diurnal distribution of 10-minute data sets of the reference mast. (V3, V4)





Fig. 15: Diurnal cycle of the wind speed distribution of the reference mast. Boxes extend from the 25th to 75th percentile for each bin. Whiskers extend to the 5th and 95th percentile for each bin. (V1, V2)





Fig. 16: Diurnal cycle of the wind speed distribution of the reference mast. Boxes extend from the 25th to 75th percentile for each bin. Whiskers extend to the 5th and 95th percentile for each bin. (V3, V4)



5.2 Wind direction at RSD and reference mast

The following figures show the distribution of the filtered reference wind direction data for the compared heights.



Fig. 17: Wind direction of the RSD (ordinate) versus wind direction at the wind vanes of the reference mast (abscissa). (V1, V2)





Fig. 18: Wind direction of the RSD (ordinate) versus wind direction at the wind vanes of the reference mast (abscissa). (V3, V4)



5.3 Ten minute mean wind speed of the data

5.3.1 Ten minute mean wind speed of the data at 103.8 m

The results of the analysis comparing the reference data at anemometer V1 and the RSD data of the 105.7 m height measurement are shown in the following figures.



Fig. 19: Wind speed of the RSD (ordinate) versus wind speed reference mast (abscissa). (upper) Red data points represent unfiltered data and green points the filtered data. (Lower) Ordinary least square (OLS) fit based on the bin means. Blue shows the OLS fit not forced and red a forced OLS fit through origin.





Fig. 20: Turbulence intensity of the RSD (ordinate) versus turbulence intensity reference mast (abscissa). (Upper) Red data points represent unfiltered data and green points the filtered data. (Lower) Ordinary least square (OLS) fit based on the bin means. Blue shows the OLS fit not forced and red a forced OLS fit through origin.





Fig. 21: Difference of wind speed between RSD and reference data versus reference data in m/s: (Upper) absolute difference in m/s; (Lower) relative difference. Boxes extend from the 25th to 75th percentile for each bin. Whiskers extend to the 5th and 95th percentile for each bin. Outliers are represented by small black points.





Fig. 22: Difference of turbulence intensity between RSD and reference data versus reference turbulence intensity in %: (Upper) absolute difference; (Lower) relative difference. Boxes extend from the 25th to 75th percentile for each bin. Whiskers extend to the 5th and 95th percentile for each bin. Outliers are represented by small black points.




Fig. 23: Difference of turbulence intensity between RSD and reference data versus reference data in m/s: (Upper) absolute difference; (Lower) relative difference. Boxes extend from the 25th to 75th percentile for each bin. Whiskers extend to the 5th and 95th percentile for each bin. Outliers are represented by small black points.



5.3.2 Ten minute mean wind speed of the data at 100.9m

The results of the analysis comparing the reference data at anemometer V2 and the RSD data of the 100.7 m height measurement are shown in the following figures.



Fig. 24: Wind speed of the RSD (ordinate) versus wind speed reference mast (abscissa). (Upper) Red data points represent unfiltered data and green points the filtered data. (Lower) Ordinary least square (OLS) fit based on the bin means. Blue shows the OLS fit not forced and red a forced OLS fit through origin.





Fig. 25: Turbulence intensity of the RSD (ordinate) versus turbulence intensity reference mast (abscissa). (Upper) Red data points represent unfiltered data and green points the filtered data. (Lower) Ordinary least square (OLS) fit based on the bin means. Blue shows the OLS fit not forced and red a forced OLS fit through origin.





Fig. 26: Difference of wind speed between RSD and reference data versus reference data in m/s: (Upper) absolute difference in m/s; (Lower) relative difference. Boxes extend from the 25th to 75th percentile for each bin. Whiskers extend to the 5th and 95th percentile for each bin. Outliers are represented by small black points.





Fig. 27: Difference of turbulence intensity between RSD and reference data versus reference turbulence intensity in %: (Upper) absolute difference; (Lower) relative difference. Boxes extend from the 25th to 75th percentile for each bin. Whiskers extend to the 5th and 95th percentile for each bin. Outliers are represented by small black points.





Fig. 28: Difference of turbulence intensity between RSD and reference data versus reference data in m/s: (Upper) absolute difference; (Lower) relative difference. Boxes extend from the 25th to 75th percentile for each bin. Whiskers extend to the 5th and 95th percentile for each bin. Outliers are represented by small black points.



5.3.3 Ten minute mean wind speed of the data at 80.1 m

The results of the analysis comparing the reference data at anemometer V3 and the RSD data of the 80.7 m height measurement are shown in the following figures.



Fig. 29: Wind speed of the RSD (ordinate) versus wind speed reference mast (abscissa). (Upper) Red data points represent unfiltered data and green points the filtered data. (Lower) Ordinary least square (OLS) fit based on the bin means. Blue shows the OLS fit not forced and red a forced OLS fit through origin.





Fig. 30: Turbulence intensity of the RSD (ordinate) versus turbulence intensity reference mast (abscissa). (Upper) Red data points represent unfiltered data and green points the filtered data. (Lower) Ordinary least square (OLS) fit based on the bin means. Blue shows the OLS fit not forced and red a forced OLS fit through origin.





Fig. 31: Difference of wind speed between RSD and reference data versus reference data in m/s: (Upper) absolute difference in m/s; (Lower) relative difference. Boxes extend from the 25th to 75th percentile for each bin. Whiskers extend to the 5th and 95th percentile for each bin. Outliers are represented by small black points.





Fig. 32: Difference of turbulence intensity between RSD and reference data versus reference turbulence intensity in %: (Upper) absolute difference; (Lower) relative difference. Boxes extend from the 25th to 75th percentile for each bin. Whiskers extend to the 5th and 95th percentile for each bin. Outliers are represented by small black points.





Fig. 33: Difference of turbulence intensity between RSD and reference data versus reference data in m/s: (Upper) absolute difference; (Lower) relative difference. Boxes extend from the 25th to 75th percentile for each bin. Whiskers extend to the 5th and 95th percentile for each bin. Outliers are represented by small black points.



5.3.4 Ten minute mean wind speed of the data at 60.1 m

The results of the analysis comparing the reference data at anemometer V4 and the RSD data of the 60.7 m height measurement are shown in the following figures.



Fig. 34: Wind speed of the RSD (ordinate) versus wind speed reference mast (abscissa). (Upper) Red data points represent unfiltered data and green points the filtered data. (Lower) Ordinary least square (OLS) fit based on the bin means. Blue shows the OLS fit not forced and red a forced OLS fit through origin.





Fig. 35: Turbulence intensity of the RSD (ordinate) versus turbulence intensity reference mast (abscissa). (Upper) Red data points represent unfiltered data and green points the filtered data. (Lower) Ordinary least square (OLS) fit based on the bin means. Blue shows the OLS fit not forced and red a forced OLS fit through origin.





Fig. 36: Difference of wind speed between RSD and reference data versus reference data in m/s: (Upper) absolute difference in m/s; (Lower) relative difference. Boxes extend from the 25th to 75th percentile for each bin. Whiskers extend to the 5th and 95th percentile for each bin. Outliers are represented by small black points.





Fig. 37: Difference of turbulence intensity between RSD and reference data versus reference turbulence intensity in %: (Upper) absolute difference; (Lower) relative difference. Boxes extend from the 25th to 75th percentile for each bin. Whiskers extend to the 5th and 95th percentile for each bin. Outliers are represented by small black points.





Fig. 38: Difference of turbulence intensity between RSD and reference data versus reference data in m/s: (Upper) absolute difference; (Lower) relative difference. Boxes extend from the 25th to 75th percentile for each bin. Whiskers extend to the 5th and 95th percentile for each bin. Outliers are represented by small black points.



5.4 Wind direction distribution



5.4.1 Distribution of ten minute mean wind at V1 (wind vane D1 at 97.1 m)

Fig. 39: Difference of wind speed between RSD and reference data versus reference direction in degrees: (Upper) absolute difference; (Lower) relative difference. Boxes extend from the 25th to 75th percentile for each bin. Whiskers extend to the 5th and 95th percentile for each bin. Outliers are represented by small black points. Measurements at 103.8 m (V1) at the reference mast, 105.7 m at the RSD and the wind vane at 97.1 m (D1) height.





Fig. 40: Difference of turbulence intensity between RSD and reference data versus reference direction in degrees: (Upper) absolute difference; (Lower) relative difference. Boxes extend from the 25th to 75th percentile for each bin. Whiskers extend to the 5th and 95th percentile for each bin. Outliers are represented by small black points. Measurements at 103.8 m (V1) at the reference mast, 105.7 m at the RSD and the wind vane at 97.1 m (D1) height.



5.4.2 Distribution of ten minute mean wind at 100 m (wind vane D1 at 97.1 m)



Fig. 41: Difference of wind speed between RSD and reference data versus reference direction in degrees at: (Upper) absolute difference; (Lower) relative difference. Boxes extend from the 25th to 75th percentile for each bin. Whiskers extend to the 5th and 95th percentile for each bin. Outliers are represented by small black points. Measurements at 100.9 m (V2) at the reference mast, 100.7 m at the RSD and the wind vane at 97.1 m (D1) height.





Fig. 42: Difference of turbulence intensity between RSD and reference data versus reference direction in degrees at: (Upper) absolute difference; (Lower) relative difference. Boxes extend from the 25th to 75th percentile for each bin. Whiskers extend to the 5th and 95th percentile for each bin. Outliers are represented by small black points. Measurements at 100.9 m (V2) at the reference mast, 100.7 m at the RSD and the wind vane at 97.1 m (D1) height.



5.4.3 Distribution of ten minute mean wind at V3 (wind vane D2 at 75.1 m)



Fig. 43: Difference of wind speed between RSD and reference data versus reference direction in degrees at: (Upper) absolute difference; (Lower) relative difference. Boxes extend from the 25th to 75th percentile for each bin. Whiskers extend to the 5th and 95th percentile for each bin. Outliers are represented by small black points. Measurements at 80.1 m (V3) at the reference mast, 80.7 m at the RSD and the wind vane at 75.1 m (D2) height.





Fig. 44: Difference of turbulence intensity between RSD and reference data versus reference direction in degrees: (Upper) absolute difference; (Lower) relative difference. Boxes extend from the 25th to 75th percentile for each bin. Whiskers extend to the 5th and 95th percentile for each bin. Outliers are represented by small black points. Measurements at 80.1 m (V3) at the reference mast, 80.7 m at the RSD and the wind vane at 75.1 m (D2) height.



5.4.4 Distribution of ten minute mean wind at V4 (wind vane D3 at 55.1 m)



Fig. 45: Difference of wind speed between RSD and reference data versus reference direction in degrees at: (Upper) absolute difference; (Lower) relative difference. Boxes extend from the 25th to 75th percentile for each bin. Whiskers extend to the 5th and 95th percentile for each bin. Outliers are represented by small black points. Measurements at 60.1 m (V4) at the reference mast, 60.7 m at the RSD and the wind vane at 55.1 m (D3) height.





Fig. 46: Difference of turbulence intensity between RSD and reference data versus reference direction in degrees: (Upper) absolute difference; (Lower) relative difference. Boxes extend from the 25th to 75th percentile for each bin. Whiskers extend to the 5th and 95th percentile for each bin. Outliers are represented by small black points. Measurements at 60.1 m (V4) at the reference mast, 60.7 m at the RSD and the wind vane at 55.1 m (D3) height.



5.5 Acceptance criteria of the data

Within the verification process the remote sensing device needs to fulfil several acceptance criteria to proof its valid operation. The acceptance criteria are mainly based on the demands of [1] and [9] and on own investigations.

- Availability: For each height the RSD should acquire at least 80 % of the maximum possible number of valid 10-min measurement data sets (unfiltered) within the verification campaign.
- Valid data amount: 600 valid measurement data sets at each height after applying all relevant data filters to RSD and reference met mast (Ref).
- Completeness: 150 valid measurement data sets at each height for two wind speed bins (4 m/s – 8 m/s, 8 m/s – 16 m/s) after applying all relevant data filters to RSD and Ref.
- Wind speed deviation: At all heights the comparison of the 10-min data sets between RSD and Ref should not show higher values than 0.2 m/s for the 'absolute mean deviation'.
- Linear regression: For each height a linear regression based on the mean wind speed bins of RSD and Ref and forced through origin needs to have a slope within the range of 0.985 and 1.015.
- Correlation: For each height and based on the mean wind speed bins of RSD and Ref the coefficient of determination needs to have values of R² >0.996.

5.5.1 Verification results of the data regarding the acceptance criteria

Based on the results obtained within this verification campaign and presented in this chapter the verified RSD defined in this report shows following performance regarding the acceptance criteria defined above:

Acceptance criteria	Requirement	Value	Passed / Failed
Availability	> 80 %	99.7%	Passed
Valid data sets	600	1465	Passed
Valid data sets at U_{RSD} with $U_{Ref} \ge 4$ m/s and <8 m/s	150	1408	Passed
Valid data sets at U_{RSD} with $U_{Ref} \ge 8$ m/s and <16 m/s	150	57	Failed
Absolute mean deviation between RSD and Ref	< 0.2 m/s	0.013 m/s	Passed
Slope (m) of the linear regression between RSD and Ref	0.985≤m≤1.015	1.0038	Passed
Coefficient of determination between RSD and Ref	R ² > 0.996	1	Passed

Tab. 12: Summary of the acceptance criteria for the verification of the RSD for 105.7 m (V1):



Acceptance criteria	Requirement	Value	Passed / Failed
Availability	> 80 %	99.6 %	Passed
Valid data sets	600	1456	Passed
Valid data sets at U_{RSD} with $U_{Ref} \ge 4$ m/s and <8 m/s	150	1406	Passed
Valid data sets at U_{RSD} with $U_{Ref} \ge 8$ m/s and <16 m/s	150	50	Failed
Absolute mean deviation between RSD and Ref	< 0.2 m/s	0.007 m/s	Passed
Slope (m) of the linear regression between RSD and Ref	0.985≤m≤1.015	1.0012	Passed
Coefficient of determination between RSD and Ref	R ² > 0.996	1	Passed

Tab. 13: Summary of the acceptance criteria for the verification of the RSD for 100.7 m (V2):

Tab. 14: Summary of the acceptance criteria for the verification of the RSD for 80.7 m (V3):

Acceptance criteria	Requirement	Value	Passed / Failed
Availability	> 80 %	100 %	Passed
Valid data sets	600	1400	Passed
Valid data sets at U_{RSD} with $U_{Ref} \ge 4$ m/s and <8 m/s	150	1374	Passed
Valid data sets at U_{RSD} with $U_{Ref} \ge 8$ m/s and <16 m/s	150	26	Failed
Absolute mean deviation between RSD and Ref	< 0.2 m/s	< 0.024 m/s	Passed
Slope (m) of the linear regression between RSD and Ref	0.985≤m≤1.015	1.0057	Passed
Coefficient of determination between RSD and Ref	R ² > 0.996	1	Passed

Tab. 15: Summary of the acceptance criteria for the verification of the RSD for 60.7 m (V4):

Acceptance criteria	Requirement	Value	Passed / Failed
Availability	> 80 %	100 %	Passed
Valid data sets	600	1156	Passed
Valid data sets at U_{RSD} with $U_{Ref} \ge 4$ m/s and <8 m/s	150	1145	Passed
Valid data sets at U_{RSD} with $U_{Ref} \ge 8$ m/s and <16 m/s	150	11	Failed
Absolute mean deviation between RSD and Ref	< 0.2 m/s	< 0.041 m/s	Passed
Slope (m) of the linear regression between RSD and Ref	0.985≤m≤1.015	0.9938	Passed
Coefficient of determination between RSD and Ref	R ² > 0.996	1	Passed

The results for the verified heights at 105.7 m, 100.7 m 80.7 m and 60.7 m are in good compliance with the criteria for the coefficient of determination.

A numerical value of 1 for the coefficient of correlation is the result of rounding to the fourth decimal digit.



6 UNCERTAINTIES

The uncertainty of the wind speed measurements of the RSD is defined for each wind speed bin and for each height individually. It is assumed that all sources of uncertainty are uncorrelated/independent from each other. Therefore the total uncertainty of the measurement is calculated as the square root of the sum of the square of the single uncertainties that are relevant in the measurement/verification process:

$$Total = \sqrt[2]{Ref^{2} + \overline{\left(U_{RSD} - U_{Ref}\right)^{2}} + \left(\frac{\sigma(U_{RSD})}{\sqrt{n}}\right)^{2} + Mount^{2} + Site^{2}}$$

where

Total = Total RSD uncertainty in % (k=1), *Ref* = Reference sensor uncertainty in %,

 $\overline{(U_{RSD} - U_{Ref})}$ = Mean deviation in %,

 $\frac{\sigma(U_{RSD})}{\sqrt{n}}$ = Precision of the RSD in %,

Mount = Uncertainty caused by the RSD mounting in %,

Site = Uncertainty caused by site effects in %.

The RSD mounting effects (*Mount*) are small as the inclination of the RSD was small.

The RSD is placed approximately 102 m beside the mast. This distance is close enough to allow a good correlation between mast and RSD. Considering also the flat terrain without any significant variation in terrain height within the relevant distance a low uncertainty for the site effects of 0.5 % for the upper heights has been chosen. For the lower measurement heights (81 m, 61 m) an influence of the nearby forests could be seen. As the sectors could not be excluded an uncertainty of 1 % resp. 1.5 % has been used for this heights.

The uncertainty contributions of the reference sensor are all stated with a coverage factor of one (k=1). According to ISO 17025 the total uncertainty of the RSD wind speed measurement is based on a coverage factor k=2 in order to reach a coverage of 95 %.



6.1 Uncertainties of the speed bins

Tab. 16:	Results of the binned data comparison and uncertainty calculation with the total uncertainty
	(k=1, "Total") and the total uncertainty with a coverage factor of 2 (k=2, "Total*2") at 105.7 m.

	Binr	ned med	asurements				Binu	uncertaint	ies		
$\overline{U_{ref}}$	$\overline{U_{RSD}}$	n	U_{RSD} range	$\sigma(U_{RSD})$	$\sigma(U_{RSD})$	$\overline{U_{RSD} - U_{ref}}$	Ref	Mount	Site	Total	Total * 2
m s⁻¹	m s-1	-	m s ⁻¹	m s-1	\sqrt{n} $\%_{ m R}$	%r	%r	%r	%r	%r	%R
4.027	4.091	187	3.76 - 5.36	0.217	0.394	1.586	4.251	0.5	0.5	4.581	9.163
4.491	4.472	246	3.82 - 5.08	0.252	0.357	-0.436	3.818	0.5	0.5	3.891	7.783
4.987	4.945	233	3.77 - 5.43	0.282	0.37	-0.841	3.446	0.5	0.5	3.601	7.201
5.508	5.505	189	3.83 - 6.34	0.319	0.421	-0.051	3.127	0.5	0.5	3.195	6.389
5.979	6.014	173	5.08 - 6.78	0.249	0.316	0.58	2.887	0.5	0.5	3.004	6.007
6.467	6.459	153	4.21 - 7.14	0.373	0.467	-0.116	2.676	0.5	0.5	2.764	5.529
6.988	7.051	121	5.97 - 7.8	0.309	0.402	0.906	2.484	0.5	0.5	2.721	5.441
7.492	7.587	81	6.91 - 8.18	0.243	0.361	1.264	2.324	0.5	0.5	2.716	5.432
7.96	8.011	39	7.27 - 8.89	0.291	0.585	0.642	2.193	0.5	0.5	2.412	4.823
8.505	8.569	18	8.27 - 8.89	0.199	0.552	0.758	2.06	0.5	0.5	2.318	4.637
9.003	8.985	18	8.3 - 9.59	0.339	0.886	-0.204	1.953	0.5	0.5	2.212	4.424
9.492	9.488	5	9.29 - 9.75	0.195	0.92	-0.042	1.859	0.5	0.5	-	-
9.785	9.76	2	9.73 - 9.79	0.042	0.307	-0.255	1.808	0.5	0.5	-	-

Tab. 17:Results of the binned data comparison and uncertainty calculation with the total uncertainty
(k=1, "Total") and the total uncertainty with a coverage factor of 2 (k=2, "Total*2") at 100.7 m.

	Binn	ed mea	surements				Bin u	ncertaint	ies		
$\overline{U_{ref}}$	$\overline{U_{RSD}}$	n	U_{RSD} range	$\sigma(U_{RSD})$	$\sigma(U_{RSD})$	$\overline{U_{RSD} - U_{ref}}$	Ref	Mount	Site	Total	Total * 2
m s ⁻¹	m s⁻¹	-	m s ⁻¹	m s-1	\sqrt{n} %	%r	%r	%r	%r	%r	%R
4.032	4.085	197	3.76 - 5.16	0.216	0.381	1.303	2.53	0.5	0.5	2.914	5.829
4.491	4.488	264	3.83 - 5.2	0.241	0.331	-0.063	2.282	0.5	0.5	2.36	4.721
4.997	4.965	226	4.17 - 5.7	0.253	0.337	-0.622	2.063	0.5	0.5	2.237	4.475
5.521	5.507	193	3.88 - 6.16	0.278	0.363	-0.258	1.879	0.5	0.5	1.995	3.989
5.994	6.02	173	5.27 - 6.72	0.258	0.327	0.425	1.742	0.5	0.5	1.889	3.779
6.477	6.461	141	5.51 - 7.43	0.295	0.384	-0.25	1.623	0.5	0.5	1.759	3.518
6.983	7.027	119	5.99 - 7.75	0.277	0.364	0.626	1.517	0.5	0.5	1.754	3.507
7.478	7.523	68	7.19 - 8.13	0.213	0.346	0.596	1.428	0.5	0.5	1.662	3.324
7.94	7.965	34	7.25 - 8.95	0.318	0.687	0.32	1.355	0.5	0.5	1.631	3.262
8.464	8.511	20	8.06 - 8.79	0.193	0.511	0.561	1.283	0.5	0.5	1.572	3.144
8.999	8.948	17	8.25 - 9.51	0.315	0.849	-0.562	1.219	0.5	0.5	1.665	3.33
9.5	9.423	3	9.32 - 9.54	0.111	0.672	-0.807	1.165	0.5	0.5	-	-
9.77	9.68	1	9.68 - 9.68	-	-	-0.921	1.139	0.5	0.5	-	-



	Binn	ed mea	surements				Bin ur	ncertaint	ies		
$\overline{U_{ref}}$	$\overline{U_{RSD}}$	n	U_{RSD} range	$\sigma(U_{RSD})$	$\sigma(U_{RSD})$	$\overline{U_{RSD} - U_{ref}}$	Ref	Mount	Site	Total	Total * 2
m s-1	m s-1	-	m s-1	m s-1	\sqrt{n} $\%_{ m R}$	$%_{R}$	% _R	% _R	% _R	\mathcal{R}_{R}	$\%_{R}$
4.023	4.062	271	3.76 - 4.63	0.185	0.279	0.979	2.535	0.5	1	2.909	5.819
4.497	4.497	308	3.95 - 5.06	0.221	0.28	-0.009	2.279	0.5	1	2.505	5.009
5	5.031	241	4.41 - 5.75	0.249	0.321	0.613	2.062	0.5	1	2.393	4.787
5.496	5.535	180	4.83 - 6.2	0.242	0.328	0.703	1.887	0.5	1	2.272	4.544
5.972	5.975	153	5.27 - 6.64	0.25	0.339	0.046	1.747	0.5	1	2.042	4.084
6.466	6.499	118	5.8 - 7.17	0.287	0.409	0.515	1.625	0.5	1	2.018	4.037
6.935	6.965	61	5.64 - 7.68	0.302	0.557	0.429	1.526	0.5	1	1.955	3.911
7.485	7.548	27	7.11 - 8.07	0.223	0.574	0.834	1.426	0.5	1	2.015	4.03
8.007	8.079	30	7.18 - 8.89	0.308	0.702	0.893	1.345	0.5	1	2.025	4.05
8.494	8.474	5	8.21 - 8.85	0.237	1.246	-0.235	1.279	0.5	1	-	-
8.892	8.694	5	8.34 - 9.3	0.413	2.078	-2.227	1.231	0.5	1	-	-
9.62	9.44	1	9.44 - 9.44	-	-	-1.871	1.154	0.5	1	-	-

Tab. 18: Results of the binned data comparison and uncertainty calculation with the total uncertainty (k=1, "Total") and the total uncertainty with a coverage factor of 2 (k=2, "Total*2") at 80.7 m.

Tab. 19:Results of the binned data comparison and uncertainty calculation with the total uncertainty
(k=1, "Total") and the total uncertainty with a coverage factor of 2 (k=2, "Total*2") at 60.7 m.

	Binn	ed mea	surements				Bin ur	ncertaint	ies		
$\overline{U_{ref}}$	$\overline{U_{RSD}}$	n	U_{RSD} range	$\sigma(U_{RSD})$	$\sigma(U_{RSD})$	$\overline{U_{RSD} - U_{ref}}$	Ref	Mount	Site	Total	Total * 2
m s⁻¹	m s-1	-	m s ⁻¹	m s-1	\sqrt{n} $\%_{ m R}$	%r	%r	%r	%r	%r	%R
4.028	4.013	287	3.76 - 4.61	0.18	0.264	-0.375	2.533	0.5	1.5	2.979	5.958
4.484	4.437	315	3.87 - 5.58	0.25	0.314	-1.052	2.285	0.5	1.5	2.946	5.892
5.004	4.957	181	4.3 - 5.88	0.262	0.389	-0.946	2.06	0.5	1.5	2.746	5.492
5.476	5.42	154	4.77 - 5.99	0.243	0.357	-1.024	1.893	0.5	1.5	2.648	5.295
5.97	5.91	97	5.22 - 6.54	0.275	0.468	-1.013	1.748	0.5	1.5	2.559	5.119
6.464	6.425	54	5.75 - 7.12	0.264	0.557	-0.61	1.626	0.5	1.5	2.361	4.722
6.964	6.921	31	5.72 - 7.27	0.286	0.737	-0.614	1.521	0.5	1.5	2.341	4.683
7.501	7.552	16	7.06 - 8.65	0.389	1.297	0.679	1.424	0.5	1.5	2.534	5.068
7.951	7.862	13	7.17 - 8.81	0.363	1.267	-1.128	1.353	0.5	1.5	2.638	5.276
8.527	8.47	4	8.24 - 9.03	0.377	2.212	-0.674	1.275	0.5	1.5	-	-
8.88	8.463	3	8.17 - 9.02	0.482	3.136	-4.692	1.232	0.5	1.5	-	-
9.37	9.25	1	9.25 - 9.25	-	-	-1.281	1.179	0.5	1.5	-	-



7 SUMMARY AND CONCLUSIONS

Congruent wind measurements with a remote sensing device anemometer (RSD) and cup anemometers have been carried out at a site close to Fimmerstad, Sweden. The aim of this measurement is to verify the RSD measurement against a well-known high quality standard (First Class cup anemometers with MEASNET calibration).

From the met mast (Ref) four measurement heights at 103.8 m, 100.9 m, 80.1 m and 60.1 m were available for wind speed comparisons. The verification measurement started on 05.09.2014 and ended on 20.09.2014 (approx. 15 days). The duration of the test period was long enough to successfully pass 3 of 4 data criteria. Because of a low wind speed situation during the measurement campaign not enough data sets could be sampled within the data interval for higher wind speeds. Nevertheless the results of the data gathered are considered as sufficient for the purpose of characterizing the performance of the AQ510 SoDAR (Serial no.: 003).

Between the heights of 40.7 m and 200.7 m above ground level (a. g. l.) 33 measurement heights have been configured at the RSD. The total system availability was between 97.6 % (60.7 m a. g. l.) and 94.2 % (105.7 m a. g. l.).

The measurements at 60.7 m a. g. l. and at 80.7 m a. g. l. are affected by forests in the northwest and southeast. Because omitting these sectors would have reduced the number of available data sets below a minimum quantity these sectors were not excluded but considered with a higher site effect uncertainty.

A data filtering has been applied to filter unrepresentative data sets resulting in data availabilities between 67.4 % (105.7 m a. g. l) and 53.1 % (60.7 m a. g. l.).

Several wind speed, wind direction and turbulence comparisons were carried out for each congruent measurement height. The wind speeds at all considered heights correlated very well, showing a good compliance to the cup wind speeds in terms of linear regression slopes and coefficient of determination values.

In summary, this verification campaign shows that the SODAR AQ510 003 is able to reproduce cup anemometer wind speeds at a highly accurate level at all speed bin means.

Based on the verification process described in this document the AQ510 003 has successfully passed the BBB Umwelttechnik GmbH (BBB) acceptance tests at all considered heights. Therefore this remote sensing device can be considered as verified for the use in wind and energy yield assessments in this and similar terrain types. Nevertheless the application in complex terrain needs to be designed and performed carefully considering guidelines (e. g. [10]) and the manufacturer manual defining the best practice for this application.

Care needs to be taken with respect to the use of RSD turbulence and extreme wind speed measurements, not treated in detail within this verification procedure but shown in recent studies to be different from classical cup anemometry measurements.



8 REFERENCES

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- [5] MEASNET, "Cup Anemometer Calibration Procedure," 09/1997.
- [6] AQSystem Stockholm AB, "Description of the Fimmerstadt met mast and surroundings," 19/03/2014.
- [7] GL Garrad Hassan Deutschland GmbH, "Technical Conformance of AQS Met Mast and Test Site in Fimmerstadt, Sweden," 17/05/2013.
- [8] R Core Team, A Language and Environment for Statistical Computing, Vienna: R Foundation for Statistical Computing, 2014.
- [9] D. Kindler, "Best Practice Test and Verification Procedure for Wind LiDARs on the Hovsore Test Site. GLGH-D Report WT 6960/09 for EU-Project NORSEWIND," 2009.
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Appendix A: LIST OF ABBREVIATIONS

Abbreviation	Description
Acronym	Description
a. g. l.	Above ground level
BBB	BBB Umwelttechnik erneuerbare Energien GmbH
DIN	German Institute for Standardization, Deutsches Institut für Normung
DNV	Det Norske Veritas
EN	European Standard
IEC	International Electrotechnical Commission
IEA	International Energy Agency
k	Coverage factor
Met mast	Meteorological mast
n	Sample size
NAN	Not a number
OLS	Ordinary least square
Ref	Reference, here meteorological mast
RSD	Remote sensing device
U _{Ref}	Horizontal wind speed measured with the reference (in m/s)
Ursd	Horizontal wind speed measured with the remote sensing device (in m/s)
UTC	Coordinated Universal Time







Appendix C: CALIBRATION CERTIFICATES

Verification Report SoDAR AQ510 003



Deutsche Wi	ndGuard		Deutsche		Seite 2 Page			10060 D-K- 15140-01-00 01/2013
Wind Tunnel	Services GmbH, V	arel	windGu	ard	Kalibriergegenstand Object	Cup Anemometer		
akkreditiert durch d	ie / accredited by the				Kalibrierverfahren			
Deutsche Ak	kreditierungsstelle	GmbH	DAkks		Calibration procedure	IEC 61400-12-1 – Power perform producing wind turbines – 2005-	ance measurements of elect 12	ricity
als Kalibrierlaborato	prium im / as calibration lab	oratory in the	Deut	sche editierungsstelle 15140-01-00	Ort der Kalibrierung	ISO 3966 - Measurement of fluid	i in closed conduits – 2008-0	/
Deutschen K	alibrierdienst	DKD		10060	Place of calibration	winatunnel of Deutsche WindGu	aru, Varei	
- cutoenen K	and received at			D-K-	Test Conditions	wind tunnel area ²⁾	10000 cm ²	
Kalibrierschein Calibration certificate			Calibration mark	01/2013		anemometer frontal area 21	257 cm ²	
						diameter of mounting pipe ³⁾	27 mm	
Gegenstand Object	Cup Anemometer	Dieser Kal führung at	ibrierschein dokumentie af nationale Normale zu	ert die Rück- ur Darstellung		blockage ratio 4)	0.026 [-]	
Hersteller	Vaicala	der Einhe Internation	iten in Übereinstimmu alen Einheitensystem (SI	ung mit dem I).		blockage correction ^{Si}	1.000 [-]	
Manufacturer	FIN 00421 Helsinki	Übereinko Accreditati	ist Unterzeichner der mmen der European co on (FA) und der	-operation for	Umgebungsbedingungen			
Тур Туре	WAA252	Laboratory	Accreditation Cooperat	tion (ILAC) zur ibrierscheine.	Test conditions	air temperature	20.4 °C ± 0.1 K	
Fabrikat/Serien-Nr.	Body: G15403	Für die Ein Wiederhol	haltung einer angemess ung der Kalibrierung ist	enen Frist zur der Benutzer		air pressure	1026.9 hPa ± 0.3 hPa	•
Auftraggeber	FDS Mätteknik AB	verantworf This colit	tlich. bration certificate do	cuments the		relative air humidity	41.2 % ± 2.0 %	
Customer	61291 Finspång, SWEDEN	traceability the units	to national standards, of measurement acco	which realize ording to the	Akkreditierung Accreditation	05/2011		
Auftragsnummer Order No.	VT130141	Internation The DAkk	ai System of Units (SI). S is signatory to the	e multilateral	Anmerkungen			
Anzahl der Seiten des Ka Number of pages of the certifi	alibrierscheines 3 coste	agreement Accreditati	s of the European co- on (EA) and of the	operation for International	Remarks			
Datum der Kalibrierung Date of calibration	07.01.2013	the mutual The user recalibrate	recognition of calibratio is obliged to have d at appropriate interval	n certificates. n the object s.	Auswertesoftware Software version	7.0		
Dieser Kalibrierschein darf nu sowohl der Deutschen Akkred Gültigkeit. This calibration certificate ma issuing laboratory. Calibration	r vollständig und unverändert weiterver litierungsstelle als auch des ausstellende y not be reproduced other than in full ex certificates without signoture are not va	breitet werden. Auszüge ode Kalibrierlaboratoriums. Kalil zept with the permission of b id.	er Änderungen bedürfen de brierscheine ohne Untersch oth the German Accreditatic	r Genehmigung rift haben keine on Body and the	¹⁰ Querschnittelliche der Auslassölse des ²⁰ Vereiellachte Querschnittelliche (Schatt ²⁰ Durchmesser des Montagereihs ⁴⁰ Verhältnis von 2) au 3) ²⁰ Komeikungkafor durch die Verdrängung Anmerkung: Aufgrund der spetiellen Kons Remark: Dur o the special construction o	Windkansk temun) des Präfings inkl. Montagershr der Stofbrung durch des Präfing atträtten der Messstecke ist klans Korrektur nötig. Alle besta steften solksdage correction is messaary		
	Dipl. Phys. D. Westermann	Technik	er Dirk Henninges	10050	Deutsche WindGuard Wind Tunnel Services GmbH, Anhang Anner	Varel		WindGuard
Seite 3 Page			-	D-K- 15140-01-00 01/2013	1 Detailed Cal	libration Results		gind Gua,
Kalibrierergebnis: Result:					DKD calibration no.	10060	Sk	MAANDA #
File:	100	0			Serial no. 1 Serial no. 2	Body: G15403 Cup: G154	i de	
Test liam (1/s) Turvel Spe	ed (m/s)	Uncertainty (k=2) (m/s)		Date Air temperature	20.4 °C	.4	easity
56.380	4,15	5	0.05		Air pressure Humidity	1026.9 hPa 41.2 %	786	
74.180	7.90	0	0.05	_	Linear regression analysis			
111.651	11.6	8	0.05		Slope	0.10295 (m/s)/(1/s) ±	0.00020 (m/s)/(1/s)	
130.344	13.6	8	0.05		Offset St.err(Y)	0.2485 m/s ±0.020 m 0.020 m/s	/s	
138.009	14.5	6	0.05		Correlation coefficient	0.999979		
121.026	12.70	9	0.05		Remarks	no		
83.365	8.80	1	0.05					
64.891 47.910	5.17	5	0.05	-				
					20 Search With Stant 15 10	Calibration No: 10060; Body: G1	5403; Cup: G154	0.2 0.1
Angegeben ist die erwe dem Erweiterungsfakto Wahrscheinlichkeit von	iterte Messunsicherheit, die sich r k=2 ergibt. Sie wurde gemäß DA 95 % im zugeordneten Wertinter	aus der Standardmessi kkS-DKD-3 ermittelt. De all.	unsicherheit durch Mul r Wert der Messgröße	Itiplikation mit liegt mit einer	S			0.1
Die Deutsche Akkreditie operation for Accreditat Anerkennung der Kalibri Internetseiten von EA (v	rungsstelle GmbH ist Unterzeichn ion (EA) und der International Lal ierscheine. Die weiteren Unterzei www.european-accreditation.org)	erin der multilateralen (ioratory Accreditation C chner innerhalb und auf und ILAC (www.ilac.org	Jbereinkommen der Eu ooperation (ILAC) zur g Ierhalb Europas sind de I zu entnehmen.	iropean co- iegenseitigen in	0 slope: 0.1029 mis/tis offict: 0.248 mis/ correlation: 0.999979 Output at 10 mis: 94	50 100 Anemometer output / 723 1/s • Resklush = Wind	150 I/s	0.2
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Anhang .			10060				
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Ort der Kalibrierung	producing wind turbines – 2005- ISO 3966 – Measurement of fluid	12 i in closed conduits – 2008-07		Test Item (Hz 81.412	:) Tunnel Sj 3.1	peed (m/s) 392	Uncertainty (k=2) (m/s) 0.050
Place of calibration	Windtunnel of Deutsche WindGu	aard, Varel		124.293	5.1	951 076	0.050
Messbedingungen Test Conditions	wind tunnel area 1)	10000 cm ²		213.892	10.	171	0.051
	anemometer frontal area 2)	230 cm ²		300.823	14.	106	0.051
	diamator of mounting pine 3)			344.720	16.	149	0.050
	blackage satic 4)	54 mm		280.010	13.	168	0.051
	DIOCKAGE LADO	0.025 [-]		235.487	11.	103	0.051
	blockage correction ³⁷	1.000 [-]		191.629	9.1	065	0.050
Umgebungsbedingungen				102.209	4.9	344	0.050
Test conditions	air temperature	21.1 °C ± 0.1 K					
	air pressure	994.1 hPa ± 0.3 hPa					
	relative air humidity	37.0 % ± 2.0 %					
Akkreditierung Accreditation	01/2013						
Anmerkungen							
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tierungsstel 40-01-00

1420649

D-K-15140-01-00

02/2014

en Frist zu



Kalibrierergebnis:

File:	1420650	
Test Item (Hz)	Tunnel Speed (m/s)	Uncertainty (k=2) (m/s)
81.991	3.993	0.050
124.154	5.955	0.050
170.156	8.076	0.050
213.543	10.096	0.051
258.676	12.171	0.051
300.875	14.109	0.051
344.960	16.152	0.050
324.195	15.180	0.051
280.281	13.164	0.051
235.713	11.104	0.051
192.101	9.101	0.051
147.932	7.063	0.050
101.987	4.949	0.050



Anhang Annex

Body no. Cup no.

Air tempe Air pressu Humidity

Slope Offset St.err(Y)

Remarks

Corre

Linear regression analysis

ion coefficient

Deutsche WindGuard Wind Tunnel Services GmbH, Varel

Deutsche WindGuard

Auftraggeber

Auftragsnummer Order No.

Wind Tunnel Services GmbH, Varel

VT140181

Anzahl der Seiten des Kalibrierscheines 3 Number of pages of the certificate Datum der Kalibrierung 01.02.2014

1 Detailed Calibration Results

DKD calibration no. 1420650



01142024

01.02.2014

21.0 °C 993.9 hPa 37.0 %

no

0.04615 (m/s)/(Hz) ±0.00003 (m/s)/(Hz) 0.2290 m/s ±0.007 m/s 0.004 m/s 0.999997



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

Die Deutsche Akkreditierungsstelle GmbH ist Unterzeichnerin der multilateralen Übereinkommen der European operation for Accreditation (EA) und der International Laboratory Accreditation Cooperation (ILAC) zur gegense Anerkennung der Kalbrierscheine. Die weiteren Unterzeichner innerhalb und außerhalb Europs sind den Internetselten von EA (www.european-accreditation.org) und ILAC (www.ilac.org) zu entnehmen.

The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty the coverage factor k = 2. It has been determined in accordance with DAMS-DKD-3. The value of the measurand lie within the assigned range of values with a probability of 95%. nty by

pen ist die erweiterte Messunsicherheit, die sich aus der Standardmessunsicherheit durch Multiplikation weiterungsfaktor k=2 ergibt. Sie wurde gemäß DAkk5-DKD-3 ermittelt. Der Wert der Messgröße liegt mit ei einlichkeit von 55 % im zugeordneten Wertintervall.

The DAkkS is signatory to the multilateral agree-ments of the European co-operation for Accredita-tion (E/ International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certific n (EA) and of the

Deutsche WindGuard		
Wind Tunnel Services G	mhH Varel	
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1420650

WindGuard

WindGuard

2 Instrumentation Pos. Senso 1 Pitot static tube Wind tunnel control
CAN-BUS / PC -24 x 16 bit

Table 1 Description of the data acquisition Remark: Last Re-accreditation see page 2

Anhong Annex

3 Photo of the calibration set-up



Calibration set-up of the anemometer calibration in the wind tunnel of Deutsche WindGuard, Varel. The anemome and orientation shown may differ from the calibrated one. Remark: The proportion of the set-up is not true to scal due to imaging geometry.

4 Deviation to IEC procedure The calibration procedure is in all aspects in accordance with the IEC 61400-12-1 Procedure

5 References

5 Régrences [1] D. Westermann, 2009 – Verfahrensanweisung DKD-Kalibrierung von Windgeschwindigkeitssensorer [2] IEC 61400-12-1 12/2005 – Power performance measurements of electricity producing wind turbine: [3] ISO 3966 2008 – Measurement of fluid flow in closed conduits

Deutsche WindGuard Wind Tunnel Services GmbH, Varel



Internationa tion (ILAC) zu der Ammonit Measurement GmbH D-10997 Berlin documents the ds, which realize ccording to the

econity to national standards, which realize units of measurement according to the matoianal System of Units (SJ). DANAS is signatory to the multilateral terments of the European co-operation for editation (FA) and of the International aratary Accreditation Cooperation (UAA) for mutual recognition of collabration certificates. user is obliged to have the object librated of appropriate intervals.

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Seite 2 Page				1420649 D-K- 15140-01-00 02/2014	Seite 3 Page			1420649 D-К- 15140-01-00 02/2014
alibriergegenstand bject	Cup Anemometer				Kalibrierergebnis: Result:			
alibrierverfahren alibration procedure	IEC 61400-12-1 – Power performa producing wind turbines – 2005-1	nce measurem 2	ents of electricity		File: Test Item (Hz)	1420649 Tunnel Speed (m/s)	Uncertainty (k=2) (m/s)
t der Kalibrierung	ISO 3966 – Measurement of fluid	in closed condu	its – 2008-07		81.492	3.995	0.050	
sce of calibration	Windtunnel of Deutsche WindGua	ird, Varel			169.766	8.082	0.050	
essbedingungen at Conditions	wind tunnel area 1)	10000 cm²			213.781 258.433	10.097	0.051	
	anemometer frontal area 2)	230 cm ²			300.835	14.109	0.051	
	diameter of mounting pipe 3)	34 mm			345.198 324.041	16.152	0.050	
	blockage ratio 4)	0.023 [-]			279.645	13.165	0.051	
	blockage correction 5)	1.000 [-]			191.881	9.102	0.051	
					147.642	7.062	0.050	
gebungsbedingungen t conditions	air temperature	20.8 °C	± 0.1 K		101.000	4.500	0.000	
	air pressure	994.0 hPa	± 0.3 hPa					
	relative air humidity	37.2 %	± 2.0 %					
reditierung	01/2013							
reditation	01/2013							
nerkungen narks	-							
wertesoftware	7.60							
ware version	7.60				Angegeben ist die erweiterte Messi dem Erweiterungsfaktor k=2 ergibt.	unsicherheit, die sich aus der Standar Sie wurde gemäß DAkkS-DKD-3 ermit	dmessunsicherheit durch Mu telt. Der Wert der Messgröße	ltiplikation i liegt mit eir
mittitis von 2) zu 1) reisturfaktor durch die Verdrängung enkung: Aufgrund der speziellen Konsi erkr: Due to the spezial construction of seer Kalibrierschein wurde e calibration certificate has	der Strömung duch den Früfling truktion der Messtrecke ist keine Korrektur nölig. If de test section no blockage correction is necessary elektronisch erzeugt been generated electronically				Internetseiten von EA (www.europe The expanded uncertainty assigned the coverage factor k = 2. It has beer within the assigned range of values The DAkkS is signatory to the multilla International Laboratory Accreditation	an-accreditation.org) und ILAC (www.i to the measurement results is obtained a determined in accordance with DAkk with a probability of 95%. teral agree-ments of the European co- an Cooperation (ILAC) for the mutual r	lac.org) zu entnehmen. (by multiplying the standard 5-DKD-3. The value of the mea operation for Accredita-tion (ecognition of calibration certi	uncertainty b asurand lies EA) and of th ficates.
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utsche WindGuard nd Tunnel Services GmbH, ' ^{hong} nex	Varel		Deutsche Win	1420649	Deutsche WindGuard Wind Tunnel Services GmbH, Varel Anhong Annex		Deutsche Wind	14206
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eutschen Kalibrier	lienst 🗾	KD	1420648	Ort der Kalibrierung Place of calibration	Windtunnel of Deutsche WindG	uard, Varel		
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			02/2014		anemometer frontal area ²⁾	230 cm ²		
nstand Cup Anem	ometer	Dieser Kalibrierschein d	okumentiert die Rück-		diameter of mounting pipe 3)	34 mm		
		führung auf nationale N der Einheiten in Über	ormale zur Darstellung einstimmung mit dem		blockage ratio 4)	0.023 [-]		
teller Thies Clim	a	Die DAkkS ist Unterzeich	system (51). nner der multilateralen		blockage correction 5)	1.000 [.]		
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13 WindGuard

Akkreditierungsstell D-K-15140-01-00

1420647

D-K-15140-01-00

Anhong Annex

Pos.	Sensor	Manufa.	Type	Range
1	Pitot static tube	Airflow	NPL 8 mm	
2	Pitot static tube	Airflow	NPL 8 mm	
3	Pitot static tube	Airflow	NPL 8 mm	
4	Pitot static tube	Airflow	NPL 8 mm	
5	Pressure transducer	Setra	C 239	250 Pa
6	Pressure transducer	Setra	C 239	250 Pa
7	Pressure transducer	Setra	C 239	250 Pa
8	Pressure transducer	Setra	C 239	250 Pa
9	El. Barometer	Vaisala	3.11.57.10.000	800hPa -1200 hPa
10	El. Thermometer	Galltec	KPK 1/6-ME	10° C - 40° C
11	El. Humidity sensor	Galltec	KPK 1/6-ME	0-100 %
12	Wind tunnel control			
13	CAN-BUS / PC	esd	24 x 16 bit	

Remark: Last Re-accreditation see page 2

3 Photo of the calibration set-up



Calibration set-up of the anemometer calibration in the wind tunnel of Deutsche WindGuard, Varel. The anemome and orientation shown may differ from the calibrated one. Remark: The proportion of the set-up is not true to scale due to imaging geometry.

4 Deviation to IEC procedure The calibration procedure is in all aspects in accordance with the IEC 61400-12-1 Procedure

Cup Anemometer

wind tunnel area 1)

blockage ratio 4)

air temperature

air pressure

01/2013

7.60

relative air humidity

blockage correction 5)

anemometer frontal area 2)

diameter of mounting pipe 3)

IEC 61400-12-1 – Power performance measurements of electricity producing wind turbines – 2005-12 ISO 3966 – Measurement of fluid in closed conduits – 2008-07

10000 cm²

230 cm²

34 mm

0.023 [-]

1.000 [-]

20.5 °C

37.3 %

±0.1 K

± 2.0 %

994.1 hPa ± 0.3 hPa

Windtunnel of Deutsche WindGuard, Varel

5 References

Seite 2 Page

Kalibriergegenstand Object

Kalibrierverfahren

Messbedingungen

Umgebungsbedingungen Test conditions

Akkreditierung

Anmerkungen Remarks

Querschnittsfläche der Au

ittsfläche (Sch Durchmesser des Montagerohrs Verhältnis von 2) zu 1)

Deutsche WindGuard Wind Tunnel Services GmbH, Varel

ang: Aufgrund der speziellen Konstruktion der Messstrecke ist keine Due to the special construction of the test section no blockage corr

Dieser Kalibrierschein wurde elektronisch erzeugt This calibration certificate has been generated electronically

Calibration proce Ort der Kalibrierung Place of calibration

5 References [1] D. Westermann, 2009 – Verfahrensanweisung DKD-Kalibrierung von Windgeschwindigkeitssensoren [2] IEC 61400-12-112/2005 – Power performance measurements of electricity producing wind turbines [3] ISO 3966 2008 – Measurement of fluid flow in closed conduits

Deutsche WindGuard Wind Tunnel Services GmbH, Varel

WindGuard

1420647

D-K-15140-01-00

02/2014

1420648

Deutsche WindGuard

akkreditiert durch die / accredited by the

Deutschen Kalibrierdienst

Wind Tunnel Services GmbH, Varel

Deutsche Akkreditierungsstelle GmbH

als Kalibrierlaboratorium im / as calibration laboratory in the



DKD

cate may not be reproduced other than in full except with the permission of both the German Accreditation Body and the



		1420647
Seite 3 Page		D-K- 15140-01-00
		02/2014

Kalibrierergebnis:

File:	1420647	
Test Item (Hz)	Tunnel Speed (m/s)	Uncertainty (k=2) (m/s)
81.727	3.996	0.050
123.945	5.956	0.050
170.024	8.080	0.051
213.557	10.097	0.051
258.229	12.175	0.051
300.431	14.111	0.051
345.058	16.153	0.050
323.873	15.183	0.051
280.269	13.170	0.051
234.993	11.102	0.051
192.464	9.103	0.051
147.997	7.074	0.050
101.902	4.959	0.050

gegeben ist die erweiterte Messunsicherheit, die sich aus der Standardmessunsicherheit durch Multiplikation mit m Erweiterungsfaktor H=2 ergibt. Sie wurde gemäß DAkk5-DKD-3 ermittelt. Der Wert der Messgröße liegt mit einer hirscheinlichkeit von 95 % im zugeordneten Wertintervall.

Die Deutsche Akkreditierungsstelle GmbH ist Unterzeichnerin der multilateralen Übereinkommen der European co-operation for Accreditation (EA) und der International Laboratory Accreditation Cooperation (ILAC) zur gegenseitigen Anerkennung der Labibrierscheine. Die weiteren Unterzeichner innerhalb und außerhalb Europas sind den Internetseiten von EA (www.european-accreditation.org) und ILAC (www.ilac.org) zu entnehmen.

e expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty by coverage factor k = 2. It has been determined in accordance with DAkS-DKD-3. The value of the measurand lies thin the assigned range of values with a probability of 55%.

The DAkkS is signatory to the multilateral agree-ments of the European co-operation for Accredita-tion (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates.

Deutsche WindGuard Wind Tunnel Services GmbH, Varel WindGuard









1420646

-0.1

-0.2 400

300



0.050

0.05

DKD calibration no.	1420646	
n d	01112020	SA
Body no.	01142028	SK
Date	01.02.2014	0 K
Air temperature	20.2 °C	. H
Air pressure	994.4 hPa	TH
Humidity	37.5 %	4 W
Linear regression analysis		
Slope	0.04603 (m/s)/(Hz) ±0	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	
	Calibration No: 1420646: 0	11142028
20	0011010101110. 1420040, 0	

Angegeben ist die erweiterte Messundicherheit, die sich aus der Standardmessundicherheit durch Multiplikation dem Erweiterungsfaktor kr2-ergibt. Sie wurde gemäß DAkkG-DKD-3 ermittelt. Der Wert der Messgröße liegt mit e Wahrscheinlichkeit von 55 % im zugeordineten Wertnierervall.

10.948

8.986 6.999 4.955

Die Deutsche Akkreditierungsstelle GmbH ist Unterzeichnerin der multilateralen Übereinkommen der European operation for Accreditation (EA) und der International Laboratory Accreditation Cooperation (ILAC) zur gegensei Anerkennung der Kalbierscheine. Die weiteren Unterzeichner innerhalb und außerhalb Europs sind den Internetseiten von EA (www.european-accreditation.org) und ILAC (www.ilac.org) zu entnehmen. itige

The expanded uncertainty assigned to the measurement results is obtained by multiplying the standard uncertainty the coverage (pctor k = 2. It has been determined in accordance with DAMS-DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%. inty by

The DAkkS is signatory to the multilateral agree-ments of the European co-operation for Accredita-tion (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates.

Deutsche WindGuard Wind Tunnel Services GmbH, Varel	WindGuard

1420646

WindGuard

Mind

0 50 1 slope: 0.04603 m/s/Hz offset: 0.265 m/s correlation: 0.999993 -Output at 10 m/s: 211.48 Hz

2 Instrumentation

Anhang Annex

231.699

189.013 146.059 101.470

Pos.	Sensor	Manufa.	Type	Range
1	Pitot static tube	Airflow	NPL 8 mm	
2	Pitot static tube	Airflow	NPL 8 mm	
3	Pitot static tube	Airflow	NPL 8 mm	
4	Pitot static tube	Airflow	NPL 8 mm	
5	Pressure transducer	Setra	C 239	250 Pa
6	Pressure transducer	Setra	C 239	250 Pa
7	Pressure transducer	Setra	C 239	250 Pa
8	Pressure transducer	Setra	C 239	250 Pa
9	El. Barometer	Vaisala	3.11.57.10.000	800hPa -1200 hPa
10	El. Thermometer	Galitec	KPK 1/6-ME	10° C - 40° C
11	El. Humidity sensor	Galltec	KPK 1/6-ME	0-100 %
12	Wind tunnel control		*	
13	CAN-BUS / PC	esd	24 x 16 bit	

3 Photo of the calibration set-up



Calibration set-up of the anemometer calibration in the wind tunnel of Deutsche WindGuard, Varel. The anemome and orientation shown may differ from the calibrated one. Remark: The proportion of the set-up is not true to scale due to imaging geometry.

4 Deviation to IEC procedure The calibration procedure is in all aspects in accordance with the IEC 61400-12-1 Procedure

5 References

regerences
 II.D. Westermann, 2009 – Verfahrensanweisung DKD-Kalibrierung von Windgeschwindigkeitssensoren
 ISI CE 61400-12-112/2005 – Power performance measurements of electricity producing wind turbines
 ISO 3966 2008 – Measurement of fluid flow in closed conduits

Deutsche WindGuard Wind Tunnel Services GmbH, Varel

Deutsche WindGuard Wind Tunnel Services GmbH, Varel WindGuard

200 250 output /Hz

• Residuals . Wind speed

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