WS170

Independent performance verification of Seawatch Wind Lidar Buoy at the LEG offshore platform

FUGRO NORWAY AS

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Independent performance verification of Seawatch Wind Lidar Buoy at the LEG offshore platform

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Reference to part of this report which may lead to misinterpretation is not permissible.

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DNV Performance Verification Summary

General measurement configuration	
Associated Report	10298247-R-1, Issue A
Customer	Fugro Norway AS
DNV entity	GL Garrad Hassan Deutschland GmbH
Location	LEG offshore platform
Reference Lidar (REF)	Windcube 258
Floating Lidar System (FLS)	Fugro WS170 with ZX Lidars unit 585
Evaluated heights above mean sea level [m]	240, 190, 165, 140, 115, 90, 62
Separation Distance [m]	240
Measurement start	2021-05-01
Measurement end	2021-05-22
Verification standard and/or criteria	OWA roadmap (2018) and IEC 61400-12-1 (2017)
Deviations	One incomplete BIN and failed R^2 in 4-16 m/s range at 240 m

WS170 verification results[1]

Bin range [m/s]	2 to 3	3 to 4	4 to 5	5 to 6	6 to 7	7 to 8	8 to 9	9 to 10	10 to 11	11 to 12	12 to 14	14 to 16	16 to 18	18 to 20	20 to 22	22 to 24	24 to 26	26 to 28	28 to 30
Bin Center [m/s]	**2.5**	**3.5**	**4.5**	**5.5**	**6.5**	**7.5**	**8.5**	**9.5**	**10.5**	**11.5**	**13**	**15**	**17**	**19**	**21**	**23**	**25**	**27**	**29**
Level [m]	**# of reference data points left after filtering**																		
240	45	65	208	205	191	183	109	111	101	110	122	22	24	51	30	84	72	26	2
190	84	120	284	295	316	251	154	159	131	161	146	54	80	43	46	104	63	16	
165	101	146	277	324	387	250	176	167	148	156	155	67	93	41	66	100	52	12	
140	115	169	289	336	396	269	165	155	162	130	163	76	95	39	78	98	44	4	
115	136	191	286	378	404	239	171	146	174	119	152	81	93	32	93	90	30	2	
90	154	198	295	430	393	223	171	171	153	104	146	98	63	36	102	81	21		
62	157	207	330	493	349	223	170	168	133	86	136	102	34	68	99	60	5		

Verification Height [m]	62	90	115	140	165	190	240
Wind speed slope (X_{mws})	0.993	0.990	0.989	0.990	0.988	0.989	0.992
Wind speed correlation coefficient (R^2_{mws})	0.996	0.996	0.996	0.996	0.995	0.994	0.993
Wind direction slope (M_{mwd})	1.007	1.008	1.011	1.010	1.013	1.014	1.010
Wind direction offset (OFF_{mwd})	2.073	1.645	1.540	1.296	0.967	0.786	0.805
Wind direction correlation coefficient (R^2_{mwd})	0.994	0.991	0.988	0.981	0.979	0.979	0.981

KPI	Passed Best practice
KPI	Passed Minimum
KPI	Deviation

[1] The shown results are for the wind speed range above 2 m/s. Wind speed results for the 4-16 m/s range can be found in chapter 5.2.

1 INTRODUCTION

Fugro Norway AS (“Fugro” or the Client) retained GL Garrad Hassan Deutschland GmbH, a member of DNV Group (“DNV”), to complete a post-deployment verification of SEAWATCH Wind Lidar Buoy WS170 moored next to the LEG offshore platform between 2021-05-01 and 2021-05-22. The

Before WS170 was used for the latest RvO projects at Hollandse Kust (west) Wind Farm Zone (HKWWFZ), the WS170 data was compared to data of WS187 and to data of WS188, which were both deployed offshore near WS170, to check the consistency of the WS170 data [10].

This verification was performed at LEG against a fixed offshore industry accepted Lidar (Reference Lidar or REF). Wind speed and wind direction comparisons are performed using the method provide in the Roadmap towards Commercial Acceptance [1] against corresponding Key Performance Indicators (KPIs) and Acceptance Criteria (ACs; see APPENDIX A).

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

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

2 SITE INFORMATION

2.1 Site description

A detailed description of the test site can be found on the following website:

https://www.windopzee.net/en/locations/lichteiland-goeree/leg-rapportage/

The coordinates of the measurement site are provided in Table 2-1.

Table 2-1 REF and FLS coordinates

ID	Longitude [°]	Latitude [°]	Distance to REF [m]	Horizontal travel around anchor [m]
REF	3.66844	51.92503	NA	NA
WS170	3.66568	51.92634	240	100

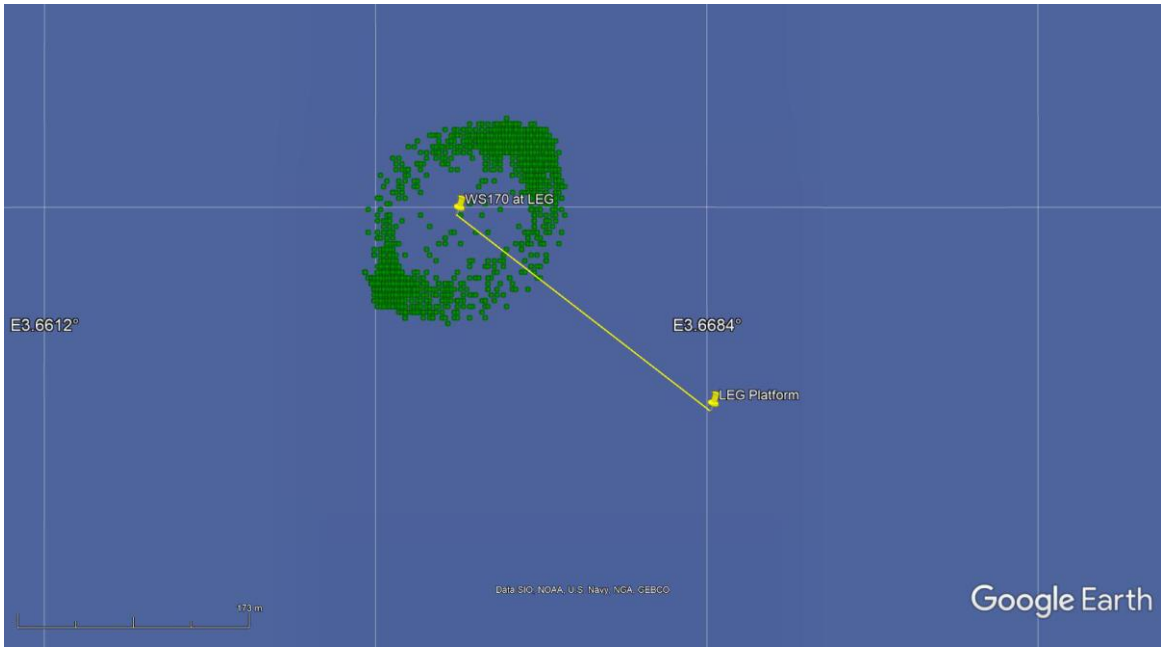


Figure 2-1 Positions of WS170 and REF

2.2 Measuring equipment

This section provides a description of the remote sensing devices. It is noted that DNV has not been involved in the data collection. Data from the SWLB and data from the REF were provided by email from Fugro.

2.2.1 Reference lidar (REF)

REF is a Leosphere Windcube v2 that is specifically designed to measure wind speeds in the lower boundary layer of the atmosphere. The REF was configured with a height offset of 23 m to account for the difference in mean sea level and the height of the lidar window above ground. Table 2-2 provides the wind speed and wind direction measurement heights from FLS and REF heights used in the performance verification. Figure 2-2 shows the REF.

The REF was validated from July 2019 to September 2019 and was found to reproduce cup anemometer wind speeds and wind directions at an accurate and acceptable level for the wind speeds observed on site during the test.

Figure 2-2 Reference Lidar WINDCUBEv2 WLS7-258 (photo source: TNO report 2020 R10866)

2.2.2 The SEAWATCH Wind Lidar Buoy (SWLB)

The SWLB has achieved “Roadmap-Pre-Commercial” stage [2]. During the verification campaign, the lidar unit 585 was configured with a height offset of 2 m to account for the height difference between the lidar window and mean sea level. Table 2-2 provides the wind speed and wind direction measurement heights from lidar and reference lidar heights used in the performance verification. Figure 2-3 shows the SWLB WS170.

The SWLB is moored in 23 m of water depth, and the mooring array allows a horizontal sway around the anchor of approximately 100 m.

SWLB Lidar wind statistics are processed by a central controller unit GENI that collects 1-second raw data from the on-board ZX Lidar to calculate 10-minute wind data statistics. The SWLB recorded wave measurements in 10-minute intervals. The SWLB wind direction data was stored as two separate datasets – one dataset is based on DGPS correction and the other one is based on magnetic compass correction. All results in this report are based on the compass wind direction signal.

Figure 2-3 Photo of WS170 (without keel weight)

Table 2-2 FLS and REF measurement heights above mean sea level (AMSL)

Device	Height	Measurement heights[2]													
WS170	Configured	38	60	78	88	100	113	138	148	163	188	-	238	-	-
	AMSL	40	**62**	80	**90**	102	**115**	**140**	150	**165**	**190**	-	**240**	-	-
REF	Configured	-	40	-	68	-	93	118	-	143	168	193	218	243	268
	AMSL	-	**62**	-	**90**	-	**115**	**140**	-	**165**	**190**	215	**240**	265	290

[2] Wind speed and wind direction comparison heights are highlighted in bold typeface.

Fugro informed DNV that the SWLB under test has undergone design modification since the SWLB was trailed IJmuiden in 2014/2015 [3]. These changes are as follows:

(1) A ZX Lidars ZX300M, which is the marine version, has been integrated in the SWLB. The marine version uses more corrosion resistant materials relative to the standard onshore ZX300. DNV considers that this will not affect the quality of the wind data measured by the Lidar.

(2) The buoy assembly has been supplied with an extra buoyancy ring. DNV has performed a high-level desktop assessment of the change in buoy design with regards to motion in response to waves and currents. This assessment was based on drawings of the new buoy design provided by Fugro [4]. Based on this documentation, DNV considers that changes in motion types like rotation, pitch, and role will be negligible, and that the motion damping seems to be improved. Fugro's internal mooring design report no. C75342-02-03 [5], shows that the anchoring and mooring array design has properly been adapted for wave loading, and accounts for changes in weight, total buoyancy, and size. Therefore, DNV considers that the original wind data quality and availability related Roadmap achievements [1, 3] should be valid for the new buoy design. DNV's conclusion is supported by a 6-month Type Validation of the Seawatch Wind Lidar buoy with extra buoyancy at the East Anglia (EA1) Met Mast in the UK in 2016. The Type Validation was organized by Carbon Trust and completed by Natural Power [6].

(3) In addition to the (Type Validated) magnetic compass, a differential global positioning system (DGPS) has been included as a heading source. DNV has compared the magnetic compass and DGPS in several SWLB pre-deployment validations and has found that the performance with DGPS is the same or better than the magnetic compass correction.

3 LIDAR PERFORMANCE VERIFICATION APPROACH

3.1 OWA Roadmap Verification

In accordance with the Roadmap [1], DNV has assessed the data coverage of the floating lidar system. The following describes the general methods used for this verification:

- All comparisons are based on 10-minute averages from a primary reference that is either a fixed industry accepted Lidar, which has been successfully verified, or a reference mast with MEASNET calibrated cup anemometers, 3D sonic anemometers, and wind vanes and concurrent wind speed and wind direction data from the FLS under test.
- Only undisturbed free-stream wind data at both the reference and FLS under test are used in the analysis.
- The following data coverage requirements are regarded as achievable for a typical test period of four weeks:
    - A minimum number of 40 data points required in each 1 m/s bin wide reference wind speed bin centred between 2.5 m/s and 11.5 m/s, i.e., covering a range between 2 and 12 m/s.
    - Minimum number of 40 data points required in each 2 m/s bin wide reference wind speed bin centred on 13 m/s and 15 m/s, i.e., covering a range 12 m/s to 16 m/s.
    - A minimum number of 40 data points in each 2 m/s bin wide reference wind speed bin centred on 17 m/s and above, i.e. covering a range above 16 m/s only if such data is available. This criterion is not mandatory.
- System availability was defined as the ratio between the number of 10-minute data points available for at least one measurement as compared to the number of possible records. The number of possible records excludes power outages and this availability is reported seperately.
- Wind speed in this lidar performance verification are assessed by means of linear regressions through the origin of the form

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

  between FLS (y-axis) wind speeds and reference (x-axis) wind speeds. Data are compared for all greater than 2 m/s and from 4 m/s to 16 m/s.
- Wind directions were compared quantitatively by two variant regressions solving for the slope, m, and the interception of the best-fit line with the y-axis, b, (according to y = m x + b), as defined in APPENDIX A.

The performance of the FLS under test is based on a number of KPIs and ACs. The evaluation approach is provided in in APPENDIX A.

3.2 IEC Standard, Annex L verification

The verification was completed in accordance with the International Standard IEC 61400-12-1: 2017 (IEC Standard) [7]. This approach is based on a wind speed bin averaged procedure in order to compare the horizontal wind speed measurements acquired by the remote sensing device (RSD) and the reference sensors at the mast or reference lidar. The objective of the IEC approach is to calculate the bin-wise deviation of the two sources and report the associated uncertainty.

The bin averaging procedure was performed using 0.5 m/s wide wind speed bins centred on integers of from 4 to 16 m/s. In order to achieve statistical relevance this IEC approach requires the following:

- A minimum of three (3) 10-minute values available within each wind speed bin; and
- 180 hours or 1080 10-minute records of valid data

According to chapter L.4.3 of the IEC Standard [7] and RP 105+Note 32 of [9], the verification uncertainty consists of the following independent uncertainty components:

1. Reference/anemometer uncertainty
2. Mean deviation of the remote sensor measurements and the reference measurements
3. Standard uncertainty of the measurement of the RSD
4. Mounting uncertainty of the remote sensor at the verification test
5. Uncertainty due to non-homogenous flow
6. Uncertainty due to separation distance

The different uncertainty components are added in quadrature for each wind speed bin. Details on the calculation of the separate uncertainty components are described in APPENDIX E.

3.3 Data Filtering

Table 3-1 below summarizes the data filters applied.

Table 3-1 Data filtering

	Filter	Criteria for removal				
1	FLS and REF Wind Speed [m/s]	WS_FLS > 59	OR	WS_FLS < 0	OR	WS_REF < 2
2	REF Wind direction [°]	WD_REF > 360	OR	WD_REF < 0		
3	FLS Wind Direction [°]	WD_FLS > 360	OR	WD_FLS < 0		
4	REF Availability	< 80 %				

4 METEOROLOGICAL AND SEA STATE CONDITIONS DURING THE VERIFICATION TRIAL

The SWLB encountered a wide range of wind conditions during the verification. Table 4-1 shows the Maximum 10-minute averaged wind speeds at the REF between 25.1 m/s at the lowest comparison level (62 m) and 28.3 m/s at the upper most level (240 m). The air temperatures during the campaign ranged from 4.2°C to 15.1°C. A time series of the temperature at the FLS is displayed in APPENDIX D.

The significant wave heights observed were up to 3.82 m, with 16.9 % of the observations above 1.5 m. The experienced maximum wave heights observed cover a range up to 6.17 m.

Additional wave statistics observed during the measurement campaign are provided in APPENDIX D.

WS MAX	REF	SWLB
Height / m	WS / m/s	
240	28.34	28.50
190	27.58	28.22
165	27.30	27.74
140	26.96	27.83
115	26.38	26.93
90	25.97	26.70
62	25.06	25.13

Table 4-1 Maximum 10 min averaged wind speeds

5 RESULTS OF THE OWA VERIFICATION

5.1 System and data availability

Data for the FLS verification were available from 2021-05-01 to 2021-05-22. The FLS campaign duration was 21.3 days, which represents 3064 concurrent data points. As indicated by the system availability, there were no maintenance visits (MV) during this verification, there were no unscheduled outage (UO) and DNV understands that all data from the FLS were transmitted remotely, and the communication uptime (CU) is assumed to be 100%. The OWA roadmap does not define KPIs for MV, OU and CU, but are reflected in the system availability.

Considering all 10-minute FLS records, there were 3064 records available for one or more measurement heights, and therefore the FLS device has achieved a system availability of 100.0% as presented in Table 5-1. This meets the acceptance criterion for overall system availability (KPI OSA_{CA}) of ≥ 95 % (for Stage 2) and ≥ 97 % (for Stage 3).

The valid lidar data availability from 62 m to 240 m range is between 98.3 % to 99.6 %. The acceptance criterion for overall post-processed data availability (KPI $OPDA_{CA}$) is ≥ 85 % for Stage 2 and ≥ 90 % for Stage 3. The acceptance criterion for monthly post-processed data availability (KPI $MPDA_{1M}$) is ≥ 80 % for Stage 2 and ≥ 85 % for Stage 3.

Table 5-1 Summary of system and data availabilities

	LiDAR Availability Assessment						
Height / m	**240**	**190**	**165**	**140**	**115**	**90**	**62**
Max. # of 10-min points in period	3064	3064	3064	3064	3064	3064	3064
After accounting power outages	3064	3064	3064	3064	3064	3064	3064
Data present	3064	3064	3064	3064	3064	3064	3064
System availability (**KPI OSA_{CA}**)	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Total # of 10-minute valid data	3011	3021	3024	3025	3033	3050	3052
Data availability (**KPI ODA_{CA}**)	98.3%	98.6%	98.7%	98.7%	99.0%	99.5%	99.6%
# after external filtering	1761	2507	2718	2783	2817	2839	2820
Data availability for comparison	57.5%	81.8%	88.7%	90.8%	91.9%	92.7%	92.0%

Figure 5-1 shows the lidar system availability and the data recovery rate for each measurement height.

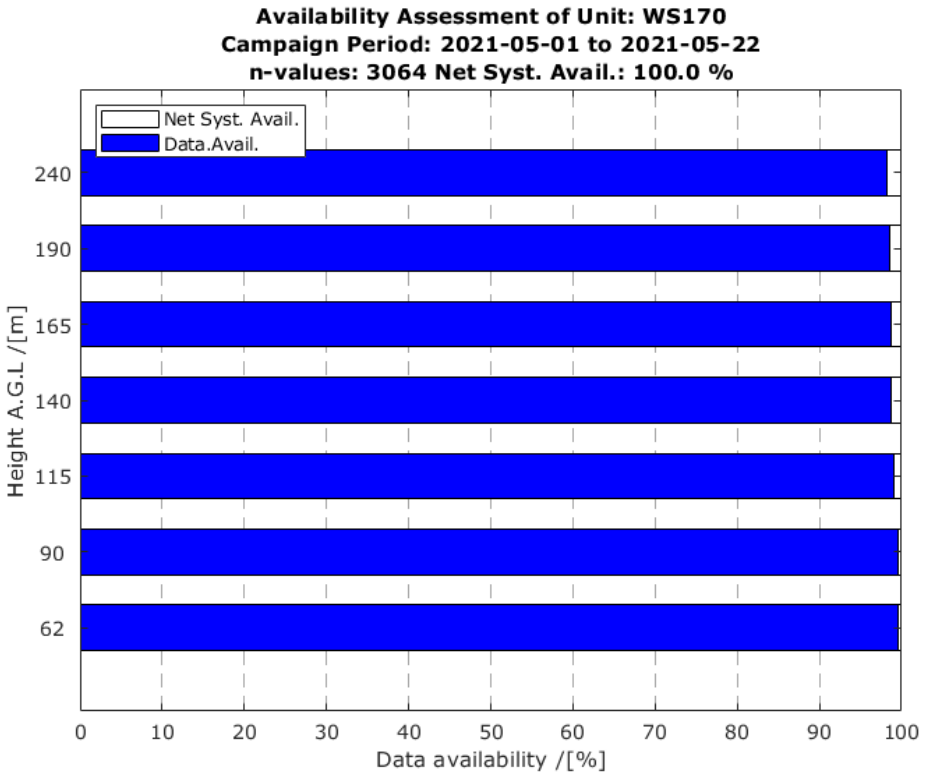


Figure 5-1 FLS availability

Data coverage by wind speed bin are presented in Table 5-2. The database requirements for all mandatory wind speed ranges are fulfilled for the heights 62 m to 190 m. At 240 m, the BIN 14-16 m/s is not complete.

Table 5-2 Valid concurrent REF 10-minute data points for each verification height

WS Bin / [m/s]	2 to 3	3 to 4	4 to 5	5 to 6	6 to 7	7 to 8	8 to 9	9 to 10	10 to 11	11 to 12	12 to 14	14 to 16	16 to 18	18 to 20	20 to 22	22 to 24	24 to 26	26 to 28	28 to 30
Bin Center / [m/s]	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	13	15	17	19	21	23	25	27	29
Level / [m]	# of data points left after filtering																		
240	45	65	208	205	191	183	109	111	101	110	122	22	24	51	30	84	72	26	2
190	84	120	284	295	316	251	154	159	131	161	146	54	80	43	46	104	63	16	0
165	101	146	277	324	387	250	176	167	148	156	155	67	93	41	66	100	52	12	0
140	115	169	289	336	396	269	165	155	162	130	163	76	95	39	78	98	44	4	0
115	136	191	286	378	404	239	171	146	174	119	152	81	93	32	93	90	30	2	0
90	154	198	295	430	393	223	171	171	153	104	146	98	63	36	102	81	21	0	0
62	157	207	330	493	349	223	170	168	133	86	136	102	34	68	99	60	5	0	0

5.2 Wind speed comparison

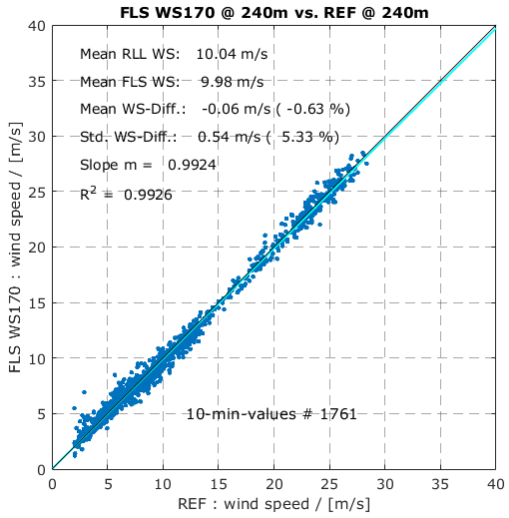
Table 5-3 summarizes the wind speed regression results for all verfication heights and shows that the FLS achieved a high level of accuracy relative to the REF. The regression slopes are close to unity with a good regression coefficient. Figure 5-2 provides the corresponding regression plots for wind speeds greater than or equal to 2 m/s. The failed R^2 result in the wind speed range 4-16 m/s at 240 m is not considered critical since at measuring heights above 200 m an increased uncertainty is expected [3].

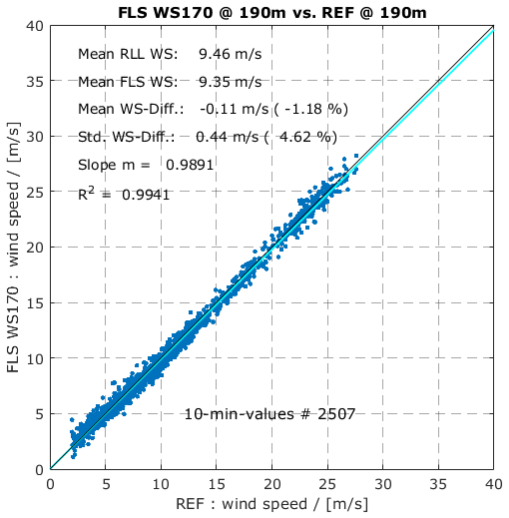
The concurrent time series of wind speeds from the FLS and REF at 240 m and 62 m are shown in APPENDIX B.

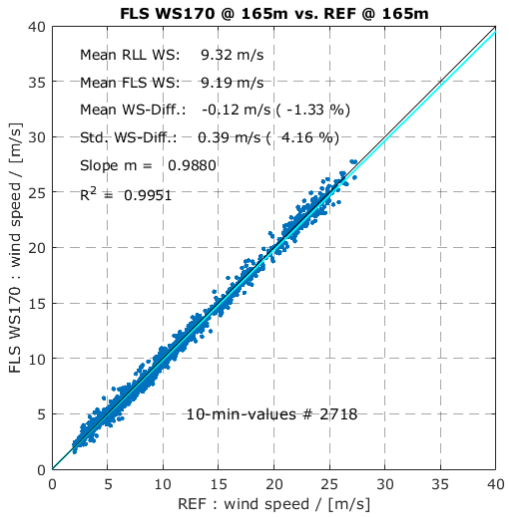
Table 5-3 Regression results for comparison

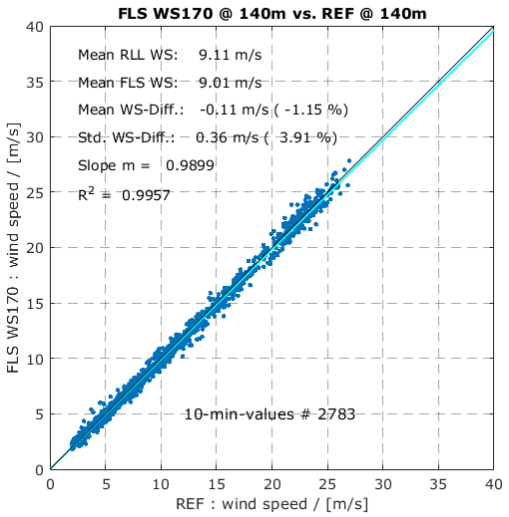
	# values	slope	R^2	WS-avg REF (Reference)	WS-avg WS170 (Test)	mean diff.	rel. mean difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		**KPI X_{mws}**	**KPI R^2_{mws}**				
240 m level							
All >= 2 m/s	1761	0.992	0.993	10.04	9.98	-0.063	-0.63%
4 - 16 m/s	1362	0.982	0.969	7.97	7.87	-0.096	-1.20%
190 m level							
All >= 2 m/s	2507	0.989	0.994	9.46	9.35	-0.112	-1.18%
4 - 16 m/s	1951	0.980	0.981	7.97	7.83	-0.144	-1.80%
165 m level							
All >= 2 m/s	2718	0.988	0.995	9.32	9.19	-0.124	-1.33%
4 - 16 m/s	2107	0.981	0.985	8.00	7.86	-0.147	-1.84%
140 m level							
All >= 2 m/s	2783	0.990	0.996	9.11	9.01	-0.105	-1.15%
4 - 16 m/s	2141	0.983	0.989	7.94	7.82	-0.129	-1.62%
115 m level							
All >= 2 m/s	2817	0.989	0.996	8.88	8.78	-0.102	-1.15%
4 - 16 m/s	2150	0.985	0.992	7.90	7.78	-0.118	-1.50%
90 m level							
All >= 2 m/s	2839	0.990	0.996	8.62	8.54	-0.088	-1.02%
4 - 16 m/s	2184	0.986	0.994	7.85	7.75	-0.105	-1.34%
62 m level							
All >= 2 m/s	2820	0.993	0.996	8.30	8.24	-0.062	-0.75%
4 - 16 m/s	2190	0.989	0.993	7.69	7.61	-0.084	-1.10%

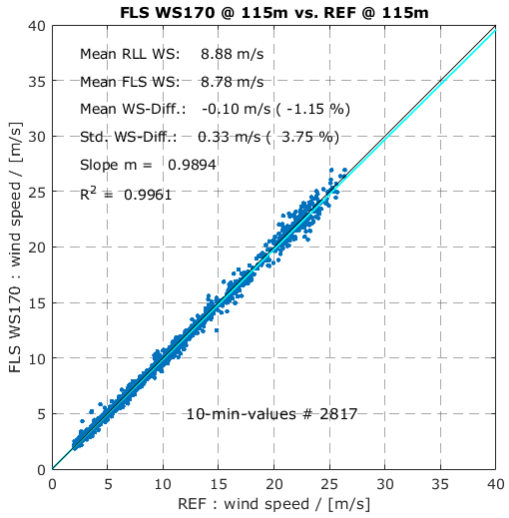
[3] In the manual of the ZXlidars software Waltz, it is noted in chapter 6.1.2.1 that Z300 units have only been validated up to 200 m and therefore any measurements taken beyond this height have not been verified.

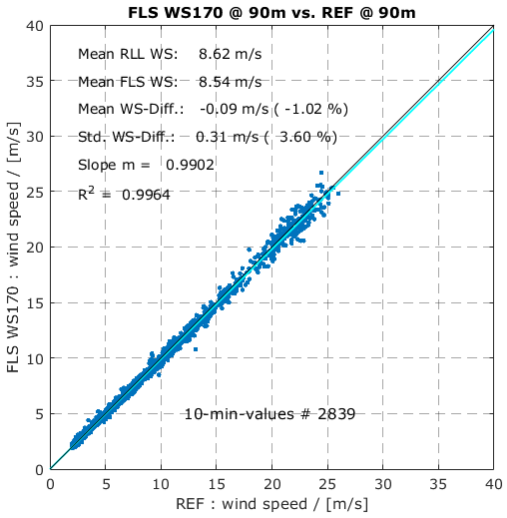

FLS WS170 @ 240m vs. REF @ 240m
Mean RLL WS: 10.04 m/s
Mean FLS WS: 9.98 m/s
Mean WS-Diff.: -0.06 m/s (-0.63 %)
Std. WS-Diff.: 0.54 m/s (5.33 %)
Slope m = 0.9924
R² = 0.9926
10-min-values # 1761
FLS WS170 : wind speed / [m/s]
REF : wind speed / [m/s]


FLS WS170 @ 190m vs. REF @ 190m
Mean RLL WS: 9.46 m/s
Mean FLS WS: 9.35 m/s
Mean WS-Diff.: -0.11 m/s (-1.18 %)
Std. WS-Diff.: 0.44 m/s (4.62 %)
Slope m = 0.9891
R² = 0.9941
10-min-values # 2507
FLS WS170 : wind speed / [m/s]
REF : wind speed / [m/s]


FLS WS170 @ 165m vs. REF @ 165m
Mean RLL WS: 9.32 m/s
Mean FLS WS: 9.19 m/s
Mean WS-Diff.: -0.12 m/s (-1.33 %)
Std. WS-Diff.: 0.39 m/s (4.16 %)
Slope m = 0.9880
R² = 0.9951
10-min-values # 2718
FLS WS170 : wind speed / [m/s]
REF : wind speed / [m/s]


FLS WS170 @ 140m vs. REF @ 140m
Mean RLL WS: 9.11 m/s
Mean FLS WS: 9.01 m/s
Mean WS-Diff.: -0.11 m/s (-1.15 %)
Std. WS-Diff.: 0.36 m/s (3.91 %)
Slope m = 0.9899
R² = 0.9957
10-min-values # 2783
FLS WS170 : wind speed / [m/s]
REF : wind speed / [m/s]





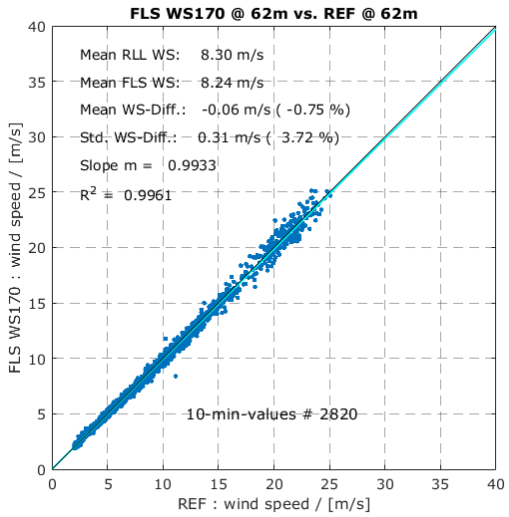


Figure 5-2 Linear wind speed regression results

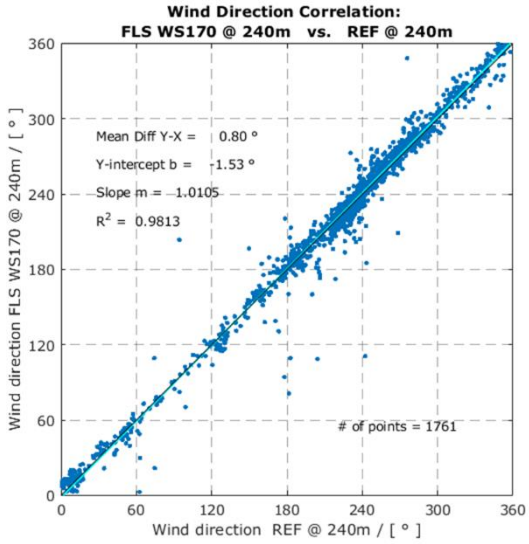
5.3 Wind direction comparison

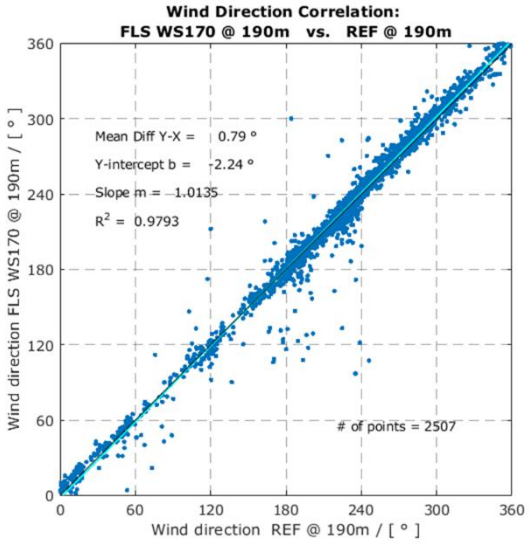
Table 5-4 summarizes the wind direction regression results for all verfication heights and shows that the FLS achieved a high level of accuracy relative to the REF. The regression slopes are close to unity with a good regression coefficient and a low offset. Figure 5-3 provides the corresponding regression plots for wind speeds greater than or equal to 2 m/s.

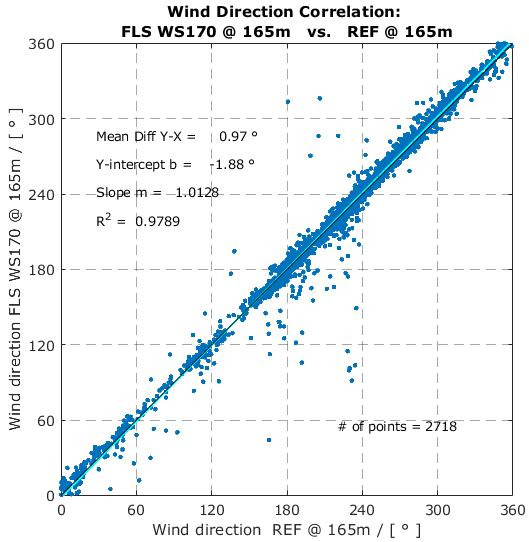
Time series of wind direction, raw data correlations, and wind direction distribution statistics can be found in APPENDIX C.

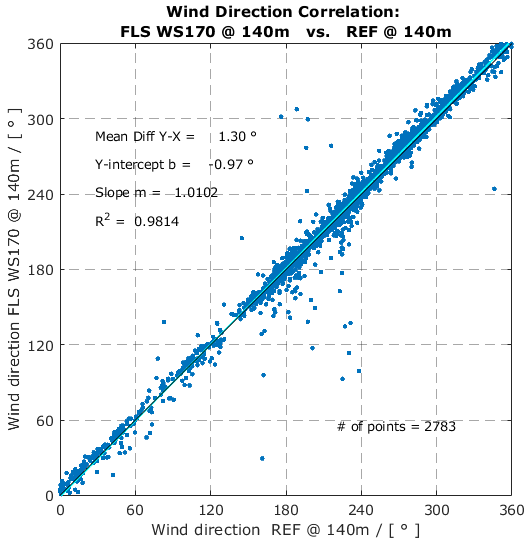
Table 5-4 Summary of wind direction comparison

WS filtering for WS > 2 m/s				
Height level	**# values**	**slope**	**offset [°]**	**R^2**
[m]	[-]	**KPI M_{mwd}**	**KPI OFF_{mwd}**	**KPI R^2_{mwd}**
240	1761	1.010	0.805	0.981
190	2507	1.014	0.786	0.979
165	2718	1.013	0.967	0.979
140	2783	1.010	1.296	0.981
115	2817	1.011	1.540	0.988
90	2839	1.008	1.645	0.991
62	2816	1.007	2.073	0.994


Wind Direction Correlation:
FLS WS170 @ 240m vs. REF @ 240m
Mean Diff Y-X = 0.80 °
Y-intercept b = -1.53 °
Slope m = 1.0105
R² = 0.9813
# of points = 1761
Wind direction FLS WS170 @ 240m / [°]
Wind direction REF @ 240m / [°]


Wind Direction Correlation:
FLS WS170 @ 190m vs. REF @ 190m
Mean Diff Y-X = 0.79 °
Y-intercept b = -2.24 °
Slope m = 1.0135
R² = 0.9793
# of points = 2507
Wind direction FLS WS170 @ 190m / [°]
Wind direction REF @ 190m / [°]


Wind Direction Correlation:
FLS WS170 @ 165m vs. REF @ 165m
Mean Diff Y-X = 0.97 °
Y-intercept b = -1.88 °
Slope m = 1.0128
R² = 0.9789
# of points = 2718
Wind direction FLS WS170 @ 165m / [°]
Wind direction REF @ 165m / [°]


Wind Direction Correlation:
FLS WS170 @ 140m vs. REF @ 140m
Mean Diff Y-X = 1.30 °
Y-intercept b = -0.97 °
Slope m = 1.0102
R² = 0.9814
# of points = 2783
Wind direction FLS WS170 @ 140m / [°]
Wind direction REF @ 140m / [°]

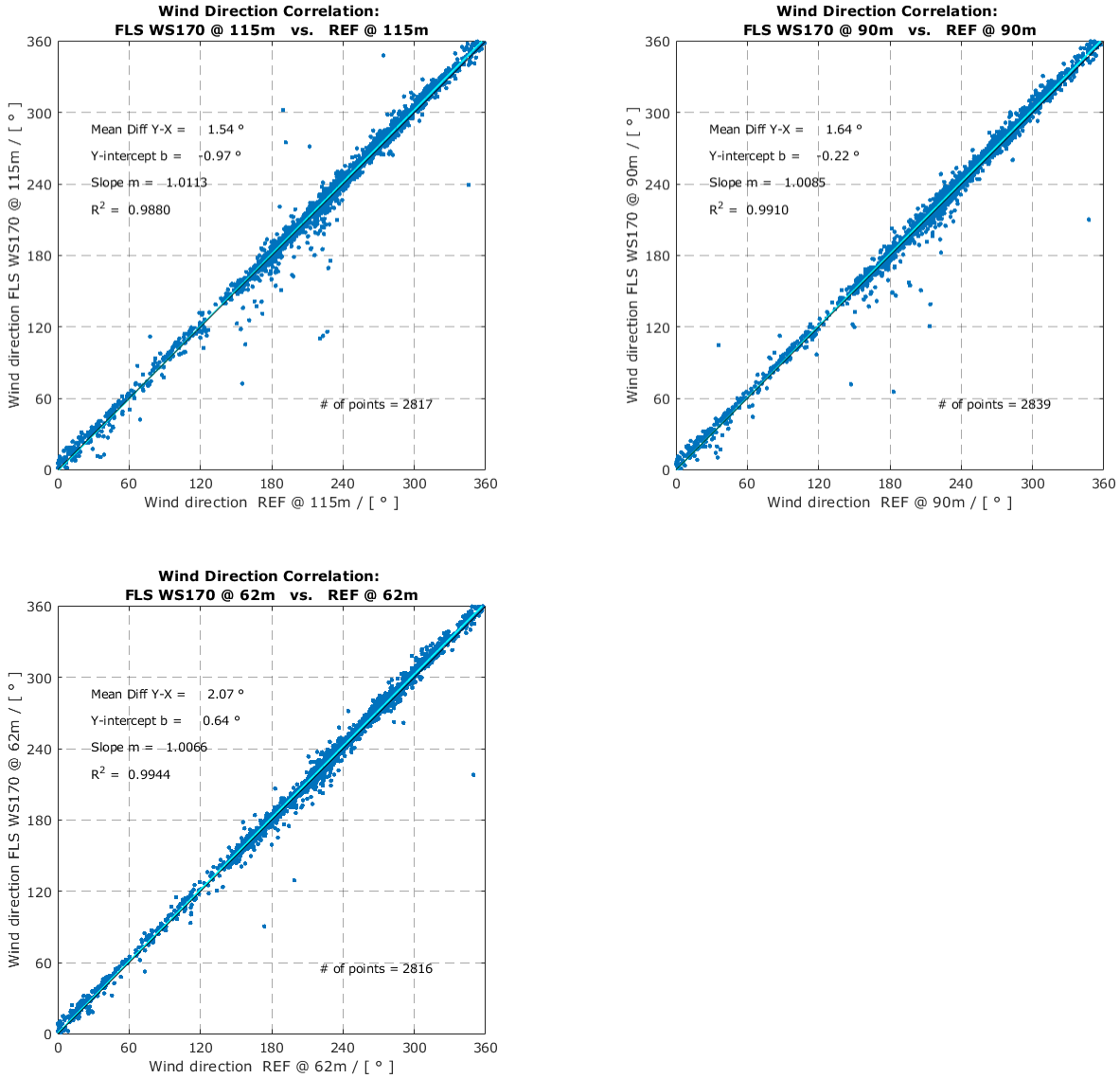
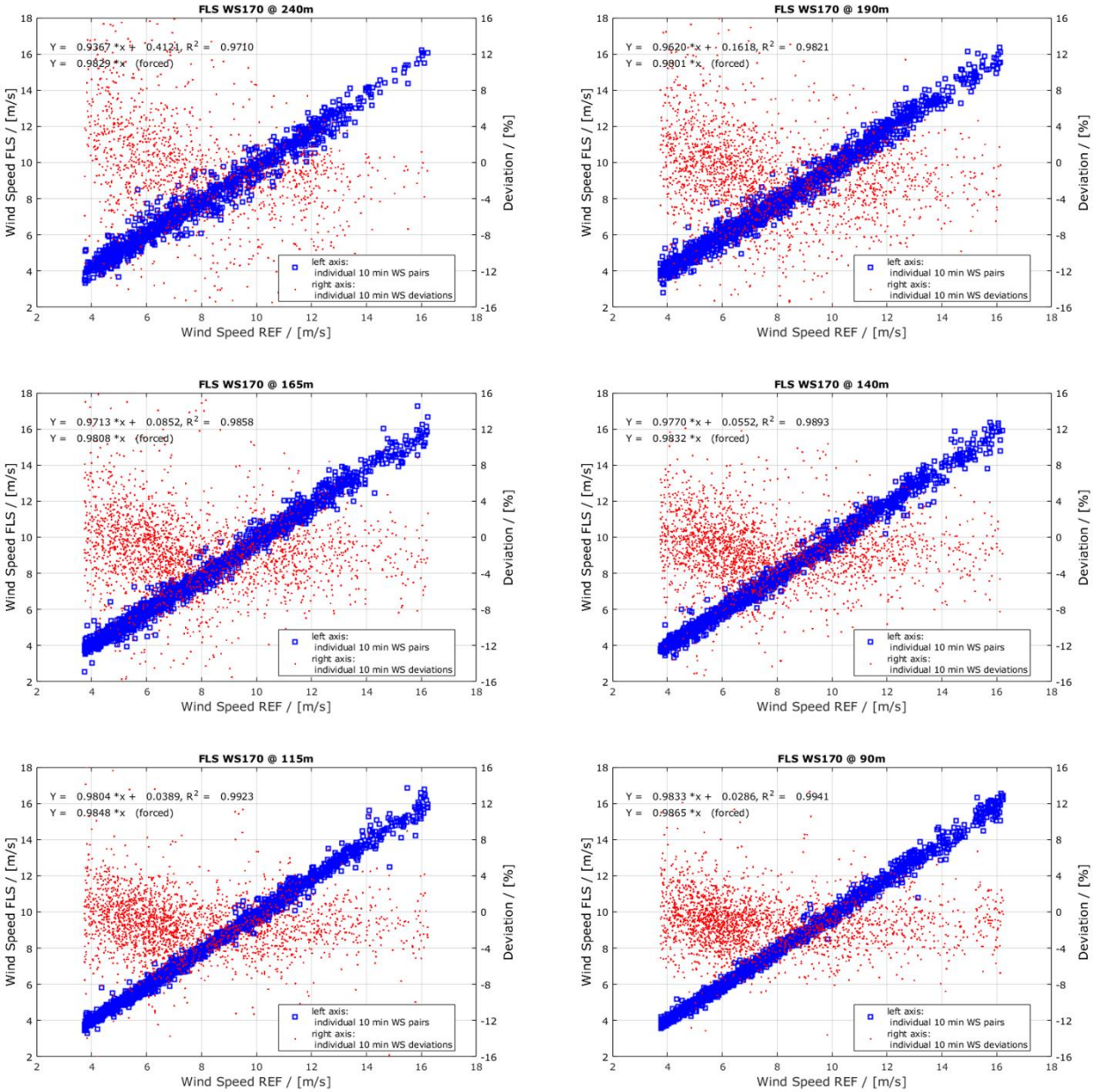


Figure 5-3 Regression plot of wind direction comparisons

6 PERFORMANCE VERIFICATION ACCORDING TO IEC STANDARD, ANNEX L

This section presents verification results as defined in the IEC Standard. This approach is described in Section 3.2. DNV notes that due to the difference in bin size and bin centres defined by the OWA Roadmap and the IEC, the counts and statistics reported in this section are slightly different than reported in Section 5.

Figure 6-1 shows scatter plots of the wind speed comparison based on 10-minute averages between the data pairs of the FLS and the REF at all comparison heights respectively. In addition, the 10-minute averaged deviation for each data point of the two data sets is plotted.



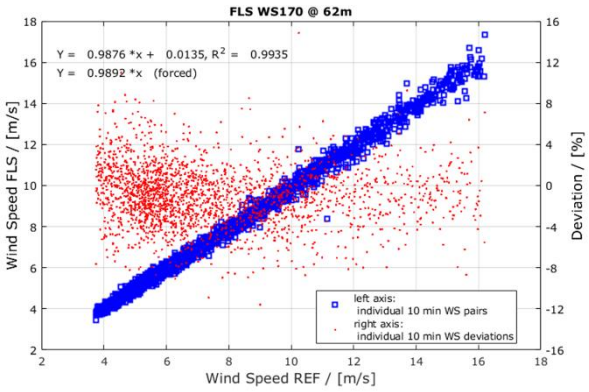


Figure 6-1 Comparison of the horizontal wind speed component

Table 6-1 Statistical parameters of wind speed deviation

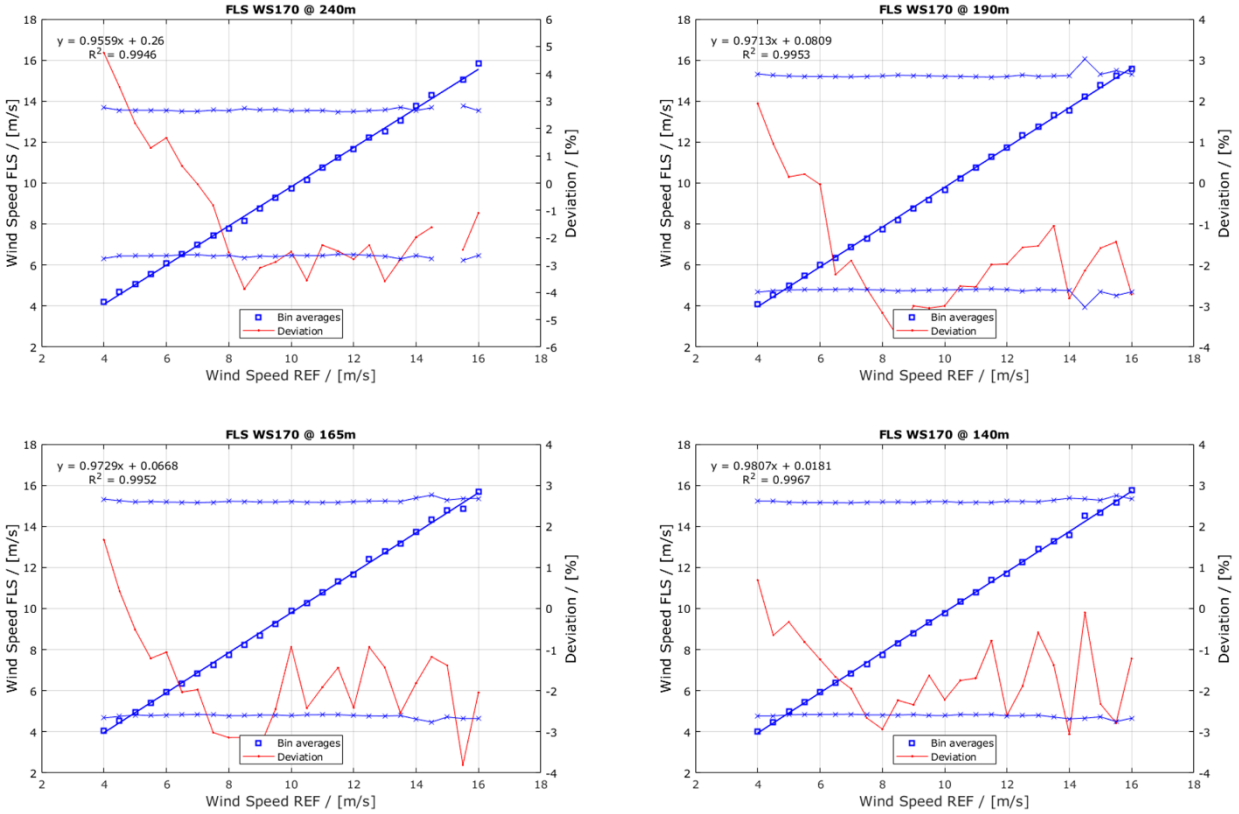
Height level	Coefficient of Determination	Mean Deviation		STD of Deviations	Data Points
[m]	(R^2)	[m/s]	[%]	[%]	#
240	0.9710	-0.09	-0.36%	6.78%	1397
190	0.9821	-0.14	-1.38%	5.40%	2001
165	0.9858	-0.14	-1.57%	4.73%	2175
140	0.9893	-0.13	-1.44%	3.90%	2212
115	0.9923	-0.11	-1.33%	3.25%	2230
90	0.9941	-0.10	-1.19%	2.87%	2263
62	0.9935	-0.08	-0.97%	2.87%	2259

6.1 Performance verification uncertainty

The IEC database requirement for the lidar verification of 180 hours between 4 m/s and 16 m/s has been met for each comparison height. The additional database requirement of a minimum of 3 data pairs in each 0.5 m/s wind speed bin has been fulfilled for each comparison height.

The bin-averaged wind speeds of the lidar and the reference measurements are shown in Figure 6-2. The bin-averaged deviation, shown as a solid red line in the figures below, can be compared to the standard uncertainty of the REF with the binned verification statistical uncertainty. The low sample size at higher wind speeds has resulted in a greater verification uncertainty.

The correlation coefficient, mean deviation, and standard deviation of the deviations are provided in Table 6-2 through Table 6-8. The relative deviation of the data pairs are calculated in relation to the REF wind speeds as the reference.



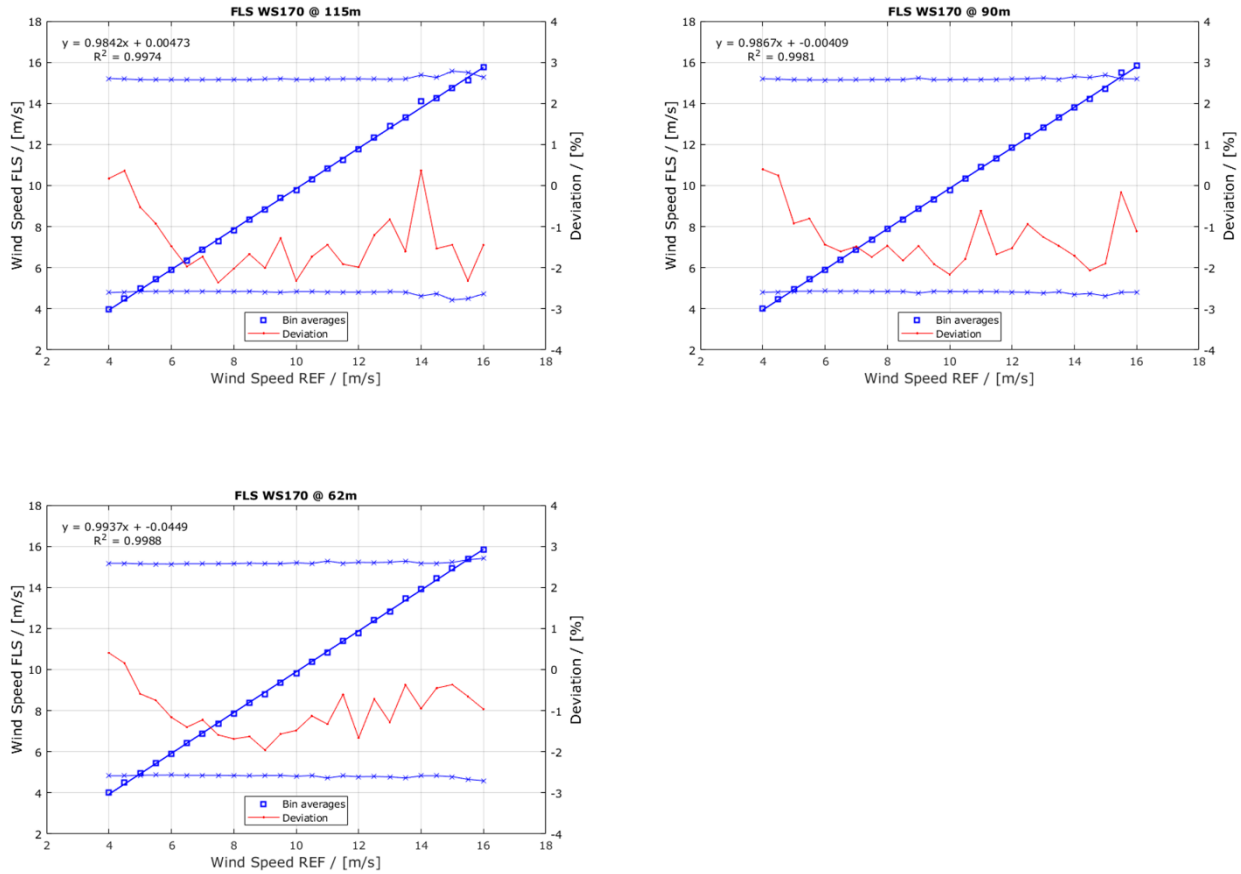


Figure 6-2 Bin-wise comparison of the horizontal wind speed component

Table 6-2 Uncertainty calculation at 240 m

WS170 height 240 m													
BIN lower [m/s]	BIN upper [m/s]	# of 10 min data sets	V_{rsd} [m/s]	V_{ref} [m/s]	V_{maxrsd} [m/s]	V_{minrsd} [m/s]	Std_{Vrsd} [m/s]	$Std_{Vrsd}/\sqrt{n}$ [m/s]	Mean deviation [%]	RSD Mounting uncertainty [%]	Separation Uncertainty [%]	V_{ref} Uncertainty [%]	**V_{RSD} Uncertainty (k=1) [%]**
3.75	4.25	65	4.21	4.02	5.18	3.35	0.35	0.044	4.77%	0.50%	0.01%	2.51%	**5.51%**
4.25	4.75	113	4.69	4.53	5.96	3.80	0.38	0.036	3.51%	0.50%	0.01%	2.51%	**4.41%**
4.75	5.25	95	5.07	4.96	5.94	3.67	0.38	0.039	2.19%	0.50%	0.01%	2.51%	**3.46%**
5.25	5.75	118	5.55	5.48	8.48	4.59	0.46	0.042	1.29%	0.50%	0.01%	2.51%	**2.96%**
5.75	6.25	102	6.08	5.99	7.76	5.08	0.46	0.045	1.66%	0.50%	0.01%	2.51%	**3.14%**
6.25	6.75	94	6.54	6.50	8.08	5.44	0.39	0.040	0.63%	0.50%	0.01%	2.51%	**2.71%**
6.75	7.25	109	7.00	7.00	8.70	5.82	0.44	0.042	-0.04%	0.50%	0.01%	2.51%	**2.63%**
7.25	7.75	85	7.45	7.51	9.50	5.99	0.54	0.059	-0.82%	0.50%	0.01%	2.51%	**2.80%**
7.75	8.25	70	7.79	7.99	9.51	6.08	0.46	0.055	-2.53%	0.50%	0.01%	2.51%	**3.67%**
8.25	8.75	57	8.17	8.49	9.48	6.84	0.62	0.082	-3.87%	0.50%	0.01%	2.51%	**4.75%**
8.75	9.25	50	8.76	9.04	9.99	7.57	0.50	0.071	-3.10%	0.50%	0.01%	2.51%	**4.10%**
9.25	9.75	51	9.27	9.54	10.84	7.83	0.59	0.082	-2.89%	0.50%	0.01%	2.51%	**3.96%**
9.75	10.25	56	9.74	9.99	10.86	8.20	0.50	0.067	-2.51%	0.50%	0.01%	2.51%	**3.65%**
10.25	10.75	51	10.14	10.51	11.41	8.67	0.53	0.075	-3.57%	0.50%	0.01%	2.51%	**4.45%**
10.75	11.25	41	10.75	10.99	11.82	9.24	0.51	0.080	-2.27%	0.50%	0.01%	2.51%	**3.50%**
11.25	11.75	59	11.25	11.53	12.01	10.09	0.45	0.058	-2.49%	0.50%	0.01%	2.51%	**3.61%**
11.75	12.25	69	11.66	12.00	12.73	10.05	0.55	0.066	-2.79%	0.50%	0.01%	2.51%	**3.83%**
12.25	12.75	39	12.21	12.49	13.05	10.79	0.54	0.086	-2.27%	0.50%	0.01%	2.51%	**3.49%**
12.75	13.25	28	12.52	12.99	13.45	11.44	0.54	0.103	-3.59%	0.50%	0.01%	2.51%	**4.49%**
13.25	13.75	13	13.07	13.44	14.12	12.22	0.53	0.147	-2.79%	0.50%	0.01%	2.51%	**3.95%**
13.75	14.25	14	13.77	14.05	14.16	13.03	0.37	0.100	-1.98%	0.50%	0.01%	2.51%	**3.32%**
14.25	14.75	4	14.28	14.52	14.57	13.87	0.30	0.151	-1.62%	0.50%	0.01%	2.51%	**3.21%**
14.75	15.25	2											
15.25	15.75	5	15.06	15.44	15.37	14.37	0.42	0.190	-2.45%	0.50%	0.01%	2.51%	**3.76%**
15.75	16.25	7	15.85	16.02	16.20	15.48	0.29	0.109	-1.09%	0.50%	0.01%	2.51%	**2.87%**

Table 6-3 Uncertainty calculation at 190 m

WS170 height 190 m													
BIN lower [m/s]	BIN upper [m/s]	# of 10 min data sets	V_{rsd} [m/s]	V_{ref} [m/s]	V_{maxrsd} [m/s]	V_{minrsd} [m/s]	Std_{Vrsd} [m/s]	$Std_{Vrsd}/\sqrt{n}$ [m/s]	Mean deviation [%]	RSD Mounting uncertainty [%]	Separation Uncertainty [%]	V_{ref} Uncertainty [%]	**V_{RSD} Uncertainty (k=1) [%]**
3.75	4.25	115	4.10	4.03	5.26	2.80	0.33	0.031	1.94%	0.50%	0.01%	2.51%	**3.30%**
4.25	4.75	129	4.55	4.51	5.67	3.72	0.32	0.028	0.96%	0.50%	0.01%	2.51%	**2.80%**
4.75	5.25	148	4.99	4.98	6.42	3.93	0.32	0.027	0.15%	0.50%	0.01%	2.51%	**2.62%**
5.25	5.75	150	5.49	5.48	7.73	4.66	0.33	0.027	0.22%	0.50%	0.01%	2.51%	**2.61%**
5.75	6.25	171	6.02	6.02	7.79	4.91	0.37	0.028	-0.03%	0.50%	0.01%	2.51%	**2.60%**
6.25	6.75	147	6.35	6.50	7.98	4.97	0.34	0.028	-2.23%	0.50%	0.01%	2.51%	**3.42%**
6.75	7.25	160	6.86	7.00	8.09	5.92	0.36	0.028	-1.89%	0.50%	0.01%	2.51%	**3.21%**
7.25	7.75	115	7.29	7.48	8.63	5.97	0.39	0.036	-2.58%	0.50%	0.01%	2.51%	**3.67%**
7.75	8.25	95	7.72	7.98	9.34	6.54	0.41	0.042	-3.17%	0.50%	0.01%	2.51%	**4.11%**
8.25	8.75	79	8.18	8.50	9.59	7.15	0.47	0.053	-3.76%	0.50%	0.01%	2.51%	**4.60%**
8.75	9.25	71	8.74	9.01	9.97	7.67	0.45	0.053	-3.00%	0.50%	0.01%	2.51%	**3.99%**
9.25	9.75	78	9.18	9.47	10.17	8.09	0.46	0.052	-3.05%	0.50%	0.01%	2.51%	**4.02%**
9.75	10.25	76	9.67	9.97	10.89	8.45	0.43	0.050	-3.00%	0.50%	0.01%	2.51%	**3.97%**
10.25	10.75	67	10.23	10.50	11.44	9.28	0.42	0.051	-2.51%	0.50%	0.01%	2.51%	**3.62%**
10.75	11.25	72	10.74	11.02	12.06	9.88	0.38	0.045	-2.53%	0.50%	0.01%	2.51%	**3.62%**
11.25	11.75	87	11.27	11.50	12.27	10.29	0.40	0.043	-1.99%	0.50%	0.01%	2.51%	**3.26%**
11.75	12.25	61	11.74	11.98	12.70	10.75	0.42	0.054	-1.97%	0.50%	0.01%	2.51%	**3.26%**
12.25	12.75	47	12.32	12.52	14.12	11.36	0.55	0.080	-1.57%	0.50%	0.01%	2.51%	**3.07%**
12.75	13.25	33	12.76	12.95	13.40	11.92	0.36	0.063	-1.53%	0.50%	0.01%	2.51%	**3.02%**
13.25	13.75	24	13.30	13.44	14.01	12.58	0.35	0.071	-1.04%	0.50%	0.01%	2.51%	**2.81%**
13.75	14.25	24	13.55	13.95	14.63	12.97	0.40	0.081	-2.81%	0.50%	0.01%	2.51%	**3.85%**
14.25	14.75	8	14.22	14.53	15.16	13.26	0.67	0.238	-2.13%	0.50%	0.01%	2.51%	**3.73%**
14.75	15.25	21	14.77	15.01	16.14	13.92	0.48	0.105	-1.59%	0.50%	0.01%	2.51%	**3.09%**
15.25	15.75	10	15.24	15.46	16.03	14.49	0.49	0.155	-1.43%	0.50%	0.01%	2.51%	**3.11%**
15.75	16.25	13	15.56	16.00	16.38	14.93	0.41	0.114	-2.72%	0.50%	0.01%	2.51%	**3.80%**

Table 6-4 Uncertainty calculation at 165 m

WS170 height 165 m													
BIN lower [m/s]	BIN upper [m/s]	# of 10 min data sets	V_{rsd} [m/s]	V_{ref} [m/s]	V_{maxrsd} [m/s]	V_{minrsd} [m/s]	Std_{Vrsd} [m/s]	$Std_{Vrsd}/\sqrt{n}$ [m/s]	Mean deviation [%]	RSD Mounting uncertainty [%]	Separation Uncertainty [%]	V_{ref} Uncertainty [%]	**V_{RSD} Uncertainty (k=1) [%]**
3.75	4.25	119	4.06	4.00	5.38	2.56	0.34	0.031	1.67%	0.50%	0.01%	2.51%	**3.15%**
4.25	4.75	135	4.54	4.52	6.41	3.81	0.32	0.028	0.42%	0.50%	0.01%	2.51%	**2.66%**
4.75	5.25	155	4.97	5.00	5.65	4.06	0.26	0.021	-0.51%	0.50%	0.01%	2.51%	**2.64%**
5.25	5.75	161	5.42	5.49	7.24	3.94	0.35	0.028	-1.21%	0.50%	0.01%	2.51%	**2.88%**
5.75	6.25	183	5.93	6.00	7.23	4.52	0.34	0.025	-1.06%	0.50%	0.01%	2.51%	**2.80%**
6.25	6.75	184	6.36	6.49	7.39	4.57	0.33	0.025	-2.03%	0.50%	0.01%	2.51%	**3.29%**
6.75	7.25	178	6.83	6.97	7.64	5.89	0.30	0.022	-1.97%	0.50%	0.01%	2.51%	**3.25%**
7.25	7.75	121	7.26	7.49	8.61	6.31	0.32	0.029	-3.02%	0.50%	0.01%	2.51%	**3.98%**
7.75	8.25	108	7.73	7.98	9.40	7.00	0.43	0.042	-3.14%	0.50%	0.01%	2.51%	**4.09%**
8.25	8.75	86	8.24	8.50	9.72	7.17	0.40	0.043	-3.14%	0.50%	0.01%	2.51%	**4.08%**
8.75	9.25	80	8.69	8.99	9.43	7.69	0.33	0.037	-3.36%	0.50%	0.01%	2.51%	**4.25%**
9.25	9.75	84	9.26	9.50	10.33	8.29	0.36	0.039	-2.45%	0.50%	0.01%	2.51%	**3.56%**
9.75	10.25	70	9.87	9.96	10.92	9.13	0.43	0.051	-0.93%	0.50%	0.01%	2.51%	**2.77%**
10.25	10.75	77	10.25	10.50	11.13	9.21	0.35	0.040	-2.42%	0.50%	0.01%	2.51%	**3.55%**
10.75	11.25	84	10.78	10.99	12.04	9.95	0.37	0.040	-1.91%	0.50%	0.01%	2.51%	**3.22%**
11.25	11.75	86	11.32	11.48	12.38	10.58	0.38	0.041	-1.44%	0.50%	0.01%	2.51%	**2.96%**
11.75	12.25	51	11.67	11.96	12.64	10.74	0.41	0.057	-2.41%	0.50%	0.01%	2.51%	**3.55%**
12.25	12.75	46	12.41	12.53	13.71	11.58	0.46	0.068	-0.94%	0.50%	0.01%	2.51%	**2.78%**
12.75	13.25	47	12.80	12.99	13.92	11.55	0.49	0.072	-1.44%	0.50%	0.01%	2.51%	**2.99%**
13.25	13.75	33	13.14	13.49	13.82	11.98	0.39	0.067	-2.54%	0.50%	0.01%	2.51%	**3.64%**
13.75	14.25	15	13.74	13.99	14.35	12.93	0.46	0.118	-1.82%	0.50%	0.01%	2.51%	**3.25%**
14.25	14.75	18	14.33	14.50	16.02	12.45	0.65	0.153	-1.18%	0.50%	0.01%	2.51%	**3.01%**
14.75	15.25	18	14.77	14.98	15.46	13.90	0.42	0.098	-1.39%	0.50%	0.01%	2.51%	**2.99%**
15.25	15.75	15	14.84	15.43	15.61	14.09	0.48	0.124	-3.80%	0.50%	0.01%	2.51%	**4.66%**
15.75	16.25	21	15.67	16.00	17.26	14.56	0.59	0.129	-2.04%	0.50%	0.01%	2.51%	**3.38%**

Table 6-5 Uncertainty calculation at 140 m

WS170 height 140 m													
BIN lower [m/s]	BIN upper [m/s]	# of 10 min data sets	V_{rsd} [m/s]	V_{ref} [m/s]	V_{maxrsd} [m/s]	V_{minrsd} [m/s]	Std_{Vrsd} [m/s]	$Std_{Vrsd}/\sqrt{n}$ [m/s]	Mean deviation [%]	RSD Mounting uncertainty [%]	Separation Uncertainty [%]	V_{ref} Uncertainty [%]	**V_{RSD} Uncertainty (k=1) [%]**
3.75	4.25	119	4.01	3.98	5.14	3.45	0.25	0.023	0.69%	0.50%	0.01%	2.51%	**2.71%**
4.25	4.75	146	4.48	4.51	5.99	3.34	0.30	0.025	-0.65%	0.50%	0.01%	2.51%	**2.70%**
4.75	5.25	167	4.98	4.99	5.92	4.23	0.25	0.019	-0.32%	0.50%	0.01%	2.51%	**2.61%**
5.25	5.75	184	5.45	5.49	6.55	4.52	0.25	0.018	-0.81%	0.50%	0.01%	2.51%	**2.71%**
5.75	6.25	180	5.94	6.01	7.14	5.18	0.26	0.019	-1.24%	0.50%	0.01%	2.51%	**2.86%**
6.25	6.75	192	6.38	6.49	7.49	5.86	0.26	0.018	-1.67%	0.50%	0.01%	2.51%	**3.07%**
6.75	7.25	181	6.84	6.98	7.68	6.17	0.25	0.019	-1.95%	0.50%	0.01%	2.51%	**3.23%**
7.25	7.75	130	7.27	7.47	8.26	6.07	0.33	0.029	-2.66%	0.50%	0.01%	2.51%	**3.71%**
7.75	8.25	92	7.75	7.98	8.54	6.70	0.31	0.032	-2.93%	0.50%	0.01%	2.51%	**3.92%**
8.25	8.75	82	8.31	8.50	9.60	7.41	0.32	0.035	-2.24%	0.50%	0.01%	2.51%	**3.42%**
8.75	9.25	88	8.78	8.99	9.76	8.03	0.29	0.031	-2.34%	0.50%	0.01%	2.51%	**3.49%**
9.25	9.75	72	9.33	9.48	10.60	8.35	0.39	0.046	-1.63%	0.50%	0.01%	2.51%	**3.07%**
9.75	10.25	72	9.76	9.98	10.93	8.78	0.43	0.050	-2.22%	0.50%	0.01%	2.51%	**3.43%**
10.25	10.75	89	10.34	10.53	11.14	9.25	0.33	0.035	-1.75%	0.50%	0.01%	2.51%	**3.12%**
10.75	11.25	82	10.80	10.99	11.81	9.68	0.38	0.042	-1.69%	0.50%	0.01%	2.51%	**3.09%**
11.25	11.75	73	11.38	11.46	12.16	10.72	0.32	0.038	-0.78%	0.50%	0.01%	2.51%	**2.70%**
11.75	12.25	45	11.71	12.02	12.41	10.18	0.42	0.063	-2.60%	0.50%	0.01%	2.51%	**3.69%**
12.25	12.75	55	12.26	12.50	13.42	11.19	0.46	0.063	-1.89%	0.50%	0.01%	2.51%	**3.22%**
12.75	13.25	38	12.92	12.99	13.74	11.71	0.36	0.058	-0.59%	0.50%	0.01%	2.51%	**2.66%**
13.25	13.75	33	13.29	13.48	14.22	11.80	0.51	0.089	-1.38%	0.50%	0.01%	2.51%	**2.98%**
13.75	14.25	18	13.59	14.01	14.47	12.97	0.49	0.116	-3.05%	0.50%	0.01%	2.51%	**4.07%**
14.25	14.75	23	14.50	14.52	15.89	13.73	0.53	0.111	-0.10%	0.50%	0.01%	2.51%	**2.67%**
14.75	15.25	22	14.66	15.01	15.78	13.79	0.45	0.095	-2.32%	0.50%	0.01%	2.51%	**3.52%**
15.25	15.75	12	15.14	15.58	15.97	13.81	0.55	0.160	-2.78%	0.50%	0.01%	2.51%	**3.93%**
15.75	16.25	17	15.75	15.94	16.36	14.66	0.50	0.121	-1.22%	0.50%	0.01%	2.51%	**2.94%**

Table 6-6 Uncertainty calculation at 115 m

WS170 height 115 m													
BIN lower [m/s]	BIN upper [m/s]	# of 10 min data sets	V_{rsd} [m/s]	V_{ref} [m/s]	V_{maxrsd} [m/s]	V_{minrsd} [m/s]	Std_{Vrsd} [m/s]	$Std_{Vrsd}/\sqrt{n}$ [m/s]	Mean deviation [%]	RSD Mounting uncertainty [%]	Separation Uncertainty [%]	V_{ref} Uncertainty [%]	**V_{RSD} Uncertainty (k=1) [%]**
3.75	4.25	121	3.98	3.97	4.60	3.30	0.23	0.021	0.17%	0.50%	0.01%	2.51%	**2.62%**
4.25	4.75	143	4.52	4.50	5.83	4.01	0.23	0.020	0.36%	0.50%	0.01%	2.51%	**2.62%**
4.75	5.25	182	4.98	5.00	5.62	4.22	0.20	0.015	-0.52%	0.50%	0.01%	2.51%	**2.63%**
5.25	5.75	185	5.44	5.50	6.11	4.73	0.22	0.016	-0.93%	0.50%	0.01%	2.51%	**2.74%**
5.75	6.25	203	5.91	6.00	6.53	5.29	0.23	0.016	-1.48%	0.50%	0.01%	2.51%	**2.97%**
6.25	6.75	210	6.36	6.49	7.15	5.61	0.26	0.018	-1.97%	0.50%	0.01%	2.51%	**3.24%**
6.75	7.25	168	6.86	6.98	7.61	5.91	0.25	0.019	-1.73%	0.50%	0.01%	2.51%	**3.10%**
7.25	7.75	121	7.29	7.47	7.91	6.69	0.25	0.023	-2.37%	0.50%	0.01%	2.51%	**3.50%**
7.75	8.25	75	7.82	7.98	8.33	7.39	0.21	0.024	-2.02%	0.50%	0.01%	2.51%	**3.28%**
8.25	8.75	99	8.36	8.50	8.87	7.85	0.24	0.024	-1.67%	0.50%	0.01%	2.51%	**3.07%**
8.75	9.25	76	8.83	9.01	10.24	8.31	0.31	0.036	-2.01%	0.50%	0.01%	2.51%	**3.28%**
9.25	9.75	74	9.39	9.51	10.59	8.21	0.38	0.044	-1.28%	0.50%	0.01%	2.51%	**2.90%**
9.75	10.25	84	9.79	10.02	10.74	8.79	0.32	0.035	-2.32%	0.50%	0.01%	2.51%	**3.47%**
10.25	10.75	78	10.28	10.47	10.97	9.54	0.32	0.036	-1.73%	0.50%	0.01%	2.51%	**3.11%**
10.75	11.25	88	10.83	10.99	11.88	10.05	0.41	0.044	-1.44%	0.50%	0.01%	2.51%	**2.97%**
11.25	11.75	58	11.25	11.46	11.95	10.09	0.37	0.049	-1.91%	0.50%	0.01%	2.51%	**3.23%**
11.75	12.25	47	11.78	12.01	12.50	10.79	0.35	0.051	-1.99%	0.50%	0.01%	2.51%	**3.27%**
12.25	12.75	42	12.35	12.50	13.49	11.73	0.33	0.052	-1.21%	0.50%	0.01%	2.51%	**2.86%**
12.75	13.25	44	12.89	12.99	13.81	12.26	0.32	0.048	-0.83%	0.50%	0.01%	2.51%	**2.72%**
13.25	13.75	33	13.32	13.54	13.85	12.44	0.32	0.056	-1.60%	0.50%	0.01%	2.51%	**3.05%**
13.75	14.25	23	14.09	14.04	15.60	13.33	0.56	0.118	0.37%	0.50%	0.01%	2.51%	**2.72%**
14.25	14.75	19	14.24	14.46	15.07	13.51	0.38	0.088	-1.53%	0.50%	0.01%	2.51%	**3.05%**
14.75	15.25	16	14.74	14.96	15.43	12.48	0.67	0.167	-1.44%	0.50%	0.01%	2.51%	**3.15%**
15.25	15.75	14	15.11	15.47	16.87	14.09	0.60	0.159	-2.32%	0.50%	0.01%	2.51%	**3.61%**
15.75	16.25	27	15.77	16.00	16.78	14.21	0.53	0.101	-1.44%	0.50%	0.01%	2.51%	**3.01%**

Table 6-7 Uncertainty calculation at 90 m

WS170 height 90 m													
BIN lower [m/s]	BIN upper [m/s]	# of 10 min data sets	V_{rsd} [m/s]	V_{ref} [m/s]	V_{maxrsd} [m/s]	V_{minrsd} [m/s]	Std_{Vrsd} [m/s]	$Std_{Vrsd}/\sqrt{n}$ [m/s]	Mean deviation [%]	RSD Mounting uncertainty [%]	Separation Uncertainty [%]	V_{ref} Uncertainty [%]	**V_{RSD} Uncertainty (k=1) [%]**
3.75	4.25	112	4.01	3.99	4.64	3.57	0.20	0.019	0.39%	0.50%	0.01%	2.51%	**2.63%**
4.25	4.75	148	4.48	4.47	5.19	3.95	0.23	0.019	0.24%	0.50%	0.01%	2.51%	**2.60%**
4.75	5.25	185	4.95	5.00	5.45	4.25	0.19	0.014	-0.92%	0.50%	0.01%	2.51%	**2.73%**
5.25	5.75	218	5.44	5.49	6.00	4.68	0.21	0.014	-0.80%	0.50%	0.01%	2.51%	**2.69%**
5.75	6.25	239	5.91	5.99	6.52	5.29	0.22	0.014	-1.44%	0.50%	0.01%	2.51%	**2.95%**
6.25	6.75	191	6.39	6.49	7.31	5.87	0.23	0.017	-1.60%	0.50%	0.01%	2.51%	**3.03%**
6.75	7.25	156	6.88	6.98	7.47	6.25	0.21	0.017	-1.48%	0.50%	0.01%	2.51%	**2.97%**
7.25	7.75	111	7.36	7.49	7.94	6.76	0.24	0.023	-1.74%	0.50%	0.01%	2.51%	**3.11%**
7.75	8.25	91	7.90	8.02	8.48	7.34	0.23	0.025	-1.47%	0.50%	0.01%	2.51%	**2.97%**
8.25	8.75	91	8.35	8.51	8.91	7.73	0.24	0.025	-1.82%	0.50%	0.01%	2.51%	**3.16%**
8.75	9.25	67	8.88	9.01	10.41	8.17	0.42	0.051	-1.47%	0.50%	0.01%	2.51%	**3.01%**
9.25	9.75	92	9.31	9.49	9.80	8.70	0.23	0.024	-1.91%	0.50%	0.01%	2.51%	**3.21%**
9.75	10.25	85	9.78	10.00	10.48	8.49	0.30	0.032	-2.17%	0.50%	0.01%	2.51%	**3.37%**
10.25	10.75	72	10.33	10.51	11.26	9.60	0.31	0.036	-1.79%	0.50%	0.01%	2.51%	**3.14%**
10.75	11.25	71	10.92	10.99	11.88	10.24	0.31	0.037	-0.61%	0.50%	0.01%	2.51%	**2.65%**
11.25	11.75	52	11.31	11.50	11.90	10.75	0.30	0.042	-1.67%	0.50%	0.01%	2.51%	**3.08%**
11.75	12.25	39	11.83	12.01	12.66	11.30	0.31	0.050	-1.52%	0.50%	0.01%	2.51%	**3.01%**
12.25	12.75	44	12.39	12.51	13.17	11.50	0.37	0.056	-0.94%	0.50%	0.01%	2.51%	**2.76%**
12.75	13.25	45	12.83	12.99	13.87	10.79	0.49	0.073	-1.25%	0.50%	0.01%	2.51%	**2.91%**
13.25	13.75	27	13.30	13.49	13.74	12.77	0.26	0.051	-1.47%	0.50%	0.01%	2.51%	**2.97%**
13.75	14.25	24	13.79	14.03	14.67	12.85	0.48	0.099	-1.71%	0.50%	0.01%	2.51%	**3.16%**
14.25	14.75	19	14.23	14.54	15.04	13.48	0.38	0.087	-2.07%	0.50%	0.01%	2.51%	**3.35%**
14.75	15.25	12	14.70	14.98	15.61	14.12	0.43	0.125	-1.90%	0.50%	0.01%	2.51%	**3.30%**
15.25	15.75	36	15.48	15.51	16.32	14.48	0.43	0.071	-0.16%	0.50%	0.01%	2.51%	**2.60%**
15.75	16.25	36	15.82	16.00	16.55	15.04	0.40	0.067	-1.11%	0.50%	0.01%	2.51%	**2.82%**

Table 6-8 Uncertainty calculation at 62 m

WS170 height 62 m													
BIN lower [m/s]	BIN upper [m/s]	# of 10 min data sets	V_{rsd} [m/s]	V_{ref} [m/s]	V_{maxrsd} [m/s]	V_{minrsd} [m/s]	Std_{Vrsd} [m/s]	$Std_{Vrsd}/\sqrt{n}$ [m/s]	Mean deviation [%]	RSD Mounting uncertainty [%]	Separation Uncertainty [%]	V_{ref} Uncertainty [%]	**V_{RSD} Uncertainty (k=1) [%]**
3.75	4.25	132	4.02	4.01	4.41	3.46	0.18	0.015	0.41%	0.50%	0.01%	2.51%	**2.62%**
4.25	4.75	153	4.50	4.50	5.12	4.02	0.22	0.018	0.16%	0.50%	0.01%	2.51%	**2.59%**
4.75	5.25	214	4.97	5.00	5.56	4.43	0.20	0.013	-0.59%	0.50%	0.01%	2.51%	**2.64%**
5.25	5.75	260	5.45	5.49	6.05	5.00	0.20	0.013	-0.75%	0.50%	0.01%	2.51%	**2.68%**
5.75	6.25	222	5.91	5.98	6.43	5.35	0.20	0.013	-1.16%	0.50%	0.01%	2.51%	**2.82%**
6.25	6.75	173	6.42	6.51	7.11	5.71	0.25	0.019	-1.40%	0.50%	0.01%	2.51%	**2.93%**
6.75	7.25	139	6.89	6.98	7.49	6.39	0.24	0.020	-1.22%	0.50%	0.01%	2.51%	**2.85%**
7.25	7.75	112	7.36	7.48	8.00	6.56	0.23	0.022	-1.59%	0.50%	0.01%	2.51%	**3.03%**
7.75	8.25	94	7.84	7.98	8.35	7.10	0.25	0.026	-1.69%	0.50%	0.01%	2.51%	**3.08%**
8.25	8.75	85	8.38	8.52	9.39	7.79	0.31	0.033	-1.63%	0.50%	0.01%	2.51%	**3.06%**
8.75	9.25	81	8.81	8.98	9.31	7.96	0.27	0.030	-1.96%	0.50%	0.01%	2.51%	**3.24%**
9.25	9.75	90	9.37	9.52	10.18	8.84	0.28	0.029	-1.57%	0.50%	0.01%	2.51%	**3.02%**
9.75	10.25	67	9.82	9.97	11.76	9.26	0.37	0.046	-1.48%	0.50%	0.01%	2.51%	**2.99%**
10.25	10.75	81	10.38	10.50	11.21	9.54	0.31	0.034	-1.13%	0.50%	0.01%	2.51%	**2.82%**
10.75	11.25	48	10.83	10.98	11.71	8.39	0.51	0.073	-1.33%	0.50%	0.01%	2.51%	**2.96%**
11.25	11.75	42	11.40	11.46	11.90	10.65	0.28	0.044	-0.61%	0.50%	0.01%	2.51%	**2.66%**
11.75	12.25	42	11.79	11.99	12.70	10.87	0.40	0.062	-1.67%	0.50%	0.01%	2.51%	**3.10%**
12.25	12.75	41	12.40	12.49	13.20	11.33	0.38	0.060	-0.72%	0.50%	0.01%	2.51%	**2.70%**
12.75	13.25	33	12.81	12.97	13.73	12.02	0.40	0.070	-1.28%	0.50%	0.01%	2.51%	**2.91%**
13.25	13.75	32	13.46	13.51	14.98	12.62	0.50	0.089	-0.37%	0.50%	0.01%	2.51%	**2.67%**
13.75	14.25	26	13.90	14.03	14.67	13.44	0.27	0.053	-0.95%	0.50%	0.01%	2.51%	**2.76%**
14.25	14.75	27	14.43	14.50	15.14	13.96	0.28	0.055	-0.45%	0.50%	0.01%	2.51%	**2.63%**
14.75	15.25	27	14.94	14.99	15.75	14.01	0.39	0.076	-0.37%	0.50%	0.01%	2.51%	**2.64%**
15.25	15.75	23	15.40	15.50	16.71	14.11	0.58	0.121	-0.66%	0.50%	0.01%	2.51%	**2.76%**
15.75	16.25	15	15.84	15.99	17.35	15.29	0.55	0.143	-0.96%	0.50%	0.01%	2.51%	**2.88%**

7 IMPORTANT REMARKS AND LIMITATIONS

The reported FLS verification presents a reasonable means to assure overall system integrity of the floating lidar unit before deployment and is meant to give an indication of the quality of wind data produced by the floating lidar unit. Any statement given in the context of system integrity and data quality related results within this report are limited to the given test site conditions that include sea states and meteorological conditions observed during the verification.

The IEC-compliant bin-wise uncertainty results provided in this report may serve as a traceable means to judge the uncertainty of the lidar unit.

In general, DNV recommends that a floating lidar unit undergoes a pre-deployment verification test no greater than one year before its application deployment. A post-deployment verification of a FLS maybe necessary when:

- Inconsistencies in the data captured during the wind resource campaign are observed;
- Inconsistencies in buoy operation are observed; or
- Known or assumed incidents to the buoy or floating lidar measurement system have occurred.

Otherwise, a pre-deployment verification campaign may be considered sufficient.

8 OBSERVATIONS AND RECOMMENDATIONS

Concurrent FLS and REF measurements were conducted to validate FLS WS170. Measurement heights between 62 m and 240 m were available for wind speed correlations. The duration of the verification was 21.3 days. The test period and wind data coverage were considered sufficient to evaluate the FLS against the OWA Roadmap.

WS170 has demonstrated its capability to produce accurate wind speed and direction data across the range of sea states and meteorological conditions experienced in this verification that includes significant wave heights observed by the Buoy of up to 3.82 m (and 6.17 m for maximum wave height) and wind speeds recorded at REF of up to 25.1 m/s at 62 m and 28.3 m/s at 250 m.

DNV recommends that care be taken with respect to the formal use of floating lidar turbulence and extreme wind speed measurements as they are known to be different from classical anemometry measurements. DNV notes that good measurement and data collection practices need to be maintained for all wind speed measurements, be they lidar or more conventional anemometry. Therefore, special care needs to be exercised in the transportation, installation, and ongoing maintenance of the FLS as it may be exposed to a wide range of environmental conditions. 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 FLS installation and maintenance are instigated from the outset.

9 REFERENCES

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9. IEA Wind Recommended Practice 18: Floating Lidar Systems, First Edition, September 2017

10. “SEAWATCH WIND LIDAR BUOY WS170 OFFSHORE IN SITU VERIFICATION – Quality assessment of the Fugro Seawatch Wind Lidar Buoy WS170”, 10166838-R-1, Rev. A, DNV GL, 29 August 2019

10 GLOSSARY

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

Abbreviation Acronym	Meaning
AC	Acceptance Criterion
DGPS	Differential Global Positioning System
DNV	New company name, successor of legacy GL GH
IEC	International Electro-technical Commission
FLS	Floating Lidar System
GH-D	GL Garrad Hassan Deutschland GmbH
KPI	Key Performance Indicator
LPV	Lidar Performance Verification
MSL	Mean Sea Level
MWD	Mean Wind Direction
MWS	Mean Wind Speed
RSD	Remote Sensing Device
SL	actual Sea Level
SWLB	Seawatch Wind Lidar Buoy
TI	Turbulence Intensity
WD	Wind direction
WS	Wind speed

APPENDIX A KEY PERFORMANCE INDICATORS AND ACCEPTANCE CRITERIA

Table A-1 List of KPIs and ACs relevant for Wind Data Accuracy assessment according to [1]

KPI	Definition / Rationale	Acceptance Criteria [1]	
		Best Practice	Minimum
X_{mws}	**Mean Wind Speed – Slope** Slope returned from single variant regression with the regression analysis constrained to pass through the origin. A tolerance is imposed on the Slope value. Analysis shall be applied to wind speed ranges a) all above 2 m/s b) 4 to 16 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 Coefficient value. Analysis shall be applied to wind speed ranges a) all above 2 m/s b) 4 to 16 m/s given achieved data coverage requirements.	>0.98	>0.97
M_{mwd}	**Mean Wind Direction – Slope** Slope returned from a two-variant regression. A tolerance is imposed on the Slope value. Analysis shall be applied to a) all wind directions b) all wind speeds above 2 m/s regardless of coverage requirements.	0.97– 1.03	0.95 – 1.05
OFF_{mwd}	**Mean Wind Direction – Offset (absolute value)** (same as for M_{mwd})	< 5°	< 10°
R^2_{mwd}	**Mean Wind Direction – Coefficient of Determination** (same as for M_{mwd})	> 0.97	> 0.95

[1] Acceptance Criteria in the form of "**best practice**" and "**minimum**" allowable tolerances have been imposed on mean differences, slope and offset values as well as on coefficient of determination returned from each reference height for KPIs related to the primary parameters of interest; wind speed and wind direction. KPIs outside the best practice or minimum acceptance criteria are marked as "**deviation**".

APPENDIX B TIME SERIES OF WIND SPEED

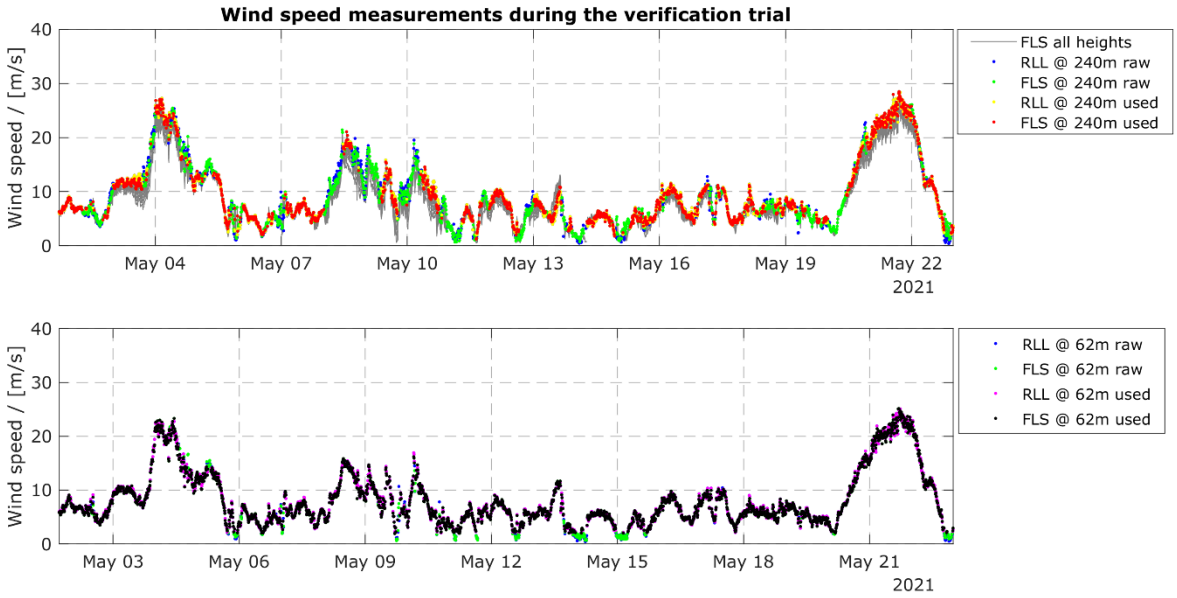

Figure 10-1 Wind Speed time series for 240 m (upper panel) and 62 m (lower panel).

APPENDIX C WIND DIRECTION

The scatter plots of wind direction below show wind directions for wind speed greater than 2 m/s. The red dots are the raw wind speeds and the green dots show the 180° ambiguity corrected data between REF and FLS measures.

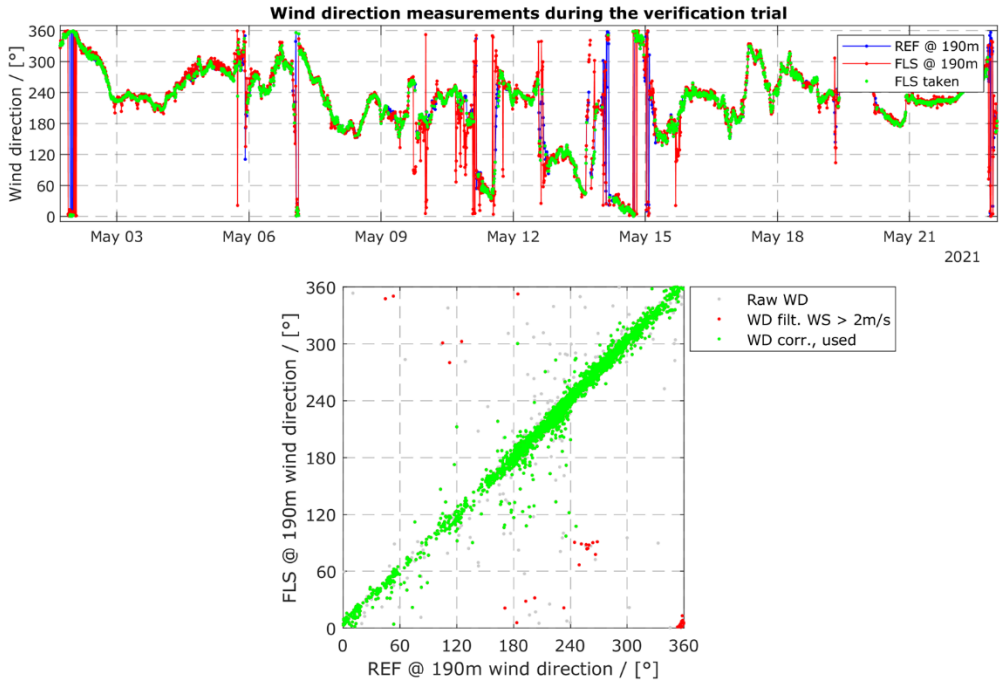

Figure 10-2 Wind direction time series and scatter plot of the FLS and REF at 190 m.

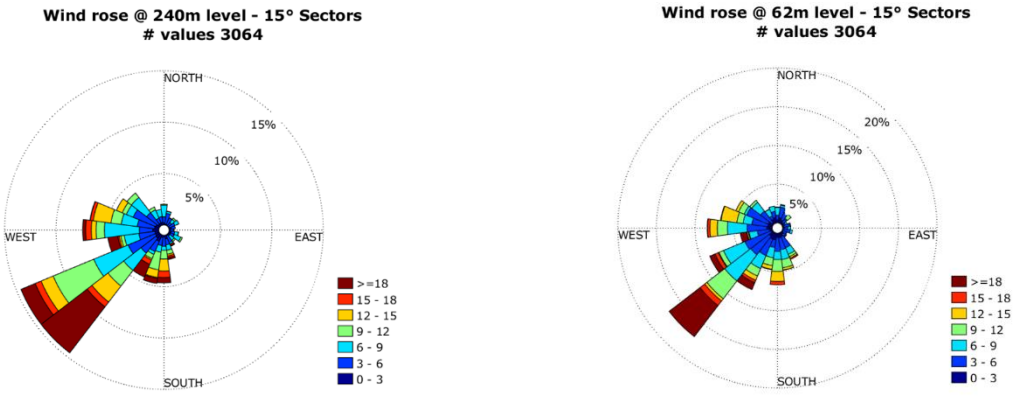

Figure 10-3 Wind rose and sector averaged wind speed distribution at 240 m and 62 m

Table D-1 Mean wave period and significant wave height distribution.

Joint occurrence of:

Tm02 Mean wave period (Tm02) (s)
Hm0 Significant wave height (m)

Location: LEG
SWLB S/N: WS170
Sampling interval: 10 minutes
Period start: 01/05/2021 17:10
Period end: 22/05/2021 23:40

Tm02 (s)	2	3	4	5	6	7	8	9	10	11	12	13	14	15	>=	SUM	% OF	SUM	CUM.	MIN.	AVE.	MAX.
Hm0 (m)	3	4	5	6	7	8	9	10	11	12	13	14	15	16	16		TOTAL	ACC.	PROB.			
0.0 - 0.5	39	460	186	1												686	22.4	686	0.22396	2.4	3.7	5.0
0.5 - 1.0	4	852	654	95												1605	52.4	2291	0.74796	2.5	4.1	5.6
1.0 - 1.5		101	46	108												255	8.3	2546	0.83121	3.3	4.5	5.6
1.5 - 2.0			46	77	1											124	4.0	2670	0.87169	4.1	5.1	6.0
2.0 - 2.5			10	122												132	4.3	2802	0.91479	4.5	5.3	6.0
2.5 - 3.0			5	108	2											115	3.8	2917	0.95233	4.9	5.4	6.1
3.0 - 3.5				100	30											130	4.2	3047	0.99478	5.3	5.7	6.3
3.5 - 4.0				5	10											15	0.5	3062	0.99967	5.7	6.1	6.4
4.0 - 4.5																		3062	0.99967			
4.5 - 5.0																		3062	0.99967			
5.0 - 5.5																		3062	0.99967			
5.5 - 6.0																		3062	0.99967			
6.0 - 6.5																		3062	0.99967			
6.5 - 7.0																		3062	0.99967			
>= 7.0																		3062	0.99967			
SUM	43	1413	947	616	43											3062	100	3062	0.99967	2.4	4.2	6.4
% OF TOTAL	1.4	46.1	30.9	20.1	1.4											100						
SUM ACCUM.	43	1456	2403	3019	3062	3062	3062	3062	3062	3062	3062	3062	3062	3062	3062	3062						
CUM. PROB.	0.01404	0.47535	0.78452	0.98563	0.99967	0.99967	0.99967	0.99967	0.99967	0.99967	0.99967	0.99967	0.99967	0.99967	0.99967	0.99967						
MIN. VALUE	0.22	0.17	0.22	0.42	1.97											0.17						
AVE. VALUE	0.38	0.62	0.75	2.04	3.30											0.98						
MAX. VALUE	0.57	1.45	2.77	3.61	3.82											3.82						

Table D-2 Highest wave period and maximum wave height distribution.

Joint occurrence of:

THmax Period of highest wave (s)
Hmax Maximum wave height (m)

Location: LEG
SWLB S/N: WS170
Sampling interval: 10 minutes
Period start: 01/05/2021 17:10
Period end: 22/05/2021 23:40

THmax (s)	2	3	4	5	6	7	8	9	10	11	12	13	14	15	>=	SUM	% OF	SUM	CUM.	MIN.	AVE.	MAX.
Hmax (m)	3	4	5	6	7	8	9	10	11	12	13	14	15	16	16		TOTAL	ACC.	PROB.			
0.0 - 0.5	4	12	16	11	13	39	32	20	4	10	11	11	6	6	4	199	6.8	199	0.06760	2.9		16.9
0.5 - 1.0	11	241	208	202	134	154	68	47	12	5	4	3	5	5	2	1101	37.4	1300	0.44158	2.7		16.3
1.0 - 1.5		141	250	206	136	81	10	4								828	28.1	2128	0.72283	3.0	5.3	9.9
1.5 - 2.0		52	62	32	46	21	13									226	7.7	2354	0.79959	3.3	5.3	8.7
2.0 - 2.5		6	19	34	22	17	7	1								106	3.6	2460	0.83560	3.5	5.9	9.4
2.5 - 3.0			7	20	40	12	1									80	2.7	2540	0.86277	4.4	6.2	8.5
3.0 - 3.5			2	29	46	16	1									94	3.2	2634	0.89470	4.5	6.3	8.0
3.5 - 4.0				17	44	11	1									73	2.5	2707	0.91950	5.4	6.5	8.1
4.0 - 4.5				9	41	23	8									81	2.8	2788	0.94701	5.6	6.9	8.8
4.5 - 5.0				7	47	28	4									86	2.9	2874	0.97622	5.5	6.8	8.4
5.0 - 5.5					34	16	3									53	1.8	2927	0.99423	6.0	6.9	8.1
5.5 - 6.0				1	5	7										13	0.4	2940	0.99864	5.9	6.9	7.8
6.0 - 6.5					2	1										3	0.1	2943	0.99966	6.6	7.0	7.9
6.5 - 7.0																		2943	0.99966			
>= 7.0																		2943	0.99966			
SUM	15	452	564	568	610	426	148	72	16	15	15	14	11	11	6	2943	100	2943	0.99966	2.7	3.2	16.9
% OF TOTAL	0.5	15.4	19.2	19.3	20.7	14.5	5.0	2.4	0.5	0.5	0.5	0.5	0.4	0.4	0.2	100						
SUM ACCUM.	15	467	1031	1599	2209	2635	2783	2855	2871	2886	2901	2915	2926	2937	2943	2943						
CUM. PROB.	0.00510	0.15863	0.35020	0.54314	0.75034	0.89504	0.94531	0.96977	0.97520	0.98030	0.98539	0.99015	0.99389	0.99762	0.99966	0.99966						
MIN. VALUE	0.40	0.40	0.38	0.38	0.34	0.34	0.30	0.32	0.40	0.35	0.33	0.33	0.37	0.40	0.34	0.30						
AVE. VALUE	0.62	1.05	1.18	1.50	2.36	1.87	1.28	0.65	0.62	0.50	0.48	0.45	0.51	0.48	0.54	1.53						
MAX. VALUE	0.85	2.42	3.12	5.56	6.17	6.05	5.23	2.21	0.85	0.86	0.83	0.59	0.69	0.60	0.79	6.17						

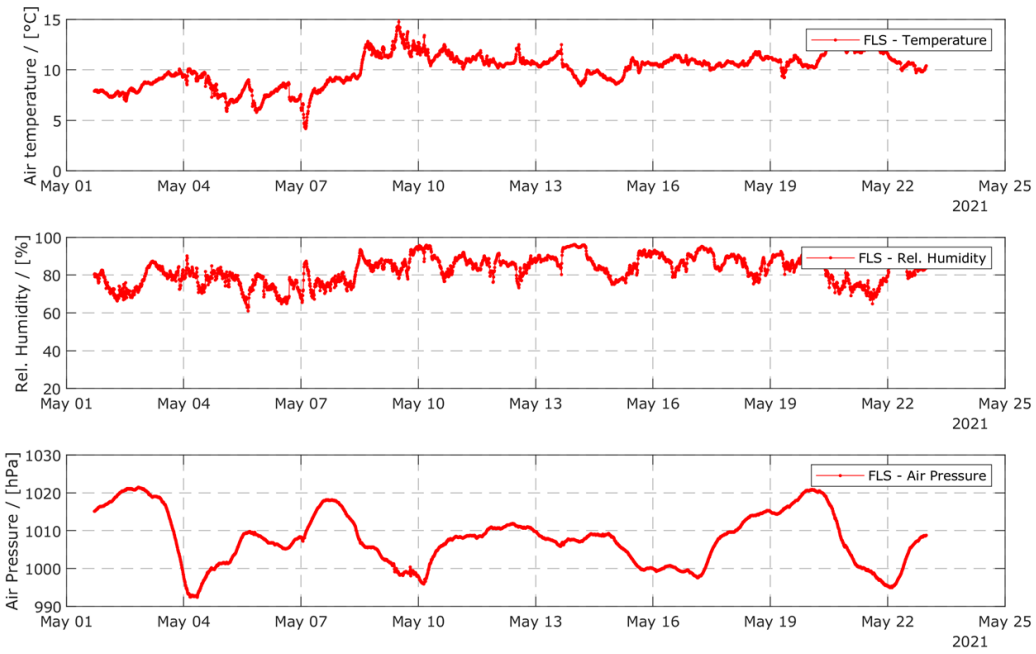

Figure 10-4 Time series of air temperature, relative humidity and air pressure at the FLS

1. Reference uncertainty

The reference uncertainty of the specific reference heights is calculated based on the verification of the REF, the REF Lidar type classification and the mounting effects. Since there was no detailed information by the time of writing this report, the following uncertainty components were assumed (for the whole wind speed range):

- REF verification: 1.5%
- REF classification: 1.5%
- REF mounting effects: 0.2%

2. Mean deviation of the remote sensor measurements and the reference measurements

This is the relative deviation between the bin averages of the FLS and the REF measurement divided by the reference measurement.

3. Standard uncertainty of the measurement of the remote sensing device

The standard deviation of the measurements was divided by the square root of the number of data records per bin. The relative uncertainty was calculated by dividing the value by the bin average wind speed of the reference measurement.

4. Mounting uncertainty of the remote sensor at the verification test

The uncertainty of the remote sensing device due to non-ideal levelling was estimated to be 0.5 %.

5. Uncertainty due to non-homogenous flow

The FLS device is located offshore. As a result, the uncertainty due to non-homogenous flow within the measurement volume is considered to be negligible.

6. Uncertainty due to separation distance

DNV considered the uncertainty due to the separation distance between FLS and REF according to the proposed formula (4) in [8]. For a separation distance, D, of 240 m at an offshore site, the uncertainty was calculated to be 0.012%.

$$Usep = \frac{D \cdot 0.05 \frac{\%}{km}}{1000}$$

DNV notes that the above calculation is different from the approach in the IEC but reflects a broad knowledge of FLS investigations.

About DNV

DNV is the independent expert in risk management and assurance, operating in more than 100 countries. Through its broad experience and deep expertise DNV advances safety and sustainable performance, sets industry benchmarks, and inspires and invents solutions.

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