DNV·GL

WS199

Independent performance verification of Seawatch Wind Lidar Buoy at Frøya, Norway

Fugro Norway AS

Report No.: 10189146-R-3, Rev. B
Date: 2021-01-12

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

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DNV GL Performance Verification Summary

General measurement configuration	
Associated Report	10189146-R-3, Issue B
Customer	Fugro Norway AS
DNV GL entity	GL Garrad Hassan Deutschland GmbH
Location	Frøya, Norway
Reference Land Lidar (RLL)	ZX Lidars ZX428
Floating Lidar System (FLS)	Fugro SWLB WS199 with ZX898M
Evaluated heights above mean sea level [m]	40, 60, 80, 100, 120, 140, 160, 180, 200, 250
Separation Distance [m]	450
Measurement start	2019-11-19
Measurement end	2019-12-18
Verification standard and/or criteria	OWA roadmap (2018) and IEC 61400-12-1 (2017)
Significant deviations	None

WS199 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**	**11**	**12**	**13**	**15**	**17**	**19**	**21**	**23**	**25**	**27**	**29**
Level [m]	**# of reference data points left after filtering**																		
250	44	107	204	225	186	171	174	164	175	183	425	315	170	80	57	71	38	6	
200	44	97	240	259	185	194	196	185	181	200	443	309	152	77	68	67	23	2	
180	54	95	247	273	188	193	215	184	175	216	454	308	138	76	77	63	15	2	
160	54	105	255	298	177	201	218	200	176	226	468	296	134	80	81	55	10	2	
140	61	112	274	317	182	204	234	206	184	239	485	273	128	85	97	39	5		
120	61	130	299	321	195	223	250	202	194	257	482	250	129	98	88	31	3		
100	79	168	342	288	227	229	250	197	223	282	454	224	129	102	84	20	3		
80	104	198	347	290	253	239	250	203	241	298	418	201	127	112	68	12	1		
60	111	248	354	296	262	254	253	228	261	279	378	175	142	108	43	9			
40	106	290	371	322	260	295	257	252	252	261	319	154	147	84	28	3			

Verification Height [m]	**40**	**60**	**80**	**100**	**120**	**140**	**160**	**180**	**200**	**250**
Wind speed slope (X_{mws})	1.002	1.000	1.000	1.000	1.004	1.004	1.006	1.008	1.010	1.013
Wind speed correlation coefficient (R^2_{mws})	0.988	0.991	0.991	0.991	0.992	0.992	0.991	0.990	0.989	0.980
Wind direction slope (M_{mwd})	0.997	0.996	0.995	0.995	0.994	0.996	0.995	0.996	0.995	0.999
Wind direction offset (OFF_{mwd})	-1.599	-1.486	-1.325	-1.226	-1.092	-1.042	-0.880	-0.667	-0.511	-0.005
Wind direction correlation coefficient (R^2_{mwd})	0.998	0.998	0.997	0.998	0.996	0.997	0.996	0.994	0.995	0.991

KPI	Passed Best practice
KPI	Passed Minimum
KPI	Failed

[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 GL Group ("DNV GL"), to complete a pre-deployment verification of a SEAWATCH Wind Lidar Buoy moored next to the Island Frøya in the Norwegian Sea between 2019-11-19 and 2019-12-18.

This verification was performed at Frøya, Norway against a fixed onshore industry accepted Lidar (Reference Land Lidar or RLL). 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 GL is accredited according to ISO 17025 for measurements on wind turbines and for wind resource measurements, energy assessments and Lidar verifications. DNV GL 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

The following section decribes the Frøya, Norway test location and verification set-up.

Coordinates for the measurement site is provided in Table 2-1.

Table 2-1 RLL and FLS coordinates

ID	Longitude [°]	Latitude [°]	Distance to RLL [m]	Horizontal travel around anchor [m]
RLL	8.31011	63.66292	NA	NA
WS199	8.31110	63.65890	450	125

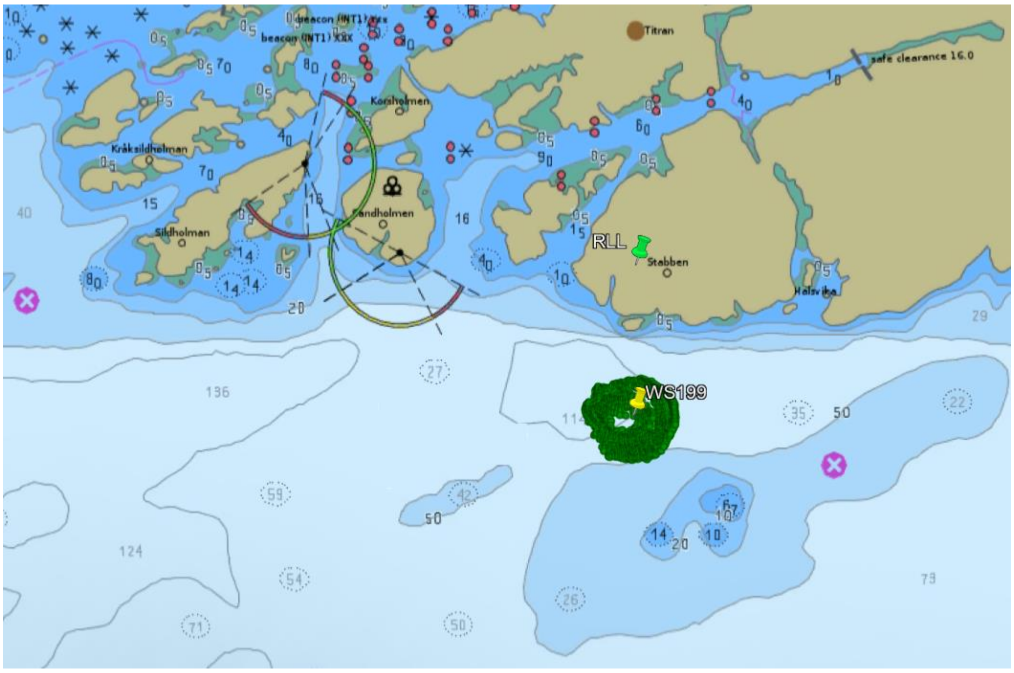


Figure 2-1 Positions of WS199 and RLL

2.1 Site Description

The test site is located at Frøya Island approximately 100 km west-north-west of Trondheim. The site has simple terrain with grassland and rock outcrops.

DNV GL performed a site visit at the Frøya site [2] and concluded that the location is suitable for FLS verifications. This was further supported by -

- Documentation provided by Fugro to DNV GL, and
- Considering the spatial separation distance, a number of verifications completed by DNV GL have shown reasonable agreement between FLS and RLL over the full range of heights.

2.2 Measuring equipment

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

2.2.1 Reference lidar (RLL)

RLL is a ZephIR Z300 continuous wave (CW) laser that is specifically designed to measure wind speeds in the lower boundary layer of the atmosphere. The RLL was configured with a height offset of 15 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 RLL used in the performance verification. Figure 2-2 shows the RLL under test.

The RLL Z428 was validated in May/June 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 [3].

Figure 2-2 Reference Lidar Z428

2.2.2 The SEAWATCH Wind Lidar Buoy (SWLB)

The SWLB has achieved “Roadmap-Pre-Commercial” stage [4]. The ZX300M lidar ZX898M onboard of WS199 was successfully validated onshore in June/July 2019 [5].

During the measurement campaign, the lidar ZX898M 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 typical setup of the SWLB offshore near RLL.

The SWLB is moored in 100 m of water depth, and the mooring array allows a horizontal sway around the anchor of approximately 125 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.

Figure 2-3 WS199[2] installed offshore in the Norwegian Sea

[2] The shown LiDAR buoy is similar to the validated one

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

Device	Height	Measurement heights[3]										
WS199	Configured	28	38	58	78	98	118	138	158	178	198	248
	AMSL	30	**40**	**60**	**80**	**100**	**120**	**140**	**160**	**180**	**200**	**250**
RLL	Configured	38	25	45	65	85	105	125	145	165	185	235
	AMSL	52	**40**	**60**	**80**	**100**	**120**	**140**	**160**	**180**	**200**	**250**

Fugro informed DNV GL that the SWLB under test has undergone design modification since the SWLB was trailed IJmuiden in 2014/2015 [6]. 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 GL 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 GL 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 [7]. Based on this documentation, DNV GL 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 [8], 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 GL considers that the original wind data quality and availability related Roadmap achievements [1, 6] should be valid for the new buoy design. DNV GL'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 [9].

(3) In addition to the (Type Validated) magnetic compass, a differential global positioning system (DGPS) has been included as a heading source. DNV GL 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] Wind speed and wind direction comparison heights are highlighted in bold typeface.

3 LIDAR PERFORMANCE VERIFICATION APPROACH

It is important to note that the verification scope is to evaluate the primary wind data from the floating lidar system. Therefore, while the SWLB currently features additional measurements the scope of this document is limited to its primary wind data measurements. The SWLB wind direction measurement is based on DGPS correction.

DNV GL understands that the tested SWLB Floating Lidar unit is planned to be deployed after the verification campaign, and the results from this verification will serve as the pre-deployment verification.

DNV GL understands and assumes that there is agreement between Fugro and their client that a pre-deployment verification of the “Roadmap-Pre-Commercial” staged FLS against a fixed onshore industry accepted Lidar used as the only verification reference (RLL) is acceptable.

It is further understood that the following requirements have met:

- The RLL was successfully and independently verified by DNV GL at the UK Remote Sensing Test Site near Pershore, UK [3];
- The Lidar mounted on the SWLB was and independently verified by DNV GL at the UK Remote Sensing Test Site near Pershore, UK [5];
- The Frøya test site is a suitable verification location as indicated in Section 2.1; and
- RLL installation is compliant with industry best practice, as detailed in the installation report from DNV GL [2]

The representativeness of wave conditions experienced at the Frøya test site for the projected deployment site should ideally be shown, but the range of conditions may not always be attained for a shorter trial duration.

In general, the test site has conditions which are representative for the Dutch site Ten Noorden van de Waddeneilanden (TWD). From the SWLB type verification trial at Ijmuiden [6] and further historical evidence DNV GL is confident that the performance of the SWLB device WS199 as shown in this shorter pre-deployment verification campaign can be transferred to more demanding wave conditions than seen in this short verification period at Frøya.

3.1 OWA Roadmap Verification

In accordance with the Roadmap [1], DNV GL 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

Verification was completed in accordance with the International Standard IEC 61400-12-1: 2017 (IEC Standard) [10]. 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 [10] and RP 105+Note 32 of [12], 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		
Wind Speed [m/s]	WS > 59	OR	WS < 0
Wind direction [°]	WD > 360	OR	WD < 0
Repeating Timestamps (ts)	FLS ts_i = FLS ts_{ii}	OR	RLL ts_i = RLL ts_{ii}
Special conditions	See below		

DNV GL notes that special atmospheric conditions have been detected during the measurement campaign as presented in Table 3-2 below.

Table 3-2 Excluded events

Excluded Periods		
Start	**End**	**Excluded data points**
03/12/2019 00:20	03/12/2019 02:20	13
	Total excluded data	13

During the event period, the wind speed correlation between FLS and RLL shows outliers. Two main reasons for the outliers were identified:

- At the test site, there are sometimes extreme flow separation events visible in the data. Those events often appear quickly and with different intensity at RLL and FLS, which leads to outliers in the correlation.
- Due to the separation distance, some outliers occur when the wind reaches the RLL position and the FLS position with a delay.

A plot of the excluded period is presented in APPENDIX F.

Given the extraordinary behaviour of the RLL and FLS, DNV GL excluded this special event from the further analysis.

APPENDIX G shows the results of an evaluation without exclusion of the special event.

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 RLL between 22.3 m/s at the lowest comparison level (40 m) and 28.0 m/s at the upper most level (250 m). The air temperatures during the campaign ranged from -2.1°C to 8.2°C. A time series of the temperature at the RLL is displayed in APPENDIX D.

The significant wave heights observed were up to 3.61 m, with 25.6 % of the observations above 1.5 m. The experienced maximum wave heights observed cover a range up to 5.44 m.

The tidal or water levels observed at Mausund in North of Frøya during the measurement campaign varied between -116.4 cm and 157.7 cm over MSL.

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

Table 4-1 Maximum 10 min averaged wind speeds

WS MAX	RLL	SWLB
Height / m	WS / m/s	
250	27.98	27.36
200	27.09	26.77
180	26.85	26.80
160	26.45	25.87
140	25.96	25.62
120	25.29	25.69
100	24.64	24.65
80	24.03	24.75
60	23.25	23.69
40	22.30	23.14

5 RESULTS OF THE OWA VERIFICATION

5.1 Data coverage requirements for accuracy assessment

Data coverage by wind speed bin are presented in Table 5-1. The database requirements for all mandatory wind speed ranges are fulfilled.

Table 5-1 Valid concurrent RLL 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**																		
250	44	107	204	225	186	171	174	164	175	183	425	315	170	80	57	71	38	6	0
200	44	97	240	259	185	194	196	185	181	200	443	309	152	77	68	67	23	2	0
180	54	95	247	273	188	193	215	184	175	216	454	308	138	76	77	63	15	2	0
160	54	105	255	298	177	201	218	200	176	226	468	296	134	80	81	55	10	2	0
140	61	112	274	317	182	204	234	206	184	239	485	273	128	85	97	39	5	0	0
120	61	130	299	321	195	223	250	202	194	257	482	250	129	98	88	31	3	0	0
100	79	168	342	288	227	229	250	197	223	282	454	224	129	102	84	20	3	0	0
80	104	198	347	290	253	239	250	203	241	298	418	201	127	112	68	12	1	0	0
60	111	248	354	296	262	254	253	228	261	279	378	175	142	108	43	9	0	0	0
40	106	290	371	322	260	295	257	252	252	261	319	154	147	84	28	3	0	0	0

5.2 Wind speed comparison

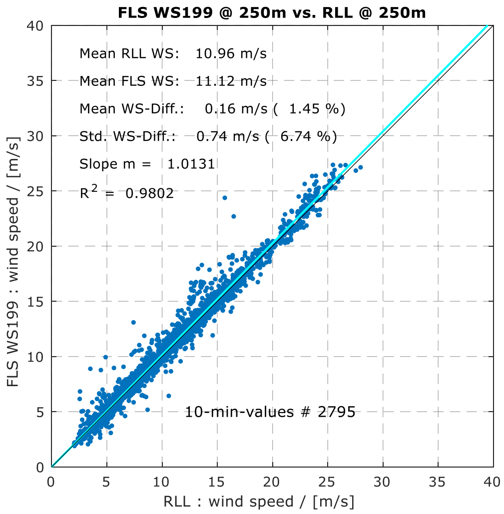
Table 5-2 summarizes the wind speed regression results for all verfication heights and shows that the FLS achieved a high level of accuracy relative to the RLL. The regression slopes are close to unity with a good regression coefficient. Figure 5-1 provides the corresponding regression plots for wind speeds greater than or equal to 2 m/s. The failed R^2 result in the restricted wind speed range 4-16 m/s at 250 m is not considered critical since at measuring heights above 200 m an increased uncertainty is expected[4].

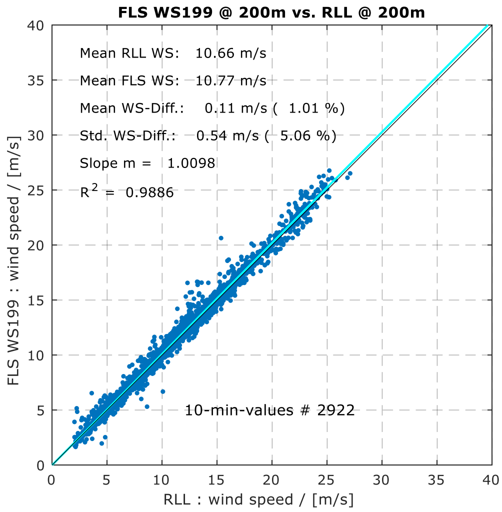
The concurrent time series of wind speeds from the FLS and RLL at 250 m and 40 m are shown in APPENDIX B.

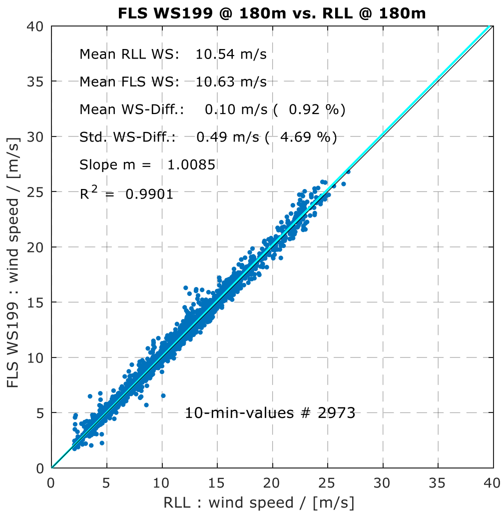
Table 5-2 Regression results for comparison

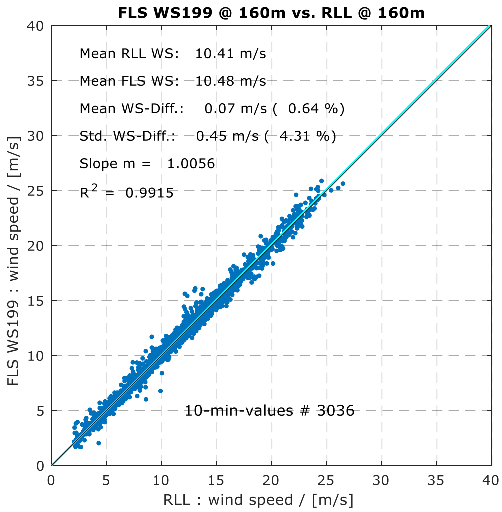
	# values	slope	R^2	WS-avg RLL (Reference)	WS-avg WS199 (Test)	mean diff.	rel. mean difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{mws}				
250 m level							
All >= 2 m/s	2795	1.013	0.980	10.96	11.12	0.159	1.45%
4 - 16 m/s	2222	1.015	0.959	9.82	9.97	0.150	1.52%
200 m level							
All >= 2 m/s	2922	1.010	0.989	10.66	10.77	0.108	1.01%
4 - 16 m/s	2392	1.010	0.979	9.65	9.75	0.098	1.02%
180 m level							
All >= 2 m/s	2973	1.008	0.990	10.54	10.63	0.097	0.92%
4 - 16 m/s	2453	1.009	0.983	9.62	9.72	0.091	0.94%
160 m level							
All >= 2 m/s	3036	1.006	0.991	10.41	10.48	0.067	0.64%
4 - 16 m/s	2515	1.007	0.985	9.57	9.64	0.066	0.69%
140 m level							
All >= 2 m/s	3125	1.004	0.992	10.25	10.30	0.048	0.47%
4 - 16 m/s	2598	1.005	0.987	9.48	9.53	0.047	0.50%
120 m level							
All >= 2 m/s	3213	1.004	0.992	10.05	10.09	0.041	0.40%
4 - 16 m/s	2673	1.003	0.987	9.35	9.38	0.034	0.36%
100 m level							
All >= 2 m/s	3301	1.000	0.991	9.78	9.78	0.005	0.05%
4 - 16 m/s	2716	1.000	0.985	9.23	9.24	0.003	0.03%
80 m level							
All >= 2 m/s	3362	1.000	0.991	9.50	9.49	-0.011	-0.11%
4 - 16 m/s	2740	0.999	0.985	9.11	9.10	-0.016	-0.18%
60 m level							
All >= 2 m/s	3401	1.000	0.991	9.19	9.17	-0.021	-0.23%
4 - 16 m/s	2740	0.999	0.983	8.95	8.93	-0.023	-0.25%
40 m level							
All >= 2 m/s	3401	1.002	0.988	8.82	8.82	-0.004	-0.05%
4 - 16 m/s	2743	1.003	0.978	8.73	8.74	0.008	0.09%

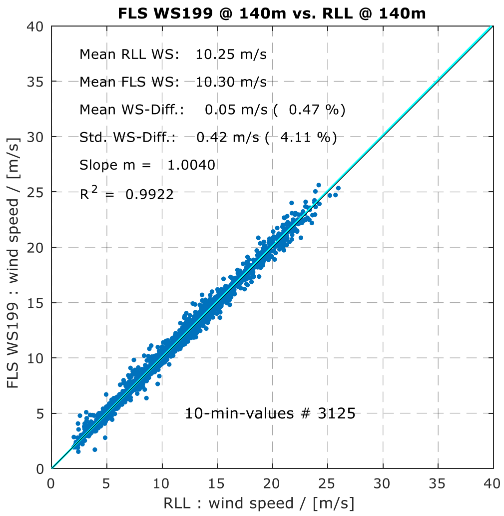
[4] In the manual of the ZXlidars software Waltz, it is noted in chapter 6.1.2.1 that Z300 units have only been validated up to 200 m and therefore any measurements taken beyond this height have not been verified.

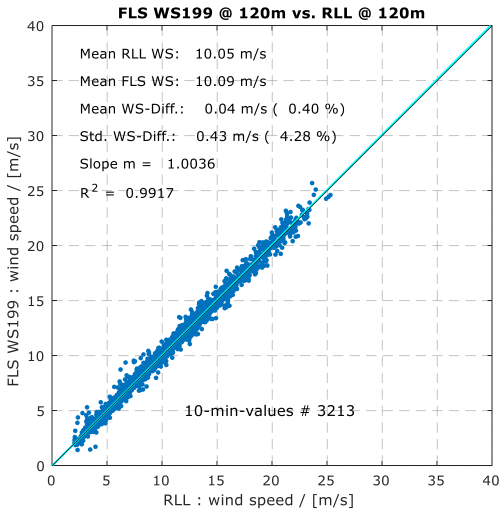

FLS WS199 @ 250m vs. RLL @ 250m
Mean RLL WS: 10.96 m/s
Mean FLS WS: 11.12 m/s
Mean WS-Diff.: 0.16 m/s (1.45 %)
Std. WS-Diff.: 0.74 m/s (6.74 %)
Slope m = 1.0131
R 2 = 0.9802
10-min-values # 2795
FLS WS199 : wind speed / [m/s]
RLL : wind speed / [m/s]


FLS WS199 @ 200m vs. RLL @ 200m
Mean RLL WS: 10.66 m/s
Mean FLS WS: 10.77 m/s
Mean WS-Diff.: 0.11 m/s (1.01 %)
Std. WS-Diff.: 0.54 m/s (5.06 %)
Slope m = 1.0098
R 2 = 0.9886
10-min-values # 2922
FLS WS199 : wind speed / [m/s]
RLL : wind speed / [m/s]


FLS WS199 @ 180m vs. RLL @ 180m
Mean RLL WS: 10.54 m/s
Mean FLS WS: 10.63 m/s
Mean WS-Diff.: 0.10 m/s (0.92 %)
Std. WS-Diff.: 0.49 m/s (4.69 %)
Slope m = 1.0085
R 2 = 0.9901
10-min-values # 2973
FLS WS199 : wind speed / [m/s]
RLL : wind speed / [m/s]


FLS WS199 @ 160m vs. RLL @ 160m
Mean RLL WS: 10.41 m/s
Mean FLS WS: 10.48 m/s
Mean WS-Diff.: 0.07 m/s (0.64 %)
Std. WS-Diff.: 0.45 m/s (4.31 %)
Slope m = 1.0056
R 2 = 0.9915
10-min-values # 3036
FLS WS199 : wind speed / [m/s]
RLL : wind speed / [m/s]


FLS WS199 @ 140m vs. RLL @ 140m
Mean RLL WS: 10.25 m/s
Mean FLS WS: 10.30 m/s
Mean WS-Diff.: 0.05 m/s (0.47 %)
Std. WS-Diff.: 0.42 m/s (4.11 %)
Slope m = 1.0040
R 2 = 0.9922
10-min-values # 3125
FLS WS199 : wind speed / [m/s]
RLL : wind speed / [m/s]


FLS WS199 @ 120m vs. RLL @ 120m
Mean RLL WS: 10.05 m/s
Mean FLS WS: 10.09 m/s
Mean WS-Diff.: 0.04 m/s (0.40 %)
Std. WS-Diff.: 0.43 m/s (4.28 %)
Slope m = 1.0036
R 2 = 0.9917
10-min-values # 3213
FLS WS199 : wind speed / [m/s]
RLL : wind speed / [m/s]

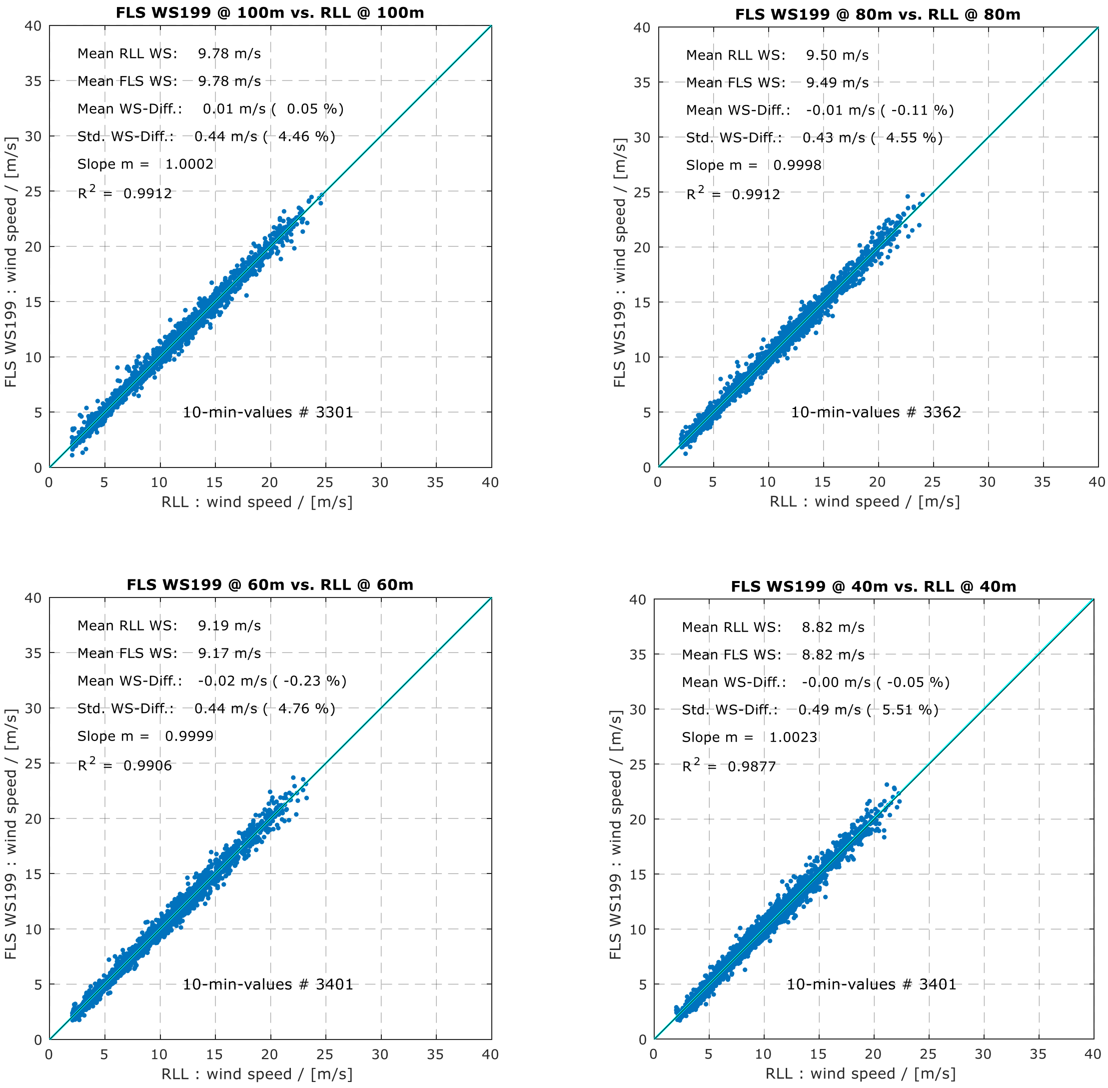


Figure 5-1 Linear wind speed regression results

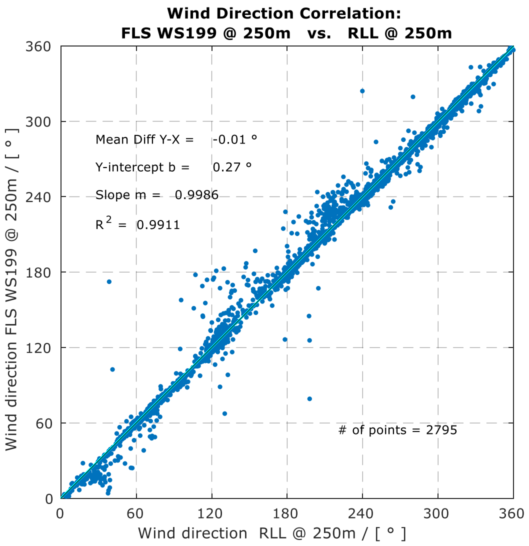
5.3 Wind direction comparison

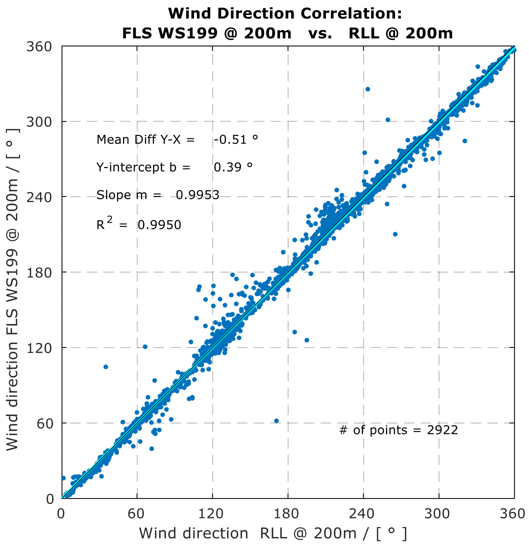
Table 5-3 summarizes the wind direction regression results for all verfication heights and shows that the FLS achieved a high level of accuracy relative to the RLL. The regression slopes are close to unity with a good regression coefficient and a low offset. Figure 5-2 provides the corresponding regression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

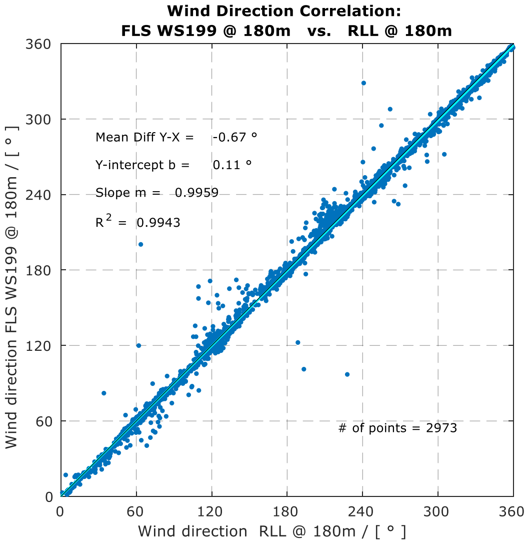
Time series of wind direction, raw data correlations, and wind direction distribution statistics can be found in APPENDIX C.

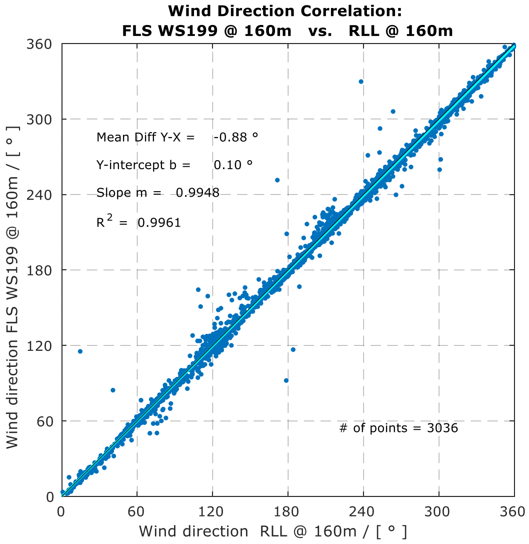
Table 5-3 Summary of wind direction comparison

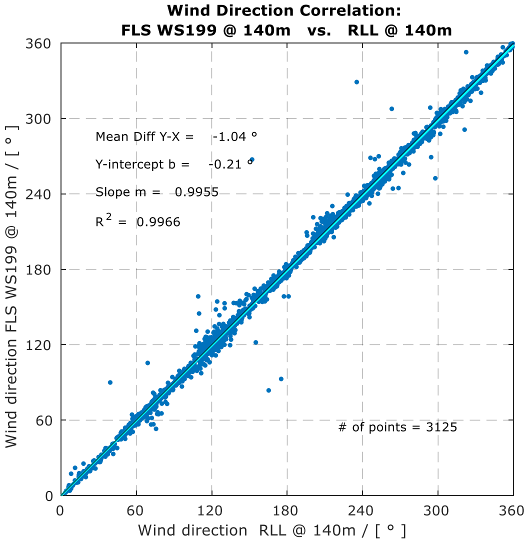
WS filtering for WS > 2 m/s				
Height level	**# values**	**slope**	**offset [°]**	**R^2**
[m]	[-]	**KPI M_{mwd}**	**KPI OFF_{mwd}**	**KPI R^2_{mwd}**
250	2795	0.999	-0.005	0.991
200	2922	0.995	-0.511	0.995
180	2973	0.996	-0.667	0.994
160	3036	0.995	-0.880	0.996
140	3125	0.996	-1.042	0.997
120	3213	0.994	-1.092	0.996
100	3300	0.995	-1.226	0.998
80	3362	0.995	-1.325	0.997
60	3401	0.996	-1.486	0.998
40	3401	0.997	-1.599	0.998

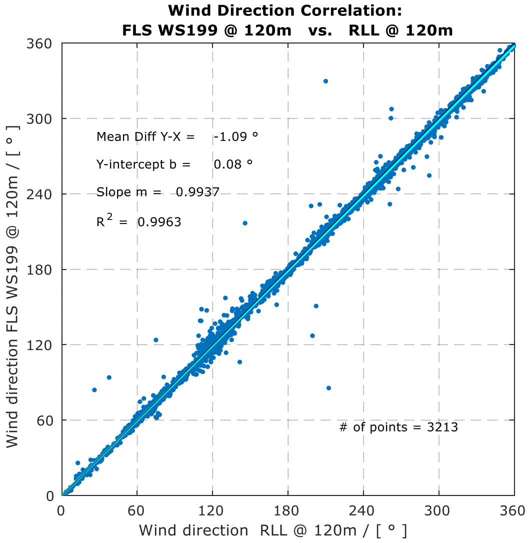

Wind Direction Correlation:
FLS WS199 @ 250m vs. RLL @ 250m
Mean Diff Y-X = -0.01 °
Y-intercept b = 0.27 °
Slope m = 0.9986
R 2 = 0.9911
# of points = 2795
Wind direction FLS WS199 @ 250m / [°]
Wind direction RLL @ 250m / [°]


Wind Direction Correlation:
FLS WS199 @ 200m vs. RLL @ 200m
Mean Diff Y-X = -0.51 °
Y-intercept b = 0.39 °
Slope m = 0.9953
R 2 = 0.9950
# of points = 2922
Wind direction FLS WS199 @ 200m / [°]
Wind direction RLL @ 200m / [°]


Wind Direction Correlation:
FLS WS199 @ 180m vs. RLL @ 180m
Mean Diff Y-X = -0.67 °
Y-intercept b = 0.11 °
Slope m = 0.9959
R 2 = 0.9943
# of points = 2973
Wind direction FLS WS199 @ 180m / [°]
Wind direction RLL @ 180m / [°]


Wind Direction Correlation:
FLS WS199 @ 160m vs. RLL @ 160m
Mean Diff Y-X = -0.88 °
Y-intercept b = 0.10 °
Slope m = 0.9948
R 2 = 0.9961
# of points = 3036
Wind direction FLS WS199 @ 160m / [°]
Wind direction RLL @ 160m / [°]


Wind Direction Correlation:
FLS WS199 @ 140m vs. RLL @ 140m
Mean Diff Y-X = -1.04 °
Y-intercept b = -0.21 °
Slope m = 0.9955
R 2 = 0.9966
# of points = 3125
Wind direction FLS WS199 @ 140m / [°]
Wind direction RLL @ 140m / [°]


Wind Direction Correlation:
FLS WS199 @ 120m vs. RLL @ 120m
Mean Diff Y-X = -1.09 °
Y-intercept b = 0.08 °
Slope m = 0.9937
R 2 = 0.9963
# of points = 3213
Wind direction FLS WS199 @ 120m / [°]
Wind direction RLL @ 120m / [°]

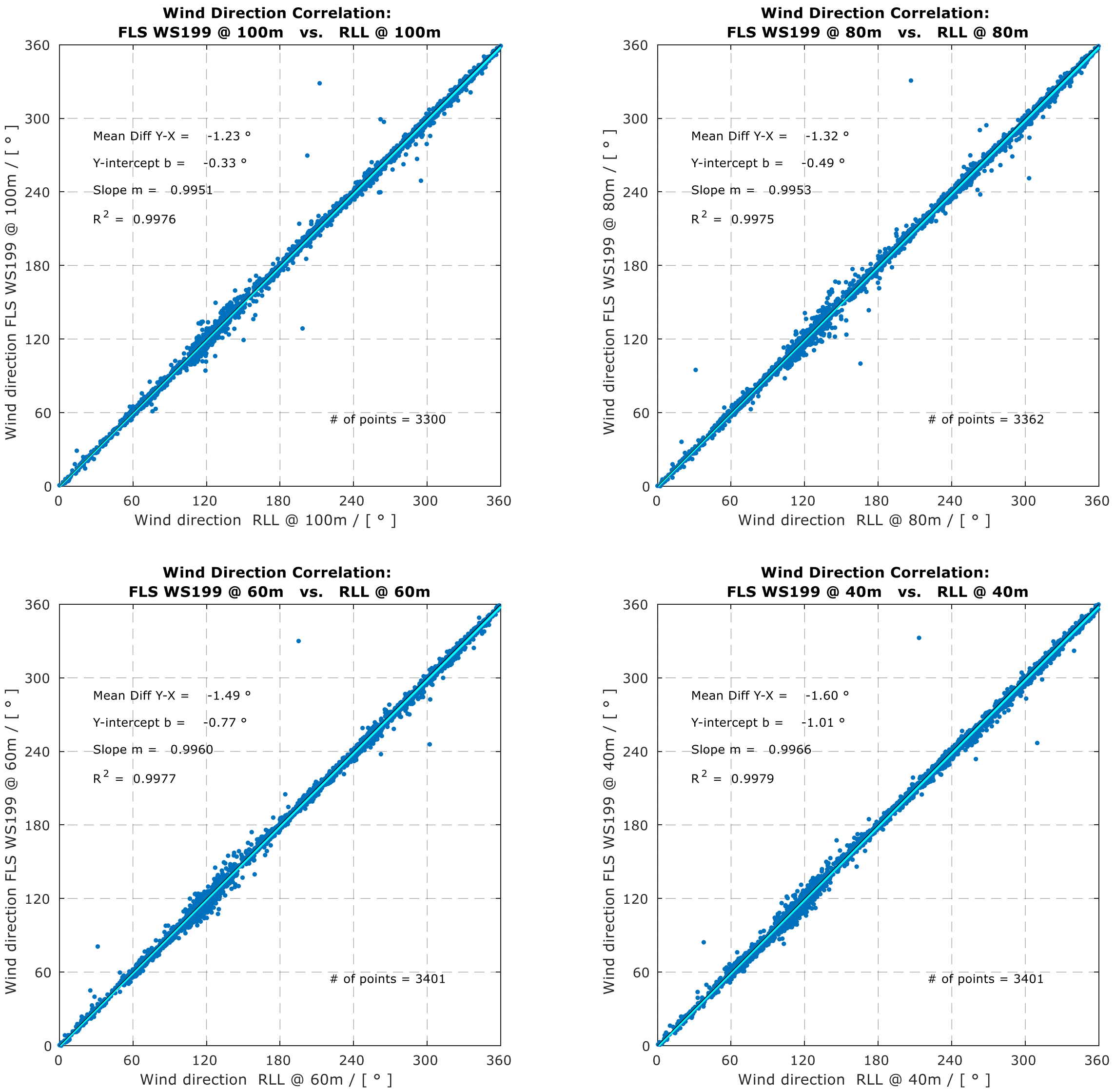


Figure 5-2 Regression plot of wind direction comparisons

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 GL 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 through Figure 6-4 how scatter plots of the wind speed comparison based on 10-minute averages between the data pairs of the FLS and the RLL at 120 m, 100 m, 80 m, and 60 m respectively. In addition, the 10-minute averaged deviation for each data point of the two data sets is plotted.

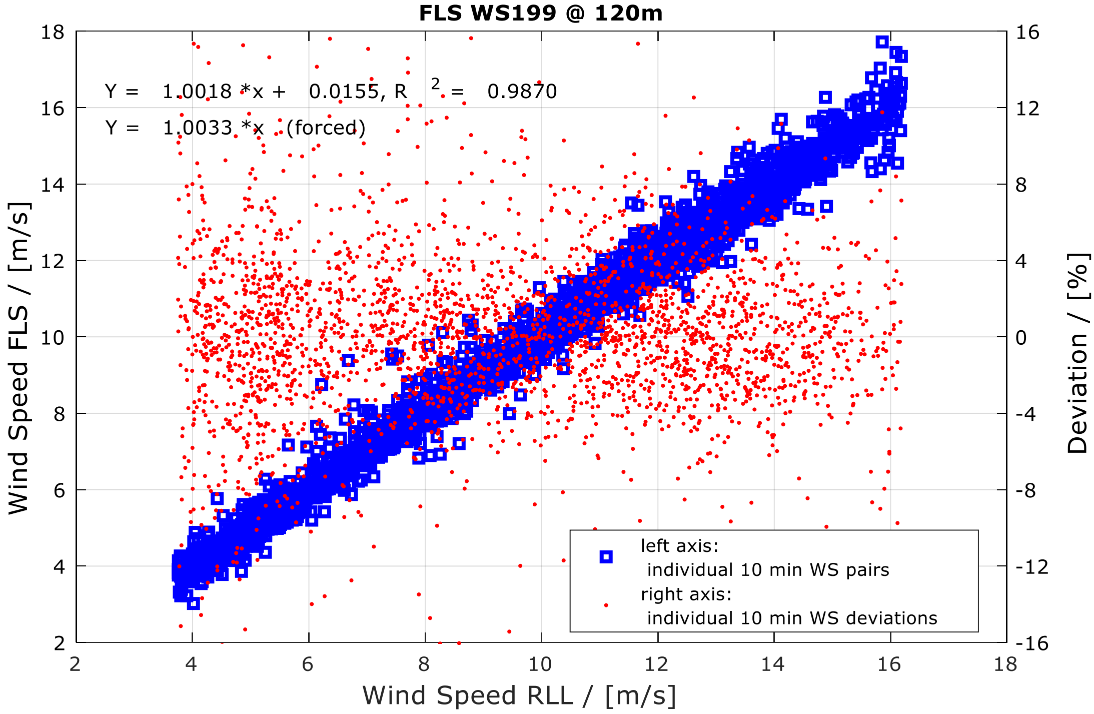


Figure 6-1 Comparison of the horizontal wind speed component at 120 m

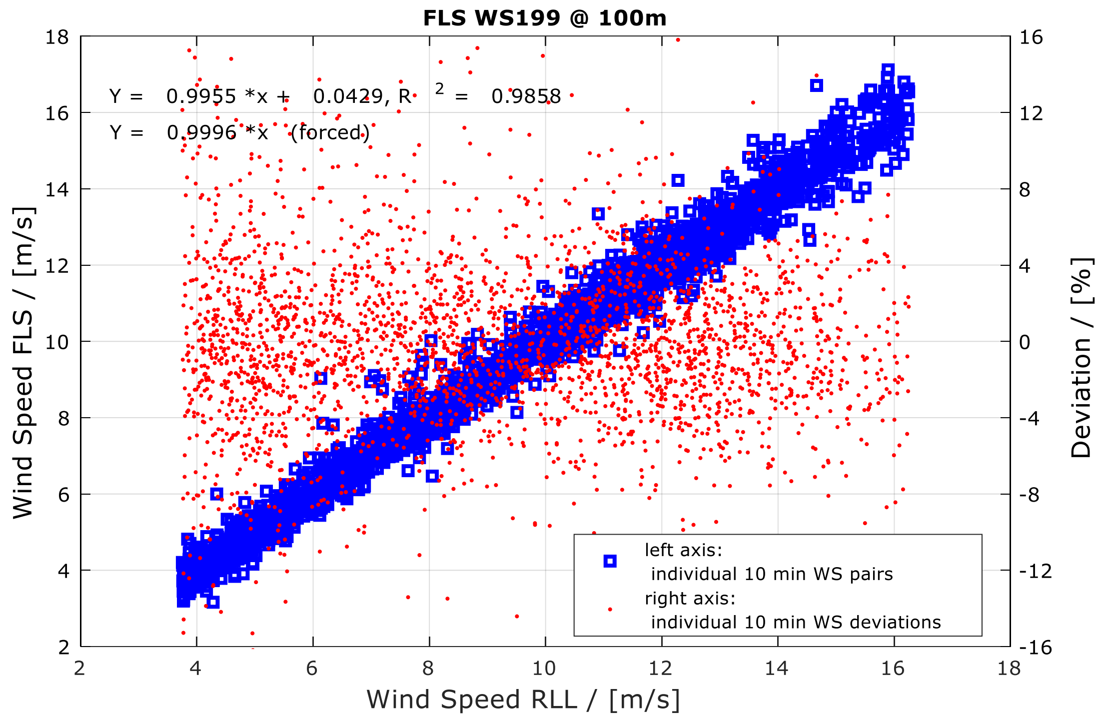


Figure 6-2 Comparison of the horizontal wind speed component at 100 m

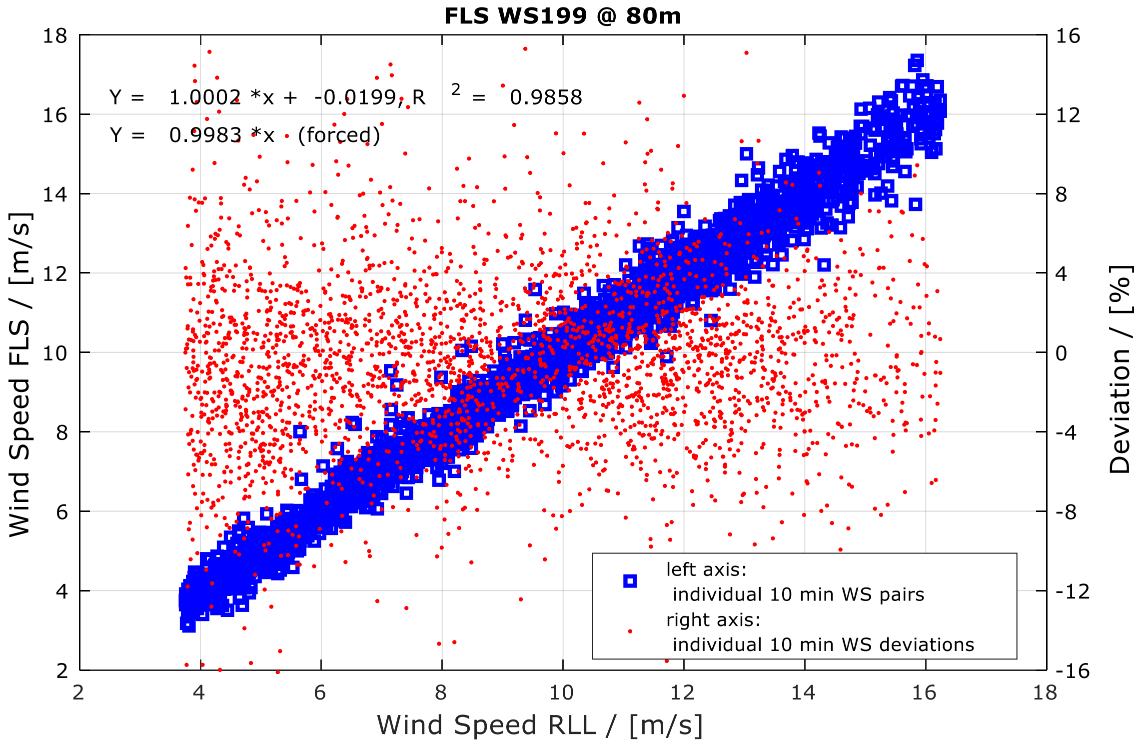


Figure 6-3 Comparison of the horizontal wind speed component at 80 m

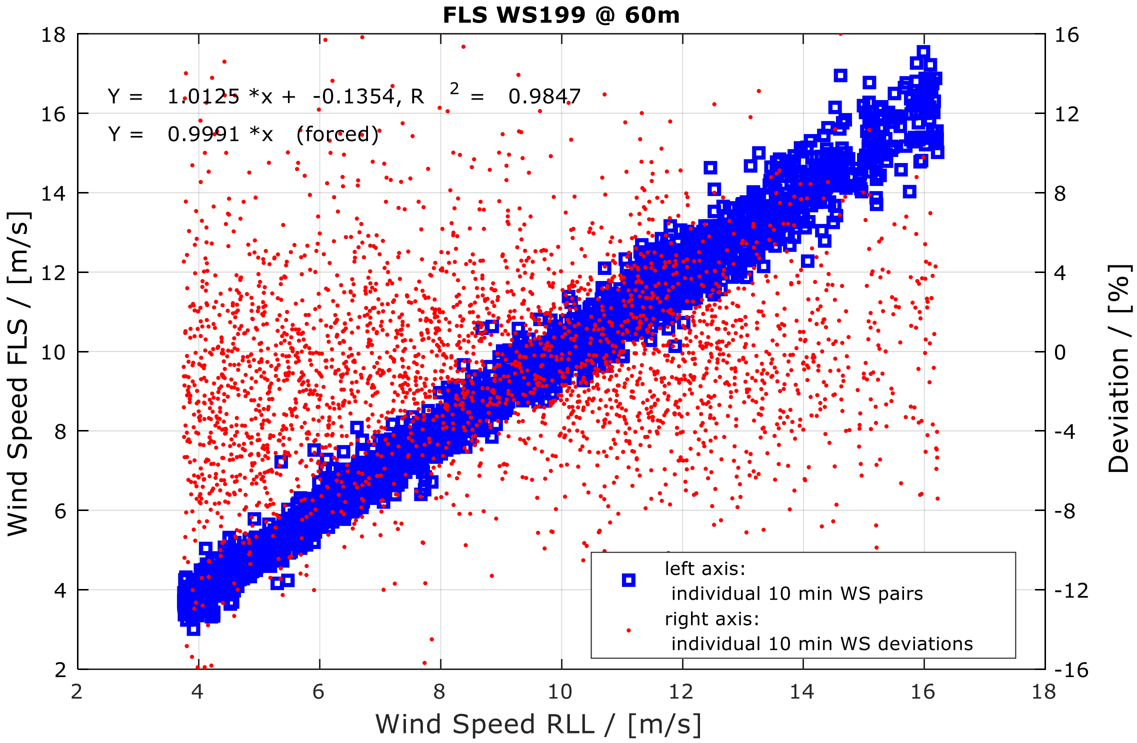


Figure 6-4 Comparison of the horizontal wind speed component at 60 m

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]	[%]	[%]	#
120	0.9870	0.03	0.33%	4.78%	2740
100	0.9858	0.00	0.05%	4.83%	2803
80	0.9858	-0.02	-0.28%	4.74%	2840
60	0.9847	-0.02	-0.57%	4.88%	2852

6.1 Performance verification uncertainty

The bin sizes and bin limits according to the OWA Roadmap [1] are different to the IEC [10]. Since the uncertainty components of the RLL verification [3] are based on the IEC bin definition, the uncertainty estimation for this FLS verification has been done according to the IEC bin definition.

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 6-5 through Figure 6-8. The bin-averaged deviation, shown as a solid red line in the figures below, can be compared to the standard uncertainty of the RLL 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 6-5. The relative deviation of the data pairs are calculated in relation to the RLL wind speeds as the reference.

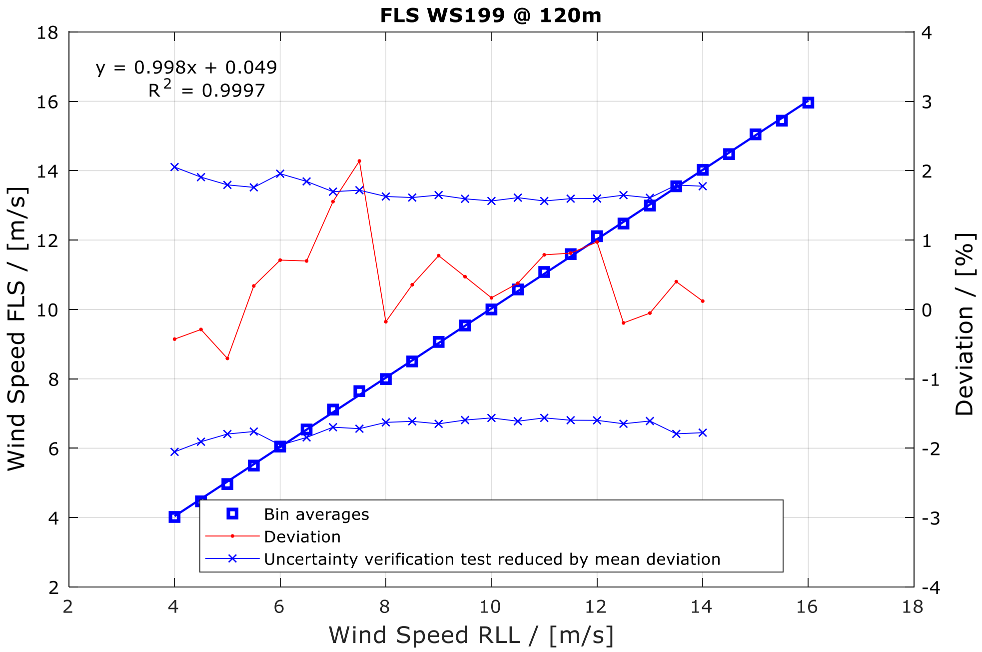


Figure 6-5 Bin-wise comparison of the horizontal wind speed component at 120 m

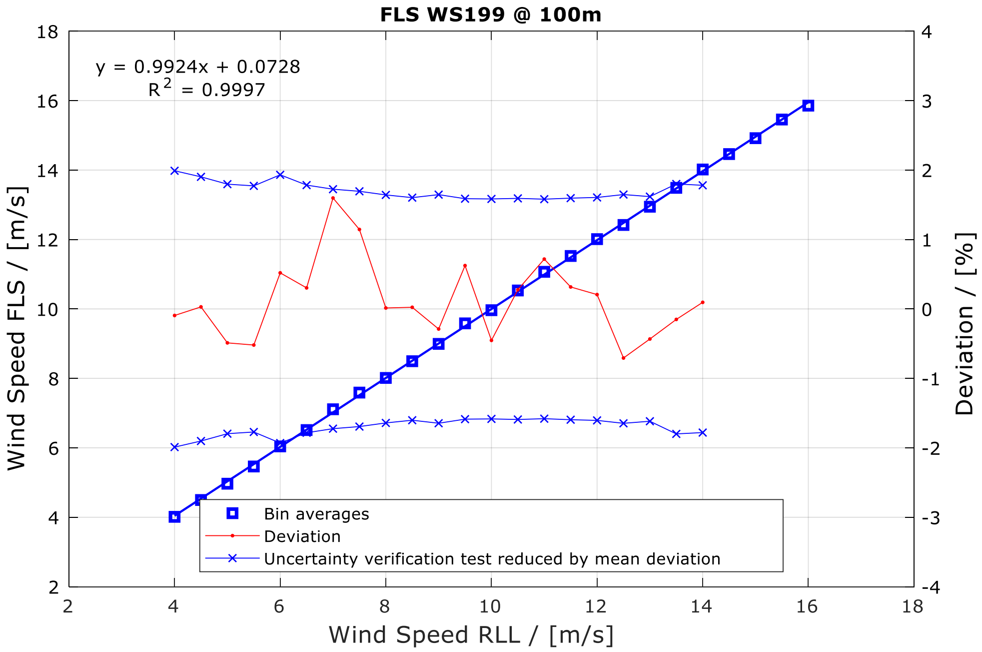


Figure 6-6 Bin-wise comparison of the horizontal wind speed component at 100 m

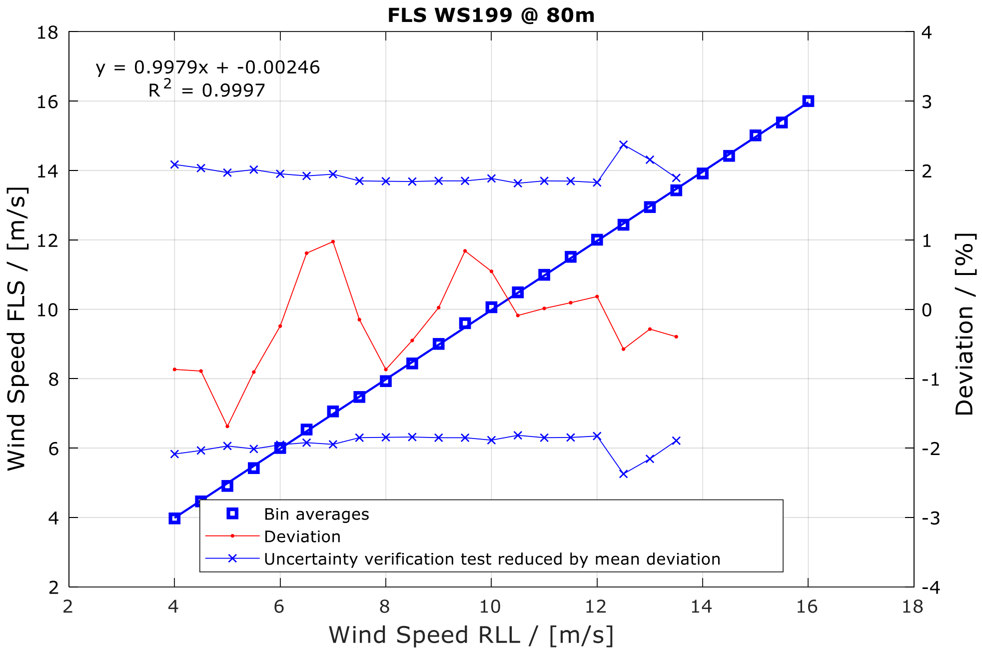


Figure 6-7 Bin-wise comparison of the horizontal wind speed component at 80 m

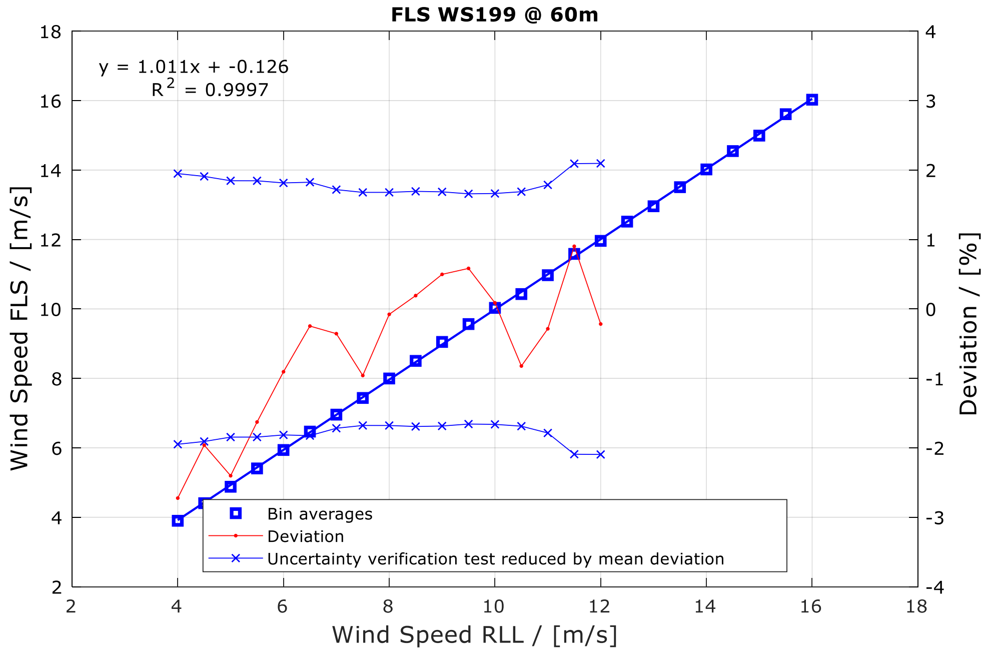


Figure 6-8 Bin-wise comparison of the horizontal wind speed component at 60 m

Table 6-2 Uncertainty calculation at 120 m

WS199 height 120 m													
BIN lower [m/s]	BIN upper [m/s]	# of 10 min data sets	V_{rsd} [m/s]	V_{mm} [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_{RLL} Uncertainty [%]	**V_{RSD} Uncertainty (k=1) [%]**
3.75	4.25	128	4.02	4.04	4.88	1.73	0.37	0.033	-0.43%	0.50%	0.23%	1.84%	**2.12%**
4.25	4.75	126	4.47	4.48	5.77	3.71	0.29	0.026	-0.29%	0.50%	0.23%	1.76%	**1.95%**
4.75	5.25	192	4.97	5.00	5.74	3.86	0.31	0.022	-0.71%	0.50%	0.23%	1.67%	**1.95%**
5.25	5.75	172	5.50	5.48	7.17	4.36	0.30	0.023	0.34%	0.50%	0.23%	1.64%	**1.81%**
5.75	6.25	102	6.05	6.01	8.75	5.20	0.48	0.047	0.71%	0.50%	0.23%	1.73%	**2.10%**
6.25	6.75	102	6.54	6.49	9.38	5.42	0.45	0.045	0.70%	0.50%	0.23%	1.65%	**1.99%**
6.75	7.25	91	7.11	7.01	8.22	6.22	0.39	0.040	1.55%	0.50%	0.23%	1.52%	**2.31%**
7.25	7.75	113	7.64	7.48	9.55	7.06	0.45	0.042	2.14%	0.50%	0.23%	1.55%	**2.75%**
7.75	8.25	122	7.99	8.01	9.78	6.83	0.39	0.036	-0.18%	0.50%	0.23%	1.49%	**1.66%**
8.25	8.75	137	8.50	8.47	10.44	6.93	0.43	0.037	0.36%	0.50%	0.23%	1.47%	**1.67%**
8.75	9.25	98	9.06	8.99	10.31	8.34	0.35	0.036	0.78%	0.50%	0.23%	1.52%	**1.84%**
9.25	9.75	98	9.54	9.49	10.73	7.99	0.45	0.045	0.47%	0.50%	0.23%	1.44%	**1.68%**
9.75	10.25	105	10.00	9.98	11.29	9.02	0.39	0.038	0.17%	0.50%	0.23%	1.43%	**1.59%**
10.25	10.75	85	10.58	10.54	11.45	9.16	0.41	0.045	0.38%	0.50%	0.23%	1.47%	**1.67%**
10.75	11.25	124	11.08	10.99	12.02	9.82	0.39	0.035	0.79%	0.50%	0.23%	1.45%	**1.76%**
11.25	11.75	122	11.59	11.50	13.51	10.56	0.50	0.045	0.81%	0.50%	0.23%	1.47%	**1.81%**
11.75	12.25	144	12.11	11.99	13.54	11.23	0.39	0.032	0.97%	0.50%	0.23%	1.49%	**1.88%**
12.25	12.75	132	12.48	12.50	14.20	11.06	0.47	0.040	-0.19%	0.50%	0.23%	1.54%	**1.68%**
12.75	13.25	131	12.99	13.00	14.32	11.93	0.43	0.038	-0.05%	0.50%	0.23%	1.50%	**1.63%**
13.25	13.75	102	13.55	13.50	14.96	11.97	0.49	0.048	0.40%	0.50%	0.23%	1.69%	**1.85%**
13.75	14.25	97	14.02	14.01	15.69	13.05	0.52	0.053	0.12%	0.50%	0.23%	1.66%	**1.80%**
14.25	14.75	71											
14.75	15.25	63											
15.25	15.75	40											
15.75	16.25	43											

Table 6-3 Uncertainty calculation at 100 m

WS199 height 100 m														
BIN lower [m/s]	BIN upper [m/s]	# of 10 min data sets	V_{rsd} [m/s]	V_{mm} [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_{RLL} Uncertainty [%]	**V_{RSD} Uncertainty (k=1) [%]**
3.75	4.25	150	4.01	4.02	4.88	3.19	0.30	0.025	-0.09%	0.50%	0.23%	1.84%	**2.01%**
4.25	4.75	161	4.50	4.50	6.00	3.16	0.32	0.025	0.03%	0.50%	0.23%	1.76%	**1.92%**
4.75	5.25	180	4.97	4.99	6.07	3.91	0.30	0.023	-0.49%	0.50%	0.23%	1.67%	**1.88%**
5.25	5.75	153	5.46	5.49	6.65	4.77	0.32	0.026	-0.52%	0.50%	0.23%	1.64%	**1.87%**
5.75	6.25	111	6.04	6.01	9.03	5.42	0.46	0.043	0.52%	0.50%	0.23%	1.73%	**2.02%**
6.25	6.75	110	6.51	6.49	7.81	5.72	0.33	0.031	0.30%	0.50%	0.23%	1.65%	**1.83%**
6.75	7.25	112	7.11	7.00	9.10	6.11	0.49	0.046	1.60%	0.50%	0.23%	1.52%	**2.36%**
7.25	7.75	113	7.59	7.50	9.07	6.61	0.38	0.036	1.14%	0.50%	0.23%	1.55%	**2.06%**
7.75	8.25	129	8.01	8.01	10.02	6.47	0.45	0.040	0.01%	0.50%	0.23%	1.49%	**1.66%**
8.25	8.75	141	8.49	8.49	9.95	7.19	0.40	0.033	0.02%	0.50%	0.23%	1.47%	**1.62%**
8.75	9.25	97	8.99	9.02	10.18	8.31	0.34	0.035	-0.29%	0.50%	0.23%	1.52%	**1.69%**
9.25	9.75	98	9.58	9.53	10.77	8.14	0.43	0.043	0.62%	0.50%	0.23%	1.44%	**1.72%**
9.75	10.25	88	9.96	10.01	11.44	8.87	0.43	0.046	-0.45%	0.50%	0.23%	1.43%	**1.67%**
10.25	10.75	115	10.53	10.50	11.80	9.60	0.39	0.036	0.28%	0.50%	0.23%	1.47%	**1.63%**
10.75	11.25	123	11.07	10.99	13.34	9.75	0.49	0.044	0.72%	0.50%	0.23%	1.45%	**1.75%**
11.25	11.75	141	11.52	11.49	13.00	9.76	0.53	0.044	0.32%	0.50%	0.23%	1.47%	**1.64%**
11.75	12.25	148	12.01	11.99	13.37	10.53	0.45	0.037	0.21%	0.50%	0.23%	1.49%	**1.64%**
12.25	12.75	138	12.42	12.51	14.22	11.14	0.47	0.040	-0.71%	0.50%	0.23%	1.54%	**1.81%**
12.75	13.25	118	12.94	13.00	14.32	11.71	0.48	0.044	-0.43%	0.50%	0.23%	1.50%	**1.69%**
13.25	13.75	89	13.49	13.51	15.27	12.57	0.50	0.053	-0.15%	0.50%	0.23%	1.69%	**1.82%**
13.75	14.25	90	14.02	14.00	15.29	12.81	0.53	0.056	0.09%	0.50%	0.23%	1.66%	**1.80%**
14.25	14.75	67											
14.75	15.25	60											
15.25	15.75	30											
15.75	16.25	41											

Table 6-4 Uncertainty calculation at 80 m

WS199 height 80 m													
BIN lower [m/s]	BIN upper [m/s]	# of 10 min data sets	V_{rsd} [m/s]	V_{mm} [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_{RLL} Uncertainty [%]	**V_{RSD} Uncertainty (k=1) [%]**
3.75	4.25	175	3.97	4.01	4.80	3.11	0.28	0.021	-0.87%	0.50%	0.23%	1.96%	**2.28%**
4.25	4.75	177	4.46	4.50	5.82	3.51	0.33	0.025	-0.89%	0.50%	0.23%	1.90%	**2.24%**
4.75	5.25	164	4.91	4.99	5.93	3.94	0.28	0.022	-1.69%	0.50%	0.23%	1.86%	**2.61%**
5.25	5.75	156	5.42	5.47	8.00	4.43	0.38	0.030	-0.90%	0.50%	0.23%	1.88%	**2.23%**
5.75	6.25	109	6.00	6.02	7.14	5.25	0.30	0.028	-0.24%	0.50%	0.23%	1.83%	**1.98%**
6.25	6.75	122	6.53	6.48	8.23	5.72	0.40	0.036	0.81%	0.50%	0.23%	1.78%	**2.10%**
6.75	7.25	124	7.06	6.99	9.54	6.06	0.50	0.045	0.97%	0.50%	0.23%	1.78%	**2.19%**
7.25	7.75	115	7.47	7.48	8.35	6.45	0.31	0.029	-0.15%	0.50%	0.23%	1.74%	**1.87%**
7.75	8.25	129	7.93	8.00	9.37	6.78	0.36	0.031	-0.87%	0.50%	0.23%	1.73%	**2.05%**
8.25	8.75	148	8.44	8.48	10.15	7.55	0.41	0.034	-0.45%	0.50%	0.23%	1.73%	**1.91%**
8.75	9.25	83	9.00	9.00	10.24	8.13	0.40	0.044	0.02%	0.50%	0.23%	1.72%	**1.87%**
9.25	9.75	113	9.60	9.52	11.58	8.14	0.45	0.042	0.84%	0.50%	0.23%	1.73%	**2.05%**
9.75	10.25	104	10.06	10.01	11.01	9.01	0.41	0.040	0.55%	0.50%	0.23%	1.78%	**1.98%**
10.25	10.75	120	10.49	10.50	11.68	9.52	0.40	0.037	-0.09%	0.50%	0.23%	1.71%	**1.83%**
10.75	11.25	135	10.99	10.99	12.20	9.63	0.38	0.032	0.01%	0.50%	0.23%	1.76%	**1.87%**
11.25	11.75	156	11.51	11.50	12.73	9.89	0.53	0.043	0.09%	0.50%	0.23%	1.74%	**1.86%**
11.75	12.25	133	12.01	11.98	13.55	10.66	0.48	0.042	0.18%	0.50%	0.23%	1.72%	**1.85%**
12.25	12.75	128	12.44	12.51	13.37	10.80	0.44	0.039	-0.57%	0.50%	0.23%	2.30%	**2.45%**
12.75	13.25	100	12.95	12.98	15.00	11.59	0.59	0.059	-0.29%	0.50%	0.23%	2.05%	**2.19%**
13.25	13.75	88	13.43	13.48	14.86	12.21	0.48	0.051	-0.40%	0.50%	0.23%	1.79%	**1.95%**
13.75	14.25	73											
14.25	14.75	66											
14.75	15.25	42											
15.25	15.75	43											
15.75	16.25	37											

Table 6-5 Uncertainty calculation at 60 m

WS199 height 60 m													
BIN lower [m/s]	BIN upper [m/s]	# of 10 min data sets	V_{rsd} [m/s]	V_{mm} [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_{RLL} Uncertainty [%]	**V_{RSD} Uncertainty (k=1) [%]**
3.75	4.25	185	3.90	4.01	5.04	3.01	0.30	0.022	-2.72%	0.50%	0.23%	1.81%	**3.36%**
4.25	4.75	172	4.41	4.49	5.31	3.64	0.30	0.023	-1.96%	0.50%	0.23%	1.78%	**2.75%**
4.75	5.25	167	4.88	5.00	5.78	4.33	0.26	0.020	-2.40%	0.50%	0.23%	1.74%	**3.04%**
5.25	5.75	141	5.41	5.50	7.22	4.16	0.35	0.030	-1.63%	0.50%	0.23%	1.70%	**2.48%**
5.75	6.25	131	5.94	5.99	7.52	5.13	0.39	0.034	-0.90%	0.50%	0.23%	1.66%	**2.05%**
6.25	6.75	127	6.47	6.48	8.08	5.78	0.39	0.035	-0.25%	0.50%	0.23%	1.68%	**1.86%**
6.75	7.25	135	6.96	6.98	8.17	6.21	0.34	0.029	-0.36%	0.50%	0.23%	1.59%	**1.77%**
7.25	7.75	131	7.44	7.51	8.35	6.40	0.35	0.030	-0.96%	0.50%	0.23%	1.55%	**1.95%**
7.75	8.25	126	8.00	8.00	9.10	6.71	0.36	0.032	-0.08%	0.50%	0.23%	1.55%	**1.70%**
8.25	8.75	140	8.50	8.49	10.59	7.59	0.42	0.035	0.19%	0.50%	0.23%	1.57%	**1.72%**
8.75	9.25	102	9.05	9.00	10.63	7.85	0.44	0.043	0.50%	0.50%	0.23%	1.54%	**1.78%**
9.25	9.75	125	9.56	9.51	10.81	8.73	0.39	0.035	0.58%	0.50%	0.23%	1.54%	**1.77%**
9.75	10.25	121	10.03	10.02	11.38	8.94	0.42	0.038	0.09%	0.50%	0.23%	1.54%	**1.68%**
10.25	10.75	124	10.43	10.51	12.10	9.27	0.46	0.041	-0.82%	0.50%	0.23%	1.57%	**1.89%**
10.75	11.25	135	10.97	11.00	12.33	9.87	0.47	0.040	-0.29%	0.50%	0.23%	1.68%	**1.82%**
11.25	11.75	146	11.58	11.48	12.84	10.28	0.51	0.042	0.90%	0.50%	0.23%	2.00%	**2.29%**
11.75	12.25	125	11.96	11.99	13.16	10.13	0.52	0.047	-0.22%	0.50%	0.23%	2.00%	**2.12%**
12.25	12.75	121											
12.75	13.25	87											
13.25	13.75	77											
13.75	14.25	66											
14.25	14.75	55											
14.75	15.25	37											
15.25	15.75	27											
15.75	16.25	49											

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 GL 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 measurement in the Norwegian Sea and RLL measurements on Frøya Island were conducted to validate FLS WS199. Measurement heights between 40 m and 250 m were available for wind speed correlations. The duration of the verification was 28.8 days. The test period and wind data coverage were considered sufficient to evaluate the FLS against the OWA Roadmap.

The performance verification and uncertainty calculation have been carried out in accordance with the IEC Standard yielding a traceable uncertainty measure.

WS199 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 3.61 m (and 5.44 m for maximum wave height) and wind speeds recorded at RLL of up to 22.3 m/s at 40 m and 28.0 m/s at 250 m.

DNV GL 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 GL 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

1. Carbon Trust Offshore Wind Accelerator roadmap for the commercial acceptance of floating lidar technology, Version 2.0, The Carbon Trust, 9 October 2018.

2. "Technical note for inspection of Reference Land Lidar at Frøya", GLGH-4275 13 10378 271-T-0003-A, DNV GL, August 2017.

3. "ZX428 Independent analysis and reporting of ZX Lidars performance verification executed by ZX Lidars at the UK Remote Sensing Test Site", 10159431-R-6-A, DNV GL, 2 July 2019.

4. "A Roadmap for the commercial acceptance of the Furgo/Oceanor SEAWATCH wind lidar buoy", GLGH-4257 13 10378 266-R-0002, Issue B, DNV GL, 29 January 2015.

5. "ZX898M Independent analysis and reporting of ZX Lidars performance verification executed by ZX Lidars at the UK Remote Sensing Test Site" 10159431-R-11-A, DNV GL, 2 August 2019.

6. "Assessment of the Furgo/Ocean SEAWATCH floating lidar verification at RWE Ijmuiden met mast", GLGH-4257 13 10378 266-R-0003, Issue B, DNV GL, 30 January 2015.

7. "Extra buoyancy lidar buoy - implementation", Arve Berg, Fugro OCEANOR, 05 May 2015.

8. "Lidar for Carbon Trust Wavescan hull with extra buoyancy", No. C75342-02-03, Fredrik Dessen, Fugro OCEANOR, 12 June 2015.

9. "Floating Lidar Validation Analysis SEAWATCH Wind Lidar Buoy". Andreas Athanasopous and Andy Cheng, Natural Power, 07 December 2016

10. International Standard: IEC 61400-12-1: Wind turbines – Part 12-1: Power performance measurements of electricity producing wind turbines. Ed. 2., Apr. 2017

11. OWA Report 2017-001: Lidar Uncertainty Standard Review Methodology Review and Recommendations, June 2018.

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

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 GL	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

KPI	Definition / Rationale	Acceptance Criteria [1]	
		Best Practice	**Minimum**
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

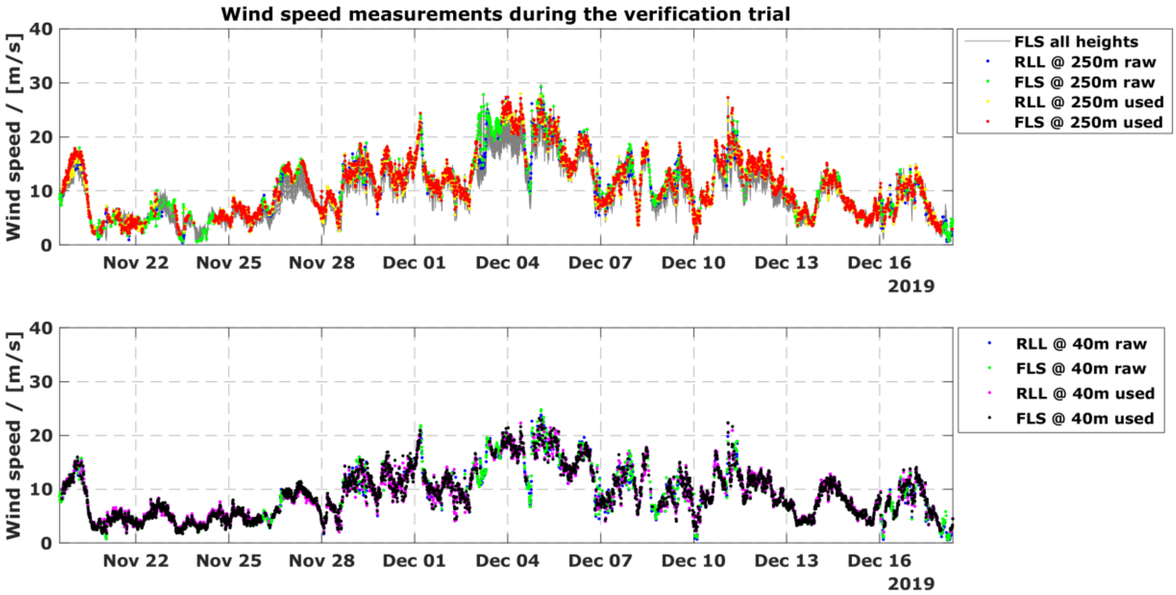


Figure B-1 Wind Speed time series for 250 m (upper panel) and 40 m (lower panel).

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 wind vane and Lidar measures.

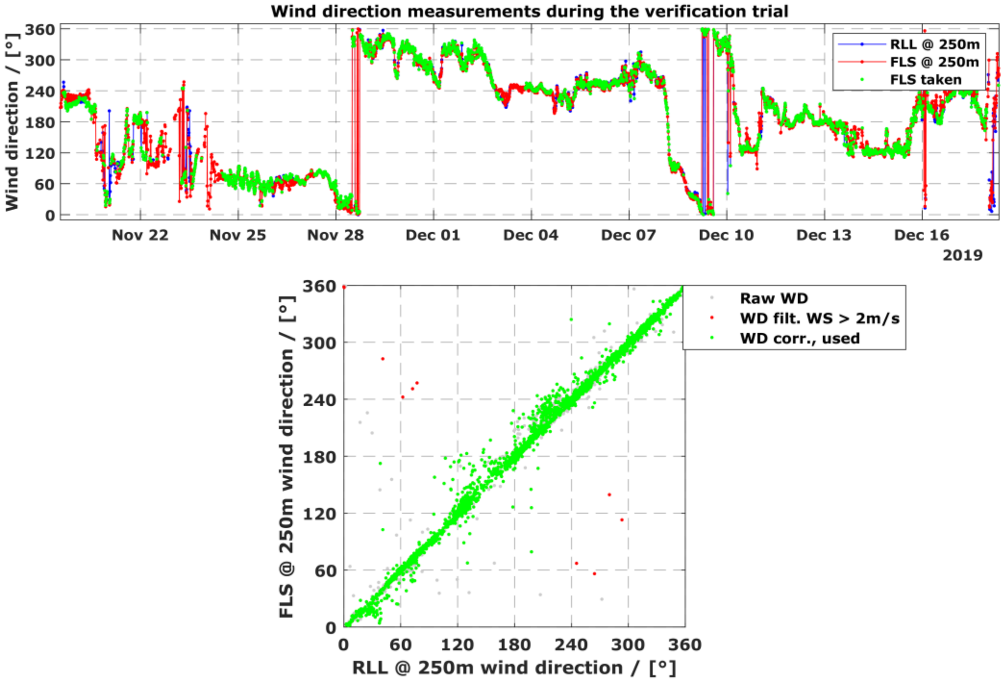


Figure C-1 Wind direction time series and scatter plot of the FLS and RLL at 250 m.

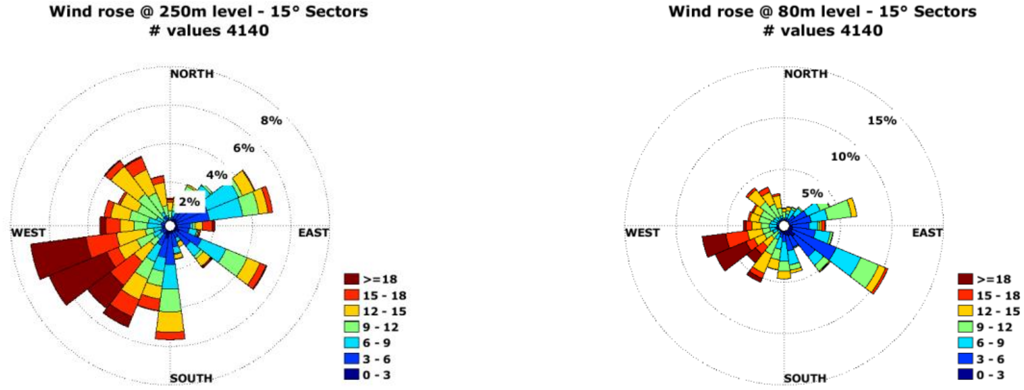


Figure C-2 Wind rose and sector averaged wind speed distribution at 250 m and 80 m

APPENDIX D SEA STATES AND METEOROLOGICAL CONDITIONS

Figure D-1 Time series of air temperature and air pressure at the RLL

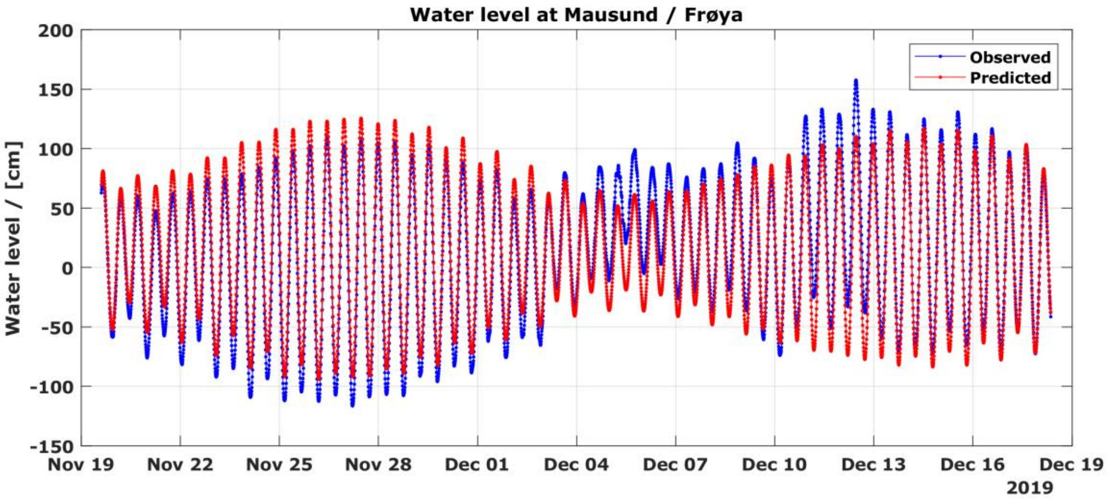


Figure D-2 Time series of tidal or water level at Mausund, Frøya.

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: Frøya, Norway
SWLB S/N: WS199
Sampling interval: 10 minutes
Period start: 19/11/2019 13:00
Period end: 18/12/2019 08:30

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	105	184	194	259	218	23										983	23.7	983	0.23681	2.6	4.9	7.5
0.5 - 1.0		99	531	309	269	116	41	3								1368	33.0	2351	0.56637	3.2	5.4	9.2
1.0 - 1.5		35	277	255	157	10		3								737	17.8	3088	0.74392	3.7	5.3	9.4
1.5 - 2.0			118	132	126	7										383	9.2	3471	0.83618	4.4	5.6	7.2
2.0 - 2.5			7	121	199	40										367	8.8	3838	0.92460	5.0	6.2	7.8
2.5 - 3.0				29	180	12										221	5.3	4059	0.97784	5.6	6.3	7.5
3.0 - 3.5					77	13										90	2.2	4149	0.99952	6.1	6.7	7.9
3.5 - 4.0							1									1	0.0	4150	0.99976	8.1	8.1	8.1
4.0 - 4.5																		4150	0.99976			
4.5 - 5.0																		4150	0.99976			
5.0 - 5.5																		4150	0.99976			
5.5 - 6.0																		4150	0.99976			
6.0 - 6.5																		4150	0.99976			
6.5 - 7.0																		4150	0.99976			
>= 7.0																		4150	0.99976			
SUM	105	318	1127	1105	1226	221	42	6								4150	100	4150	0.99976	2.6	5.4	9.4
% OF TOTAL	2.5	7.7	27.2	26.6	29.5	5.3	1.0	0.1								100						
SUM ACCUM.	105	423	1550	2655	3881	4102	4144	4150	4150	4150	4150	4150	4150	4150	4150	4150						
CUM. PROB.	0.02530	0.10190	0.37340	0.63960	0.93496	0.98820	0.99831	0.99976	0.99976	0.99976	0.99976	0.99976	0.99976	0.99976	0.99976	0.99976						
MIN. VALUE	0.16	0.12	0.12	0.10	0.10	0.41	0.65	0.86								0.10						
AVE. VALUE	0.30	0.50	0.91	1.07	1.50	1.23	0.89	0.98								1.10						
MAX. VALUE	0.47	1.16	2.14	2.98	3.43	3.49	3.61	1.04								3.61						

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: Frøya, Norway
SWLB S/N: WS199
Sampling interval: 10 minutes
Period start: 19/11/2019 13:00
Period end: 18/12/2019 08:30

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	1	4	1	6	4	14	24	16	3	9	4	10	7	4	77	184	5.3	184	0.05250	3.0	15.0	24.9
0.5 - 1.0	1	15	9	9	19	92	155	145	83	43	34	19	3	6	13	646	18.4	830	0.23680	3.0	9.4	24.9
1.0 - 1.5		6	36	78	129	170	172	137	106	49	62	29	7	1	2	984	28.1	1814	0.51755	3.7	8.6	16.9
1.5 - 2.0		2	35	51	83	82	91	69	55	22	12	12	3			517	14.8	2331	0.66505	3.7	8.1	14.7
2.0 - 2.5			5	38	65	37	60	43	31	15	7	1				302	8.6	2633	0.75121	4.5	8.1	13.1
2.5 - 3.0			1	26	53	39	46	43	46	17	2	1				274	7.8	2907	0.82939	5.0	8.4	13.6
3.0 - 3.5				11	34	25	41	49	32	28	21	3				244	7.0	3151	0.89900	5.4	9.2	13.7
3.5 - 4.0				2	17	29	22	36	31	11	6	2				156	4.5	3307	0.94351	5.6	9.1	13.7
4.0 - 4.5					8	23	26	31	23	6	5	1				123	3.5	3430	0.97860	6.3	9.1	13.3
4.5 - 5.0					1	7	9	12	11	7	2		1			50	1.4	3480	0.99287	6.9	9.6	14.3
5.0 - 5.5						4	6	11	2	1						24	0.7	3504	0.99971	7.4	9.1	11.8
5.5 - 6.0																		3504	0.99971			
6.0 - 6.5																		3504	0.99971			
6.5 - 7.0																		3504	0.99971			
>= 7.0																		3504	0.99971			
SUM	2	27	87	221	413	522	652	592	423	208	155	78	21	11	92	3504	100	3504	0.99971	3.0	9.1	24.9
% OF TOTAL	0.1	0.8	2.5	6.3	11.8	14.9	18.6	16.9	12.1	5.9	4.4	2.2	0.6	0.3	2.6	100						
SUM ACCUM.	2	29	116	337	750	1272	1924	2516	2939	3147	3302	3380	3401	3412	3504	3504						
CUM. PROB.	0.00057	0.00827	0.03310	0.09615	0.21398	0.36291	0.54893	0.71783	0.83852	0.89786	0.94208	0.96434	0.97033	0.97347	0.99971	0.99971						
MIN. VALUE	0.47	0.33	0.49	0.35	0.35	0.35	0.35	0.33	0.33	0.31	0.39	0.33	0.37	0.33	0.29	0.29						
AVE. VALUE	0.52	0.78	1.46	1.81	2.01	1.85	1.79	1.96	2.07	1.99	1.72	1.29	1.07	0.68	0.44	1.83						
MAX. VALUE	0.57	1.69	2.96	3.59	4.83	5.16	5.44	5.42	5.10	5.14	4.57	4.20	4.65	1.43	1.12	5.44						

APPENDIX E IEC ANNEX L UNCERTAINTY ANALYSES

1. Reference uncertainty

The reference uncertainty of the specific reference heights is calculated based on the verification of the RLL [3], the RLL Lidar type classification and the mounting effects. Table D-1 shows the applied RLL uncertainty components.

Table E-1 RLL uncertainty components

	RLL uncertainty (in %) for 120m & 100m				RLL uncertainty (in %) for 80m				RLL uncertainty (in %) for 60m			
WS bin	RLL Verif.	RLL Class.	RLL Mount.	Combined	RLL Verif.	RLL Class	RLL Mount.	Combined	RLL Verif.	RLL Class.	RLL Mount.	Combined
4	1.49	1.05	0.2	**1.84**	1.36	1.4	0.2	**1.96**	1.38	1.15	0.2	**1.81**
4.5	1.39	1.05	0.2	**1.76**	1.27	1.4	0.2	**1.90**	1.34	1.15	0.2	**1.78**
5	1.28	1.05	0.2	**1.67**	1.20	1.4	0.2	**1.86**	1.28	1.15	0.2	**1.74**
5.5	1.24	1.05	0.2	**1.64**	1.23	1.4	0.2	**1.88**	1.23	1.15	0.2	**1.70**
6	1.36	1.05	0.2	**1.73**	1.16	1.4	0.2	**1.83**	1.17	1.15	0.2	**1.66**
6.5	1.25	1.05	0.2	**1.65**	1.07	1.4	0.2	**1.78**	1.20	1.15	0.2	**1.68**
7	1.08	1.05	0.2	**1.52**	1.07	1.4	0.2	**1.78**	1.08	1.15	0.2	**1.59**
7.5	1.12	1.05	0.2	**1.55**	1.01	1.4	0.2	**1.74**	1.02	1.15	0.2	**1.55**
8	1.03	1.05	0.2	**1.49**	1.00	1.4	0.2	**1.73**	1.02	1.15	0.2	**1.55**
8.5	1.01	1.05	0.2	**1.47**	0.99	1.4	0.2	**1.73**	1.04	1.15	0.2	**1.57**
9	1.08	1.05	0.2	**1.52**	0.97	1.4	0.2	**1.72**	1.00	1.15	0.2	**1.54**
9.5	0.96	1.05	0.2	**1.44**	0.99	1.4	0.2	**1.73**	1.00	1.15	0.2	**1.54**
10	0.95	1.05	0.2	**1.43**	1.07	1.4	0.2	**1.78**	1.00	1.15	0.2	**1.54**
10.5	1.01	1.05	0.2	**1.47**	0.96	1.4	0.2	**1.71**	1.04	1.15	0.2	**1.57**
11	0.97	1.05	0.2	**1.45**	1.04	1.4	0.2	**1.76**	1.20	1.15	0.2	**1.68**
11.5	1.00	1.05	0.2	**1.47**	1.01	1.4	0.2	**1.74**	1.62	1.15	0.2	**2.00**
12	1.04	1.05	0.2	**1.49**	0.98	1.4	0.2	**1.72**	1.62	1.15	0.2	**2.00**
12.5	1.10	1.05	0.2	**1.54**	1.81	1.4	0.2	**2.30**	-	1.15	0.2	-
13	1.05	1.05	0.2	**1.50**	1.48	1.4	0.2	**2.05**	-	1.15	0.2	-
13.5	1.30	1.05	0.2	**1.69**	1.09	1.4	0.2	**1.79**	-	1.15	0.2	-
14	1.27	1.05	0.2	**1.66**	-	1.4	0.2	-	-	1.15	0.2	-
14.5	-	1.05	0.2	-	-	1.4	0.2	-	-	1.15	0.2	-
15	-	1.05	0.2	-	-	1.4	0.2	-	-	1.15	0.2	-
15.5	-	1.05	0.2	-	-	1.4	0.2	-	-	1.15	0.2	-
16	-	1.05	0.2	-	-	1.4	0.2	-	-	1.15	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 RLL 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 RLL (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 Lidar device is located a few meters to the east of the tower base. As a result, the uncertainty due to non-homogenous flow within the measurement volume is considered to be negligible.

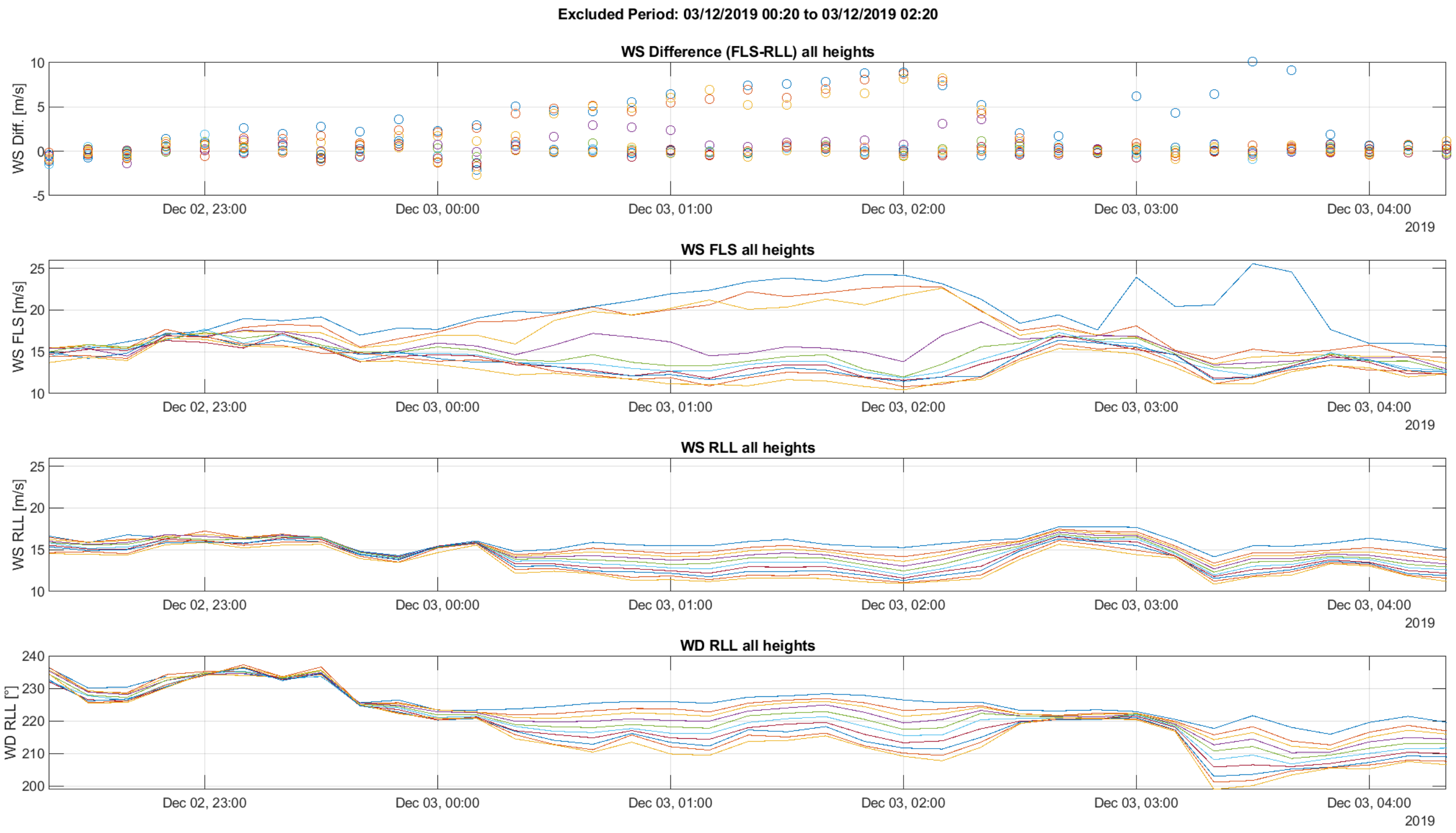
6. Uncertainty due to separation distance

DNV GL considered the uncertainty due to the separation distance between FLS and RLL according to the proposed formula (4) in [11]. For a separation distance, D, of 450 m at a coastal site, the uncertainty was calculated to be 0.225%.

$$Usep = \frac{D \cdot 0.5 \frac{\%}{km}}{1000}$$

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

APPENDIX F SPECIAL EVENT



APPENDIX G UNFILTERED RESULTS

For information, an evaluation has been done without exclusion of special events. The results below show, that all wind speed slopes and all wind direction results reach best practice AC.

	# values	slope	R^2	WS-avg RLL (Reference)	WS-avg WS199 (Test)	mean diff.	rel. mean difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{mws}				
250 m level							
All >= 2 m/s	2808	1.016	0.973	10.98	11.17	0.189	1.72%
4 - 16 m/s	2233	1.019	0.946	9.85	10.03	0.182	1.85%
200 m level							
All >= 2 m/s	2935	1.013	0.982	10.68	10.81	0.134	1.26%
4 - 16 m/s	2405	1.015	0.965	9.68	9.81	0.131	1.35%
180 m level							
All >= 2 m/s	2986	1.011	0.984	10.55	10.67	0.121	1.15%
4 - 16 m/s	2466	1.013	0.970	9.65	9.77	0.120	1.25%
160 m level							
All >= 2 m/s	3049	1.006	0.991	10.43	10.50	0.074	0.71%
4 - 16 m/s	2528	1.008	0.984	9.60	9.67	0.075	0.78%
140 m level							
All >= 2 m/s	3138	1.004	0.992	10.26	10.31	0.049	0.48%
4 - 16 m/s	2611	1.005	0.987	9.50	9.55	0.048	0.51%
120 m level							
All >= 2 m/s	3226	1.004	0.992	10.06	10.10	0.041	0.40%
4 - 16 m/s	2686	1.003	0.987	9.37	9.40	0.034	0.36%
100 m level							
All >= 2 m/s	3314	1.000	0.991	9.79	9.79	0.005	0.05%
4 - 16 m/s	2729	1.000	0.985	9.25	9.25	0.003	0.03%
80 m level							
All >= 2 m/s	3375	1.000	0.991	9.51	9.50	-0.010	-0.11%
4 - 16 m/s	2753	0.999	0.985	9.13	9.11	-0.016	-0.17%
60 m level							
All >= 2 m/s	3414	1.000	0.991	9.20	9.18	-0.021	-0.23%
4 - 16 m/s	2753	0.999	0.983	8.97	8.95	-0.022	-0.24%
40 m level							
All >= 2 m/s	3414	1.002	0.988	8.83	8.83	-0.005	-0.05%
4 - 16 m/s	2756	1.003	0.978	8.75	8.76	0.008	0.09%

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}
250	2808	0.999	0.059	0.991
200	2935	0.996	-0.447	0.995
180	2986	0.996	-0.605	0.994
160	3049	0.995	-0.856	0.996
140	3138	0.996	-1.038	0.997
120	3226	0.994	-1.090	0.996
100	3313	0.995	-1.223	0.998
80	3375	0.995	-1.322	0.997
60	3414	0.996	-1.485	0.998
40	3414	0.997	-1.595	0.998

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**																		
250	44	107	204	225	186	171	174	164	175	183	425	315	170	80	57	71	38	6	0
200	44	97	240	259	185	194	196	185	181	200	443	309	152	77	68	67	23	2	0
180	54	95	247	273	188	193	215	184	175	216	454	308	138	76	77	63	15	2	0
160	54	105	255	298	177	201	218	200	176	226	468	296	134	80	81	55	10	2	0
140	61	112	274	317	182	204	234	206	184	239	485	273	128	85	97	39	5	0	0
120	61	130	299	321	195	223	250	202	194	257	482	250	129	98	88	31	3	0	0
100	79	168	342	288	227	229	250	197	223	282	454	224	129	102	84	20	3	0	0
80	104	198	347	290	253	239	250	203	241	298	418	201	127	112	68	12	1	0	0
60	111	248	354	296	262	254	253	228	261	279	378	175	142	108	43	9	0	0	0
40	106	290	371	322	260	295	257	252	252	261	319	154	147	84	28	3	0	0	0

About DNV GL

DNV GL is a global quality assurance and risk management company. Driven by our purpose of safeguarding life, property and the environment, we enable our customers to advance the safety and sustainability of their business. We provide classification, technical assurance, software and independent expert advisory services to the maritime, oil & gas, power and renewables industries. We also provide certification, supply chain and data management services to customers across a wide range of industries. Operating in more than 100 countries, our experts are dedicated to helping customers make the world safer, smarter and greener.