WS181

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

Fugro Norway AS

Report No.: 10281716-R-2, Rev. B
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Independent performance verification of Seawatch Wind Lidar Buoy at Frøya, Norway

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Seawatch Wind lidar buoy, Floating Lidar, performance verification

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

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A	2021-02-25	First issue	Andreas Mark	Bastian Schmidt	Bastian Schmidt
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DNV GL Performance Verification Summary

General measurement configuration	
Associated Report	10281716-R-2, Issue B
Customer	Fugro Norway AS
DNV GL entity	GL Garrad Hassan Deutschland GmbH
Location	Frøya, Norway
Reference Land Lidar (RLL)	ZX Lidars unit 428
Floating Lidar System (FLS)	Fugro WS181 with ZX Lidars unit 759
Evaluated heights above mean sea level [m]	40, 60, 80, 100, 120, 140, 160, 180, 200, 250
Separation Distance [m]	370
Measurement start	2021-01-15
Measurement end	2021-02-04
Verification standard and/or criteria	OWA roadmap (2018) and IEC 61400-12-1 (2017)
Deviations	None

WS181 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**																		
250	127	148	127	187	146	164	164	200	114	140	156	172	94	28	1				
200	139	174	162	195	168	173	183	208	117	149	158	183	86	19	1				
180	144	190	174	194	176	180	200	200	126	144	162	191	76	20					
160	142	214	194	201	161	193	206	203	132	136	161	188	82	19					
140	131	227	220	201	165	193	206	202	136	141	154	188	75	15					
120	116	257	241	199	160	194	207	207	142	133	157	182	80	13					
100	91	242	179	164	132	161	177	182	133	112	120	171	77	10					
80	80	250	187	164	127	152	196	175	131	110	117	172	72	9					
60	74	257	196	147	119	164	182	186	135	96	125	168	72	7					
40	74	225	218	147	117	170	194	183	130	85	134	159	68	1					

Verification Height [m]	**40**	**60**	**80**	**100**	**120**	**140**	**160**	**180**	**200**	**250**
Wind speed slope (X_{mws})	0.987	0.998	1.001	1.002	1.006	1.006	1.007	1.007	1.007	1.003
Wind speed correlation coefficient (R^2_{mws})	0.988	0.991	0.991	0.992	0.992	0.991	0.992	0.991	0.990	0.986
Wind direction slope (M_{mwd})	0.993	0.996	0.997	0.996	0.996	0.993	0.992	0.994	0.993	0.992
Wind direction offset (OFF_{mwd})	-1.539	-1.494	-1.626	-1.650	-1.532	-1.646	-1.527	-1.458	-1.329	-1.003
Wind direction correlation coefficient (R^2_{mwd})	0.997	0.997	0.998	0.997	0.997	0.996	0.995	0.993	0.991	0.985

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 2021-01-15 and 2021-02-04.

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
WS181	8.30359	63.66124	370	125

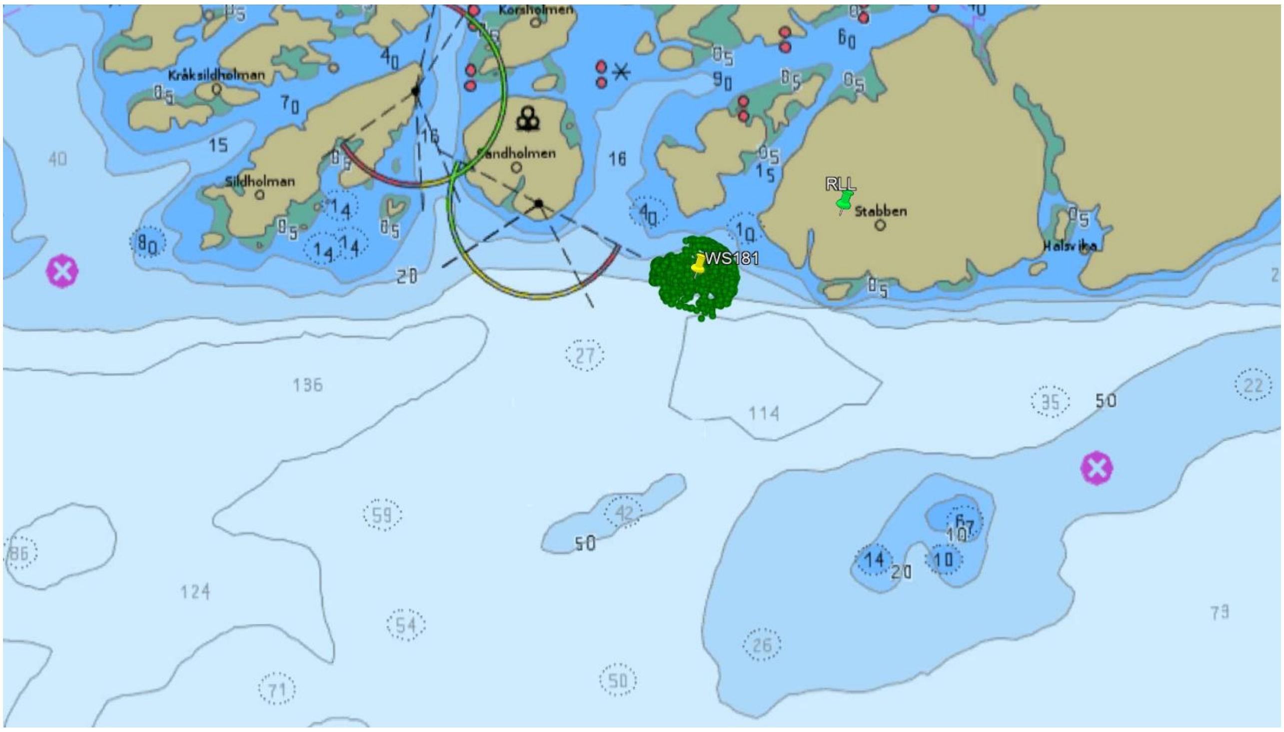


Figure 2-1 Positions of WS181 and RLL

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 heights 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 unit 759 onboard of WS181 was successfully validated onshore in November 2020 [5].

During the measurement campaign, the lidar unit 759 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.

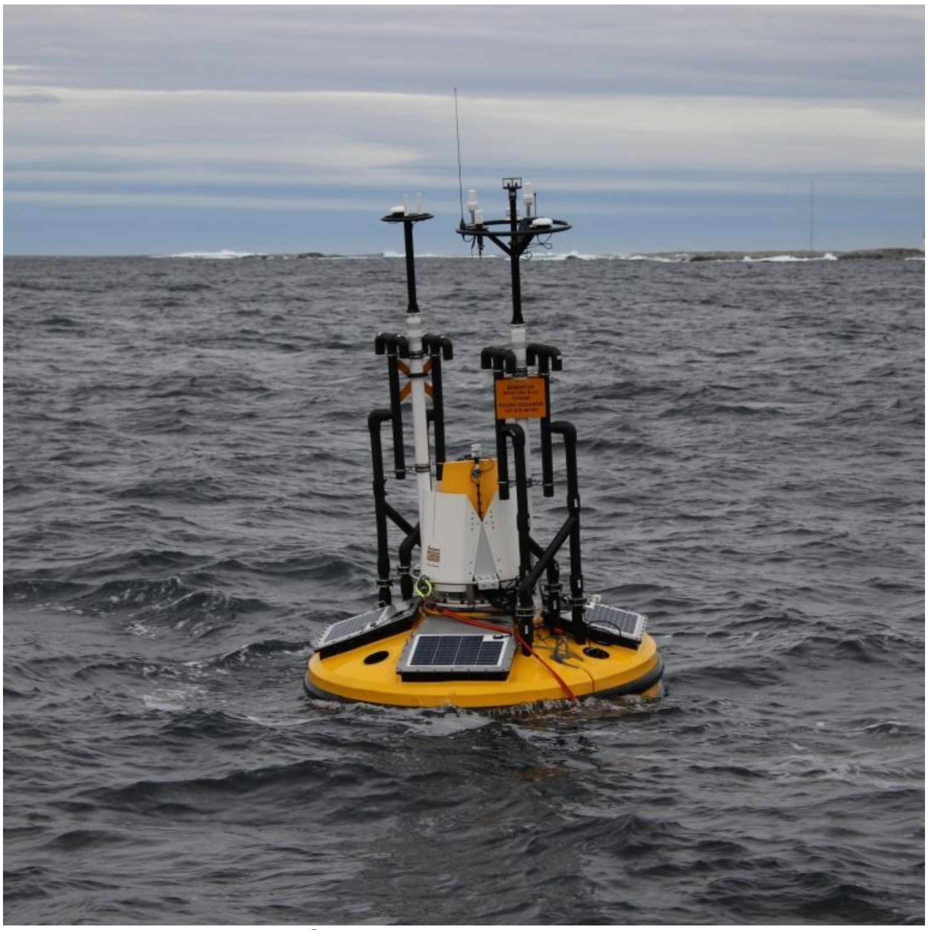


Figure 2-3 WS181[2] installed offshore in the Norwegian Sea

[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]										
WS181	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 WS181 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				
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	Additional filter	See description and Table 3-2 below				

Due to coastal effects in combination with the large separation distance between RLL and FLS, some datasets are not suitable for the validation because the wind conditions are different between both positions. Therefore, such datasets are excluded from the evaluation using the following filters.

1. For levels 40 to 100m, only wind from 90° to 320° is used to avoid disturbed wind from land. This filter is only applied for the WS comparison but not for the WD comparison.

2. Data is excluded in case the absolute wind shear difference between FLS_alpha_200_120[4] and FLS_alpha_120_40[5] is higher than 0.5. This filter is applied for WS and WD comparison. [6]
3. Since the above filters didn't catch all disturbed events, an additional period filter had to be applied. Plots of the excluded periods are shown in APPENDIX G.

Table 3-2 Additional filter criteria

Exclude data if:	Applied for WS comparison	Applied for WD comparison
HEIGHT <= 100 & (WD_REF < 90 | WD_REF > 320)	Yes	No
abs(FLS_alpha_200_120 – FLS_alpha_120_40) > 0.5	Yes	Yes
17/01/2021 14:00<= Timestamp <= 18/01/2021 00:00 21/01/2021 07:30<= Timestamp <= 21/01/2021 09:30	Yes	Yes

An evaluation without application of the additional filters is shown in APPENDIX F.

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 18.4 m/s at the lowest comparison level (40 m) and 20.4 m/s at the upper most level (250 m). The air temperatures during the campaign ranged from -11.1°C to 4.9°C. A time series of the temperature at the RLL is displayed in APPENDIX D.

The significant wave heights observed were up to 2.04 m, with 4.8 % of the observations above 1.5 m. The experienced maximum wave heights observed cover a range up to 3.96 m.

The tidal or water levels observed at Mausund in North of Frøya during the measurement campaign varied between -121.7 cm and 119.6 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	20.36	21.12
200	20.04	20.63
180	19.87	20.94
160	19.70	20.68
140	19.45	19.82
120	19.30	20.05
100	19.30	19.60
80	19.11	19.19
60	18.34	19.48
40	18.36	18.07

[4] FLS_alpha_200_120 = ln(FLS_WindSpeed_200m/FLS_WindSpeed120m)/ln(200/120)

[5] FLS_alpha_120_40 = ln(FLS_WindSpeed_120m/FLS_WindSpeed40m)/ln(120/40)

[6] It was observed that there are sometimes unusual wind shear events at Frøya. During those events, the wind profile at RLL position is very different to the wind profile at the FLS position. In previous validations, such periods were manually excluded. To avoid such manual period filtering, several filters were tested to detect such events. The selected wind shear difference filter works well to exclude such events without removing too much data.

5 RESULTS OF THE OWA VERIFICATION

5.1 System and data availability

Data for the FLS verification were available from 2021-01-15 to 2021-02-04. The FLS campaign duration was 19.9 days, which represents 2863 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 GL 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 2861 records available for one or more measurement heights, and therefore the FLS device has achieved a system availability of 99.9% 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 40 m to 250 m range is between 93.5 % to 98.9 %. 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	**250**	**200**	**180**	**160**	**140**	**120**	**100**	**80**	**60**	**40**
Max. # of 10-min points in period	2863	2863	2863	2863	2863	2863	2863	2863	2863	2863
After accounting power outages	2863	2863	2863	2863	2863	2863	2863	2863	2863	2863
Data present	2861	2861	2861	2861	2861	2861	2861	2861	2861	2861
System availability (**KPI OSA_{CA}**)	99.9%	99.9%	99.9%	99.9%	99.9%	99.9%	99.9%	99.9%	99.9%	99.9%
Total # of 10-minute valid data	2678	2700	2718	2728	2728	2740	2761	2768	2831	2727
Data availability (**KPI ODA_{CA}**)	93.5%	94.3%	94.9%	95.3%	95.3%	95.7%	96.4%	96.7%	98.9%	95.2%
# after external filtering	1968	2115	2177	2232	2254	2288	1951	1942	1928	1905
Data availability for comparison	68.7%	73.9%	76.0%	78.0%	78.7%	79.9%	68.1%	67.8%	67.3%	66.5%

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

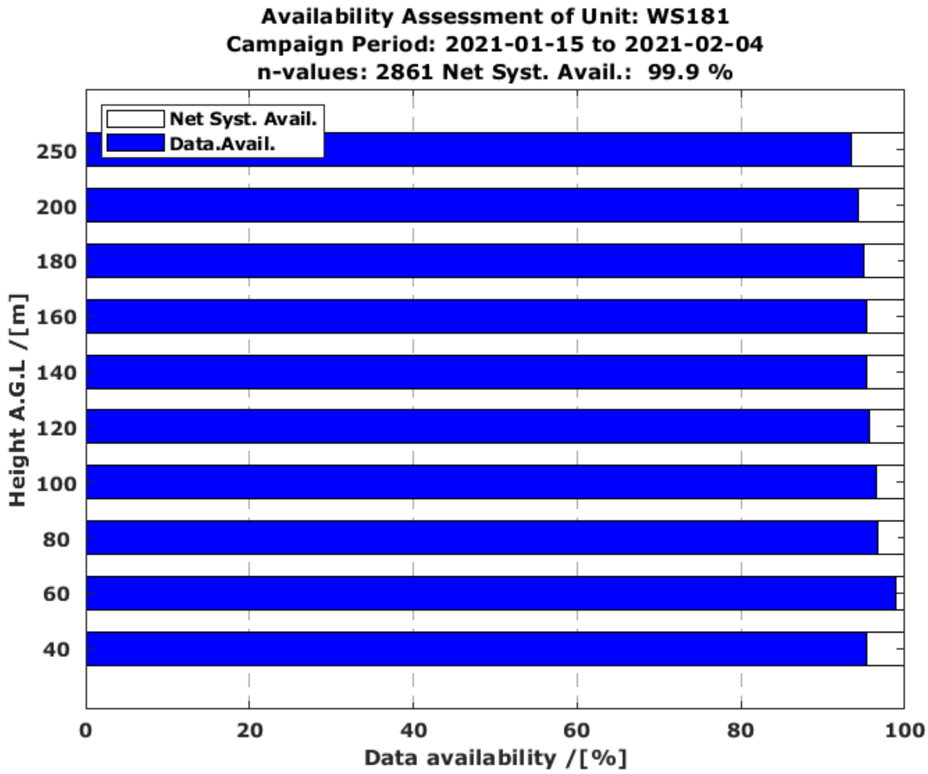


Figure 5-1 FLS availability

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 40 m to 250 m.

Table 5-2 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	127	148	127	187	146	164	164	200	114	140	156	172	94	28	1	0	0	0	0
200	139	174	162	195	168	173	183	208	117	149	158	183	86	19	1	0	0	0	0
180	144	190	174	194	176	180	200	200	126	144	162	191	76	20	0	0	0	0	0
160	142	214	194	201	161	193	206	203	132	136	161	188	82	19	0	0	0	0	0
140	131	227	220	201	165	193	206	202	136	141	154	188	75	15	0	0	0	0	0
120	116	257	241	199	160	194	207	207	142	133	157	182	80	13	0	0	0	0	0
100	91	242	179	164	132	161	177	182	133	112	120	171	77	10	0	0	0	0	0
80	80	250	187	164	127	152	196	175	131	110	117	172	72	9	0	0	0	0	0
60	74	257	196	147	119	164	182	186	135	96	125	168	72	7	0	0	0	0	0
40	74	225	218	147	117	170	194	183	130	85	134	159	68	1	0	0	0	0	0

5.2 Wind speed comparison

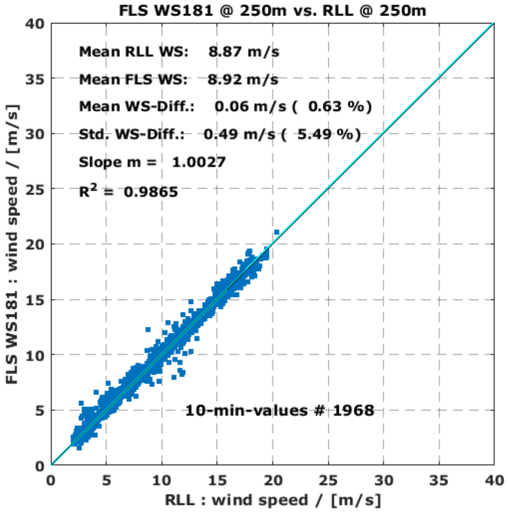
Table 5-3 summarizes the wind speed regression results for all verfication heights and shows that the FLS achieved a high level of accuracy relative to the RLL. The regression slopes are close to unity with a good regression coefficient. Figure 5-2 provides the corresponding regression plots for wind speeds greater than or equal to 2 m/s. The slightly worse results at 250 m are not considered critical since at measuring heights above 200 m an increased uncertainty is expected [7].

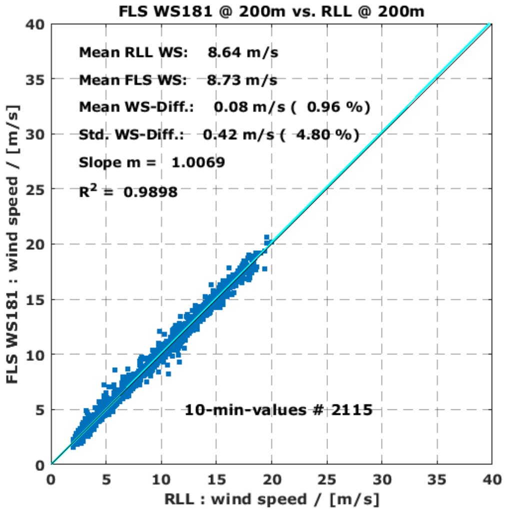
The concurrent time series of wind speeds from the FLS and RLL at 250 m and 40 m are shown in APPENDIX B.

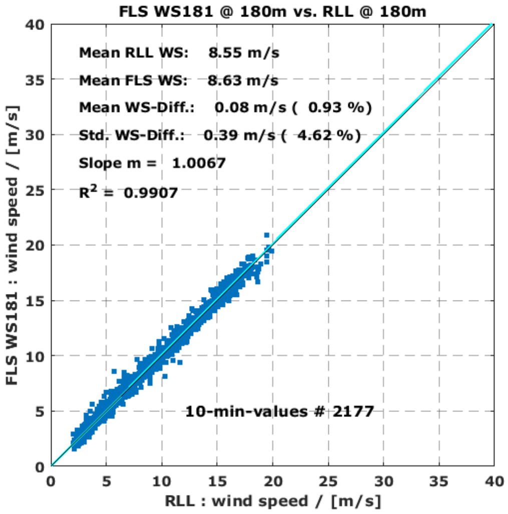
Table 5-3 Regression results for comparison

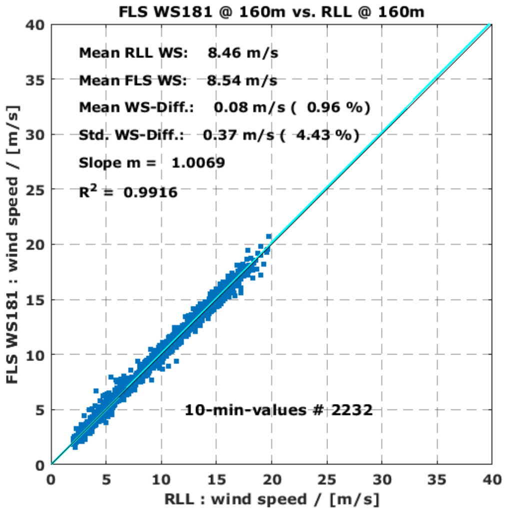
	# values	slope	R^2	WS-avg RLL (Reference)	WS-avg WS181 (Test)	mean diff.	rel. mean difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{mws}				
250 m level							
All >= 2 m/s	1968	1.003	0.986	8.87	8.92	0.056	0.63%
4 - 16 m/s	1570	1.003	0.978	9.23	9.28	0.052	0.57%
200 m level							
All >= 2 m/s	2115	1.007	0.990	8.64	8.73	0.083	0.96%
4 - 16 m/s	1696	1.008	0.984	9.13	9.21	0.088	0.96%
180 m level							
All >= 2 m/s	2177	1.007	0.991	8.55	8.63	0.079	0.93%
4 - 16 m/s	1747	1.009	0.986	9.11	9.20	0.090	0.99%
160 m level							
All >= 2 m/s	2232	1.007	0.992	8.46	8.54	0.081	0.96%
4 - 16 m/s	1775	1.009	0.987	9.02	9.11	0.092	1.03%
140 m level							
All >= 2 m/s	2254	1.006	0.991	8.36	8.43	0.070	0.83%
4 - 16 m/s	1806	1.007	0.987	8.94	9.02	0.076	0.85%
120 m level							
All >= 2 m/s	2288	1.006	0.992	8.28	8.35	0.070	0.84%
4 - 16 m/s	1822	1.007	0.988	8.86	8.94	0.074	0.83%
100 m level							
All >= 2 m/s	1951	1.002	0.992	8.38	8.42	0.037	0.44%
4 - 16 m/s	1531	1.003	0.987	8.99	9.03	0.039	0.43%
80 m level							
All >= 2 m/s	1942	1.001	0.991	8.35	8.37	0.021	0.25%
4 - 16 m/s	1531	1.001	0.987	8.97	8.99	0.020	0.22%
60 m level							
All >= 2 m/s	1928	0.998	0.991	8.33	8.33	-0.001	-0.01%
4 - 16 m/s	1518	0.998	0.987	8.97	8.97	-0.005	-0.06%
40 m level							
All >= 2 m/s	1905	0.987	0.988	8.28	8.21	-0.077	-0.93%
4 - 16 m/s	1537	0.989	0.983	8.88	8.80	-0.079	-0.89%

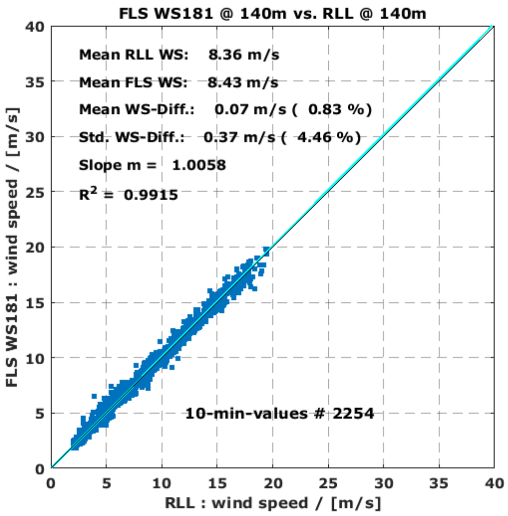
[7] In the manual of the ZXlidars software Waltz, it is noted in chapter 6.1.2.1 that Z300 units have only been validated up to 200 m and therefore any measurements taken beyond this height have not been verified.

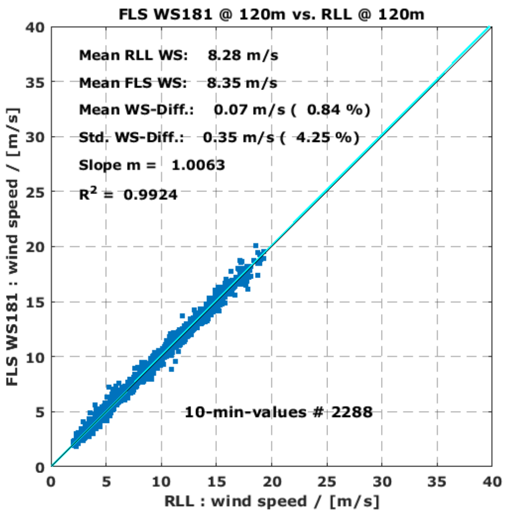

FLS WS181 @ 250m vs. RLL @ 250m
Mean RLL WS: 8.87 m/s
Mean FLS WS: 8.92 m/s
Mean WS-Diff.: 0.06 m/s (0.63 %)
Std. WS-Diff.: 0.49 m/s (5.49 %)
Slope m = 1.0027
R² = 0.9865
10-min-values # 1968
FLS WS181 : wind speed / [m/s]
RLL : wind speed / [m/s]


FLS WS181 @ 200m vs. RLL @ 200m
Mean RLL WS: 8.64 m/s
Mean FLS WS: 8.73 m/s
Mean WS-Diff.: 0.08 m/s (0.96 %)
Std. WS-Diff.: 0.42 m/s (4.80 %)
Slope m = 1.0069
R² = 0.9898
10-min-values # 2115
FLS WS181 : wind speed / [m/s]
RLL : wind speed / [m/s]


FLS WS181 @ 180m vs. RLL @ 180m
Mean RLL WS: 8.55 m/s
Mean FLS WS: 8.63 m/s
Mean WS-Diff.: 0.08 m/s (0.93 %)
Std. WS-Diff.: 0.39 m/s (4.62 %)
Slope m = 1.0067
R² = 0.9907
10-min-values # 2177
FLS WS181 : wind speed / [m/s]
RLL : wind speed / [m/s]


FLS WS181 @ 160m vs. RLL @ 160m
Mean RLL WS: 8.46 m/s
Mean FLS WS: 8.54 m/s
Mean WS-Diff.: 0.08 m/s (0.96 %)
Std. WS-Diff.: 0.37 m/s (4.43 %)
Slope m = 1.0069
R² = 0.9916
10-min-values # 2232
FLS WS181 : wind speed / [m/s]
RLL : wind speed / [m/s]


FLS WS181 @ 140m vs. RLL @ 140m
Mean RLL WS: 8.36 m/s
Mean FLS WS: 8.43 m/s
Mean WS-Diff.: 0.07 m/s (0.83 %)
Std. WS-Diff.: 0.37 m/s (4.46 %)
Slope m = 1.0058
R² = 0.9915
10-min-values # 2254
FLS WS181 : wind speed / [m/s]
RLL : wind speed / [m/s]


FLS WS181 @ 120m vs. RLL @ 120m
Mean RLL WS: 8.28 m/s
Mean FLS WS: 8.35 m/s
Mean WS-Diff.: 0.07 m/s (0.84 %)
Std. WS-Diff.: 0.35 m/s (4.25 %)
Slope m = 1.0063
R² = 0.9924
10-min-values # 2288
FLS WS181 : wind speed / [m/s]
RLL : wind speed / [m/s]

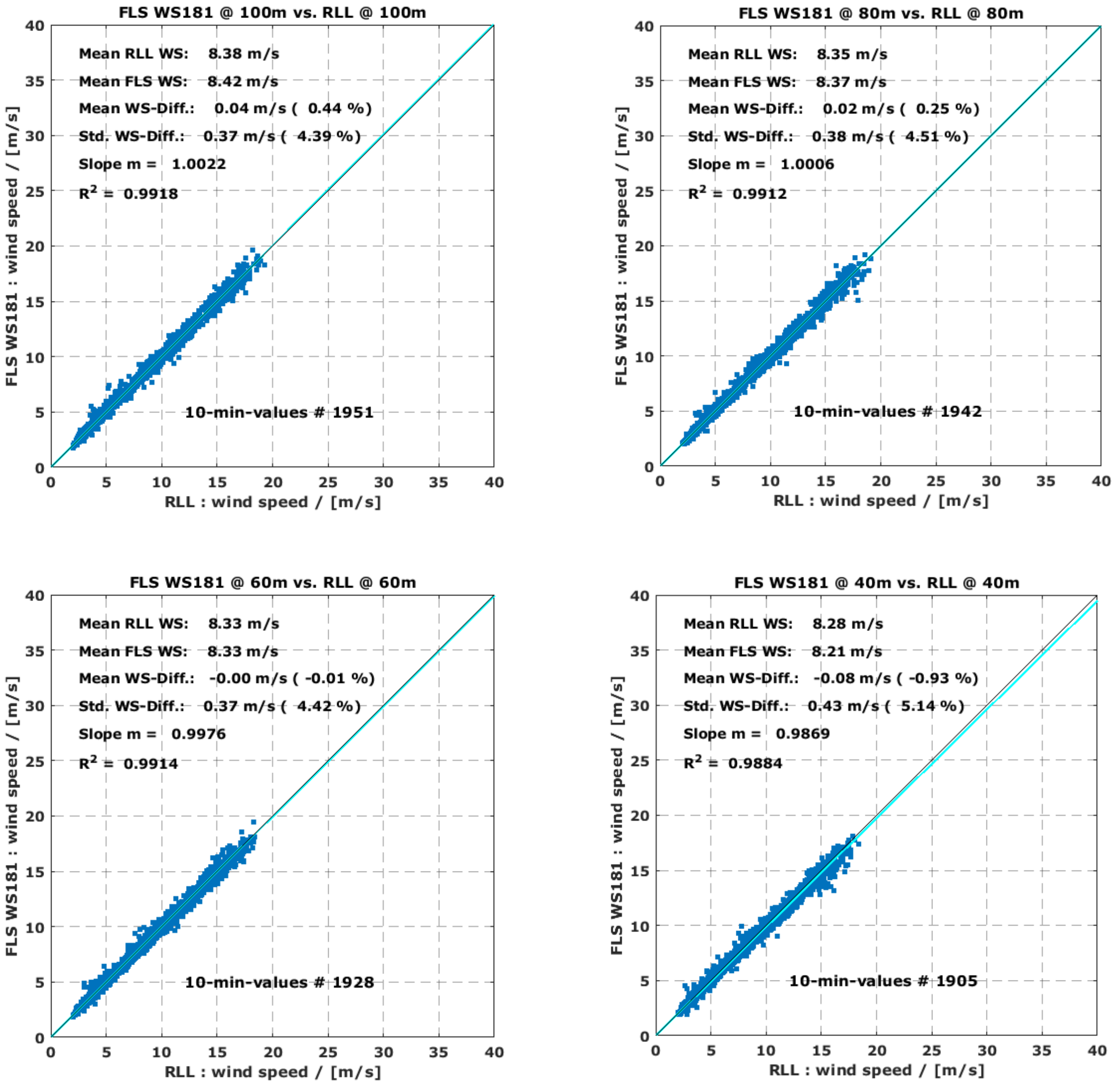


Figure 5-2 Linear wind speed regression results

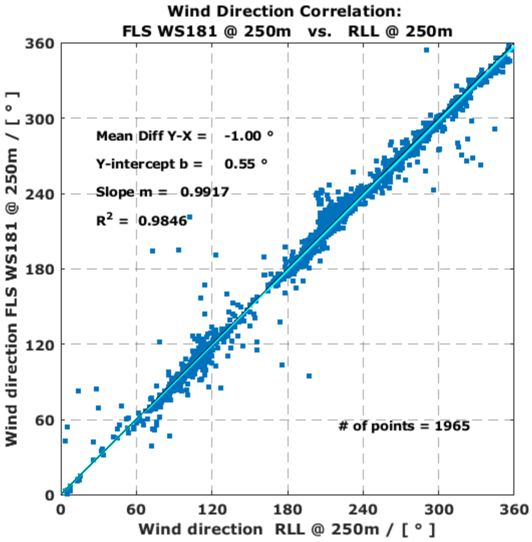
5.3 Wind direction comparison

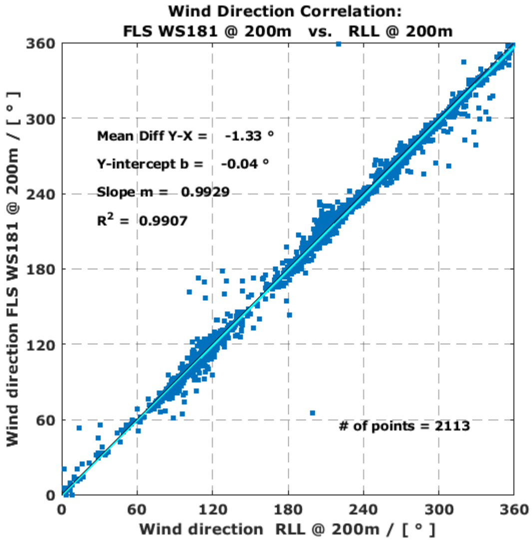
Table 5-4 summarizes the wind direction regression results for all verfication heights and shows that the FLS achieved a high level of accuracy relative to the RLL. The regression slopes are close to unity with a good regression coefficient and a low offset. Figure 5-3 provides the corresponding regression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

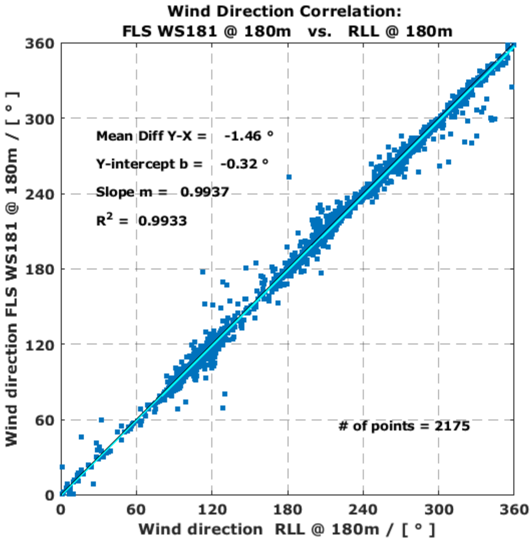
Time series of wind direction, raw data correlations, and wind direction distribution statistics can be found in APPENDIX C.

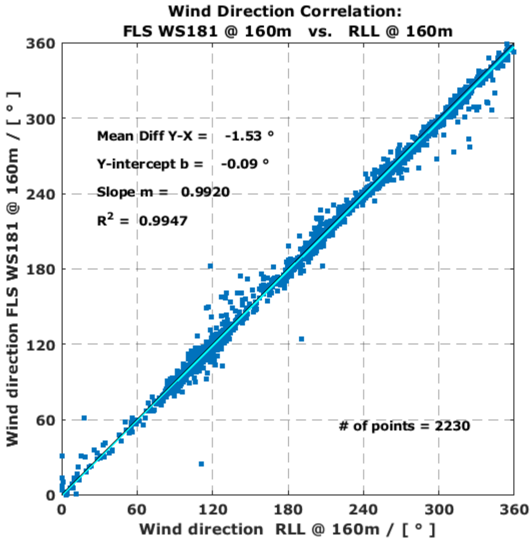
Table 5-4 Summary of wind direction comparison

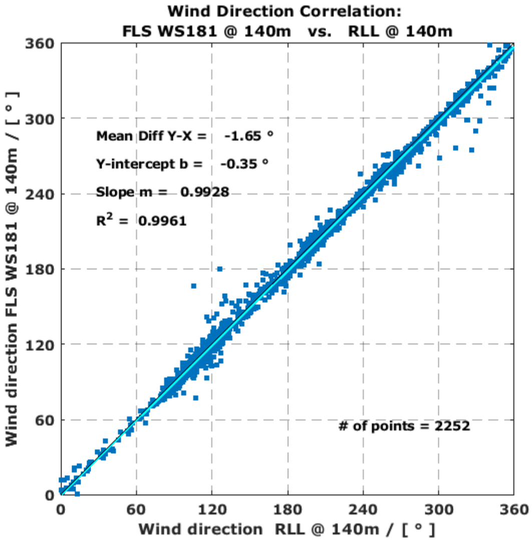
WS filtering for WS > 2 m/s				
Height level [m]	**# values** [-]	**slope** KPI M_{mwd}	**offset [°]** KPI OFF_{mwd}	R^2 KPI R^2_{mwd}
250	1965	0.992	-1.003	0.985
200	2113	0.993	-1.329	0.991
180	2175	0.994	-1.458	0.993
160	2230	0.992	-1.527	0.995
140	2252	0.993	-1.646	0.996
120	2287	0.996	-1.532	0.997
100	2300	0.996	-1.650	0.997
80	2313	0.997	-1.626	0.998
60	2322	0.996	-1.494	0.997
40	2322	0.993	-1.539	0.997

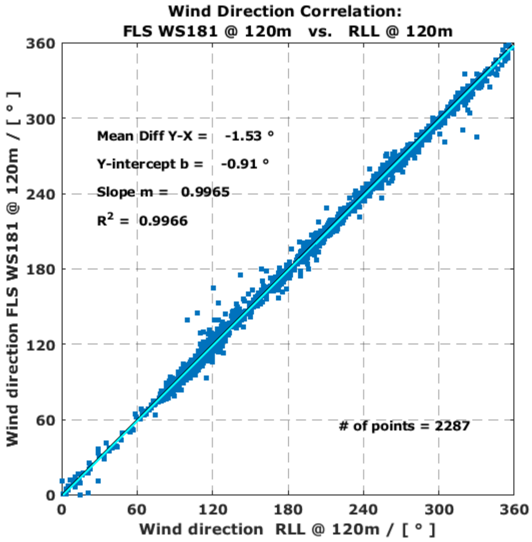

Wind Direction Correlation:
FLS WS181 @ 250m vs. RLL @ 250m
Mean Diff Y-X = -1.00 °
Y-intercept b = 0.55 °
Slope m = 0.9917
R2 = 0.9846
# of points = 1965
Wind direction RLL @ 250m / [°]
Wind direction FLS WS181 @ 250m / [°]


Wind Direction Correlation:
FLS WS181 @ 200m vs. RLL @ 200m
Mean Diff Y-X = -1.33 °
Y-intercept b = -0.04 °
Slope m = 0.9929
R2 = 0.9907
# of points = 2113
Wind direction RLL @ 200m / [°]
Wind direction FLS WS181 @ 200m / [°]


Wind Direction Correlation:
FLS WS181 @ 180m vs. RLL @ 180m
Mean Diff Y-X = -1.46 °
Y-intercept b = -0.32 °
Slope m = 0.9937
R2 = 0.9933
# of points = 2175
Wind direction RLL @ 180m / [°]
Wind direction FLS WS181 @ 180m / [°]


Wind Direction Correlation:
FLS WS181 @ 160m vs. RLL @ 160m
Mean Diff Y-X = -1.53 °
Y-intercept b = -0.09 °
Slope m = 0.9920
R2 = 0.9947
# of points = 2230
Wind direction RLL @ 160m / [°]
Wind direction FLS WS181 @ 160m / [°]


Wind Direction Correlation:
FLS WS181 @ 140m vs. RLL @ 140m
Mean Diff Y-X = -1.65 °
Y-intercept b = -0.35 °
Slope m = 0.9928
R2 = 0.9961
# of points = 2252
Wind direction RLL @ 140m / [°]
Wind direction FLS WS181 @ 140m / [°]


Wind Direction Correlation:
FLS WS181 @ 120m vs. RLL @ 120m
Mean Diff Y-X = -1.53 °
Y-intercept b = -0.91 °
Slope m = 0.9965
R2 = 0.9966
# of points = 2287
Wind direction RLL @ 120m / [°]
Wind direction FLS WS181 @ 120m / [°]

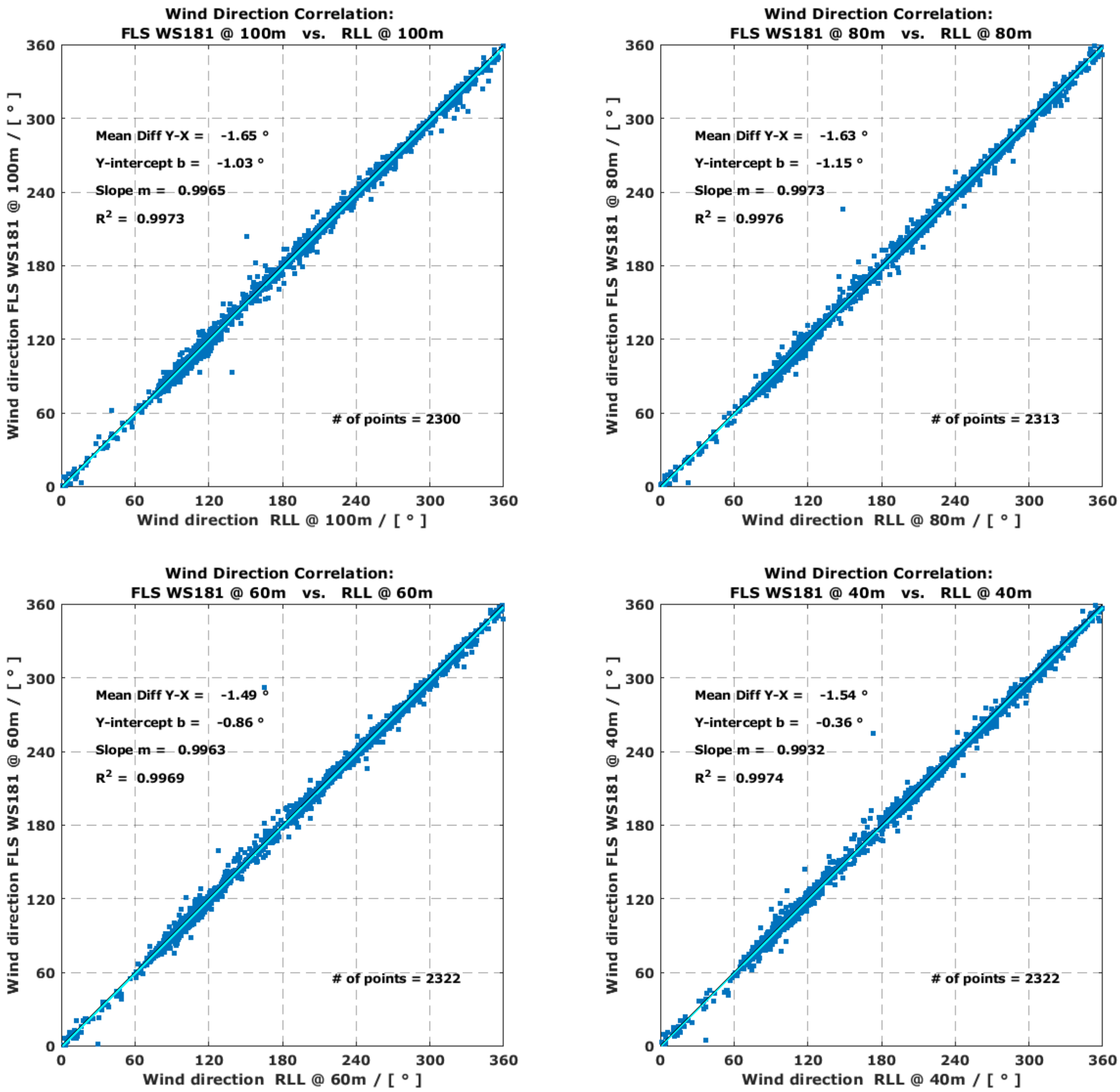


Figure 5-3 Regression plot of wind direction comparisons

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 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.

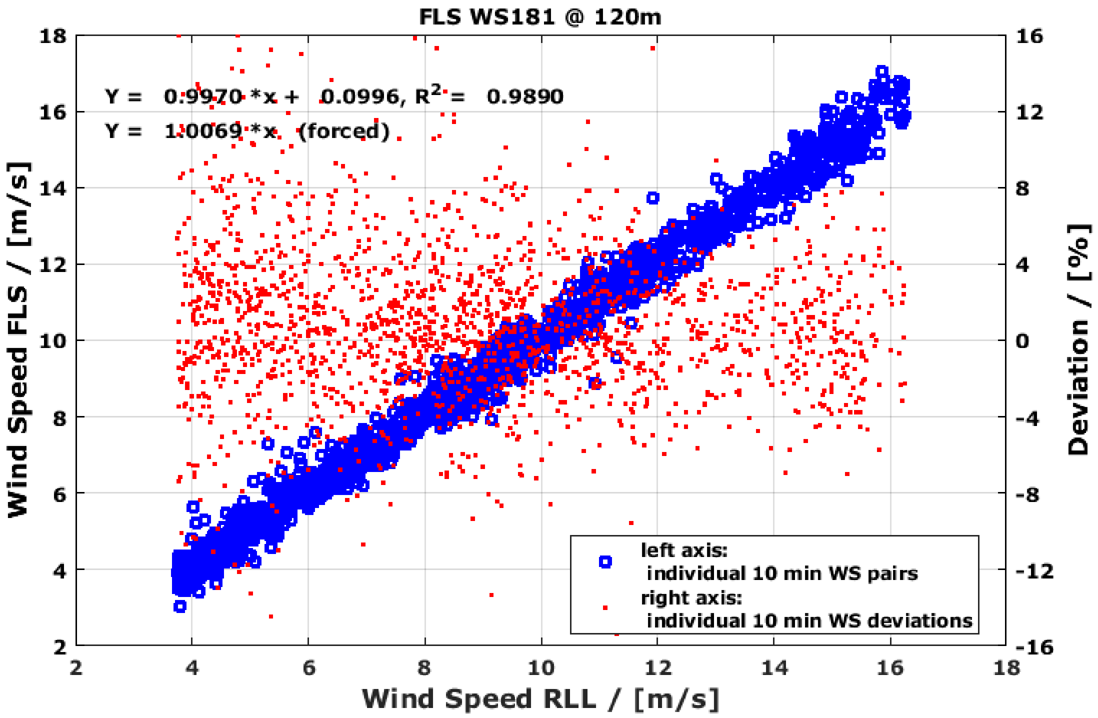


Figure 6-1 Comparison of the horizontal wind speed component at 120 m

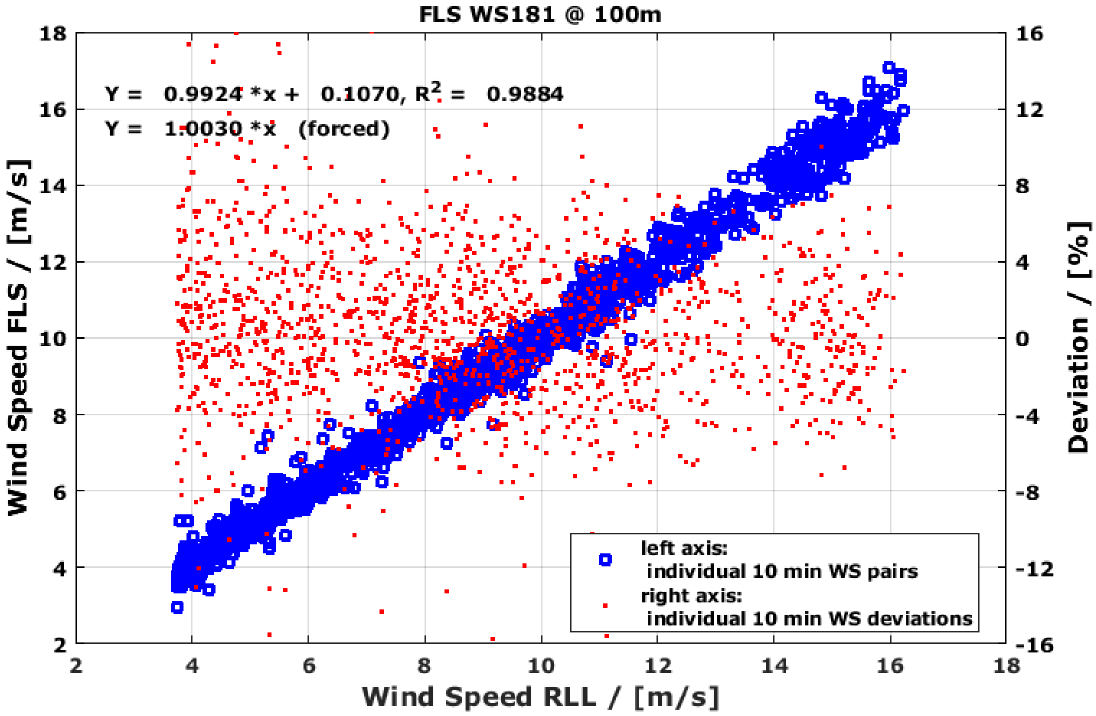


Figure 6-2 Comparison of the horizontal wind speed component at 100 m

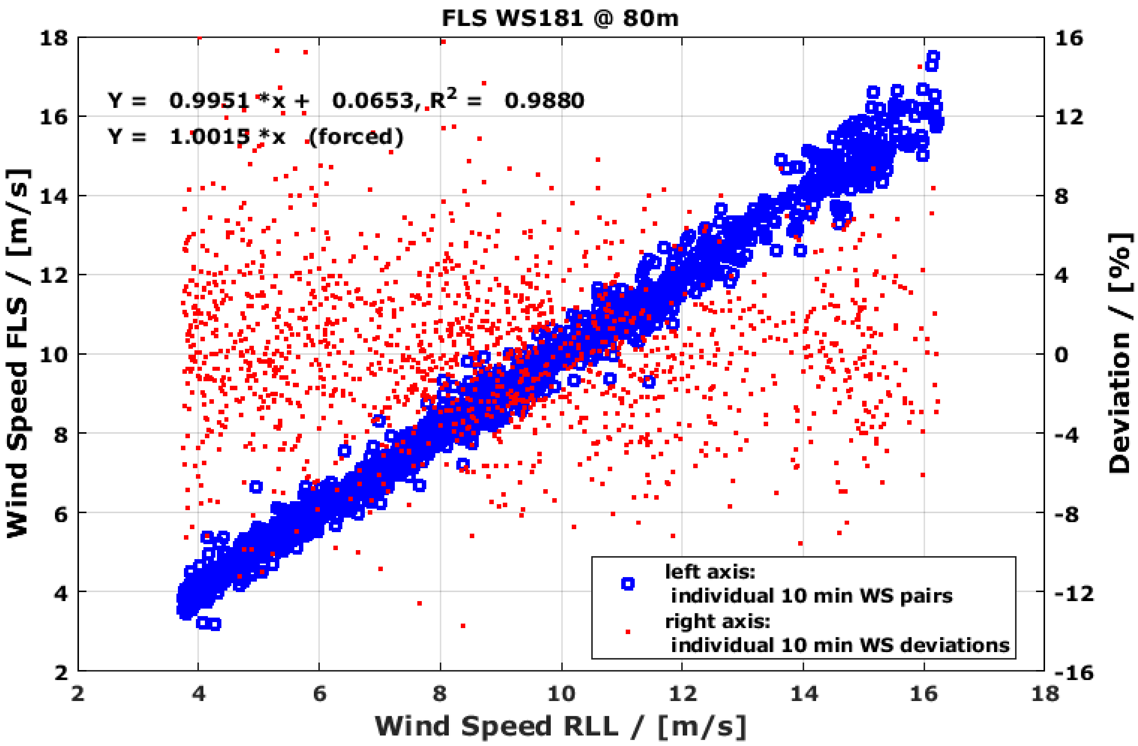


Figure 6-3 Comparison of the horizontal wind speed component at 80 m

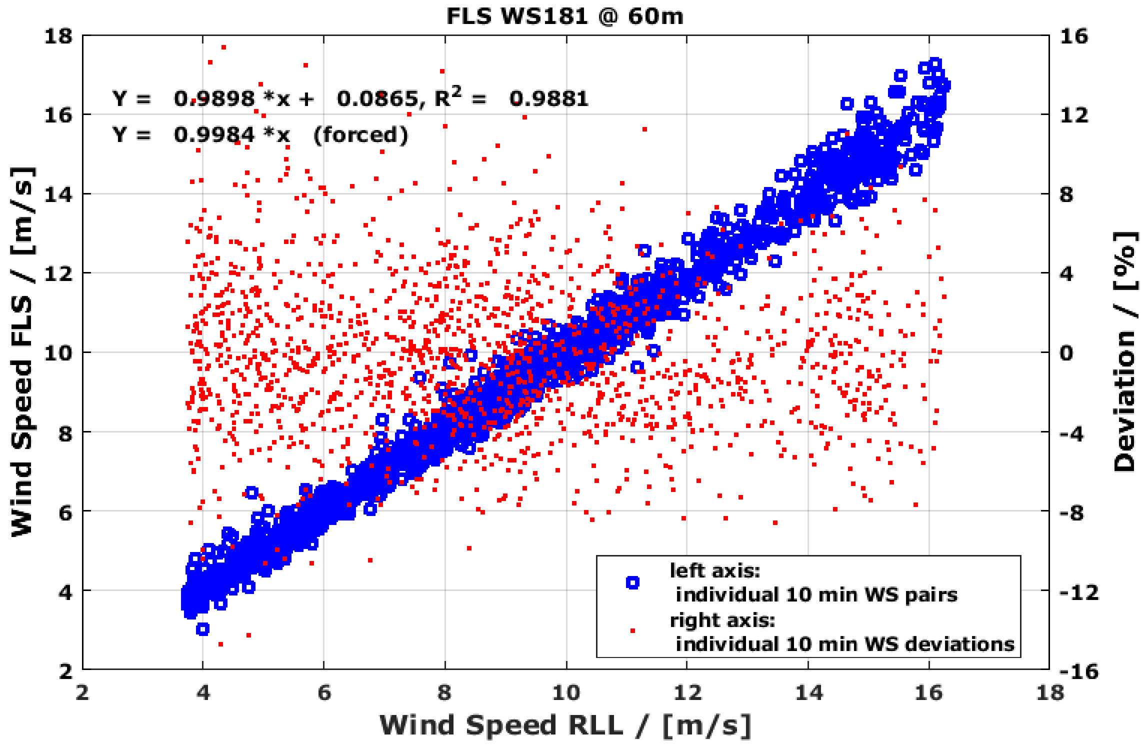


Figure 6-4 Comparison of the horizontal wind speed component at 60 m

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	0.9890	0.07	1.03%	4.66%	1884
100	0.9884	0.04	0.68%	4.67%	1607
80	0.9880	0.02	0.39%	4.43%	1598
60	0.9881	0.00	0.14%	4.46%	1604

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.

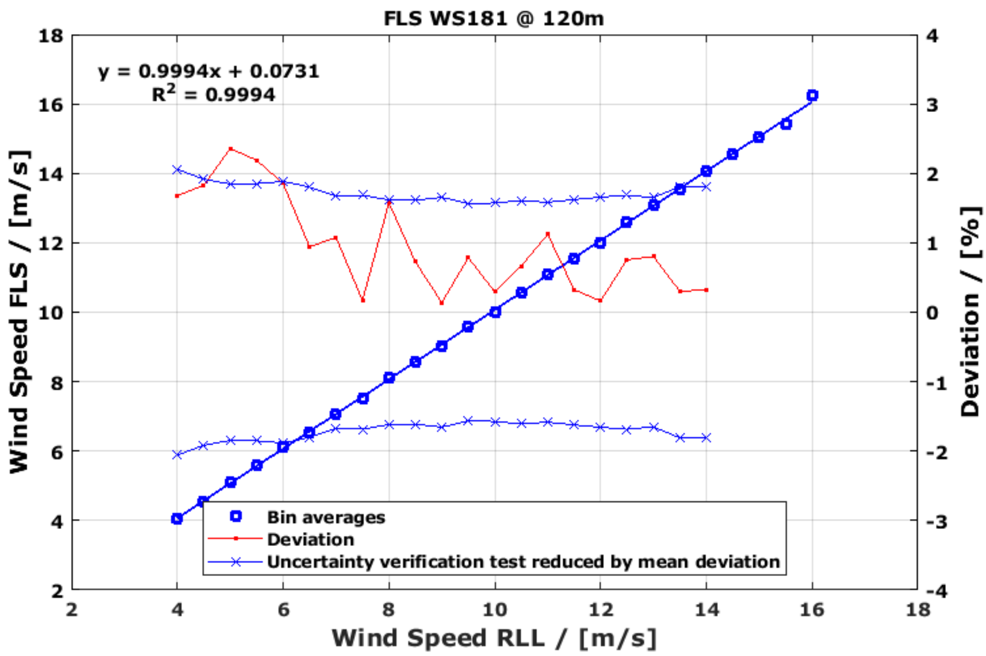


Figure 6-5 Bin-wise comparison of the horizontal wind speed component at 120 m

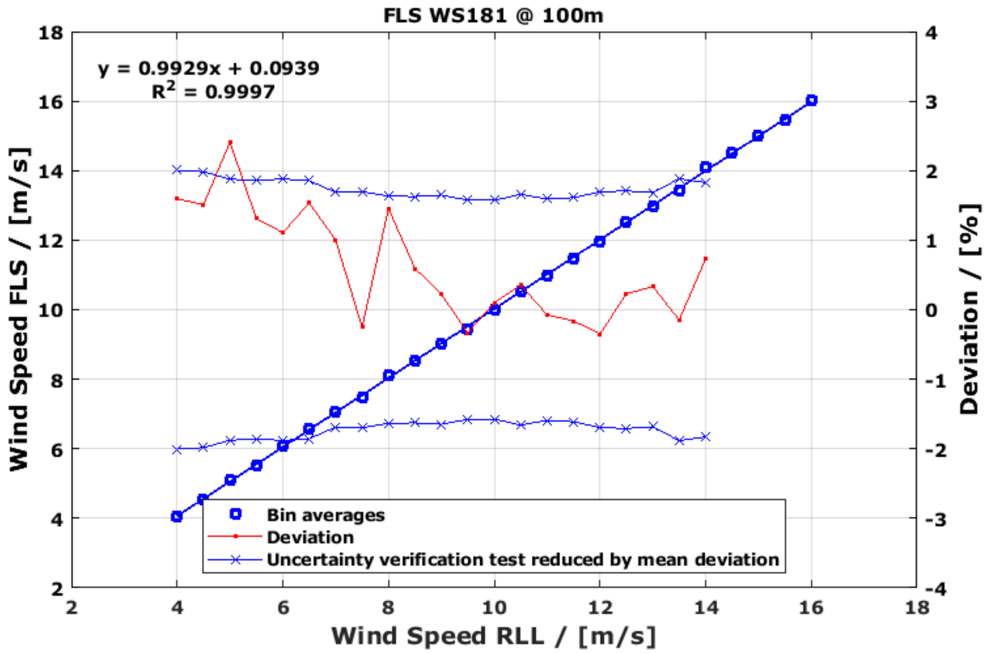


Figure 6-6 Bin-wise comparison of the horizontal wind speed component at 100 m

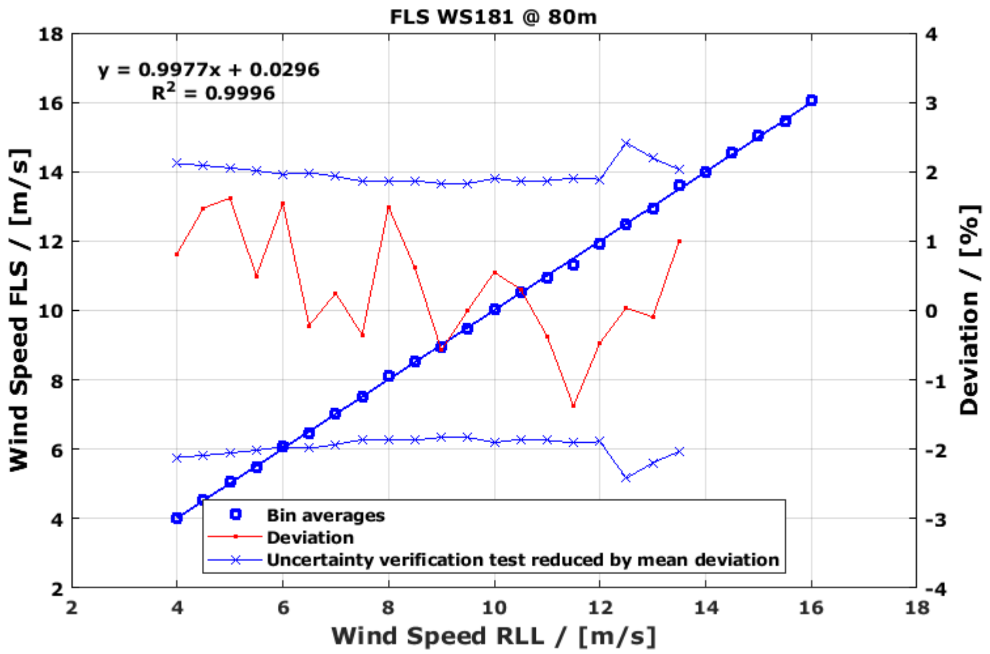


Figure 6-7 Bin-wise comparison of the horizontal wind speed component at 80 m

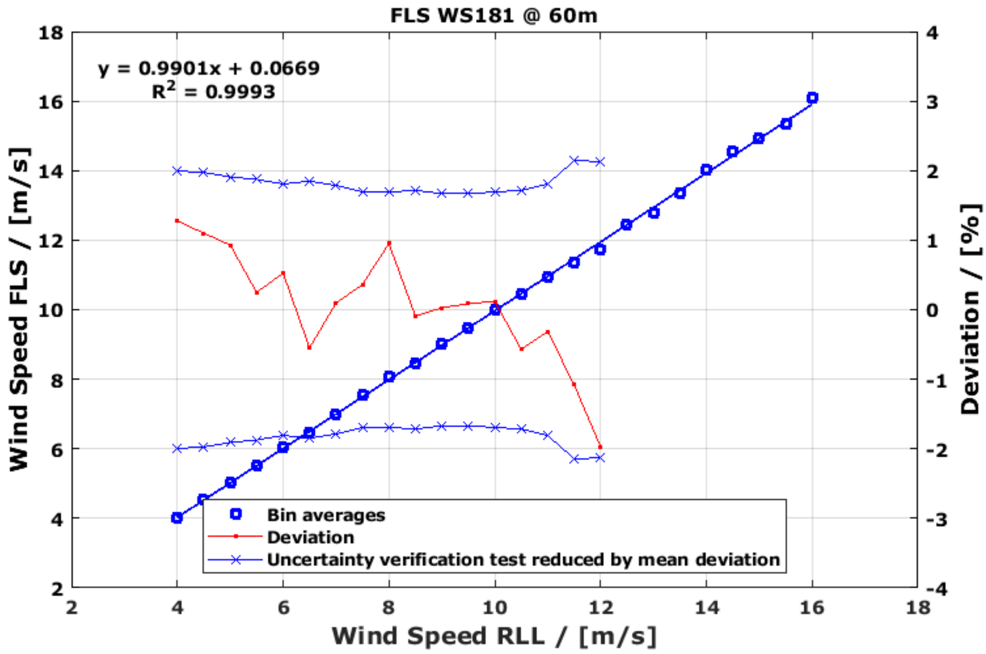


Figure 6-8 Bin-wise comparison of the horizontal wind speed component at 60 m

Table 6-2 Uncertainty calculation at 120 m

WS181 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	115	4.07	4.00	5.65	3.04	0.36	0.033	1.68%	0.50%	0.19%	1.84%	**2.67%**
4.25	4.75	118	4.56	4.48	5.47	3.63	0.30	0.028	1.83%	0.50%	0.19%	1.76%	**2.66%**
4.75	5.25	113	5.11	4.99	6.38	4.20	0.34	0.032	2.36%	0.50%	0.19%	1.67%	**3.00%**
5.25	5.75	107	5.61	5.49	7.28	4.58	0.41	0.040	2.19%	0.50%	0.19%	1.64%	**2.88%**
5.75	6.25	89	6.12	6.01	7.59	5.59	0.32	0.034	1.86%	0.50%	0.19%	1.73%	**2.65%**
6.25	6.75	70	6.55	6.48	7.30	5.99	0.30	0.036	0.94%	0.50%	0.19%	1.65%	**2.05%**
6.75	7.25	81	7.08	7.00	7.98	6.21	0.31	0.035	1.08%	0.50%	0.19%	1.52%	**2.00%**
7.25	7.75	100	7.51	7.50	8.99	6.74	0.33	0.033	0.17%	0.50%	0.19%	1.55%	**1.71%**
7.75	8.25	100	8.12	8.00	9.47	7.35	0.32	0.032	1.57%	0.50%	0.19%	1.49%	**2.27%**
8.25	8.75	110	8.55	8.49	9.51	7.70	0.38	0.036	0.73%	0.50%	0.19%	1.47%	**1.78%**
8.75	9.25	102	9.03	9.02	10.01	7.93	0.38	0.038	0.14%	0.50%	0.19%	1.52%	**1.67%**
9.25	9.75	114	9.58	9.50	10.53	8.51	0.37	0.034	0.79%	0.50%	0.19%	1.44%	**1.76%**
9.75	10.25	65	10.00	9.97	10.77	9.20	0.34	0.042	0.29%	0.50%	0.19%	1.43%	**1.61%**
10.25	10.75	62	10.55	10.48	11.44	9.92	0.34	0.043	0.66%	0.50%	0.19%	1.47%	**1.75%**
10.75	11.25	91	11.09	10.96	12.19	8.88	0.44	0.046	1.12%	0.50%	0.19%	1.45%	**1.95%**
11.25	11.75	70	11.53	11.50	12.46	9.56	0.47	0.056	0.32%	0.50%	0.19%	1.47%	**1.67%**
11.75	12.25	52	12.01	11.99	13.74	11.12	0.45	0.063	0.16%	0.50%	0.19%	1.49%	**1.68%**
12.25	12.75	38	12.62	12.52	13.41	11.78	0.38	0.061	0.76%	0.50%	0.19%	1.54%	**1.86%**
12.75	13.25	44	13.07	12.97	14.23	12.38	0.41	0.062	0.80%	0.50%	0.19%	1.50%	**1.85%**
13.25	13.75	35	13.54	13.50	14.31	12.99	0.35	0.059	0.30%	0.50%	0.19%	1.69%	**1.85%**
13.75	14.25	30	14.07	14.02	14.77	13.17	0.40	0.073	0.32%	0.50%	0.19%	1.66%	**1.85%**
14.25	14.75	53											
14.75	15.25	58											
15.25	15.75	45											
15.75	16.25	22											

Table 6-3 Uncertainty calculation at 100 m

WS181 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	127	4.05	3.99	5.23	2.96	0.30	0.027	1.60%	0.50%	0.19%	1.84%	**2.58%**
4.25	4.75	72	4.55	4.49	5.25	3.43	0.31	0.037	1.51%	0.50%	0.19%	1.76%	**2.51%**
4.75	5.25	86	5.09	4.97	7.12	4.57	0.34	0.037	2.41%	0.50%	0.19%	1.67%	**3.06%**
5.25	5.75	92	5.53	5.46	7.44	4.51	0.40	0.041	1.31%	0.50%	0.19%	1.64%	**2.29%**
5.75	6.25	82	6.10	6.03	7.35	5.49	0.30	0.033	1.11%	0.50%	0.19%	1.73%	**2.19%**
6.25	6.75	54	6.58	6.48	7.76	6.04	0.34	0.047	1.54%	0.50%	0.19%	1.65%	**2.42%**
6.75	7.25	65	7.07	7.00	8.23	6.08	0.31	0.038	1.00%	0.50%	0.19%	1.52%	**1.97%**
7.25	7.75	79	7.49	7.51	8.17	6.22	0.32	0.036	-0.25%	0.50%	0.19%	1.55%	**1.73%**
7.75	8.25	90	8.11	8.00	9.34	7.47	0.36	0.038	1.46%	0.50%	0.19%	1.49%	**2.20%**
8.25	8.75	89	8.55	8.50	9.58	7.27	0.39	0.041	0.59%	0.50%	0.19%	1.47%	**1.74%**
8.75	9.25	93	9.03	9.01	10.07	7.73	0.34	0.036	0.22%	0.50%	0.19%	1.52%	**1.68%**
9.25	9.75	100	9.45	9.48	10.34	8.55	0.39	0.039	-0.33%	0.50%	0.19%	1.44%	**1.62%**
9.75	10.25	60	9.99	9.98	10.62	9.13	0.33	0.042	0.10%	0.50%	0.19%	1.43%	**1.59%**
10.25	10.75	56	10.54	10.50	11.87	9.82	0.46	0.062	0.36%	0.50%	0.19%	1.47%	**1.71%**
10.75	11.25	82	10.97	10.98	12.01	9.40	0.44	0.049	-0.07%	0.50%	0.19%	1.45%	**1.61%**
11.25	11.75	60	11.46	11.48	12.28	9.95	0.40	0.052	-0.16%	0.50%	0.19%	1.47%	**1.63%**
11.75	12.25	38	11.95	11.99	12.90	10.98	0.47	0.077	-0.35%	0.50%	0.19%	1.49%	**1.75%**
12.25	12.75	38	12.54	12.51	13.29	11.61	0.44	0.071	0.23%	0.50%	0.19%	1.54%	**1.74%**
12.75	13.25	29	12.97	12.93	13.77	12.24	0.41	0.076	0.33%	0.50%	0.19%	1.50%	**1.73%**
13.25	13.75	23	13.42	13.44	14.42	12.69	0.45	0.093	-0.15%	0.50%	0.19%	1.69%	**1.90%**
13.75	14.25	28	14.12	14.02	14.87	13.25	0.43	0.082	0.73%	0.50%	0.19%	1.66%	**1.98%**
14.25	14.75	49											
14.75	15.25	56											
15.25	15.75	40											
15.75	16.25	19											

Table 6-4 Uncertainty calculation at 80 m

WS181 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	111	4.02	3.98	5.37	3.21	0.28	0.026	0.82%	0.50%	0.19%	1.96%	**2.29%**
4.25	4.75	85	4.54	4.47	5.36	3.18	0.31	0.033	1.48%	0.50%	0.19%	1.90%	**2.57%**
4.75	5.25	89	5.05	4.97	6.66	4.29	0.36	0.038	1.62%	0.50%	0.19%	1.86%	**2.63%**
5.25	5.75	85	5.48	5.45	6.14	4.90	0.28	0.031	0.50%	0.50%	0.19%	1.88%	**2.09%**
5.75	6.25	85	6.10	6.01	6.77	5.44	0.29	0.031	1.54%	0.50%	0.19%	1.83%	**2.51%**
6.25	6.75	48	6.46	6.48	7.56	5.66	0.34	0.049	-0.22%	0.50%	0.19%	1.78%	**2.02%**
6.75	7.25	69	7.03	7.01	8.30	6.25	0.35	0.042	0.25%	0.50%	0.19%	1.78%	**1.96%**
7.25	7.75	80	7.51	7.54	8.20	6.70	0.29	0.033	-0.35%	0.50%	0.19%	1.74%	**1.90%**
7.75	8.25	87	8.13	8.02	9.32	7.46	0.36	0.038	1.49%	0.50%	0.19%	1.73%	**2.40%**
8.25	8.75	94	8.54	8.48	9.92	7.23	0.43	0.044	0.62%	0.50%	0.19%	1.73%	**1.98%**
8.75	9.25	88	8.94	8.99	10.01	8.20	0.33	0.035	-0.57%	0.50%	0.19%	1.72%	**1.93%**
9.25	9.75	113	9.48	9.48	10.50	8.58	0.34	0.032	0.00%	0.50%	0.19%	1.73%	**1.84%**
9.75	10.25	49	10.03	9.98	10.97	9.16	0.33	0.047	0.55%	0.50%	0.19%	1.78%	**1.99%**
10.25	10.75	63	10.54	10.51	11.65	9.74	0.44	0.055	0.30%	0.50%	0.19%	1.71%	**1.89%**
10.75	11.25	72	10.92	10.96	11.62	9.37	0.38	0.044	-0.37%	0.50%	0.19%	1.76%	**1.92%**
11.25	11.75	57	11.32	11.47	12.66	9.30	0.53	0.070	-1.38%	0.50%	0.19%	1.74%	**2.37%**
11.75	12.25	40	11.91	11.96	12.98	10.77	0.46	0.072	-0.46%	0.50%	0.19%	1.72%	**1.96%**
12.25	12.75	37	12.49	12.48	13.65	11.72	0.43	0.071	0.04%	0.50%	0.19%	2.30%	**2.43%**
12.75	13.25	30	12.95	12.96	13.65	11.80	0.44	0.081	-0.10%	0.50%	0.19%	2.05%	**2.21%**
13.25	13.75	21	13.60	13.46	14.89	12.60	0.52	0.113	1.00%	0.50%	0.19%	1.79%	**2.28%**
13.75	14.25	35											
14.25	14.75	48											
14.75	15.25	62											
15.25	15.75	29											
15.75	16.25	21											

Table 6-5 Uncertainty calculation at 60 m

WS181 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	113	4.02	3.97	5.04	3.03	0.30	0.029	1.28%	0.50%	0.19%	1.81%	**2.39%**
4.25	4.75	96	4.54	4.49	5.44	3.66	0.32	0.033	1.10%	0.50%	0.19%	1.78%	**2.28%**
4.75	5.25	95	5.03	4.98	6.46	4.08	0.32	0.032	0.93%	0.50%	0.19%	1.74%	**2.14%**
5.25	5.75	73	5.53	5.52	6.53	4.79	0.30	0.035	0.25%	0.50%	0.19%	1.70%	**1.91%**
5.75	6.25	73	6.04	6.01	6.61	5.19	0.28	0.033	0.53%	0.50%	0.19%	1.66%	**1.90%**
6.25	6.75	51	6.44	6.48	7.12	5.93	0.29	0.040	-0.55%	0.50%	0.19%	1.68%	**1.95%**
6.75	7.25	66	6.99	6.98	8.29	6.05	0.37	0.046	0.10%	0.50%	0.19%	1.59%	**1.81%**
7.25	7.75	86	7.54	7.51	9.37	6.80	0.33	0.036	0.36%	0.50%	0.19%	1.55%	**1.75%**
7.75	8.25	101	8.09	8.02	9.72	7.29	0.37	0.037	0.95%	0.50%	0.19%	1.55%	**1.95%**
8.25	8.75	82	8.47	8.47	9.91	7.58	0.39	0.043	-0.09%	0.50%	0.19%	1.57%	**1.73%**
8.75	9.25	106	9.02	9.01	10.35	8.23	0.39	0.038	0.03%	0.50%	0.19%	1.54%	**1.68%**
9.25	9.75	98	9.47	9.46	10.68	8.57	0.39	0.039	0.09%	0.50%	0.19%	1.54%	**1.68%**
9.75	10.25	53	10.01	10.00	10.75	9.28	0.37	0.051	0.12%	0.50%	0.19%	1.54%	**1.71%**
10.25	10.75	67	10.46	10.52	11.38	9.49	0.43	0.052	-0.57%	0.50%	0.19%	1.57%	**1.82%**
10.75	11.25	66	10.93	10.97	11.85	9.64	0.42	0.052	-0.31%	0.50%	0.19%	1.68%	**1.85%**
11.25	11.75	50	11.36	11.48	12.56	10.04	0.48	0.067	-1.08%	0.50%	0.19%	2.00%	**2.41%**
11.75	12.25	40	11.75	11.99	12.85	10.94	0.43	0.068	-1.97%	0.50%	0.19%	2.00%	**2.92%**
12.25	12.75	34											
12.75	13.25	30											
13.25	13.75	26											
13.75	14.25	38											
14.25	14.75	52											
14.75	15.25	57											
15.25	15.75	27											
15.75	16.25	24											

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 WS181. Measurement heights between 40 m and 250 m were available for wind speed correlations. The duration of the verification was 19.9 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.

WS181 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 2.04 m (and 3.96 m for maximum wave height) and wind speeds recorded at RLL of up to 18.4 m/s at 40 m and 20.4 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

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

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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
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

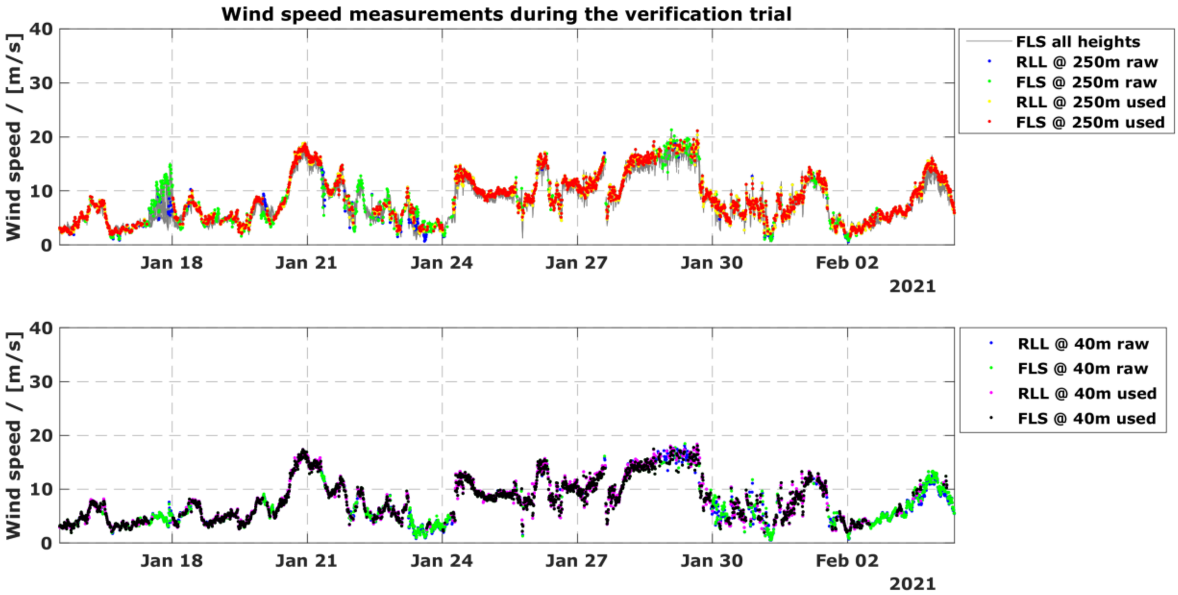


Figure 10-1 Wind Speed time series for 250 m (upper panel) and 40 m (lower panel).

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.

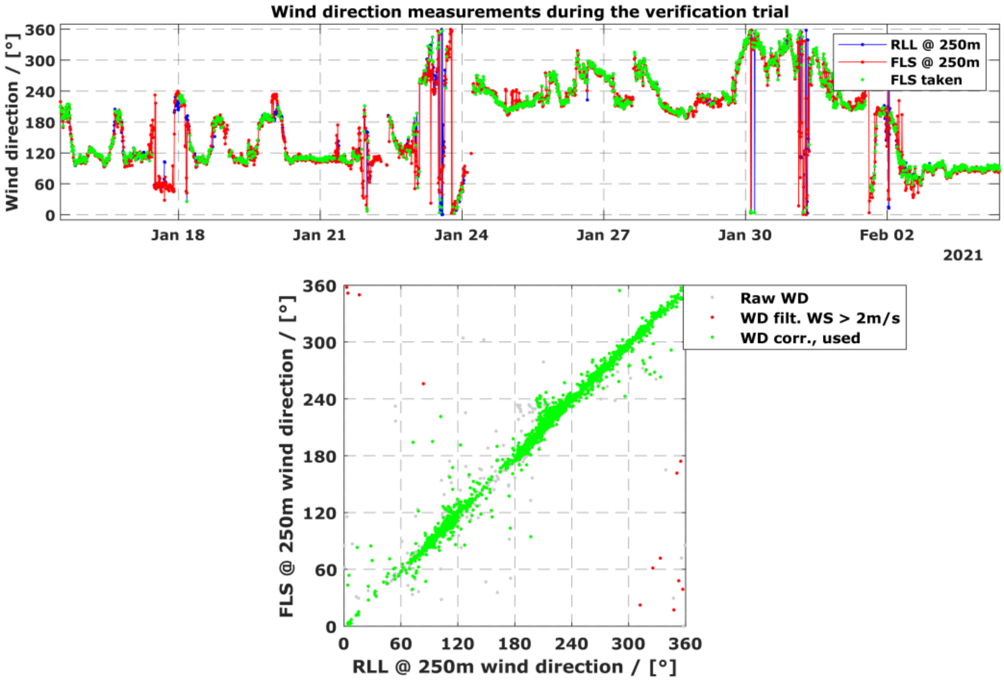


Figure 10-2 Wind direction time series and scatter plot of the FLS and RLL at 250 m.

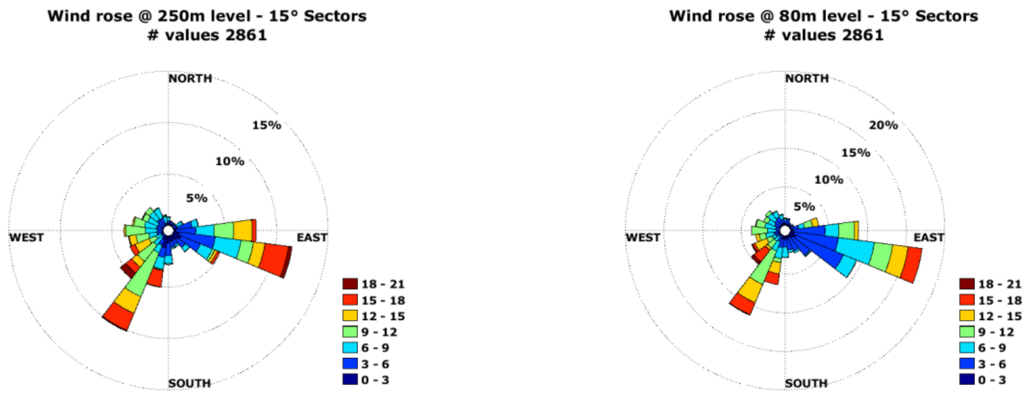


Figure 10-3 Wind rose and sector averaged wind speed distribution at 250 m and 80 m

APPENDIX D SEA STATES AND METEOROLOGICAL CONDITIONS

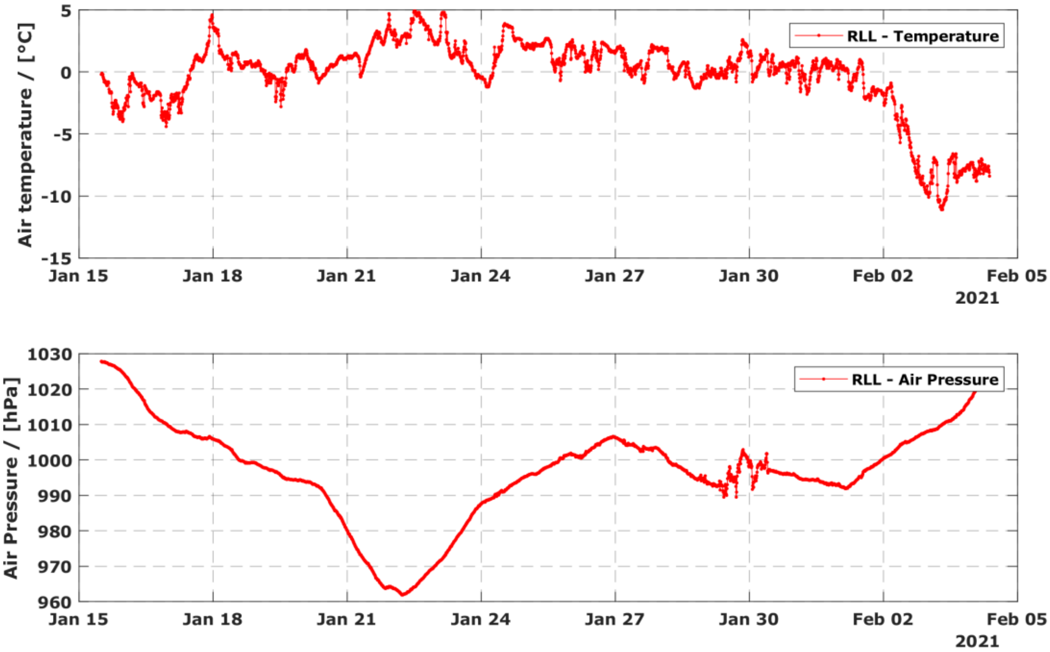


Figure 10-4 Time series of air temperature and air pressure at the RLL

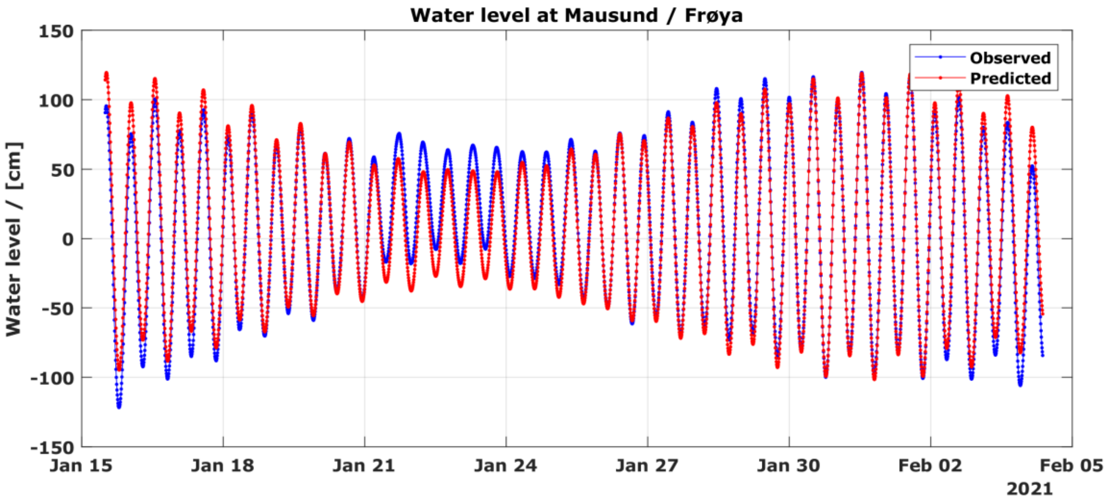


Figure 10-5 Time series of tidal or water level at Mausund, Frøya.

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: WS181
Sampling interval: 10 minutes
Period start: 15/01/2021 12:00
Period end: 04/02/2021 09:00

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	90	316	318	108	55	2										889	31.1	889	0.31062	2.7	4.2	7.3
0.5 - 1.0		678	309	392	121	72	12									1584	55.4	2473	0.86408	3.1	4.7	8.9
1.0 - 1.5		93	145	7			5									250	8.7	2723	0.95143	3.6	4.2	8.6
1.5 - 2.0			135													135	4.7	2858	0.99860	4.2	4.5	5.0
2.0 - 2.5			1	2												3	0.1	2861	0.99965	5.0	5.1	5.1
2.5 - 3.0																		2861	0.99965			
3.0 - 3.5																		2861	0.99965			
3.5 - 4.0																		2861	0.99965			
4.0 - 4.5																		2861	0.99965			
4.5 - 5.0																		2861	0.99965			
5.0 - 5.5																		2861	0.99965			
5.5 - 6.0																		2861	0.99965			
6.0 - 6.5																		2861	0.99965			
6.5 - 7.0																		2861	0.99965			
>= 7.0																		2861	0.99965			
SUM	90	1087	908	509	176	74	17									2861	100	2861	0.99965	2.7	4.5	8.9
% OF TOTAL	3.1	38.0	31.7	17.8	6.2	2.6	0.6									100						
SUM ACCUM.	90	1177	2085	2594	2770	2844	2861	2861	2861	2861	2861	2861	2861	2861	2861	2861						
CUM. PROB.	0.03145	0.41125	0.72851	0.90636	0.96785	0.99371	0.99965	0.99965	0.99965	0.99965	0.99965	0.99965	0.99965	0.99965	0.99965	0.99965						
MIN. VALUE	0.23	0.21	0.23	0.25	0.29	0.47	0.57									0.21						
AVE. VALUE	0.38	0.65	0.82	0.60	0.58	0.74	0.93									0.69						
MAX. VALUE	0.49	1.35	2.04	2.04	0.94	0.98	1.16									2.04						

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: WS181
Sampling interval: 10 minutes
Period start: 15/01/2021 12:00
Period end: 04/02/2021 09:00

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	2	9	3	5	13	28	50	38	19	16	24	24	20	14	148	413	14.6	413	0.14558	3.0	14.3	24.9
0.5 - 1.0	5	133	79	126	202	234	198	124	103	45	63	39	16	10	41	1418	50.0	1831	0.64540	2.9	8.1	24.9
1.0 - 1.5		31	118	106	141	80	62	43	34	12	8	2	2			639	22.5	2470	0.87064	3.5	6.8	14.2
1.5 - 2.0		7	81	62	28	8	3	6	4	1						200	7.1	2670	0.94114	4.0	5.6	11.3
2.0 - 2.5			29	51	19	6	1									106	3.7	2776	0.97850	4.2	5.5	8.8
2.5 - 3.0			7	27	10	3										47	1.7	2823	0.99507	4.6	5.6	7.0
3.0 - 3.5				5	3											8	0.3	2831	0.99789	5.2	5.8	6.3
3.5 - 4.0				2	3											5	0.2	2836	0.99965	5.7	6.2	6.6
4.0 - 4.5																		2836	0.99965			
4.5 - 5.0																		2836	0.99965			
5.0 - 5.5																		2836	0.99965			
5.5 - 6.0																		2836	0.99965			
6.0 - 6.5																		2836	0.99965			
6.5 - 7.0																		2836	0.99965			
>= 7.0																		2836	0.99965			
SUM	7	180	317	384	419	359	314	211	160	74	95	65	38	24	189	2836	100	2836	0.99965	2.9	8.4	24.9
% OF TOTAL	0.2	6.3	11.2	13.5	14.8	12.7	11.1	7.4	5.6	2.6	3.3	2.3	1.3	0.8	6.7	100						
SUM ACCUM.	7	187	504	888	1307	1666	1980	2191	2351	2425	2520	2585	2623	2647	2836	2836						
CUM. PROB.	0.00247	0.06591	0.17765	0.31301	0.46070	0.58724	0.69792	0.77229	0.82869	0.85478	0.88826	0.91117	0.92457	0.93303	0.99965	0.99965						
MIN. VALUE	0.34	0.40	0.40	0.46	0.34	0.40	0.34	0.37	0.34	0.31	0.34	0.37	0.34	0.34	0.31	0.31						
AVE. VALUE	0.56	0.84	1.37	1.43	1.13	0.89	0.81	0.79	0.82	0.73	0.65	0.59	0.56	0.49	0.46	0.97						
MAX. VALUE	0.87	1.96	2.66	3.78	3.96	2.93	2.10	1.99	1.78	1.55	1.25	1.19	1.40	0.63	0.84	3.96						

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 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 370 m at a coastal site, the uncertainty was calculated to be 0.19%.

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

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 UNFILTERED RESULTS

For information, an evaluation has been done without application of the additional filter (see chapter 3.3).

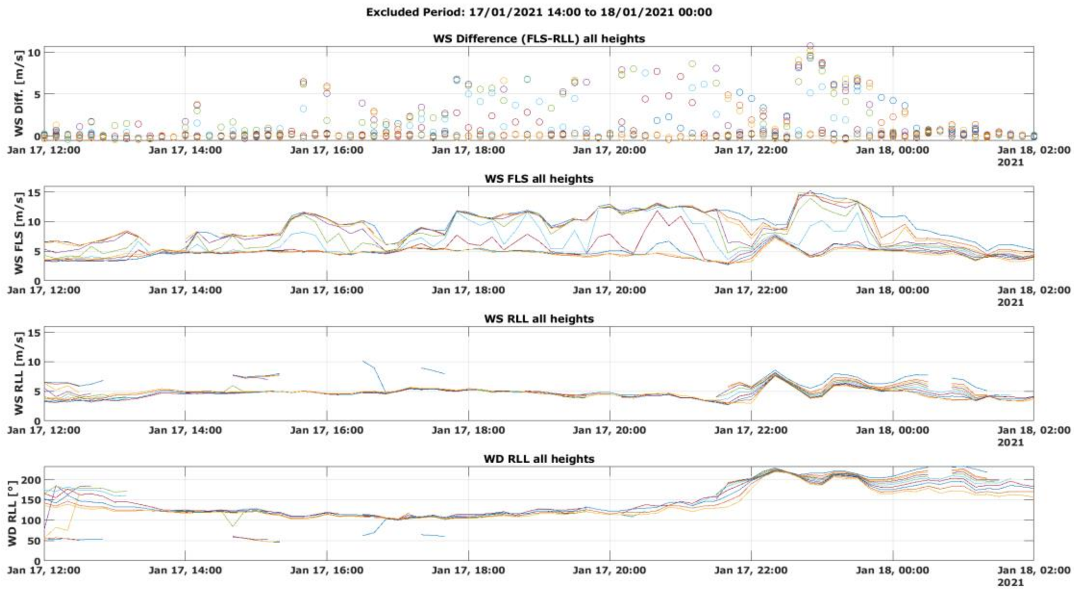
	# values	slope	R^2	WS-avg RLL (Reference)	WS-avg WS181 (Test)	mean diff.	rel. mean difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{mws}				
250 m level							
All >= 2 m/s	2156	1.003	0.963	8.69	8.77	0.085	0.98%
4 - 16 m/s	1708	1.003	0.933	9.06	9.13	0.075	0.83%
200 m level							
All >= 2 m/s	2311	1.008	0.969	8.49	8.61	0.115	1.35%
4 - 16 m/s	1828	1.008	0.947	9.00	9.11	0.110	1.22%
180 m level							
All >= 2 m/s	2396	1.009	0.967	8.41	8.54	0.127	1.52%
4 - 16 m/s	1898	1.010	0.945	8.96	9.09	0.131	1.46%
160 m level							
All >= 2 m/s	2466	1.010	0.968	8.32	8.46	0.138	1.66%
4 - 16 m/s	1944	1.011	0.946	8.85	9.00	0.149	1.68%
140 m level							
All >= 2 m/s	2525	1.009	0.970	8.24	8.37	0.130	1.58%
4 - 16 m/s	1996	1.010	0.956	8.78	8.92	0.134	1.52%
120 m level							
All >= 2 m/s	2604	1.008	0.982	8.20	8.30	0.106	1.30%
4 - 16 m/s	2035	1.009	0.971	8.71	8.82	0.116	1.33%
100 m level							
All >= 2 m/s	2669	1.004	0.987	8.09	8.16	0.064	0.79%
4 - 16 m/s	2070	1.006	0.982	8.67	8.73	0.069	0.80%
80 m level							
All >= 2 m/s	2694	1.002	0.991	8.00	8.04	0.038	0.47%
4 - 16 m/s	2086	1.004	0.986	8.60	8.65	0.041	0.48%
60 m level							
All >= 2 m/s	2767	1.000	0.991	7.96	7.98	0.020	0.25%
4 - 16 m/s	2130	1.001	0.987	8.57	8.59	0.019	0.22%
40 m level							
All >= 2 m/s	2667	0.992	0.987	7.64	7.62	-0.024	-0.31%
4 - 16 m/s	2096	0.994	0.982	8.33	8.31	-0.021	-0.25%

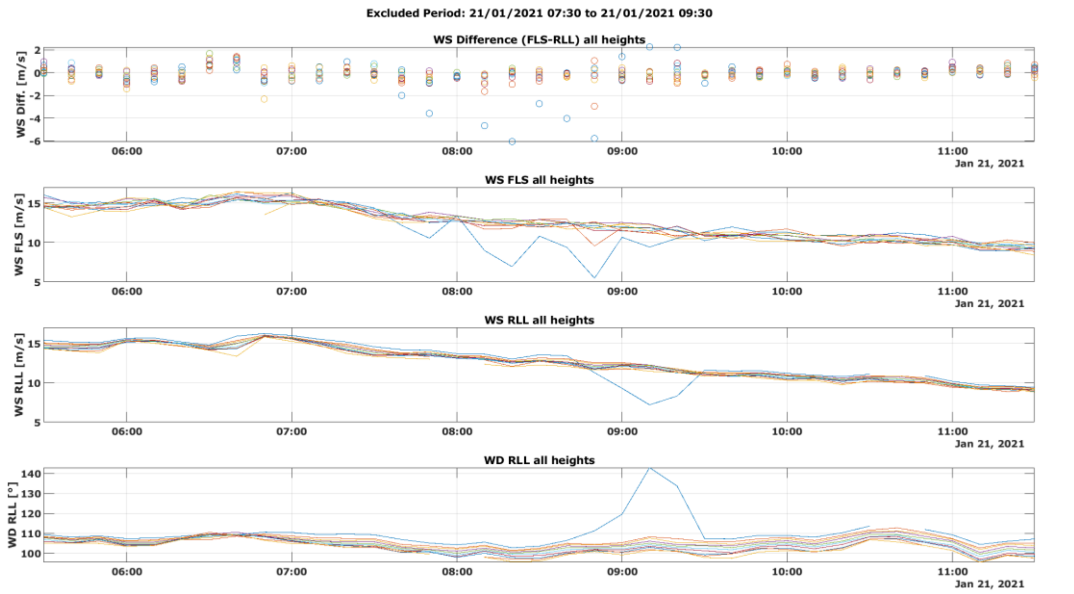
WS filtering for WS > 2 m/s				
Height level	# values	slope	offset [°]	R^2
[m]	[-]	KPI M_{mwd}	KPI OFF_{mwd}	KPI R^2_{mwd}
250	2152	0.989	-0.893	0.977
200	2309	0.992	-1.240	0.986
180	2394	0.992	-1.600	0.984
160	2464	0.992	-1.959	0.985
140	2523	0.995	-2.338	0.988
120	2603	0.998	-1.929	0.993
100	2669	0.997	-1.838	0.995
80	2694	0.996	-1.578	0.997
60	2767	0.996	-1.406	0.996
40	2667	0.993	-1.445	0.997

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	142	173	165	198	179	183	178	205	116	142	164	178	104	28	1	0	0	0	0
200	163	201	190	226	190	187	193	211	119	154	170	188	98	20	1	0	0	0	0
180	173	213	213	227	197	195	212	203	128	150	175	198	91	21	0	0	0	0	0
160	171	232	249	236	183	204	219	205	135	141	176	196	96	23	0	0	0	0	0
140	164	251	289	232	186	206	221	203	140	149	169	201	95	19	0	0	0	0	0
120	148	292	315	234	185	209	220	210	146	142	176	198	106	23	0	0	0	0	0
100	144	331	314	258	181	219	223	208	156	141	170	200	105	19	0	0	0	0	0
80	139	352	322	267	186	212	241	204	155	136	170	193	102	15	0	0	0	0	0
60	133	382	345	271	179	231	228	217	160	127	172	200	113	9	0	0	0	0	0
40	139	354	373	278	182	231	237	213	147	108	162	165	76	2	0	0	0	0	0

APPENDIX G PLOTS OF MANUALLY EXCLUDED PERIODS

Two periods were excluded from the evaluation because they showed unusual behaviour in the RLL data and the FLS data approximately simultaneously. Due to this simultaneity it can be assumed that this behaviour is caused by special atmospheric conditions.





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