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FUGRO SEAWATCH WIND LIDAR BUOY WS 187
PRE-DEPLOYMENT VALIDATION

Assessment of the Fugro Seawatch Wind LiDAR Buoy WS 187 Pre-Deployment Validation at Frøya, Norway

Fugro Norway AS

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Task and objective: 3rd Party Assessment of an Offshore/Nearshore Pre-Deployment Validation of the Fugro/Oceanor SEAWATCH Wind LiDAR Buoy WS187 at the Island Frøya, Norway

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E	2019-11-28	Change of data filtering method.	A. Mark	B. Schmidt	B. Schmidt

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List of abbreviations

Abbreviation	Meaning
SWLB	Seawatch Wind Lidar Buoy
DNV GL	GL Garrad Hassan Deutschland GmbH, part of DNV GL group
RLL	Reference Land Lidar
RSD	Remote Sensing Device
FLS	Floating Lidar System
MSL	Mean Sea Level
MWD	Mean Wind Direction
MWS	Mean Wind Speed
SL	actual Sea Level
LAT	Lowest astronomical tide
KPI	Key Performance Indicator
AC	Acceptance Criterion
WS	Wind Speed
WD	Wind Direction
TCM	Tilt-Compensated Magnetic Compass
DGPS	Differential Global Positioning System
&	Logic operator for AND
|	Logic operator for OR

1 INTRODUCTION

On 2019-01-23, Fugro Norway AS (Fugro or the Client) commissioned GL Garrad Hassan Deutschland GmbH (DNV GL) to perform a pre-deployment validation including uncertainty assessment of a SEAWATCH Wind LiDAR Buoy unit with the serial number WS187 moored next to the Island Frøya in the Norwegian Sea (see Figure 1).

The pre-deployment validation of this Floating Lidar System (FLS), which is already "Roadmap-Pre-Commercial" staged [1], was performed over a period of around 17.6 days against a fixed/land based industry accepted Lidar (Reference Land Lidar or RLL), that was used as the only validation reference. data evaluation is performed based on Key Performance Indicators (KPIs) and Acceptance Criteria (AC) delineated in the Roadmap towards Commercial Acceptance [2].

DNV GL has not been involved in the data collection. Data from both the SWLB and the RLL were provided by Fugro.

This report is used to document the results with respect to the pre-deployment validation trial of the Fugro Seawatch Wind Lidar Buoy (SWLB) with S/N WS187 against a Reference Land Lidar (RLL) of type ZX Lidars Z300 with the S/N ZP495 at the Fugro test site near and on the Norwegian Island Frøya at a place called Stabben, in the Norwegian Sea.

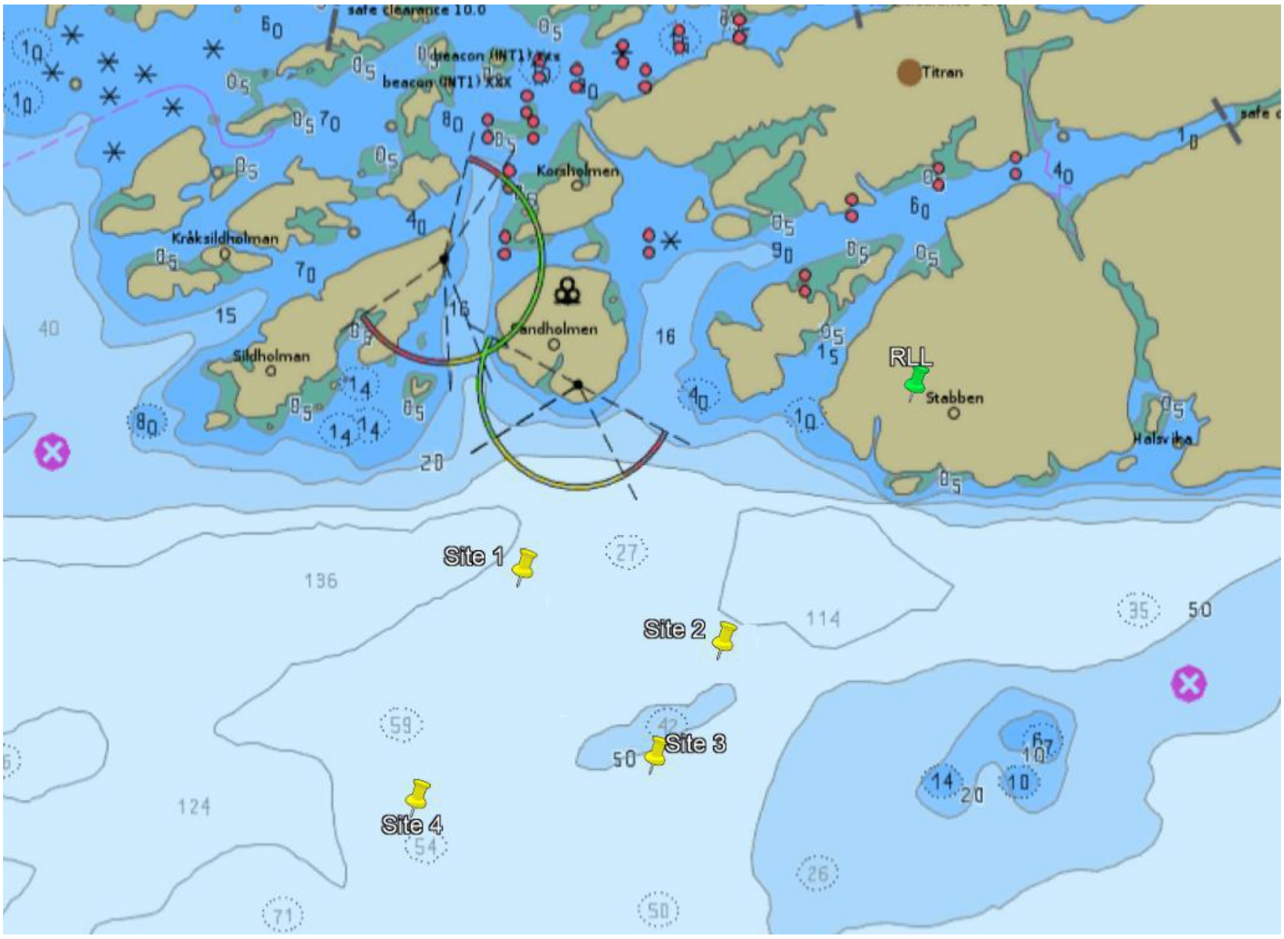


Figure 1: Positions of SWLB (WS187 was deployed at Site 2) and RLL (Land Lidar) near or at the Island Frøya /Stabben.

1.1 Clarification Note

It is important to note that the validation approach applied for this campaign focusses on the capabilities of floating LiDAR technology (namely in this case for the SWLB with the buoy's S/N WS187 employing a ZX Lidars ZX300 Lidar with the S/N ZX818) measuring primary wind data, namely wind speed and wind direction. Therefore, while the SWLB currently features additional measures the scope of this document is limited to its primary wind data measurements. The SWLB wind direction data was stored as two separate datasets – one dataset is based on DGPS correction and the other one is based on magnetic compass correction. All results in this report are based on the compass wind direction signal.

DNV GL understands that the tested SWLB Floating Lidar unit is planned to be deployed after the campaign analyzed in this report. The analyzed campaign serves as the according pre-deployment validation.

DNV GL understands and assumes that there is agreement between Fugro and their client that a pre-deployment validation of an already "Roadmap-Pre-Commercial" staged FLS against a fixed/land based industry accepted Lidar to be used as the only validation reference (RLL) is acceptable.

It is further understood that the following conditions have to be fulfilled in this validation context:

- The RLL has successfully been validated against an IEC compliant onshore met mast: → this is fulfilled by a Lidar validation performed at the ZX Lidars UK Remote Sensing Test Site near Pershore, UK, independently verified by DNV GL [4]
- The Lidar mounted on the SWLB has successfully been validated against an IEC compliant onshore met mast → this is fulfilled by a Lidar validation performed at the ZX Lidars UK Remote Sensing Test Site near Pershore, UK, which was reviewed by DNV GL [5]
- The suitability of Frøya test site, i.e. given comparativeness of wind conditions between locations of Reference Land Lidar (RLL) and SWLB
- Setup of RLL in compliance with industry best practice → confirmed by installation report from DNV GL [3]
- The wind speed data coverage and bin wise completeness according to the Roadmap [1] is achieved.
- The wind speed and wind direction comparison results yielded according to relevant Roadmap KPIs and ACs meet at least the Roadmap Minimum Acceptance Criteria.

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 Hollandse Kust (west). From the SWLB type verification trial at Ijmuiden [6] and further historical evidence DNV GL is confident that the performance of the SWLB device WS187 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.

All conclusions on the capabilities of the Fugro SWLB drawn from this Frøya pre-deployment validation campaign are valid under sea state and meteorological conditions similar to those experienced during the campaign duration, only.

2 SETUP OF THE SWLB PRE-DEPLOYMENT VALIDATIONS

DNV GL has performed a site visit at the Stabben/Frøya site on 2015-03-25 [3] in order to inspect the suitability to serve as a test site for FLS validations. In addition to this, substantial evidence has now been collected by

1. acknowledging the information provided by Fugro to DNV GL on the side upfront,
2. seeing the generally consistent resemblance between SWLB and RLL at the given spatial separation of 690 m and over the full height range as shown in this report and
3. from the site inspection itself, considering the terrain as rather benign.

With this DNV GL considers Stabben/Frøya test site is suitable for pre-deployment verifications of FLS.

2.1 Positions of installed SWLB and RLL Units

Position of ZephIR Reference Land Lidar, see Figure 2, right:

- The location is called Stabben on the Island Frøya and the RLL is placed at 14 m above sea level (mean sea level or MSL).
- The GPS position of the RLL is Latitude 63.66292°, Longitude 8.31011°

Position of Seawatch Wind Lidar Buoy (SWLB) Floating Lidar Device, see Figure 2, left:

- The SWLB is deployed at position Latitude 63.65735°, Longitude 8.30393° (see Figure 1, Site 2)
- It is moored in 50 m of water depth and the mooring array allows a horizontal sway freedom of movement around the anchor of about 115 m.
- The mooring point is about 550 m from the shore of a place called Stabben and approx. 690 m to the South West of the RLL position, see Figure 1.

These positions were confirmed during a site visit and RLL inspection by DNV GL, on 2015-03-25 [3] (for the RLL) and from direct GPS recordings in the FLS data.

Figure 2: Seawatch Wind Lidar Buoy (left[1]) and Reference Land Lidar as installed near/at Frøya test site.

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

2.2 Settings and Specs of SWLB and RLL Units

SWLB Floating Lidar:

- SWLB S/N WS187
- ZephIR S/N ZX818
- Height settings 250, 200, 180, 160, 140, 120, 100, 80, 60, 30, 40 m relative to actual sea level

Reference Land Lidar:

- ZephIR S/N ZP495
- Height settings 250, 200, 180, 160, 140, 120, 100, 80, 60, 40, 52 m above mean sea level

Table 1: List of heights relevant for wind data comparisons between SWLB and RLL (green shading, targeted heights above MSL/SL

	Land Reference Lidar (Lidar Window 14m AMSL)		Floating Lidar System (Lidar Window 2m AMSL)	
Height Index	Height AMSL	Configured Height	Height AMSL	Configured Height
1	250	236	250	248
2	200	186	200	198
3	180	166	180	178
4	160	146	160	158
5	140	126	140	138
6	120	106	120	118
7	100	86	100	98
8	80	66	80	78
9	60	46	60	58
10	40	26	30	28
Ref Height (non-configurable)	52	38	40	38

The assessment of the KPIs and their respective Acceptance Criteria regarding wind data accuracy was performed at height levels between 40 m and 250 m as mentioned in Table 1.

3 VALIDATION RESULTS

For the pre-deployment validation of Fugro's SWLB against the RLL data from the employed FLS with a ZX Lidars Lidar with the serial number ZX818 and from the RLL ZephIR with the serial number ZP495 were provided by Fugro for a campaign period lasting 2019-01-04 to 2019-01-21, yielding a duration of 17.6 days.

3.1 Data provision

The Following remarks and reservations with respect to data transfer, traceability and processing are noted:

- RLL and SWLB data were provided to DNV GL for the whole campaign period by Fugro, directly.
- SWLB Lidar wind statistics were returned by the central controller unit (called GENI) installed on the SWLB. This unit collected the 1-sec raw data from the on-board ZephIR 300 Lidar to calculate the 10-minute wind data statistics.

3.2 Meteorological and sea state conditions during the trial

During the validation period of the SWLB the device encountered a wide range of wind conditions facing 10-minute averaged wind speeds at the RLL of up to 26.0 m/s at the lowest comparison level (40 m) and 30.1 m/s at the upper most level (250 m) – see Table 2. The air temperatures covered during the campaign at the RLL location and on the SWLB buoy range from -5.6°C to 7.0°C, related time series are displayed in Appendix B.

The significant wave heights observed during the trial period at Frøya were in a range up to 4.38 m, with 50.5 % of the observations above 1.5 m. The experienced maximum wave heights cover a range up to 8.1 m. Compare Appendix C for wave statistics as provided by Fugro. The wave measurements were recorded by the neighbouring (280 m southwest) SWLB WS188 using a 10 min data acquisition and processing interval.

The tidal or water level as observed during the campaign at a place in the North of Frøya called Mausund varies between -120.0 cm and 113.3 cm over MSL. See related time series plot in Appendix C.

Table 2: Maximum 10 min averaged wind speeds measure at the RLL and by the SWLB across the total campaign period.

WS MAX	RLL	SWLB
Height / m	WS / m/s	
250	30.12	30.13
200	29.22	28.51
180	28.64	27.77
160	28.05	29.07
140	27.70	27.47
120	27.45	27.34
100	27.23	26.35
80	26.88	26.50
60	28.51	27.54
40	25.98	25.95

3.3 Data filtering

Due to coastal effects in combination with the large separation distance between RLL and FLS, some datasets are not usable for the validation because the wind conditions are different between both positions. Therefore, such datasets are excluded from the evaluation using the following two 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 when the ratio between the reference wind speed and its moving mean (see footnote [2]) is outside the range 0.85 to 1.15. This filter is applied for WS and WD comparison for wind speeds above 4 m/s (see footnote [3]).

Table 3: Special filter criteria

Exclude data if:	Applied for WS comparison	Applied for WD comparison
HEIGHT <= 100 & (WD_REF < 90 | WD_REF > 320)	Yes	No
WS_REF > 4 & (WS_RATIO < 0.85 | WS_RATIO > 1.15)	Yes	Yes

3.4 Accuracy

DNV GL has analyzed the wind data against the relevant KPIs and Acceptance Criteria given in [1] and in Appendix A which are related to the WS and WD accuracy of the SWLB unit.

The comparisons in this section are based on ten-minute average values at both the floating LiDAR unit and the RLL. For the analysis conducted in this section, a low wind speed cut-off of 2 m/s has been applied for the wind speed comparisons and the wind direction comparisons.

3.4.1 Data coverage requirements for accuracy assessment

In accordance with the data coverage requirements outlined in the Roadmap [1], DNV GL has assessed the data coverage of the floating LiDAR system at the ten (10) measurement heights considered. This has been conducted according to the following requirements:

a) 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.
→ This criterion has been fulfilled.

b) 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.
→ This criterion has been fulfilled

c) 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 number of data is available. → This criterion is not mandatory.

Table 4 gives an overview of the data coverage. It shows that for all probing levels, all WS bins up to 16 m/s have sufficiently been filled.

[2] WS_REF_MOV is a moving mean with a window size of 5. This means that the moving mean value is calculated from the current value, the two past values and the two future values. WS_RATIO is calculated by WS_REF/WS_REF_MOV.

[3] To avoid that too many datasets are excluded at lower wind speeds, the filter was only applied for wind speeds above 4 m/s.

Table 4: Wind speed data coverage per WS bin. Bins including at least 40 values marked in green.

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	69	60	66	69	80	60	90	128	152	167	188	126	96	56	45	57	27	12	6
200	71	60	90	69	92	57	94	135	132	170	185	135	80	62	43	64	17	15	4
180	67	68	93	74	93	59	96	135	139	164	171	133	83	57	49	61	24	9	2
160	62	80	89	74	93	58	103	137	133	154	174	134	77	52	63	49	29	4	1
140	64	81	90	81	90	61	110	133	136	145	171	136	70	55	71	43	26	4	0
120	63	79	104	97	92	65	112	140	143	136	164	127	64	56	78	41	19	3	0
100	54	65	99	81	56	42	81	86	86	72	90	64	32	34	61	31	12	2	0
80	55	64	99	81	58	44	85	87	81	70	85	66	35	43	54	32	5	1	0
60	49	63	100	91	60	53	115	107	87	58	85	60	51	79	49	28	6	7	1
40	47	63	87	90	52	71	124	93	79	57	84	59	42	83	42	13	7	0	0

3.4.2 Wind speed accuracy

A summary of the findings for each wind-speed-related KPI is presented in Table 5. The wind speed accuracy assessment has been conducted at ten heights between 40 and 250 m above MSL. The slopes (X_{mws}) and Coefficient of Determination (R^2_{mws}) are presented for all compared heights.

It can be seen that the KPI for slope at all heights fulfills the best practice AC [$0.98 < X_{mws} < 1.02$] as given in [1] for both wind speed ranges.

With regards to the Coefficient of Determination (R^2_{mws}) the best practice AC [$R^2_{mws} > 0.98$] is fulfilled for all heights for the wind speed range > 2 m/s. For the wind speed range 4 – 16 m/s, the minimum AC [$R^2_{mws} > 0.97$] is passed at all heights.

Plots for WS regression results together with WS time series plots selected for some comparison levels can be found in Appendix B.

The reason for the lower R^2 values at 4-16m/s is assumed to be based on several factors:

- When the correlation coefficient of a so-called "restricted range" is calculated, this leads to a reduced R^2 in most cases (also see "Bland, J. & Altman, D. – Correlation in restricted ranges of data. BMJ 2011; 342 doi: https://doi.org/10.1136/bmj.d556 (Published 11 March 2011)." or https://www.statisticshowto.datasciencecentral.com/restricted-range/)
- Due to the separation distance between RLL and FLS, quick wind speed changes at the RLL position occur at the FLS position with a delay (or vice versa) – this leads to outliers.
- When the validation measurement takes only a short period (<1 month) each outlier has a higher influence

DNV GL has no doubt that the lower R^2 values in the 4-16m/s range are caused by the increased separation distance and cannot be interpreted as indicator for bad performance of the buoy in this case. This has been observed in previous validation measurements at Frøya.

Table 5: Overview of linear regression analysis results for wind speed comparisons between the SWL Buoy and the reference Lidar at all available comparison levels. Colour shading indicates the compliance with the prescribed best practice or minimum KPI's Acceptance Criteria (see legend).

	# values	slope	R^2	WS-avg RLL (Reference)	WS-avg WS187 (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	1555	1.003	0.991	11.57	11.61	0.041	0.35%
4 - 16 m/s	1126	1.004	0.976	10.18	10.22	0.040	0.39%
200 m level							
All >= 2 m/s	1575	0.996	0.991	11.37	11.33	-0.037	-0.33%
4 - 16 m/s	1159	0.998	0.978	10.06	10.04	-0.023	-0.23%
180 m level							
All >= 2 m/s	1577	0.995	0.991	11.26	11.21	-0.048	-0.43%
4 - 16 m/s	1157	0.997	0.979	9.96	9.93	-0.031	-0.31%
160 m level							
All >= 2 m/s	1566	0.994	0.990	11.18	11.12	-0.064	-0.57%
4 - 16 m/s	1149	0.995	0.977	9.97	9.93	-0.046	-0.46%
140 m level							
All >= 2 m/s	1567	0.990	0.990	11.07	10.97	-0.105	-0.95%
4 - 16 m/s	1153	0.992	0.977	9.92	9.84	-0.078	-0.79%
120 m level							
All >= 2 m/s	1583	0.987	0.990	10.85	10.72	-0.128	-1.18%
4 - 16 m/s	1180	0.990	0.978	9.71	9.62	-0.094	-0.97%
100 m level							
All >= 2 m/s	1048	0.991	0.990	10.31	10.24	-0.074	-0.72%
4 - 16 m/s	757	0.994	0.979	9.15	9.11	-0.038	-0.42%
80 m level							
All >= 2 m/s	1045	0.991	0.990	10.21	10.14	-0.068	-0.67%
4 - 16 m/s	756	0.995	0.979	9.09	9.05	-0.034	-0.38%
60 m level							
All >= 2 m/s	1149	0.993	0.989	10.49	10.43	-0.055	-0.52%
4 - 16 m/s	816	0.997	0.975	8.94	8.92	-0.019	-0.22%
40 m level							
All >= 2 m/s	1093	0.997	0.988	10.17	10.15	-0.014	-0.13%
4 - 16 m/s	796	1.002	0.975	8.96	8.97	0.013	0.14%

Legend	
KPI	Passed Best practice
KPI	Passed Minimum
KPI	Failed

3.4.3 Wind direction accuracy

The wind direction data comparison was conducted at heights between 40 and 250 m above MSL. All results in this report are based on the compass wind direction signal. Since the RLL refers to true north and the FLS to magnetic north, an offset of -2.47° was applied to the RLL wind direction data to consider the magnetic declination of the test site.

The results for the wind direction comparison are shown in Table 6 where the Wind Direction Regression Slope (M_{mwd}), the Mean Offset (OFF_{mwd}) and the Coefficient of Determination (R^2_{mwd}) are presented. KPI values for R^2_{mwd} and M_{mwd} fall within the best practice acceptance criteria. The KPI OFF_{mwd} is fulfilled in all heights. Plots for WD regression results selected for all heights are found in Appendix B. Appendix E shows a comparison between the wind direction results of WS187 (compass) and WS188[4] (DGPS).

[4] WS188 was validated in parallel to WS187 at Frøya.

Table 6: Overview of linear regression results for WD comparisons between SWLB and reference Lidar at ten comparison levels. Colour shading indicates compliance with prescribed best practice or minimum KPI's Acceptance Criteria (see legend).

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	1555	0.984	-1.273	0.985
200	1575	0.984	-0.856	0.989
180	1577	0.985	-1.294	0.991
160	1566	0.985	-1.107	0.992
140	1567	0.983	-0.729	0.993
120	1583	0.984	-0.628	0.991
100	1578	0.985	-0.647	0.994
80	1575	0.983	-0.754	0.995
60	1692	0.982	-0.712	0.996
40	1619	0.981	-0.325	0.995

Legend	
KPI	Passed Best practice
KPI	Passed Minimum
KPI	Failed

3.5 Summary of verification results

3.5.1 Campaign Duration

The duration of the verification campaign was 17.6 days. The data requirement for completeness has been fulfilled in all required WS bins for data analysis.

3.5.2 Wind Measurement Accuracy

The wind speeds of both the SWLB and the RLL at all comparison heights correlated very well, showing a low level of scattering and good agreement regarding linear regression analyses. This pre-deployment verification results indicate that the SWLB can reproduce fixed Lidar wind speeds at a high level of accuracy.

The KPI for slope at 40 to 250m fulfills the best practice AC [$0.98 < X_{mws} < 1.02$] as given in [1] for both wind speed ranges. With regards to the Coefficient of Determination (R^2_{mws}) the best practice AC [$R^2_{mws} > 0.98$] is fulfilled for all heights for the wind speed range > 2 m/s. For the wind speed range 4 – 16 m/s, the minimum AC [$R^2_{mws} > 0.97$] is passed at all heights.

For wind direction, the best practice criteria for the KPIs "Mean Wind Direction – Slope", "Mean Wind Direction – Coefficient of Determination" and "Mean Wind Direction – Offset" were passed at all heights.

Overall, the obtained results indicate the SWLB's capability of reproducing fixed Lidar wind directions at an acceptable high level of accuracy. The detailed results with respect to KPIs and ACs for wind speed and wind direction comparisons are given in Table 7 below.

WS187 has performed comparatively well as previous buoys tested for the Hollandse Kust campaigns.

Table 7: Summary of achievement after 17.6 days with regards to KPIs and Acceptance Criteria for the data accuracy assessment

KPI	Definition / Rationale	Acceptance Criteria across total campaign duration	
		Best Practice	Minimum
X_{mws}	**Mean Wind Speed – Slope** Assessed for wind speed range [all above 2 m/s] [4-16 m/s]	0.98 – 1.02 Results: [0.987 to 1.003] Passed at all heights [0.990 to 1.004] Passed at all heights	0.97 – 1.03
R^2_{mws}	**Mean Wind Speed – Coefficient of Determination** Assessed for wind speed range [all above 2 m/s] [4 – 16 m/s]	>0.98 Results: [0.988 o 0.991] Passed at all heights	>0.97 Results: [0.975 to 0.979] Passed at all heights
M_{mwd}	**Mean Wind Direction – Slope** Asessed for wind speed range [all above 2 m/s]	0.97 – 1.03 Results: [0.981 to 0.985] Passed at all heights	0.95 – 1.05
R^2_{mwd}	**Mean Wind Direction – Coefficient of Determination** (same as for Mmwd)	> 0.97 Results: [0.985 to 0.996] Passed at all heights	> 0.95
OFF_{mwd}	**Mean Wind Direction – Offset, in terms of the mean absolute WD difference over the total campaign duration** (same as for M_{mwd})	< 5° Results: [-1.3 to -0.3°] Passed at all heights	< 10°

4 PERFORMANCE VERIFICATION ACCORDING TO IEC STANDARD, ANNEX L

This subsection represents as a supplement to the standard LiDAR DNV GL / NORSEWInD performance verification test with respect to a FLS validation approach as described in the latest edition of the IEC standard for power performance tests [10]. This approach is based on a wind speed bin averaged procedure in order to compare the horizontal wind speed measurements acquired by the FLS and the RLL. 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 statistic relevance this IEC approach requires

- a minimum of three (3) 10-minute values available within each wind speed bin and
- a total amount of 180 hours of valid data (corresponding to a number of 1080 10-min values)

Figures 3 to 6 show scatter plots of the wind speed comparison based on 10 min averages between the data pairs of the FLS and RLL at 60 m, 80 m, 100 m and 120 m, respectively. In addition, the 10-minute averaged deviation for each data point of the two data sets is plotted (red dots).

The uncertainties have been calculated for wind speed bins and heights where the uncertainty of the RLL was available. Uncertainty values from the closest available height have been taken if height difference between the RLL verification and FLS verification were present.

Furthermore, the correlation coefficient, mean deviation and standard deviation of the deviations are shown in Table 8. The relative deviation of the data pairs was calculated in relation to the cup wind speeds as reference.

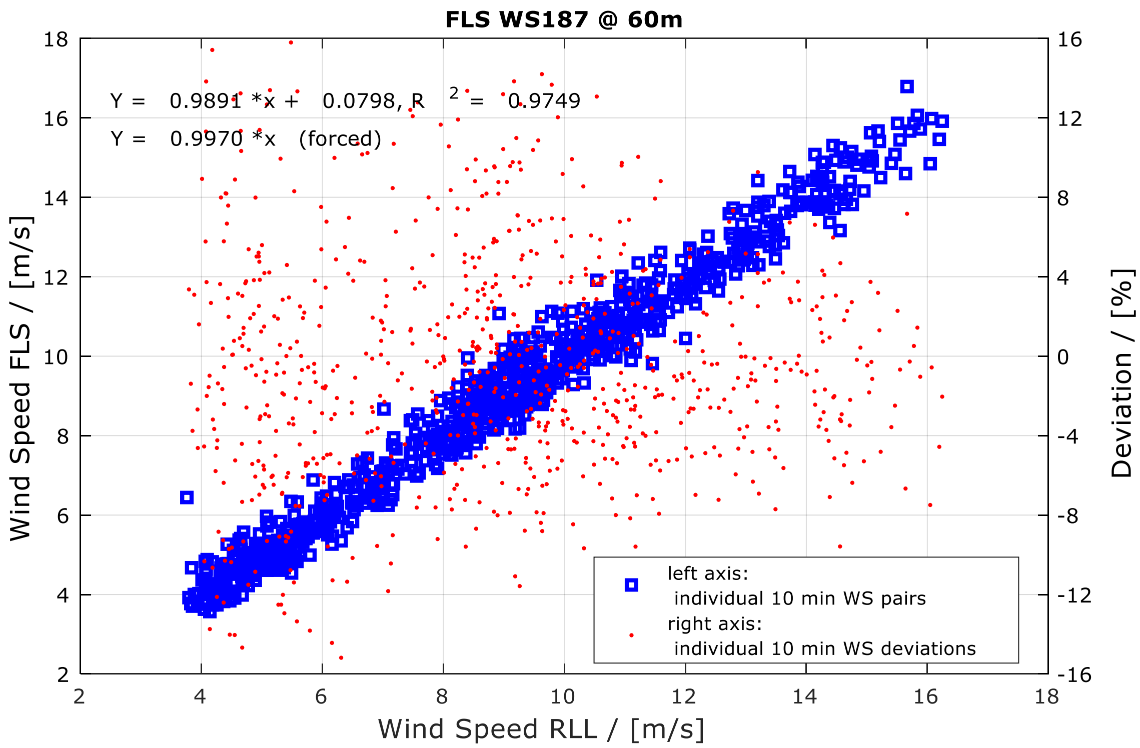


Figure 3: Comparison of the horizontal wind speed component at 60 m

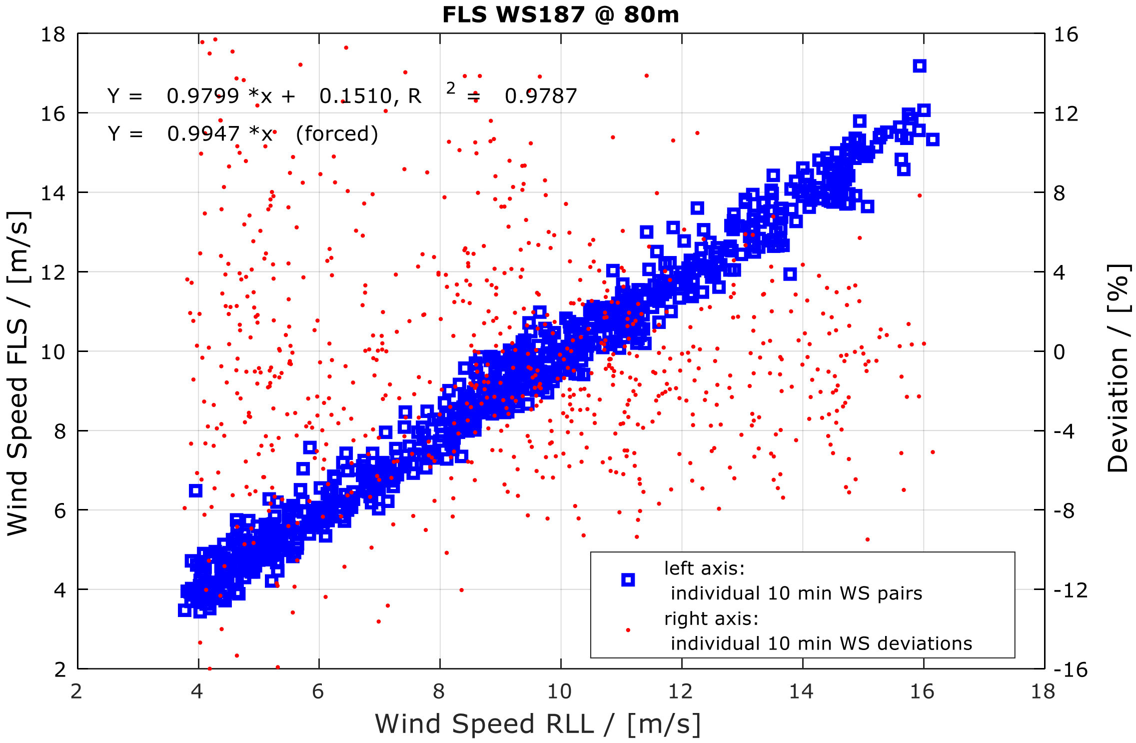


Figure 4: Comparison of the horizontal wind speed component at 80 m

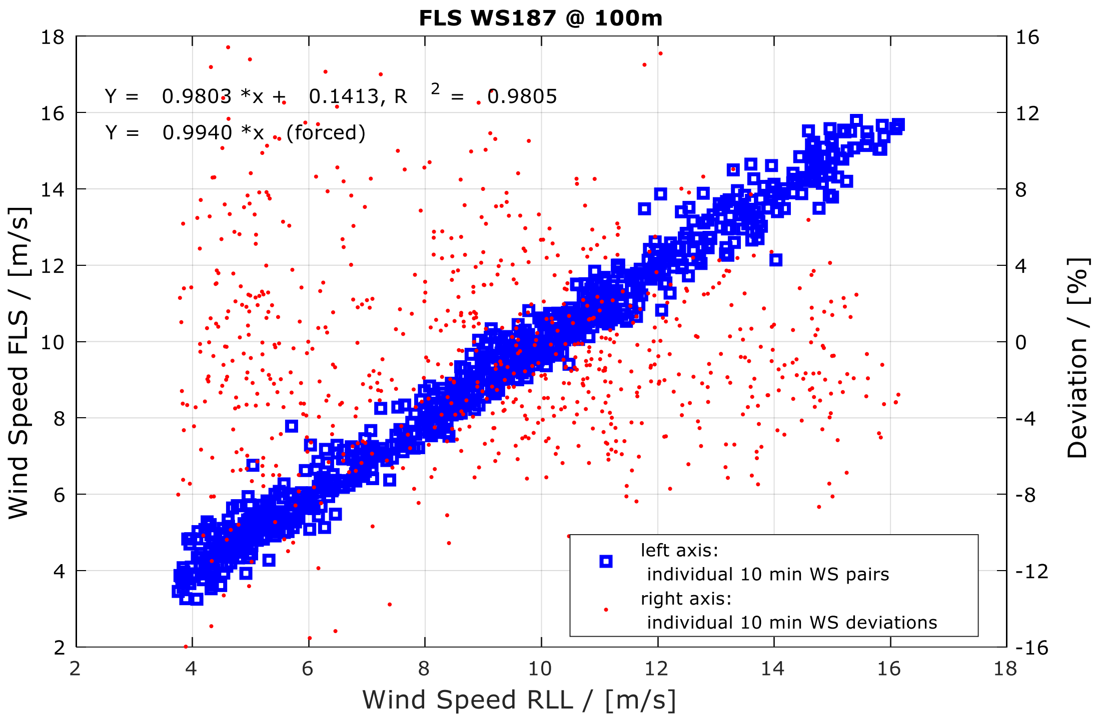


Figure 5: Comparison of the horizontal wind speed component at 100 m

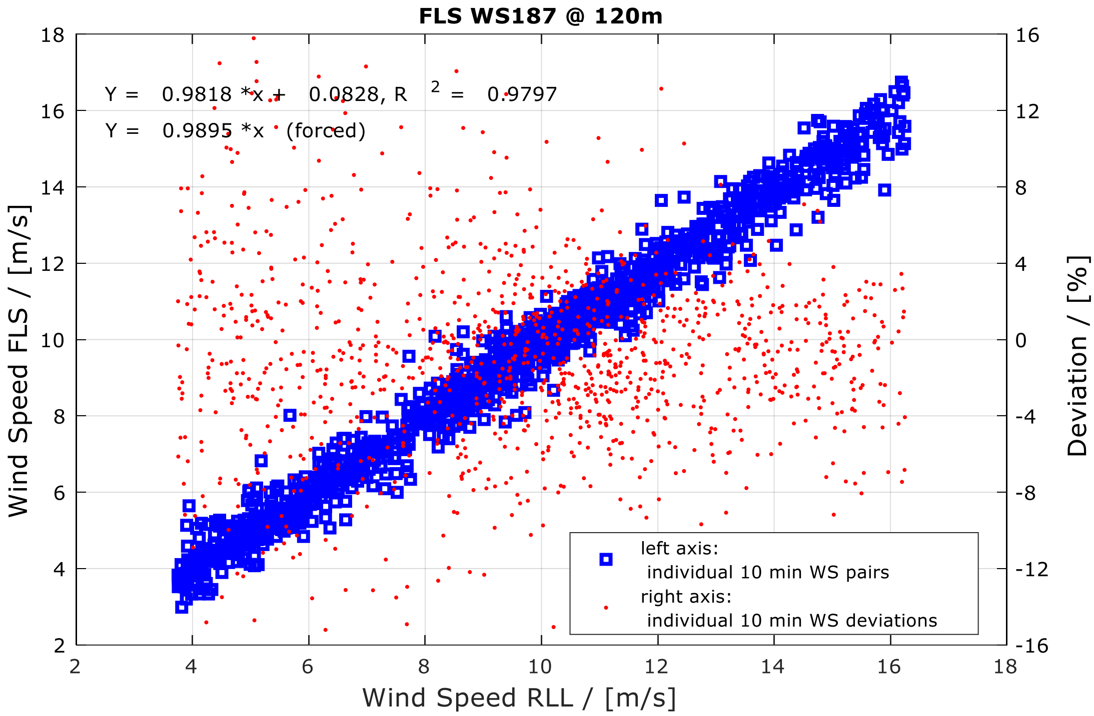


Figure 6: Comparison of the horizontal wind speed component at 120 m

Table 8: Statistical parameters of wind speed deviation

Height level	Coefficient of Determination	Mean Deviation		STD of Deviations	Data Points
[m]	(R^2)	[m/s]	[%]	[%]	#
120	0.9797	-0.09	-0.80%	6.09%	1220
100	0.9805	-0.04	-0.20%	6.19%	776
80	0.9787	-0.03	-0.08%	6.49%	770
60	0.9749	-0.02	-0.11%	6.54%	829

4.1 Performance verification uncertainty

Bin-averaged wind speeds of the FLS and the RLL are shown in Figures 7 to 10. The bin-averaged deviation (solid red line in the graphs) can be compared to the standard uncertainty of the FLS combined with the statistical uncertainty of the comparison for each of the WS bins. The plots (and the wording in the legend "reduced by mean deviation") are based on IEC 61400-12-1:2017, Figure L.6.

The relative uncertainty was calculated according to IEC 61400-12-1:2017, Annex L.4.3 (Uncertainty resulting from the RSD calibration test):

Relative uncertainty = SQRT($a^2+c^2+d^2+e^2$)

(e.g. 3.2% at 60m, 4m/s bin)

with:

a)

the standard uncertainty of the reference (V_{RLL} uncertainty e.g. 2.56%=0.0256 at 60m, 4m/s bin);

b)

the mean deviation of the remote sensing device measurements and the reference sensor measurements (NOTE: This component is not included in the formula above because the uncertainty is "reduced by the mean deviation")

c)

the standard deviation of the measurement of the FLS calculated as the standard deviation of the measurements divided by the square root of the number of data records per bin (e.g. 0.074/4 at 60m, 4m/s bin);

d)

uncertainty of the FLS due to mounting effects (here: 0.5%=0.005);

e)

uncertainty due to non-homogenous flow (here: negligible)

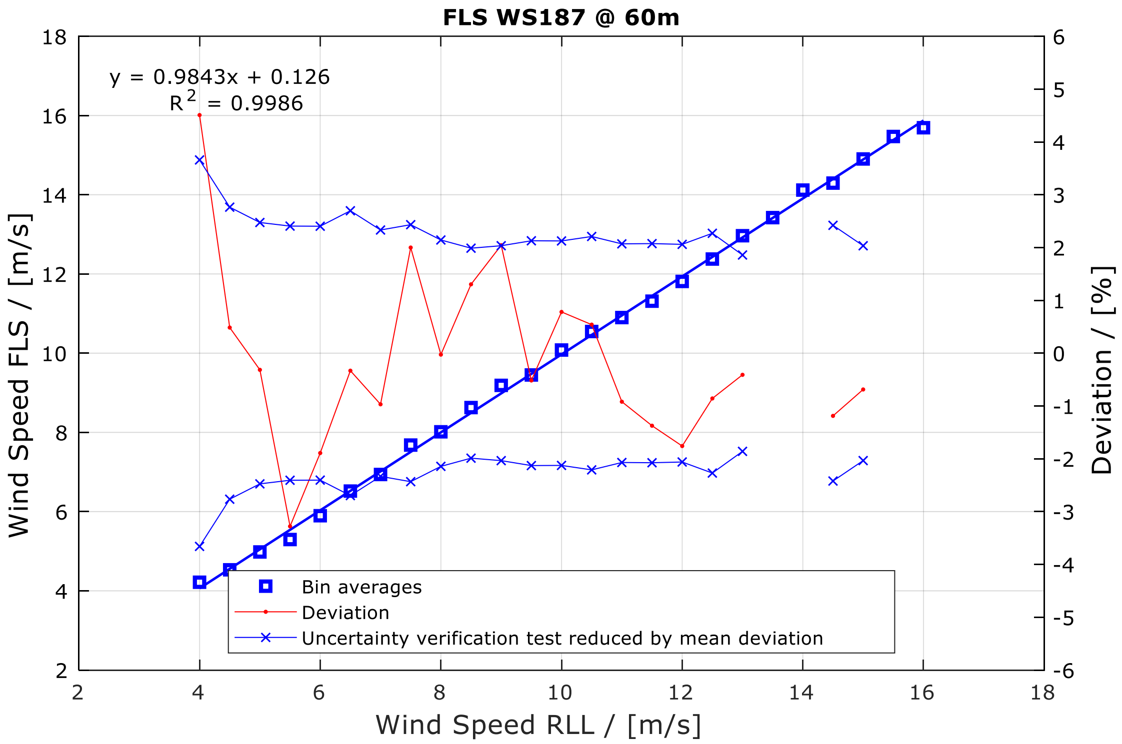


Figure 7: Bin-wise comparison of the horizontal wind speed component at 60 m

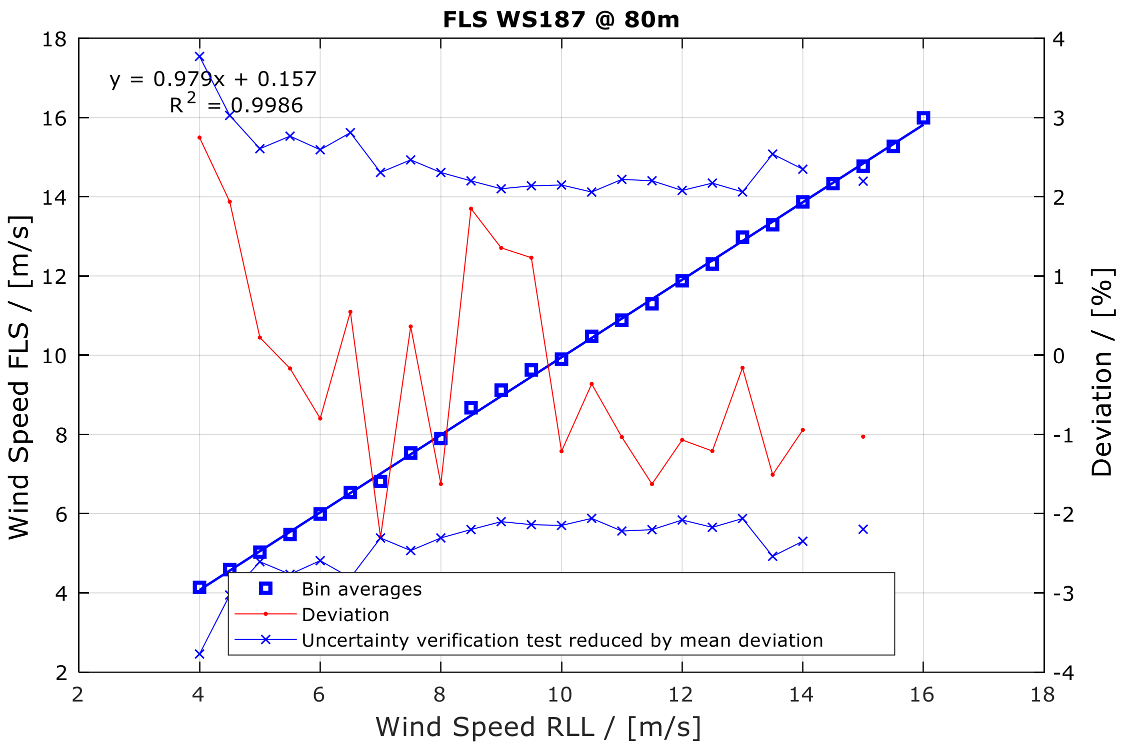


Figure 8: Bin-wise comparison of the horizontal wind speed component at 80 m

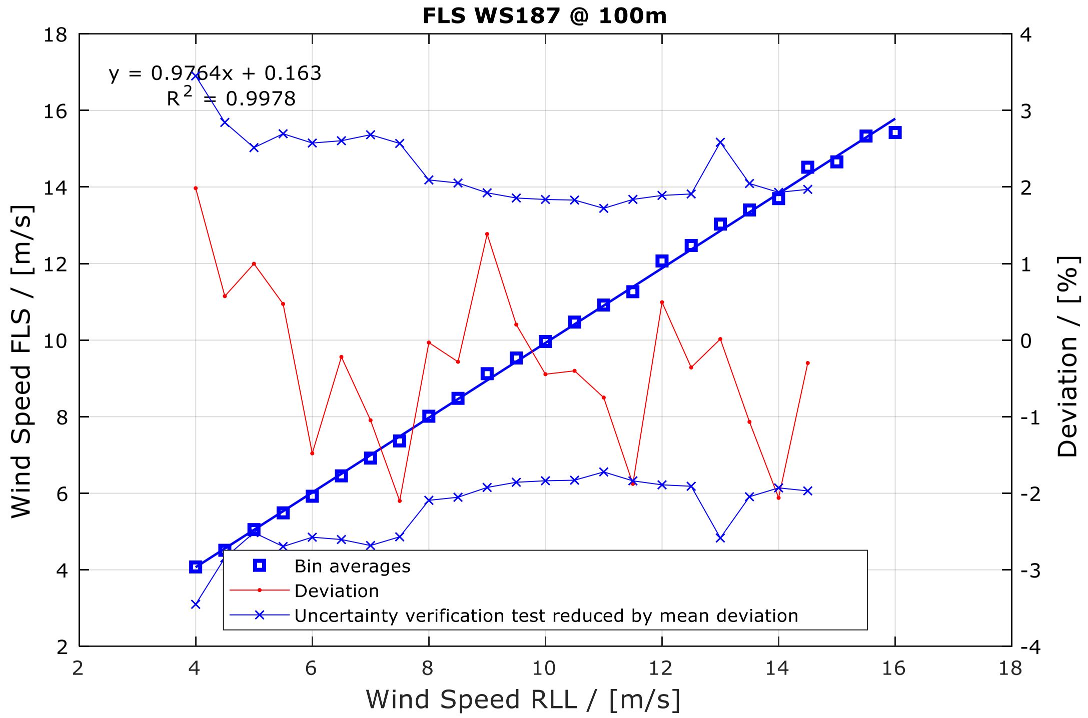


Figure 9: Bin-wise comparison of the horizontal wind speed component at 100 m

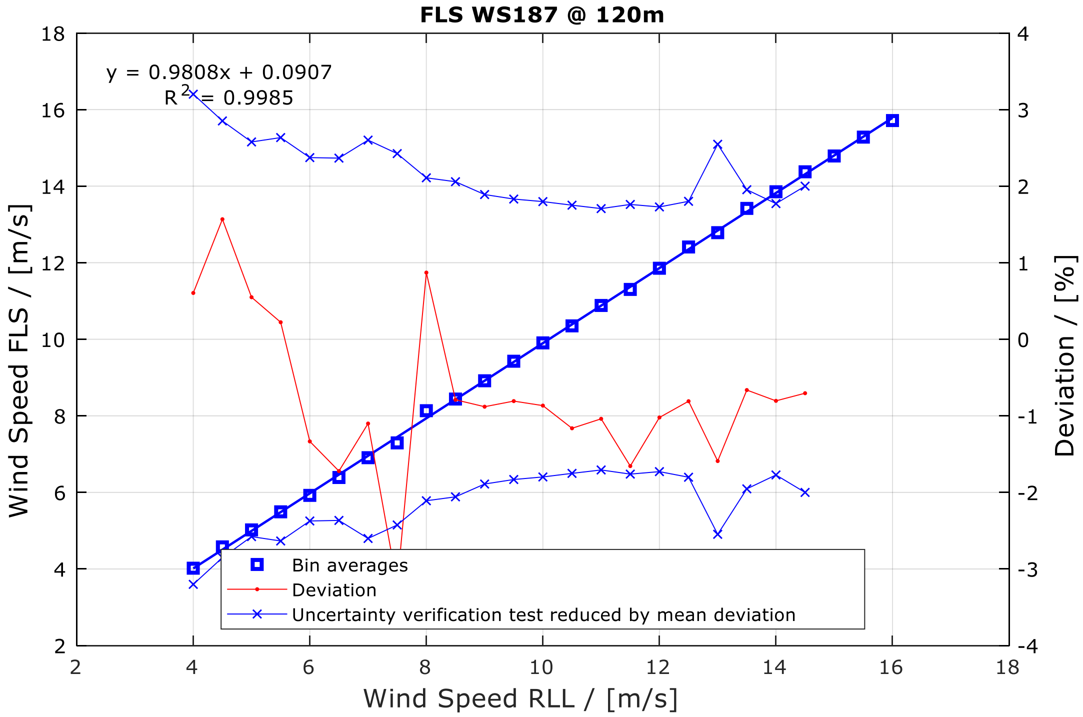


Figure 10: Bin-wise comparison of the horizontal wind speed component at 120 m

According to the IEC standard, the verification uncertainty consists of five independent uncertainty components, which are summarized below:

1. Reference Lidar uncertainty,
2. Mean deviation of the remote sensor measurements and the reference measurements,
3. Standard uncertainty of the measurement of the remote sensing device,
4. Mounting uncertainty of the remote sensor at the verification test,
5. Uncertainty due to non-homogenous flow,
6. Uncertainty due to separation distance from FLS to RLL,

The different uncertainty components are added in quadrate for each wind speed bin. Details on the calculation of the separate uncertainty components are described in Appendix D.

The results of the uncertainty calculation for the IEC compliant verification of the LiDAR device at every comparison level are plotted in
Table 10 to Table 13. For all assessed levels the combined uncertainties of the floating lidar system (V_{RSD}) at hand for the WS bins and comparison levels show result values well below 4.5%.

For the current IEC uncertainty assessment, the completeness requirement to yield 180 hours of valid and useable concurrent data (which translates into 7.5 days of data) in the WS range 4 and 16 m/s between the RSD and the reference is met for each comparison level.

The additional requirement of yielding a minimum of 3 data pairs in each 0.5 m/s wind speed bin in the same WS range is fulfilled for all available heights. See table

Table 9: IEC standard data coverage completeness

	Center of WS bin / m/s																								
	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5	16.0
# values at 120m	54	47	61	45	43	46	42	37	33	60	56	83	67	66	88	62	55	35	38	41	36	28	43	30	24
# values at 100m	31	54	56	40	29	26	31	15	27	41	47	45	41	40	54	29	28	20	21	24	17	22	24	7	7
# values at 80m	32	49	61	38	32	19	32	18	29	45	48	47	41	35	49	32	22	18	24	24	16	28	17	8	6
# values at 60m	28	54	51	49	40	21	34	18	39	61	62	58	38	44	47	27	24	18	27	20	15	27	13	7	7

DNV GL notes that 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 [4] are based on the IEC bin definition, the uncertainty estimation for this FLS verification has been done according to the IEC bin definition as well.

Table 10: Uncertainty calculation for 60 m level

Height level 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	28	4.22	4.04	6.44	3.57	0.58	0.109	4.51%	0.50%	0.35%	2.56%	**5.83%**
4.25	4.75	54	4.53	4.51	5.57	3.74	0.45	0.062	0.48%	0.50%	0.35%	2.39%	**2.86%**
4.75	5.25	51	4.98	5.00	5.97	4.23	0.34	0.047	-0.32%	0.50%	0.35%	2.25%	**2.54%**
5.25	5.75	49	5.29	5.47	6.35	4.54	0.42	0.059	-3.28%	0.50%	0.35%	2.11%	**4.11%**
5.75	6.25	40	5.90	6.01	6.88	4.99	0.39	0.062	-1.89%	0.50%	0.35%	2.13%	**3.10%**
6.25	6.75	21	6.52	6.54	7.44	5.35	0.55	0.120	-0.33%	0.50%	0.35%	1.97%	**2.78%**
6.75	7.25	34	6.94	7.00	8.67	6.25	0.52	0.089	-0.97%	0.50%	0.35%	1.92%	**2.58%**
7.25	7.75	18	7.68	7.53	8.54	6.98	0.47	0.111	2.00%	0.50%	0.35%	1.90%	**3.17%**
7.75	8.25	39	8.01	8.02	9.22	7.18	0.48	0.077	-0.03%	0.50%	0.35%	1.86%	**2.18%**
8.25	8.75	61	8.63	8.52	9.96	7.57	0.47	0.061	1.30%	0.50%	0.35%	1.80%	**2.41%**
8.75	9.25	62	9.19	9.00	11.07	8.14	0.60	0.076	2.04%	0.50%	0.35%	1.80%	**2.91%**
9.25	9.75	58	9.45	9.50	11.00	8.19	0.54	0.071	-0.52%	0.50%	0.35%	1.93%	**2.23%**
9.75	10.25	38	10.08	10.00	11.13	9.20	0.52	0.084	0.78%	0.50%	0.35%	1.90%	**2.30%**
10.25	10.75	44	10.55	10.49	11.91	9.33	0.47	0.071	0.54%	0.50%	0.35%	2.05%	**2.30%**
10.75	11.25	47	10.90	11.00	12.35	9.89	0.56	0.082	-0.92%	0.50%	0.35%	1.87%	**2.30%**
11.25	11.75	27	11.31	11.47	12.61	9.81	0.60	0.115	-1.37%	0.50%	0.35%	1.76%	**2.53%**
11.75	12.25	24	11.81	12.02	12.72	10.45	0.48	0.098	-1.76%	0.50%	0.35%	1.83%	**2.74%**
12.25	12.75	18	12.38	12.48	13.59	11.64	0.49	0.115	-0.86%	0.50%	0.35%	2.02%	**2.46%**
12.75	13.25	27	12.97	13.02	14.42	12.07	0.57	0.110	-0.41%	0.50%	0.35%	1.59%	**1.94%**
13.25	13.75	20											
13.75	14.25	15											
14.25	14.75	27	14.29	14.47	15.30	13.16	0.55	0.106	-1.19%	0.50%	0.35%	2.26%	**2.72%**
14.75	15.25	13	14.90	15.01	15.67	13.82	0.53	0.147	-0.69%	0.50%	0.35%	1.72%	**2.18%**
15.25	15.75	7											
15.75	16.25	7											

Table 11: Uncertainty calculation for 80 m level

Height level 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	32	4.14	4.03	6.48	3.44	0.58	0.103	2.75%	0.50%	0.35%	2.85%	**4.71%**
4.25	4.75	49	4.59	4.50	5.75	3.72	0.48	0.068	1.94%	0.50%	0.35%	2.62%	**3.63%**
4.75	5.25	61	5.03	5.02	6.28	4.21	0.39	0.050	0.22%	0.50%	0.35%	2.37%	**2.65%**
5.25	5.75	38	5.47	5.48	7.04	4.47	0.54	0.087	-0.17%	0.50%	0.35%	2.26%	**2.83%**
5.75	6.25	32	5.99	6.04	7.57	5.35	0.46	0.082	-0.80%	0.50%	0.35%	2.18%	**2.76%**
6.25	6.75	19	6.53	6.50	7.43	5.72	0.52	0.120	0.55%	0.50%	0.35%	2.12%	**2.92%**
6.75	7.25	32	6.81	6.97	7.96	6.03	0.38	0.067	-2.30%	0.50%	0.35%	2.06%	**3.29%**
7.25	7.75	18	7.53	7.50	8.47	6.89	0.44	0.105	0.36%	0.50%	0.35%	2.00%	**2.54%**
7.75	8.25	29	7.90	8.03	9.00	7.06	0.48	0.090	-1.63%	0.50%	0.35%	1.97%	**2.86%**
8.25	8.75	45	8.67	8.52	9.86	7.35	0.52	0.078	1.85%	0.50%	0.35%	1.95%	**2.90%**
8.75	9.25	48	9.12	9.00	10.02	8.42	0.46	0.066	1.35%	0.50%	0.35%	1.91%	**2.53%**
9.25	9.75	47	9.63	9.51	10.98	8.61	0.54	0.079	1.23%	0.50%	0.35%	1.92%	**2.49%**
9.75	10.25	41	9.90	10.02	10.83	8.95	0.43	0.067	-1.21%	0.50%	0.35%	1.99%	**2.50%**
10.25	10.75	35	10.48	10.51	11.12	9.41	0.47	0.079	-0.36%	0.50%	0.35%	1.86%	**2.13%**
10.75	11.25	49	10.88	11.00	12.03	10.08	0.40	0.058	-1.03%	0.50%	0.35%	2.10%	**2.48%**
11.25	11.75	32	11.30	11.48	13.00	10.19	0.67	0.118	-1.63%	0.50%	0.35%	1.90%	**2.77%**
11.75	12.25	22	11.88	12.01	13.11	11.00	0.47	0.101	-1.07%	0.50%	0.35%	1.84%	**2.37%**
12.25	12.75	18	12.30	12.45	13.60	11.49	0.50	0.119	-1.21%	0.50%	0.35%	1.90%	**2.52%**
12.75	13.25	24	12.98	13.00	13.94	12.04	0.51	0.104	-0.16%	0.50%	0.35%	1.84%	**2.10%**
13.25	13.75	24	13.29	13.50	14.43	12.62	0.51	0.104	-1.51%	0.50%	0.35%	2.37%	**2.98%**
13.75	14.25	16	13.87	14.00	14.61	11.94	0.61	0.153	-0.94%	0.50%	0.35%	2.03%	**2.57%**
14.25	14.75	28											
14.75	15.25	17	14.77	14.93	15.79	13.64	0.62	0.151	-1.03%	0.50%	0.35%	1.90%	**2.46%**
15.25	15.75	8											
15.75	16.25	6											

Table 12: Uncertainty calculation for 100 m level

Height level 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	31	4.08	4.00	5.08	3.25	0.49	0.089	1.98%	0.50%	0.35%	2.70%	**4.04%**
4.25	4.75	54	4.51	4.48	5.64	3.52	0.45	0.061	0.57%	0.50%	0.35%	2.48%	**2.95%**
4.75	5.25	56	5.05	5.00	6.76	3.93	0.46	0.061	1.00%	0.50%	0.35%	2.17%	**2.75%**
5.25	5.75	40	5.49	5.46	7.78	4.27	0.53	0.084	0.47%	0.50%	0.35%	2.21%	**2.80%**
5.75	6.25	29	5.92	6.01	7.29	5.08	0.49	0.092	-1.48%	0.50%	0.35%	2.05%	**3.03%**
6.25	6.75	26	6.45	6.47	7.28	5.13	0.54	0.106	-0.22%	0.50%	0.35%	2.02%	**2.68%**
6.75	7.25	31	6.92	6.99	8.25	6.35	0.40	0.072	-1.05%	0.50%	0.35%	2.44%	**2.92%**
7.25	7.75	15	7.37	7.52	8.34	6.37	0.50	0.130	-2.10%	0.50%	0.35%	1.89%	**3.38%**
7.75	8.25	27	8.01	8.01	8.84	7.21	0.44	0.084	-0.03%	0.50%	0.35%	1.76%	**2.14%**
8.25	8.75	41	8.48	8.50	9.34	7.52	0.41	0.064	-0.28%	0.50%	0.35%	1.85%	**2.11%**
8.75	9.25	47	9.12	9.00	10.34	8.22	0.51	0.074	1.39%	0.50%	0.35%	1.68%	**2.40%**
9.25	9.75	45	9.53	9.51	10.44	8.72	0.42	0.062	0.20%	0.50%	0.35%	1.67%	**1.90%**
9.75	10.25	41	9.96	10.01	10.81	9.05	0.43	0.068	-0.45%	0.50%	0.35%	1.64%	**1.93%**
10.25	10.75	40	10.47	10.51	11.52	9.40	0.46	0.073	-0.40%	0.50%	0.35%	1.63%	**1.91%**
10.75	11.25	54	10.92	11.00	11.84	10.13	0.36	0.049	-0.75%	0.50%	0.35%	1.59%	**1.91%**
11.25	11.75	29	11.27	11.48	12.00	10.53	0.48	0.090	-1.88%	0.50%	0.35%	1.60%	**2.66%**
11.75	12.25	28	12.07	12.01	13.87	10.82	0.60	0.114	0.50%	0.50%	0.35%	1.57%	**1.99%**
12.25	12.75	20	12.47	12.52	13.52	11.72	0.50	0.112	-0.36%	0.50%	0.35%	1.62%	**1.98%**
12.75	13.25	21	13.03	13.03	13.89	12.26	0.51	0.111	0.01%	0.50%	0.35%	2.39%	**2.61%**
13.25	13.75	24	13.40	13.54	14.65	12.60	0.54	0.111	-1.07%	0.50%	0.35%	1.81%	**2.34%**
13.75	14.25	17	13.70	13.99	14.61	12.14	0.54	0.130	-2.06%	0.50%	0.35%	1.63%	**2.86%**
14.25	14.75	22	14.52	14.56	15.52	13.87	0.44	0.093	-0.30%	0.50%	0.35%	1.80%	**2.02%**
14.75	15.25	24											
15.25	15.75	7											
15.75	16.25	7											

Table 13: Uncertainty calculation for 120 m level

Height level 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	54	4.02	4.00	5.64	2.99	0.51	0.070	0.60%	0.50%	0.35%	2.70%	**3.32%**
4.25	4.75	47	4.58	4.51	5.27	3.33	0.43	0.062	1.57%	0.50%	0.35%	2.48%	**3.29%**
4.75	5.25	61	5.02	4.99	6.82	4.07	0.53	0.068	0.55%	0.50%	0.35%	2.17%	**2.69%**
5.25	5.75	45	5.49	5.48	8.02	4.77	0.52	0.077	0.22%	0.50%	0.35%	2.21%	**2.70%**
5.75	6.25	43	5.92	6.00	7.02	4.84	0.44	0.067	-1.33%	0.50%	0.35%	2.05%	**2.77%**
6.25	6.75	46	6.39	6.50	7.41	5.06	0.52	0.076	-1.72%	0.50%	0.35%	2.02%	**2.97%**
6.75	7.25	42	6.91	6.98	7.98	6.17	0.35	0.055	-1.10%	0.50%	0.35%	2.44%	**2.86%**
7.25	7.75	37	7.29	7.54	9.56	6.00	0.68	0.112	-3.21%	0.50%	0.35%	1.89%	**4.07%**
7.75	8.25	33	8.13	8.06	10.09	7.18	0.50	0.087	0.87%	0.50%	0.35%	1.76%	**2.31%**
8.25	8.75	60	8.44	8.51	10.20	7.40	0.50	0.065	-0.79%	0.50%	0.35%	1.85%	**2.24%**
8.75	9.25	56	8.92	9.00	10.09	7.70	0.49	0.066	-0.88%	0.50%	0.35%	1.68%	**2.12%**
9.25	9.75	83	9.43	9.50	10.60	7.84	0.50	0.055	-0.81%	0.50%	0.35%	1.67%	**2.04%**
9.75	10.25	67	9.91	9.99	11.13	8.67	0.45	0.056	-0.87%	0.50%	0.35%	1.64%	**2.03%**
10.25	10.75	66	10.35	10.47	11.16	9.46	0.37	0.045	-1.16%	0.50%	0.35%	1.63%	**2.13%**
10.75	11.25	88	10.88	11.00	12.17	9.70	0.40	0.042	-1.04%	0.50%	0.35%	1.59%	**2.03%**
11.25	11.75	62	11.30	11.49	12.89	10.10	0.51	0.065	-1.66%	0.50%	0.35%	1.60%	**2.45%**
11.75	12.25	55	11.86	11.98	13.65	10.70	0.49	0.065	-1.02%	0.50%	0.35%	1.57%	**2.04%**
12.25	12.75	35	12.41	12.51	13.73	11.45	0.46	0.079	-0.81%	0.50%	0.35%	1.62%	**2.01%**
12.75	13.25	38	12.78	12.99	14.14	11.44	0.58	0.094	-1.59%	0.50%	0.35%	2.39%	**3.03%**
13.25	13.75	41	13.42	13.51	14.25	12.07	0.47	0.073	-0.66%	0.50%	0.35%	1.81%	**2.10%**
13.75	14.25	36	13.85	13.97	14.63	12.47	0.43	0.071	-0.80%	0.50%	0.35%	1.63%	**1.98%**
14.25	14.75	28	14.37	14.48	15.74	12.87	0.57	0.107	-0.70%	0.50%	0.35%	1.80%	**2.15%**
14.75	15.25	43											
15.25	15.75	30											
15.75	16.25	24											

5 REMARKS AND LIMITATIONS

5.1 General

The presented results have to be regarded under the following reservations and limitations:

- Both data sets, the one for the Reference Land Lidar (RLL) and the one for the SWLB were visible to Fugro, i.e., they've had full access to the data from the tested device and the reference data. However, DNV GL has received the .ZPH data of the Reference Land Lidar (RLL) directly from the FTP server from Fugro.
- All conclusions on the capabilities of the SWLB drawn from this Frøya pre-deployment verification campaign are valid under sea states and meteorological conditions similar to those experienced during this trial, only.

5.2 Pre- and Post-Deployment Verification

In general, DNV GL recommends that an FLS unit undergoes a pre-deployment verification test no greater than one year before its application deployment.

A post-deployment verification of a FLS can be necessary, in case of e.g.

- Inconsistencies in the data time series or the operation of the buoy being observed
- known or assumed incidents to the buoy or FLS measurement system

during wind resource measurement campaign. Otherwise, a pre-deployment verification campaign may be considered sufficient.

5.3 Design Specifics of WS187

DNV GL has been informed by Fugro that this buoy WS187 has received design changes compared to the unit trialed in the FLS type verification at IJmuiden in 2014/2015 [6] with regards to using a marinized version of the employed ZX300 type Lidar (1), by adding extra buoyancy to the buoy assembly (2) and (3) adding DGPS heading source.

(1) The ZX Lidars ZX300 Lidar with S/N ZX818 used on the buoy is a marinized version with improved connectors, i.e., more corrosion resistant materials have been used compared to the standard onshore type. DNV GL considers that this will not affect the quality of 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, based on drawings of the new buoy design provided by Fugro [7]. As a result, based on this documentation DNV GL considers the change negligible for motion types like rotation, pitch, and role. The motion damping seems to be improved. Based on the documentation of the change available to DNV GL and noticing that the anchoring and mooring array design has properly been adapted and reviewed by Fugro in response to changes of weight, total buoyancy, and size, and therefore for wave loadings as documented in Fugro's internal mooring design report no. C75342-02-03 [8], DNV GL considers that the statements with regards to wind data quality and data availability given for the former (original) buoy design in relation to the Roadmap-related achievements [1, 6] should as well hold for the new buoy design.

DNV GL's consideration is supported by the fact that a Seawatch Wind Lidar buoy with extra buoyancy has undergone a second 6-month type validation at the East Anglia (EA1) Met Mast in the UK in 2015-16 organized by Carbon Trust. The assessment was done by Natural Power [9].

(3) In addition to the (type validated) magnetic compass heading source, a DGPS heading source was implemented by Fugro as additional feature which is assumed to improve the performance. According to previous SWLB pre-deployment validations where both heading sources were available and evaluated by DNV GL, it can be confirmed that the performance with DGPS is the same or better than using magnetic compass correction.

6 CONCLUSIONS ON SWL BUOY TECHNOLOGY IN CONTEXT OF COMMERCIAL ROADMAP

An evaluation of the Fugro Seawatch Wind Lidar Buoy floating LiDAR system was completed by comparing its measurements against data of a Reference Land Lidar installed on the Island Frøya in the Norwegian Sea. Sufficient data regarding WS data completeness and coverage were collected to allow an assessment in line with the Roadmap for commercialization of Floating Lidar Devices [1].

DNV GL concludes that the Fugro SWLB unit with the S/N WS187 has demonstrated its capability to produce accurate wind speed and direction data across the range of sea states and meteorological conditions experienced in this trial. I.e., the Buoy recorded significant wave heights of up to 4.38 m (and 8.1 m for maximum wave height). The Lidar wind speeds recorded at Frøya covered a range of up to 26.0 m/s at 40 m and 30.1 m/s at 250 m.

The assessments of the Roadmap KPIs for the complete data set (from 2019-01-04 until 2019-01-21) show that all FLS-Roadmap Acceptance Criteria for wind speed are met at heights between 40 and 250 m and all FLD-Roadmap Acceptance Criteria for wind directions are met at heights between 40 and 250 m, passing best practice or minimum CT Roadmap acceptance criteria.

FLS Roadmap-related WS bin-wise data completeness was achieved for all WS bins up to 16 m/s at all treated comparison heights.

7 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] DNV GL Report GLGH-4257 13 10378 266-R-0002 Issue B , "A ROADMAP FOR THE COMMERCIAL ACCEPTANCE OF THE FUGRO/OCEANOR SEAWATCH WIND LIDAR BUOY", dated 2015-01-29.

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

[4] DNV GL Report GLGH-4275 17 14682 271-R-0004-A, "ZP495 Independent analysis and reporting of ZephIR Lidar performance verification executed by ZephIR Ltd. at Pershore test site including IEC compliant validation analysis", dated 2017-10-13

[5] DNV GL Report 10108274-R-0016-A, "ZX818 Independent analysis and reporting of ZX Lidars performance verification executed by Zephir Ltd. at Pershore test site, including IEC compliant" dated 2018-10-30.

[6] DNV GL Report GLGH-4257 13 10378 266-R-0003 Issue B , "ASSESSMENT OF THE FUGRO/OCEANOR SEAWATCH FLOATING LIDAR VERIFICATION AT RWE IJMUIDEN MET MAST", dated 2015-01-30.

[7] Arve Berg, Fugro OCEANOR Report , "EXTRA BUOYANCY LIDAR BUOY - IMPLEMENTATION", dated 2015-05-05.

[8] Fredrik Dessen, Fugro OCEANOR Mooring design report No. C75342-02-03, "Lidar for Carbon Trust Wavescan hull with extra buoyancy", dated 2015-06-12

[9] Andreas Athanasopous & Andy Cheng: Floating Lidar Validation Analysis SEAWATCH Wind Lidar Buoy. Natural Power, 7th 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 (https://www.carbontrust.com/media/676998/owa-w-lusr_nov-2018.pdf)

APPENDIX A – APPLIED KEY PERFORMANCE INDICATORS AND ACCEPTANCE CRITERIA FOR FLS PRE-DEPLOYMENT VALIDATION

Wind Data Accuracy assessment

The KPIs and Acceptance Criteria relating to accuracy are defined in the following table. To assess the accuracy a statistical linear regression approach has been selected which is based on:

a) a two variant regression y = mx+b (with m slope and b offset) to be applied to wind direction data comparisons between floating instrument and the reference; and,

b) a single variant regression, with the regression analysis constrained to pass through origin (y = mx+b; b = 0) to be applied to wind speed, turbulence intensity and wind shear data comparisons between floating instrument and the reference.

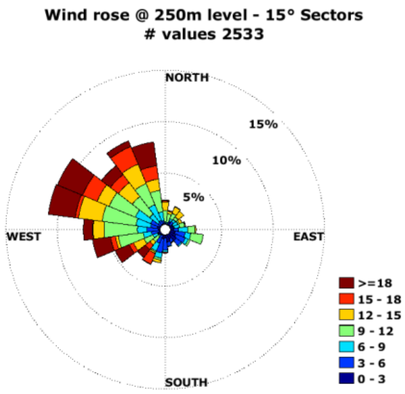
In addition, Acceptance Criteria in the form of "best practise" and "minimum" allowable tolerances have been imposed on slope and offset values as well as on coefficient of determination returned from each reference height for KPIs related to the primary parameters of interest; wind speed and wind direction.

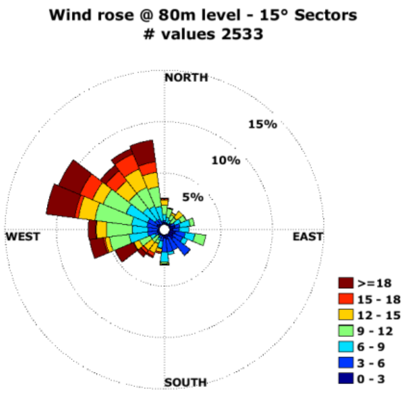
KPI	Definition / Rationale	Acceptance Criteria	
		Best Practice	Minimum
X_{mws}	**Mean Wind Speed – Slope** Slope returned from single variant regression with the regression analysis constrained to pass through the origin. A tolerance is imposed on the Slope value. Analysis shall be applied to wind speed range a) 4 to 16 m/s b) all above 2 m/s given achieved data coverage requirements.	0.98 – 1.02	0.97 – 1.03
R^2_{mws}	**Mean Wind Speed – Coefficient of Determination** Coefficient returned from single variant regression A tolerance is imposed on the Coefficient value. Analysis shall be applied to wind speed range a) 4 to 16 m/s b) all above 2 m/s given achieved data coverage requirements.	>0.98	>0.97

KPI	Definition / Rationale	Acceptance Criteria	
		Best Practice	**Minimum**
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, in terms of the mean WD difference over the total campaign duration** (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

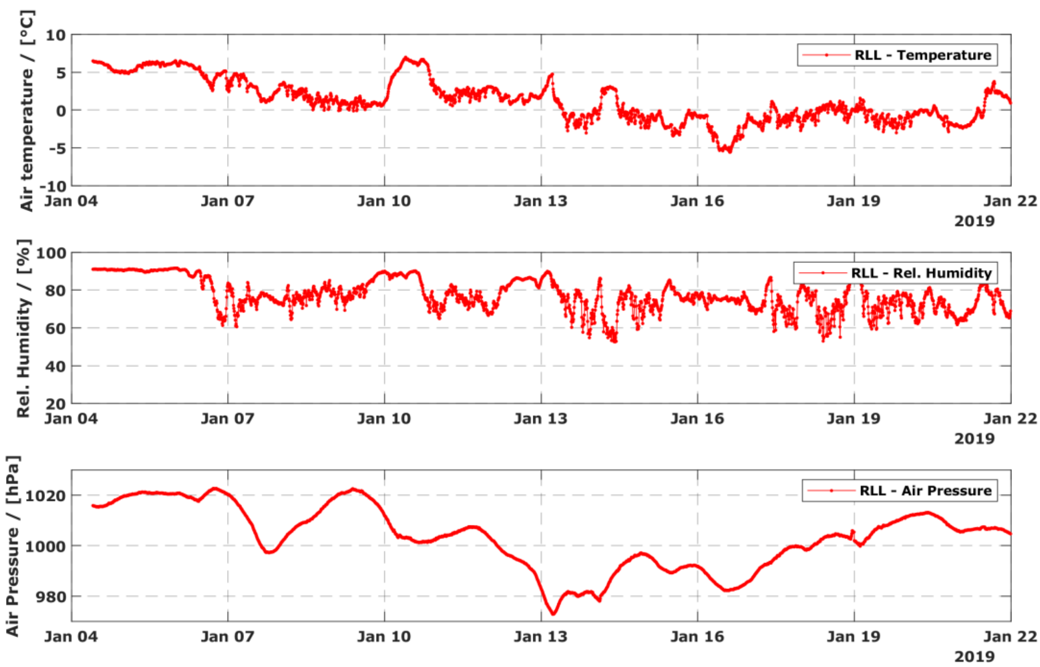
APPENDIX B – CAMPAIGN METEOROLOGICAL CONDITIONS, TIME SERIES AND WS/WD CORRELATION PLOTS

Polar plots of wind directions and wind speed for 250 m and 80 m comparison heights:

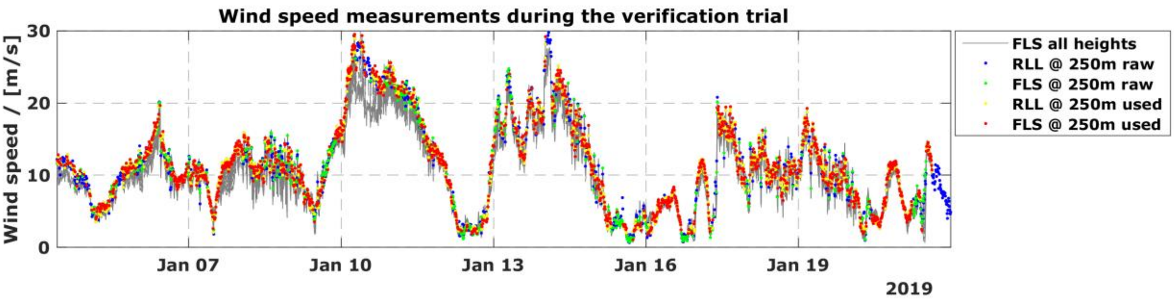


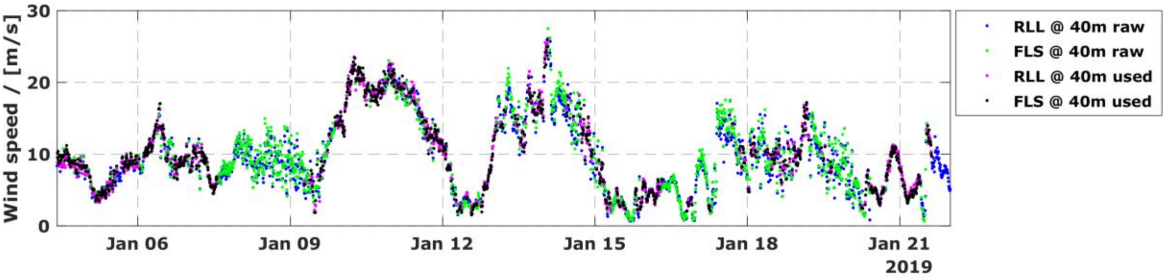


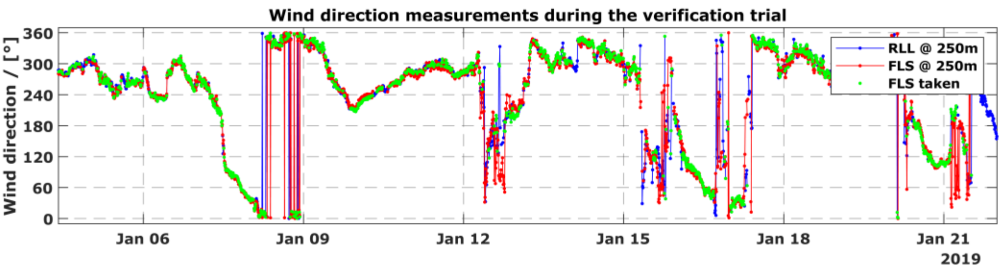
Time series of air temperature, Relative humidity and air pressure of RLL measurement:

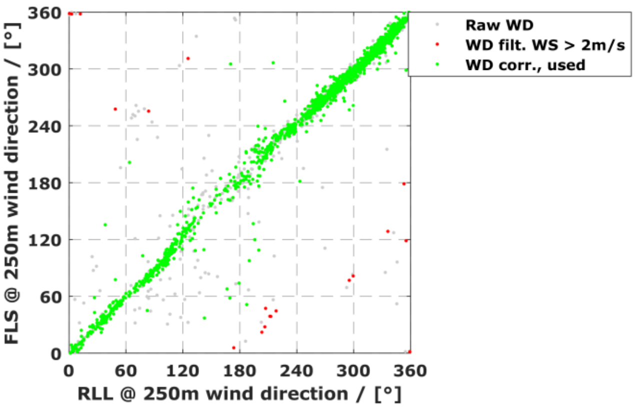


Wind speed and wind directions time series for 40 m and 250 m comparison heights:

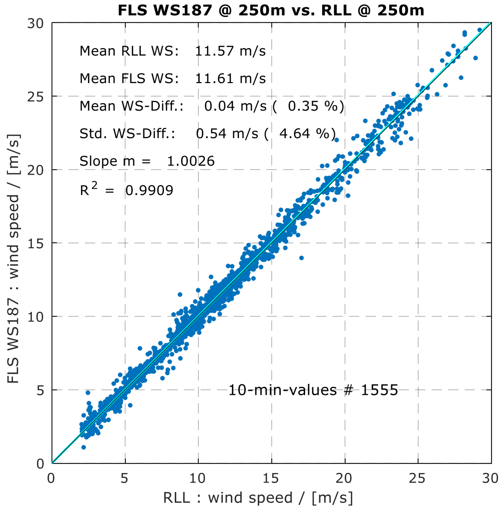


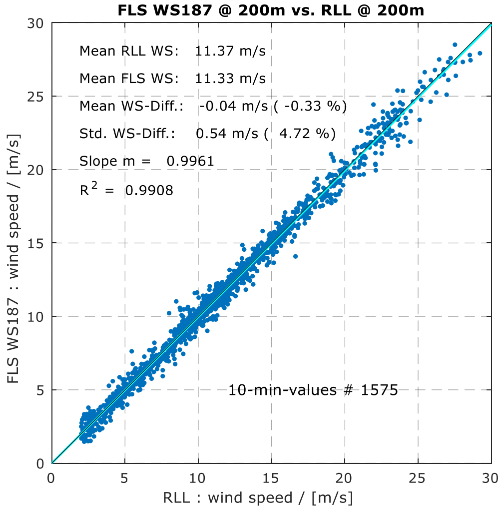


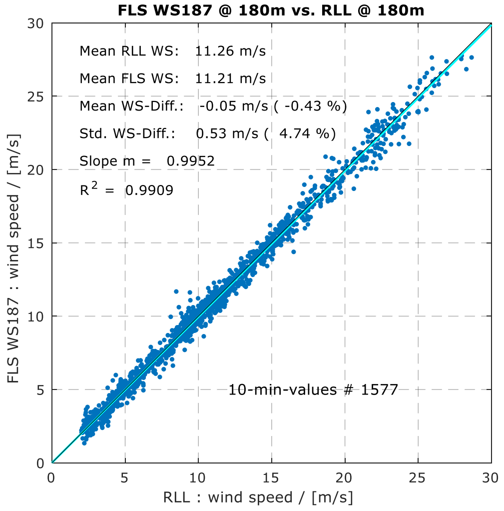


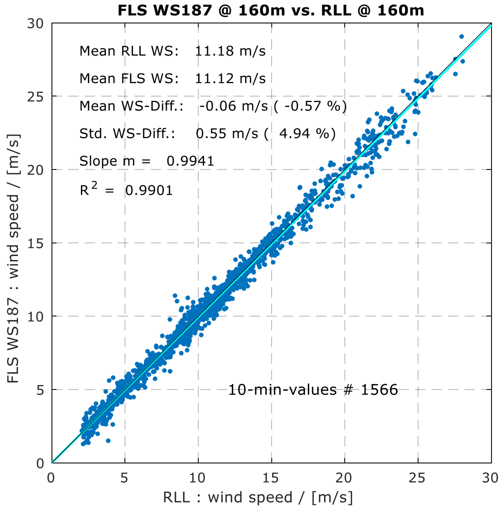


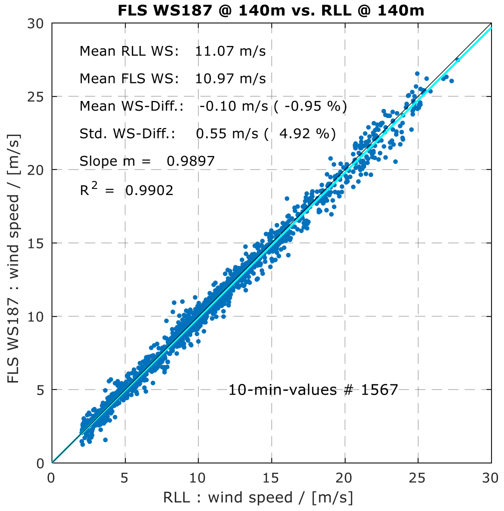
<u>WS regression plots all selected comparison heights, i.e between 40 and 250 m above MSL</u>

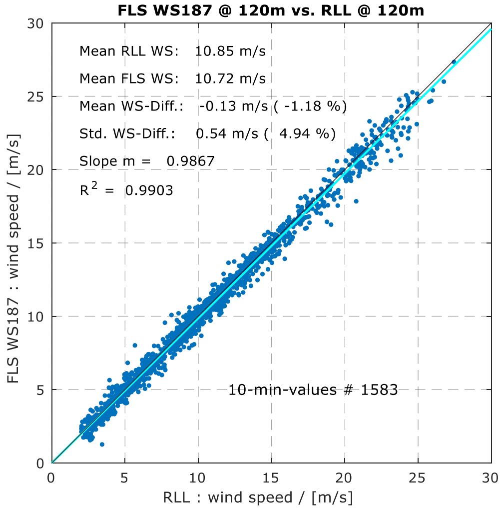


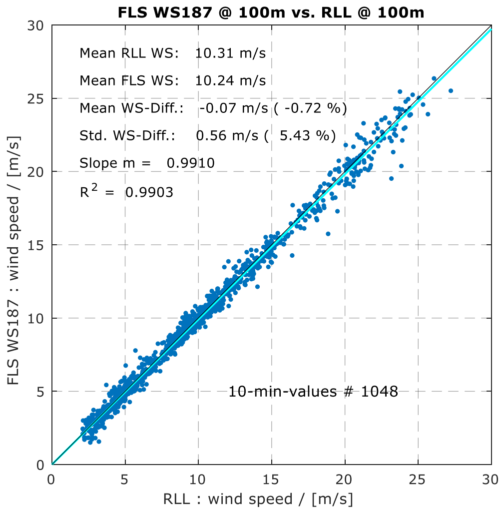


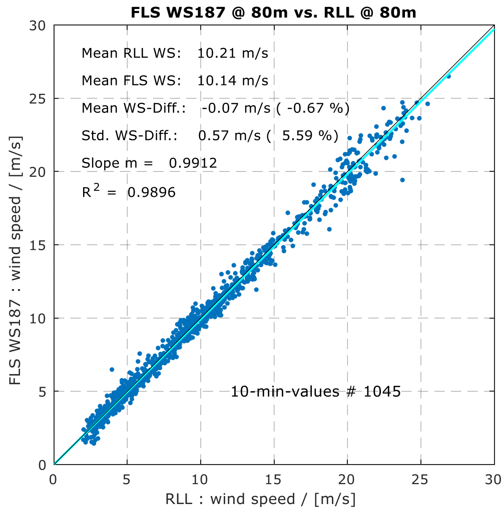


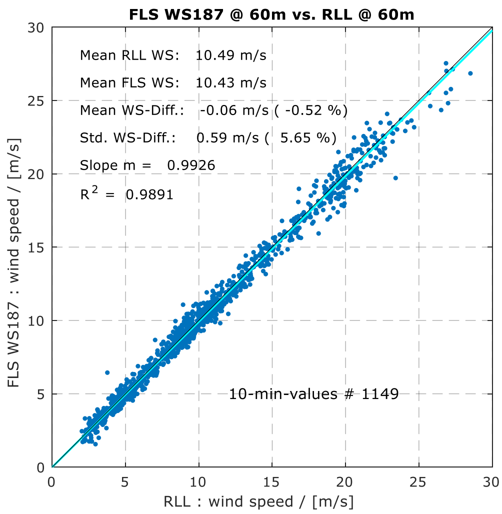


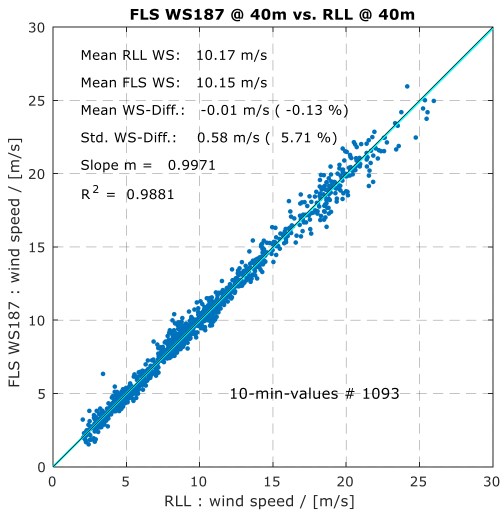




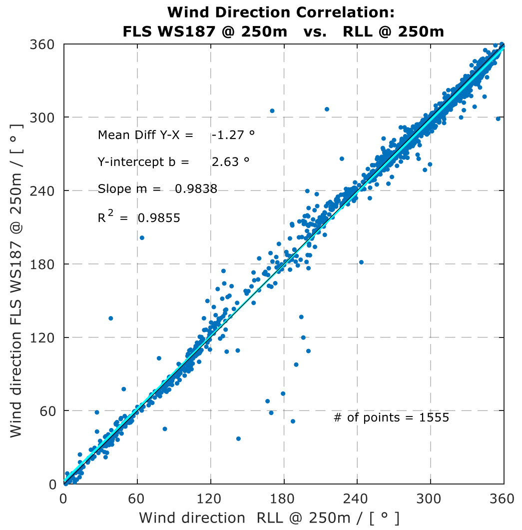

FLS WS187 @ 100m vs. RLL @ 100m
Mean RLL WS: 10.31 m/s
Mean FLS WS: 10.24 m/s
Mean WS-Diff.: -0.07 m/s (-0.72 %)
Std. WS-Diff.: 0.56 m/s (5.43 %)
Slope m = 0.9910
R2 = 0.9903
10-min-values # 1048
FLS WS187 : wind speed / [m/s]
RLL : wind speed / [m/s]

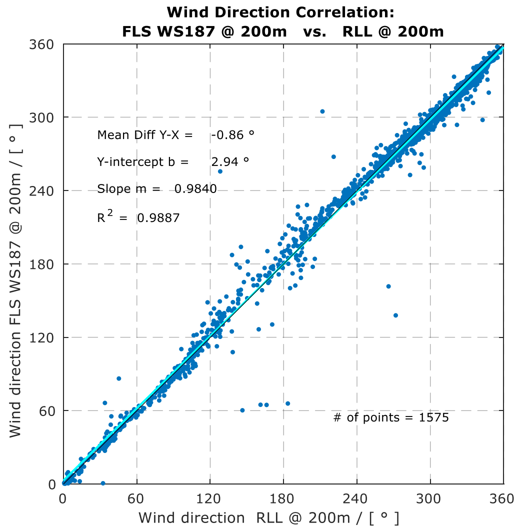

FLS WS187 @ 80m vs. RLL @ 80m
Mean RLL WS: 10.21 m/s
Mean FLS WS: 10.14 m/s
Mean WS-Diff.: -0.07 m/s (-0.67 %)
Std. WS-Diff.: 0.57 m/s (5.59 %)
Slope m = 0.9912
R2 = 0.9896
10-min-values # 1045
FLS WS187 : wind speed / [m/s]
RLL : wind speed / [m/s]

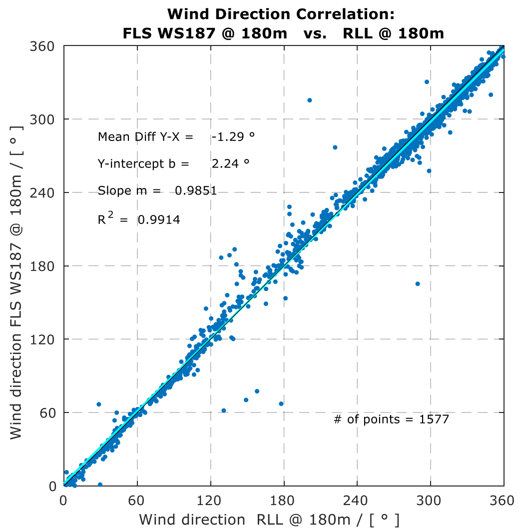

FLS WS187 @ 60m vs. RLL @ 60m
Mean RLL WS: 10.49 m/s
Mean FLS WS: 10.43 m/s
Mean WS-Diff.: -0.06 m/s (-0.52 %)
Std. WS-Diff.: 0.59 m/s (5.65 %)
Slope m = 0.9926
R2 = 0.9891
10-min-values # 1149
FLS WS187 : wind speed / [m/s]
RLL : wind speed / [m/s]

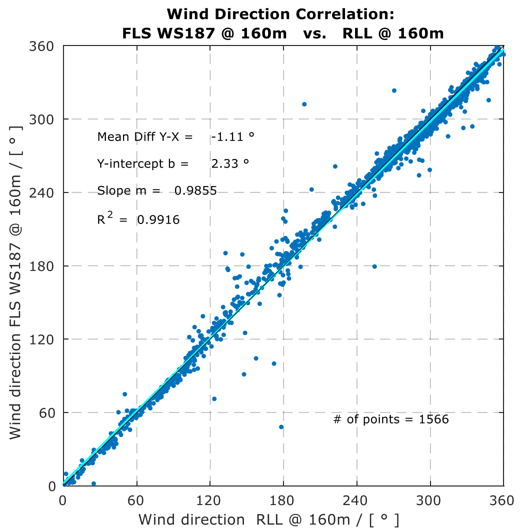

FLS WS187 @ 40m vs. RLL @ 40m
Mean RLL WS: 10.17 m/s
Mean FLS WS: 10.15 m/s
Mean WS-Diff.: -0.01 m/s (-0.13 %)
Std. WS-Diff.: 0.58 m/s (5.71 %)
Slope m = 0.9971
R2 = 0.9881
10-min-values # 1093
FLS WS187 : wind speed / [m/s]
RLL : wind speed / [m/s]

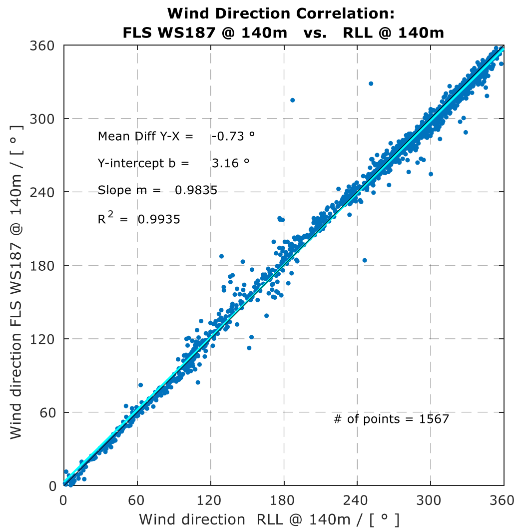
WD correlation plots for all selected comparison heights, i.e. between 40 m and 250 m above MSL

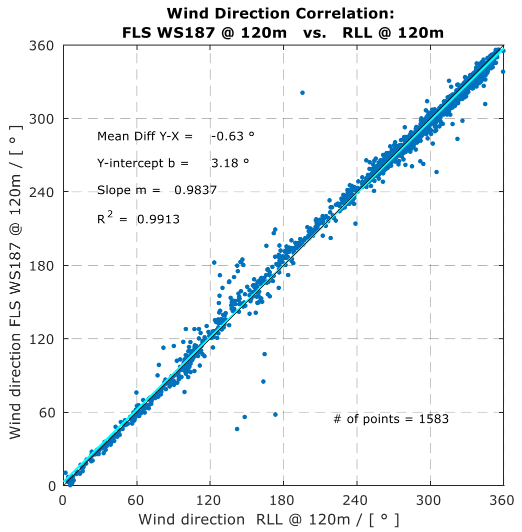


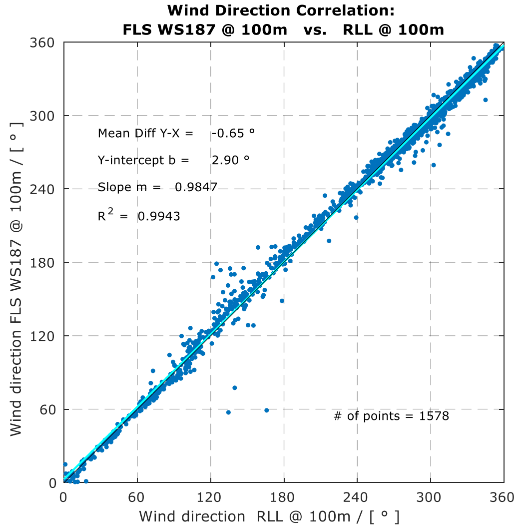




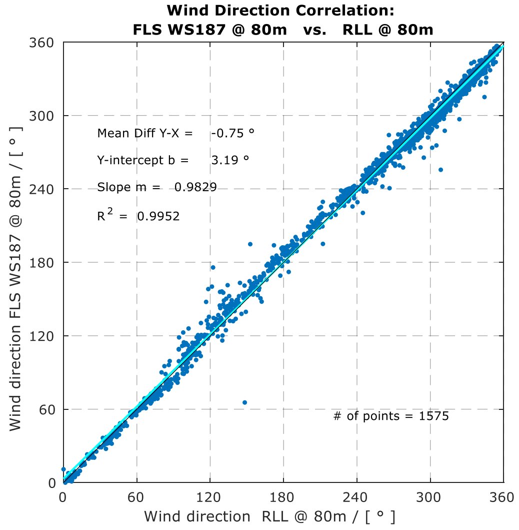




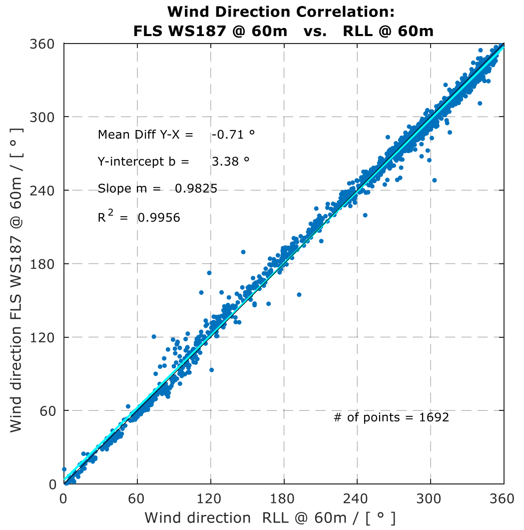




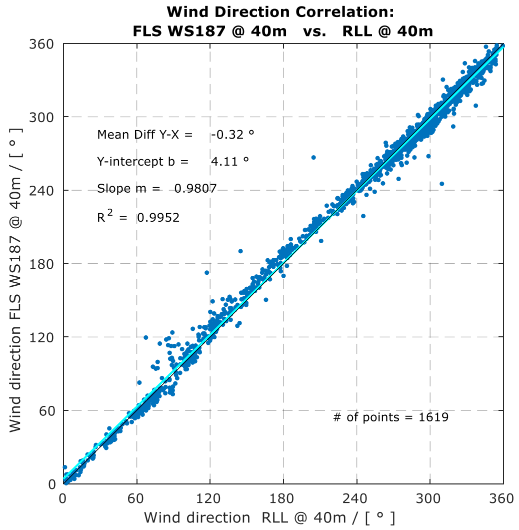
Wind Direction Correlation:
FLS WS187 @ 100m vs. RLL @ 100m
Mean Diff Y-X = -0.65 °
Y-intercept b = 2.90 °
Slope m = 0.9847
R 2 = 0.9943
# of points = 1578
Wind direction RLL @ 100m / [°]
Wind direction FLS WS187 @ 100m / [°]



Wind Direction Correlation:
FLS WS187 @ 80m vs. RLL @ 80m
Mean Diff Y-X = -0.75 °
Y-intercept b = 3.19 °
Slope m = 0.9829
R 2 = 0.9952
# of points = 1575
Wind direction RLL @ 80m / [°]
Wind direction FLS WS187 @ 80m / [°]



Wind Direction Correlation:
FLS WS187 @ 60m vs. RLL @ 60m
Mean Diff Y-X = -0.71 °
Y-intercept b = 3.38 °
Slope m = 0.9825
R 2 = 0.9956
# of points = 1692
Wind direction RLL @ 60m / [°]
Wind direction FLS WS187 @ 60m / [°]



Wind Direction Correlation:
FLS WS187 @ 40m vs. RLL @ 40m
Mean Diff Y-X = -0.32 °
Y-intercept b = 4.11 °
Slope m = 0.9807
R 2 = 0.9952
# of points = 1619
Wind direction RLL @ 40m / [°]
Wind direction FLS WS187 @ 40m / [°]

APPENDIX C – WAVES AND TIDES

Mean wave period and significant wave height distribution across total campaign period:

Joint occurrence of:

Tm02 Mean wave period (Tm02) (s) Slettringen, SWLB WS188
Hm0 Significant wave height (m) Slettringen, SWLB WS188

Measuring depth: 0.00 m
Water depth: 50.00 m
Sampling interval: 10 min.
Period 2019.01.04 10:10 - 2019.01.19 23:59

Tm02 (s) Hm0 (m)	2 3	3 4	4 5	5 6	6 7	7 8	8 9	9 10	10 11	11 12	12 >= 13	 13	SUM	% OF TOTAL	SUM ACC.	CUM. PROB.	MIN.	AVE.	MAX.	STD. DEV.
0.0 - 0.5													0	0	0	0				
0.5 - 1.0			1	27	70	25	4						127	5.7	127	0.05662	5	6.5	8.6	0.7
1.0 - 1.5			110	348	289	141	74	24					986	44	1113	0.49621	4.4	6.3	9.8	1.1
1.5 - 2.0			42	94	270	128	41	21	2				598	26.7	1711	0.76282	4.4	6.7	10.2	1.1
2.0 - 2.5			3	51	156	20	2	2	1				235	10.5	1946	0.86759	5	6.4	10.1	0.7
2.5 - 3.0				8	37	27							72	3.2	2018	0.89969	5.4	6.8	7.4	0.5
3.0 - 3.5				2	65	33							100	4.5	2118	0.94427	5.9	6.7	7.6	0.5
3.5 - 4.0					40	47							87	3.9	2205	0.98306	6.1	7.1	7.9	0.4
4.0 - 4.5					3	34							37	1.7	2242	0.99955	6.8	7.5	7.9	0.3
>= 4.5													0	0	2242	0.99955				
SUM	0	0	156	530	930	455	121	47	3	0	0	0	2242	100	2242	0.99955	4.4	6.5	10.2	1.02
% OF TOTAL	0	0	7	23.6	41.5	20.3	5.4	2.1	0.1	0	0	0	100							
SUM ACCUM.	0	0	156	686	1616	2071	2192	2239	2242	2242	2242	2242	2242							
CUM. PROB.	0	0	0.0695	0.3058	0.7205	0.9233	0.9773	0.9982	0.9996	0.9996	0.9996	0.9996	0.99955							
MIN. VALUE			0.72	0.61	0.63	0.69	0.84	1.14	1.73				0.61							
AVE. VALUE			1.37	1.43	1.85	2.11	1.45	1.57	1.88				1.74							
MAX. VALUE			2.1	3.06	4.24	4.38	2.12	2.02	2.16				4.38							
STD. DEV.			0.26	0.39	0.73	1.05	0.25	0.26	0.19				0.75							

Highest wave period and maximum wave height distribution across total campaign period:

Joint occurrence of:

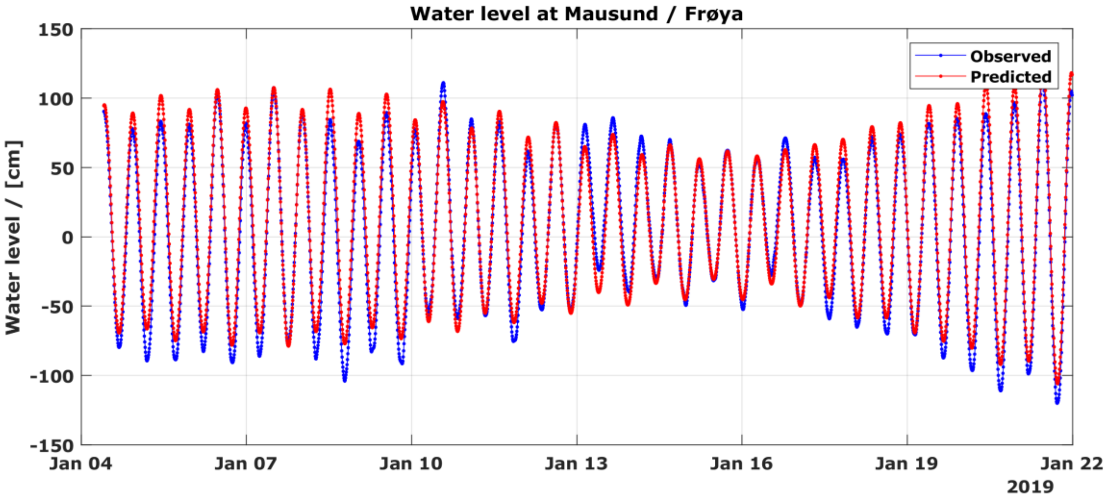
THmax Period of highest wave (s) Slettringen, SWLB WS188
Hmax Maximum wave height (m) Slettringen, SWLB WS188

Measuring depth 0.00 m
Water depth 50.00 m
Sampling interval
Period 2019.01.04 10:10 - 2019.01.19 23:59

THmax (s) Hmax (m)	2 3	3 4	4 5	5 6	6 7	7 8	8 9	9 10	10 11	11 12	12 13	13 14	14 >= 15	 15	SUM	% OF TOTAL	SUM ACC.	CUM. PROB.	MIN.	AVE.	MAX.	STD. DEV.
0.0 - 0.5															0	0	0	0				
0.5 - 1.0							1	9	4	2					16	0.7	16	0.00713	8.6	10	11.8	0.8
1.0 - 1.5				7	3	11	26	45	44	30	15	2	1		184	8.2	200	0.08917	5.1	9.9	14.7	1.7
1.5 - 2.0			6	15	41	78	94	164	152	75	37	18	5	5	690	30.8	890	0.39679	4.6	9.6	17.3	1.9
2.0 - 2.5			3	12	30	56	97	96	118	60	37	6	8	3	526	23.5	1416	0.6313	4.7	9.6	15.7	1.9
2.5 - 3.0			1	4	16	45	59	82	58	37	15	7			324	14.5	1740	0.77575	4.9	9.5	13.5	1.6
3.0 - 3.5			1		14	35	33	24	47	13	8	2			177	7.9	1917	0.85466	4.9	9.3	13.8	1.7
3.5 - 4.0					8	9	12	19	10	5	7	8			78	3.5	1995	0.88943	6.1	9.7	13.3	2
4.0 - 4.5					1	8	10	11	12	5	4	2			53	2.4	2048	0.91306	6.9	9.7	13.8	1.7
4.5 - 5.0					1	13	22	9	9	1	1	3			59	2.6	2107	0.93937	6.3	9.1	13.6	1.6
5.0 - 5.5						15	15	14	9		3			1	57	2.5	2164	0.96478	7	9.1	15	1.5
5.5 - 6.0						8	19	8	8	1	2				46	2.1	2210	0.98529	7	9.1	12	1.2
6.0 - 6.5							6	3	5	5	1				20	0.9	2230	0.9942	8.5	10.1	12.8	1.2
6.5 - 7.0						2		2	1		1				6	0.3	2236	0.99688	7.5	9.4	12.8	1.8
7.0 - 7.5							3								3	0.1	2239	0.99822	8.2	8.3	8.4	0.1
7.5 - 8.0							2								2	0.1	2241	0.99911	8.5	8.8	9	0.2
8.0 - 8.5							1								1	0	2242	0.99955	9	9	9	0
>= 8.5															0	0	2242	0.99955				
SUM	0	0	11	38	114	280	400	486	477	234	131	48	14	9	2242	100	2242	0.99955	4.6	9.6	17.3	1.8
% OF TOTAL	0	0	0.5	1.7	5.1	12.5	17.8	21.7	21.3	10.4	5.8	2.1	0.6	0.4	100							
SUM ACCUM.	0	0	11	49	163	443	843	1329	1806	2040	2171	2219	2233	2242	2242							
CUM. PROB.	0	0	0.0049	0.0218	0.0727	0.1975	0.3758	0.5925	0.8052	0.9095	0.9679	0.9893	0.9955	0.9996	0.99955							
MIN. VALUE			1.69	1.37	1.35	1.25	0.98	0.86	0.74	0.92	1.02	1.18	1.33	1.65	0.74							
AVE. VALUE			2.18	1.93	2.37	2.79	2.87	2.45	2.44	2.25	2.45	2.61	1.98	2.37	2.53							
MAX. VALUE			3	2.84	4.57	6.83	8.12	6.97	6.57	6.26	6.63	4.73	2.41	5.42	8.12							
STD. DEV.			0.44	0.38	0.69	1.18	1.4	1.1	1.05	0.93	1.08	1	0.34	1.11	1.13							

Note that the number of Hmax observations is lower than the number of Hm0 observations. As of Fugro this is because the single waves can’t be identified properly in nearly calm sea states.

Time series of tidal/water level at Mausund, Frøya over total campaign period:



APPENDIX D – UNCERTAINTY

1. Reference uncertainty

The reference uncertainty of the specific reference heights is calculated based on the verification of the RLL, the RLL Lidar type classification and the mounting effects. Table 14 shows the applied RLL uncertainty components.

Table 14: 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	2.48	1.05	0.2	**2.70**	2.47	1.4	0.2	**2.85**	2.28	1.15	0.2	**2.56**
4.5	2.24	1.05	0.2	**2.48**	2.2	1.4	0.2	**2.62**	2.08	1.15	0.2	**2.39**
5	1.89	1.05	0.2	**2.17**	1.9	1.4	0.2	**2.37**	1.92	1.15	0.2	**2.25**
5.5	1.93	1.05	0.2	**2.21**	1.76	1.4	0.2	**2.26**	1.76	1.15	0.2	**2.11**
6	1.75	1.05	0.2	**2.05**	1.66	1.4	0.2	**2.18**	1.78	1.15	0.2	**2.13**
6.5	1.71	1.05	0.2	**2.02**	1.57	1.4	0.2	**2.12**	1.58	1.15	0.2	**1.97**
7	2.19	1.05	0.2	**2.44**	1.49	1.4	0.2	**2.06**	1.52	1.15	0.2	**1.92**
7.5	1.55	1.05	0.2	**1.89**	1.41	1.4	0.2	**2.00**	1.5	1.15	0.2	**1.90**
8	1.39	1.05	0.2	**1.76**	1.37	1.4	0.2	**1.97**	1.45	1.15	0.2	**1.86**
8.5	1.51	1.05	0.2	**1.85**	1.34	1.4	0.2	**1.95**	1.36	1.15	0.2	**1.80**
9	1.29	1.05	0.2	**1.68**	1.28	1.4	0.2	**1.91**	1.36	1.15	0.2	**1.80**
9.5	1.28	1.05	0.2	**1.67**	1.29	1.4	0.2	**1.92**	1.54	1.15	0.2	**1.93**
10	1.24	1.05	0.2	**1.64**	1.39	1.4	0.2	**1.99**	1.49	1.15	0.2	**1.90**
10.5	1.22	1.05	0.2	**1.63**	1.2	1.4	0.2	**1.86**	1.68	1.15	0.2	**2.05**
11	1.17	1.05	0.2	**1.59**	1.55	1.4	0.2	**2.10**	1.46	1.15	0.2	**1.87**
11.5	1.18	1.05	0.2	**1.60**	1.26	1.4	0.2	**1.90**	1.31	1.15	0.2	**1.76**
12	1.14	1.05	0.2	**1.57**	1.18	1.4	0.2	**1.84**	1.41	1.15	0.2	**1.83**
12.5	1.21	1.05	0.2	**1.62**	1.26	1.4	0.2	**1.90**	1.65	1.15	0.2	**2.02**
13	2.14	1.05	0.2	**2.39**	1.17	1.4	0.2	**1.84**	1.07	1.15	0.2	**1.59**
13.5	1.46	1.05	0.2	**1.81**	1.9	1.4	0.2	**2.37**	-	1.15	0.2	-
14	1.22	1.05	0.2	**1.63**	1.45	1.4	0.2	**2.03**	-	1.15	0.2	-
14.5	1.44	1.05	0.2	**1.80**	-	1.4	0.2	-	1.93	1.15	0.2	**2.26**
15	-	1.05	0.2	-	1.26	1.4	0.2	**1.90**	1.26	1.15	0.2	**1.72**
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 FLS and the RLL

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

3. Standard uncertainty of the measurement of FLS

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 was estimated to be 0.5 %.

5. Uncertainty due to non-homogenous flow

The FLS device is located in close proximity of the RLL in simple terrain. As a result the uncertainty due to non-homogenous flow within the measurement volume is considered to be negligible.

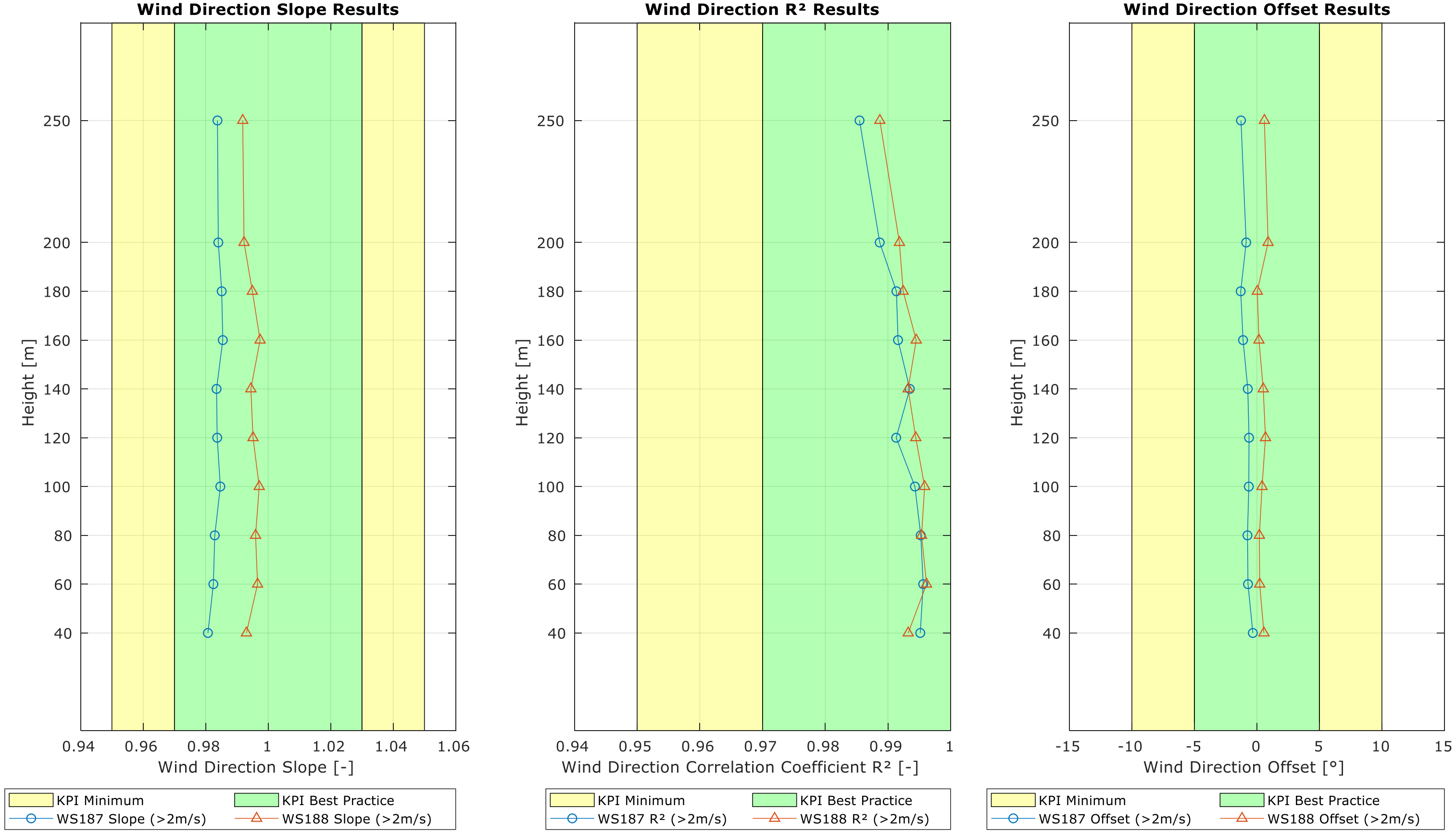
6. Uncertainty due to separation distance

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 of 690 m at a coastal site, the uncertainty was calculated to be 0.35%.

$$Usep = \frac{690m \cdot 0.5\frac{\%}{km}}{1000}$$

DNV GL notes that this calculation differs from the recommended approach stated in the IEC for power curve measurement but reflects a broad knowledge of FLS investigations.

APPENDIX E – COMPARISON OF WD RESULTS WS187 (COMPASS) AND WS188 (DGPS)



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