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SEAWATCH WIND LIDAR BUOY WS170 OFFSHORE IN SITU VERIFICATION

Quality assessment of the Fugro Seawatch Wind Lidar Buoy WS170

Fugro Norway AS

Report No.: 10166838-R-1, Rev. A
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Task and objective: 3rd Party Assessment of an offshore in situ verification of the Fugro Seawatch Wind Lidar Buoy WS170 at Hollandse Kust (west) Wind Farm Zone, Netherlands

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

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List of abbreviations

Abbreviation	**Meaning**
SWLB	Seawatch Wind Lidar Buoy
GH-D	GL Garrad Hassan Deutschland GmbH, part of DNV GL group
REF	Reference Lidar
FLS	Floating LiDAR System
MSL	Mean Sea Level
SL	actual Sea Level
KPI	Key Performance Indicator
AC	Acceptance Criterion
WS	Wind Speed
WD	Wind Direction

1 INTRODUCTION

On 2019-08-19, Fugro Norway AS (Fugro or the Client) commissioned GL Garrad Hassan Deutschland GmbH ("GH-D"), part of the DNV GL group ("DNV GL") to perform an offshore in situ verification and to provide a technical note for a Seawatch Wind Lidar Buoy (SWLB) unit with the serial number WS170.

DNV GL was asked by Fugro to compare data of WS170 to data of WS187 and to data of WS188, which were both deployed offshore near WS170 (see Figure 1). The validation of this already "Roadmap-Pre-Commercial" staged Floating Lidar System (FLS) [1] was performed against another verified SWLB of the same type. Data evaluation was performed for specific wind data quality related Key Performance Indicators (KPIs) and Acceptance Criteria (AC) as formulated in the Roadmap towards Commercial Acceptance [2].

DNV GL has not been involved in the data collection. The data were provided by Fugro on 2019-08-15. The campaign covers the period 2019-06-16 00:00 to 2019-08-11 21:00.

This report is used to document the results with respect to the offshore in situ verification of the Fugro SWLB WS170 against two other validated SWLB (WS187 and WS188).

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 WS170 employing a ZephIR Lidar with the S/N ZP585) 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.

1.2 Settings and Specs of SWLB and REF Units

SWLB Floating Lidar System (FLS):

- SWLB S/N WS170
- ZephIR S/N ZP585
- Height settings 250, 200, 180, 160, 140, 120, 100, 80, 60, 40, 30 m above mean sea level

Reference Lidar (REF1):

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

Reference Lidar (REF2):

- SWLB S/N WS188
- ZephIR S/N ZX802
- Height settings 250, 200, 180, 160, 140, 120, 100, 80, 60, 40, 30 m above mean sea level

The assessment of the KPIs and their respective Acceptance Criteria regarding wind data accuracy was performed at height levels between 30 m and 250 m.

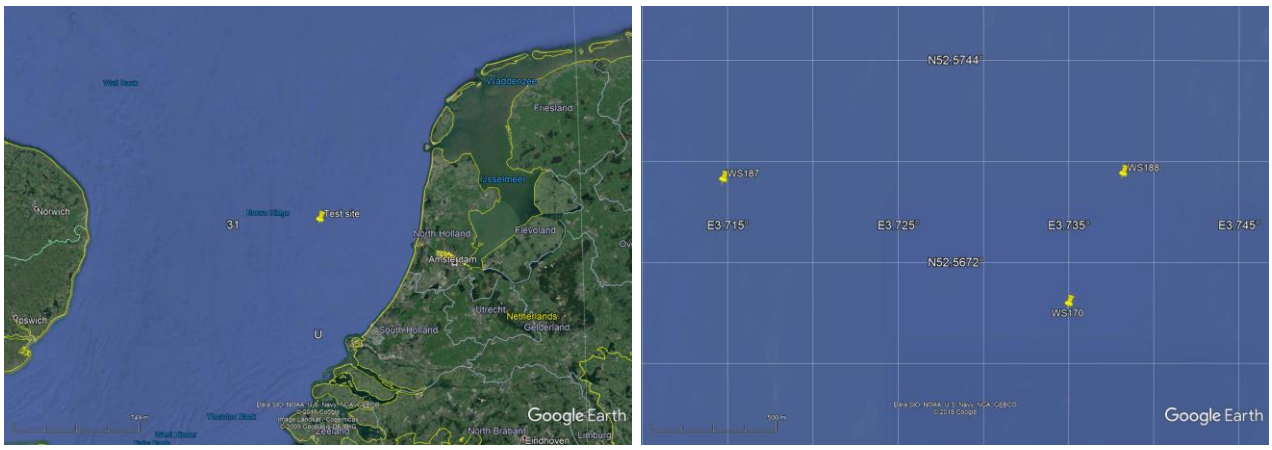


Figure 1: Location of the offshore in situ verification. (Source: Google Earth).

The reference buoy WS187 was deployed approx. 1460 m north-west of the tested buoy WS170. The reference buoy WS188 was deployed approx. 560 m north-east of the tested buoy WS170. The mooring arrays of the buoys allow a horizontal sway freedom of movement around the anchors of about 100 m. The mooring coordinates of the buoys are shown in Table 1.

Table 1: Coordinates of the tested Buoy (WS170) and the reference (WS188)

	Longitude	Latitude	Longitude	Latitude	East	North
	Decimal Degrees		Degrees, Decimal Minutes		UTM Zone 31U	
WS170	3.7347°	52.5656°	3° 44.082	52° 33.936'	549799	5824202
WS187 (REF1)	3.7150°	52.5699°	3° 42.900'	52° 34.194'	548459	5824667
WS188 (REF2)	3.7378°	52.5701°	3° 44.268'	52° 34.206'	550004	5824705

2 VALIDATION RESULTS

For the offshore in situ verification of Fugro's SWLB WS170, the following period was evaluated:

- WS170 vs. WS187: 2019-06-16 00:00 to 2019-08-11 21:00 (56.9 days)
- WS170 vs. WS188: 2019-06-16 00:00 to 2019-08-11 21:00 (56.9 days)

2.1 Data provision

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

- The data was 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.

2.2 Meteorological conditions during the trial

During the validation period of WS170, the device encountered a wide range of wind conditions facing 10-minute averaged wind speeds of up to 24 m/s at the lowest comparison level (30 m) and 29 m/s at the upper most level (250 m).

Related time series are displayed in Appendix B and Appendix C.

Table 2: Maximum 10 min averaged wind speeds measured at the reference buoys and by the tested FLS across the total campaign period.

WS MAX	WS187 REF	WS170 TEST	WS MAX	WS188 REF	WS170 TEST
Height / m	WS / m/s		Height / m	WS / m/s	
250	28.20	28.55	250	29.14	28.55
200	28.08	28.31	200	28.37	28.31
180	28.51	28.55	180	28.43	28.55
160	27.64	28.37	160	28.25	28.37
140	27.93	27.83	140	27.89	27.83
120	27.50	27.89	120	27.65	27.89
100	27.45	26.76	100	26.94	26.76
80	26.28	26.58	80	26.16	26.58
60	25.81	25.45	60	25.99	25.45
40	24.98	24.32	40	24.62	24.32
30	23.95	23.66	30	23.96	23.66

2.3 Accuracy

DNV GL has analysed 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 of the floating LiDAR units. 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 for the wind direction comparisons.

2.3.1 Data coverage results

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 eleven measurement heights considered. This has been conducted according to the following requirements:

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) 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 3: 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]	WS187 # of data points left after filtering																		
250	250	355	462	595	599	647	714	641	431	352	556	378	155	45	20	29	38	23	2
200	262	379	456	568	584	684	690	675	416	362	574	367	121	35	21	39	32	13	1
180	273	380	449	571	600	685	682	674	436	348	614	319	115	31	23	38	27	16	2
160	309	375	414	602	596	689	704	674	455	343	603	298	110	28	27	33	29	12	0
140	304	358	450	594	623	685	704	680	467	331	607	274	88	30	25	39	25	10	0
120	297	369	435	637	655	681	704	718	458	333	577	234	72	23	30	37	24	6	0
100	296	368	475	629	714	684	716	729	440	364	516	194	48	28	28	33	22	3	0
80	312	367	483	682	746	722	773	665	451	372	440	145	38	29	34	32	15	1	0
60	313	375	590	731	852	800	955	699	462	381	336	113	24	32	40	29	12	0	0
40	314	414	634	845	959	873	908	624	438	319	217	75	28	36	42	24	3	0	0
30	321	473	671	955	958	866	917	675	350	237	173	53	28	34	41	21	0	0	0

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]	WS188 # of data points left after filtering																		
250	298	378	576	671	681	699	719	762	507	433	619	462	224	55	18	31	44	26	2
200	311	403	595	641	662	738	700	784	530	416	639	448	190	43	19	38	37	20	2
180	324	417	561	668	630	750	723	815	520	400	671	428	172	34	22	40	36	16	1
160	349	409	540	678	641	737	765	794	554	405	676	409	140	35	25	40	30	13	2
140	359	408	523	711	672	733	767	824	537	401	677	368	119	31	32	39	29	9	0
120	359	417	529	719	709	739	783	840	546	398	657	318	104	26	29	42	29	6	0
100	364	426	548	712	785	767	763	881	545	406	610	259	78	28	35	41	22	5	0
80	384	405	577	770	789	800	835	824	550	430	538	202	67	23	41	41	15	1	0
60	400	414	679	836	923	900	962	900	547	462	401	169	49	23	51	32	12	0	0
40	390	468	709	972	1003	966	970	839	527	370	255	128	37	37	47	25	3	0	0
30	396	498	769	1083	1021	1004	991	814	427	292	202	109	29	43	46	17	0	0	0

2.3.2 Wind speed accuracy

A summary of the findings for each wind-speed-related KPI is presented in Table 4. The wind speed accuracy assessment has been conducted at eleven heights between 30 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 heights between 30 and 250 m fulfils the best practice acceptance criterion [$0.98 < X_{MWS} < 1.02$] as given in [1] for both comparisons.

With regards to the Coefficient of Determination (R^2_{mws}) the best practice acceptance criterion [$R^2_{mws} > 0.98$] is passed at all heights in the wind speed range >2 m/s for both comparisons. In the wind speed range 4 – 16 m/s of the comparison WS170 vs. WS187, the minimum acceptance criterion [$R^2_{mws} > 0.97$] is fulfilled at 60 m and 80 m but failed at 30 m and 40 m. At the comparison WS170 vs. WS188, the best practice acceptance criterion for R^2_{mws} is passed at all heights and wind speed ranges. Plots for WS regression results together with WS time series plots selected for a few comparison levels can be found in Appendix B.

Table 4: Overview of linear regression analysis results for wind speed comparisons. Colour shading indicates the compliance with the prescribed best practice or minimum KPI's Acceptance Criteria (see legend).

	# values	slope	R^2	WS-avg WS187 (Reference)	WS-avg WS170 (Test)	mean diff.	rel. mean difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{mws}				
250 m level							
All >= 2 m/s	6292	1.005	0.991	8.85	8.89	0.046	0.52%
4 - 16 m/s	5375	1.004	0.984	8.86	8.90	0.039	0.44%
200 m level							
All >= 2 m/s	6279	1.005	0.991	8.76	8.80	0.048	0.55%
4 - 16 m/s	5376	1.005	0.985	8.89	8.93	0.042	0.47%
180 m level							
All >= 2 m/s	6283	1.005	0.991	8.72	8.76	0.043	0.50%
4 - 16 m/s	5378	1.004	0.985	8.87	8.91	0.040	0.45%
160 m level							
All >= 2 m/s	6301	1.004	0.991	8.64	8.68	0.038	0.44%
4 - 16 m/s	5378	1.004	0.985	8.85	8.89	0.035	0.40%
140 m level							
All >= 2 m/s	6294	1.004	0.991	8.57	8.60	0.033	0.38%
4 - 16 m/s	5415	1.003	0.985	8.78	8.81	0.027	0.31%
120 m level							
All >= 2 m/s	6290	1.004	0.990	8.44	8.48	0.036	0.42%
4 - 16 m/s	5432	1.003	0.983	8.69	8.72	0.032	0.37%
100 m level							
All >= 2 m/s	6287	1.004	0.989	8.28	8.31	0.034	0.41%
4 - 16 m/s	5461	1.003	0.981	8.56	8.58	0.029	0.33%
80 m level							
All >= 2 m/s	6307	1.005	0.988	8.08	8.12	0.040	0.49%
4 - 16 m/s	5479	1.004	0.978	8.37	8.41	0.036	0.43%
60 m level							
All >= 2 m/s	6744	1.002	0.985	7.87	7.88	0.015	0.19%
4 - 16 m/s	5919	1.001	0.973	8.13	8.14	0.009	0.11%
40 m level							
All >= 2 m/s	6753	1.000	0.983	7.54	7.55	0.006	0.07%
4 - 16 m/s	5892	0.999	0.970	7.81	7.81	-0.003	-0.04%
30 m level							
All >= 2 m/s	6773	1.000	0.982	7.31	7.32	0.004	0.06%
4 - 16 m/s	5855	0.999	0.967	7.62	7.62	-0.004	-0.05%

	# values	slope	R^2	WS-avg WS188 (Reference)	WS-avg WS170 (Test)	mean diff.	rel. mean difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{mws}				
250 m level							
All >= 2 m/s	7205	0.999	0.994	8.93	8.91	-0.012	-0.14%
4 - 16 m/s	6129	0.999	0.990	8.89	8.88	-0.013	-0.15%
200 m level							
All >= 2 m/s	7216	0.999	0.994	8.83	8.82	-0.008	-0.10%
4 - 16 m/s	6153	0.999	0.990	8.90	8.89	-0.007	-0.08%
180 m level							
All >= 2 m/s	7228	0.999	0.995	8.78	8.77	-0.015	-0.17%
4 - 16 m/s	6166	0.999	0.991	8.91	8.90	-0.015	-0.17%
160 m level							
All >= 2 m/s	7242	0.998	0.995	8.71	8.70	-0.018	-0.21%
4 - 16 m/s	6199	0.999	0.991	8.90	8.89	-0.016	-0.18%
140 m level							
All >= 2 m/s	7239	0.998	0.994	8.62	8.60	-0.017	-0.19%
4 - 16 m/s	6213	0.998	0.990	8.84	8.83	-0.017	-0.19%
120 m level							
All >= 2 m/s	7250	0.998	0.994	8.51	8.49	-0.016	-0.18%
4 - 16 m/s	6238	0.998	0.989	8.76	8.74	-0.015	-0.17%
100 m level							
All >= 2 m/s	7275	0.998	0.993	8.36	8.34	-0.018	-0.21%
4 - 16 m/s	6276	0.998	0.989	8.64	8.62	-0.019	-0.22%
80 m level							
All >= 2 m/s	7292	0.998	0.993	8.18	8.17	-0.016	-0.20%
4 - 16 m/s	6315	0.998	0.988	8.47	8.46	-0.019	-0.22%
60 m level							
All >= 2 m/s	7760	0.996	0.992	7.94	7.91	-0.032	-0.40%
4 - 16 m/s	6779	0.996	0.986	8.23	8.20	-0.033	-0.40%
40 m level							
All >= 2 m/s	7746	0.996	0.990	7.62	7.58	-0.034	-0.44%
4 - 16 m/s	6739	0.995	0.982	7.93	7.89	-0.039	-0.49%
30 m level							
All >= 2 m/s	7741	0.995	0.990	7.39	7.35	-0.035	-0.47%
4 - 16 m/s	6712	0.994	0.982	7.71	7.68	-0.039	-0.51%

KPI	Passed Best practice
KPI	Passed Minimum
KPI	Failed

2.3.3 Wind direction accuracy

The wind direction data comparison was conducted at the same eleven heights between 30 and 250 m above MSL.

The results for the wind direction comparison are shown in Table 5 where the Wind Direction Regression Slope (M_{mwd}), the Mean Offset (OFF_{mwd}) and the Coefficient of Determination (R^2_{mwd}) are presented. The KPI values for M_{mwd}, R^2_{mwd} and OFF_{mwd} pass the best practice criterion at all tested heights. Plots for WD regression results selected for a few heights can be found in Appendix B.

Table 5: Overview of linear regression results for WD comparisons. Colour shading indicates compliance with prescribed best practice or minimum KPI's Acceptance Criteria (see legend).

WS187	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	6291	0.995	0.848	0.996
200	6278	0.996	0.873	0.996
180	6282	0.994	0.754	0.995
160	6300	0.995	0.770	0.996
140	6294	0.996	0.597	0.997
120	6288	0.996	0.730	0.997
100	6287	0.996	0.747	0.997
80	6305	0.996	0.709	0.997
60	6743	0.995	0.707	0.997
40	6750	0.995	0.714	0.997
30	6772	0.995	0.678	0.997

WS188	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	7204	1.000	0.456	0.997
200	7214	1.000	0.401	0.997
180	7228	1.001	0.377	0.998
160	7240	1.001	0.424	0.997
140	7237	1.001	0.433	0.998
120	7247	1.000	0.489	0.998
100	7275	1.001	0.464	0.998
80	7288	1.000	0.455	0.998
60	7758	1.000	0.403	0.999
40	7743	1.000	0.332	0.999
30	7738	1.001	0.371	0.999

KPI	Passed Best practice
KPI	Passed Minimum
KPI	Failed

2.4 Summary of verification results

2.4.1 Campaign Duration

The duration of the verification campaign was 56.9 days. The test period was sufficient to achieve the required data completeness in all required WS bins for data analysis, being compliant to the Roadmap in terms of significance of SWLB wind data accuracy results.

2.4.2 Wind Measurement Accuracy

The wind speeds of WS170 and both reference buoys correlated very well at all comparison heights, showing a low level of scatter and good agreement in terms of linear regression analyses. This comparison campaign indicates that the WS170 is able to reproduce the reference Lidars wind speeds at a relatively high level of accuracy. The Best Practice criteria for the KPI "Mean Wind Speed – Slope" were passed at heights between 30 and 250 m. The "Mean Wind Speed – Coefficient of Determination" passed the best practice acceptance criterion at heights between 30 and 250 m in the wind speed range >2 m/s. At the comparison WS170 vs. WS188, the best practice acceptance criterion for R^2_{mws} is passed at all heights and wind speed ranges. In the wind speed range 4 – 16 m/s of the comparison WS170 vs. WS187, the minimum acceptance criterion is fulfilled at 60 m and 80 m but slightly failed at 30 m and

40 m. This small deviation is assumed to be caused by the higher separation distance between WS170 and WS187 (1460 m) and no indication for low performance of the tested FLS WS170.

For the wind direction KPI "Mean Wind Direction – Slope", for the KPI "Mean Wind Direction – Coefficient of Determination" and for the KPI "Mean Wind Direction – Offset" the Best Practice criterion is passed at all heights.

This indicates the SWLB's capability of reproducing the reference Lidar wind directions at an acceptable level of accuracy up to 250 m. The detailed results with respect to KPIs and ACs for wind speed and wind direction comparisons are given in Table 6 below.

Table 6: Summary of achievement with regards to KPIs and Acceptance Criteria for the data accuracy assessment

KPI	Definition / Rationale	Acceptance Criteria	Result	Acceptance Criteria	Result
		Best Practice		Minimum	
X_{mws}	**Mean Wind Speed – Slope** Assessed for wind speed range a) [4 to 16 m/s] b) [all above 2 m/s]	0.98 – 1.02	a) [0.999 – 1.005] @ WS187 Passed at all heights [0.994 – 0.999] @ WS188 Passed at all heights b) [1.000 – 1.005] @ WS187 Passed at all heights [0.995 – 0.999] @ WS188 Passed at all heights	0.97 – 1.03	
R^2_{mws}	**Mean Wind Speed – Coefficient of Determination** Assessed for wind speed range a) [4 to 16 m/s] b) [all above 2 m/s]	>0.98	a) [0.981 – 0.985] @ WS187 Passed at 100m to 250m [0.994 – 0.999] @ WS188 Passed at all heights b) [0.982 – 0.991] @ WS187 Passed at all heights [0.995 – 0.999] @ WS188 Passed at all heights	>0.97	a) [0.973 – 0.978] @ WS187 Passed at 60m to 80m [0.967 – 0.970] @ WS187 Failed at 30m to 40m
M_{mwd}	**Mean Wind Direction – Slope** Assessed for wind speed range [all above 2 m/s]	0.97 – 1.03	[0.994 – 0.996] @ WS187 Passed at all heights [1.000 – 1.001] @ WS188 Passed at all heights	0.95 – 1.05	
R^2_{mwd}	**Mean Wind Direction – Coefficient of Determination** Assessed for wind speed range [all above 2 m/s]	> 0.97	[0.995 – 0.997] @ WS187 Passed at all heights [0.997 – 0.997] @ WS188 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** Assessed for wind speed range [all above 2 m/s]	< 5°	[0.60 – 0.87] @ WS187 Passed at all heights [0.33 – 0.49] @ WS188 Passed at all heights	< 10°	

3 CONCLUSIONS ON SWL BUOY TECHNOLOGY IN CONTEXT OF COMMERCIAL ROADMAP

An evaluation of the Fugro Seawatch Wind Lidar Buoy WS170 was completed by comparing its measurements against data of two Reference Floating Lidar Systems (WS187 and WS188) deployed near WS170.

DNV GL concludes that the Fugro SWBL unit WS170 has demonstrated its capability to produce accurate wind speed and direction data (in relation to the available reference buoys WS187 and WS188) across the range of meteorological conditions experienced in this trial.

The assessments of the Roadmap KPIs for the complete data sets of WS170 vs. WS187 show that all FLS-Roadmap Acceptance Criteria for wind speed are met at heights between 30 and 250 m for the wind speed range >2 m/s passing best practice CT Roadmap acceptance criteria. In the wind speed range 4 -16 m/s of the comparison WS170 vs. WS187, the minimum acceptance criterion is fulfilled at 60 m and 80 m but failed at 30 m and 40 m. This small deviation is assumed to be caused by the higher separation distance between WS170 and WS187 (1460 m). All FLS-Roadmap Acceptance Criteria for wind directions are met at heights between 30 and 250 m, passing best practice CT Roadmap acceptance criteria.

The assessments of the Roadmap KPIs for the complete data sets of WS170 vs. WS188 show that all FLS-Roadmap Acceptance Criteria for wind speed are met at heights between 30 and 250 m and all FLS-Roadmap Acceptance Criteria for wind directions are met at heights between 30 and 250 m, passing best practice CT Roadmap acceptance criteria.

4 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", 2015-01-29.

[3] DNV GL Report 10129033-R-6, Rev. D, "Assessment of the Fugro Seawatch Wind LiDAR Buoy WS 187 Pre-Deployment Validation at Frøya, Norway", 2019-07-29.

[4] DNV GL Report 10129033-R-7, Rev. C, "Assessment of the Fugro Seawatch Wind LiDAR Buoy WS 188 Pre-Deployment Validation at Frøya, Norway", 2019-07-10.

[5] DNV GL Report GLGH-4270 17 14462-R-0002, Rev. C, "Assessment of the Fugro OCEANOR Seawatch Wind LiDAR Buoy WS 170 Pre-Deployment Validation at Frøya, Norway", 2017-07-25.

[6] DNV GL Report GLGH-4270 17 14462-R-0010, Rev. B, "Quality assessment of the Fugro Seawatch Wind LiDAR Buoy WS170", 2018-10-15.

APPENDIX A – APPLIED KEY PERFORMANCE INDICATORS AND ACCEPTANCE CRITERIA FOR FLS 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.

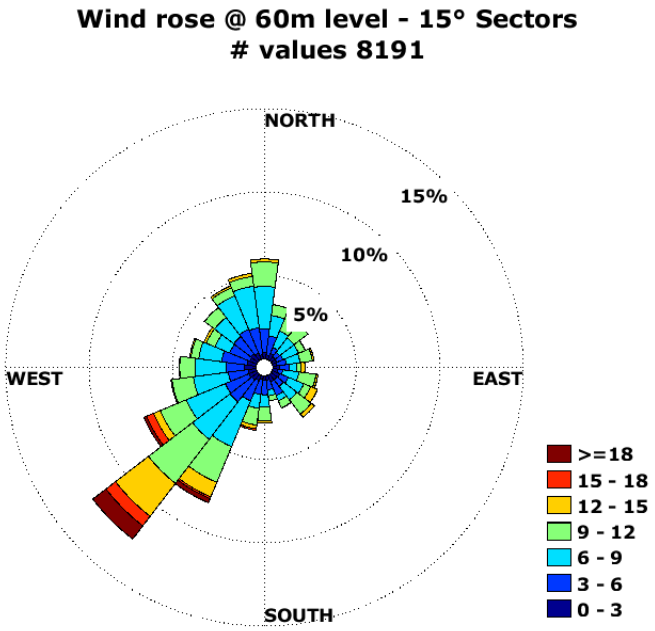
In addition, Acceptance Criteria in the form of "best practise" and "minimum" allowable tolerances have been imposed on slope and offset values as well as on coefficient of determination returned from each reference height for KPIs related to the primary parameters of interest; wind speed and wind direction.

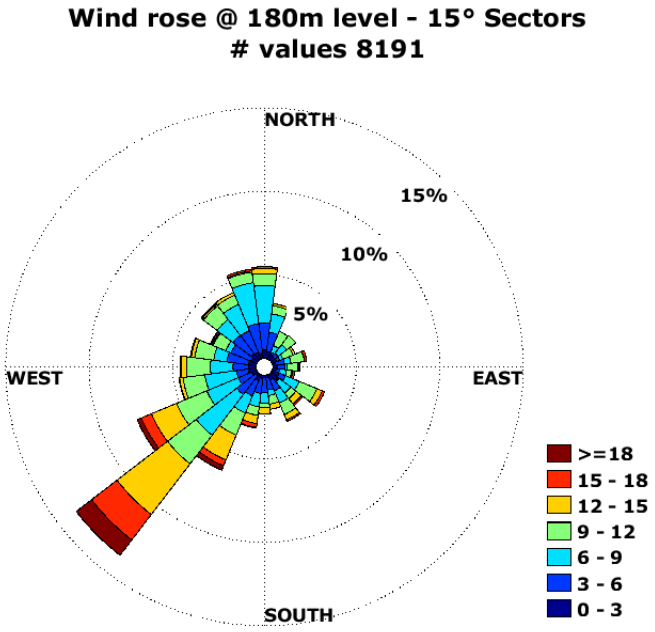
KPI	Definition / Rationale	Acceptance Criteria	
		Best Practice	Minimum
X_{mws}	**Mean Wind Speed – Slope** Slope returned from single variant regression with the regression analysis constrained to pass through the origin. A tolerance is imposed on the Slope value. Analysis shall be applied to wind speed 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

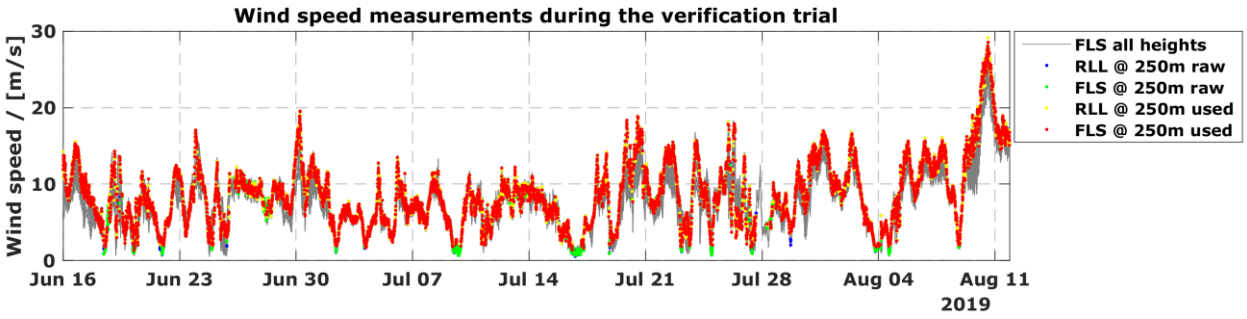
APPENDIX B – CAMPAIGN METEOROLOGICAL CONDITIONS, TIME SERIES AND WS/WD CORRELATION PLOTS

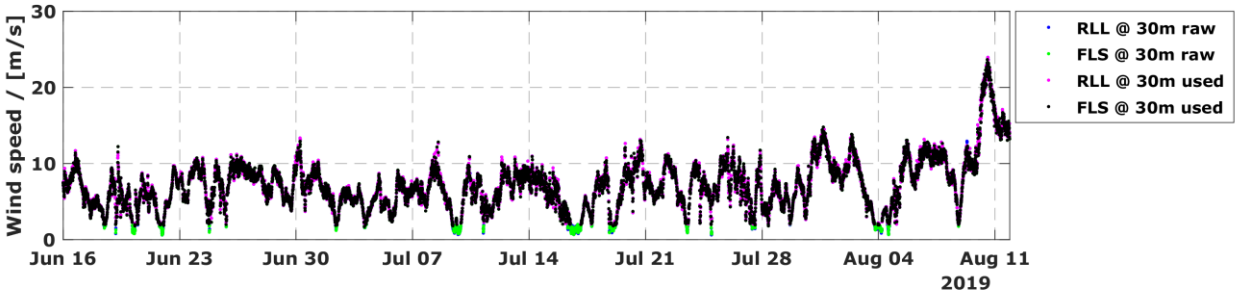
Polar plots of wind directions and wind speed for 60 m and 180 m comparison heights:

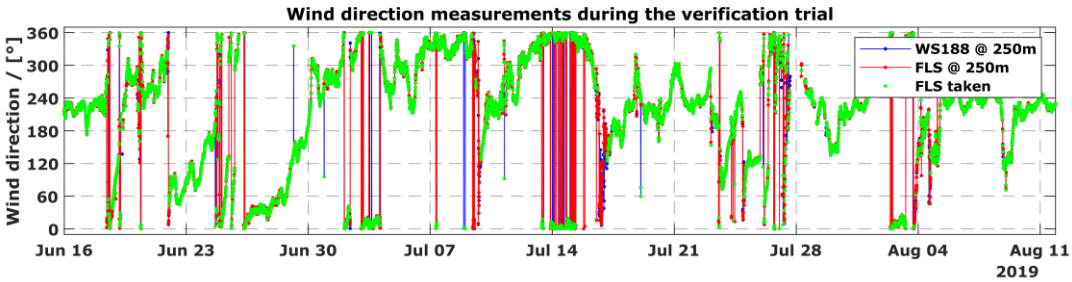


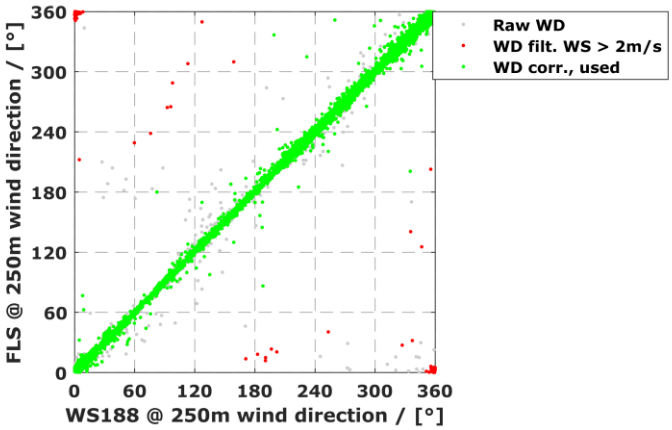


Wind speed and wind directions time series for 30 m and 250 m comparison heights:



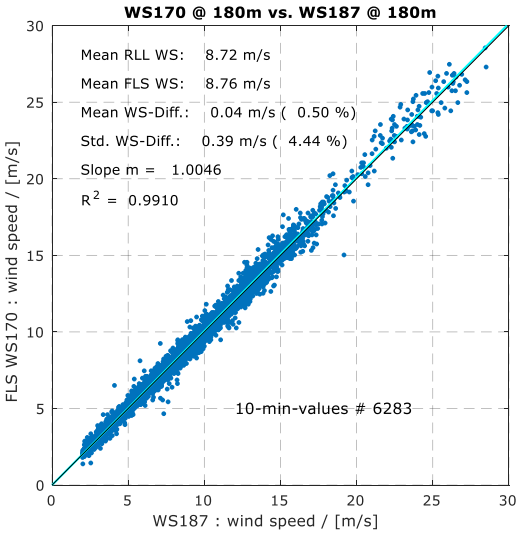


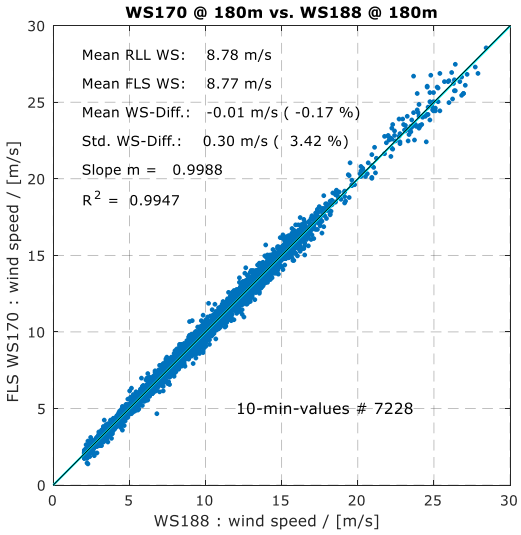


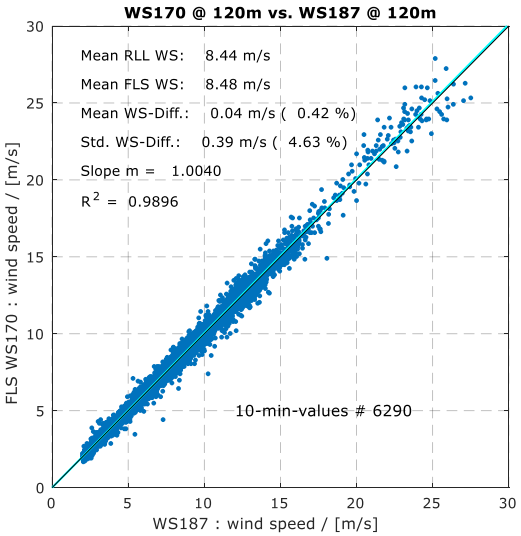


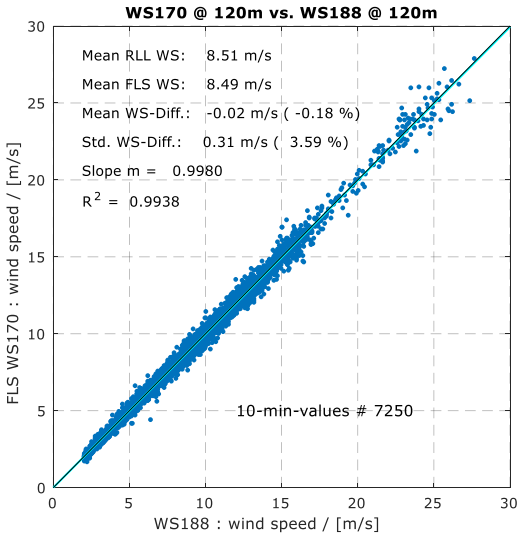
Note: DNV GL applied a correction method to consider the ZephIR/ZX Lidars typical 180° ambiguity. It is expected that the small number of outliers which remain after that correction do not have a significant influence on the final results.

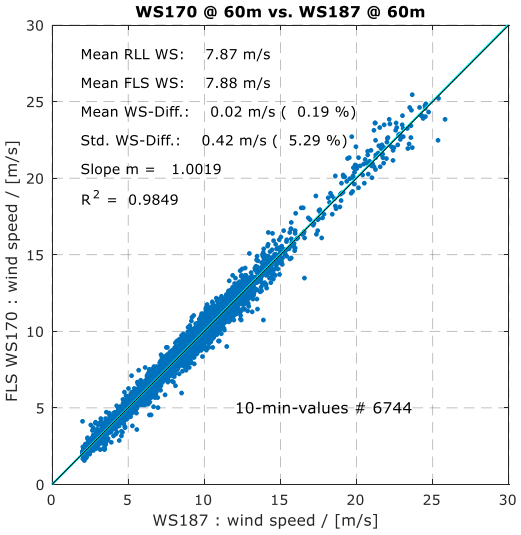
WS regression plots for three (3) selected comparison heights, i.e. at 180, 120 and 60 m above MSL

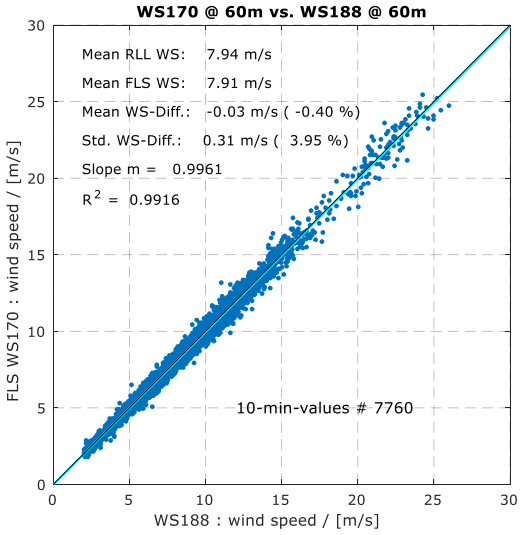




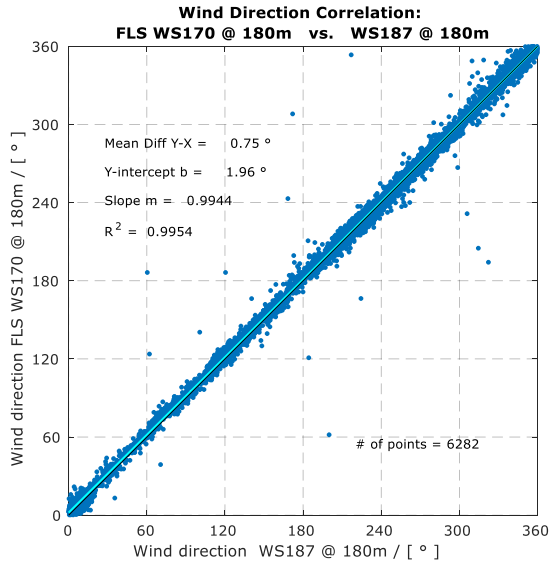


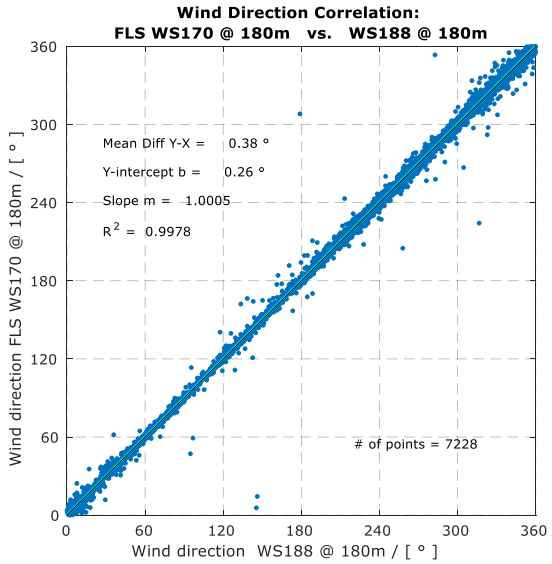


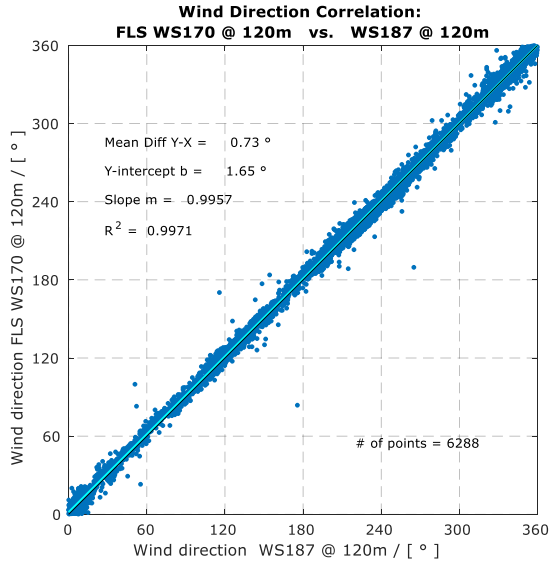


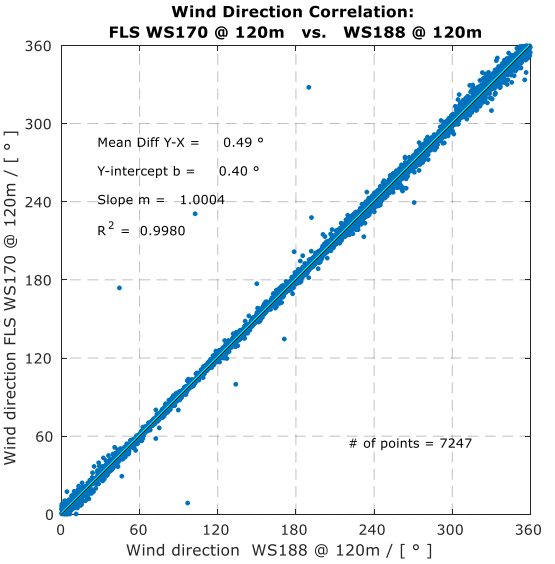


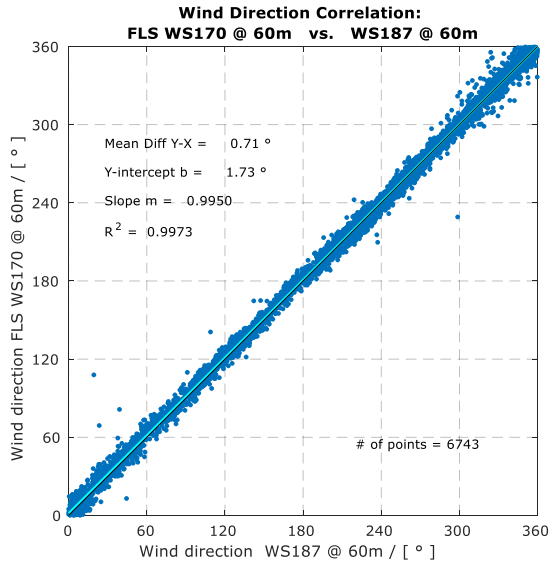
WD correlation plots for three (3) selected comparison heights, i.e. at 180, 120 and 60 m above MSL

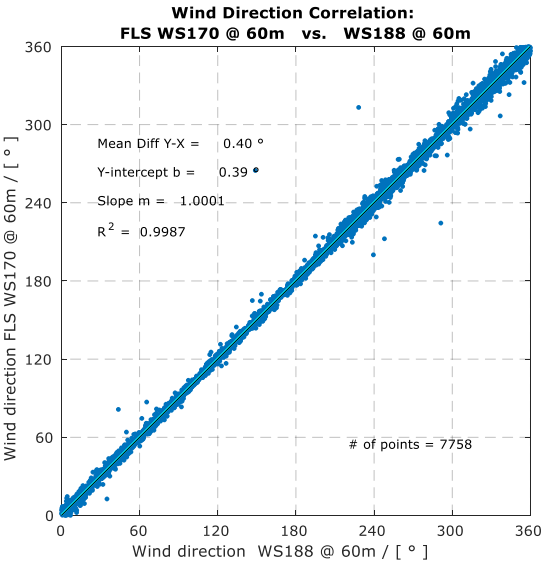












About DNV GL

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