SEAWATCH WIND LIDAR BUOY WS158 OFFSHORE IN SITU VERIFICATION

Quality assessment of the Fugro Seawatch Wind LiDAR Buoy WS158

Fugro Norway AS

Report No.: 10148549-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 WS158 at Hollandse Kust (noord) Wind Farm Zone, Netherlands

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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
FLD	Floating LiDAR Device
MSL	Mean Sea Level
SL	actual Sea Level
LAT	Lowest astronomical tide
KPI	Key Performance Indicator
AC	Acceptance Criterion
WS	Wind Speed
WD	Wind Direction

1 INTRODUCTION

On 2019-02-12, 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 WS158.

DNV GL was asked by Fugro to compare data of WS158 (test) to data of WS156 (the reference), which were both deployed offshore (see Figure 1). The comparison is performed like the previous pre- and post-validations by DNV GL.

The validation of this already "Roadmap-Pre-Commercial" staged Floating Lidar Device (FLD) [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 2019-02-12. The campaign covers the period 2018-11-25 09:00 to 2019-01-31 23:50.

This report is used to document the results with respect to the offshore in situ verification of the Fugro SWLB WS158 against another validated SWLB (WS156).

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 WS158 employing a ZephIR Lidar with the S/N Z417) 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 Unit

The two buoys were validated against a Reference Land Lidar at Fugro's test site at Frøya (see [3] and [4]). Since the unit Z513 which was initially mounted on WS158 had to be sent to the manufacturer for service, the unit Z417 was removed from WS140 and mounted on WS158.

SWLB Floating Lidar Device (FLD):

- SWLB S/N WS158
- ZephIR S/N Z417
- Height settings 200, 180, 160, 140, 120, 100, 80, 60, 40, 30 m above mean sea level

Reference Lidar (REF):

- SWLB S/N WS156
- ZephIR S/N Z501
- Height settings 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 200 m.

DNV GL has been informed by Fugro that the Lidar unit Z501 of buoy WS156 was sent to the manufacturer in 2018 for service and maintenance. DNV GL has the compliance that the maintenance work will have no impact of the performance and validation of the Lidar. No optical components have been modified or worked on. A re-verification of the Z501 is not required.

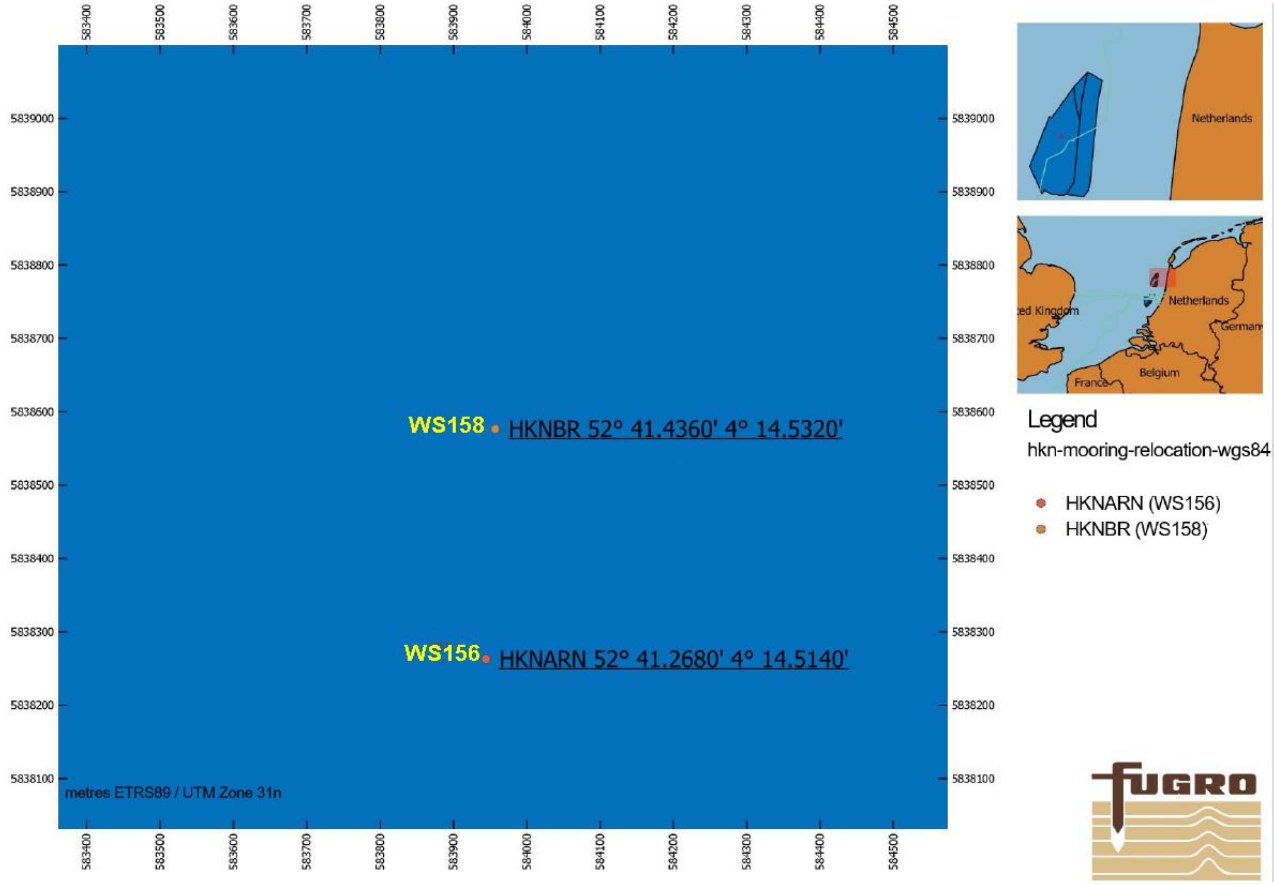


Figure 1: Location of the offshore in situ verification. WS158 was deployed at the HKNB position. WS156 was deployed at the HKNA position. (Source: Fugro, edited by DNV GL).

The reference buoy WS156 was deployed approx. 310 m south of the tested buoy WS158. Both buoys are moored in 25 m of water depth and the mooring arrays allow a horizontal sway freedom of movement around the anchors of about 100 m. The mooring coordinates of both buoys are shown in Table 1.

Table 1: Coordinates of the tested Buoy (WS158) and the reference (WS156)

	Longitude	Latitude	Longitude	Latitude	East	North
	Decimal Degrees		Degrees, Decimal Minutes		UTM Zone 31U	
HKNA (WS156)	4.2419°	52.6878°	4° 14.514	52° 41.268'	583943	5838265
HKNB (WS158)	4.2422°	52.6906°	4° 14.532'	52° 41.436'	583957	5838577

2 VALIDATION RESULTS

For the offshore in situ verification of Fugro's SWLB WS158, the following period was evaluated:

- WS158 vs. WS156: 2018-11-25, 09:00 to 2019-01-31, 23:50 (67.6 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 WS158 vs. WS156, the device encountered a wide range of wind conditions facing 10 minute averaged wind speeds of up to 22.3 m/s at the lowest comparison level (30 m) and 25.7 m/s at the upper most level (200 m).

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

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

WS MAX	WS156-Ref	WS158-Test
Height / m	WS / m/s	
200	25.66	25.72
180	25.31	25.66
160	25.37	25.37
140	25.20	25.20
120	24.32	24.84
100	24.08	24.26
80	23.91	24.49
60	23.67	23.79
40	22.85	22.62
30	22.03	22.27

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 at both the floating LiDAR unit and the REF. 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 ten (10) 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]	# of data points left after filtering																		
200	63	132	259	241	317	486	518	530	484	473	688	882	642	405	214	174	30	0	0
180	67	125	260	250	306	494	509	537	503	454	734	901	625	386	218	155	15	0	0
160	65	128	267	239	318	492	546	529	500	463	757	915	591	369	213	138	10	0	0
140	70	127	260	247	314	509	543	543	512	463	788	952	550	333	216	108	5	0	0
120	65	136	255	244	332	508	551	568	511	469	810	982	521	288	209	86	3	0	0
100	70	133	261	242	330	534	577	539	529	481	891	950	472	283	178	67	3	0	0
80	73	137	257	243	346	555	611	532	531	504	947	923	434	236	170	40	0	0	0
60	71	156	274	238	355	598	606	552	551	512	1040	824	394	216	129	25	0	0	0
40	82	168	256	263	405	639	596	593	557	557	1065	728	337	205	85	4	0	0	0
30	88	180	252	285	437	696	569	625	577	604	1063	635	279	204	46	1	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 ten heights between 30 and 200 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 200 m fulfils the best practice acceptance criterion [$0.98 > X_{MWS} > 1.02$] as given in [1].

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. 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 WS158 vs. WS156 at ten 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 WS156-Ref (Reference)	WS-avg WS158-Test (Test)	mean diff.	rel. mean difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{mws}				
200 m level							
All >= 2 m/s	6538	1.004	0.993	12.04	12.08	0.047	0.39%
4 - 16 m/s	4878	1.005	0.989	10.32	10.36	0.045	0.43%
180 m level							
All >= 2 m/s	6539	1.003	0.993	11.96	12.00	0.036	0.30%
4 - 16 m/s	4948	1.003	0.988	10.36	10.39	0.033	0.32%
160 m level							
All >= 2 m/s	6540	1.003	0.993	11.86	11.89	0.033	0.28%
4 - 16 m/s	5026	1.003	0.989	10.37	10.40	0.033	0.32%
140 m level							
All >= 2 m/s	6540	1.002	0.993	11.74	11.77	0.033	0.28%
4 - 16 m/s	5131	1.004	0.989	10.41	10.45	0.040	0.38%
120 m level							
All >= 2 m/s	6538	1.003	0.993	11.60	11.64	0.037	0.32%
4 - 16 m/s	5230	1.004	0.989	10.43	10.47	0.041	0.39%
100 m level							
All >= 2 m/s	6540	1.002	0.992	11.44	11.47	0.033	0.29%
4 - 16 m/s	5334	1.003	0.988	10.41	10.45	0.035	0.34%
80 m level							
All >= 2 m/s	6539	1.002	0.991	11.25	11.28	0.030	0.27%
4 - 16 m/s	5449	1.003	0.987	10.39	10.42	0.032	0.31%
60 m level							
All >= 2 m/s	6541	1.003	0.990	10.99	11.03	0.039	0.35%
4 - 16 m/s	5550	1.003	0.986	10.30	10.34	0.037	0.36%
40 m level							
All >= 2 m/s	6540	1.002	0.989	10.69	10.72	0.031	0.29%
4 - 16 m/s	5659	1.003	0.985	10.18	10.22	0.034	0.33%
30 m level							
All >= 2 m/s	6541	1.003	0.989	10.42	10.46	0.040	0.39%
4 - 16 m/s	5743	1.004	0.984	10.06	10.11	0.047	0.47%

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 ten (10) heights between 30 and 200 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. 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 WS158 vs. WS156 at the ten (10) WD 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 X_{mwd}	KPI OFF_{mwd}	KPI R^2_{mwd}
200	6535	1.045	5.937	0.989
180	6532	1.047	5.924	0.990
160	6537	1.046	5.814	0.989
140	6536	1.046	5.816	0.990
120	6535	1.046	5.654	0.990
100	6537	1.047	5.624	0.989
80	6535	1.046	5.600	0.989
60	6534	1.046	5.350	0.989
40	6532	1.047	5.343	0.990
30	6536	1.048	5.543	0.990

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 67.6 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 both the SWLB and the REF at all comparison heights correlated very well, showing a low level of scatter and good agreement in terms of linear regression analyses. This comparison campaign indicates that the SWBL is able to reproduce the reference Lidar 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 200 m. The "Mean Wind Speed – Coefficient of Determination" passed the best practice acceptance criterion at heights between 30 and 200 m.

For wind direction KPI "Mean Wind Direction – Slope" the Minimum criterion is passed at all heights, for the KPI "Mean Wind Direction – Coefficient of Determination" the Best Practice criterion is passed at all heights and for the KPI "Mean Wind Direction – Offset" the minimum criterion is passed at all comparison heights. This indicates the SWLB's capability of reproducing the reference Lidar wind directions at an acceptable level of accuracy up to 200 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

<table>
<tr><th rowspan="2">KPI</th><th rowspan="2">Definition / Rationale</th><th colspan="2">Acceptance Criteria across total campaign duration</th></tr>
<tr><th>Best Practice</th><th>Minimum</th></tr>
<tr><td>X_{mws}</td><td>Mean Wind Speed – Slope
Assessed for wind speed range
[all above 2 m/s]

[4 to 16 m/s]</td><td>0.98 – 1.02
Results:
[1.002 – 1.004
Passed at all heights
[1.003 – 1.005
Passed at all heights</td><td>0.97 – 1.03</td></tr>
<tr><td>R^2_{mws}</td><td>Mean Wind Speed – Coefficient of Determination
Assessed for wind speed range
[all above 2 m/s]

[4 to 16 m/s]</td><td>>0.98
Results:
[0.989 – 0.993]
Passed at all heights
[0.984 – 0.989]
Passed at all heights</td><td>>0.97</td></tr>
<tr><td>M_{mwd}</td><td>Mean Wind Direction – Slope
Assessed for wind speed range
[all above 2 m/s]</td><td>0.97 – 1.03</td><td>0.95 – 1.05
Results:
[1.045 – 1.048]
Passed at all heights</td></tr>
<tr><td>R^2_{mwd}</td><td>Mean Wind Direction – Coefficient of Determination
(same as for M_{mwd})</td><td>> 0.97
Results:
[0.989 – 0.990]
Passed at all compared heights</td><td>> 0.95</td></tr>
<tr><td>OFF_{mwd}</td><td>Mean Wind Direction – Offset, in terms of the mean absolute WD difference over the total campaign duration
(same as for M_{mwd})</td><td>< 5°</td><td>< 10°
Results:
[5.343 – 5.937]
Passed at all heights</td></tr>
</table>

3 CONCLUSIONS ON SWL BUOY TECHNOLOGY IN CONTEXT OF COMMERCIAL ROADMAP

An evaluation of the Fugro Seawatch Wind Lidar Buoy WS158 was completed by comparing its measurements against data of a Reference Floating Lidar Device (WS156) deployed near WS158.

DNV GL concludes that the Fugro SWBL unit WS158 has demonstrated its capability to produce accurate wind speed and direction data (in relation to the available reference buoy WS156) across the range of meteorological conditions experienced in this trial.

The assessments of the Roadmap KPIs for the complete data set (from 2018-11-25 until 2019-01-31) show that all FLD-Roadmap Acceptance Criteria for wind speed are met at heights between 30 and 200 m and all FLD-Roadmap Acceptance Criteria for wind directions are met at heights between 30 and 200 m, passing best practice or minimum 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", dated 2015-01-29.

[3] DNV GL Report GLGH-4257 13 10378-R-0005, Rev., "Assessment of the Fugro OCEANOR Seawatch Wind LiDAR Buoy WS 156 Pre-Deployment Validation on Frøya, Norway", dated 2016-04-12.

[4] DNV GL Report GLGH-4270 16 13920-R-0001, Rev. D, "Assessment of the Fugro OCEANOR Seawatch Wind LiDAR Buoy WS 158 Pre-Deployment Validation on Frøya, Norway", dated 2016-07-04.

[5] 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.

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

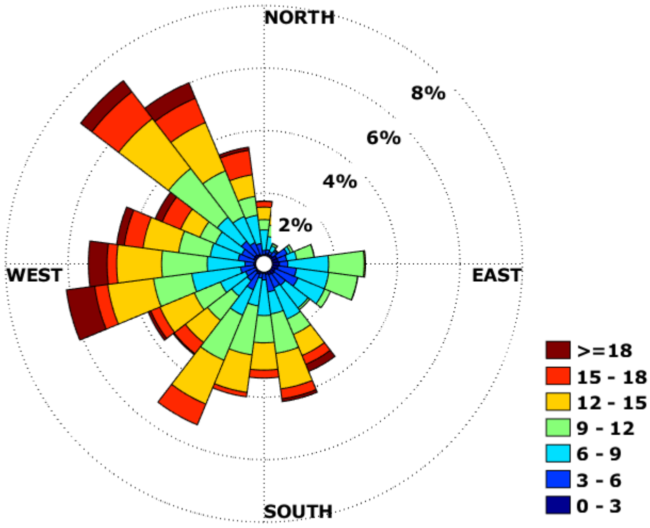
KPI	**Definition / Rationale**	**Acceptance Criteria**	
		Best Practice	**Minimum**
X_{mws}	**Mean Wind Speed – Slope** Slope returned from single variant regression with the regression analysis constrained to pass through the origin. A tolerance is imposed on the Slope value. Analysis shall be applied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

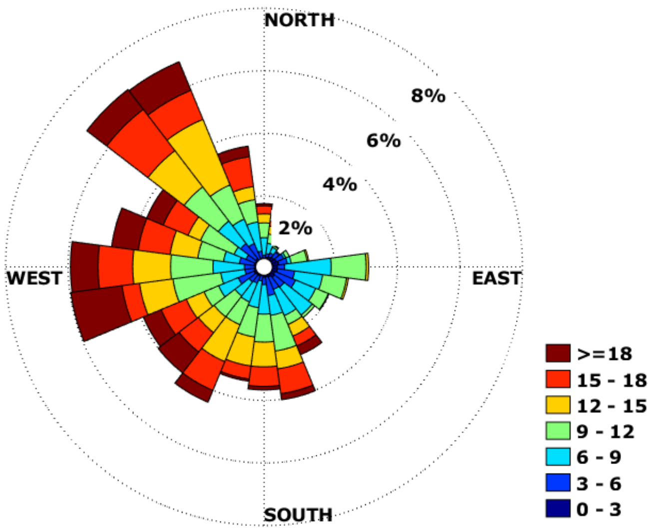
APPENDIX B – CAMPAIGN METEOROLOGICAL CONDITIONS, TIME SERIES AND WS/WD CORRELATION PLOTS – WS158 VS. WS156

<u>Polar plots of wind directions and wind speed for 40 m and 160 m comparison heights:</u>

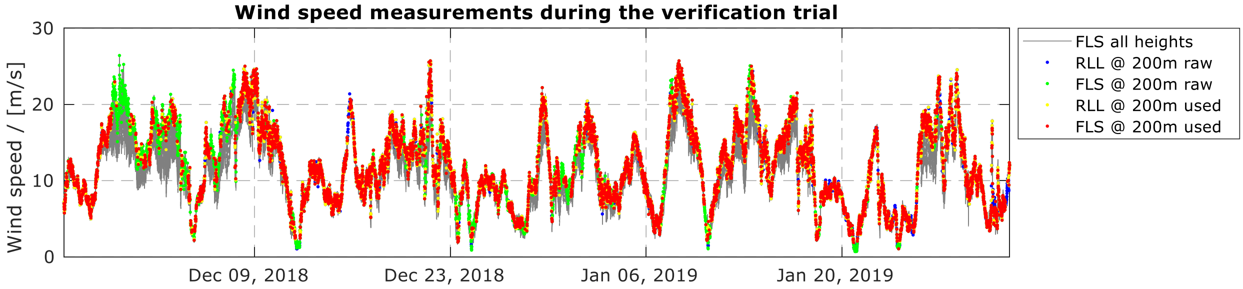
Wind rose @ 40m level - 15° Sectors
 # values 9738

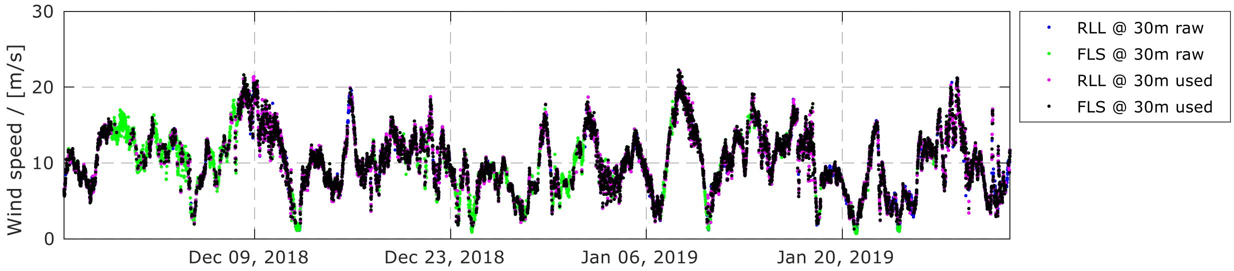


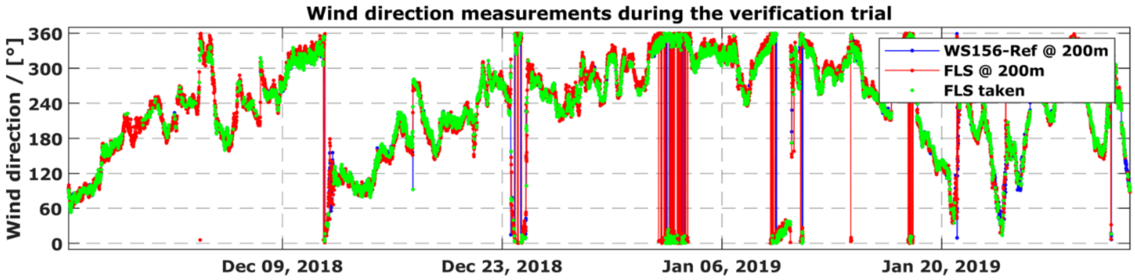
Wind rose @ 160m level - 15° Sectors
 # values 9738

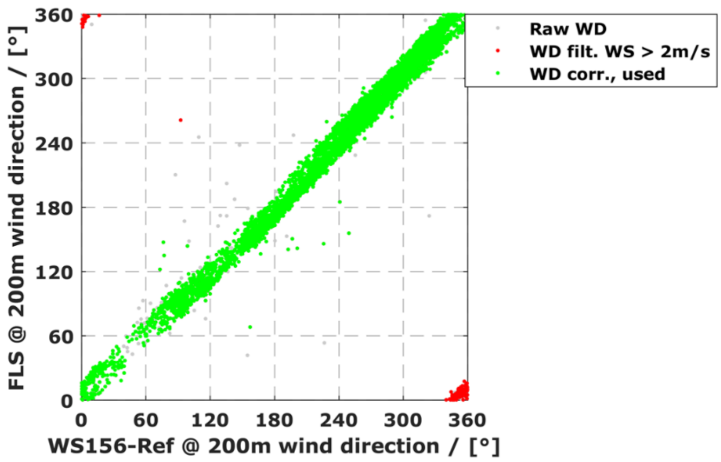


Wind speed and wind directions time series for 30 m and 200 m comparison heights:



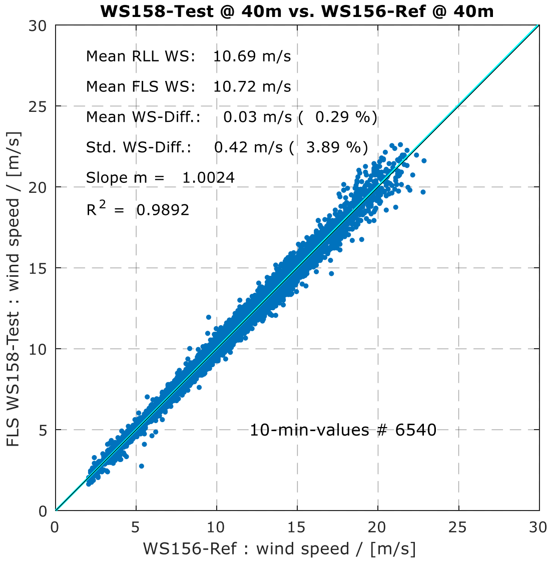


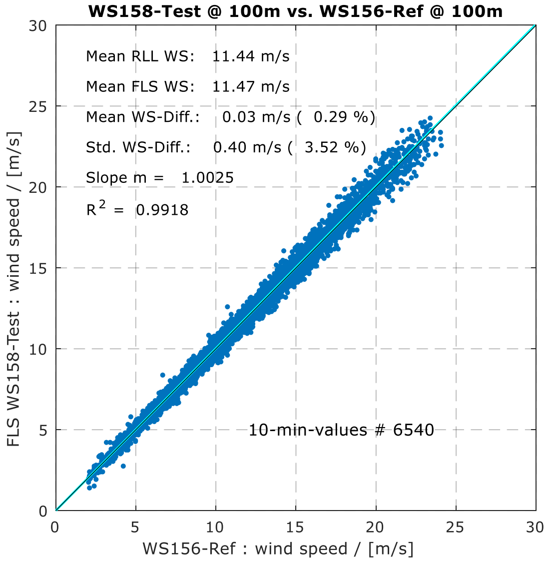


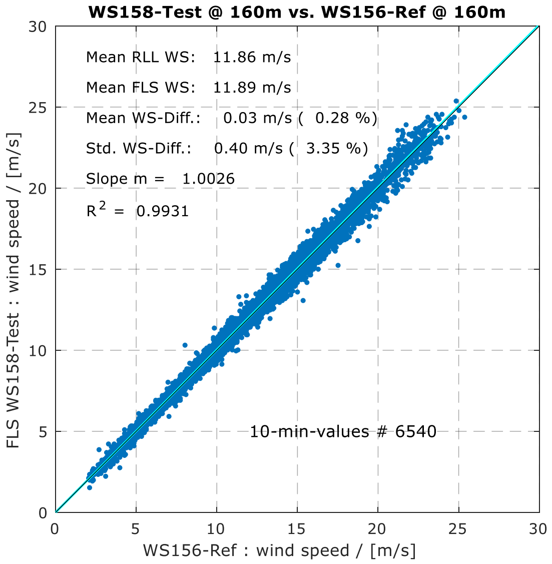


WS regression plots for three (3) selected comparison heights, i.e. at 40, 100 and 160 m above MSL

Shown are results for linear WS regressions "forced" through the origin as discussed above, and for information "un-forced" linear WS regressions, yielding as well the WS offset in terms of intercept of the regression line of the y-axis.

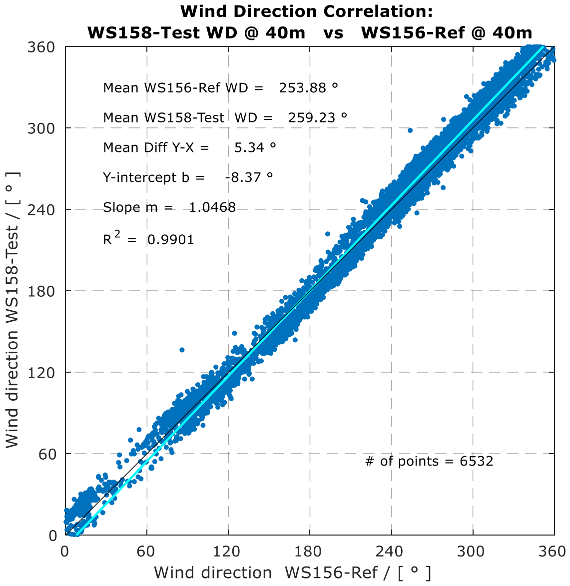


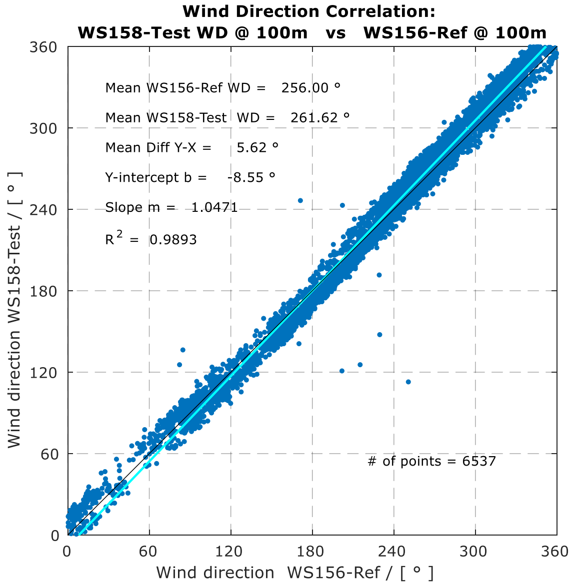


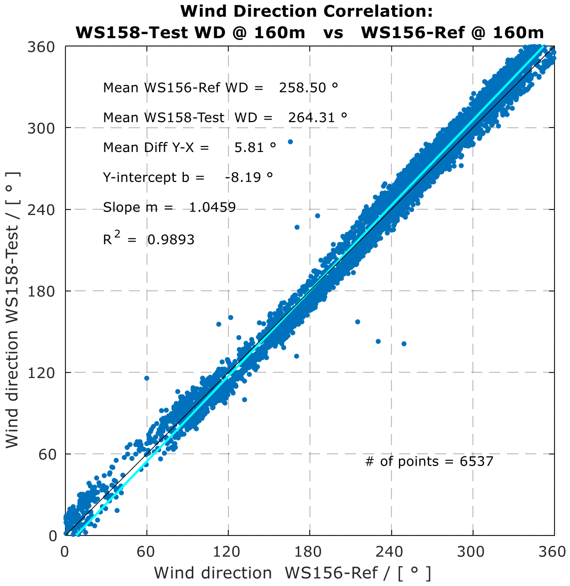


WD correlation plots for three (3) selected comparison heights, i.e. at 40, 100 and 160 m above MSL

Shown are results for linear "un-forced" WD regressions "un-forced" linear WS regressions, yielding as well the WD offset in terms of intercept of the regression line of the y-axis and in terms of the mean WD difference.







End of report

About DNV GL

Driven by our purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification and technical assurance along with software and independent expert advisory services to the maritime, oil and gas, and energy industries. We also provide certification services to customers across a wide range of industries. Operating in more than 100 countries, our 16,000 professionals are dedicated to helping our customers make the world safer, smarter and greener.