SEAWATCH WIND LIDAR BUOY WS140 VS. WS149 COMPARISON

Post- Incident data quality assessment of the Fugro OCEANOR Seawatch Wind LiDAR Buoy WS140

Fugro Norway AS

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Task and objective: 3rd Party Assessment of an Onshore Comparison of the Fugro/Oceanor SEAWATCH Wind LiDAR Buoy WS 149 at IJmuiden, Netherlands

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Table of contents

List of abbreviations

Abbreviation	**Meaning**
SWLB	Seawatch Wind Lidar Buoy
GH-D	GL Garrad Hassan Deutschland GmbH, part of DNV GL group
FO	Fugro OCEANOR
RLL	Reference Land 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 2017-05-09, Fugro OCEANOR AS (FO or the Client) commissioned GL Garrad Hassan Deutschland GmbH ("GH-D"), part of the DNV GL group ("DNV GL") to perform an onshore comparison and to provide a technical note for a SEAWATCH Wind LiDAR Buoy (SWLB) unit with the serial number WS140.

On February 5th, the WS140 was recovered from the HKZA position while the WS156 was deployed in its place at HKZA on the same mooring. During the recovery of the WS140, the buoy impacted into the deck from height. Initial report during debrief described the keel weight getting stuck at the stern of the vessel and the lifting strap failing, resulting in the buoy falling on its fender from approximately 1 meter.[1] There is no visual damage on anything. However, because of the rough landing, everything should be checked thoroughly before the buoy is used again.

After the incident, ZephIR have already reviewed diagnostic data from the unit and have found no problems with prism rotation or focus stage, or any other flags. As additional check, DNV GL was asked by FO to compare data of WS140 to data of WS149, which were both installed onshore (Latitude 52.4614°, Longitude 4.5719°) incl. hulls separated by a few meters' distance for 2.8 days (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 over a period of 2.8 days against a fixed/land based industry accepted Lidar (Reference Land Lidar or RLL). 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. Data from both the SWLB and the RLL were provided by FO. The campaign covers the period 2017-04-17 12:00 to 2017-04-07 06:00.

This report is aimed in documenting the results with respect to the onshore validation trial of the Fugro OCEANOR SWLB with S/N WS140 against another SWLB with S/N WS149. Since the data evaluation tools of DNV GL are prepared for comparisons to a Reference Land Lidar (RLL), this abbreviation was used for WS149 in this report.

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 WS 140 employing a ZephIR Lidar with the S/N ZP417) 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 RLL Units

SWLB Floating Lidar Device (FLD):

- SWLB S/N WS140
- ZephIR S/N ZP417
- Height settings 200, 180, 160, 140, 120, 100, 80, 60, 40 m above mean sea level

Reference Land Lidar (RLL):

- SWLB S/N WS149
- ZephIR S/N ZP428
- Height settings 200, 180, 160, 140, 120, 100, 80, 60, 40 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 40 m and 200 m.

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[1] A video of the incident was provided to DNV GL

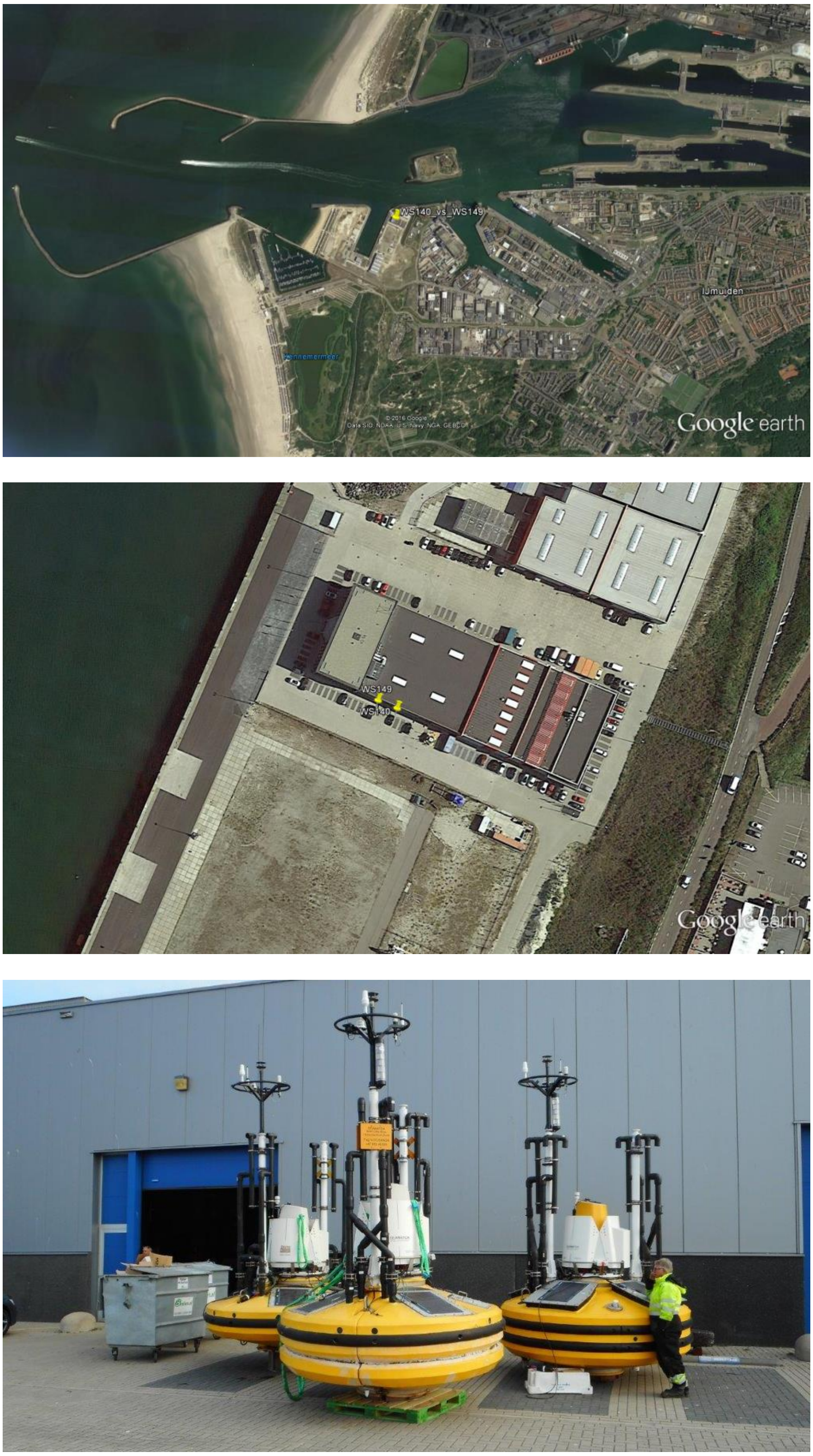


Figure 1: Location of the onshore comparison WS140 vs. WS149 at Ijmuiden (Source: Google Earth [1st and 2nd picture], Fugro [3rd picture]).

2 VALIDATION RESULTS

For the validation of FO's SWLB against the RLL data from the employed FLD ZephIR 300 LiDAR with the serial number ZP417 and from the RLL ZephIR with the serial number ZP428 were provided by FO for a campaign period lasting 2017-04-17 12:00 to 2017-04-07 06:00, yielding a duration of 2.8 days.

2.1 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 FO, 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 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 12.1 m/s at the lowest comparison level (40 m) and 13.6 m/s at the upper most level (200 m) – see Table 1.Related time series are displayed in Appendix B.

Table 1: Maximum 10 min averaged wind speeds measure at the RLL and by the SWLB across the total campaign period.

WS Max	RLL	SWLB
Level / [m]	WS [m/s]	
40	12.07	11.95
60	12.71	12.66
80	13.07	12.95
100	13.24	13.13
120	13.36	13.24
140	13.36	13.30
160	13.48	13.36
180	13.54	13.42
200	13.59	13.48

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 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 for the wind direction comparisons.

2.3.1 Data coverage results

The duration of the verification campaign was 2.8 days. Of course, such a short period is not sufficient to complete all required WS bins for data analysis, being compliant to the Roadmap in terms of significance of SWLB wind data accuracy results. Nevertheless, the database covers wind speeds between 2 and 14 m/s. For the RLL, the wind speed bins 6 to 9 m/s were completed for all heights. The wind speed bins 4 to 6 m/s are complete for 7 of 9 heights each.

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 nine (9) 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 not 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 not been fulfilled.

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 2 shows an overview of the data coverage.

Table 2: Wind speed data coverage per WS bin. Bins including at least 40 values marked in green.

RLL	WS Bins / [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
WS149	Bin Center	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]	RLL number of 10 min data entries per WS bin - AFTER filtering for data to be used for regression analysis																		
	40	10	34	66	59	69	52	53	22	14	10	1	0	0	0	0	0	0	0	0
	60	10	17	62	62	59	62	64	23	18	10	5	0	0	0	0	0	0	0	0
	80	8	16	45	67	60	61	76	23	16	12	8	0	0	0	0	0	0	0	0
	100	9	15	38	56	64	66	80	25	16	14	8	0	0	0	0	0	0	0	0
	120	9	15	40	46	59	65	89	31	14	16	8	0	0	0	0	0	0	0	0
	140	9	16	40	41	54	65	85	41	14	16	10	0	0	0	0	0	0	0	0
	160	9	14	43	37	50	72	79	48	13	16	11	0	0	0	0	0	0	0	0
	180	8	17	39	39	47	74	70	57	12	18	11	0	0	0	0	0	0	0	0
	200	6	17	40	40	45	77	65	57	16	17	12	0	0	0	0	0	0	0	0

FLD	WS Bins / [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
WS140	Bin Center	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]	FLD number of 10 min data entries per WS bin - AFTER filtering for data to be used for regression analysis																		
	40	13	36	59	62	65	60	50	18	17	10	0	0	0	0	0	0	0	0	0
	60	10	17	68	60	57	61	66	24	14	10	5	0	0	0	0	0	0	0	0
	80	8	18	47	67	59	60	76	23	15	12	7	0	0	0	0	0	0	0	0
	100	10	14	41	54	71	60	79	27	15	12	8	0	0	0	0	0	0	0	0
	120	11	14	39	51	60	63	88	29	14	15	8	0	0	0	0	0	0	0	0
	140	8	16	38	49	53	66	80	43	11	18	8	0	0	0	0	0	0	0	0
	160	9	15	39	44	52	68	77	50	10	17	10	0	0	0	0	0	0	0	0
	180	8	15	41	41	53	69	68	58	11	17	10	0	0	0	0	0	0	0	0
	200	9	18	35	44	51	69	64	61	11	18	11	0	0	0	0	0	0	0	0

2.3.2 Wind speed accuracy

A summary of the findings for each wind-speed-related KPI is presented in Table 3. The wind speed accuracy assessment has been conducted at nine heights between 40 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 40 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 3: 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).

WS comparison		slope	regr. coeff.	WS RLL avg	WS FLD avg	WS diff.	relative WS diff.
		KPIs					
Level / [m]	#	X_{mws}	R^2_{mws}				
40	390	0.994	0.996	6.51	6.47	-0.04	-0.6%
60	392	0.993	0.998	6.82	6.77	-0.05	-0.7%
80	392	0.992	0.997	7.05	6.99	-0.06	-0.8%
100	391	0.993	0.998	7.20	7.14	-0.06	-0.8%
120	392	0.991	0.998	7.30	7.23	-0.07	-0.9%
140	391	0.991	0.997	7.38	7.32	-0.07	-0.9%
160	392	0.990	0.997	7.45	7.38	-0.08	-1.0%
180	392	0.989	0.997	7.51	7.43	-0.08	-1.1%
200	392	0.988	0.994	7.56	7.47	-0.09	-1.2%

Legend	
KPI	failed
KPI	passed minimum
KPI	passed best practice

2.3.3 Wind direction accuracy:

The wind direction data comparison was conducted at the same nine (9) heights between 40 and 200 m above MSL.

The results for the wind direction comparison are shown in Table 4 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 4: Overview of linear regression results for WD comparisons between SWLB and reference Lidar at the nine (9) WD comparison levels. Colour shading indicates compliance with prescribed best practice or minimum KPI's Acceptance Criteria (see legend).

WD comparison		slope	regr. Coeff.	mean diff.
		KPIs		
Level / [m]	#	M_{mwd}	R^2_{mwd}	OFF_{mwd}
40	390	1.004	0.956	-1.89
60	392	0.999	0.962	-2.33
80	392	0.998	0.967	-2.17
100	390	1.020	0.956	-0.64
120	392	1.034	0.965	-1.91
140	391	1.009	0.959	-2.47
160	392	1.005	0.968	-1.82
180	391	0.998	0.967	-0.74
200	392	1.021	0.973	-1.99

Legend	
KPI	failed
KPI	passed minimum
KPI	passed best practice

2.4 Summary of verification results

2.4.1 Campaign Duration

As already stated in chapter 2.3.1, the campaign duration was 2.8 days, which is too short to complete all required WS bins for data analysis, being compliant to the Roadmap. Nevertheless, the database covers wind speeds between 2 and 14 m/s, which is sufficient for a sanity check.

2.4.2 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 scatter and good agreement in terms of linear regression analyses. This comparison campaign indicates that the SWBL is able to reproduce fixed Lidar wind speeds at a high level of accuracy.

The Best Practice criteria for the KPI "Mean Wind Speed – Slope" were passed at heights between 40 and 200 m. The "Mean Wind Speed – Coefficient of Determination" passed the best practice acceptance criterion at heights between 40 and 200 m.

For wind direction KPI "Mean Wind Direction – Slope" the Best Practice criterion is passed at all heights except 120m, for the KPI "Mean Wind Direction – Coefficient of Determination" the Best Practice criterion is passed at 200 m and the minimum criterion at 40 to 180m, and for the KPI "Mean Wind Direction – Offset" the best practice criterion is passed at all comparison heights. This indicates the SWLB's capability of reproducing fixed Lidar wind directions at a high 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 5 below.

Table 5: Summary of achievement after 2.8 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]	0.98 – 1.02 Results: Passed at all compared heights	0.97 – 1.03
R^2_{mws}	**Mean Wind Speed – Coefficient of Determination** Assessed for wind speed range [all above 2 m/s]	>0.98 Results: Passed at all compared heights	>0.97
M_{mwd}	**Mean Wind Direction – Slope** Assessed for wind speed range [all above 2 m/s]	0.97 – 1.03 Results: Passed at all compared heights except 120 m	0.95 – 1.05 Results: Passed at 120 m
R^2_{mwd}	**Mean Wind Direction – Coefficient of Determination** (same as for M_{mwd})	> 0.97 Results: Passed at 200 m	> 0.95 Results: Passed at compared heights 40 to 180 m
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: Passed at all compared heights	< 10°

3 CONCLUSIONS ON SWL BUOY TECHNOLOGY IN CONTEXT OF COMMERCIAL ROADMAP

An evaluation of the Fugro/OCEAN Seawatch Wind Lidar Buoy floating LiDAR system (WS140) was completed by comparing its measurements against data of a Reference Land Lidar (WS149) installed alongside the WS140 for 2.8 days in Ijmuiden.

DNV GL concludes that the FO SWBL unit with the S/N 140 has demonstrated its capability to produce accurate wind speed and direction data across the range of meteorological conditions experienced in this trial. The Lidar wind speeds covered a range of up to 12.1 m/s at 40 m and 13.6 m/s at 200 m.

The assessments of the Roadmap KPIs for the complete data set (from 2017-02-03 until 2017-02-22) show that all FLD-Roadmap Acceptance Criteria for wind speed are met at heights between 40 and 200 m and all FLD-Roadmap Acceptance Criteria for wind directions are met at heights between 40 and 200 m, passing best practice or minimum CT Roadmap acceptance criteria.

DNV GL has no doubts that the good results of this evaluation confirms that the FLD WS140 is fit for purpose after the impact.

4 REFERENCES

[1] Carbon Trust Offshore Wind Accelerator roadmap for the commercial acceptance of floating LIDAR technology. CTC 819 Version 1.0, The Carbon Trust, 21 November 2013.

[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.

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.

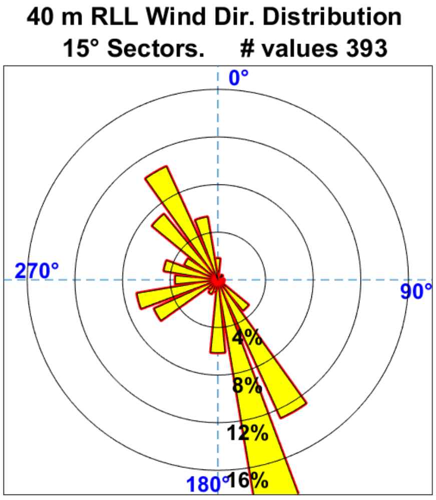
In addition, Acceptance Criteria in the form of "best practise" and "minimum" allowable tolerances have been imposed on slope and offset values as well as on coefficient of determination returned from each reference height for KPIs related to the primary parameters of interest; wind speed and wind direction.

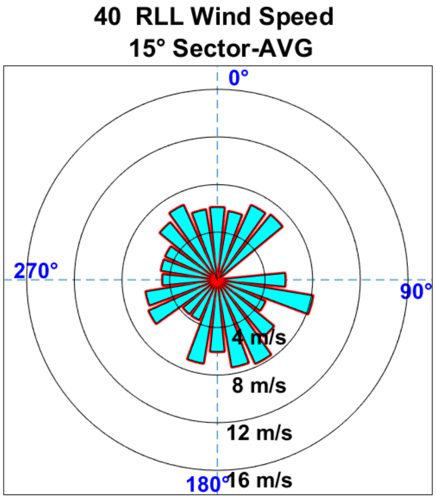
KPI	Definition / Rationale	Acceptance Criteria	
		Best Practice	**Minimum**
X_{mws}	**Mean Wind Speed – Slope** Slope returned from single variant regression with the regression analysis constrained to pass through the origin. A tolerance is imposed on the Slope value. Analysis shall be applied to wind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

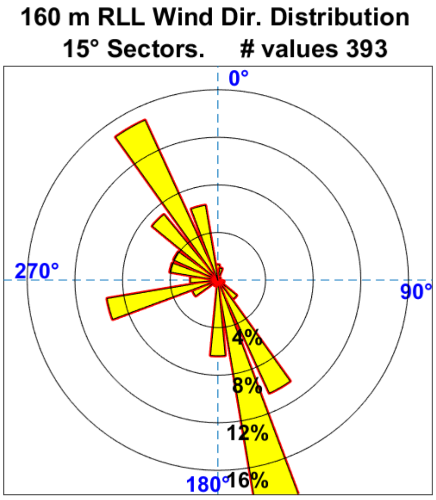
KPI	Definition / Rationale	Acceptance Criteria	
		Best Practice	Minimum
M_{mwd}	**Mean Wind Direction – Slope** Slope returned from a two-variant regression. A tolerance is imposed on the Slope value. Analysis shall be applied to a) all wind directions b) all wind speeds above 2 m/s regardless of coverage 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

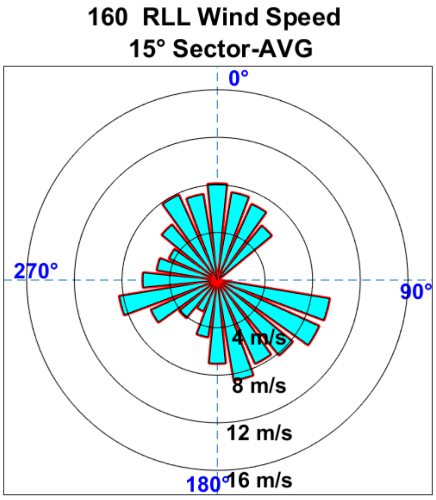
APPENDIX B – CAMPAIGN METEOROLOGICAL CONDITIONS, TIME SERIES AND WS/WD CORRELATION PLOTS

Polar plots of wind directions and wind speed for 40 m and 160 m comparison heights:

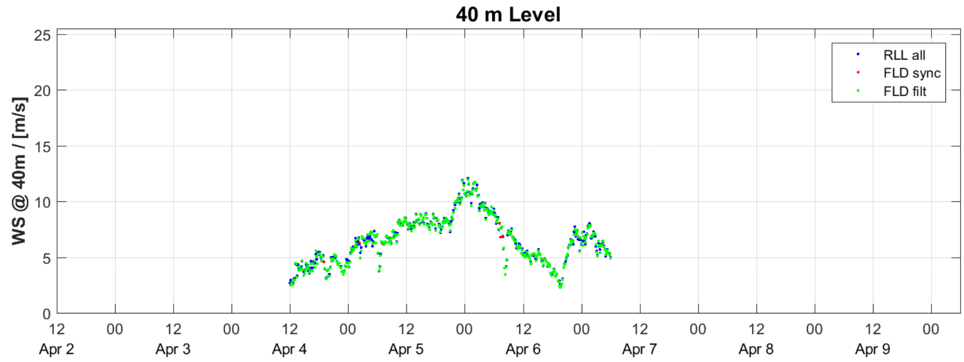


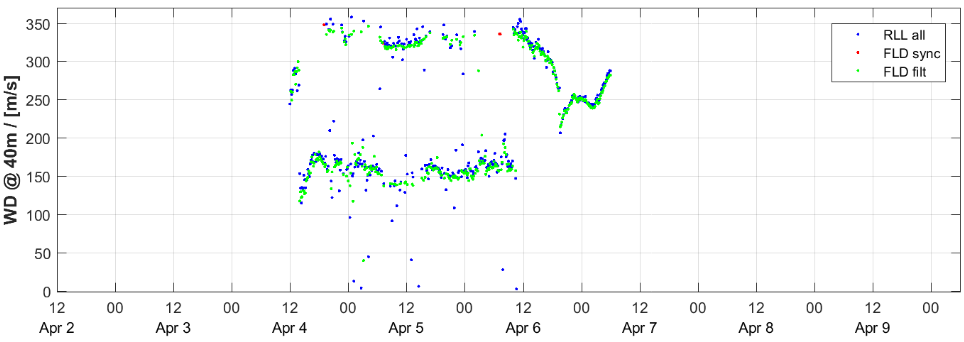


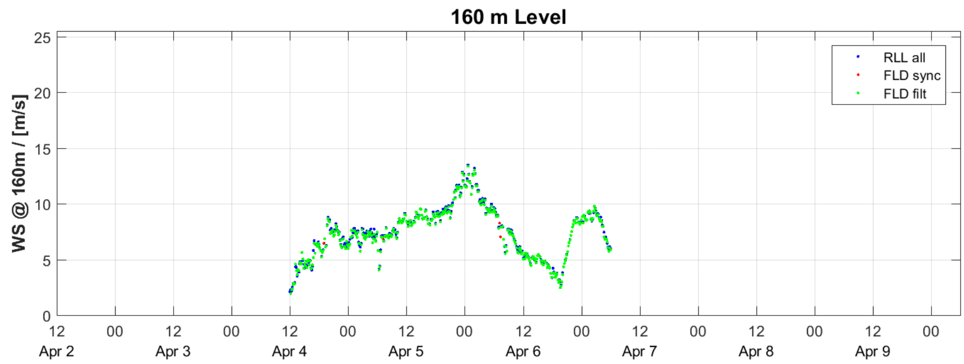


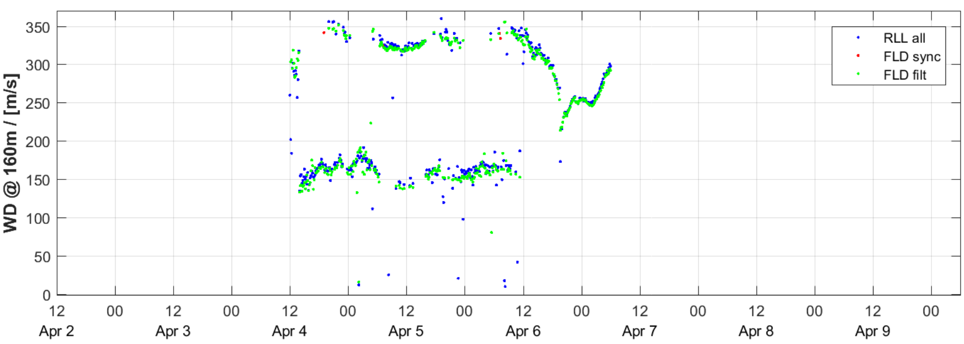


Wind speed and wind directions time series for 40 m and 160 m comparison heights:



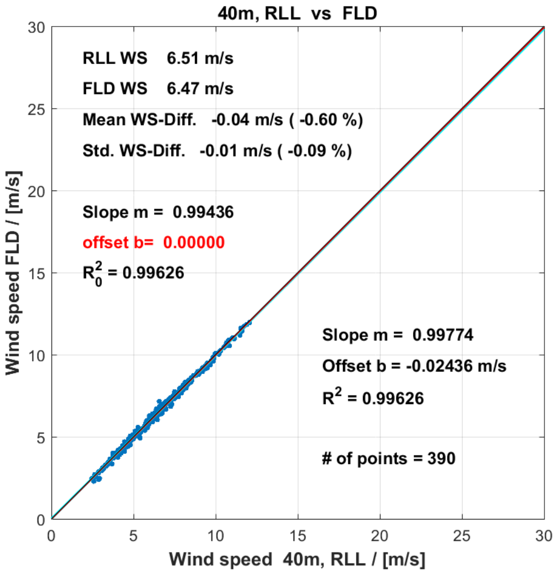


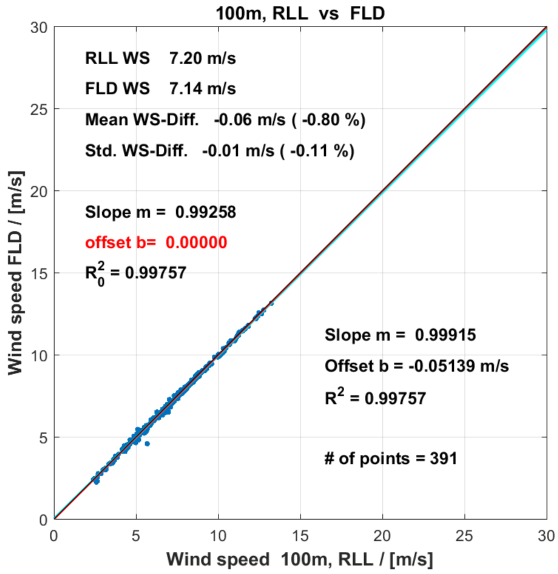


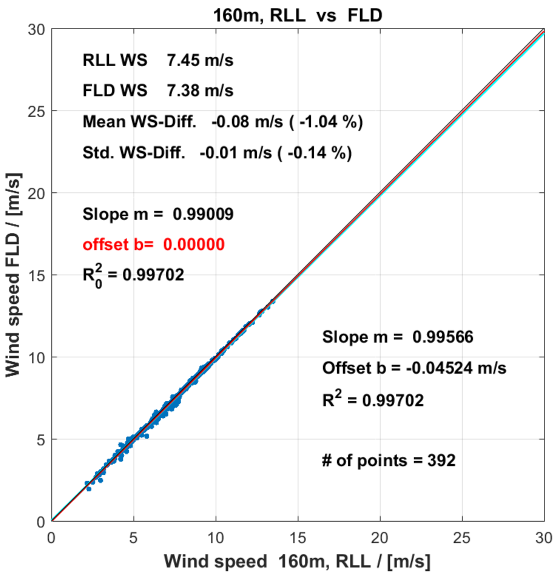


WS regression plots for three (3) selected comparison heights, i.e. at 40, 100 and 160 m above MSL

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.

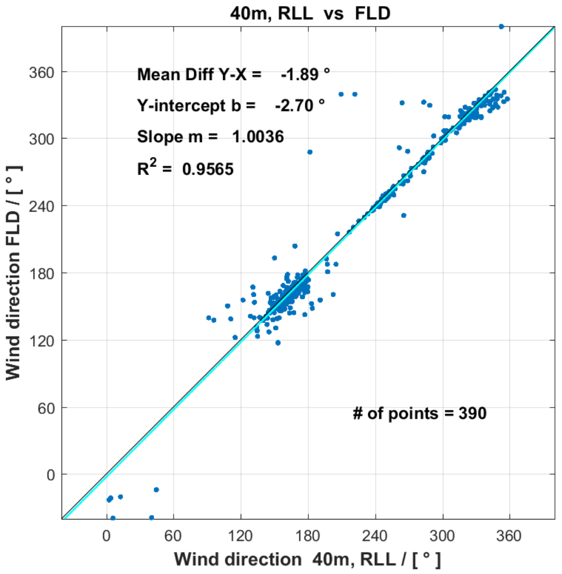


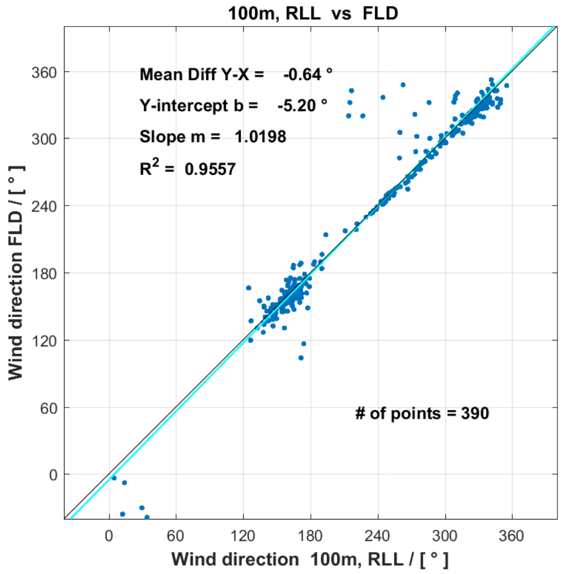


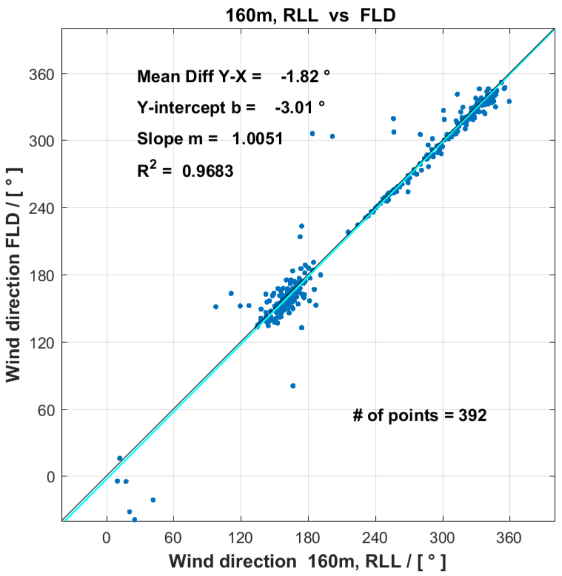


WD correlation plots for three (3) selected comparison heights, i.e. at 40, 100 and 160 m above MSL

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