

FRØYA SEAWATCH WIND LIDAR BUOY WS 156
PRE-DEPLOYMENT VALIDATION

Assessment of the Fugro OCEANOR Seawatch Wind LiDAR Buoy WS 156 Pre- Deployment Validation on Frøya, Norway

Fugro/OCEANOR AS

Report No.: GLGH-4257 13 10378-R-0005, Rev. E

Date: 2016-04-12



IMPORTANT NOTICE AND DISCLAIMER

1. This document is intended for the sole use of the Client as detailed on the front page of this document to whom the document is addressed and who has entered into a written agreement with the DNV GL entity issuing this document ("DNV GL"). To the extent permitted by law, neither DNV GL nor any group company (the "Group") assumes any responsibility whether in contract, tort including without limitation negligence, or otherwise howsoever, to third parties (being persons other than the Client), and no company in the Group other than DNV GL shall be liable for any loss or damage whatsoever suffered by virtue of any act, omission or default (whether arising by negligence or otherwise) by DNV GL, the Group or any of its or their servants, subcontractors or agents. This document must be read in its entirety and is subject to any assumptions and qualifications expressed therein as well as in any other relevant communications in connection with it. This document may contain detailed technical data which is intended for use only by persons possessing requisite expertise in its subject matter.
2. This document is protected by copyright and may only be reproduced and circulated in accordance with the Document Classification and associated conditions stipulated or referred to in this document and/or in DNV GL's written agreement with the Client. No part of this document may be disclosed in any public offering memorandum, prospectus or stock exchange listing, circular or announcement without the express and prior written consent of DNV GL. A Document Classification permitting the Client to redistribute this document shall not thereby imply that DNV GL has any liability to any recipient other than the Client.
3. This document has been produced from information relating to dates and periods referred to in this document. This document does not imply that any information is not subject to change. Except and to the extent that checking or verification of information or data is expressly agreed within the written scope of its services, DNV GL shall not be responsible in any way in connection with erroneous information or data provided to it by the Client or any third party, or for the effects of any such erroneous information or data whether or not contained or referred to in this document.
4. Any wind or energy forecasts estimates or predictions are subject to factors not all of which are within the scope of the probability and uncertainties contained or referred to in this document and nothing in this document guarantees any particular wind speed or energy output.

KEY TO DOCUMENT CLASSIFICATION

Strictly Confidential	:	For disclosure only to named individuals within the Client's organisation.
Private and Confidential	:	For disclosure only to individuals directly concerned with the subject matter of the document within the Client's organisation.
Commercial in Confidence	:	Not to be disclosed outside the Client's organisation.
DNV GL only	:	Not to be disclosed to non-DNV GL staff
Client's Discretion	:	Distribution for information only at the discretion of the Client (subject to the above Important Notice and Disclaimer and the terms of DNV GL's written agreement with the Client).
Published	:	Available for information only to the general public (subject to the above Important Notice and Disclaimer).

Project name:	Frøya Seawatch Wind LiDAR Buoy WS 156 Pre-Deployment Validation	DNV GL / GL Garrad Hassan Deutschland GmbH
Report title:	Assessment of the Fugro OCEANOR Seawatch Wind LiDAR Buoy WS 156 Pre-Deployment Validation on Frøya, Norway	Section Offshore Germany Brooktorkai 18 20457 Hamburg Germany
Customer:	Fugro/OCEANOR AS, Trondheim, Norway	
Contact person:	Arve Berg	Tel: +49 40 36149 8693
Date of issue:	2016-04-12	DE 118 606 038
Project No.:	4257 13 10378	
Report No.:	GLGH-4257 13 10378-R-0005, Rev. E	

Task and objective: 3rd Party Assessment of an Offshore/Nearshore Pre-Deployment Validation of the Fugro/Oceanor SEAWATCH Wind LiDAR Buoy WS 156 at the Island Frøya, Norway

Prepared by:	Verified by:	Approved by:
D.Stein Global Head of Practice Resource Measurements	P. Schwenk Project Engineer	Michael Lange Head of Section Project Engineering

<input type="checkbox"/> Strictly Confidential <input type="checkbox"/> Private and Confidential <input type="checkbox"/> Commercial in Confidence <input type="checkbox"/> DNV GL only <input type="checkbox"/> Client's Discretion <input checked="" type="checkbox"/> Published	Keywords: LiDAR, Floating Lidar Device, Pre-deployment Verification
---	---

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

Rev. No.	Date	Reason for Issue	Prepared by	Verified by	Approved by
A	2016-01-22	Preliminary draft	DeSte	Pasch	
B	2016-01-29	Final issue (electronic only)	DeSte	Pasch	MicLan
C	2016-02-01	Final issue (electronic only)	DeSte	Pasch	MicLan
D	2016-03-09	Issue for public use by RvO	DeSte	Pasch	MicLan
E	2016-04-12	Minor corrections applied	DeSte	Pasch	MicLan

Table of contents

1	INTRODUCTION.....	2
1.1	Clarification Note	3
2	SETUP OF THE SWLB PRE-DEPLOYMENT VALIDATIONS	4
2.1	Positions of Installed SWLB and RLL Units	4
2.2	Settings and Specs of SWLB and RLL Units	5
3	VALIDATION RESULTS.....	6
3.1	Data provision	6
3.2	Meteorological and sea state conditions during the trial	6
3.3	Accuracy	7
3.4	Summary of verification results	9
4	REMARKS AND LIMITATIONS.....	11
5	CONCLUSIONS ON SWL BUOY TECHNOLOGY IN CONTEXT OF COMMERCIAL ROADMAP	12
6	REFERENCES.....	13
APPENDIX A – APPLIED KEY PERFORMANCE INDICATORS AND ACCEPTANCE CRITERIA FOR FLD PRE-DEPLOYMENT VALIDATION		14
APPENDIX B – CAMPAIGN METEOROLOGICAL CONDITIONS, TIME SERIES AND WS/WD CORRELATION PLOTS		16
APPENDIX C – WAVES AND TIDES		20

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

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 a pre-deployment validation campaign and to provide a validation report for a SEAWATCH Wind LIDAR Buoy (SWLB) unit with the serial number WS 156 moored next to the Island Frøya in the Norwegian Sea.

The pre-deployment validation of this already “Roadmap-Pre-Commercial” staged Floating Lidar Device (FLD) [1] was performed over a period of 90 days against a fixed/land based industry accepted Lidar (Reference Land Lidar or RLL), that was used as the only validation reference. 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 started 2015-07-01 with the deployment of the SWLB at a position South of Frøya in 75 m water depth, see Figure 1 “Lidar buoy”. The mooring point is about 820 m to the Southwest of the shore of a place called Stabben and 960 m from the “Land Lidar” at Stabben. The campaign was finished by the recovery of the SWLB on 2015-09-29.

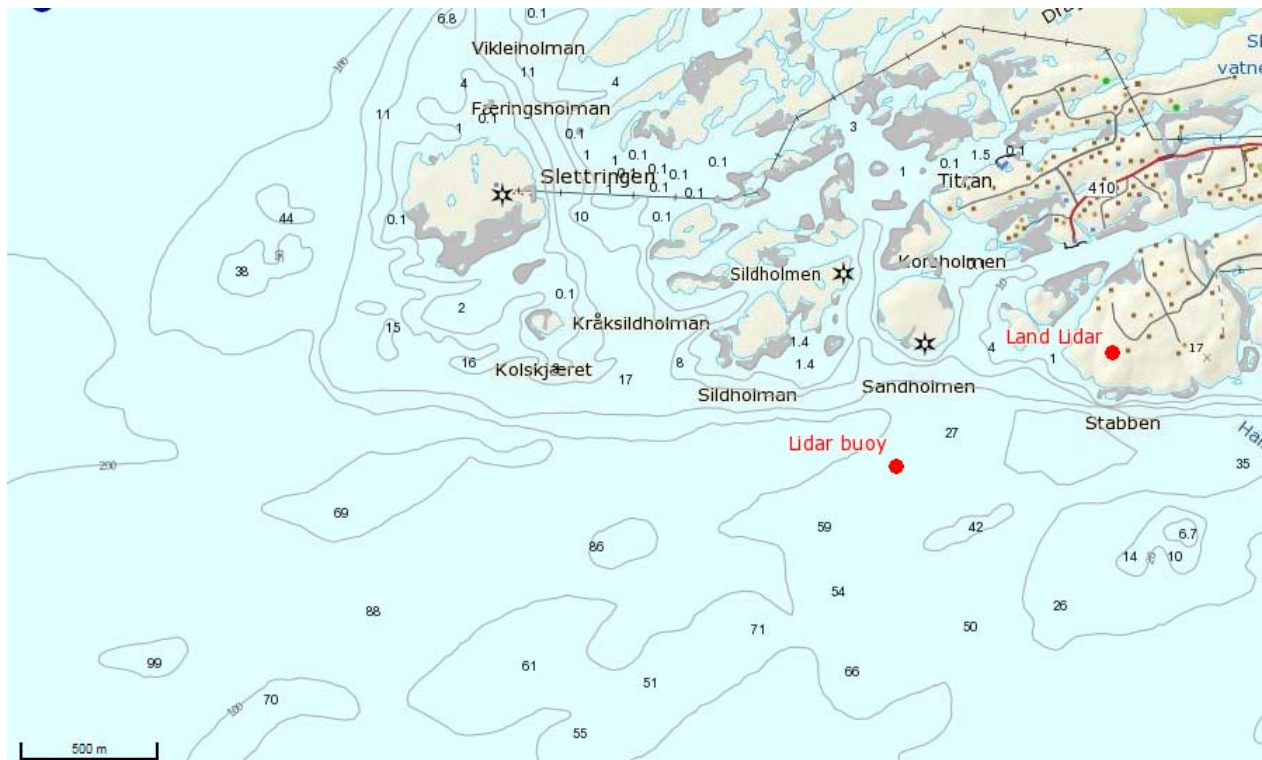


Figure 1: Positions of SWLB (Lidar buoy) and RLL (Land Lidar) near or at the Island Frøya /Stabben.

This report is aimed in documenting the results with respect to the pre-deployment validation trial of the Fugro OCEANOR Seawatch Wind Lidar Buoy (SWLB) with S/N WS 156 against a Reference Land Lidar (RLL) of type ZephIR with the S/N Z495 at the FO test site near and on the Norwegian Island Frøya at a place call Stabben, in the Norwegian Sea.

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 156 employing a ZephIR Lidar with the S/N Z501) 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.

DNV GL understands that the tested SWLB Floating Lidar unit is planned to be deployed in the Dutch offshore wind planning area Borssele in the Dutch North Sea sector, and that this campaign serves as the according pre-deployment validation.

DNV GL understands and assumes that there is agreement between FO and their client *Rijksdienst voor Ondernemend Nederland* (RvO) that a pre-deployment validation of an already "Roadmap-Pre-Commercial" staged FLD against a fixed/land based industry accepted Lidar to be used as the only validation reference (Reference Land Lidar, 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 ZephIR site in Pershore, UK, independently validated by DNV GL [4]
- The ZephIR 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 ZephIR site in Pershore, UK [5]
- The suitability of Frøya test site, i.e. given comparativeness of wind conditions between locations of Reference Land Lidar (RLL) and SWBL
- 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 (Borssele in this case) is shown.

All conclusions on the capabilities of the FO 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 FLD validations. Subject to further evidence based on data from substantially longer verification trials at this site, but by

1. acknowledging the information provided by FO to DNV GL on the side upfront,
2. seeing the generally consistent resemblance between SWLB and RLL over the full height range in this report and
3. from the inspection itself,

DNV GL considers this test site suitable for pre-deployment verifications of Floating Lidar Devices (FLD).

2.1 Positions of Installed SWLB and RLL Units

Position of ZephIR Reference Land Lidar (RLL), 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 63° 39' 46.60" N, 008° 18' 35.50" E.

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

- The SWLB is deployed at a position of 63° 39' 29.40" N, 008° 17' 39.10" E.
- It is moored in 75 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 820 m from the shore of a place called Stabben and about 960 m to the South West of the RLL position.

These positions were confirmed during a site visit and RLL inspection by DNV GL, on 2015-03-25 [3].

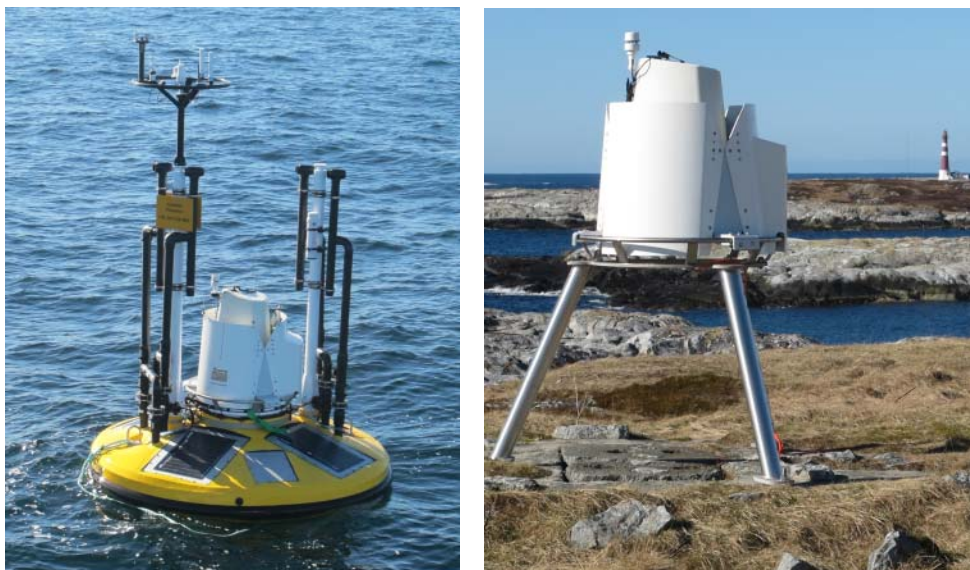


Figure 2: Seawatch Wind Lidar Buoy (left) and Reference Land Lidar as installed near/at Frøya test site.

2.2 Settings and Specs of SWLB and RLL Units

SWLB Floating Lidar:

- SWLB S/N WS 156
- ZephIR S/N Z501
- Height settings 200, 180, 160, 140, 120, 100, 80, 60, 41 m relative to actual sea level

Reference Land Lidar:

- ZephIR S/N Z495
- Height settings 200, 180, 160, 140, 120, 100, 80, 60, 40 m above mean sea level

These specs and height settings confirmed from

- original ZephIR product data (ZPH-files) provided by FO, and
- during the site visit and RLL inspection by DNV GL, on March 25th 2015 [3].

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

	Reference Land Lidar (RLL)		Floating Lidar (SWLB)	
Window Height above sea level (SL)	14		2	
Height level #	True Height above MSL [m]	Configured Height [m]	True Height above SL [m]	Configured Height [m]
0			4	Gill Sonic
1	30	16	30	28
2	41	27	40	38
3	52	not configurable	40	not configurable
4	60	46	60	58
5	80	66	80	78
6	100	86	100	98
7	120	106	120	118
8	140	126	140	138
9	160	146	160	158
10	180	166	180	178
11	200	186	200	198

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 as mentioned in Table 1.

All data collected from the deployment 2015-07-01 of SWLB until its decommissioning on 2015-09-29 were taken into account in the overall data processing scheme, regardless of the environmental conditions.

3 VALIDATION RESULTS

For the pre-deployment validation of FO's SWLB against the RLL data from the employed FLD ZephIR 300 LiDAR with the serial number Z501 and from the RLL ZephIR with the serial number Z495 were provided by FO for a campaign period lasting 2015-07-01 to 2015-09-29, yielding a duration of 90 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 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 ZephIR 300 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 average wind speeds at the RLL of up to 17.5 m/s at the lowest comparison level (40 m) and 22.4 m/s at the upper most level (200 m) – see Table 2. The air temperatures covered during the campaign at the RLL location and on the SWLB buoy range from +7°C to +27°C, related time series are displayed in Appendix B.

The significant wave heights observed during the trial period at Frøya were in the range of above 0.5 to 2.5 m, with 2.7 % of the observations above 1.5 m. The experienced maximum wave heights cover a range up to 3.5 m. Compare Appendix C for wave statistics as provided by FO. The wave measurements were recorded by the SWLB under trial itself using a 30 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 –1.5 and +1.5 m 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
Level / [m]	WS [m/s]	
40	17,51	18,52
60	18,25	19,51
80	19,45	19,34
100	19,95	19,45
120	20,44	21,04
140	20,92	21,97
160	21,70	22,09
180	22,07	21,74
200	22,38	22,09

3.3 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.

A wind direction sector filtering needed to be applied for a North-easterly to South-easterly sector due to a risk of wind flow deflections potentially caused by topographic features from the nearby Island Frøya and the Islands to the East of the test site. I.e. wind speed and direction data from a 100° wide sector between 40° and 140° were omitted from the comparison analysis.

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

- Minimum number of 40 data points required in each 1 m/s bin wide reference wind speed bin centred between 2.5 m/s and 11.5 m/s, i.e. covering a range between 2 and 12 m/s.
- Minimum number of 40 data points required in each 2 m/s bin wide reference wind speed bin centred on 13 m/s and 15 m/s, i.e. covering a range 12 m/s to 16 m/s.
- 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 is not mandatory.

For the period considered in this report, the Roadmap related WS bin wise data completeness – to include more than 40 values per bin – was achieved for all WS bins up to 16 m/s at all treated comparison heights, and up to 18 m/s with the exception in the WS bin centred at 17 m/s at the 40 m level. All other bins above and below this bin include more than 40 values, compare Table 3.

Table 3: Wind speed data coverage per WS bin. Bins including at least 40 values marked in green

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
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
Level / [m]	RLL number of 10 min data entries per WS bin - AFTER filtering for data to be used for regression analysis															
40	811	886	900	889	708	589	381	377	357	304	412	198	24	-	-	-
60	747	863	883	836	720	654	450	356	384	324	435	259	47	1	-	-
80	752	828	847	815	700	662	510	370	372	357	476	278	62	7	-	-
100	792	756	831	808	700	583	562	387	382	374	507	301	69	12	-	-
120	774	729	821	773	674	581	558	428	377	363	552	307	83	16	1	-
140	763	661	830	724	656	563	570	453	367	384	542	334	92	29	1	-
160	685	675	794	718	627	576	524	482	362	398	563	366	93	28	6	-
180	662	652	776	712	653	565	540	476	343	406	592	389	107	27	7	1
200	655	623	766	689	671	563	528	476	368	398	604	401	116	28	9	1

3.3.2 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 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 for the data period considered here KPIs for slope at heights between 60 and 200 m fall within the best practice acceptance criterion [$0.98 > X_{MWS} > 1.02$] as given in [1], at 40 m this KPI is within the minimum acceptance criterion [$0.97 > X_{MWS} > 1.03$]. With regards to the Coefficient of Determination (R^2_{mws}) the best practice 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 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	6836	1,025	0,980	6,70	6,90	0,20	3,0%
60	6959	1,015	0,984	6,93	7,05	0,12	1,8%
80	7036	1,010	0,986	7,09	7,17	0,08	1,1%
100	7064	1,008	0,987	7,21	7,28	0,07	1,0%
120	7037	1,007	0,987	7,32	7,38	0,06	0,8%
140	6969	1,005	0,987	7,44	7,48	0,04	0,5%
160	6897	1,003	0,985	7,58	7,62	0,03	0,5%
180	6908	1,001	0,985	7,68	7,71	0,02	0,3%
200	6896	0,999	0,981	7,77	7,78	0,02	0,2%

Legend	
KPI	failed
KPI	passed minimum
KPI	passed best practice

3.3.3 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 presented 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. Most of the KPI values for R^2_{mwd} fall within the best practice acceptance criteria. All other KPI values for OFF_{mwd} and M_{mwd} meet the minimum criteria, except for the slope at the level of 200 m. As this is just outside the acceptance range and as it is at the upper most level, only, this deviation is considered insignificant. Plots for WD regression results selected for a few heights can be found in Appendix C.

Table 5: 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	6835	0,958	0,987	-7,09
60	6956	0,959	0,987	-7,04
80	7035	0,959	0,986	-6,88
100	7061	0,958	0,987	-6,82
120	7035	0,955	0,985	-6,79
140	6965	0,955	0,983	-7,14
160	6891	0,951	0,981	-7,06
180	6905	0,950	0,978	-6,67
200	6894	0,948	0,978	-6,37

Legend	
KPI	failed
KPI	passed minimum
KPI	passed best practice

3.4 Summary of verification results

3.4.1 Campaign Duration

The campaign duration with almost 3 months is considered rather long, compared to a typically expected duration of 6 to 8 weeks. However, due to the summer season this duration was needed to achieve the required data completeness in useable WS bins for data analysis and results to be compliant to the Roadmap in terms of significance of SWLB wind data accuracy results.

3.4.2 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 KPIs "Mean Wind Speed – Slope" and "Mean Wind Speed – Coefficient of Determination" were passed with a minor exception at 40 m.

For wind direction Best Practice criteria or Minimum criteria were passed at all comparison heights for the KPIs "Mean Wind Direction – Slope", "Mean Wind Direction – Coefficient of Determination" and "Mean Wind Direction – Offset" (except for the slope showing a minor deviation at 40 m), indicating the SWLB's capability of reproducing fixed Lidar wind directions at a good level of accuracy.

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 after 90 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: [0.999 to 1.015] Passed at compared heights 60 to 200 m	0.97 – 1.03 Results: [1.025] Passed at compared height 40 m
R^2_{mws}	Mean Wind Speed – Coefficient of Determination Assessed for wind speed range [all above 2 m/s]	>0.98 Results: [0.980 to 0.987] Passed at all compared heights	>0.97
M_{mwd}	Mean Wind Direction – Slope Assessed for wind speed range [all above 2 m/s] (WD filtering/clipping applied for Easterly sector from 40° to 140° due to potential wind flow deflection by land masses / islands)	0.97 – 1.03	0.95 – 1.05 Results: [0.950 to 0.959] Passed at compared heights 60 to 200 m [0.948] Just missed at 200 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°	< 10° Results: [-7.14 to -6.37] Passed at all compared heights
R^2_{mwd}	Mean Wind Direction – Coefficient of Determination (same as for M_{mwd})	> 0.97 Results: [0.978 to 0.987] Passed at all compared heights	> 0.95

4 REMARKS AND LIMITATIONS

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

- Both data sets, (a) the one for the Reference Land Lidar (RLL) and (b) the one for the SWLB were provided to DNV GL by Fugro/OCEANOR (FO), i.e. they've had full access to the data from the tested device and from the reference data.
- In the WS regressions for the treated heights between 40 m and 200 m a decrease (improvement) of the slope towards unity with increasing height can be detected. This indicates a slight ground friction effect on the RLL data which tends to decrease with height. However, all "forced" (through the origin) regression slopes are within the Roadmap allowance, i.e. below 1.03. And the yielded coefficients of determination are excellent. They are indicating that non-synchronicity at the mentioned distance between SWLB and RLL of about 940 m is no issue.
- 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 CONCLUSIONS ON SWL BUOY TECHNOLOGY IN CONTEXT OF COMMERCIAL ROADMAP

An evaluation of the Fugro/OCEAN 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 in terms of 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 FO SWBL unit with the S/N 156 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. significant wave heights of > 2 m (and > 3 m for maximum wave height) were recorded by the Buoy. The Lidar wind speeds recorded at Frøya covered a range of up to 17.5 m/s at 40 m and 22.4 m/s at 200 m.

The assessments of the Roadmap KPIs for the complete data set (from 2015-07-01 until 2015-09-29) show that all FLD-Roadmap Acceptance Criteria are met at all relevant heights between 40 and 200 m above MSL for wind speed and – with a minor deviation – as well for wind direction related Key Performance Indicators (KPI), passing at least the minimum Roadmap Acceptance Criteria but mostly the best practice criteria.

FLD Roadmap related WS bin wise data completeness was achieved for all WS bins up to 16 m/s at all treated comparison heights, and up to 18 m/s with a marginal deviation at 40 m.

6 REFERENCES

- [1] 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.
- [3] DNV GL Report GLGH-4275 13 10378 271-T-0003-A, Draft, "Technical note for inspection of Reference Land Lidar at Frøya", May 2015.
- [4] DNV GL Report GLGH-4257 13 11068 267-R-0021-A, "ZP495 Independent analysis and reporting of ZephIR Lidar performance verification executed by ZephIR Ltd. At their test site and reference mast in Pershore, UK", dated 2015-03-27
- [5] ZephIR internal report "Functional test & full performance verification of ZephIR 300 Lidar ZP501" dated 2015-03-31.

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

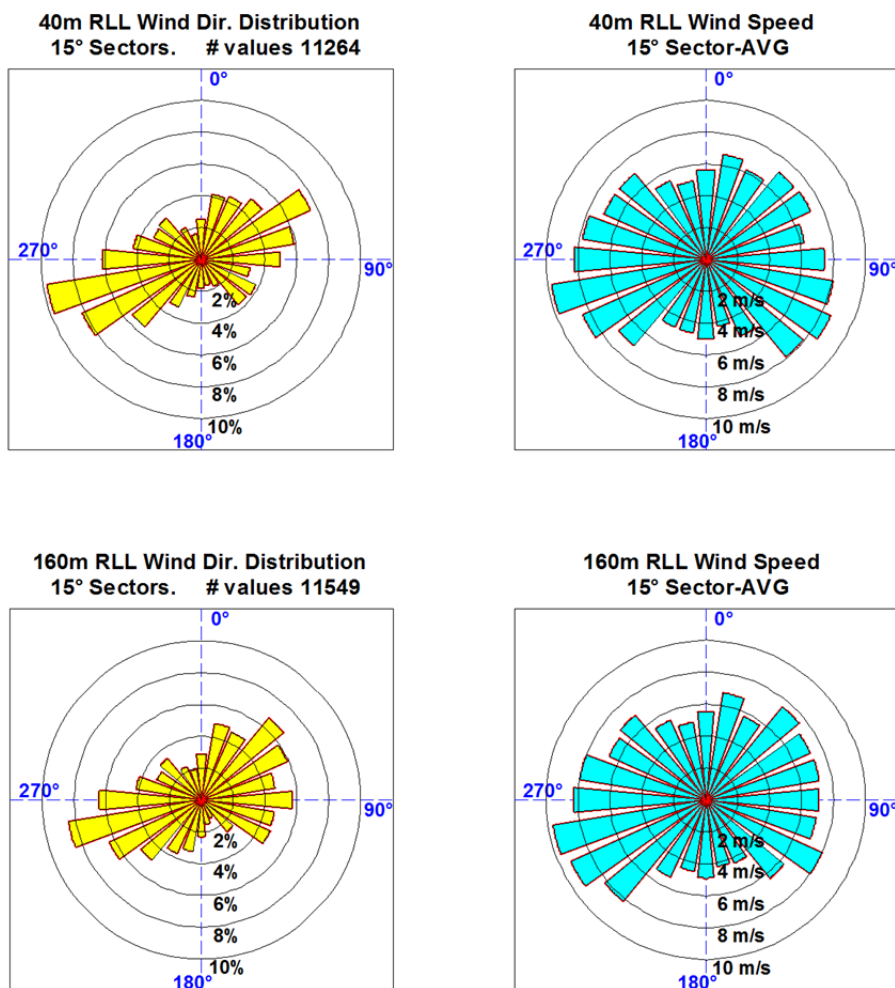
In addition, Acceptance Criteria in the form of “best practise” and “minimum” allowable tolerances have been imposed on slope and offset values as well as on coefficient of determination returned from each reference height for KPIs related to the primary parameters of interest; wind speed and wind direction.

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) 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

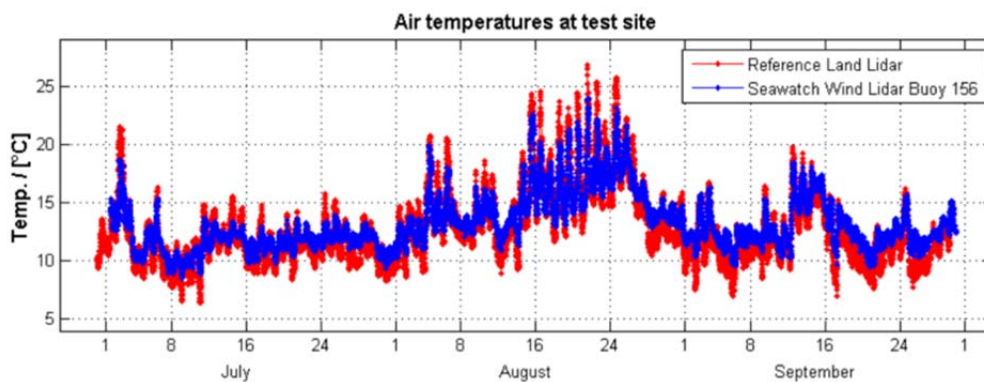
KPI	Definition / Rationale	Acceptance Criteria	
		Best Practice	Minimum
M_{mwd}	Mean Wind Direction – Slope Slope returned from a two-variant regression. A tolerance is imposed on the Slope value. Analysis shall be applied to <ul style="list-style-type: none"> a) all wind directions b) all wind speeds 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

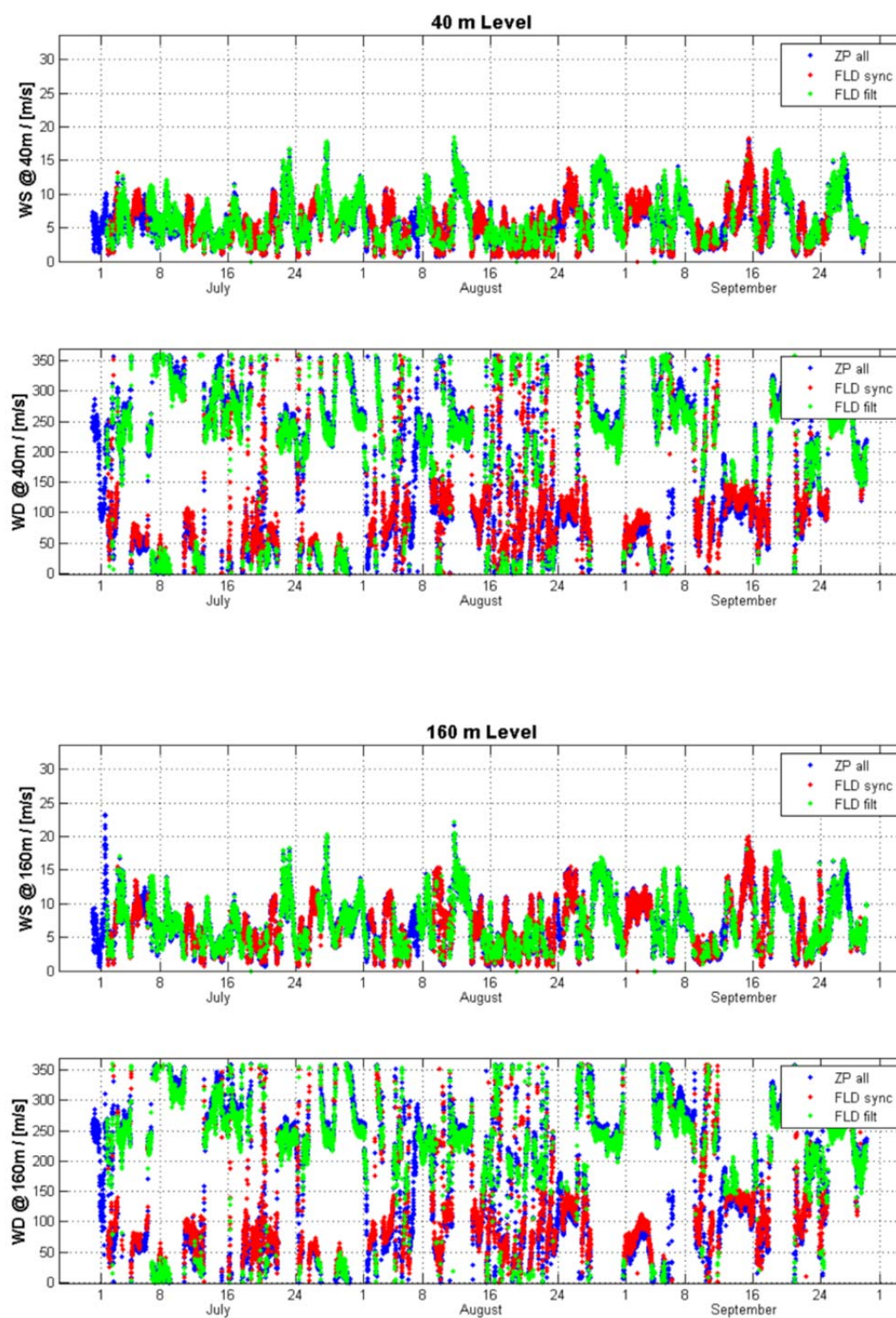
Polar plots of wind directions probability and wind speed for 40 m and 160 m comparison heights:



Time series of air temperature at RLL location and on SWLB:

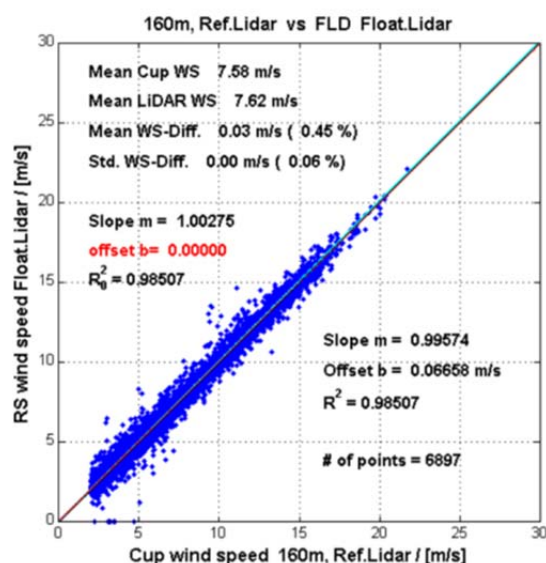
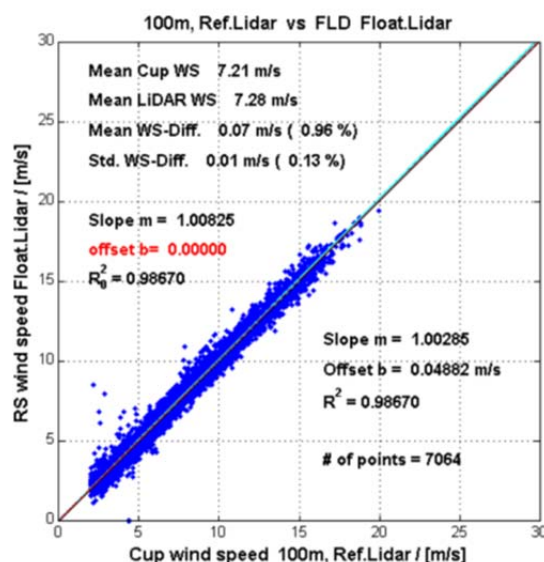
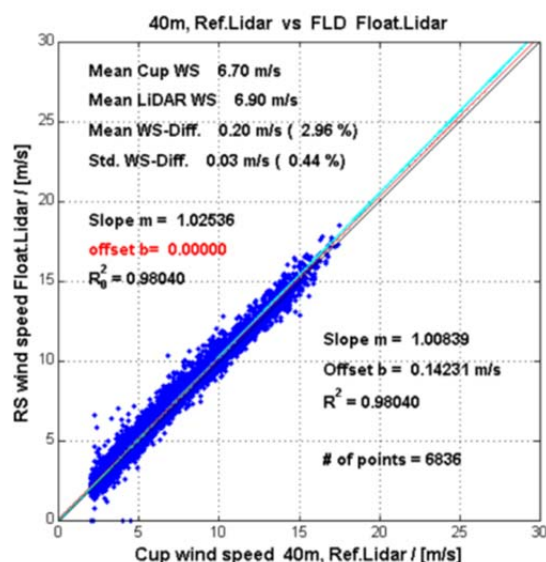


Wind speed and wind directions time series for 40 m and 160 m comparison heights:



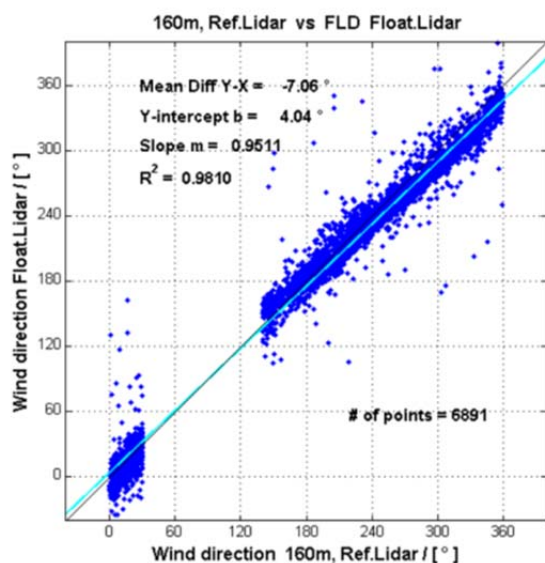
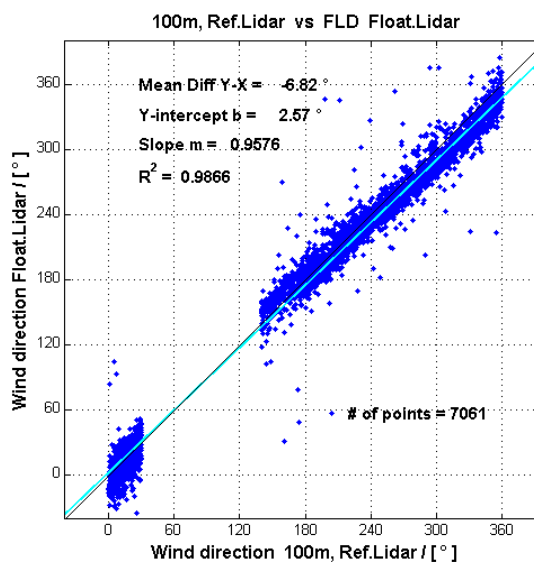
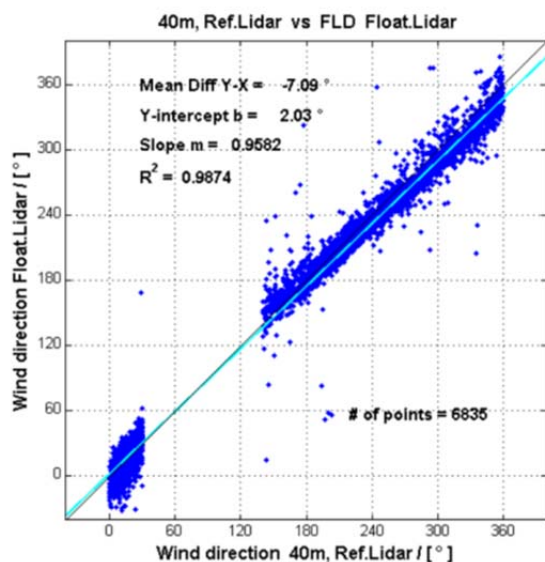
WS regression plots for four (4) selected comparison heights, i.e. at 40, 100 and 160 m above MSL

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 four (4) 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.



APPENDIX C – WAVES AND TIDES

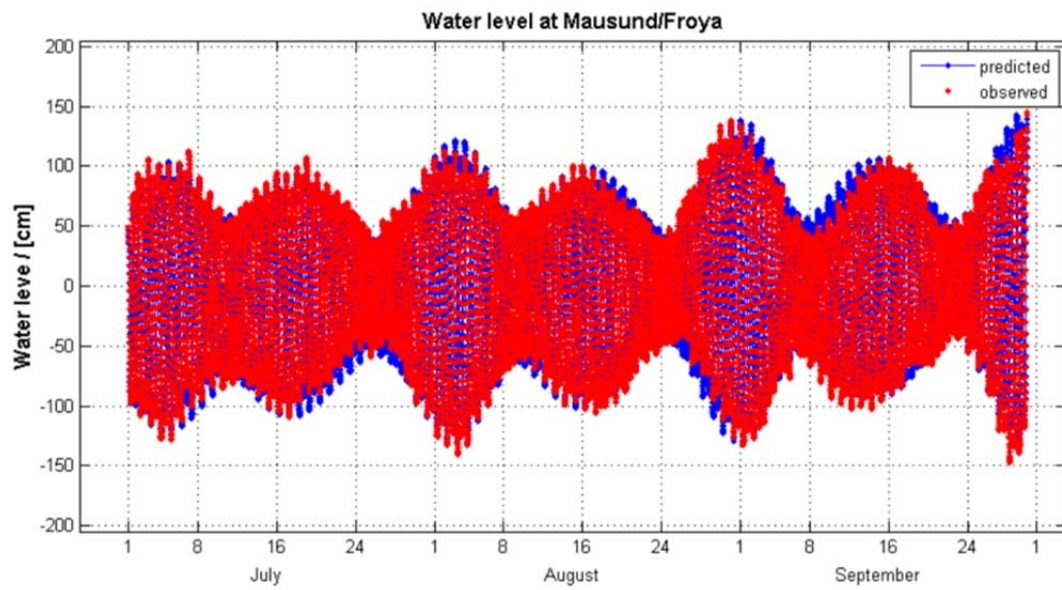
Mean wave period and significant wave height:

Tm02 Mean wave period (Tm02) (s) Slettringen, Wavescan buoy														
Hm0 Significant wave height (m) Slettringen, Wavescan buoy														
Measuring depth : 0.00 m														
Water depth : 75.00 m														
Sampling interval:														
Period : 2015.07.01 16:00 - 2015.09.29 08:19														
Tm02 (s)	2	3	4	5	6	7	8	9	10	11	12 >=	SUM	% OF	
Hm0 (m)	3	4	5	6	7	8	9	10	11	12	13	13	TOTAL	
0.0 - 0.5	364	1176	1605	1716	1001	264	30	1				6157	47,9	
0.5 - 1.0	7	744	1256	885	747	678	316	44				4677	36,4	
1.0 - 1.5		118	855	206	83	184	136	87	2			1671	13	
1.5 - 2.0			178	71	7	68	24					348	2,7	
2.0 - 2.5				1								1	0	
>= 2.5												0	0	
SUM	371	2038	3894	2879	1838	1194	506	132	2	0	0	12854	100	
% OF TOT/	2,9	15,9	30,3	22,4	14,3	9,3	3,9	1	0	0	0	0	100	
SUM ACCI	371	2409	6303	9182	11020	12214	12720	12852	12854	12854	12854	12854		
CUM. PRO	0,0289	0,1874	0,4903	0,7143	0,8573	0,9501	0,9895	0,9998	0,9999	0,9999	0,9999	0,9999	0,99992	
MIN. VALL	0,16	0,08	0	0,08	0,08	0,23	0,23	0,31	1,17			0		
AVE. VALL	0,3	0,49	0,71	0,5	0,52	0,77	0,89	1,07	1,29			0,61		
MAX. VAL	0,55	1,33	1,95	2,03	1,88	1,95	1,95	1,41	1,41			2,03		
STD. DEV.	0,09	0,26	0,42	0,34	0,23	0,36	0,3	0,22	0,12			0,37		

Highest wave period and maximum wave height:

THmax Period of highest wave (s) Slettringen, Wavescan buoy														
Hmax Maximum wave height (m) Slettringen, Wavescan buoy														
Measuring depth : 0.00 m														
Water depth : 75.00 m														
Sampling interval:														
Period : 2015.07.01 16:00 - 2015.09.29 08:19														
THmax (s)	2	3	4	5	6	7	8	9	10	11	12 >=	SUM	% OF	
Hmax (m)	3	4	5	6	7	8	9	10	11	12	13	13	TOTAL	
0.0 - 0.5	7	12	21	45	146	239	254	129	72	54	67	353	1399	14
0.5 - 1.0	5	89	220	382	621	1015	1076	504	232	90	62	138	4434	44,5
1.0 - 1.5		14	287	293	313	322	338	306	219	94	20	21	2227	22,3
1.5 - 2.0			199	283	245	151	101	102	107	86	33	14	1321	13,2
2.0 - 2.5			34	137	74	49	40	45	31	13	2	3	428	4,3
2.5 - 3.0			9	51	35	19	13	10	12	3			152	1,5
3.0 - 3.5				5	2	1	2	1					11	0,1
>= 3.5													0	0
SUM	12	115	770	1196	1436	1796	1824	1097	673	340	184	529	9972	100
% OF TOT/	0,1	1,2	7,7	12	14,4	18	18,3	11	6,7	3,4	1,8	5,3	100	
SUM ACCI	12	127	897	2093	3529	5325	7149	8246	8919	9259	9443	9972	9972	
CUM. PRO	0,0012	0,0127	0,0899	0,2099	0,3539	0,5339	0,7168	0,8268	0,8943	0,9284	0,9469	0,9999	0,9999	
MIN. VALL	0,35	0,35	0,35	0,35	0,35	0,35	0,35	0,35	0,35	0,35	0,35	0,35	0	
AVE. VALL	0,55	0,77	1,27	1,36	1,12	0,93	0,89	1,02	1,13	1,16	0,87	0,57	1,04	
MAX. VAL	0,82	1,41	2,7	3,16	3,16	3,05	3,16	3,16	2,81	2,7	2,34	2,46	3,16	
STD. DEV.	0,13	0,19	0,45	0,61	0,55	0,46	0,42	0,48	0,51	0,55	0,5	0,3	0,52	

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



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.