BUOY 120

Independent performance verification of Floating Lidar Buoy 120 at Martha's Vineyard Coastal Observatory

Ocean Tech Services, LLC

Report No.: 10161669-R-01, Rev. C
Date 16 June 2020

IMPORTANT NOTICE AND DISCLAIMER

1. This document is intended for the sole use of the Customer 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 Customer), 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 Customer. 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 Customer to redistribute this document shall not thereby imply that DNV GL has any liability to any recipient other than the Customer.

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 Customer 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 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 energy output, including factors such as wind speed or irradiance.

KEY TO DOCUMENT CLASSIFICATION

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

Project name:	Buoy 120	DNV GL – Energy
Report title:	Independent performance verification of Floating Lidar Buoy 120 at Martha's Vineyard Coastal Observatory	DNV GL Energy USA, Inc. 1560 Wilson Blvd. Suite 800 Arlington, VA 22209
Customer:	Ocean Tech Services, LLC 20 Jonathan Bourne Drive Pocasset, MA 02559 USA	
Contact person:	Ben Riker	
Date of issue:	16 June 2020	
Project No.:	10161669	
Report No.:	10161669-R-01, Rev. C	

Task and objective:

Independent performance verification of Floating Lidar Buoy 120 at Martha's Vineyard Coastal Observatory

Prepared by:	Verified by:	Approved by:
Reesa Dexter Technical Lead, Turbine Testing	Bastian Schmidt Team Leader, Remote Sensing Loads & Power Performance & Wind Resource	Alana Duerr Director, Offshore Wind North America

☐ Strictly Confidential
☐ Private and Confidential
☐ Commercial in Confidence
☐ DNV GL only
☒ Customer's Discretion
☐ Published

Rev. No.	Date	Reason for Issue	Prepared by	Verified by	Approved by
A	11 May 2020	Draft report (electronic version, only)	Reesa Dexter	Bastian Schmidt	Alana Duerr
B	26 May 2020	Typographical edits	Reesa Dexter	Bastian Schmidt	Alana Duerr
C	16 June 2020	Typographical edits	Reesa Dexter	Bastian Schmidt	Alana Duerr

Table of contents

Appendices

List of tables

List of figures

DNV GL Performance Verification Summary

General measurement configuration	
Associated report	10161669-R-01, Issue C
Customer	Ocean Tech Services, LLC
DNV GL entity	DNV GL Energy USA, Inc.
Location	Martha's Vineyard Coastal Observatory
Device make and model	AXYS Flidar WindSentinel 6M
Measurement heights above mean sea level [m]	202, 182, 162, 142, 122, 102, 92, 82, 72, 62, 52, 42
Measurement start [EST]	21 February 2020 00:00
Measurement end [EST]	17 April 2020 00:00
Verification standard and/or criteria	OWA roadmap and IEC 61400-12-1 Ed. 2 (2017)
Deviation from above standard	none
Special filters	The verification is limited to turbulence intensities ≤0.15 from the top mounted cup anemometer on the reference mast. This limitation is due to filtering required during the reference lidar verification.

Buoy 120 Verification results summary against reference lidar											
	KPI OWA Acceptance Criteria [1]	**Verification Height [m]**									
		202	**182**	**162**	**142**	**122**	**102**	**92**	**82**	**62**	**52**
OWA database completion	See Section 3.1 [2]	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
IEC database completion	See Section 3.2 [2]	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
System availability [%]	-	100									
Concurrent availability for verification [%]	-	64.8	71.9	78.4	84.0	86.9	87.2	86.4	85.7	84.8	84.4
Wind speed correlation coefficient, R^2 [3]	$R^2_{mw} > 0.98$	0.998	0.997	0.997	0.997	0.997	0.997	0.997	0.996	0.996	0.996
Wind speed correlation slope, m [3]	$0.98 \geq X_{mws} \leq 1.02$	0.993	0.991	0.991	0.991	0.991	0.990	0.991	0.992	0.993	0.984
Wind direction correlation coefficient, R^2 [3]	$R^2_{mwd} > 0.97$	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Wind direction slope, m [3]	$0.98 \geq M_{mwd} \leq 1.02$	1.002	1.001	1.001	1.001	1.001	1.001	1.000	1.000	1.000	1.000
Wind direction Y-intercept, b [°] [3]	$OFF_{mwd} < \pm 5.0$	1.9	2.0	2.0	2.0	1.9	1.9	1.9	1.9	1.9	1.7
IEC uncertainty, V_{RSD} (K=1) [%]	See Section 6.1 [2]	2.99 to 4.44	2.99 to 4.39	3.03 to 4.44	3.00 to 4.37	2.84 to 3.56	2.54 to 3.54	2.44 to 3.45	2.38 to 3.43	2.46 to 3.58	2.69 to 3.58
Verification concerns	Except for the 52 m comparison, the floating lidar measured heights 2.8 m above the reference lidar measurement heights. Ideally measurements should be made at the same height. However, given the low wind shear this difference is within an acceptable limit for comparison.										
Device recommendation	The Buoy 120 is able to reproduce wind speeds and wind directions at an accurate and acceptable level. However, this conclusion is limited to the environmental conditions observed during the verificaiton. DNV GL considers that the Buoy 120 can be used for formal wind potential and long-term wind resource assessments if the aforemention limitation is considered.										

[1] Defined in Appendix B of 10161669-R-01-C
[2] 10161669-R-01-C
[3] All wind speeds greater than 2 m/s.

1 INTRODUCTION

Ocean Tech Services, LLC (OTS) retained DNV GL Energy USA, Inc. (DNV GL), to complete a pre-deployment verification of an AXYS Flidar WindSentinel (Buoy 120) moored in the Atlantic Ocean at the Martha's Vineyard Coastal Observatory (MVCO) operated by Woods Hole Oceanographic Institution (WHOI) between 2020-02-21 and 2020-04-17.

This verification was performed against a fixed industry accepted lidar (reference lidar WLS7-436). Wind speed and wind direction comparisons are performed using the method provided in the Roadmap towards Commercial Acceptance [1] against corresponding Key Performance Indicators (KPI) and Acceptance Criteria (AC; see APPENDIX A).

DNV GL is accredited according to ISO 17025 for measurements on wind turbines and for wind resource measurements, energy assessments, and lidar verifications. DNV GL is also a full member of the network of measurement institutes in Europe, MEASNET, and in the FGW (Fördergesellschaft Windenergie und anderer Erneuerbaren Energien).

2 SITE INFORMATION

The following section decribes the at the Martha's Vineyard Coastal Observatory (MVCO) test location and verification set-up.

Coordinates for the measurement site is provided in Table 2-1 and the locations of Buoy 120 during verification is provide in Figure 2-2.

Table 2-1 MVCO and test site coordinates (WGS84, UTM Zone 51R)

ID	Easting [m]	Northing [m]	Elevation above mean sea level [m]	Distance to verification mast [m] (orientation [° true north])	Horizontal travel around anchor [m]
Reference Lidar	368885	4576020	12.63	NA	NA
Buoy 120	368730	4576077	2.43	165 (290)	~ 75

Figure 2-1 Map of MVCO

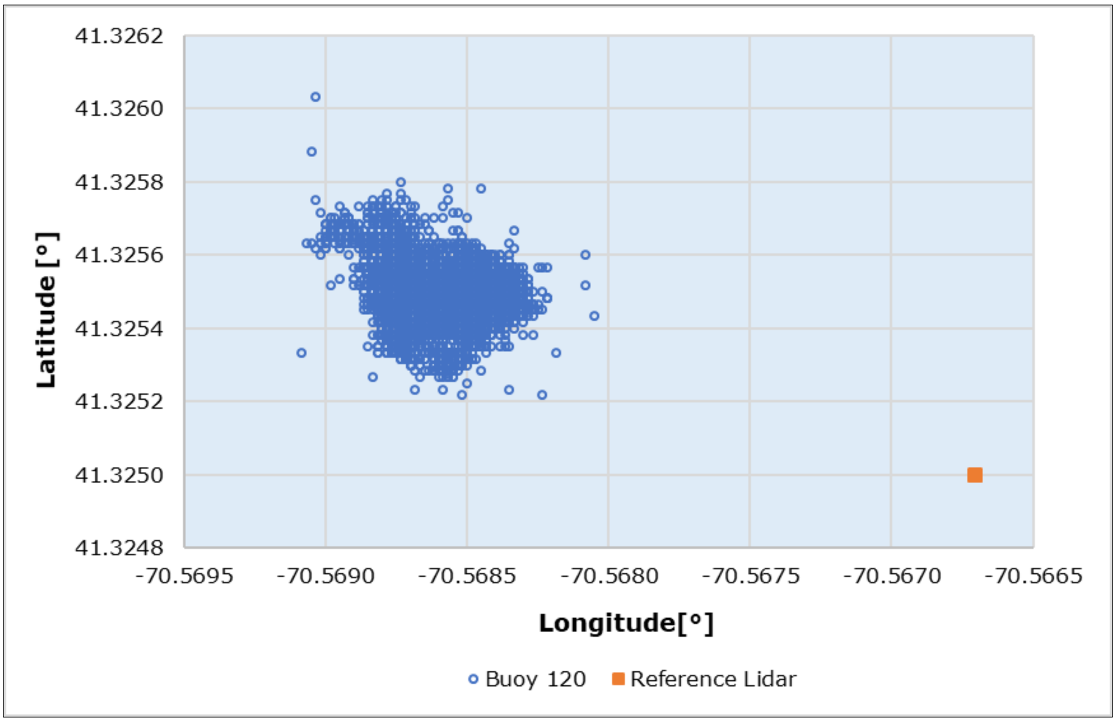


Figure 2-2 Locations of Buoy 120 during verification

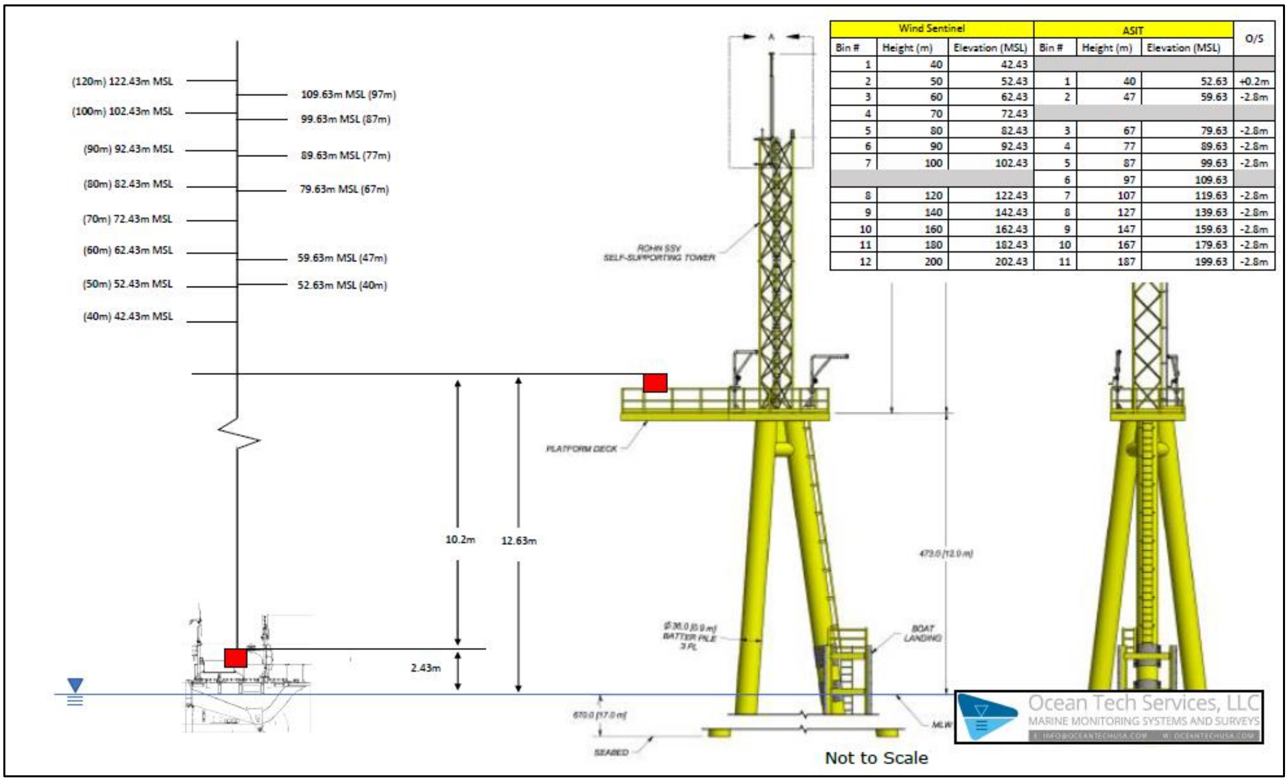
2.1 Site description

MVCO is approximately 3 km south of Marth's Vineyard Island and is operated by WHOI. DNV GL has not visited the MVCO test site and all site information has been provided by the Customer.

2.2 Measuring equipment

This section provides a description of the MVCO equipment and Buoy 120. It is noted that DNV GL witnessed the port site acceptance test for Buoy 120 in New Bedford, MA on 08 January 2020 [1]. DNV GL has not been involved in the data collection or installations. Data from the Buoy 120 were provided through secure file transfer from OTS and the AXYS portal. Data from MVCO Air-Sea Interaction Tower (ASIT) and reference lidar were provided by email from WHOI directly to DNV GL.

Figure 2-3 is schematic diagram of the verification configuration and Figure 2-4 is a photo of the commissioned Buoy 120.



Wind Sentinel			ASIT			O/S
Bin #	Height (m)	Elevation (MSL)	Bin #	Height (m)	Elevation (MSL)	
1	40	42.43				
2	50	52.43	1	40	52.63	+0.2m
3	60	62.43	2	47	59.63	-2.8m
4	70	72.43				
5	80	82.43	3	67	79.63	-2.8m
6	90	92.43	4	77	89.63	-2.8m
7	100	102.43	5	87	99.63	-2.8m
			6	97	109.63	
8	120	122.43	7	107	119.63	-2.8m
9	140	142.43	8	127	139.63	-2.8m
10	160	162.43	9	147	159.63	-2.8m
11	180	182.43	10	167	179.63	-2.8m
12	200	202.43	11	187	199.63	-2.8m

Figure 2-3 Schematic diagram of the verification configuration

(Provided by OTS)

Figure 2-4 MVCO ASIT and floating lidars under test

2.2.1 MVCO ASIT and reference lidar

The reference lidar is a Windcube V2 (WLS7-436) pulsed Doppler Lidar that is specifically designed to measure wind speeds at heights in the lower boundary layer of the atmosphere. During the measurement campaign, WLS7-436 was configured to record wind speed measurements at eleven discrete heights between 52.63 m and 199.63 m above mean sea level (amsl). Lidar WLS7-436 sits on the ASIT mast deck as shown in Figure 2-3. It should be noted that the lidar was not configured to account for the 12.63 m between mean sea level (msl) and the lidar window. This difference was accounted for in the analysis and shown in Table 2-2.

Windcube V2 WLS7-436 was validated between 23 August and 16 September 2019 and was found to reproduce cup anemometer wind speeds and wind directions at an accurate and acceptable level for cup turbulence intensities (TI) less than 0.15 [2]. As a result, data from the primary anemometer at 26 m amsl on the ASIT mast was used to limit TI to less than 0.15.

2.2.2 The AXYS Flidar WindSentinel 6M (Buoy 120)

The AXYS Flidar WindSentinel 6M has achieved the "Roadmap-Pre-Commercial" stage [3] and Buoy 120 includes Windcube lidar WLS866-25[1]. It is noted that lidar WLS866-25 has not undergone a third-party validation prior to this deployment.

During this measurement campaign, the lidar was configured to record wind speed measurements at thirteen discrete heights between 42.43 m and 202.43 m amsl. It should be noted that the lidar was not configured to account for the 2.43 m between msl and the lidar window. This difference was accounted for in the analysis and shown in Table 2-2.

Buoy 120 is moored at approximately 15 m of water depth, and the mooring array allows a horizontal sway around the anchor of about 70 m.

Table 2-2 Lidar and reference mast measurement heights above mean sea level

Device	Buoy 120	Reference lidar
Measurement heights above mean sea level [m] [1]	42.43	-
	52.43	**52.63**
	62.43	**59.63**
	72.43	-
	82.43	**79.63**
	92.43	**89.63**
	102.43	**99.63**
	-	109.63
	122.43	**119.63**
	142.43	**139.63**
	162.43	**159.63**
	182.43	**179.63**
	202.43	**199.63**

[1] Wind speed and wind direction comparison heights are highlighted in bold typeface.

3 LIDAR PERFORMANCE VERIFICATION APPROACH

It is important to note that the verification scope is to evaluate the primary wind data from Buoy 120. Therefore, while Buoy 120 currently features additional measurements, the scope of this document is limited to its primary wind data measurements.

DNV GL understands that the tested Buoy 120 Floating Lidar unit is planned to be deployed after the verification campaign, and the results from this verification will serve as the pre-deployment verification.

[1] The March 2018 OWA report D04 [4] indicates that the AXYS Flidar WindSentinal has independently reported maturity Stage 2 with both a ZephIR 300 and WindCube V2. However, the Stage 2 judgement for the FLiDAR WindSentinel was completed with the ZX Lidar. DNV GL further notes that the FLiDAR WindSentinel has been verified by third parties, such as DNV GL, with both the ZX and Windcube lidar, and there have been a few commercial campaigns for both lidar models.

DNV GL understands and assumes that there is agreement between OTS and their client that a pre-deployment verification of the "Roadmap-Pre-Commercial" staged floating lidar system (FLS) against a fixed industry accepted lidar used as the only verification reference (WLS7-436) is acceptable.

It is further understood that the following requirements have met:

- The Windcube WLS7-436 was successfully and independently verified by DNV GL at the West Texas A&M University (WTAMU) Test Site [2];
- The MVCO ASIT test site is a suitable verification location as indicated in Section 2.1; and
- WLS7-436 installation is compliant with industry best practice, though an installation report was not provided to DNV GL.

All conclusions on the capabilities of Buoy 120 drawn from this pre-deployment verification campaign are valid under sea state and meteorological conditions similar to those experienced during the campaign duration, only.

3.1 OWA Roadmap verification

In accordance with the Roadmap [1], DNV GL has assessed the data coverage of Buoy 120. The following describes the general methods used for this verification:

- All comparisons are based on 10-minute averages from a primary reference that is either a fixed industry accepted Lidar, which has been successfully verified, or a reference mast with MEASNET calibrated cup anemometers, 3D sonic anemometers, and wind vanes and concurrent wind speed and wind direction data from the float lidar under test.
- Only undisturbed free-stream wind data at both the reference and floating lidar under test are used in the analysis.
- The following data coverage requirements are regarded as achievable for a typical test period of four weeks:
  - A minimum of 40, 10-minute valid data points in each 1 m/s wind speed bin from 2 m/s to 12 m/s;
  - A minimum of 40, 10-minute valid data points in each 2 m/s wind speed bin from 13 m/s to 15 m/s;
  - A minimum of 40, 10-minute valid data points in each 2 m/s wind speed bin at 17 m/s and above if available;
- System availability was defined as the ratio between the number of 10-minute data points available for at least one measurement as compared to the number of possible records. The number of possible records excludes power outages and this availability is reported seperately.
- Wind speeds in this lidar performance verification are assessed by means of linear regressions through the origin of the form

  $$y = m\,x + b \text{ and } b=:0$$

  between floating lidar (y-axis) wind speeds and reference (x-axis) wind speeds. Data are compared for all greater than 2 m/s and from 4 m/s to 16 m/s [2].

[2] In consistency with the IEC bin selection criteria, the actual range spans from 3.75 to 16.25 since 4 m/s and 16 m/s are the central points of the corresponding 0.5 m/s wide bins.

- Wind directions were compared quantitatively by two variant regressions solving for the slope, m, and the interception of the best-fit line with the y-axis, b, (according to y = m x + b), as defined in APPENDIX A .

The performance of the lidar under test is based on a number of KPIs and ACs. The evaluation approach is provided in in APPENDIX A .

3.2 IEC Standard, Annex L verification

Verification was completed in accordance with the International Standard IEC 61400-12-1: 2017 (IEC Standard) [5]. This approach is based on a wind speed bin averaged procedure in order to compare the horizontal wind speed measurements acquired by the remote sensing device (RSD) and the reference sensors at the mast or reference lidar. The objective of the IEC approach is to calculate the bin-wise deviation of the two sources and report the associated uncertainty.

The bin averaging procedure was performed using 0.5 m/s wide wind speed bins centred on integers of from 4 to 16 m/s. In order to achieve statistical relevance this IEC approach requires the following:

- A minimum of three (3) 10-minunte values available within each wind speed bin; and
- 180 hours or 1080 10-minute records of valid data

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

1. Reference/anemometer uncertainty
2. Mean deviation of the remote sensor measurements and the reference measurements
3. Standard uncertainty of the measurement of the RSD
4. Mounting uncertainty of the remote sensor at the verification test
5. Uncertainty due to non-homogenous flow

The different uncertainty components are added in quadrature for each wind speed bin. The uncertainty due to non-homogenous flow is assumed to be negligible due to the benign flow conditions at the remote sensing test site and that both devices are lidars. Details on the calculation of the separate uncertainty components are described in APPENDIX E .

3.3 Data filtering

Table 3-1 below summarizes the filters applied to the 10-minute datasets. The lidar data availability and Carrier-to-noise ratio filters are based on manufacture filtering best practices.

Table 3-1 Data filtering

Filter	Criteria for removal		
Wind direction [m/s]	WD < 0	OR	WD > 360
Wind speed [m/s]	WS ≤ 2	OR	WS > 50
Lidar data availability [%]	Data Availability < 80%		
Carrier-to-noise ratio [dB]	CNR < -23	OR	CNR > 18
Turbulence intensity (TI)	Met_Wspd1_winsd_std/Met_Wspd1_winsd_mean> 0.15		

4 METEOROLOGICAL AND SEA STATE CONDITIONS DURING THE VERIFICATION TRIAL

Buoy 120 encountered a wide range of wind conditions during the verification. Table 4-1 shows the maximum 10-minute averaged wind speeds at the reference lidar are between 25.85 m/s at the lowest comparison level (52 m) and 35.87 m/s at the upper most level (202 m). The air temperatures observed by the ASIT mast ranged from -0.1°C to 14.1°C. A time series of the temperature at the ASIT are displayed in APPENDIX D .

The mean wave heights (20-minute averaged) observed by the floating lidar were between 0 m and 3.7 m with 16% of the observations above 1.0 m.

Timeseries plots of the waves observed during the measurement campaign are provided in APPENDIX D .

Table 4-1 Maximum 10-minute average wind speeds

Height [m]	Reference lidar maximum wind speed [m/s]	Buoy 120 lidar maximum wind speed [m/s]
52	25.85	25.16
62	26.34	25.92
82	27.95	27.23
92	28.71	27.89
102	29.41	28.45
122	30.84	29.6
142	32.24	30.71
162	33.52	31.82
182	34.81	32.80
202	35.87	33.72

5 RESULTS OF THE OWA VERIFICATION

5.1 System and data availability

Data for the floating lidar verification were available from 2020-02-21 to 2020-04-17. The floating lidar campaign duration was 56.0 days, which represents 8064 concurrent data points. As indicated by the system availability, there were no maintenance visits (MV) during this verification, there was one unscheduled outage (UO) at the buoy, and DNV GL understands that all data from the floating lidar were transmitted remotely, and the communication uptime (CU) is assumed to be 100%. The OWA roadmap does not define KPIs for MV, OU and CU, but are reflected in the system availability.

After excluding data gaps at the reference mast and lidar shown in Table 5-1, the floating lidar possible availability is reduced to 6876 records. Considering all 10-minute floating lidar records, there were 6875 records available for at least one measurement height, and therefore the floating lidar device has achieved a system availability of 100% (52.75 days) as presented in Table 5-2. This meets the acceptance criterion for system availability (KPI OSA_{CA}) of ≥ 95 %.

Table 5-1 Description of reference lidar and mast data gaps

Excluded periods		
Start	**End**	**Excluded data points**
2020-Feb-25 14:50:00	2020-Mar-04 17:00:00	1166
2020-Mar-07 07:10:00	2020-Mar-07 07:20:00	2
2020-Mar-25 12:30:00	2020-Mar-25 13:00:00	4
2020-Mar-27 20:30:00	2020-Mar-27 20:40:00	2
2020-Apr-02 12:50:00	2020-Apr-02 13:00:00	2
2020-Apr-02 13:30:00	2020-Apr-02 13:40:00	2
2020-Apr-05 01:30:00	2020-Apr-05 01:40:00	2
2020-Apr-08 13:30:00	2020-Apr-08 13:40:00	2
2020-Apr-08 19:50:00	2020-Apr-08 20:00:00	2
2020-Apr-13 23:30:00	2020-Apr-13 23:40:00	2
2020-Apr-14 02:10:00	2020-Apr-14 02:20:00	2
Total excluded data		1188

Table 5-2 Summary of system and data availabilities

	Availability assessment									
Height [m]	**202**	**182**	**162**	**142**	**122**	**102**	**92**	**82**	**62**	**52**
Maximum 10-minute points in period	8064	8064	8064	8064	8064	8064	8064	8064	8064	8064
After accounting power outages	6876	6876	6876	6876	6876	6876	6876	6876	6876	6876
Data present	6875	6875	6875	6875	6875	6875	6875	6875	6875	6875
System availability (KPI OSA_{CA}) [%]	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Total valid 10-minute points in period	5396	5879	6318	6539	6589	6612	6625	6654	6684	6694
Data availability (KPI $OPDA_{CA}$) [%]	78.5	85.5	91.9	95.1	95.8	96.2	96.3	96.8	97.2	97.4
Valid 10-minute points after external filtering	4458	4946	5393	5777	5975	5994	5940	5892	5831	5804
Data availability for comparison [%]	64.8	71.9	78.4	84.0	86.9	87.2	86.4	85.7	84.8	84.4

Figure 5-1 shows the lidar system availability and the data recovery rate for each of the twelve (12) measurement heights. The valid lidar data availability from 42 m to 202 m ranges from 97.4% to 78.5%. Except for 202 m, the acceptance criterion for data availability (KPI $OPDA_{CA}$) of ≥ 85 % has been met successfully for the floating lidar.

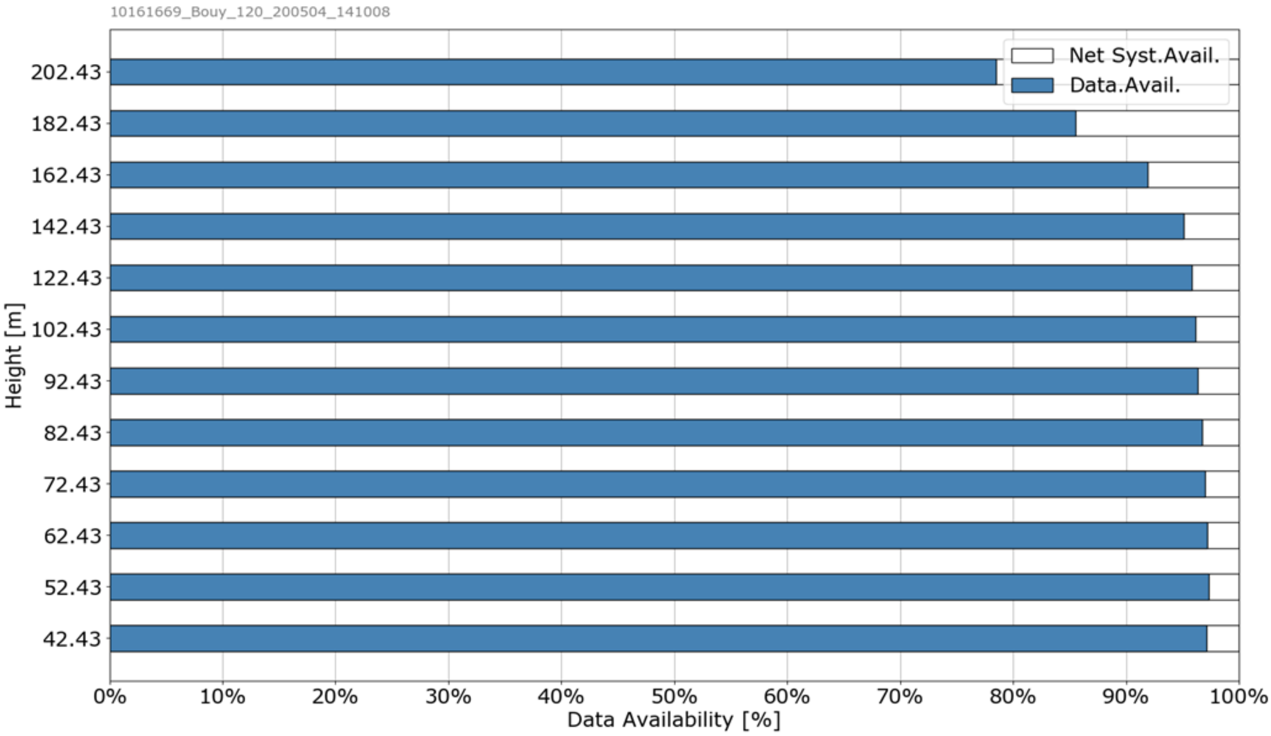


Figure 5-1 Buoy 120 data availability

Data coverage by wind speed bin is presented in

Table 5-3. As outlined in Section 3.1, the database requirements for all wind speed ranges are fulfilled.

Table 5-3 OWA Valid concurrent mast and floating lidar 10-minute data points for each verification height

WS Bin [m/s]	Bin Center [m/s]	Height [m]									
		52	62	82	92	102	122	142	162	182	202
2 to 3	2.5	97	93	83	81	78	68	67	62	54	44
3 to 4	3.5	198	178	149	141	138	131	120	100	83	76
4 to 5	4.5	257	261	228	220	217	192	157	117	112	102
5 to 6	5.5	358	336	309	308	319	313	294	269	229	193
6 to 7	6.5	504	499	463	477	458	452	411	365	315	266
7 to 8	7.5	539	509	497	468	453	433	389	320	280	249
8 to 9	8.5	520	517	507	506	511	454	417	380	334	262
9 to 10	9.5	521	539	517	506	515	523	453	366	311	269
10 to 11	10.5	550	547	527	516	514	496	494	430	338	317
11 to 12	11.5	503	505	494	470	455	437	438	406	375	331
12 to 14	13	889	898	948	963	942	840	787	768	676	587
14 to 16	15	423	428	495	531	583	687	705	636	601	534
16 to 18	17	273	310	301	300	289	293	321	389	429	403
18 to 20	19	114	143	269	288	292	302	264	229	228	246
20 to 22	21	40	41	60	110	163	203	225	240	199	168
22 to 24	23	15	21	27	29	33	100	136	143	164	162
24 to 26	25	3	3	13	19	23	23	57	111	125	120
26 to 28	27	0	3	5	4	8	22	23	26	52	79
28 to 30	29	0	0	0	3	3	4	15	25	17	14

5.2 Wind speed comparison

Table 5-4 summarizes the wind speed regression results for all ten (10) verfication heights and shows that the floating lidar achieved a high level of accuracy relative to the reference lidar. It should be noted, however, that except for the 52 m comparison the floating lidar measures wind speeds 2.8 m above the reference lidar. Ideally measurements should be made at the same height. However, given the low wind shear this difference is within an acceptable limit for comparison. The regression slopes (m) are close to unity with a good regression coefficient R^2 (**KPI** R^2_{mws}). Figure 5-2 and Figure 5-3 provide the corresponding regression plots for wind speeds greater than 2 m/s.

The lidar has passed the following wind speed KPIs and ACs for all verification heights:

- ✓ The OWA Acceptance Criterion for slope (**KPI** X_{mws}) to be between 0.98 and 1.02.
- ✓ The OWA Acceptance Criterion for R^2 (**KPI** R^2_{mws}) to be > 0.98.

The concurrent time series of wind speeds from the lidar and met mast at 160 m and 40 m are shown in APPENDIX B .

Table 5-4 Regression results for comparison

52 m height	Number of Points	slope	R^2	Reference Lidar Mean WS	Lidar Mean WS	Mean Difference	Relative Difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{ms}				
All > 2 m/s	5804	0.984	0.996	10.02	9.87	-0.149	-1.49%
4 - 16 m/s	5064	0.986	0.995	9.71	9.58	-0.134	-1.38%

62 m height	Number of Points	slope	R^2	Reference Lidar Mean WS	Lidar Mean WS	Mean Difference	Relative Difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{ms}				
All > 2 m/s	5831	0.993	0.996	10.20	10.14	-0.060	-0.59%
4 - 16 m/s	5039	0.994	0.993	9.76	9.71	-0.048	-0.49%

82 m height	Number of Points	slope	R^2	Reference Lidar Mean WS	Lidar Mean WS	Mean Difference	Relative Difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{ms}				
All > 2 m/s	5892	0.992	0.996	10.67	10.59	-0.076	-0.71%
4 - 16 m/s	4985	0.993	0.994	9.95	9.88	-0.062	-0.63%

92 m height	Number of Points	slope	R^2	Reference Lidar Mean WS	Lidar Mean WS	Mean Difference	Relative Difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{ms}				
All > 2 m/s	5940	0.991	0.997	10.85	10.76	-0.089	-0.82%
4 - 16 m/s	4965	0.992	0.995	9.99	9.92	-0.072	-0.72%

102 m height	Number of Points	slope	R^2	Reference Lidar Mean WS	Lidar Mean WS	Mean Difference	Relative Difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{ms}				
All > 2 m/s	5994	0.990	0.997	11.02	10.92	-0.093	-0.85%
4 - 16 m/s	4967	0.992	0.995	10.04	9.97	-0.075	-0.74%

122 m height	Number of Points	slope	R^2	Reference Lidar Mean WS	Lidar Mean WS	Mean Difference	Relative Difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{ms}				
All > 2 m/s	5975	0.991	0.997	11.40	11.31	-0.092	-0.81%
4 - 16 m/s	4827	0.993	0.995	10.14	10.07	-0.069	-0.68%

142 m height	Number of Points	slope	R^2	Reference Lidar Mean WS	Lidar Mean WS	Mean Difference	Relative Difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{ms}				
All > 2 m/s	5777	0.991	0.997	11.80	11.71	-0.085	-0.72%
4 - 16 m/s	4545	0.994	0.994	10.28	10.22	-0.058	-0.57%

162 m height	Number of Points	slope	R^2	Reference Lidar Mean WS	Lidar Mean WS	Mean Difference	Relative Difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{ms}				
All > 2 m/s	5391	0.991	0.997	12.31	12.21	-0.096	-0.78%
4 - 16 m/s	4057	0.994	0.993	10.40	10.34	-0.059	-0.57%

182 m height	Number of Points	slope	R^2	Reference Lidar Mean WS	Lidar Mean WS	Mean Difference	Relative Difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{ms}				
All > 2 m/s	4946	0.991	0.997	12.75	12.65	-0.099	-0.78%
4 - 16 m/s	3571	0.994	0.995	10.46	10.40	-0.061	-0.58%

202 m height	Number of Points	slope	R^2	Reference Lidar Mean WS	Lidar Mean WS	Mean Difference	Relative Difference
	-	-	-	[m/s]	[m/s]	[m/s]	%
WS-range		KPI X_{mws}	KPI R^2_{ms}				
All > 2 m/s	4458	0.993	0.998	13.11	13.02	-0.083	-0.63%
4 - 16 m/s	3110	0.995	0.995	10.50	10.45	-0.053	-0.50%

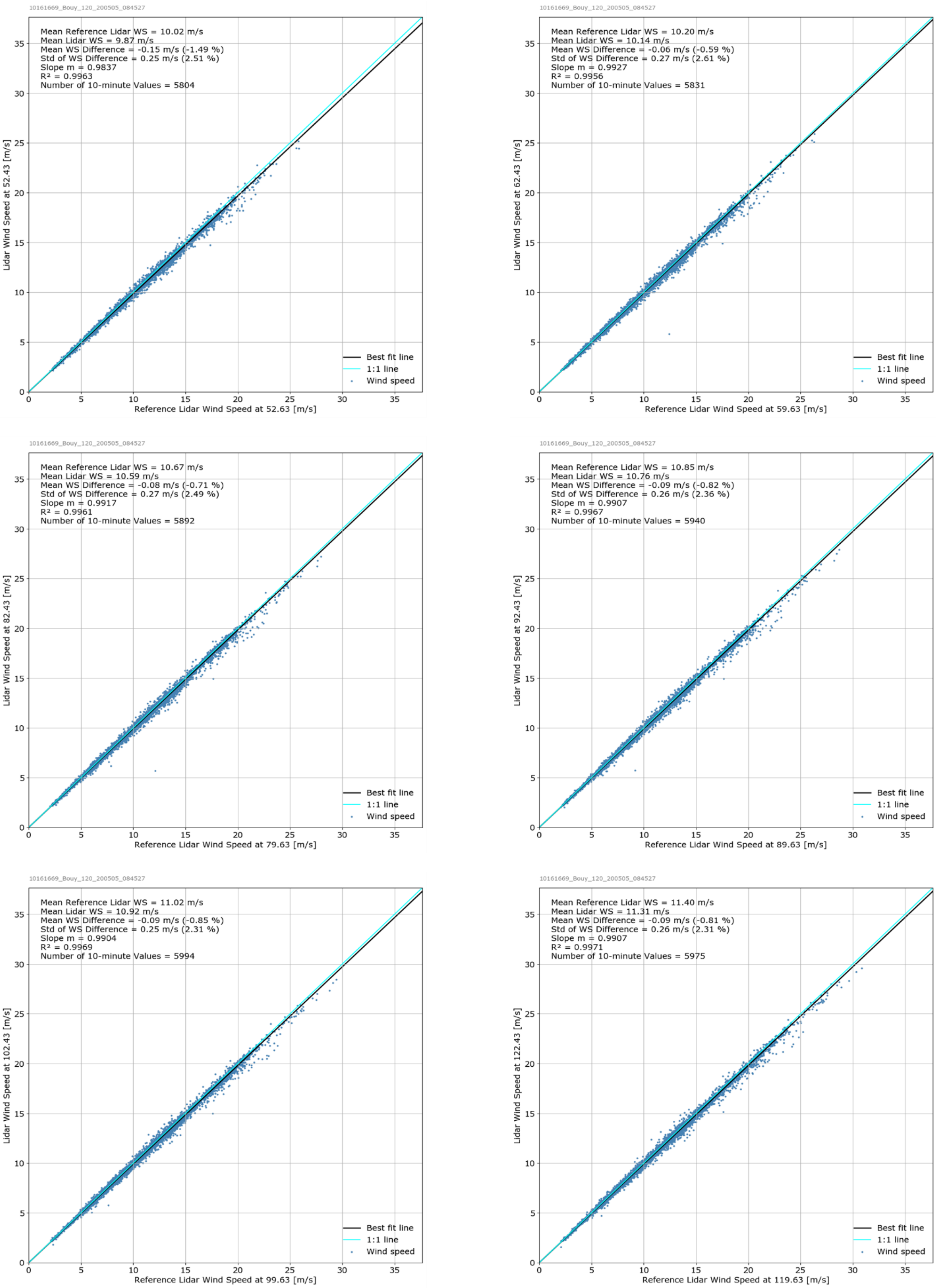


Figure 5-2 Linear wind speed regression results between Buoy 120 from 52 m to 122 m and the reference lidar from 53 m to 120 m

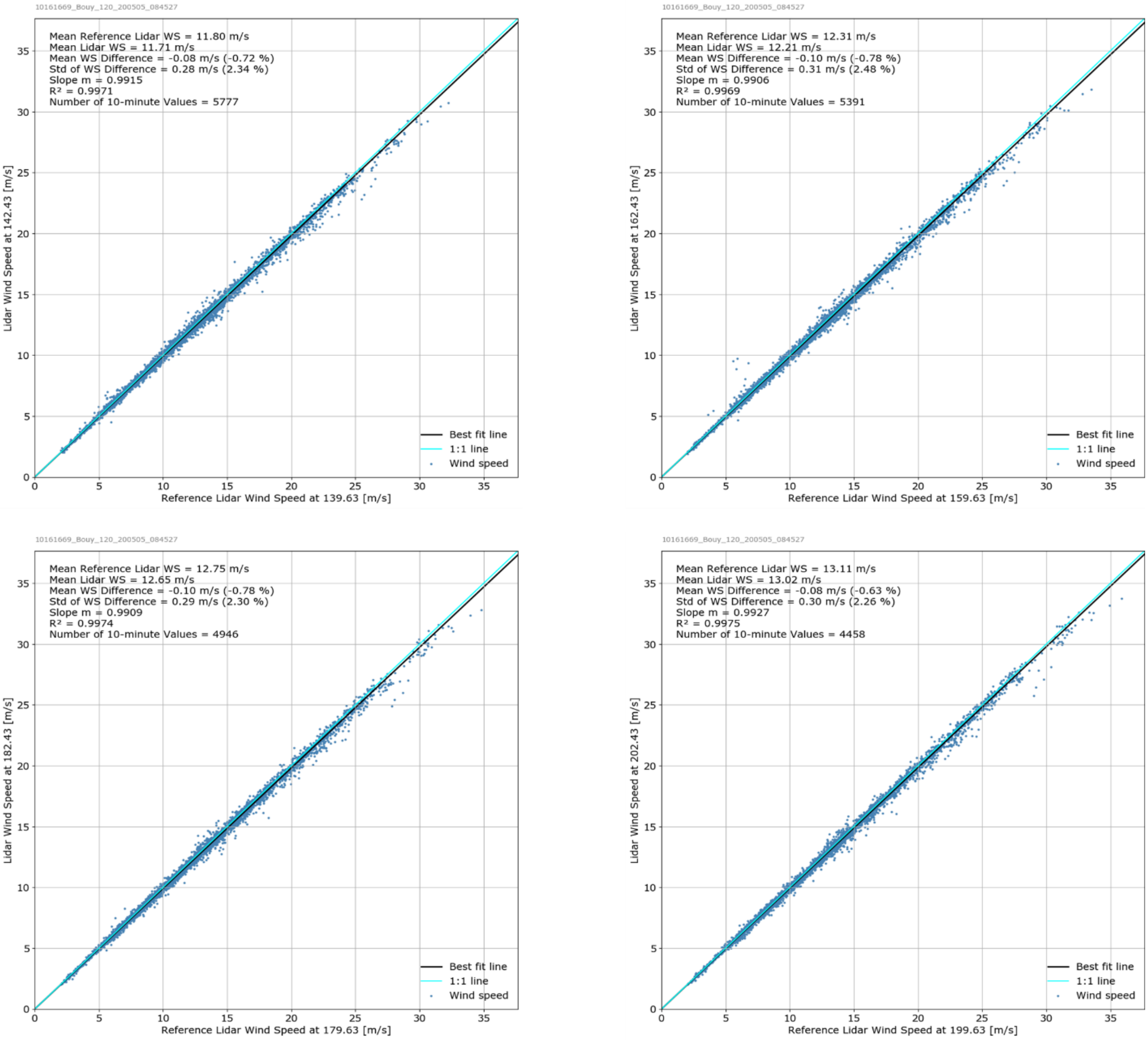


Figure 5-3 Linear wind speed regression results between Buoy 120 from 142 m to 202 m and the reference lidar from 140 m to 200 m

5.3 Wind direction comparison

Figure 5-4 and Figure 5-5 present scatter plots of valid reference lidar (x-axis) and floating lidar (y-axis) wind directions when wind speeds are greater than 2 m/s.

Table 5-3 summarizes the wind direction comparisons for all ten (10) verfication heights and show that the lidar wind direction passes KPIs for the mean wind direction slope (M_{mwd}), absolute offset (OFF_{mwd}), and coefficient of determination (R^2_{mwd}).

Time series of wind direction, raw data correlations, and wind direction distribution statistics can be found in APPENDIX C .

Table 5-5 Summary of wind direction comparison above 2 m/s

Height	Number of points	slope	offset [°]	R^2
[m]	[-]	KPI X_{mwd}	KPI OFF_{mwd}	KPI R^2_{mwd}
52	5804	1.000	1.697	1.000
62	5831	1.000	1.864	1.000
82	5892	1.000	1.919	1.000
92	5940	1.000	1.916	1.000
102	5994	1.001	1.911	1.000
122	5975	1.001	1.946	1.000
142	5777	1.001	1.987	1.000
162	5391	1.001	1.980	1.000
182	4946	1.001	1.971	1.000
202	4458	1.002	1.943	1.000

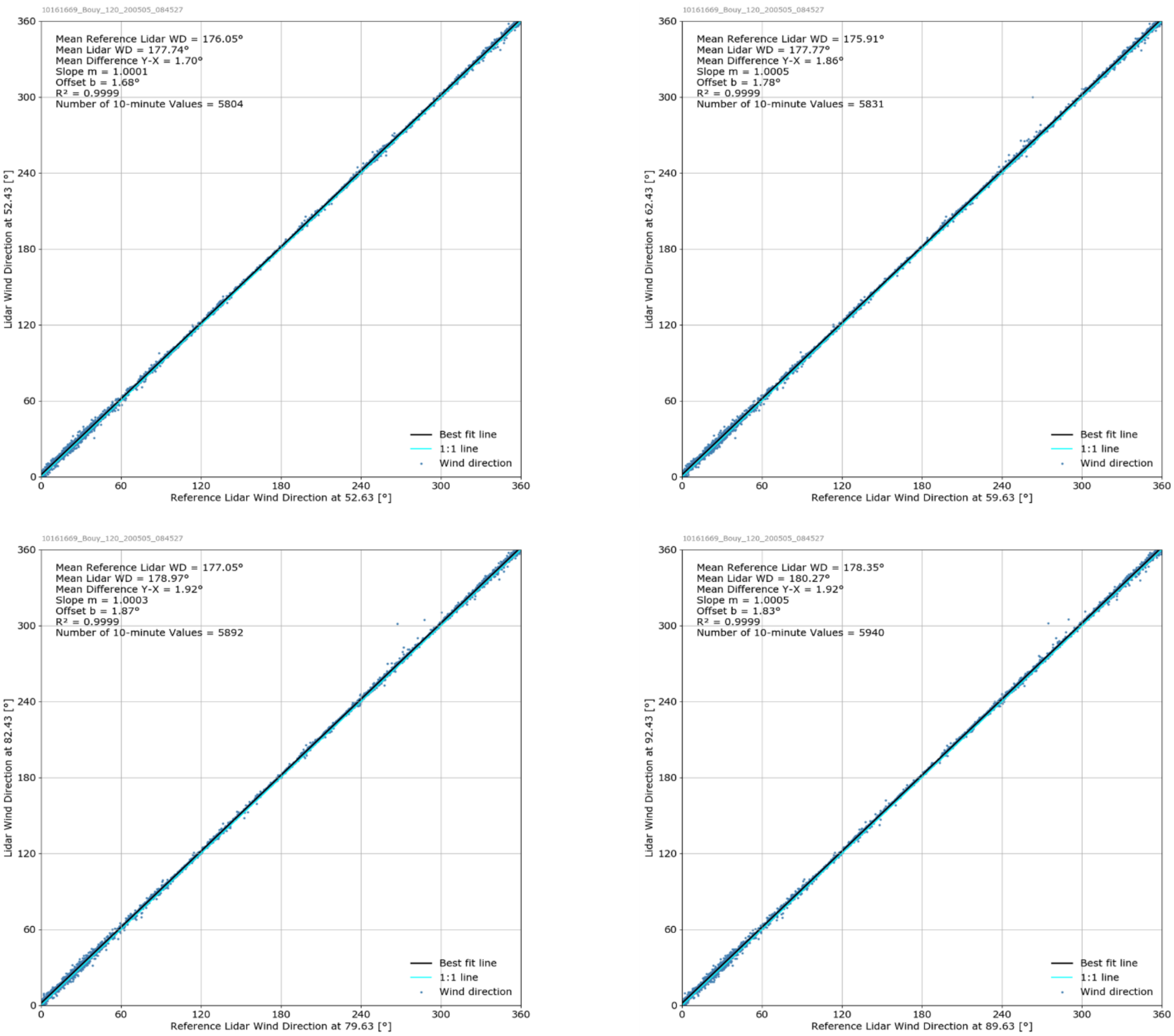


Figure 5-4 Regression plot of wind direction comparisons between Buoy 120 from 52 m to 92 m and the reference lidar from 53 m to 90 m

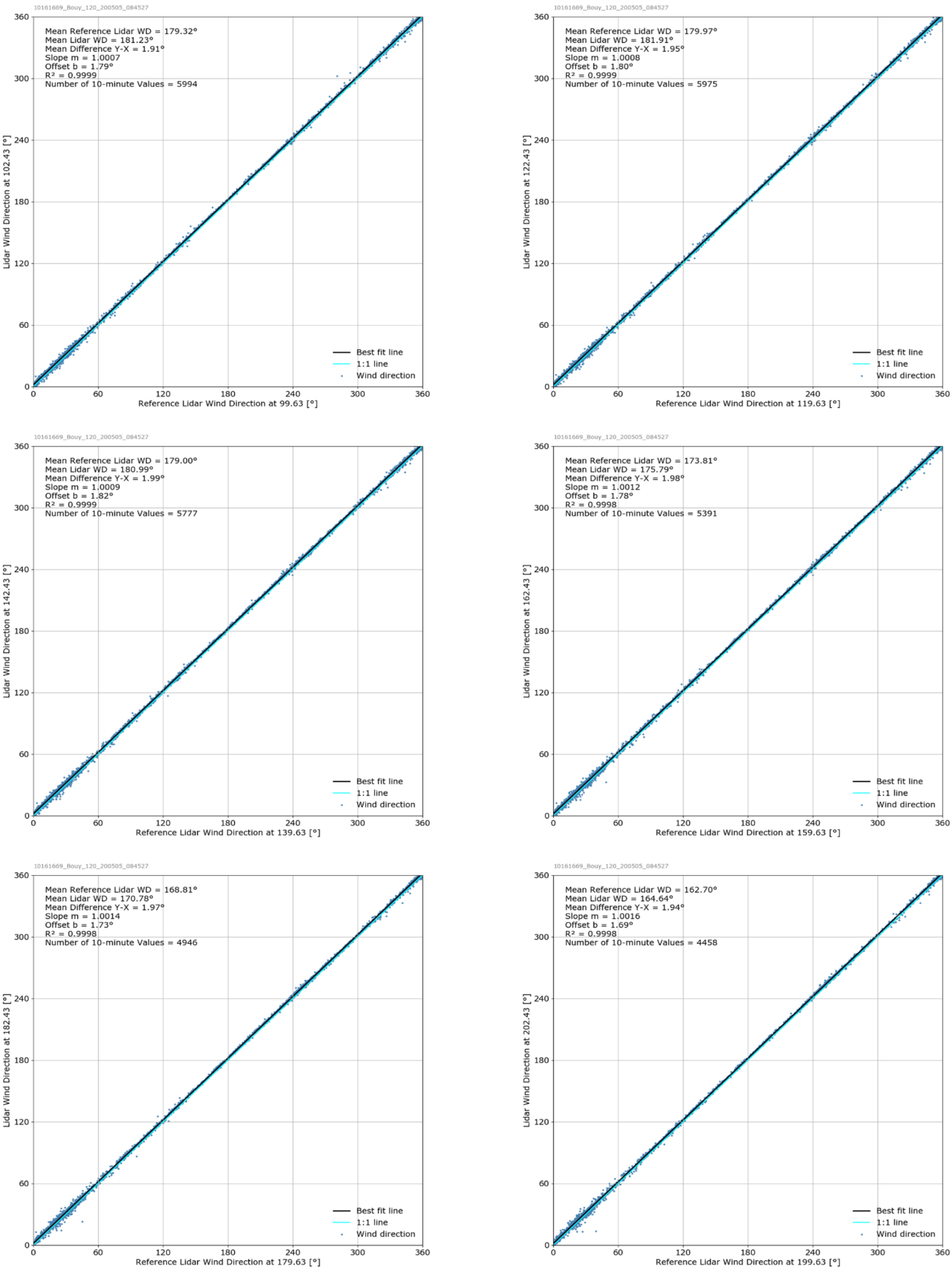


Figure 5-5 Regression plot of wind direction comparisons between Buoy 120 from 102 m to 202 m and the reference lidar from 100 m to 200 m

6 PERFORMANCE VERIFICATION ACCORDING TO IEC STANDARD, ANNEX L

This section presents verification results as defined in the IEC Standard. This approach is described in Section 3.2. DNV GL notes that due to the difference in bin size and bin centres defined by the OWA Roadmap and the IEC, the counts and statistics reported in this section are slightly different than reported in Section 5.

Figure 6-1 through Figure 6-10 show scatter plots of the wind speed comparison based on 10-minute averages between the data pairs of the floating lidar and the reference lidar. It should be noted that the reference lidar was validated onshore between 60 m to 130 m. In addition, the 10-minute averaged deviation for each data point of the two data sets is plotted.

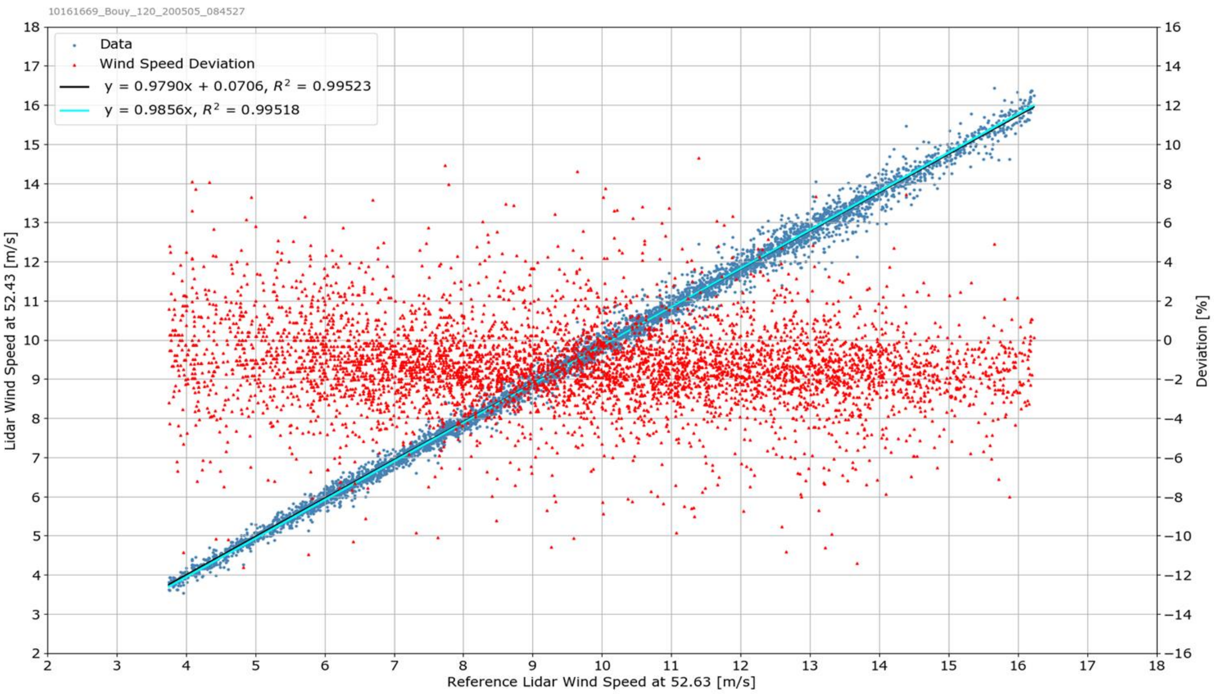


Figure 6-1 Comparison of the horizontal wind speed component at 52 m

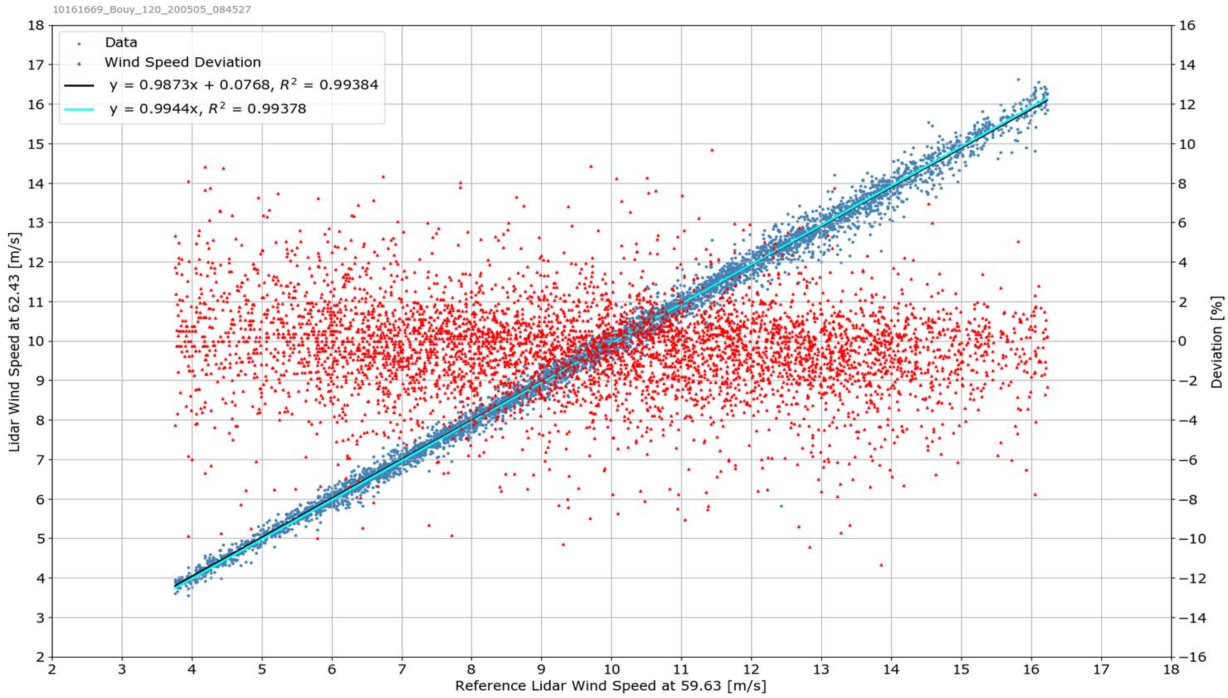


Figure 6-2 Comparison of the horizontal wind speed component at 62 m

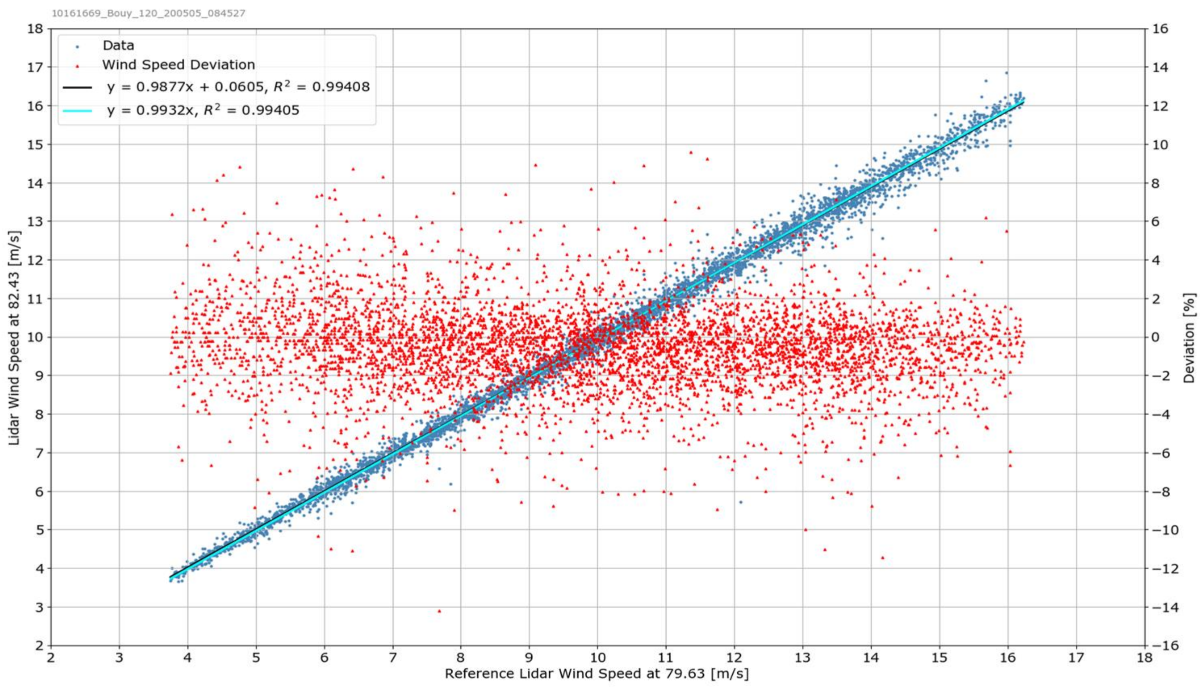


Figure 6-3 Comparison of the horizontal wind speed component at 82 m

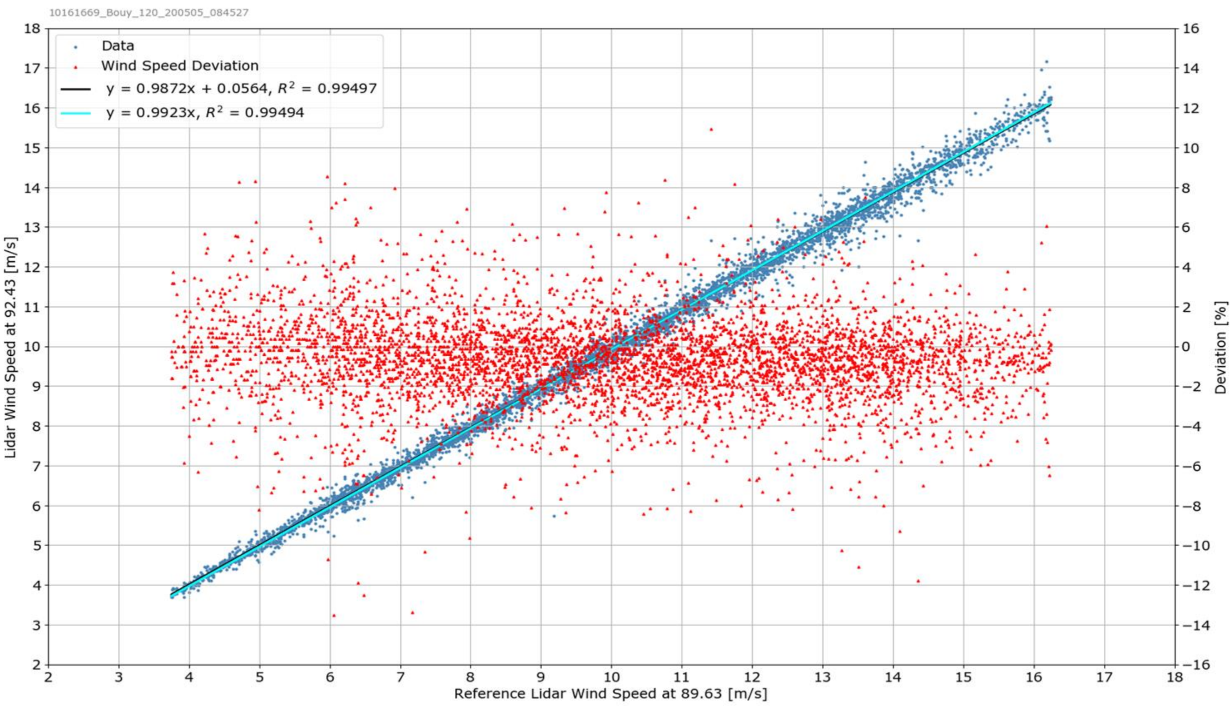


Figure 6-4 Comparison of the horizontal wind speed component at 92 m

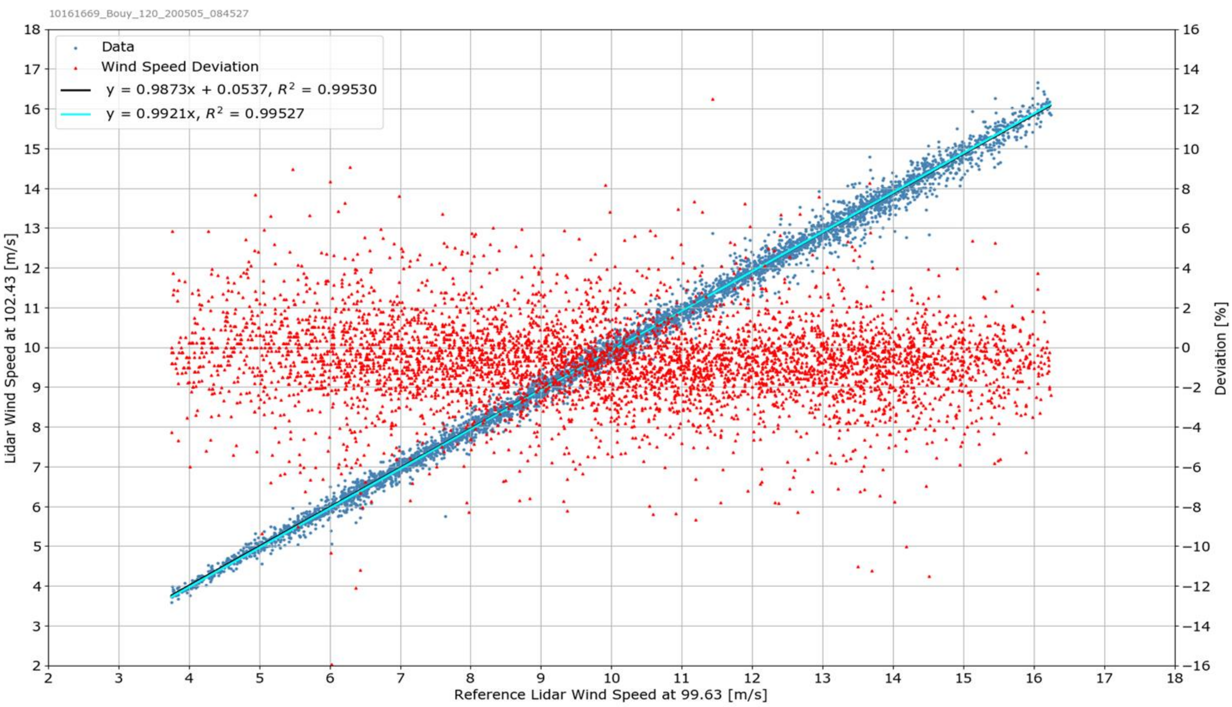


Figure 6-5 Comparison of the horizontal wind speed component at 102 m

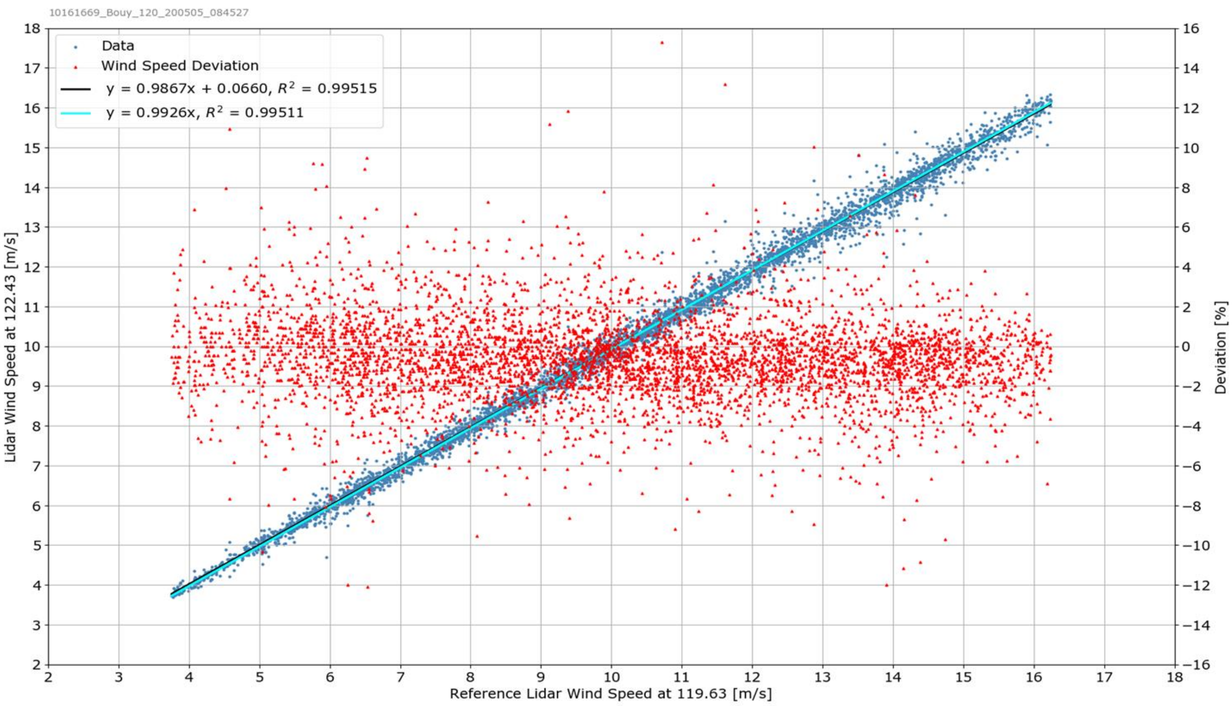


Figure 6-6 Comparison of the horizontal wind speed component at 122 m

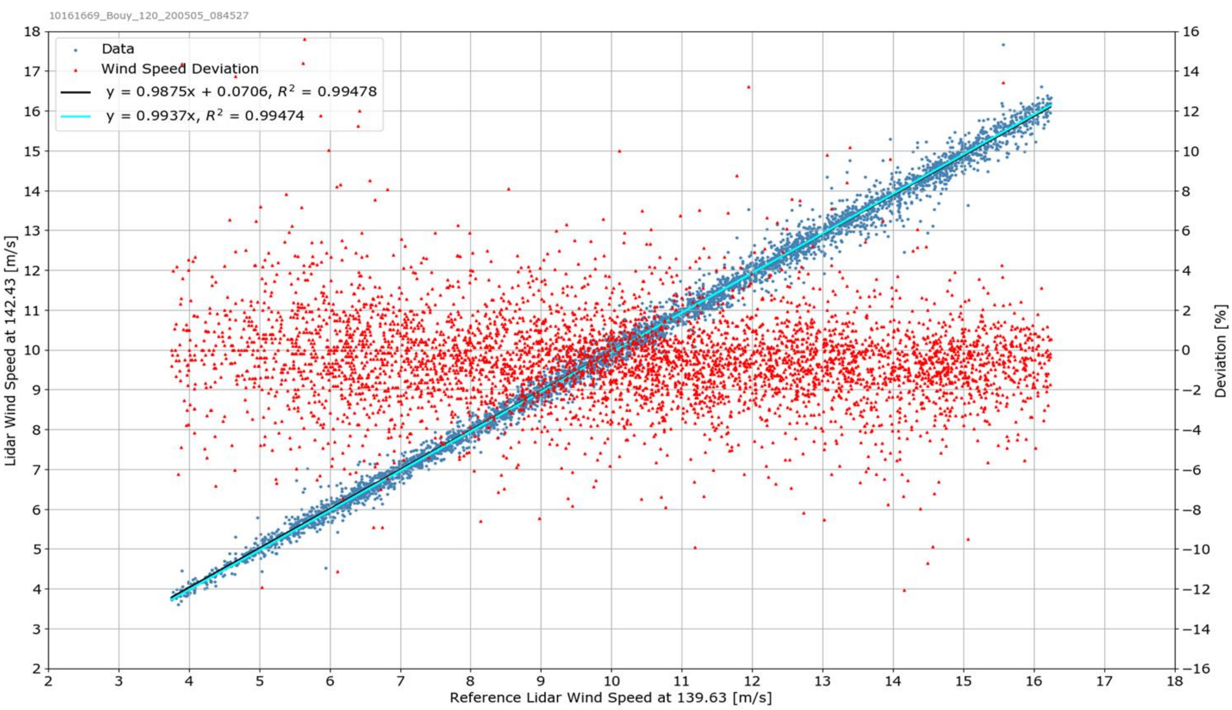


Figure 6-7 Comparison of the horizontal wind speed component at 142 m

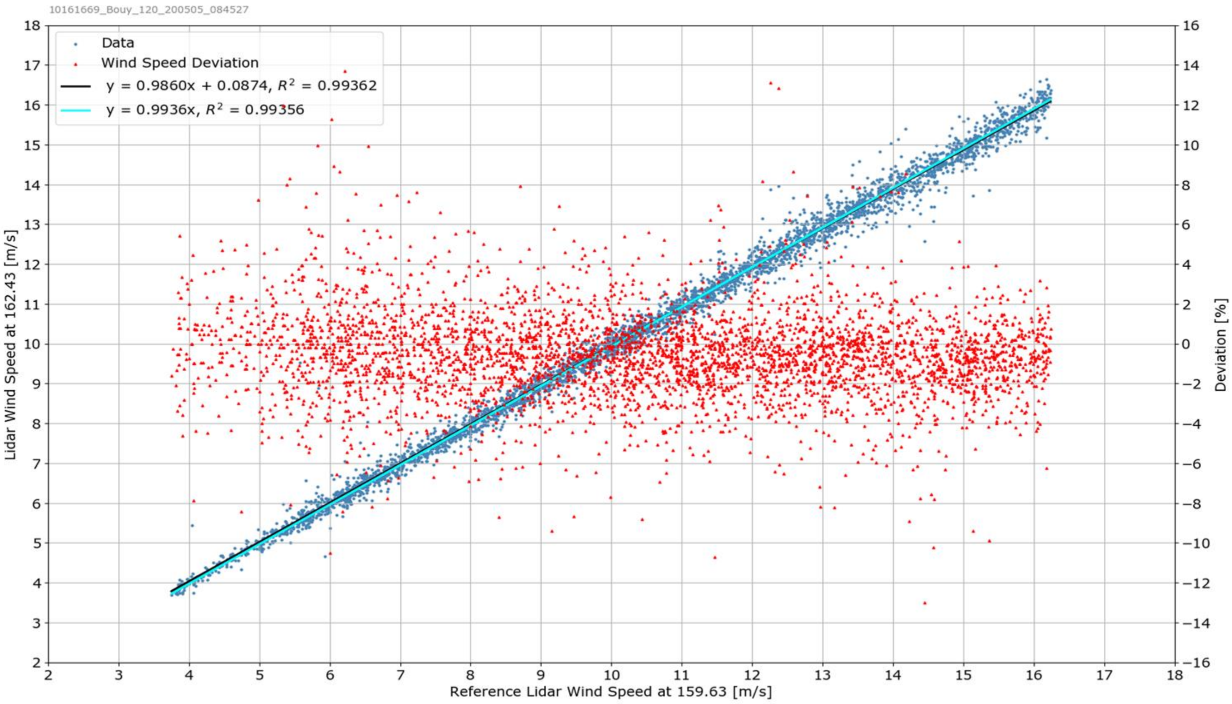


Figure 6-8 Comparison of the horizontal wind speed component at 162 m

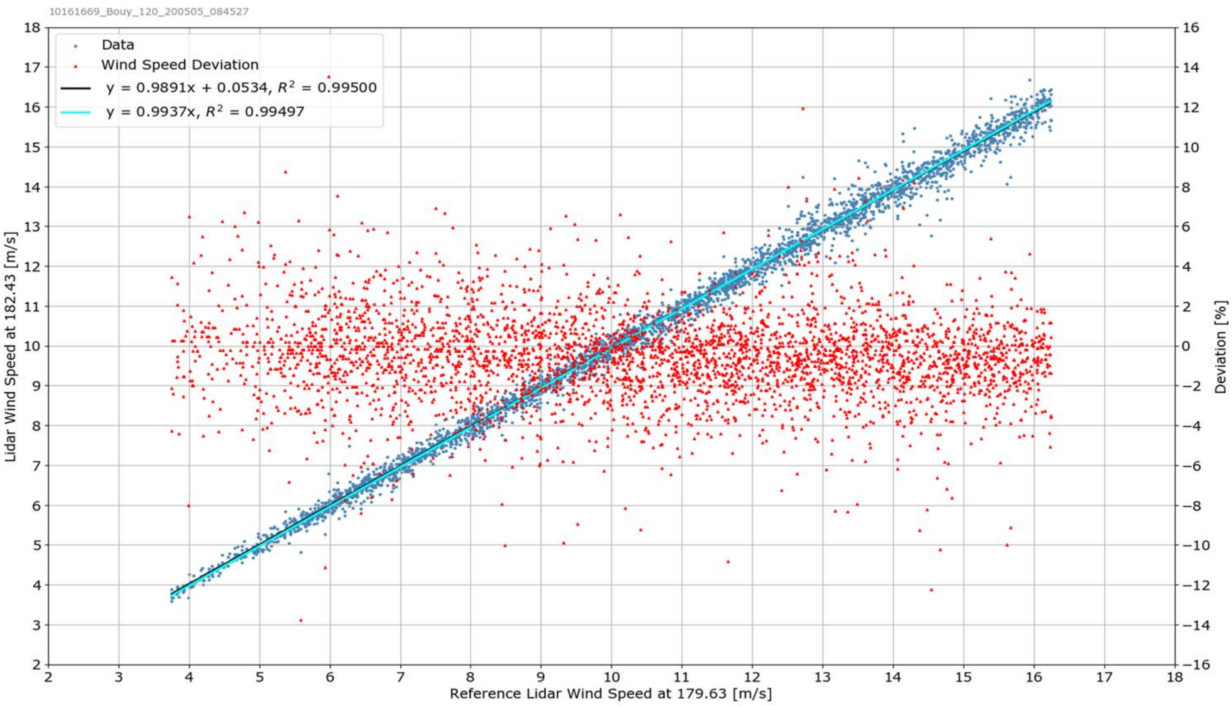


Figure 6-9 Comparison of the horizontal wind speed component at 182 m

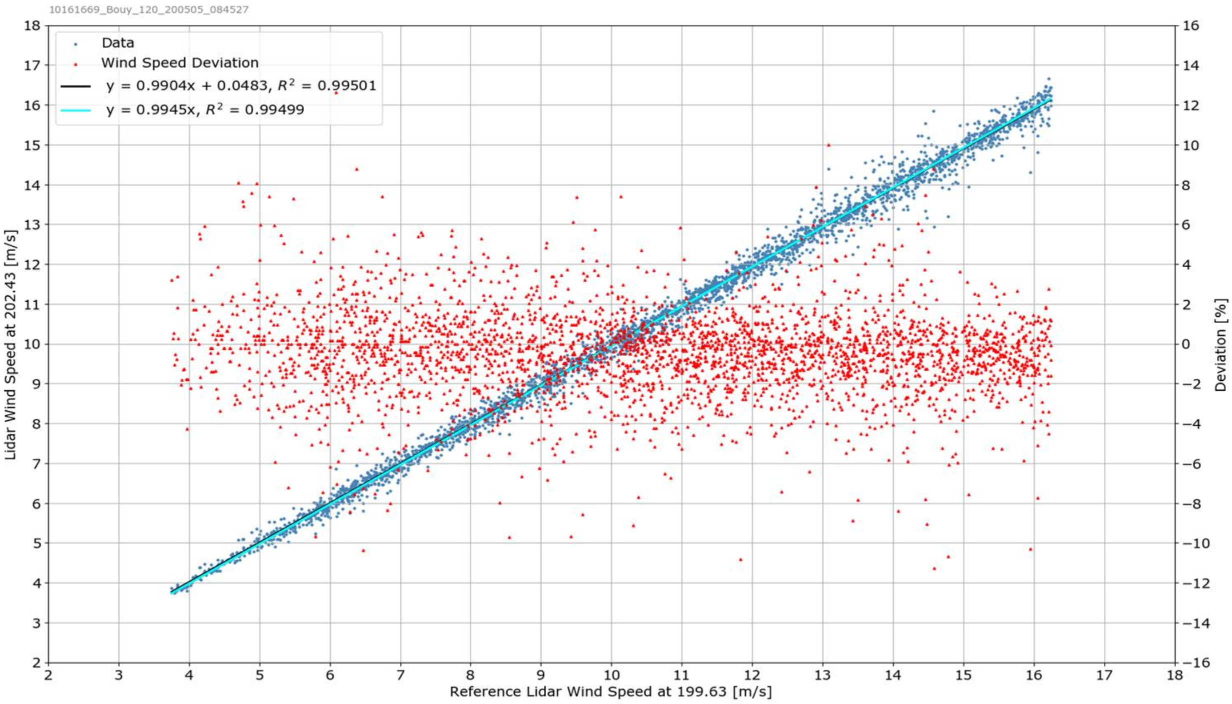


Figure 6-10 Comparison of the horizontal wind speed component at 202 m

Table 6-1 Statistical parameters of wind speed deviation

Height	Coefficient of Determination	Mean Deviation		STD of Deviations	Data Points
[m]	(R^2)	[m/s]	[%]	[%]	#
52	0.9952	-0.13	-1.29	2.16	5164
62	0.9938	-0.05	-0.39	2.38	5131
82	0.9941	-0.06	-0.55	2.32	5051
92	0.9950	-0.07	-0.65	2.20	5047
102	0.9953	-0.07	-0.67	2.14	5040
122	0.9951	-0.07	-0.60	2.19	4909
142	0.9948	-0.06	-0.48	2.34	4632
162	0.9936	-0.06	-0.46	2.98	4159
182	0.9950	-0.06	-0.52	2.21	3661
202	0.9950	-0.05	-0.45	2.18	3184

6.1 Performance verification uncertainty

The bin sizes and bin limits for the OWA Roadmap [3] are different than the IEC [5]. Since the uncertainty components of the reference lidar verification [2] are based on the IEC bin definition, the uncertainty estimation for this FLS verification has been done according to the IEC bin definition.

The IEC database requirement for the lidar verification of 180 hours between 4 m/s and 16 m/s has been met for each comparison height. The additional database requirement of a minimum of 3 data pairs in each 0.5 m/s wind speed bin has also been fulfilled for all comparison heights.

The bin-averaged wind speeds of the FLS and the reference lidar measurements are shown in Figure 6-11 through Figure 6-20. The bin-averaged deviation, shown as a solid red line in the figures below, can be compared to the standard uncertainty of the reference lidar with the binned verification statistical uncertainty.

The correlation coefficient, mean deviation, and standard deviation of the deviations are provided in Table 6-2 through Table 6-11. The relative deviation of each data pair is calculated in relation to the lidar WLS7-436 as the reference.

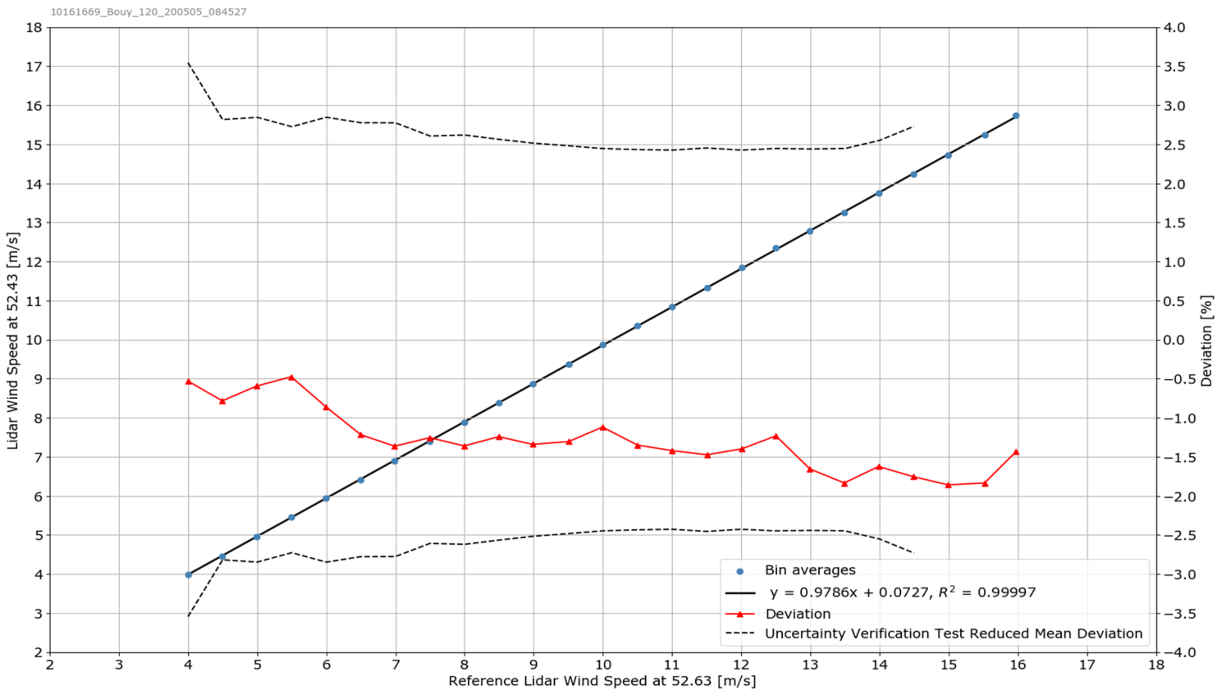


Figure 6-11 Bin-wise comparison of the horizontal wind speed component at 52 m

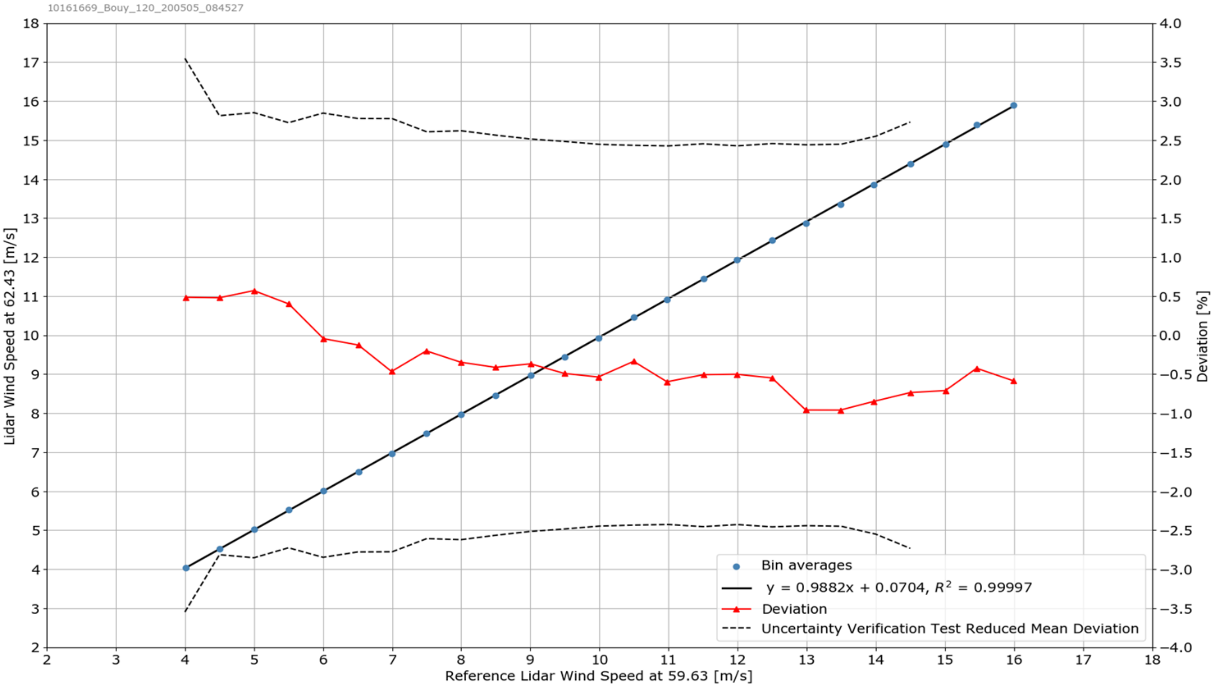


Figure 6-12 Bin-wise comparison of the horizontal wind speed component at 62 m

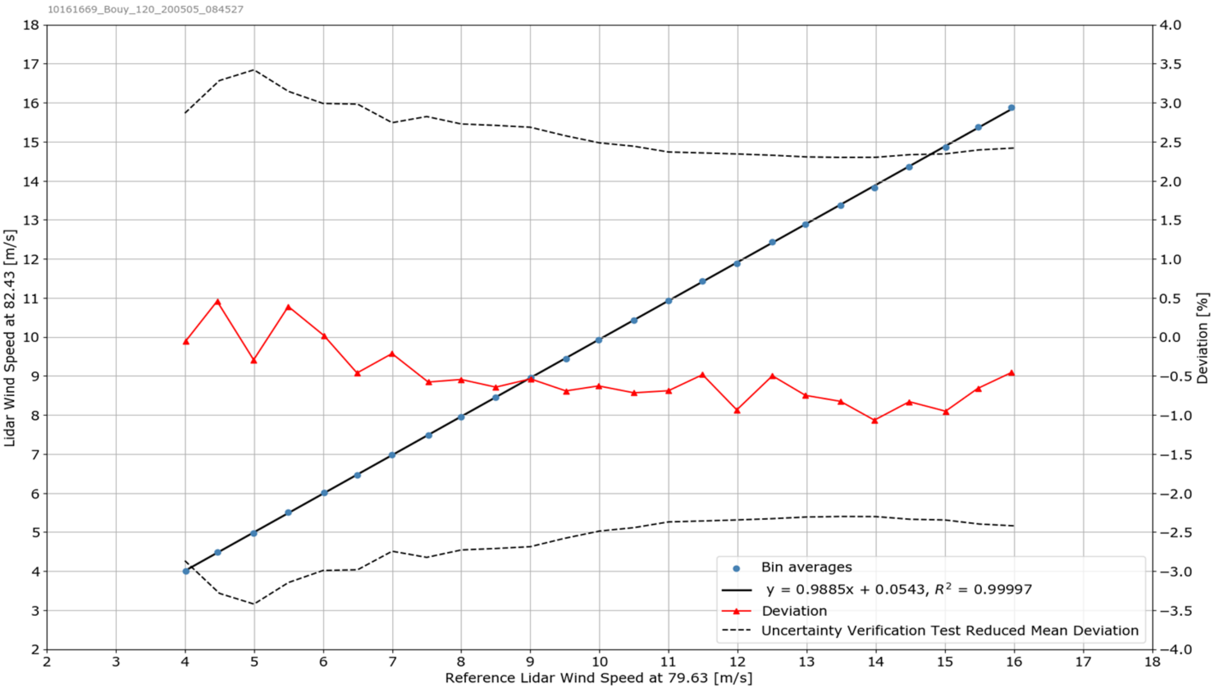


Figure 6-13 Bin-wise comparison of the horizontal wind speed component at 82 m

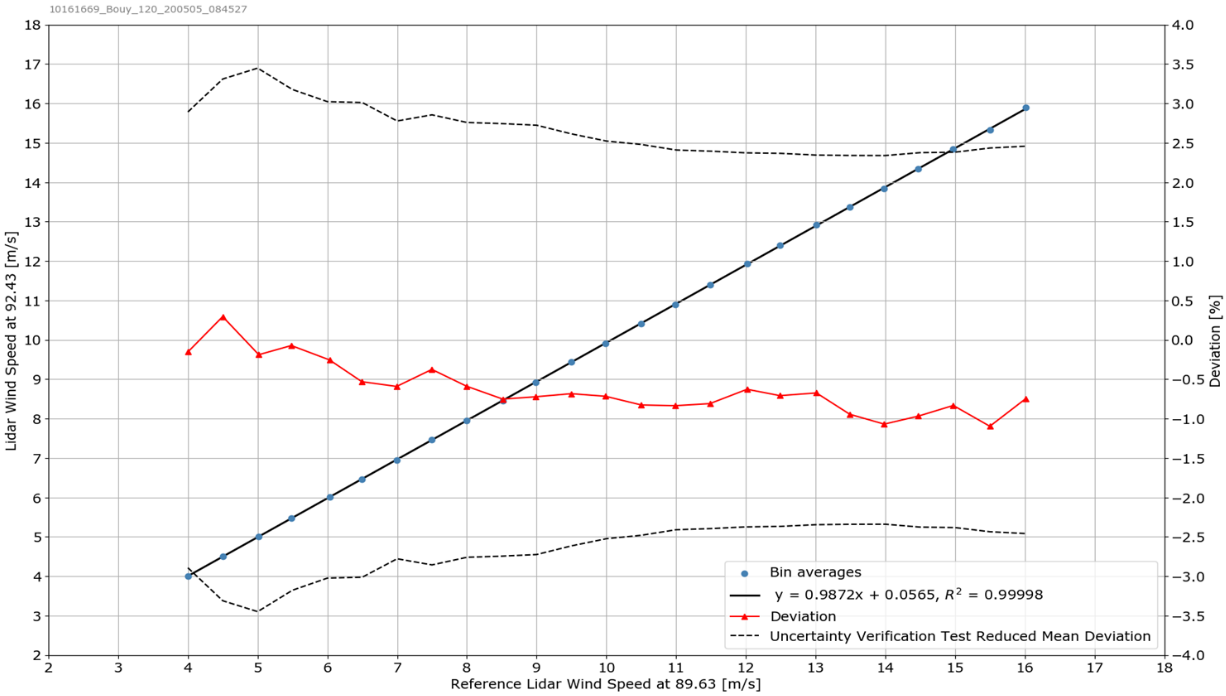


Figure 6-14 Bin-wise comparison of the horizontal wind speed component at 92 m

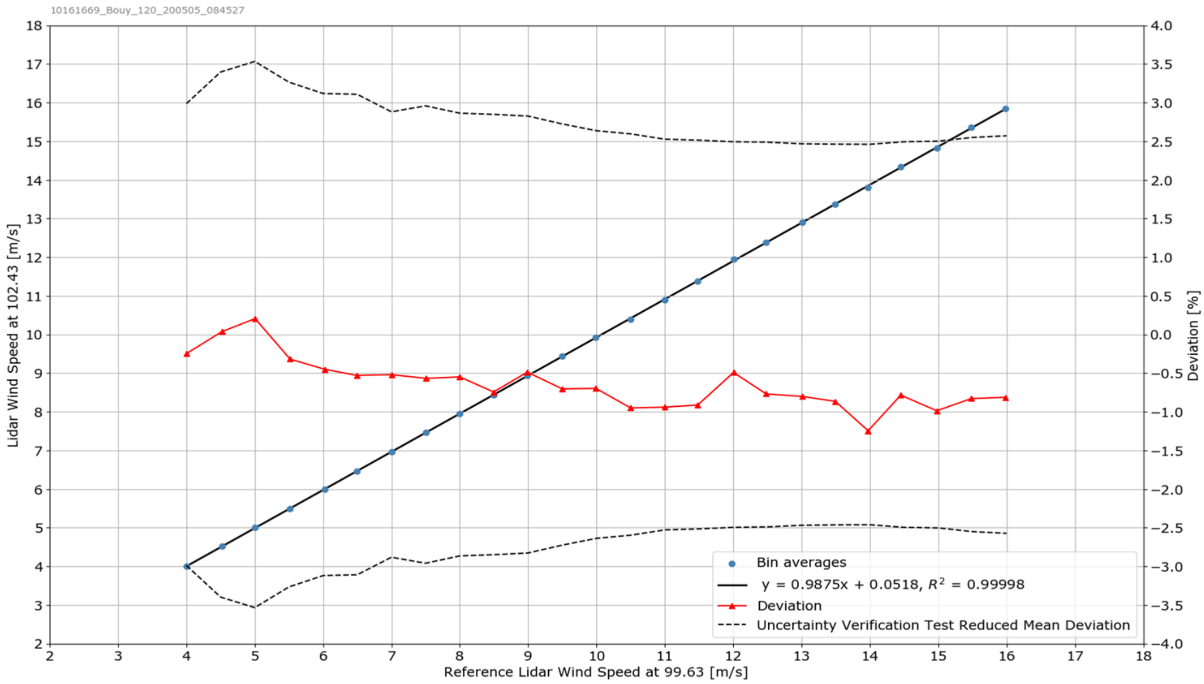


Figure 6-15 Bin-wise comparison of the horizontal wind speed component at 102 m

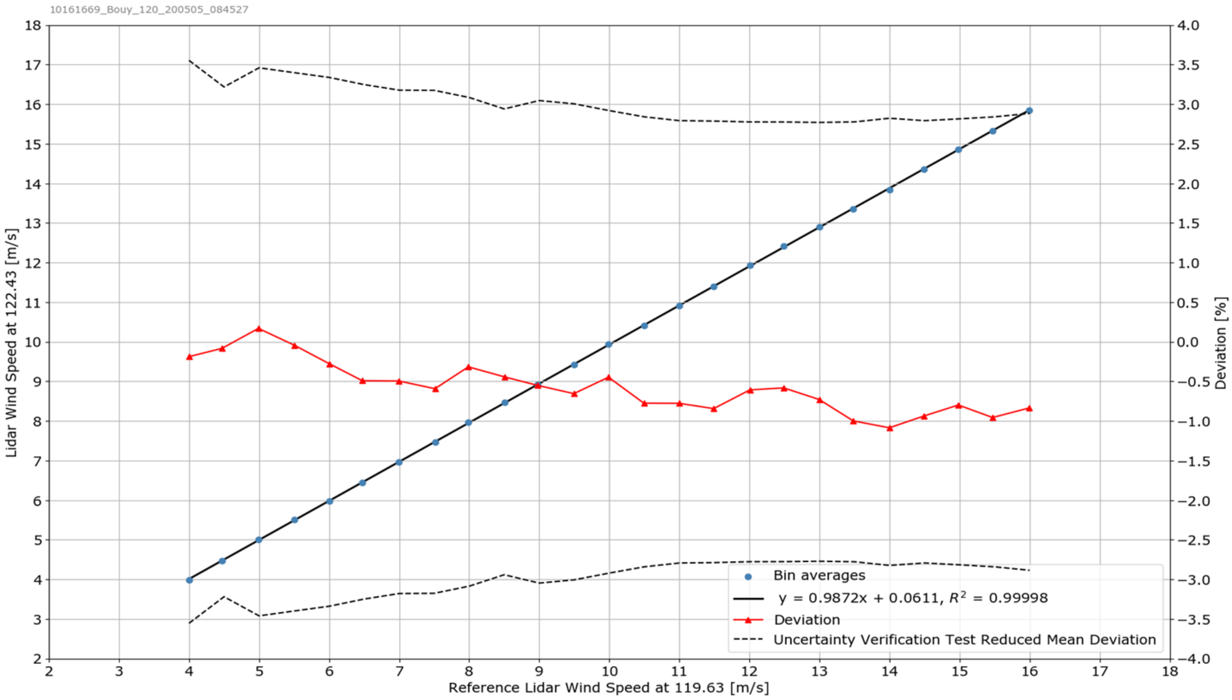


Figure 6-16 Bin-wise comparison of the horizontal wind speed component at 122 m

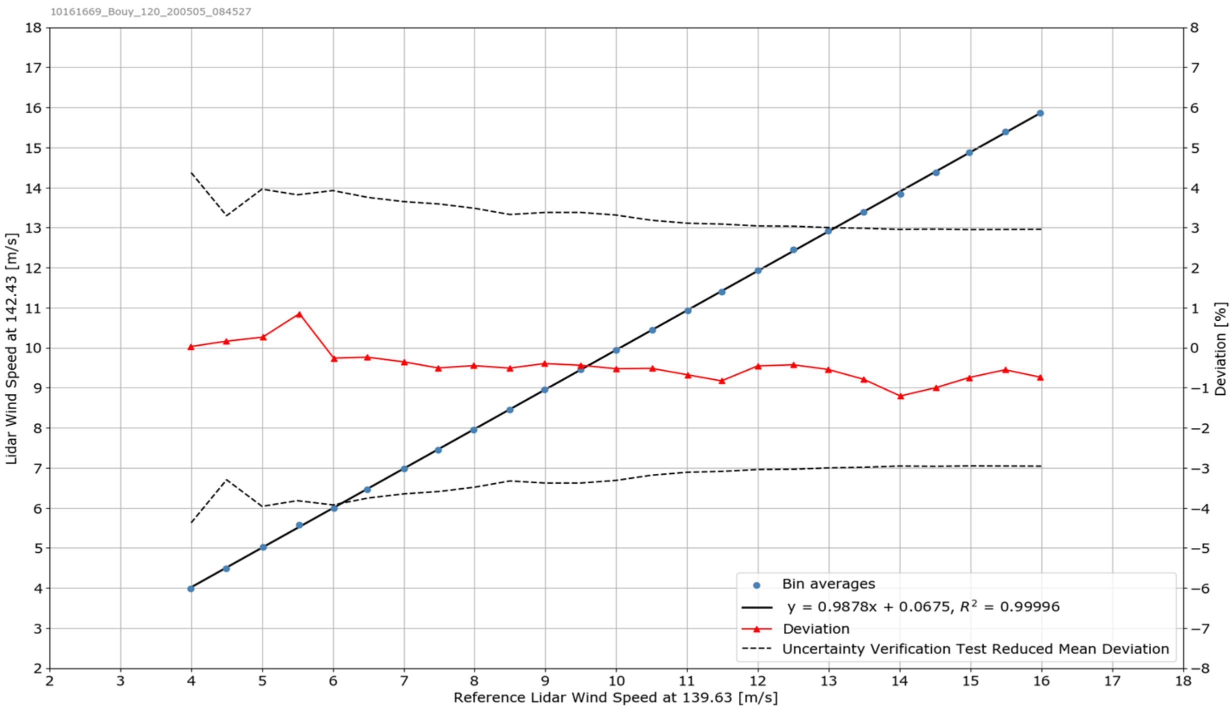


Figure 6-17 Bin-wise comparison of the horizontal wind speed component at 142 m

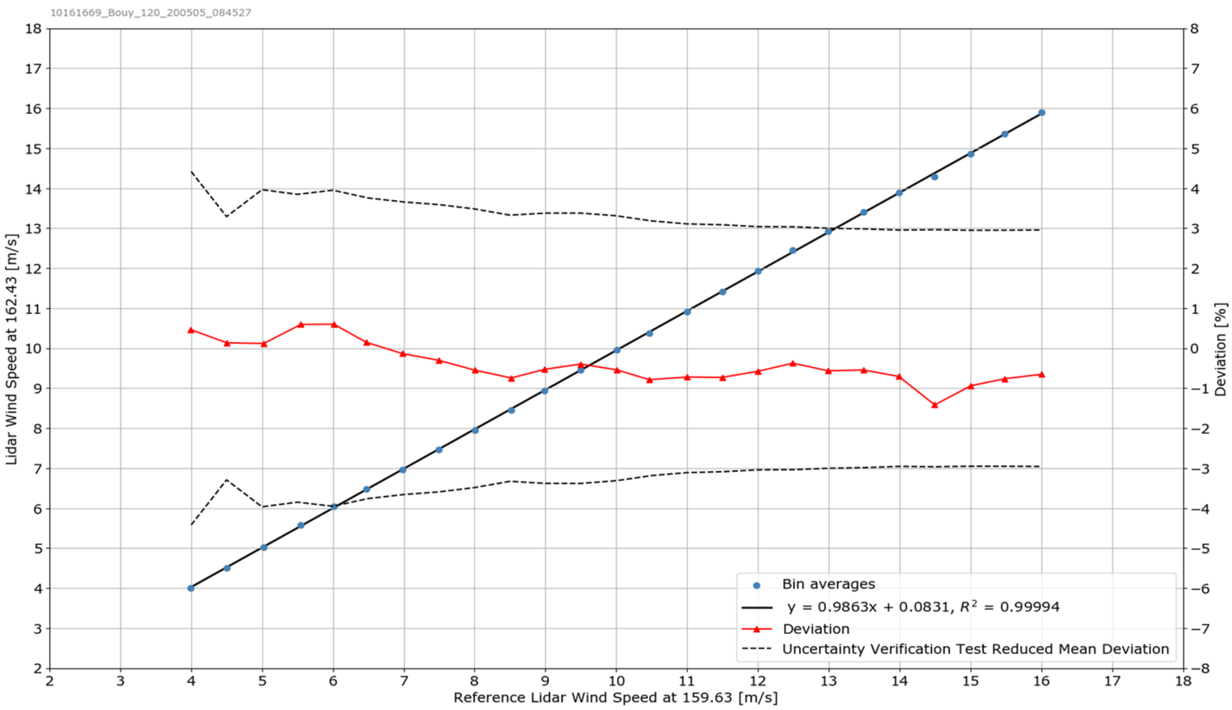


Figure 6-18 Bin-wise comparison of the horizontal wind speed component at 162 m

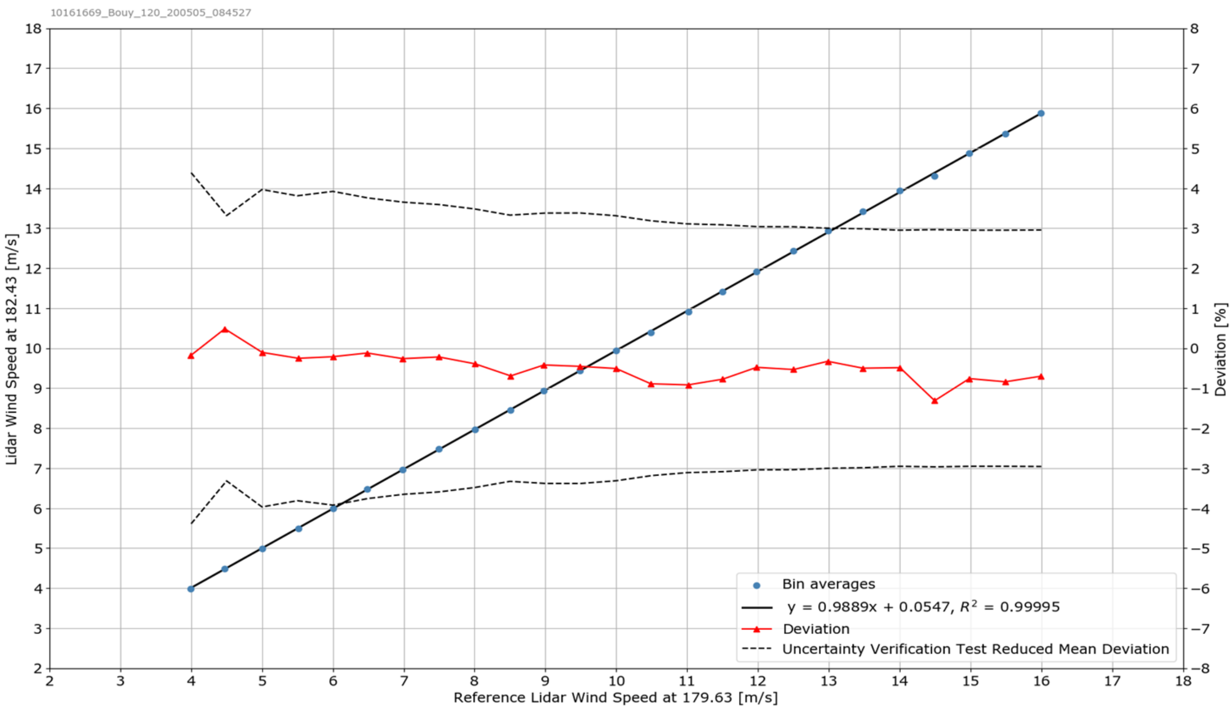


Figure 6-19 Bin-wise comparison of the horizontal wind speed component at 182 m

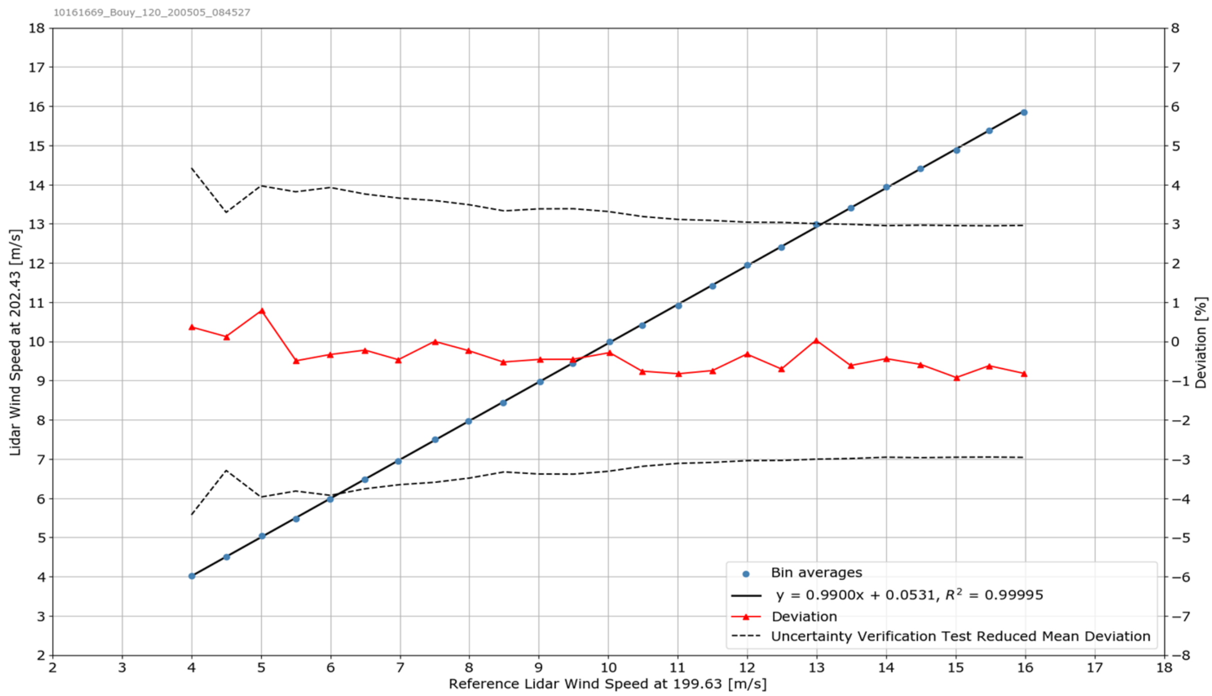


Figure 6-20 Bin-wise comparison of the horizontal wind speed component at 202 m

Table 6-2 Uncertainty calculation at 52 m

Bin Lower [m/s]	Bin Upper [m/s]	N	Vrsd [m/s]	Vmm [m/s]	Vmaxrsd [m/s]	Vminrsd [m/s]	StdVrsd [m/s]	StdVrsd/√n [m/s]	Mean Deviation [%]	RSD Mounting Uncertainty [%]	Vlidar Uncertainty [%]	Separation Uncertainty [%]	Vrsd Uncertainty (k=1) [%]	Vrsd Uncertainty Reduced Mean Deviation [%]
3.75	4.25	135	3.98	4.00	4.46	3.53	0.17	0.015	-0.53%	0.50%	3.49%	0.08%	3.58%	3.54%
4.25	4.75	112	4.46	4.50	4.92	3.98	0.20	0.019	-0.78%	0.50%	2.74%	0.08%	2.92%	2.82%
4.75	5.25	146	4.96	4.99	5.30	4.27	0.18	0.015	-0.59%	0.50%	2.79%	0.08%	2.91%	2.85%
5.25	5.75	155	5.47	5.49	6.07	4.89	0.20	0.016	-0.47%	0.50%	2.66%	0.08%	2.77%	2.73%
5.75	6.25	258	5.94	5.99	6.50	5.13	0.21	0.013	-0.86%	0.50%	2.79%	0.08%	2.97%	2.85%
6.25	6.75	245	6.42	6.50	7.17	5.75	0.19	0.012	-1.22%	0.50%	2.72%	0.08%	3.03%	2.78%
6.75	7.25	258	6.89	6.99	7.34	6.40	0.19	0.012	-1.36%	0.50%	2.72%	0.08%	3.09%	2.78%
7.25	7.75	272	7.40	7.50	8.42	6.60	0.21	0.013	-1.25%	0.50%	2.55%	0.08%	2.89%	2.61%
7.75	8.25	277	7.88	7.99	8.58	7.42	0.19	0.011	-1.36%	0.50%	2.57%	0.08%	2.95%	2.62%
8.25	8.75	253	8.39	8.49	9.32	7.69	0.23	0.015	-1.24%	0.50%	2.51%	0.08%	2.85%	2.56%
8.75	9.25	246	8.86	8.98	9.60	8.10	0.23	0.015	-1.34%	0.50%	2.46%	0.08%	2.85%	2.52%
9.25	9.75	261	9.38	9.50	10.47	8.29	0.27	0.017	-1.30%	0.50%	2.42%	0.08%	2.80%	2.48%
9.75	10.25	300	9.88	9.99	10.90	9.13	0.26	0.015	-1.12%	0.50%	2.39%	0.08%	2.69%	2.45%
10.25	10.75	265	10.36	10.50	11.30	9.53	0.26	0.016	-1.35%	0.50%	2.38%	0.08%	2.78%	2.43%
10.75	11.25	279	10.85	11.00	11.71	9.94	0.27	0.016	-1.42%	0.50%	2.37%	0.08%	2.81%	2.43%
11.25	11.75	256	11.34	11.51	12.45	10.31	0.29	0.018	-1.47%	0.50%	2.40%	0.08%	2.86%	2.45%
11.75	12.25	221	11.84	12.01	12.63	10.99	0.26	0.018	-1.40%	0.50%	2.37%	0.08%	2.80%	2.43%
12.25	12.75	228	12.35	12.50	13.18	11.29	0.30	0.020	-1.23%	0.50%	2.39%	0.08%	2.74%	2.45%
12.75	13.25	236	12.78	12.99	14.04	11.82	0.33	0.021	-1.66%	0.50%	2.38%	0.08%	2.95%	2.44%
13.25	13.75	216	13.24	13.49	14.01	11.99	0.30	0.021	-1.83%	0.50%	2.39%	0.08%	3.06%	2.45%
13.75	14.25	170	13.76	13.99	14.88	12.79	0.32	0.024	-1.62%	0.50%	2.49%	0.08%	3.02%	2.55%
14.25	14.75	128	14.24	14.50	15.46	13.45	0.29	0.026	-1.75%	0.50%	2.68%	0.08%	3.25%	2.73%
14.75	15.25	93	14.72	15.00	15.54	13.87	0.27	0.028	-1.86%	0.50%		0.08%		
15.25	15.75	74	15.24	15.52	16.43	14.43	0.32	0.037	-1.83%	0.50%		0.08%		
15.75	16.25	80	15.74	15.97	16.37	14.61	0.31	0.035	-1.43%	0.50%		0.08%		

Table 6-3 Uncertainty calculation at 63 m

Bin Lower [m/s]	Bin Upper [m/s]	N	Vrsd [m/s]	Vmm [m/s]	Vmaxrsd [m/s]	Vminrsd [m/s]	StdVrsd [m/s]	StdVrsd/√n [m/s]	Mean Deviation [%]	RSD Mounting Uncertainty [%]	Vlidar Uncertainty [%]	Separation Uncertainty [%]	Vrsd Uncertainty (k=1) [%]	Vrsd Uncertainty Reduced Mean Deviation [%]
3.75	4.25	128	4.04	4.02	4.56	3.56	0.18	0.016	0.49%	0.50%	3.49%	0.08%	3.58%	3.55%
4.25	4.75	113	4.52	4.50	4.94	3.99	0.19	0.018	0.48%	0.50%	2.74%	0.08%	2.85%	2.81%
4.75	5.25	140	5.03	5.00	5.62	4.39	0.21	0.018	0.57%	0.50%	2.79%	0.08%	2.91%	2.85%
5.25	5.75	156	5.53	5.50	5.90	5.04	0.19	0.015	0.40%	0.50%	2.66%	0.08%	2.75%	2.72%
5.75	6.25	240	6.00	6.01	6.48	5.22	0.20	0.013	-0.04%	0.50%	2.79%	0.08%	2.85%	2.85%
6.25	6.75	239	6.50	6.51	7.29	5.83	0.21	0.014	-0.13%	0.50%	2.72%	0.08%	2.78%	2.78%
6.75	7.25	253	6.96	6.99	7.43	6.43	0.20	0.013	-0.46%	0.50%	2.72%	0.08%	2.81%	2.78%
7.25	7.75	252	7.48	7.49	7.96	6.70	0.21	0.013	-0.20%	0.50%	2.55%	0.08%	2.62%	2.61%
7.75	8.25	277	7.96	7.99	8.58	7.46	0.22	0.013	-0.35%	0.50%	2.57%	0.08%	2.64%	2.62%
8.25	8.75	259	8.46	8.49	9.27	7.78	0.23	0.014	-0.41%	0.50%	2.51%	0.08%	2.60%	2.56%
8.75	9.25	260	8.97	9.00	9.53	8.14	0.24	0.015	-0.37%	0.50%	2.46%	0.08%	2.54%	2.52%
9.25	9.75	244	9.45	9.50	10.57	8.35	0.29	0.018	-0.49%	0.50%	2.42%	0.08%	2.53%	2.48%
9.75	10.25	286	9.93	9.98	10.90	9.21	0.25	0.015	-0.54%	0.50%	2.39%	0.08%	2.50%	2.45%
10.25	10.75	267	10.46	10.50	11.44	9.62	0.27	0.017	-0.34%	0.50%	2.38%	0.08%	2.46%	2.43%
10.75	11.25	267	10.91	10.98	11.82	10.02	0.26	0.016	-0.60%	0.50%	2.37%	0.08%	2.50%	2.43%
11.25	11.75	266	11.45	11.50	12.55	10.40	0.29	0.018	-0.51%	0.50%	2.40%	0.08%	2.51%	2.45%
11.75	12.25	232	11.93	11.99	12.80	11.01	0.29	0.019	-0.50%	0.50%	2.37%	0.08%	2.48%	2.43%
12.25	12.75	238	12.43	12.50	13.42	5.82	0.51	0.033	-0.55%	0.50%	2.39%	0.08%	2.52%	2.46%
12.75	13.25	233	12.86	12.99	14.21	11.49	0.33	0.021	-0.96%	0.50%	2.38%	0.08%	2.62%	2.44%
13.25	13.75	200	13.36	13.49	14.25	11.99	0.34	0.024	-0.96%	0.50%	2.39%	0.08%	2.63%	2.45%
13.75	14.25	201	13.85	13.97	14.79	12.28	0.33	0.023	-0.85%	0.50%	2.49%	0.08%	2.69%	2.55%
14.25	14.75	137	14.39	14.50	15.54	13.65	0.34	0.029	-0.74%	0.50%	2.68%	0.08%	2.83%	2.73%
14.75	15.25	98	14.90	15.01	15.53	14.03	0.28	0.029	-0.71%	0.50%		0.08%		
15.25	15.75	71	15.39	15.46	15.98	14.62	0.27	0.032	-0.42%	0.50%		0.08%		
15.75	16.25	74	15.90	15.99	16.62	14.81	0.37	0.043	-0.58%	0.50%		0.08%		

Table 6-4 Uncertainty calculation at 82 m

Bin Lower [m/s]	Bin Upper [m/s]	N	Vrsd [m/s]	Vmm [m/s]	Vmaxrsd [m/s]	Vminrsd [m/s]	StdVrsd [m/s]	StdVrsd/√n [m/s]	Mean Deviation [%]	RSD Mounting Uncertainty [%]	Vlidar Uncertainty [%]	Separation Uncertainty [%]	Vrsd Uncertainty (k=1) [%]	Vrsd Uncertainty Reduced Mean Deviation [%]
3.75	4.25	83	4.01	4.01	4.50	3.65	0.18	0.019	-0.05%	0.50%	2.78%	0.08%	2.87%	2.87%
4.25	4.75	114	4.49	4.47	4.94	4.06	0.19	0.018	0.46%	0.50%	3.22%	0.08%	3.32%	3.28%
4.75	5.25	140	4.98	5.00	5.48	4.54	0.18	0.015	-0.29%	0.50%	3.37%	0.08%	3.43%	3.42%
5.25	5.75	138	5.52	5.50	5.93	4.98	0.18	0.016	0.39%	0.50%	3.09%	0.08%	3.17%	3.15%
5.75	6.25	229	6.01	6.01	6.64	5.30	0.22	0.015	0.02%	0.50%	2.94%	0.08%	2.99%	2.99%
6.25	6.75	221	6.46	6.49	7.04	5.70	0.22	0.015	-0.46%	0.50%	2.93%	0.08%	3.02%	2.98%
6.75	7.25	236	6.98	7.00	7.51	6.37	0.22	0.015	-0.21%	0.50%	2.69%	0.08%	2.75%	2.74%
7.25	7.75	252	7.48	7.52	8.04	6.59	0.22	0.014	-0.58%	0.50%	2.77%	0.08%	2.88%	2.82%
7.75	8.25	245	7.95	8.00	8.57	6.19	0.25	0.016	-0.54%	0.50%	2.67%	0.08%	2.78%	2.73%
8.25	8.75	261	8.45	8.50	9.29	7.84	0.22	0.014	-0.64%	0.50%	2.66%	0.08%	2.79%	2.71%
8.75	9.25	255	8.95	9.00	9.90	8.12	0.23	0.015	-0.54%	0.50%	2.63%	0.08%	2.74%	2.69%
9.25	9.75	244	9.45	9.51	10.14	8.53	0.26	0.017	-0.69%	0.50%	2.52%	0.08%	2.67%	2.58%
9.75	10.25	281	9.93	9.99	11.06	9.14	0.25	0.015	-0.63%	0.50%	2.43%	0.08%	2.56%	2.49%
10.25	10.75	256	10.42	10.50	11.62	9.46	0.27	0.017	-0.72%	0.50%	2.38%	0.08%	2.55%	2.44%
10.75	11.25	265	10.92	11.00	11.91	10.09	0.25	0.015	-0.69%	0.50%	2.31%	0.08%	2.47%	2.37%
11.25	11.75	233	11.44	11.49	12.67	10.55	0.30	0.020	-0.48%	0.50%	2.30%	0.08%	2.41%	2.36%
11.75	12.25	247	11.88	11.99	12.71	5.71	0.48	0.030	-0.93%	0.50%	2.27%	0.08%	2.52%	2.34%
12.25	12.75	219	12.44	12.50	13.22	11.43	0.28	0.019	-0.50%	0.50%	2.27%	0.08%	2.38%	2.33%
12.75	13.25	247	12.89	12.98	13.71	11.74	0.30	0.019	-0.75%	0.50%	2.25%	0.08%	2.42%	2.31%
13.25	13.75	253	13.38	13.49	14.45	11.85	0.32	0.020	-0.82%	0.50%	2.24%	0.08%	2.44%	2.30%
13.75	14.25	196	13.83	13.98	14.78	12.55	0.33	0.024	-1.07%	0.50%	2.24%	0.08%	2.54%	2.30%
14.25	14.75	151	14.37	14.49	15.21	13.35	0.29	0.024	-0.83%	0.50%	2.27%	0.08%	2.48%	2.34%
14.75	15.25	121	14.87	15.01	15.79	14.10	0.31	0.028	-0.95%	0.50%	2.28%	0.08%	2.53%	2.34%
15.25	15.75	99	15.37	15.48	16.65	14.32	0.33	0.034	-0.66%	0.50%	2.33%	0.08%	2.49%	2.40%
15.75	16.25	65	15.89	15.96	16.86	14.96	0.30	0.037	-0.46%	0.50%	2.35%	0.08%	2.46%	2.42%

Table 6-5 Uncertainty calculation at 92 m

Bin Lower [m/s]	Bin Upper [m/s]	N	Vrsd [m/s]	Vmm [m/s]	Vmaxrsd [m/s]	Vminrsd [m/s]	StdVrsd [m/s]	StdVrsd/√n [m/s]	Mean Deviation [%]	RSD Mounting Uncertainty [%]	Vlidar Uncertainty [%]	Separation Uncertainty [%]	Vrsd Uncertainty (k=1) [%]	Vrsd Uncertainty Reduced Mean Deviation [%]
3.75	4.25	84	4.00	4.01	4.46	3.69	0.16	0.018	-0.15%	0.50%	2.81%	0.08%	2.90%	2.89%
4.25	4.75	116	4.51	4.50	5.10	4.10	0.18	0.017	0.30%	0.50%	3.25%	0.08%	3.32%	3.31%
4.75	5.25	124	5.01	5.02	5.35	4.58	0.17	0.015	-0.19%	0.50%	3.40%	0.08%	3.45%	3.45%
5.25	5.75	152	5.48	5.48	6.08	4.94	0.21	0.017	-0.07%	0.50%	3.12%	0.08%	3.18%	3.18%
5.75	6.25	210	6.01	6.03	6.72	5.24	0.23	0.016	-0.25%	0.50%	2.97%	0.08%	3.03%	3.02%
6.25	6.75	242	6.46	6.49	7.08	5.64	0.22	0.014	-0.53%	0.50%	2.96%	0.08%	3.06%	3.01%
6.75	7.25	211	6.95	6.99	7.52	6.21	0.21	0.014	-0.59%	0.50%	2.72%	0.08%	2.84%	2.78%
7.25	7.75	234	7.47	7.50	8.03	6.59	0.21	0.014	-0.38%	0.50%	2.80%	0.08%	2.88%	2.86%
7.75	8.25	270	7.95	8.00	8.54	7.21	0.21	0.013	-0.59%	0.50%	2.71%	0.08%	2.82%	2.76%
8.25	8.75	246	8.45	8.51	9.18	7.89	0.23	0.015	-0.75%	0.50%	2.69%	0.08%	2.85%	2.74%
8.75	9.25	236	8.92	8.98	9.49	5.73	0.30	0.019	-0.72%	0.50%	2.67%	0.08%	2.82%	2.72%
9.25	9.75	258	9.43	9.50	10.20	8.57	0.27	0.017	-0.68%	0.50%	2.56%	0.08%	2.70%	2.61%
9.75	10.25	271	9.92	9.99	10.69	9.16	0.24	0.015	-0.72%	0.50%	2.47%	0.08%	2.62%	2.52%
10.25	10.75	252	10.41	10.50	11.21	9.58	0.26	0.016	-0.83%	0.50%	2.42%	0.08%	2.61%	2.48%
10.75	11.25	248	10.89	10.99	11.97	9.91	0.29	0.018	-0.84%	0.50%	2.35%	0.08%	2.55%	2.41%
11.25	11.75	256	11.39	11.48	12.67	10.60	0.28	0.018	-0.81%	0.50%	2.34%	0.08%	2.53%	2.39%
11.75	12.25	228	11.94	12.02	12.75	10.89	0.27	0.018	-0.63%	0.50%	2.31%	0.08%	2.45%	2.37%
12.25	12.75	221	12.40	12.49	13.36	11.41	0.28	0.019	-0.71%	0.50%	2.31%	0.08%	2.47%	2.37%
12.75	13.25	247	12.93	13.01	13.86	12.11	0.29	0.018	-0.67%	0.50%	2.29%	0.08%	2.44%	2.35%
13.25	13.75	243	13.36	13.49	14.63	11.91	0.34	0.022	-0.94%	0.50%	2.28%	0.08%	2.52%	2.34%
13.75	14.25	221	13.84	13.99	14.57	12.71	0.31	0.021	-1.07%	0.50%	2.28%	0.08%	2.57%	2.34%
14.25	14.75	157	14.33	14.47	15.01	12.67	0.33	0.026	-0.97%	0.50%	2.31%	0.08%	2.57%	2.38%
14.75	15.25	140	14.85	14.98	15.87	14.05	0.30	0.026	-0.83%	0.50%	2.32%	0.08%	2.52%	2.38%
15.25	15.75	98	15.33	15.50	16.22	14.44	0.33	0.033	-1.10%	0.50%	2.37%	0.08%	2.67%	2.43%
15.75	16.25	82	15.90	16.02	17.16	15.01	0.34	0.037	-0.74%	0.50%	2.39%	0.08%	2.57%	2.46%

Table 6-6 Uncertainty calculation at 102 m

Bin Lower [m/s]	Bin Upper [m/s]	N	Vrsd [m/s]	Vmm [m/s]	Vmaxrsd [m/s]	Vminrsd [m/s]	StdVrsd [m/s]	StdVrsd/√n [m/s]	Mean Deviation [%]	RSD Mounting Uncertainty [%]	Vlidar Uncertainty [%]	Separation Uncertainty [%]	Vrsd Uncertainty (k=1) [%]	Vrsd Uncertainty Reduced Mean Deviation [%]
3.75	4.25	89	4.00	4.01	4.27	3.59	0.16	0.017	-0.24%	0.50%	2.92%	0.08%	3.00%	2.99%
4.25	4.75	107	4.52	4.52	4.90	4.10	0.17	0.016	0.04%	0.50%	3.34%	0.08%	3.40%	3.40%
4.75	5.25	124	5.02	5.01	5.50	4.56	0.17	0.016	0.21%	0.50%	3.48%	0.08%	3.54%	3.53%
5.25	5.75	167	5.50	5.52	6.09	4.95	0.20	0.015	-0.32%	0.50%	3.21%	0.08%	3.28%	3.27%
5.75	6.25	193	5.99	6.02	6.66	5.06	0.22	0.016	-0.45%	0.50%	3.07%	0.08%	3.15%	3.12%
6.25	6.75	237	6.46	6.49	7.12	5.60	0.22	0.014	-0.53%	0.50%	3.06%	0.08%	3.15%	3.11%
6.75	7.25	228	6.96	7.00	7.56	6.40	0.21	0.014	-0.52%	0.50%	2.83%	0.08%	2.93%	2.88%
7.25	7.75	222	7.47	7.51	8.11	5.76	0.24	0.016	-0.57%	0.50%	2.91%	0.08%	3.01%	2.96%
7.75	8.25	254	7.96	8.00	8.56	7.31	0.21	0.013	-0.55%	0.50%	2.81%	0.08%	2.92%	2.86%
8.25	8.75	246	8.43	8.49	9.25	7.89	0.21	0.013	-0.74%	0.50%	2.80%	0.08%	2.94%	2.85%
8.75	9.25	250	8.94	8.99	9.57	8.17	0.23	0.015	-0.49%	0.50%	2.78%	0.08%	2.87%	2.83%
9.25	9.75	250	9.43	9.50	10.14	8.60	0.27	0.017	-0.70%	0.50%	2.67%	0.08%	2.81%	2.72%
9.75	10.25	287	9.92	9.99	10.74	9.22	0.25	0.015	-0.70%	0.50%	2.58%	0.08%	2.73%	2.64%
10.25	10.75	238	10.40	10.50	11.22	9.70	0.26	0.017	-0.95%	0.50%	2.54%	0.08%	2.76%	2.60%
10.75	11.25	252	10.89	10.99	12.00	10.00	0.25	0.016	-0.94%	0.50%	2.47%	0.08%	2.70%	2.53%
11.25	11.75	230	11.38	11.48	12.87	10.65	0.28	0.018	-0.91%	0.50%	2.46%	0.08%	2.68%	2.52%
11.75	12.25	225	11.95	12.00	12.84	11.08	0.28	0.019	-0.49%	0.50%	2.44%	0.08%	2.54%	2.49%
12.25	12.75	222	12.39	12.48	13.53	11.36	0.30	0.020	-0.77%	0.50%	2.43%	0.08%	2.60%	2.49%
12.75	13.25	232	12.90	13.01	13.93	11.92	0.29	0.019	-0.80%	0.50%	2.41%	0.08%	2.59%	2.47%
13.25	13.75	247	13.38	13.49	14.80	12.01	0.35	0.022	-0.86%	0.50%	2.40%	0.08%	2.61%	2.46%
13.75	14.25	214	13.80	13.97	14.42	12.77	0.28	0.019	-1.25%	0.50%	2.40%	0.08%	2.76%	2.46%
14.25	14.75	192	14.34	14.45	15.18	12.84	0.30	0.022	-0.78%	0.50%	2.44%	0.08%	2.61%	2.49%
14.75	15.25	141	14.83	14.98	15.94	14.07	0.29	0.025	-0.99%	0.50%	2.44%	0.08%	2.69%	2.50%
15.25	15.75	113	15.35	15.48	16.26	14.54	0.30	0.028	-0.83%	0.50%	2.49%	0.08%	2.68%	2.55%
15.75	16.25	80	15.85	15.98	16.66	15.05	0.29	0.033	-0.81%	0.50%	2.51%	0.08%	2.70%	2.57%

Table 6-7 Uncertainty calculation at 122 m

Bin Lower [m/s]	Bin Upper [m/s]	N	Vrsd [m/s]	Vmm [m/s]	Vmaxrsd [m/s]	Vminrsd [m/s]	StdVrsd [m/s]	StdVrsd/√n [m/s]	Mean Deviation [%]	RSD Mounting Uncertainty [%]	Vlidar Uncertainty [%]	Separation Uncertainty [%]	Vrsd Uncertainty (k=1) [%]	Vrsd Uncertainty Reduced Mean Deviation [%]
3.75	4.25	84	3.99	4.00	4.39	3.70	0.17	0.019	-0.19%	0.50%	3.49%	0.08%	3.56%	3.55%
4.25	4.75	81	4.47	4.47	5.08	4.10	0.19	0.021	-0.08%	0.50%	3.14%	0.08%	3.22%	3.22%
4.75	5.25	130	5.00	4.99	5.40	4.52	0.17	0.015	0.17%	0.50%	3.41%	0.08%	3.46%	3.46%
5.25	5.75	157	5.50	5.51	6.06	5.02	0.20	0.016	-0.04%	0.50%	3.35%	0.08%	3.40%	3.40%
5.75	6.25	198	5.98	6.00	6.56	4.70	0.23	0.016	-0.28%	0.50%	3.29%	0.08%	3.35%	3.34%
6.25	6.75	244	6.44	6.47	7.15	5.50	0.22	0.014	-0.49%	0.50%	3.20%	0.08%	3.29%	3.25%
6.75	7.25	203	6.96	6.99	7.69	6.40	0.22	0.016	-0.49%	0.50%	3.13%	0.08%	3.22%	3.18%
7.25	7.75	212	7.47	7.51	8.01	6.89	0.20	0.014	-0.59%	0.50%	3.13%	0.08%	3.23%	3.18%
7.75	8.25	227	7.96	7.99	8.62	7.32	0.21	0.014	-0.32%	0.50%	3.04%	0.08%	3.10%	3.09%
8.25	8.75	229	8.47	8.51	9.13	7.87	0.23	0.015	-0.44%	0.50%	2.89%	0.08%	2.97%	2.94%
8.75	9.25	217	8.93	8.98	10.14	8.13	0.26	0.018	-0.55%	0.50%	3.00%	0.08%	3.10%	3.05%
9.25	9.75	262	9.43	9.49	10.49	8.59	0.26	0.016	-0.65%	0.50%	2.96%	0.08%	3.08%	3.01%
9.75	10.25	288	9.94	9.99	10.70	9.24	0.23	0.014	-0.45%	0.50%	2.87%	0.08%	2.95%	2.92%
10.25	10.75	242	10.41	10.49	12.36	9.67	0.26	0.017	-0.77%	0.50%	2.79%	0.08%	2.94%	2.84%
10.75	11.25	238	10.91	11.00	11.85	9.90	0.25	0.017	-0.78%	0.50%	2.74%	0.08%	2.90%	2.79%
11.25	11.75	241	11.39	11.49	13.14	10.79	0.29	0.019	-0.84%	0.50%	2.74%	0.08%	2.91%	2.79%
11.75	12.25	187	11.93	12.01	12.88	11.34	0.28	0.020	-0.61%	0.50%	2.72%	0.08%	2.84%	2.78%
12.25	12.75	227	12.42	12.49	13.36	11.36	0.29	0.019	-0.58%	0.50%	2.72%	0.08%	2.84%	2.78%
12.75	13.25	202	12.90	13.00	14.16	11.73	0.30	0.021	-0.73%	0.50%	2.72%	0.08%	2.86%	2.77%
13.25	13.75	202	13.35	13.48	14.81	12.37	0.34	0.024	-1.00%	0.50%	2.72%	0.08%	2.95%	2.78%
13.75	14.25	229	13.85	14.00	15.08	12.24	0.35	0.023	-1.09%	0.50%	2.77%	0.08%	3.02%	2.82%
14.25	14.75	232	14.36	14.49	15.40	12.83	0.32	0.021	-0.94%	0.50%	2.74%	0.08%	2.95%	2.79%
14.75	15.25	155	14.86	14.98	15.59	14.12	0.25	0.020	-0.80%	0.50%	2.77%	0.08%	2.93%	2.82%
15.25	15.75	126	15.32	15.47	16.00	14.45	0.28	0.025	-0.96%	0.50%	2.79%	0.08%	3.00%	2.84%
15.75	16.25	96	15.85	15.99	16.33	14.89	0.28	0.028	-0.84%	0.50%	2.83%	0.08%	3.00%	2.88%

Table 6-8 Uncertainty calculation at 142 m

Bin Lower [m/s]	Bin Upper [m/s]	N	Vrsd [m/s]	Vmm [m/s]	Vmaxrsd [m/s]	Vminrsd [m/s]	StdVrsd [m/s]	StdVrsd/√n [m/s]	Mean Deviation [%]	RSD Mounting Uncertainty [%]	Vlidar Uncertainty [%]	Separation Uncertainty [%]	Vrsd Uncertainty (k=1) [%]	Vrsd Uncertainty Reduced Mean Deviation [%]
3.75	4.25	69	3.99	3.99	4.46	3.61	0.17	0.020	0.03%	0.50%	4.31%	0.08%	4.37%	4.37%
4.25	4.75	70	4.49	4.49	5.30	4.02	0.21	0.025	0.16%	0.50%	3.21%	0.08%	3.30%	3.30%
4.75	5.25	117	5.02	5.01	5.78	4.43	0.20	0.018	0.27%	0.50%	3.91%	0.08%	3.97%	3.96%
5.25	5.75	147	5.57	5.53	7.02	5.05	0.27	0.022	0.85%	0.50%	3.76%	0.08%	3.91%	3.82%
5.75	6.25	181	6.00	6.01	6.66	4.52	0.25	0.019	-0.26%	0.50%	3.88%	0.08%	3.93%	3.93%
6.25	6.75	226	6.46	6.48	7.19	5.89	0.22	0.015	-0.23%	0.50%	3.71%	0.08%	3.76%	3.75%
6.75	7.25	191	6.98	7.00	7.49	6.38	0.22	0.016	-0.35%	0.50%	3.61%	0.08%	3.67%	3.65%
7.25	7.75	177	7.45	7.49	7.95	7.00	0.20	0.015	-0.50%	0.50%	3.55%	0.08%	3.62%	3.59%
7.75	8.25	207	7.95	7.99	8.64	7.41	0.21	0.015	-0.45%	0.50%	3.44%	0.08%	3.51%	3.48%
8.25	8.75	206	8.45	8.49	9.23	7.79	0.24	0.017	-0.51%	0.50%	3.28%	0.08%	3.37%	3.33%
8.75	9.25	216	8.95	8.99	9.77	8.22	0.24	0.016	-0.39%	0.50%	3.34%	0.08%	3.40%	3.38%
9.25	9.75	231	9.46	9.50	10.23	8.68	0.25	0.016	-0.44%	0.50%	3.34%	0.08%	3.41%	3.38%
9.75	10.25	238	9.94	9.99	11.12	9.08	0.27	0.017	-0.52%	0.50%	3.27%	0.08%	3.35%	3.31%
10.25	10.75	267	10.45	10.50	11.20	9.64	0.24	0.015	-0.52%	0.50%	3.14%	0.08%	3.22%	3.18%
10.75	11.25	224	10.93	11.00	11.72	9.92	0.26	0.017	-0.67%	0.50%	3.06%	0.08%	3.18%	3.11%
11.25	11.75	224	11.39	11.49	12.45	10.48	0.28	0.019	-0.83%	0.50%	3.04%	0.08%	3.20%	3.09%
11.75	12.25	199	11.94	12.00	13.53	11.14	0.30	0.021	-0.45%	0.50%	2.99%	0.08%	3.07%	3.04%
12.25	12.75	217	12.45	12.50	13.63	11.50	0.31	0.021	-0.42%	0.50%	2.99%	0.08%	3.06%	3.03%
12.75	13.25	201	12.92	12.99	14.34	11.91	0.31	0.022	-0.54%	0.50%	2.95%	0.08%	3.05%	3.00%
13.25	13.75	194	13.38	13.49	14.75	12.63	0.30	0.021	-0.78%	0.50%	2.94%	0.08%	3.08%	2.98%
13.75	14.25	164	13.84	14.01	15.30	12.45	0.37	0.029	-1.20%	0.50%	2.90%	0.08%	3.19%	2.95%
14.25	14.75	205	14.37	14.52	15.22	12.94	0.31	0.022	-0.99%	0.50%	2.91%	0.08%	3.12%	2.96%
14.75	15.25	196	14.87	14.98	15.76	13.63	0.29	0.021	-0.74%	0.50%	2.90%	0.08%	3.04%	2.95%
15.25	15.75	149	15.40	15.49	17.66	14.48	0.36	0.030	-0.55%	0.50%	2.90%	0.08%	3.00%	2.95%
15.75	16.25	116	15.87	15.99	16.61	14.99	0.28	0.026	-0.73%	0.50%	2.91%	0.08%	3.05%	2.96%

Table 6-9 Uncertainty calculation at 162 m

Bin Lower [m/s]	Bin Upper [m/s]	N	Vrsd [m/s]	Vmm [m/s]	Vmaxrsd [m/s]	Vminrsd [m/s]	StdVrsd [m/s]	StdVrsd/√n [m/s]	Mean Deviation [%]	RSD Mounting Uncertainty [%]	Vlidar Uncertainty [%]	Separation Uncertainty [%]	Vrsd Uncertainty (k=1) [%]	Vrsd Uncertainty Reduced Mean Deviation [%]
3.75	4.25	58	4.01	3.99	5.44	3.69	0.25	0.033	0.47%	0.50%	4.31%	0.08%	4.44%	4.42%
4.25	4.75	57	4.51	4.50	4.87	4.07	0.18	0.024	0.14%	0.50%	3.21%	0.08%	3.29%	3.29%
4.75	5.25	82	5.03	5.02	5.49	4.69	0.19	0.020	0.12%	0.50%	3.91%	0.08%	3.97%	3.96%
5.25	5.75	138	5.58	5.55	9.53	5.00	0.41	0.035	0.60%	0.50%	3.76%	0.08%	3.89%	3.85%
5.75	6.25	171	6.05	6.01	9.73	4.67	0.44	0.033	0.60%	0.50%	3.88%	0.08%	4.00%	3.95%
6.25	6.75	189	6.48	6.47	8.04	5.98	0.27	0.020	0.15%	0.50%	3.71%	0.08%	3.76%	3.76%
6.75	7.25	159	6.97	6.98	9.38	6.29	0.30	0.024	-0.13%	0.50%	3.61%	0.08%	3.66%	3.66%
7.25	7.75	163	7.47	7.49	8.07	6.97	0.22	0.017	-0.30%	0.50%	3.55%	0.08%	3.60%	3.59%
7.75	8.25	180	7.96	8.00	8.59	7.29	0.23	0.017	-0.55%	0.50%	3.44%	0.08%	3.53%	3.48%
8.25	8.75	178	8.46	8.52	9.39	7.67	0.25	0.019	-0.74%	0.50%	3.28%	0.08%	3.41%	3.33%
8.75	9.25	188	8.94	8.98	9.71	8.29	0.22	0.016	-0.53%	0.50%	3.34%	0.08%	3.42%	3.38%
9.25	9.75	195	9.46	9.50	10.05	8.65	0.25	0.018	-0.39%	0.50%	3.34%	0.08%	3.40%	3.38%
9.75	10.25	196	9.95	10.01	10.73	9.15	0.25	0.018	-0.54%	0.50%	3.27%	0.08%	3.36%	3.31%
10.25	10.75	205	10.38	10.46	11.21	9.52	0.25	0.017	-0.79%	0.50%	3.14%	0.08%	3.28%	3.18%
10.75	11.25	227	10.92	11.00	11.57	10.08	0.25	0.016	-0.72%	0.50%	3.06%	0.08%	3.19%	3.11%
11.25	11.75	213	11.41	11.49	12.33	10.24	0.30	0.020	-0.73%	0.50%	3.04%	0.08%	3.17%	3.09%
11.75	12.25	175	11.93	12.00	13.14	11.26	0.28	0.021	-0.58%	0.50%	2.99%	0.08%	3.09%	3.04%
12.25	12.75	193	12.45	12.49	13.96	11.53	0.36	0.026	-0.37%	0.50%	2.99%	0.08%	3.06%	3.04%
12.75	13.25	206	12.92	12.99	13.73	11.91	0.30	0.021	-0.56%	0.50%	2.95%	0.08%	3.05%	3.00%
13.25	13.75	191	13.41	13.49	14.58	12.44	0.31	0.022	-0.54%	0.50%	2.94%	0.08%	3.03%	2.98%
13.75	14.25	157	13.89	13.99	15.39	12.94	0.37	0.029	-0.70%	0.50%	2.90%	0.08%	3.04%	2.95%
14.25	14.75	161	14.29	14.50	14.98	12.57	0.35	0.028	-1.42%	0.50%	2.91%	0.08%	3.28%	2.96%
14.75	15.25	181	14.87	15.01	15.71	13.72	0.28	0.021	-0.94%	0.50%	2.90%	0.08%	3.10%	2.95%
15.25	15.75	159	15.37	15.49	16.07	13.85	0.31	0.024	-0.76%	0.50%	2.90%	0.08%	3.05%	2.95%
15.75	16.25	137	15.89	16.00	16.64	15.08	0.31	0.026	-0.65%	0.50%	2.91%	0.08%	3.03%	2.96%

Table 6-10 Uncertainty calculation at 182 m

Bin Lower [m/s]	Bin Upper [m/s]	N	Vrsd [m/s]	Vmm [m/s]	Vmaxrsd [m/s]	Vminrsd [m/s]	StdVrsd [m/s]	StdVrsd/√n [m/s]	Mean Deviation [%]	RSD Mounting Uncertainty [%]	Vlidar Uncertainty [%]	Separation Uncertainty [%]	Vrsd Uncertainty (k=1) [%]	Vrsd Uncertainty Reduced Mean Deviation [%]
3.75	4.25	53	3.99	3.99	4.42	3.59	0.18	0.025	-0.18%	0.50%	4.31%	0.08%	4.39%	4.39%
4.25	4.75	46	4.50	4.47	4.95	4.13	0.20	0.030	0.49%	0.50%	3.21%	0.08%	3.35%	3.32%
4.75	5.25	75	5.00	5.00	5.45	4.55	0.19	0.022	-0.10%	0.50%	3.91%	0.08%	3.97%	3.97%
5.25	5.75	114	5.50	5.51	5.91	4.82	0.19	0.018	-0.25%	0.50%	3.76%	0.08%	3.82%	3.81%
5.75	6.25	160	5.99	6.00	6.79	5.27	0.21	0.017	-0.21%	0.50%	3.88%	0.08%	3.93%	3.92%
6.25	6.75	149	6.48	6.49	7.49	5.90	0.23	0.019	-0.12%	0.50%	3.71%	0.08%	3.76%	3.76%
6.75	7.25	157	6.97	6.99	8.26	6.35	0.24	0.019	-0.26%	0.50%	3.61%	0.08%	3.66%	3.65%
7.25	7.75	129	7.48	7.50	8.14	7.04	0.21	0.018	-0.22%	0.50%	3.55%	0.08%	3.60%	3.59%
7.75	8.25	178	7.97	8.01	8.56	7.44	0.22	0.016	-0.39%	0.50%	3.44%	0.08%	3.51%	3.48%
8.25	8.75	139	8.45	8.51	9.03	7.64	0.22	0.019	-0.69%	0.50%	3.28%	0.08%	3.40%	3.33%
8.75	9.25	164	8.94	8.98	9.67	8.43	0.23	0.018	-0.42%	0.50%	3.34%	0.08%	3.41%	3.38%
9.25	9.75	153	9.45	9.49	10.06	8.40	0.25	0.020	-0.45%	0.50%	3.34%	0.08%	3.41%	3.38%
9.75	10.25	178	9.95	10.00	10.80	9.25	0.25	0.018	-0.51%	0.50%	3.27%	0.08%	3.35%	3.31%
10.25	10.75	171	10.40	10.49	11.08	9.45	0.25	0.019	-0.89%	0.50%	3.14%	0.08%	3.31%	3.18%
10.75	11.25	170	10.91	11.02	11.47	10.14	0.24	0.018	-0.92%	0.50%	3.06%	0.08%	3.24%	3.11%
11.25	11.75	190	11.41	11.50	12.25	10.40	0.25	0.018	-0.77%	0.50%	3.04%	0.08%	3.18%	3.09%
11.75	12.25	174	11.93	11.98	12.91	11.29	0.27	0.020	-0.48%	0.50%	2.99%	0.08%	3.08%	3.04%
12.25	12.75	164	12.44	12.50	14.24	11.52	0.34	0.027	-0.53%	0.50%	2.99%	0.08%	3.08%	3.04%
12.75	13.25	182	12.94	12.98	14.21	12.09	0.31	0.023	-0.33%	0.50%	2.95%	0.08%	3.02%	3.00%
13.25	13.75	173	13.42	13.48	14.65	12.24	0.36	0.027	-0.50%	0.50%	2.94%	0.08%	3.03%	2.99%
13.75	14.25	166	13.94	14.01	15.32	13.19	0.31	0.024	-0.49%	0.50%	2.90%	0.08%	2.99%	2.95%
14.25	14.75	130	14.30	14.50	15.47	12.76	0.36	0.032	-1.31%	0.50%	2.91%	0.08%	3.24%	2.97%
14.75	15.25	160	14.87	14.98	15.75	13.70	0.31	0.025	-0.76%	0.50%	2.90%	0.08%	3.05%	2.95%
15.25	15.75	155	15.36	15.49	16.27	14.06	0.33	0.027	-0.84%	0.50%	2.90%	0.08%	3.07%	2.95%
15.75	16.25	131	15.88	15.99	16.68	15.07	0.30	0.026	-0.70%	0.50%	2.91%	0.08%	3.04%	2.96%

Table 6-11 Uncertainty calculation at 202 m

Bin Lower [m/s]	Bin Upper [m/s]	N	Vrsd [m/s]	Vmm [m/s]	Vmaxrsd [m/s]	Vminrsd [m/s]	StdVrsd [m/s]	StdVrsd/√n [m/s]	Mean Deviation [%]	RSD Mounting Uncertainty [%]	Vlidar Uncertainty [%]	Separation Uncertainty [%]	Vrsd Uncertainty (k=1) [%]	Vrsd Uncertainty Reduced Mean Deviation [%]
3.75	4.25	34	4.01	4.00	4.47	3.75	0.20	0.034	0.37%	0.50%	4.31%	0.08%	4.44%	4.42%
4.25	4.75	50	4.50	4.50	5.08	4.25	0.17	0.024	0.12%	0.50%	3.21%	0.08%	3.29%	3.29%
4.75	5.25	65	5.05	5.01	5.52	4.68	0.18	0.023	0.79%	0.50%	3.91%	0.08%	4.05%	3.97%
5.25	5.75	89	5.48	5.51	5.88	5.02	0.20	0.021	-0.49%	0.50%	3.76%	0.08%	3.85%	3.82%
5.75	6.25	135	5.97	5.99	6.86	5.24	0.23	0.020	-0.33%	0.50%	3.88%	0.08%	3.94%	3.93%
6.25	6.75	138	6.48	6.50	7.24	5.76	0.24	0.020	-0.22%	0.50%	3.71%	0.08%	3.77%	3.76%
6.75	7.25	120	6.95	6.98	7.42	6.25	0.22	0.020	-0.47%	0.50%	3.61%	0.08%	3.68%	3.65%
7.25	7.75	123	7.50	7.50	8.17	6.92	0.22	0.020	0.00%	0.50%	3.55%	0.08%	3.59%	3.59%
7.75	8.25	135	7.96	7.98	8.58	7.45	0.22	0.019	-0.23%	0.50%	3.44%	0.08%	3.49%	3.49%
8.25	8.75	145	8.44	8.49	8.99	7.72	0.24	0.020	-0.53%	0.50%	3.28%	0.08%	3.37%	3.33%
8.75	9.25	136	8.98	9.02	9.54	8.42	0.23	0.020	-0.46%	0.50%	3.34%	0.08%	3.41%	3.38%
9.25	9.75	123	9.44	9.49	10.21	8.51	0.27	0.025	-0.46%	0.50%	3.34%	0.08%	3.41%	3.38%
9.75	10.25	150	9.99	10.02	10.88	9.32	0.24	0.019	-0.29%	0.50%	3.27%	0.08%	3.33%	3.31%
10.25	10.75	163	10.41	10.49	10.99	9.37	0.25	0.019	-0.76%	0.50%	3.14%	0.08%	3.27%	3.18%
10.75	11.25	149	10.92	11.01	11.62	10.06	0.26	0.021	-0.82%	0.50%	3.06%	0.08%	3.22%	3.11%
11.25	11.75	167	11.41	11.50	12.06	10.83	0.23	0.017	-0.74%	0.50%	3.04%	0.08%	3.17%	3.09%
11.75	12.25	161	11.96	11.99	12.88	10.55	0.27	0.021	-0.32%	0.50%	2.99%	0.08%	3.06%	3.04%
12.25	12.75	147	12.41	12.49	13.37	11.50	0.29	0.024	-0.70%	0.50%	2.99%	0.08%	3.12%	3.04%
12.75	13.25	137	13.00	12.99	14.39	11.99	0.33	0.028	0.03%	0.50%	2.95%	0.08%	3.00%	3.00%
13.25	13.75	157	13.41	13.49	14.60	12.24	0.34	0.027	-0.61%	0.50%	2.94%	0.08%	3.05%	2.99%
13.75	14.25	137	13.94	14.00	14.83	12.89	0.33	0.028	-0.44%	0.50%	2.90%	0.08%	2.99%	2.95%
14.25	14.75	144	14.41	14.49	15.85	12.94	0.37	0.031	-0.59%	0.50%	2.91%	0.08%	3.02%	2.97%
14.75	15.25	124	14.87	15.01	15.58	13.20	0.36	0.032	-0.92%	0.50%	2.90%	0.08%	3.10%	2.95%
15.25	15.75	129	15.38	15.48	15.98	14.61	0.25	0.022	-0.62%	0.50%	2.90%	0.08%	3.01%	2.95%
15.75	16.25	126	15.85	15.98	16.66	14.31	0.34	0.030	-0.82%	0.50%	2.91%	0.08%	3.07%	2.96%

7 IMPORTANT REMARKS AND LIMITATIONS

The reported floating lidar verification presents a reasonable means to assure overall system integrity of the floating lidar unit before deployment and is meant to give an indication of the quality of wind data produced by the floating lidar unit. Any statement given in the context of system integrity and data quality related results within this report are limited to the given test site conditions that include sea states and meteorological conditions observed during the verification.

The IEC-complaint bin-wise uncertainty results provided in this report may serve as a traceable means to judge the uncertainty of the lidar unit.

In general, DNV GL recommends that a floating lidar unit undergoes a pre-deployment verification test no more than one year before its application deployment. A post-deployment verification of a floating lidar maybe necessary when:

- Inconsistencies in the data captured during the wind resource campaign are observed;
- Inconsistencies in buoy operation are observed; or
- Known or assumed incidents to the buoy or floating lidar measurement system have occurred.

Otherwise, a pre-deployment verification campaign may be considered sufficient.

8 OBSERVATIONS AND RECOMMENDATIONS

An AXYS Flidar WindSentinel (Buoy 120) moored in the Atlantic Ocean at the MVCO was verified against the reference lidar at the ASIT. Measurement heights between 52 m and 202 m were available for wind speed correlations. The duration of the verification was 56 days. The test period and wind data coverage were considered sufficient to evaluate the floating lidar against the OWA Roadmap for commercialization of Floating Lidar Devices.

The following are noteworthy aspects of the test:

- Verification of Buoy 120 is limited to turbulence intensities ≤ 0.15 from the top mounted cup anemometer on the ASIT reference mast. This limitation is due to filtering required during the reference lidar WLS7-436 verification for reasons detailed in [2].
- Except for the 52 m comparison, the floating lidar measured heights 2.8 m above the reference lidar measurement heights. Ideally measurements should be made at the same height. However, given the low wind shear this difference is within an acceptable limit for comparison.

The results of the verification are summarized in Table 8-1.

Table 8-1 OWA verification results summary

	Verification height [m]									
	202	**182**	**162**	**142**	**122**	**102**	**92**	**82**	**62**	**52**
OWA database completion	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
System availability [%]	100									
Concurrent availability for verification [%]	64.8	71.9	78.4	84.0	86.9	87.2	86.4	85.7	84.8	84.4
Wind speed correlation coefficient, R^2	0.998	0.997	0.997	0.997	0.997	0.997	0.997	0.996	0.996	0.996
Wind speed correlation slope, m	0.993	0.991	0.991	0.991	0.991	0.990	0.991	0.992	0.993	0.984
Wind direction correlation coefficient, R^2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Wind direction slope, m	1.002	1.001	1.001	1.001	1.001	1.001	1.000	1.000	1.000	1.000
Wind direction Y-intercept, b [°]	1.9	2.0	2.0	2.0	1.9	1.9	1.9	1.9	1.9	1.7

[1] See APPENDIX A
[2] All wind speed greater than 2 m/s.

The performance verification and uncertainty calculation have been carried out in accordance with the IEC Standard yielding a traceable uncertainty measure.

In summary, the OTS AXYS Flidar WindSentinel Buoy 120 has demonstrated its capability to produce accurate wind speed and direction data. The wind speeds recorded at reference lidar were up to 25.85 m/s at 52 m and 35.87 m/s at 200 m. DNV GL notes that all conclusions on the capabilities of the Buoy 120 drawn from this pre-deployment verification campaign are valid under sea state and meteorological conditions similar to those experienced during the campaign duration, only.

DNV GL recommends that care be taken with respect to the formal use of floating lidar turbulence and extreme wind speed measurements as they are known to be different from classical anemometry measurements. DNV GL notes that good measurement and data collection practices need to be maintained for all wind speed measurements, be they floating lidar or more conventional anemometry. Therefore, special care needs to be exercised in the transportation, installation, and ongoing maintenance of the floating lidar as it may be exposed to a wide range of environmental conditions. A key element of any formal wind study is the traceability of the wind speed data uncertainty. Hence, a strict uncertainty assessment (which is not part of this report) should be employed. Furthermore, it is recommended that thorough practices of documenting the salient features of floating lidar installation and maintenance are instigated from the outset.

9 REFERENCES

1. “Port Site Acceptance Test of AXYS WindSentinel Buoy 120,” 10161669-HOU-T-01-B, DNV GL 28 January 2020.

2. “Independent performance verification of the WHOI ASIT Windcube V2 at the West Texas A&M University Test Site”, 10161669-HOU-R-01-B, DNV GL, 19 December 2019.

3. Carbon Trust Offshore Wind Accelerator roadmap for the commercial acceptance of floating lidar technology, Version 2.0, The Carbon Trust, 9 October 2018.

4. OWA Floating LiDAR Roadmap Update – Deployments of Floating LiDAR Systems, D04, Version 2.0, The Carbon Trust, 21 March 2018.

5. International Standard: IEC 61400-12-1: Wind turbines – Part 12-1: Power performance measurements of electricity producing wind turbines. Ed. 2., Apr. 2017

6. OWA Report 2017-001: Lidar Uncertainty Standard Review Methodology Review and Recommendations, June 2018.

7. "Summary of Classification of Remote Sensing Device Type: Leosphere Wind Cube,” PP18030.A1, Deutsche WindGuard Consulting GmbH, 24 May 2018.

10 GLOSSARY

The following table lists abbreviations and acronyms used in this report.

Abbreviation Acronym	**Meaning**
AC	Acceptance Criterion
amsl	Above mean sea level
ASIT	Air-Sea Interaction Tower
Buoy 120	AXYS Flidar WindSentinel 6M
DNV GL	DNV GL Energy USA, Inc.
FLS	Floating lidar system
IEC	International Electro-technical Commission
KPI	Key Performance Indicator
msl	Mean sea level
MVCO	Martha’s Vineyard Coastal Observatory
MWD	Mean Wind Direction
MWS	Mean Wind Speed
OTS	Ocean Tech Services, LLC
OWA	Offshore Wind Accelerator roadmap for the commercial acceptance of floating LIDAR technology
RSD	Remote Sensing Device
STD	Standard deviation
TI	Turbulence Intensity
WD	Wind direction
WHOI	Woods Hole Oceanographic Institution
WS	Wind speed

APPENDIX A – KEY PERFORMANCE INDICATORS AND ACCEPTANCE CRITERIA ACCORDING TO [3]

Table A-1 List of KPIs and ACs relevant for Wind Data Accuracy assessment

KPI	Definition / Rationale	Acceptance Criteria [1]	
		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 ranges a) all above 2 m/s b) 4 to 16 m/s given achieved data coverage requirements.	0.98 – 1.02	0.97 – 1.03
R^2_{mws}	**Mean Wind Speed – Coefficient of Determination** Correlation Co-efficient returned from single variant regression A threshold is imposed on the Correlation Coefficient value. Analysis shall be applied to wind speed ranges a) all above 2 m/s b) 4 to 16 m/s given achieved data coverage requirements.	>0.98	>0.97
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

KPI	Definition / Rationale	Acceptance Criteria [1]	
		Best Practice	Minimum
OFF_{mwd}	**Mean Wind Direction – Offset (absolute value)** (same as for M_{mwd})	< 5°	< 7.5°
R^2_{mwd}	**Mean Wind Direction – Coefficient of Determination** (same as for M_{mwd})	> 0.97	> 0.95

[1] Acceptance Criteria in the form of "**best practice**" and "**minimum**" allowable tolerances have been imposed on mean differences, 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. KPIs outside the best practice or minimum acceptance criteria are marked as "**deviation**".

APPENDIX B – TIME SERIES OF WIND SPEED

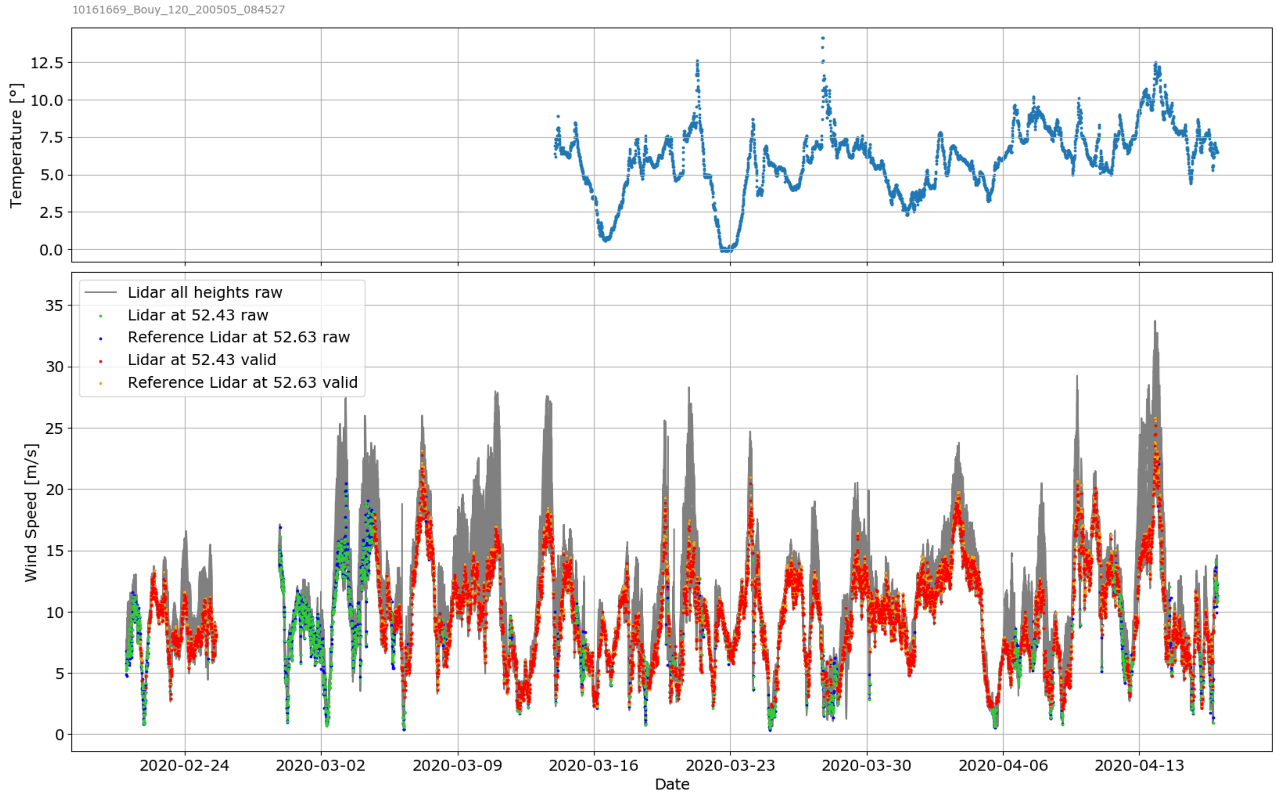


Figure B-1 Wind Speed at 52 m and Mast temperature time series

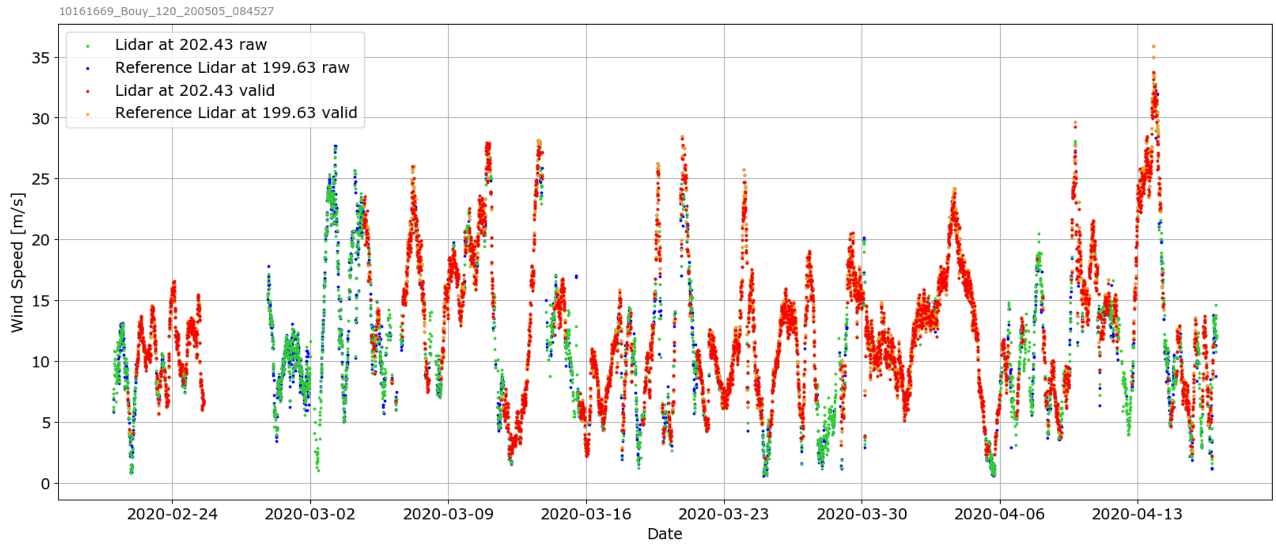


Figure B-2 Wind Speed time series for 200 m

APPENDIX C – WIND DIRECTION

The scatter plots of wind direction below show wind directions for wind speed greater than 2 m/s.

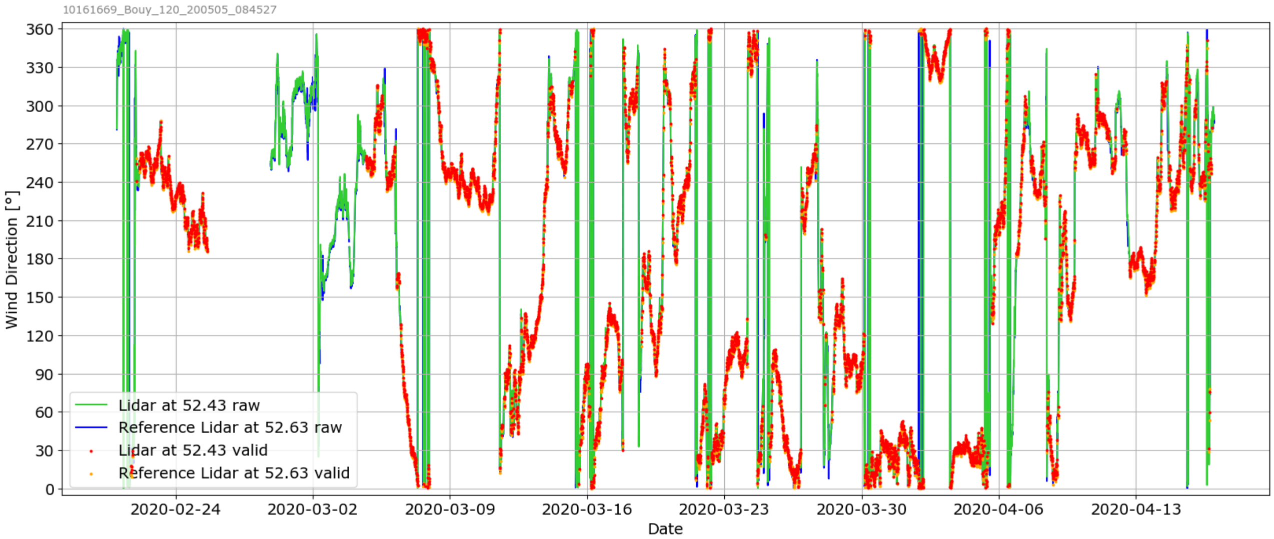


Figure C-1 Wind direction time series of the floating lidar and reference lidar at 52 m

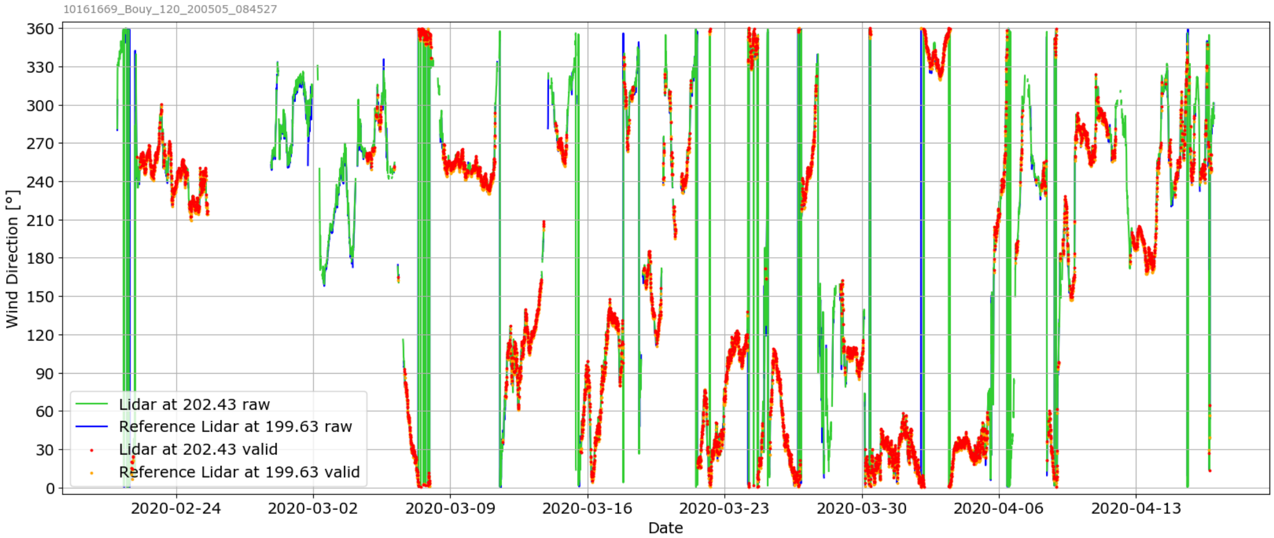


Figure C-2 Wind direction time series and scatter plot of the floating lidar and reference lidar at 202 m

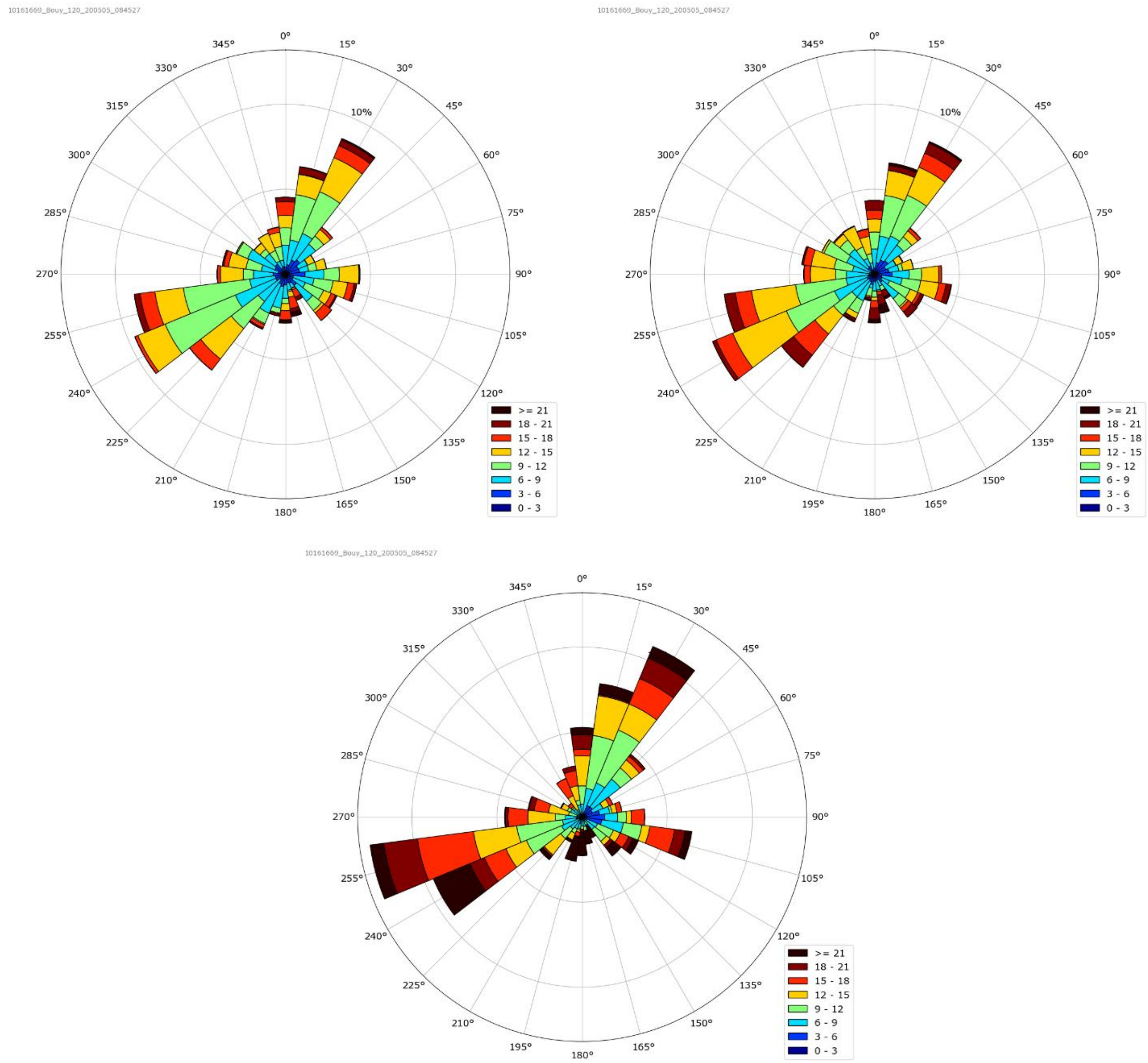


Figure C-3 Buoy 120 wind rose and sector averaged wind speed distribution for the valid measurement sectors at 52 m (top left), 92 m (top right) and 202 m (bottom)

(Radial lines in 5% intervals)

APPENDIX D – SEA STATES AND METEOROLOGICAL CONDITIONS

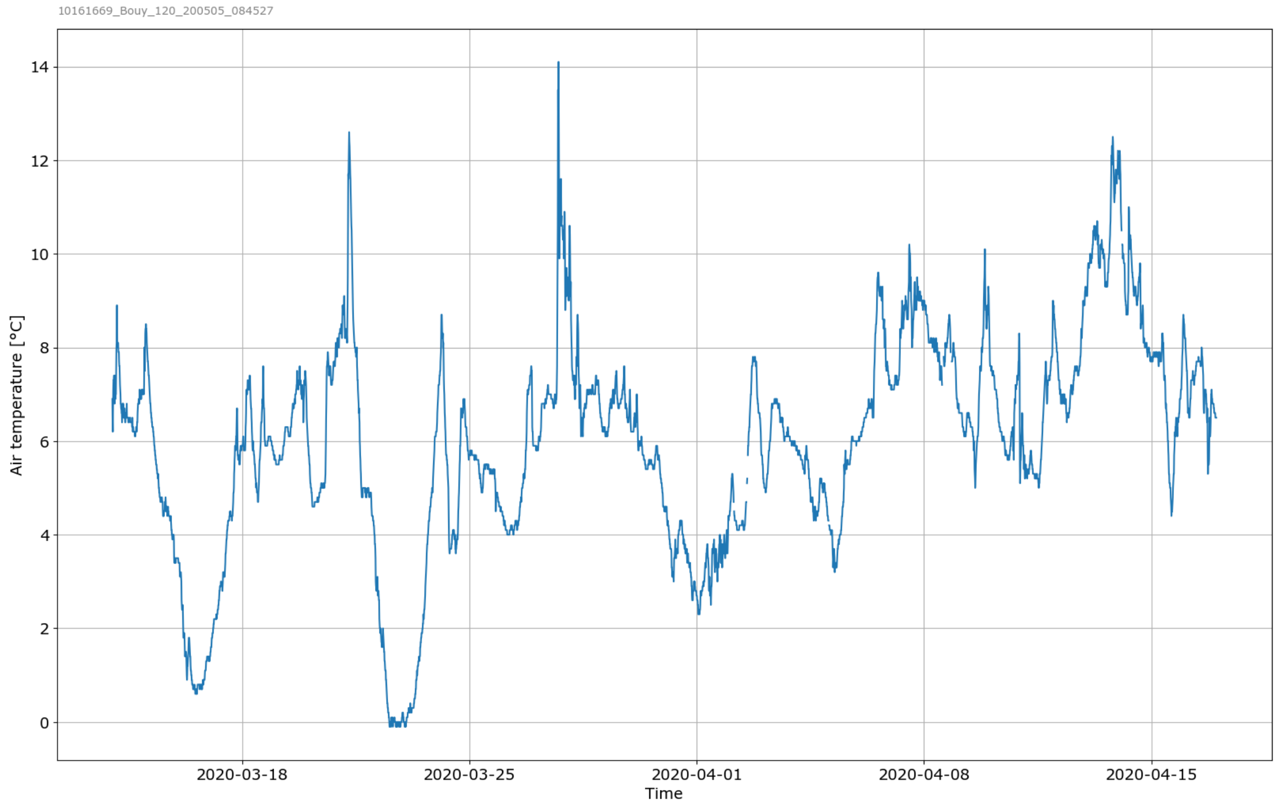


Figure D-1 Time series of air temperature at the reference mast

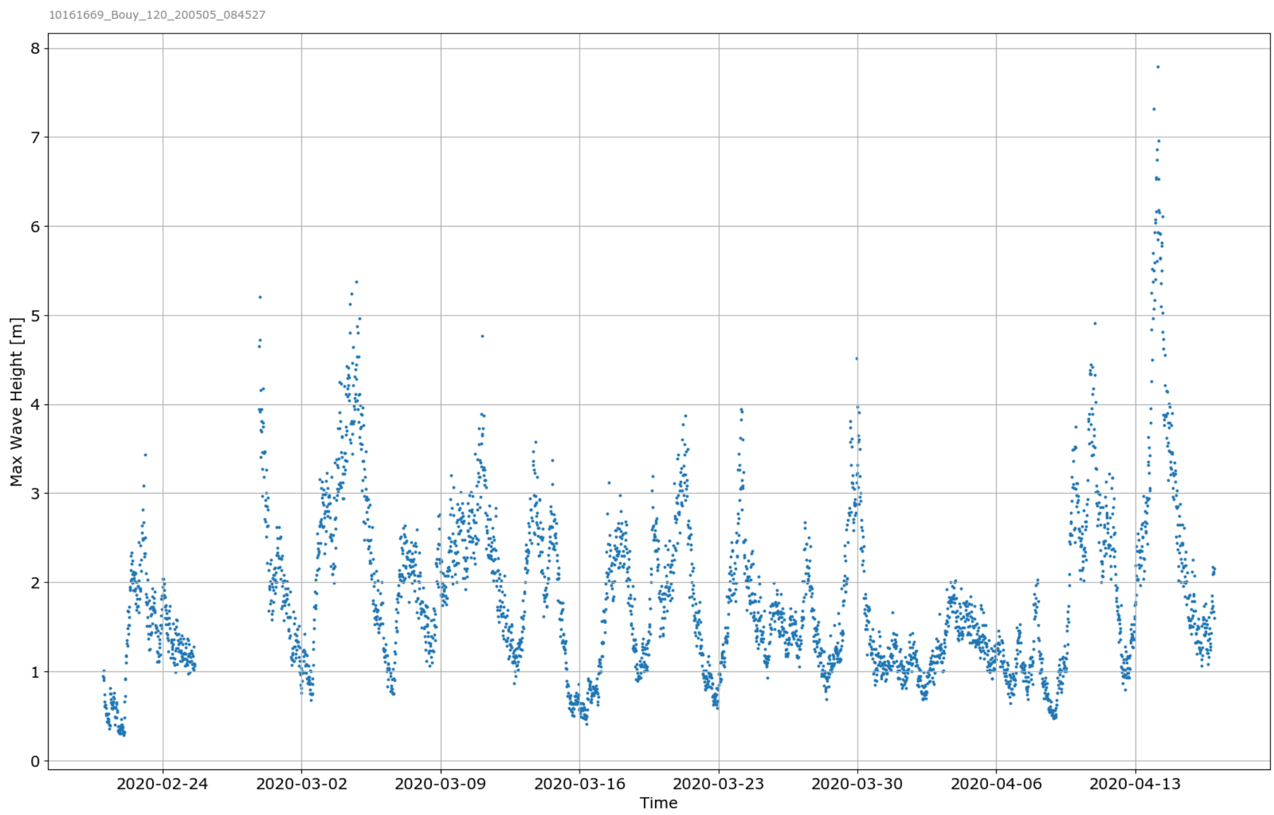


Figure D-2 Maximum Wave Height at Buoy 120

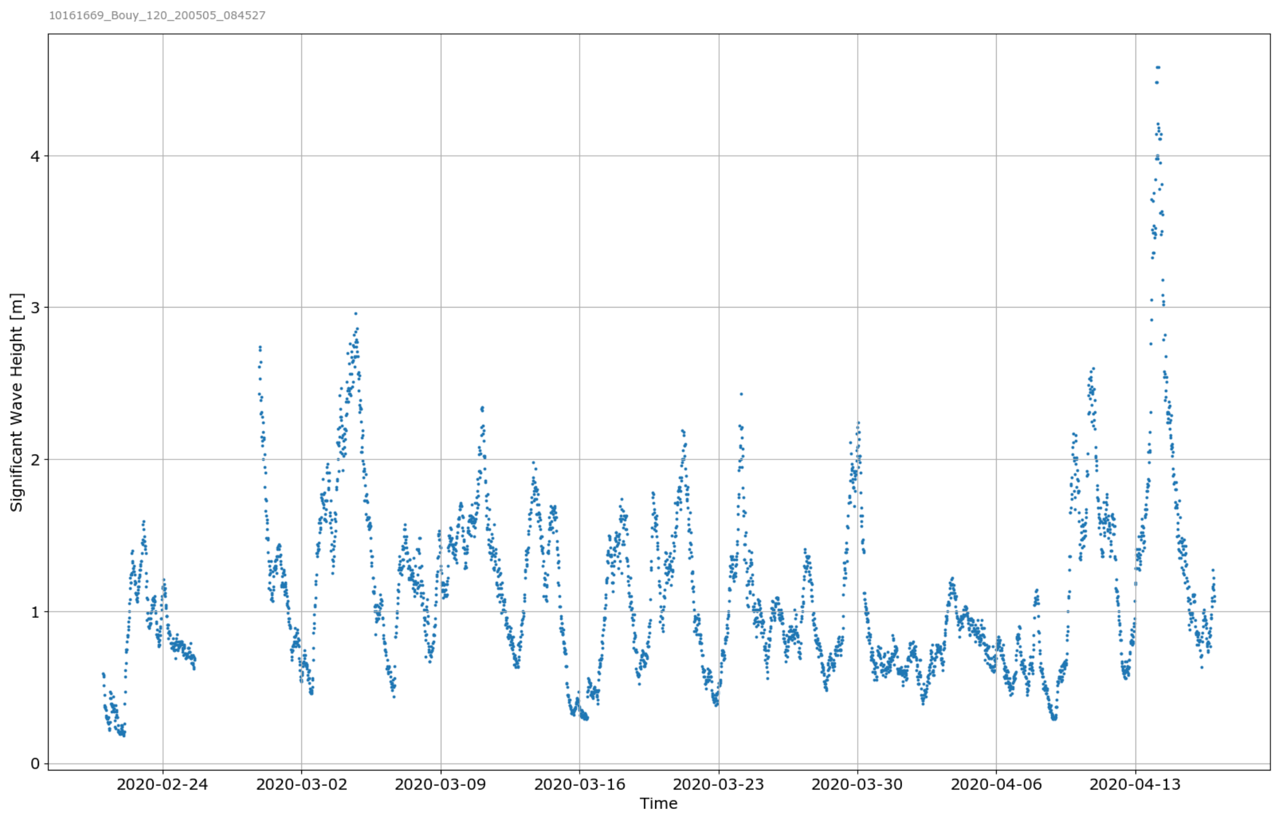


Figure D-3 Significant Wave Height at Buoy 120

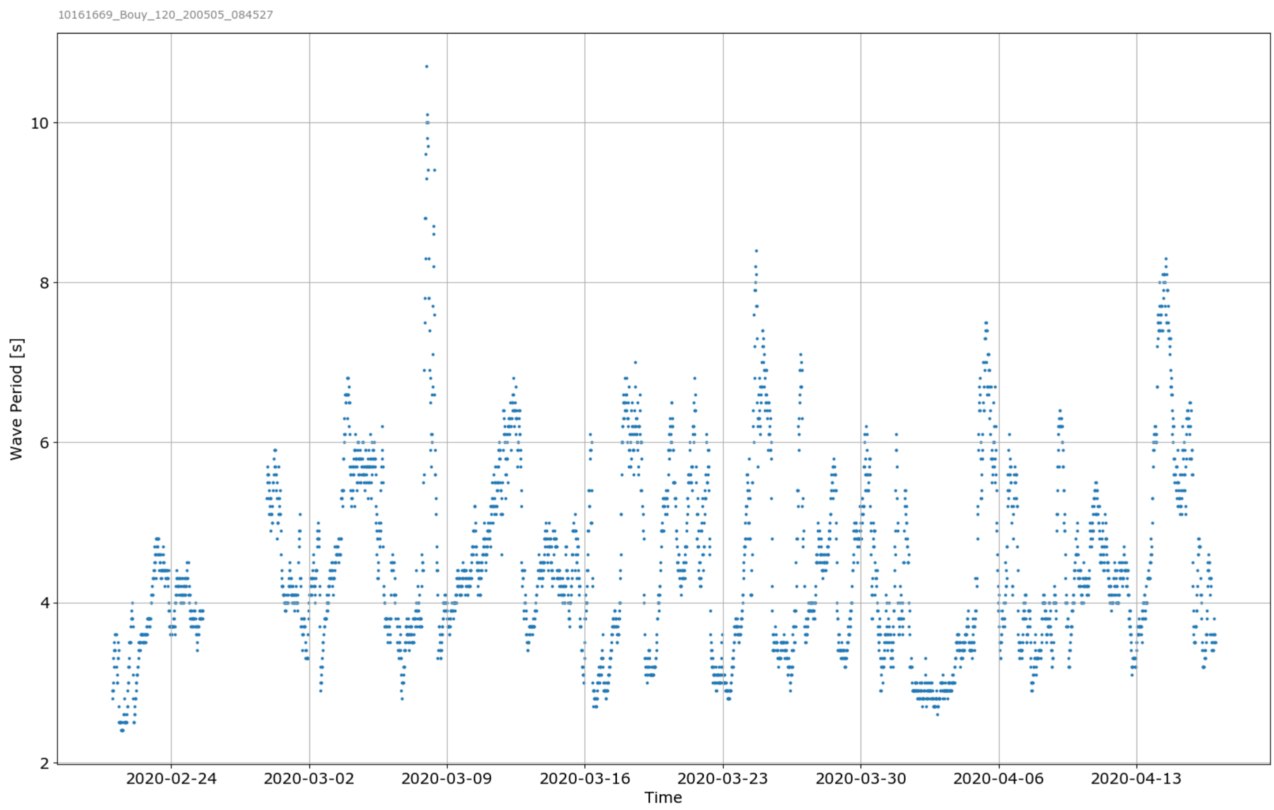


Figure D-4 Average Wave Period at Buoy 120

APPENDIX E – IEC ANNEX L UNCERTAINTY ANALYSES

1. Reference uncertainty

The reference uncertainty of the specific reference heights is calculated based on the verification of the reference lidar [2], the reference lidar Lidar Type Classification [7], and the mounting effects. Table E-1 shows the applied reference lidar verification uncertainty components. The classification uncertainty is provided in Table E-2. A mounting uncertainty of 0.2% was applied for all measurement heights.

Table E-1 reference lidar verification uncertainty

Lidar WLS7-436 Uncertainty (k=1) %				
Bin [m/s]	130m	125m	95 m	60 m
4.0	3.56	2.70	2.29	3.02
4.5	2.09	2.24	2.81	2.11
5.0	3.06	2.60	2.98	2.17
5.5	2.87	2.52	2.66	2.01
6.0	3.02	2.44	2.48	2.18
6.5	2.80	2.32	2.47	2.09
7.0	2.66	2.22	2.18	2.09
7.5	2.58	2.22	2.28	1.86
8.0	2.43	2.09	2.16	1.88
8.5	2.20	1.87	2.14	1.80
9.0	2.28	2.03	2.11	1.73
9.5	2.28	1.97	1.97	1.68
10.0	2.18	1.84	1.85	1.63
10.5	1.98	1.71	1.79	1.61
11.0	1.86	1.63	1.69	1.60
11.5	1.82	1.62	1.67	1.64
12.0	1.74	1.60	1.64	1.60
12.5	1.73	1.60	1.63	1.63
13.0	1.67	1.59	1.60	1.62
13.5	1.64	1.60	1.59	1.63
14.0	1.58	1.68	1.59	1.78
14.5	1.60	1.63	1.64	2.03
15.0	1.58	1.67	1.65	-
15.5	1.58	1.71	1.72	-
16.0	1.59	1.78	1.75	-

Table E-2 reference lidar classification uncertainty

Height [m]	[%]	Height [m]	[%]
135.0	2.43	85.0	1.62
130.0	2.31	80.0	1.56
125.0	2.25	75.0	1.62
120.0	2.19	70.0	1.62
115.0	2.08	65.0	1.67
110.0	2.02	60.0	1.73
105.0	1.96	55.0	1.73
100.0	1.79	50.0	1.79
95.0	1.73	45.0	1.79
90.0	1.62	40.0	1.85

2. Mean deviation of the remote sensor measurements and the reference measurements

This is the relative deviation between the bin averages of the floating lidar and the reference lidar measurement divided by the reference measurement.

3. Standard uncertainty of the measurement of the remote sensing device

The standard deviation of the measurements was divided by the square root of the number of data records per bin. The relative uncertainty was calculated by dividing the value by the bin average wind speed of the mast (reference) measurement.

4. Mounting uncertainty of the remote sensor at the verification test

The uncertainty of the remote sensing device due to non-ideal levelling was estimated to be 0.5 %.

5. Uncertainty due to non-homogenous flow

This is considered to be negligible offshore.

6. Uncertainty due to separation distance

DNV GL considered the uncertainty due to the separation distance between floating lidar and reference lidar according to the proposed formula (4) in [6]. For a separation distance, D, of 165 m at a coastal site, the uncertainty was calculated to be 0.08%.

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

DNV GL notes that the above calculation is different from the approach in the IEC but reflects a broad knowledge of floating lidar investigations.

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, technical assurance, software, and independent expert advisory services to the maritime, oil & gas, and energy industries. We also provide certification services to customers across a wide range of industries. Combining leading technical and operational expertise, risk methodology and in-depth industry knowledge, we empower our customers' decisions and actions with trust and confidence. We continuously invest in research and collaborative innovation to provide our customers and society with operational and technological foresight. Operating in more than 100 countries, we are dedicated to helping our customers make the world safer, smarter, and greener.