Verification of WS170 at Lichteiland Goeree (LEG) during May 2021

Revision	Reason	Date
1	Initial Document	27/08/2021
2	Updated from feedback comments Final Document.	23/09/2021

Status	Name	Date
Author	M Young	23/09/2021
Checked By	A Oldroyd	23/09/2021
Approved By	A Oldroyd	23/09/2021

List of Contents

List of Figures

List of Tables

1 Introduction

This report verifies wind speed and direction measurements from the Fugro Seawatch wind LiDAR onboard buoy WS170 deployed next to the Lichteiland Goeree (LEG) platform during May 2021. LEG is situated ~20 km NW from the coast of the Netherlands in the North Sea (Figure 1-1). Concurrent wind measurements from a LiDAR installed on the platform are used to verify the measurements from WS170. Two verification protocols are used to evaluate WS170 wind speeds – the Carbon Trust protocol (Carbon Trust Offshore Wind Accelerator Roadmap for the commercial acceptance of floating lidar technology) and a new Simplified verification protocol. Wind direction verifications are based on Carbon Trust.

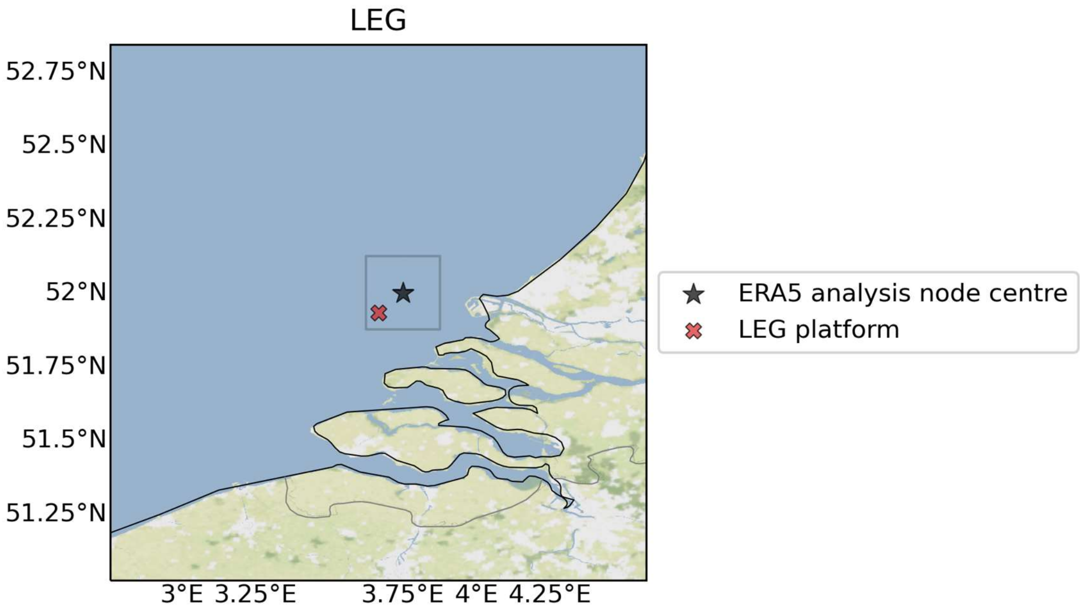

Figure 1-1: Map of LEG location at 51.93°N, 3.67°E relative to ERA5 0.25° node with centre location 52°N, 3.75°E. The grey square depicts the boundary of the node.

2 Datasets

10-min wind speed and direction measurements are analysed from the Fugro Seawatch wind LiDAR onboard buoy WS170 and the Leosphere Windcube LiDAR on the LEG platform. The verification period is from 1650 on 01-05-2021 to 23:50 on 17-05-2021. Measurements are evaluated at the seven equivalent heights observed by both LiDARs (Table 2-1).

During initial validations, a systematic bias of ~6-7° in wind direction measurements at WS170 was discovered. When the buoy was recovered and inspected, the bias appeared to be a result of the main mast being twisted and bent affecting the differential GPS measurements used as reference for the LiDAR wind directions. The LiDAR wind directions were therefore re-processed by Fugro using the back-up magnetic compass as reference instead.

A 10-minute lag was evident between measurements from WS170 and the LEG LiDAR. The datasets were therefore synchronized by shifting all WS170 measurements backwards by 10 min.

	Measurement heights (m)
LEG LiDAR	62, 90, 115, 140, 165, 190, 215, 240, 265, 290
WS170	40, 62, 80, 90, 102, 115, 140, 150, 165, 190, 240
Verified	62, 90, 115, 140, 165, 190, 240

Table 2-1: Measurement heights of each LiDAR dataset and the concurrent heights used for verification.

Winds and atmospheric variables from the ERA5 re-analysis dataset obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) are also used to examine the winds during the measurement period and compare with each LiDAR measurement. The area covered by the ERA5 analysis node in relation to LEG is shown in Figure 1-1.

Please note that the LEG platform data is provided as a quality controlled dataset and no further checks are made on the reference data, unless an artefact in the correlation analysis requires further investigation.

3 Verification approaches

3.1 Carbon Trust

For the Carbon Trust verification protocol, data availability is benchmarked against the Overall Post-processed Data Availability ($OPDA_{CA}$) data availability KPI. The required $OPDA_{CA}$ data availability acceptance criteria are ≥ 85% for the Stage 2 (pre-commercial) and ≥ 90% for Stage 3 (commercial).

For wind speed accuracy assessments, the Carbon Trust approach recommends a minimum of 40 data points within different wind speed bins to ensure an adequate data population is distributed across a given wind speed range. The recommended reference wind speed bins are spaced every 1 m/s from 2 to 12 m/s, every 2 m/s from 12 to 16 m/s with an optional final bin for measurements > 16 m/s.

If the data population meets these criteria, the wind speed accuracy is assessed across reference LiDAR wind speeds

1) > 2 m/s

2) 4-16m/s

Accuracy is quantified for wind speeds at each height level, applying a single-variant linear regression between the reference and verification wind speeds with the y-intercept constrained to zero. The resulting slope and r-squared values from the regression are the key performance indicators (KPIs) used to evaluate the FLS performance against the acceptance criteria (AC) shown in Table 3-1

Accuracy for wind direction is quantified by a two-variant linear regression between reference and estimated wind directions for wind speeds > 2 m/s and evaluating slope, r-squared and mean difference (bias) against the criteria in Table 3-1.

Verification	KPI	Minimum	Best Practice
Speed	Slope	0.97 – 1.03	0.98 – 1.02
	R-squared	> 0.97	> 0.98
Direction	Slope	0.95 – 1.05	0.97 – 1.03
	R-squared	> 0.95	> 0.97
	Mean difference	< 10°	< 5°

Table 3-1: Carbon Trust Floating LiDAR verification acceptance criteria for wind speed and direction KPIs.

3.2 Simplified Verification Protocol

The Simplified verification aims to simplify the data population required for a wind speed verification assessment with an additional examination of wind speed distributions to establish whether an upper-range wind speed filter should be applied to the verification data population.

In the Simplified approach, data availability is also based on the Carbon Trust $OPDA_{CA}$ KPI. However, to maximise the data available for a short-term campaign, the acceptable $OPDA_{CA}$ threshold is fixed to ≥ 90%, which is equivalent to Carbon Trust maturity stage 3. This is opposed to allowing a possible lower threshold of ≥ 85% that would be acceptable for maturity stage 2.

The Simplified verification data population requirements are:

1. Measurement minimum duration – 14 days;
2. Minimum data points of 1440 > 2m/s (after post-processing and required filtering);
3. All data > 2m/s to be available for analysis.

Additionally, the application of an upper range wind speed filter is considered to ensure that verification results are not biased by variations in data population across the wind speed distribution. To diagnose this, a Quantile-Quantile (Q-Q) plot is used to compare the verification wind speed distributions from the reference LiDAR and evaluated LiDAR. For wind speed ranges in which there are clear deviations between the distributions, both the number of data points and data distributions across those ranges are examined to check for possible errors and decide whether an upper range filter should be applied to the data before conducting the accuracy assessment.

Once all filtering has been applied, wind speed accuracy is quantified using the same approach as the Carbon Trust protocol, applying a single-variant linear regression between the reference and verification wind speeds with the y-intercept constrained to zero. The resulting slope and r-squared values from the regression are used to evaluate the FLS performance against the *minimum* and *best practice* AC as defined by the Carbon Trust protocol (Table 3-1).

4 Results

4.1 Summary of winds during verification period

Frequency distributions of ERA5 hourly wind speed (115m) and direction (100m) during the verification period are shown in Figure 4-1. For comparison with LiDAR wind speeds, ERA5 100m wind speeds were extrapolated to the closest LiDAR height of 115m using the time-varying power law exponent calculated between 10m and 100m wind speeds during the period. The mean ERA5 115m wind speed was 7.57 m/s and wind directions were predominantly south westerly.

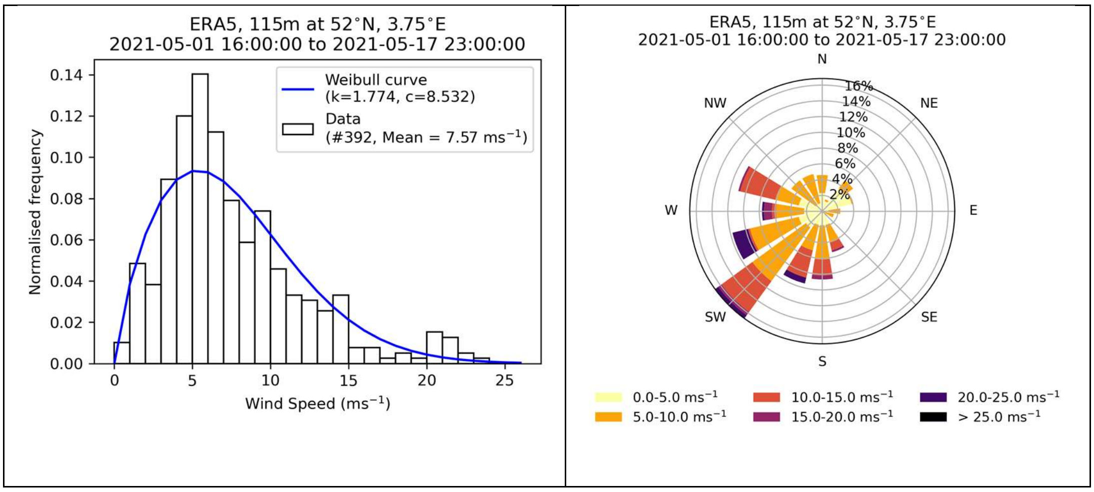

Figure 4-1: Wind speed frequency histogram (left) and wind rose (right) derived from ERA5 hourly wind speeds (115m extrapolated from 100m using shear exponent between 10m and 100m) and wind directions (100m).

The distributions of 10-min wind speed and direction observations at 115 m from LEG LiDAR and WS170 during the verification period are shown in Figure 4-2 and Figure 4-3. The mean 115m wind speed was 7.82 m/s at LEG LiDAR and 7.72 m/s at WS170 (see Table 4-1 for means at other height levels) and both exhibit similar Weibull distributions. The in-situ mean wind speeds are marginally higher than ERA5. Like ERA5, the in-situ wind directions are also predominantly south westerly during the period. However, the wind rose distributions from LEG and WS170 are more alike than ERA5. ERA5 observes more frequent winds from the west-north-west sector.

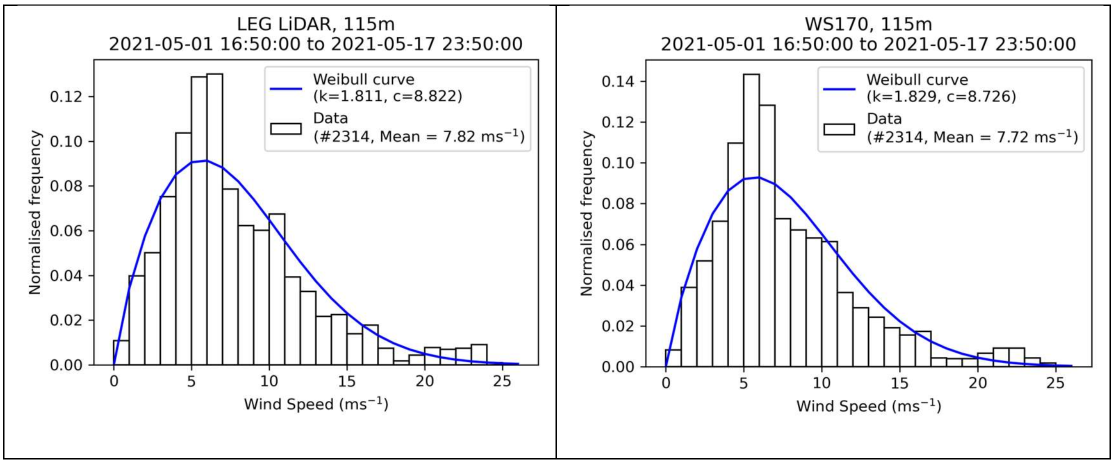

Figure 4-2: 10-min wind speed frequency histograms and Weibull parameters at 115m from LEG LiDAR (left) and WS170 (right).

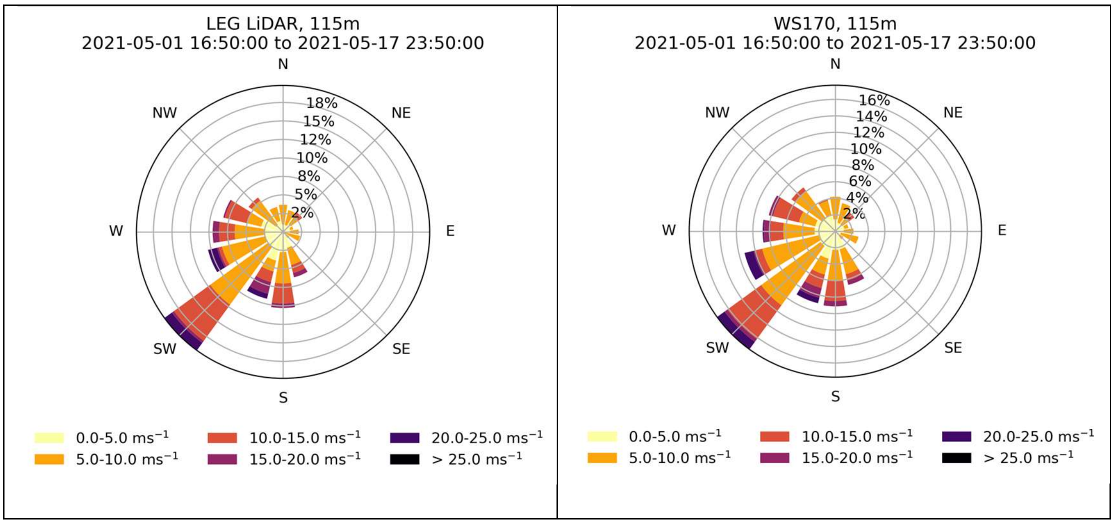

Figure 4-3: Wind roses derived from 10-min wind speed and direction measurements at 115m from LEG LiDAR (left) and WS170 (right).

Maximum 115m wind speeds of 24.2 m/s (LEG) and 24.5 m/s (WS170) occurred during a storm on 4th May which was associated with the minimum air pressure of 992.4 hPa during the verification period (Figure 4-4; Table 4-1).

Following the storm, the rest of the period was generally characterized by low to moderate wind speeds (2-16 m/s). The predominant wind directions were south-westerly to westerly, but periods of northerly to north easterly winds were also observed on 11th, 13th and 14th May.

The mean vertical wind shear (shear exponent between 62m and 115m) was 0.104 at LEG LiDAR and 0.102 at WS170. Strong shear and increased shear variability occurred during the second half of the period which was also associated with both warmer temperatures and higher humidity.

The mean air temperature at WS170 was 9.7°C and ranged from a minimum of 4.2°C on 7th May to a max of 15.1°C on 9th May. The mean air pressure was 1007.5 hPa with a maximum of 1021.5 hPa on 2nd May.

Sea conditions were rough during and following the storm on 4th May where maximum values in the significant wave height H_{mo} of 3.8m and maximum wave height H_{max} of 6.1m were recorded. However, throughout the rest of the period the sea state ranged mostly from calm to moderate with median wave heights of 0.7 m for H_{mo} and 1.1m for H_{max}.

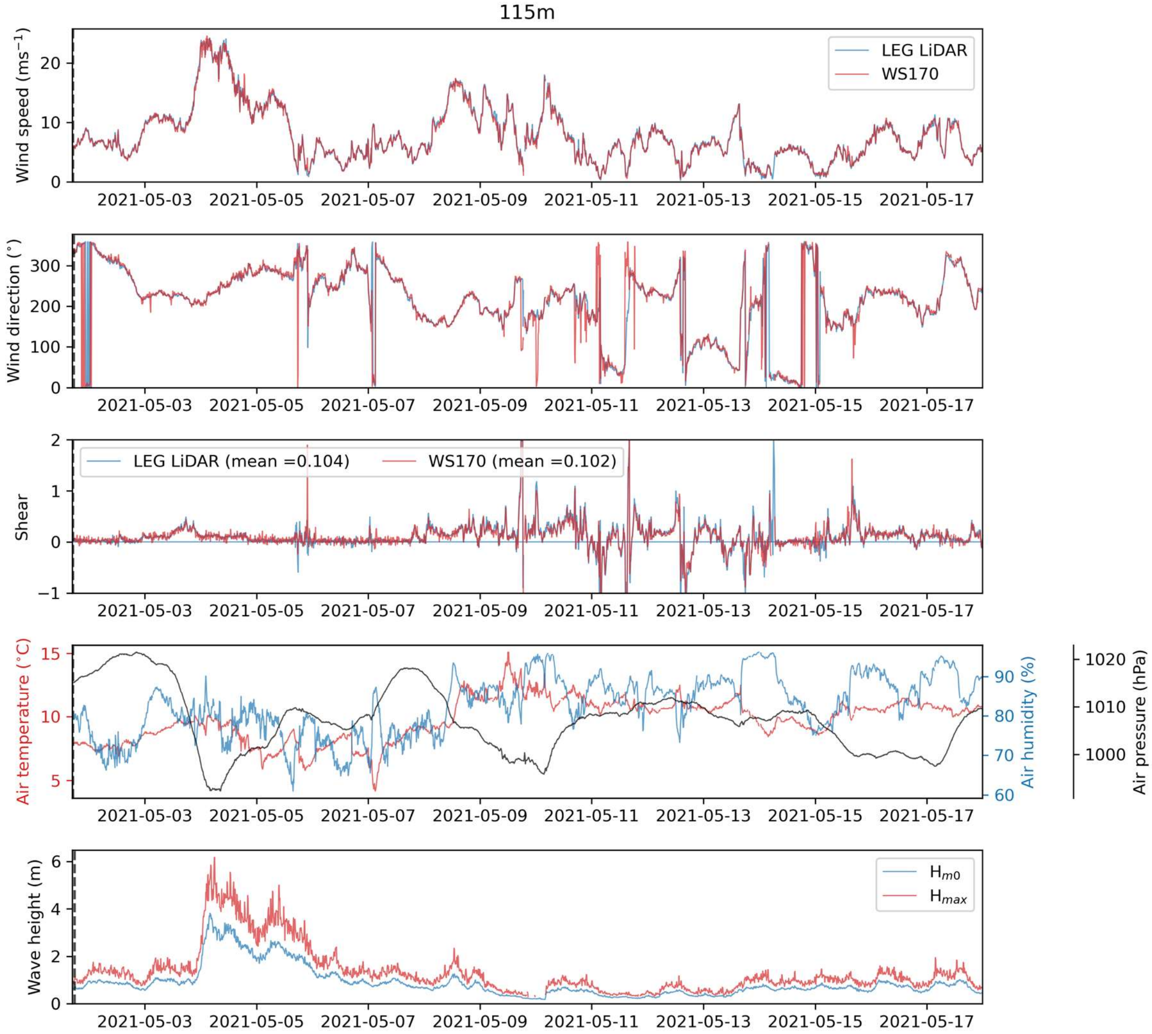

Figure 4-4: Timeseries of 10-min measurements of 115m wind speed, 115m wind direction, vertical wind shear (shear exponent calculated between 62m and 115m wind speed) from LEG LiDAR and WS170; and air temperature, humidity, air pressure and wave height at WS170.

Figure 4-5 compares the temporal variation in hourly wind speed, direction and vertical wind shear from ERA5 and both LiDAR systems during the verification period. ERA5 wind speeds exhibit reasonable agreement with the LiDAR measurements with an r-squared of 0.87. For wind direction, primary variations are captured but the correlation is low due to mismatches between the variability observed by ERA5 and the in-situ observations. ERA5 also underestimates vertical wind shear and shear variations captured by the LiDAR observations, with a mean of 0.088 compared to means of 0.135 at LEG and 0.134 at WS170. The overall underestimation of wind variability in ERA5 can be expected due to the coarser spatial and temporal resolution in the reanalysis compared the direct in-situ observations.

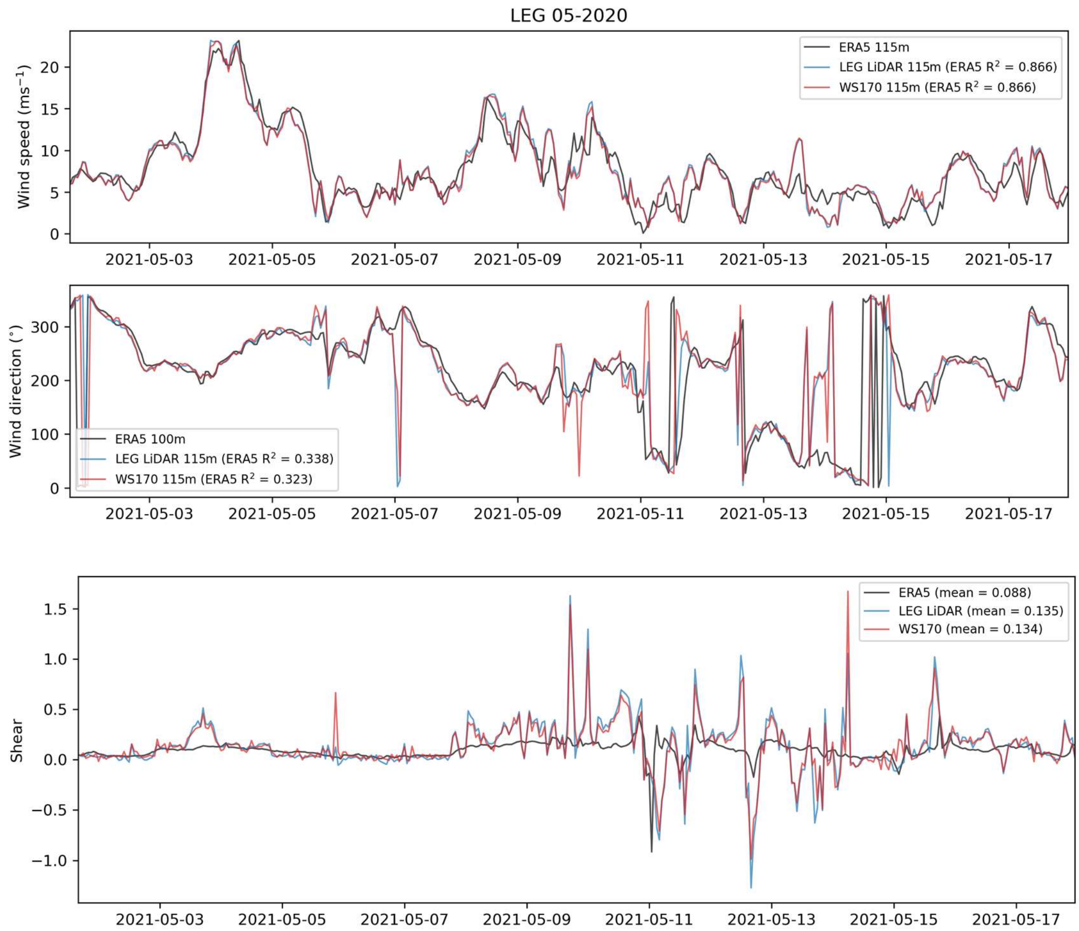

Figure 4-5: Timeseries of hourly 115m wind speed, wind direction and vertical wind shear (power law exponent) estimated by ERA5, LEG and WS170. The shear exponent is calculated using 10m and 100m wind speeds in ERA5 and 62m and 115m wind speeds in LEG and WS170.

4.2 Data availability

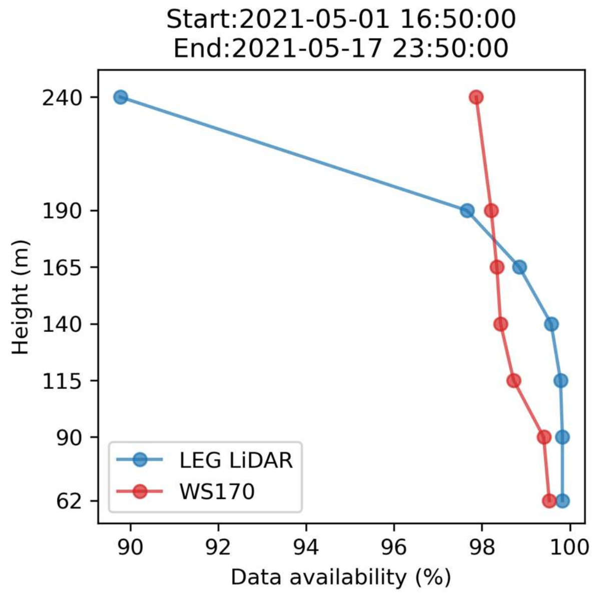

Figure 4-6: Wind speed data availability for LEG LiDAR and WS170 during verification period.

Data availabilities for both LEG LiDAR and WS170 throughout the verification period were above 97% at all height levels except 240m at LEG LiDAR where availability was 89.8% (Figure 4-6 and Table 4-1). The data availabilities therefore pass the Carbon Trust stage 2 $OPDA_{CA}$ threshold of 85%, and, except for 240m, pass the Carbon Trust stage 3 and Simplified verification $OPDA_{CA}$ threshold of ≥ 90%.

	LEG LiDAR			WS170		
Height (m)	**Availability (%)**	**Mean (m/s)**	**Max (m/s)**	**Availability (%)**	**Mean (m/s)**	**Max (m/s)**
62	99.83	7.22	22.74	99.53	7.17	23.30
90	99.83	7.56	23.48	99.40	7.50	23.69
115	99.79	7.78	24.17	98.72	7.73	24.51
140	99.57	7.99	24.86	98.42	7.94	24.94
165	98.85	8.22	25.58	98.34	8.14	25.97
190	97.66	8.38	26.25	98.21	8.29	26.39
240	89.77	8.66	27.27	97.87	8.59	27.05

Table 4-1: Wind speed data availability, mean and maximum measured by LEG LiDAR and WS170 during the verification period.

The reference wind speed data populations binned according to the Carbon Trust protocol are shown in Figure 4-7. At all height levels, the data populations exceed the 40 data point minimum within all bins across the required wind speed range of 2 to 16 m/s. However, many of the optional bins above 16 m/s do not reach the 40 data point minimum.

For the Simplified protocol, the number of data points > 2 m/s exceed the required 1440 data point minimum at all height levels.

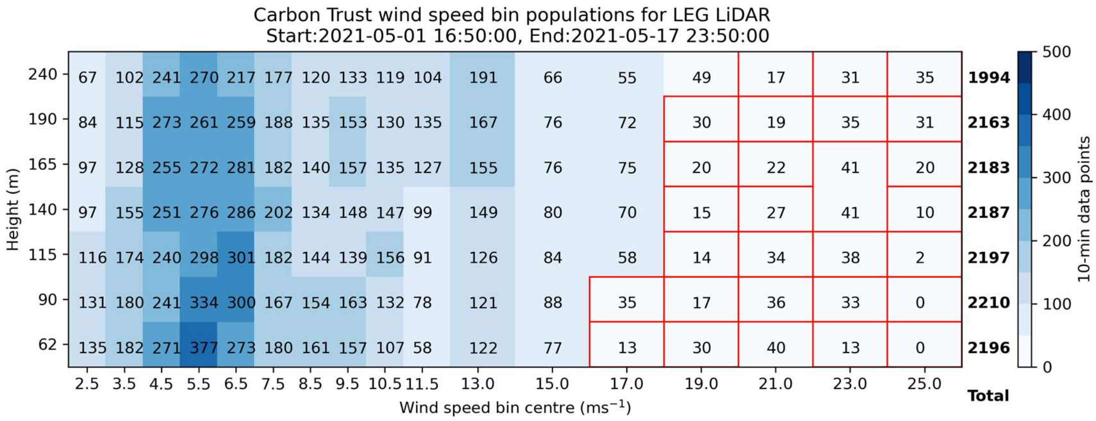

Figure 4-7: Binned wind speed data populations per height level from LEG LiDAR measurements during verification period. Data are binned according to the Carbon Trust protocol. Red boxes

highlight bins where the data population is less than the required minimum of 40 data points. On right-hand side, the total samples in bold represent the total at each height level within the range 2 m/s to 26 m/s; wind speeds above 26 m/s are excluded from this total.

4.3 Wind speed distributions

Quantile-quantile (Q-Q) plots comparing wind speed distributions observed by LEG LiDAR and WS170 are shown for measurements at 62m in Figure 4-8 and and 240m in Figure 4-9. Q-Q plots were generated for all height levels but only 62m and 240m are presented here as they are similar for other height levels.

At 62m, the wind speed distributions agree well for wind speeds up to 15-16 m/s after which WS170 is lower than LEG across the 16-20 m/s wind speed range (Figure 4-8). This is also reflected by lower 50th and 75th percentile wind speeds in WS170 compared to LEG. A similar relationship is also present at 240m although the underestimation by WS170 is more pronounced after 7 m/s (Figure 4-9). At both height levels, the largest deviations between the distributions begin to occur above 15 m/s. Distributions for the other height levels exhibit similar behaviour and therefore an upper filter of 15 m/s is applied at all heights for the simplified verification.

Interestingly, WS170 wind speeds at both height levels are larger than LEG at low LEG wind speeds of 0 -7 m/s and lower than LEG at LEG wind speeds above 6-7 m/s. This signal is also observed at other height levels, increasing in strength with height to reach a maximum at 240m.

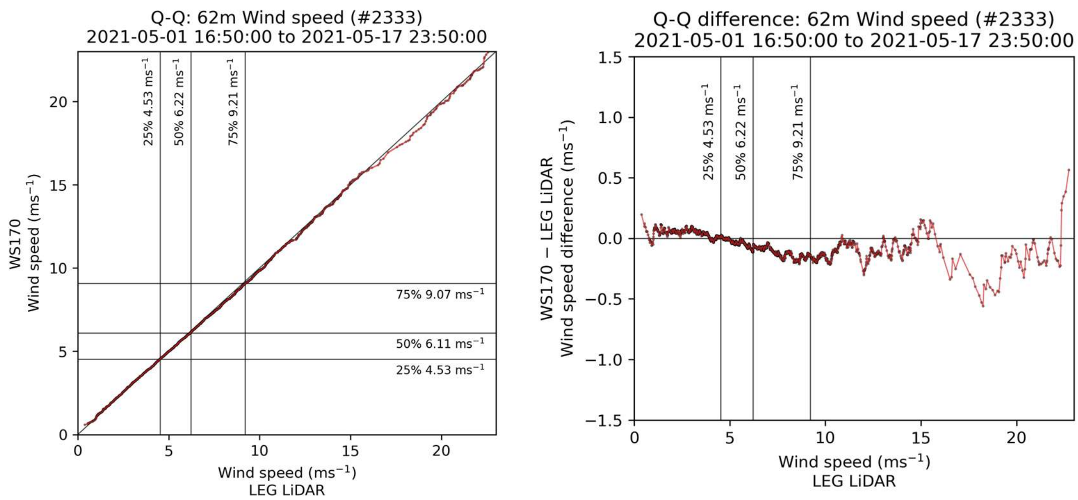

Figure 4-8: Quantile-Quantile (Q-Q) plot comparing quantiles of wind speeds measured at 62m by LEG LiDAR with WS170. Right: Difference between quantiles observed by WS170 and LEG LiDAR as a function of LEG LiDAR quantiles.

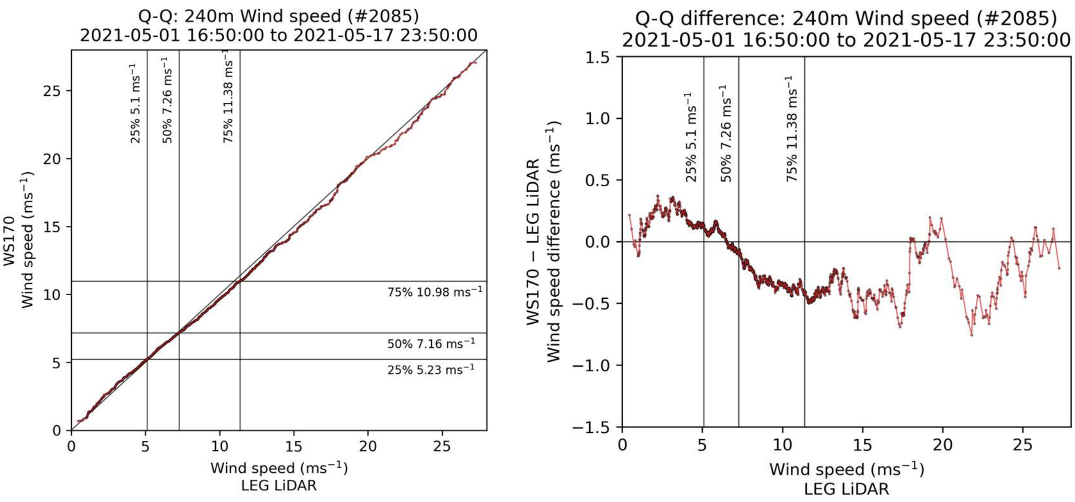

Figure 4-9: As Figure 4-8 but for wind speeds measured at 240m.

4.4 Verification results

4.4.1 Wind speed

KPIs for each wind speed verification test at all height levels are shown in Figure 4-10, Table 4-2 and Table 4-3.

For the > 2 m/s verification, WS170 passes the Carbon Trust best practice thresholds in slope (0.98-1.02) and r-squared (0.98), although slope marginally passes best practice at heights above 140m.

For the 4-16 m/s verification, all heights except 190m and 240m pass best-practice KPIs. Both 190m and 240m pass the minimum threshold for slope but only 190m passes the minimum threshold for r-squared. Similar results are also found for the Simplified 2-15 m/s verification test, although slopes and r-squared are marginally higher at certain height levels.

For both tests, the low r-squared values at 240m are similar and therefore seems to be a result of the filtered wind speed distribution rather than data population. The poorer correlation at 240m relative to other lower height levels is further illustrated by comparing scatter plots between WS170 and LEG wind speeds at 62m and 240m (Figure 4-11). The scatter is tightly constrained along the 1:1 line for wind speeds at 62m whereas at 240m it is much more dispersed, particularly in the low to medium wind speed range of 2-15 m/s where the data population is largest.

A systematic underestimation of wind speeds by WS170 is apparent in all verification tests with slopes consistently below 1 and negative biases at all height levels. Slight reductions in the negative bias are evident when the upper-range filters are applied for both the 4-16 m/s and Simplified 2-15 m/s tests. This suggests that part of the bias is a consequence of underestimating high wind speeds. However, the Q-Q distributions in Section 4.3 indicate that the negative bias is present for all wind speeds > 6 m/s (Figure 4-8 and Figure 4-9).

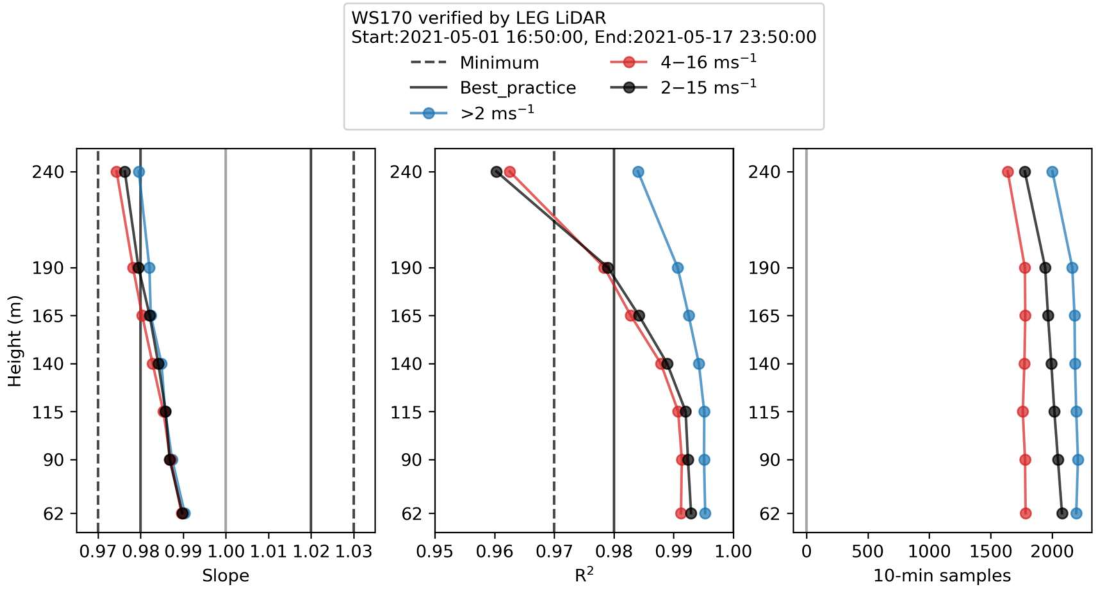

Figure 4-10: Slope, R^2 and number of samples for each wind speed verification test.

Height (m)	> 2 m/s				4-16 m/s			
	N	Slope	R^2	Bias (m/s)	N	Slope	R^2	Bias (m/s)
62	2196	0.990	0.995	-0.07	1784	0.990	0.991	-0.08
90	2210	0.987	0.995	-0.09	1779	0.987	0.991	-0.10
115	2196	0.986	0.995	-0.11	1761	0.985	0.991	-0.11
140	2186	0.985	0.994	-0.12	1774	0.983	0.988	-0.13
165	2182	0.982	0.993	-0.14	1781	0.980	0.983	-0.15
190	2164	0.982	0.991	-0.15	1778	0.978	0.978	-0.16
240	2002	0.980	0.984	-0.14	1638	0.974	0.963	-0.16

Table 4-2: Wind speed verification statistics for WS170 for > 2m/s and 4-16 m/s.

Height (m)	N	Slope	R^2	Bias (m/s)
62	2080	0.990	0.993	-0.06
90	2047	0.987	0.992	-0.08
115	2018	0.986	0.992	-0.09
140	1993	0.984	0.989	-0.10
165	1966	0.982	0.984	-0.12
190	1943	0.980	0.979	-0.13
240	1777	0.976	0.960	-0.12

Table 4-3: Wind speed verification statistics for WS170 using the Simplified verification approach of a wind speed range of > 2 m/s to the upper-filter of 15 m/s.

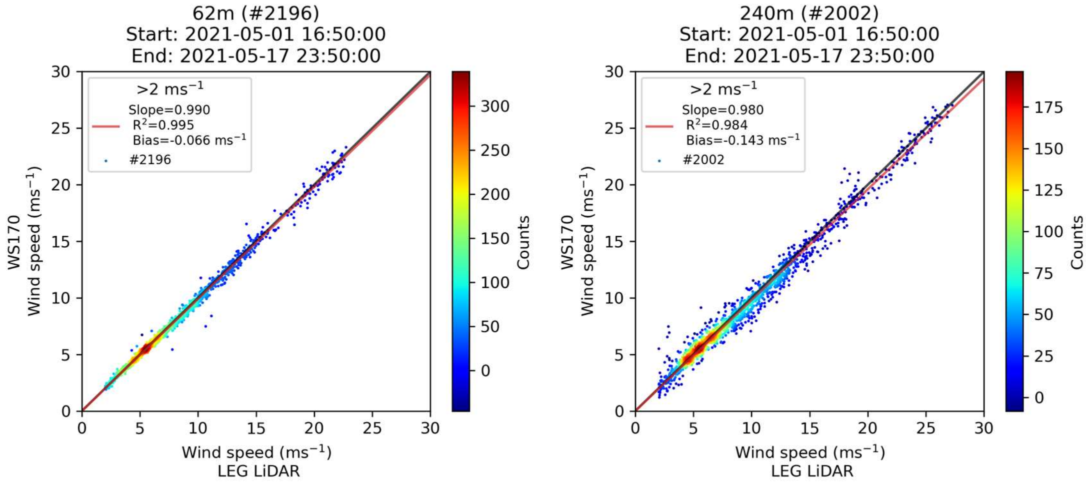

Figure 4-11: Scatter plots comparing wind speeds > 2 m/s from LEG LiDAR and WS170 at 62m (left) and 240m (right).

4.4.2 Wind direction

KPIs for the wind direction verification tests are presented in Figure 4-12 and Table 4-4. Wind direction passes the acceptance criteria for slope and mean difference at all height levels, but not for r-squared for 140m to 240m. Slopes increase with height, whereas r-squared and mean difference reduce with height.

The reduction in r-squared and mean difference at higher height levels can be partly explained by the presence of deviations > 50° in wind directions, most apparent at 140m-240m (see Figure 4-13 for comparisons of 62m and 240m). The deviations are primarily where WS170 wind directions are lower than LEG, which both reduces the correlation and mean difference.

To remove these deviations from the comparison, an additional filter is applied removing wind directions where the absolute difference between WS170 and LEG > 50°. This leads to substantial improvements in r-squared, passing best practice at all height levels. However, after applying this filter, the mean difference increases at every height level to between 1.2°-2.2°. Even with all occurrences of 180° banding excluded, a bias of similar magnitude is evident at all height levels from near the beginning of the verification period (Figure 4-14).

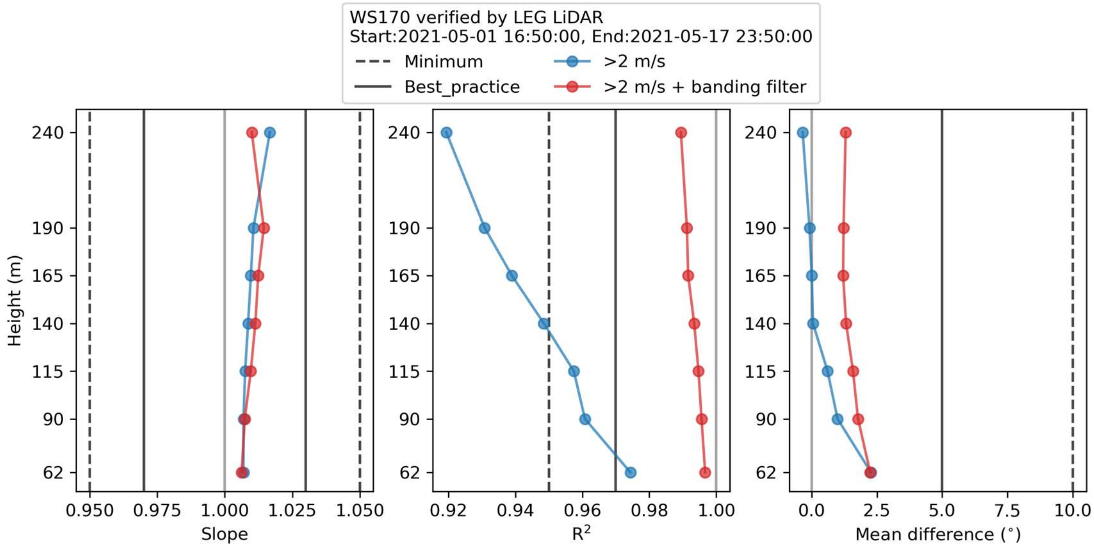

Figure 4-12: Slope, R^2 and mean difference (bias) for wind direction verification tests.

Height (m)	> 2 m/s					> 2 m/s + banding filter				
	N	Slope	Int	R^2	Bias (°)	N	Slope	Int	R^2	Bias (°)
62	2195	1.007	0.81	0.974	2.27	2178	1.006	0.93	0.997	2.24
90	2209	1.007	-0.49	0.961	0.99	2185	1.007	0.19	0.996	1.78
115	2195	1.008	-1.01	0.957	0.61	2166	1.010	-0.49	0.995	1.59
140	2185	1.009	-1.82	0.949	0.05	2149	1.011	-1.14	0.993	1.32
165	2181	1.010	-2.10	0.939	0.01	2140	1.012	-1.50	0.992	1.21
190	2163	1.011	-2.40	0.931	-0.08	2110	1.014	-1.95	0.991	1.22
240	2001	1.017	-4.04	0.919	-0.34	1945	1.010	-0.92	0.989	1.30

Table 4-4: Wind direction verification statistics for WS170 for wind speeds > 2 m/s, and wind speeds > 2m/s + banding filter.

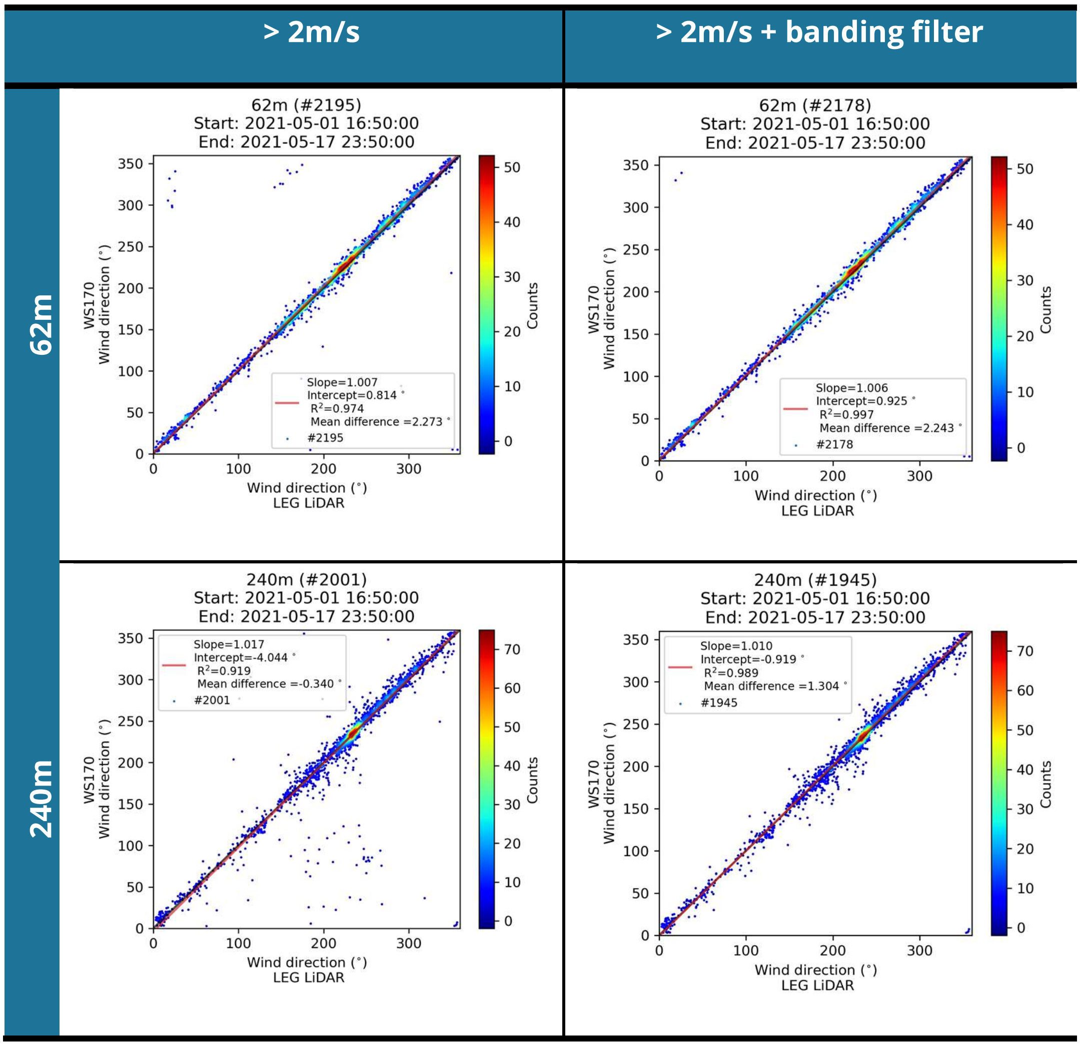

Figure 4-13: Scatter plots comparing wind directions from LEG LiDAR and WS170 at 62m and 240m for wind speeds > 2m/s and > 2m/s + banding filter.

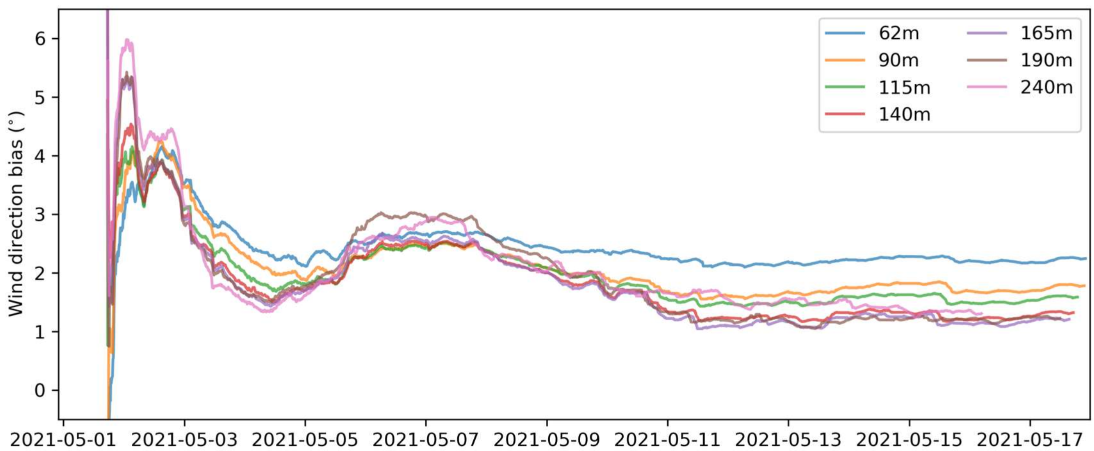

Figure 4-14: Temporal evolution of WS170 wind direction biases (mean wind direction difference) per height level after filtering for wind speeds > 2 m/s + banding. Number of samples used to calculate the biases increases in time.

5 Summary

This report has verified wind speed measurements during May 2021 from the Fugro Seawatch wind LiDAR onboard buoy WS170 next to the LEG offshore platform in the North Sea. The verification was conducted using concurrent wind speed observations from a reference LiDAR situated on the platform.

Two verification approaches were used; the Carbon Trust protocol and a new Simplified verification protocol. The main difference between the protocols is that the Simplified approach simplifies the data population criteria and compares wind speed distributions to establish an upper-range wind speed filter.

7 equivalent heights observed by both LiDARS were verified from 1650 on 01-05-2021 to 2350 on 18-05-2021. The period was characterised by predominant south westerly winds with mean wind speeds at LEG ranging from 7.2 m/s at 64m to 8.7 m/s at 240m. Maximum wind speeds ranged from 22.7 m/s at 64m to 27.2 m/s at 240m and were observed during a storm on the 4th May which was associated with rough sea conditions at WS170.

Data availabilities for both LEG LiDAR and WS170 passed the Carbon Trust stage 3 and Simplified verification $OPDA_{CA}$ threshold of 90% at all height levels except for 240m at LEG where availability was 89.8% passing the Carbon Trust stage 2 $OPDA_{CA}$ threshold of 85%.

As part of the Simplified verification protocol, a Q-Q analysis was used to compare wind speed distributions between LEG and WS170. Distributions agreed well at the lowest height level of 62m for low to moderate wind speeds of 2 to 15 m/s. Above 15m/s, deviations between distributions increased for all height levels and therefore an upper-filter of 15m/s was chosen for the Simplified verification. At all height levels, WS170 underestimated the LEG distribution at wind speeds above 6-7 m/s.

WS170 passed the Carbon Trust best practice thresholds for wind speed at all height levels for the ≥ 2 m/s verification. Furthermore, all heights except 190m and 240m passed for the 4-16 m/s verification and Simplified 2-15 m/s verification tests. 190m passed the minimum criteria for slope and r-squared, whereas 240m passed for slope but failed for r-squared. A systematic underestimation of wind speeds by WS170 was also apparent in all verification tests with slopes consistently below 1 and negative biases on the order of 0.1 m/s at all height levels. The negative bias increased with height and was present when reference LEG wind speeds were above 6 m/s.

For wind direction, WS170 passed minimum and best practice thresholds for slope and bias, whereas r-squared failed at heights of 140m to 240m. Some deviations were apparent in the wind directions, with some WS170 wind directions lower than LEG particularly at 140m-240m, explaining the lower correlations at these heights. When deviations were removed, the r-squared values improved to pass the acceptance criteria. However, the mean difference increased at all height levels to 1.2-2.2°. It was evident that this bias remained consistent throughout the verification period.