

OWA Report

Remote Wind Measurements Offshore Using Scanning LiDAR Systems

Offshore Wind Accelerator – Wakes

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Remote Wind Measurements Offshore Using Scanning LiDAR Systems

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Abstract:

The use of long range scanning LiDAR to measure spatial variation in wind resource offshore is demonstrated in a landmark measurement campaign in Dublin Bay. Four scanning LiDARs, provided by Leosphere and Lockheed Martin Coherent Technologies, were deployed with scanning patterns designed to measure horizontal wind speed throughout a 58 km² near shore offshore wind farm development area. Three vertically scanning ground-based LiDARs were deployed (one offshore) to provide reference measurements enabling validation of the scanning LiDAR measurements. Use of scanning LiDAR systems operating in single and dual Doppler mode has been demonstrated at ranges up to 15km.

Dual Doppler measurements show excellent agreement with reference measurements and facilitate a significant reduction in the uncertainty in an energy yield assessment for a hypothetical offshore wind farm by reducing uncertainty of the horizontal extrapolation of the primary wind resource measurement to turbine locations. Single Doppler measurement accuracy is found to be insufficient to provide a reduction in energy yield prediction uncertainty relative to current industry standard methods of mapping spatial variation in wind resource offshore.

List of Acronyms:

CNR:	Carrier to Noise Ratio	TI:	Turbulence Intensity
ITM:	Irish Transverse Mercator coordinate system	TWG:	Technical Working Group
LMCT:	Lockheed Martin Coherent Technologies	VL:	Validation LiDAR
LOS:	Line of Sight	WP1:	Remote Wind Measurements Using Scanning LiDAR Work Package 1
MSL:	Mean Sea Level	WP2:	Remote Wind Measurements Using Scanning LiDAR Work Package 2
OEM:	Original Equipment Manufacturer	WP3:	Remote Wind Measurements Using Scanning LiDAR Work Package 3
OWA:	Offshore Wind Accelerator	WP4:	Remote Wind Measurements Using Scanning LiDAR Work Package 4
PPI:	Plan Position Indicator	WP5:	Remote Wind Measurements Using Scanning LiDAR Work Package 5
RES:	Renewable Energy Systems Ltd	WP6:	Remote Wind Measurements Using Scanning LiDAR Work Package 6
RHI:	Range Height Indicator	WS:	Wind Speed
RSD:	Remote Sensing Device		
SL:	Scanning LiDAR		

1.0 INTRODUCTION

Accurate mapping of wind resource variability across a potential offshore wind site would result in reduced uncertainty associated with pre-construction energy yield assessments and hence reduced risk for project investors. As such, any means by which the mapping of energy resource across potential sites can be improved can result in significant reduction in the cost of financing offshore wind energy projects. In addition, knowledge of the spatial variation in energy resource can be used to improve other project decisions. Layout design optimisation could be performed based on knowledge of the relative windiness of different regions of the development area. Similarly, decisions relating to the type and location of primary wind speed assessment instrumentation could benefit from information provided by measurements of spatial variation. In markets where mesoscale models (current industry standard method for measuring spatial variation in wind resource offshore) are not well validated LiDAR measurements of the wind resource across a site may prove especially valuable.

Scanning LiDAR has the potential to accurately measure wind at long ranges. As such, scanning LiDAR has been identified as a technology that may be capable of providing developers with three dimensional measurements of the spatial variability in wind resource for regions representative of offshore wind sites as identified in the literature review of WP1 [1]. However, there is currently no systematic validation of these devices operating at the ranges required for this use case (typically 10 to 20 km), or demonstration of their use to measure spatial variation for offshore locations [1]. The OWA Remote Wind Measurements Using Scanning LiDAR Systems project aims to assess the capability of long range scanning LiDAR to measure the spatial variation in wind resource within a potential offshore wind farm site by experimental means.

To this end, two measurement campaigns (at Anholt Wind Farm and Dublin Bay) were designed during WP2 [2], with the Dublin Bay campaign identified as the preferred option. In WP3 tender for LiDAR OEMs was performed [3] with Lockheed Martin Coherent Technologies (LMCT) and Leosphere being selected to provide long range scanning LiDAR systems. Leosphere were also selected to provide vertically scanning LiDARs to acquire wind data against which the long range demonstration systems are to be validated. RES has performed analysis of the scanning LiDAR measurements against the validation LiDAR measurements. The results of the analysis are presented in this report:

- Measurement campaign design is described in Section 2.0
- Key details of the device operation, including deployment and decommissioning, are given in Section 3.0
- Design and subsequent verification of the long range LiDAR scanning patterns is detailed in Section 4.0
- Analysis results pertaining to the absolute accuracy of the scanning LiDAR systems wind speed measurements are presented in Section 5.0
- Analysis results pertaining to the capability of the systems to measure spatial variation in wind resource offshore are presented in Section 6.0
- In Section 7.0 key results from the analysis are discussed in detail
- The conclusions of the work are given in Section 8.0

2.0 CAMPAIGN DESIGN

Measurement campaigns were designed based on instrument deployments at Anholt Wind Farm and Dublin Bay. Following consultation with the OWA TWG the Dublin Bay experiment was identified as the preferred option [2]. Figure 1 provides an illustration of device deployment locations and measurement locations outlined below:

- Both LMCT and Leosphere deployed two long range scanning LiDARs onshore. The scanning LiDAR devices are deployed at East Pier and Baily Lighthouse, enabling offshore wind measurements to be taken at the demonstration points shown in Figure 1.

- Vertically scanning LiDARs are deployed at Kish Lighthouse, East Pier and Poolbeg locations. The long range scanning LiDARs will also acquire wind measurements at these points to enable wind speed measurement validation.
- The demonstration points cover a wide offshore area analogous to a near shore offshore wind farm development site.

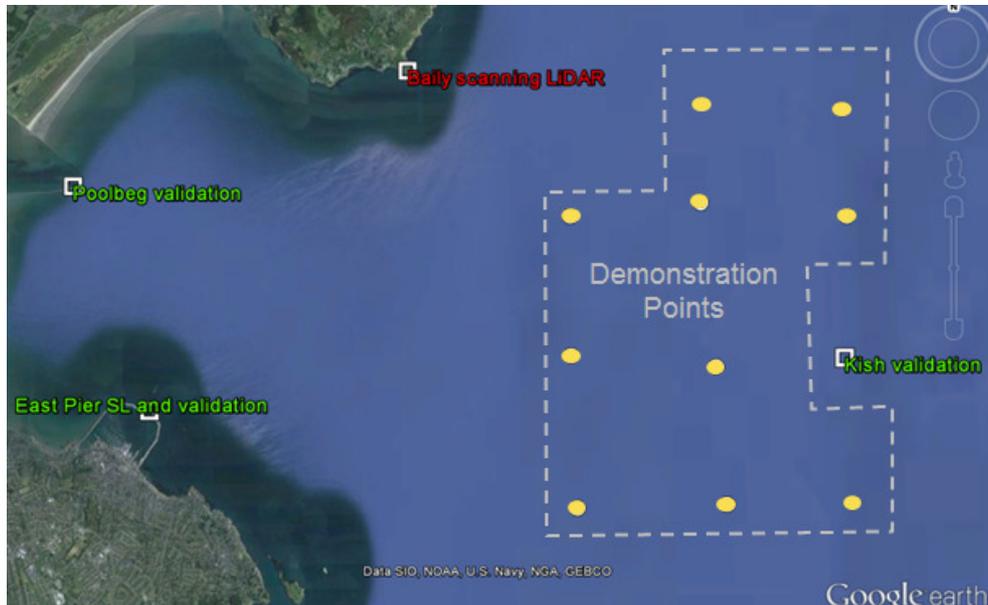


Figure 1: LiDAR deployment and measurement locations within Dublin Bay

The Dublin Bay experiment is considered representative of the proposed use case based on the following criteria [2]:

- The predominant wind directions at Dublin Bay are southerly and westerly. An appreciable component of the wind velocity therefore exists along the line of sight (LOS) for at least one of the scanning LiDAR deployment locations for predominant conditions.
- A large measurement field representative of the proposed use case is available.
- Line of sight from the long range scanning LiDARs to demonstration and validation measurement points is unobstructed.
- Multiple locations are available for the deployment of vertically scanning validation LiDARs.
- A number of potential hard targets are present on the Dublin skyline meaning the scanning LiDAR measurement configuration can be verified and calibrated on an ongoing basis, thus reducing the uncertainty associated with the subsequent data analysis.
- The measurement distances associated with the demonstration and validation points are representative of the future use case.
- An appreciable wind speed gradient of approximately 10% is expected across the demonstration area. This is advantageous for demonstration purposes as the likelihood that measured wind speed gradients exceed measurement uncertainty is increased.

The following potential drawbacks of the Dublin Bay campaign were identified as:

- High aerosol content for certain wind directions (due to proximity to shore) may result in data capture being increased relative to that expected for far offshore locations.
- Naval activity could result in temporary LOS blockages and therefore reduced data capture.

3.0 Campaign Operational History

Key dates and details of the deployment, operation and decommissioning of the validation LiDARs (Section 3.1), LMCT scanning LiDARs (Section 3.2) and Leosphere scanning LiDARs (Section 3.3) are given in this section.

3.1 Vertically Scanning Validation LiDARs

Three vertically scanning Leosphere Windcube V2 LiDARs were deployed at East Pier, Kish Lighthouse and Poolbeg locations respectively to provide validation data for the long range scanning LiDARs. The deployment dates and locations are summarised Table 1:

Location	Easting (m) [ITM]	Northing (m) [ITM]	Elevation above MSL (m)	Commissioned [DD/MM/YYYY]	Decommissioned [DD/MM/YYYY]
East Pier	724850.8	729653.4	11 ± 0.1	17/12/2015	12/05/2016
Poolbeg ¹	723082.9	734023.6	4.6 ± 0.1	21/12/2015	30/12/2015
	723084.1	734021.6	5.5 ± 0.1	03/02/2016	18/05/2016
Kish Lighthouse	738225.9	730950.4	32.7 ± 1.0	12/01/2016	18/05/2016

Table 1: Deployment locations and measurement period for the validation V2s. Locations for the devices at East Pier and Poolbeg are given in reference [8]. The location for the device at Kish Lighthouse is given in reference [9].

The V2 devices deployed at East Pier and Poolbeg were configured to measure horizontal and vertical wind speeds and wind direction at multiple heights above MSL, including 100m and 150m (the heights of the scanning LiDARs measurements). Measurement heights were programmed accounting for the elevation of the unit [9].

Figure 2 shows the data coverage for each V2 unit at 100m and 150m measurement heights. The time period considered is from first to last 10 minute data record concurrent with any scanning LiDAR for each device. The unit at the Kish achieves data coverage of greater than 95.6% for both measurement heights. The V2 at East Pier has data coverage of greater than 98.5% at both heights. The Poolbeg V2 data coverage is greater than 97.8% at both heights.

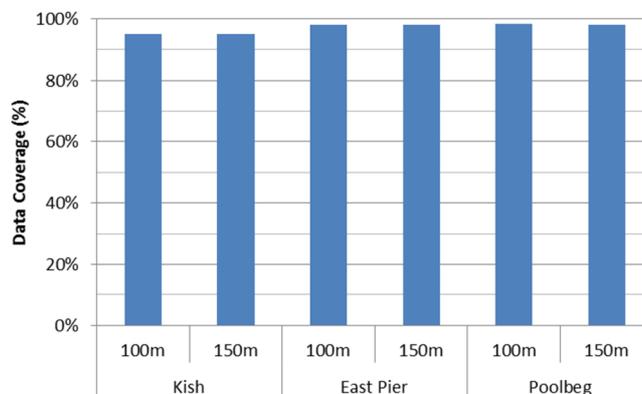


Figure 2: 10 minute data coverage of each V2 unit at 100m and 150m measurement heights.

¹ The Poolbeg V2 was initially deployed on 16/12/2015, however, due to flooding during Storm Frank was decommissioned on 30/12/2015.

All three V2 validation LiDARs were verified against Leosphere’s reference Windcube V2 unit prior to deployment and certified by Danish Technical University (DTU). All verification acceptance tests were passed for all devices [10] [11] [12].

3.2 LMCT

LMCT WindTracer scanning LiDARs were deployed at East Pier and Baily Lighthouse locations; deployment locations and key dates are summarised in Table 2:

Location	Easting (m) [ITM]	Northing (m) [ITM]	Elevation above MSL (m)	Commissioned [DD/MM/YYYY]	Decommissioned [DD/MM/YYYY]
East Pier	724849.2	729646.1	48.9 ± 0.2	03/02/2016	17/05/2016
Baily Lighthouse	729542.2	736539.7	12.3 ± 0.2	28/01/2016	12/05/2016

Table 2: Deployment locations and measurement dates for the LMCT WindTracer scanning LiDARs. Deployment locations are taken from reference [8].

The locations at which the LMCT devices were configured to provide wind measurements are shown in Figure 3:



Figure 3: Measurement points for LMCT WindTracers

For the device at Baily Lighthouse only data acquired since 09/02/2016 is considered for data analysis purposes as the final scanning pattern and device configuration was implemented from this date. Figure 4 and Figure 5 show the data coverage for the Baily and East Pier WindTracer respectively at each measurement point. Data coverage refers to the period from the first 10 minute data point to device decommissioning.

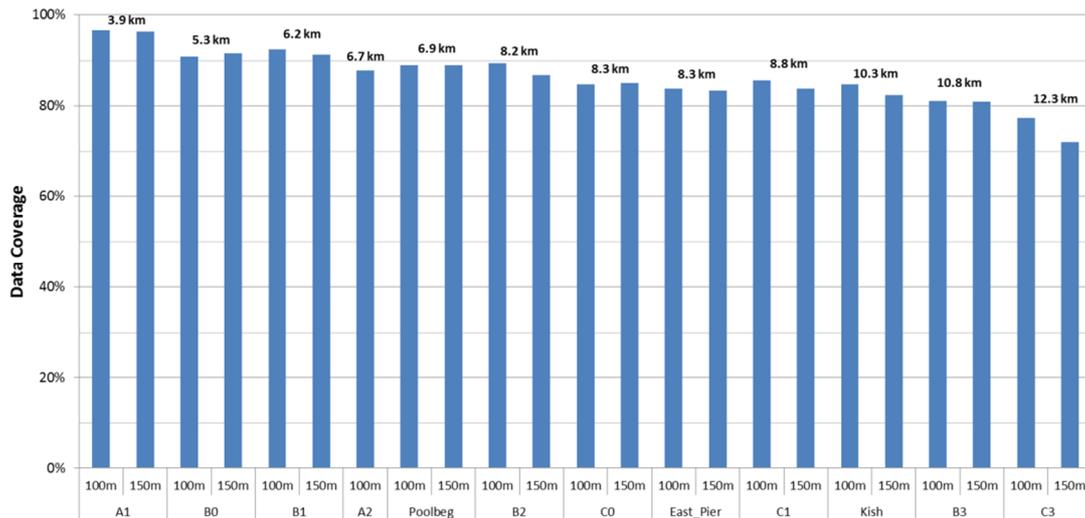


Figure 4: 10 minute data coverage of the LMCT Wind Tracer deployed at Baily Lighthouse for the various measurement locations. The distance from scanning LiDAR to measurement location is also shown.

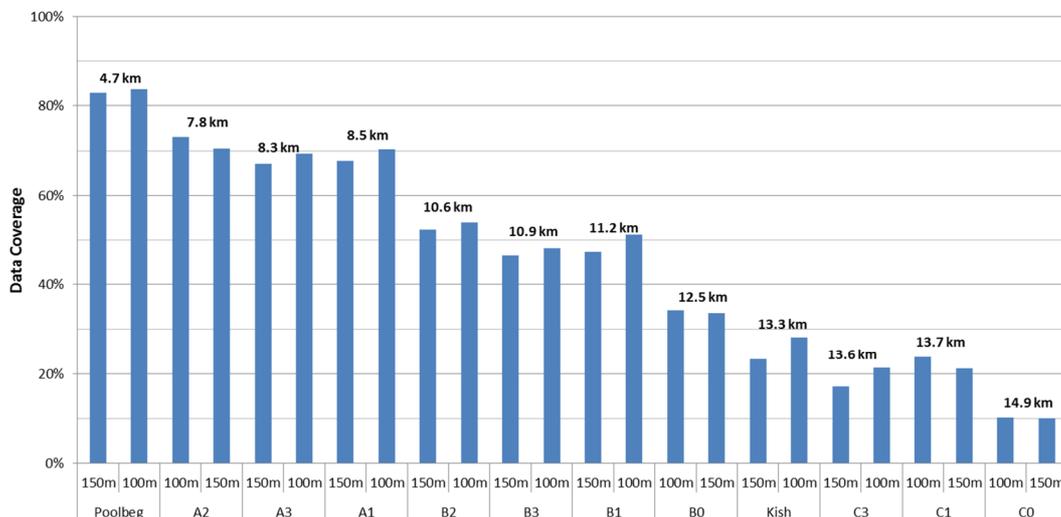


Figure 5: 10 minute data coverage of the LMCT Wind Tracer deployed at East Pier for the various measurement locations. The distance from scanning LiDAR to measurement location is also shown.

It can be seen from Figure 4 and Figure 5 that the WindTracer at East Pier achieves lower data coverage than the Baily Lighthouse device. The East Pier system featured a new shelter design (smaller than that of the device at Baily Lighthouse) and represents the first deployment of such a system. LMCT have carried out an internal investigation into the reasons for the reduced data coverage of the East Pier device and found that it was related to the configuration of the transceiver within the new shelter design. A methodology to mitigate the issue has been identified and LMCT do not envisage the issue reoccurring in future campaigns.

Due to laser safety requirements, performing hard target checks for the WindTracer units was not possible. However, visual hard target checks using Poolbeg towers and Kish Lighthouse were used to perform calibration of device azimuth and elevation angle offsets [4] [5]. These visual checks indicated no change in azimuth and elevation angle offset throughout the measurement campaign for the East Pier device. The East Pier device levelling could not be checked during decommissioning as no LMCT staff member was present at the time. For the device deployed at Baily Lighthouse visual hard target checks and levelling checks performed at decommissioning confirmed a change in the offset of azimuth and elevation angles during the campaign due to sinking of the north-west leg of the structure. The observed offsets in azimuth and elevation angles were -0.170° and -0.062° respectively. The measured elevation angle offset is valid only in the vicinity of Poolbeg Tower and will vary at other locations. It is worth noting that the model of scanner in the Baily Lighthouse WindTracer has a

stated accuracy of $\pm 0.1^\circ$. A previous realignment of the Baily Lighthouse beam was performed on 22/02/2016 to account for elevation and azimuth offsets measured at that time (LMCT staff were on site on this date).

3.3 Leosphere

Leosphere Windcube 400S scanning LiDARs were deployed at East Pier and Baily Lighthouse locations; deployment locations and key dates are summarised in Table 3. The device deployed at the East Pier is a prototype Windcube 400S device featuring a higher energy pulse than the Windcube 400S at Baily Lighthouse [13].

Location	Easting (m) [ITM]	Northing (m) [ITM]	Elevation above MSL (m)	Commissioned [DD/MM/YYYY]	Decommissioned [DD/MM/YYYY]
East Pier	724852.5	729655.3	12.2 \pm 0.1	26/01/2016	13/04/2016
Baily Lighthouse	729640.8	736350.5	28.0 \pm 0.1	27/01/2016	22/05/2016

Table 3: Deployment locations and measurement dates for the Windcube 400S scanning LiDARs. Deployment locations are taken from reference [8].

The locations at which the Windcube 400S devices are configured to provide wind measurements are shown in Figure 6:

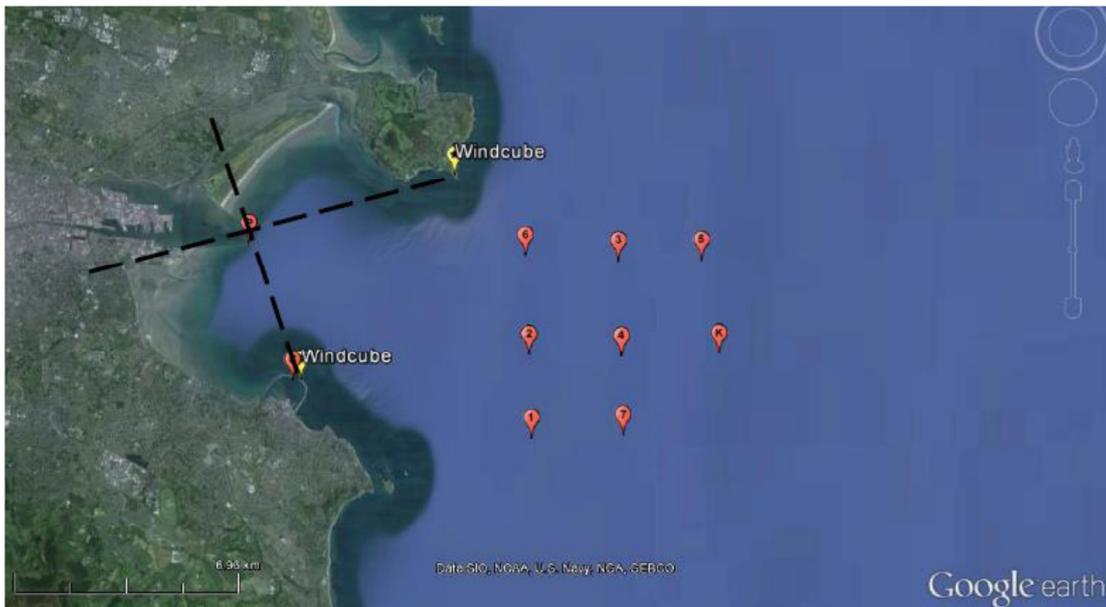


Figure 6: Illustration of Leosphere measurement points. Black dashed lines to the Poolbeg location indicate that data at this location is only provided in the form of Dual Doppler data based on simultaneous measurements from each scanning LiDAR.

Figure 7 and Figure 8 show the data coverage for the Baily and East Pier Windcube 400S devices respectively at each measurement point. Data coverage refers to the period from the first 10 minute data point recorded by the device to decommissioning.

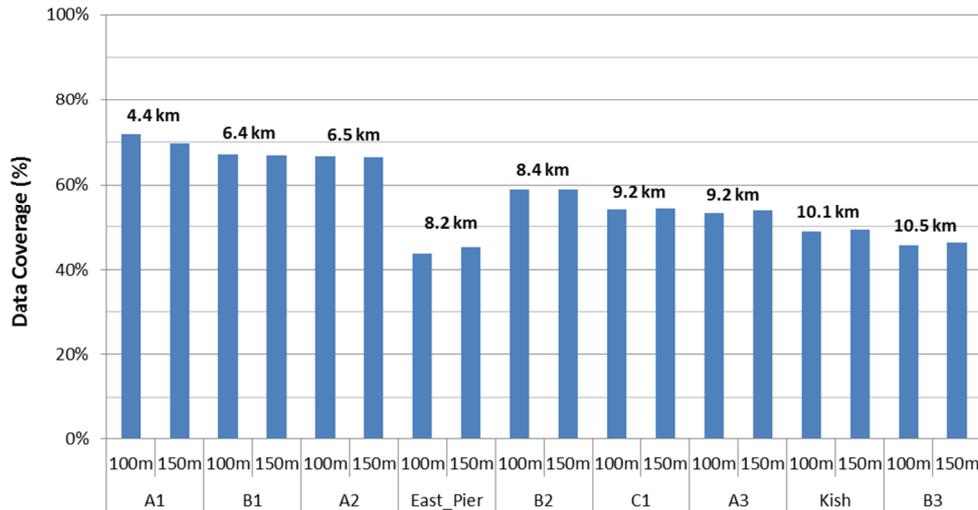


Figure 7: 10 minute data coverage of the Windcube 400S deployed at Baily Lighthouse for the various measurement locations. The distance from scanning LiDAR to measurement location is also shown.

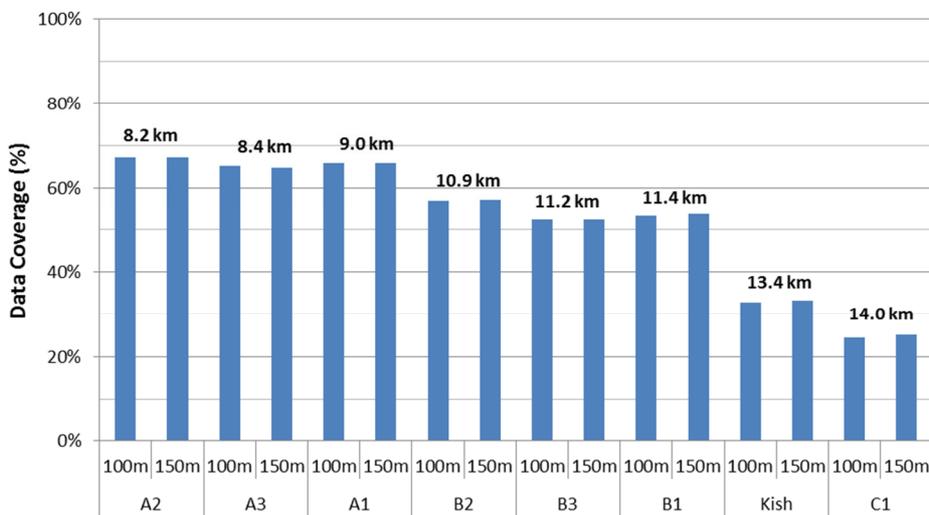


Figure 8: 10 minute data coverage of the Windcube 400S deployed at East Pier for the various measurement locations. The distance from scanning LiDAR to measurement location is also shown.

Hard target checks are performed once per day by both Leosphere scanning LiDARs so that the calibration of azimuth and elevation angle can be checked on an ongoing basis. This is performed by means of measuring maximum CNR as a function of elevation and azimuth angle in the vicinity of the hard target (see Figure 9 and Figure 10). As the expected location of the hard target is known any changes in the azimuth and/or elevation angle calibration in the vicinity of the hard target can be determined. Hard target checks are performed by the Baily Windcube 400S once per day using the Kish Lighthouse; hard target checks using Poolbeg chimneys are not performed daily for this device. Hard target checks are performed by the Baily Windcube 400S once per day using the Kish Lighthouse hard target checks using Poolbeg chimneys are not performed daily for this device.

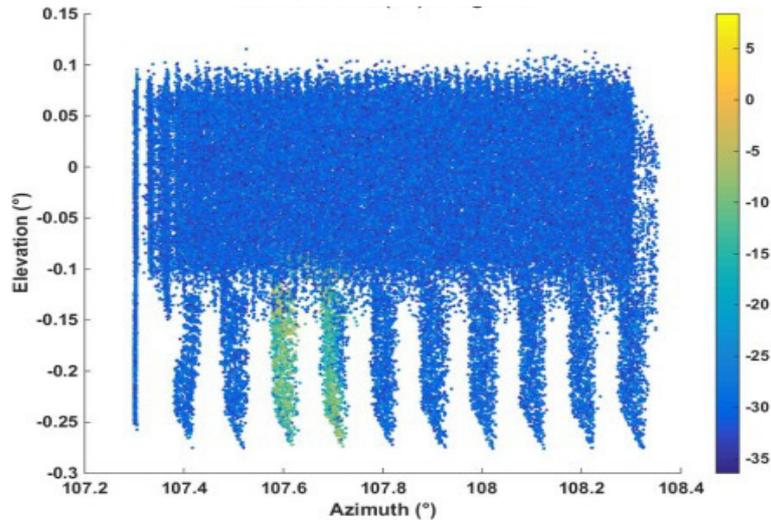


Figure 9: Maximum CNR around Kish Lighthouse as a function of azimuth and elevation angles acquired by the Windcube 400S deployed at Baily Lighthouse

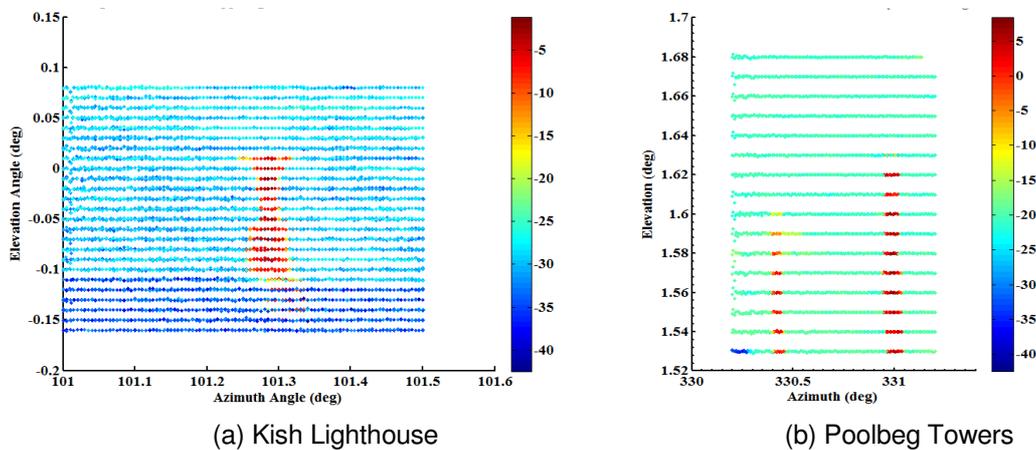


Figure 10: Maximum CNR around Kish Lighthouse and Poolbeg Towers as a function of azimuth and elevation angles acquired by the Windcube 400S deployed at East Pier

The elevation angle offset required for the Windcube 400S at Baily Lighthouse was observed to change from 0.11° at installation to 0.05° at decommissioning; no change in azimuth angle offset was required [6]. No change in azimuth or elevation angle offset over the measurement period was observed for the prototype Windcube 400S deployed at East Pier [7].

4.0 Scanning Pattern Design And Verification

Details of the scanning pattern designed and implemented by LMCT and Leosphere are presented in the sections 4.1 and 4.2 respectively. Where there is data available to verify the implementation of the scanning pattern the results of the verification are also summarised.

4.1 LMCT

In order to provide 10 minute wind measurements at the demonstration points a number of PPI scans were performed by the WindTracer devices located at Baily Lighthouse and East Pier. The scanning patterns enabled measurement at the offshore and onshore demonstration points, including Poolbeg, to be performed in each 10 minute averaging period. LMCT configured the PPI scans such that each measurement location was visited at least twice during each 10 minute period, citing good results achieved in the BAO experiment with this number of visits [16] [17]. Both scanning LiDARs also performed a 0° tilt scan during each 10 minute period in order to measure the device range performance on an ongoing basis.

The Baily Lighthouse device performed 9 PPI scans as detailed in Figure 11. The scan speed for the Baily PPI scans was 2.32°/s.

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Levels Covered (+/- 5 meters):
100.0
150.0

Tilt Angles:
0.188 degrees from 133.464 to 144.650 covering 2 sectors. Scan 41.187 deg from 120.831 to 162.017
0.247 degrees from 105.594 to 121.935 covering 2 sectors. Scan 46.342 deg from 92.961 to 139.302
0.329 degrees from 85.033 to 133.649 covering 2 sectors. Scan 78.616 deg from 72.400 to 151.016
0.418 degrees from 114.537 to 133.464 covering 2 sectors. Scan 48.926 deg from 101.904 to 150.831
0.499 degrees from 84.952 to 144.650 covering 3 sectors. Scan 89.698 deg from 72.319 to 162.017
0.628 degrees from 85.033 to 134.221 covering 4 sectors. Scan 79.188 deg from 72.400 to 151.588
0.910 degrees from 114.537 to 114.537 covering 1 sectors. Scan 30.000 deg from 101.904 to 131.904
1.052 degrees from 84.952 to 84.952 covering 1 sectors. Scan 30.000 deg from 72.319 to 102.319
1.427 degrees from 134.221 to 134.221 covering 1 sectors. Scan 30.000 deg from 121.588 to 151.588

Points Covered: 18
Degrees of scan: 473.957

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Figure 11: Start and end azimuth angle and elevation angle for the PPI scans implemented by the Baily Lighthouse WindTracer to provide wind speed measurements at the demonstration points [16].

The East Pier device performed 9 PPI scans as detailed in Figure 12. The scan speed for the Baily PPI scans was 2.47°/s.

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Levels Covered (+/- 5.0 meters):
100.0
150.0

Tilt Angles:
0.270 degrees from 59.133 to 96.674 covering 3 sectors. Scan 67.541 deg from 46.440 to 113.981
0.314 degrees from 53.492 to 83.612 covering 2 sectors. Scan 60.121 deg from 40.799 to 100.919
0.400 degrees from 67.123 to 99.583 covering 3 sectors. Scan 62.460 deg from 54.430 to 116.890
0.461 degrees from 59.133 to 59.133 covering 1 sectors. Scan 30.000 deg from 46.440 to 76.440
0.507 degrees from 61.310 to 104.401 covering 5 sectors. Scan 73.091 deg from 48.617 to 121.708
0.576 degrees from 53.492 to 82.487 covering 2 sectors. Scan 58.996 deg from 40.799 to 99.794
0.656 degrees from 67.123 to 99.583 covering 3 sectors. Scan 62.460 deg from 54.430 to 116.890
0.883 degrees from 61.310 to 104.401 covering 2 sectors. Scan 73.091 deg from 48.617 to 121.708
0.972 degrees from 82.487 to 82.487 covering 1 sectors. Scan 30.000 deg from 69.794 to 99.794

Points Covered: 22
Degrees of scan: 517.759

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Figure 12: Start and end azimuth angle and elevation angle for the PPI scans implemented by the East Pier WindTracer to provide wind speed measurements at the demonstration points [16].

RES have not been provided with high frequency time series data of the azimuth and elevation angles of the LMCT scanning LiDARs and as such the proper implementation of the scanning patterns could not be independently verified. Internal verification of the scanning pattern implementation has been carried out by LMCT however.

The LMCT single LiDAR wind speed measurements use data retrieved from 30 degree arcs around the measurement target location to reconstruct the 3D wind vector. As a large number of PPI scans were implemented, each of the target locations was visited with high accuracy and so no vertical extrapolation or interpolation of wind speed measurements to target height was required.

The dual Doppler wind measurements were based on standard reconstruction of the 3D wind vector from two radial measurements approximately collocated in space and synchronised on a 10 minute time scale.

4.2 Leosphere

In order to provide 10 minute wind measurements at the demonstration points 3 PPI scans with different elevation angle where performed by both Windcube 400S devices. Interpolation of measurements to target heights (100m and 150m) was then performed as a post-processing step. The arcs covered by the PPI scans from each of the devices are illustrated in Figure 13. It can be seen that all offshore demonstration points are covered by both the scan arcs and the East Pier validation demonstration point is covered by the Baily Lighthouse device’s PPI scan arc. Measurements at the Poolbeg demonstration point, which is not covered by

either PPI scan, are provided by means of Dual Doppler measurements based on simultaneous RHI scan measurements performed by each LiDAR at Poolbeg. In addition to the scans performed to acquire wind speed measurements a PPI scan of a hard target is performed daily by each scanning LiDAR to calibrate the azimuth and elevation angle offsets.



Figure 13: Illustration of PPI scan arcs for Windcube 400S devices

The start and end azimuth angles and the elevation angle for the three PPI scans performed by the Baily Lighthouse device are summarised in Table 4. For each of these PPI scans a scan speed of 3°/s was implemented. This scan speed corresponds to 5 scan iterations in each 10 minute period for PPI 1 and PPI 2, and 4 iterations for PPI 3 [13]. The proper implementation of the Baily PPI scans has been verified using high frequency azimuth and elevation angle data (see Figure 14); the proper implementation of the scans has been confirmed.

Scan Type	Start Angle (°)	End Angle (°)	Elevation (°)
PPI 1	160.5	75.5	0.40
PPI 2	75.5	224.0	0.68
PPI 3	224	75.5	1.03

Table 4: Start and end azimuth angle and elevation angle for the PPI scans implemented by the Baily Lighthouse Windcube 400S to provide wind speed measurements at the demonstration points.

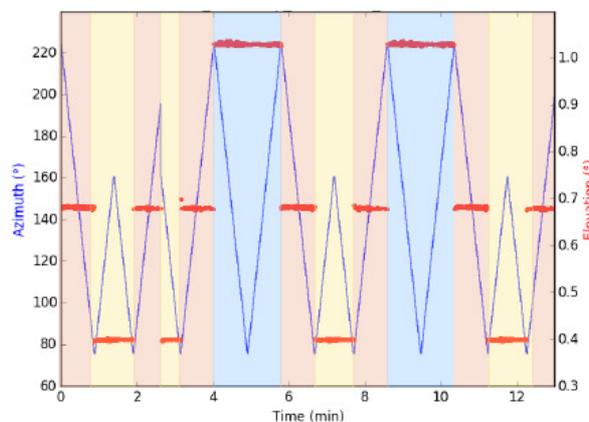


Figure 14: Example verification of the Baily Windcube 400S PPI 1, PPI 2 and PPI 3 scans (Table 4) using 1Hz time series data. Data corresponds to the period from 22:37 to 22:50 on 24th February 2016.

The start and end azimuth angles and the elevation angle for the three PPI scans performed by the East Pier device are summarised in Table 5. For each of these PPI scans a scan speed of 6°/s was implemented. This scan speed corresponds to 14 scan iterations in each 10 minute period for PPI 1 and PPI 2, and 13 iterations for PPI 3 [13]. The proper implementation of the East Pier PPI scans has been verified using high frequency azimuth and elevation angle data (see Figure 15); the proper implementation of the scans has been confirmed.

Scan Type	Start Azimuth Angle (°)	End Azimuth Angle (°)	Elevation (°)
PPI_RT A1	130.76	45.76	0.45
PPI_RT A2	45.76	130.76	0.66
PPI_RT A3	130.76	45.76	0.92

Table 5: Start and end azimuth angle and elevation angle for the PPI scans implemented by the East Pier Windcube 400S to provide wind speed measurements at the demonstration points.

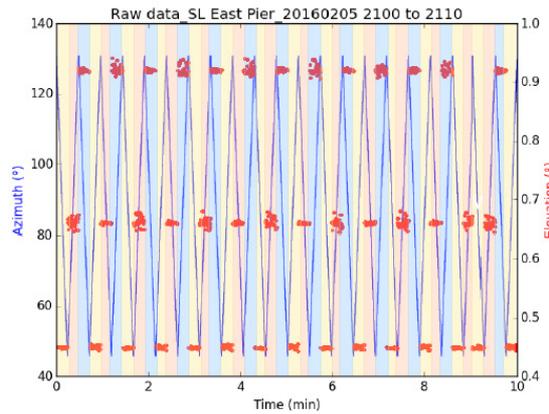


Figure 15: Example verification of the East Pier Windcube 400S PPI 1, PPI 2 and PPI 3 scans (Table 5) using 1Hz time series data. Data corresponds to the period from 21:00 to 21:10 on 5th February 2016.

The RHI scans of the Poolbeg demonstration point and PPI scans used to perform daily hard target checks are summarised in Table 6 and Table 7 for the Baily Lighthouse and East Pier devices respectively. The verification of these scans using high frequency time series data is illustrated in Figure 16 and Figure 17. The proper implementation of these scans has been confirmed for both devices. Both devices perform the RHI scan at Poolbeg using a scan speed of 0.1°/s meaning 36 iterations of the RHI scan are performed in a ten minute period.

Scan Type	Start Azimuth Angle (°)	End Azimuth Angle (°)	Start Elevation Angle (°)	End Elevation Angle (°)
RHI 1	252		0.58	2.28
PPI	107.3	108.3	-0.25	-0.12

Table 6: Start and end azimuth and elevation angles for the RHI scan and PPI scan implemented by the Baily Lighthouse Windcube 400S to provide wind speed measurements at Poolbeg and hard target checks respectively.

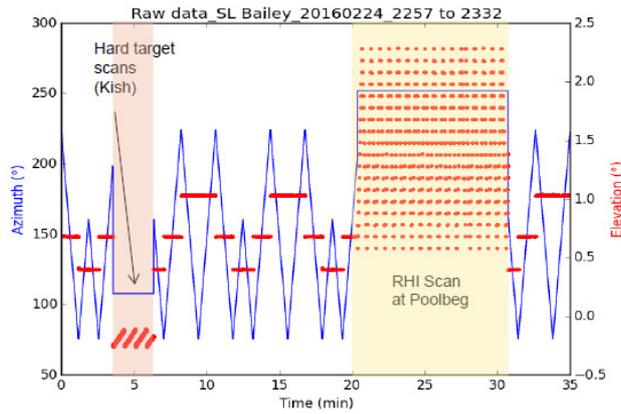


Figure 16: Example verification of the Baily Lighthouse Windcube 400S hard target PPI scan and Poolbeg RHI scan (see Table 6) using 1Hz time series data. Data corresponds to the period from 22:57 to 23:32 on 24th February 2016.

Scan Type	Start Azimuth Angle (°)	End Azimuth Angle (°)	Start Elevation Angle (°)	End Elevation Angle (°)
RHI Poolbeg1		339	0.58	2.28
PPI_HT	330.2	331.20	1.59	1.69°

Table 7: Start and end azimuth and elevation angles for the RHI scan and PPI scan implemented by the East Pier Windcube 400S to provide wind speed measurements at Poolbeg and hard target checks respectively.

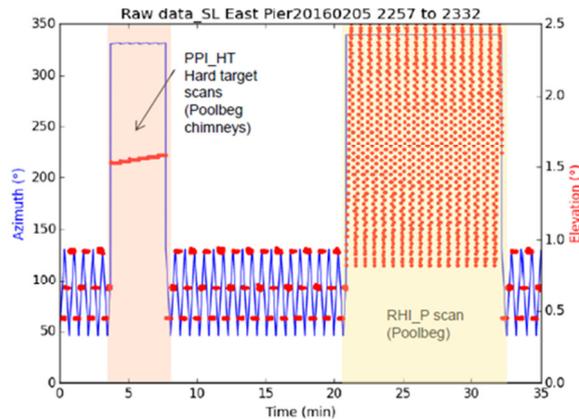


Figure 17: Example verification of the East Pier Windcube 400S hard target PPI scan and Poolbeg RHI scan (see Table 7) using 1Hz time series data. Data corresponds to the period from 22:57 to 23:32 on 5th February 2016.

In order to reconstruct the 3D wind velocity vector from PPI scan measurements for the single LiDAR measurements, spatial averaging is performed over a 45° arc in the vicinity of the target location. This can result in a large region being used for spatial averaging when the measurement range is large as illustrated in Figure 18:

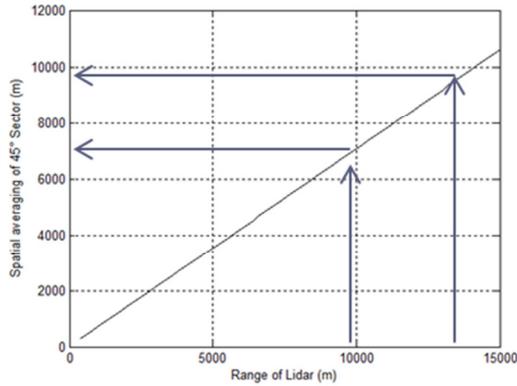


Figure 18: Relationship between length of arc used for reconstruction of 3D wind vector and measurement range for a 45° sector (from [13]).

The scan geometry implemented results in measurements not always being available at the target measurement height. Leosphere have used linear interpolation or extrapolation to calculate the measurements at target heights. As an example, the elevation angles used for the East Pier LiDAR PPI scans results in the lowest measurements at Kish Lighthouse demonstration point being approximately 120m above MSL; 20m above the target height. In this case Leosphere used linear extrapolation in their post-processing to calculate wind speed at the 100m target height.

The dual Doppler wind measurements based on PPI and RHI scan geometries were based on standard reconstruction of the 3D wind vector from two radial measurements [14] [15] collocated (approximately in the case of PPI scans) in space and synchronised on a 10 minute time scale.

5.0 Validation of Absolute Accuracy

The anticipated use case for long range scanning LiDAR in offshore wind resource assessment is to measure spatial variation in energy resource across a prospective wind farm site area. It should be noted, however, that the uncertainty achieved in such relative wind speed measurements relies heavily on the absolute accuracy of the device. As such, validation of the scanning LiDARs absolute accuracy in measuring horizontal wind speed at the ranges required forms a key part of the analysis in this project. The following sub sections present results of the validation of LMCT and Leosphere scanning LiDAR devices against the vertically scanning V2 validation LiDARs deployed at Kish Lighthouse, East Pier and Poolbeg.

For single and dual Doppler measurements, the horizontal wind speed measured by the scanning LiDAR is compared to that measured by the validation V2 LiDAR. To investigate the possibility that reconstruction of the 3D wind vector using data acquired by a single scanning LiDAR may be considered less precise when the wind direction is orthogonal to the beam direction, the relationship between scanning LiDAR and V2 horizontal wind speed measurements is characterised for sectors when the beam is 'across LOS' and 'along LOS' as well as using the entire dataset. The single LiDAR datasets are split into sectors; when wind direction is within 45° of the line of sight between scanning LiDAR and target location the measurement is in a radial sector ('along LOS'), otherwise it is in an orthogonal sector ('across LOS') as shown in Figure 19.

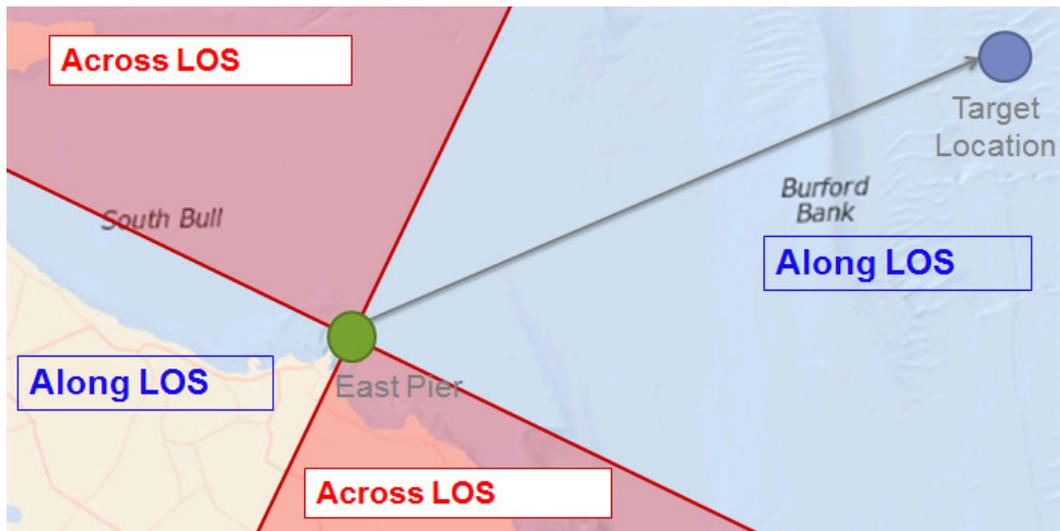


Figure 19: Illustration of the process by which the single Doppler wind measurement data is split into 'along LOS' and 'across LOS' datasets.

The accuracy of the radial wind speed (RWS) measurements from which the horizontal wind speed (HWS) is calculated in single and dual Doppler post-processing is also validated. As the scanning LiDAR hardware measures radial wind speed directly, and then reconstructs the full wind vector as a post-processing calculation, this comparison can inform on the main sources of inaccuracy in the scanning LiDAR measurements (i.e. is the actual measurement of the radial wind or reconstruction of the vector the dominant source of error). For validation of RWS, validation LiDAR HWS and wind direction are used to reconstruct the wind speed along the scanning LiDAR beam LOS to give a validation LiDAR measurement of RWS.

All validation results are shown for both target heights (100m and 150m above MSL) unless stated otherwise.

5.1 LMCT

Radial Wind Speed Validation

The validation of the Baily Lighthouse WindTracer radial wind speed measurement at the Kish Lighthouse is summarised in Figure 20 and Table 8. The scanning LiDAR is located approximately 10.3km from the target measurement location.

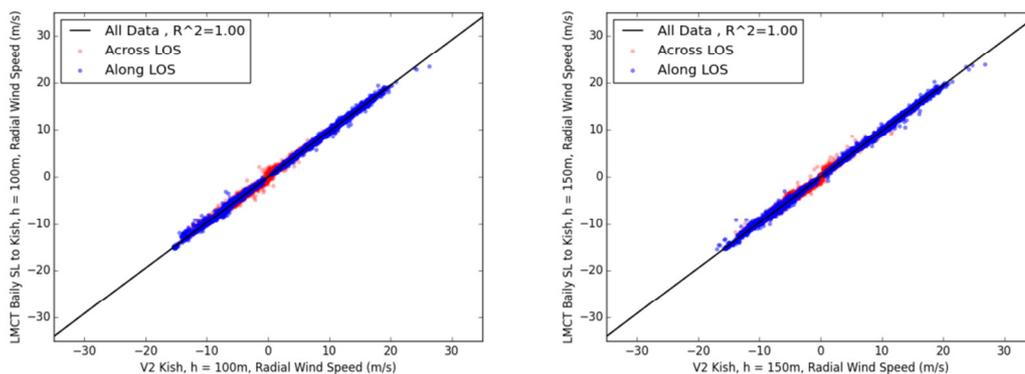


Figure 20: Baily Lighthouse WindTracer radial wind speed validation against V2 at Kish Lighthouse

Height (m)	Dataset	R ²	Slope	Intercept	Hours of data
100	All	0.997	0.973	-0.009	1864
	Along LOS	0.998	0.971	0.010	1047
	Across LOS	0.993	0.973	-0.025	817
150	All	0.998	0.973	0.003	1808
	Along LOS	0.998	0.972	0.011	1049
	Across LOS	0.992	0.972	-0.006	759

Table 8: Baily Lighthouse WindTracer radial wind speed validation against V2 at Kish Lighthouse

The validation of the Baily Lighthouse WindTracer radial wind speed measurement at the East Pier is summarised in Figure 21 and Table 9. The scanning LiDAR is located approximately 8.3km from the target measurement location.

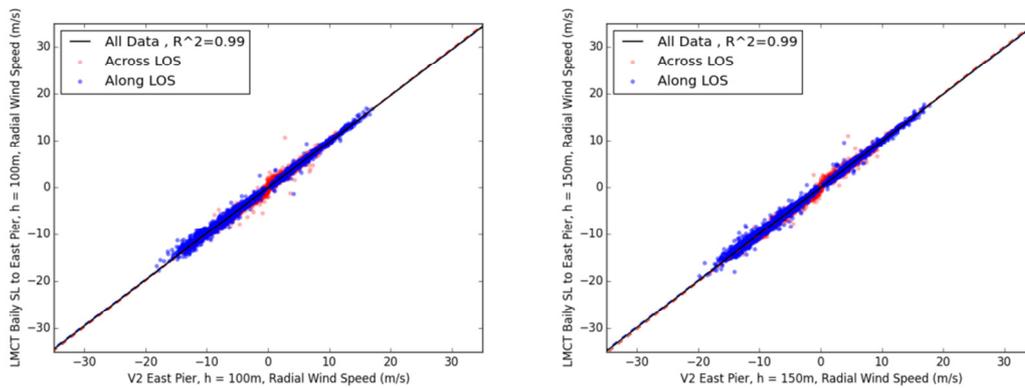


Figure 21: Baily Lighthouse WindTracer radial wind speed validation against V2 at East Pier

Height (m)	Dataset	R ²	Slope	Intercept	Hours of data
100	All	0.993	0.982	-0.038	1804
	Along LOS	0.995	0.976	0.025	699
	Across LOS	0.989	0.993	-0.069	1105
150	All	0.994	0.995	-0.016	1797
	Along LOS	0.996	0.988	0.045	738
	Across LOS	0.992	1.009	-0.051	1059

Table 9: Baily Lighthouse WindTracer radial wind speed validation against V2 at East Pier

The validation of the Baily Lighthouse WindTracer radial wind speed measurement at the Poolbeg is summarised in Figure 22 and Table 10. The scanning LiDAR is located approximately 6.9km from the target measurement location.

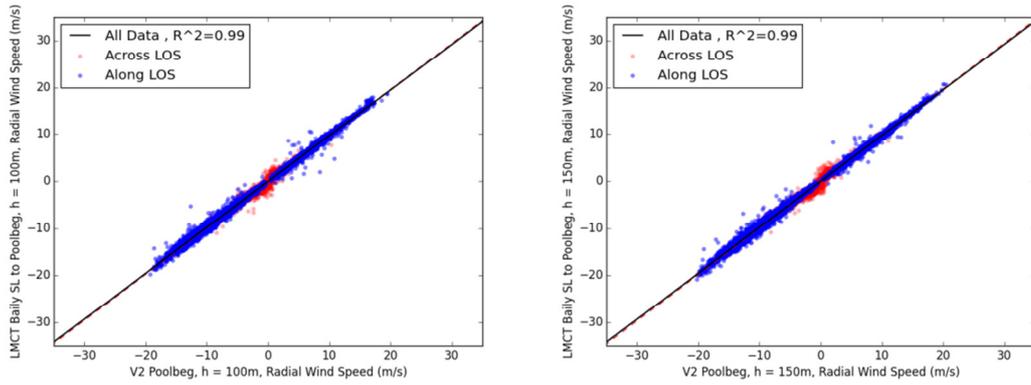


Figure 22: Baily Lighthouse WindTracer radial wind speed validation against V2 at Poolbeg

Height (m)	Dataset	R ²	Slope	Intercept	Hours of data
100	All	0.994	0.976	-0.040	2062
	Along LOS	0.996	0.975	-0.016	1261
	Across LOS	0.979	0.984	-0.073	802
150	All	0.994	0.977	-0.021	2060
	Along LOS	0.996	0.976	0.009	1262
	Across LOS	0.979	0.988	-0.062	798

Table 10: Baily Lighthouse WindTracer radial wind speed validation against V2 at Poolbeg

The validation of the East Pier WindTracer radial wind speed measurement at the Kish Lighthouse is summarised in Figure 23 and Table 11. The scanning LIDAR is located approximately 13.3km from the target measurement location.

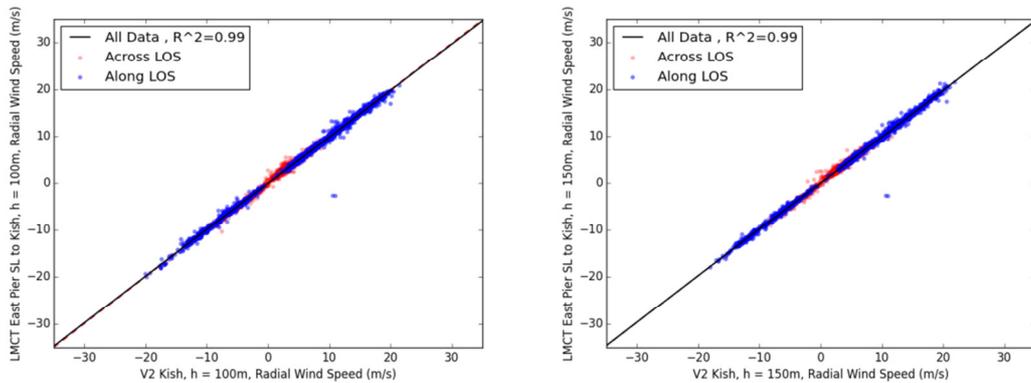


Figure 23: East Pier WindTracer radial wind speed validation against V2 at Kish Lighthouse

Height (m)	Dataset	R ²	Slope	Intercept	Hours of data
100	All	0.995	0.991	-0.033	632
	Along LOS	0.996	0.990	-0.046	338
	Across LOS	0.989	0.999	-0.029	294
150	All	0.995	0.988	0.023	517
	Along LOS	0.996	0.988	0.023	262
	Across LOS	0.990	0.990	0.019	254

Table 11: East Pier WindTracer radial wind speed validation against V2 at Kish Lighthouse

The validation of the East Pier WindTracer radial wind speed measurement at the Poolbeg is summarised in Figure 24 and Table 12. The scanning LiDAR is located approximately 4.7km from the target measurement location.

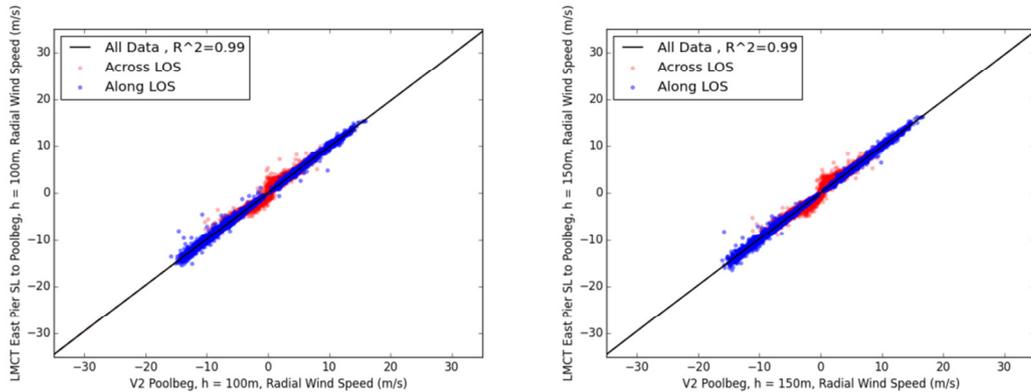


Figure 24: East Pier WindTracer radial wind speed validation against V2 at Poolbeg

Height (m)	Dataset	R ²	Slope	Intercept	Hours of data
100	All	0.990	0.985	0.020	1932
	Along LOS	0.996	0.986	-0.010	820
	Across LOS	0.971	0.983	0.041	1112
150	All	0.991	0.986	0.045	1914
	Along LOS	0.997	0.985	0.013	803
	Across LOS	0.973	0.986	0.067	1111

Table 12: East Pier WindTracer radial wind speed validation against V2 at Poolbeg

Single LiDAR Wind Speed Validation

The validation of the Baily Lighthouse WindTracer single Doppler measurement of horizontal wind speed at the Kish Lighthouse is summarised in Figure 25 and Table 13. The scanning LiDAR is located approximately 10.3km from the target measurement location.

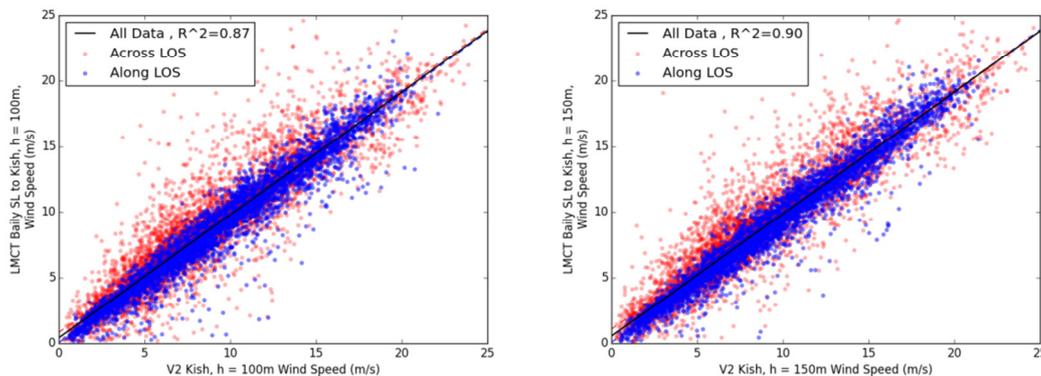


Figure 25: Baily Lighthouse WindTracer single Doppler horizontal wind speed validation against V2 at Kish Lighthouse

Height (m)	Dataset	R ²	Slope	Intercept	Hours of data
100	All	0.869	0.936	0.423	1865
	Along LOS	0.946	0.948	0.044	998
	Across LOS	0.810	0.926	0.831	868
150	All	0.898	0.930	0.551	1809
	Along LOS	0.958	0.953	0.068	1000
	Across LOS	0.851	0.908	1.078	809

Table 13: Baily WindTracer single Doppler horizontal wind speed validation against V2 at Kish Lighthouse

The validation of the Baily Lighthouse WindTracer single Doppler measurement of horizontal wind speed at the East Pier is summarised in Figure 26 and Table 14 below. The scanning LiDAR is located approximately 8.3km from the target measurement location.

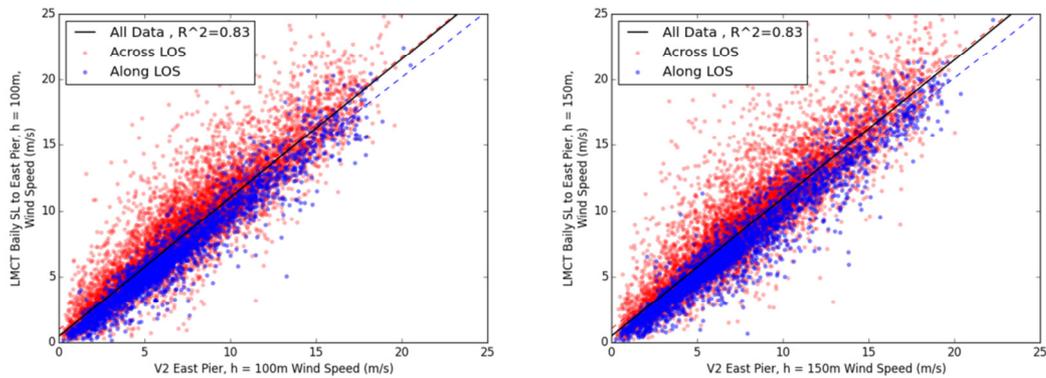


Figure 26: Baily Lighthouse WindTracer single Doppler horizontal wind speed validation against V2 at East Pier

Height (m)	Dataset	R ²	Slope	Intercept	Hours of data
100	All	0.833	1.054	0.471	1805
	Along LOS	0.931	1.018	-0.199	524
	Across LOS	0.811	1.037	0.976	1281
150	All	0.827	1.051	0.486	1797
	Along LOS	0.929	1.014	-0.167	569
	Across LOS	0.798	1.034	1.046	1229

Table 14: Baily Lighthouse WindTracer single Doppler horizontal wind speed validation against V2 at East Pier

The validation of the Baily Lighthouse WindTracer single Doppler measurement of horizontal wind speed at Poolbeg is summarised in Figure 27 and Table 15 below. The scanning LiDAR is located approximately 6.9km from the target measurement location.

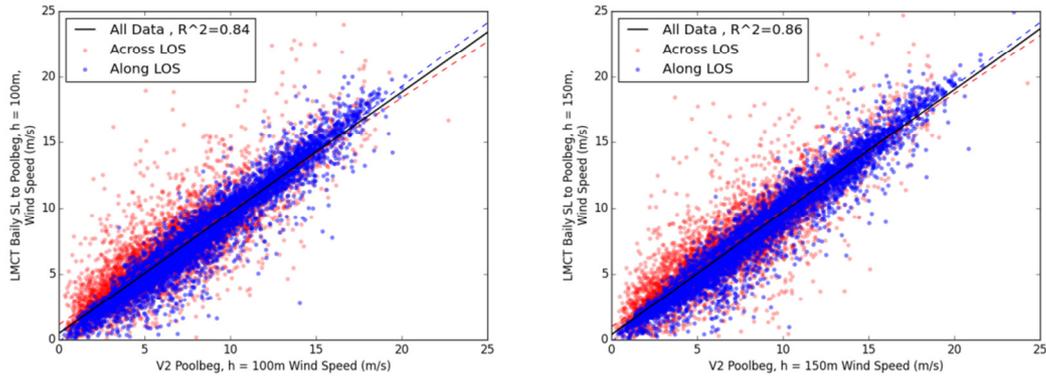


Figure 27: Baily Lighthouse WindTracer single Doppler horizontal wind speed validation against V2 at Poolbeg

Height (m)	Dataset	R ²	Slope	Intercept	Hours of data
100	All	0.837	0.918	0.474	2063
	Along LOS	0.926	0.972	-0.158	1234
	Across LOS	0.711	0.863	1.138	829
150	All	0.859	0.932	0.381	2060
	Along LOS	0.940	0.972	-0.142	1226
	Across LOS	0.743	0.887	0.978	834

Table 15: Baily Lighthouse WindTracer single Doppler horizontal wind speed validation against V2 at Poolbeg

The validation of the East Pier WindTracer single Doppler measurement of horizontal wind speed at Kish Lighthouse is summarised in Figure 28 and Table 16 below. The scanning LiDAR is located approximately 13.3km from the target measurement location.

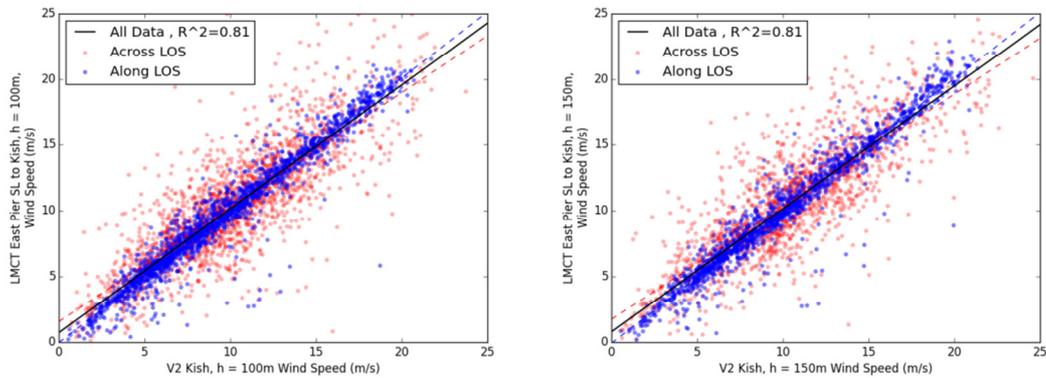


Figure 28: East Pier WindTracer single Doppler horizontal wind speed validation against V2 at Kish Lighthouse

Height (m)	Dataset	R ²	Slope	Intercept	Hours of data
100	All	0.808	0.942	0.726	637
	Along LOS	0.941	1.007	-0.031	302
	Across LOS	0.678	0.871	1.563	335
150	All	0.813	0.935	0.792	522
	Along LOS	0.938	1.007	-0.081	245
	Across LOS	0.689	0.857	1.740	277

Table 16: East Pier WindTracer single Doppler horizontal wind speed validation against V2 at Kish Lighthouse

The validation of the East Pier WindTracer single Doppler measurement of horizontal wind speed at Poolbeg is summarised in Figure 29 and Table 17 below. The scanning LiDAR is located approximately 4.7km from the target measurement location.

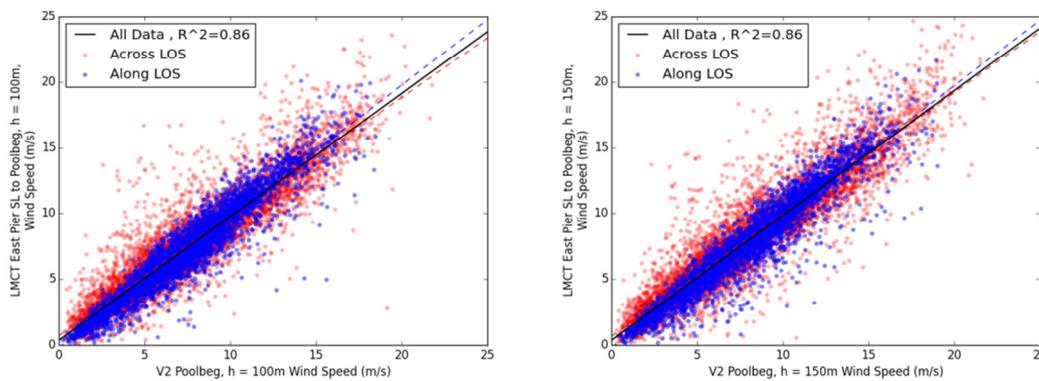


Figure 29: East Pier WindTracer single Doppler horizontal wind speed validation against V2 at Poolbeg

Height (m)	Dataset	R ²	Slope	Intercept	Hours of data
100	All	0.858	0.939	0.361	1932
	Along LOS	0.912	0.998	-0.200	796
	Across LOS	0.831	0.906	0.699	1136
150	All	0.860	0.950	0.350	1913
	Along LOS	0.911	0.997	-0.201	761
	Across LOS	0.839	0.927	0.661	1152

Table 17: East Pier WindTracer single Doppler horizontal wind speed validation against V2 at Poolbeg

Dual LiDAR Wind Speed Validation

The validation of the WindTracer dual Doppler measurement of horizontal wind speed at Kish Lighthouse is summarised in Figure 30 and Table 18.

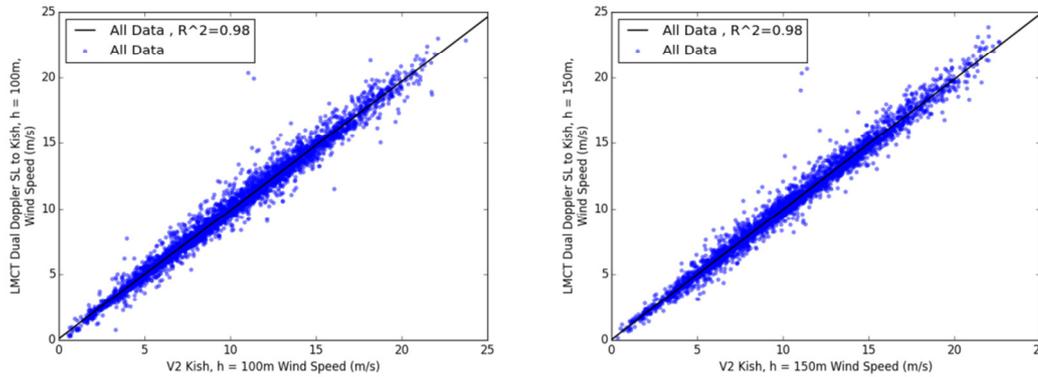


Figure 30: WindTracer dual Doppler horizontal wind speed validation against V2 at Kish Lighthouse

Height (m)	R ²	Slope	Intercept	Hours of data	Ratio of Mean WS (SL/VL)
100	0.980	0.981	0.096	748	0.991
150	0.981	0.993	0.023	609	0.995

Table 18: WindTracer dual Doppler horizontal wind speed validation against V2 at Kish Lighthouse

The validation of the WindTracer dual Doppler measurement of horizontal wind speed at Poolbeg is summarised in Figure 31 and Table 19.

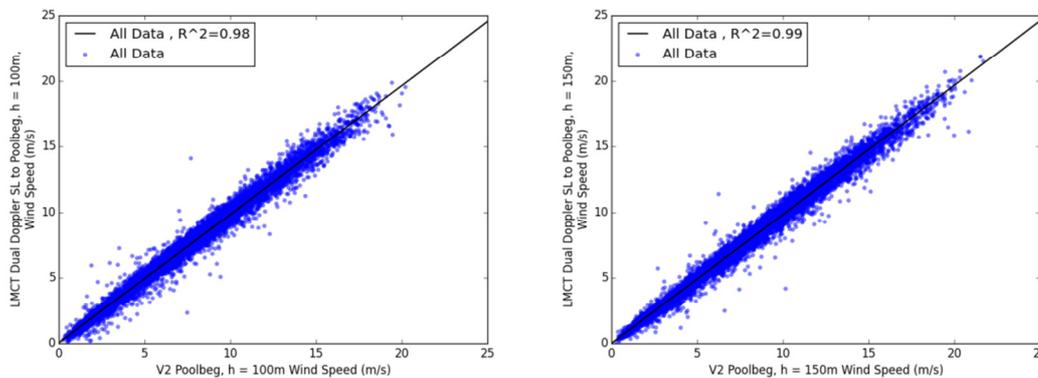


Figure 31: WindTracer dual Doppler horizontal wind speed validation against V2 at Poolbeg

Height (m)	R ²	Slope	Intercept	Hours of data	Ratio of Mean WS (SL/VL)
100	0.983	0.980	0.040	1847	0.986
150	0.986	0.984	-0.004	1827	0.984

Table 19: WindTracer dual Doppler horizontal wind speed validation against V2 at Poolbeg

5.2 Leosphere

Radial Wind Speed Validation

10 minute RWS data was supplied for Leosphere at the location of the Kish Lighthouse only and at heights of 120m and 180m. These heights correspond to the actual location of the beams at the Kish Lighthouse validation points. As such, RWS validation for Leosphere 400S devices is presented only for the Kish Lighthouse validation point at heights of 120m and 180m.

The validation of the Baily Lighthouse Windcube 400S radial wind speed measurement at the Kish Lighthouse is summarised in Figure 32 and Table 20. The scanning LiDAR is located approximately 10.1km from the target measurement location.

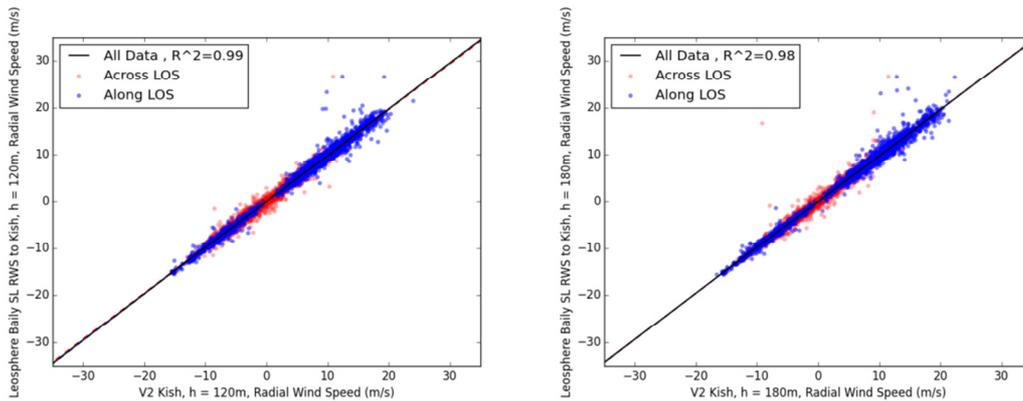


Figure 32: Baily Lighthouse Windcube 400S radial wind speed validation against V2 at Kish Lighthouse at 120m and 180m

Height (m)	Dataset	R ²	Slope	Intercept	Hours of data
120	All	0.985	0.985	0.024	810
	Along LOS	0.988	0.988	-0.010	454
	Across LOS	0.965	0.975	0.040	356
180	All	0.981	0.978	0.006	824
	Along LOS	0.988	0.978	0.001	466
	Across LOS	0.944	0.982	0.014	359

Table 20: Baily Lighthouse Windcube 400S radial wind speed validation against V2 at Kish Lighthouse at 120m and 180m

The validation of the East Pier Windcube 400S radial wind speed measurement at the Kish Lighthouse is summarised in Figure 33 and Table 21. The scanning LiDAR is located approximately 13.4km from the target measurement location.

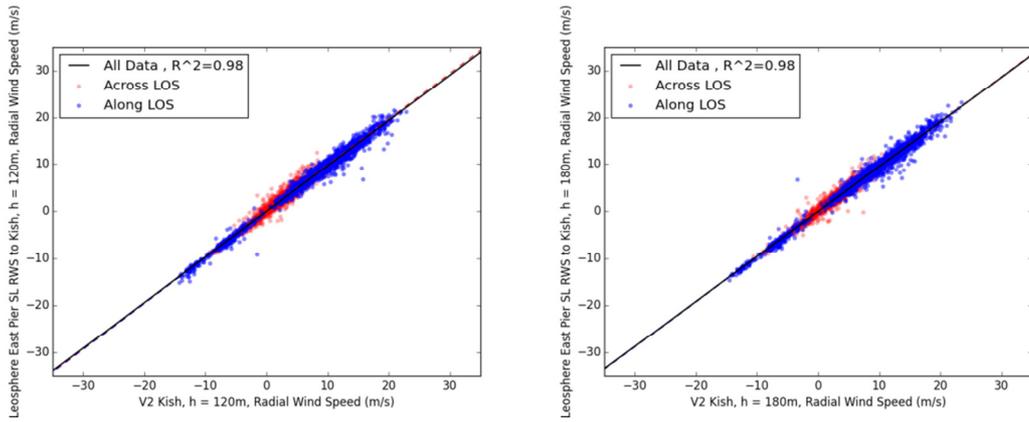


Figure 33: East Pier Windcube 400S radial wind speed validation against V2 at Kish Lighthouse at 120m and 180m

Height (m)	Dataset	R ²	Slope	Intercept	Hours of data
120	All	0.981	0.970	0.001	652
	Along LOS	0.986	0.974	-0.108	367
	Across LOS	0.938	0.981	0.068	285
180	All	0.980	0.956	-0.035	602
	Along LOS	0.985	0.958	-0.099	323
	Across LOS	0.949	0.959	0.005	280

Table 21: East Pier Windcube 400S radial wind speed validation against V2 at Kish Lighthouse at 120m and 180m

RES were provided with high frequency raw data by Leosphere and have performed in-house post-processing to create a time series of 10 min radial wind speed at validation locations. Only data recorded with a 500m radius of the each demonstration was used in the calculation of averaged 10 minute data. The data was then filtered to remove any 10 minute data points with a mean CNR less than -32dB.

The validation of the Baily Lighthouse Windcube 400S radial wind speed measurement at the Kish Lighthouse is summarised in Figure 34 and Table 22. The scanning LiDAR is located approximately 10.1km from the target measurement location. The comparison is based on measurements at heights of 120m as this is the lowest height at which radial wind speed was directly measured at the Kish Lighthouse demonstration point.

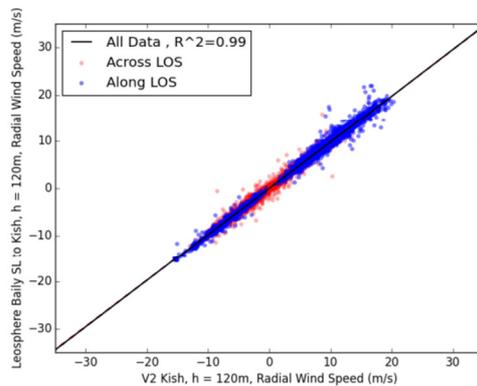


Figure 34: Baily Lighthouse Windcube 400S RES processed radial wind speed validation against V2 at Kish Lighthouse at 120m

Height (m)	Data Used	R ²	Slope	Intercept	Hours of data
120	All	0.988	-0.986	-0.034	816
	Along LOS	0.991	-0.988	-0.009	474
	Across LOS	0.970	-0.981	-0.051	342

Table 22: Baily Lighthouse Windcube 400S RES processed radial wind speed validation against V2 at Kish Lighthouse

The validation of the East Pier Windcube 400S radial wind speed measurement at the Kish Lighthouse is summarised in Figure 35 and Table 23. The scanning LiDAR is located approximately 13.4km from the target measurement location. The comparison is based on measurements at heights of 120m as this is the lowest height at which radial wind speed was directly measured at the Kish Lighthouse demonstration point.

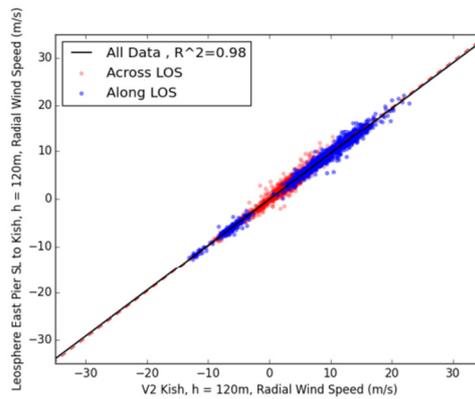


Figure 35: East Pier Windcube 400S RES processed radial wind speed validation against V2 at Kish Lighthouse at 120m

Height (m)	Data Used	R ²	Slope	Intercept	Hours of data
120	All	0.984	0.970	-0.074	432
	Along LOS	0.989	0.969	-0.096	239
	Across LOS	0.950	0.985	-0.085	194

Table 23: East Pier Windcube 400S RES processed radial wind speed validation against V2 at Kish Lighthouse

Single LiDAR Wind Speed Validation

The validation of the Baily Lighthouse Windcube 400S single Doppler measurement of horizontal wind speed at the Kish Lighthouse is summarised in Figure 36 and Table 24. The scanning LiDAR is located approximately 10.1km from the target measurement location.

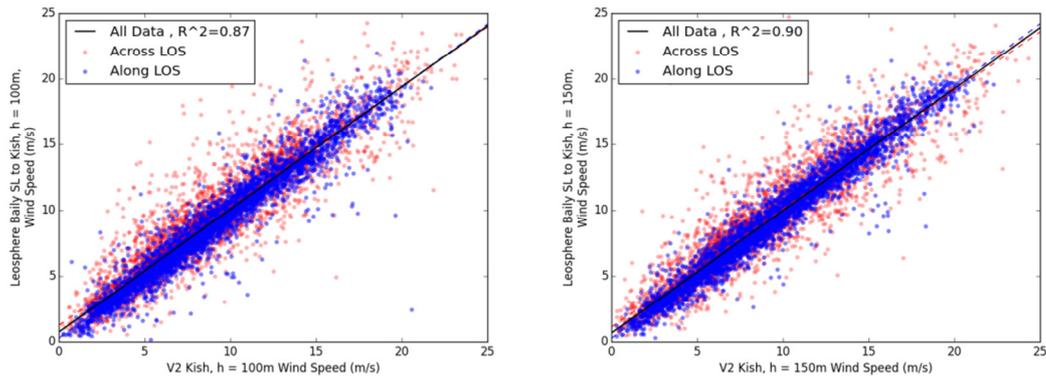


Figure 36: Baily Lighthouse Windcube 400S single Doppler horizontal wind speed validation against V2 at Kish Lighthouse

Height (m)	Data Used	R ²	Slope	Intercept	Hours of data
100	All	0.874	0.933	0.732	1248
	Along LOS	0.929	0.957	0.262	676
	Across LOS	0.823	0.909	1.245	572
150	All	0.900	0.930	0.661	1261
	Along LOS	0.948	0.958	0.256	688
	Across LOS	0.851	0.899	1.120	573

Table 24: Baily Lighthouse Windcube 400S single Doppler horizontal wind speed validation against V2 at Kish Lighthouse

The validation of the Baily Lighthouse Windcube 400S single Doppler measurement of horizontal wind speed at the East Pier is summarised in Figure 37 and Table 25. The scanning LiDAR is located approximately 8.2km from the target measurement location.

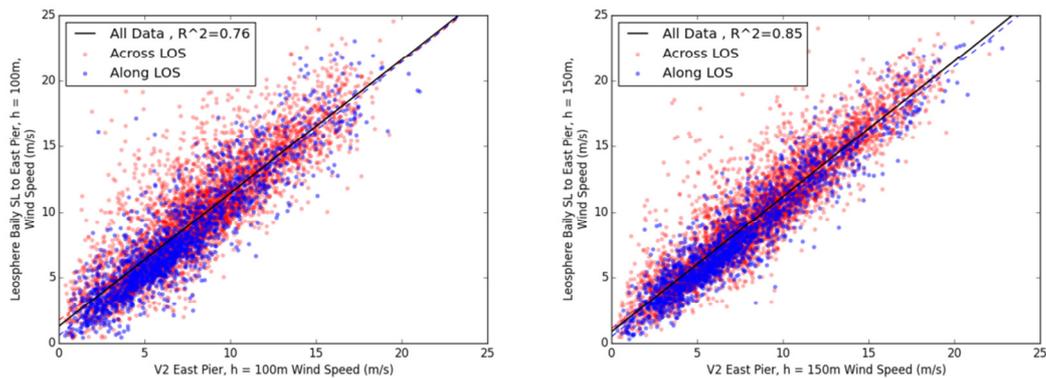


Figure 37: Baily Lighthouse Windcube 400S single Doppler horizontal wind speed validation against V2 at East Pier

Height (m)	Data Used	R ²	Slope	Intercept	Hours of data
100	All	0.760	1.018	1.271	1041
	Along LOS	0.817	1.043	0.568	300
	Across LOS	0.733	0.990	1.711	741
150	All	0.847	1.033	0.855	1072
	Along LOS	0.888	1.031	0.482	300
	Across LOS	0.830	1.022	1.093	772

Table 25: Baily Lighthouse Windcube 400S single Doppler horizontal wind speed validation against V2 at East Pier

The validation of the East Pier Windcube 400S single Doppler measurement of horizontal wind speed at the Kish Lighthouse is summarised in Figure 38 and Table 26. The scanning LiDAR is located approximately 13.4km from the target measurement location.

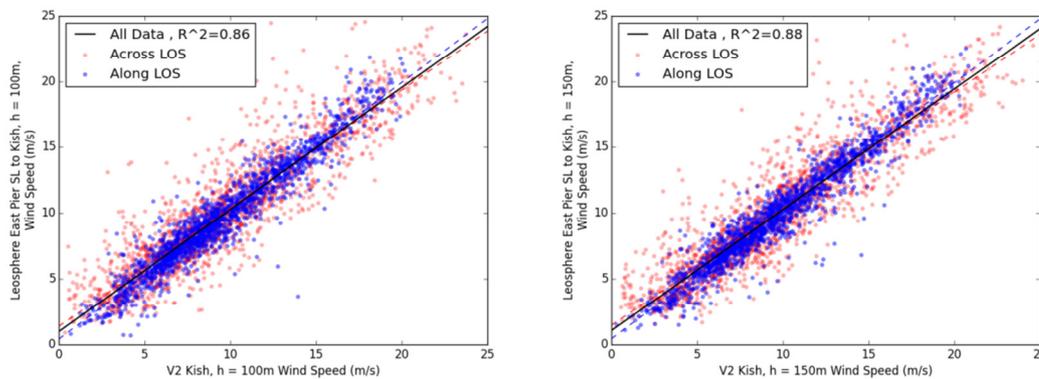


Figure 38: East Pier Windcube 400S single Doppler horizontal wind speed validation against V2 at Kish Lighthouse

Height (m)	Data Used	R ²	Slope	Intercept	Hours of data
100	All	0.859	0.929	0.985	601
	Along LOS	0.920	0.976	0.412	284
	Across LOS	0.823	0.899	1.388	317
150	All	0.875	0.919	1.066	607
	Along LOS	0.930	0.974	0.436	281
	Across LOS	0.843	0.886	1.466	326

Table 26: East Pier Windcube 400S single Doppler horizontal wind speed validation against V2 at Kish Lighthouse

Dual LiDAR Wind Speed Validation

The validation of the Windcube 400S dual Doppler measurement of horizontal wind speed at Kish Lighthouse (based on PPI scan results, see Table 4 and Table 5) is summarised in Figure 39 and Table 27.

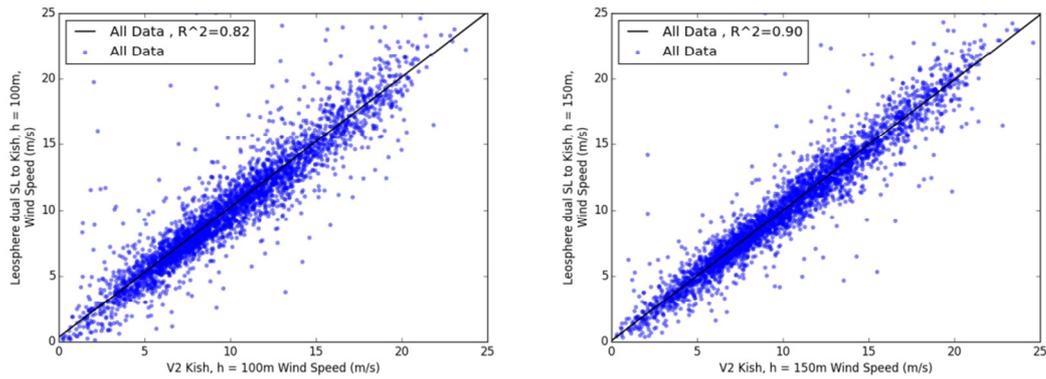


Figure 39: Leosphere Windcube 400S dual Doppler validation against V2 at Kish Lighthouse at 100m and 150m

Height (m)	R ²	Slope	Intercept	Hours of Data	Ratio of Mean WS (SL/VL)
100	0.823	0.990	0.343	563	1.024
150	0.903	0.992	0.074	564	1.000

Table 27: Windcube 400S dual Doppler validation against V2 at Kish Lighthouse at 100m and 150m

The validation of the Windcube 400S dual Doppler measurement of horizontal wind speed at Poolbeg (based on RHI scan results, see Table 6 and Table 7) is summarised in Figure 40 and Table 28.

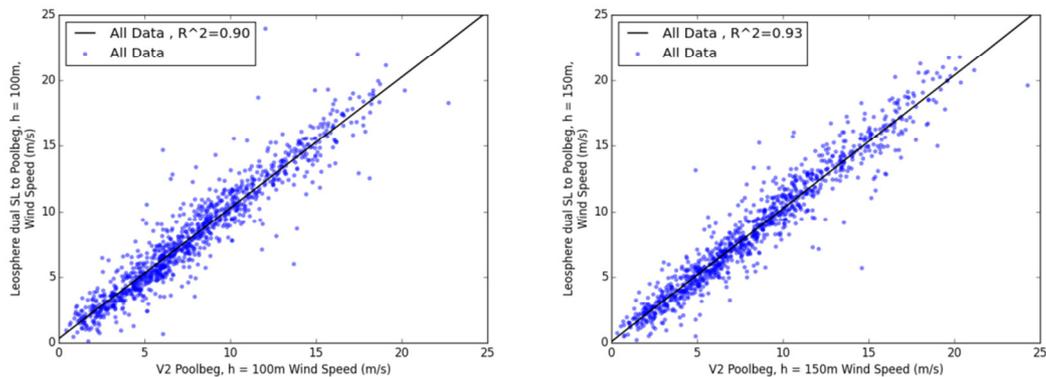


Figure 40: Windcube 400S RHI dual Doppler validation against V2 at Poolbeg at 100m and 150m

Height (m)	R ²	Slope	Intercept	Hours of data	Ratio of Mean WS (SL/VL)
100	0.902	0.998	0.309	176	1.037
150	0.929	1.015	0.087	175	1.026

Table 28: Windcube 400S RHI dual Doppler validation against V2 at Poolbeg at 100m and 150m

RES have performed a dual Doppler calculation of horizontal wind speed at the Kish Lighthouse using the 10 minute radial wind speed data calculated in-house (see Figure 34 and Figure 35). The validation of the RES-calculated Windcube 400S dual Doppler horizontal wind speed at the Kish Lighthouse is summarised in Figure 41 and Table 29.

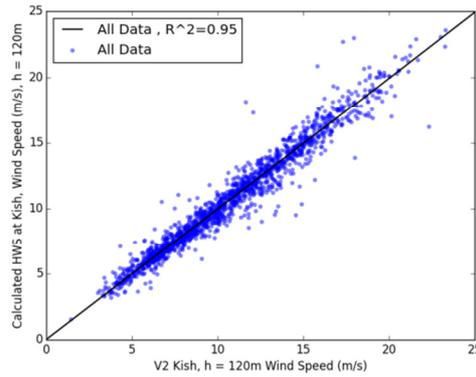


Figure 41: Windcube 400S dual Doppler validation against V2 at Kish Lighthouse at 120m. The dual Doppler wind speed is that calculated by RES from high frequency radial wind speed data.

Height (m)	R ²	Slope	Intercept	Hours of data	Ratio of Mean WS (SL/VL)
120	0.946	0.996	0.018	276	0.997

Table 29: Windcube 400S dual Doppler validation against V2 at Kish Lighthouse at 120m. The dual Doppler wind speed is that calculated by RES from based on high frequency radial wind speed data.

6.0 Validation of Relative Accuracy (Spatial Variation)

In Section 5.0 results demonstrating the absolute accuracy of scanning LiDAR measurements of horizontal wind speed is evaluated. In this section, the accuracy of relative measurements of the spatial variation in horizontal wind speed is evaluated. The vertically scanning V2 LiDARs are used to provide validation data as a pair of V2s can be used to measure relative wind speed change between two points. It is therefore possible to quantifiably validate the relative change in wind speed measured by the validation LiDARs between the locations at which V2s are deployed. The results of this quantitative validation in relative accuracy will be presented for LMCT (Section 6.1) and Leosphere (Section 6.2) dual Doppler datasets along with some qualitative visualisations of the wind speed variation measured across the demonstration zone.

The absolute accuracy of single Doppler scanning LiDAR measurements presented in Section 6.0 is not considered adequate to warrant use of this technology to quantify the spatial variation in wind resource for large offshore sites. As such, validation of relative wind speed measurements is only presented for dual Doppler measurements.

6.1 LMCT

Figure 42 shows a wind speed map of the Dublin Bay created from the measurements acquired using the LMCT dual Doppler wind speed measurements. The map refers to a target height of 100m. Spatial interpolation of the measurements has been performed using the Kriging technique.

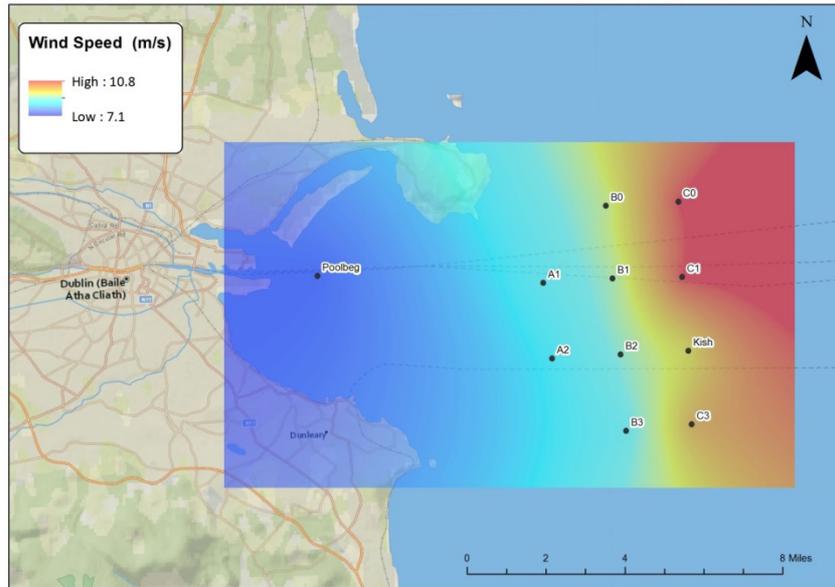


Figure 42: Map of 100m mean wind speed in the Dublin Bay area based on LMCT dual Doppler measurements

The ratio between Kish Lighthouse and Poolbeg mean wind speed (also referred to as speed up between the two locations) as measured by the WindTracer dual Doppler data and the V2s at each location are expressed in Table 30. The results shown represent the direct validation of the WindTracer dual Doppler system for measuring spatial variation in wind resource. In the comparison presented in Table 30 only data recorded concurrently at both locations by scanning LiDAR and validation LiDARs is used.

	100m	150m
Point from	Poolbeg	Poolbeg
Point to	Kish	Kish
Mean WS Poolbeg Dual Doppler_SL	7.87	8.66
Mean WS Kish Dual Doppler_SL	9.77	10.29
Mean WS Poolbeg V2	7.94	8.74
Mean WS Kish V2	9.86	10.34
Speed up SL (Kish WS / Poolbeg WS)	24.21%	18.78%
Speed up V2 (Kish WS / Poolbeg WS)	24.24%	18.28%
SL Speed Up Error	-0.02%	0.50%
Hours of data	744	605
Data coverage	31.85%	25.94%

Table 30: Poolbeg to Kish Lighthouse speed up measured by LMCT dual Doppler scanning LiDAR and V2 LiDARs.

The results of Table 30 provide a compelling validation of the LMCT dual Doppler technique for the purpose of measuring spatial variation in wind resource offshore. The large speed from Poolbeg to Kish Lighthouse (24.24% and 18.28% at 100m and 150m measured by the validation LiDARs) is measured with excellent accuracy by the WindTracers operating in dual Doppler mode; the observed speed up error is within 0.5% at both heights.

6.2 Leosphere

Figure 43 shows a wind speed map of the Dublin Bay created from the measurements acquired using the Windcube 400S dual Doppler wind speed measurements. The map refers to a target height of 100m. Spatial interpolation of the measurements has been performed using the Kriging technique.

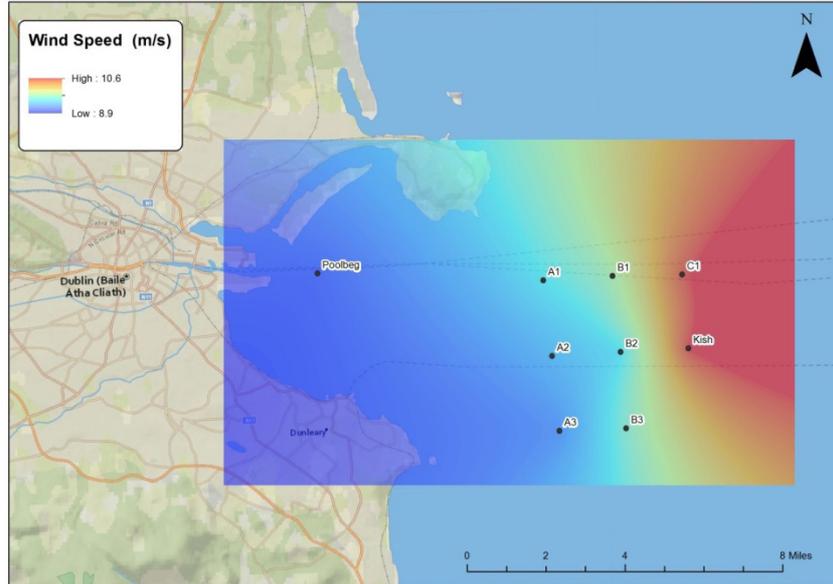


Figure 43: Map of 100m mean wind speed in the Dublin Bay area based on Leosphere dual Doppler measurements

The ratio between Kish Lighthouse and Poolbeg mean wind speed (also referred to as speed up between the two locations) as measured by the Windcube 400S dual Doppler data and the V2s at each location are expressed in Table 31. The results shown represent the validation of the Windcube 400S dual Doppler systems for measuring spatial variation in wind resource. As detailed in Section 4.2, the scanning pattern implemented by Leosphere employs RHI scan at Poolbeg for 10 minutes in every hour, with PPI scans of the other demonstration points being performed during the remaining 50 minutes. As such, it is not possible to validate the speed up measured by the dual Doppler technique using only concurrent data as no concurrent dual Doppler measurements exist corresponding to Poolbeg and Kish Lighthouse. The results in Table 31 are therefore based on non-concurrent data.

	100m	150m
Point from	Poolbeg	Poolbeg
Point to	Kish	Kish
Mean WS Poolbeg Dual Doppler_SL	8.12	8.58
Mean WS Kish Dual Doppler_SL	10.25	10.29
Mean WS Poolbeg V2	7.83	8.37
Mean WS Kish V2	10.01	10.29
Speed up SL (Kish WS / Poolbeg WS)	26.30%	19.89%
Speed up V2 (Kish WS / Poolbeg WS)	27.90%	23.04%
SL Speed Up Error	-1.60%	-3.16%
Hours of data (Poolbeg)	176	175
Hours of data (Kish)	563	564

Table 31: Poolbeg to Kish Lighthouse speed up measured by Leosphere dual Doppler scanning LiDAR and V2 LiDARs. All results are based on the Leosphere post-processing of raw data rather than that performed by RES.

The results in Table 31 show the speed up measured by the 400S in dual Doppler mode agree with that measured by the validation LiDARs to within 3.5% at both heights. The result can be considered indicative only as a true validation of speed up measurement is not possible due to the non-concurrency of the underlying data; variation in wind speed over time, as well as spatial variation, can affect the speed up measured.

7.0 Discussion

The results presented in Sections 5.0 and 6.0 are discussed in further detail in this section. Particular focus is placed on evaluating the following performance indicators for each technology:

- Precision of measurement
 - A precise measurement is indicated by a strong correlation (R^2) with the validation LiDAR measurements
- Accuracy of relative wind speed measurement (spatial variation)
 - This is determined by the difference in absolute error of wind speed measurements at two points in space. Inconsistent absolute accuracy will result in poor measurement accuracy for spatial variation. Table 32 and Table 33 summarise key results from the validation of LMCT and Leosphere scanning LiDARs respectively. In these tables the Range of WS errors provides a measure of the error that can result in a relative wind speed measurement. For example, if the errors in mean wind speed measurement at two points in space are -2% and +3% respectively, the error in the calculated speed up will be 5%.

Table 32 and Table 33 summarise key statistics relating to the validation of the absolute accuracy of LMCT and Leosphere measurements respectively. These statistics are used to infer the precision and accuracy of the various measurements and inform the discussion in this presented in the remainder of this section. Furthermore, the range of wind speed errors is presented and can inform on the capability of the devices to measure spatial variation.

	RWS	Single Doppler HWS	Dual Doppler HWS
Number of Trials	10	10	4
Min R^2	0.990	0.808	0.980
Max R^2	0.998	0.898	0.986
Average R^2	0.994	0.846	0.983
Min Mean WS Error 100m	-2.2%	-1.9%	-1.4%
Max Mean WS Error 100m	0.2%	11.8%	-0.9%
Min Mean WS Error 150m	-2.2%	-2.0%	-1.6%
Max Mean WS Error 150m	0.4%	11.1%	-0.5%
Average Mean WS Error	-0.8%	1.7%	-1.1%
Range of WS Errors 100m	2.5%	13.6%	0.5%
Range of WS Errors 150m	2.6%	13.1%	1.1%

Table 32: Summary of LMCT validation results

	RWS	Single Doppler HWS	Dual Doppler HWS
Number of Trials	4	6	4
Min R ²	0.980	0.760	0.823
Max R ²	0.985	0.900	0.929
Average R²	0.982	0.853	0.889
Min Mean WS Error 100m (120m for RWS)	-2.2%	1.3%	2.4%
Max Mean WS Error 100m (120m for RWS)	-1.3%	18.0%	3.7%
Min Mean WS Error 150m (180m for RWS)	-4.0%	0.1%	0.0%
Max Mean WS Error 150m (180m for RWS)	-1.7%	13.5%	2.6%
Average Mean WS Error	-2.3%	6.5%	2.2%
Range of WS Errors 100m (120m for RWS)	0.8%	16.6%	1.3%
Range of WS Errors 150m (180m for RWS)	2.3%	13.4%	2.6%

Table 33: Summary of Leosphere validation results. All results are based on the Leosphere post-processing of the raw data rather than that performed by RES.

Single Doppler Validation

It can be seen from Table 32 and Table 33 that single Doppler wind speed measurements are subject to large errors in mean wind speed measurement (between -1.9% and 11.8% for LMCT and between 0.1% and 18.0% for Leosphere). This can result in high errors in relative wind speed measurements between two points (up to 13.6% for LMCT and 16.6% for Leosphere based on the results available). The single Doppler horizontal wind speed measurements also show relatively poor precision with R² of the correlation to validation data ranging from 0.760 to 0.900 (similar results observed for both manufacturers).

These results imply that single Doppler LiDAR measurements are not suitable for providing accurate measurements of spatial variation in wind resource at the length scales considered in this project. At the measurement distances considered in this campaign the length of the measurement arc can be large (up to 10km). The homogeneity assumption is unlikely to be valid over these distances. This observation does not negate single Doppler validation studies at shorter distances [20] [21] where the homogeneity assumption is more likely to be valid.

Dual Doppler Validation

The dual Doppler technique gives excellent results with absolute errors between -1.6% and -0.5% for LMCT and -0.3% and 3.7% for Leosphere. This implies much lower relative errors (up to 1.1% for LMCT and 2.6% for Leosphere based on the available data measured at the same heights). The observed precision of the dual Doppler wind speed and measurements is also increased relative to single Doppler measurements (R² between 0.980 and 0.986 for LMCT and between 0.823 and 0.929 for Leosphere).

Comparison of the dual Doppler and RWS validation results shows that very little error is introduced by the process of inferring the full 3D wind vector from RWS measurements. The dual Doppler technique does not require sampling of a large measurement arc as is the case for the single Doppler technique. The relative error observed is much lower than industry standard mesoscale model uncertainty.

OEM Comparison

Although the hardware deployed by LMCT and Leosphere is fundamentally different in terms of power and cost, and therefore not strictly comparable, it is useful to compare the results for both OEMs in order to highlight sensitivity of results to hardware, campaign design and processing techniques.

The LMCT WindTracer devices achieve higher data coverage than the Leosphere devices. Specifically, LMCT report data coverage of 70% was achieved by the Baily Lighthouse WindTracer device at a distance of 14km (East Pier WindTracer data coverage is lower due to an undiagnosed technical issue) [4] [5]. The standard model Windcube 400S device achieves 70% data coverage at 9km, whilst the more powerful prototype device achieved 70% data coverage at 11km [6] [7]. Increased data coverage from the WindTracer (relative to

Windcube 400S) is expected given the higher pulse energy of the device (2.5mJ for the WindTracer, 0.16mJ and 0.24mJ for the Windcube 400S and 400S prototype respectively). Although pulse energy is the main system parameter that determines LiDAR range performance, other variables such as pulse repetition frequency (noise level decreases with the square root of PRF) and integration time are also important [18] [19].

Comparing the validation results for LMCT (Table 32) and Leosphere (Table 33) devices it can be seen the raw RWS measurements acquired by LMCT measurements exhibit higher precision and accuracy than the Leosphere measurements (mean R^2 of 0.994 opposed to 0.982 and average absolute error of 0.8% opposed to 2.3%). This difference may be due to details of the hardware used (e.g. beam power and pointing accuracy) and the scan pattern (e.g. different scan speed).

The precision of single LiDAR measurements is very similar for both Leosphere and LMCT devices (mean R^2 of 0.853 for Leosphere and 0.846 for LMCT). However, LMCT single LiDAR measurements exhibit higher accuracy (average wind speed error of 1.7% as opposed to 6.5% for Leosphere). In terms of measurement of spatial variability in wind resource, results for both technologies imply high error in speed up measurements is possible (up to 13.6% for LMCT and 16.6% for Leosphere) at the distances considered in this campaign (5km to 15km).

Dual Doppler results achieved by LMCT show higher precision and accuracy than those of Leosphere (R^2 of 0.983 opposed to 0.889 and mean wind speed error of 1.1% opposed to 3.7%). Results imply a speed up error of up to 1.1% for LMCT and 2.6% for Leosphere. Dual LiDAR measurements from both OEMs exhibit sufficient accuracy to measure the spatial variability offshore in offshore wind resource effectively, showing potential to reduce uncertainty associated with energy yield modelling during wind farm development.

The increase in LMCT single and dual LiDAR accuracy may be attributed to the increased accuracy of raw RWS measurements, differences in scan pattern and differences in the post processing techniques implemented. For example, LMCT removed data from unfavourable wind directions (wind direction across the beam LOS) whereas Leosphere did not. Furthermore, the LMCT and Leosphere scan pattern design philosophies differed greatly. The Windcube 400S beams visited measurement points with higher frequency but at lower spatial accuracy, whereas the LMCT scan resulted in fewer visitations of each measurement point during each 10 minute period but focussed on high spatial accuracy. The LMCT scanning pattern enabled direct measurement of the target heights at all demonstration points, whereas Leosphere raw RWS measurements were not at the target heights at some points (measured at 120m and 180m at Kish Lighthouse). The process of performing vertical extrapolation/interpolation during post processing may cause additional uncertainty due to lack of complete knowledge of the wind shear profile. It is also worth noting that LMCT used a lower scan speed than Leosphere; both WindTracers operate at scan speeds of less than 2.5°/s while the Windcube 400S and 400S prototype devices operate at 3°/s and 6°/s.

As Leosphere supplied 1 Hz raw RWS datasets, RES were able to carry out dual Doppler processing of the Leosphere data. Comparison of results calculated by RES (Table 29) to those of Leosphere (Table 27) shows that further improvement in the accuracy and precision of Leosphere dual LiDAR results is possible through adjustment of the filtering and dual Doppler calculation algorithm applied during post processing. However, the increased accuracy and precision may also be associated with lower data count.

Yield Uncertainty Benefit

The primary use case for long range scanning LiDAR investigated in this project is for the measurement of spatial variation in energy resource for offshore wind farms with a view to decreasing the uncertainty of pre-construction energy yield estimates. The current industry standard method is to infer spatial variation using mesoscale wind modelling. In this section, total uncertainty in yield prediction for a hypothetical wind farm located in Dublin Bay is assessed for different spatial variation uncertainty scenarios. Four scenarios representative of primary wind speed measurement offshore (at Kish Lighthouse) and onshore (at Poolbeg) locations and spatial variation quantification by mesoscale modelling and dual scanning LiDAR are considered. The magnitude of other uncertainty components are assumed based on those presented in Appendix A.2.2 of the WP1 report [1] which illustrated the sensitivity of total uncertainty on the component due to spatial variation. All uncertainty calculations utilise the method of Clerc et al [22].

A summary of the improvement in P90/P50 ratio that can be achieved when using dual SL as opposed to mesoscale wind maps to quantify the spatial variation in energy resource is given in Table 34:

Uncertainty Term	Without Scanning LiDAR	With Scanning LiDAR
Long Term WS Uncertainty	3.9%	3.9%
Other (Wakes, Power Curve, etc.)	5.4%	5.4%
Spatial	2.5%	1.3%
Total Uncertainty	7.1%	6.8%
P90/P50	90.9%	91.3%

Table 34: Impact of scanning LiDAR spatial variation measurements on energy yield prediction uncertainty for a hypothetical offshore wind farm in Dublin Bay with primary wind speed measurement onshore.

The uncertainty calculations carried out suggest a significant improvement in P90/P50 ratio of approximately 0.4% is possible using scanning LiDAR instead of industry standard methods. The calculations provide a conservative estimate of the benefit that is achievable through utilisation of dual scanning LiDAR technology.

8.0 Conclusions

A four month campaign utilising four long range scanning LiDARs supplied by LMCT (Table 2) and Leosphere (Table 3) and three vertically scanning Leosphere Windcube V2 LiDARs (Table 1) deployed in the Dublin Bay area (Figure 1) and subsequent data analysis has been undertaken to evaluate the suitability of scanning LiDAR to measure wind resource variability in offshore wind farm development areas. The accuracy and precision of SL measurements and the potential for the technique to aid in reduction of uncertainty in pre-construction yield predictions (and hence reduce project finance cost) is assessed. The key conclusions from the project are summarised below:

- For long range measurements of speed up (and therefore resource variation) dual Doppler scanning LiDAR measurements offer a substantial increase in accuracy over single LiDAR measurements.
 - A potential source of error in single LiDAR measurements is the assumption of homogeneous flow along the measurement arc which is unlikely to be valid at the ranges considered here due to the large extent of the arc. The use of large measurement arcs is not required to measure the full wind vector when using dual LiDARs.
 - Single LiDAR measurements also show high sensitivity to wind direction, with decreased wind speed accuracy when wind direction is across the beam LOS. The dual Doppler technique combines measurements from multiple devices so a large portion of the wind vector can always be measured directly. It should be noted that when the wind direction is along the beam LOS single LiDAR wind direction measurements suffer reduced accuracy. In an offshore resource assessment context this can prove costly as wake loss (one of the dominant loss factors for large offshore wind farms) is sensitive to wind direction.
- All scanning LiDAR devices tested demonstrated excellent capability to provide precise and accurate measurements of the radial wind speed at long range.
 - This provides further indication that inaccuracies are introduced via assumptions made at the post processing stage (e.g. flow homogeneity assumption for single LiDAR), rather than being inherent in the raw measurements.
- Poor data coverage of the scanning LiDAR devices at large ranges may increase the required campaign duration and therefore associated cost.
 - As this project represents the first demonstration of the scanning LiDAR to measure at multiple points over ranges of 4km to 15km further development of the technology, and therefore increased data capture rate, is anticipated.

- LMCT and Leosphere single LiDAR measurements were of similar precision, with LMCT devices measuring with slightly higher accuracy. LMCT dual Doppler measurements exhibited increased precision and accuracy relative to those of Leosphere. It should be noted that this result was expected due to the higher pulse energy of the LMCT devices.
 - Increased accuracy of LMCT results is attributed to the increased quality of the raw measurements as well as details of the post processing and scan pattern.
- Dual Doppler processing technique can have a significant effect on the accuracy and precision of the results obtained as indicated by comparison of RES and Leosphere dual Doppler processing of Windcube 400S raw data.
- Conservative estimates suggest a reduction in total energy yield uncertainty of 0.1% to 0.4% is achievable using dual scanning LiDAR in place of current industry standard methods.
 - This uncertainty reduction can result in significant cost reductions for offshore wind farm development by reducing perceived investment risk and hence cost of finance.
- Data acquired by long range scanning LiDAR campaigns may prove valuable in aspects other than the primary use case considered in this project. The technology is capable of acquiring data to aid other project decisions relating to, for example, turbine layout optimisation and resource assessment. Use of long range scanning LiDAR as a met mast replacement for resource assessment offshore is also conceivable.

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