Comparison of 2nd Generation LiDAR Wind Measurement Technique with CFD Numerical Modelling

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Abstract. With the rapid increase in both on and offshore wind turbine deployment there is a requirement for a better understanding of the flow field in which such devices are deployed. Greater understanding of the flow field is necessary for optimisation of turbine control, turbine design, and machine interaction as well as maximise operation and performance.
Advanced measurement tools can characterise the flow regime by either acoustic or laser pulses to measure the line of sight velocity of air born particles. Such technology facilitates the acquisition of detailed and precise measurements of wind speed and direction remote from the device location; some solutions can even provide detail of the flow structure of the wind in the measurement field.
In the current study an analysis of the methodology, relevance and potential of a 2nd generation LiDAR is presented along with results of a deployment at an onshore wind farm. The results demonstrate the potential of the LiDAR to capture details of wind farm flow and structures, along with the potential to corroborate numerical techniques with the measured data.
Advances in Computational Fluid Dynamics (CFD) approaches coupled with the availability of significant computational resources makes it possible to conduct a valid comparative assessment. This paper presents the details of this comparative assessment and makes a judgement on the accuracy of the approach.
The results show that remote sensing devices offer a useful and accurate capability for wind vector analysis and flow visualisation, along with the flexibility to organise bespoke measurement campaigns. The study also presents methodologies by which such devices can be used as validation tools for CFD.

1. Introduction

The deployment of Wind Energy is increasing steadily around the world, urged on by the push towards the 2020 Renewable Energy targets in Europe and the need for energy independence **[1]**. In order to maximise the potential of this renewable energy resource and truly challenge the fossil fuels sector in providing cost effective energy for the masses great improvements must be made in cost reduction and reliability. Research centres across the Wind sector are focussing on potential robust methods in which to achieve this. One key area of research is the focus on gaining a greater understanding of the flow field in which wind turbines operate, on a single turbine basis but also in the wider multi-turbine environment. As this has a significant bearing on the immediate power output of the device and the long term performance and life of the hardware it is vital to acquire a full understanding of how the flow develops both upstream and downstream of the rotor. This will allow the optimisation of turbine control, design, location and interaction allowing improvements in machine performance and longevity.

In order to capture the characteristics of the flow field remote sensing devices have been adapted to suit the needs of the wind industry. Such devices utilise either acoustic or laser pulses to measure the line of sight velocity of air born particles transported on the wind, these values are then used to ascertain wind vectors across the measurement domain. The study undertaken in **[2]** details the LiDAR operational procedures and wind speed calculations fully. The LiDAR principles and methods explored are utilised in the work tackled in this paper.

The availability of advanced wind farm and turbine specific Computational Fluid Dynamics (CFD) software allows the modelling of behaviour in these complex environments. The accuracy and efficiency of such modelling tools is increasing but they cannot be used independently to plan and corroborate potential wind farm sites. Correct site assessment generally requires at least 12 months' **[3]** worth of on-site met mast data to validate energy assessment models. In order to address these requirements and increase the role CFD can play in project development, validation of the computational methods and results is needed. The deployment of 2nd Generation LiDAR devices capable of 'all-sky scanning' provides a unique opportunity to do this. The work detailed in **[2]** gives an overview of the CFD principles utilised along with an overview of the turbulence models used.

The work undertaken pairs this state of the art measurement device with ANSYS Windmodeller CFD software allowing the comparison of the simulated domain with the measured with the aim of improving the accuracy of simulation results in the complex flow situations experienced across wind farms.

2. LiDAR Deployment

This paper presents the comparative assessment of ANSYS Windmodeller simulated results with measurements from a Galion second generation LiDAR device; the deployment has been conducted at Myers Hill test site with the assistance of SgurrEnergy Ltd **[4]** and TUV NEL **[5]**. Myers Hill test site offers clear line of site to the Siemens 2.3MW turbines on Whitelee wind farm with over a dozen within range of the Galion. The exact location within the compound and the chosen scan geometry could not be finalised until the deployment, as various factors such as on-site power access, prevailing weather conditions and the suitability of the land can only be assessed on-site during installation. These all have an impact on the bounds of the scan envelope implemented. Two LiDARs were deployed on-site, the first device carried out Plan Position Indicator (PPI) **[6]** scans throughout the duration of the deployment, sweeping in a shallow arc as close to hub height on the turbines within the scan envelope as possible. The LiDAR deployment details presented in Table 1 identify the major variables of the PPI measurement campaign, while Figure 1 shows the scan envelope in relation to Whitelee wind farm.

Deployment Dates:	January 10th – 23rd 2012
LiDAR Location: (OS Co-Ordinates)	N: 256860 E: 646514 Elevation: 325m
Scan Arc:	Azimuth 90° – 187.5° 2.5° Spacing, 5° Elevation 40 Beams
Beam Length:	Range Gates – 67 Range Gate Length – 30m Length – 2010m
Single Beam Time:	4.513s
Total Arc Time:	176s
Num. Of Points Per Scan:	2613
Number of Scans:	6794

Table 1: Myers Hill deployment details

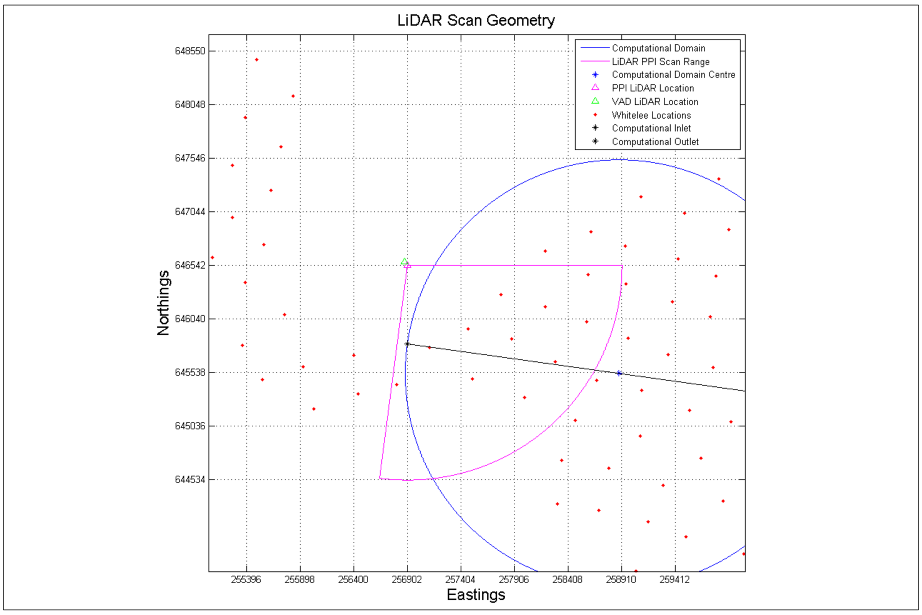


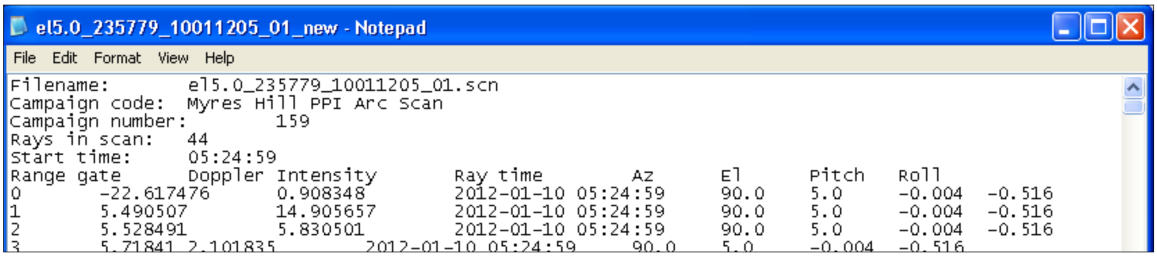
Figure 1: LiDAR Scan Envelope [7]

A 2km scan envelope was chosen to capture turbines to the South and West of the device, with the elevation chosen to allow the measurement plane to dissect the hub on the nearest turbines. This would ensure the nearest turbines along with their wakes and inflows would be clearly visible in the results.

The second device was located nearby within the compound, where electrical connections and terrain allowed. This device was programmed for Velocity Azimuth Display (VAD) scans **[8]** throughout the deployment measuring wind vectors at pre defined heights, acting as a virtual Met mast. Measurements were taken at 5m intervals from 40-105m vertically above the device. The sample rate set on the VAD LiDAR allowed 19 seconds for the measurements at all pre-set heights to be taken, with measurements taken at the North East, South East, South West and North West directions at each height. These four line-of-sight point measurements were used to create a wind velocity and direction vector at the height specified. These values are attributed to the point at the measurement height directly above the device, accounting for angle of the cone **[6]**.

3. Measurement Campaign Results

The LiDARs performed as programmed throughout the deployment and a rich data set was attained for analysis. Output from the PPI device is in CSV format, with a single file giving details of each individual scan and all the measurements taken within it. Figure 2 shows the header and top lines of a scan from the deployment.



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el5.0_235779_10011205_01_new - Notepad
File  Edit  Format  View  Help
Filename:        el5.0_235779_10011205_01.scn
Campaign code:  Myres Hill PPI Arc Scan
Campaign number:        159
Rays in scan:   44
Start time:     05:24:59
Range gate      Doppler Intensity       Ray time        Az      El      Pitch   Roll
0       -22.617476      0.908348        2012-01-10 05:24:59     90.0    5.0     -0.004  -0.516
1       5.490507        14.905657       2012-01-10 05:24:59     90.0    5.0     -0.004  -0.516
2       5.528491        5.830501        2012-01-10 05:24:59     90.0    5.0     -0.004  -0.516
3       5.71841 2.101835        2012-01-10 05:24:59     90.0    5.0     -0.004  -0.516
```

Figure 2: LiDAR sample CSV output file [4]

Each line corresponds to a different measurement point within the scan envelope. The LiDAR scans clockwise and registers Range Gate values at increasing distances from the device. The scan points are logged by Azimuth and then Range Gate. Using the Range Gate and Azimuthal values the location for the measurement can be found, the Doppler value gives the component of the wind vector aligned with the laser beam. Using three or more adjacent Doppler values a wind vector to be averaged over the area between the measurement points.

The scans files were then processed using software supplied by SgurrEnergy **[4]** to visualise each scan, an in built option in this software allows the user to choose the averaging period if required. The images in Figure 3 show a selection of the images gathered, the results are presented in individual scan, 10 minute averaged and 1 hour averaged form. Numbering the images within the figure 1-4 left to right along the top then bottom rows. Image 1 is an individual scan, Image 2 a ten minute average, Images 3 and 4 are hourly averages.

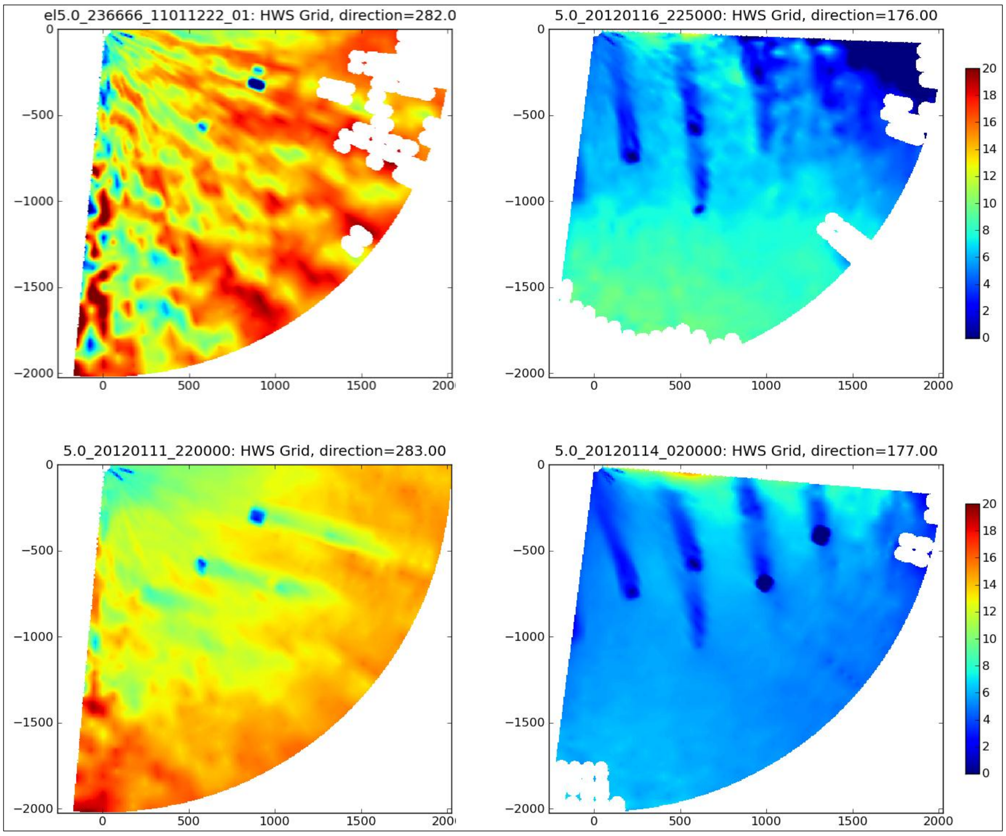

Figure 3: Sample LiDAR scan visualisations [4]

As can be seen the six turbines to the South West closest to the device were clearly visible in the ten minute and hour averaged images, their wakes were captured with a number of different wind speeds and directions. The single scan images however do not show flow structure and wake development. The turbines on the outer extremities of the scan envelope did not appear in any of the images. This can be explained by the 5° elevation of the measurement beam, at the further reaches of the beam the measurement height of the scan points has exceeded that of the rotor and corresponding wake, thus no significant velocity deficits were recorded.

4. LiDAR Deployment Analysis

From visual inspection of the results a number of averaged scan sets were selected for comparative assessment. The project outline calls for a comparison of measured and simulated data, a comparison of data points through the centre of the inflow and wake will facilitate such assessment. ANSYS Windmodeller **[8]** was selected to conduct the CFD simulation. The software has the facility to input terrain and roughness data, thrust and power curves of multiple turbines, multiple inlet speeds and heights, all analysed through four different turbulence model options. The models all incorporate the two-equation model to solving the Reynolds Averaged Navier-Stokes (RANS) equations, each model employs different closure methodologies to the equations. These models are k-ω, RNG, Standard k-ε and Modified k-ε and are explored further in previous work **[2]**. The data sets used to represent the turbine thrust and power curves were provided by SgurrEnergy and relate to the Siemens 2.3MW **[9]** turbines used on Whitelee Wind Farm. The roughness data was also provided in .map format. Topographic elements were input from OS map data garnered from the Ordnance Survey website **[10]**.

1.2. *Methodology*

The comparison of simulated to measured data requires the extraction of the relevant data points from the LiDAR scan, the key values are the geographical location (Range Gate and Azimuthal values are used to calculate the Easting, Northings and z values) and the measured wind vector. These scan points are then plotted within the computational domain and the velocity values extracted for comparison **[2]**.

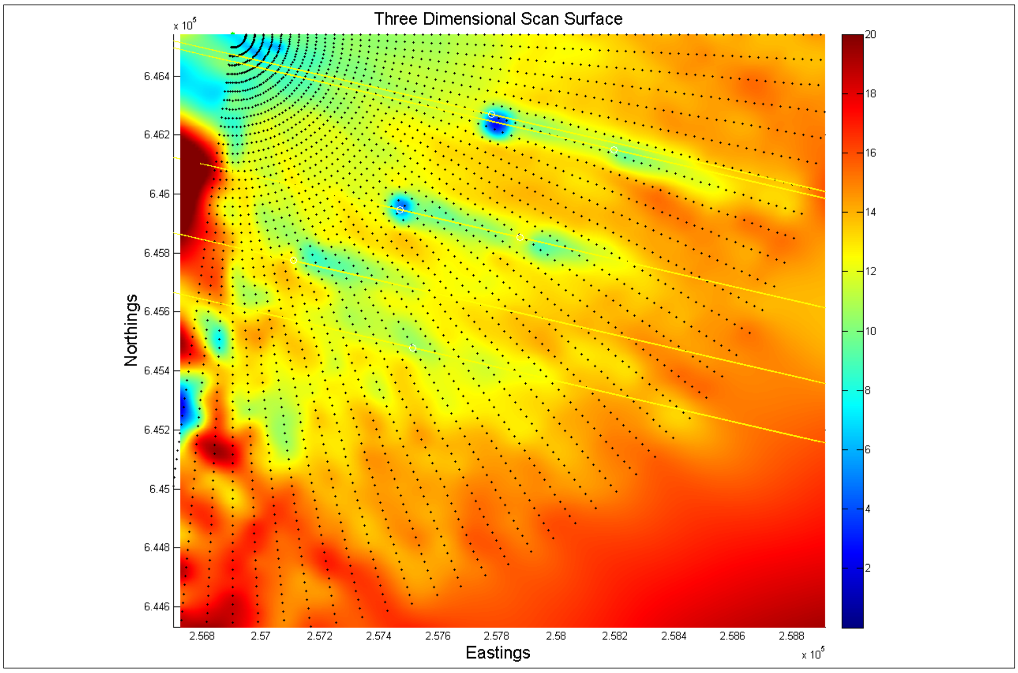

Figure 4: LiDAR visualisation with scan points and directional lines [7]

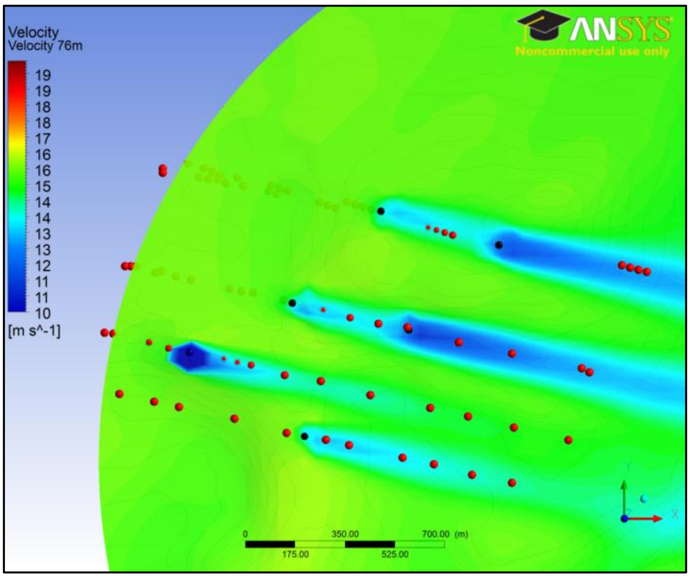

Figure 5: CFD simulation, k-ε turbulence model [9]

For each turbine appearing in the scan a line passing through the hub corresponding to the prevailing wind direction was plotted over the scan image, each of the individual scan points within the envelope were also plotted. This process can be seen in Figure 4 for a wind direction of 283°. The directional lines extend through the centre of each turbine's inflow and wake structures. To compare the wake velocities all scan points bordering the directional lines were selected and their attributes extracted from the PPI processed outfile.

4.2. CFD Domain Setup

Controlling the inlet location and corresponding values along with the domain characteristics of the CFD simulation is vital to ensuring the accuracy of the comparisons. This allows the direct comparison of results by ensuring that the same terrain effects on the measured wind vectors are accounted for in the calculated results as are present in the measured ones. Given the data sets available there are two possible methods for providing the data for inlet velocity and locations, the VAD LiDAR scans and the PPI LiDAR scans. To use either requires manipulating the locations of the CFD inlet to a point where the wind speed has been measured.

In the use of VAD scan inputs the inlet is the VAD LiDAR location and the velocity and directions used must relate to the values measured from the VAD scans averaged over the same period of time as the PPI scan being analysed.

Locating the inlet to a point within the PPI scan means that the inlet variables, height and velocity, must echo exactly that of the averaged scan point in the envelope designated the inlet. The wind direction will come from the overall direction assigned to the visualised output. Figure 1 shows a situation where the inlet has been defined as such.

In both cases the domain centre is inferred from the inlet location paired with the wind direction and specified domain radius. This is done by plotting a line from the inlet location corresponding to the wind direction and domain radius. The end point is the domain centre to be used within the CFD simulation. It is important all values used and calculated correspond to the geometric location method used i.e. OS coordinates.

Using these inlet locations in the present deployment means that both the PPI and VAD inlet cases require that the turbines and wakes are in the lower left portion of the CFD domain and in close proximity to the edge of the domain. This requires the specification of the mesh parameters to ensure that the domain setup allows for sufficient detail in the areas of interest

To ensure the detail in the mesh at the extremities where the turbines are sited the Centre Block Radius Fraction was set to 1. This will increase computational time but this is an acceptable trade to ensure accurate inlet conditions. ANSYS **[7]** suggested best practices indicate that in order to ensure the mesh allows for accurate wake extension a Background resolution of 0.4 Turbine Diameters would be appropriate.

5. Comparison Results

With the data sets available there are multiple options available for comparison and further analysis. Comparing the two inlet definition options allows a characterisation of their suitability as well as a comparison of the LiDAR to CFD data from these inlets. The averaging period also plays a key role in the comparison. The ten minute data set selected for comparison came from the period between 2230 and 2240 on the 11^{th} January 2012, the hour data came from between 2200 and 2300 hours on the same day.

Turbine 1 has both a clear inflow and turbine free wake thus making it an ideal candidate for the analysis of the above variables given there are no external factors affecting it. The images shown in Figure 6 below show the different analysis charts for the varying PPI averaging time frames. The input methods refer to the use of either PPI data as the inlet definition speed and location or of the use of VAD data

The charts show velocity, in m/s, on the y-axis plotted against absolute distance from the turbine rotor of the measurement point, in diameters (90m), on the x-axis. The flow through the rotor is going from right to left in each chart. The different models and LiDAR data are identified by the key in the bottom corner of each chart.

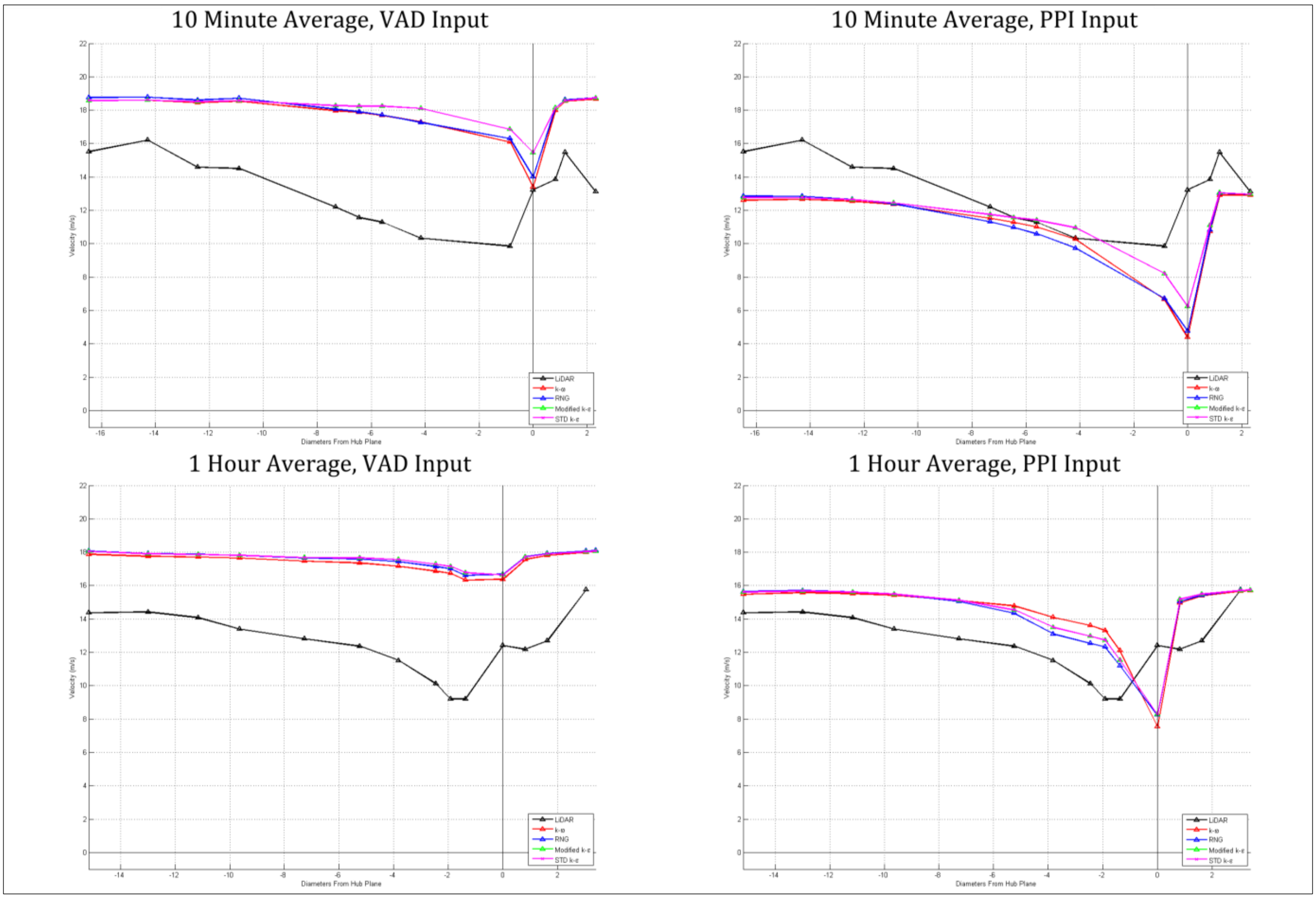

Figure 6: Turbine 1 Comparison set [7]

6. Comparison Analysis and Discussion

The overall behaviour of the data sets can be said to have a similar trend as is predicted in wind turbine theory **[11]**, a drop in flow velocity is seen through the rotor before recovering towards a free stream velocity in the wake.

The four configurations analysed in Figure 6 show a broad similarity in behaviour across the measured and simulated data. This similar trend echoes what is predicted in wind turbine theory **[10]**, a drop in flow velocity is seen through the rotor before recovering towards a free stream velocity in the wake. The four turbulence models show similar behaviour within the turbine stream tube but small variations between the values can be found, these are most prominent in the near wake up to 8 diameters distance from the rotor. The LiDAR data shows a more stochastic behaviour pattern, echoing the theory and CFD results but having slightly different values through the stream tube.

The CFD data in the VAD inlet cases is consistently higher than that of the measured LiDAR. At inlet the CFD velocities are approximately 3m/s higher than the LiDAR, this difference is preserved through the stream tube. In the PPI inlet definition case the inlet velocities are in agreement and further downstream, the behaviour is similar.

From this it is clear that utilising the VAD data and LiDAR location as input for this simulation was not the most appropriate methodology. The approaches used with the PPI inlet location offer a better data set for comparison. The reasons for this discrepancy can likely be traced to uncertainties experienced during deployment of the VAD LiDAR leading the inputs to be given at inaccurate locations for the CFD inlet definition. The PPI scan offers more agreeable inlet conditions as it is providing an inlet from the same scan the LiDAR data sets are taken from; this approach had given reasonable results for a different wind direction in **[2]**.

Overall the use of the PPI for inlet definition values has provided a good comparison methodology. In future deployment the lessons learned above will allow this comparison to be even better and the approach will offer the potential for wind turbine developers to conduct more accurate site and performance assessments. The use of the VAD scan values to define the CFD inlet in this instance has proved inappropriate given the uncertainties that developed from combining the measurements of multiple LiDARs. Improved methodologies and deployment control strategies might allow for this method to be used at another time.

7. Future Work

Certain wind orientations in the deployment outlined in this study produce data measured from a turbine operating within the wake of another. This offers an opportunity to study the comparisons and ascertain how the CFD models such situations.

Further deployments at new locations are planned, from the analysis done here and in **[1]** a number of improvements to the measurement campaign can be made to improve the accuracy of the comparisons. Using one device with alternating VAD and PPI scan patterns, averaged over an hour, will allow the choice between VAD and PPI input to the CFD domain dependent upon wind orientation. This will also reduce any error in location data for the devices. While the ground level location for the LiDAR provides satisfactory results mounting the LiDAR to a wind turbine nacelle would reduce the issues involved with incorporating an angled measurement plane into the results. Work is being undertaken to provide this opportunity.

Acknowledgements

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