# Lidar Measurements and Visualisation of Turbulence and Wake Decay Length


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Galion Lidar was used to measure the wake of a wind turbine to investigate wake length decay length. The PARK wake model using a wake decay constant of 0.038 was compared with the measured data to assess its effectiveness for wake modelling. The data was filtered to periods where there was a single wake only.

It was found that the PARK wake model generally under predicts the recovery (i.e. over predicts wake loss) towards free stream inflow wind speed as measured by the Lidar at low wind speeds with better agreement in the high inflow wind speed bins.

The PARK wake model shows best agreement with the Lidar data at high inflow wind speed and proves a good match for the 16-18 m/s inflow wind speed.

In the 5 to 14 rotor diameter downstream distance PARK is seen to over predict wake losses across wind speed bins. After this distance the comparison with the Lidar data is less consistent and a wake scan with a longer focus point to capture this area in more detail would shed more light on the comparison between the model and the data.

# 1 INTRODUCTION

A comparison of measured and modelled wind turbine generator (WTG) wake structures is important to inform the wind energy industry of the accuracy of the commonly employed wake models [1]. This in turn informs wind farm layout design and reduces the uncertainty associated with wake modelling at wind farms. The Galion Lidar allows the width and length of the WTG wakes to be measured and detailed comparisons made with wake model predictions.

The width and length of a WTG wake are generally estimated using WTG wake models such as the PARK wake model. This model was chosen to compare with the Lidar data as it is a widely used model and is employed in the WAsP wind analysis package. This has been developed from a theoretical basis and validated using point anemometry measurements or by analysing operational wind farm production data. However, these validation techniques are limited by paucity of data, and significant associated uncertainty.

Second generation scanning Lidar technology now allows wake structures to be measured and visualised directly, allowing wake models to be fully calibrated and validated. The results of these validations should then allow wind farm layouts to be better optimised in terms of maximising energy yield and minimising WTG loading. In addition, more accurate energy yield predictions should also be realised. The visualisation of the wakes allows for the interaction of the wakes within the wind farm to be analysed to assess their effect on WTG performance.

This report shall address the extent of the wake hub height velocity deficit. The measurements for these cases will be compared with the output from the PARK wake model for WTG wakes.

# 2 BACKGROUND TO MEASUREMENTS

The focus of this campaign is to measure WTG wakes within an operational offshore wind farm in the North Sea. For the measurement campaign three G4000 Galion units were installed on an Areva M5000 Multibrid WTG, two on the nacelle and one on the transition piece. The two Lidars on the nacelle measure the inflow and outflow conditions concurrently in order to compare the inflow conditions with the outflow and to measure the length and width of the WTG wake. The wake decay rate and wake width were measured for various inflow wind conditions to determine the structure of wake recovery in various climatic conditions.

With wake losses of the order of 10 to 20% of power output in large wind farms the need to accurately measure the length and width of wakes in the offshore environment is essential for wind farm planning and optimisation [2]. The use of Lidar to measure the wake of a WTG allows for the wake to be analysed at multiple distances to accurately estimate how wakes will behave under different conditions and their effect on other WTGs downstream. With direct measurements of WTG wakes, CFD modelling can be adjusted to allow for more accurate wind farm modelling [3] [4].

# 3 CAMPAIGN DESIGN

## 3.1 DATA PROCESSING TECHNIQUE

The Galion produces raw scan files for each completion of a scan. This file details the raw Doppler value and associated return signal strength for each 30m interval (known as the range gate) along the line of sight for every beam in the scanned geometry. Every beam is marked with its associated elevation and azimuth to denote the physical orientation of the beam and the time at which the measurement was made. The timestamp of the Galion was set to record in time with the time clock on the Areva supervisory control and data acquisition (SCADA) network.

These raw .scn files were post-processed using the Galion Toolbox software into one database structure which allows filtering, fitting and averaging for further analysis.

## 3.2 ANALYSIS METHODOLOGY

The rear facing device on the nacelle (Unit 23) performed a horizontal arc scan for the majority of the campaign with a view to capturing the wake profiles from AV07 and the other WTGs in the wind farm. In this report the wake of AV07 will be investigated for the time periods when the wind direction is coming from a free stream direction so that a reference inflow wind speed from FINO1 and Unit 25 can be used to assess the effect of the wake on unperturbed wind speeds. The data was also filtered to periods where there was a single wake only as outlined in Section 3.2.3.

### 3.2.1 HORIZONTAL ARC INFLOW REFERENCE

In order to produce this list of reference wind speeds the wind speed and direction 2.24 rotor diameters upwind at hub height was extracted from each of the arc scans performed by Unit 25. These were then filtered to wind directions from a free stream sector defined as between 210° and 330° as outlined in Figure 1.

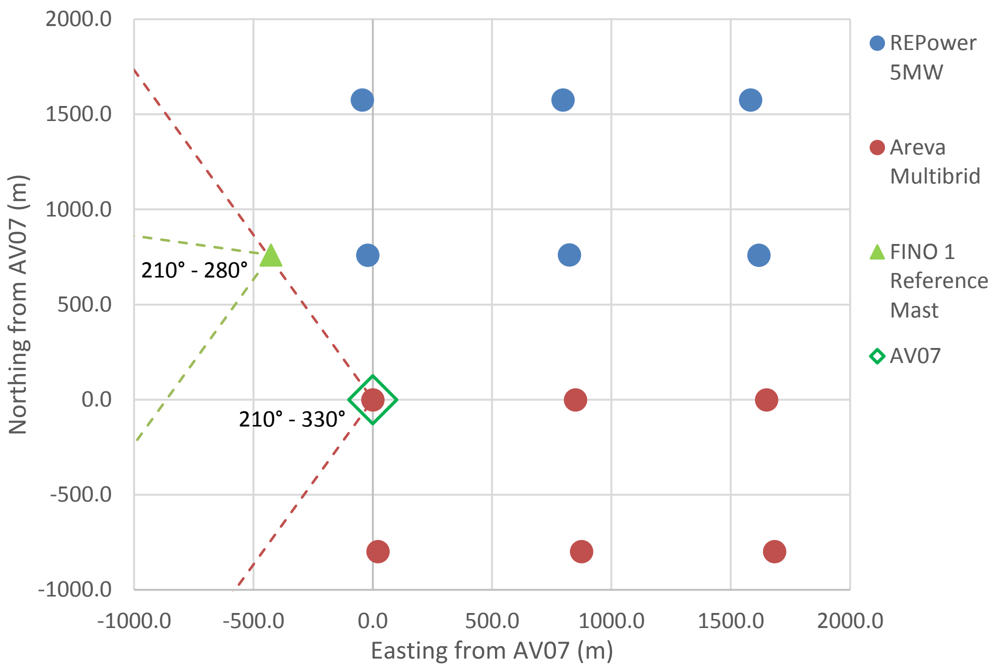


**Figure 1: Wind farm layout with free stream sector**

If, for a ten minute time period, this was not available a reference was taken from FINO1 provided it was also from a free stream direction (i.e. between 210° and 280° and outlined in Figure 1. Mast data for the sector between 280° and 350° for FINO1 was not considered acceptable due to issues with the tower shadowing the anemometers. Analysis of the FINO1 mast and mast shadowing is documented [5]. This produced a list of reference wind speeds that could be used to normalise the outflow wind speeds recorded by Unit 23 to assess recovery of the wake.

### 3.2.2 WAKE CENTRELINE IDENTIFICATION

In order to extract the centreline of the wake in each scan from Unit 23 and a selection of range gates for width analysis a script was developed in Python. This script read in the processed output files from the Galion Toolbox and a file with timestamps that had been extracted from AV07's SCADA data at times when the nacelle orientation was between 210° and 330°. Matching timestamps were then analysed for wake centreline extraction. AV07's wake centreline was then identified by the script. The centreline wake direction of AV07 is defined by the azimuth in the Lidar scan geometry that has the lowest Doppler value and hence largest velocity deficit. This centreline wake direction is derived by finding the beam azimuth with the lowest Doppler for each range gate between range gates 1 and 15 (0.3 to 4 rotor diameters), averaging the corresponding azimuths and returning the nearest measured azimuth on the Lidar. This method allows for any small yaw errors to be removed. The data for the centreline analysis was then output to a file and at the same time a selection of range gates for those timestamps were output to another file for width analysis.

#### 3.2.3 FILTERING TO REJECT OVERLAPPING WAKES

Once the Python script had output the wake data it was then aligned with the reference inflow data and SCADA data for AV07. The nacelle orientation from the SCADA data was then used to correct the beam azimuths in the Lidar data to the true beam orientation so that it was clear whether or not the beams in the scan would be intersecting the other WTGs downwind. The reference inflow wind speed was also used to normalise the outflow wind speeds so that they could be assessed as a percentage of the inflow.

Each individual ten minute period was then plotted and visually inspected to check whether or not the wake was overlapping with another downstream WTG or its wake. The periods that were selected from this process were then used to lookup the Galion Toolbox output images and these images were then visually inspected again to verify that the selected periods were definitely not periods with overlapping wakes.

The result of this filtering was 302 ten minute averaged periods where there was a high level of confidence that the wake of AV07 was not perturbed downstream for wake centreline analysis.

#### 3.2.4 HORIZONTAL ARC WIND SPEED BINNING

The ten minute average periods in the wake data were then aligned with the ten minute periods in the inflow reference data. This allowed for the wake data to be binned by inflow wind speed and normalised so that the outflow wind speed was a percentage of the inflow. This would allow for each inflow wind speed to be evaluated to check the variation in recovery of the wake and for each bin to be compared directly to the PARK wake model.

#### 3.2.5 PARK WAKE MODEL CALCULATION

In order to identify how the measured wakes compared to commonly used wake models a wake profile was calculated for each ten minute period in the filtered dataset using the PARK wake model. The PARK wake model developed by Jensen (1983) models a linearly expanding wake with a velocity deficit dependant on distance, which has a constant value across its width and height. The PARK wake model is a widely used model that is implemented within wind flow modelling software WAsP, developed by Risoe. To do this the wake decay coefficient (k) was first calculated using the axial induction factor (A), the hub height of the WTG (h), the surface roughness (z0) and Equation [1].

$$k = \frac{A}{\ln\left[\frac{h}{z0}\right]} \quad [1]$$

The PARK model wake width was also calculated from the rotor diameter (D), the wake decay coefficient, the downstream distance (d) and Equation [2].

$$Wake\ Width = D + 2 * k * d \quad [2]$$

The width was then used along with the thrust coefficient (Ct) and rotor diameter in Equation [3] to calculate the PARK model wake profile.

$$PARK\ Model = 1 - \left[\left(1 - \left((1 - Ct)^{1/2}\right)\right)\right] * \left[\frac{D}{Wake\ Width}\right]^2 \quad [3]$$

The values for the thrust coefficient were dependent on the power curve and were looked up for each inflow wind speed based on data for AV07, the WTG the Galions were mounted on.

A value of 0.0002 was used for the surface roughness, 90 m for hub height and 0.5 for the axial induction factor leading to a value of 0.038 for the wake decay coefficient. The wake width was calculated using a value of 116 m for the rotor diameter, 0 – 20 D for the downstream distances and the calculated value of the wake decay coefficient. Once a wake profile was calculated for each inflow wind speed they were binned and averaged in the same manner as the Lidar data so that for each inflow wind speed bin the PARK wake model could be compared to the Lidar measurements to see how well the conditions were predicted. Since the PARK wake model is only considered capable of modelling wakes from approximately 4 rotor diameters (D) downwind of the rotor, closer attention will be made to the comparison after this point.

## 4 RESULTS

With the filtering to freestream inflow and non-overlapping wakes complete the ten minute averages for those time periods were binned by inflow wind speed and plotted in Figure 2. As one can see from the plots in Figure 2, even with a careful amount of screening, as the wakes propagate downstream the influence of other WTG wakes or some other atmospheric effects can be seen to be having an effect on the wake. An example of this is highlighted in the 14-16 m/s bin in Figure 2. The fact that some of these structures feature across different wind speed bins would point to this being the influence of other WTGs downstream but atmospheric effects cannot be ruled out. This is perhaps unavoidable in a closely arranged grid structure such as an offshore wind farm. However, the influence on the centreline of the wake appears to be minimal hence allowing for the recovery at multiple distances to be assessed and compared with the PARK wake model.

It is also quite clear in this plot that the size of the wake deficit in the near wake distances is higher with low wind speeds and becomes less as the inflow wind speed increases. This is apparent from the change from the dark blue inner wake for the low wind speeds and light blue in the high wind speed bins showing a larger maximum deficit at low wind speed. The wake also appears to narrow with increasing inflow wind speed and as the WTG approaches rated speed. As the WTG approaches 12 m/s and begins to pitch its blades out of the wind this will reduce the maximum deficit seen in the inner wake and should be considered when comparing the wind speed bins.

The Lidar is measuring the centreline at zero elevation from just above the nacelle, so the measurements are likely to include the wake due to the nacelle obstruction and the wake of the rotor blades. As the air is deflected round the nacelle it loses less wind speed than that passing directly through the blades. As the two flow deficits combine together the wind speed drops to the maximum deficit as this slower parcel of air mixes with the faster air surrounding the nacelle. This shape has been recorded by others using Lidar to measure wakes propagating downstream of a WTG [6].

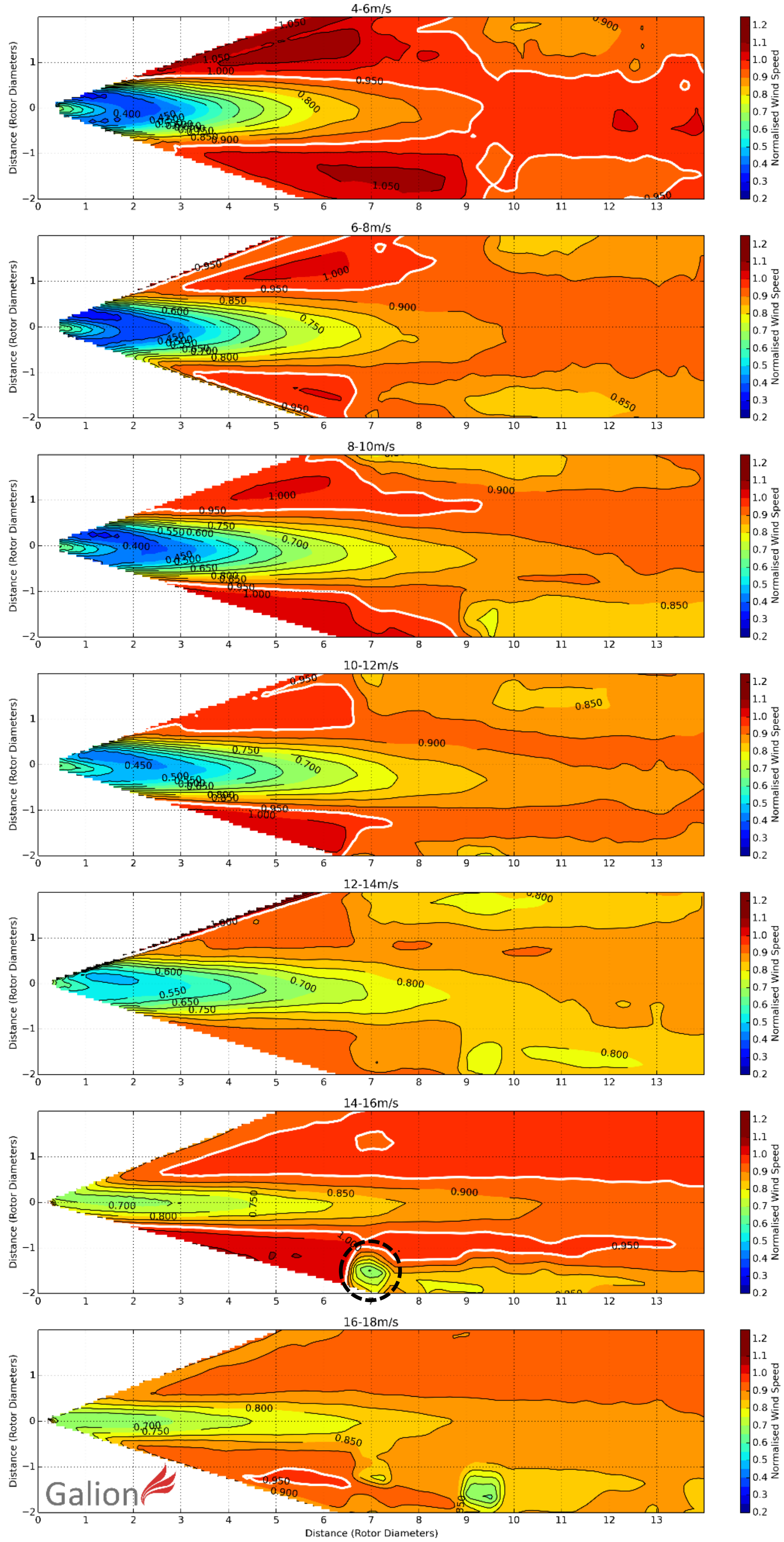


**Figure 2: Average horizontal flow maps binned by inflow wind speed**

## 4.1 Wake Decay Length

### 4.1.1 Wind Speed Binned

The binning process outlined in Section 3.2.4 resulted in seven inflow wind speed bins which were plotted together and appear in Figure 3. In Figure 3 it can be observed that the maximum wake deficit tends to decrease with increasing inflow wind speed with a maximum deficit located between 1.5 and 2.5 rotor diameters downstream.

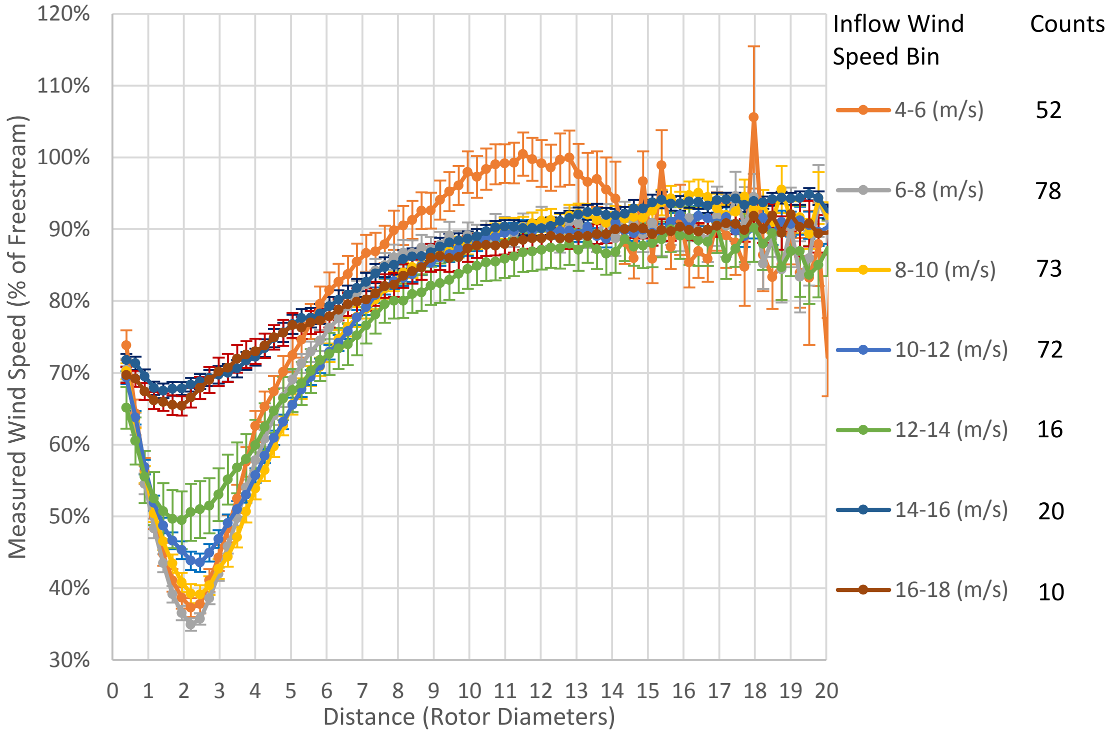


**Figure 3: Average profiles binned by inflow wind speed bin**

The error bars on the plot are ± 1 standard error (SE) which is calculated using Equation [4] with *s* equal to the standard deviation of the sample and *n* the number of counts.

$$SE = \frac{s}{\sqrt{n}} \qquad [4]$$

There also seems to be a quicker recovery towards freestream wind speeds for the 4-6 m/s wind speed bin, but the pattern is less clear for the other wind speed bins. At approximately 7 rotor diameters the profiles are all located at around 80% of freestream velocity which, for this WTG, is consistent with the measurements of others [6].

When comparing Figure 3 and Figure 2 the same conclusions can be drawn as the two plots show similar patterns between the wind speed bins with high deficit at low wind speeds and low deficit at high wind speeds. In Figure 2 it is observed that the WTGs downstream of AV07, with wakes from after about seven rotor diameters, have wakes that have widened to the extent that they begin to merge. However the centrelines do appear unperturbed as the wake progresses downstream which will allow for comparison with the model.

### 4.1.2 COMPARISON WITH MODEL

Once the PARK wake profiles had been calculated and binned as detailed in Section 3.2.5 the wind speed bins were plotted together as they were for the Lidar data in Figure 3. The result of this is seen in Figure 4 below.

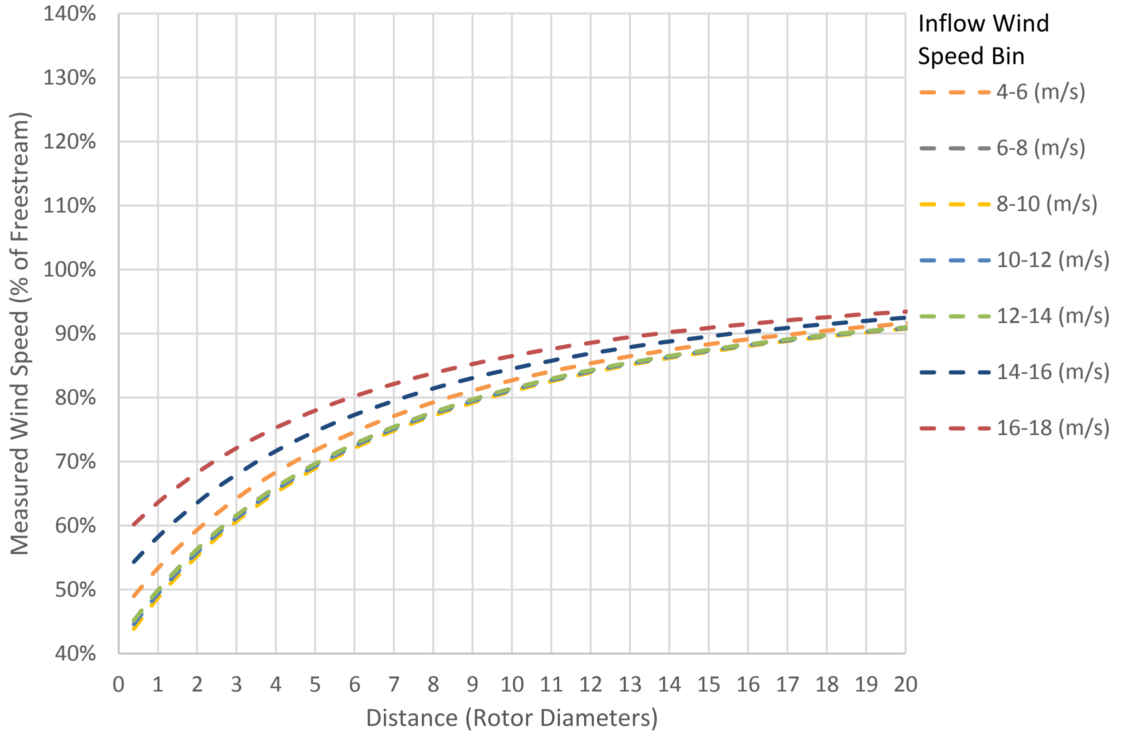


**Figure 4: Average PARK wake profiles by inflow wind speed bin**

When the two plots are compared it is difficult to see how each Lidar bin compares with its PARK wake model counterpart but this will be looked at in more detail in Figure 5. However, it is clear that the maximum deficit and rate of recovery differences between each bin are not well predicted by the model.

Up to five rotor diameters the Lidar measured centreline data shows a drop towards maximum deficit at approximately two rotor diameters followed by recovery. This shape is a consistent feature across all inflow wind speed bins although less pronounced with higher wind speeds.

When typical offshore wind farm grid sizes are considered, the 5 to 14 rotor diameter range may be the most important area in terms of predicting wake losses. When this region is examined in Figure 5 the PARK wake model is predicting a higher wake loss than observed which could mean that when predicting wake losses in an array an overestimate could be made. Beyond 14 rotor diameters the PARK wake model generally predicts a greater rate of recovery but this is not consistent between wind speed bins and as the lidar device was optimised for data recovery at closer distances, the lidar availability at this distance is not as high as that before 14 rotor diameters. Therefore, this needs to be examined as part of future work considerations.

In order to examine the influence of wind speed on the model performance each bin was plotted individually. This is shown in Figure 5.

In the 4-6 m/s inflow wind speed bin is compared which shows quite poor agreement between the Lidar measured wake and the one predicted by the PARK wake model. The PARK wake model predicts a steady recovery after about five rotor diameters leading to an under prediction in the recovery until about 14 rotor diameters after which point the Lidar measured wake exhibits an increased amount of scatter due to low data counts. This is evident through the increase in the error bars associated with the measurement data to the right of the plot.

The 6-8 m/s inflow bin shows a slightly larger maximum deficit than the 4-6 m/s bin but at roughly the same distance downstream. This is matched by a slightly higher deficit in the PARK wake model profile with the two crossing again at approximately five rotor diameters downstream. The PARK wake model then under predicts the recovery until around 18 rotor diameters downstream.

In the 8-10 m/s inflow bin is shown where the maximum deficit for the Lidar profile is less severe than that at lower wind speeds but the PARK wake model remains largely the same. The two profiles then cross at 6 rotor diameters after which the PARK wake model under predicts the recovery up until 20 rotor diameters.

In the 10-12 m/s inflow bin comparison there is a less severe maximum deficit for this bin in the Lidar profile with the PARK wake model maximum deficit not changing significantly from the 8-10 m/s bin. The PARK profile then under predicts the recovery after 6 rotor diameters until around 14 rotor diameters after which the PARK wake model profile is within the estimate of uncertainty in the Lidar measurement.

The 12-14 m/s inflow wind speed bin continues the trend of the maximum deficit reducing in the Lidar profile and after approximately 4.5 rotor diameters the PARK wake model is again within the uncertainty of the Lidar measurements.

At 14-16 m/s the maximum deficit in the Lidar continues to be reduced with the profile of the PARK wake model data also being reduced. The profiles match each other well between 3 and 6 rotor diameters and after that the PARK wake model under predicts the Lidar profile up to twenty rotor diameters.

In the final wind speed bin of 16-18 m/s the PARK wake model profile matches the Lidar data well after approximately 2 rotor diameters and shows the best agreement for each of the bins analysed.

The comparison by wind speed bin has shown that the PARK wake model is better able to predict the deficit in the centreline of the wake as the inflow wind speed increases with the high speed profiles showing good agreement. The model agrees best with the measurements for the two highest inflow wind speed bins such that the deficit is less. However, for the wind speeds below 14 m/s the agreement is poorer.

There is a publication pending that looks at the compression zone of this WTG that could have implications on how this result is interpreted. Specifically, the reference inflow wind speed that is used to normalise the wake could experience a larger effect as a result of the compression zone at low wind speed. This could result in a larger discrepancy between the model and the lidar measurement for the low wind speed bins. However, this analysis was undertaken with current industry standards for freestream inflow wind speeds and as such this effect needs to be considered in further work.

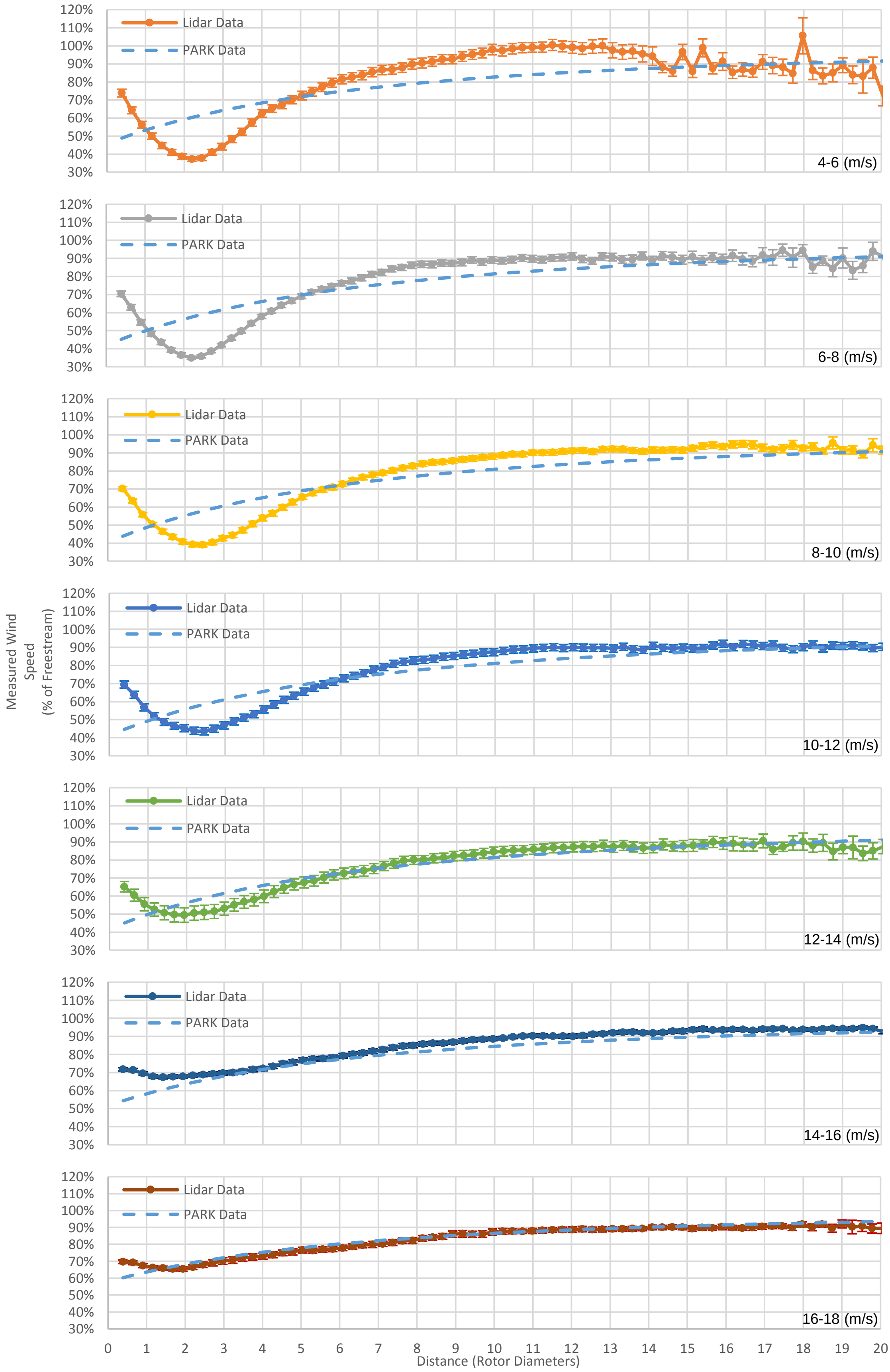


**Figure 5: PARK wake model comparison with Lidar by wind speed bin**

## 5 CONCLUSIONS

This report has investigated the single wake of an offshore WTG within an active wind farm. The conditions were investigated using the scans of two Galion Lidars mounted on the nacelle of the WTG and one on the transition piece. The Lidar measured conditions were compared with the PARK wake model to assess its effectiveness as a model for WTG wakes. The specific aspect of the wake that was investigated was the wake decay length.

To examine the wake decay length the centreline of the wake was extracted from the horizontal arc scans and binned by inflow wind speed as measured by Unit 25 and FINO1. The PARK wake model was then calculated based on the parameters of the WTG and the inflow wind speed for that period. The PARK wake model was then also binned by inflow wind speed and compared to the Lidar measured profile. Some key findings include:

- The PARK wake model is unable to predict the dip to a maximum velocity deficit at approximately two rotor diameters as measured by the Lidar and as a result of the air flow around the nacelle of the WTG. This is consistent with the published limitations of the PARK wake model since it is considered to be valid at distances greater than approximately
  4 D.
- The PARK wake model generally under predicts the recovery (i.e. over predicts wake loss) towards free stream inflow wind speed as measured by the Lidar at low wind speeds with better agreement in the high inflow wind speed bins.
- The PARK wake model shows best agreement with the Lidar data at high inflow wind speed and proves a good match for the 16-18 m/s inflow wind speed.
- In the 5 to 14 rotor diameter downstream distance PARK is seen to over predict wake losses across wind speed bins. After this distance the comparison with the Lidar data is less consistent and a wake scan with a longer focus point to capture measurement data in this area in more detail would shed more light on the comparison between the model and the data.

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