Offshore Wind Turbine Wake Characterization using Scanning Doppler Lidar

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Outline

• Offshore Wind Turbine Wakes
• OBLEX-F1 Experimental Setup
• Methodology
• Alpha Ventus Wind Turbine Wake Characteristics
• Conclusions
Offshore Wind Turbine Wakes

• Knowledge of wind turbine wakes is crucial to improve modelling of:
  – Power production and
  – Wind turbine loading in wind farms.

• Scanning Doppler Lidars:
  - Can capture the spatial and temporal characteristic of the wind turbine wakes and their dependency on the inflow characteristics
  - Can assist in wind farm control strategies (wake redirection...)

The College of Engineering at the University of Notre Dame
Time and Length Scales of Interest in Wind Energy

- Turbulence
- Wind Turbine Wake
- Wind Resource Assessment
- Forecast

Space (m) vs. Time (mins)

Adapted from A. Santiago, Leosphere
OBLEX-F1 Experimental setup

• Focus on:
  – Improved the knowledge of the marine atmospheric boundary-layer (MABL)
  – Turbulence generation processes in the water column
  – Offshore wind turbine wake propagation effects...
Site Conditions

- Alpha Ventus wind turbines
- 5 MW, D=116/126 m, d=30 m
- Wake characterization study period: Aug-Sept 2016

[Map showing the location of Alpha Ventus wind turbines in the North Sea, with a radar chart showing wind direction and frequency]
\[ v_r(R, \phi, \theta) = U \sin \phi \cos \theta + V \cos \phi \cos \theta + W \sin \theta \]

\[ V_r = \text{Radial Velocity}, \ \phi = \text{Azimuth Angle}, \ \theta = \text{Elevation angle}; \ U, V, W = \text{Components of wind speed} \]

Adapted from Calhoun, ASU
## Scanning Lidar Specifications

**WindCube 100S**

<table>
<thead>
<tr>
<th>Lidar Specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eye Safety</td>
<td>Class 1M</td>
</tr>
<tr>
<td>Wavelength (µm)</td>
<td>1.54</td>
</tr>
<tr>
<td>Pulse Energy (µJ)</td>
<td>100</td>
</tr>
<tr>
<td>PRF (Hz)</td>
<td>10000</td>
</tr>
<tr>
<td>Pulse Averaged</td>
<td>10000</td>
</tr>
<tr>
<td>Pulse Duration (ns)</td>
<td>150</td>
</tr>
<tr>
<td>Range-gate interval (m)</td>
<td>25</td>
</tr>
<tr>
<td>Velocity Precision (cm s⁻¹)</td>
<td>&lt; 20</td>
</tr>
<tr>
<td>Minimum Range (m)</td>
<td>50</td>
</tr>
<tr>
<td>Maximum Range (m)</td>
<td>3000</td>
</tr>
</tbody>
</table>
Scanning modes

**DBS/VAD**
*What:* Velocity Azimuth Displays
*How:* Conical scan or variation
*Why:* Vertical profile of the horizontal and vertical velocity

**RHI**
*What:* Range-Height Indicator
*How:* Elevation changes, azimuth fixed
*Why:* Vertical cross sections, wind shear (wind changes with height) and wind overturning events (wind direction changes with height)

**PPI**
*What:* Planned-Position Indicator
*How:* Azimuth changes, elevation fixed
*Why:* Horizontal wind field
Wake Scan Pattern
Wake Scan Pattern

Data analyzed:

<table>
<thead>
<tr>
<th>Scan</th>
<th>Azimuth (deg)</th>
<th>Elevation (deg)</th>
<th>Scan rate (deg/sec)</th>
<th>Averaging (secs)</th>
<th>Repetitions in 10 minutes (#)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPI</td>
<td>131.5 –179.5</td>
<td>4.62</td>
<td>1</td>
<td>1</td>
<td>12</td>
</tr>
</tbody>
</table>

![Graph showing wind direction and FNO1 Met Mast](image1.png)

![Map showing lidar and wind turbine](image2.png)
Methodology

• Wind turbine velocity deficit is defined as

\[ VD (R, x) = \left(1 - \frac{U(R, x)}{U_A(R, x')} \right) \times 100\% \]

Adapted from Smalikho et al., 2013
Methodology

- To account for the wake centerline deviation from the WT axis:
  - A Gaussian curve fit was applied to the velocity deficit data
    \[ VD_{fit}(R, x) = a e^{-\left(\frac{x-b}{c}\right)^2} \]
    where R is the downwind distance, x is the lateral distance and a, b & c are fit parameters
  - Wake centerline \( W_{c}(R) \) was defined as
    \[ W_{c}(R) = max[VD_{fit}(R, x)] \]
Average velocity deficit over the duration of the campaign

Higher deficit than reported in literature (Barthelmie et al., 2006 & Hirth et al., 2013 etc...), likely due to differences in:

- Measurement techniques
- Ambient wind conditions
- WT operation mode

\[ \frac{\Delta U}{U_A} = 1.50x^{-1.12} \]

*R2 of the model – 87.45%

*Averaged over 252 samples
Wake length as a function of time of the day

- (Daytime – 0700 hrs to 1800 hrs & night time – 1800 hrs to 0700 hrs)
  - Day-time wakes have 4-11% lower velocity deficits
  - Night-time wakes have 60% larger wake lengths

\[ \Delta = 11\% \]
Wind Turbine Wake Characteristics

- Deviation of the wake center from turbine location
  - Significant wake centerline deviation from the WT axis, maximum deviation of greater than 25 degrees at 8 Rotor Diameters
  - Important to understand for wind turbine siting and wind farm control strategies.
Conclusions

Alpha Ventus wind turbine wake studied (252 samples, 5 min) shows:

• A higher velocity deficit compared to previous studies (up to 20%).
• Higher velocity deficits during night time than at the daytime (11% higher) and larger wake lengths (up to 60%).
• Wake centerline deviation from the WT axis up to 25°.

Scanning lidar is a valuable tool to characterize wind field within a wind farm and thereby contribute to an improved wind power extraction and the wind turbine design.