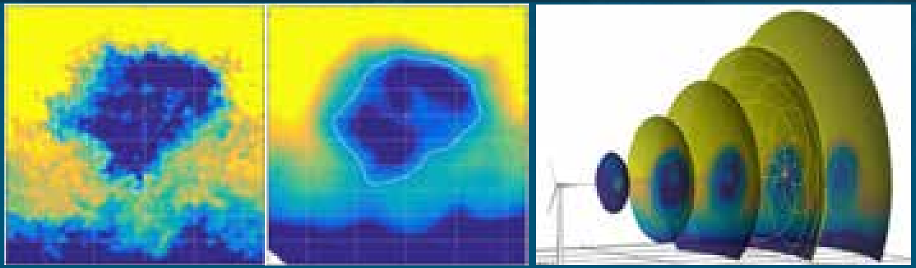
Results from the SWiFT Wake Steering Experiment



PRESENTED BY

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Outline

SWiFT facility overview

Wake Measurements

- Inflow effects
- Wind turbine effects

Observation and challenges of experiment

Upstream WTGa1 power and loads

Waked WTGa2 power and loads

Introduction

Wind turbine wakes can significantly influence both the power output and loading of wind turbines within plants

DOE SNL/SWiFT facility unique open wind plant test site from studying turbine-turbine interactions

Wake Steering Experiment performed in collaboration with Sandia National Laboratories and the National Renewable Energy Laboratory as part of the U.S. Department of Energy's Atmosphere to Electrons (A2e) program

DTU SpinnerLidar uniquely capable of capturing upstream wake deficit at the required temporal and spatial resolution for synchronization with turbines

Detailed field campaigns that provide high resolution wind turbine, met tower, and lidar data in various waked conditions remain scarce.

All data will be made available through the DOE Atmosphere to electron (A2e) Data Archive and Portal (DAP)

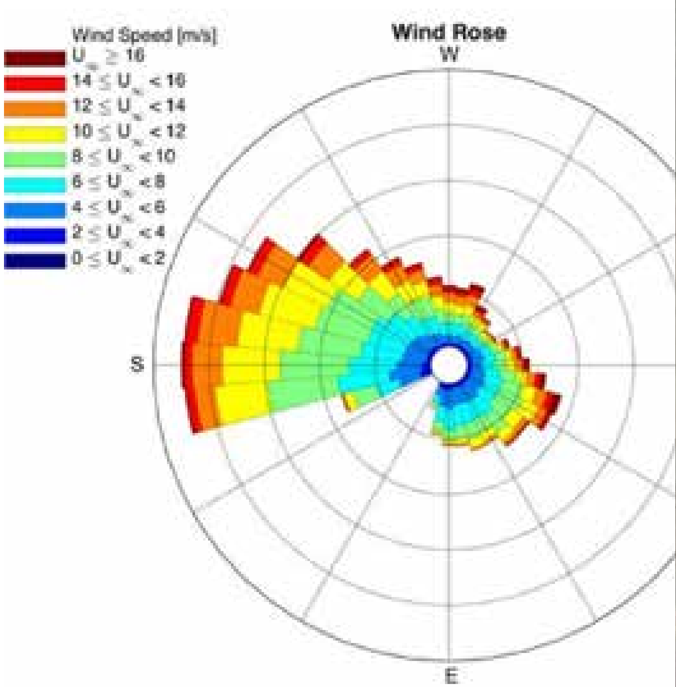
SWiFT Facility Overview

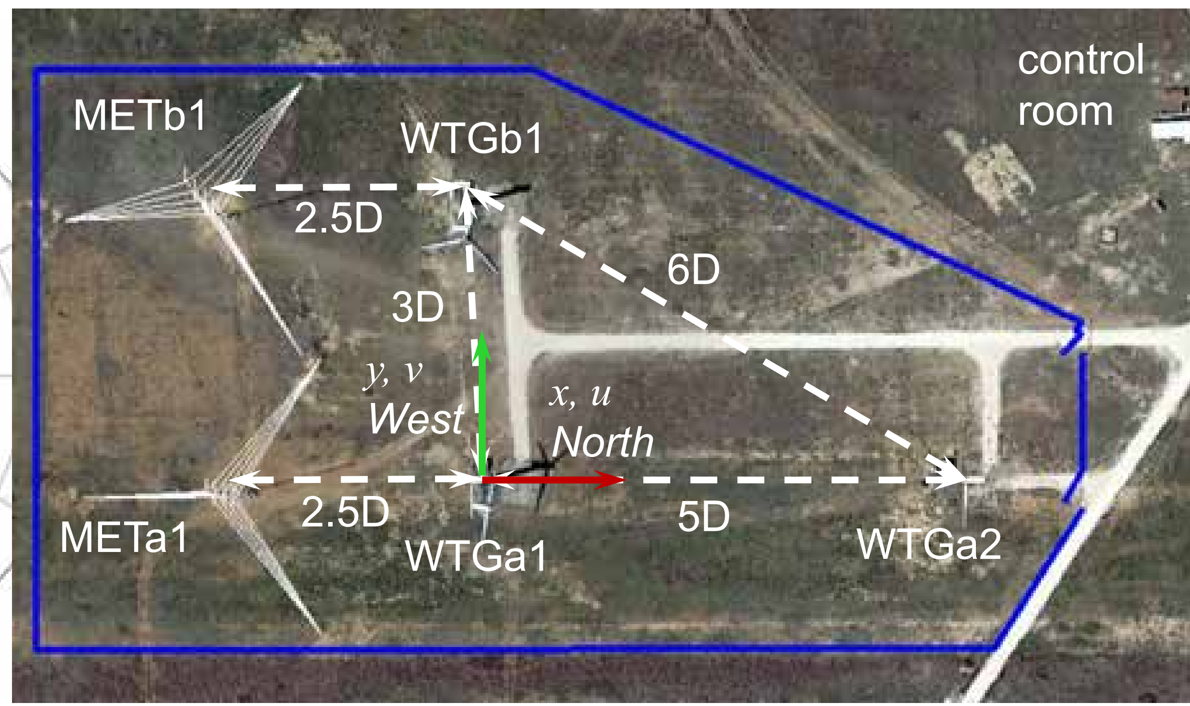
SWiFT facility created to:

- Measure wind plant flows and turbine-turbine interactions
- Perform prototype testing of innovative rotor technology

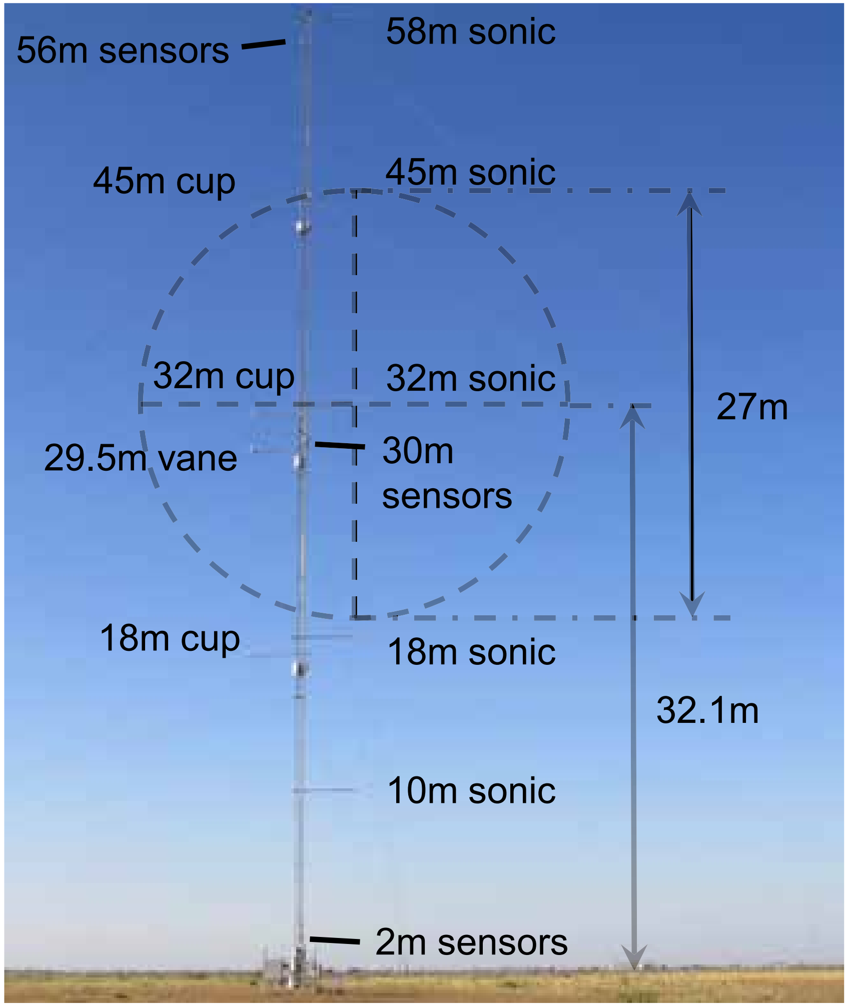
Wake steering experiment sought to quantify wake deflection vs. yaw offset and the corresponding effects on a two-turbine system

- Characterize wake shape, velocity deficit, turbulence, and dynamics under various conditions





SWiFT Site Instrumentation



All sensor channels GPS timestamped

Inflow: 59m MET Tower (5 sonics)

Turbines

- WTGa1, upstream turbine highly instrumented, 1 blade root strain measured 4/19/17 – 7/14/17
- WTGa2, waked turbine highly instrumented, 1 blade root strain measured 7/11/17 – 7/13/17

Wake Flow Diagnostic:

- DTU SpinnerLidar

Data collected:

- 12/15/16 – 7/14/17

DTU SpinnerLidar Scan Pattern

WTGa1: Lidar Simulation and Selection

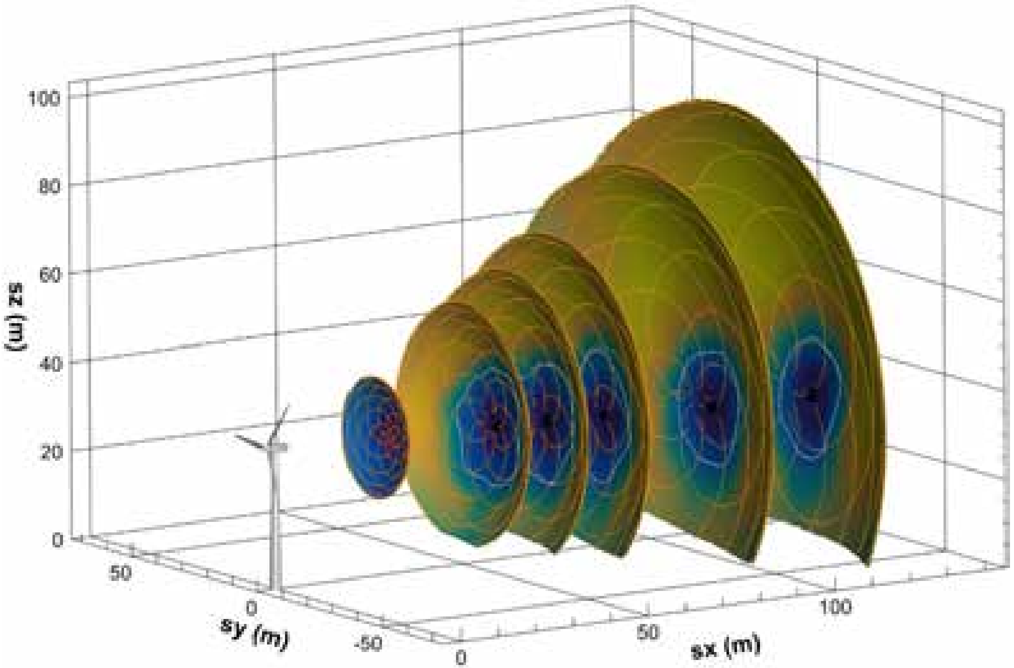
SOWFA Simulated Velocity

Simulated Lidar Measurements

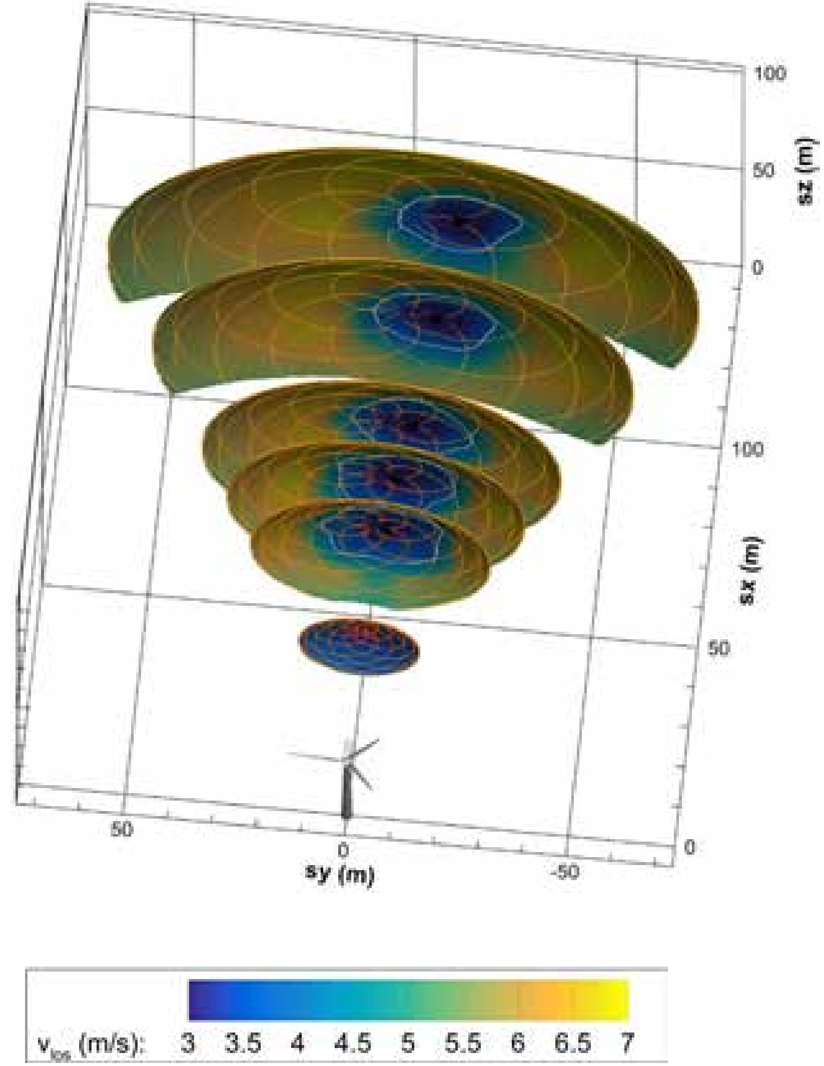
Comparison of identical time steps in order to show effect of SpinnerLidar on measurements and how that impacts wake position determination

Measurements at 3D downstream of turbine

WTGa1: Measuring impact of inflow - Stable



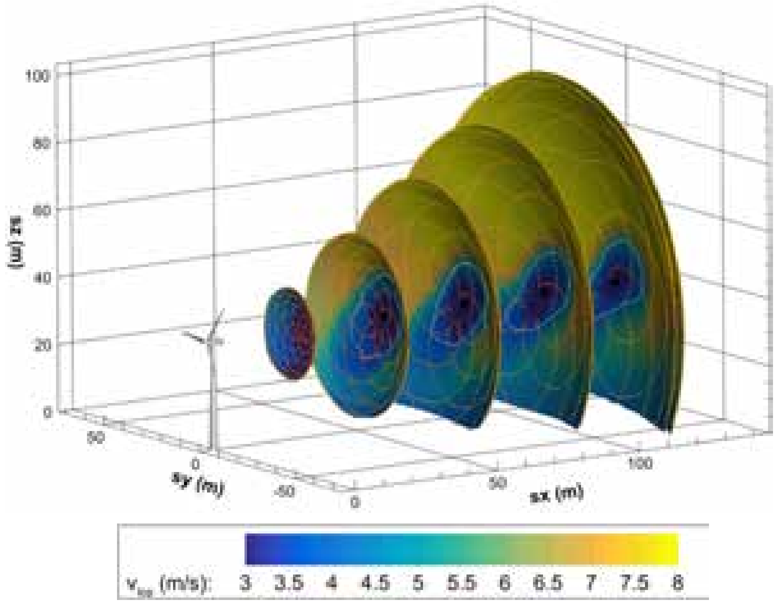
- Bulk Richardson = 1.7
- $z/L = 3.4$
- $\alpha = 0.19$
- wind speed = 6.8 m/s
- TI = 0.05
- veer = 0.1°
- yaw offset = 4.0°
- yaw heading = 236.7 degN

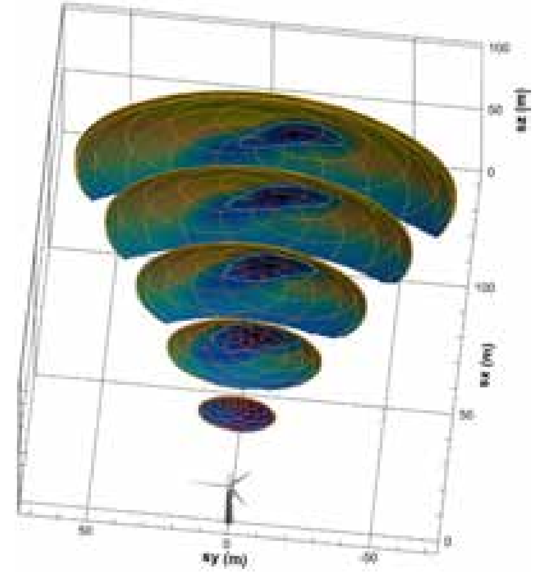


WTGa1: Wake Tracking vs Inflow

Lidar data viewed 3D (81 m) downstream looking downwind

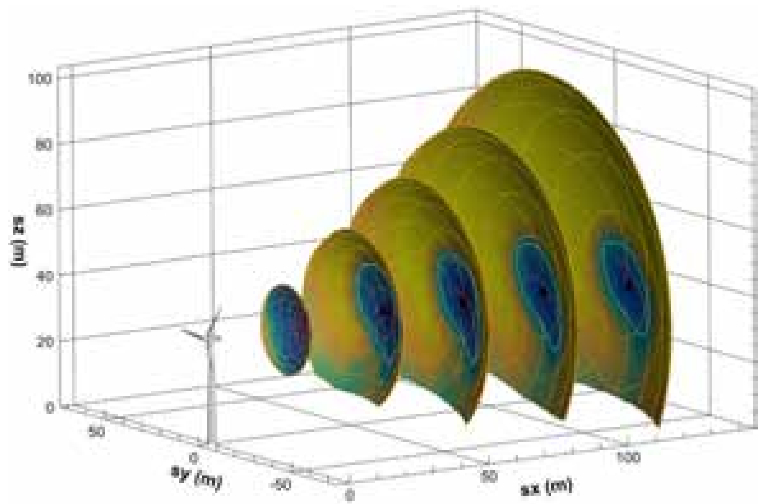
WTGa1: Measuring impact of inflow

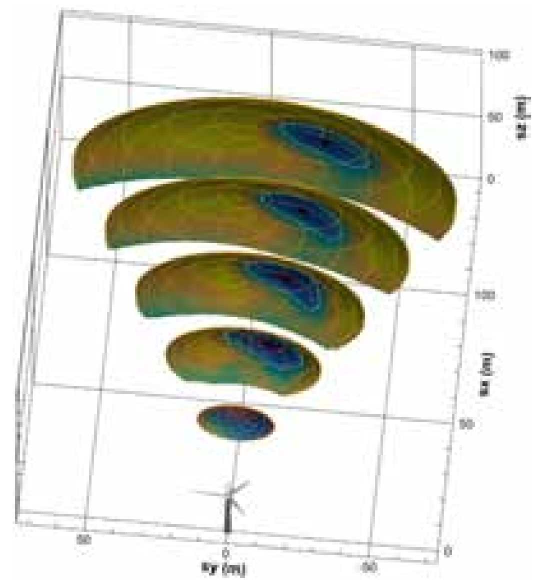




Stable ABL Positive Veer

Bulk Rich = 0.7
z/L = 2.3
α = 0.37
TI = 0.04
veer = 14.6°
yaw offset = -0.12°





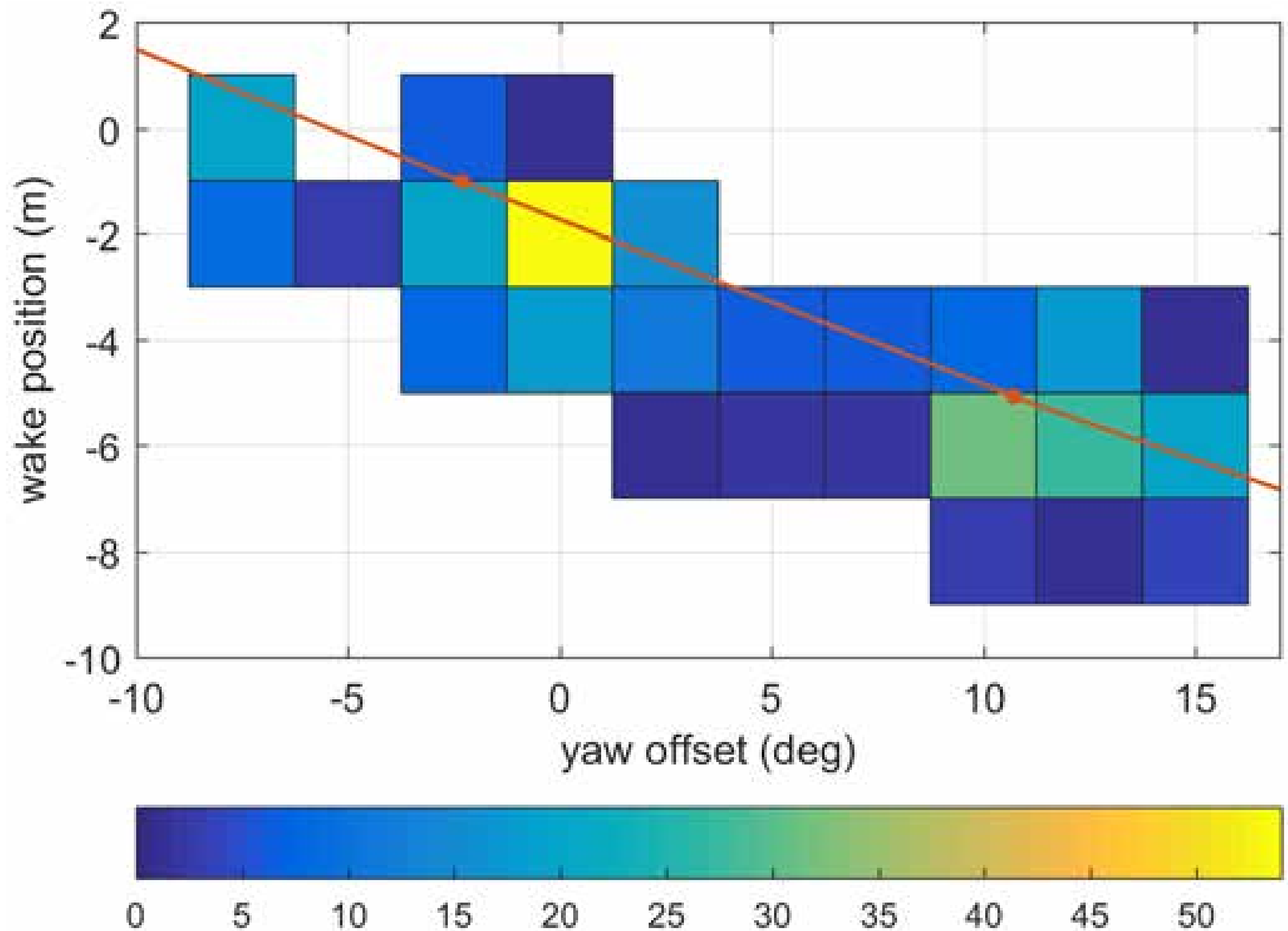
Stable ABL Negative Veer

z/L = 0.9
α = 0.15
TI = 0.08
veer = -5.0°
yaw offset = 10.9°

$$veer = \theta_{45\text{m sonic}} - \theta_{18\text{m sonic}}$$

WTGa1: Measuring impact of turbine state

- Bulk Richardson = 0.7
- $z/L = 3.1$
- $\alpha = 0.3$
- wind speed = 7.5 m/s
- TI = 0.08
- veer = 4.4°
- yaw offset = -7.5° to 15°
- Yaw heading = 159.5 degN



WTGa1: Stable BL Video at 2.5D

Obukhov length $z/L = 2.3$
$\alpha = 0.25$
wind speed = 5.7 m/s
TI = 0.04
veer = 5.7°
yaw offset = 7.43°
yaw heading = 145.6 degN

Note that you can see turbulence coming off the nacelle and tower before the turbine turns on and the wake forms

v_{los}

v'_{los}

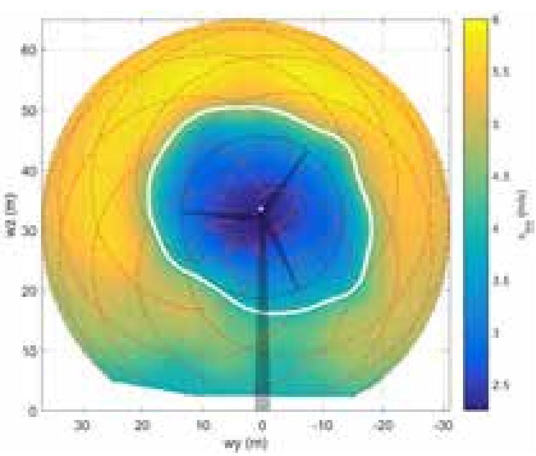
WTGa1: Neutral BL Video at 2.5D

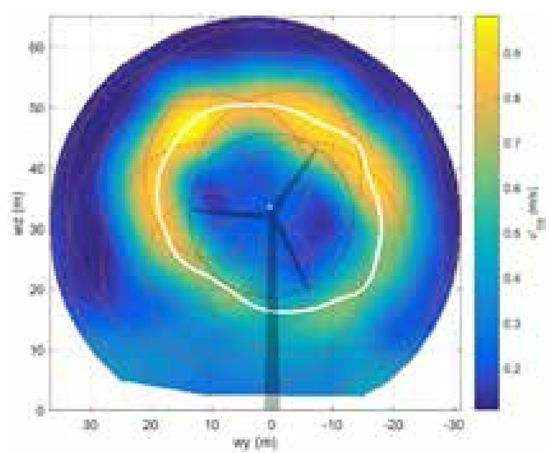
Obukhov length $z/L = 0.0$
$\alpha = 0.12$
wind speed = 9.0 m/s
TI = 0.14
veer = 0.26°
yaw offset = 5.27°
yaw heading = 198.3 degN

v_{los} v'_{los}

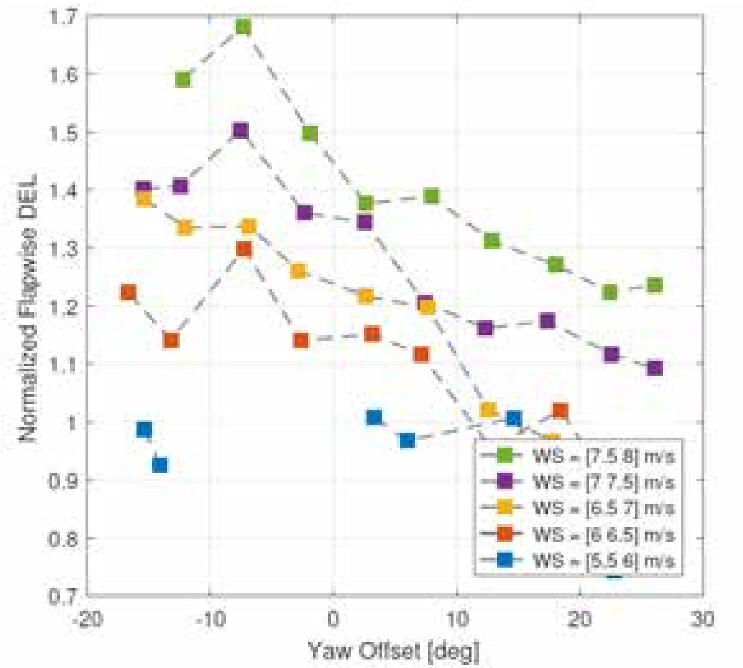
Observations and challenges

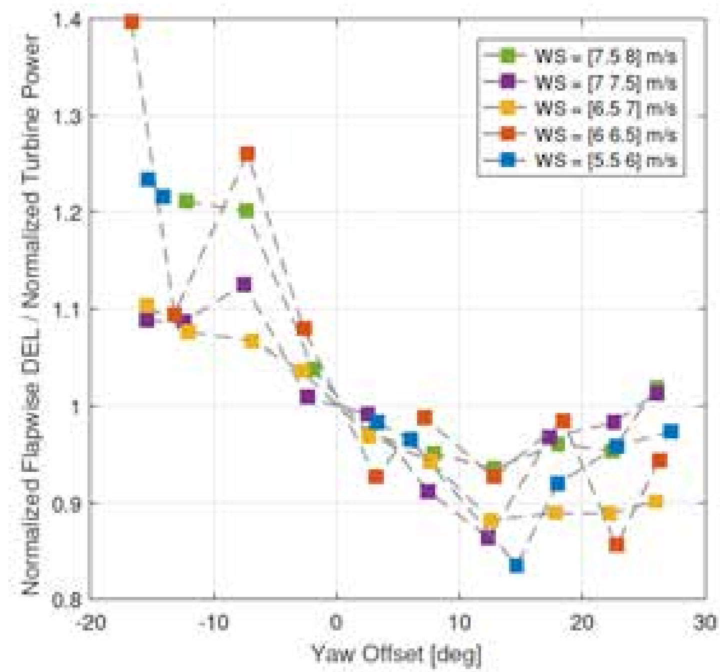
- Wake deflected ≈0.5D for 25 deg yaw offset
- Wake behavior very dependent on inflow characteristics
- Wake tracking for various inflow conditions is challenging
- Wake can be defined from lidar turbulence estimates
- Onboard turbine wind direction sensor very inaccurate
- Spatial calibration of lidar and yaw heading sensor were very important
  - 1 deg error = 2.35m at 5D
- Time synchronization was essential





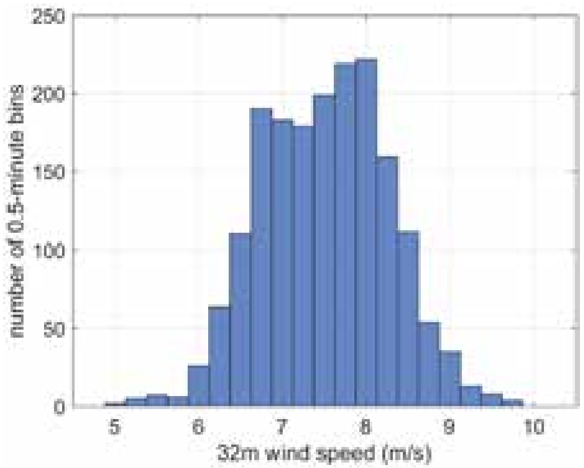
WTGa1: Power and Root Bending Fatigue Loads

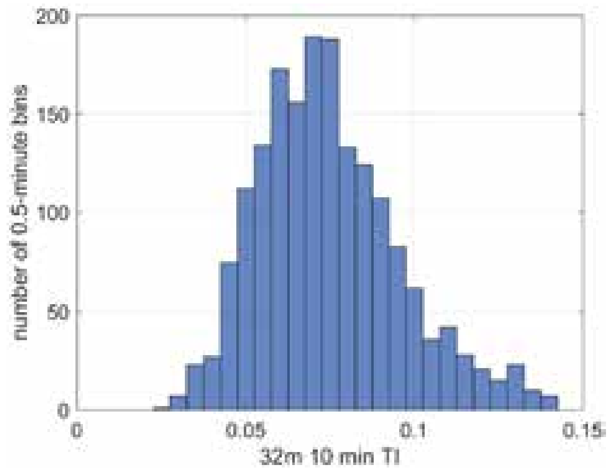


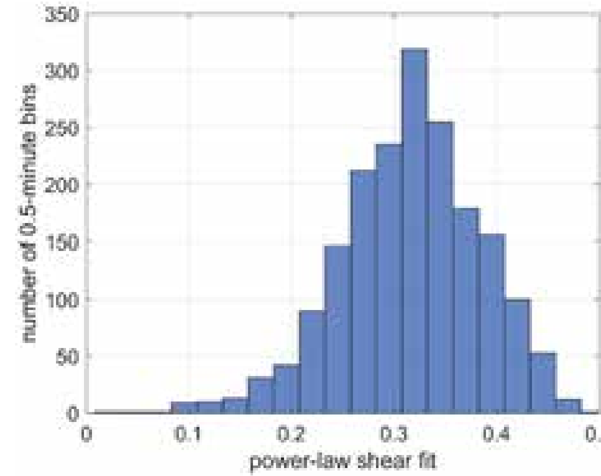


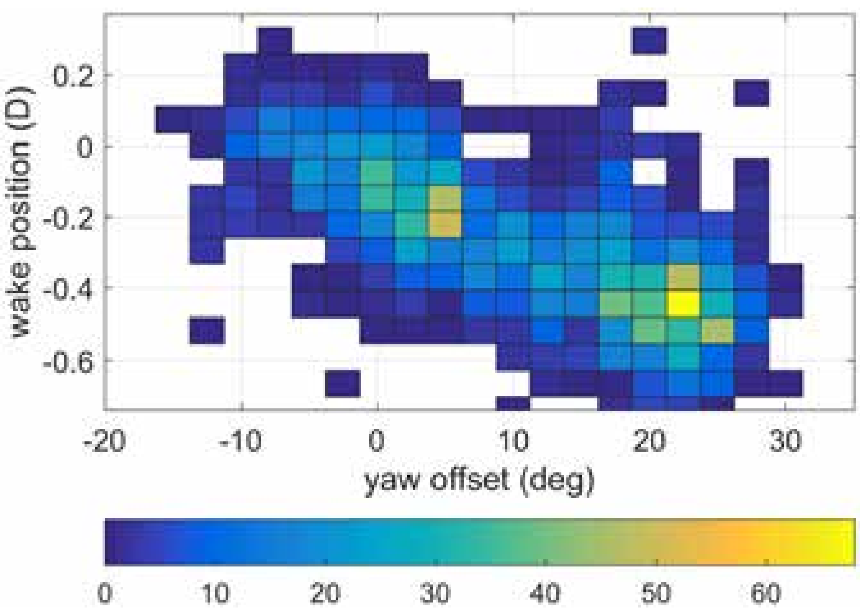
- The correlation of DEL with wind speed is seen to be as substantial as the yaw offset
- Data reveals that flapwise DEL increases with negative yaw and decreases with positive yaw as the velocity shear loading is balanced
- Yaw offset is observed to reduce power beyond around ±10°
- Yaw offset reduces power and alters the fatigue loads for wind turbines, both negatively and positively for the SWiFT turbines
- An effective "cost" is defined which compares DEL and power, normalized to the wind speed bin's zero yaw offset values
  - For the high-shear data analyzed, the SWiFT turbine has the best overall performance at around 10-12° yaw offset

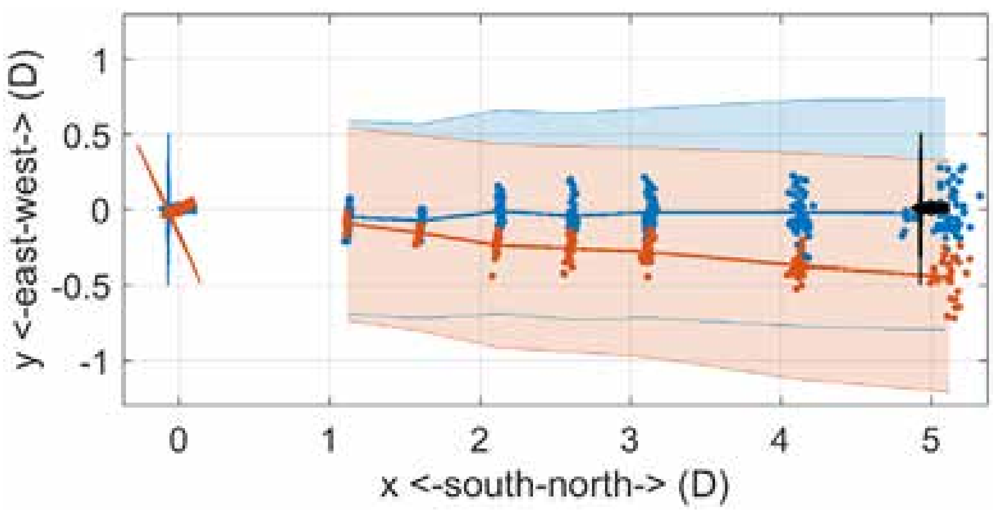
WTGa2: Inflow Conditions





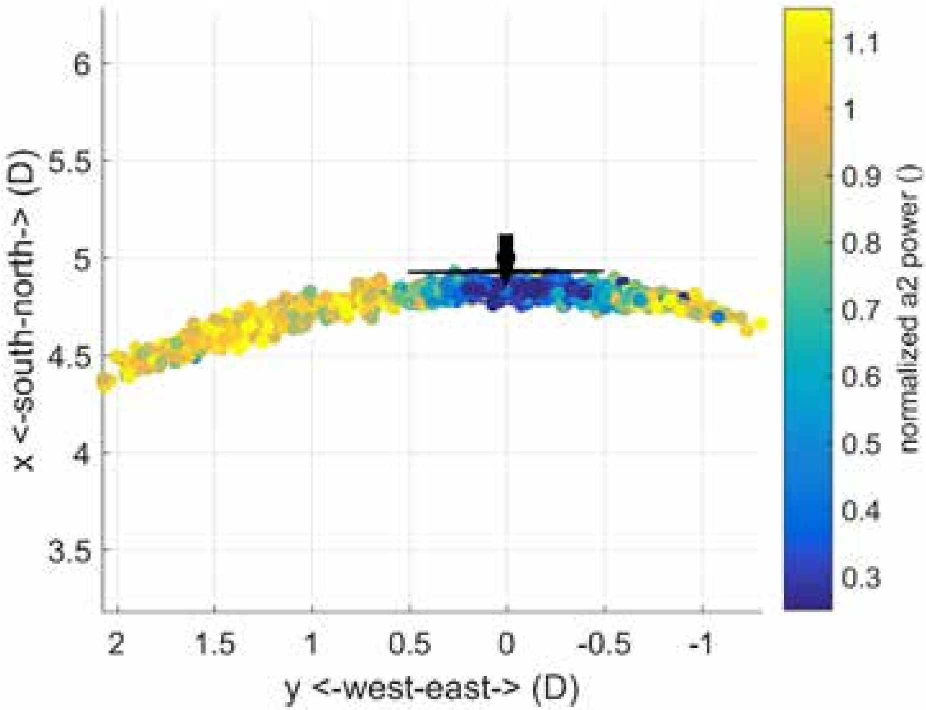


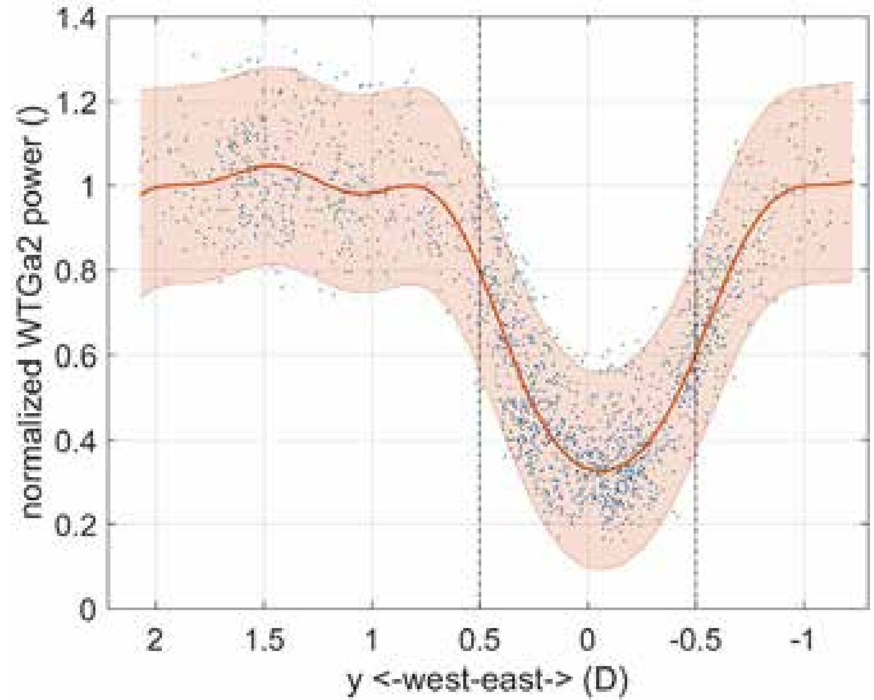




WTGa2: Waked Turbine Experiment

WTGa2: Measurement Arc and Power Output



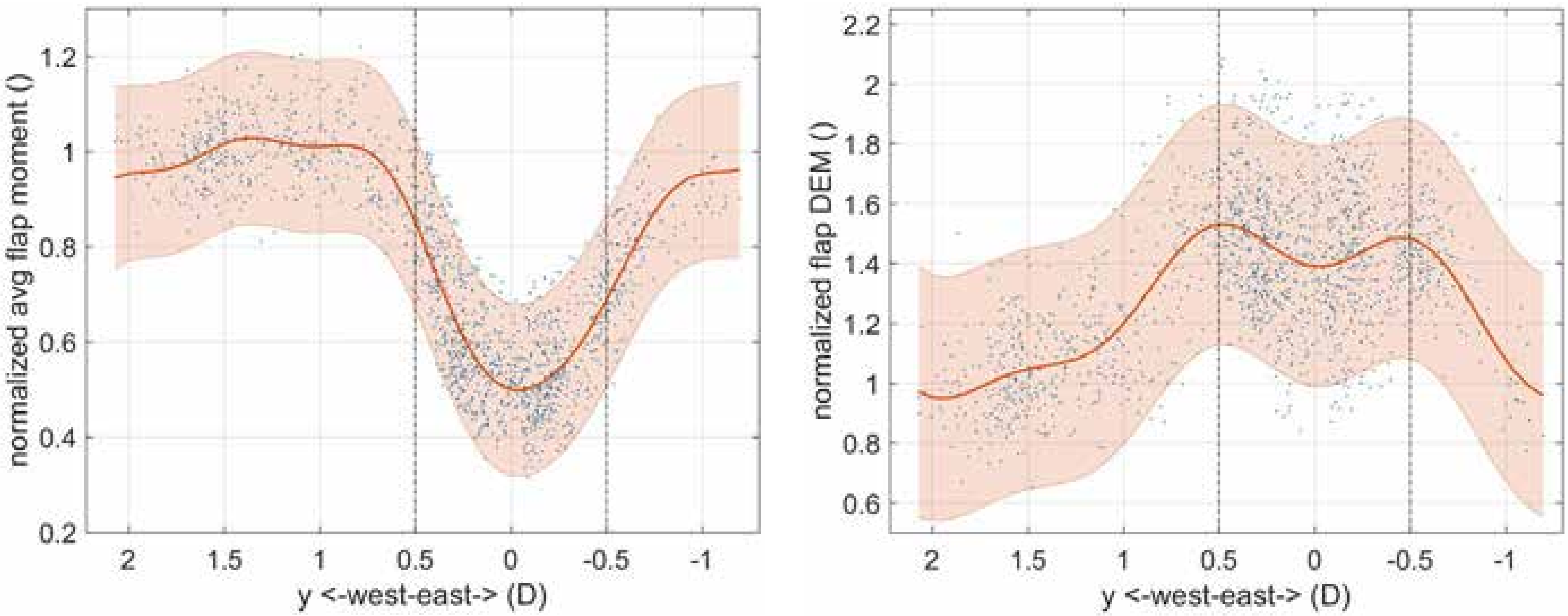


Fully waked turbine has 65% power loss on average

Power normalized by fit of power corresponding to non-waked hub height met tower wind speed

Slight power increase when wake was located next to rotor

WTGa2: Flap Moment, Average and DEM



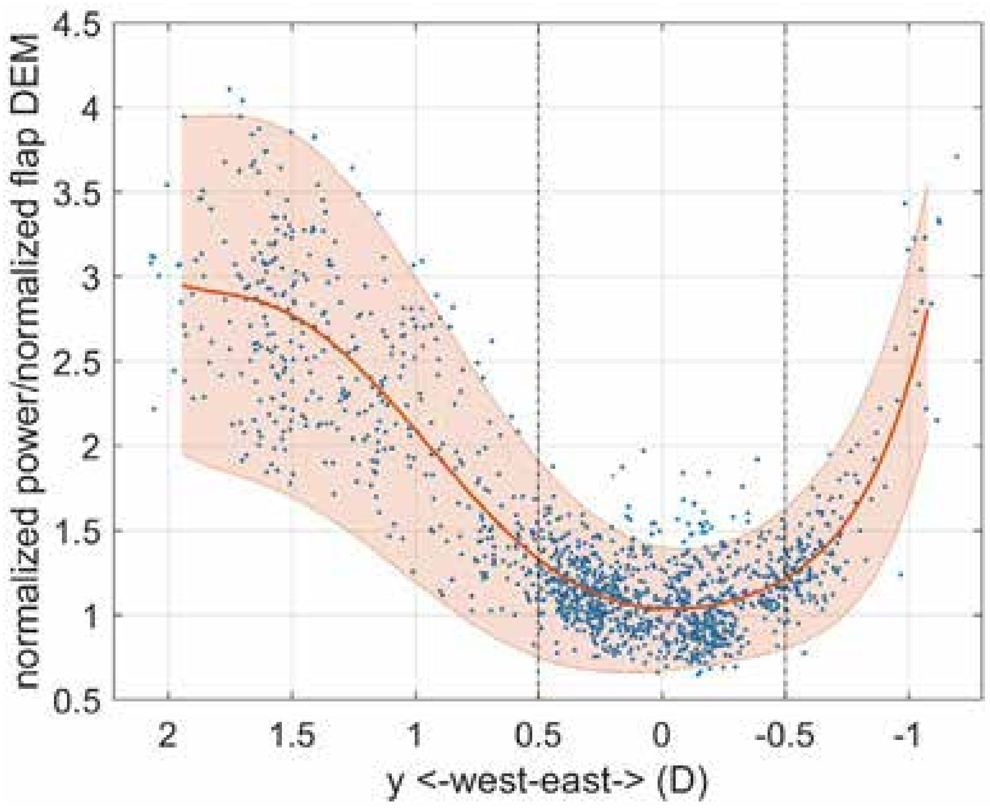
Fatigue loads higher under waked conditions

DEM normalized by fit of non-waked DEM with met tower hub height wind speed

Partially waked turbine has 10% higher DEM than fully waked case

DEM returns to non-waked conditions at lateral wake positions farther than 1.5D

WTGa2: Power/Fatigue Loads Comparison Metric



Metric created from the ratio of normalized power by normalized flap DEM fatigue damage

Revealed it was always better for the downstream turbine to be less waked

Metric indicated certain regions where shifting the wake was more beneficial than others with the wake steering control authority of the upstream wind turbine

When wake was located at edge of rotor, it was very beneficial to shift the wake away from the turbine using wake steering from both a power and fatigue loads perspective

Conclusion

Flapwise bending DEL from the SWiFT turbine was observed to increase with negative yaw and decrease with positive yaw, based on the level of shear across the rotor disk

Based on loads reduction and a relatively constant power, wind turbines may have optimal performance at a nominally positive yaw offset, based on the atmospheric conditions

The fully and partially waked conditions reduce the power output and increase the fatigue loading on the downstream wind turbine

Adjacently-waked case creates a power increase with a reduced fatigue loading relative to the fully and partially waked cases

A 10% increase in fatigue loading occurred during partial wake impingement, centered at the rotor tip, relative to when the turbine was fully waked

Certain regions of wake position where shifting the wake was more beneficial than others with the wake steering control authority of the upstream wind turbine

When wake was located at edge of rotor, it was very beneficial to shift the wake away from the turbine using wake steering from both a power and fatigue loads perspective

The complete Wake Steering experimental dataset will be available for download at **a2e.energy.gov**

Example Wake Positions

vlos

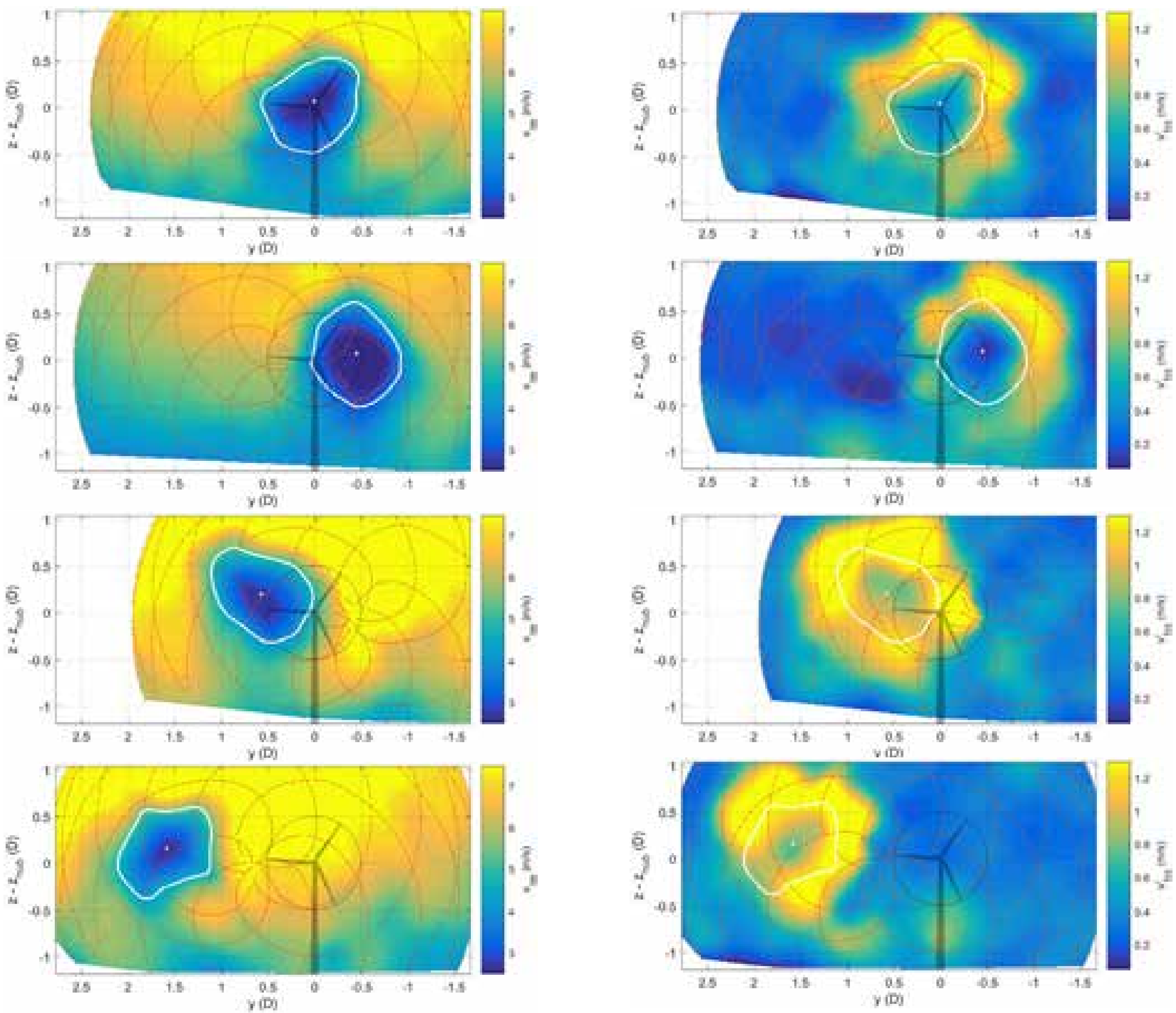
turbulence

fully waked, y = 0D

partially waked,
y = -0.5D

partially waked,
y = 0.5D

adjacently waked,
y = 1.5D



Rotational Domain Frequency of Example Wake Positions

fully waked, y = 0D

partially waked,
y = -0.5D

partially waked,
y = 0.5D

adjacently waked,
y = 1.5D