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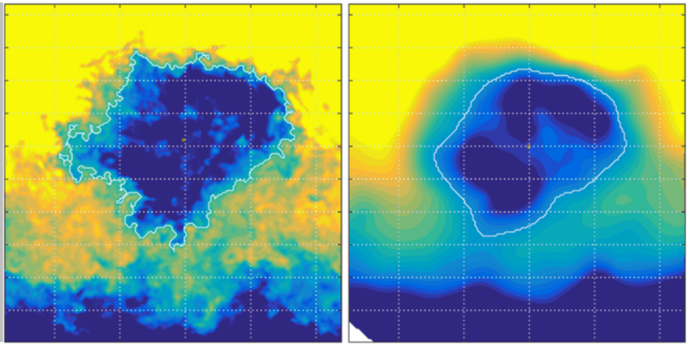

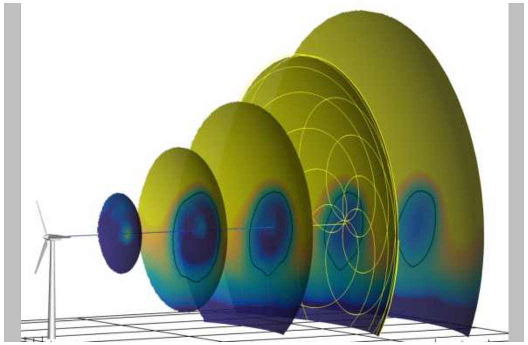

# High Resolution Wind Turbine Wake Measurements with a Scanning Lidar

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# Outline

- Experimental context: A2e Wake Steering experiment at SWiFT
- Experimental Setup
  - SWiFT Site baseline
  - Wake measurements with DTU SpinnerLidar
  - Calibration & Alignment of SpinnerLidar
- Results
  - Analysis methods
  - Impact of atmosphere (ex. Veer)
  - Impact of turbine (ex. Yaw offset)
  - Turbulence analysis
- Conclusion

# Current Experiment: A2e Wake Steering

Demonstrate the influence of wake steering control on downstream rotor power and loads using two instrumented turbines with inter-turbine wake measurements.

- Experiment is providing high-quality validation data for:
  - Control models
  - High-fidelity models
- Experiment created through the Department of Energy (DOE) Atmosphere to Electrons (A2e) program
  - All data will be made public and open through A2e Data Archive Portal (DAP) https://a2e.energy.gov/projects/wake

**Partners and Collaborators:**

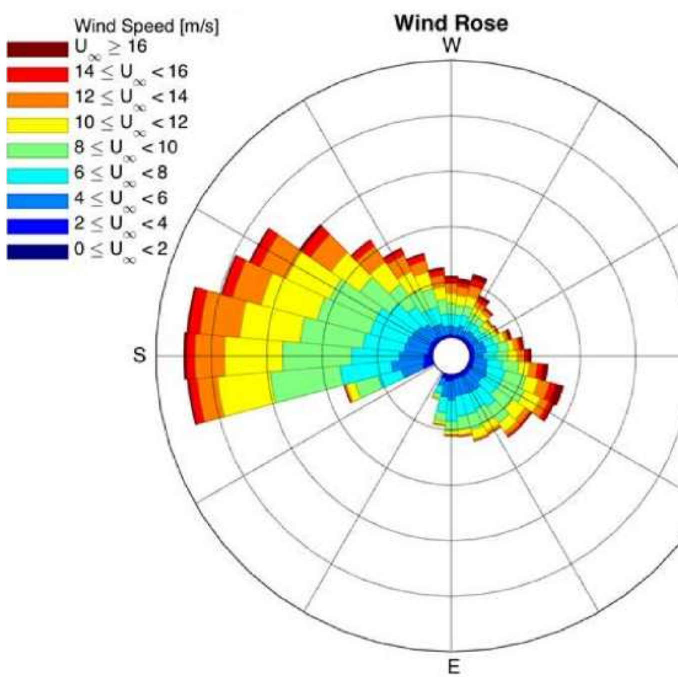
# SWiFT Facility Overview

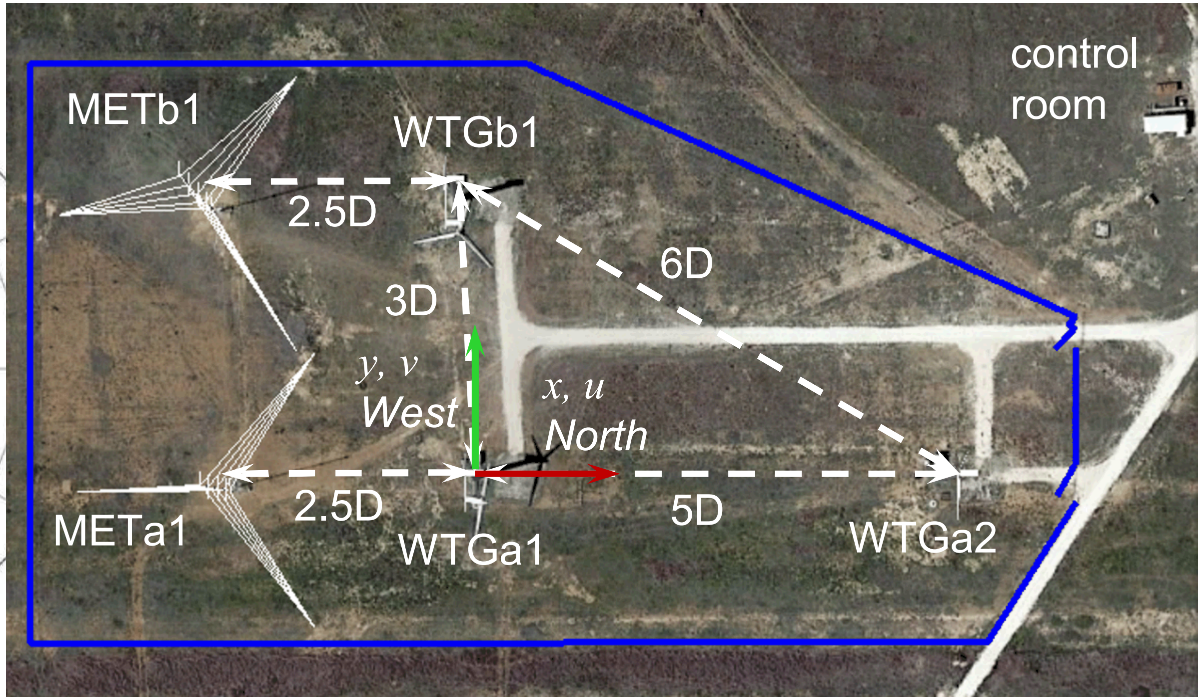
## SWiFT exists to:

- Reduce turbine-turbine interaction and wind plant underperformance
- Public, open-source validation data
- Advance wind turbine technology

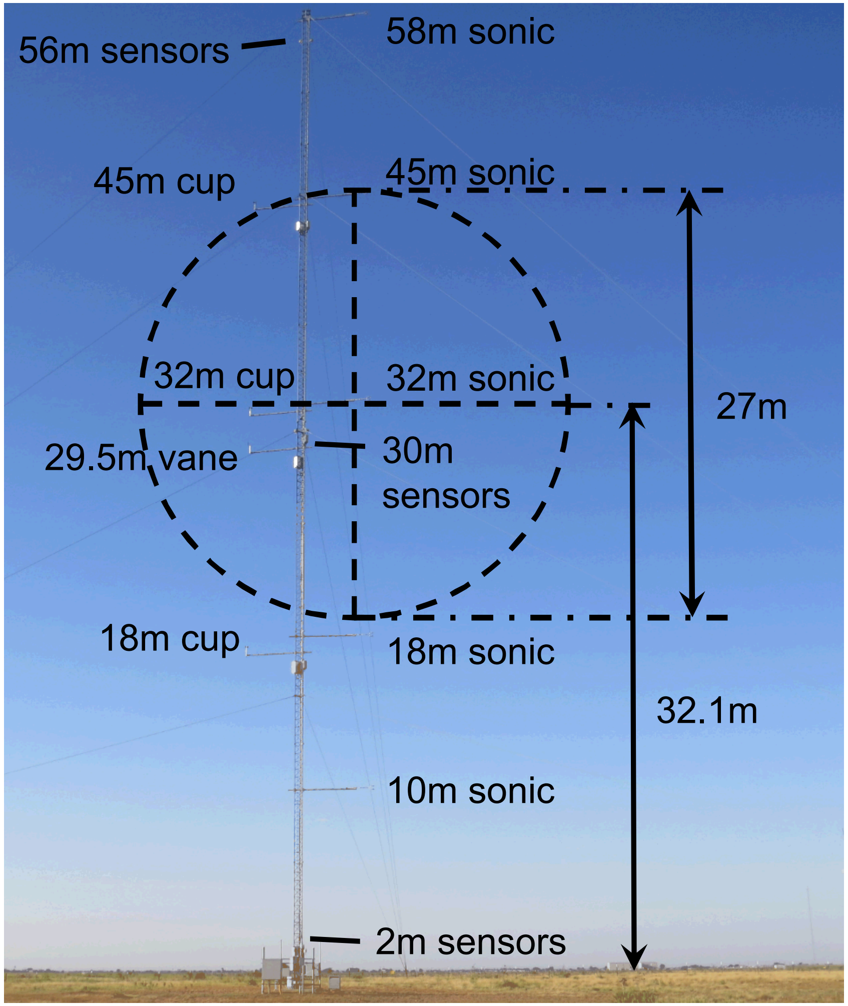
## Facilities:

- Three variable-speed variable-pitch heavily-modified V27 wind turbines with full power conversion and extensive sensor suite
- Two heavily instrumented inflow anemometer towers



# SWiFT Site Instrumentation

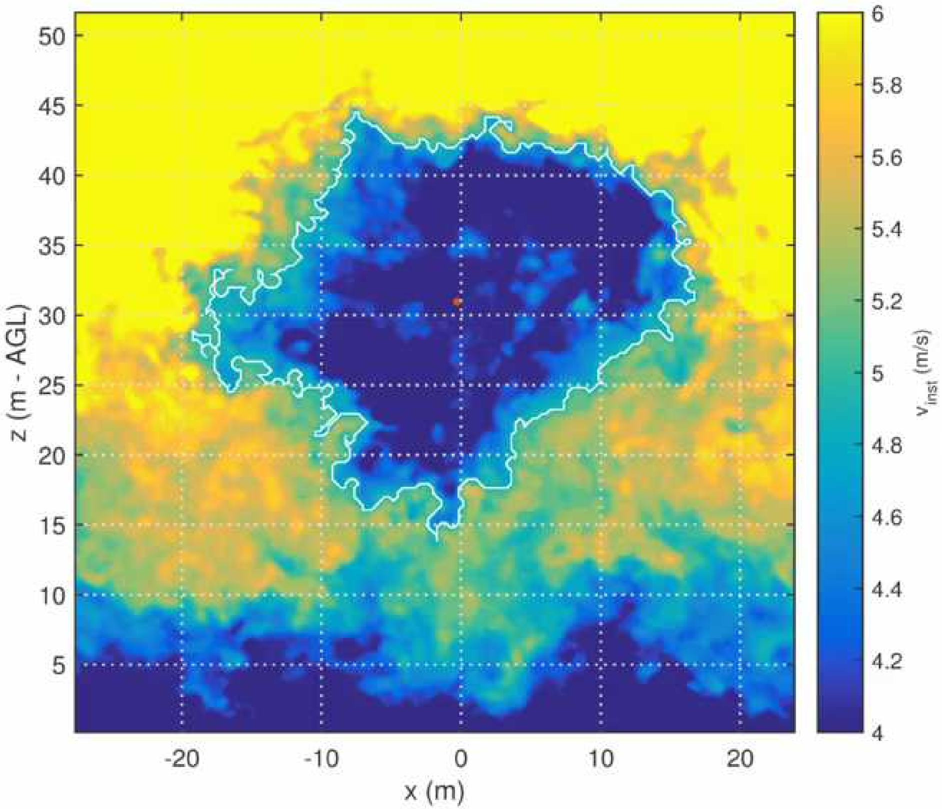



**Measurements:**

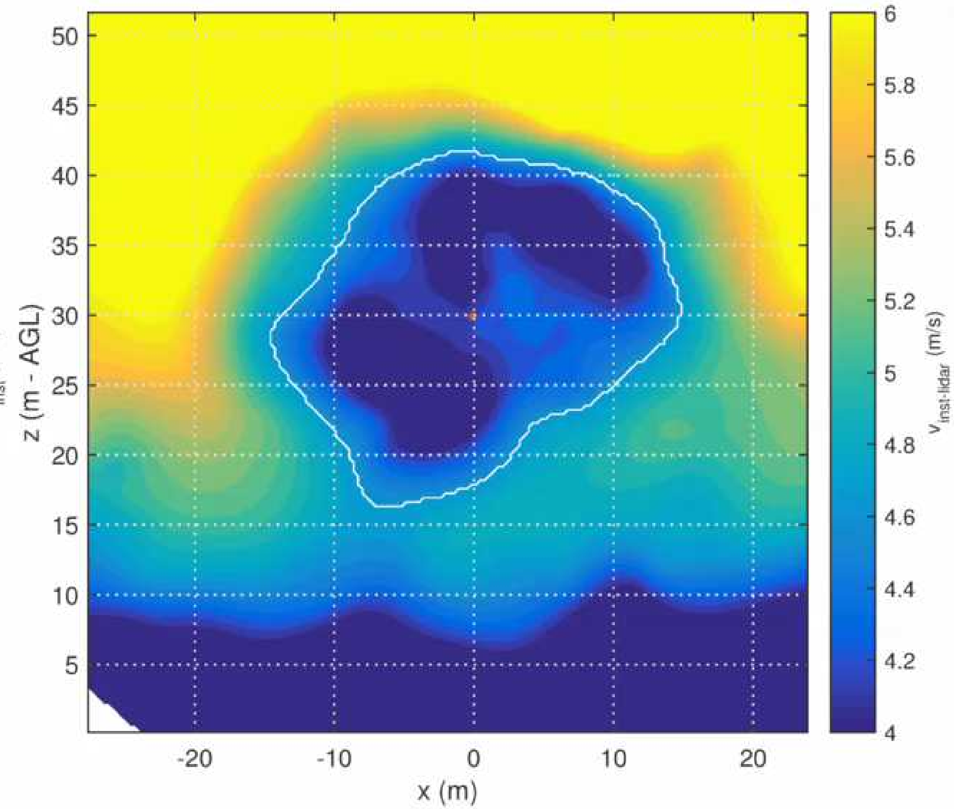
- TTU Instrumentation:
  - 200m MET, Sodar, and Radar Profiler
- Inflow: Dual 58.5m MET towers
- Rotor and tower strains and accels.
- Wake Flow Diagnostic: DTU SpinnerLidar
- **www.swift.sandia.gov**

# Lidar Simulation and Selection

**SOWFA Simulated Velocity**

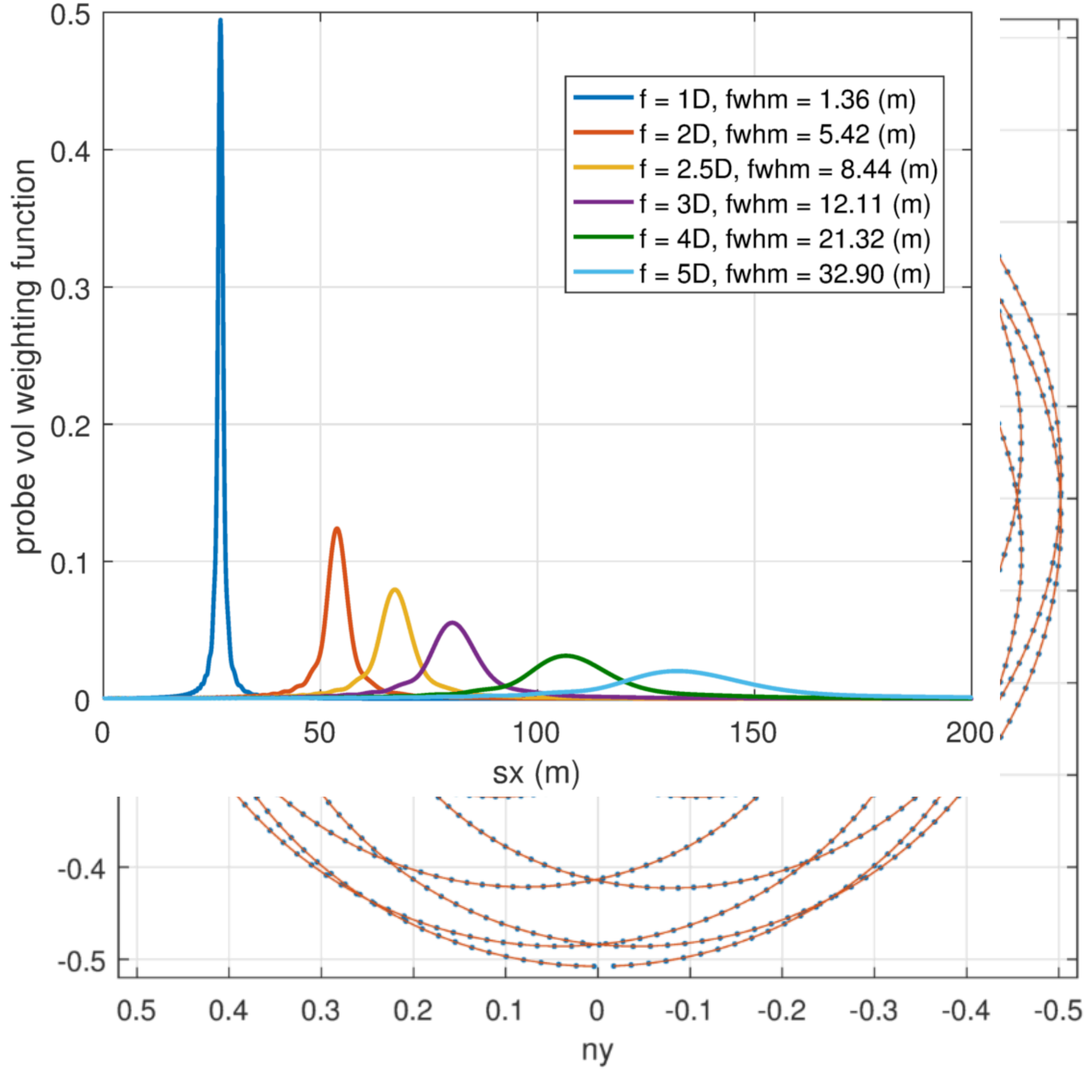


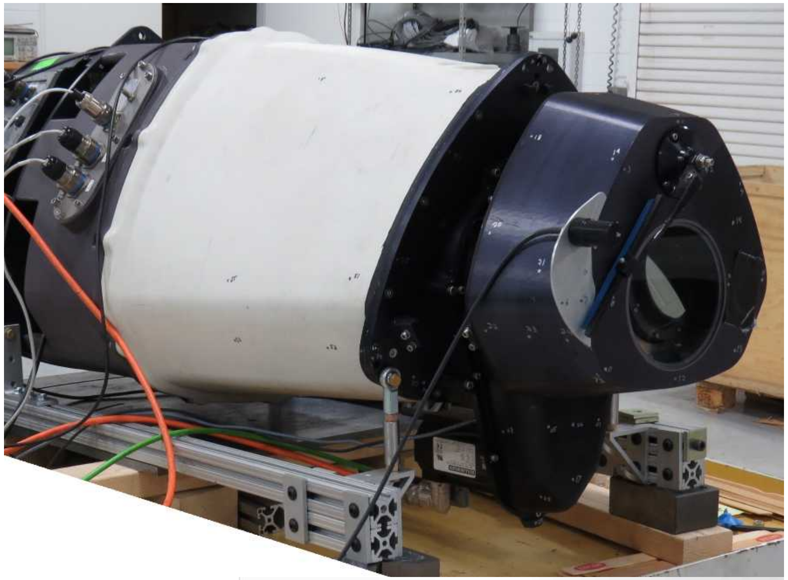

**Simulated Lidar Measurements**

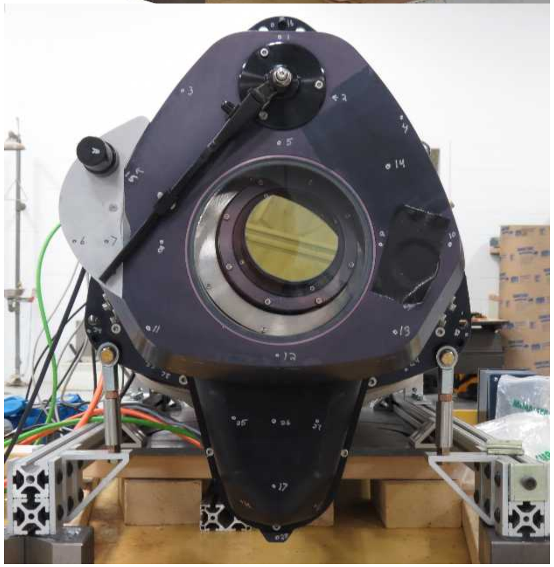



- Comparison of identical time steps in order to show effect of SpinnerLidar on measurements and how that impacts wake position determination
- Measurements at 3D downstream of turbine

# Wake Measurements: DTU SpinnerLidar





table

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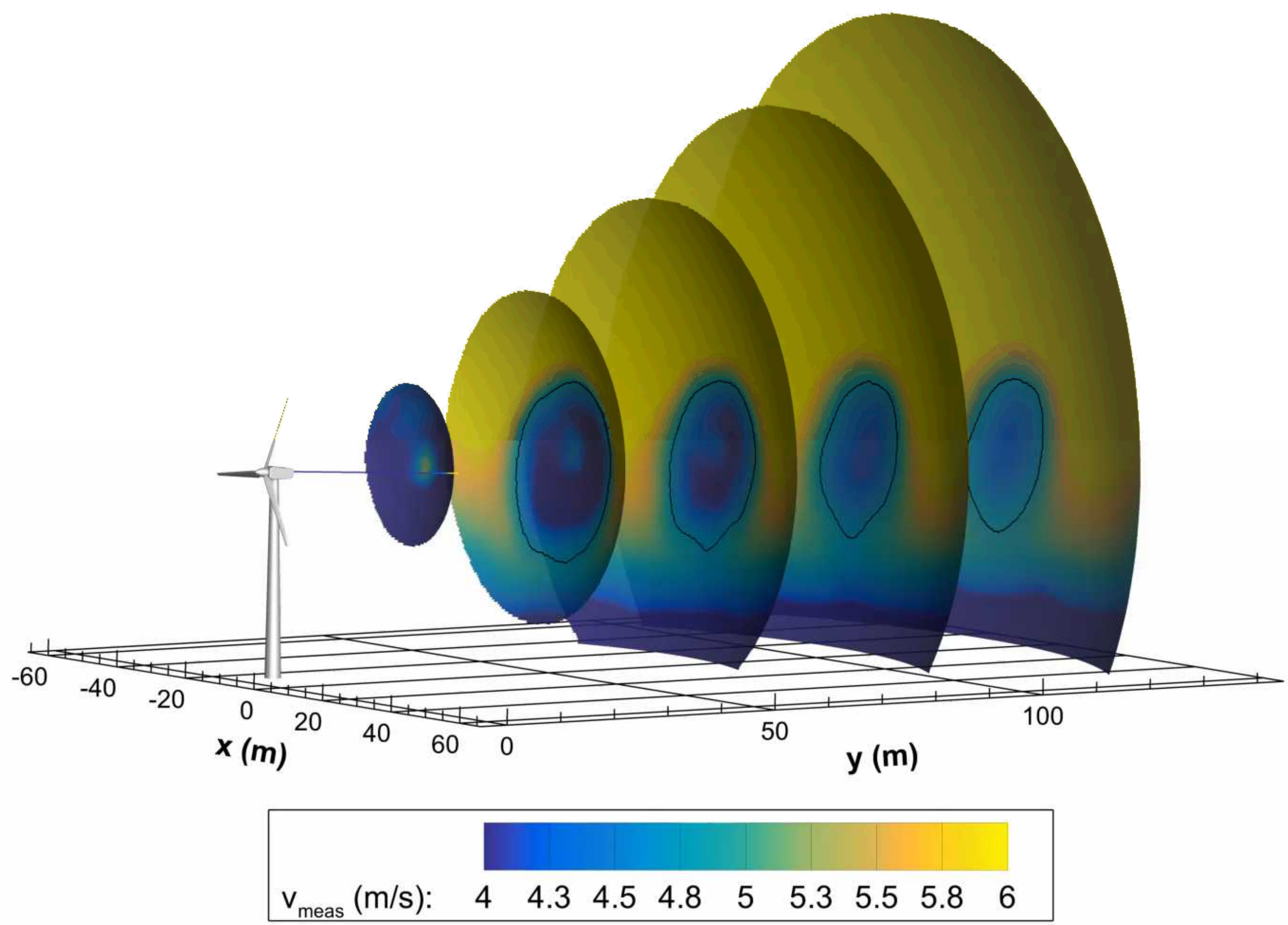
ration

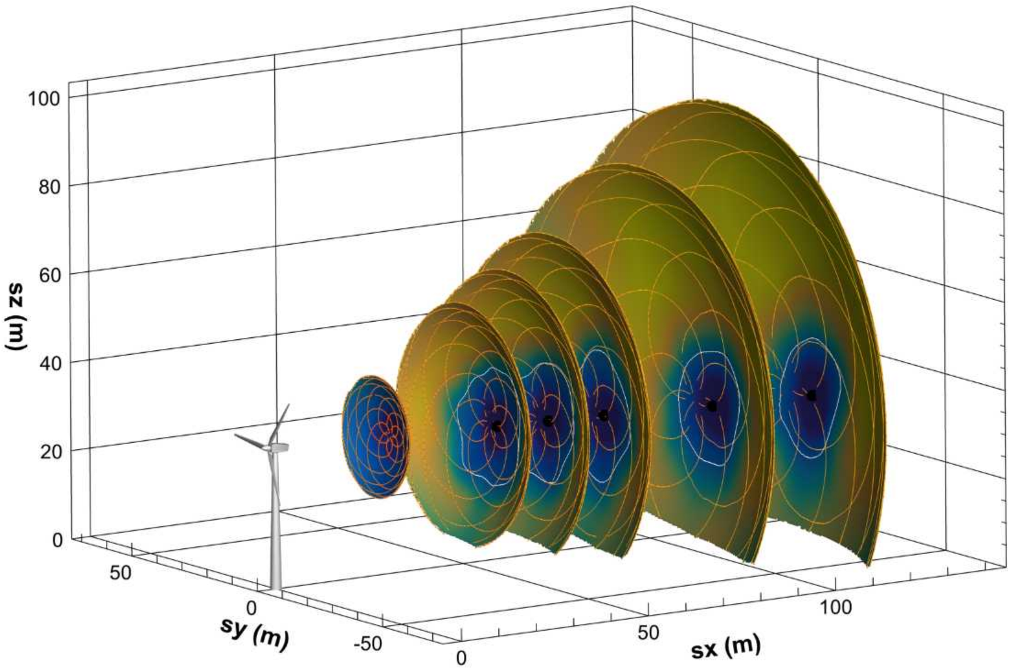
and Alignment Method for Wind Turbine Wake

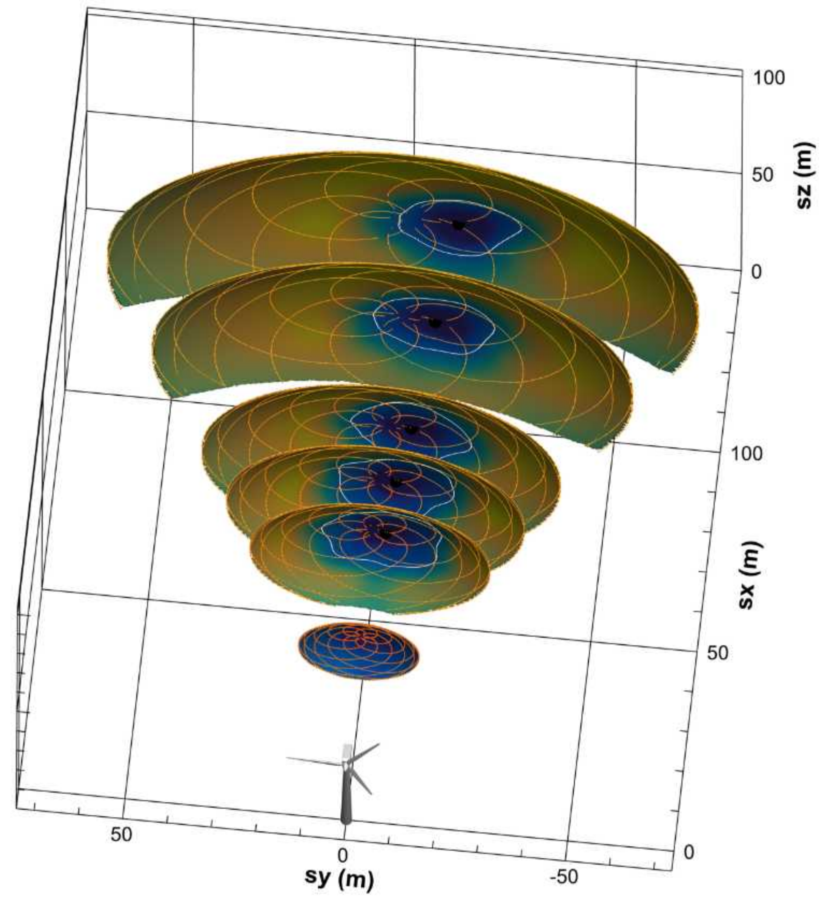
Characterization," AIAA 2017-0455.

# Wake Measurements: DTU SpinnerLidar

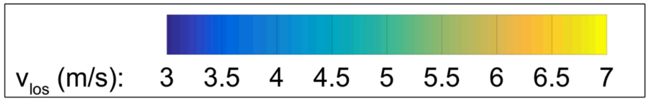


# Measuring impact of inflow: Stable



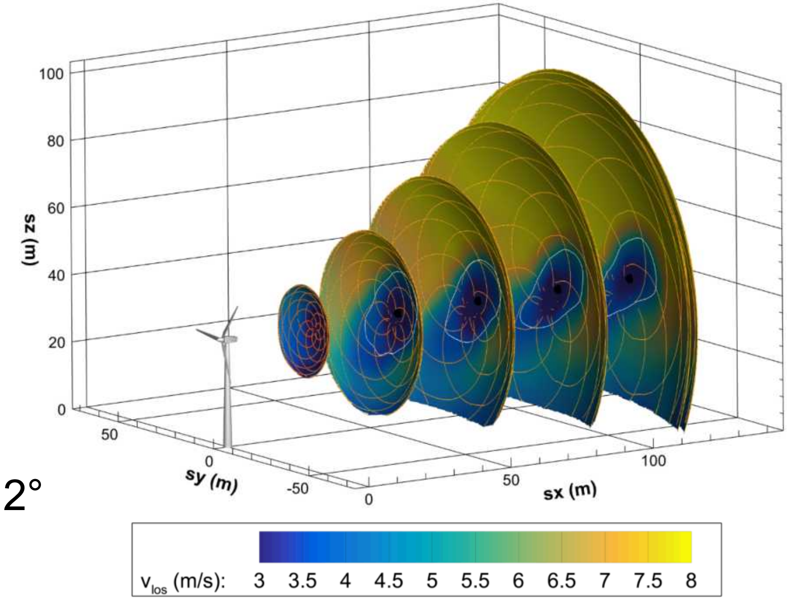

- Bulk Richardson = 1.7
- $z/L$ = 3.4
- $\alpha$ = 0.19
- wind speed = 6.8 m/s
- TI = 0.05
- veer = 0.1°
- yaw offset = 4.0°
- yaw heading = 236.7 degN

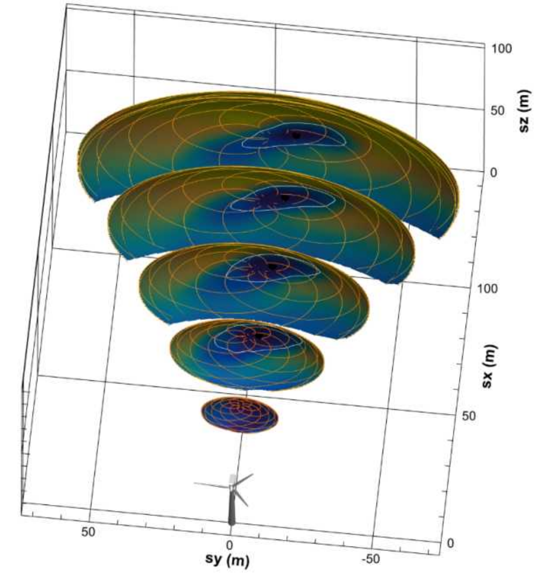


# Measuring impact of inflow

**Stable ABL**
**Positive Veer**

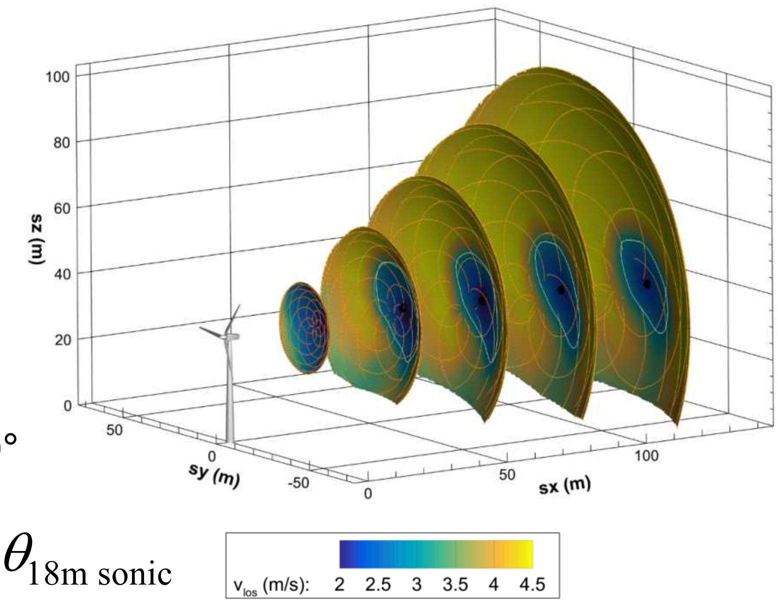
- Bulk Rich = 0.7
- $z/L$ = 2.3
- $\alpha$ = 0.37
- TI = 0.04
- veer = 14.6°
- yaw offset = -0.12°

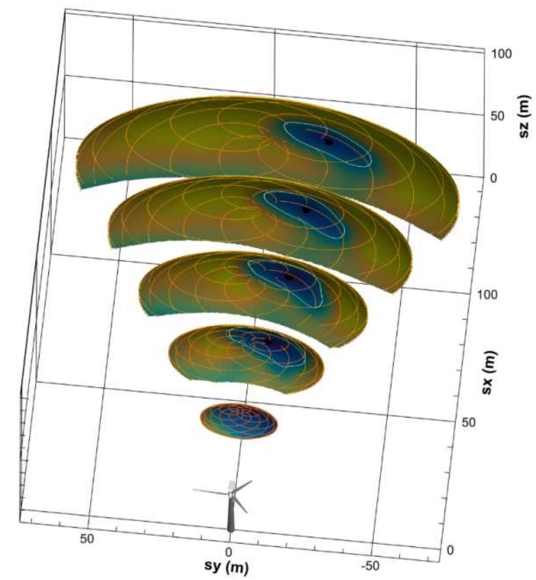



**Stable ABL**
**Negative Veer**

- $z/L$ = 0.9
- $\alpha$ = 0.15
- TI = 0.08
- veer = -5.0°
- yaw offset = 10.9°

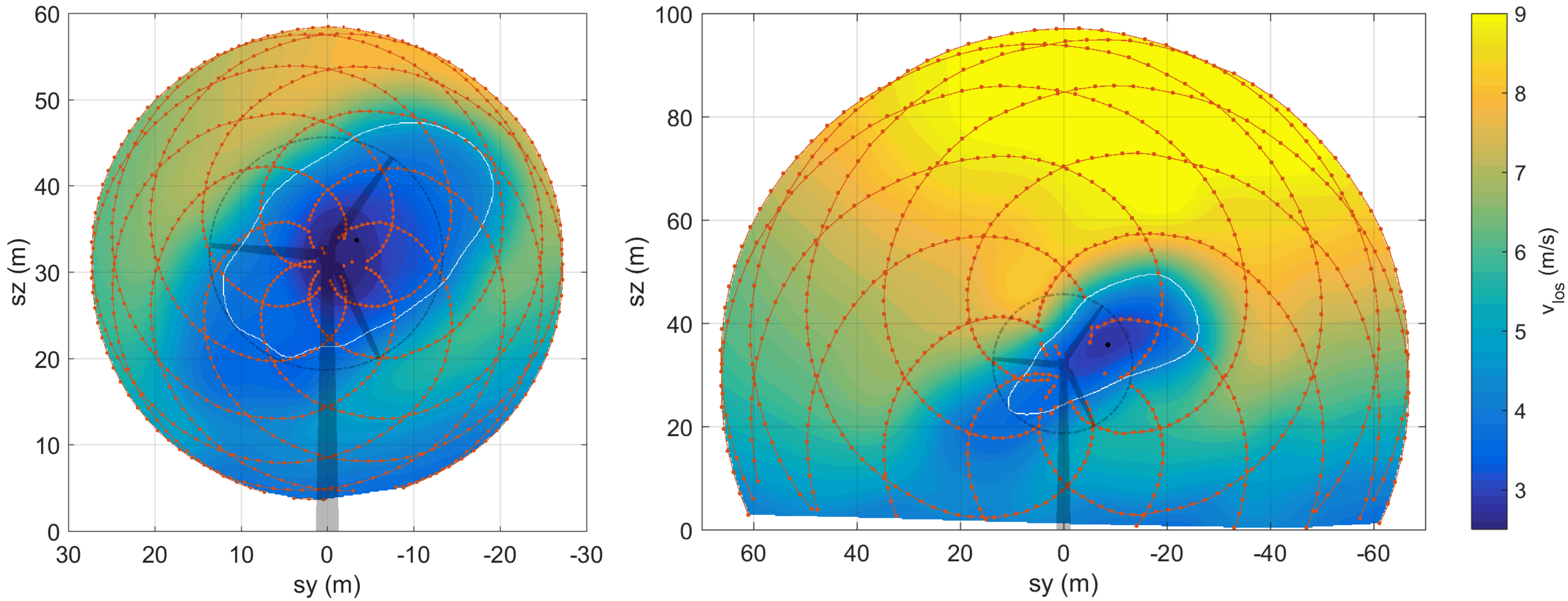



$$veer = \theta_{\text{45m sonic}} - \theta_{\text{18m sonic}}$$

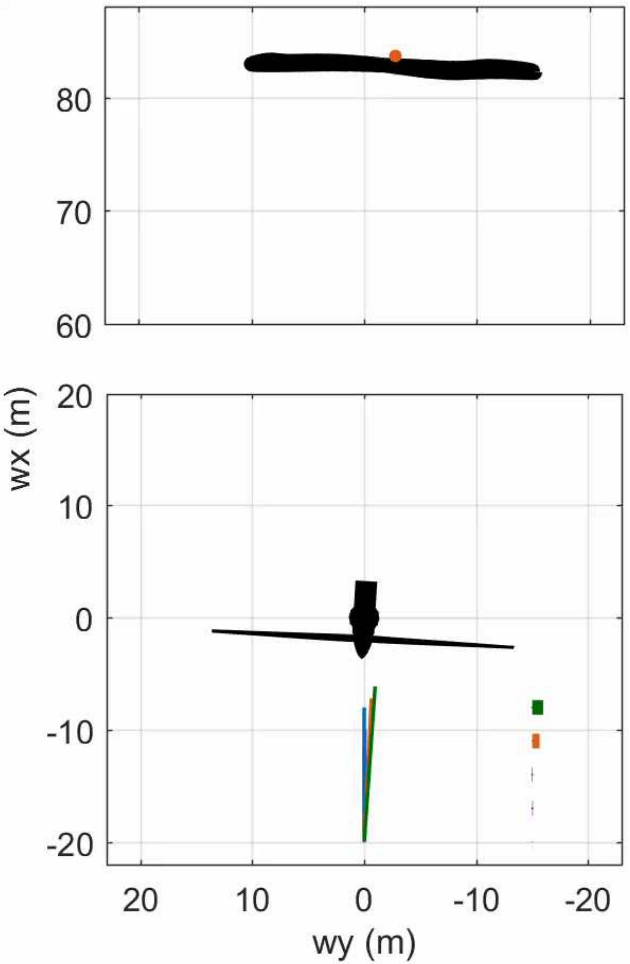
# Stable Atmosphere Positive Veer

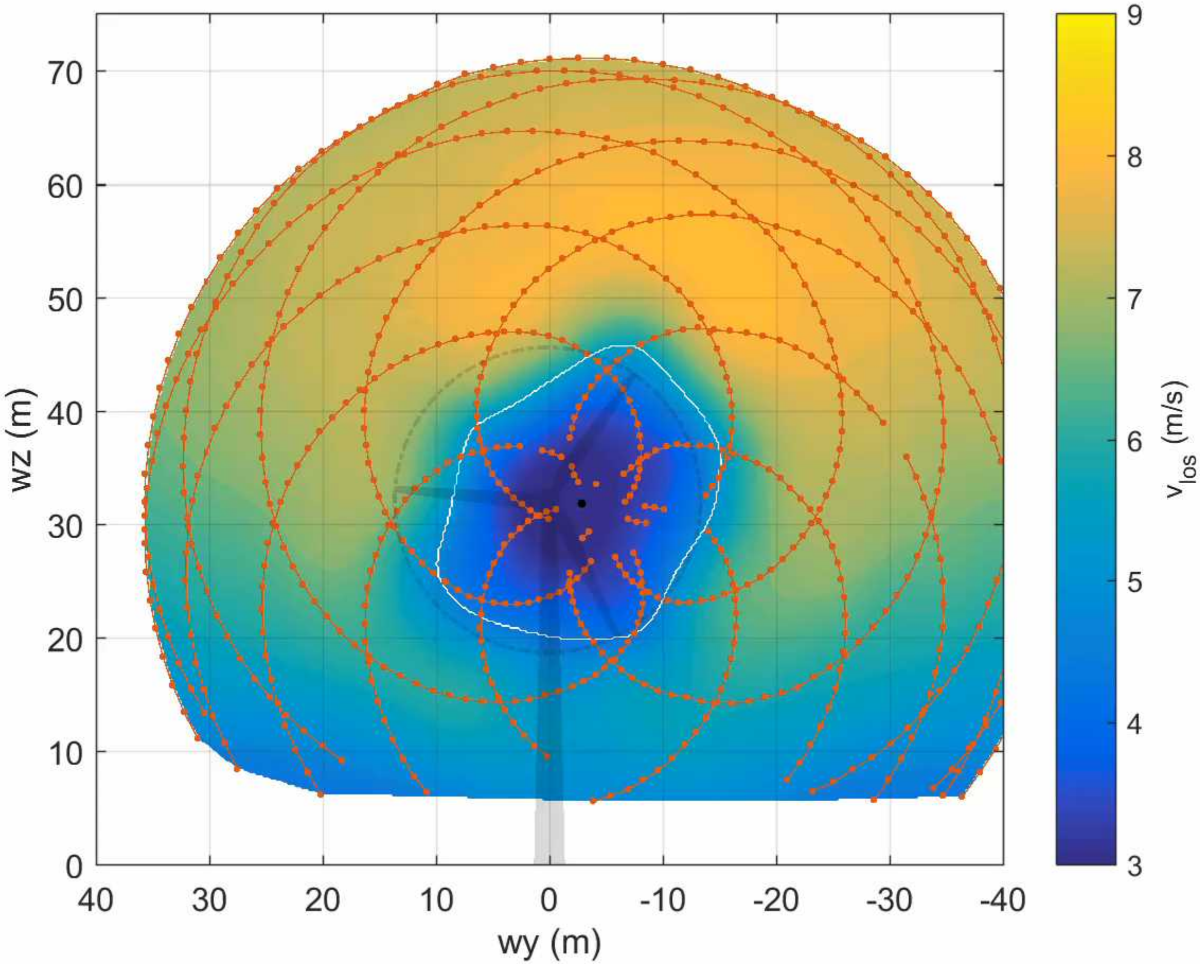
- Bulk Richardson = 0.7
- $z/L$ = 2.3
- $\alpha$ = 0.37
- wind speed = 6.9 m/s
- TI = 0.04
- veer = 14.6°
- yaw offset = -0.12°
- yaw heading = 195.3 degN



# Measuring impact of turbine state

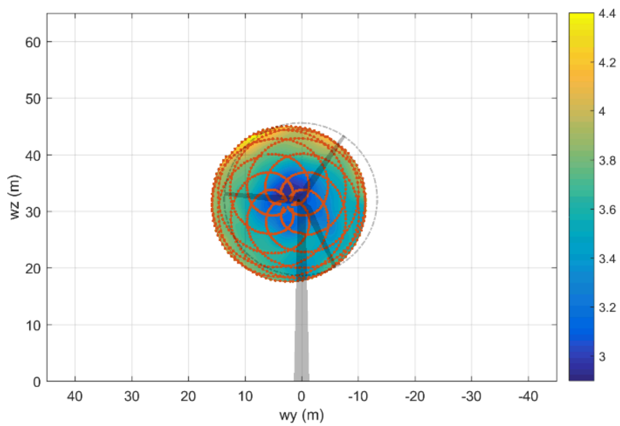
- Bulk Richardson = 0.7
- $z/L$ = 3.1
- $\alpha$ = 0.3
- wind speed = 7.5 m/s
- TI = 0.08
- veer = 4.4°
- yaw offset = -7.5° to 15°
- Yaw heading = 159.5 degN



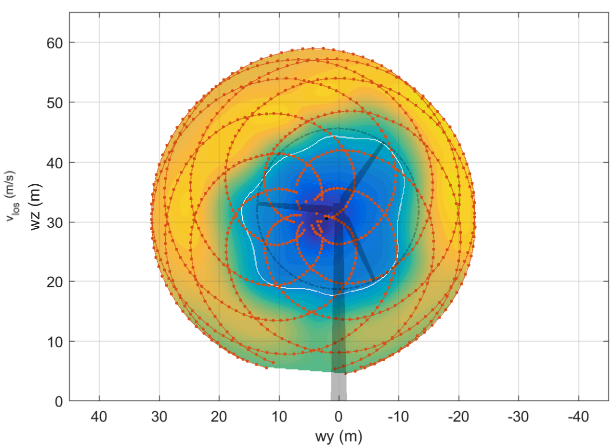



# Stable No Veer BL $v_{los}$

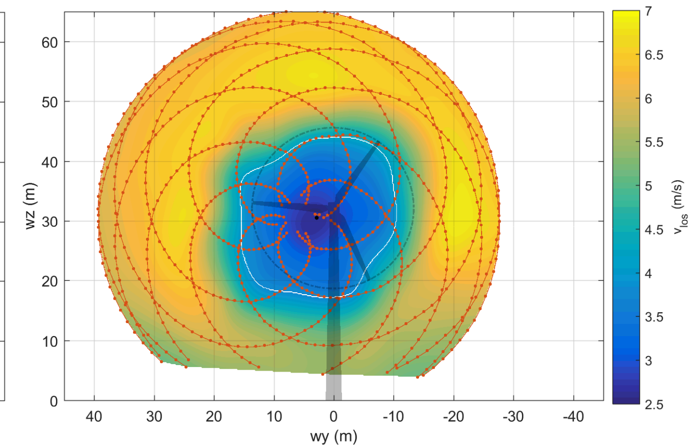
1D



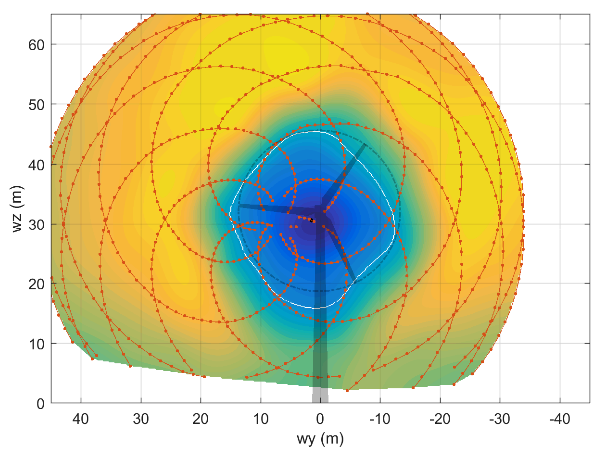

2D



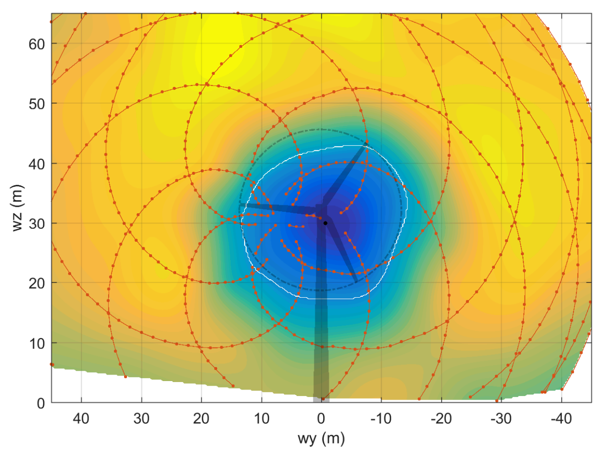

2.5D



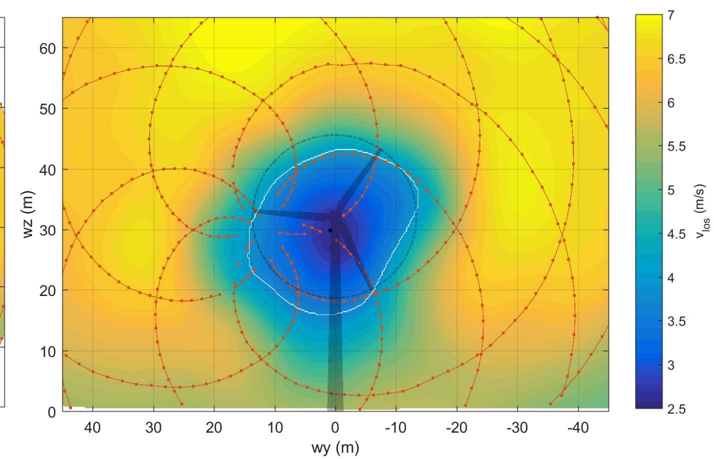

3D




4D




5D



# Stable No Veer BL $v'_{los}$

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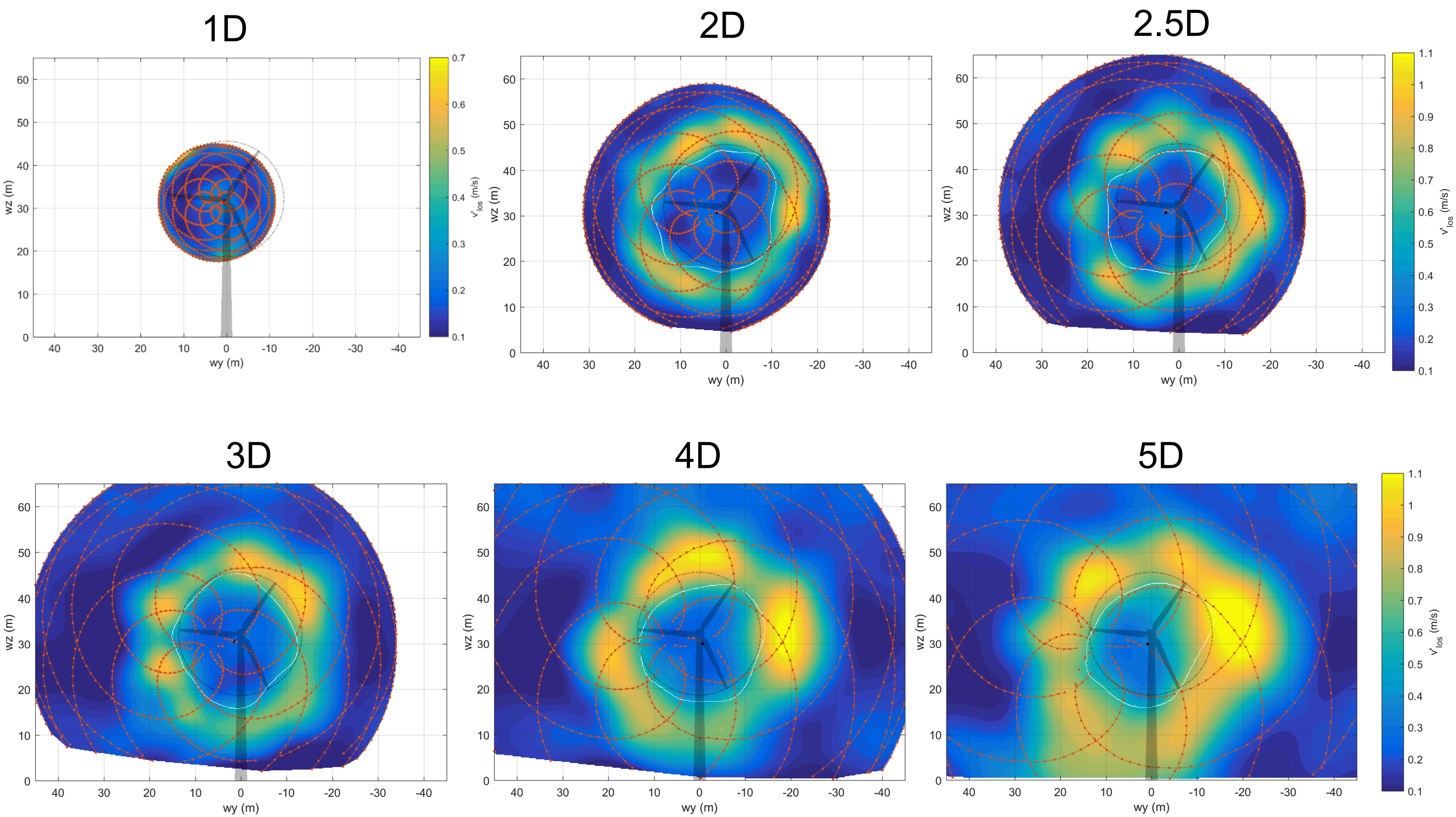
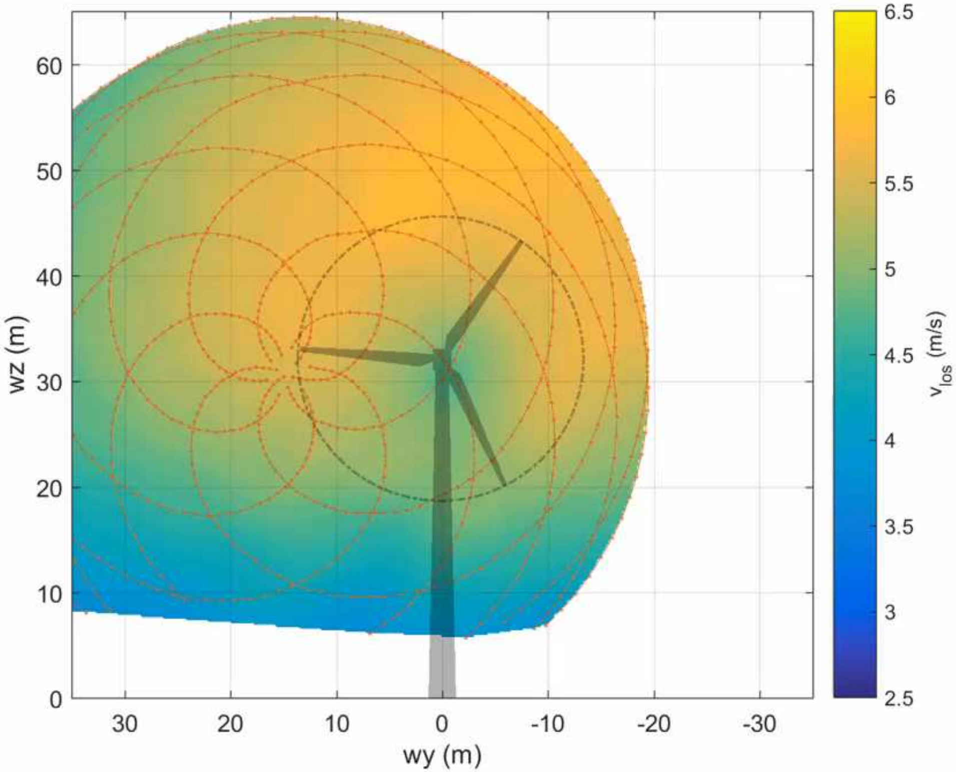


# Stable BL Video at 2.5D

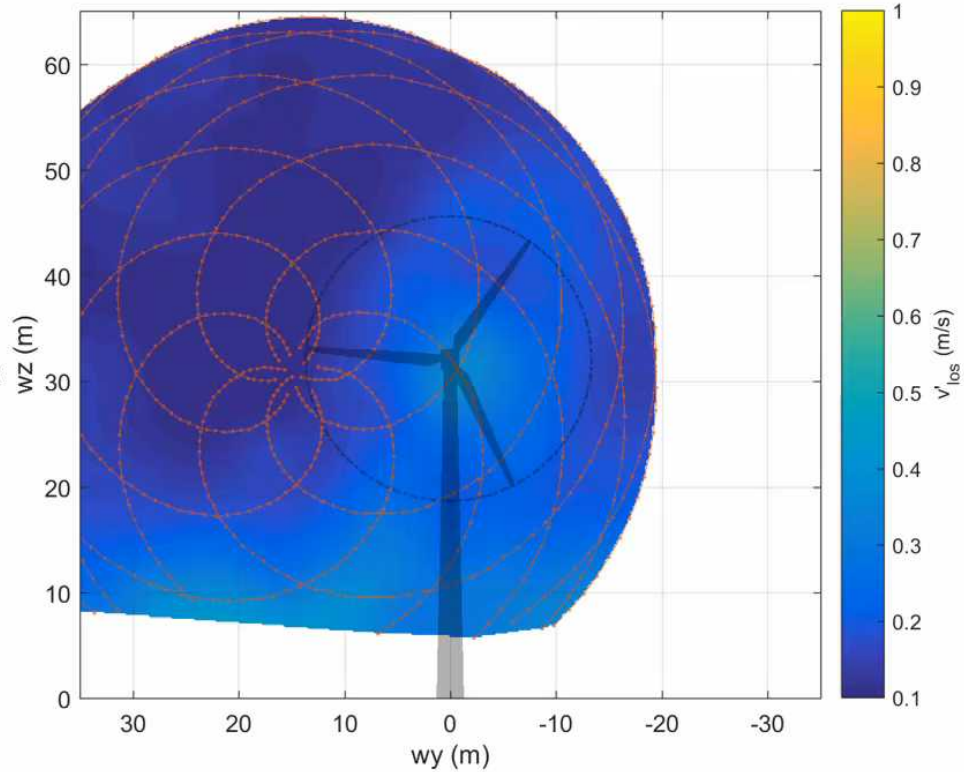
- Obukhov length $z/L$ = 2.3
- $\alpha$ = 0.25
- wind speed = 5.7 m/s
- TI = 0.04
- veer = 5.7°
- yaw offset = 7.43°
- yaw heading = 145.6 degN

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

$v_{los}$

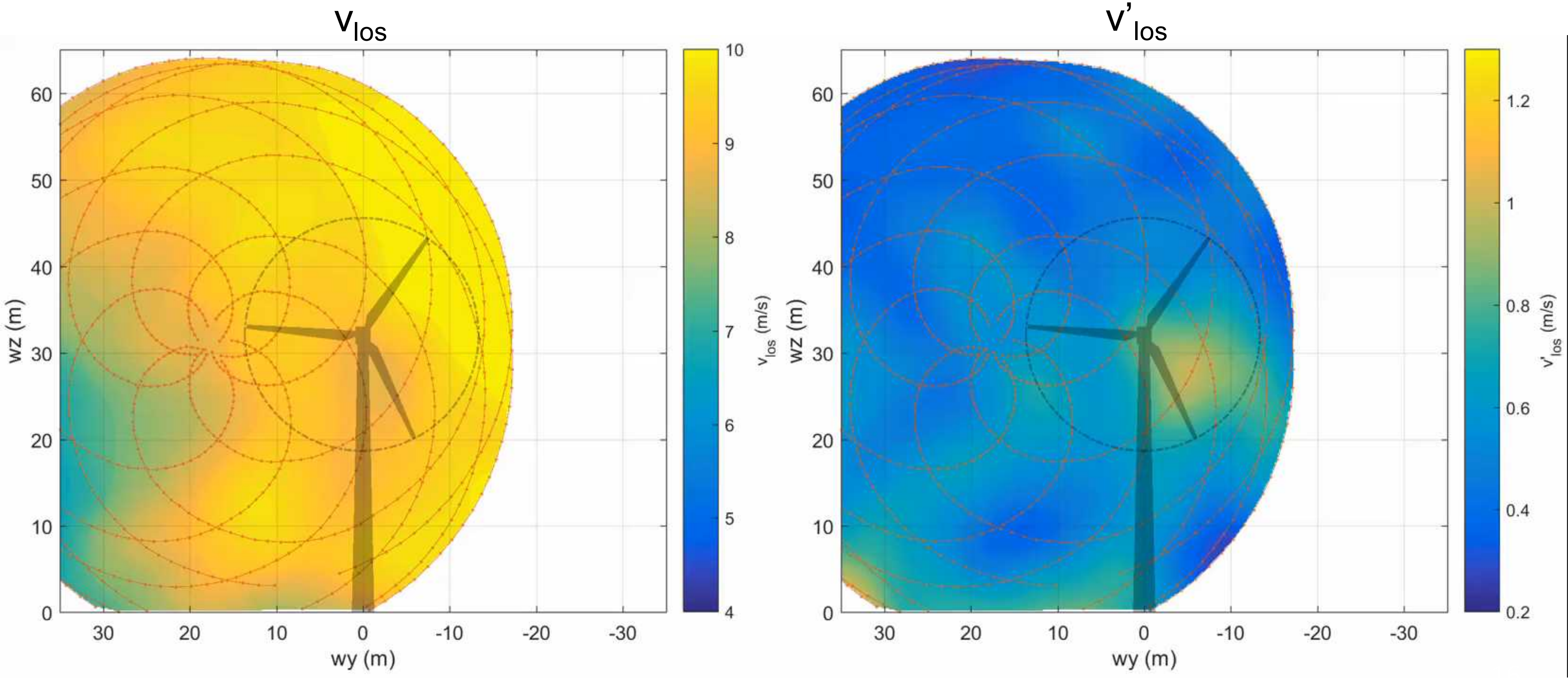



$V'_{los}$



# 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



# Conclusions

- The A2e Wake Steering Experiment is collecting inflow, turbine and wake data to validate models for controls and high-fidelity wake models
- The DTU SpinnerLidar was the primary wake measurement instrument due its capability to capture high fidelity velocity profiles at multiple ranges
- Wake data was characterized and compared under various inflow and turbine states to highlight the impact of atmospheric conditions and yaw offsets on the wake shape
- A new method to extract turbulence information was developed that could provide additional metrics for validating computational models
- First experimental data is now publically available through the Atmosphere to electrons (A2e) Data Archive Portal (DAP) (https://a2e.energy.gov/data)

# Thank You

therges@sandia.gov

https://a2e.energy.gov/data