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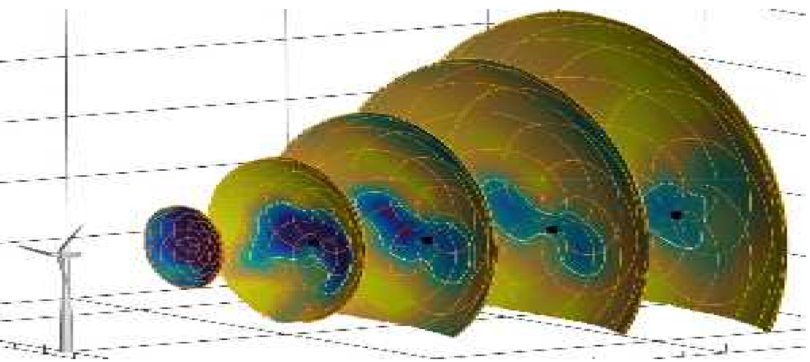

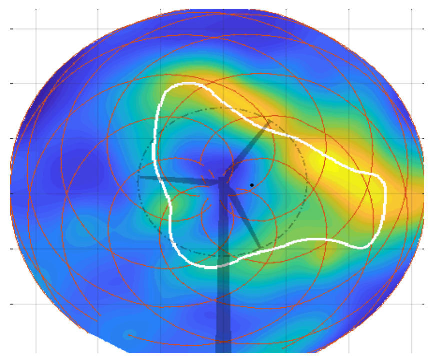

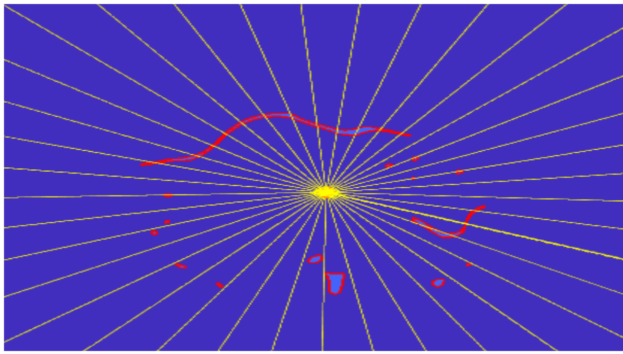

Wind Turbine Wake Definition and Identification Using Velocity Deficit and Turbulence Profile

Nadia Panossian, Thomas Herges, and David Maniaci

Sandia National Laboratories

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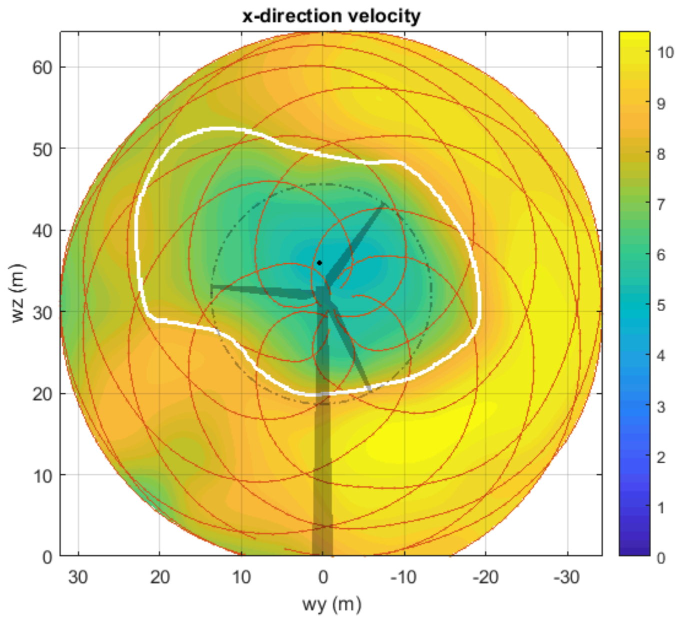
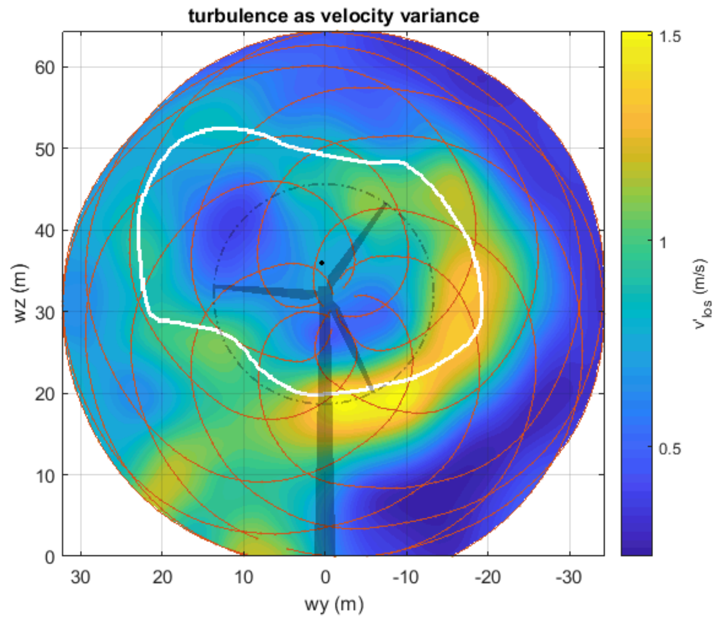
Agenda

- Definition of a Wake
- Comparison to velocity threshold techniques
- Method
- Results
- Conclusion

Wake Definition

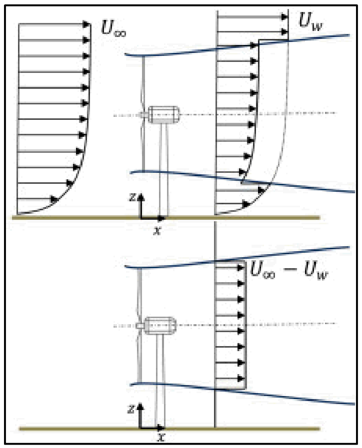
- A wake is the region of flow downstream of a turbine which has a streamwise velocity deficit and is internal to a ring of high turbulence
- Wake outline failure rate following this definition is lower than velocity threshold method for both stable and unstable cases



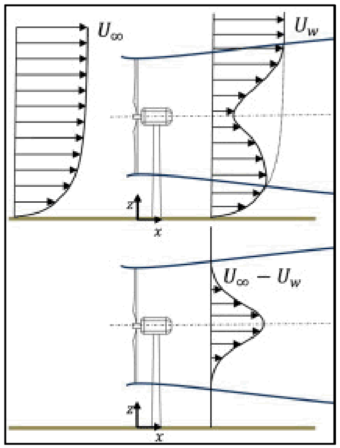


Alternative definitions

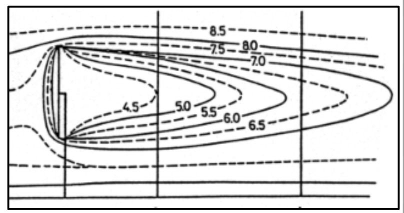
Top-Hat Fit



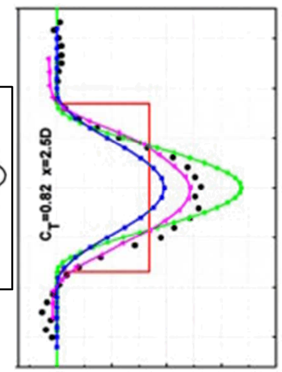
Gaussian Fit



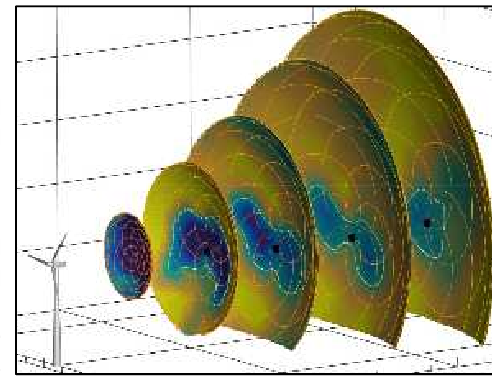
Parabolic Fit



Cosine Fit



Velocity Threshold



Top-Hat and Gaussian Fit images from reference 1
Parabolic Fit, Cosine Fit and Velocity threshold images from references 2-4 respectively

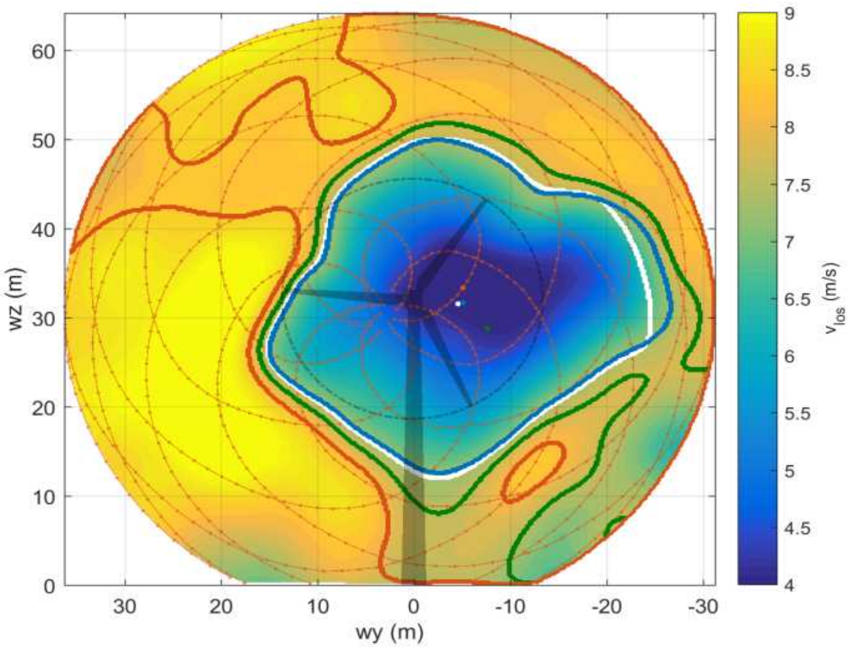
Advantages of Turbulence Ring Definition

- Non arbitrary boundary condition
- Useful for wake identification and tracking without user input
- Yields consistent results even in non-stable inflow or high yaw scenarios
- Allows for non circular wake shapes
- Accurate wake identification and non-arbitrary boundaries can be used to standardize wake tracking

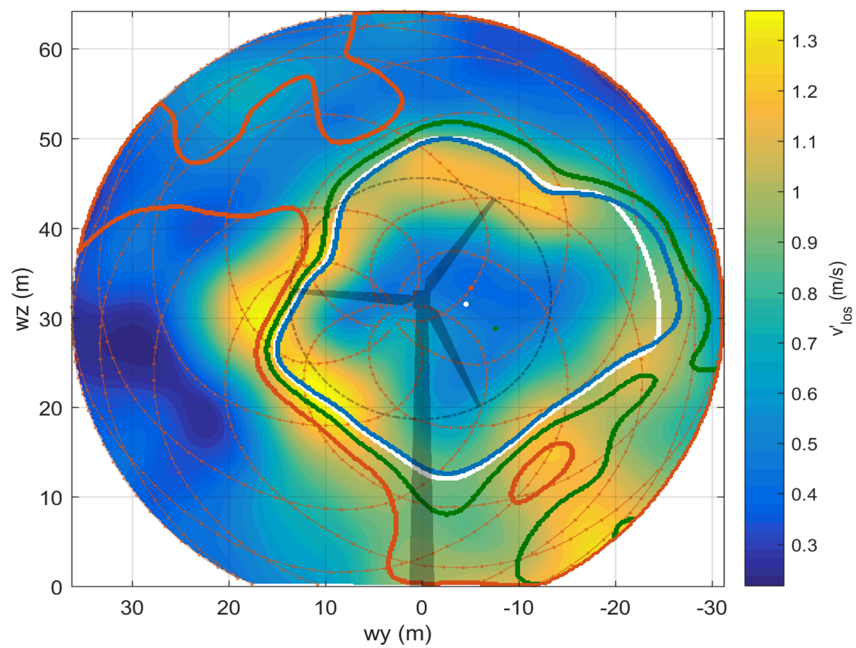
Preliminary Benchmarking

- Sample wake determination:
  - White: TI ring method
  - Blue: 1.0 m/s velocity threshold
  - Green: 0.5 m/s velocity threshold
  - Red: 0 m/s velocity threshold
- 1.0 m/s is close to TI ring method

Velocity Profile

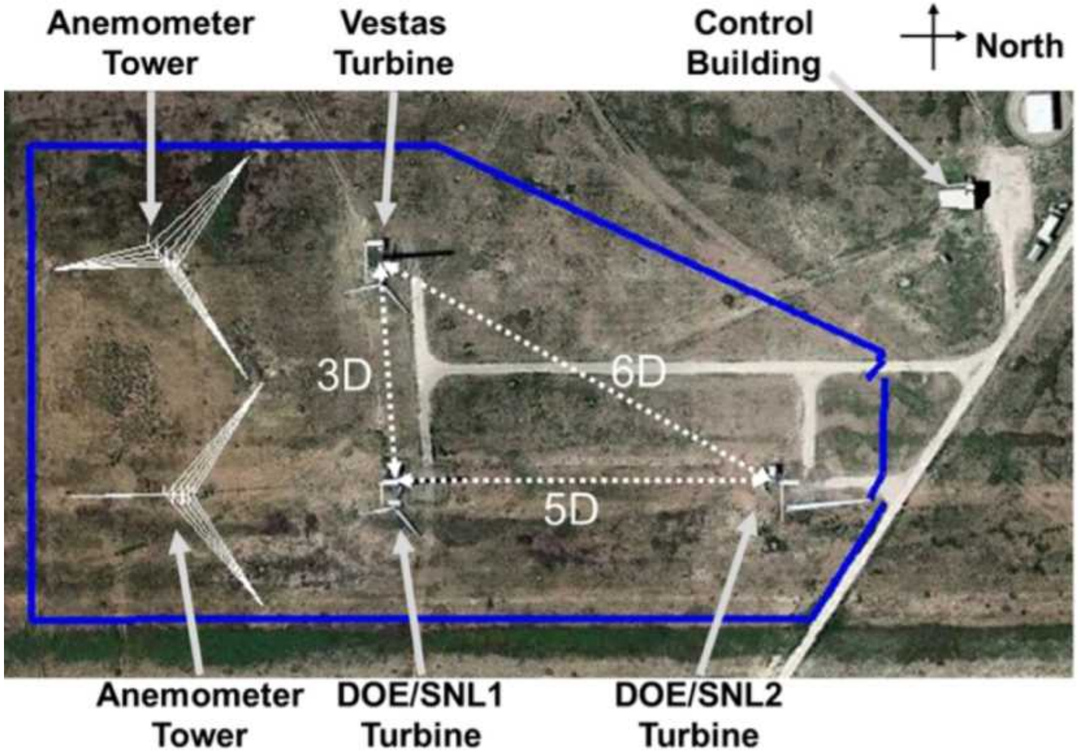


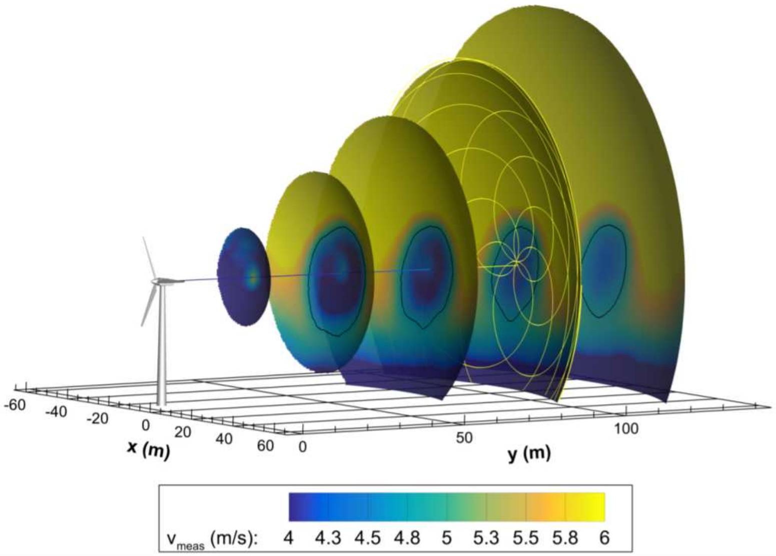
Turbulence Profile



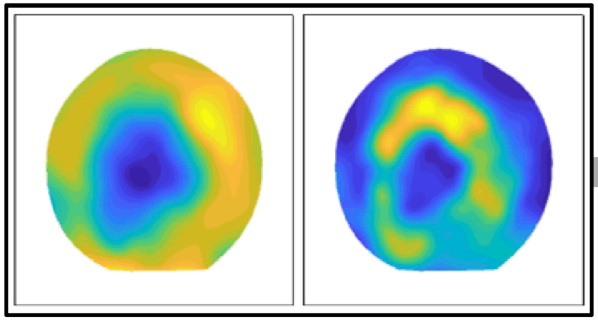
Data Collection

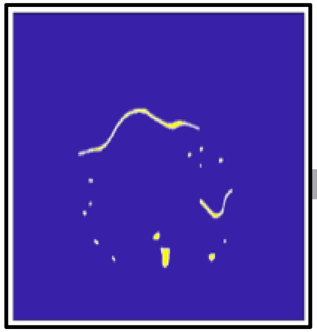
- Sandia Scaled Wind Farm Technology (SWiFT) Facility
- Denmark Technical University SpinnerLidar

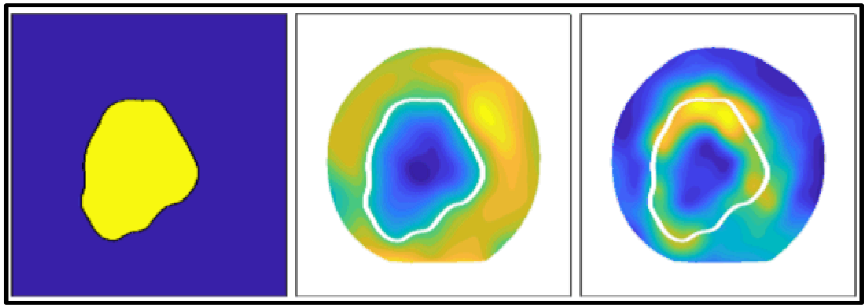




Method







Interpolate 2 second rosette scans to velocity (left) and variance (right) images

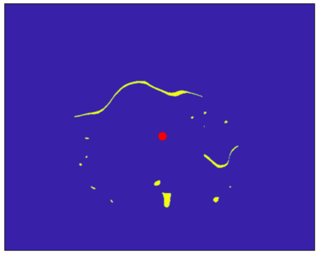
$$v_{meas} - v_{atmos} = v_{deficit}$$

$$turbulence \approx \mathrm{var}\left(v_{meas}\right)$$

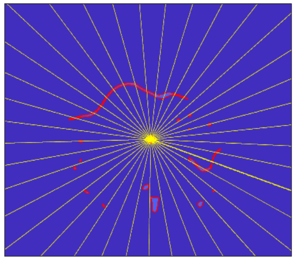
Find local maxima of turbulence intensity using the gradient zeros (yellow markings)
Fill in turbulence ring and close gaps

The wake is the region where $v_{deficit}$ is negative within the turbulence ring

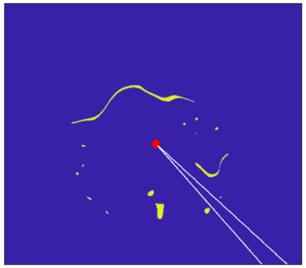
Method: filling in TI ring gaps



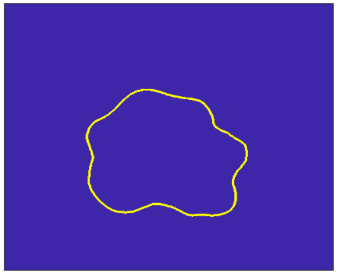
Use average y and z coordinates to find centroid of velocity deficit area



Convert turbulence local maxima coordinates into polar coordinates



Scan radially from the centroid and identify any angles without a turbulence maxima boundary



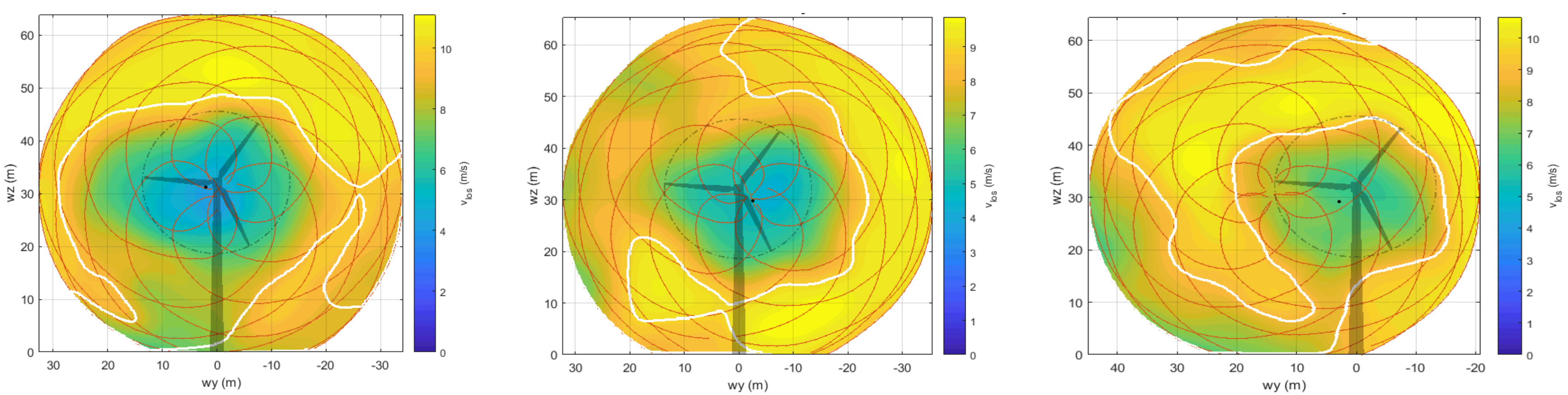
Fill in the empty angles with a linear interpolation between the radius of the boundary on either side of the gap

Benchmarking

- Percentage Failure Rate

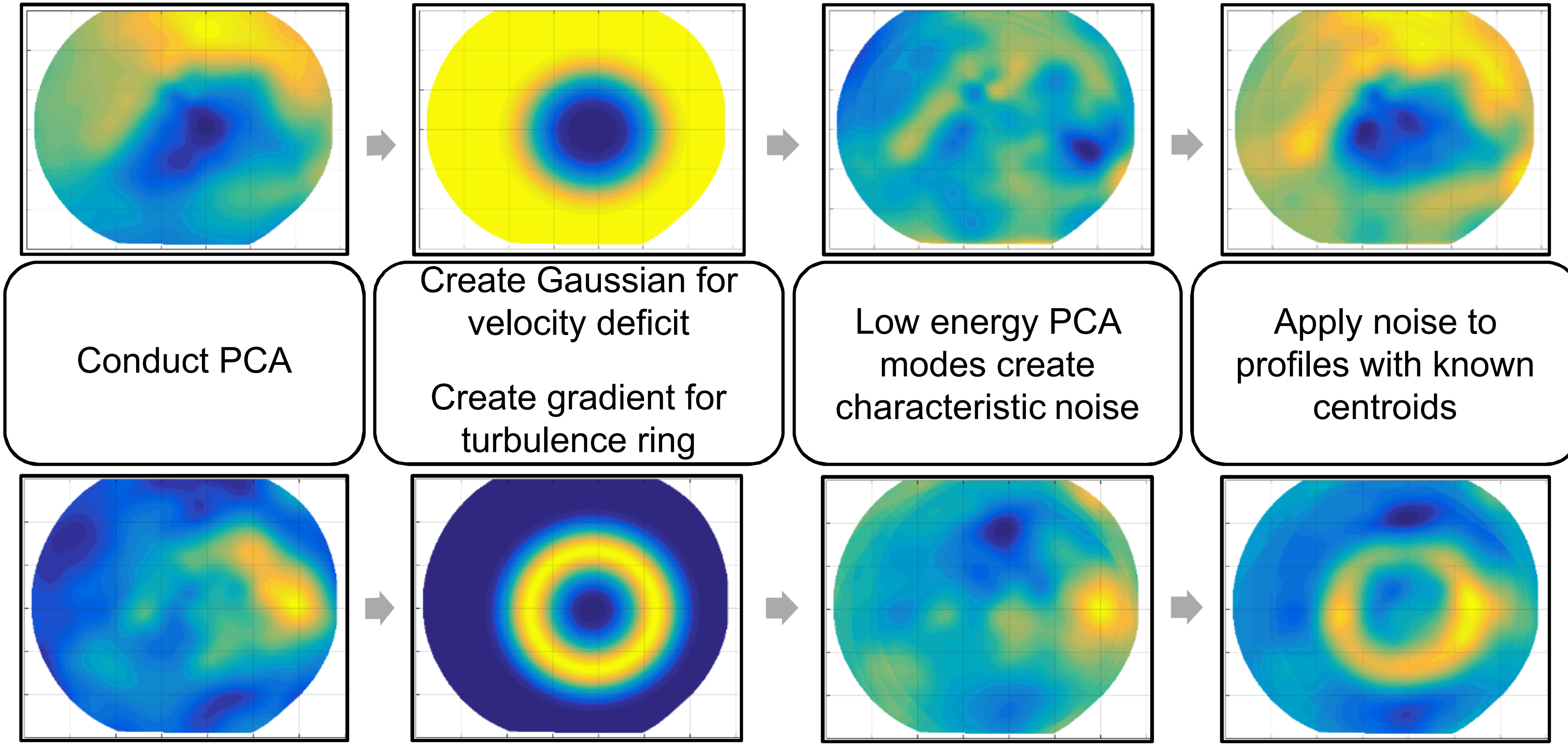
Wake Identification Method	Velocity Threshold of 0	Velocity Threshold of 0.5	Velocity Threshold of 1.0	Turbulence Intensity Ring
Stable Inflow Wake Outline Failure Rate (%)	49.2	24.4	13.0	9.84
Unstable Inflow Wake Outline Failure Rate (%)	92.9	53.5	26.5	9.86

- Examples of outline failures



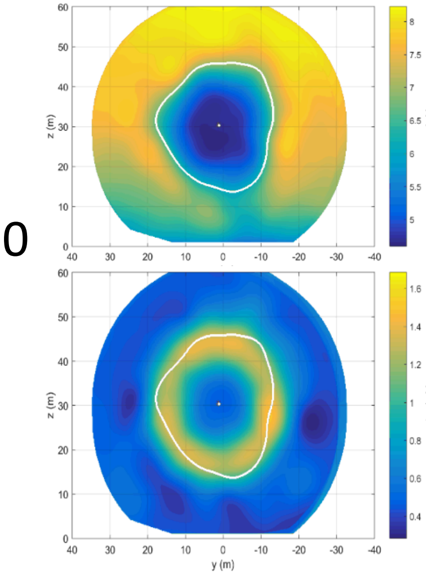
Method: Synthetic wake generation

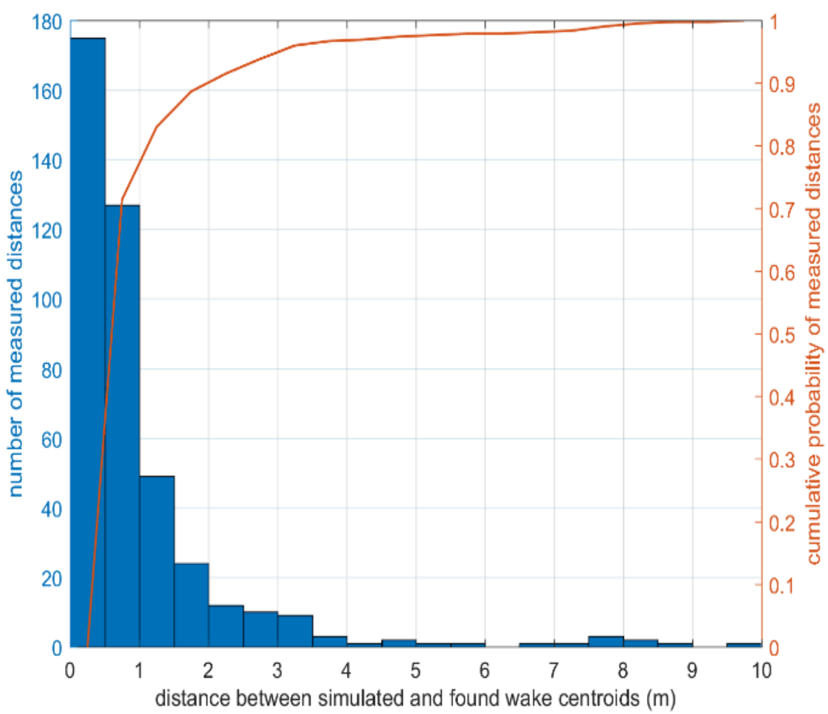
- TI method tested to compare specified turbulence ring and velocity deficit region to wake outline

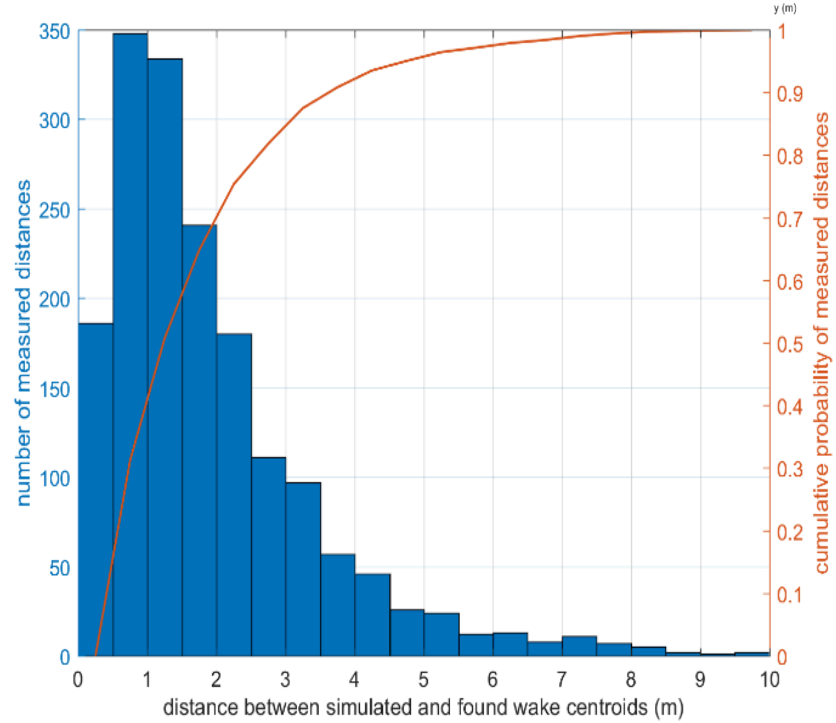


Results

- The wake identification algorithm’s centroid was within 3.0 meters of the simulated center of the wake for 95% of the 420 stable simulated wakes tested
- The wake identification algorithm’s centroid was within 5.0 meters of the simulated center of the wake for 95% of the 1700 unstable simulated wakes tested







Conclusion

- Turbulence intensity ring method outlines wakes as defined by a streamwise velocity deficit interior to a high turbulence ring
- Failure rate of turbulence intensity ring method is lower than velocity threshold techniques in both stable and unstable inflow cases

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PCA Method

- Principle Component Analysis: finds new axes with highest variance
- Eigen vectors and values of image matrix used to determine variance
- Find a mode → subtract variance along that axis → find next mode

$$P_{noisy} = \prod w_{PCA\ i} \lambda_i P$$