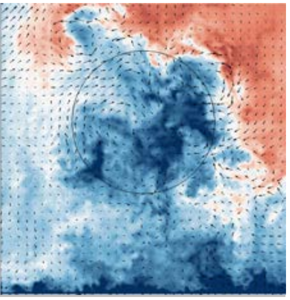
SAND2017-11752C

Wind Turbine Wake Research at the SWiFT Facility



International Conference on Future Technologies for Wind Energy
October 24-26, 2017; Boulder, Colorado, USA

David Maniaci, Thomas Herges, and Brian Naughton

Wind Energy Technologies Department
Sandia National Laboratories

Exceptional service in the national interest

SAND2017- PE

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Topics

- Overall R&D approach
- Sandia Wake Imaging System
- National Rotor Testbed
- Wake Steering Experiment
- Partnerships

V&V Framework

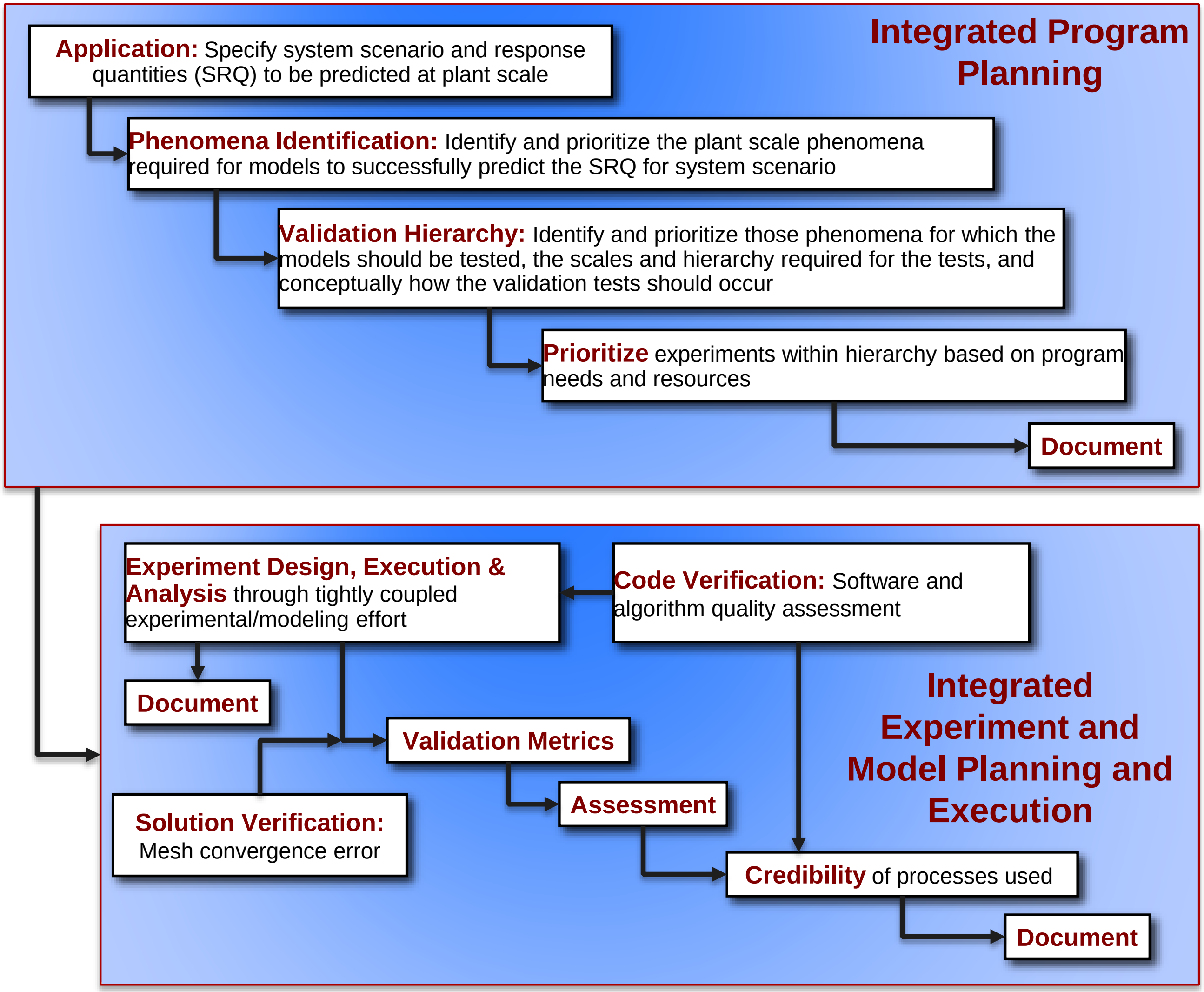
(2015 Hills, Maniaci, Naughton)

Integrated Planning

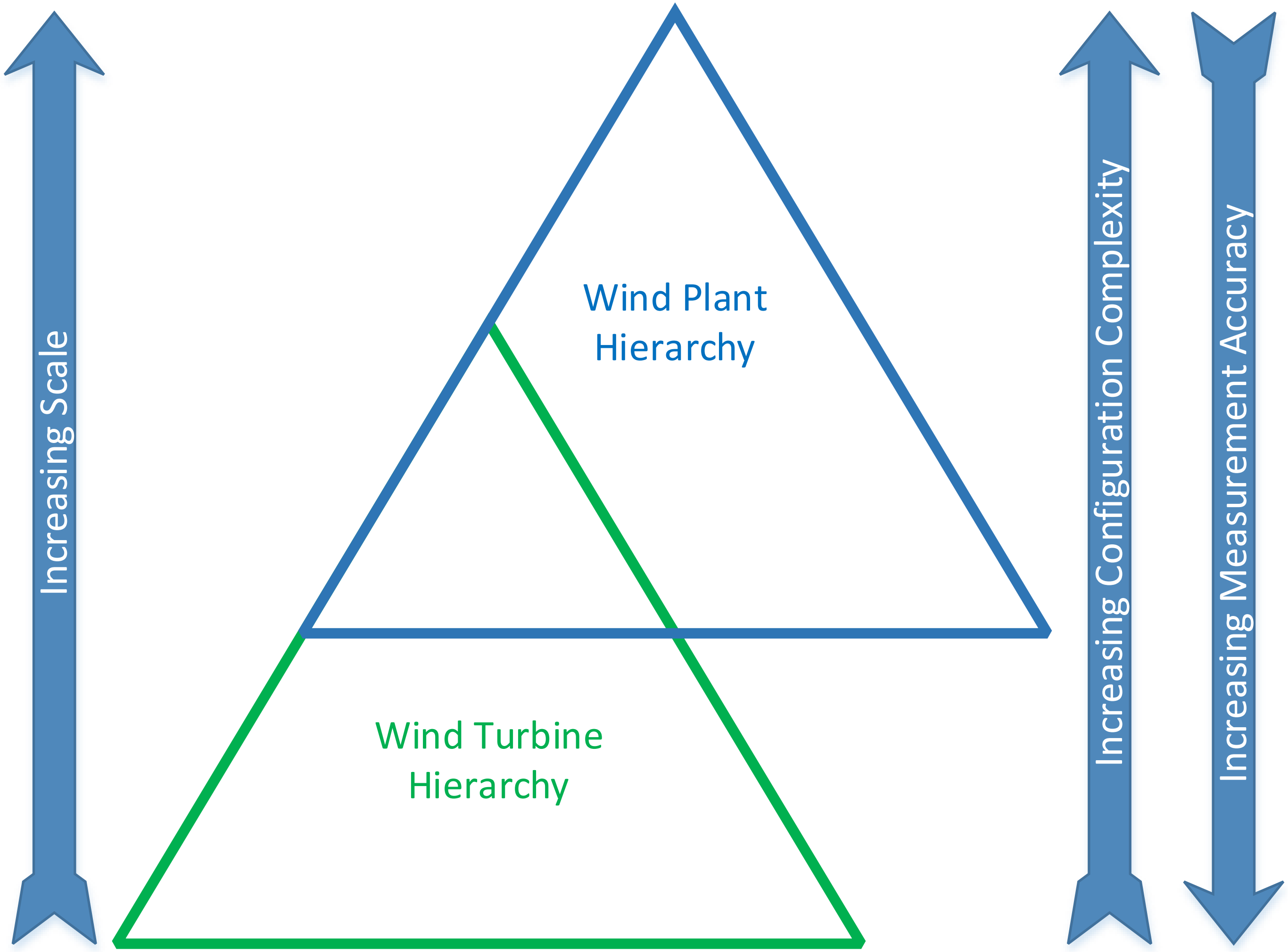
- Program leaders, modelers, software developers, experimentalists, V&V specialists

Validation Planning

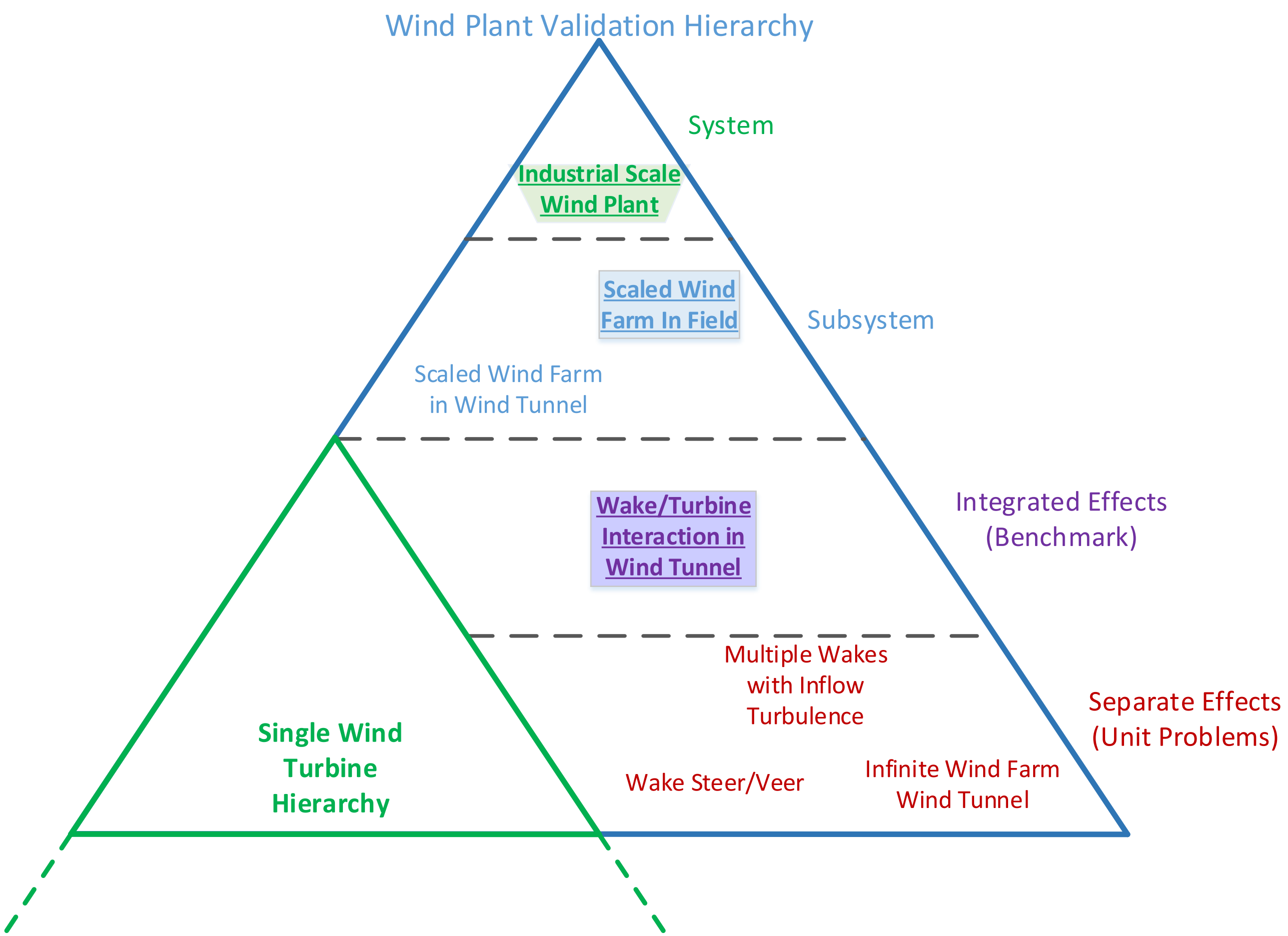
- Domain specific program leaders, modelers, experimentalists, V&V specialists, data acquisition specialists

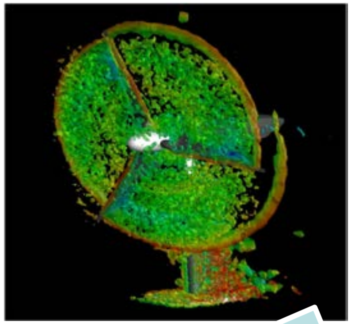


Validation Hierarchy



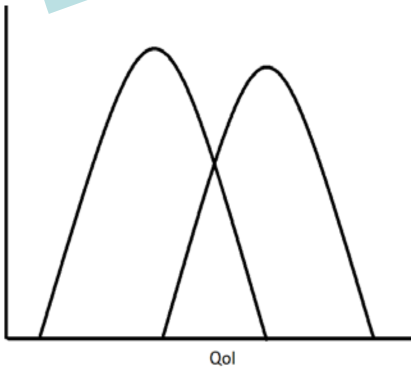
Wind Plant Validation Hierarchy

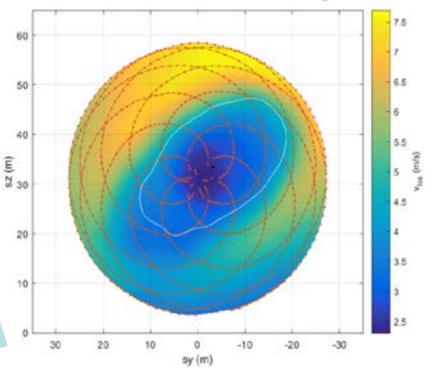




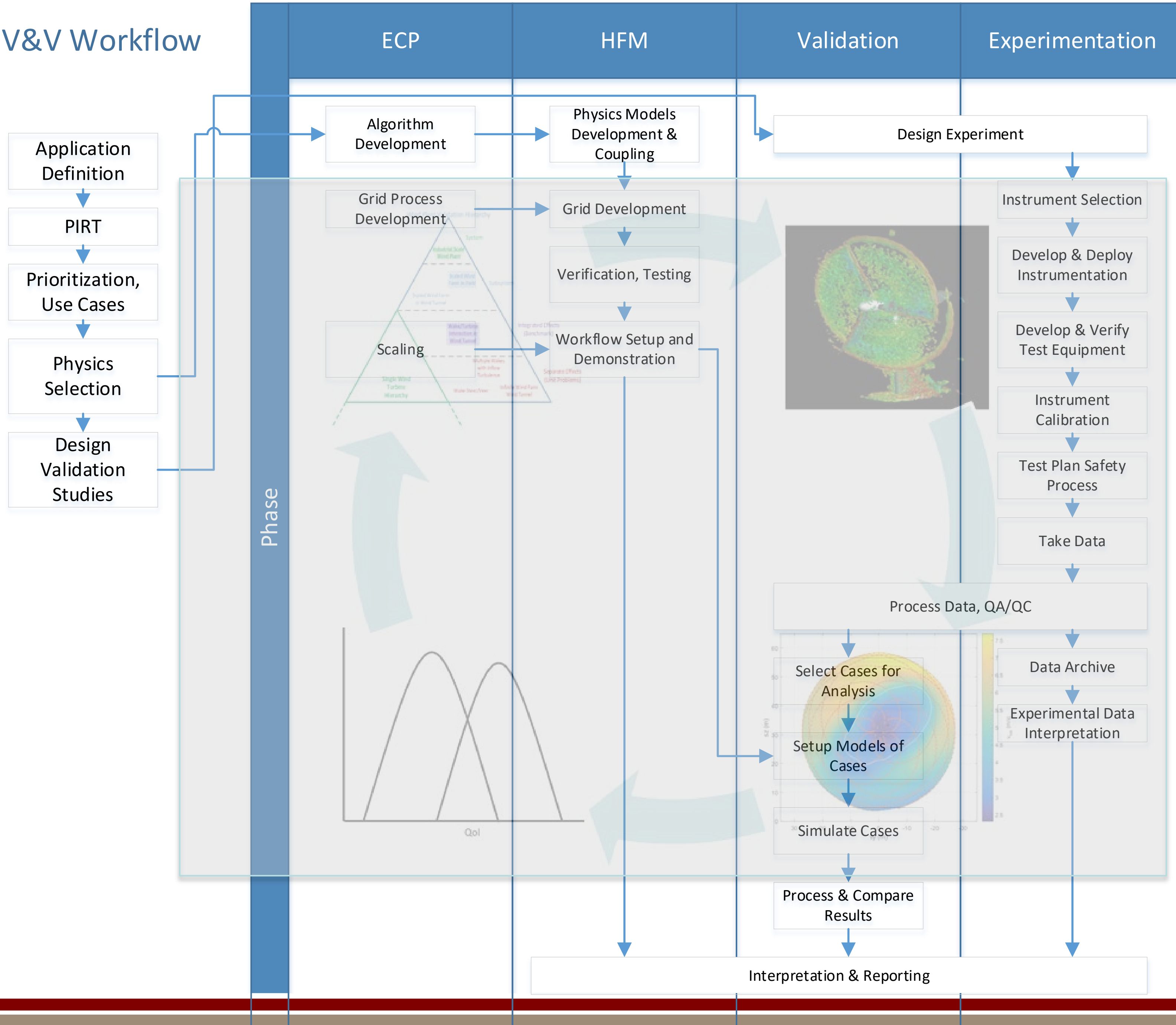
Virtuous Cycle

Validation
Model Development
Experimentation
Uncertainty Quantification





V&V Workflow

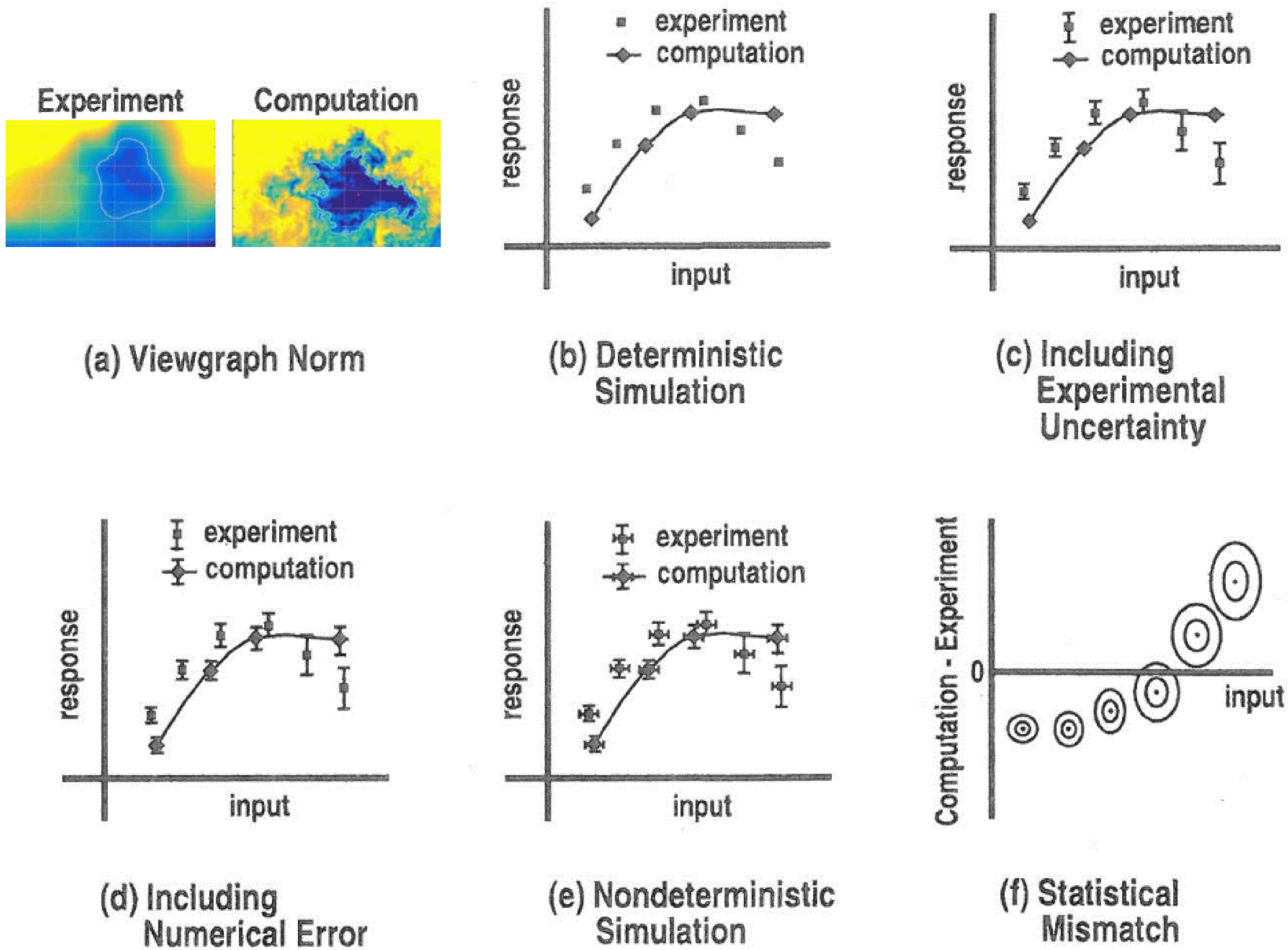


ECP
HFM
Validation
Experimentation
Phase
Application Definition
PIRT
Prioritization, Use Cases
Physics Selection
Design Validation Studies
Algorithm Development
Grid Process Development
Scaling
Physics Models Development & Coupling
Grid Development
Verification, Testing
Workflow Setup and Demonstration
Design Experiment
Instrument Selection
Develop & Deploy Instrumentation
Develop & Verify Test Equipment
Instrument Calibration
Test Plan Safety Process
Take Data
Process Data, QA/QC
Data Archive
Experimental Data Interpretation
Select Cases for Analysis
Setup Models of Cases
Simulate Cases
Process & Compare Results
Interpretation & Reporting
QoI

Uncertainty Quantification

Sandia National Laboratories

Levels of Precision



Modified from Oberkamf and Roy, 2012

SAND2014-15367M

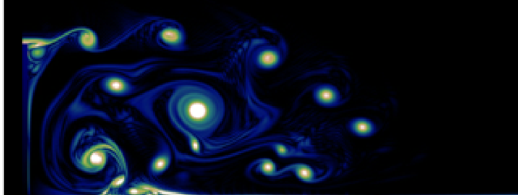
Nalu
low Mach

Nalu V1.0

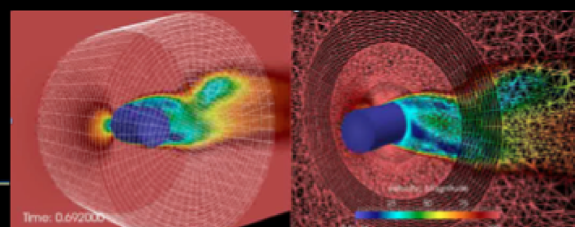
Open Source: BSD license has been granted (5/2014)

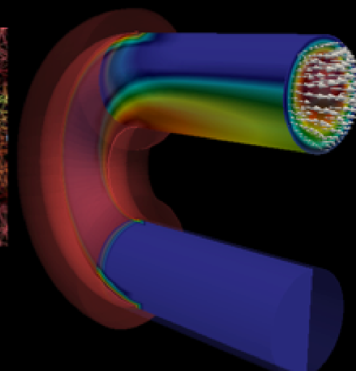
Weak scaling demonstrated to 524,000 core with 10 billion unstructured hex mesh

Generalized unstructured (CVFEM and EBVC supported)

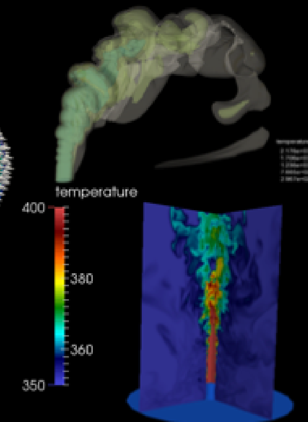


Backstep (vorticity)

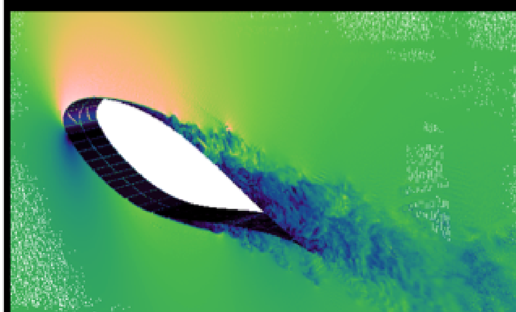




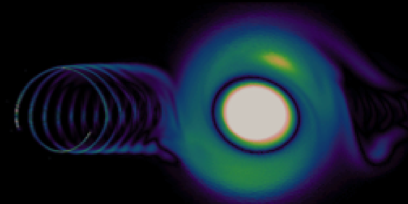
Multiphysics CHT



LES Jet
(cold and reacting)

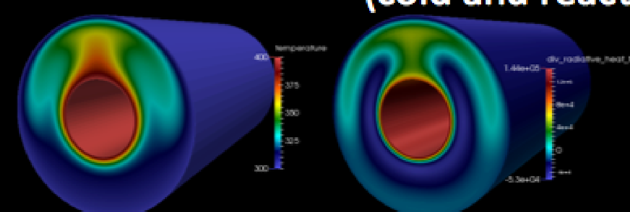


2D/3D periodic



Time: 60.000000

2D/3D sliding mesh



Multiphysics Fluids/PMR

U.S. DEPARTMENT OF ENERGY

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Trilinos

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Multi-level Uncertainty Quantification with LES

Sandia National Laboratories

Demonstrated an order of magnitude reduction in computational cost for a cylinder flow problem by coupling Nalu (CFD) to DAKOTA (UQ) and using a multilevel UQ approach.

Problem description

- (Laminar) Flow over a cylinder (Re=10-750)
- Input parameters: Density and Viscosity
- QoI: Coefficient of Drag
- 4 levels of mesh resolution

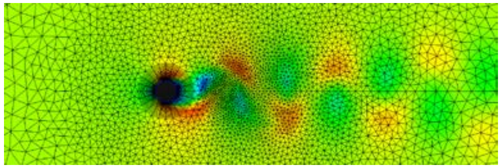
UQ approach

- Multilevel sampling-based estimator to accelerate convergence

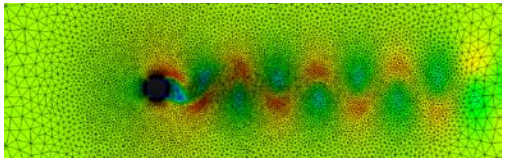
Impact

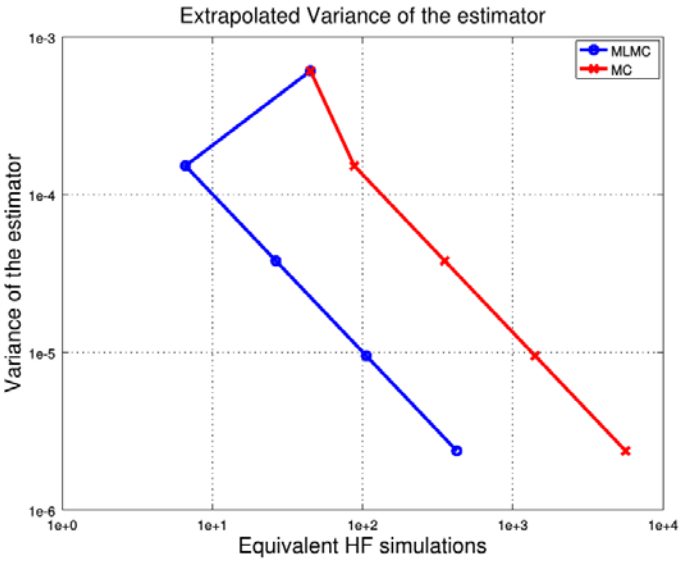
- Sampling methods are well suited for UQ problems with extremely high dimensionality (such as wind farm LES)
- Convergence is guaranteed for non smooth QoIs
- Demonstrated order of magnitude improvement in accuracy/cost of Multilevel estimators (MLMC) relative to conventional Monte Carlo (MC) for the cylinder problem

Coarse Mesh: 10 minute time to soln.



Medium Mesh: 4 hours time to soln.





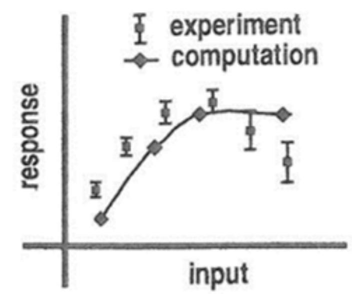
*G. Geraci, M. Ebeida, M. Eldred; SNL

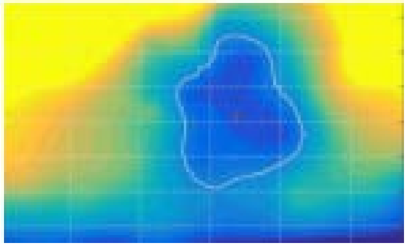
SWiFT Site Experimental Uncertainty Quantification

- Inflow Measurements
  - α
  - ρ
  - p
  - RH
  - T
  - TI (sonic)
  - U_∞ (sonic)
  - U (sonic)
  - V (sonic)
  - U_∞ (cup)
  - U_∞ (nacelle)
  - Vr (sonic)
  - WD (sonic)
  - WD (vane)

- Turbine Measurements
  - Aerodynamic power
  - Rotor speed
  - Aerodynamic torque
  - Rotor thrust
  - Individual blade root loads (instantaneous)
  - Individual blade loading profile (instantaneous)
  - Nacelle measured wind direction
  - Nacelle measured wind speed
  - Yaw heading
  - Yaw misalignment
  - Blade pitch
  - Rotor azimuth
  - Nacelle acceleration

- Wake Measurements
  - DTU Spinner Lidar
  - Wake identification and tracking
  - Turbulence estimators





Experimental Validation Campaigns

Sandia SWiFT

NWTC GE 1.5

NextEra Peetz

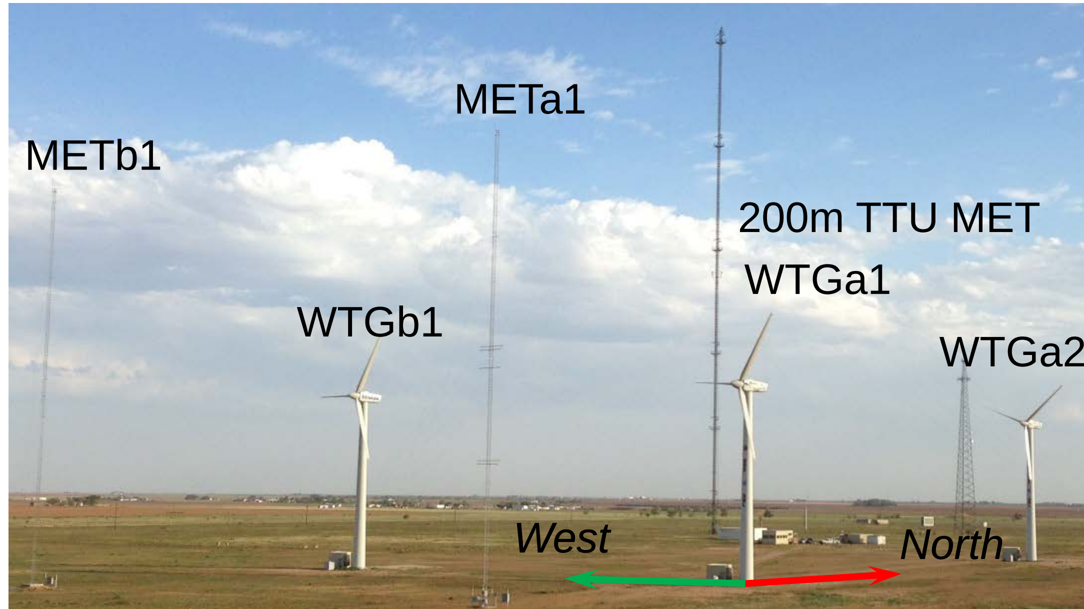
- Detailed measurement of wakes
- Wake steering demonstration
- Power and loads

Instrumentation for reduced uncertainty

- SWiFT facility overview
- Sandia Wake Imaging System
- National Rotor Testbed

SWiFT Site Layout and Capabilities

DOE/SNL Scaled Wind Farm Technology (SWiFT) facility hosted by Texas Tech University (TTU)

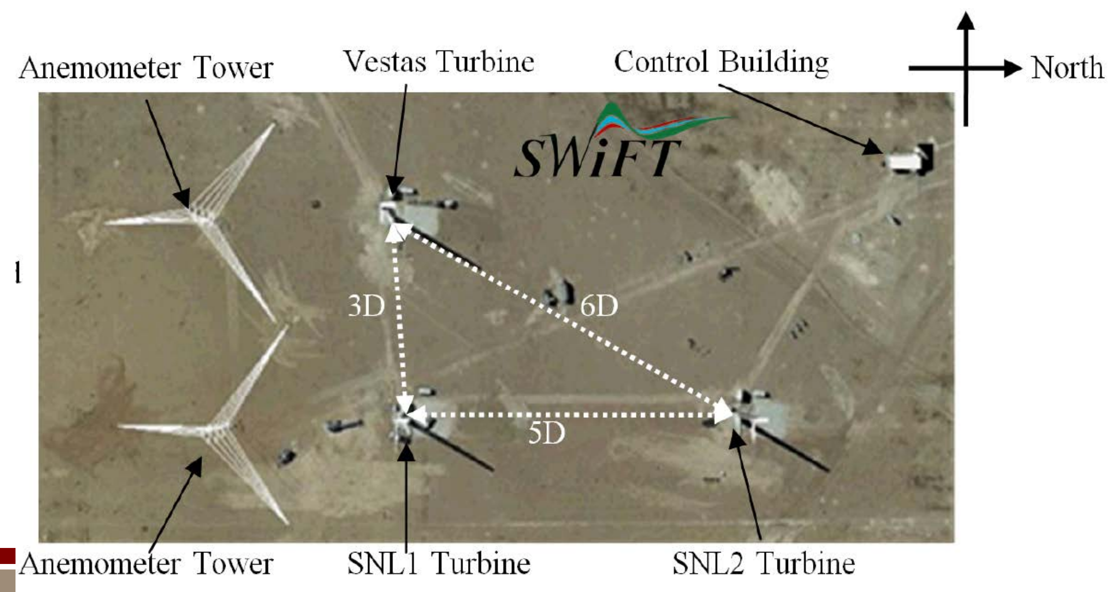


SWiFT exists to:

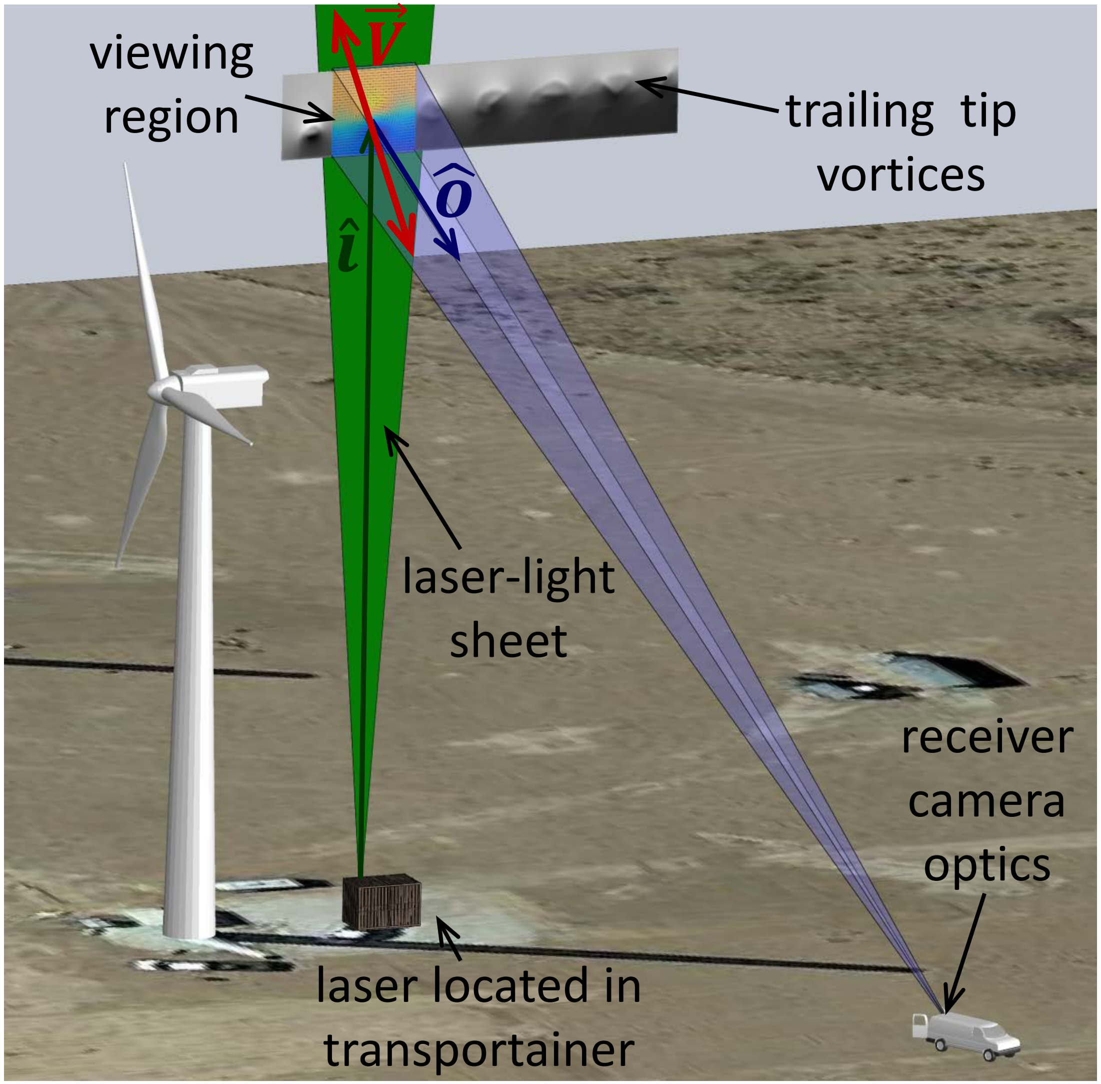
- Reduce turbine-turbine interaction and wind plant underperformance
- Public, open-source validation data
- Advance wind turbine technology

Facilities:

- Three variable-speed variable-pitch heavily-modified V27 wind turbines Two heavily instrumented inflow anemometer towers
- Site-wide time-synchronized data collection

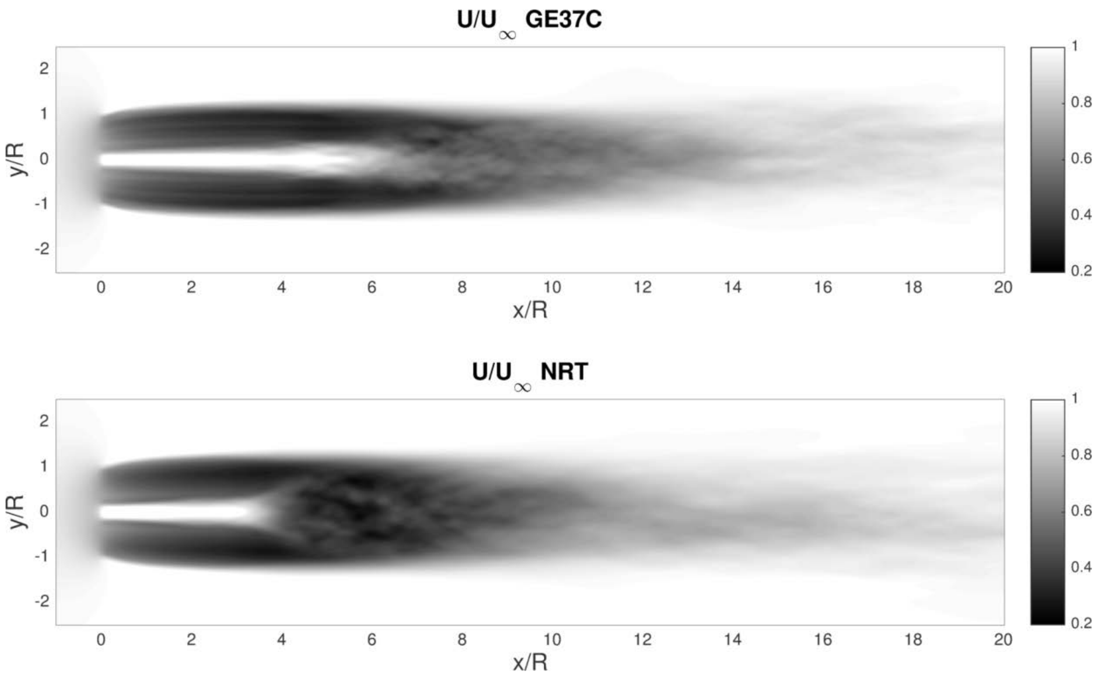


Sandia Wake Imaging System (SWIS)



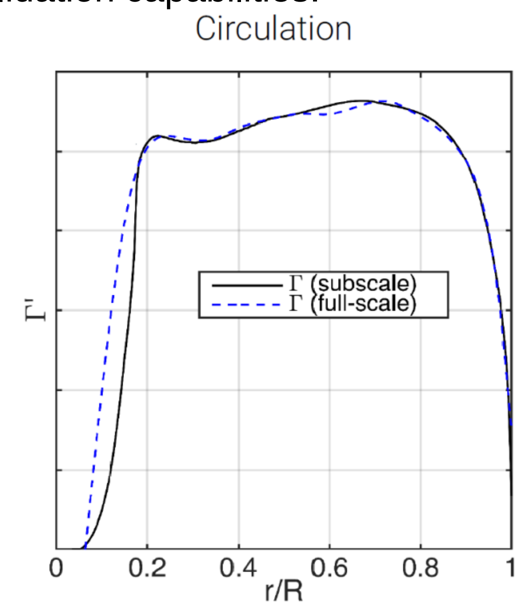
- Uses Doppler Global Velocimetry technique
- Position of laser and camera dictates the measured velocity component
- Measure velocity component along bisector angle between observation and incident vectors, $(\hat{\boldsymbol{o}} - \hat{\boldsymbol{\imath}})$
- Additional velocity components measured with additional observation angles

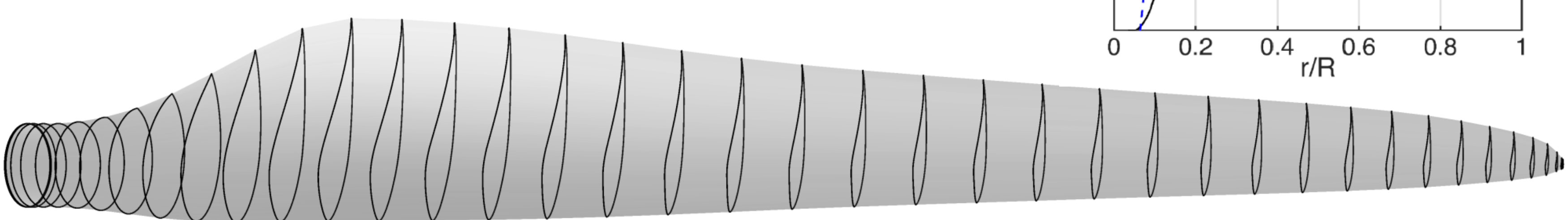
National Rotor Testbed Design



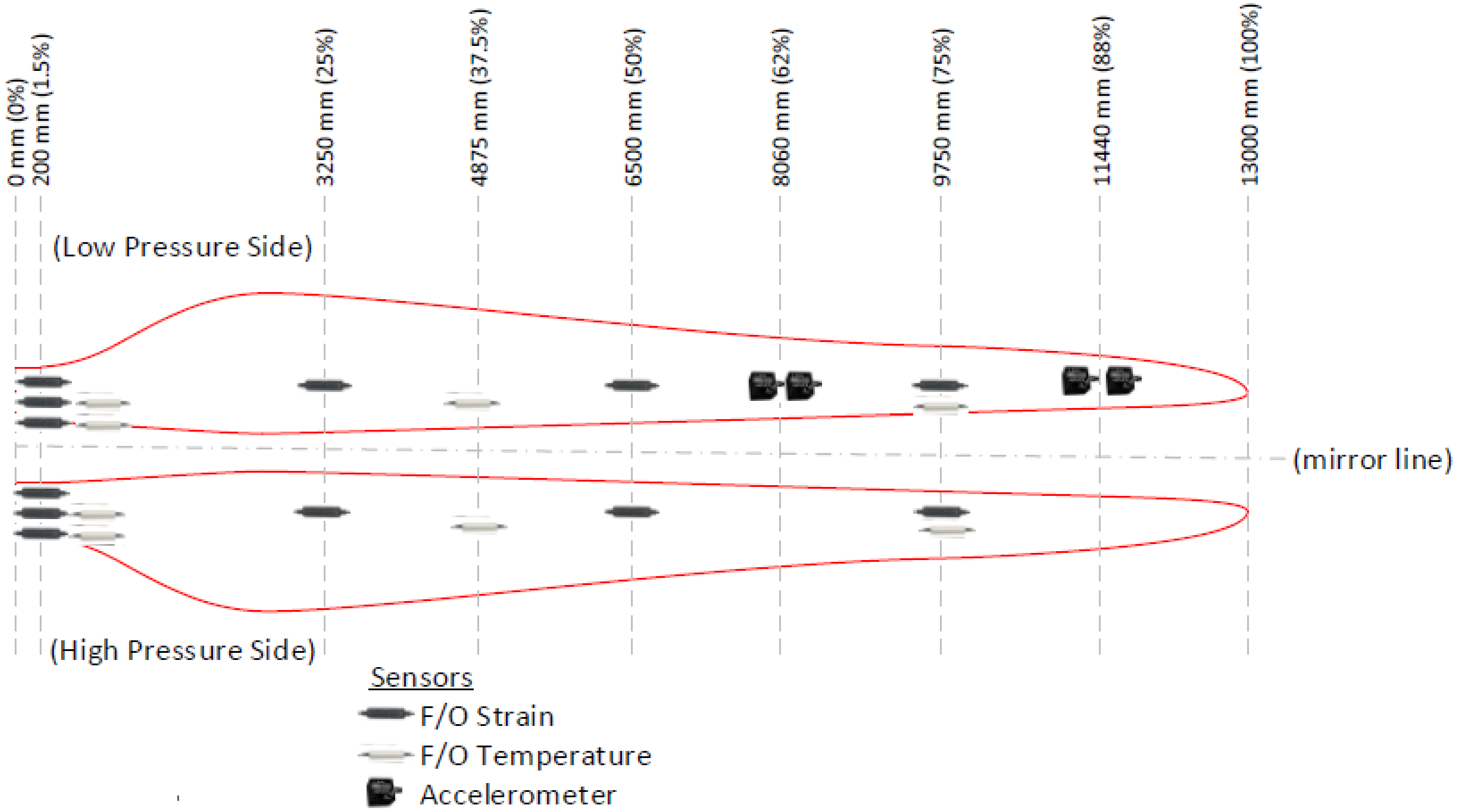
Free wake vortex simulation of the two rotors in neutral inflow.

Developed a unique design method using a variety of computational tools to functionally scale the circulation distribution of a utility-scale blade to a 14m blade to be manufactured and installed at the SWiFT facility. This enhances wake research and validation capabilities.





NRT Sensors



0 mm (0%)
200 mm (1.5%)
3250 mm (25%)
4875 mm (37.5%)
6500 mm (50%)
8060 mm (62%)
9750 mm (75%)
11440 mm (88%)
13000 mm (100%)
(Low Pressure Side)
(mirror line)
(High Pressure Side)
Sensors
F/O Strain
F/O Temperature
Accelerometer

NRT Manufacturing

NREL structural testing of NRT-00

Oak Ridge National Laboratory additive manufacturing of molds

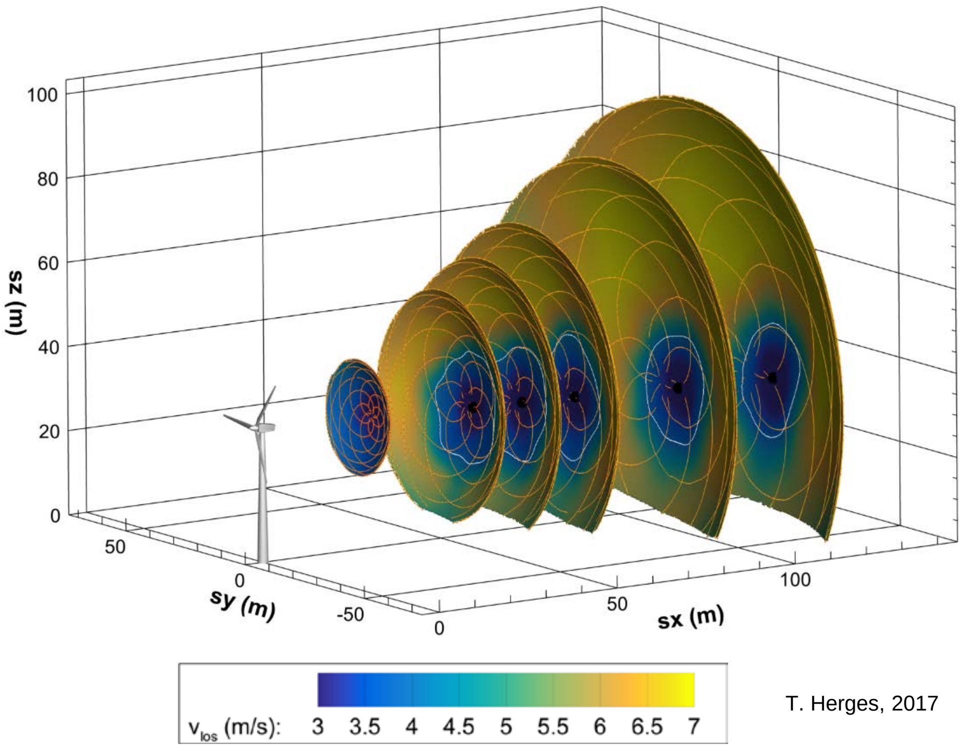
NRT Flight test

- NRT blades will be installed on WTGa1 in Oct. 2017
- The turbine will undergo commissioning tests related to the new rotor and controller for 1-2 months
- Testing will begin in October to verify the NRT design performance
- Later testing will be used to compare turbine and wake QoI to the GE 1.5 at NWTC

SWiFT Wake Measurements

DOE/SNL Scaled Wind Farm Technology (SWiFT) facility hosted by Texas Tech University (TTU)

Objective: Assess the ability of models to predict ***wake shape, strength, and deflection***.



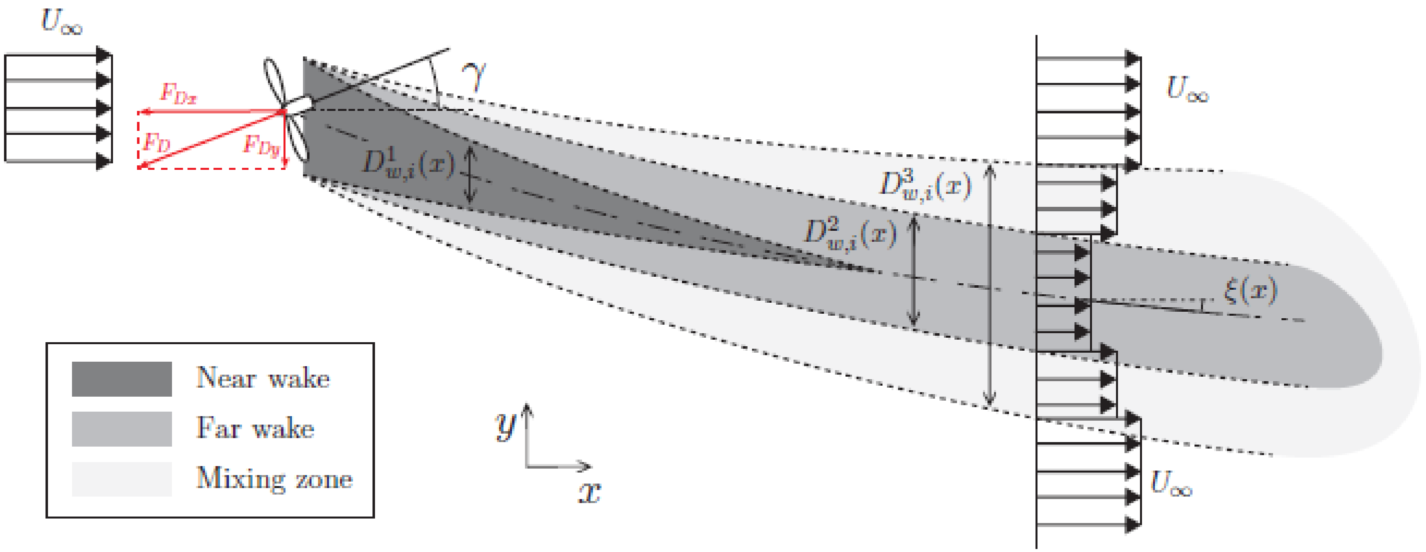
T. Herges, 2017

Wake Steering Experiment

- Goal
  - Demonstrate capability of wake steering control to improve total wind turbine array power production
- Structure
  - Phase I: Correlate inflow and turbine operating state to impact on wake characteristics
  - Phase 2: Compare power and loads for two turbines operating with and without yaw-based wake steering control

21

FLORIS Model

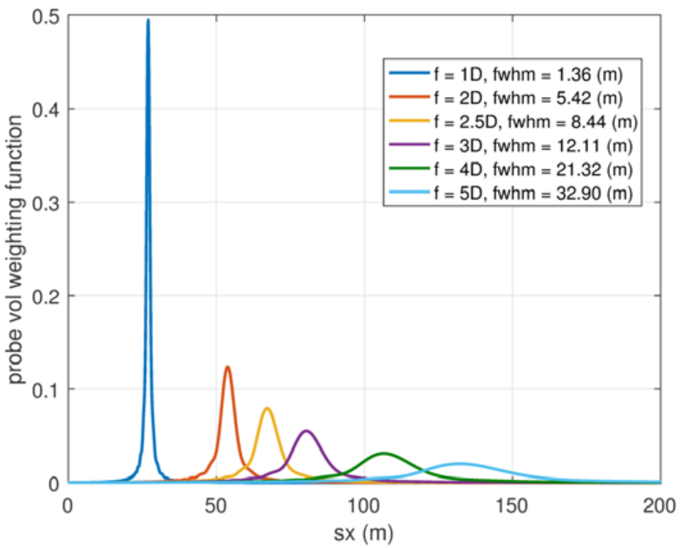


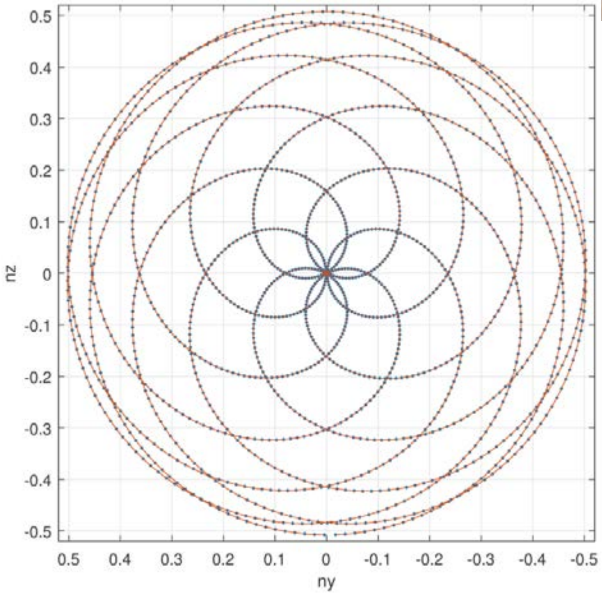
Key parameters (Guided experimental design):
- Relationship between yaw-offset and wake-steering
- Recovery to mean wind direction
- Velocity deficits, recovery and expansion of the wake zones

Atmospheric relationships (Functionality being added):
- Turbulence intensity
- Wind veer and shear
- Stability

Wake Measurements: DTU SpinnerLidar

- Uniquely capable of measuring the wind turbine wake at high temporal and spatial scales
- Capable of scanning 5D (135 m) downstream
- Configured to stream averaged Doppler spectra at a rate of 492 measurements per second

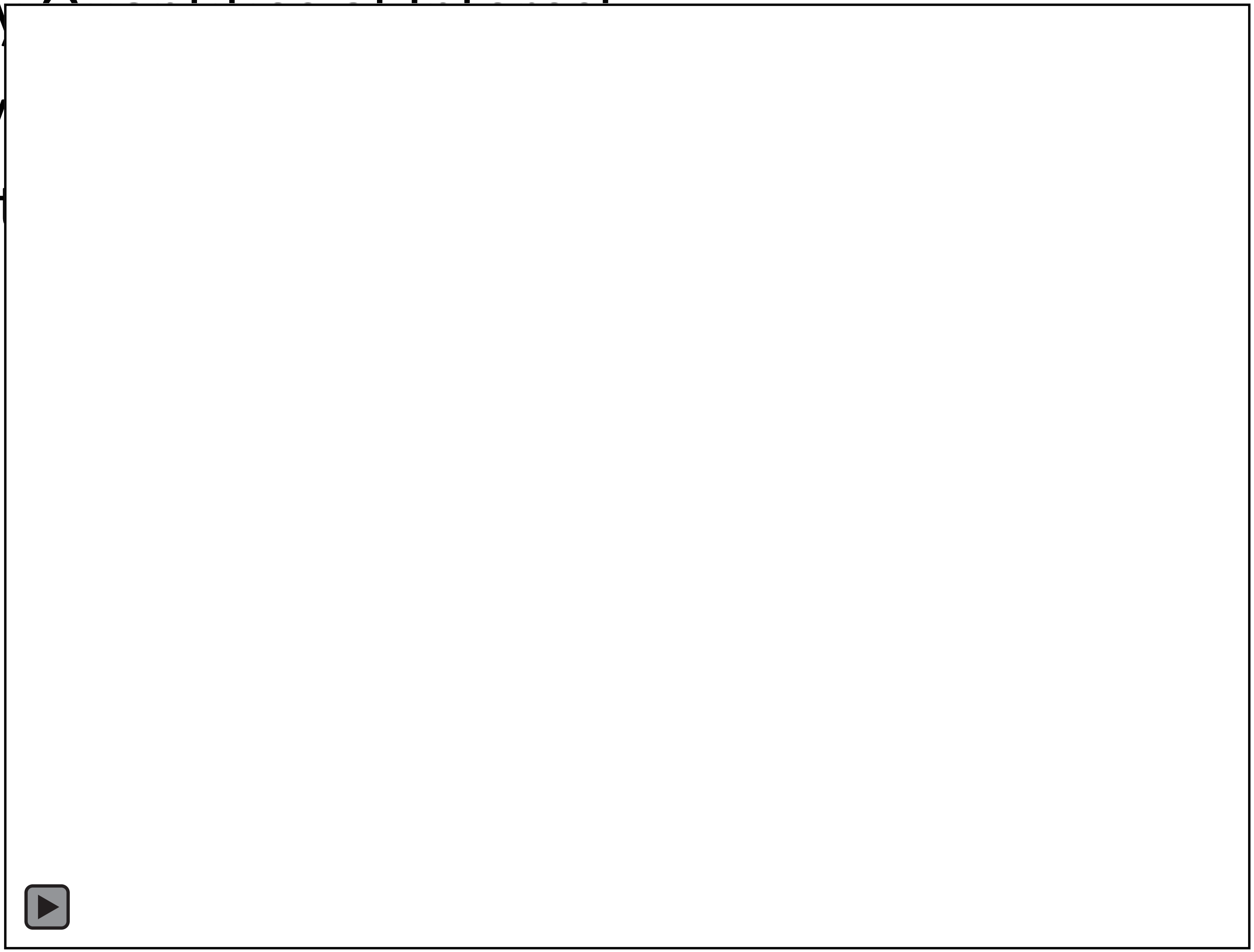




Herges, T. et. al. “Scanning Lidar Spatial Calibration and Alignment Method for Wind Turbine Wake Characterization,” AIAA 2017-0455.

Experiment Planning

- Identify
- Specify
- Simulat



Lidar Simulation and Selection

Sandia National Laboratories

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

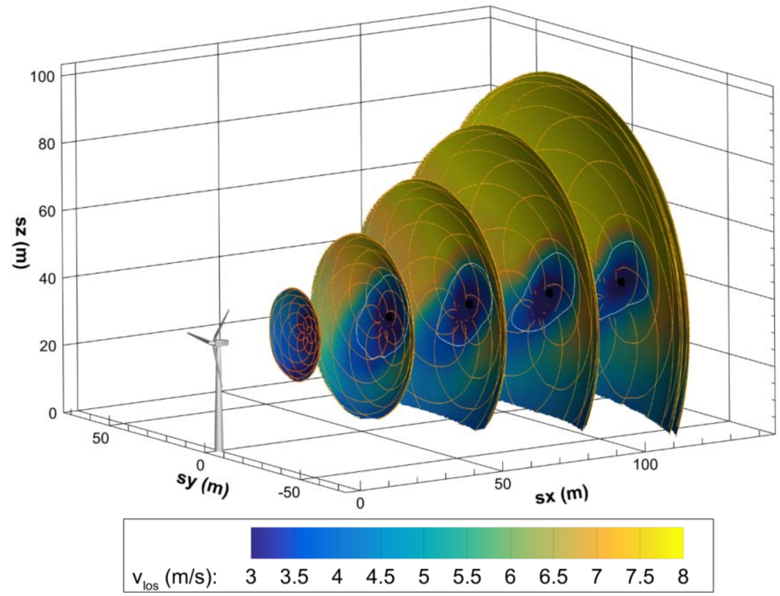
Measuring impact of turbine state

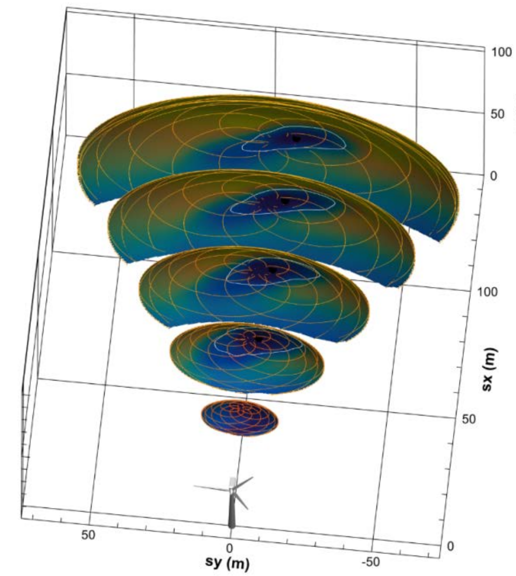
- Bulk Richardson = 0.7
- z/L = 3.1
- α = 0.3
- wind speed = 7.5 m/s
- TI = 0.08
- veer = 4.4°
- yaw offset = -7.5° to 15°
- Yaw heading = 159.5 degN

Measuring Impact of Inflow

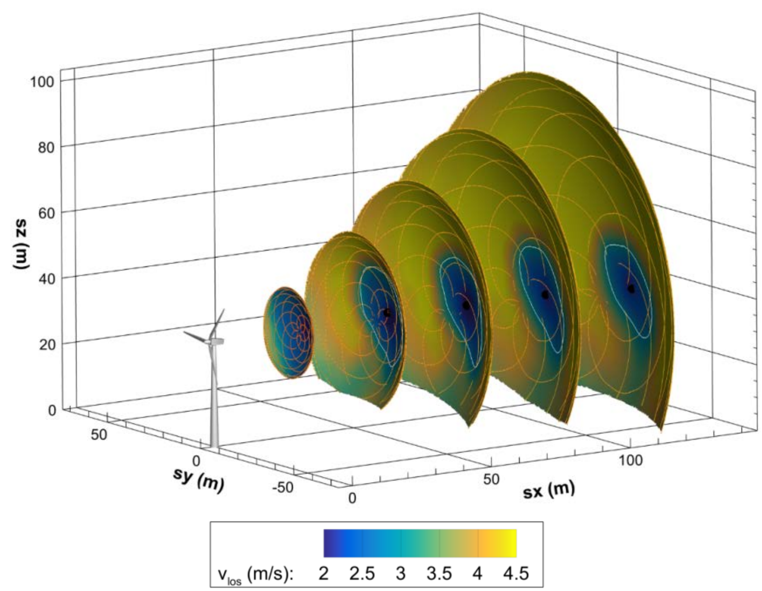
Sandia National Laboratories

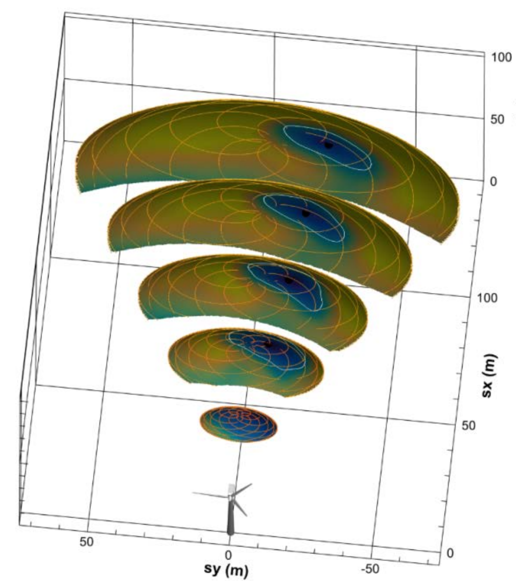
Stable ABL
Positive Veer





Stable ABL
Negative Veer





Wake Tracking

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

Wake Tracking with Higher Order QoIs

Lidar data viewed 2.5D (67.5m)

- Bulk Richardson = 0.78
- α = 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}

Initial Model Assessment

Measured and Simulated v_{los}

Initial Model Assessment

Measured and Simulated v'_{los}

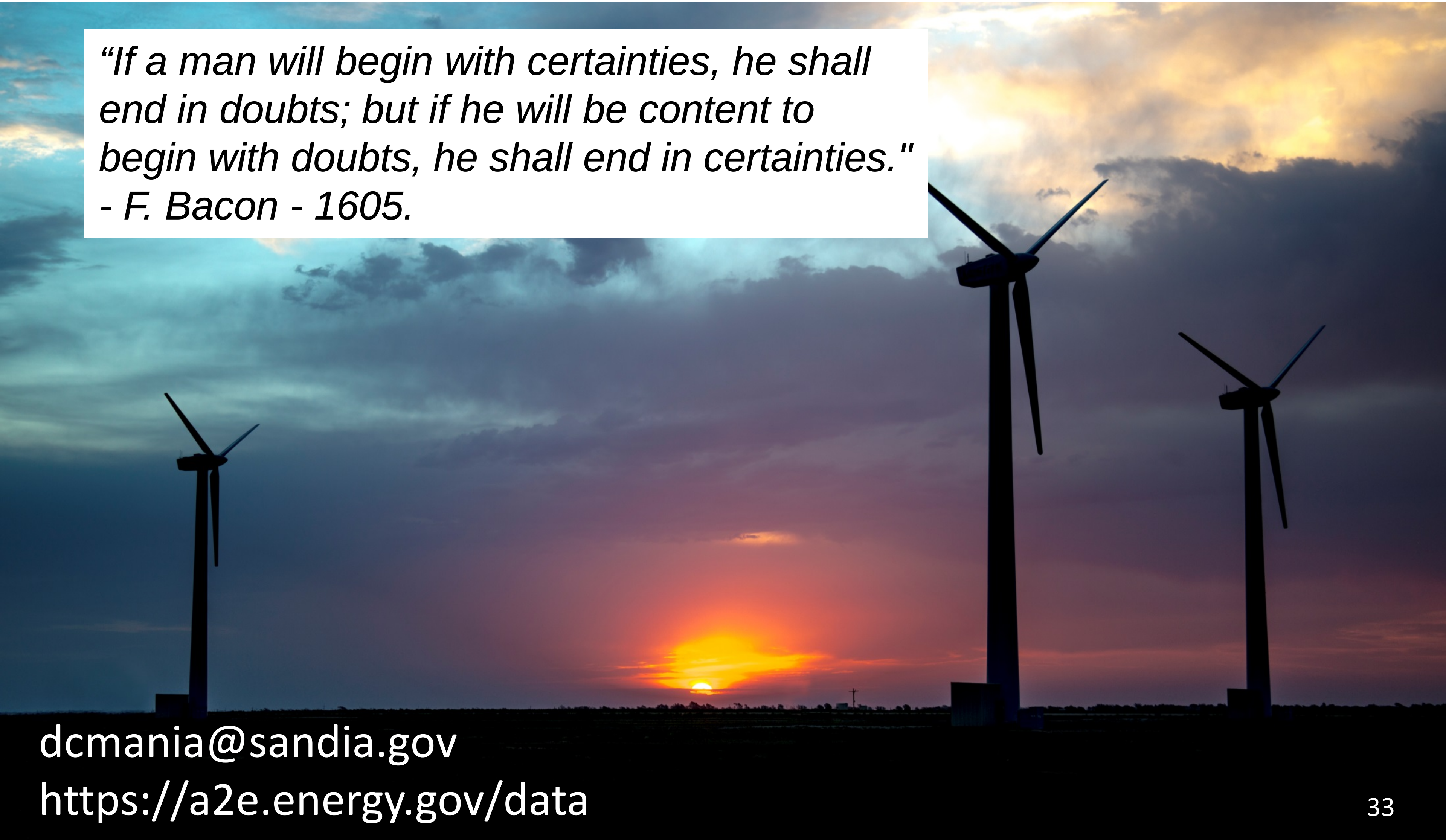
Collaboration

Vestas — Wind. It means the world to us.
LM Wind Power
GE Energy
Siemens — Siemens Wind Power
NIR Group — Renewable Energy Solutions
Micron Optics
Pentalum
Windar Photonics
ABB — Power and productivity for a better world
SkySpecs
National Instruments
BIRD — Israel-U.S. Binational Industrial Research and Development Foundation
U.S. Department of Energy — Energy Efficiency & Renewable Energy — Advanced Manufacturing Office
Texas Tech University
DTU — Technical University of Denmark
UT Dallas
NREL
Small Business Vouchers Pilot — U.S. Department of Energy

A2e Data Archive and Portal https://a2e.energy.gov/about/dap
Public validation data including experimental and simulation results.

Nalu:https://github.com/spdomin/Nalu

Thank you



“If a man will begin with certainties, he shall end in doubts; but if he will be content to begin with doubts, he shall end in certainties." - F. Bacon - 1605.

dcmania@sandia.gov
https://a2e.energy.gov/data

SAND2017- PE

A2e HFM and ExaWind Overview and Objectives

Sandia National Laboratories

Parallel HFM funding and development efforts:

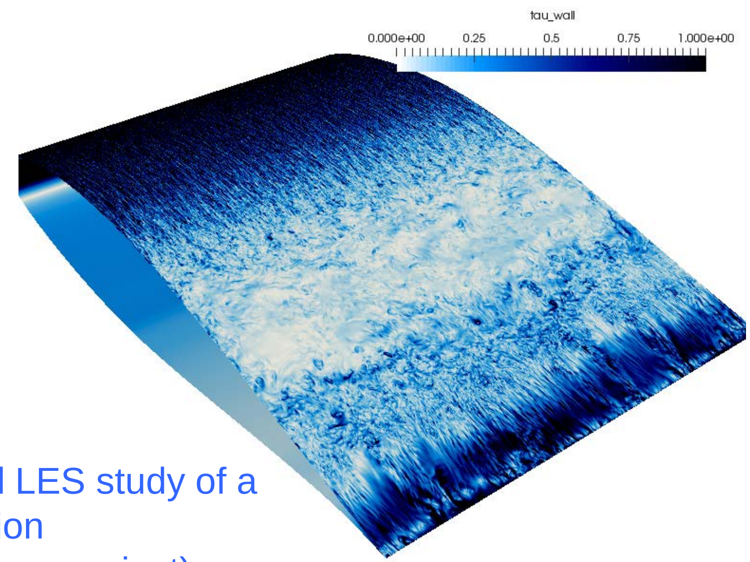
A2e HFM: Create a predictive modeling capability, with multiple levels of fidelity, that is backed by rigorous V&V (with UQ).

ExaWind: Ensure that the HFM capability is highly scalable on today's peta-scale HPC systems, and tomorrow's exascale systems

> ***10-year ExaWind Challenge Problem:*** Predictive simulation of a wind plant composed of O(100) multi-MW wind turbines sited within a 10 km×10 km area with complex terrain.

Long-term HFM research activities

- Use the code to understand the complicated wind farm flow physics, including turbine-wake interactions, multiple-wake interactions, atmospheric turbulence, and flow over complex terrain
- Ensure that the code is correctly implemented and predictive of wind plant physics through a formal verification and validation program
- Enable a next generation of lower fidelity tools that will be used for decision making and analysis in the design process



Nalu wall-resolved LES study of a turbine blade section
(Trinity Open Science project)

Nalu ABL simulation