ATMOSPHERE TO ELECTRONS

U.S. DEPARTMENT OF ENERGY

Verification, Validation, and Uncertainty Quantification (V&V/UQ)

FY-19 A2e PI & AOP Kickoff Meeting
RASEI, CU Boulder, SEEC Complex
November 6th, 2018

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V&V/UQ Background and Context

- Transform today's wind plant operating environment through advanced physics-based modeling, analysis, and simulation capabilities
- Approach
  - Development of high fidelity models
  - Collection of existing data and generation of new data through an experimental measurement campaign
  - Strategic linking of these efforts through a Validation Focused Program

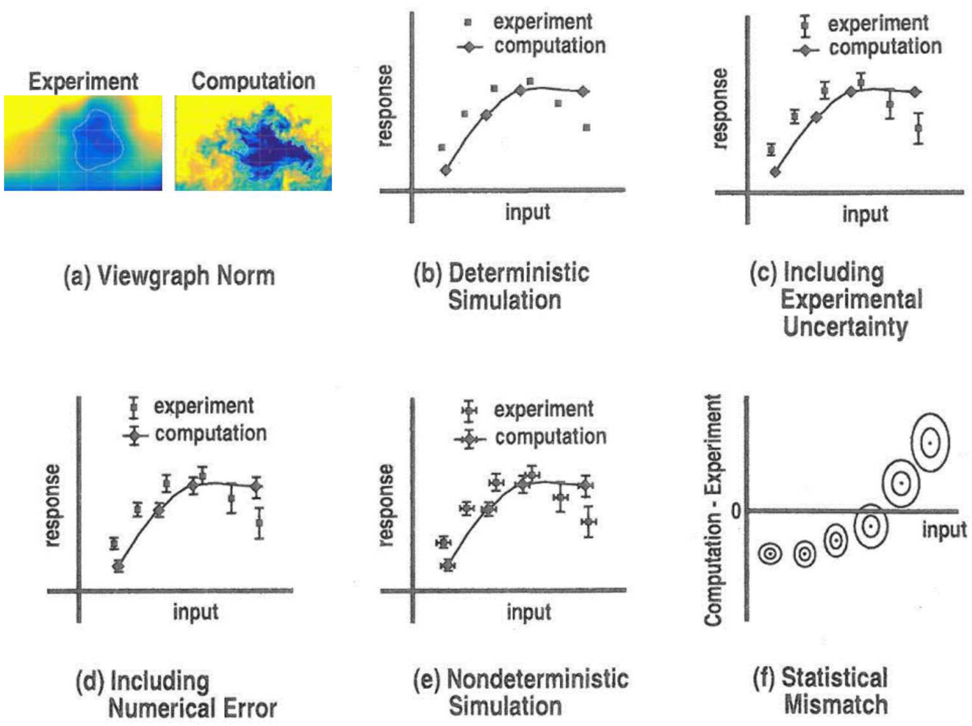
What is V&V?

- **Validation**
  - The process of determining the degree to which a model is an accurate representation of the real world, from the perspective of the intended uses of the model
    - Note that validation is not an acceptance/ rejection/ endorsement of a model
- **Verification**
  - Code verification
    - Software errors or algorithm deficiencies that corrupt simulation results.
  - Solution verification
    - Human procedural errors or numerical solution errors that corrupt the simulation

What is Uncertainty Quantification?

- Methods to codify the assimilation of observational data
  - UQ methods are critical for quantitative model validation focused on enabling predictive numerical simulations in research and advanced design
- The characterization of errors, uncertainties, and model inadequacies
- Forward predictions with confidence for untested/unstable regimes

Levels of Precision



Modified from Oberkamf and Roy, 2012

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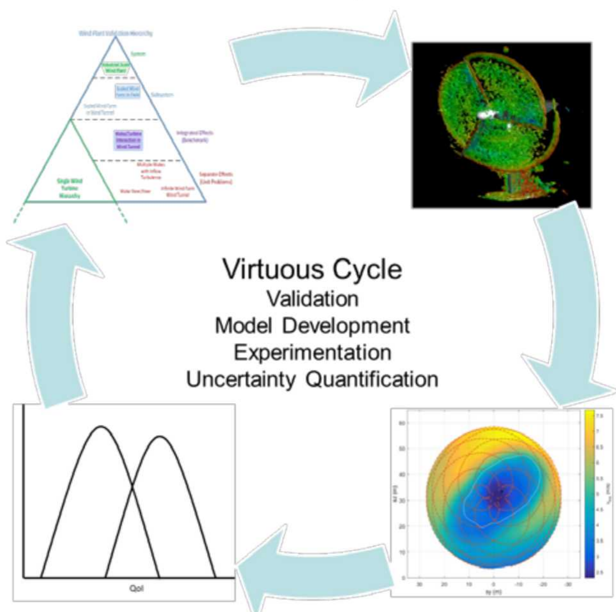
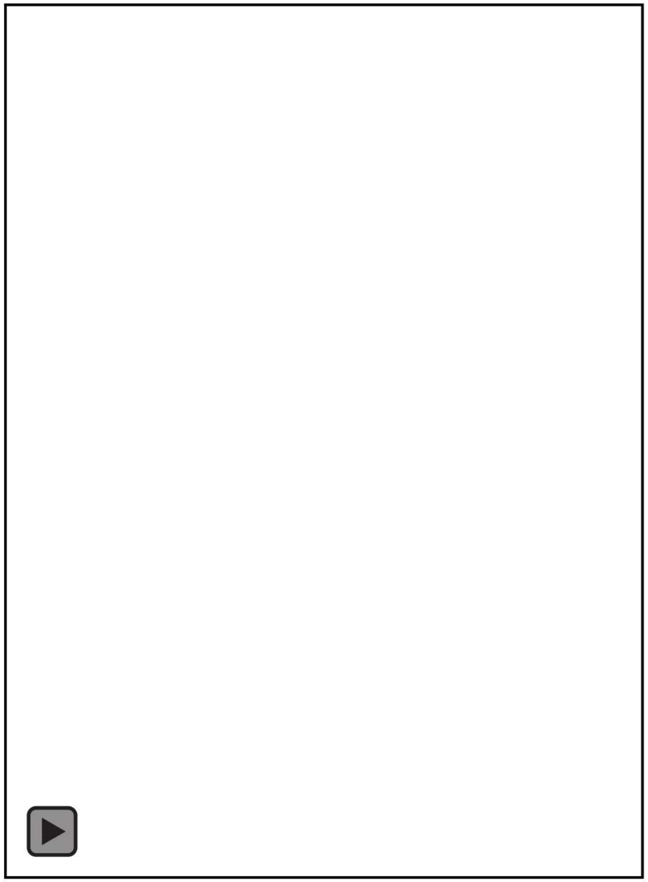
High Fidelity Modeling (HFM) and Verification & Validation (V&V)

- As wind turbine technology matures, the cost of testing and the required level of uncertainty demand a new approach.
- High fidelity models enable reduced development risk through pre-prototype qualification and optimization.
- Without a level of trust of our tools, there results are of limited value
- Recently, our ability to simulate wind turbine and wind farm simulations has outstripped our ability to know whether the results are meaningful
- The Verification and Validation Framework is the process to define the conditions where model predictions can be trusted.

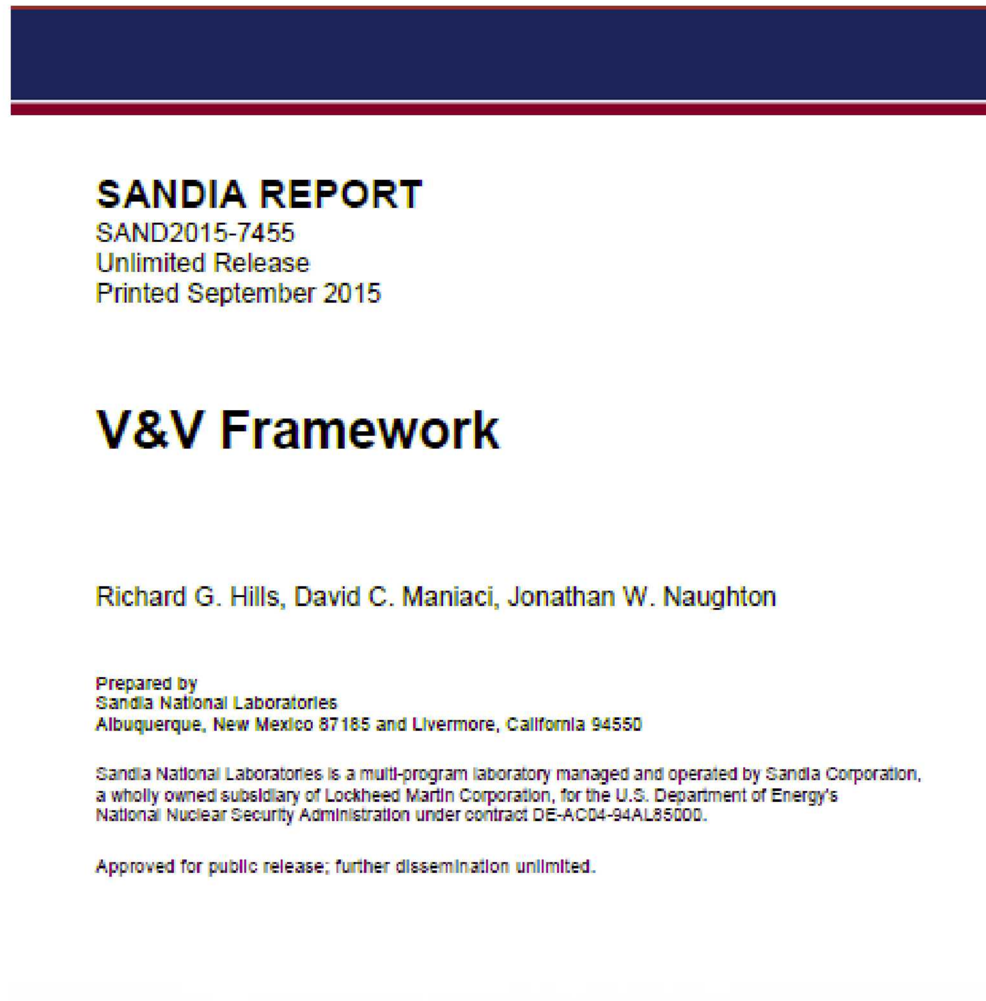




V-27 Nalu Simulation, M. Barone, S. Domino, and C. Bruner, 2017

V&V Process Overview

- **V&V Framework**
  - Phenomena Identification and Ranking Table
  - Validation Hierarchy
  - Prioritization
  - Experiment Design, Execution & Analysis
  - Verification of Code
  - Validation Metric Determination
  - Assessment
  - Determination of level of credibility



SANDIA REPORT
SAND2015-7455
Unlimited Release
Printed September 2015

V&V Framework

Richard G. Hills, David C. Maniaci, Jonathan W. Naughton

Prepared by
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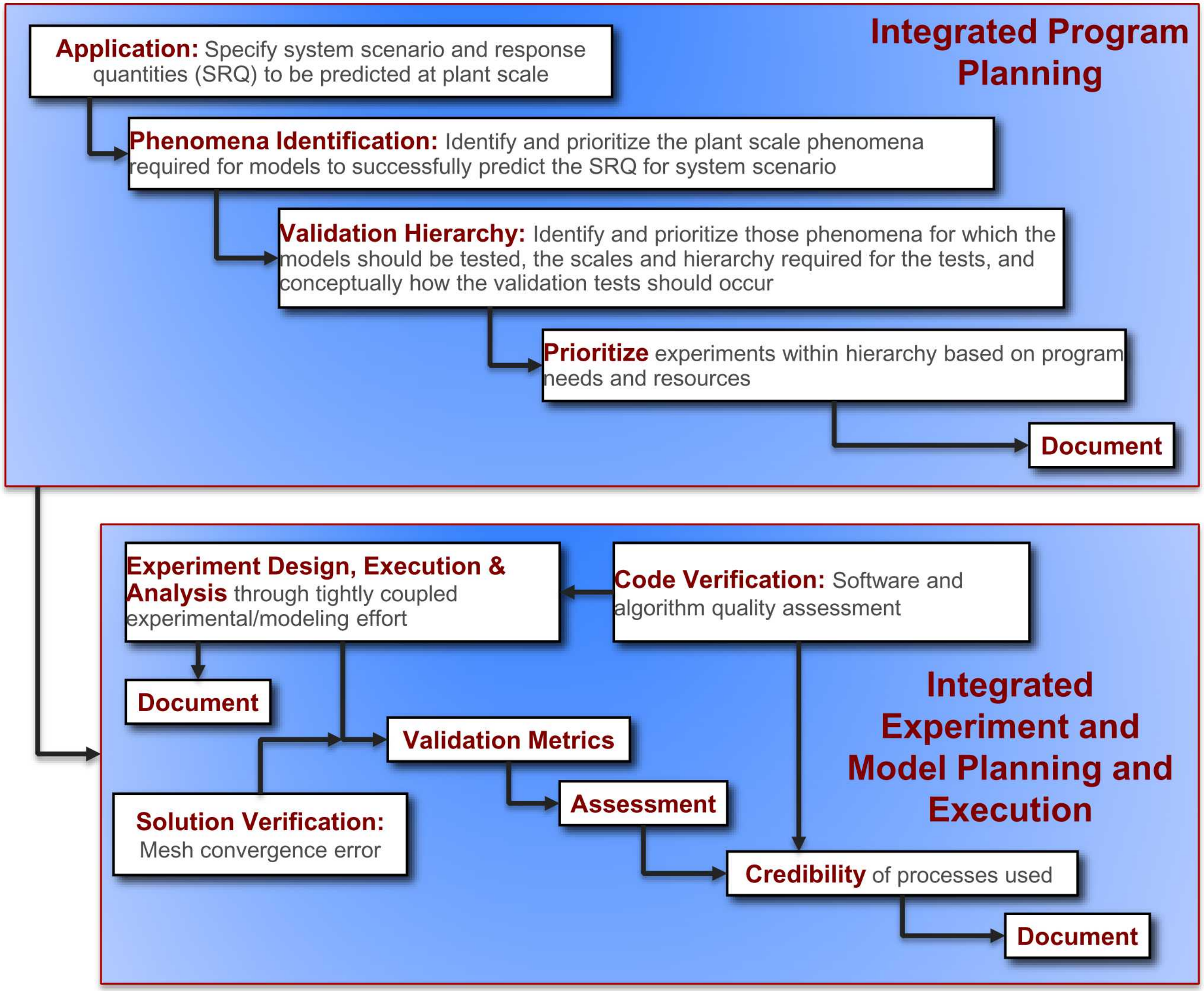
V&V Framework (2015 Hills, Maniaci, Naughton)

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



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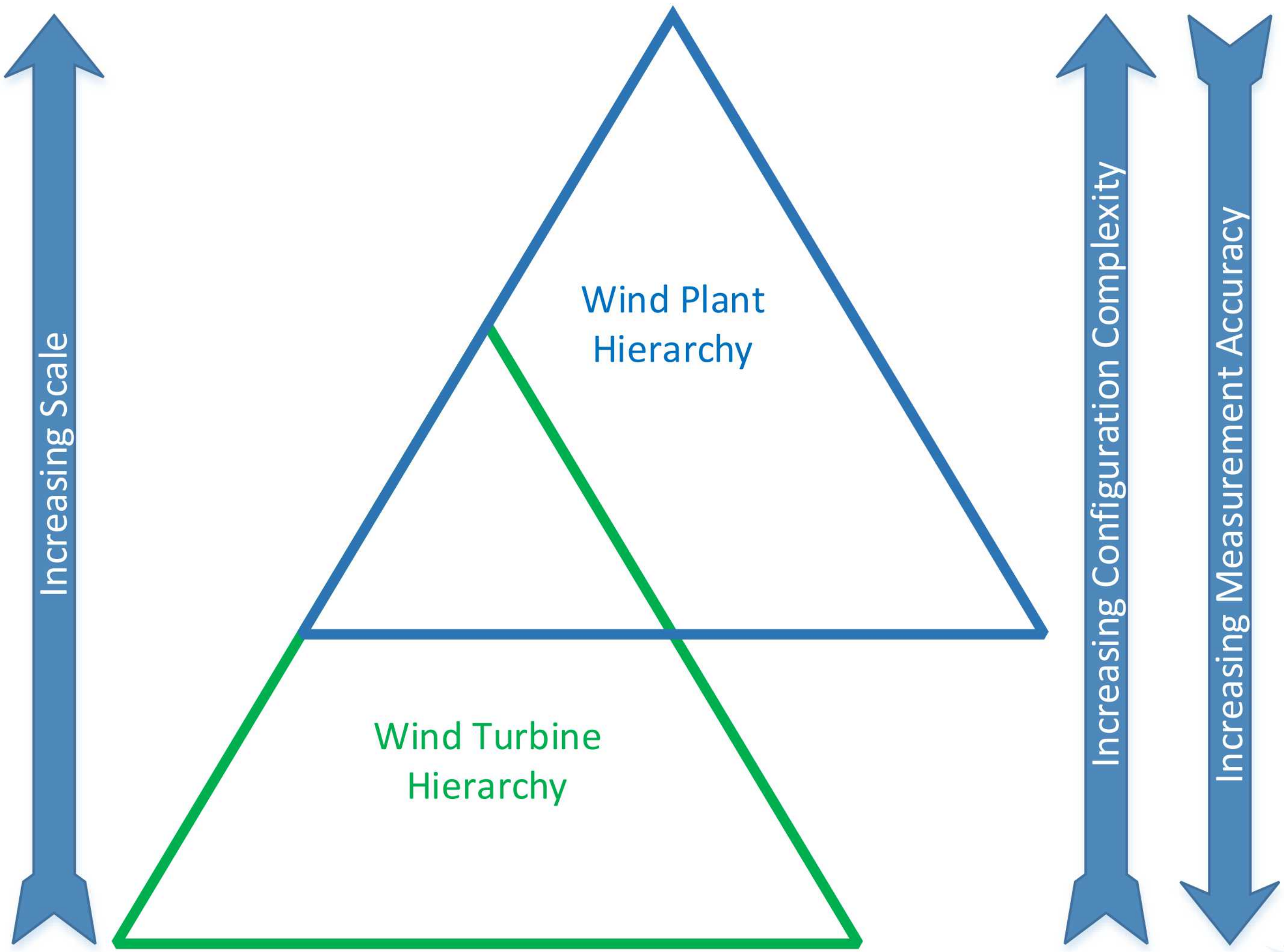
Backbone of Prioritization Process: PIRT

PIRT: Phenomenon Identification Ranking Table

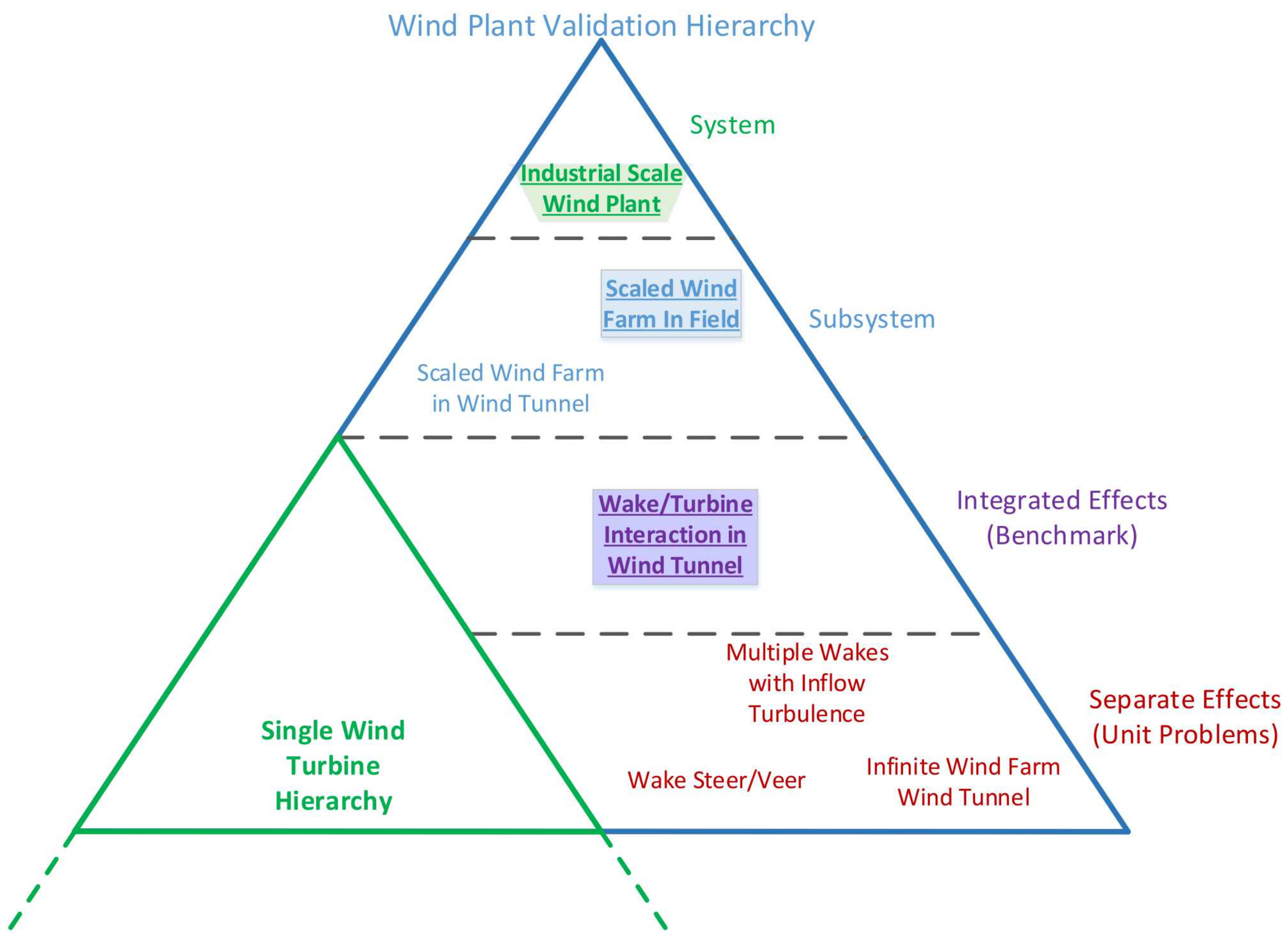
- Consensus based
- Provides gap analysis of ability to model phenomena
  - Physics gaps
  - Numerical gaps
  - Data gaps
  - Validation gaps
- Gap analysis used to prioritize planning, including experimental planning

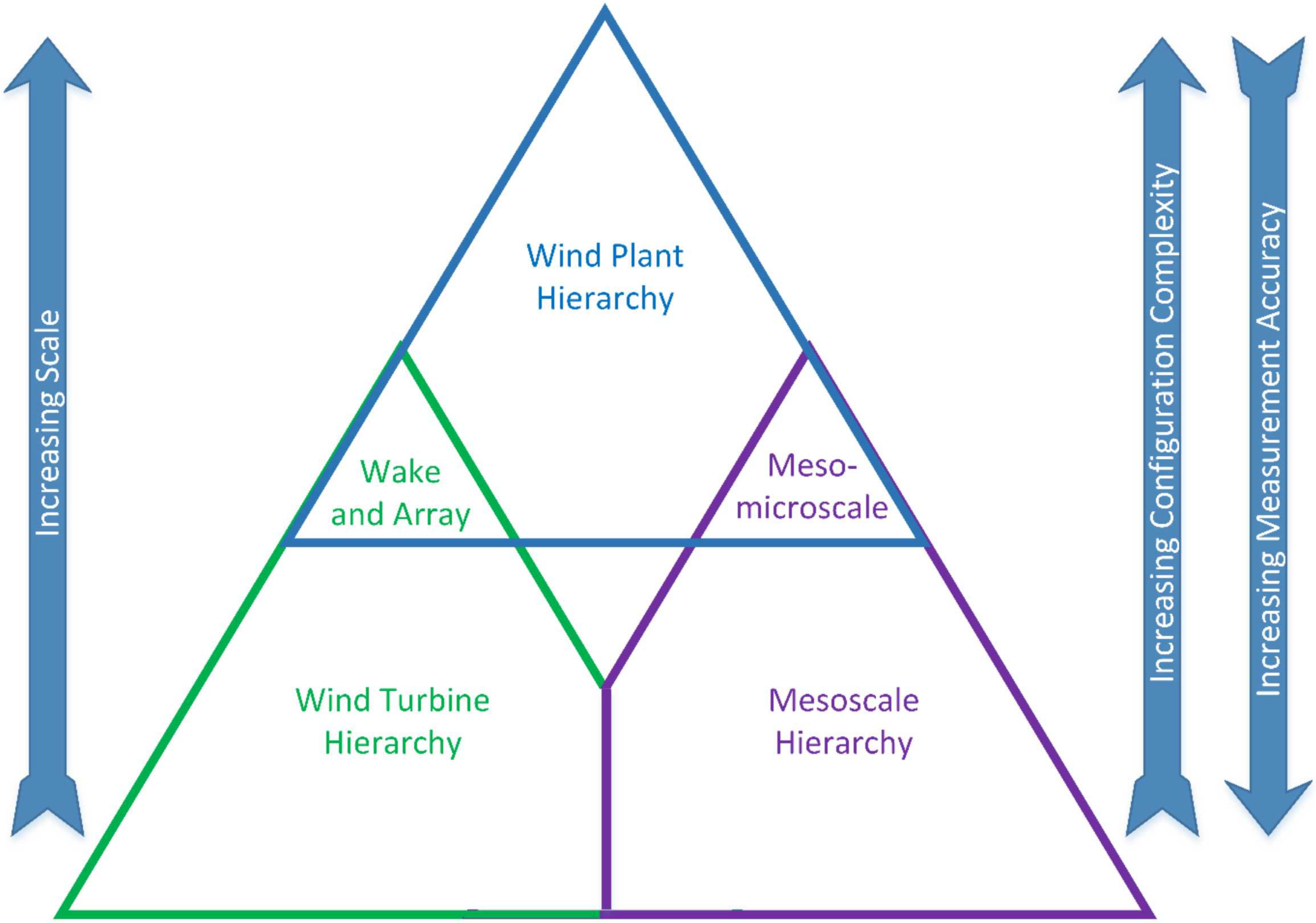
Phenomenon	Importance at Application Level	Model Adequacy		
		Physics	Code	Val
Turbine scale flow phenomena				
Blade Aero / Wake Generation				
Blade load distribution effects and rotor thrust	H	M	L	L
Tip and root vortex development, and evolution and merging	H	M	L	L
Vortex sheet and rollup (in addition to tip/root vortex)	M	M	M	L
Blade generated turbulence characteristics (energetic scales)	H	L	L	L
Root flow acceleration effect ('hub jet')	Unknown	M	L	L
Boundary layer state on turbine performance (roughness, soiling, bugs, erosion)	H	L	L	L
Boundary layer state (Re)	L	M	L	L
BL details near TE and LE	H	M	L	L
Rotational augmentation	H	L	L	L
Dynamic stall	H	L	L	L
Unsteady inflow effect (turb. intensity, spectra, coherence; veer, shear)	H	L	L	L
Blade flow control	M	L	L	L
Tower/rotor/nacelle wake interactions	H	M	L	L
Icing	L	L	L	L

Validation Hierarchy



Wind Plant Validation Hierarchy





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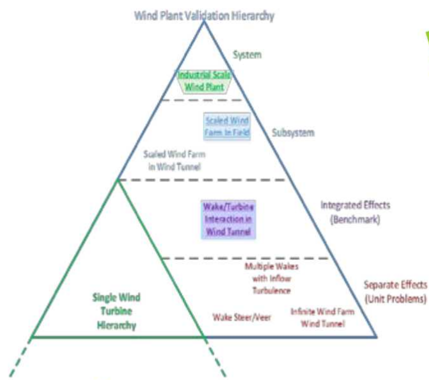
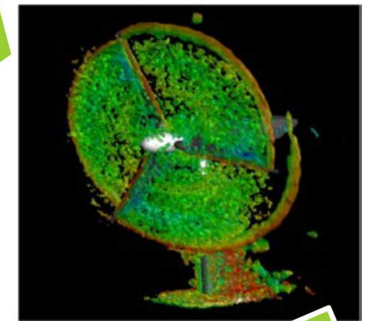
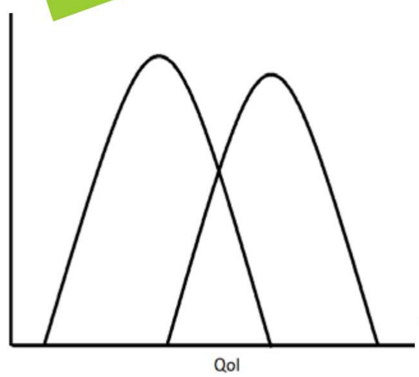
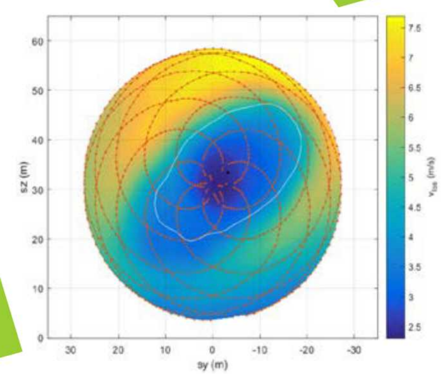




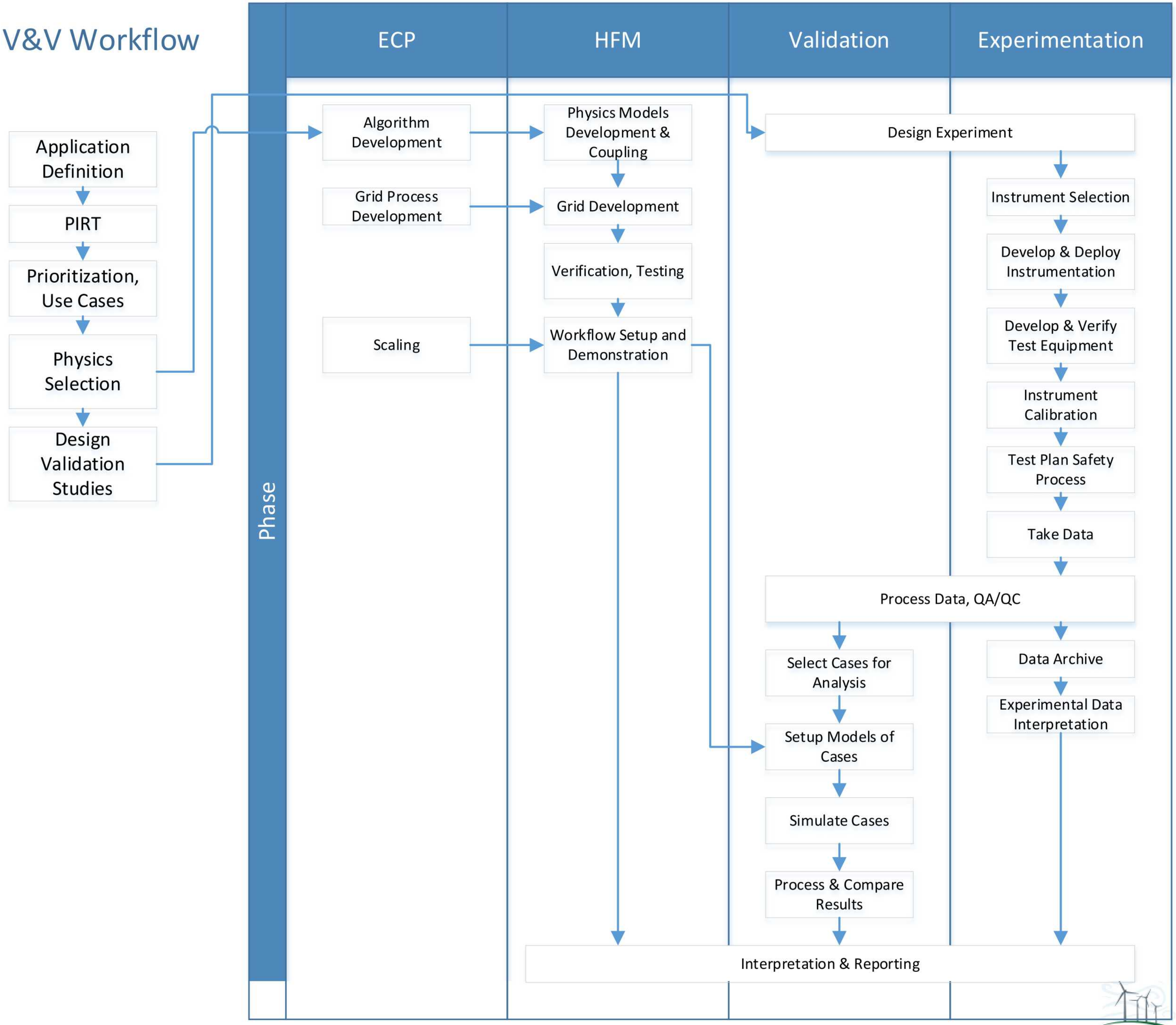
Virtuous Cycle

Validation
Model Development
Experimentation
Uncertainty Quantification





V&V Workflow



Application Definition
PIRT
Prioritization, Use Cases
Physics Selection
Design Validation Studies
Phase
ECP
HFM
Validation
Experimentation
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
Select Cases for Analysis
Setup Models of Cases
Simulate Cases
Process & Compare Results
Data Archive
Experimental Data Interpretation
Interpretation & Reporting

V&V: Communication and Documentation

1. **V&V Framework** (September 2015): the development and execution of coordinated modeling and experiential programs to assess the predictive capability of computational models of complex systems through focused, well structured, and formal processes.
2. **A2e High Fidelity Modeling: Strategic Planning Meetings** (November 2015) : A report on the foundational planning for the A2e High Fidelity Modeling effort for predictive modeling of whole wind plant physics.
3. **V&V Integrated Program Planning for Wind Plant Performance**: This document outlines the integrated program planning (IPP) process and applies it to wind plant performance prediction.
4. **Test Objectives and Prioritization for Wind Plant Performance:** Prioritization of experiments across A2e areas
5. **Validation Roadmap: Comprehensive plan for the validation of wind HFMs**
6. **Summary of A2e Validation Progress and Plans**
7. **Integration into IEA Task 31, Wakebench.** Working toward a collaborative validation process.

Project Overview and Objectives

- This project will ensure that the predictive capability of the suite of models being developed across A2e is established through formal V&V/UQ processes.
  - Quantitatively establish where models are valid and where improvements are necessary
- The result will be established V&V/UQ techniques applied to computational modeling tools spanning a range of fidelities
  - These tools will be adopted by the wind industry or used to improve in-house software

Primary Stakeholders

- **A2e Research Areas:** HFM, Wake Dynamics, ISDA, Control Science, MMC, WFIP, and offshore wind
- **International Community: IEA Tasks 29, 31, 36**
- **DOE Wind Energy Technologies Office**: improve understanding of wind plant complex flow, exploration of novel wind technology advances and validation of lower-fidelity models
- **Manufacturers**: improved energy capture and reliability of wind turbines through technology development and environment definition
- **Developers**: design optimized wind plants, quantify and reduce uncertainties in energy estimates
- **Owners/Operators**: maximize energy capture and reliability of existing farms, improved day-ahead and hourly forecasting

Application Use Cases

- **Predict**
  - Wind plant power performance and loads
  - Power production of a wind plant in at terrain, with blade-root loads
  - Diurnal flow field in complex terrain (pre-wind plant installation)
  - Loads and wakes of a next-generation turbine (qualification)
  - Forensics analyses with data assimilation to understand extreme or unusual load events
- **Discover**
  - Dominant phenomena governing wake evolution
  - New modeling approaches for wind energy
- **Innovate**
  - Explore the design space of next generation innovations to improve turbine and plant performance
  - Optimize new technology prior to demonstration testing

Status of V&V Coordination Effort

- **Integrated Program Planning nearly complete**
  - Application identified
  - PIRT completed
    - SMEs involved
    - Consensus identified
  - Validation Hierarchy developed
  - Validation experiments mapped onto prioritized phenomena (PPEM)
  - Report to appear soon
    - In revision
    - Expected release in near future

- **Integrated Experiment and Model Planning and Execution**
  - Underway for some prioritized validation experiments
  - Planning for other experiments to take place as opportunity allows
  - Other groups may use this document as well and identify other gaps in scenarios available for validation

Progress: A2e Validation Coordination Meeting

A2e Area	Validation Lead
V&V framework, processes, vision, documents	Jonathan Naughton (UWYO)
DAP	Matthew Macduff, Chitra Sivaraman (PNNL)
Offshore	Amy Robertson (NREL
ISDA	Jason Jonkman (NREL)
Wake Dynamics/HFM	Pat Moriarty (NREL)
WFIP 2	Caroline Draxl (NREL)
MMC	Caroline Draxl (NREL), Sue Haupt (NCAR)
PRUF	Jason Fields (NREL)
V&V/UQ	David Maniaci (SNL)

- **Shared progress, future work, lessons learned**
- **Internal documentation: Summary of A2e Validation Progress and Plans**

HFM Verification & Validation (V&V) *(early FY18, needs update)*

Nalu model	Relevant links	Status Verification	Status Validation*	Code V&V notes
Outflow BC	Github pull/commit Theory Verification	C-L	I	Formal verification limited to simple stratified laminar channel; future work will test BC with heated flat plate in turbulent flow. Fixed outflow issue exposed in FY18 Q1.
Top ABL BC	Github pull/commit Theory Verification	C	I	
AL coupling (FSI)	Github pull/commit Theory Elliptic wing testing	C-F	I	Implemented an FSI coupling algorithm that was demonstrated on a simple example to be second-order time accurate for lock-step time integration; in process of modifying algorithm for time-step subcycling.
Coriolis term	Theory	C	I	In process of adding online documentation showing verification results that were completed internal to project.
Buoyancy term	Github pull/commit Theory Verification	C	I	
Atmospheric forcing term	Github pull/commit Theory	C	I	In process of adding online documentation showing verification results that were completed internal to project.
Wall model	Github pull/commit Theory	C-F	I	In process of adding online documentation showing verification results that were completed internal to project. Wall model testing was also part of system-level ABL simulation test. Additional verification will examine statistics of turbulence quantities.
ABL-Precursor inflow coupling	Github pull/commit Theory Verification	C	I	

Status Key

Complete	C	Testing complete
Complete-Further	C-F	Testing complete, further studies will better quantify or reduce prediction uncertainty.
Complete-Limited	C-L	Tests complete, but the study does not capture the complete model capability.
Incomplete	I	

*Note: Validation work will transfer to the Wake Dynamics project, with support from the HFM project.

Next Steps

- **Publish IPP Report**
- **Inclusion of Atmospheric efforts into V&V framework to degree possible**
- **Use V&V Framework to Identify New Experiments**
  - Evaluate existing experiments
  - Identify need for new experiments
- **Identify Instrumentation Needs**
  - Report to come out in Fall
- **Work with DAP to Explore Use of Validation Hierarchy for Data Organization**
- **Develop 1-3 Experiments that can be used as Examples of Validation Experimental Campaigns**
- **Publicize Validation Hierarchy**

Next Steps

- **Evaluation of Validation Experiments**

  Process used in the past to characterize potential validation experiments
  - Identify and characterize existing experimental studies
  - Checklist for new validation experiments
  - Consistent means for evaluation
  - Studies that meet a sufficient number of criteria would be entered into validation database
  - The evaluation sheet would accompany all experiments in the database

Validation Experiment Evaluation

Validation Case: Descriptive name goes here

Key Personnel: List of key players in validation experimental effort

Validation Category: Unit Problem Benchmark Subsystem System

Specific Area: Name the specific area of the above validation category

References: List all references in the literature that are pertinent to the validation case

1. First Reference

Experiment Description:

A paragraph here summarizes what was performed in the experiment.

Unique Aspects:

Describe any unique aspects of the experiment that set it apart from others.

Description of Data:

General Validation Criteria addressed by the experimental effort (See definitions below)

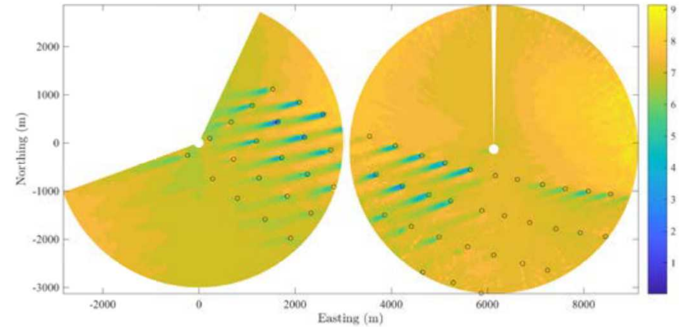
1. Applicability
2. Boundary conditions well defined
3. If applicable, subject of the experiment well defined (e.g. the wind turbine is described in sufficient detail)
4. Instrumentation fully described
5. Uncertainty of the measurements reported
6. Consistency of results
7. Documentation of the experiment sufficient (or sufficient metadata available to fully document the experiment)

Specific Validation Criteria addressed by the experimental effort (See criteria below for different types of experiments)

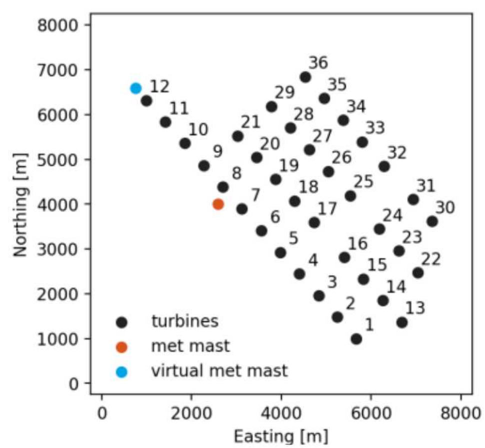
Criteria for evaluating specific experiments will obviously be dependent on the type of experiment performed. Experiments performed under controlled conditions (e.g. wind tunnels) will obviously be held to a higher standard than experiments performed in the field. Thus, different categories of experiments will use criteria relevant to their category.

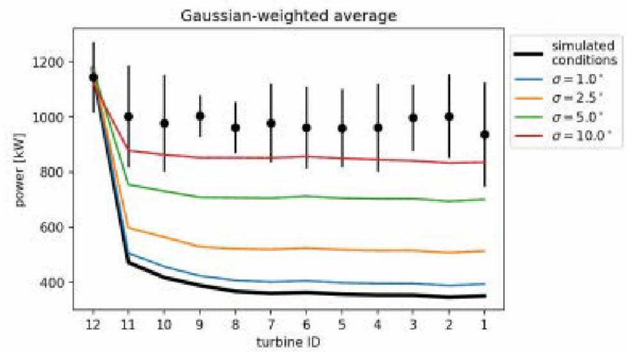
Wind Plant Validation Studies FY18 (Wake Dynamics)

- **Rodsand II Analysis**

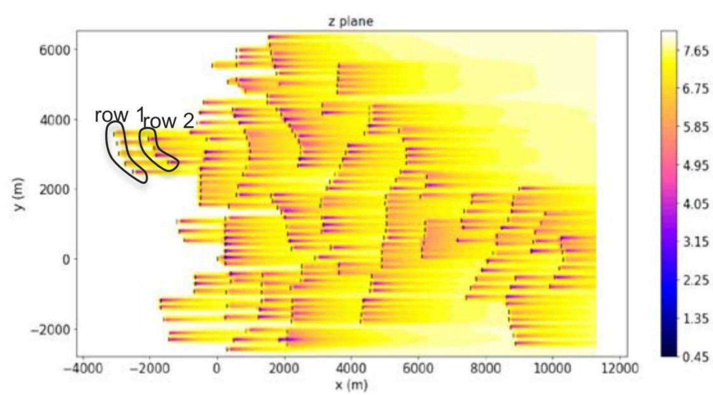


- **Validation Study of Nalu for the OWEZ Wind Plant**



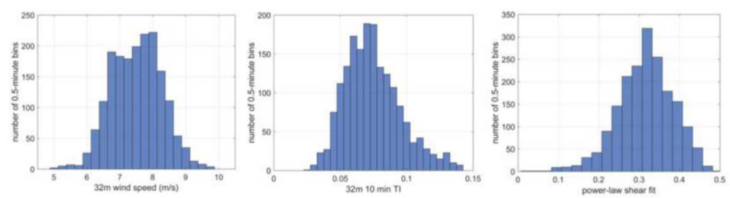


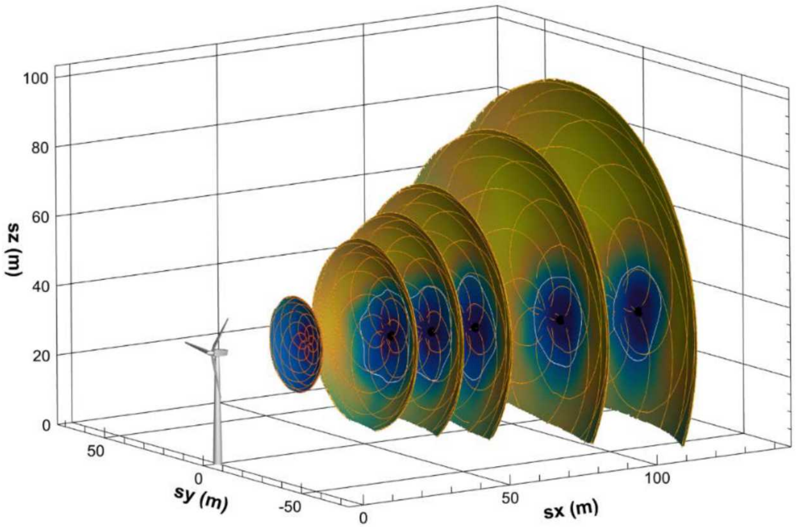
- **Biglow Canyon Validation**

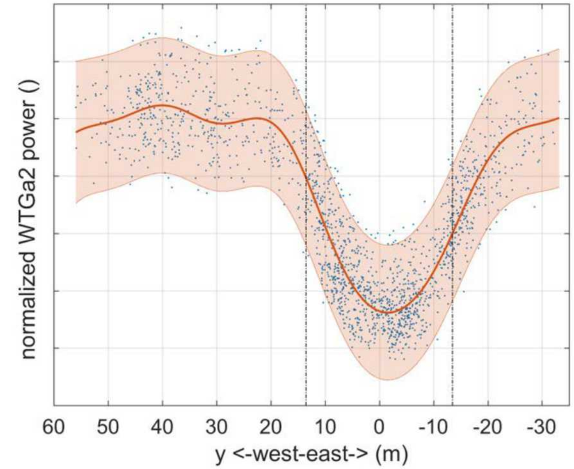


Uncertainty Quantification and High Fidelity Modeling

- Uncertainty Quantification (UQ) is critical to enable predictive numerical simulation for scientific discoveries and advanced engineering design.
- Complex high fidelity models (HFM) and large numbers of uncertain parameters lead to prohibitive computational cost for conventional UQ methods
- Multifidelity UQ aggregates several low accuracy models with a handful of high fidelity simulations







Technical Highlight: Multi-level Uncertainty Quantification with LES

Accomplished an **order of magnitude reduction in computational cost** for a cylinder flow problem by coupling Nalu to DAOKTA 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
- Time to solution 10 minutes to 4 hours

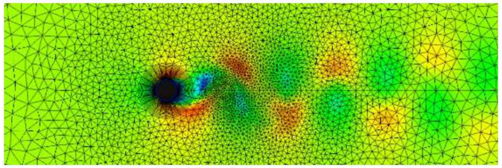
UQ approach

- Multilevel sampling-based estimator to accelerate convergence
- The QoI on each level is defined as the difference between evaluations at adjacent levels (mesh resolutions)
- Optimal sample allocation across resolution levels to reach a target accuracy

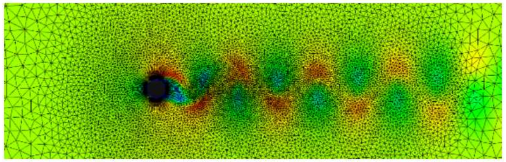
Impact

- Interface between Nalu (CFD) and Dakota (UQ) is now in place
- 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
- Possible to use an additional low-fidelity model in order to obtain an additional variance reduction (Multilevel-Multifidelity estimator)

Coarse Mesh: 10 minute time to soln.

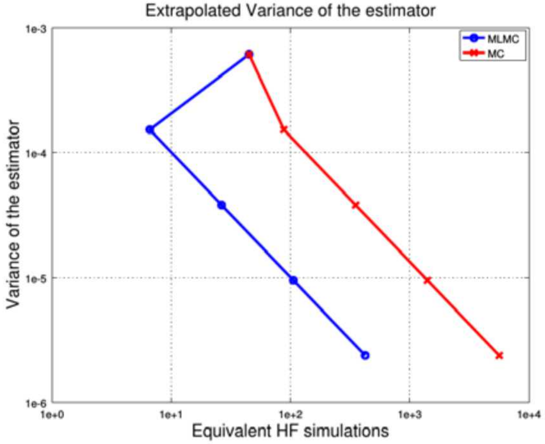


Medium Mesh: 4 hours time to soln.



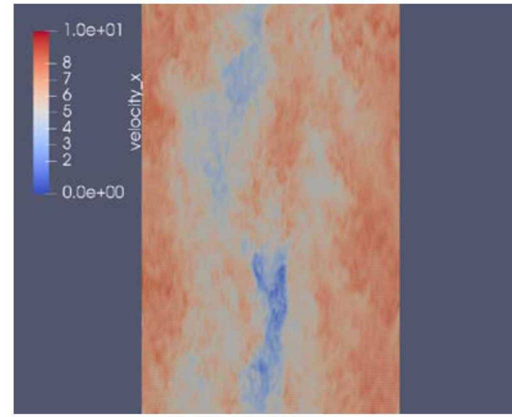
Accuracy	Multilevel simulations				Equivalent Cost	
	Coarsest	Coarser	Coarse	Medium	MLMC	MC
6.08e-05	28	20	4	1	18	221
6.08e-06	2796	194	37	3	167	2202
6.08e-07	27952	1935	364	25	1657	22140
6.08e-08	279520	19345	3640	242	16551	220130

TABLE: Optimal MLMC samples allocation Vs MC allocation



Multilevel-Multifidelity Uncertainty Quantification with LES

Demonstrated a Multilevel-Multifidelity (MLMF) uncertainty quantification method for a periodic wake case by coupling DAKOTA (UQ) to Nalu (CFD) and OpenFAST.



Problem description

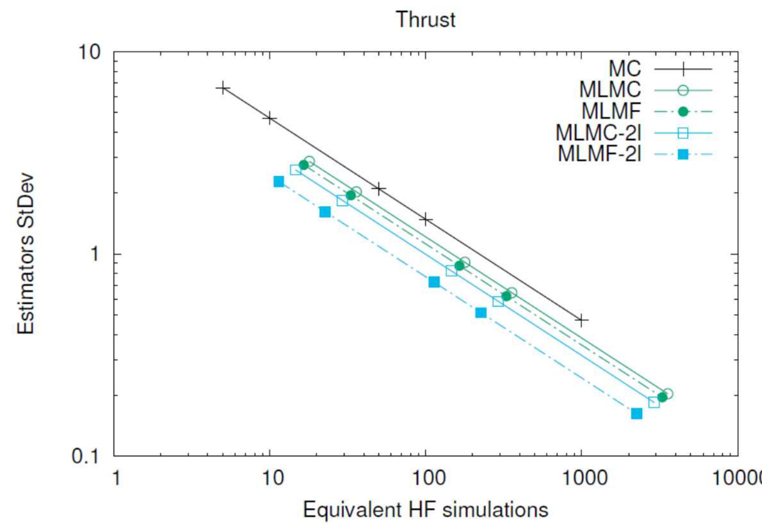
- Single turbine with periodic BC (infinite farm)
- QoI: Power and Thrust
- Low Fidelity: **OpenFAST-AeroDyn-Turbsim**
- High Fidelity: **Nalu**
  - 4 levels of mesh resolution in Nalu

UQ approach

- Multilevel-Multifidelity (MLMF) sampling-based estimator to accelerate convergence

Impact

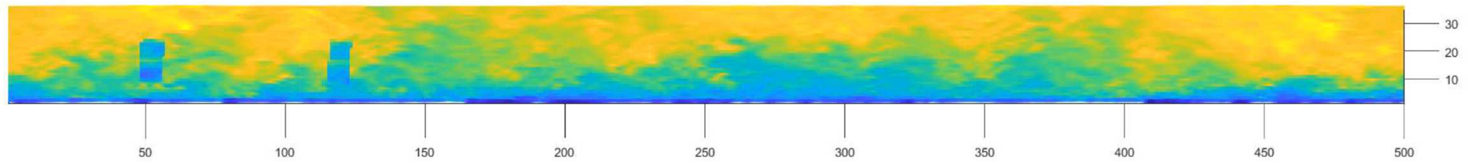
- Sampling methods are well suited for UQ problems with extremely high dimensionality (such as wind farm LES)
- Convergence is guaranteed for non smooth QoIs
- Performance of the estimators varied, with MLMF approach requiring the fewest equivalent samples for a given level of accuracy

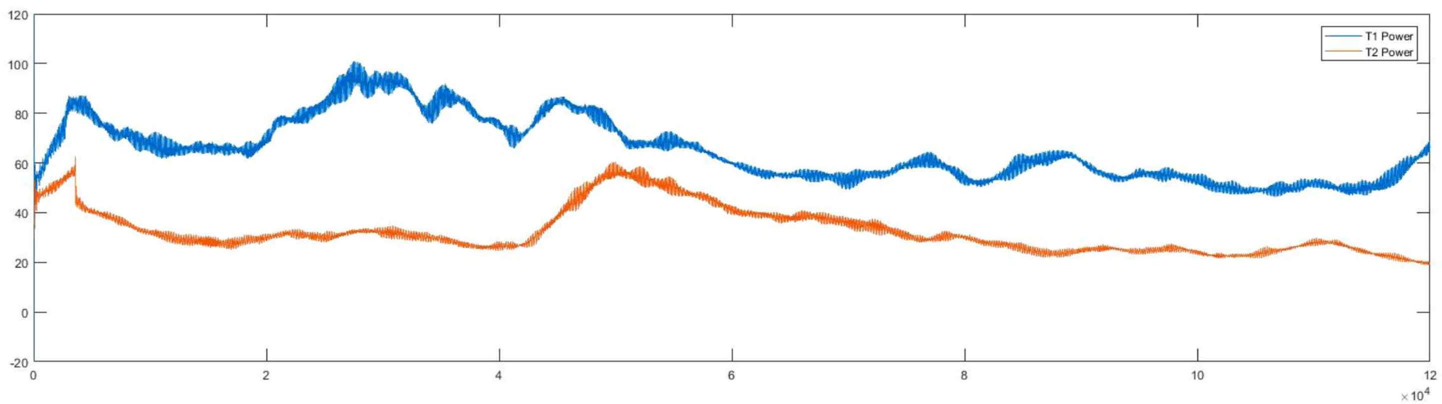


	Power			Thrust		
	MLMC	MLMF		MLMC	MLMF	
Level	Nalu	Nalu	OpenFAST	Nalu	Nalu	OpenFAST
0	161	137	2040	181	136	2887
1	36	36		34	34	
2	5	5		5	5	

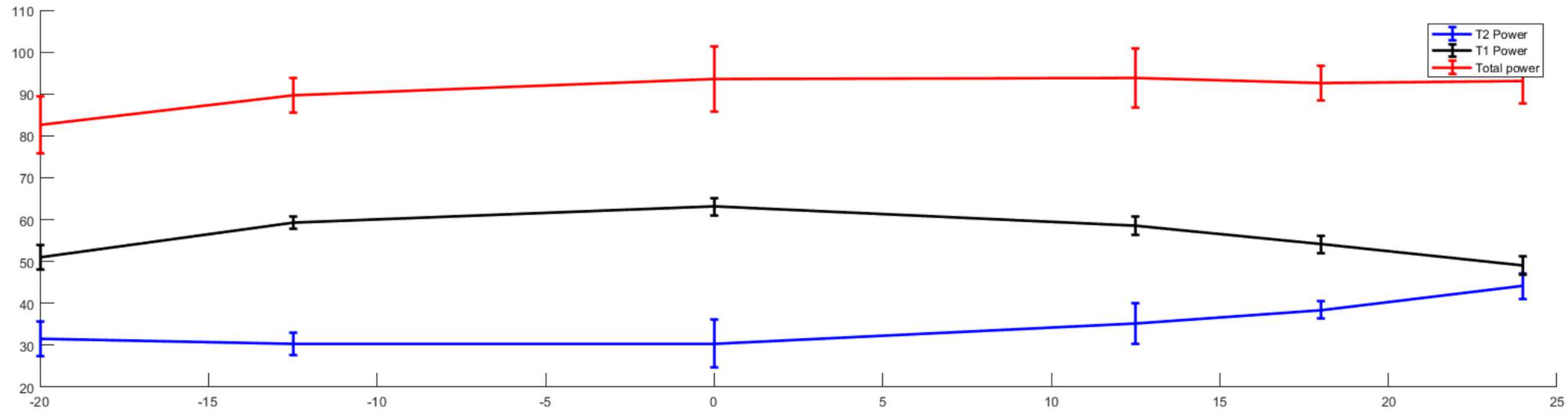
David C. Maniaci, Ari L Frankel, Gianluca Geraci, Myra L Blaylock, and Michael S Eldred; "Multilevel Uncertainty Quantification of a Wind Turbine Large Eddy Simulation Model," ECCOMAS 2018, Glasgow.

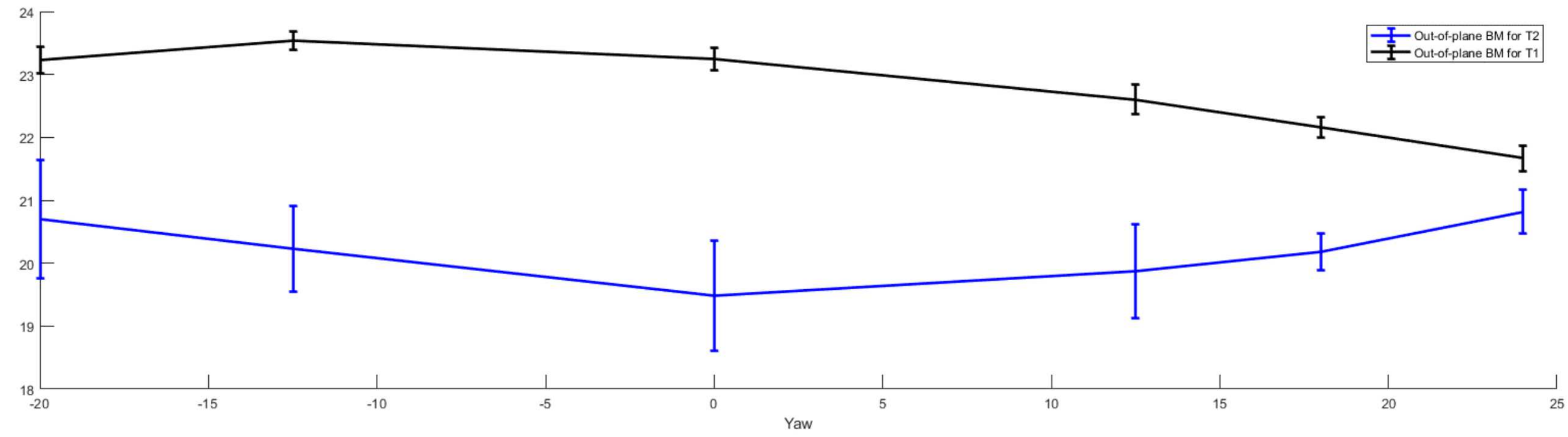
FAST.Farm + DAKOTA: Impact of Yaw, Blade Pitch and Inflow





FAST.Farm + DAKOTA: Impact of Yaw, Blade Pitch and Inflow

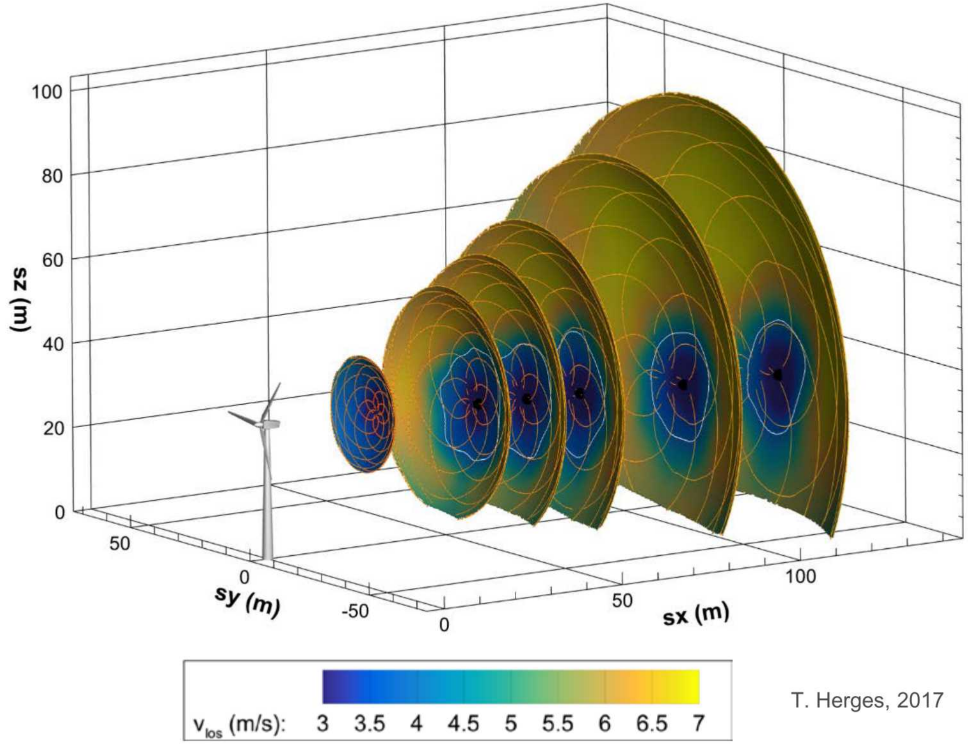




SWiFT Wake and Loads Measurements

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***.



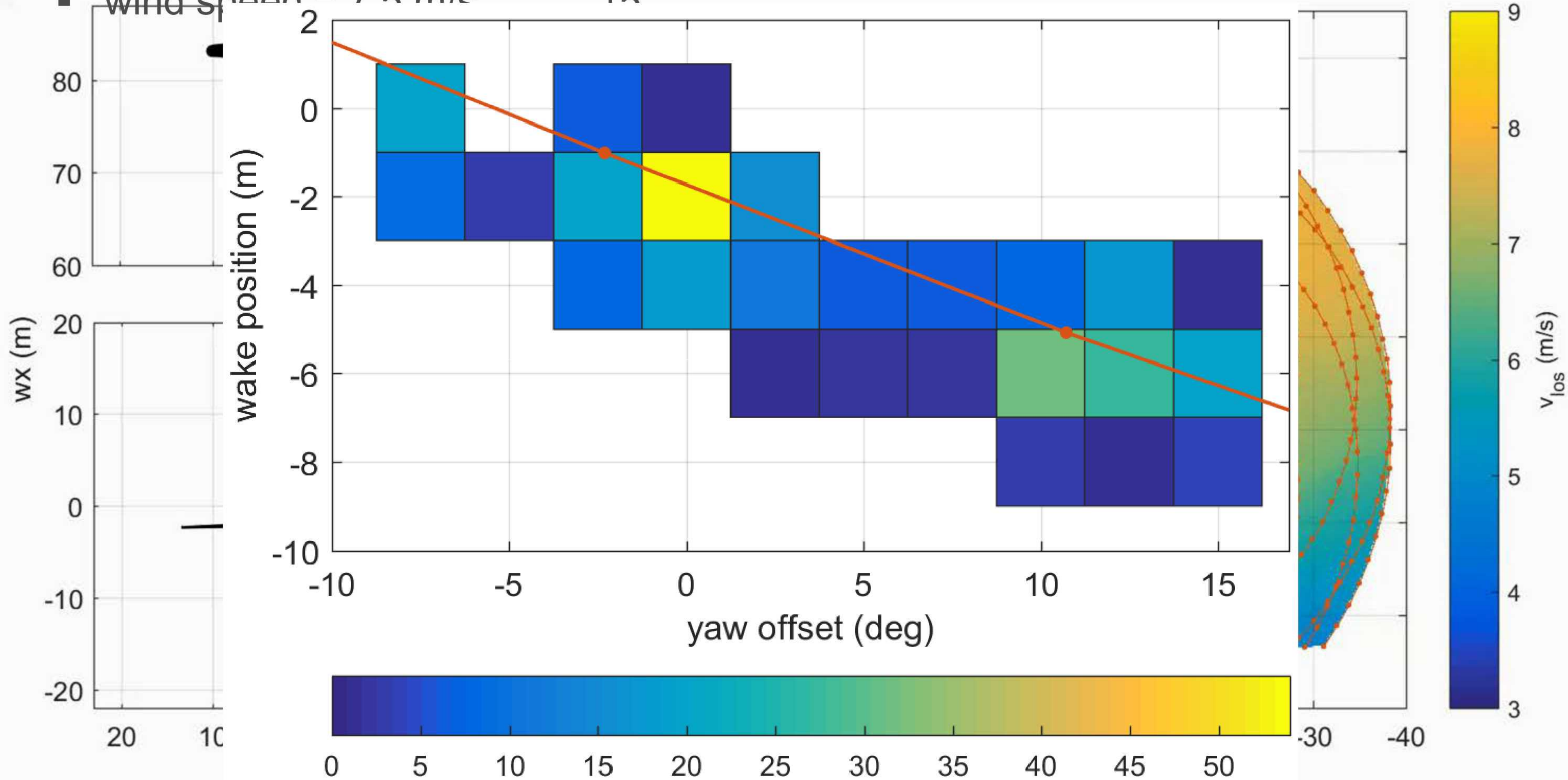
T. Herges, 2017

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°

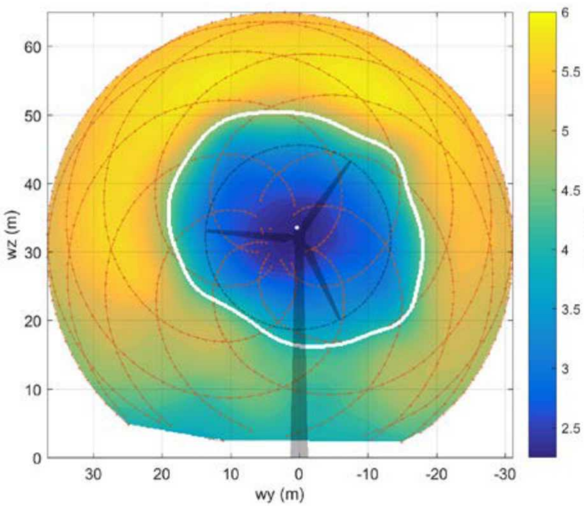
- Yaw heading = 159.5 degN

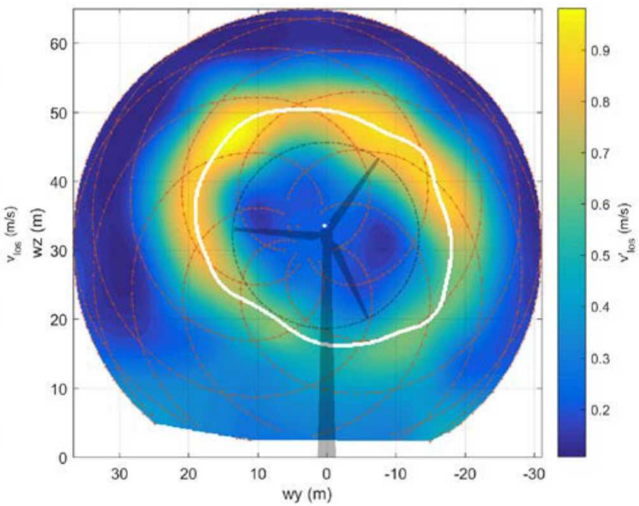


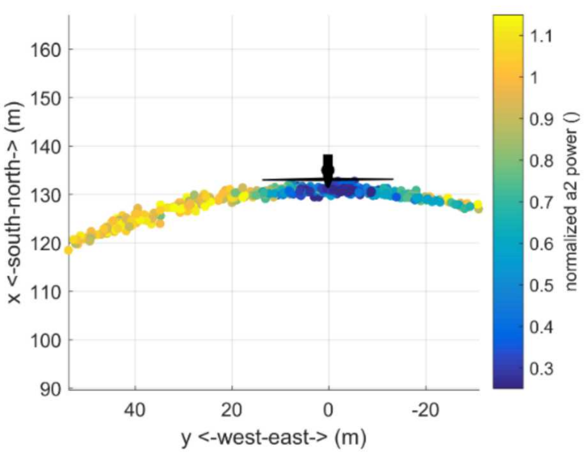
Wake Steering Experiment – Analysis and Prediction

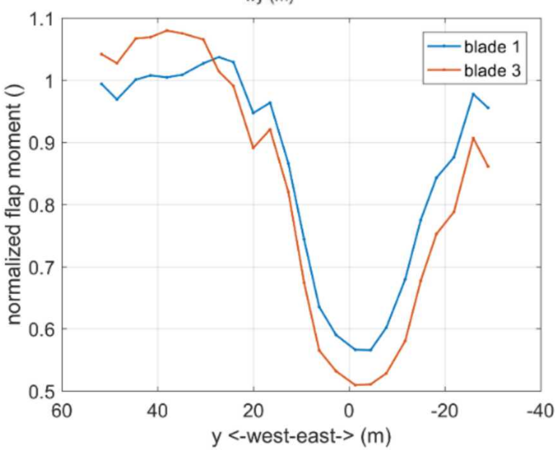
SWiFT Wake Steering Experiment concluded in FY17 Q4. Analysis has been ongoing in support of yaw-based wake control assessment and wake dynamics physics for model validation

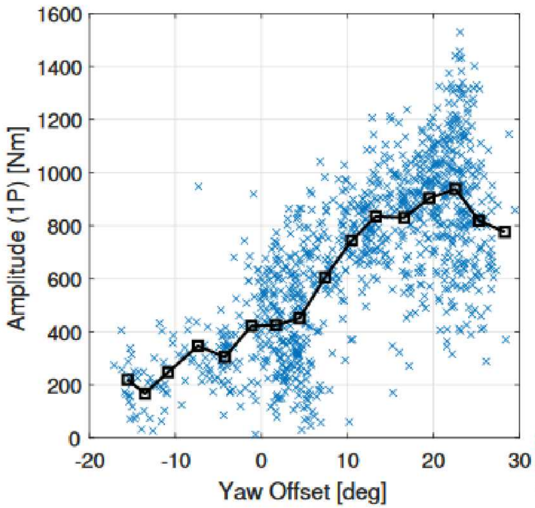
- Current: Assess Nalu for Wake QoI, predict impact of NRT rotor on wake.
- Future: Two-turbine wake steering analysis incorporating loads, DEL
- Bayesian Inference and Optimal Experimental Design











HFM FY19

- Fy19Q4 (SNL-Task2/UQ): Enable the application of Nalu to wind turbine wake validation studies through the development and demonstration of multilevel emulator-based Bayesian inference capabilities.

FY-19 UQ development activities:

- Conduct research on multi-fidelity modeling approaches for uncertainty quantification (UQ) of high-fidelity Nalu-Wind-OpenFAST simulations through collaboration with University of Colorado at Boulder (PhD student). (NREL)
- Demonstrate a multilevel-multifidelity forward-propagation uncertainty quantification capability on a SWiFT validation case.

Wake Dynamics FY19

Milestones under V&V:

- Publish the Verification and Validation Integrated Program Planning document as a public SAND report.
- Present AIAA Paper on Nalu Validation with SWiFT Wake Steering Campaign dataset.
- IEA Task 31 WakeBench presentation on summary of the international validation comparison study of the SWiFT Case at Visby Wake Conference May 22, 2019 (Joint with NREL)

V&V Activities:

- Validation Methodology Development and Coordination
- Experiment UQ
- Propagation of experiment UQ
- Validation Studies: Focused on SWiFT and other datasets from operational wind farms
- IEA Task 31 Wakebench: participation and organization of benchmark

FUTURE PLANS BEYOND FY19

Proposed Organization of V&V/UQ area

Five core research areas:

1. Validation Coordination and Application
2. Meteorological Uncertainty Quantification
3. Wind Turbine Uncertainty Quantification
4. Wind Plant Validation and Uncertainty Quantification
5. Uncertainty Quantification Methodology Development and Application

Mapping Current Work to Proposed Tasks

- **Validation Coordination and Application**
  - A2e Validation Coordination Meeting, documents
- **Meteorological Uncertainty Quantification**
  - Quantify uncertainty propagation through WRF based on model inputs and model parameterizations (under MMC)
- **Wind Turbine Uncertainty Quantification**
  - Sensitivity Analysis (under ISDA)
  - SWiFT Wake Steering loading probabilistic analysis
- **Wind Plant Validation and Uncertainty Quantification**
  - Rødsand II Analysis
  - Validation Study of Nalu for the OWEZ Wind Plant
  - Bigelow Canyon Validation
  - SWiFT: Experiment UQ, Data Assimilation and OED
- **Uncertainty Quantification Methodology Development and Application**
  - Successful deployment of Multilevel-Multifidelity Uncertainty Quantification (MLMF-UQ) Publication/presentation of first MLMF-UQ wind application at ECCOMAS-2018 conference
  - UQ with DAKOTA and FAST.Farm

Planning Future Wake Validation Campaigns

SWiFT

- Higher fidelity measurements of inflow, turbine loading, and wakes are required to reduce uncertainty in model predictions that depend on these quantities

Utility Scale

- Support planning of AWAKEN validation campaign and instrumentation

Enabling Validation and UQ methods

- Optimal Experimental Design (OED)
  - Use UQ processes with multiple fidelities of models to optimize the type, resolution, and placement of experiment instrumentation to directly address historical validation gaps

Project Team

SNL

- Mike Eldred
- Gianluca Geraci
- Myra Blaylock
- Brent Houchens
- Brian Naughton
- Brandon Ennis
- Thomas Herges
- Chris Kelley
- Robert Knaus
- Phil Sakievich
- David Maniaci

NREL

- Jason Jonkman
- Patrick Moriarty
- Ryan King
- Anna Craig
- Matt Churchfield
- Mike Sprague
- Katherine Dykes

PNNL

- Larry Berg
- Ben Kravitz
- Raj Rai

UWYO

- Jonathan Naughton

Five core research areas:

1. **Validation Coordination and Application**
2. **Meteorological UQ**
3. **Wind Turbine UQ**
4. **Wind Plant UQ**
5. **Uncertainty Quantification Methodology Development and Application**

Project Tasks

Task 1: Validation Coordination (SNL/UWYO - lead)
Validation coordination meetings
Validation processes and planning
International validation coordination
Release validation framework components
Validation effort tracking
Existing experiments process
Coordinate experimental development with needs of modeling efforts
Develop and implement a short-term demonstration validation experiment
Interface with DAP

Project Tasks

Task 2: Mesoscale Uncertainty Quantification (PNNL - lead)
Identify parameters
Bayesian inference comparison
Experiment design
UQ simulations and analysis

Project Tasks

Task 3: Wind Turbine Uncertainty Quantification (NREL - lead)
UQ of turbine measurements
Propagation to downstream turbines
Report on important parameters
Assess blade load model propagation
Development of multi-fidelity UQ process for wind turbine design

Project Tasks

Task 4: Wind Plant Uncertainty Quantification (NREL - lead)
Report on important parameters for sensitivity of a turbine in a wind plant
Propagation of wind turbine parameters to wind plant metrics
Create bridge between mid- and high-fidelity models for wind plant metrics.
Propagation of high fidelity modeling results to wind plant performance metrics

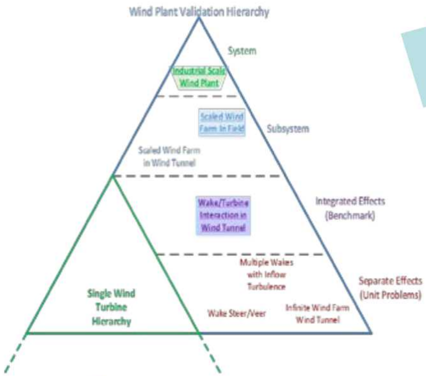
Project Tasks

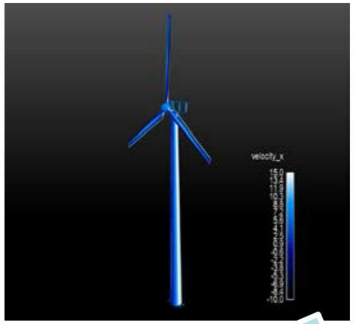
Task 5: Uncertainty Quantification Methodology Development and Application (SNL - lead)
Demonstrate MLMF fwd.-propagation
Develop multilevel emulator-based Bayesian inference capabilities
Deploy inference cap. to SWiFT dataset
Develop OED capability
Deploy OED to Near-wake experiment
UQ of SWiFT exp. results with Nalu
Deploy OED to full-scale experiment
Develop MLMF OUU capability, MINLP
Apply OUU to demonstration wind plant

A2e Project Dependencies

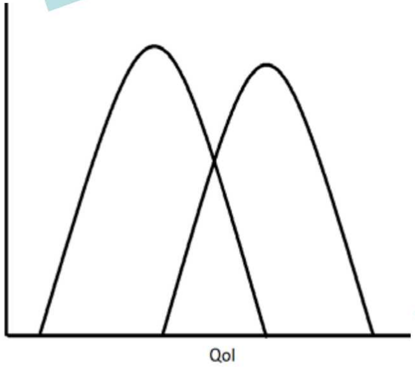
- V&V/UQ Project Dependencies:
  - Models with verified and demonstrated capabilities req'd for validation campaigns
  - Support for model deployment, including complete workflow
  - Experimental data of validation quality, with QA/QC, UQ, and with instrumentation that can be directly mapped to model QoI's and application SRQ's
  - A2e validation leads engaged on coordination activities
  - PRUF for QoI for uncertainty propagation and validation prioritization and impact
- Projects that depend on V&V/UQ:
  - HFM, Wake Dynamics, ISDA, Control Science, MMC, WFIP, PRUF, and offshore wind
  - Coordination of validation activities across A2e
  - Definition of validation framework, terminology, and methodology
  - Development and demonstration of UQ processes
  - Methods to prioritize parameters, estimate variance, and propagate to SRQ's

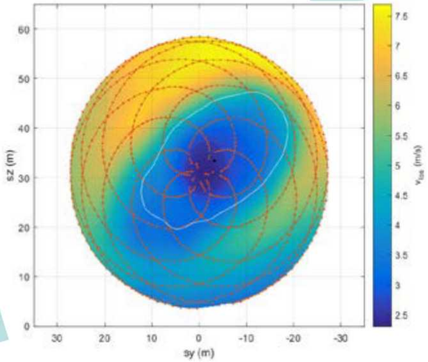
Thank you





Virtuous Cycle
Validation
Model Development
Experimentation
Uncertainty Quantification





SAND2018