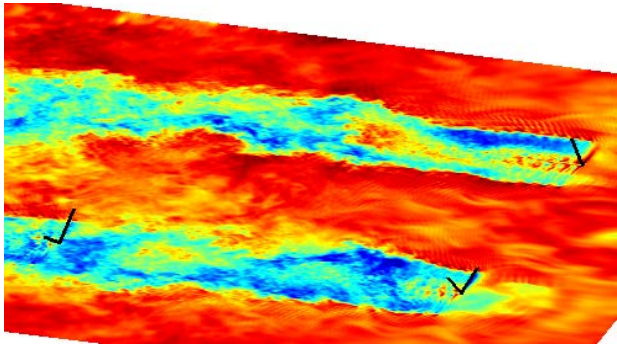
Exceptional service in the national interest



Wake Dynamics Validation Campaign Planning

David Maniaci and Daniel Griffith
Wind Energy Technologies Department
Sandia National Laboratories

Uncertainty and Risk Assessment in the Design Process for Wind, NREL Mini-Workshop
June 13, 2016

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What is V&V?

ASME definitions:

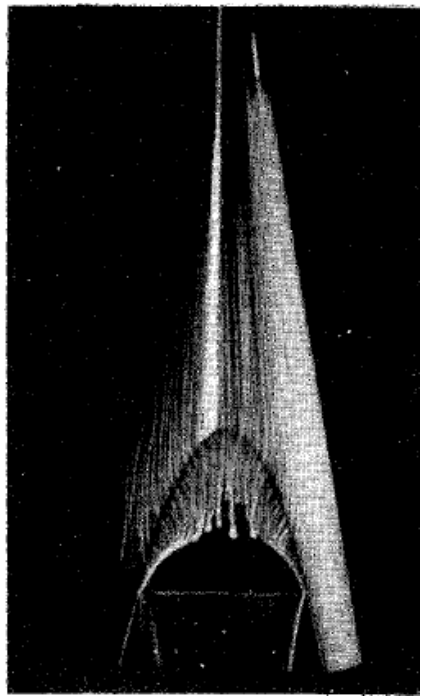
- Verification: The process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model.
- Validation: The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.
  - "Validation tests against independent data that have not also been used for calibration are necessary in order to be able to document the predictive capability of a model."
    - » Ref Gaard and Henriksen

SNL V&V Practice

AIAA JOURNAL
Vol. 30, No. 8, August 1992

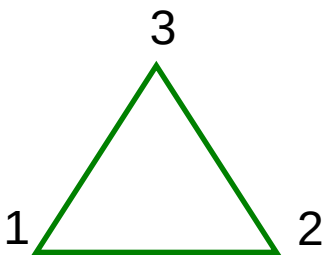
Joint Computational/Experimental Aerodynamics Research on a Hypersonic Vehicle, Part 1: Experimental Results

William L. Oberkampf* and Daniel P. Aeschliman†
Sandia National Laboratories, Albuquerque, New Mexico 87185



- "…improve confidence and accuracy in both wind-tunnel measurements and computational aerodynamic predictions… through a joint endeavor."

Case Study: Validation of Structural Models



- Model Validation is a comprehensive process
  - Carefully designed and executed *experiments*
  - Proposing appropriate physics-based *models*
  - *Correlation* techniques to improve these models using test data

- Overview of the Validation Process
  1. Develop Mathematical Model
  2. Perform Tests to Evaluate Mathematical Model
  3. If necessary, update model form and/or parameters to agree with test observations
  4. Perform additional *validation experiments* under new conditions

- Goals of Validation
  - *Predictive analysis* capability – design with minimal testing

Modal Testing is the Standard Means for Validating Structural Dynamics Models

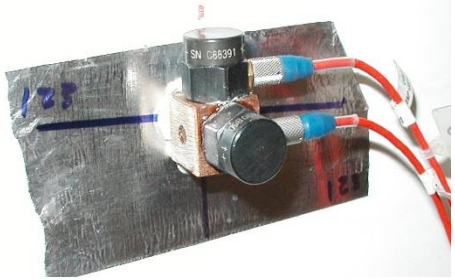
- Modal testing is used to measure the dynamic properties of the structure.
- Modes of a structure refer to structural resonances and each mode is characterized by these inherent properties:
  - *Natural frequency*
  - *Damping*
  - *Mode shapes*
- Natural frequency and mode shape can be computed from a model to compare

Experimental Considerations for Validation: *Experimental UQ*

- Uncertainty is composed of random and bias errors
  - Random errors are typically small
    - e.g. force level and location, algorithm
  - Bias errors can be large in test setup

Support conditions (boundary conditions)

Instrumentation Effects (sensors and cables)

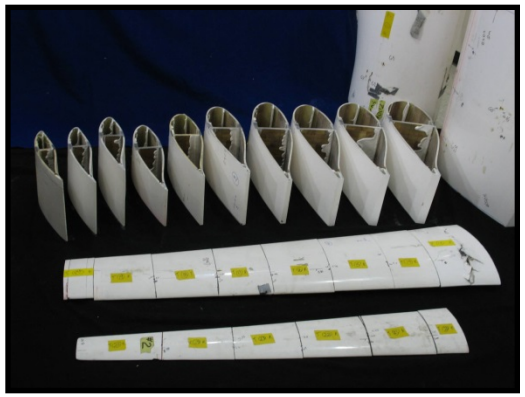


Model Calibration Strategy:

A Hybrid Approach Using Modal and Static Test Data

Modal Test

Mass, Geometric Properties

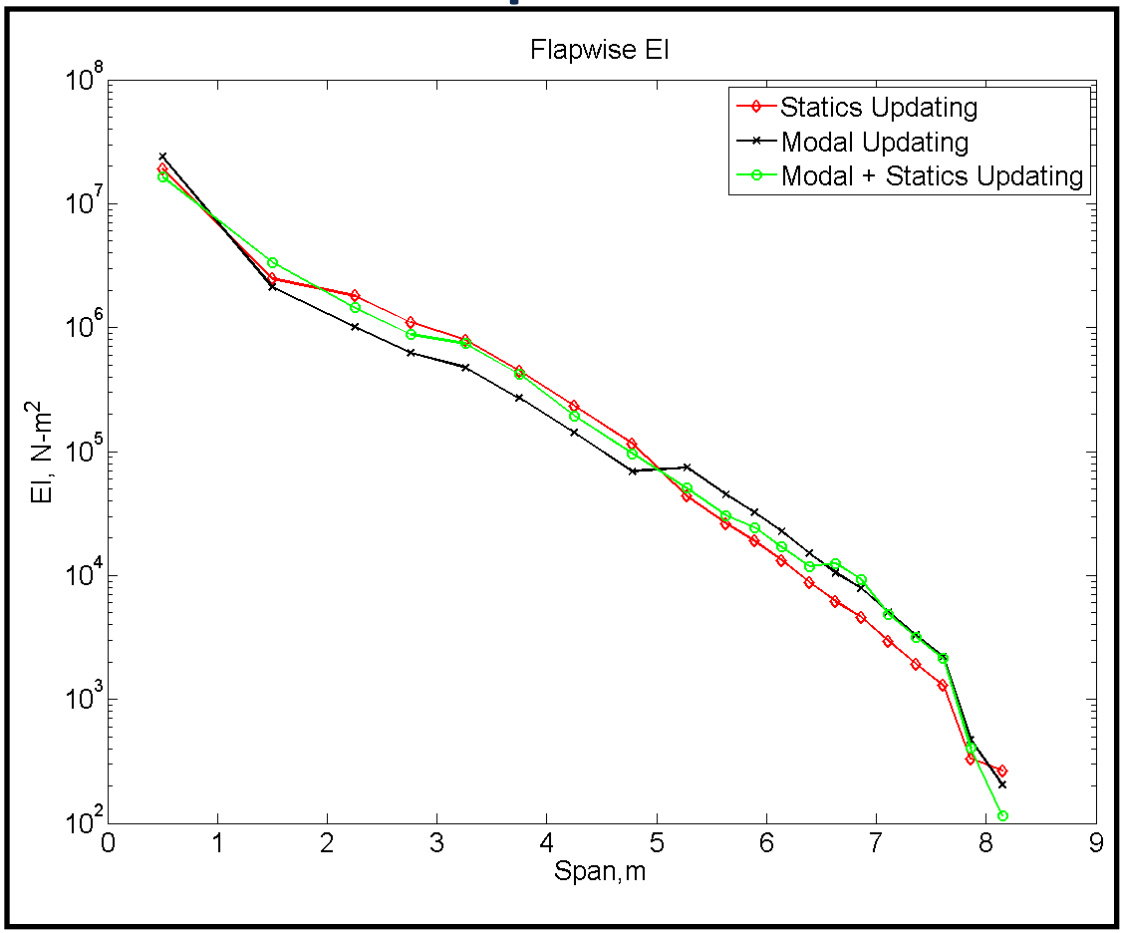


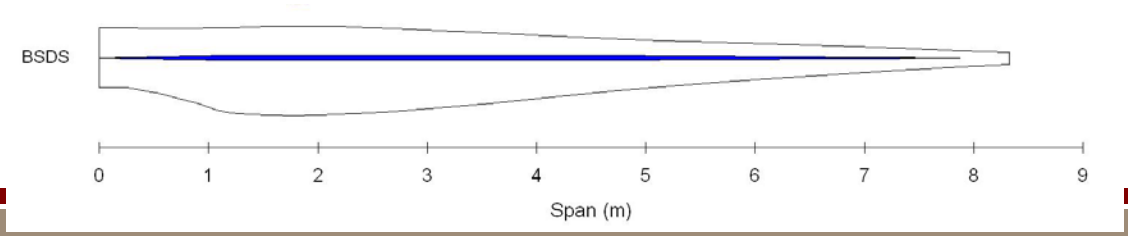
Static Test

Beam FEM Optimization

Updated Model Parameters (Stiffness in this case)

Results for Model Calibration of Flap-wise EI





Statics

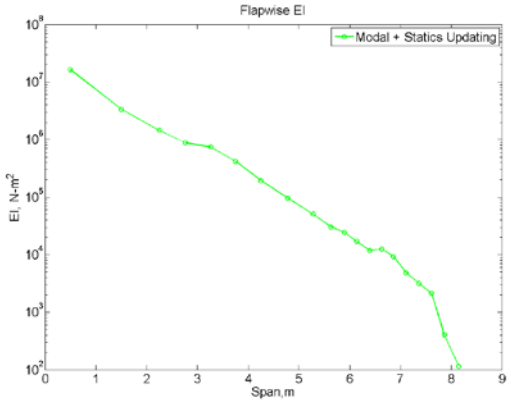
Modal

Modal plus Statics

The story is not complete! Validation experiments must be performed to assess the credibility of the calibrated model.

Model Validation Approach

Calibrated Blade Model



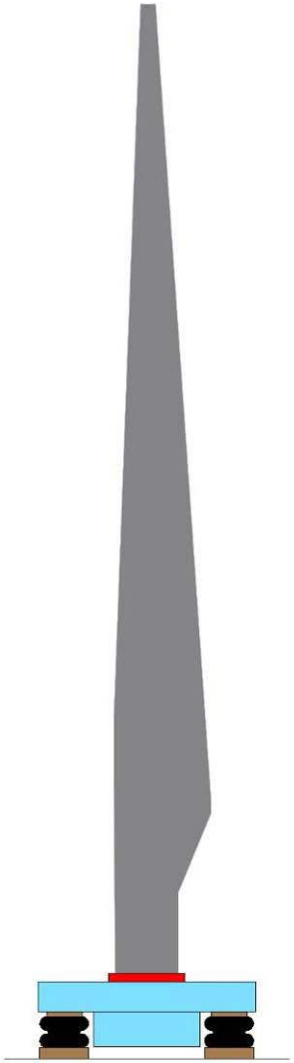
Calibrated Boundary Condition Model

Combine calibrated models, make predictions, and compare with validation test

Validation Test

Model Validation Results:

Validation metric is less than 5% error in frequency



- **This "system" has six rigid body modes, which provide a check of boundary condition model.**
  - **1.1% error in prediction of the pitching RB mode in flap-wise direction**
- **Flap-wise bending modes provide a check of flap-wise blade EI properties**
  - **Less than 3.5% error in prediction of each of the first four flap-wise frequencies**

Publications – web: www.sandia.gov/wind

1. Griffith, D.T., Carne, T.G., and Paquette, J.A., “Modal Testing for Validation of Blade Models,” *Wind Engineering*, Vol. 32, No. 2, 2008, pgs. 91-102.
2. Griffith, D.T., Carne, T.G., and Paquette, J.A., “Experimental Modal Analysis for 9-meter Research-sized Wind Turbine Blades,” Proceedings of the 28th International Modal Analysis Conference, February 1-4, 2010, Jacksonville, FL, USA.
3. Griffith, D.T., Hunter, P.S., Kelton, D.W., Carne, T.G., and Paquette, J.A., “Boundary Condition Considerations for Validation of Blade Structural Models,” Proceedings of the Society for Experimental Mechanics (SEM) Annual Conference and Exhibition, June 1-3, 2009, Albuquerque, NM, USA.
4. Griffith, D.T., “Structural Dynamics Analysis and Model Validation of Wind Turbine Structures,” 50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Presented in Special Session on “Wind Energy Technology”, May 4-7, 2009, Palms Springs, CA, USA, AIAA-2009-2408.
5. Griffith, D.T., Paquette, J.A., and Carne, T.G., “Development of Validated Blade Structural Models,” 46th AIAA Aerospace Sciences Meeting and Exhibit, 7-10 January 2008, Reno, NV, USA, AIAA 2008-1297.
6. Griffith, D.T., Carne, T.G., and Paquette, J., “Modal Test Techniques for Validation of Blade Models,” Proceedings of the American Wind Energy Conference WINDPOWER 2007 Conference and Exhibit, June 4-7, 2007, Los Angeles, CA, USA.
7. Carne, T.G., Griffith, D.T., and Casias, M., “Support Conditions for Free-Boundary Condition Modal Tests,” Proceedings of the 25th International Modal Analysis Conference, February 2007, Orlando, FL, USA.
8. Griffith, D.T., Casias, M., Smith, G., Paquette, J., and Simmermacher, T.W., "Experimental Uncertainty Quantification of a Class of Wind Turbine Blades," Proceedings of the 24th International Modal Analysis Conference, February 2006, Saint Louis, MO, USA.
9. Paquette, J., Laird, D., Griffith, D.T., and Rip, L., "Modeling and Testing of 9m Research Blades,", 44th AIAA Aerospace Sciences Meeting and Exhibit, 9-12 January 2006, Reno, Nevada, AIAA 2006-1199.

VALIDATION PROGRAM

What is a Validation Focused Program?

Goal

- Formalized highly collaborative approach to planning and executing joint experimental/modeling programs for the purpose of characterizing model accuracy for an intended application

Why?

- Provides a transparent, structured, documented approach for integrate program planning across scales
- Applicable to models of all fidelity, including reduced order models
- High quality data sets well suited for collaborative model validation efforts
- Quantifies prediction uncertainty for use by designers

Foundation of framework used

- Framework developed for nuclear energy, SNL NW, and other programs
- Framework consistent with various ASME and AIAA V&V Guides, Codes and Standards

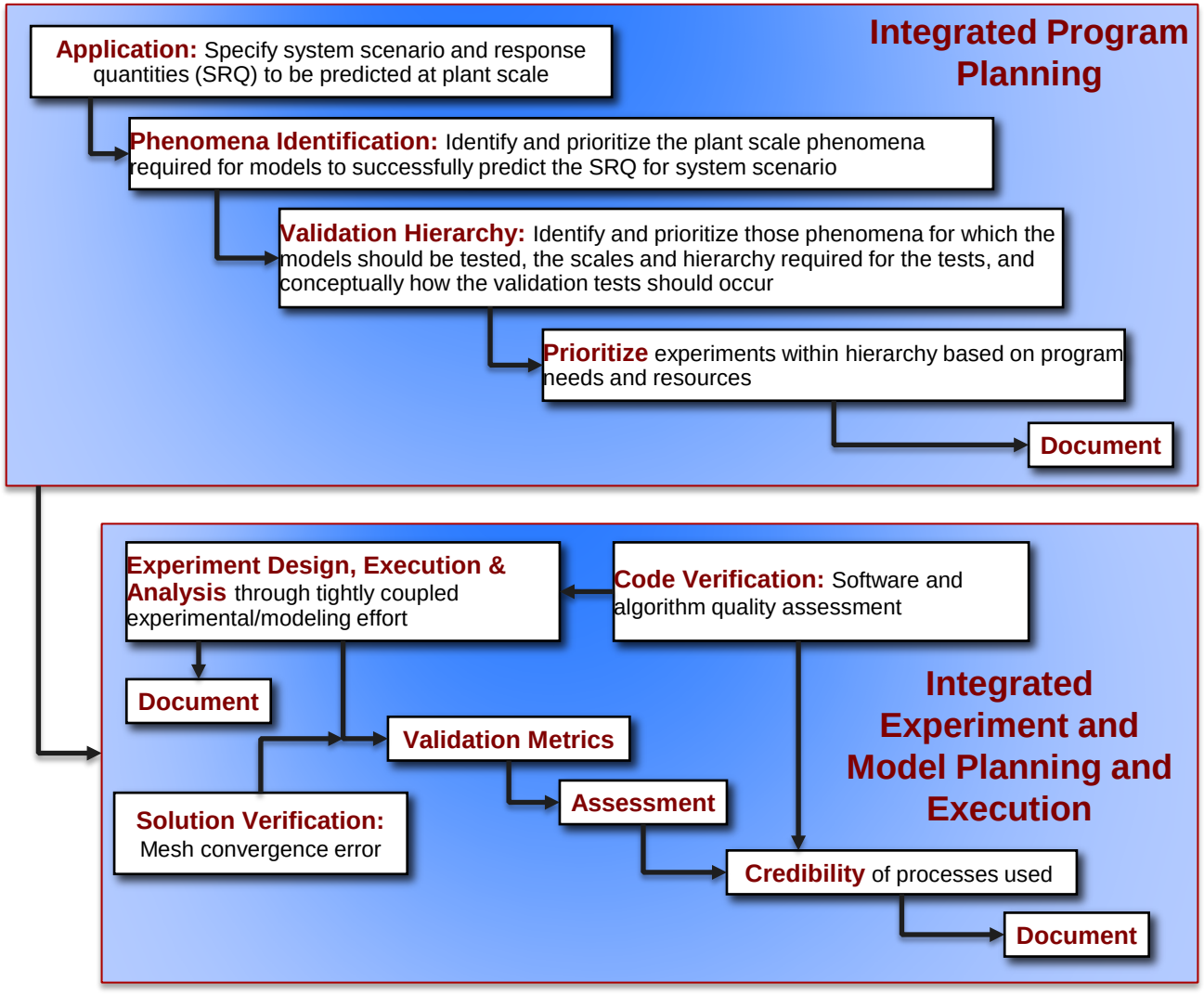
V&V Framework

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



Types of Experiments

- **Tech demonstration**: Perform subscale technology demonstration tests, but do it with rotors which meet full-scale similitude requirements

- **Model validation:** Accurately predict, assess and optimize wind plant performance utilizing High Fidelity Modeling (HFM) tools to understand and accurately predict the fundamental physics and complex flows of:
  - the atmospheric boundary layer
  - interaction with the wind plant
  - the response of individual turbines to the complex flows within that plant

- Other types of experiments include calibration, phenomena discovery, mathematical model development, or phenomena exploration

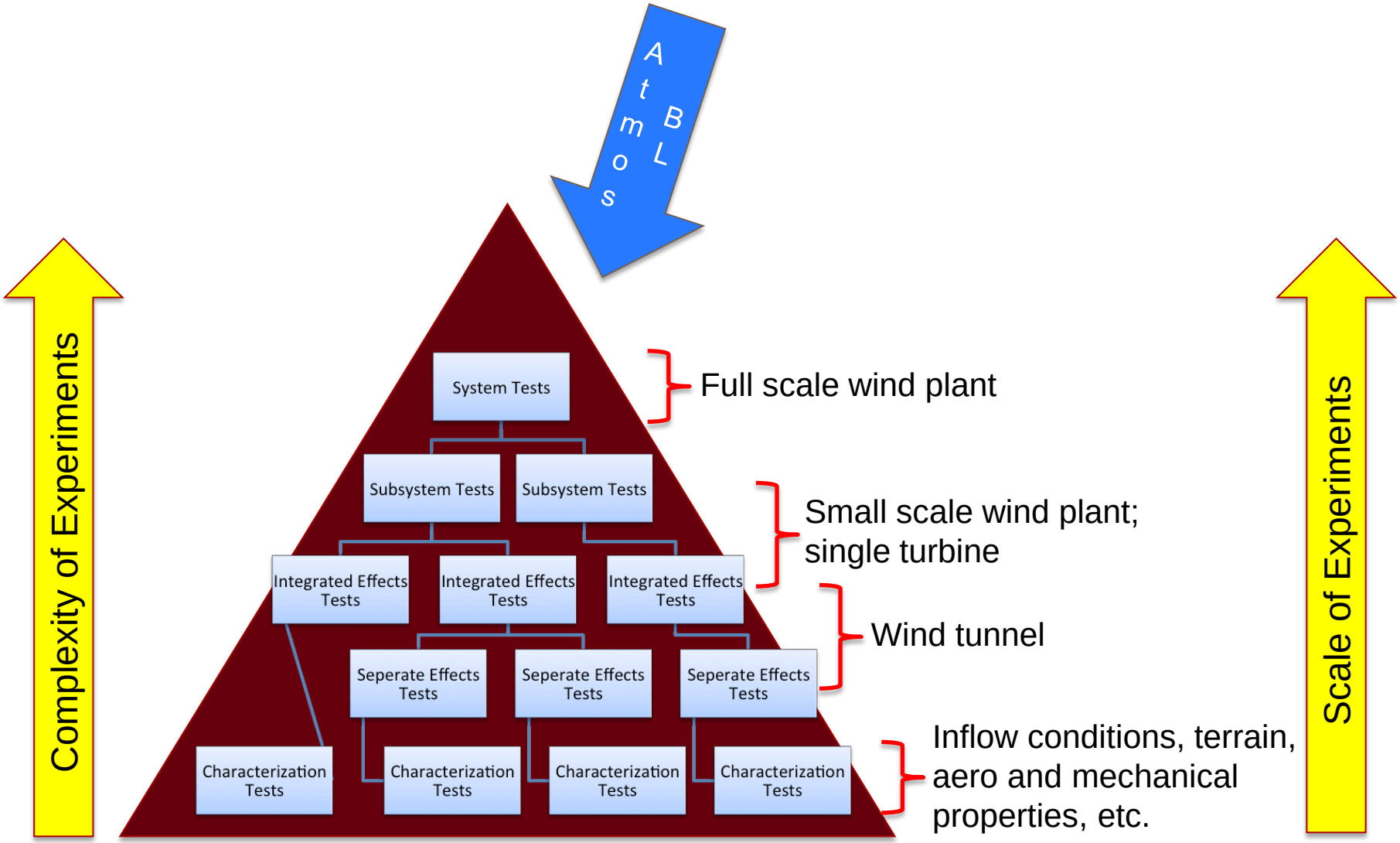
Backbone of Prioritization Process: PIRT

PIRT: Phenomenon Importance 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

PIRT Leads to the Validation Hierarchy



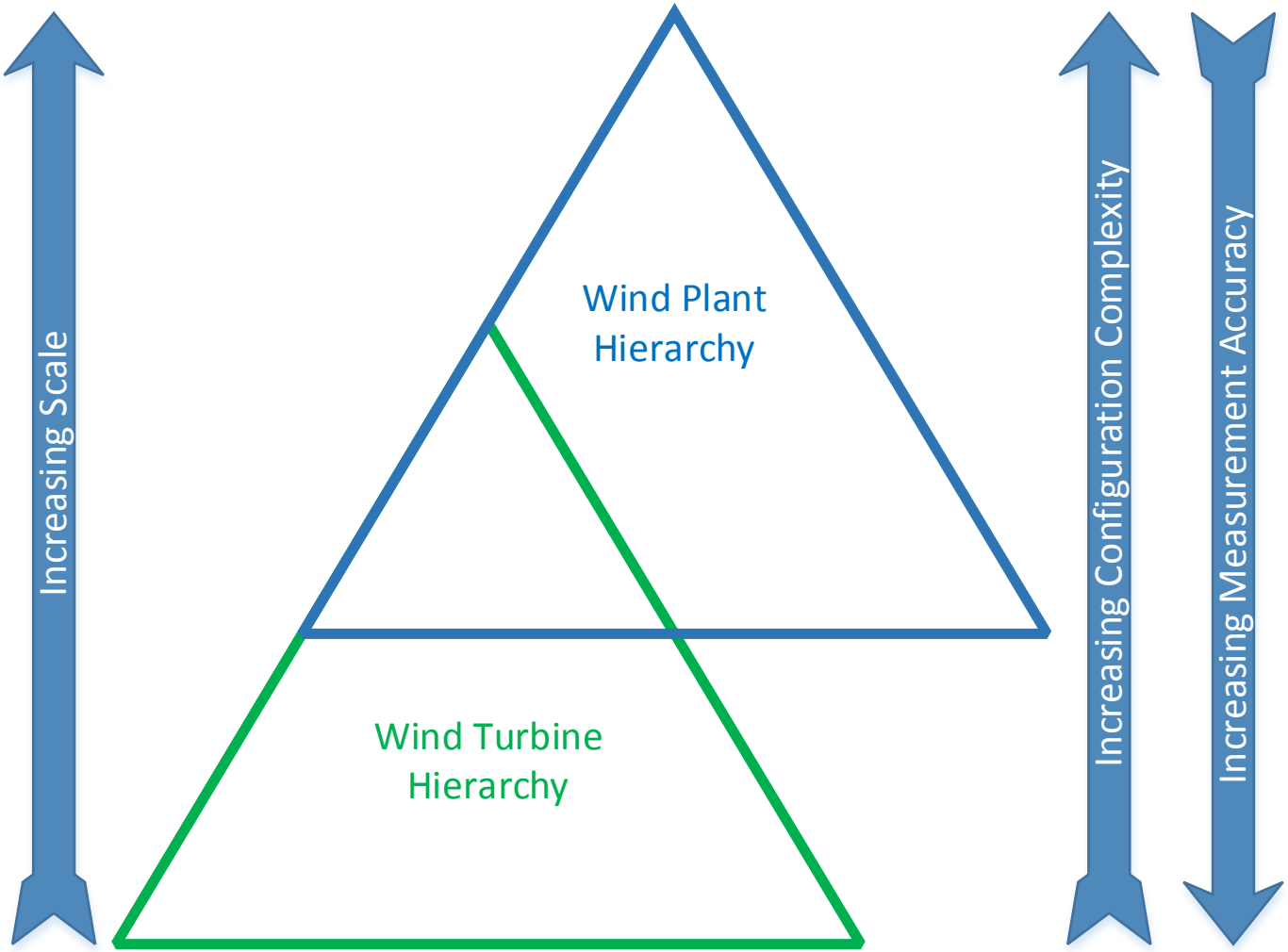
Wind Turbine Scale PIRT

Phenomenon	Importance at Application Level	Model Adequacy			Issue/Comments	Response Including Scale
		Physics	Code	Val		
Blade Aero / Wake Generation						
Blade load distribution effects and rotor thrust	H	M	L	L	Integrates to Rotor Thrust-Torque; Rotor Load Model important for LES-ALM.	Some experiments done for validation. Important to measure for experiments where rotor loading is correlated to wake
Tip and root vortex development, evolution and merging	H	M	L	L	Wake PIV Experiments performed, but error bars and QA/QC may be missing or unknown. Does not cover effect of inflow conditions.	Full-scale and sub-scale field sites, and wind tunnel testing.
Vortex sheet and rollup (in addition to tip/root vortex)	M	M	M	L	Some experimental data available that indicates phenomenon are present and may be important to wake stability. Effect of separation uncertain.	Further discovery experiments -> validation experiments.
Blade generated turbulence characteristics (energetic scales at trailing edge)	H	L	L	L	Coherent vortices shed from blade, including how they interact with the atmosphere and near-wake.	Full-scale and sub-scale field sites. High bandwidth probes, flow imaging.
Root flow acceleration effect ('hub jet')	Unknown	M	L	L	Effects root dynamic pressure and loading.	Sensitivity Study to assess importance, qualitative data available.
Boundary layer development (transition, separation)	H	M	L	L	Affects airfoil tables -> AL methods. Affects fully resolved modeling requirements (grid, transition model). Depends on incoming turbulence intensity relevant to blade surface boundary layer, depends on surface quality (roughness, soiling, bugs, erosion).	Wind tunnel and field tests.
Surface roughness effects (roughness, soiling, bugs, erosion)	H	L	L	L	Directly influences boundary layer development and blade loads.	Wind tunnel and field tests. Full scale surface quantification.
Boundary layer details near leading and trailing edge	H	M	L	L	Relates to boundary layer development, and important for aeroacoustics.	Full-scale and sub-scale field sites
Rotational augmentation	H	L	L	L	Inability of HFM models to capture stall consistently.	Tests done on multiple rotor scales, need to assess gaps remaining from
Dynamic stall	H	L	L	L	2D data based on non-specific wind turbine airfoils and/or are limited to lower Reynolds numbers than relevant to full-scale.	Tests done on multiple rotor scales, need to assess gaps remaining from
Unsteady inflow effect (veer, shear, yaw, gusts, atmospheric stability, turbulence intensity, spectra, coherence)	H	L	L	L	Larger time scale than what affects blade surface BL, but faster than that allowed by steady-state on chord scale.	Full-scale and sub-scale field sites, and wind tunnel testing.
Blade flow control	M	L	L	L	Can be used to enhance blade performance and alleviate loads.	Full-scale and sub-scale field sites, and wind tunnel testing.
Icing	H	L	L	L	Importance depends on regional climate (Northeast vs Midwest)	Full-scale and wind tunnel testing.
Wake Development (growth/recovery)						
Skew and meander of aggregate wake	H	L	L	L	Gross movement and deflection of far-wake.	Full-scale and sub-scale field sites, and wind tunnel testing.
Swirl instability	L	L	L	L	Interaction of axial and tangential momentum	Wind tunnel tests.
Vortex merging	L	L	L	L	Important for the far-wake and turbine-turbine interaction.	Sub-scale field sites and wind tunnel testing.
Wake vorticity diffusion and dissipation	H	L	L	L	Important to wake recovery and far-wake properties.	Sub-scale field sites and wind tunnel testing.
Asymmetry effects (ground plane, yaw, tilt, cone-angle)	M	M	L	L	Influence the wake stability, recovery, meander, and vertical and	Full-scale and sub-scale field sites, and wind tunnel testing.
Inflow effect (shear, veer, yaw, turb. intensity, turb. spectrum, coherence, gusts, atmos. stab.)	H	L	L	L	Full scale data often does not measure to top of turbine, limited to single vertical profile.	Full-scale and sub-scale field sites, and wind tunnel testing.

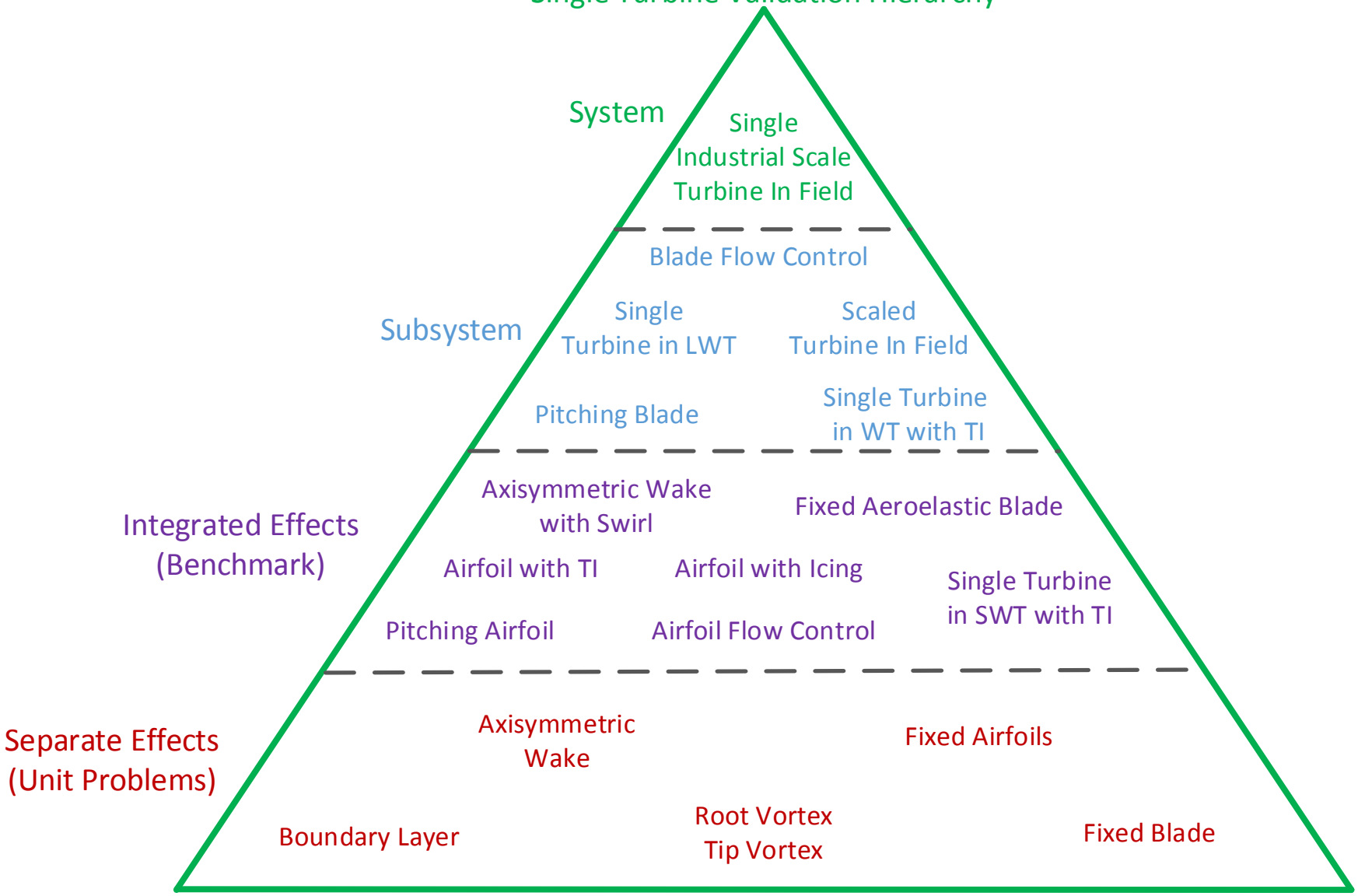
Wind Plant Scale PIRT

Phenomenon	Importance at Application Level	Model Adequacy			Issue/Comments	Response Including Scale	Interface
		Physics	Code	Val			
Inflow Turbulence/Wake Interaction							
Wind direction (shear/veer/asymetry)	H	L	M	M	Wake sensitivity to gusts, low-level jets, etc. that promote three-dimensional boundary layers	Wind tunnel and field tests.	ABL/Turbine
Turbulence characteristics (intensity, spectra, coherence, stability)	H	L	M	M	Wake sensitivity to turbulence	Wind tunnel and field tests using real and psuedo ABL spectra	ABL
Coherent turblence structure	H	L	M	L	Wake sensitivity to organized structures	Difficult to test, but could include both wind tunnel and field tests.	ABL
Surface conditions (roughness, canopy, waves, surface heat flux, topography)	H	L	M	M	Wake sensitivity to changes in ABL due to surface features	Wind tunnel and field testing looking at changes in ABL	ABL
Momentum transport (horizontal and vertical fluxes)	H	L	L	L	Wake sensitivity to momentum supplied by ABL. Side-flow is a special case, as well as the deep array.	Wind tunnel and field tests.	ABL
Multi-Turbine Wake Effects							
Wake interaction, merging, meander	H	L	L	L	Physics behind unsteady wake behavior	Wind tunnel and field tests.	
Plant flow control for optimum performance	H	M	M	L	Strategies for optimizing the wind farm rather than individual turbines	Subscale and full scale field tests. Large controlled facility tests.	
Wake steering (yaw & tilt effects)	H	L	L	L	Effect of non-normal inflow on wake behavior. Useful for control.	Wind tunnel and field tests.	
Wake dissipation	H	L	L	L	Evolution toward a neglibly small wake	Wind tunnel and field test	
Wake Impingement (full, half, etc.)	H	L	L	L	Effect of upstream wake position on downstream turbine	Wind tunnel and field test	
Deep array effects (change in turbulence, etc.)	H	L	L	L	Emphasis on the behavior of the flow within the wind plant	Wind tunnel and full scale field test	
Other Effects							
Wind plant blockage effects and plant wake	M	M	M	L	Emphasis on the effect of the wind farm on cross-stream downstream regions	Wind tunnel and full scale field test	ABL
Acoustic Propagation	H	L	L	L	Noise generation and propogation through a wind plant	Full-scale and sub-scale field sites	Turbine

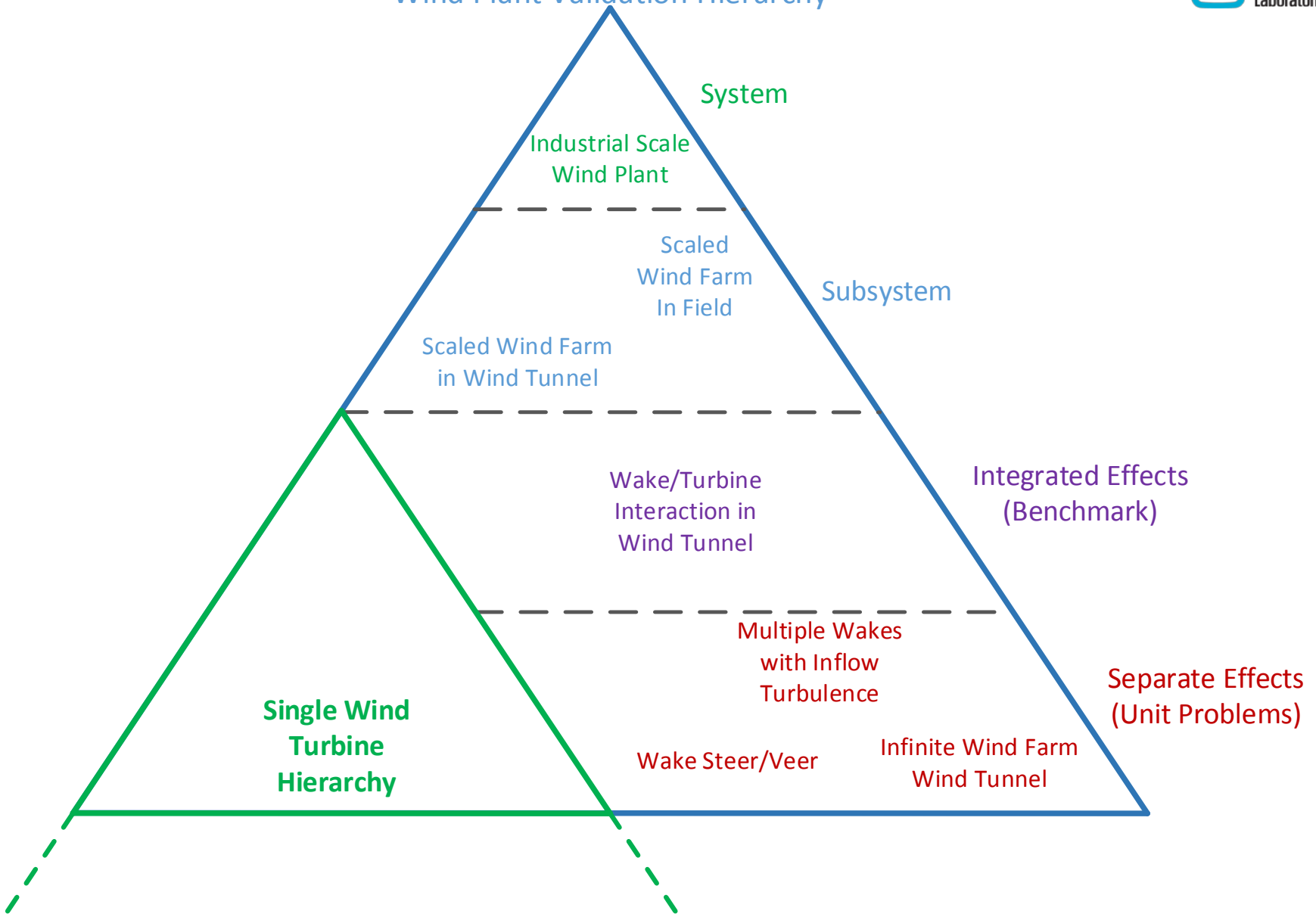
Validation Hierarchy



Single Turbine Validation Hierarchy



Wind Plant Validation Hierarchy



PPEM (Prioritized Phenomenon Experiment Mapping)

Wind Plant

Physics Present/Physics Measured

- Entirely
- Mostly
- Somewhat
- Limited
- Missing

	Multi-Turbine Wake Effects				**Inflow Turbulence Wake Interaction**			
	Interaction, Merging, Motion	Steering (Yaw/Tilt Effects)	Wake Dissipation	Wake Impingement (Full/Half/Near)	Wind Direction	Surface Conditions	Turbulence Statistics	Momentum Transport
Industrial Scale Wind Farm in (60 m rotor)								
Physics Present	Entirely	Entirely	Entirely	Entirely	Entirely	Entirely	Entirely	Entirely
Physics Capture by Measurements	Limited	Limited	Limited	Limited	Somewhat	Mostly	Limited	Limited
Scaled Wind Farm in Field (20 m rotor)								
Physics Present	Entirely	Entirely	Mostly	Entirely	Entirely	Mostly	Mostly	Mostly
Physics Capture by Measurements	Somewhat	Somewhat	Missing	Somewhat	Mostly	Mostly	Somewhat	Limited
Scaled Wind Farm in VL WT (2 m rotor)								
Physics Present	Mostly	Mostly	Somewhat	Mostly	Entirely	Somewhat	Somewhat	Somewhat
Physics Capture by Measurements	Mostly	Mostly	Mostly	Entirely	Entirely	Entirely	Mostly	Mostly

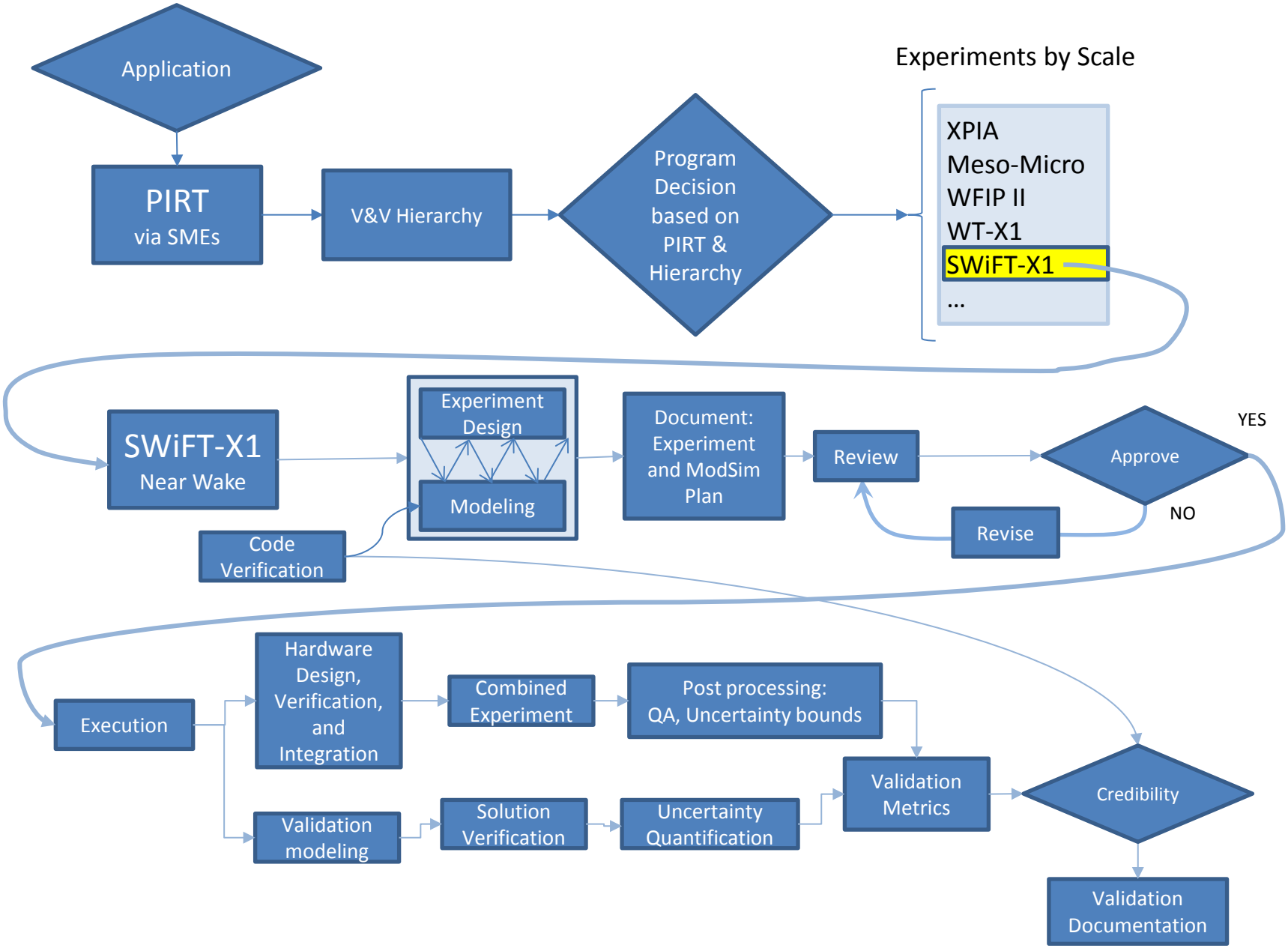
Validation Hierarchy Leads to Validation Experiments

Validation is a process of characterizing model error, not a binary statement of model validity

Characteristics of a successful validation programs

- Highly collaborative – team includes experimentalist, modelers, V&V specialist
- Models are used during the design phase to
  - Assure that the experiments are sensitive to the phenomena of interest
  - Help optimize the experiments, i.e. define sensor location, density, sampling rates, …
  - Assure that the experiments can be unambiguously modeled (failure to do this is the most common reason for the failure of a validation exercise)
- Estimates of data uncertainty and model prediction uncertainty play a key role model validation process
- Model credibility is established by following a formal verification and validation process

Verification and Validation Process Application

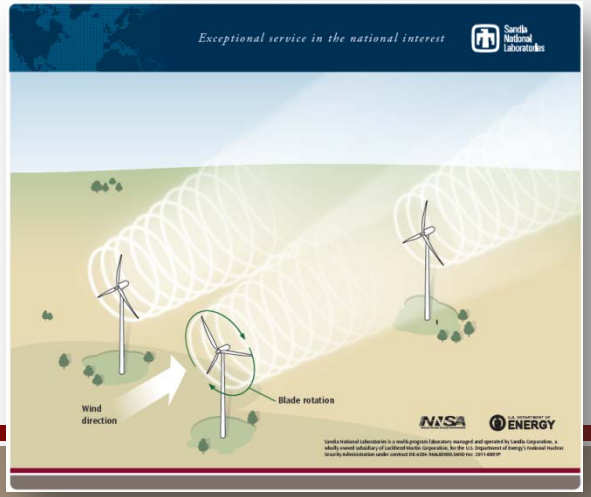


SWiFT Site Layout and Capabilities

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

SWiFT exists to:

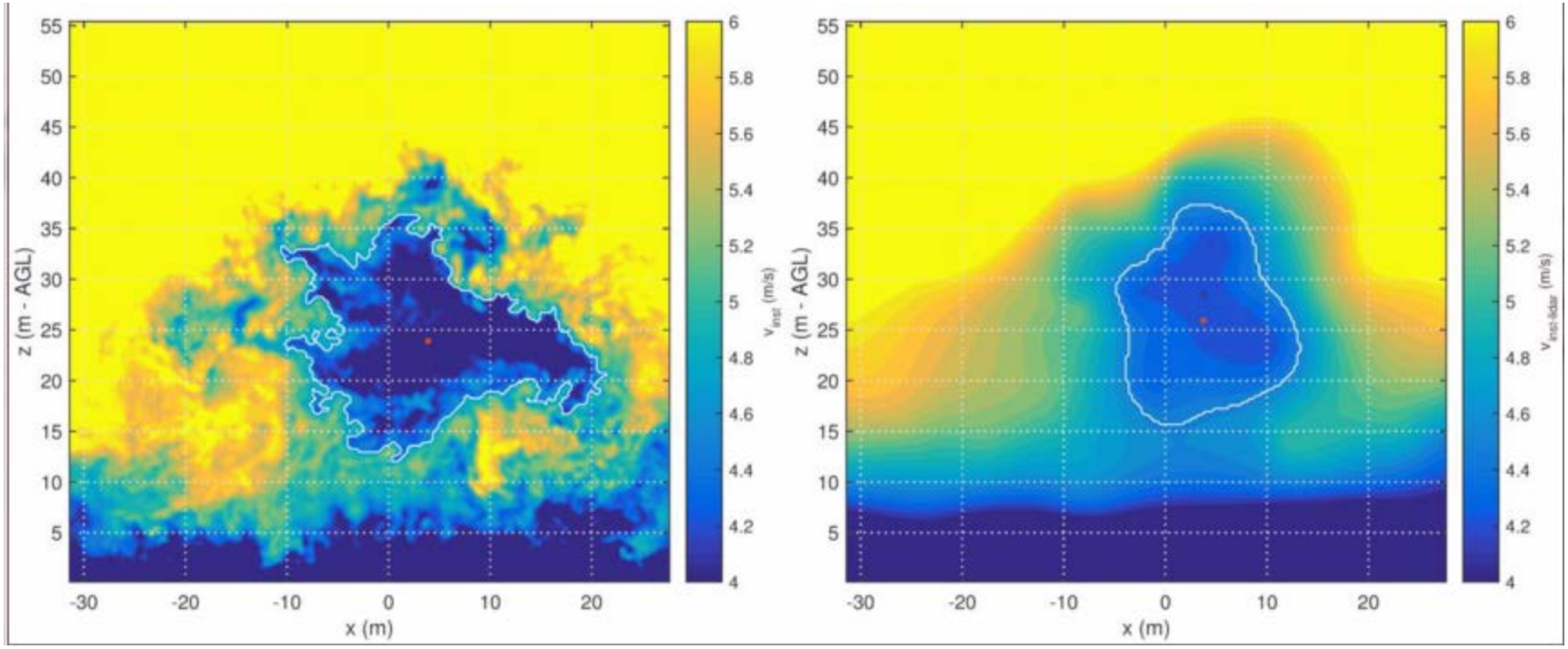
- Reduce turbine-turbine interaction and wind plant underperformance
- Public, open-source validation data
- Advance wind turbine technology



Facilities:

- Three variable-speed variable-pitch modified wind turbines with full power conversion and extensive sensor suite
- Two heavily instrumented inflow anemometer towers
- Site-wide time-synchronized data collection

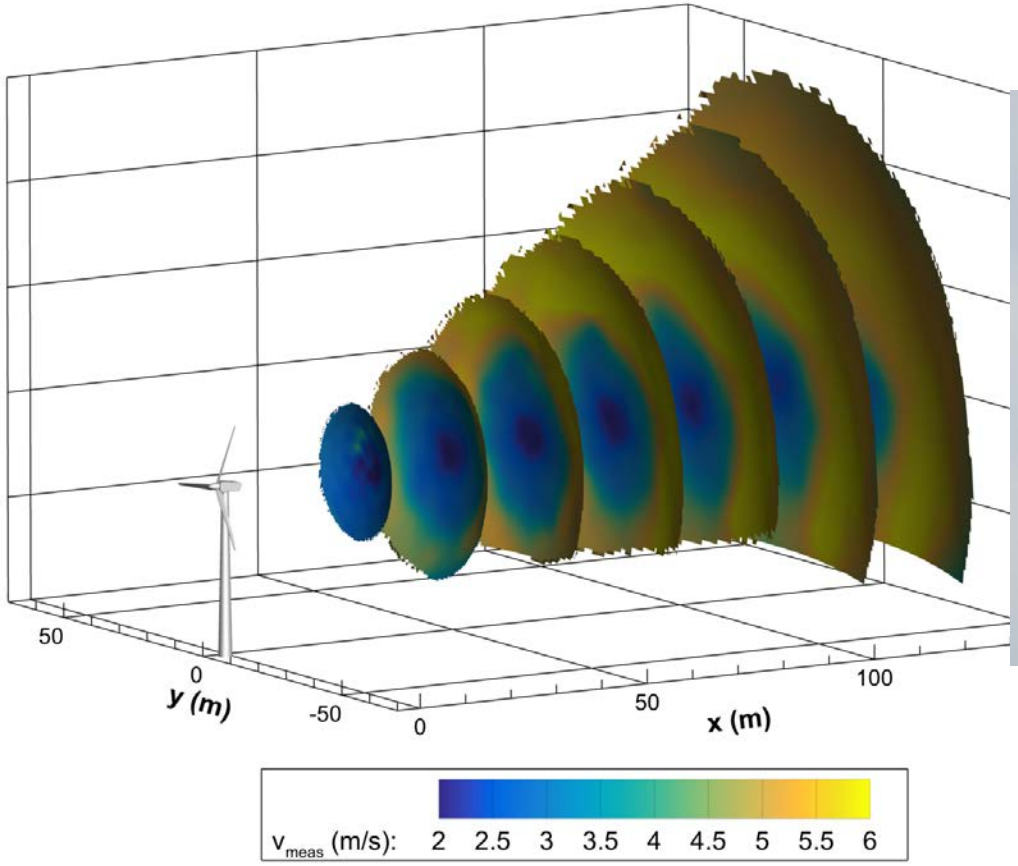
Models Integral to Experiment Planning



LES wake prediction (SOWFA)

Wake filtered through synthetic lidar.

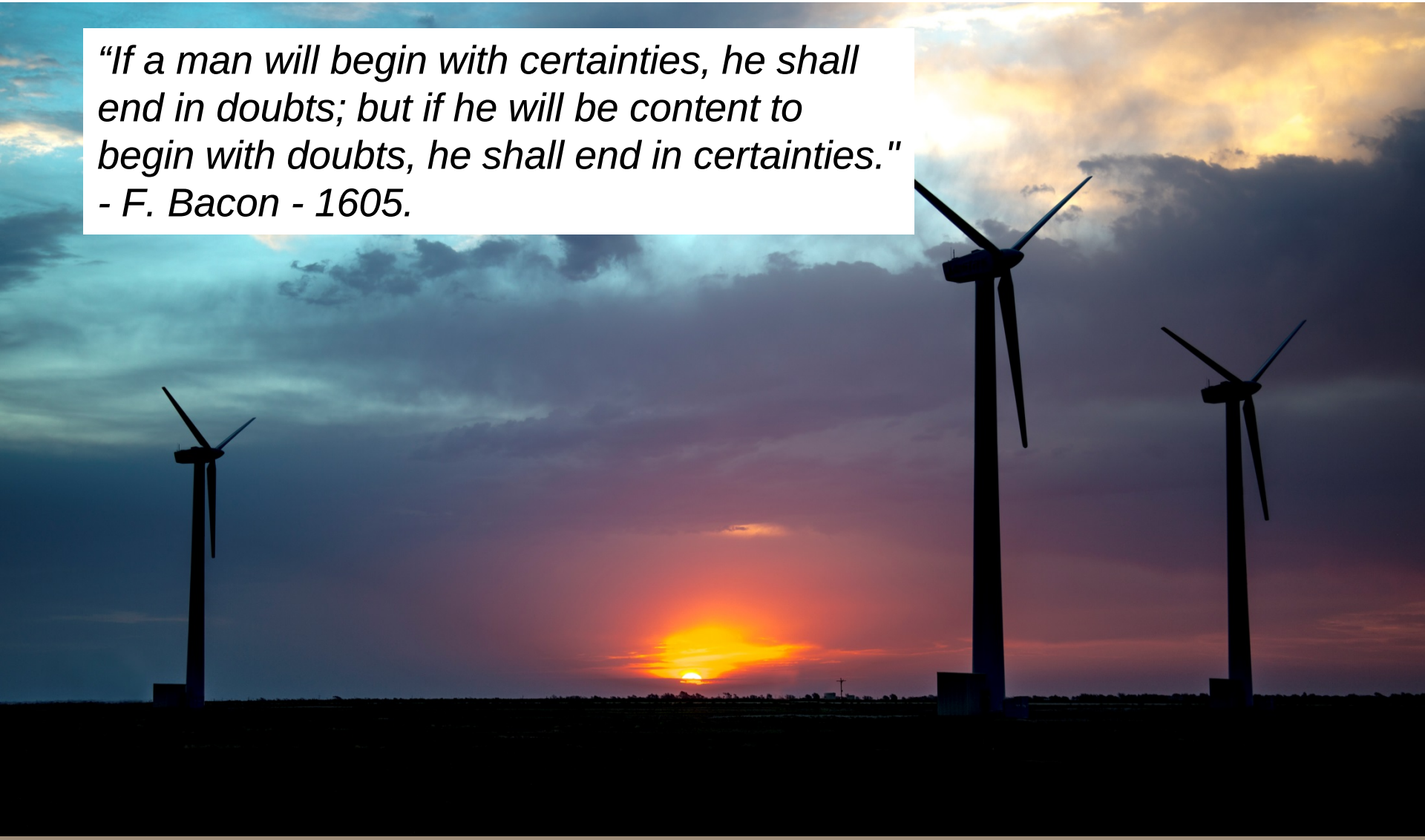
Initial Wake Measurements



Conclusions

- System complexity and uncertainty leads to a large, coupled set of physics
  - Prioritization is a challenge
- Must rely on a series of experiments, organized through a hierarchy
- Documentation is important so that the suite of test campaigns can build confidence in the code for desired applications

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.