SAND2015-0458PE

Exceptional service in the national interest

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Overview of a Sandia integrated subscale wind farm measurement campaign for model validation

January 26, 2015

U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration

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Objectives

- Communicate previously existing SWiFT-related activities
- Realignment of activities to support A2e Validation Hierarchy

Slides overview

- Sandia projects background:
  - SWiFT,
  - Rotors,
  - Wake Imaging
- Realignment of SNL FY15 AOP for A2e science objective related to rotor near wake validation
- V&V background
- High level test objective statement
- Timelines
  - Review points
  - A2e input points

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SWIFT

SWiFT – Lubbock, TX

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UNIQUE CAPABILITIES

- Purpose built to study wind farm wakes and their interaction between wind turbines
- High category wind class, with average winds of 17 mph
- Scaled research turbines allow for rapid technology development at ~1/20th the cost of full-scale testing
- Consistent wind direction and flat terrain

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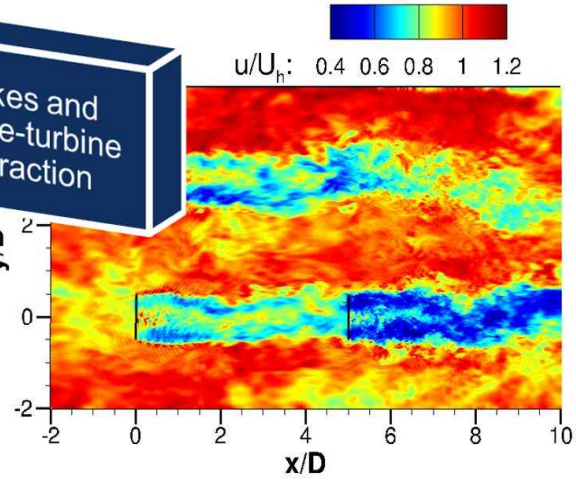
NATIONAL ROTOR TESTBED (NRT)

The National Rotor Testbed (NRT)

Aero-structural rotor design

Building connections between rotor designs and rotor wake research

Wakes and turbine-turbine interaction



A scaling distinction

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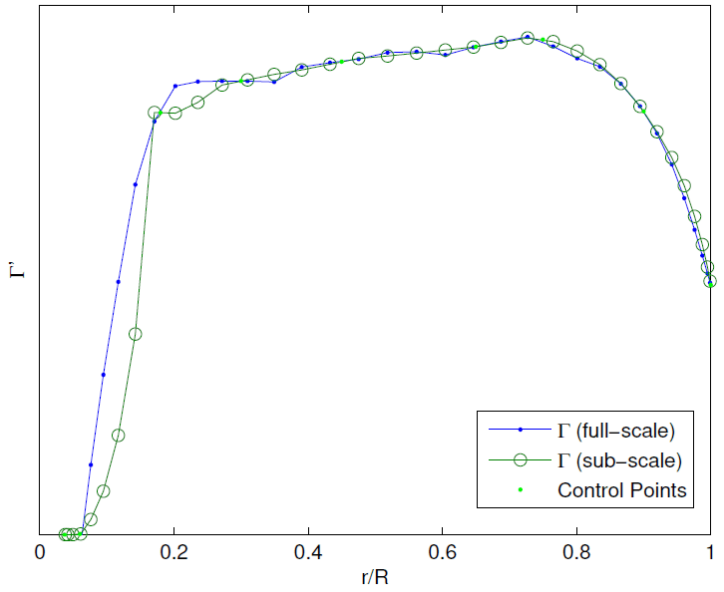
- **Tech demonstration**. Perform smaller, cost-effective technology demonstration tests at subscale, but do it with rotors which meet full-scale similitude requirements as well as possible.
- **Model validation/research**. Produce rotor designs at various scales which possess necessary similitude—i.e. by matching specifically desired quantities—to the relevant utility-scale rotors
  - A V&V goal: Validated models from subscale should be predictive at full scale

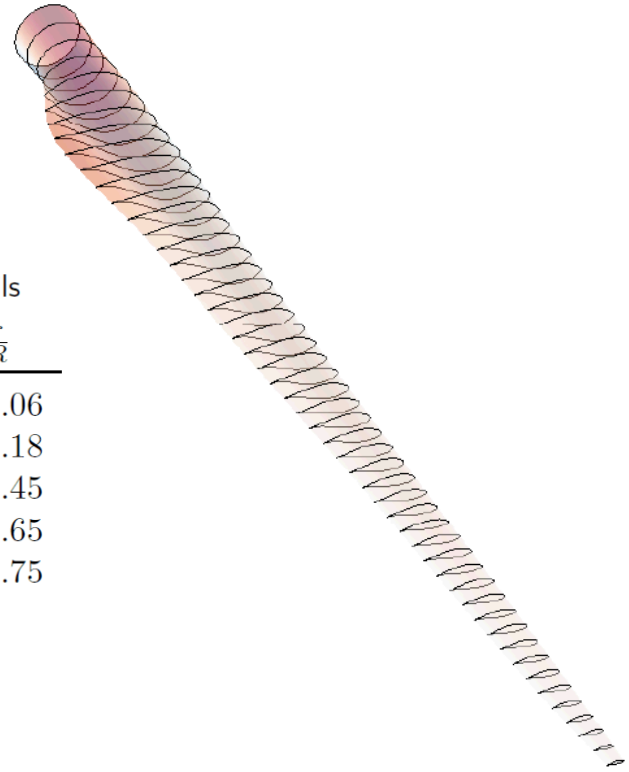
Subscale GE rotor design

Non-dimensional circulation v. span



Sandia Selected Airfoils

Section	Shape	$\frac{r}{R}$
1	Circle	0.06
2	DU 97-W-300	0.18
3	DU 91-W2-250	0.45
4	DU 93-W-210	0.65
5	DU 95-W-180	0.75



C.Kelley, 2014

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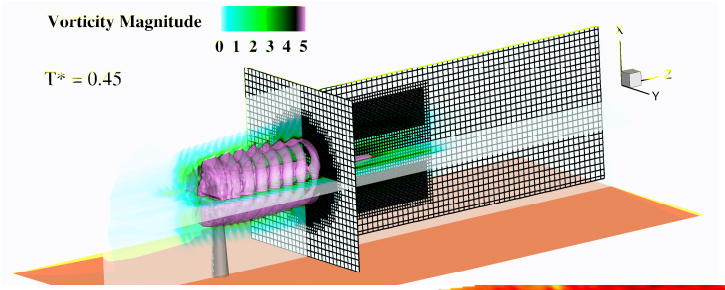
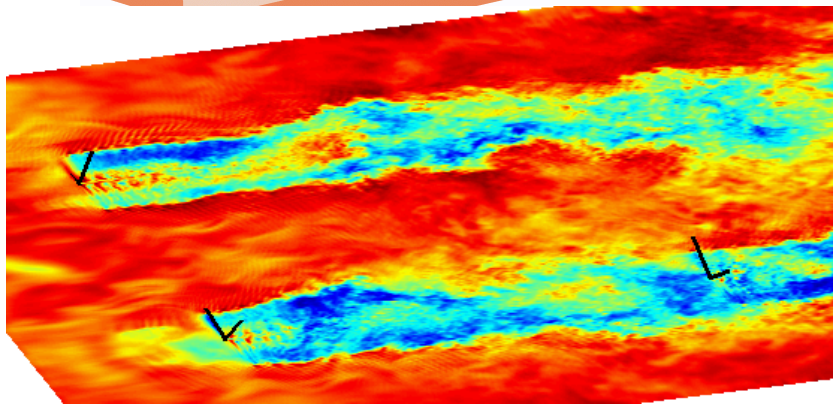
SANDIA WAKE IMAGING SYSTEM

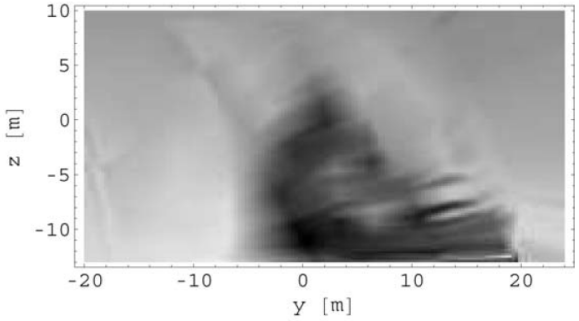
Simulations

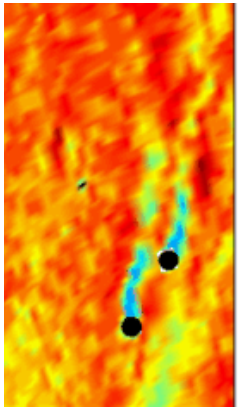




UMN Virtual Wind Simulator (VWiS)

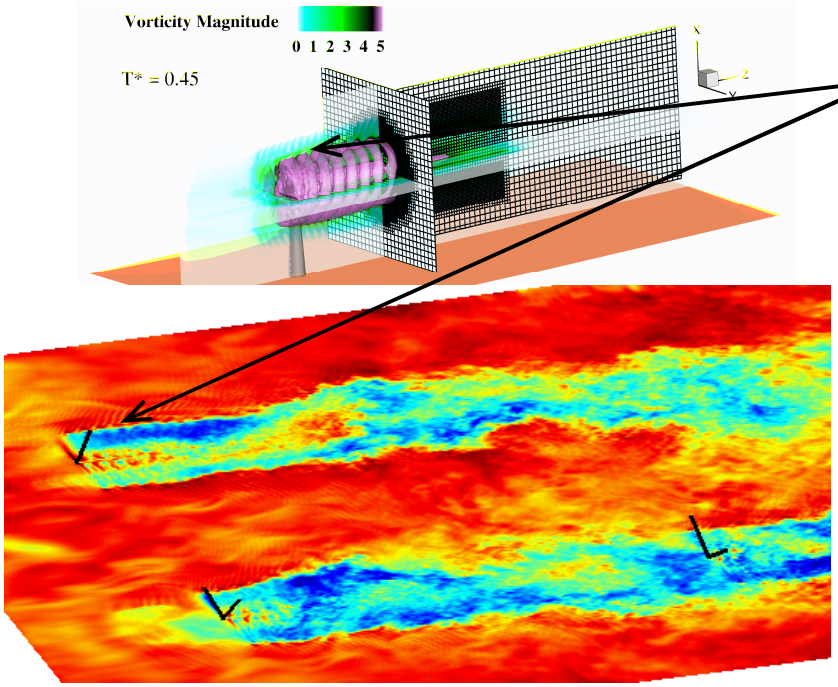
Available Flow Diagnostics





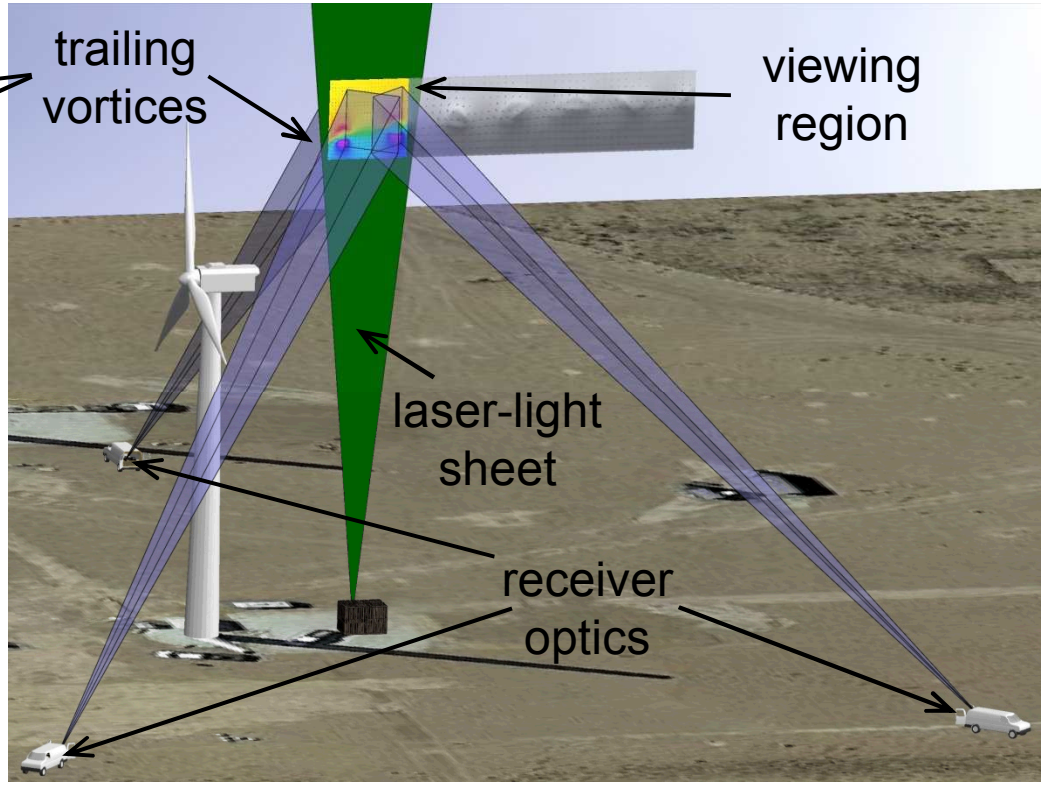
- Modelers want wake data for validation at 1% of the rotor diameter spacing (based on feedback from the NRT Review Meeting in August)
- Current field-scale flow diagnostic techniques are limited to providing several measurement points across the rotor disc
  - Spatial and temporal averaging are inherent to the diagnostics
  - Dominant wake flow structures are not resolved

Simulations



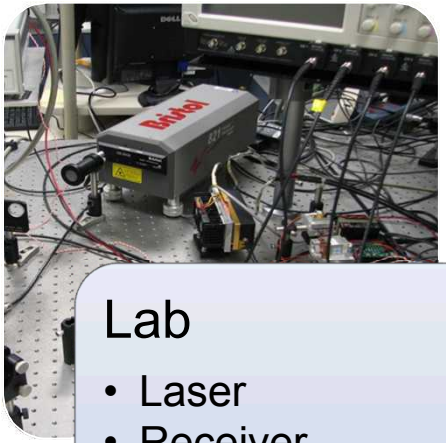
UMN Virtual Wind Simulator (VWiS)

Notional Field System



- The Wake Imaging System will provide a field deployable flow diagnostic with spatial and temporal resolution required to capture dominant near-wake flow structures

Project Arc

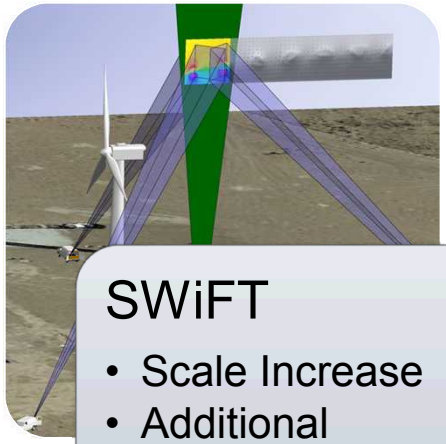


Lab

- Laser
- Receiver
- Iodine Cell
- Image Processing
- 15 cm × 15 cm

Sprung

- Aerosol
- System Sensitivity
- Measurement Uncertainty
- 2 m × 2 m



SWiFT

- Scale Increase
- Additional Velocity Components
- Outdoor Aerosol System
- 5 m × 5 m

Risk reduction approach:

- Demonstrate simplest possible system
- Address make-or-break components
- Build up from lab to field-test to SWiFT experiments
- Identify and resolve ES&H issues early
- Leverage deep expertise, equipment, and facilities at Sandia to save time and money

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REALIGNMENT OF PROJECTS FOR A2E

Three major Sandia FY15 AOP projects realigned

- SWIFT Research
  - Previously—subscale turbine technology and turbine-turbine interaction test campaigns
  - Moving forward—immediate focus on a test campaign to support DOE science and physics objectives, ie inflow, rotor, and near wake model validation
- National Rotor Testbed
  - Previously—outfit the SWiFT turbines with modern rotors
  - Moving forward—create rotors designed to support rotor/wake validation
- Wake imaging system
  - Previously—high-fidelity measurement of inflow/wakes at SWiFT
  - Moving forward—high-fidelity measurement of the tip vortex region of the near-wake with correlation to ABL inflow and blade loading

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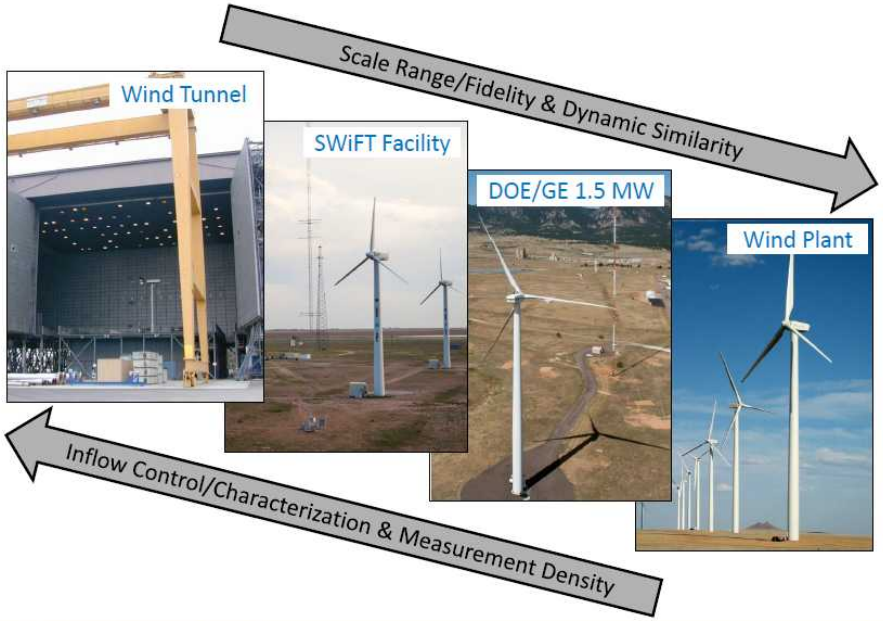
V&V BACKGROUND

DOE Experiment/Test Complex



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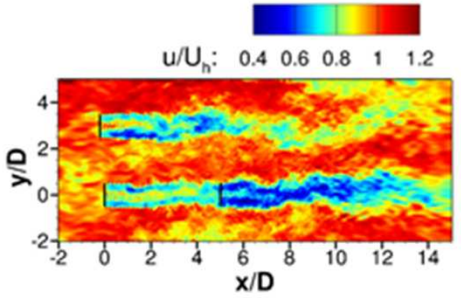
DOE ModSim Complex

- Wind Plant LES: SOWFA, VWiS, CyberWind etc.
- Wind Plant/Rotor Lower Order
- Massively parallel HPC environments and systems
- WRF
- Etc.



Initial, High Priority Strategic Planning Areas

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Strategic Planning Areas

1. **Financial Risk, Uncertainty, and Portfolio Analysis**
   - John Meissner (DOE Contractor)
2. **Verification and Validation**
   - Dr. Rich Hills (SNL)
   a. High Fidelity Modeling
      - Dr. David Womble (SNL), Dr. Steve Hammond (NREL)
   b. Experimental Measurement Campaigns
      - Dr. Scott Schreck (NREL), Dr. David Maniaci (SNL), Dr. Jim Wilczak (NOAA)
3. **Data Archive and Portal**
   - Chitra Sivaraman (PNNL)
4. **Integrated Wind Plant Control**
   - Dr. Kathryn Johnson (Colorado School of Mines/NREL)
   - Dr. Dave Wilson (SNL)
5. **Wind Plant Reliability**
   - Dr. Carsten Westergaard (SNL Contractor)
   - Dr. Jonathan Keller (NREL)
6. **Aeroacoustics and Propagation**
   - Dr. Pat Moriarty (NREL)
7. **Integrated Wind Plant Design and Analysis**
   - Sandy Butterfield (Boulder Wind)

A2e V&V Framework

Why?

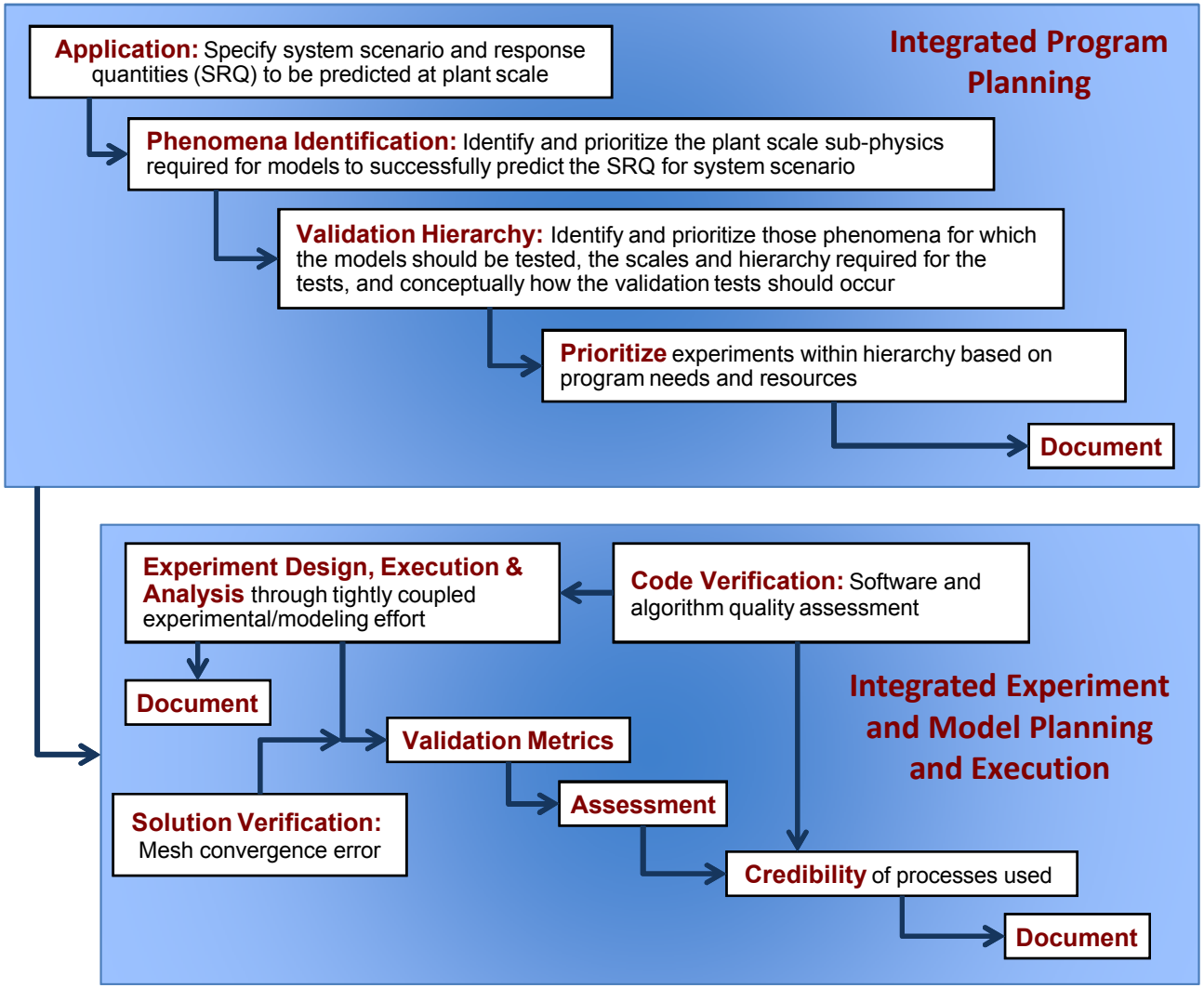
- Provides a structured approach for integrate program planning across scales
- Quantifies prediction uncertainty for use by designers
- Provides structured framework for collaboration

Foundation of framework

- Framework developed for SNL nuclear weapons program*
- Foundation adapted by current ASME and AIAA V&V Guides, Codes and Standards

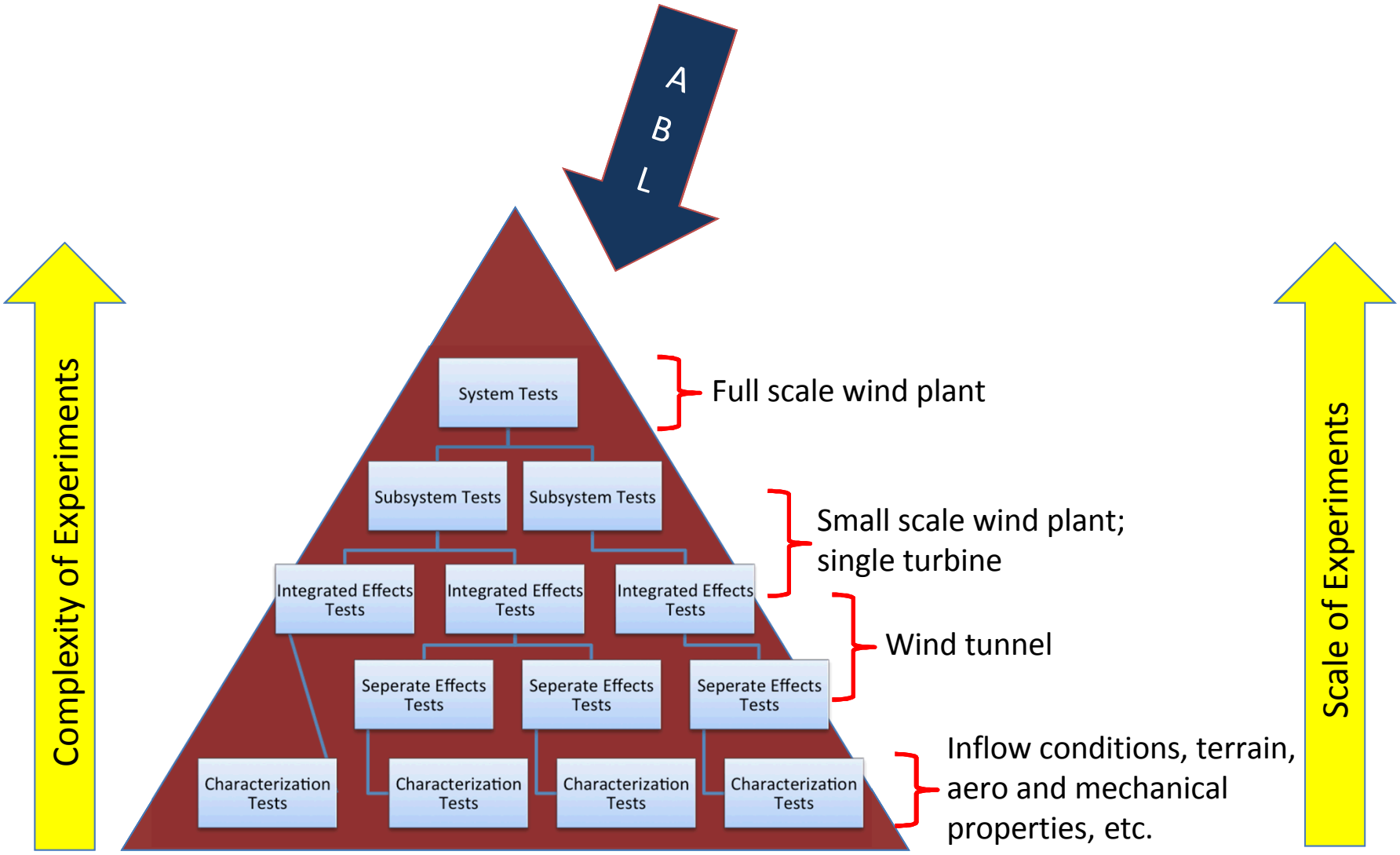
How different?

- Framework expanded and refined to address A2e multi-scale planning and prediction
- Framework methodology adapted to a highly collaborative process based on experience



*Trucano, T. G, M. Pilch, W. L. Oberkampf (2002), General Concepts for Experimental Validation of ASCI Code Applications, Sandia Report: SAND2002-0341, Sandia National Laboratories, Albuquerque, NM

Validation Hierarchy




Risk in using margins and uncertainties to support decision making
Credibility
QMU: Margins and Uncertainties
PIRT
PCMM: Validation experiment and application models
Solution verification uncertainty
Model Form (Validation): Prediction bias and validation uncertainty
Parameter uncertainty
Importance
Ability to model
Representation and Geometric Fidelity
Physics and Material Model Fidelity
Code Verification
Solution Verification
Validation
Uncertainty Quantification
Roll-up uncertainty from experiments to application
Validation experiment bias and uncertainty
Validation experiment bias and uncertainty
Validation experiment bias and uncertainty
Solution verification uncertainty
Parameter uncertainty
Validation data uncertainty
Solution verification uncertainty
Parameter uncertainty
Validation data uncertainty
Solution verification uncertainty
Parameter uncertainty
Validation data uncertainty
Judgment
Numbers

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Phenomena Important at Full Scale

Phenomenon	Overall Importance	Model Adequacy			Priority for Development and Validation	Appropriate Test Scale
		Physics Models	Computational Models	Validation		
Phenomenon 1	High	Inadequate	Adequate	Inadequate	High	System
Phenomenon 1a	Moderate	Inadequate	Adequate	Adequate	Moderate	
Phenomenon 1b	High	Adequate	Inadequate	Inadequate	High	
Phenomenon 2	Moderate	Adequate	Adequate	Adequate	Moderate	Subsystem
Phenomenon 2a	Moderate	Adequate	Adequate	Adequate	Moderate	
Phenomenon 2b	Low	Adequate	Adequate	Adequate	Low	

Wind Tunnel SME's (~3) -> Cross Scales SME's Meeting (~12) -> Community Meeting (~100)

-> Experimental Planning and Design

Consolidated PIRT

PIRT for Modeling Flow on Wind Plant Scale

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Phenomenon	Importance at Application Level	Model Adequacy			Planning Priority	Issue/Comments	Response including scale
		Physics	Code	Val			
Meso scale phenomena							
Representation of winds and turbulence through the atmos. boundary layer and/or top of rotor	**H**	**L**	**M**	**L**			**WFIP II**
Wind Plant repesentation (i.e. effect drag of turbines, etc.)	**L**	**L**	**na**	**L**			
Plant scale flow phenomena							
Wind plant blockage effects and plant	M	M	M	L			
Multi-turbine wake effects	H	M	L	L			
Wake interaction, merging, motion	H	M	L	L			
Wake steering (yaw tilt effects)	H	M	L	L			
Wake dissipation	H	M	L	L			
Turbine scale flow							
Blade Aero / Wake Generation	H						
Blade load distribution effects and rotor thrust	H	M	L	L			
Tip and root vortex development	H	M	L	L			
Boundary layer state (roughness, soiling, bugs, erosion)	L	L	L	L			

Consolidated -> Expanded PIRT

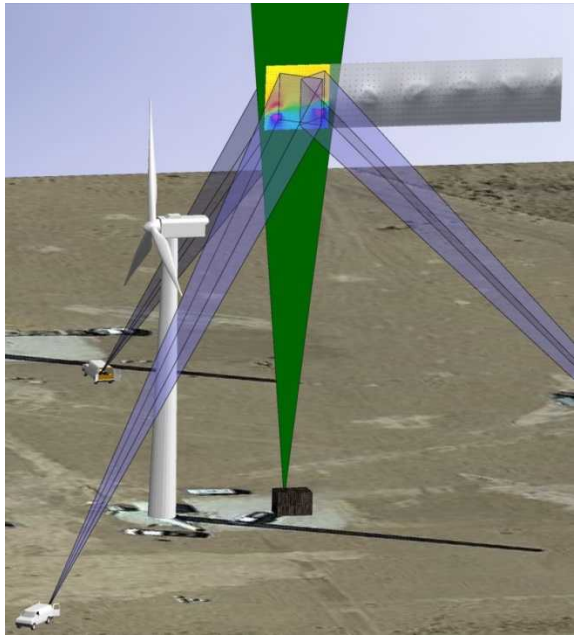
PIRT for Modeling Flow on Wind Plant Scale

Phenomenon	Importance at Application Level	Model Adequacy			Planning Priority	Issue/Comments	Response including scale
		Physics	Code	Val			
Meso scale phenomena							
Representation of winds and turbulence through the atmos. boundary layer and/or top of rotor	**H**	**L**	**M**	**L**			**WFIP II**
Wind Plant repesentation (i.e. effect drag of turbines, etc.)	**L**	**L**	**na**	**L**			
Plant scale flow phenomena							
Wind plant blockage effects and plant wake	M	M	M	L			
Multi-turbine wake effects	H	M	L	L			
Wake interaction, merging, motion	H	M	L	L			
Wake steering (yaw tilt effects)	H	M	L	L			
Wake dissipation	H	M	L	L			
Boundary and Initial Conditions							
Inflow velocity, temperature, etc.						Do models adequately capture the effect of spatial and time dependent inflow conditions?	
Surface roughness and waves						Is model calibrated for surface roughness or is there independent characterization?	
Topography and man-made structures				Low		Small structures that effect turbulence and wake propagation generally included in the model?	
Soil moisture							
Shear inflow effect on wake				Low			
Characterizing turbulence inflow structures when no direct measurements available	H			Low		Can use LES model, initiated during stable evening hours, over a sufficient large upwind scale to evolve turbulence effects that are required as inflow at the plant scale. Expensive computationally to resolve small scale phenomena using a larger than plant scale LES model.	
etc.							
Desirable model input requirements for plant scale model (i.e. to support LES modeling)						Note that these examples represent model input at the plant scale, and as such, generally don't have models associated with them. However, if there is a data reduction equation to process raw data into that data used by the plant scale model, then the issues of validation of the data reduction equation is relevant.	Responses for these items may include instrument development, testing (as is planned - XPIA), instrument purchases, data reduction development, etc.
Inflow velocity and temperature in a vertical plane (time dependent)	High	NA	NA	NA		Hard to measure with sufficient resolution	Investigate various non-point measurement techniques to measure velocity over vertical planes
Surface heat flux	High	NA	NA	NA		Easy to measure	
Topography	High	NA	NA	NA		Easy to measure	
Surface roughness, wave state	High	NA	NA	NA		Hard to characterize	
Soil moisture		NA	NA	NA			
Large scale geostrophic forcing	High					Hard to characterize with sufficient resolution	Could select cases with not important
Advective tendencies	High					Hard to characterize with sufficient resolution	Could select cases with not important

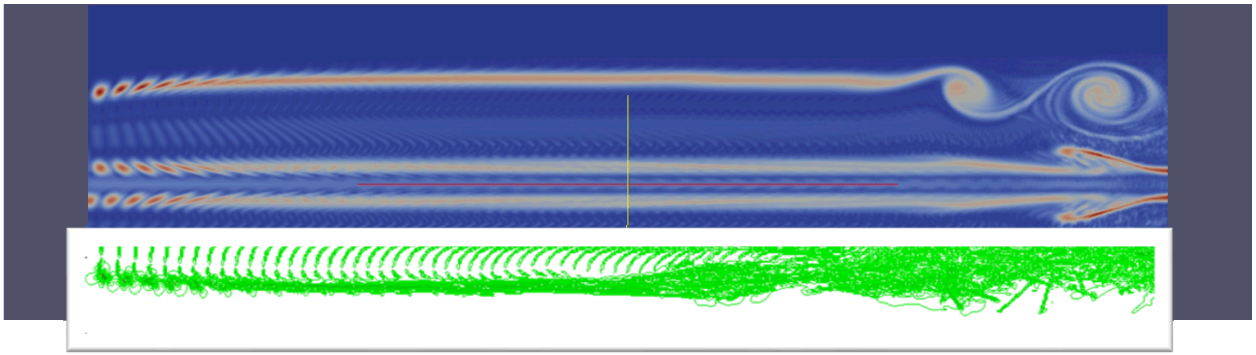
Near Wake Integrated Experiment Planning

Wind Tunnel

SWiFT

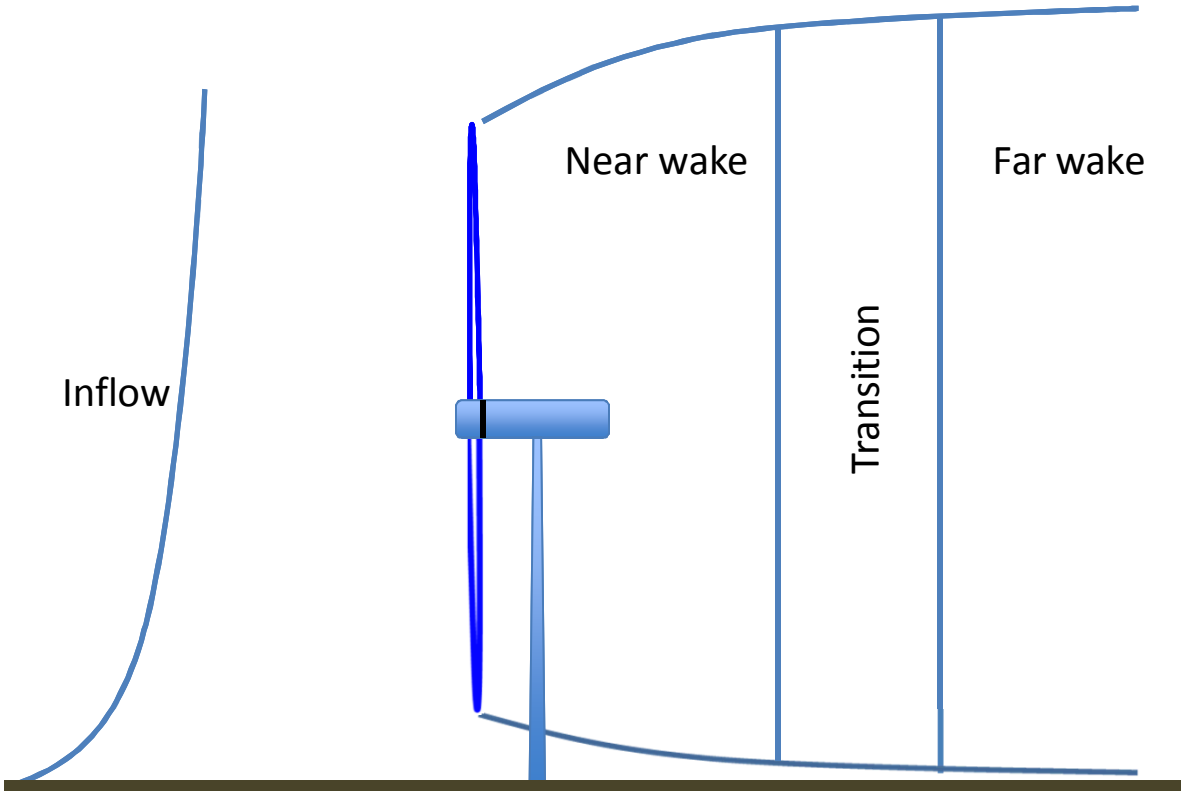


Multi Fidelity Models



SWiFT V&V Objective and Test Conceptualization

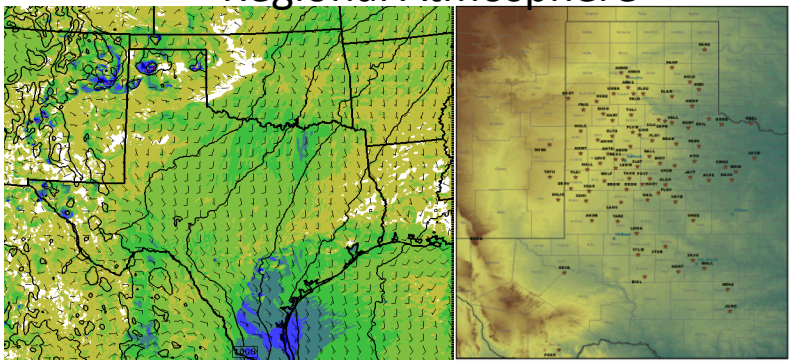
Objective: Given upwind inflow conditions at upstream boundary, predict wake structure from rotor to 5D downwind



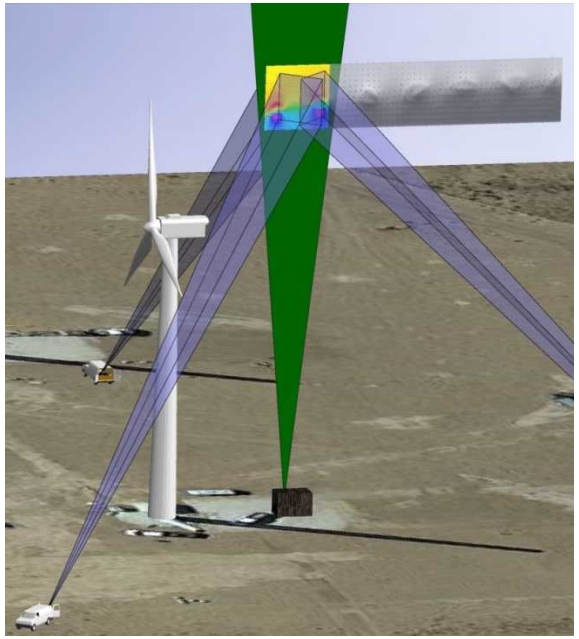
Measurement Locations: Inflow | Rotor and Turbine state | Near, mid, and far wake

SWiFT Integrated Experiment Planning

Regional Atmosphere

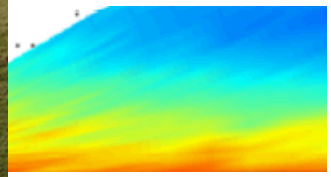


Atmospheric Boundary Layer



Wake Flow Structures

Wind Farm Flow



Array Flow

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TIMELINES: DEPENDENCIES, REVIEWS, GO/NO-GO'S

November 2014 schedule snapshot

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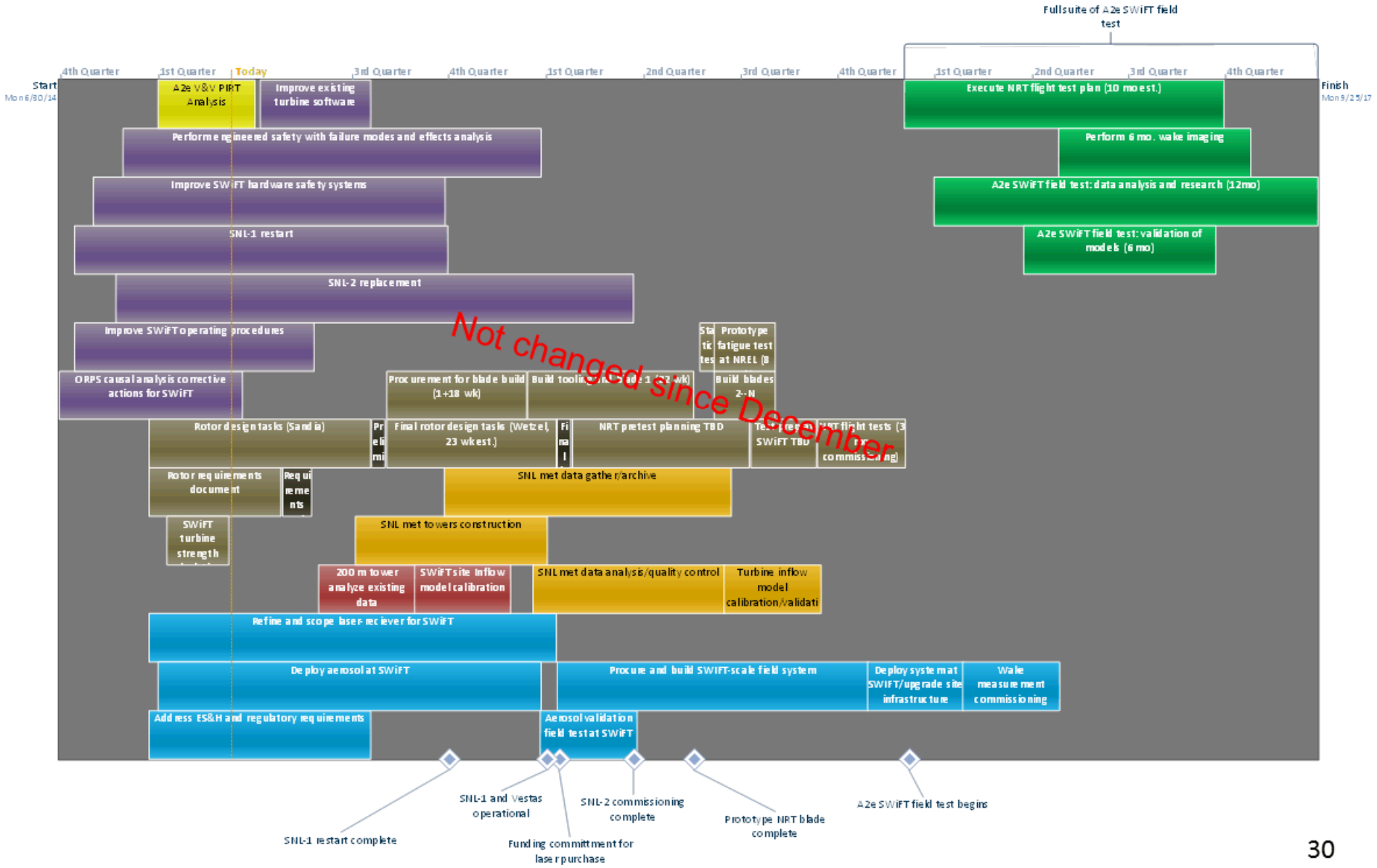
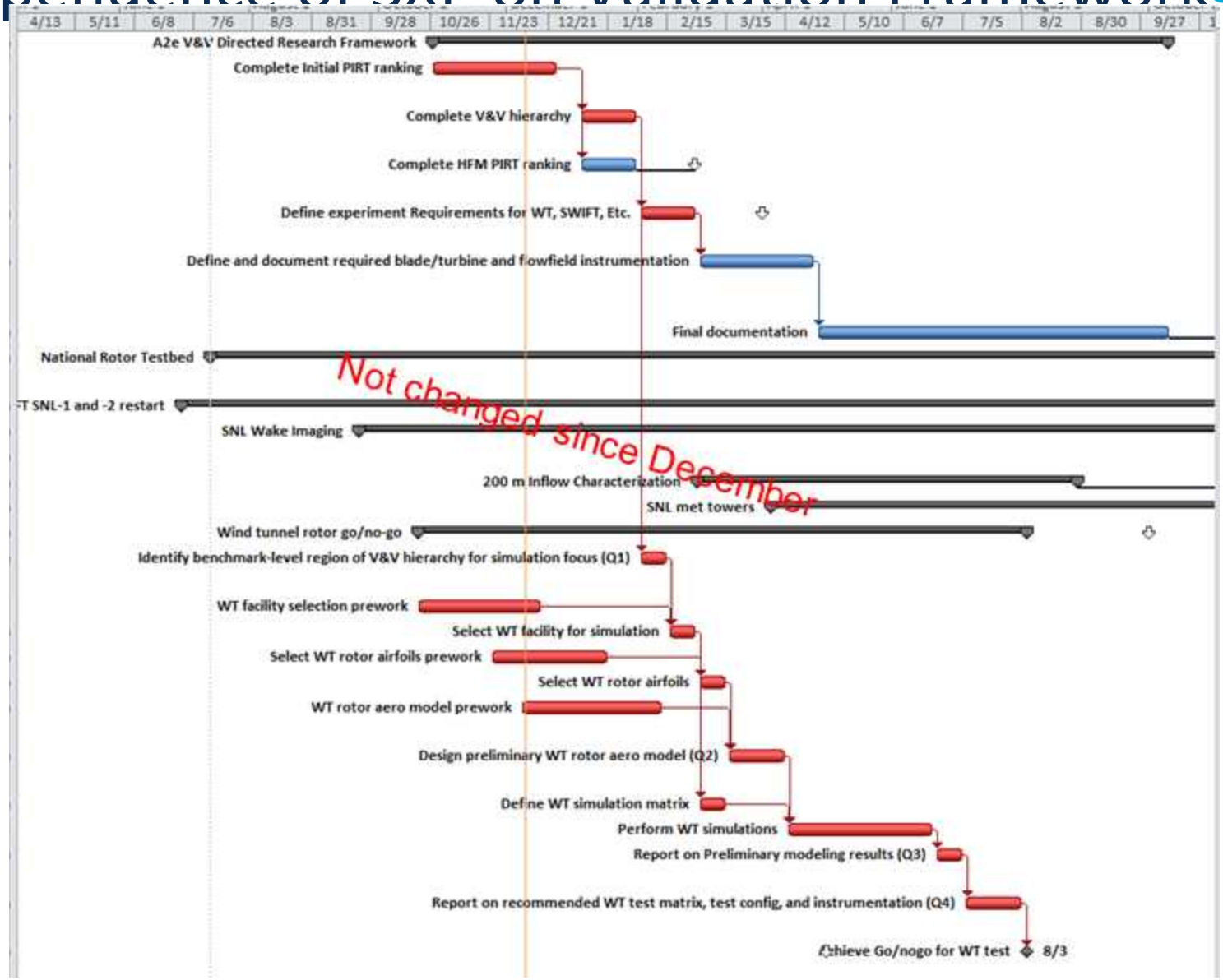
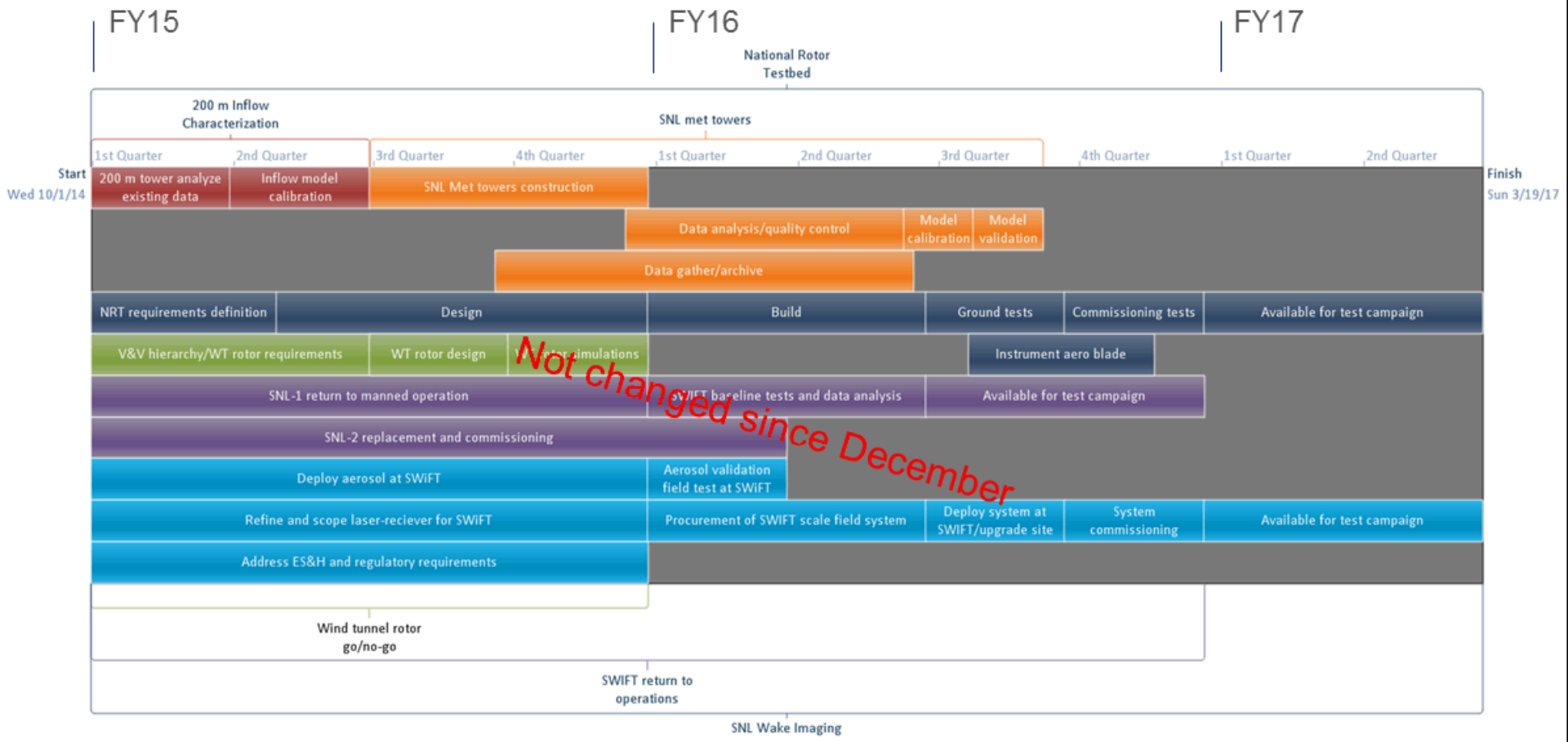


Dependence of SXP on Validation Framework



Integrated timeline (from 2014)



Red—SWiFT site characterization (unfunded at this point)
Orange—SNL met towers (FY15 within SWIFT, but not prioritized)
Blue—NRT design and build (FY15 project)
Green—A2e wind tunnel test go/no-go investigations (FY15 new project)
Purple—SWiFT facility return to operation (FY15 project)
Turquoise—Sandia Wake Imaging System (FY15 project)
Not shown—A2e V&V and HFM simulation frameworks (FY15 project)