2011 LANL Wind Energy Engineering Workshop
Modeling of Turbine-Turbine Interactions

SNL Structural Measurement and Validation Overview

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Presentation Outline

- **Current State of Industrial Measurement:**
  Drivers and Applications to the Wind Industry
- **DOE/SNL Historical Role in Developing Measurement Technology**
- **DOE/SNL Innovative Approach to Operational Monitoring**
- **DOE/SNL Current Measurement Activities**

Current State of Industrial Measurement: Drivers and Applications to the Wind Industry

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Drivers for Industrial Measurement Systems

- **Diagnostic tools for blade fabrication (QA), lab and field testing (R&D and NDI)**
- **Sensing systems to enable**
  - Smarter Structures
  - Advanced Controls
- **Increase Energy Capture**
- **Improve Reliability and Availability**
- **Decrease Operation & Maintenance (O&M) costs**
- **Decrease Cost of Energy**

Nolet/TPI Composite

Sensing Opportunities

Current location of Sensors on a utility size wind turbine

- Nacelle (drive train, gearbox, generator) – lots
- Tower Base (power electronics, tower) – lots
- Blades – **few to no sensors!**

Rational for additional sensing

- Enable advanced controls strategies
- Maximize structural and aero efficiency
- Damage detection, Condition Monitoring and Structural Health Monitoring
- Increase reliability, availability and energy capture

Goal is a Smart Wind Turbine Structure


Horns Reef wind farm in Denmark

Typical Wind Turbine
Manufacturer: GE Energy
Power Rating: 1.5 MW
Tower Height: 80 meters
Blade Length: 34 meters
Blade Weight: 6 tons
Jose's Height: 1.8 meters


Colorado Green Wind Farm
Lamar, Colorado

Sensing System Deployment Challenges

- **Assessing return on investment**
  Does increased cost buy you increased reliability and performance?

- **True capabilities versus claimed**
  Need for development of wind-specific measurement hardware

- **Reliability of the Sensing System**
  Possible new failure mode

- **Coupled Rotor (BRC) - Drivetrain (GRC) system**
  Wind-site specific

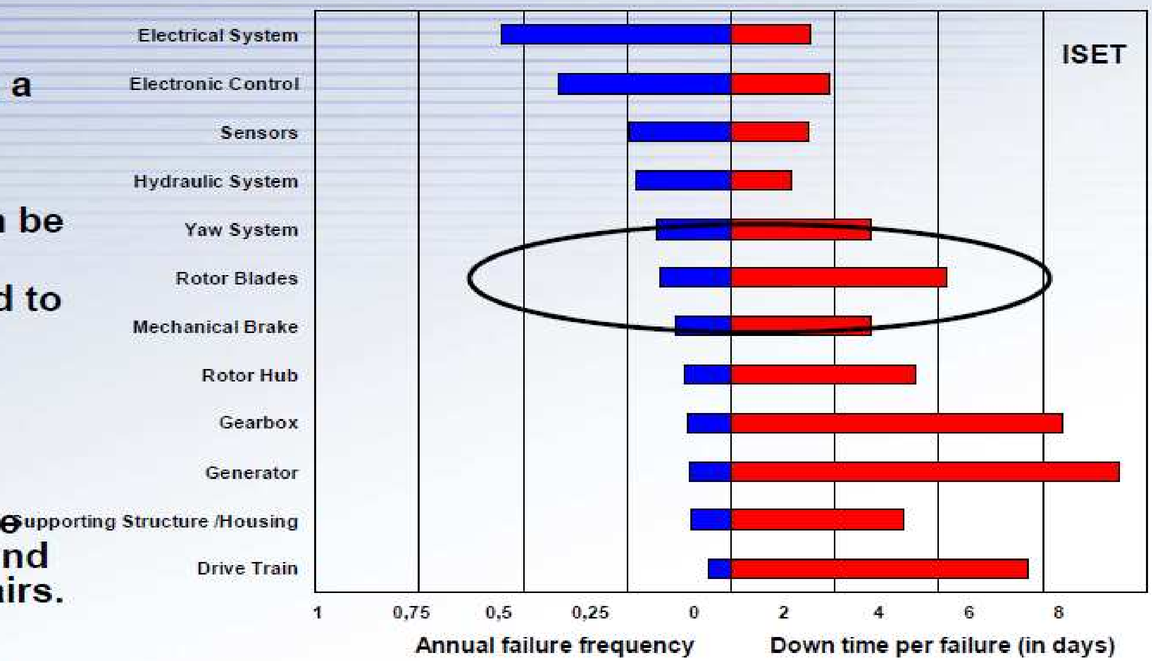
- **Composite structure of blades**
  Long, large surface area, thick composites

Challenges – Wind Turbine Reliability

"80% of the blades that require repair have never been flown."
Gary Kanaby, Knight & Carver Wind Blade Division.

Blade Reliability

- Blades are being delivered to the site in a condition that often requires additional treatment of quality issues before they can be installed
- Rare installations need to have all the blades replaced after the discovery of a batch problem
- Blade failure can cause extensive down time and lead to expensive repairs.
- *Blade reliability issues need early attention because of the lost production and cost of significant failures*



Historical European Experience (Paul Kühn, ISET)

Blades are in the middle – medium failure rate, relatively high cost. US environments may be more aggressive.

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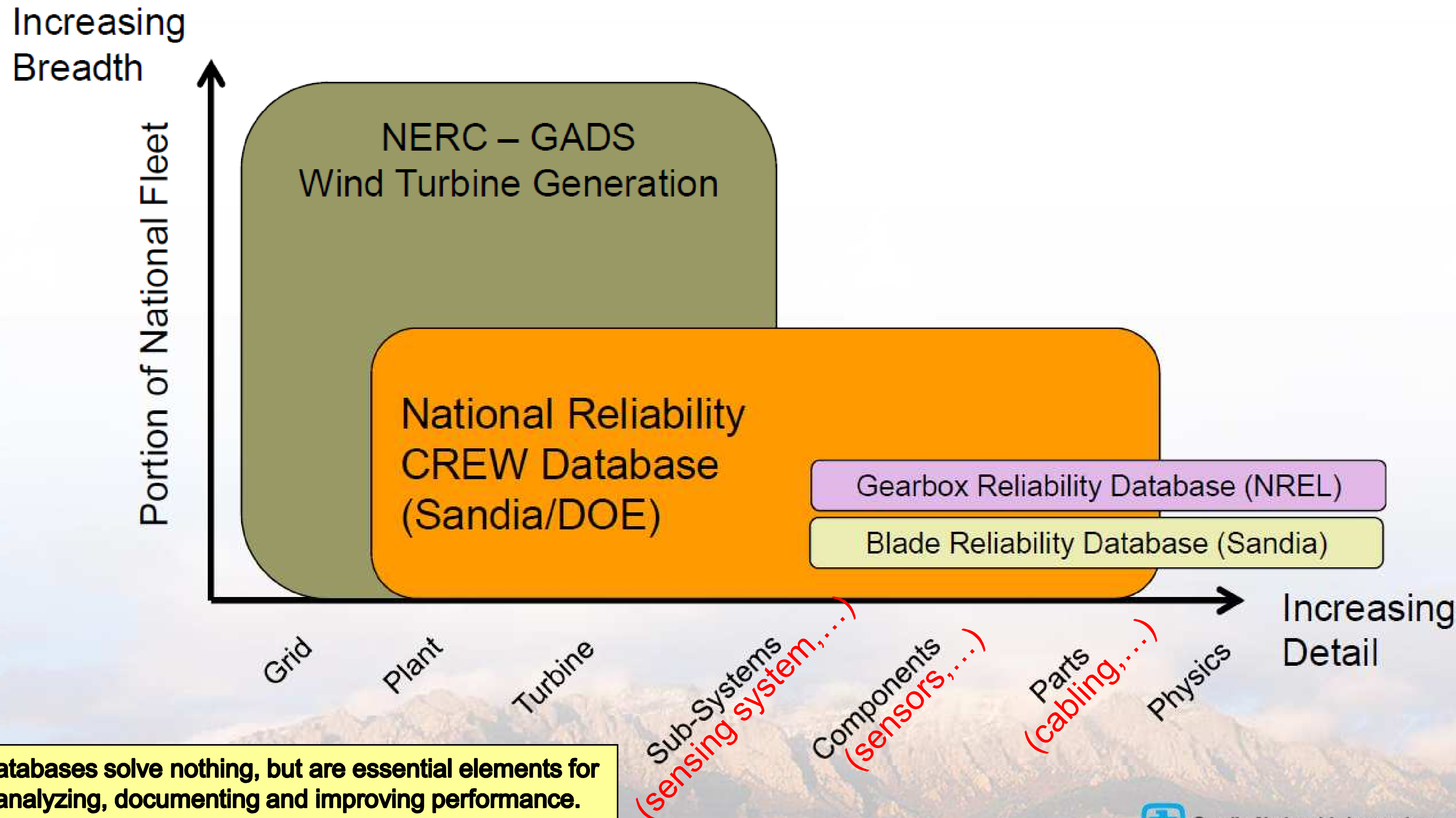
Source: Veers and Hill, 2008 Blade Workshop (http://www.sandia.gov/wind)

Relationship of Reliability Databases



Databases solve nothing, but are essential elements for analyzing, documenting and improving performance.

Source: Veers, AWEA Power Performance and Reliability Workshop – January 2010, San Diego, CA

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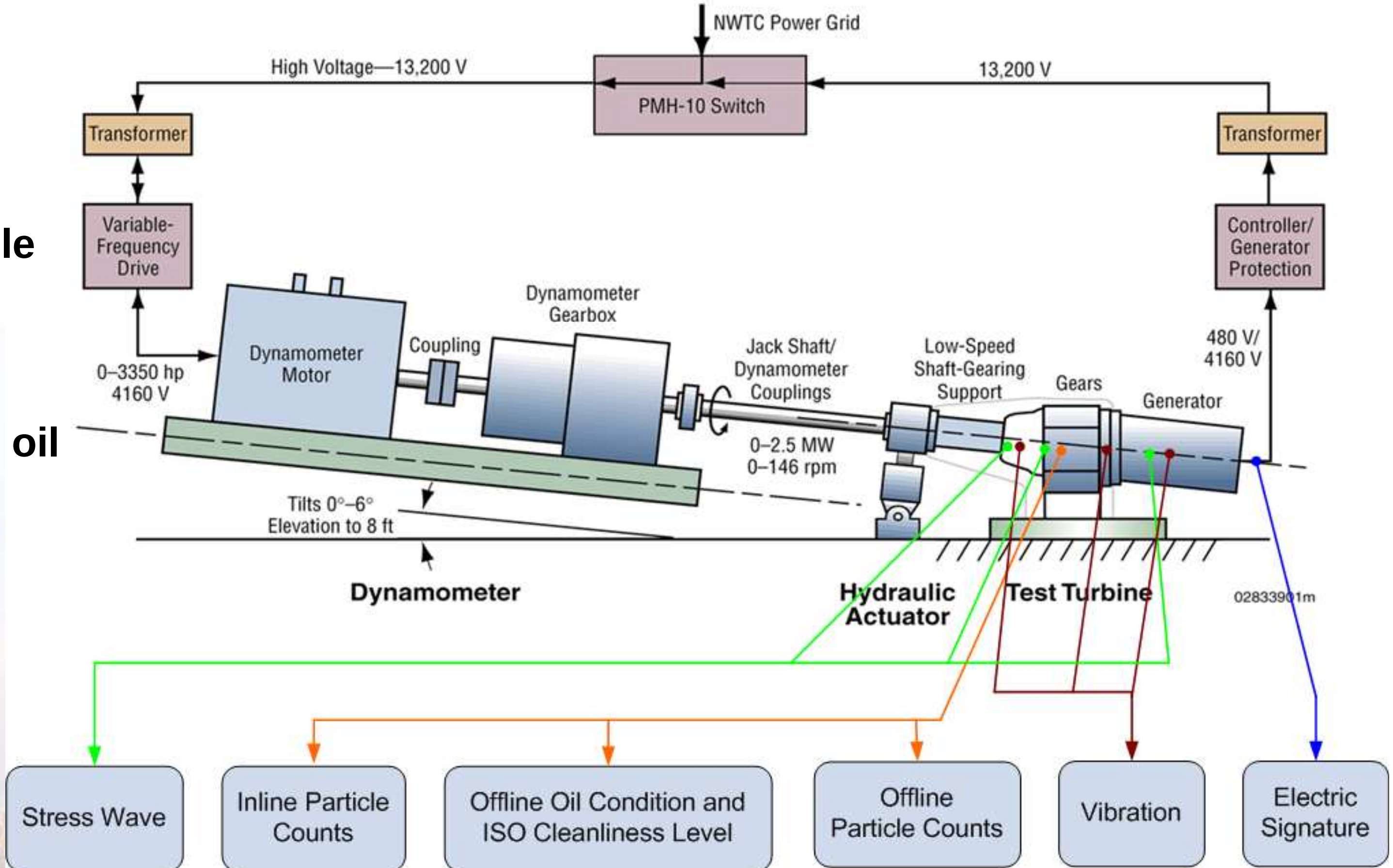
NREL/NWTC Gearbox Reliability Collaborative

Shuangwen "Shawn" Sheng: "As a research project, the GRC study is beyond typical drivetrain condition monitoring practices seen in the wind industry."

- **Stress wave analysis**
- **Vibration analysis**
- **Main filter loop particle counting**
- **Offline filter loop particle counting and oil condition monitoring**
- **Electric signature monitoring**
- **Periodic oil sample analysis**



Industrial Rotor Monitoring

- Fiber optic based load and damage monitoring with the goals of:
  - Increase energy capture
  - Improve reliability
  - Validate design and improve future designs

- OEM providers: Moog / insensys, Micron Optics, QPS Photronics, and WindForce GmbH.
  - Individual Pitch Control enabled with significant reduction in 1P hub moments
  - +1,000 systems installed with +16,000 sensors
  - Ice detection system

DOE/SNL Historical Role in Developing Measurement Technology

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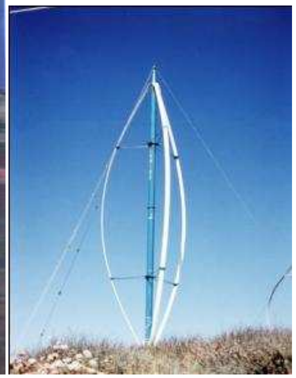
DOE-SNL History in Wind Technology R&D






1975	SNL Wind Program Established
1976	17m VAWT Project Started
1981	1st Wind Turbine VAWT Specific Airfoils
1981	2m and 5m VAWTs Projects Started
1982	FloWind Technology Transfer
1984	34m VAWT Test Bed Project Started
1988	SNL/MSU Material Database Established
1994	SNL HAWT Blade Program Started
1998	Blade Manufacturing Initiative Started
2003	SNL LIST Project Started
2003	Incorporation of Carbon in Blades (CX, TX, BSDS)
2004	GE/NREL/SNL LIST Project
2005	Knight & Carver Swept Blade Contract
2006	Reliability Program Started
2007	Renewable System Integration Program Started
2007	Sensor Blade 1 Project Started
2008	Advanced Manufacturing Initiative Program Started
2008	Water Power Program Started
2009	Sensor Blade 2 and Sensored Rotor Projects Started
2010	SMART Rotor Project Started

Mission:

To provide a knowledge base expertise in the design and advancements of composite wind turbine blades and turbine reliability, in order to accelerate the penetration of Wind Energy.

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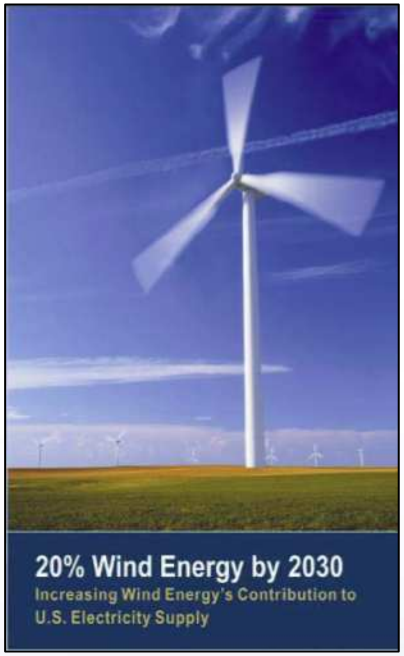
Sensing Opportunities

Sensing Technologies are required for:

Technical Area	Potential Advances	Performance and Cost Increments (Best/Expected/Least Percentages)	
		Annual Energy Production	Turbine Capital Cost
Advanced Tower Concepts	• Taller towers in difficult locations • New materials and/or processes • Advanced structures/foundations • Self-erecting, initial, or for service	+11/+11/+11	+8/+12/+20
Advanced (Enlarged) Rotors	• Advanced materials • Improved structural-aero design • Active controls • Passive controls • Higher tip speed/lower acoustics	+35/+25/+10	-6/-3/+3
Reduced Energy Losses and Improved Availability	• Reduced blade soiling losses • Damage-tolerant sensors • Robust control systems • Prognostic maintenance	+7/+5/0	0/0/0
Drivetrain (Gearboxes and Generators and Power Electronics)	• Fewer gear stages or direct-drive • Medium/low speed generators • Distributed gearbox topologies • Permanent-magnet generators • Medium-voltage equipment • Advanced gear tooth profiles • New circuit topologies • New semiconductor devices • New materials (gallium arsenide [GaAs], SiC)	+8/+4/0	-11/-6/+1
Manufacturing and Learning Curve*	• Sustained, incremental design and process improvements • Large-scale manufacturing • Reduced design loads	0/0/0	-27/-13/-3
Totals		+61/+45/+21	-36/-10/+21



Source:
DOE 20% by 2030 Wind Energy Report Table 2-1, p. 41.

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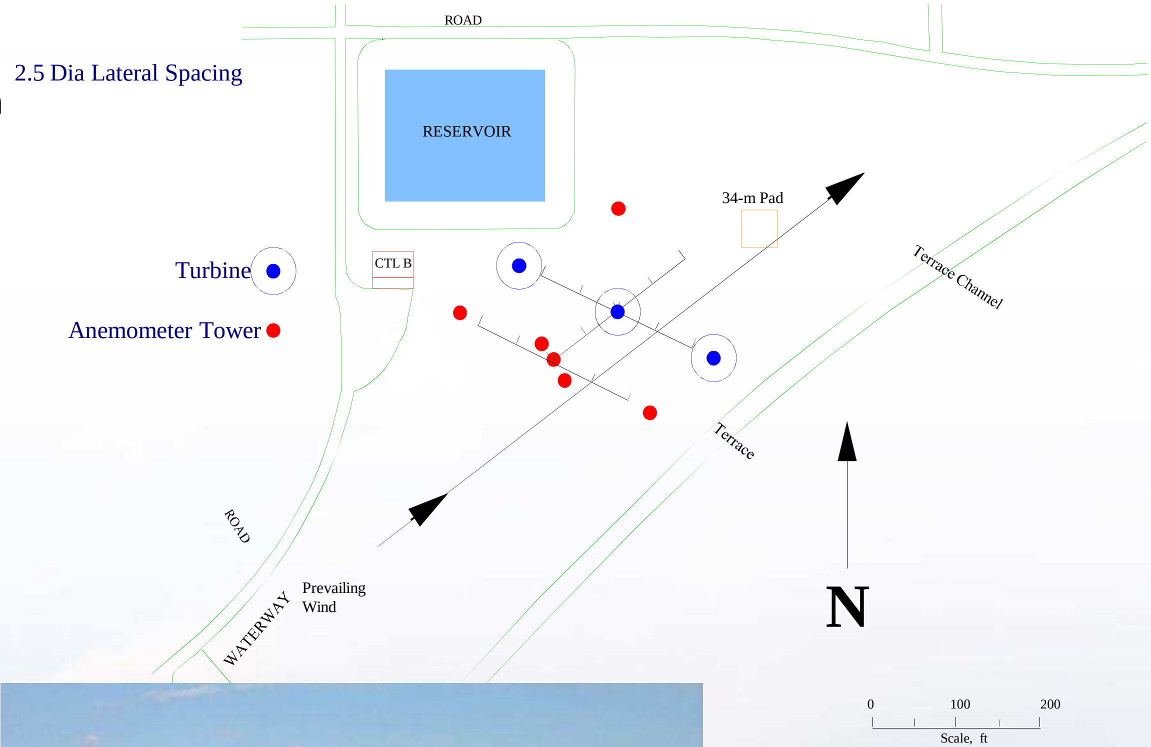
Long-term Inflow Structural Testing (LIST) Program

2003

- **Site (“Great Plains” winds)**
  - 8.7 m/s average wind speed at 80m
  - Class 5 site allows for rapid testing
  - Wildorado wind farm nearby is one of the highest capacity factor sites in U.S.
- **Test Turbines**
  - Modified Micon 65’s
  - Stall regulated, Fixed pitch
  - 55 RPM
  - Upgraded to 115kW generator
  - Redesigned braking, yaw, control systems
  - Heavily instrumented
- **Instrumentation**
  - 0-1000 Hz data recording on >50 channels
  - Inflow (multiple met towers and nacelle collecting wind speed and direction)
  - Electrical Power
  - Loads (tower, hub, and blade)
  - Acoustic noise



Sensor Blade 1 – Monitoring over life-cycle

2007

1 - Blade Fabrication

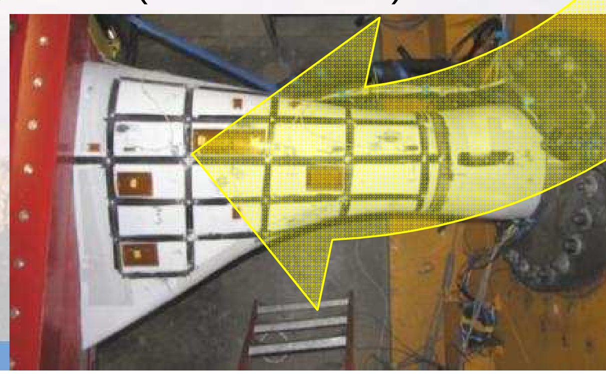
(TPI Composites)

2 - Field Testing

(USDA-ARS)

3 – Lab Testing

(NREL - NWTC)



DOE, National labs, Industry, Universities, and non-wind companies

“win-win-win-win”

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Sensor Blade 1 Team

Mark Rumsey, Joshua Paquette and Wesley Johnson – Sandia National Laboratories (Wind Energy Tech. Dept.)
Key colleagues in the department

Jason Kiddy and Chris Baldwin – Aither Engineering, Inc.
Sensor Blade shape using embedded fiberoptic-based strain sensors

Alan Turner and Tom Graver – Micron Optics, Inc.
Sensor Blade operational loads and temperature distribution using surface mounted fiberoptic-based sensors

Turning Light Into Enlightenment

Jonathan White and Douglas Adams – Purdue University
Sensor Blade shape, operational loads, and Structural Health Monitoring using accelerometers

Steve Nolet and Derek Berry – TPI Composites, Inc.
Sensor Blade manufacture in an open-shop floor environment

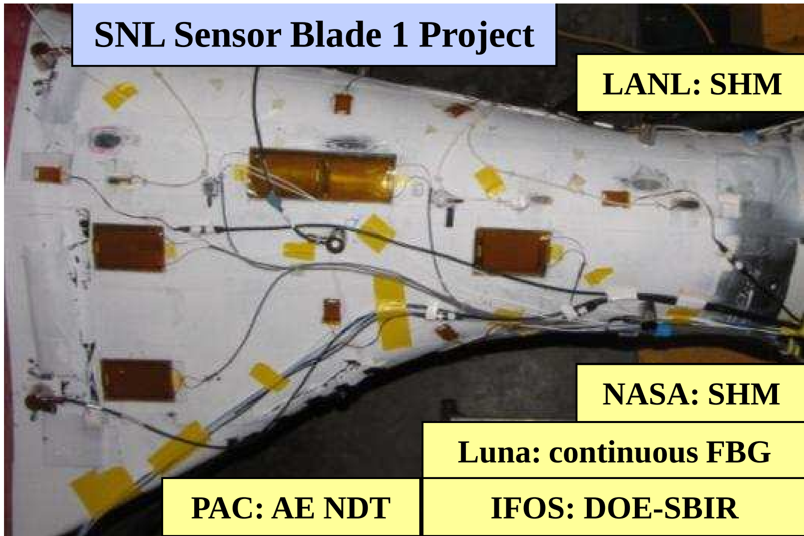
DELIVERING COMPOSITE SOLUTIONS

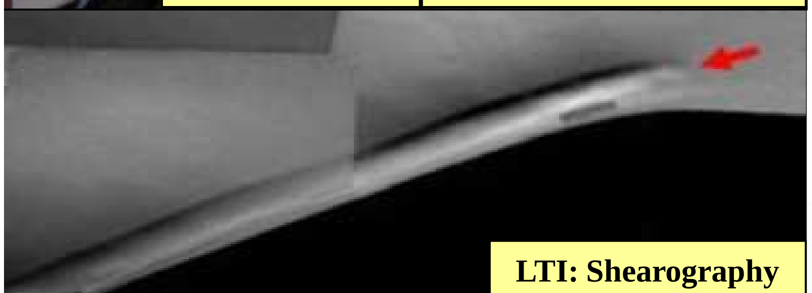
Jeff Carlson and Kevin Brink – Sandia National Laboratories (Energy Systems Analysis Dept.)
Sensor Blade tip deflections using processed video images

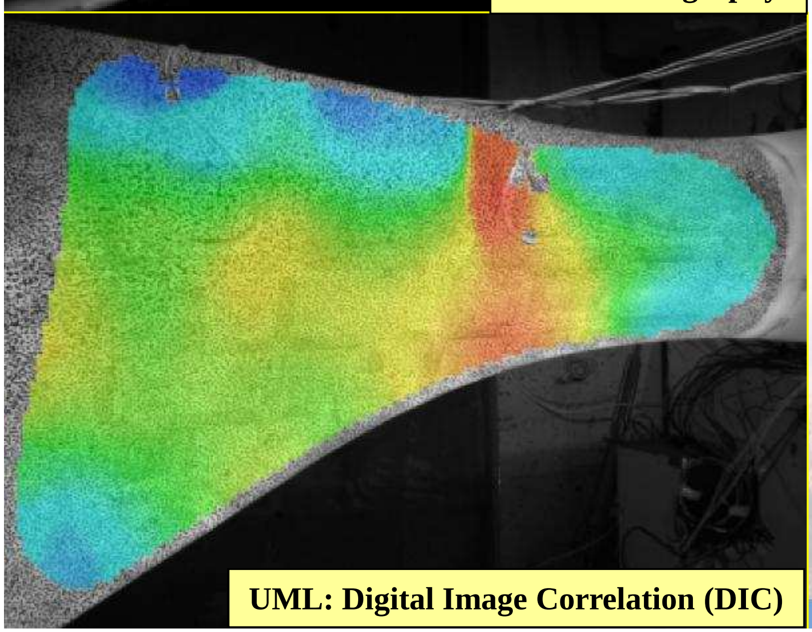
Nolan Clark, Adam Holman, Byron Neal and Donnie Cagle – USDA-ARS
Sensor Blade field test on an operational wind turbine

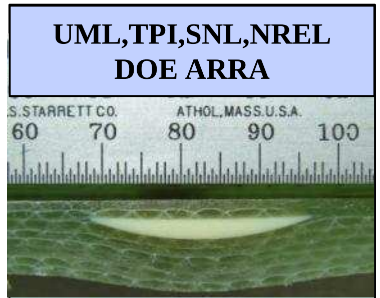
Scott Hughes, Jeroen van Dam and Mike Jenks – NREL/NWTC
Sensor Blade static and fatigue tests in the laboratory

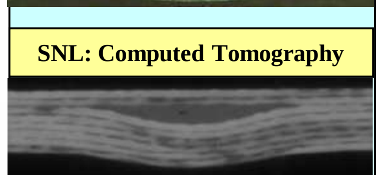
NDE/NDI/NDT and QA Tools

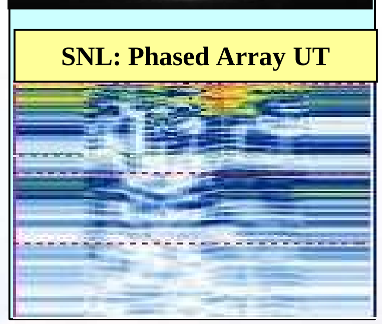


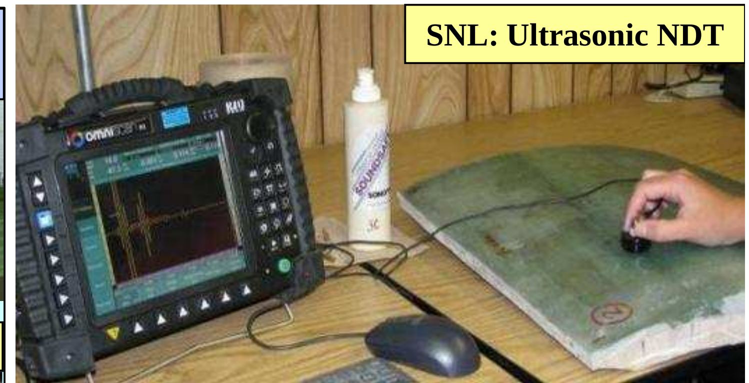


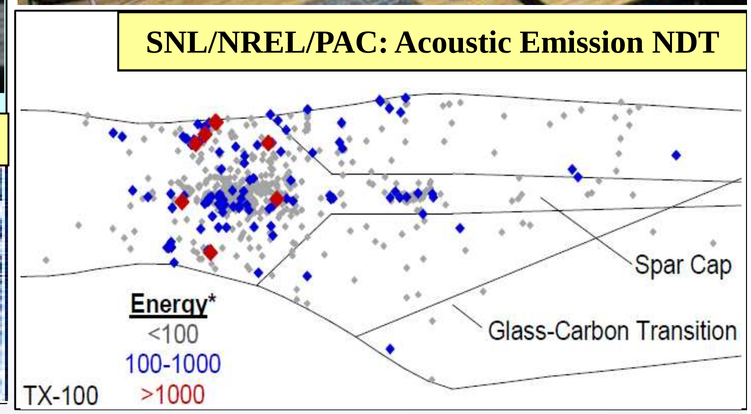


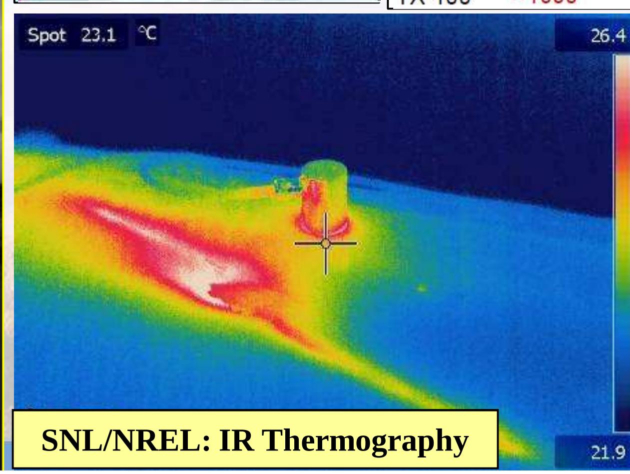


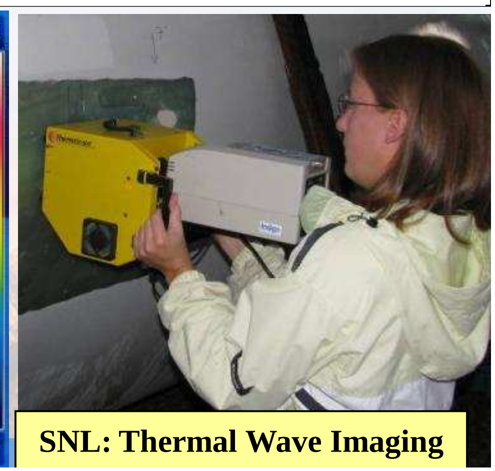












DOE/SNL Innovative Approach to Operational Monitoring

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Structural Measurement Approaches

- Three objectives to structural measurements:
  1) **Load Monitoring:** determination of operational forces, moments, deflections, velocities and acceleration.
     - Controls estimator for rotor imbalance and optimal performance tracking.
     - Estimate of extreme loading and fatigue loading.
     - Used for structural characterization and model validation.
  2) **Damage Detection:** operational estimation of existence, location, type, and magnitude of damage.
     - Improvement of existing O&M procedure.
  3) **Prognostics:** predictive control based on the load and damage state to optimize revenue and maintenance.

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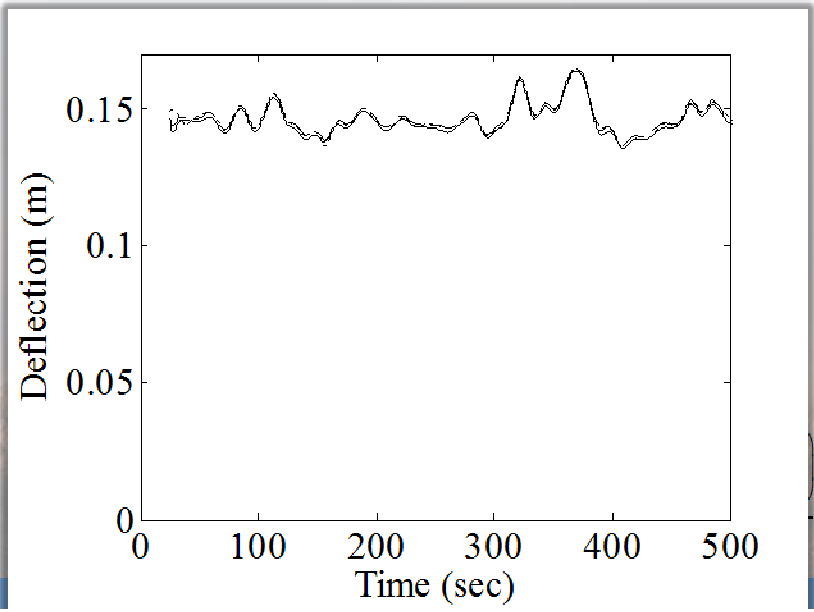
Load Monitoring

- Quasi-static and Dynamic Separation
  - Quasi-static limited to the bandwidth < 1P (< 0.93 Hz)
  - Quasi-static time scale larger than dynamic time scale

$$p(z,t) = p_s(z) + p_d(z,t)$$

$$u(z,t) = u_s(z) + u_d(z,t)$$

- Centripetal Acceleration as a Reference



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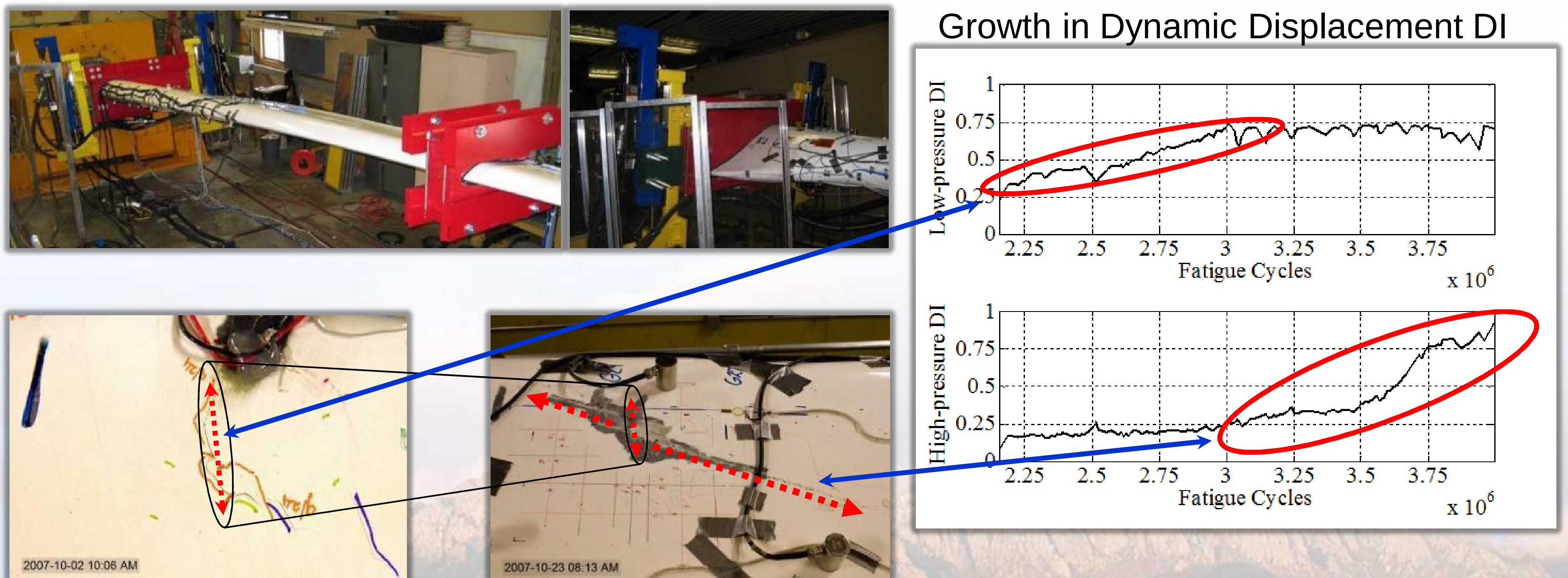
Damage Detection

- Alternating Gravitational Force Used for Damage Interrogation

TX-100 Fatigue to Failure

Growth in Dynamic Displacement DI



2.5 – 3 M Cycles

3 - 4 M Cycles

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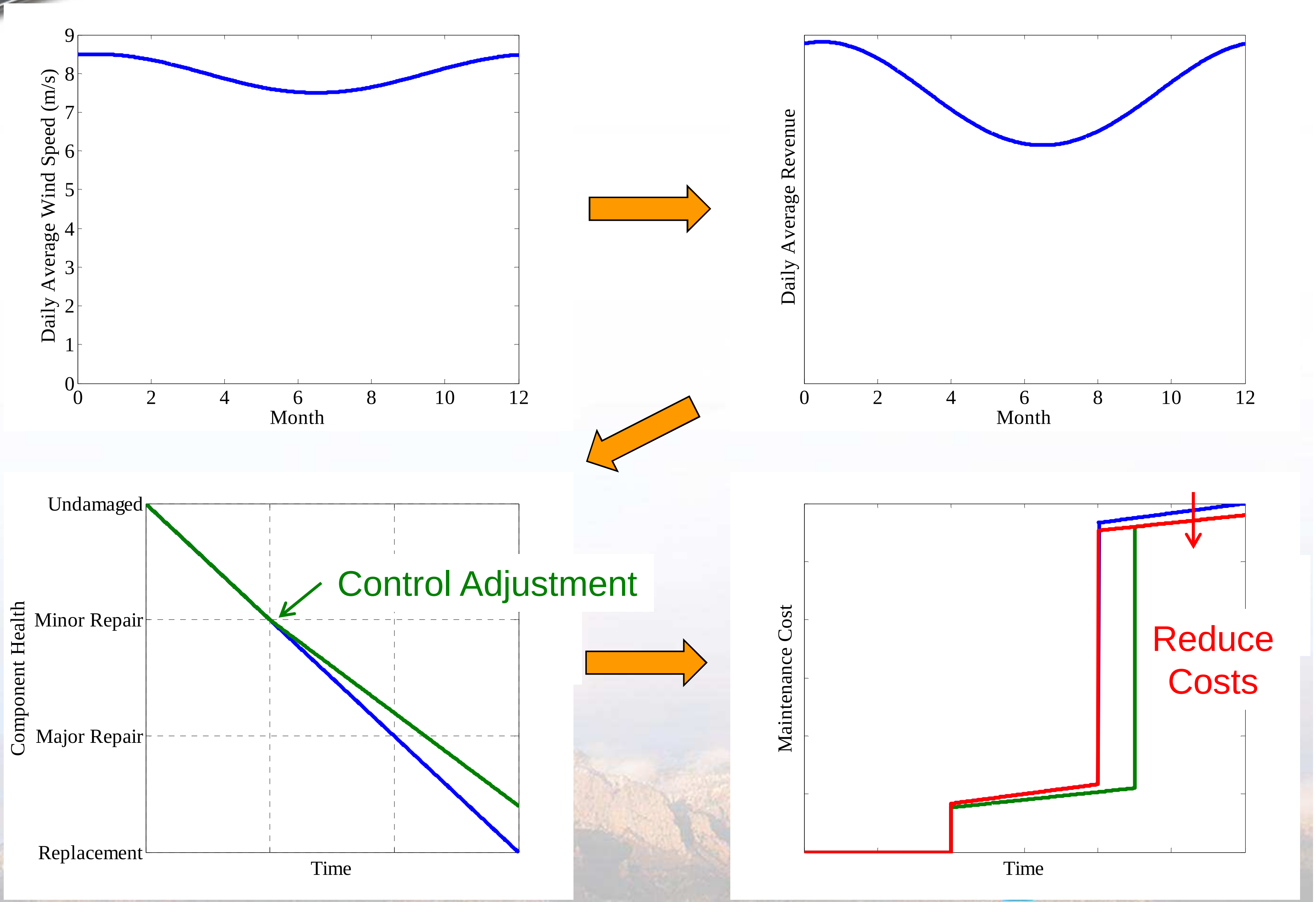
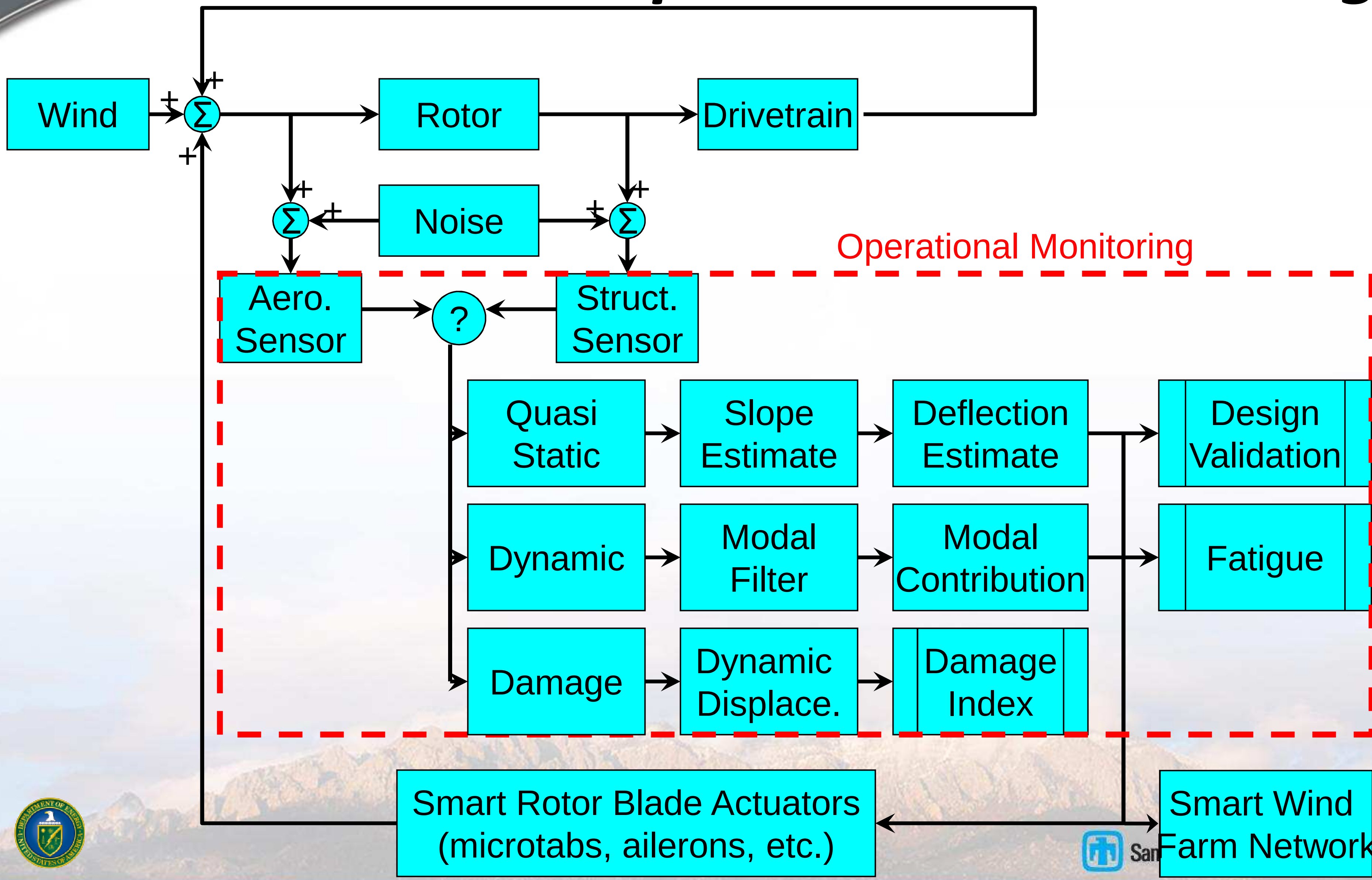
Health Prognostics and Management



Real-Time Operational Monitoring

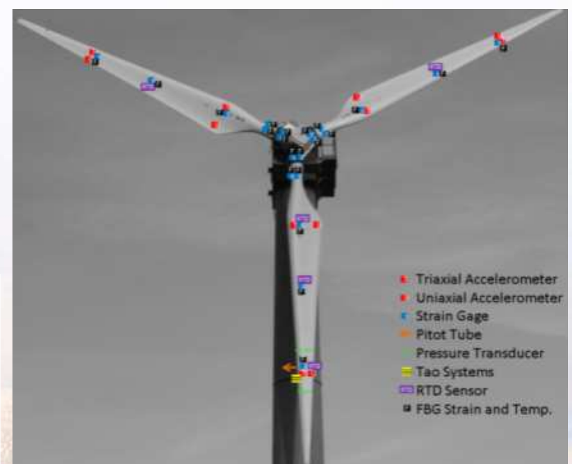


DOE/SNL Current Measurement Activities

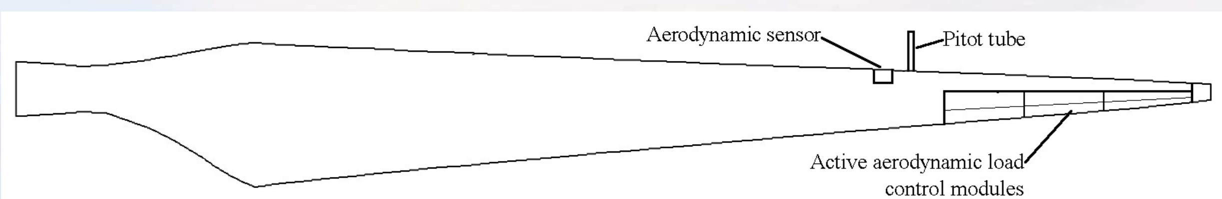
Previous / Current Projects

- **Aeroacoustic testing of BSDS blade set completed (7/10)**
  - Investigation of outboard trailing edge thickness and redesign of aeroacoustic array
- **Complete Sensor Rotor II field test (3/11)**
  - Follow-on to Sensor Blade I to further develop sensor systems
- **Begin Active Aero field test (5/11)**
  - Test of blades fitted with active aerodynamic actuation devices
- **LANL/SNL SHM Blade field test (1/12)**
  - Flight of blade integrated with LANL active diagnostics system and SNL passive load and damage monitoring technology

Aero-acoustic Testing
Source: EU Sirroco Project



S-Blade II Instrumentation



Active Aero Blade Schematic

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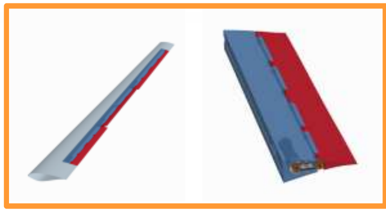
Sensored and SMART Rotor Technology

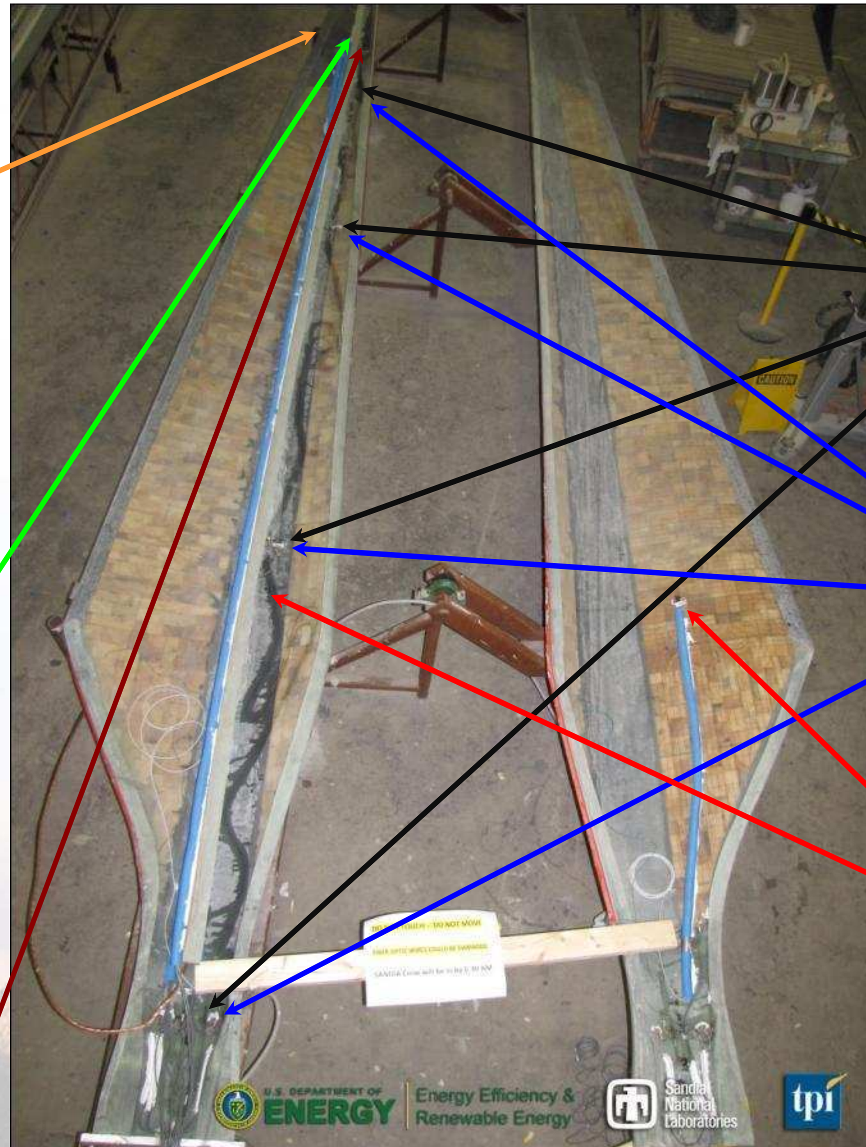
Aero Actuator



Aero Sensors

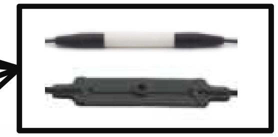
Pressure Taps
(surface pressure)

5-Hole Pitot Tube
(AOA and Velocity)

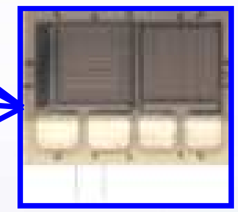


Structural Sensors

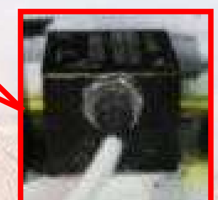
Fiber Optic
(strain and temperature)



Strain Gage
(strain)



Accelerometer
(acceleration)



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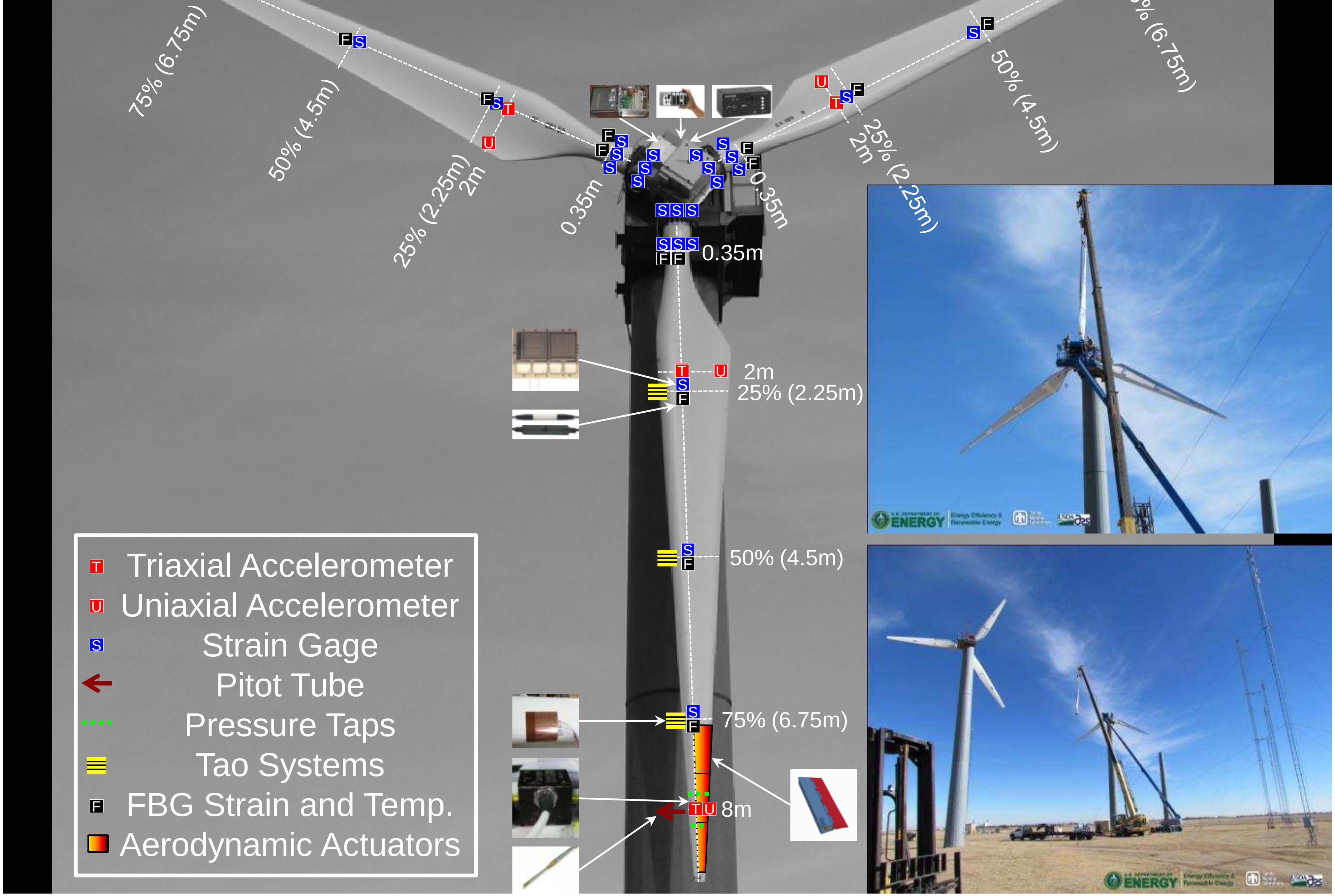
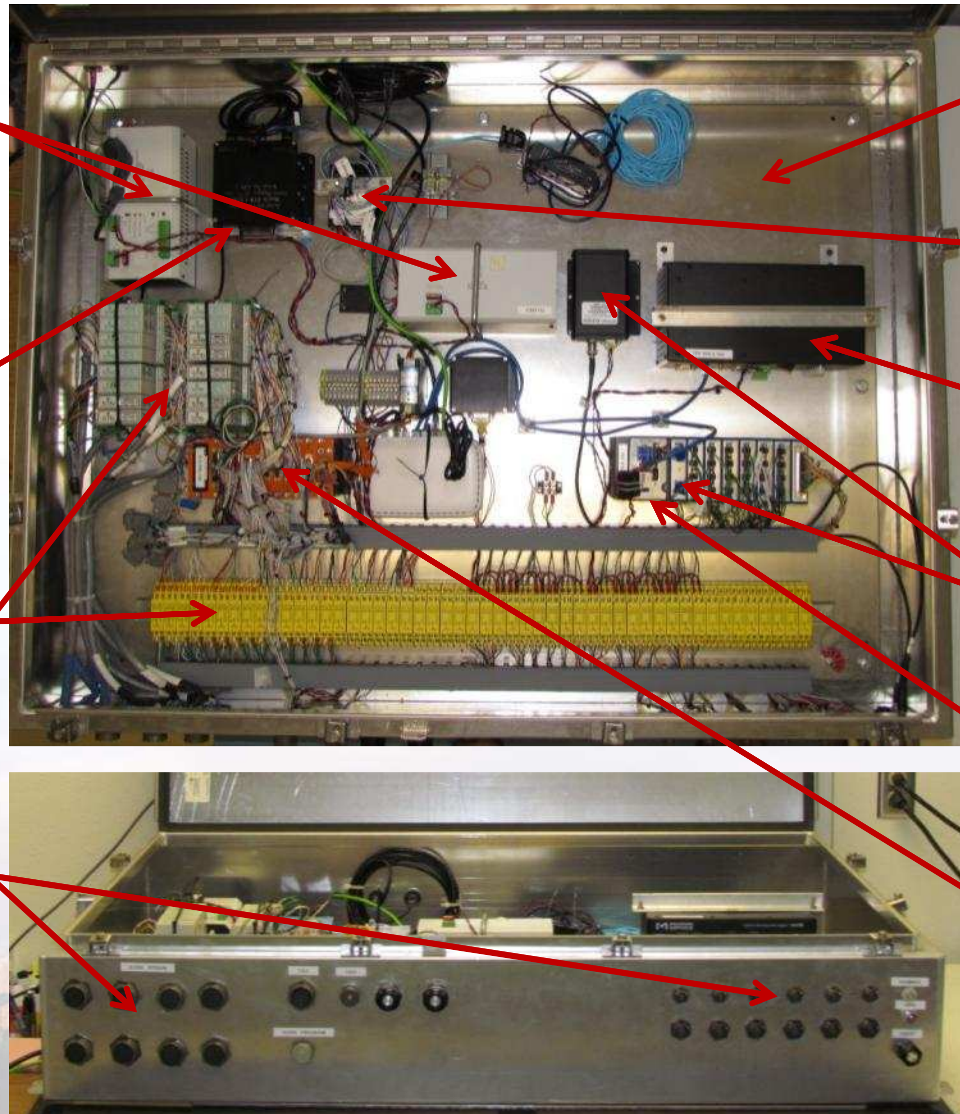
Sensor Rotor 2 and SMART Rotor 1 Instrumentation



Sensor Rotor 2 Data Acquisition



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Los Alamos and Sandia National Laboratories Structural Health Monitoring Blade

- **Objective**: Fly a rotor blade with LANL active and SNL passive diagnostics systems and LANL particle-image-velocimetry (PIV) system.
  - SHM blade will be embedded with active piezoelectric patches and traditional structural and aerodynamic sensors.
  - Remainder of rotor will be the Sensor Rotor 2 blades.
  - Hub-mounted camera for PIV measurement of SHM rotor blade.
- **Purpose**: Validate concepts and simulations for embedded sensing.
- **Timeline**: Mounted to SNL-USDA turbines following the SMART Rotor in Q2 FY12.
- **Outcome**: Development of a complete monitoring solution for rotor loads, damage and near-field flow.

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