SAND2016-0556C

Field Demonstration of the Sandia Wake Imaging System Capabilities at the Scaled Wind Farm Technology Facility

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Outline

- Project Purpose
- Investigation Objectives
- Demonstration Field Test
  - Experimental Setup
  - Simulated Measurements
  - Velocity Image Results
- Conclusions and Next Steps

Project Purpose

Sandia Wake Imaging System (SWIS) Purpose: Capture instantaneous velocity images to resolve coherent turbulent structures in the wind turbine wake region

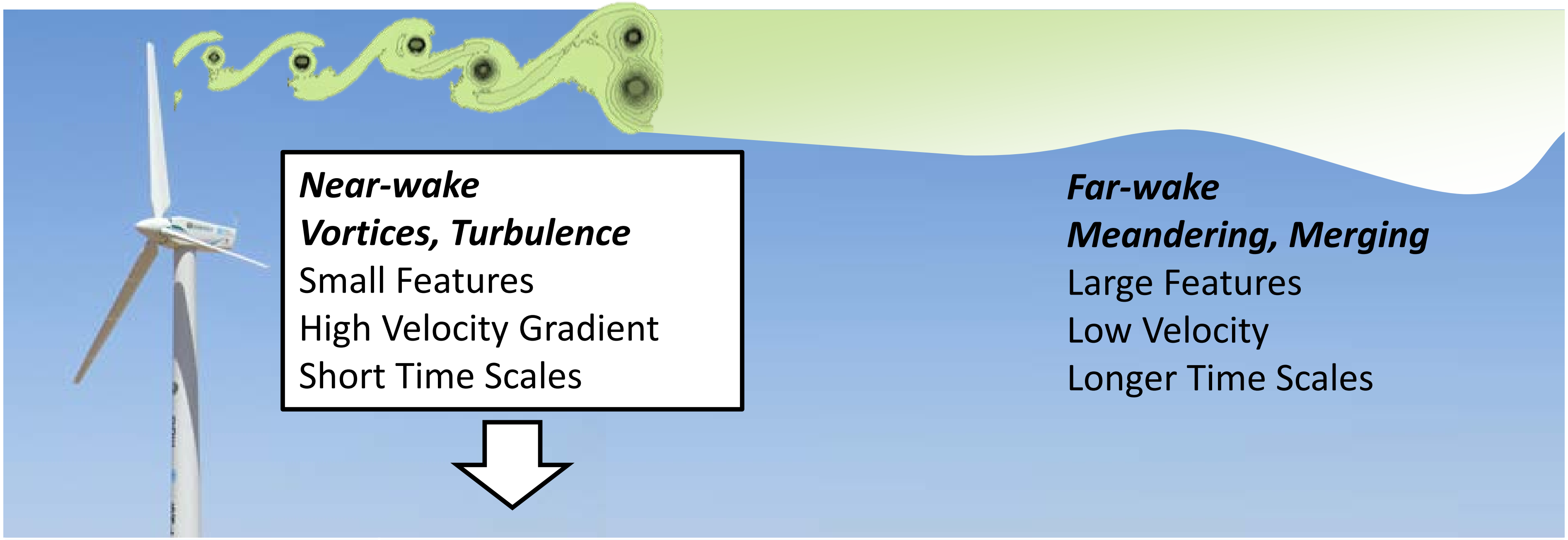
SWIS Impact:

- Enable the validation of research codes and design tools used to optimize wind plant performance
- Complement existing measurement capabilities such as lidar and radar

Project Achievements:

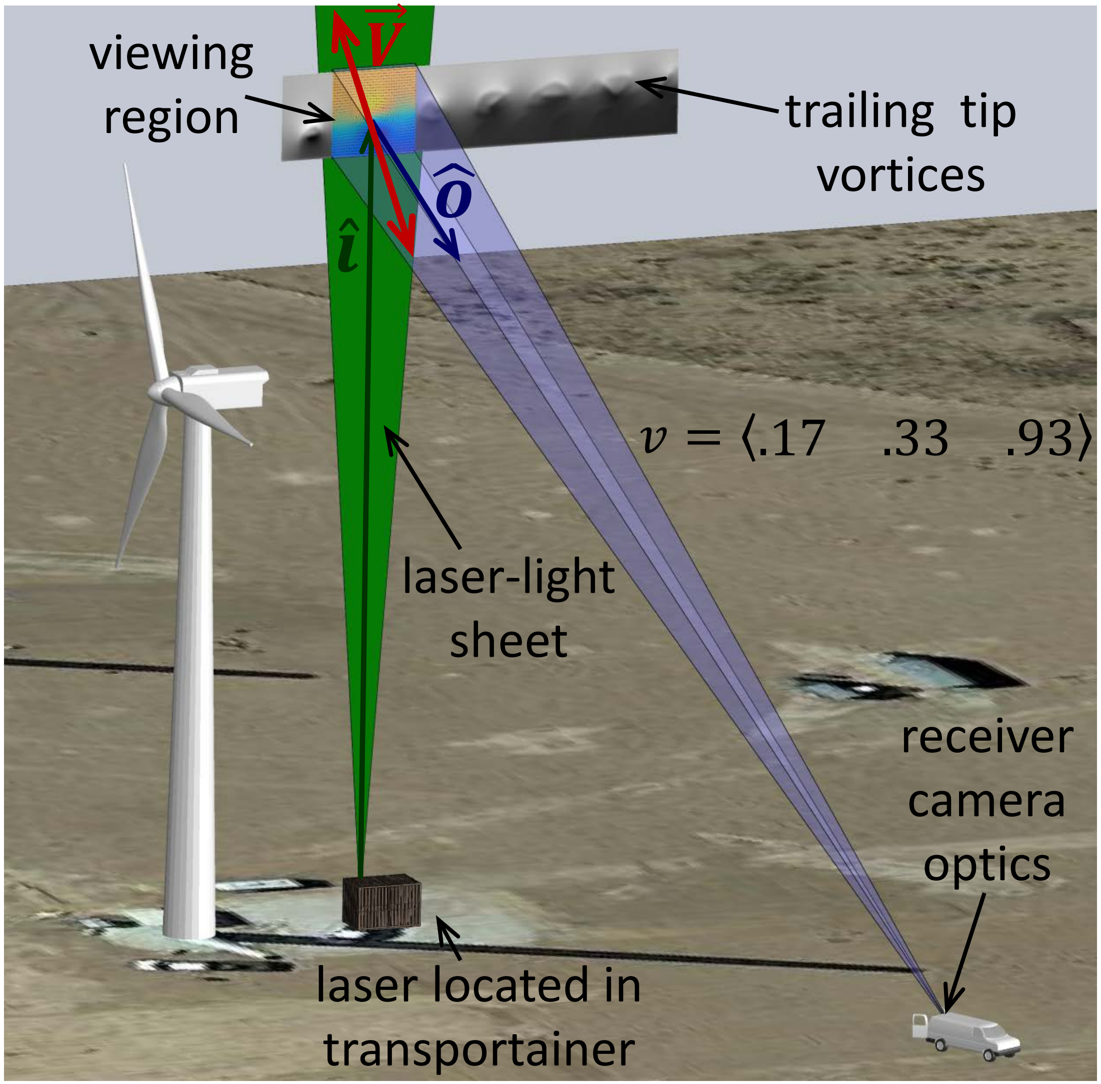
- Implement Doppler Global Velocimetry (DGV) over large field of view
- Demonstrate successful velocity image measurement of surrogate flow field
- Developed SWIS modeling tool from calibrated radiometric model for system optimization and experimental planning at SWiFT facility

Velocity Diagnostic Selection



Existing Systems	Challenges in Near-wake field testing
Particle Image Velocimetry (PIV)	**Small field of view** since individual particles need to be resolved by imaging device: • Requires extremely large tracer particles • Impractically short working distances
Scanning LIDAR	**Time and space resolution** of scanning point measurements is insufficient to capture coherent tip-vortex structures at SWiFT

Sandia Wake Imaging System (SWIS)

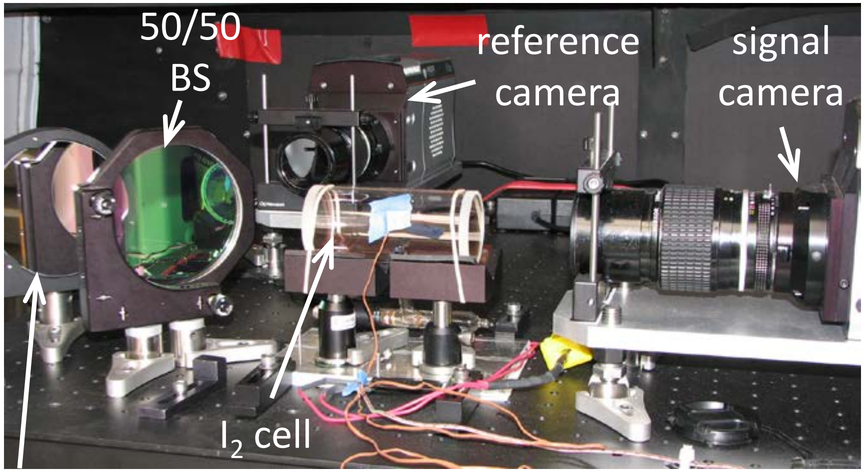


- Position of laser and camera dictates the measured velocity component
- Measure velocity component along bisector angle between observation and incident vectors, $(\hat{\boldsymbol{o}} - \hat{\boldsymbol{\imath}})$
- Additional velocity components measured with additional observation angles

Doppler frequency shift equation:

$$\Delta f_D = \frac{1}{\lambda}(\hat{\boldsymbol{o}} - \hat{\boldsymbol{\imath}}) \cdot \boldsymbol{V}$$

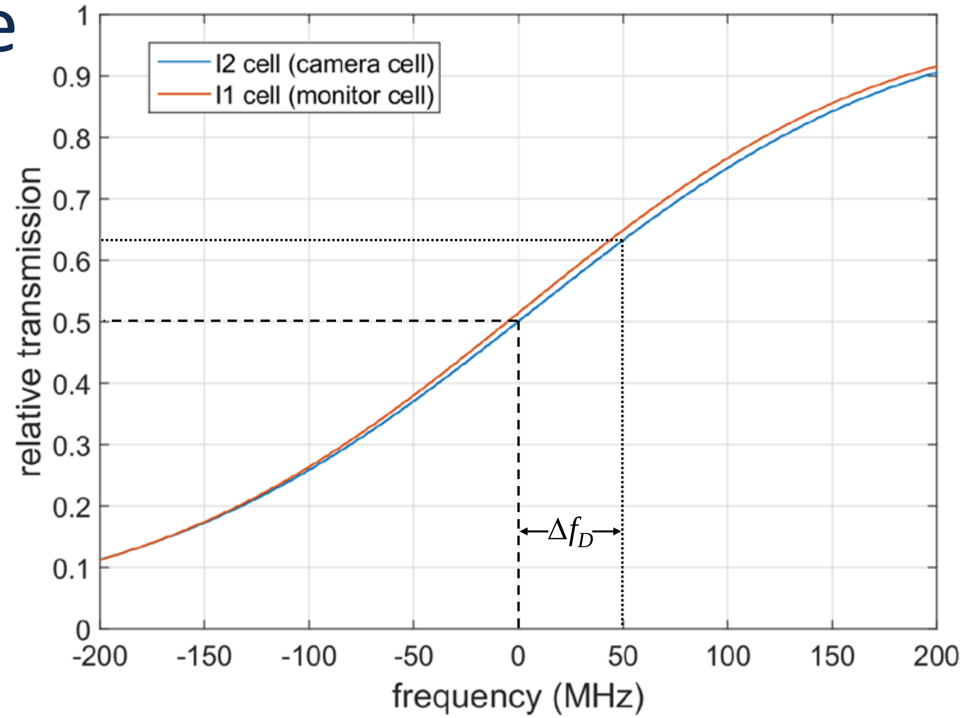
Iodine Absorption Profile Converts Frequency Shift into Intensity Change

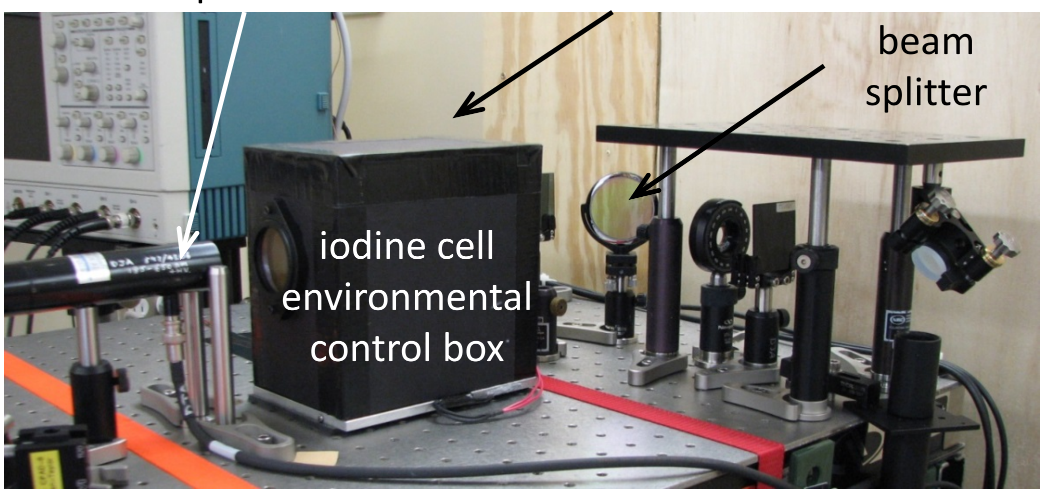


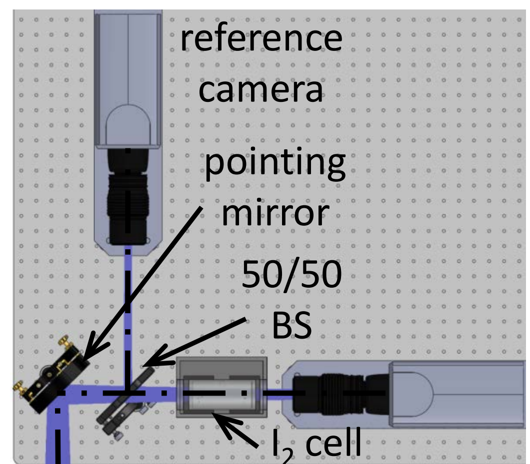
pointing mirror

signal phototube

reference phototube behind iodine cell

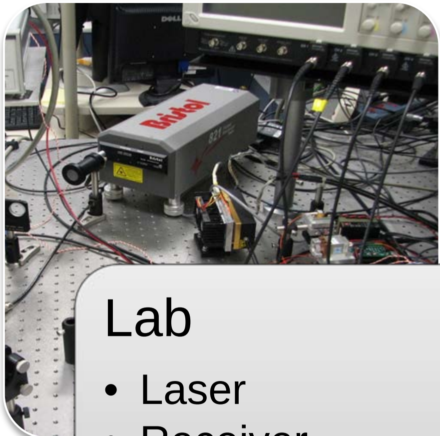






signal camera

Project Development

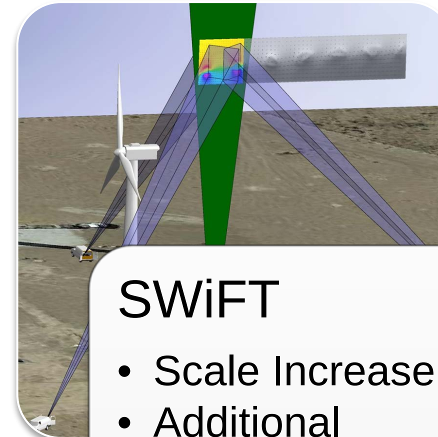


Lab

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

TA3 Sprung

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



SWiFT

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

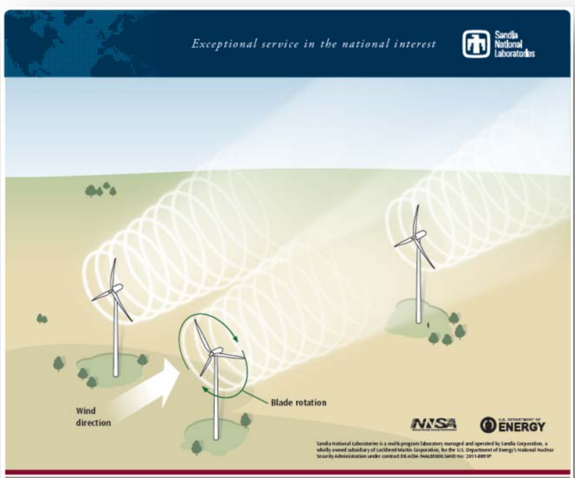
Risk reduction approach:

- Demonstrate simplest possible system
- Address make-or-break components
- Identify and resolve ES&H issues early
- Leverage deep expertise, equipment, and facilities at Sandia to save time and money
- Created radiometric model for future experimental planning

SWiFT Facility, Lubbock, TX

SWiFT exists to:

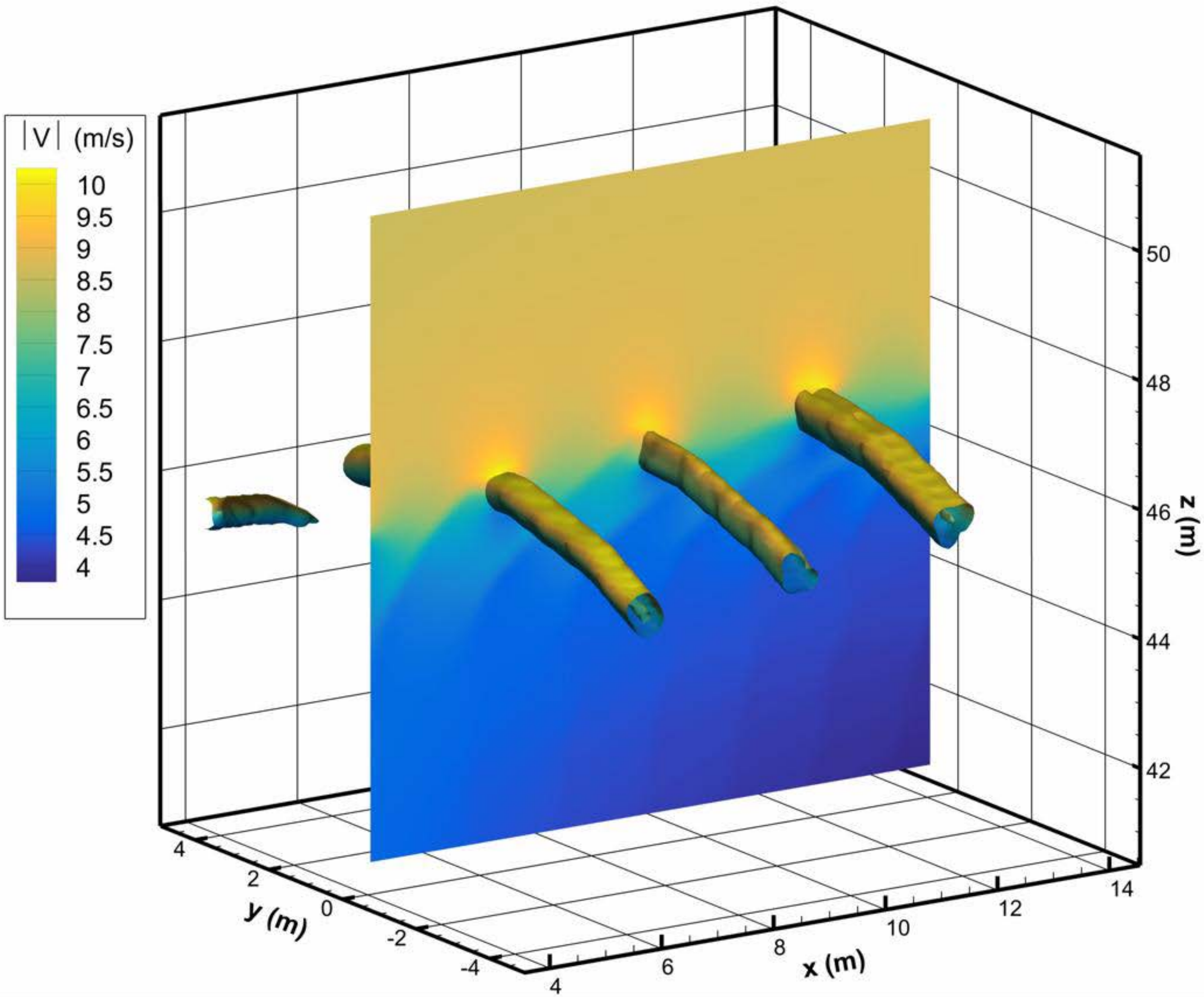
- Reduce turbine-turbine interaction and wind plant underperformance
- Develop advanced wind turbine rotors
- Public open-source to advance simulation abilities



Facilities:

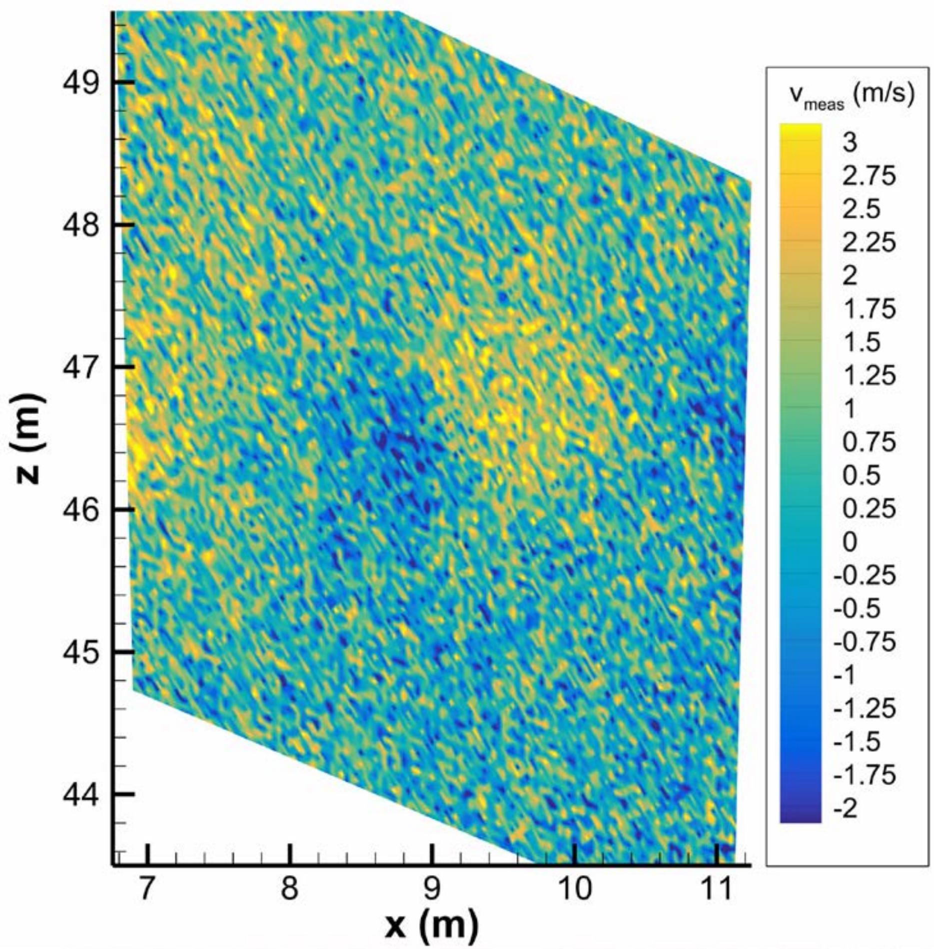
- Three variable-speed variable-pitch modified wind turbines with full power conversion and extensive sensor suite
- Two heavily instrumented inflow anemometer towers
- Site-wide time-synchronized data collection

Simulated Measurements: Representative Flow

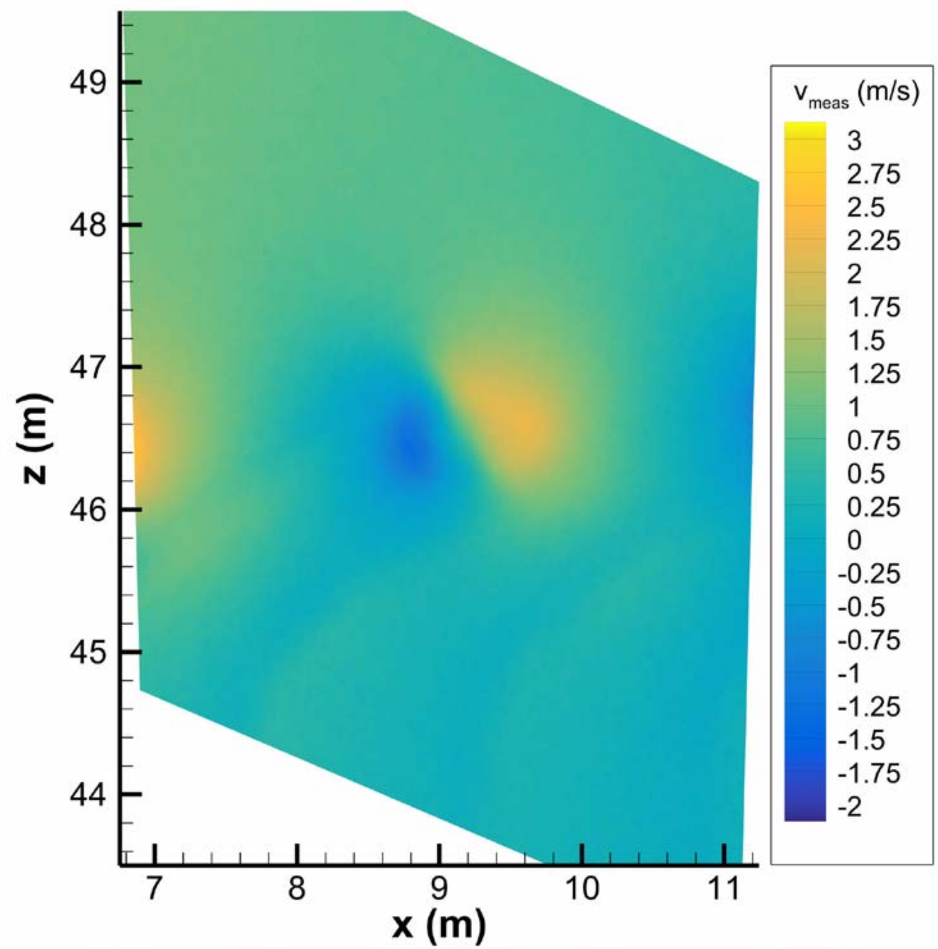


Simulated Measurements

Current System



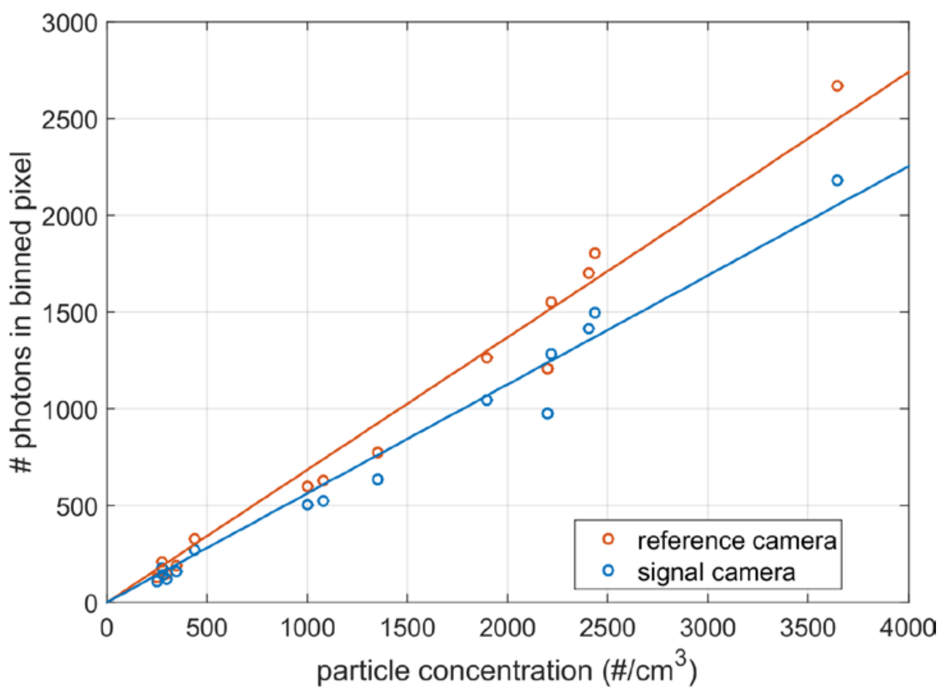
Ideal Measurement

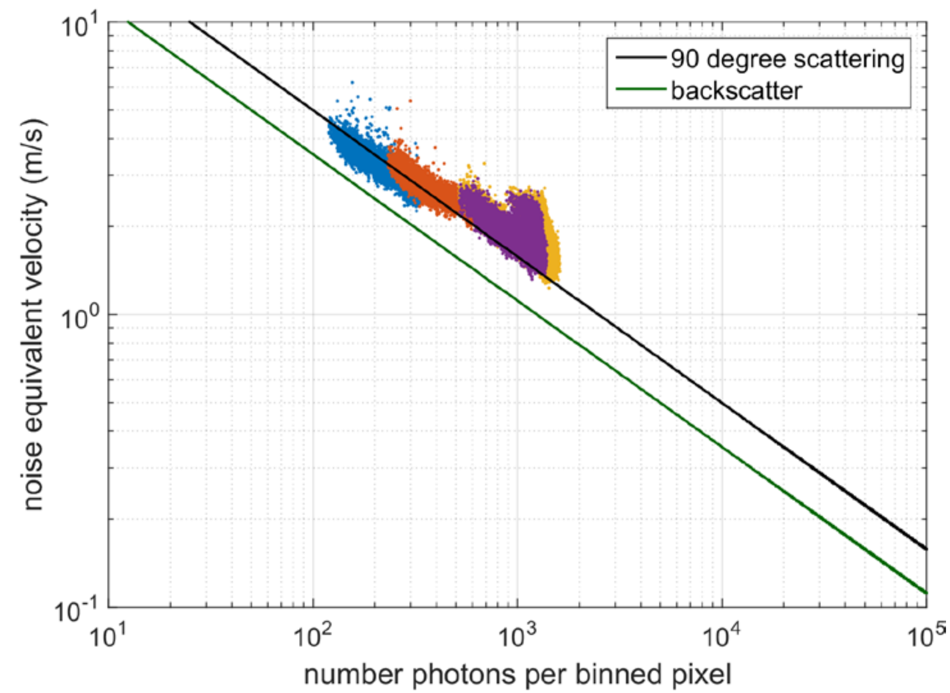


$v_{neq} = 1.43\ m/s$ $\qquad$ $v = \langle .17 \quad .33 \quad .93 \rangle$

Sensitivity Results and Implications

- Noise equivalent velocity represents the minimum resolvable velocity variation
- Shot noise equals the square root of the number of photoelectrons collected per binned pixel: $\sigma = \sqrt{N}$ $\quad NSR = \frac{\sigma}{N} = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$
- Noise equivalent velocity likely shot-noise limited and depends inversely on number of photoelectrons





Investigation Objectives

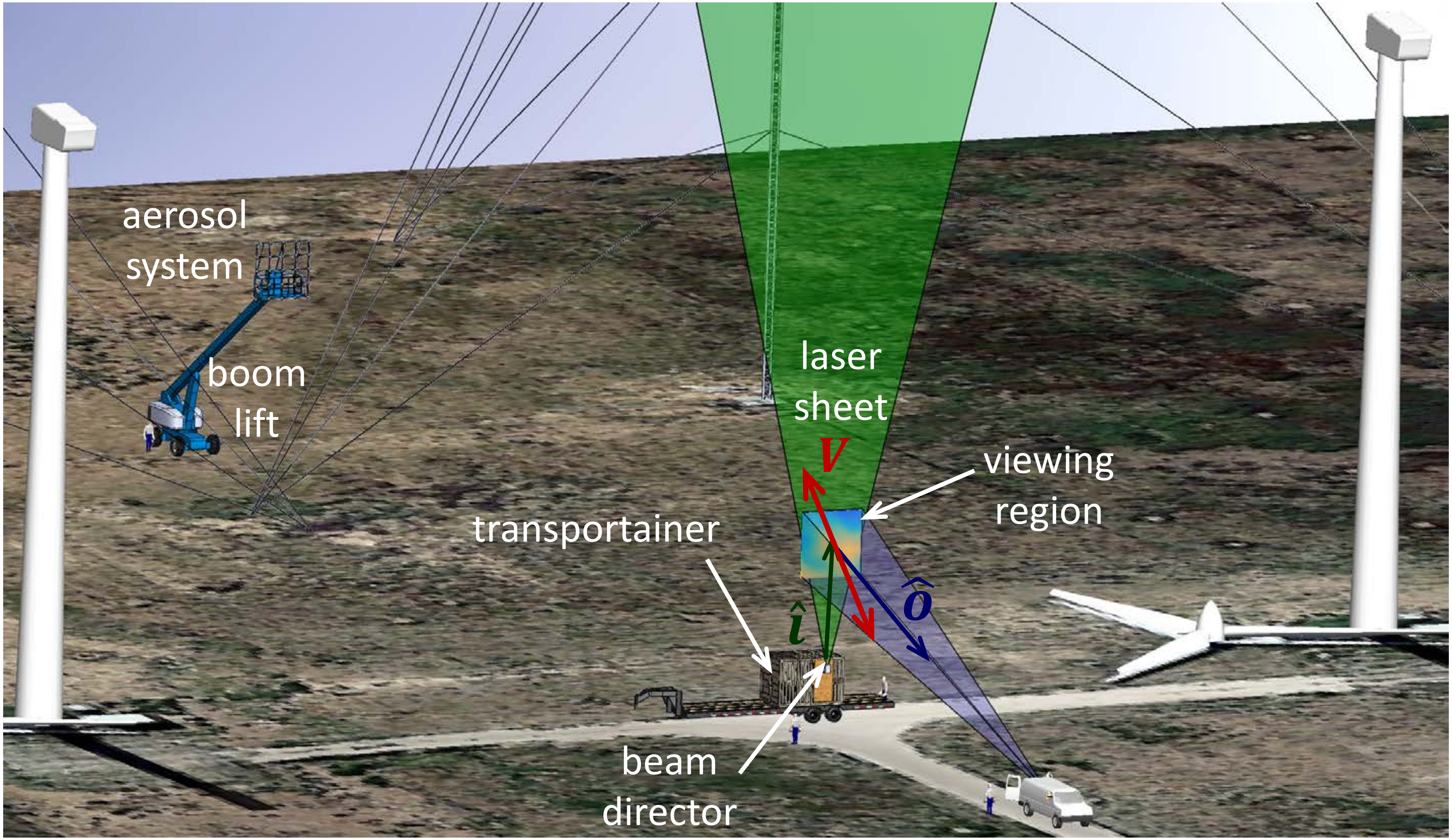
Primary Test Objective:

- Demonstrate safe, concurrent operation of the laser and aerosol system outdoors at the SWiFT facility

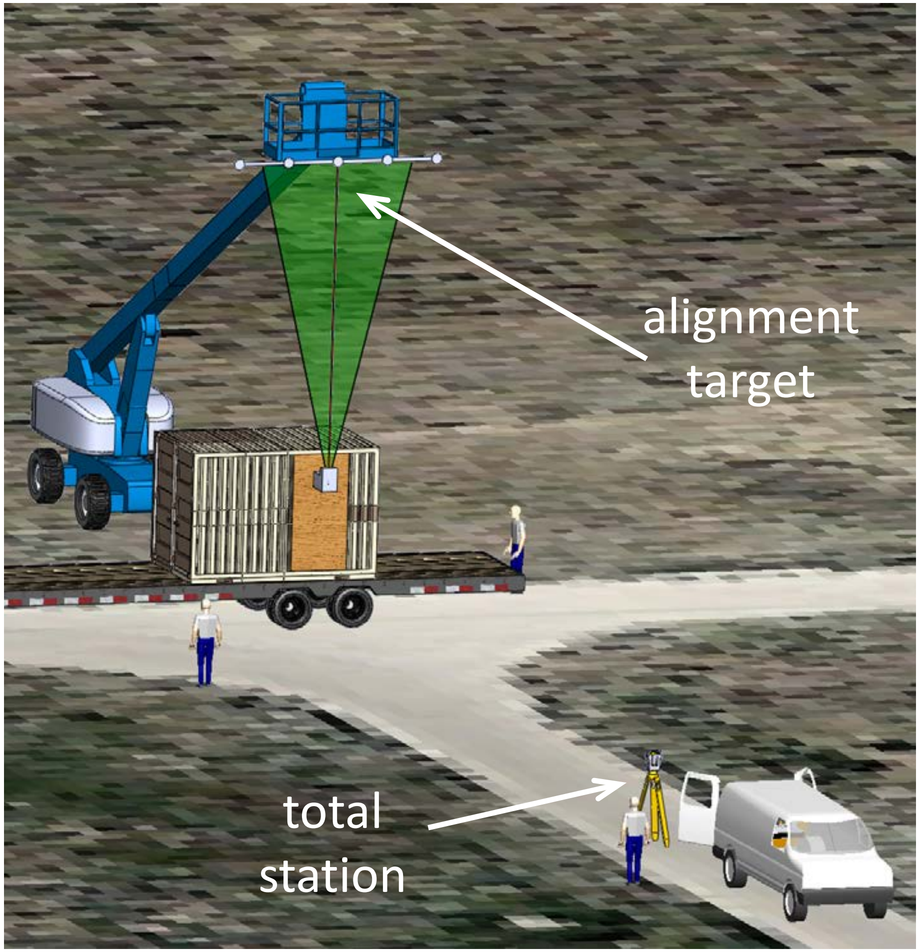
Secondary Test Objectives:

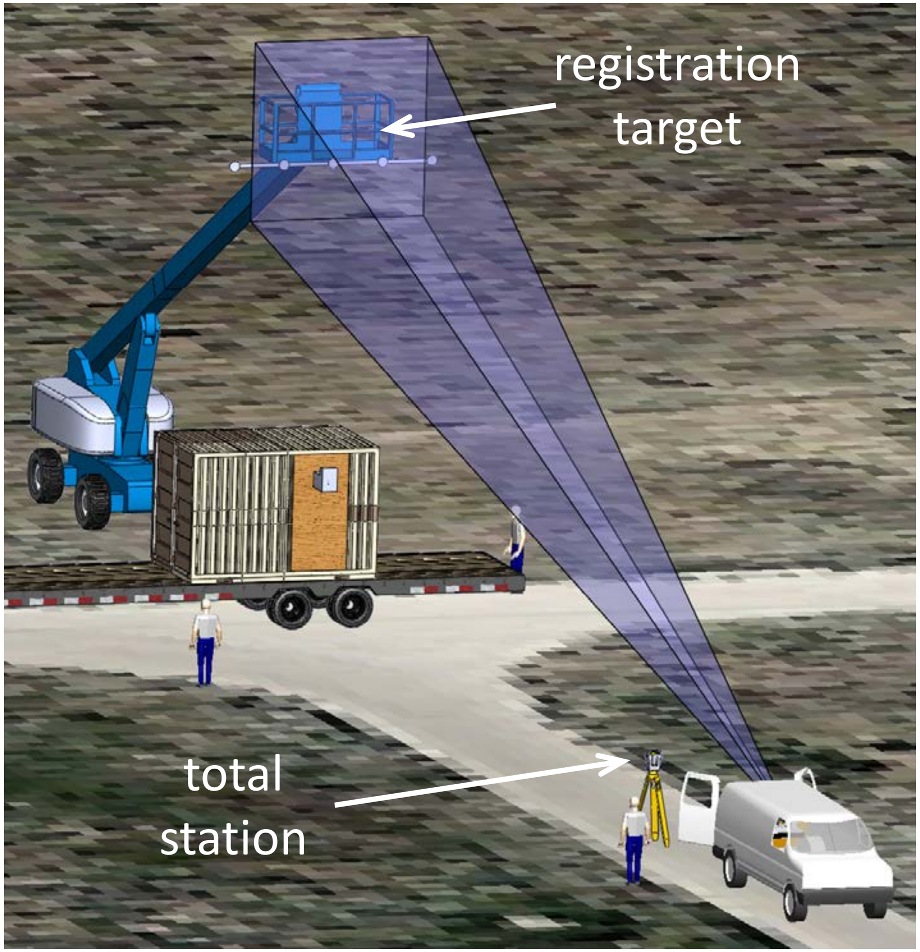
- Collect additional data sets to verify system technical capabilities

Test Configuration



Laser Alignment and Registration





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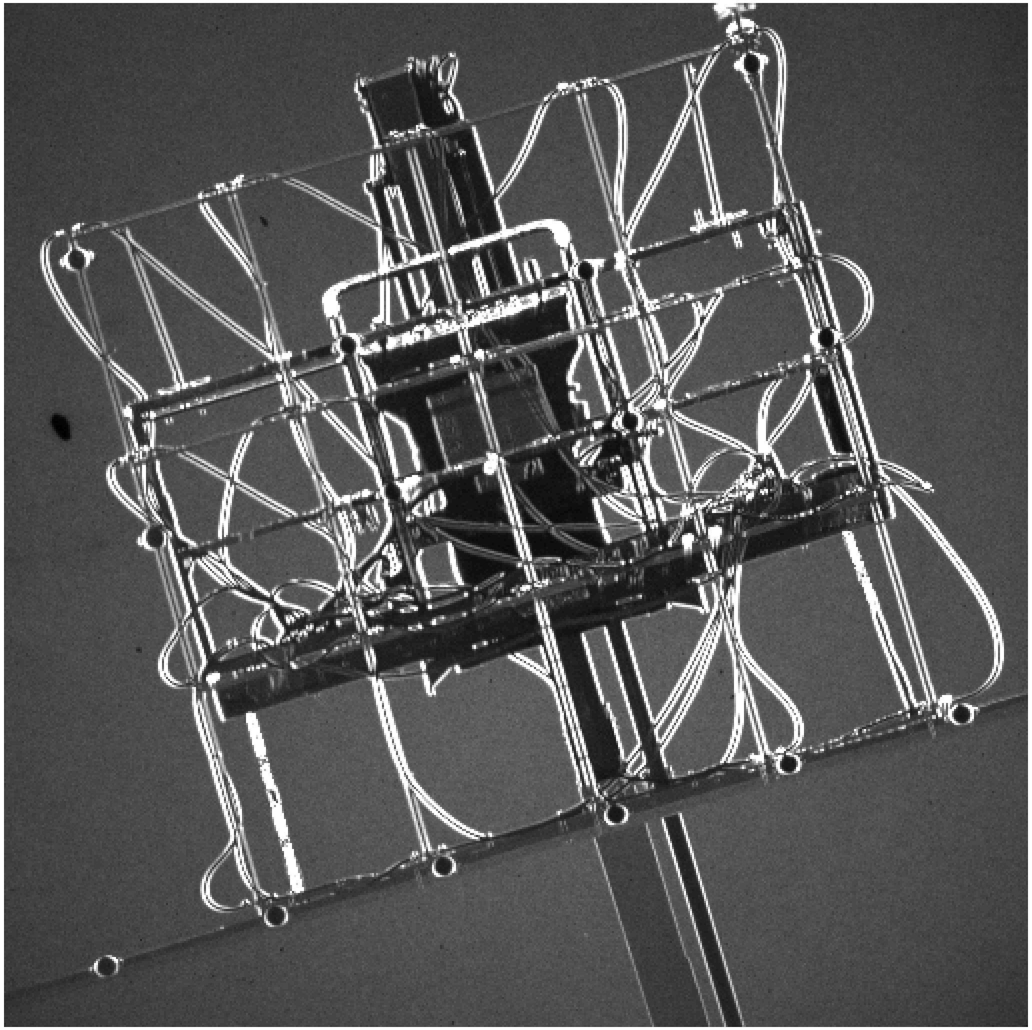
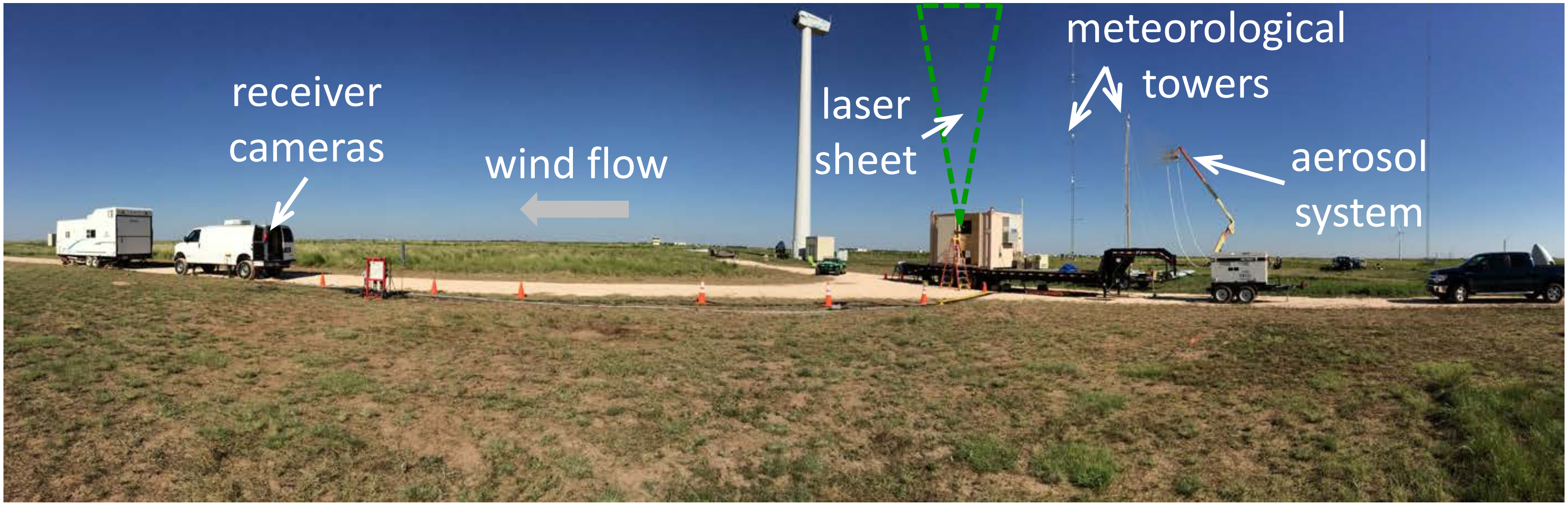
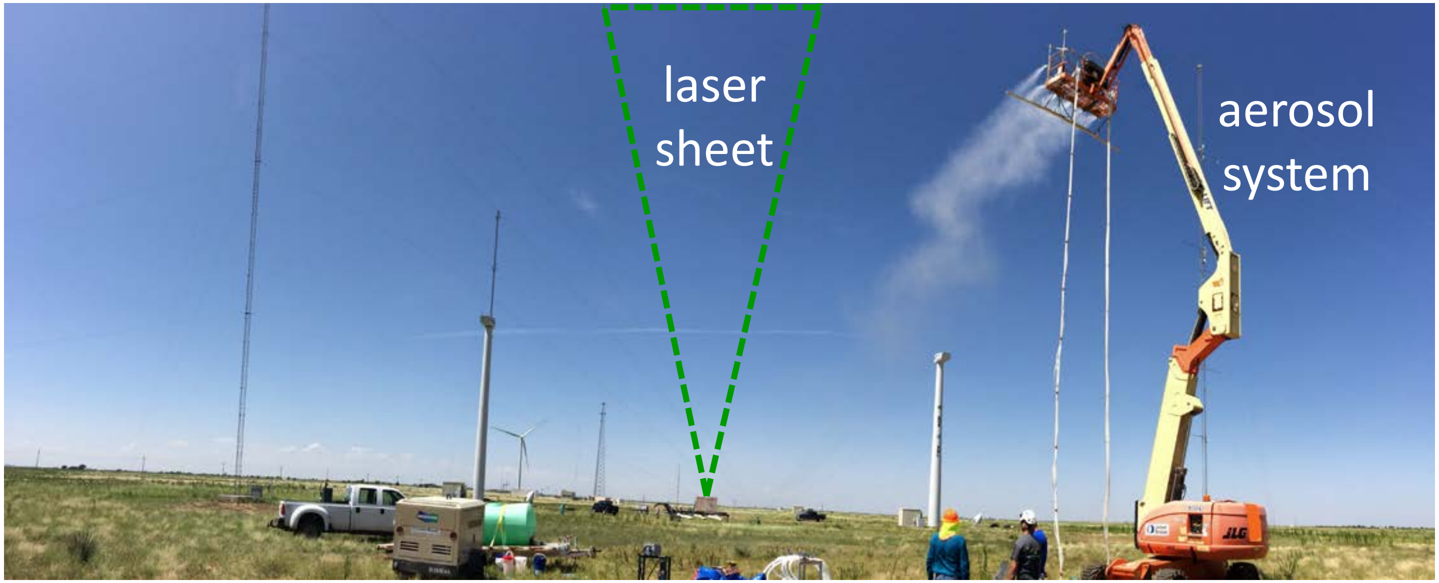


SWIS Field Demonstration

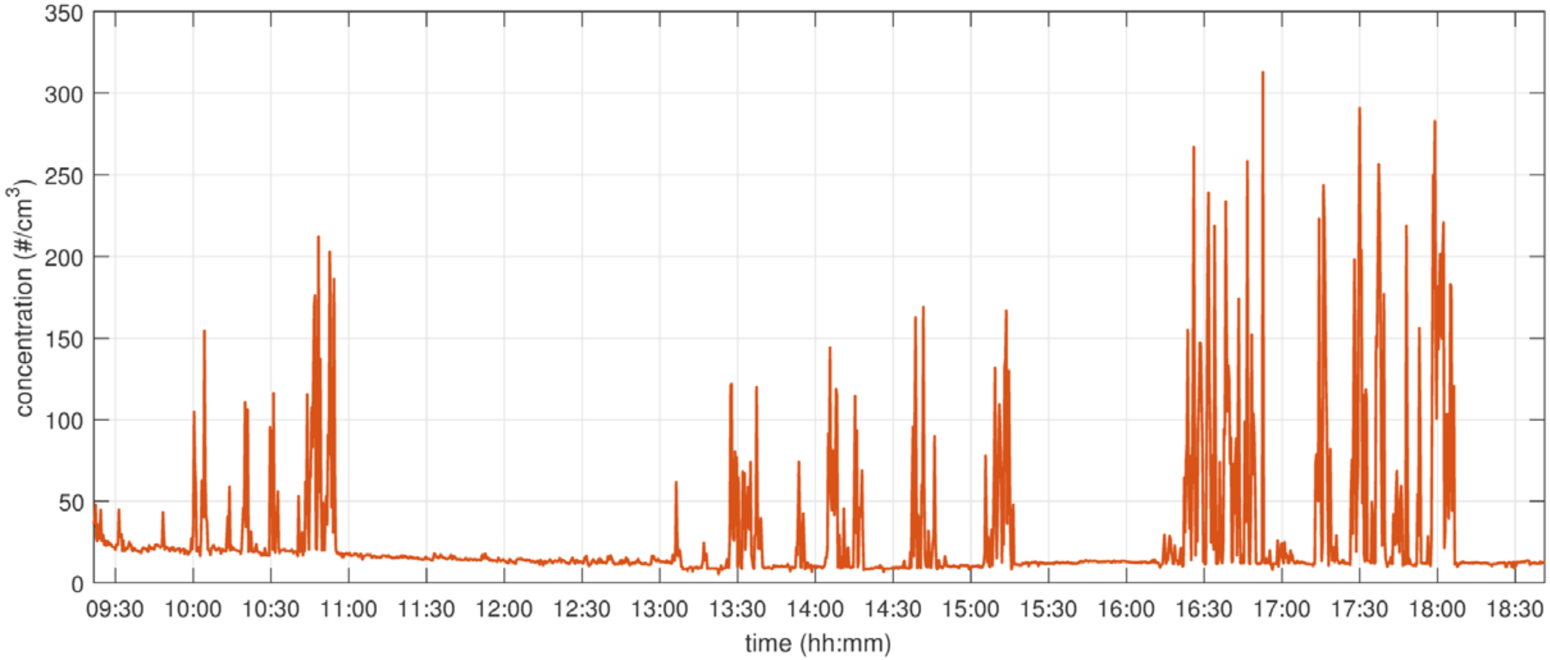




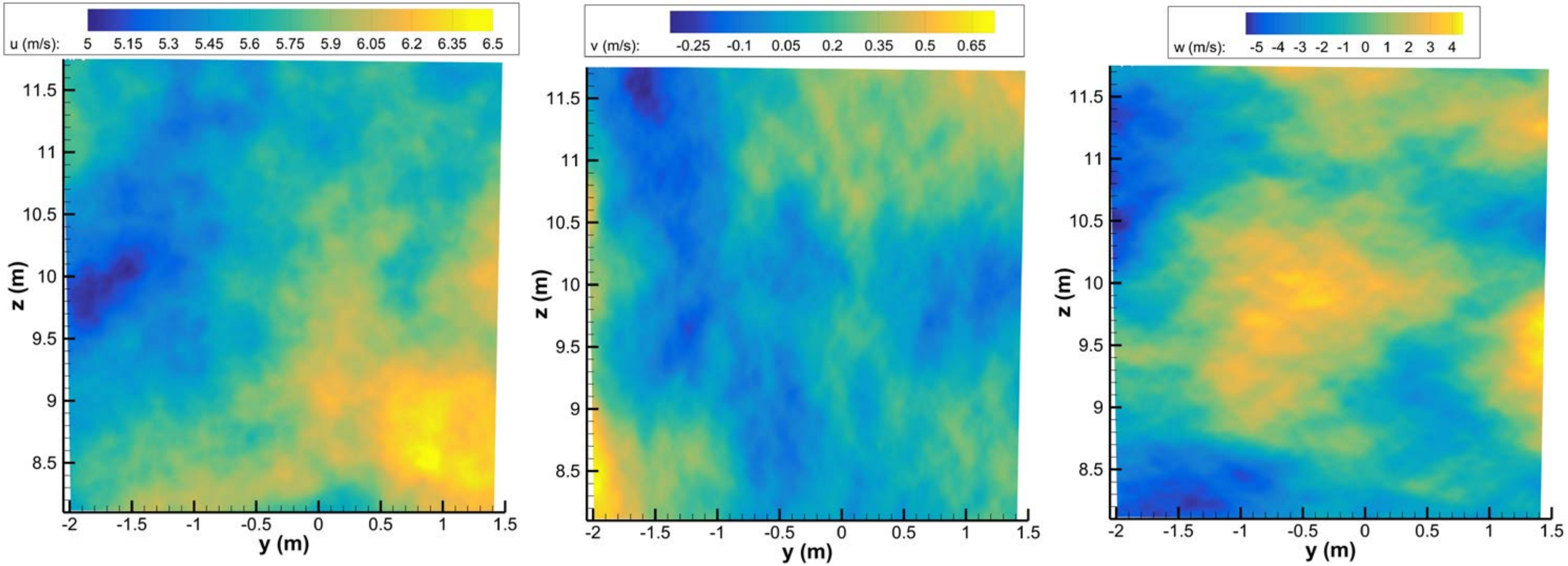
Aerosol Results

- Aerosol particulates introduced to increase receiver signal levels
- Produce KCl/water mist
- Water dries out leaving salt particles
- Drying issue forced aerosol generation further from measurement area
- Hit rate of only 28%

Aerosol Concentration



Simulated Results



- Created MATLAB based SWIS modeling tool for experimental planning and optimization
- Radiometric model calibrated from zero-velocity scaling test in Sprung
- Model incorporates 3D setup, pin-hole camera model, lens aperture size, super Gaussian laser intensity profile, Mie scattering angle, and aerosol concentration
- Imports representative flowfield and predicts measurement uncertainty/noise

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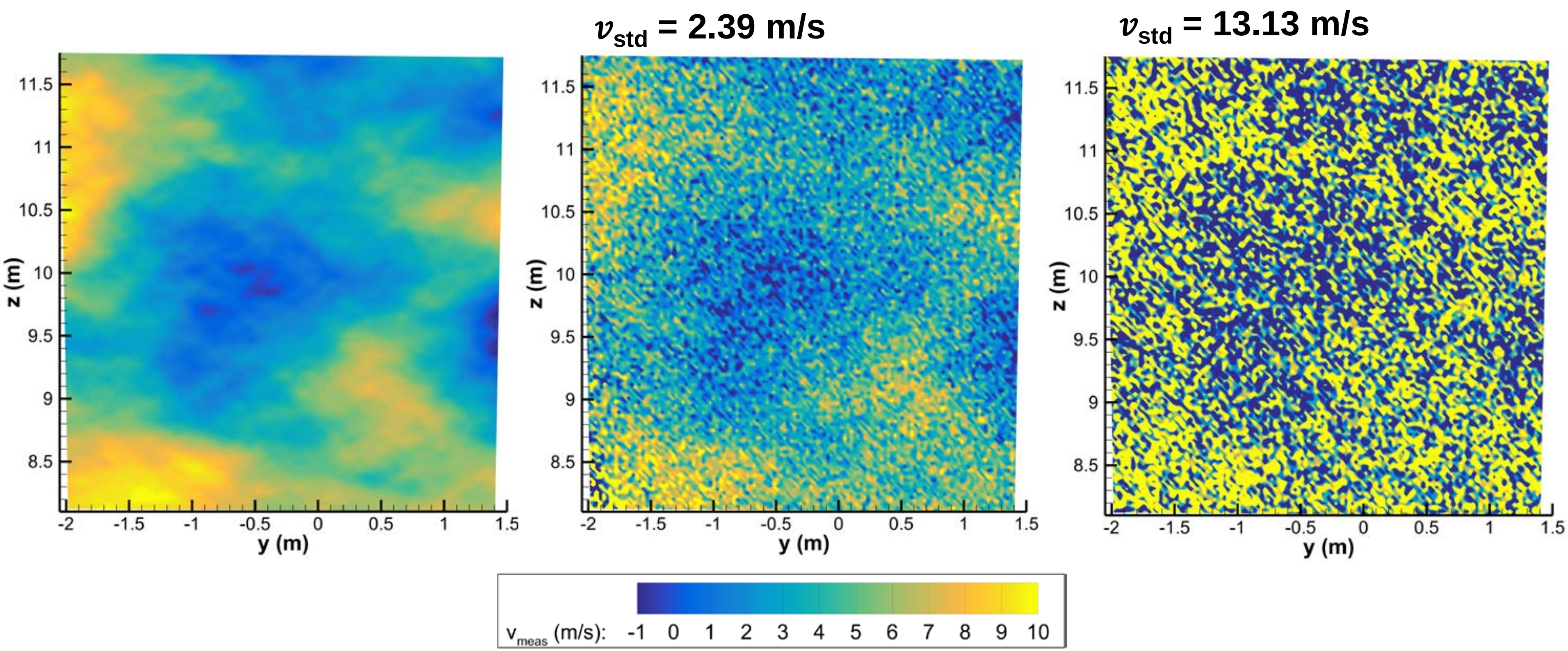

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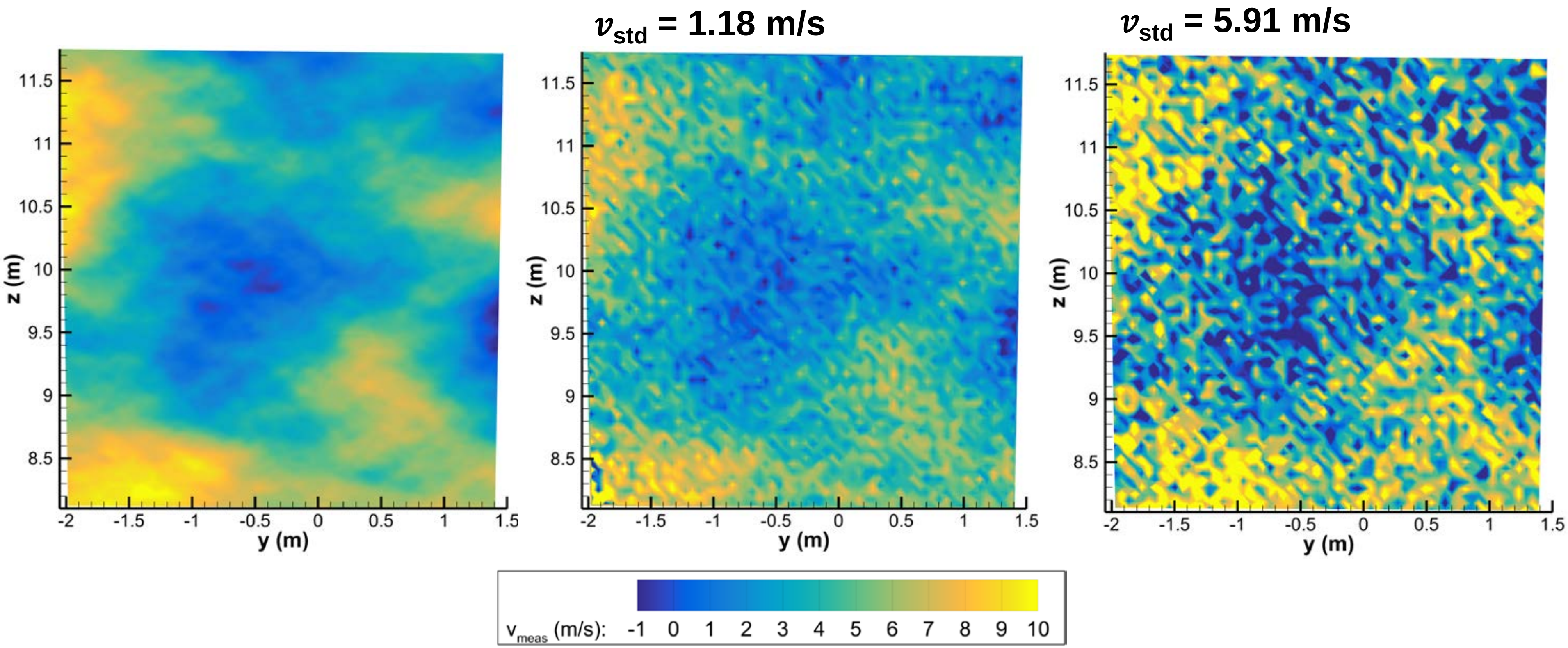

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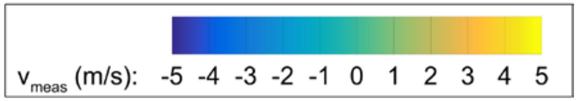
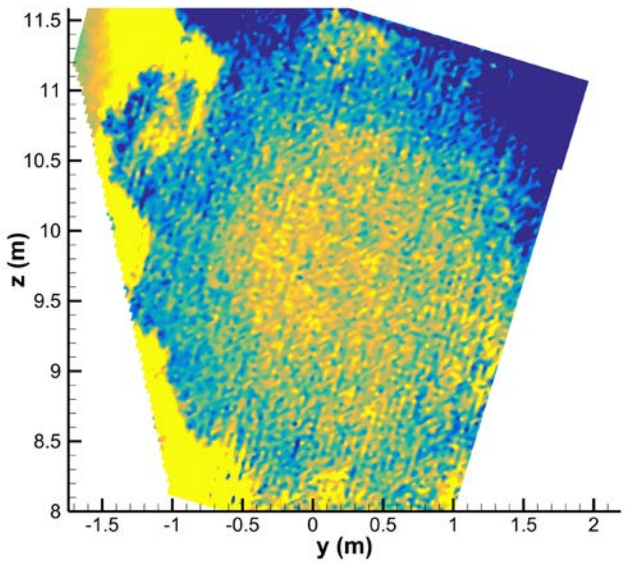
Velocity Images

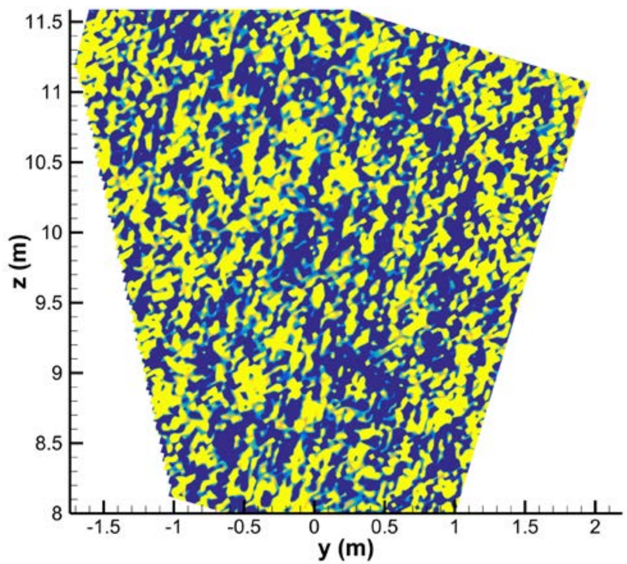


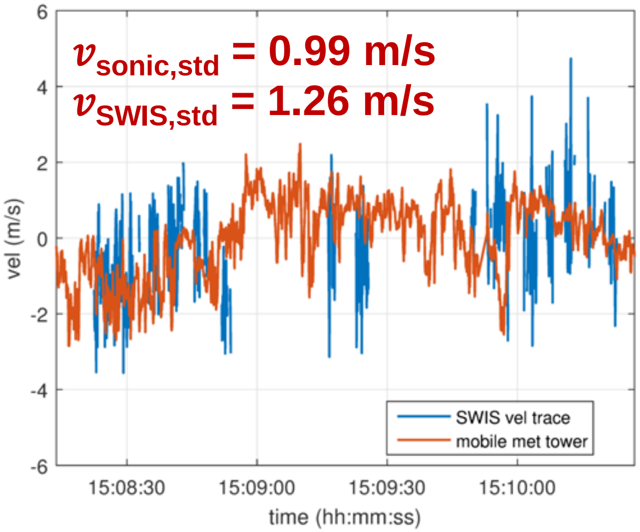
Sandia National Laboratories

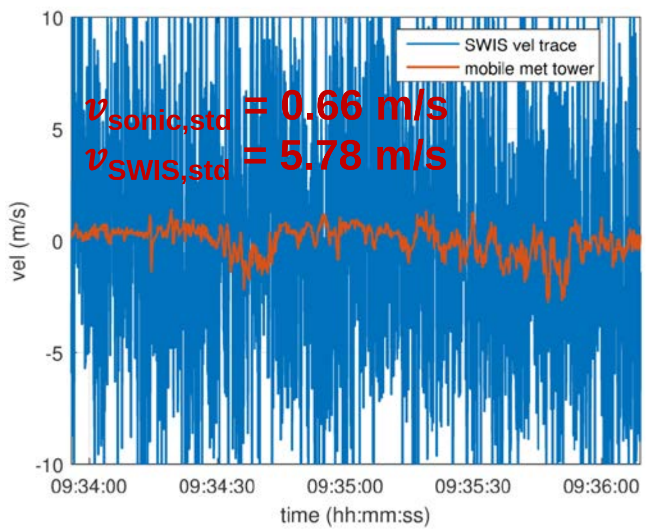
KCl Aerosol



Native Aerosol

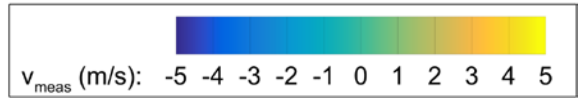






- KCl ≈ 300 #/cm^3
- Native ≈ 13 #/cm^3
- Reduced light from native aerosols increases velocity noise
- Average velocity image subtracted to remove spatial frequency variation in laser sheet
- Thus, velocity images show Δv relative to time sample average
- Specifically designed laser can improve absolute velocity measurement

Velocity Images



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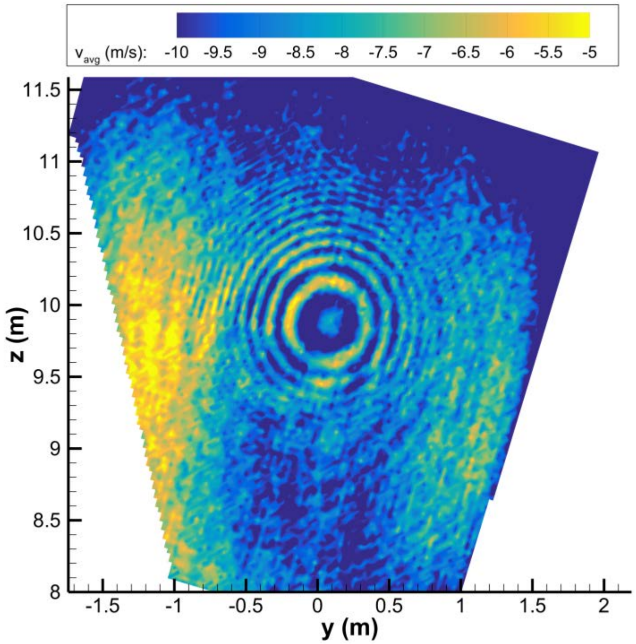

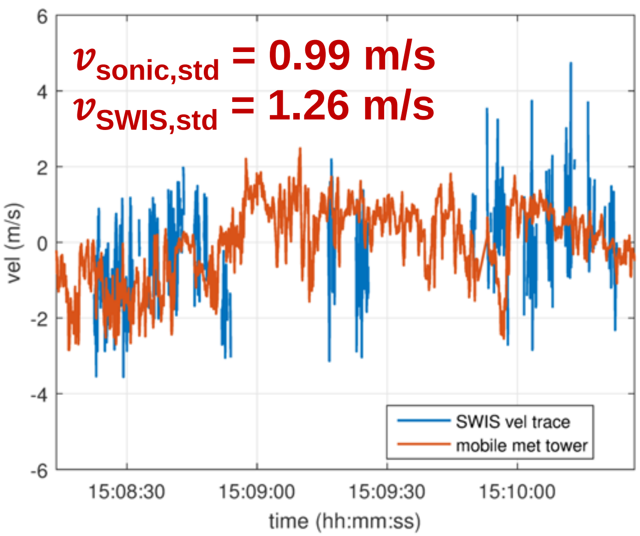

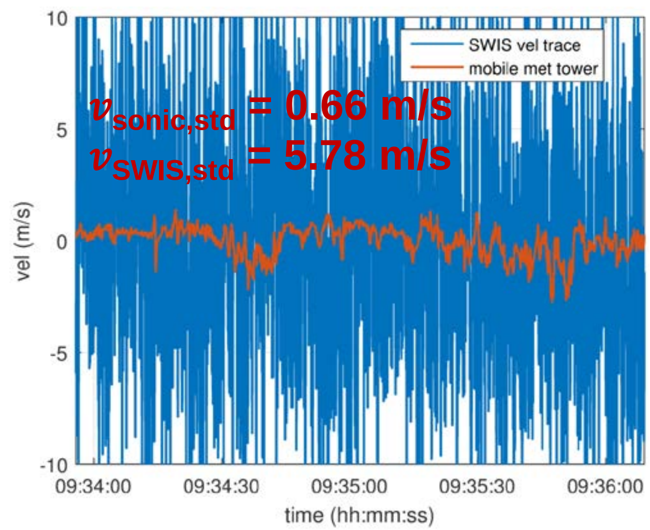

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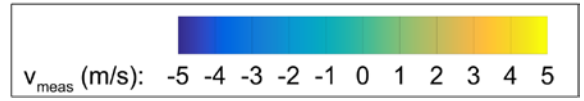

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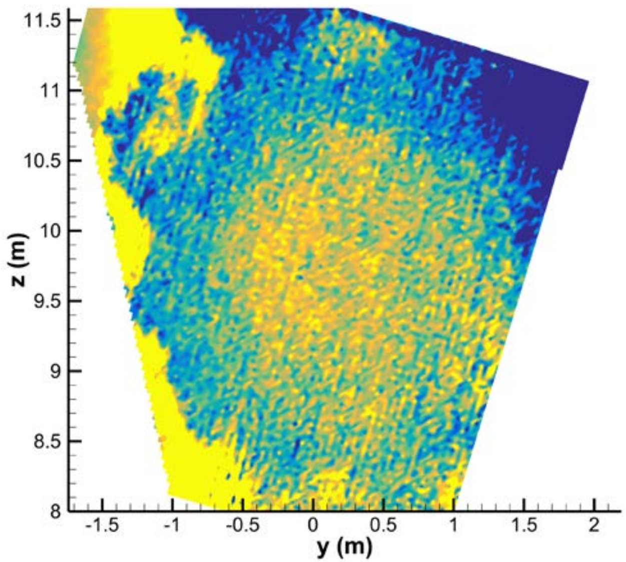

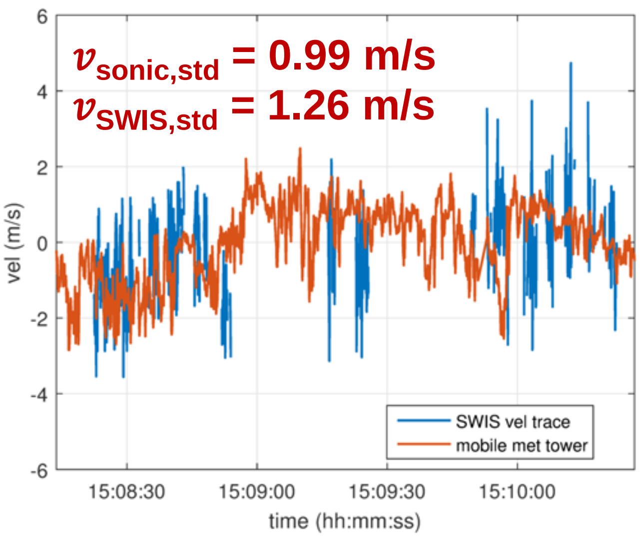

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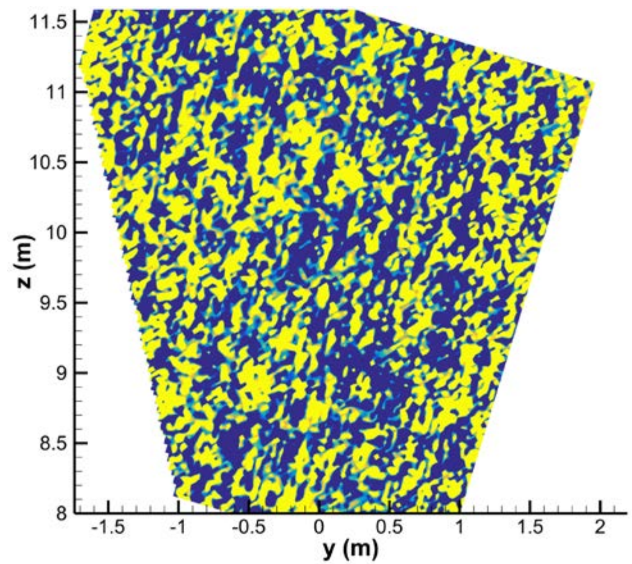

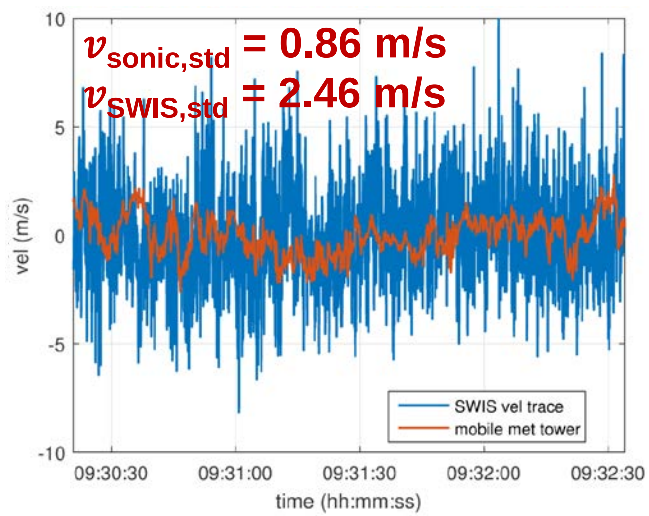

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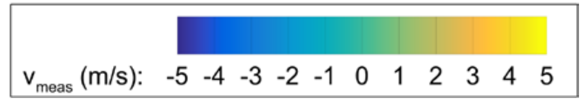

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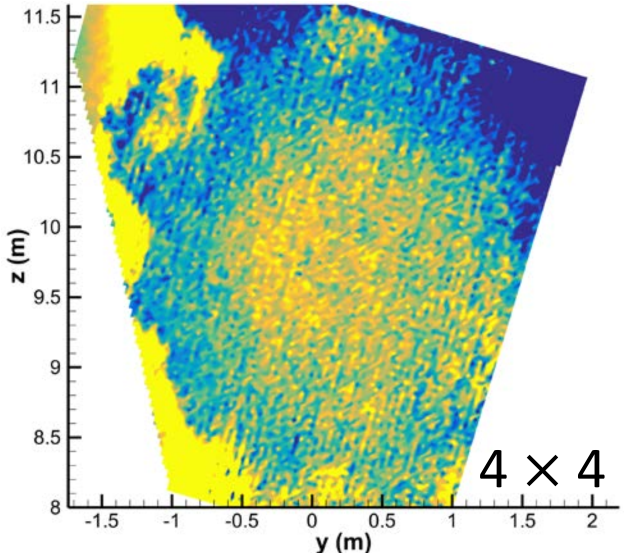

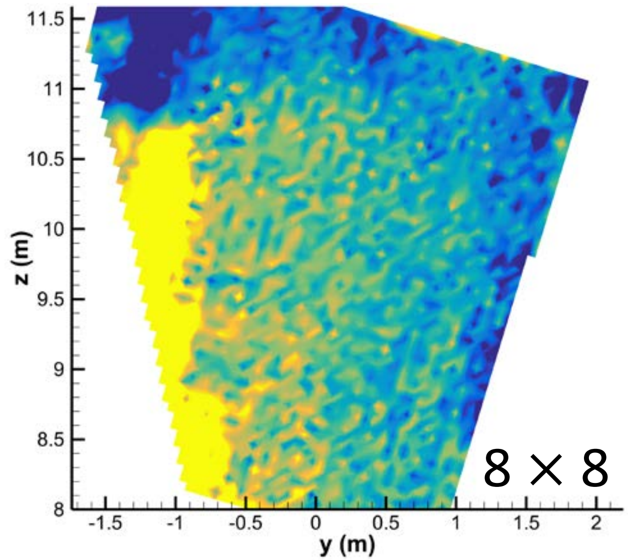

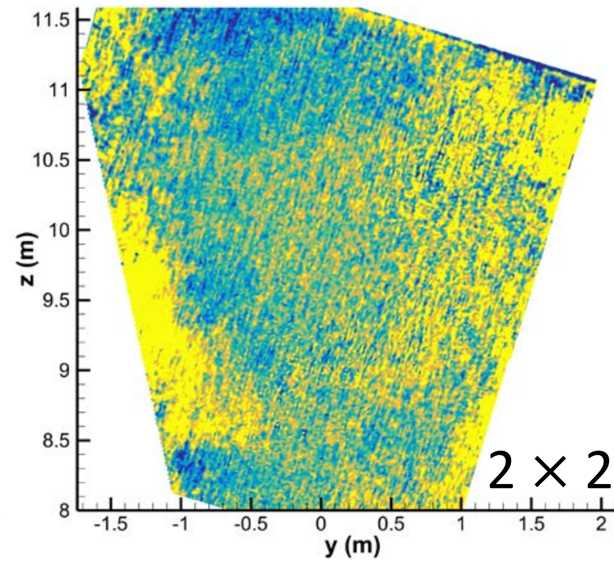

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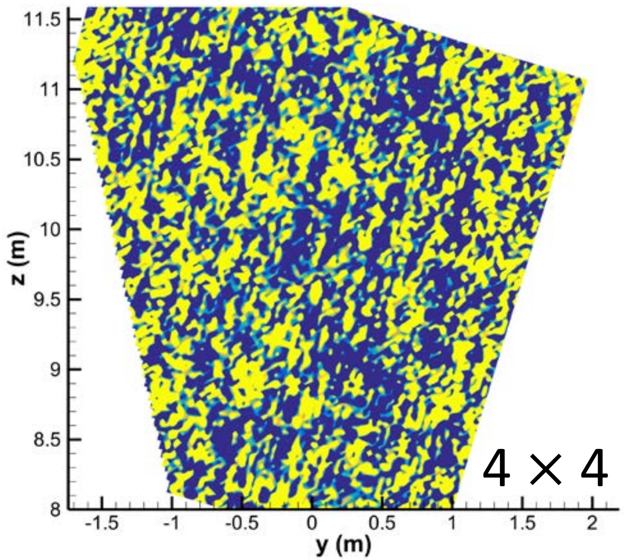

binning	aerosol	$v_{std,meas}$	v_{neq}
4 × 4	KCl (300)	±3.24	±2.39
4 × 4	native (13)	±15.77	±13.13
8 × 8	KCl (300)	±1.26	±1.18
8 × 8	native (13)	±8.55	±5.91
2 × 2	KCl (300)	±4.16	±4.88

Conclusions

- Sandia Wake Imaging System (SWIS) implements Doppler Global Velocimetry (DGV) for improved scaling capabilities
- Safely acquired velocity images outdoors over a large field of view
- Attained change-in-velocity measurements relative to the average over a 3.5 m $\times$ 3.5 m window at a height of 9.8 m
- Measurements agreed well with simulated measurement predictions
- Improved confidence in radiometric model results for future experimental planning to validate high fidelity models

Next Steps

Instrumentation Simulation

- Use SOWFA simulations and SWIS model to simulate measurements to determine system requirements
- Conclude whether upgrade cost worth meeting simulation validation needs

Possible Upgrades

- Specifically designed pulse-burst laser
- Improved aerosol generation system
- Improved iodine cells
- More receivers, more velocity components