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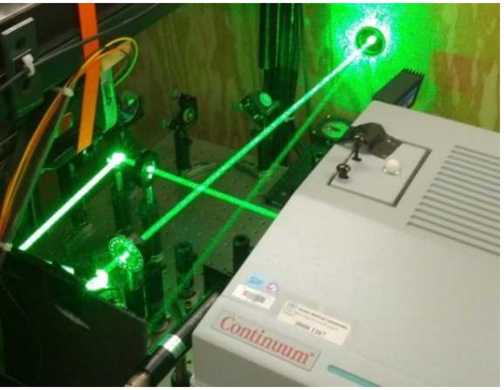

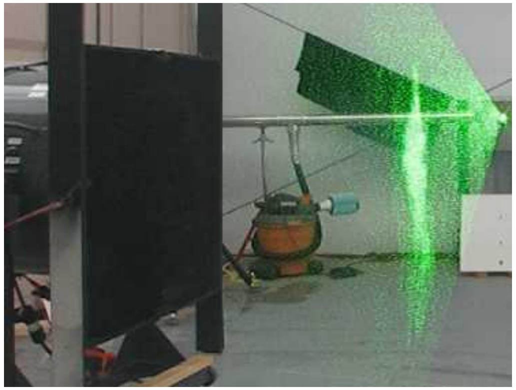

Preliminary Field Test of the Wind Turbine Wake Imaging System

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Funded by DOE Wind and Water Power Technologies Office

33rd ASME Wind Energy Symposium

1/5/2014

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Outline

- Project Purpose and Investigation Objectives
- Doppler Global Velocimetry Theory
- Notional Field System Deployed at SWiFT facility
- Preliminary Field Test (Sprung Test)
  - Experimental Setup
  - Image Processing
  - Velocity Image Results
  - Noise Equivalent Velocity
- Implications for Deployment at SWiFT facility

Purpose & Investigation Objectives

Sandia National Laboratories

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

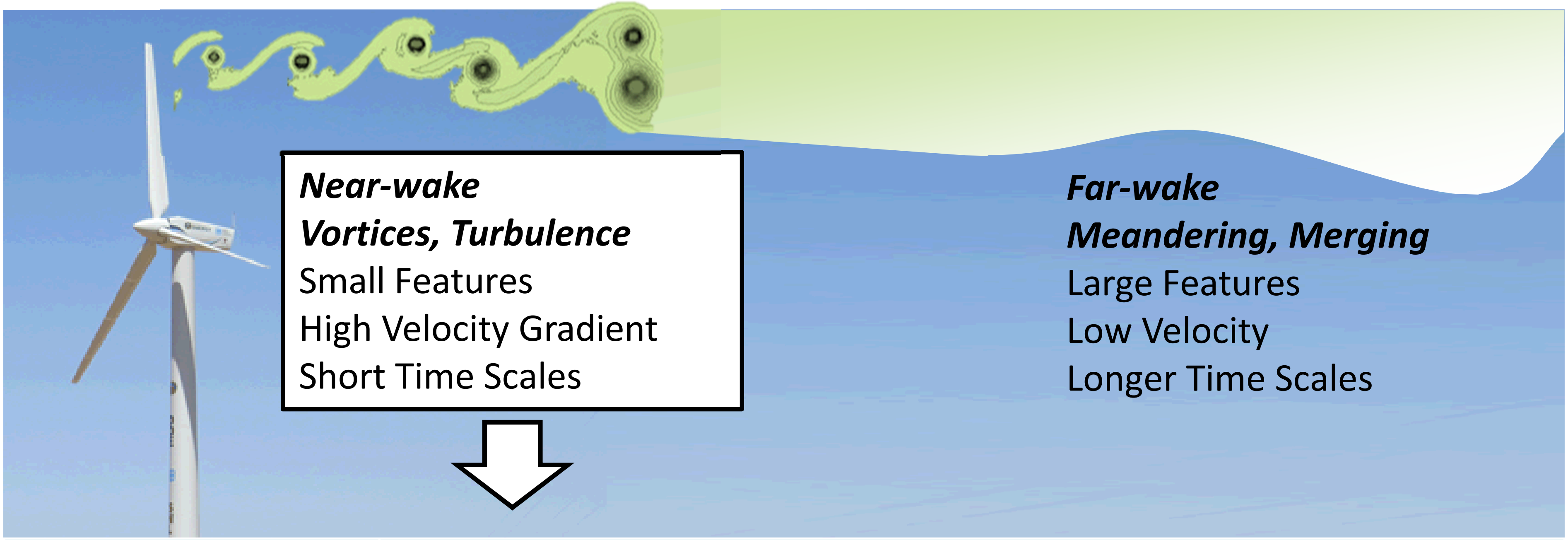
SWIS Impact:

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

Current Investigation:

- Implement Doppler Global Velocimetry (DGV) over large field of view
- Demonstrate successful velocity image measurement of surrogate flow field
- System sensitivity analysis to calibrate radiometric modeling
- Determine how system could scale to larger viewing areas applicable to planned wind turbine field testing at Scaled Wind Farm Technology (SWiFT) facility

Velocity Diagnostic Selection

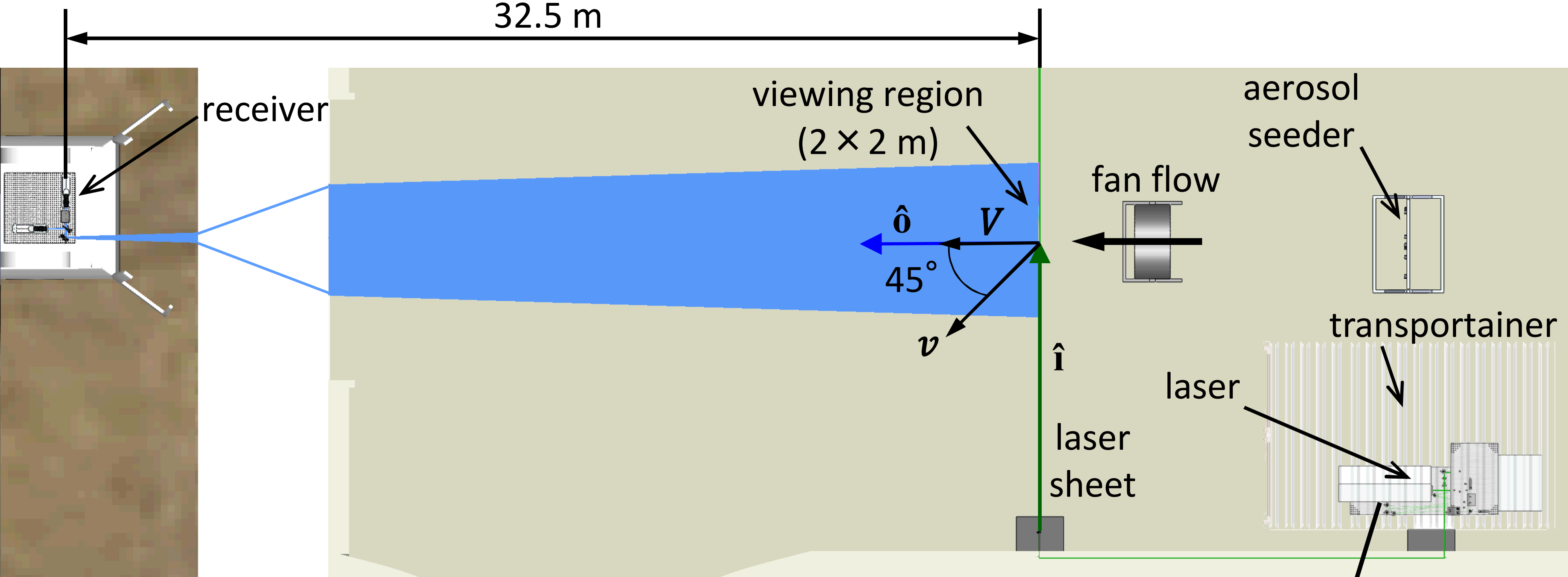


Near-wake
Vortices, Turbulence
Small Features
High Velocity Gradient
Short Time Scales

Far-wake
Meandering, Merging
Large Features
Low Velocity
Longer Time Scales

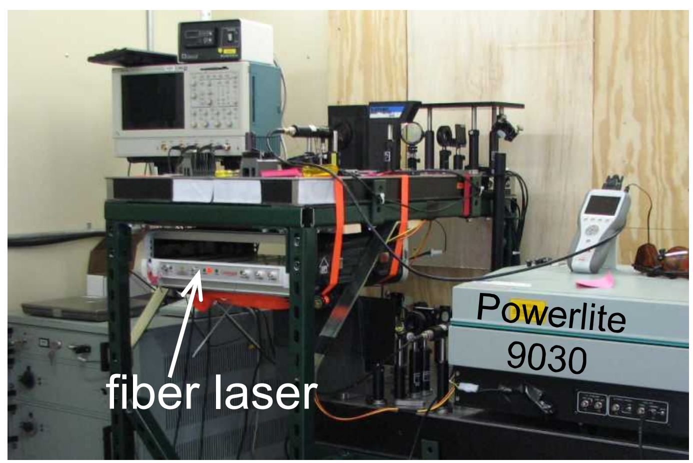
Existing Systems	Challenges in Near-wake field testing
Particle Image Velocimetry (PIV)	**Small field of view** since individual particles need to be resolved by imaging device: • Requires extremely large tracer particles • Impractically short working distances
Scanning LIDAR	**Time and space resolution**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

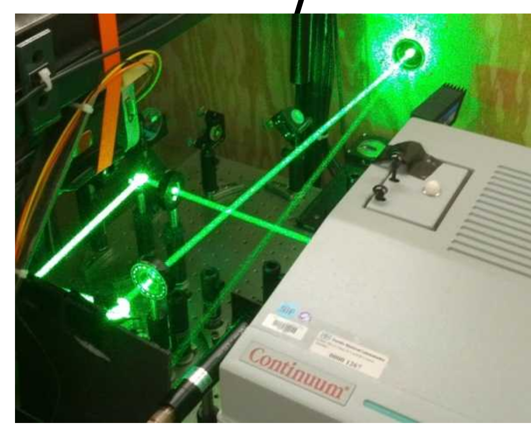
Doppler Global Velocimetry



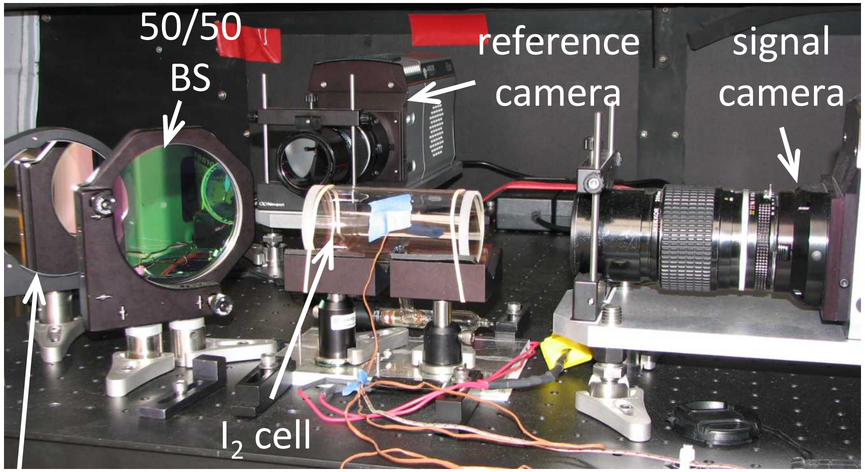
Doppler frequency shift equation:

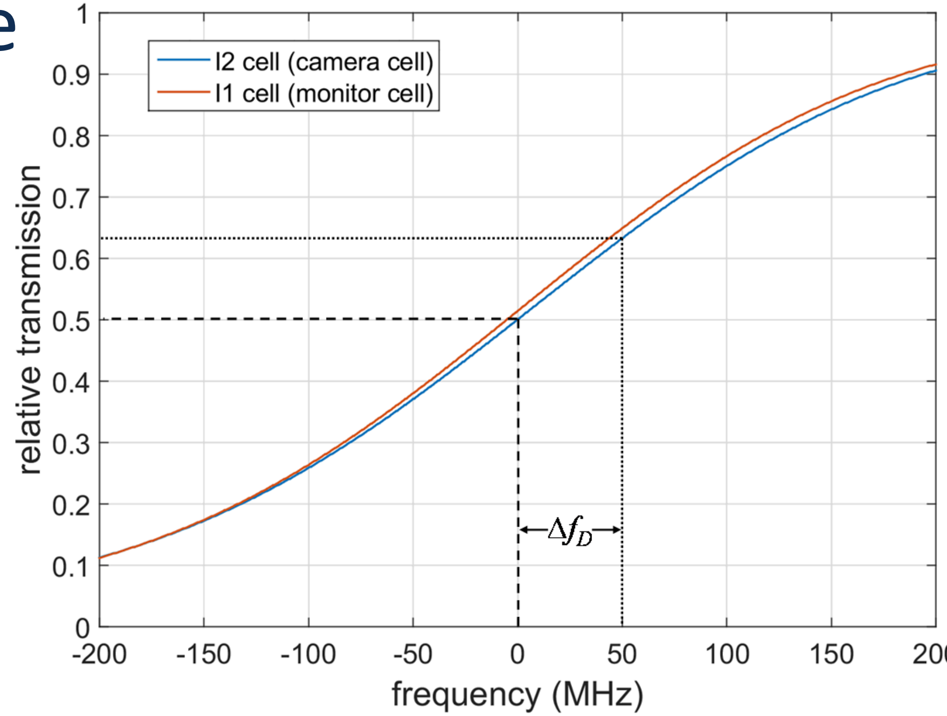
$$\Delta f_D = \frac{1}{\lambda}(\hat{\boldsymbol{o}} - \hat{\boldsymbol{\imath}}) \cdot \boldsymbol{V}$$

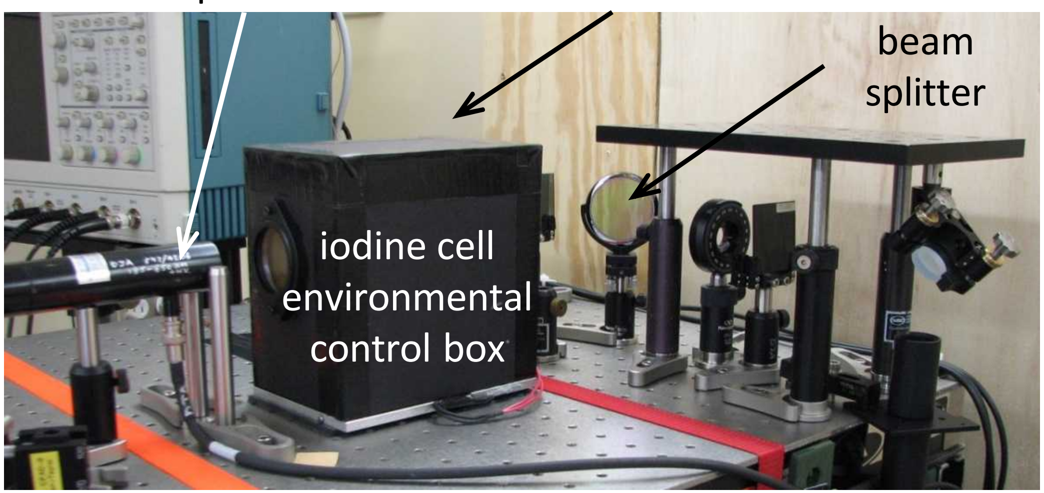


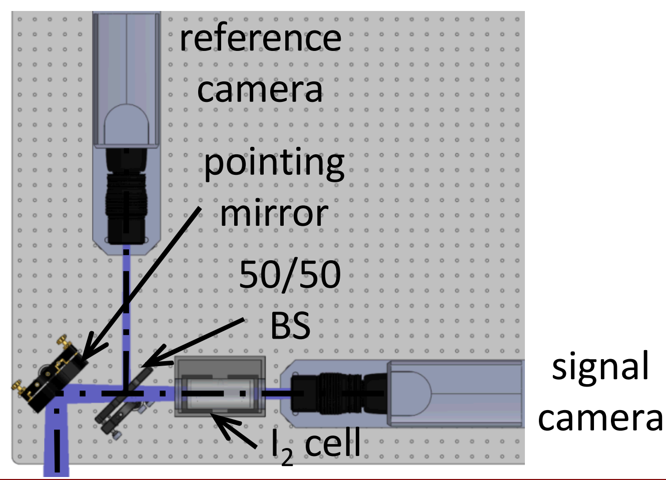


Iodine Absorption Profile Converts Frequency Shift into Intensity Change





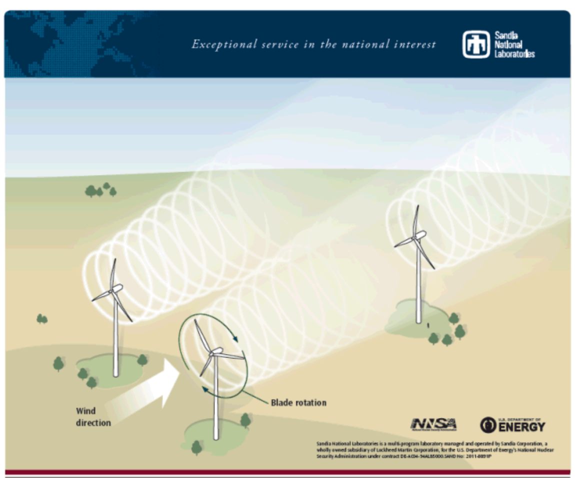




SWiFT Facility, Lubbock, TX

SWiFT exists to:

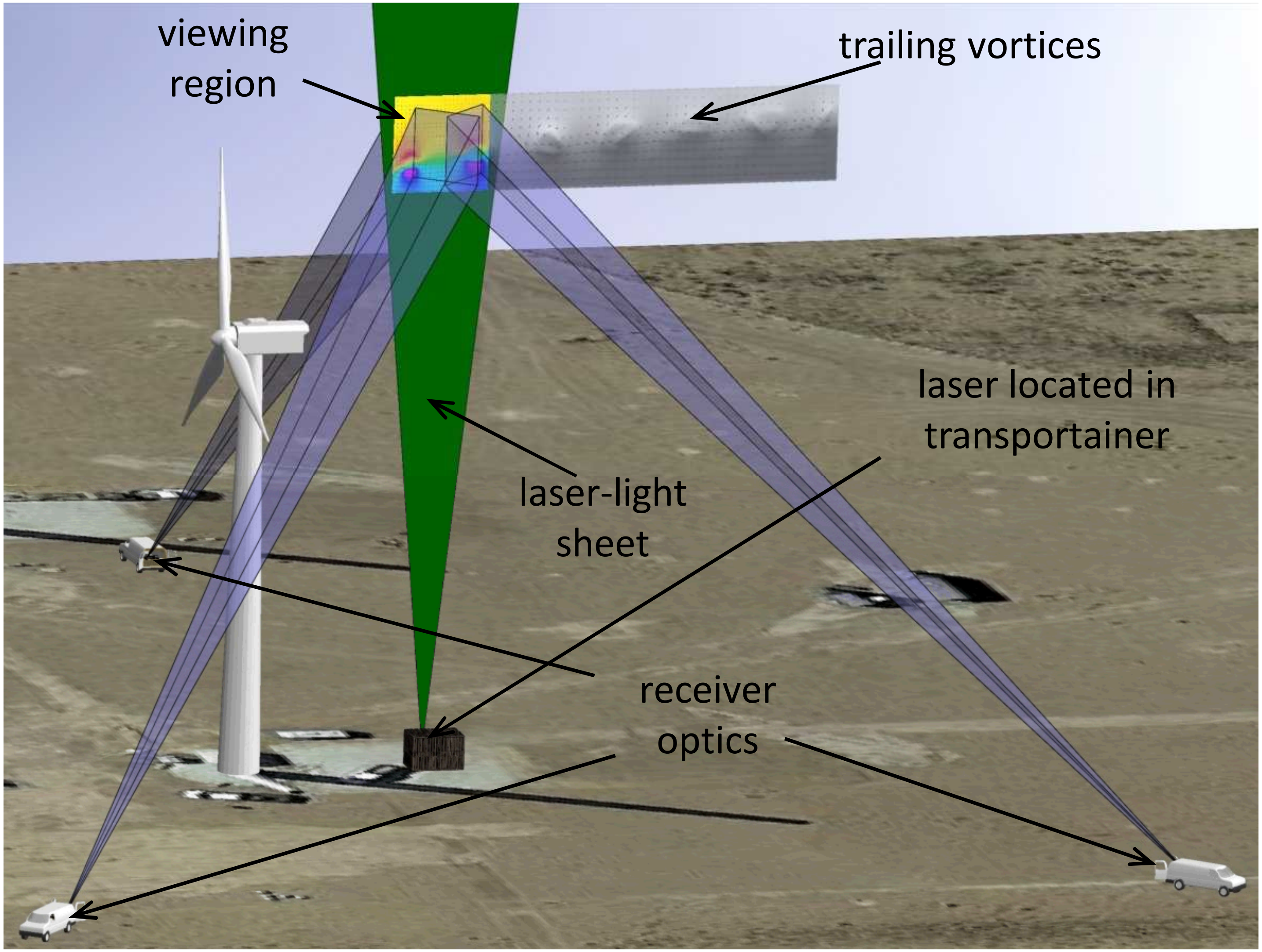
- Reduce turbine-turbine interaction and wind plant underperformance
- Develop advanced wind turbine rotors
- Public open-source to advance simulation abilities



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

Notional DGV Implementation at SWiFT Facility



Scaled Development

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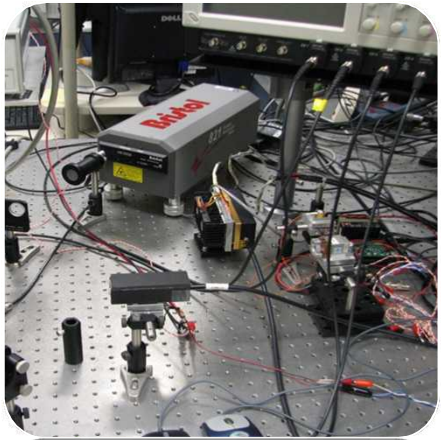
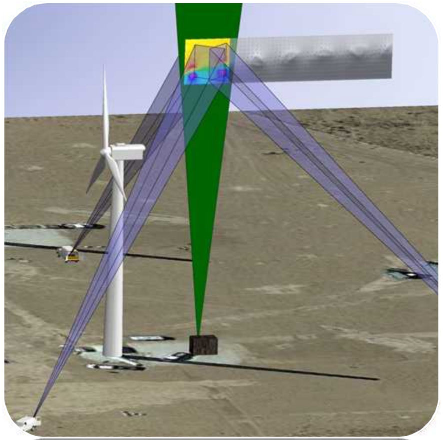


Lab

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

Sprung

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

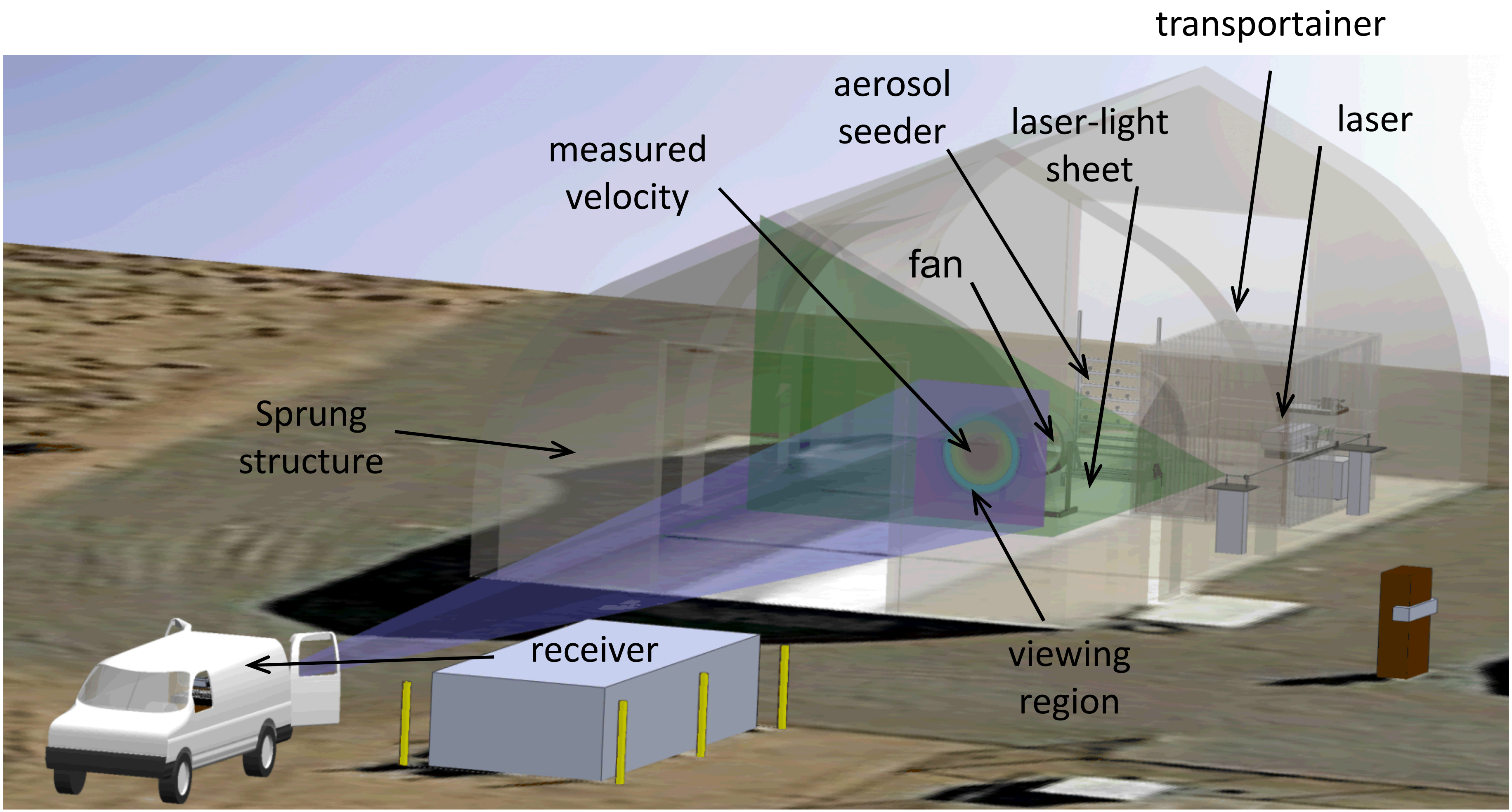


SWiFT

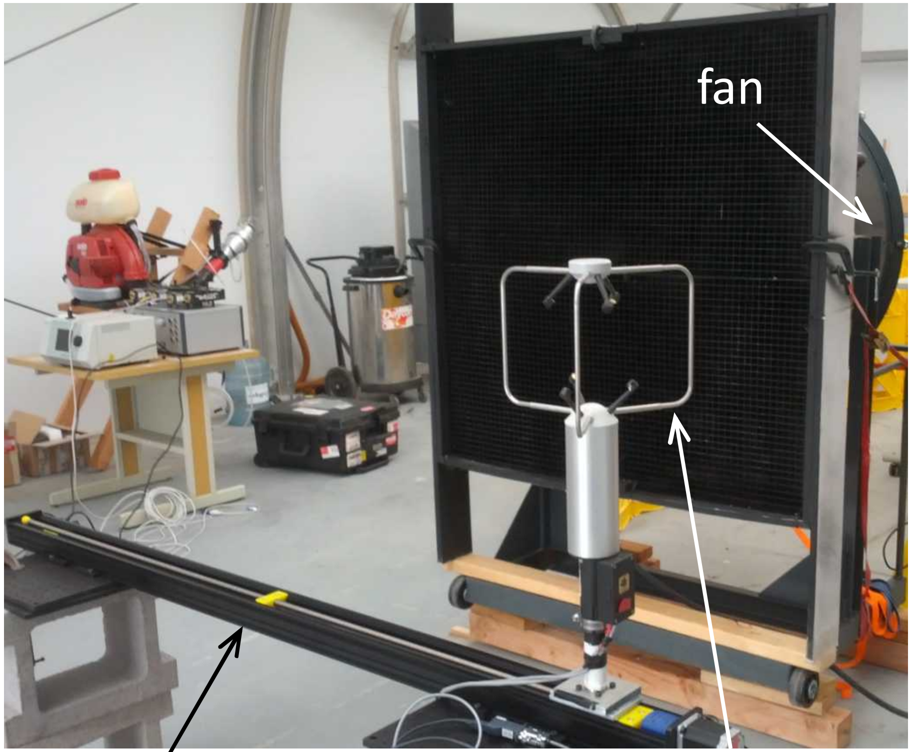
- Outdoor Laser Use
- Field Deployable Aerosol System
- Additional Velocity Components
- 5 m × 5 m

- Demonstrate simplest possible system
- Address make-or-break components
- Leverage deep expertise, equipment, and facilities at Sandia to accelerate development

Experiment Configuration



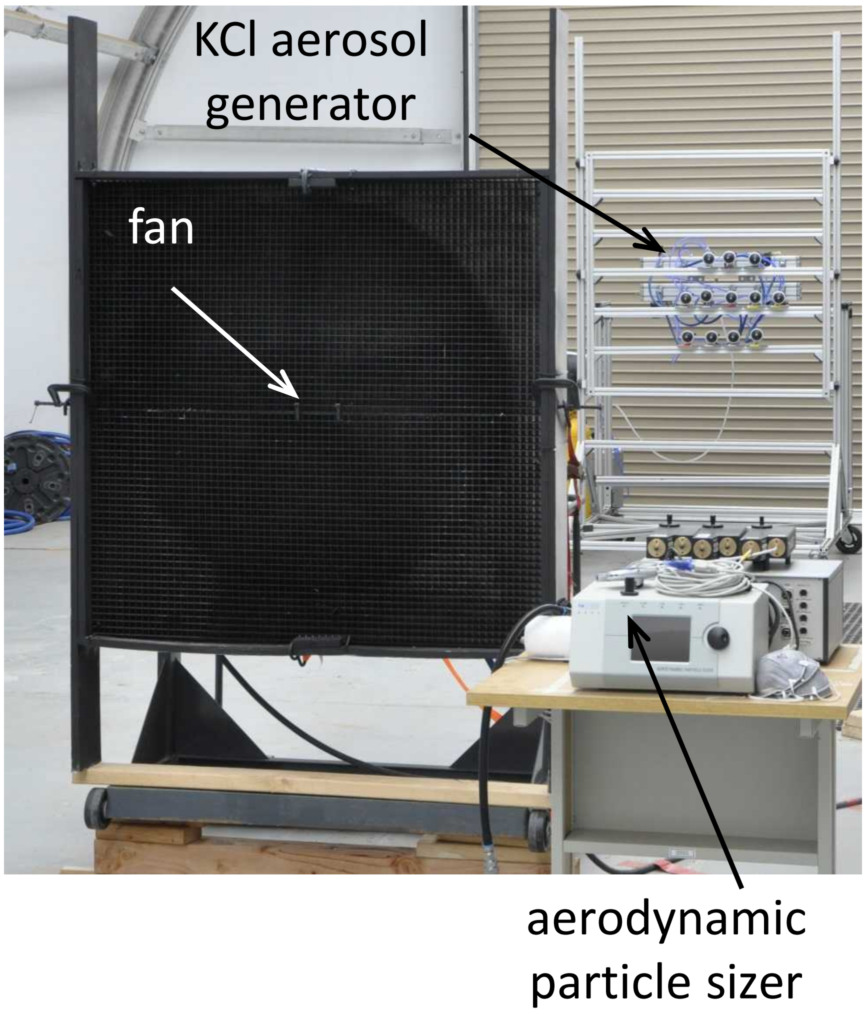
Representative Flowfield

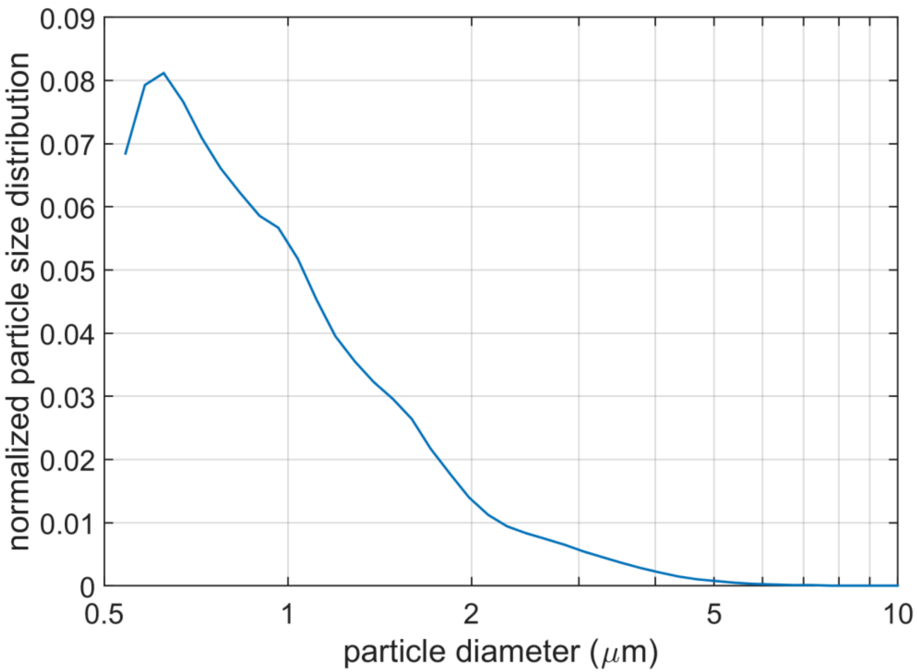


traverse

sonic
anemometer

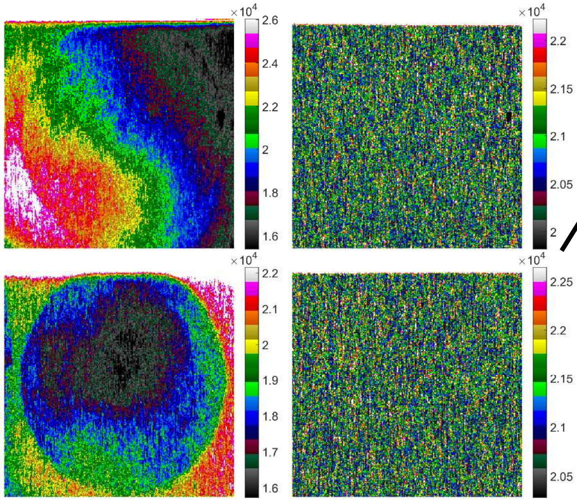
Aerosol Generation





- KCl particle generation using spray nozzles
- Mean particle size distribution consistent over wide range concentrations
- Scattering cross-section:
  $\sigma = 3.2 \times 10^{-10}$ cm^2/sr

Image Processing



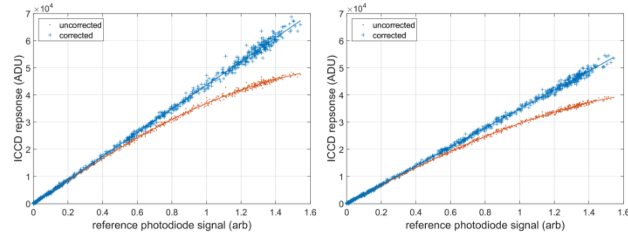


Image Flat Fielding

Image Registration

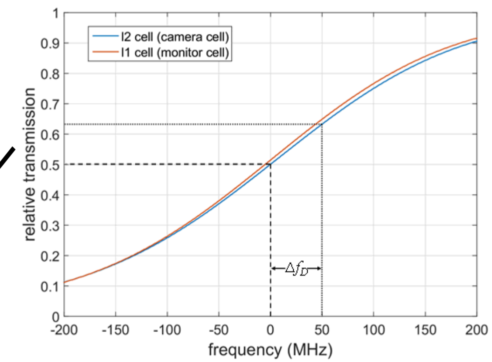
Intensity Flat Fielding

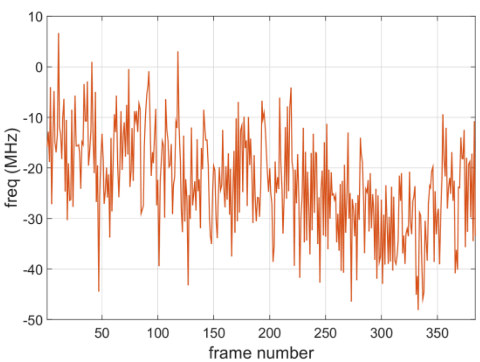
Intensity-to-Frequency Conversion

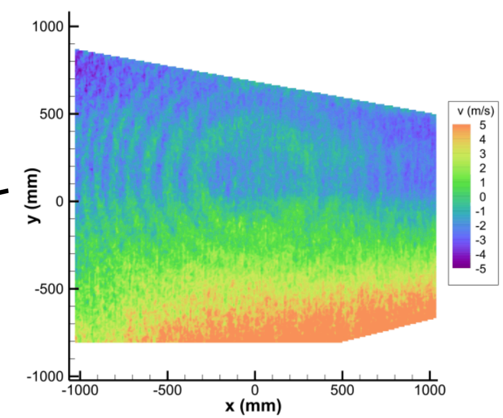
Pulse-to-pulse Frequency

Zero-Velocity Frequency Correction

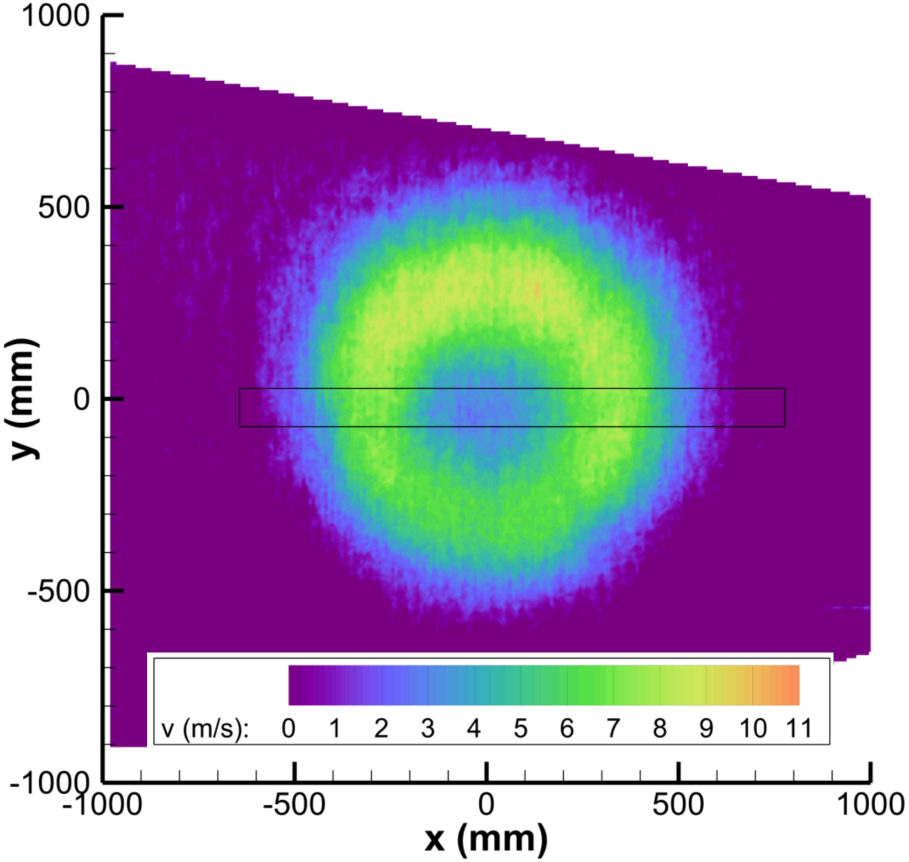
Velocity Image

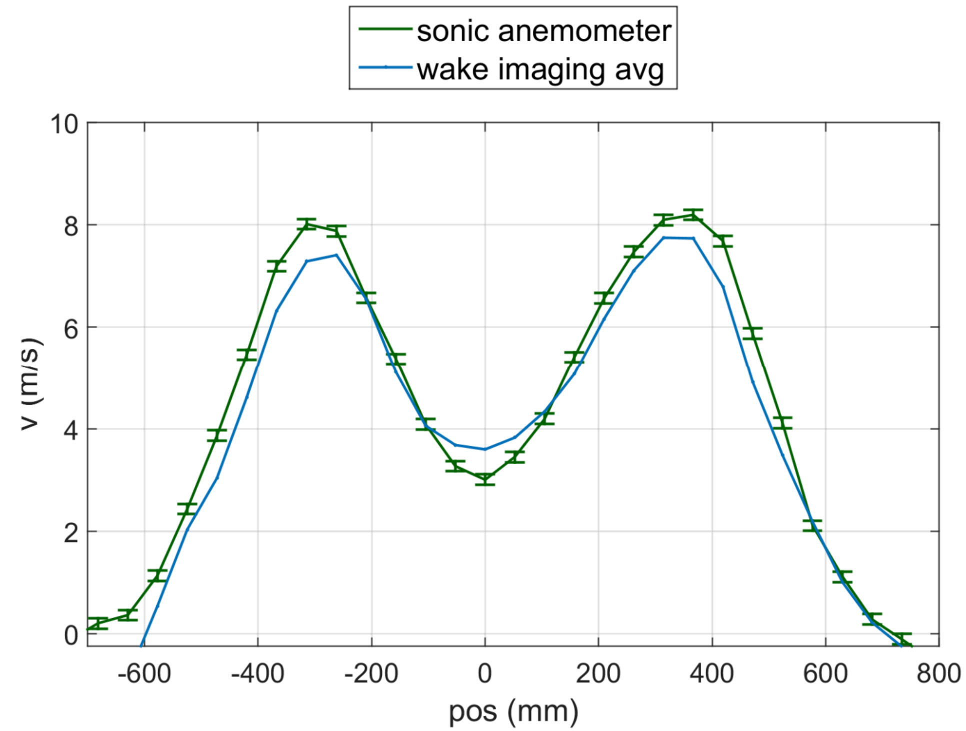


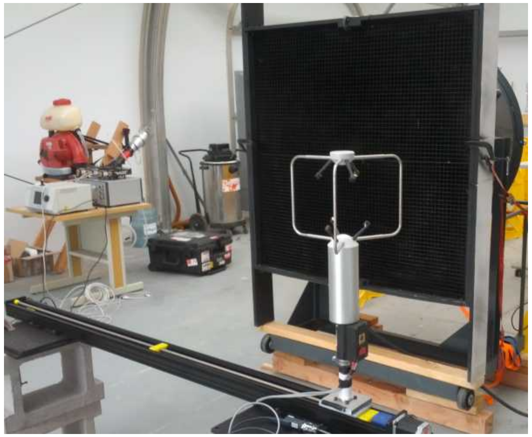




Velocity Measurement Comparison



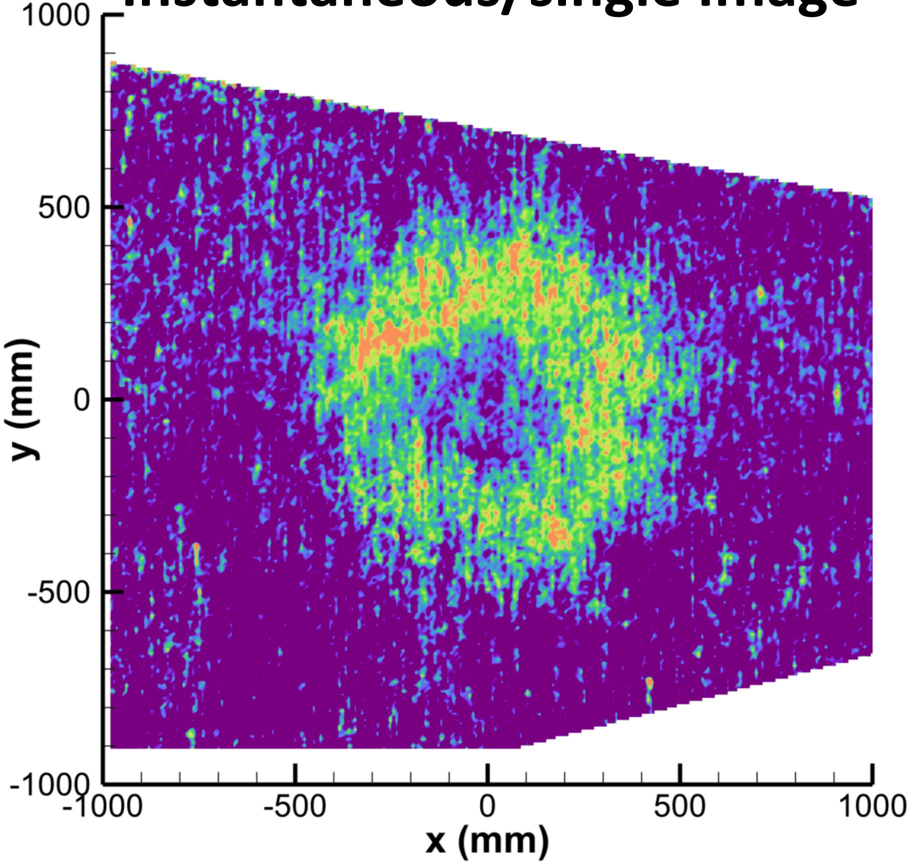




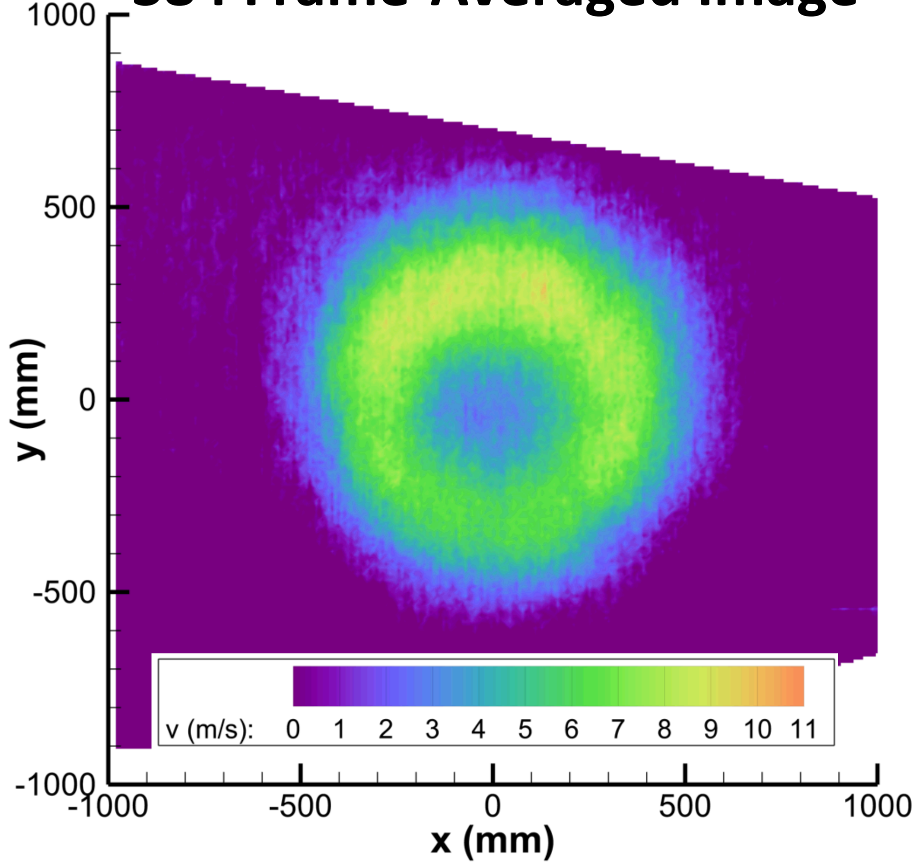
- Independent sonic anemometer data compares well
- Velocity image processed to match sonic anemometer spatial resolution
- Velocity bias exists between different SWIS data sets

Velocity Images

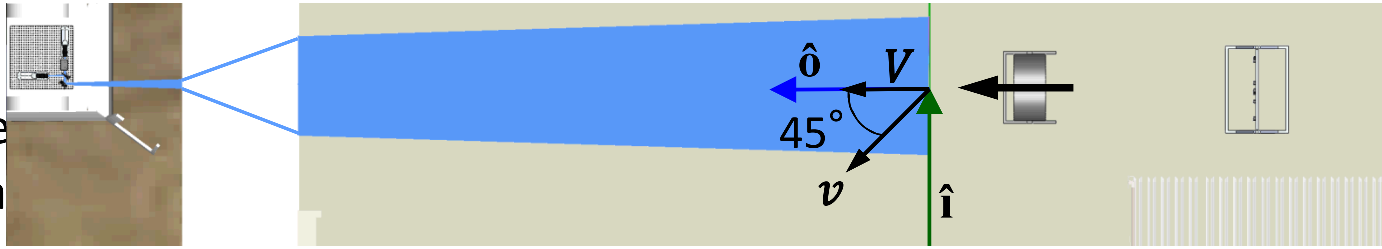
Instantaneous/single Image



384 Frame-Averaged Image

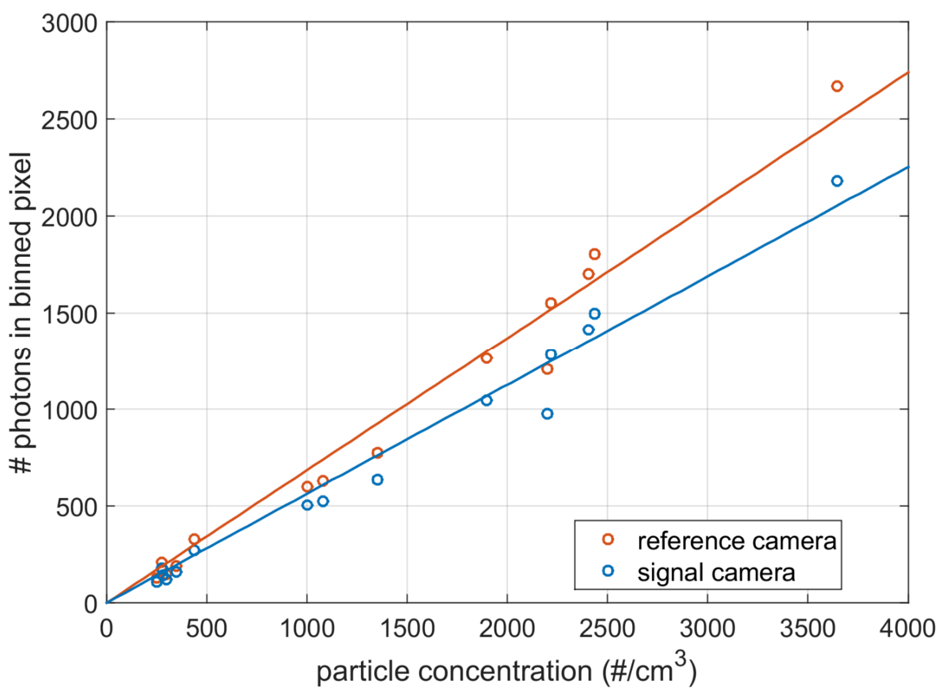


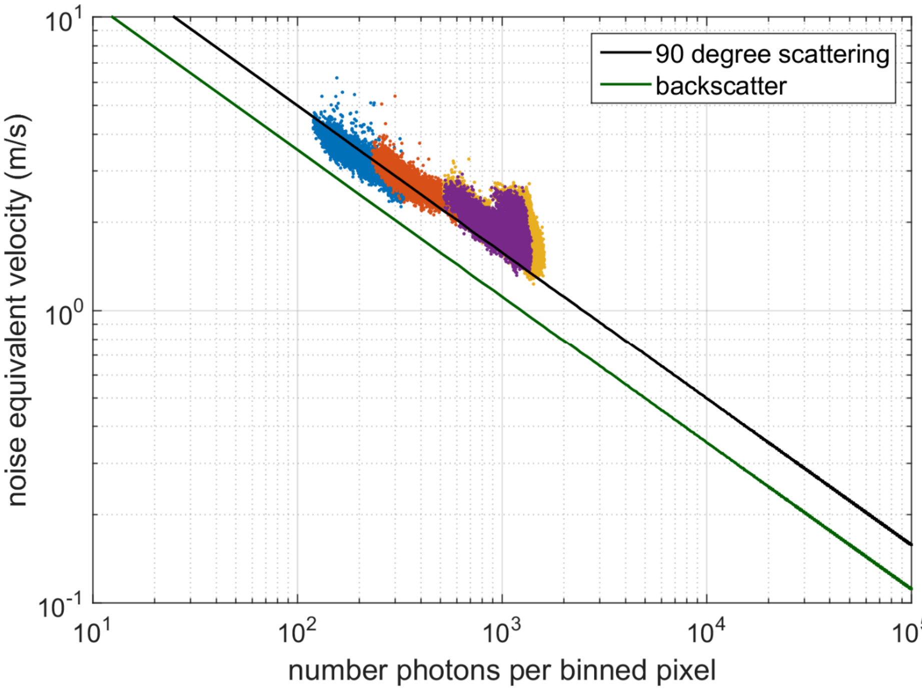
- 2 m
- Incre
- Insta



Sensitivity Results and Implications

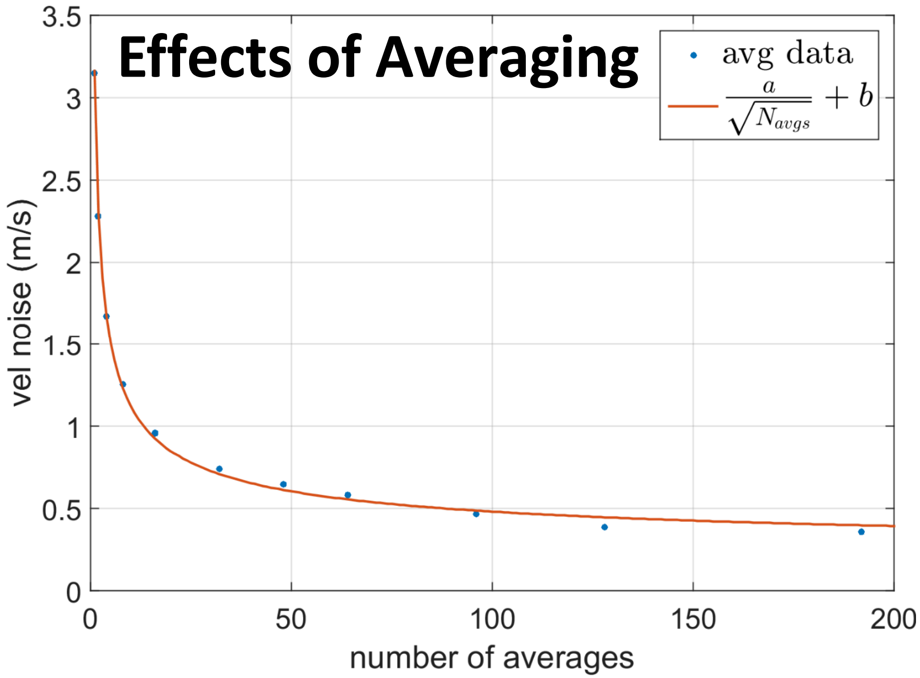
- Noise equivalent velocity represents the minimum resolvable velocity variation
- Shot noise equals the square root of the number of photoelectrons collected per binned pixel: $\sigma = \sqrt{N}$ $NSR = \frac{\sigma}{N} = \frac{\sqrt{N}}{N} = \frac{1}{\sqrt{N}}$
- Noise equivalent velocity likely shot-noise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

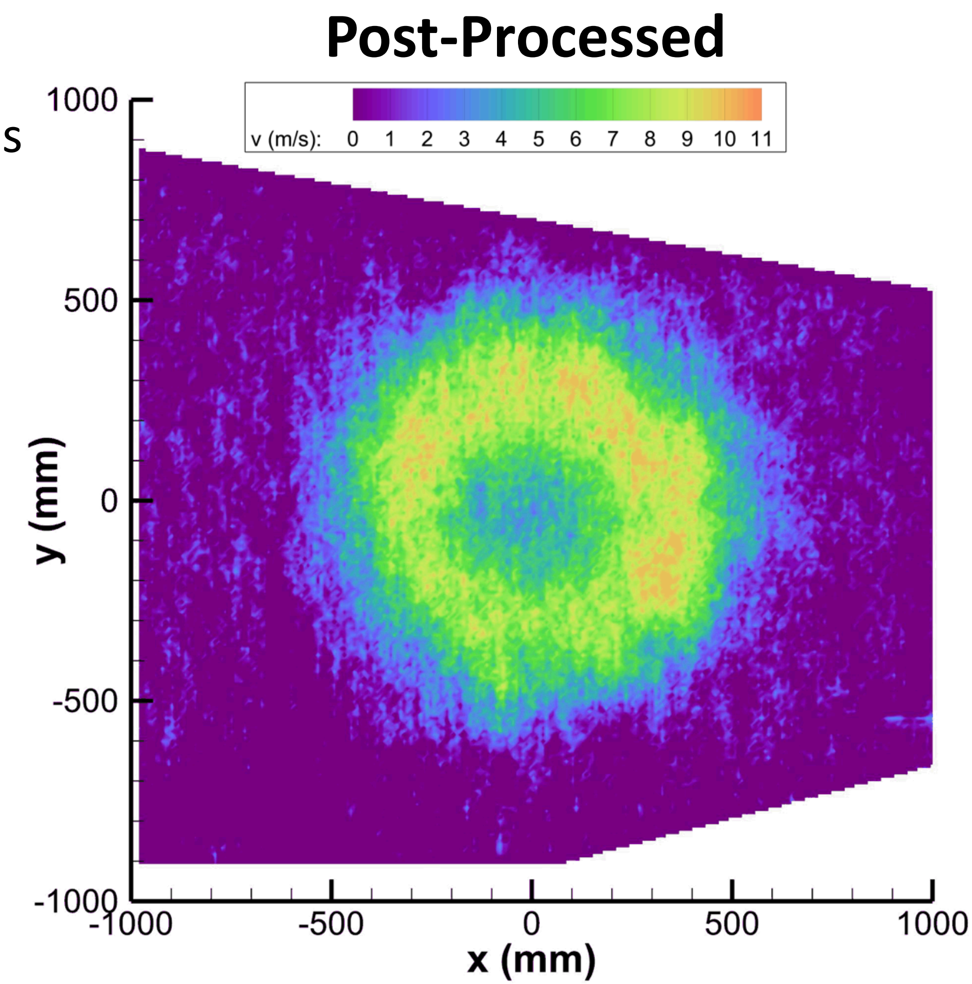




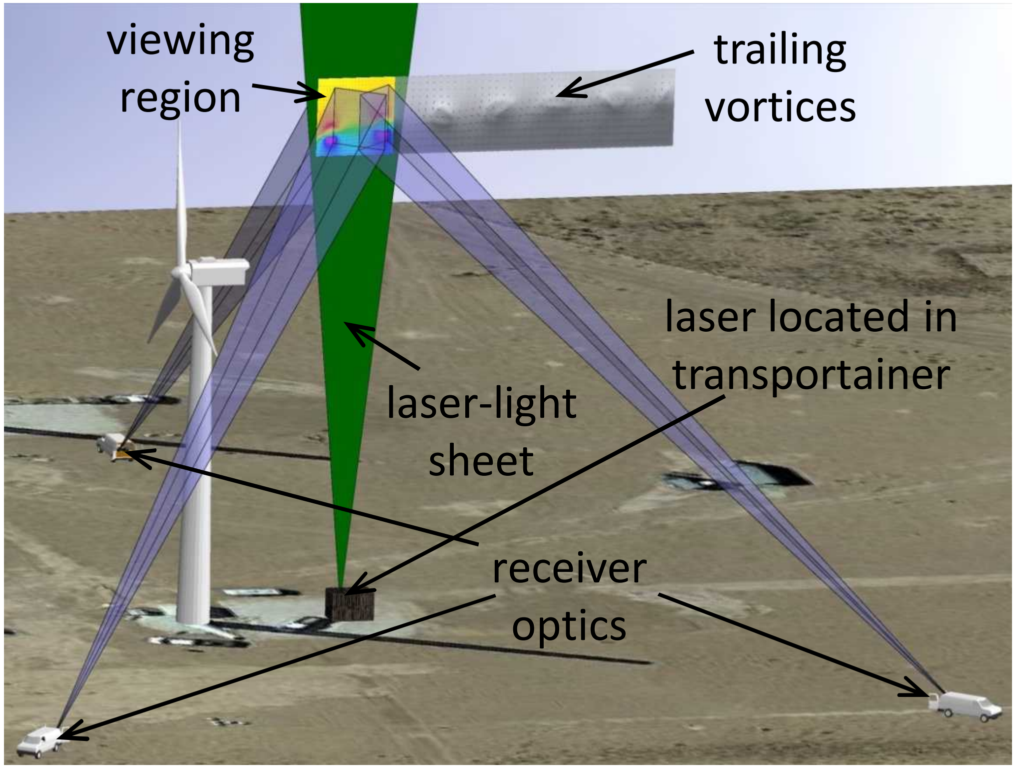
Reducing Noise for SWiFT Deployment

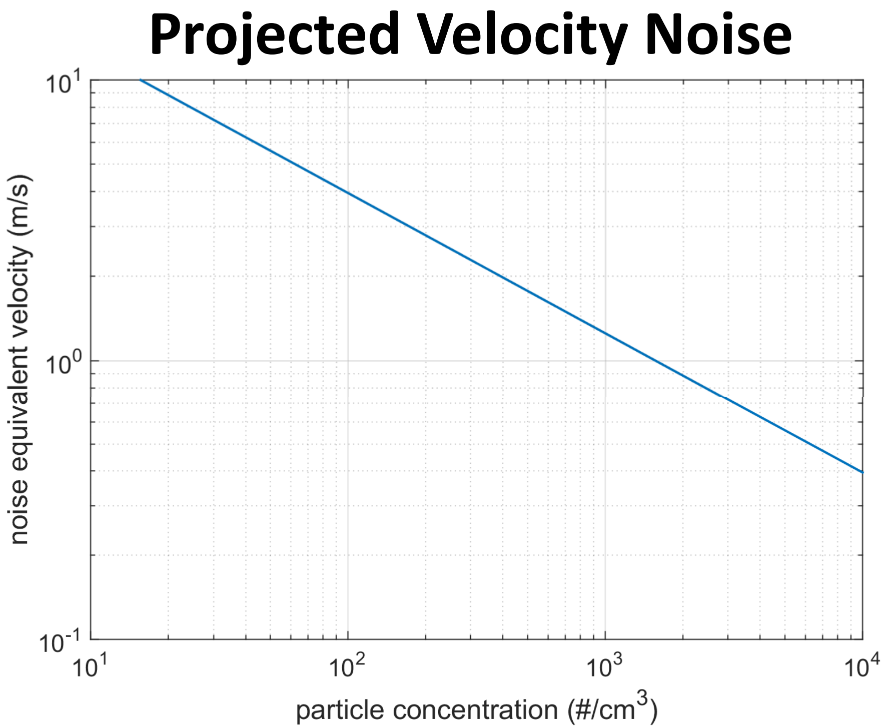
- Increase energy per laser pulse
- Receiver binning (increased signal with reduced spatial resolution)
- Higher particulate concentration
- Larger receiver aperture
- Improved post-processing techniques
  - Averaging
  - Filtering





Notional Field System





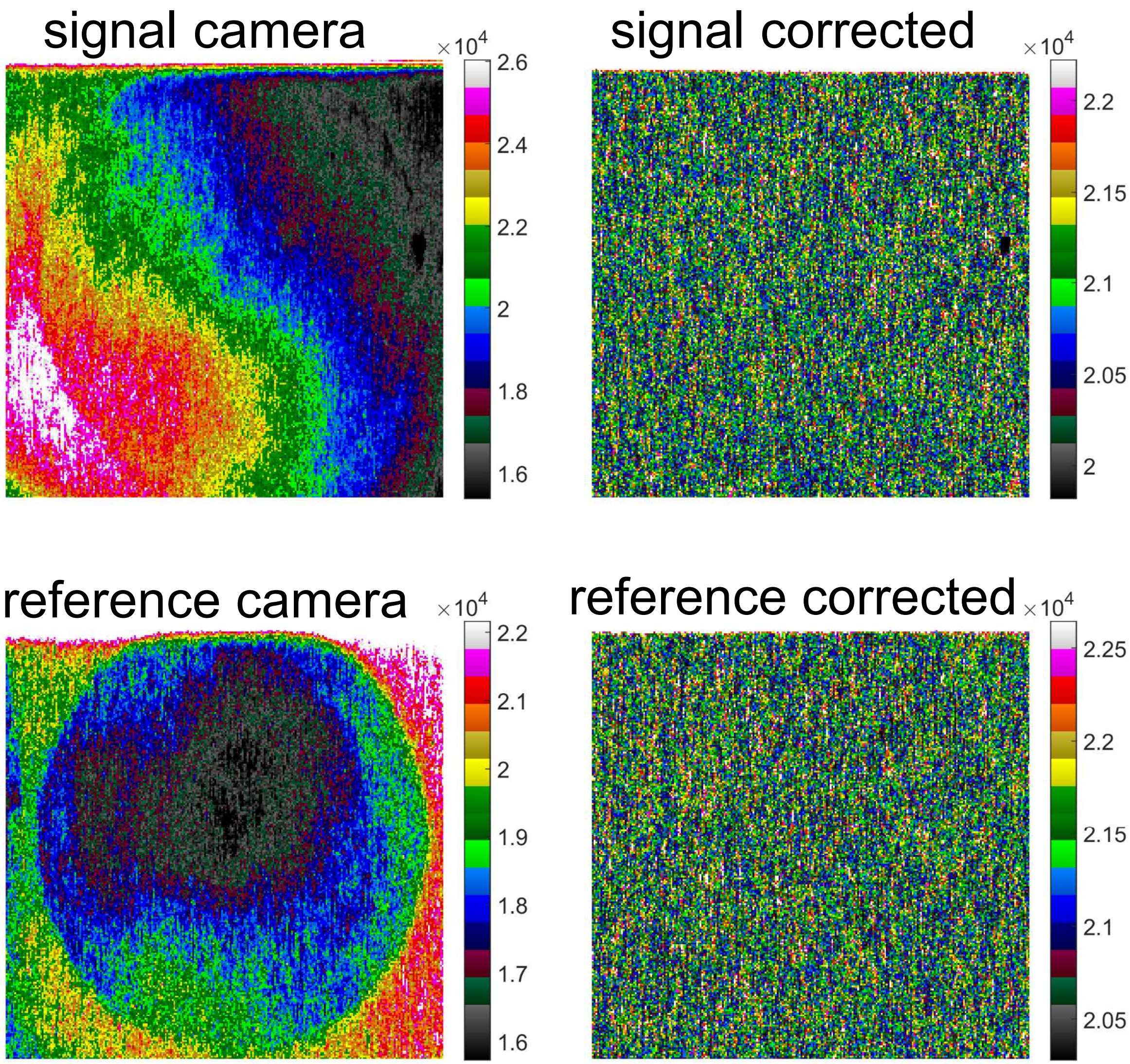
- Aerosol seeding required
- Noise equivalent velocity approaches $\pm$ 1 m/s near 2000 particles/cm^3
- Possible to adjust configuration in trade-off space for computational validation requirements, noise limits, and system cost

Conclusions

- Sandia Wake Imaging System (SWIS) implements Doppler Global Velocimetry (DGV) for improved scaling capabilities
- Successfully acquired single component velocity image of 1 m fan flow over 2 m × 2 m field of view
- Uncertainty analysis revealed performance of SWIS most likely limited by shot noise of signal photons
- Calibrated radiometric model indicates ±1 m/s velocity noise is feasible over 5 m × 5 m viewing region
- Specifications and capabilities of SWIS for deployment at Scaled Wind Farm Technology (SWiFT) facility defined with significantly higher confidence based upon current field-test results

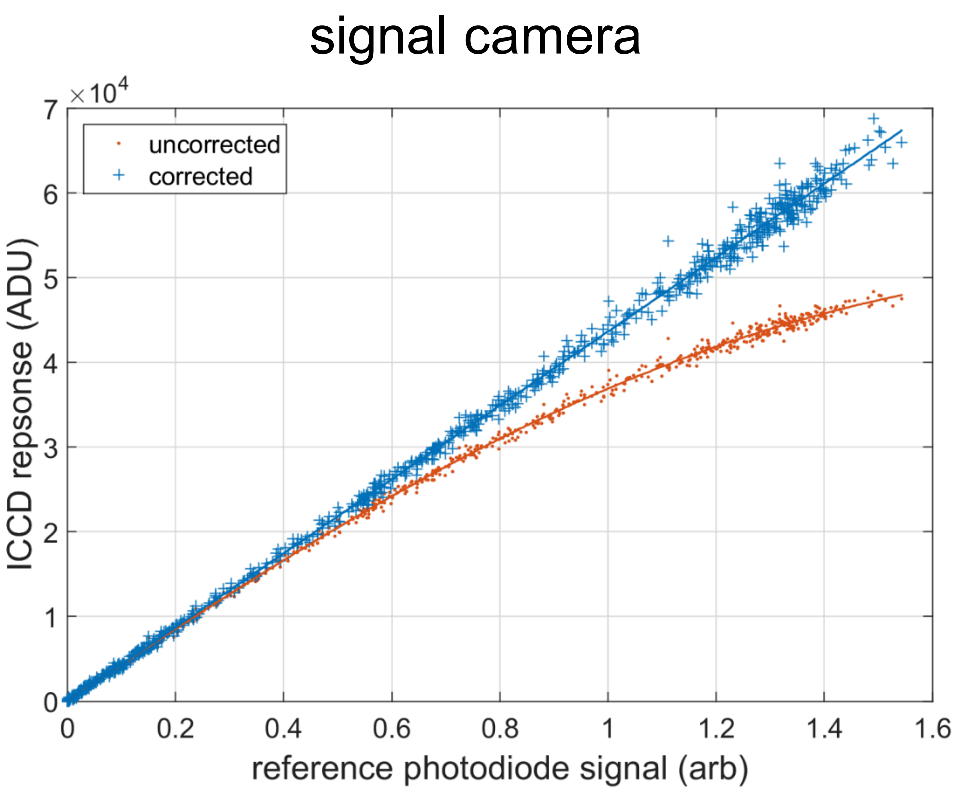
Back-Up Slides

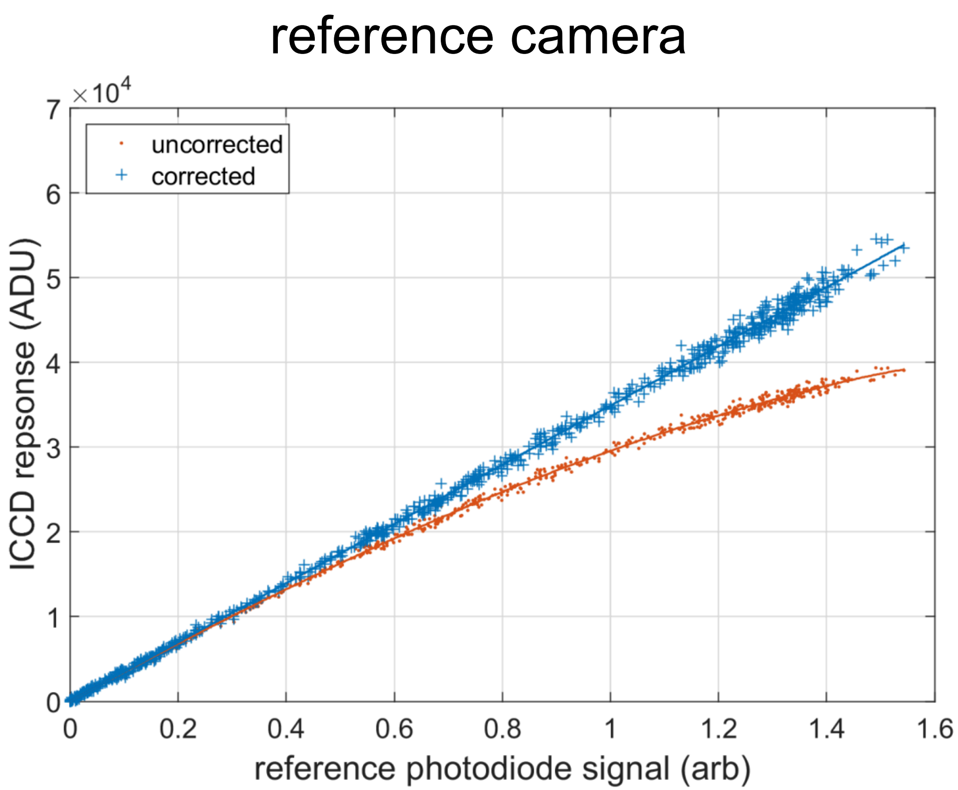
Image Flatfielding



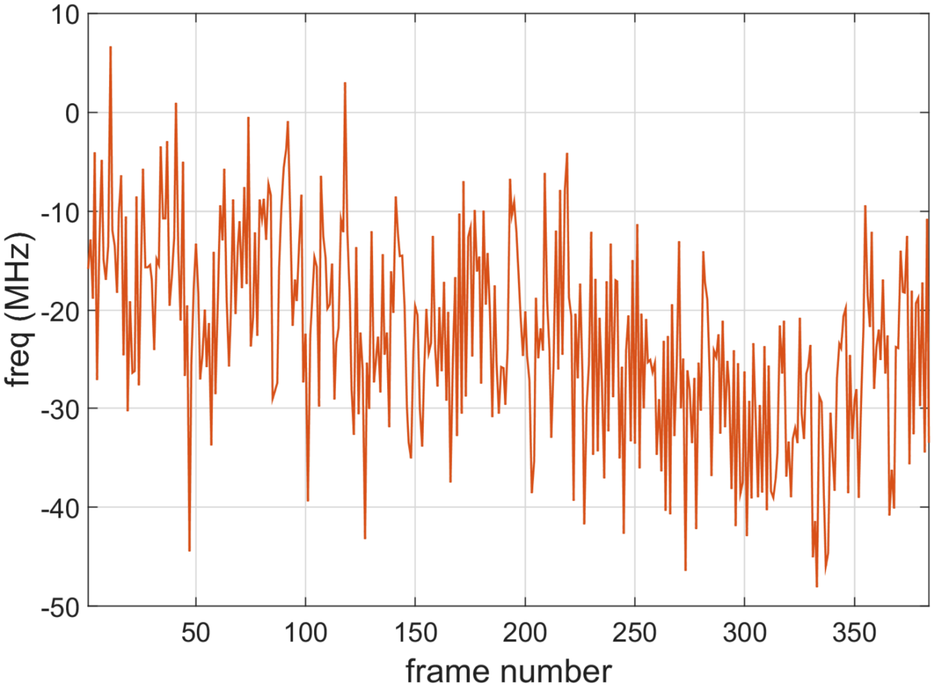
- Each ICCD camera has spatially non-uniform response to light
- Non-linear response over large dynamic range
- Result: each ICCD camera must be calibrated over a variety of illumination levels
- Spatially uniform light source was provided using an integrating sphere

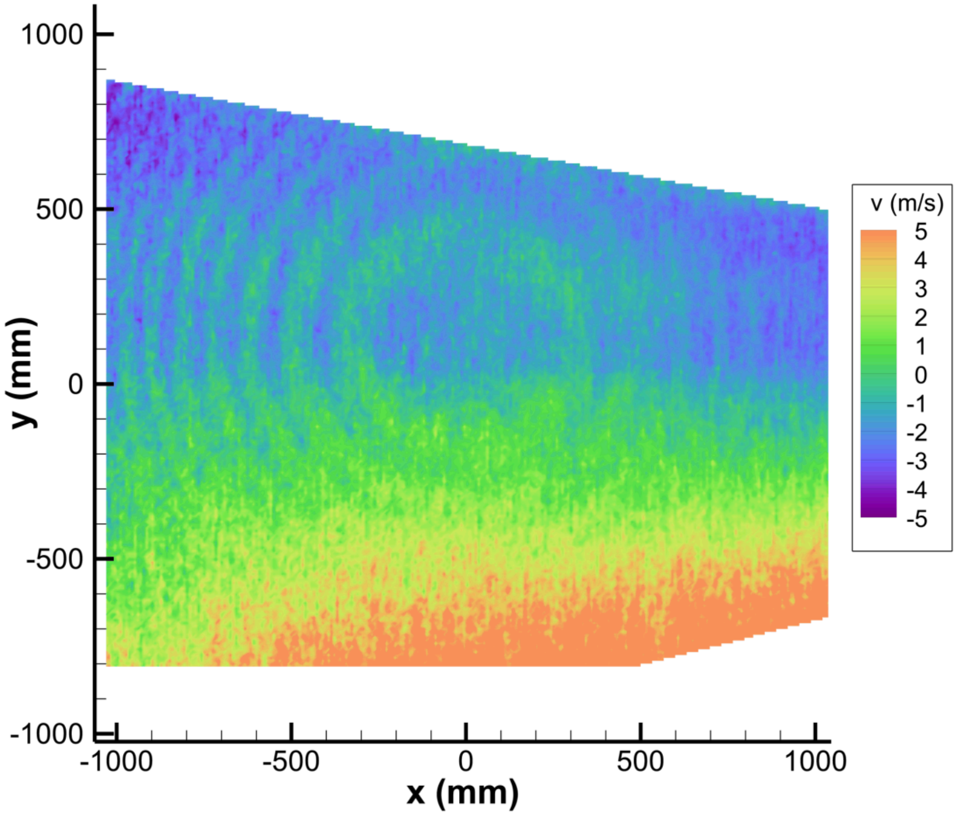
Image Flatfielding





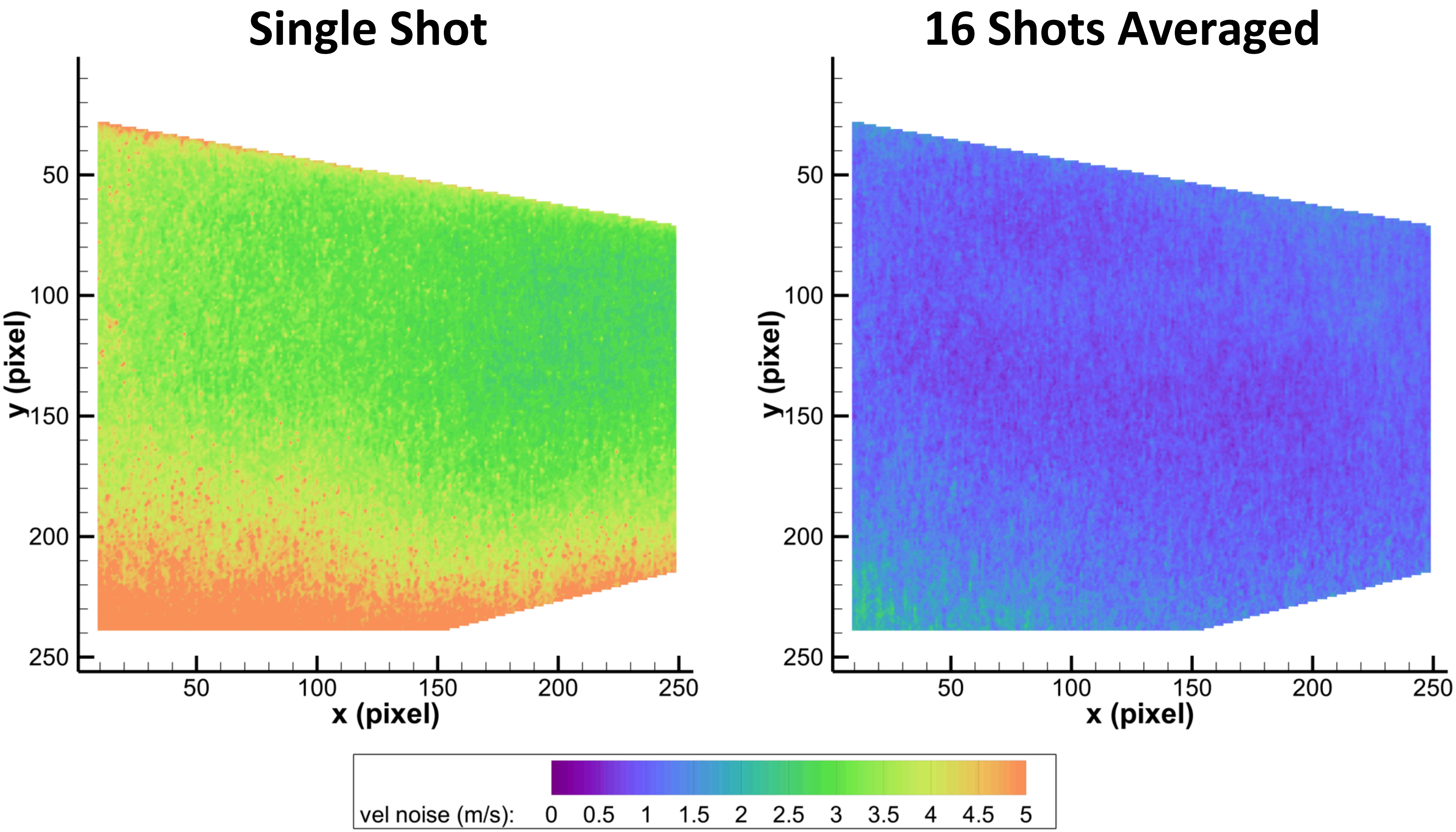
Frequency Correction



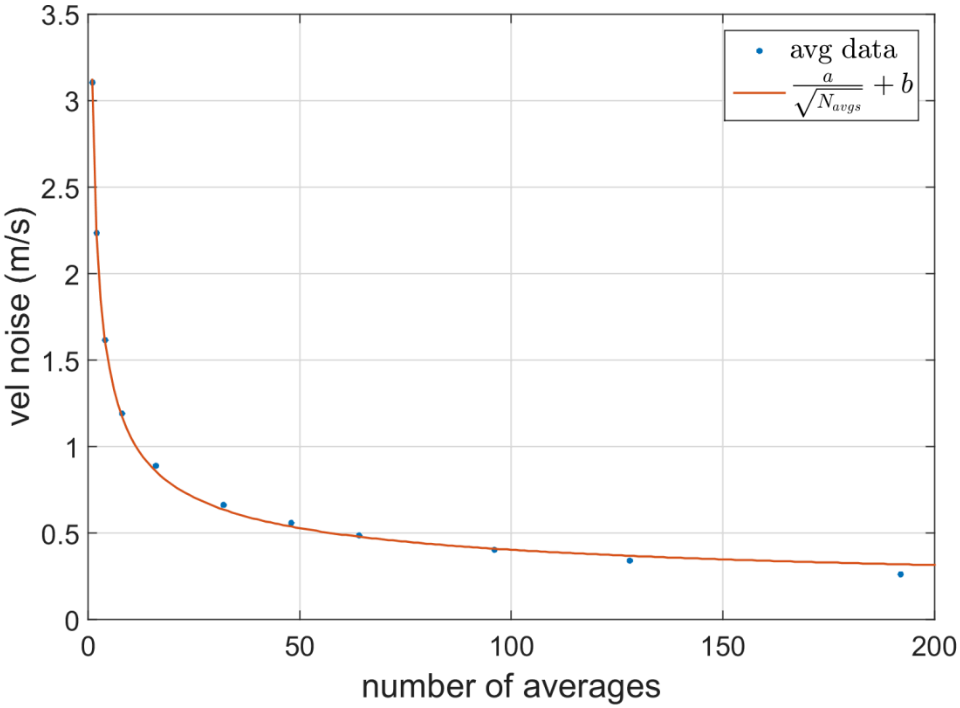


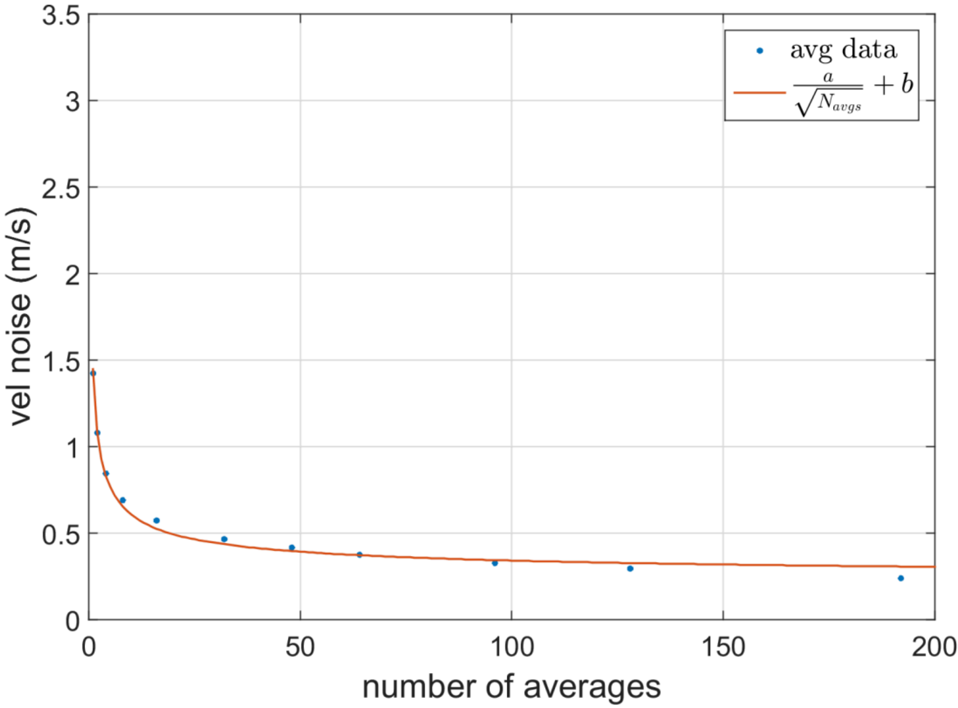
- Spatial frequency variation through laser cross section of 120 MHz
- Results in velocity variation of ± 5 m/s
- Must zero out spatial frequency variation using target with zero Doppler shift
- Track fluctuating laser pulse frequency

Velocity Noise

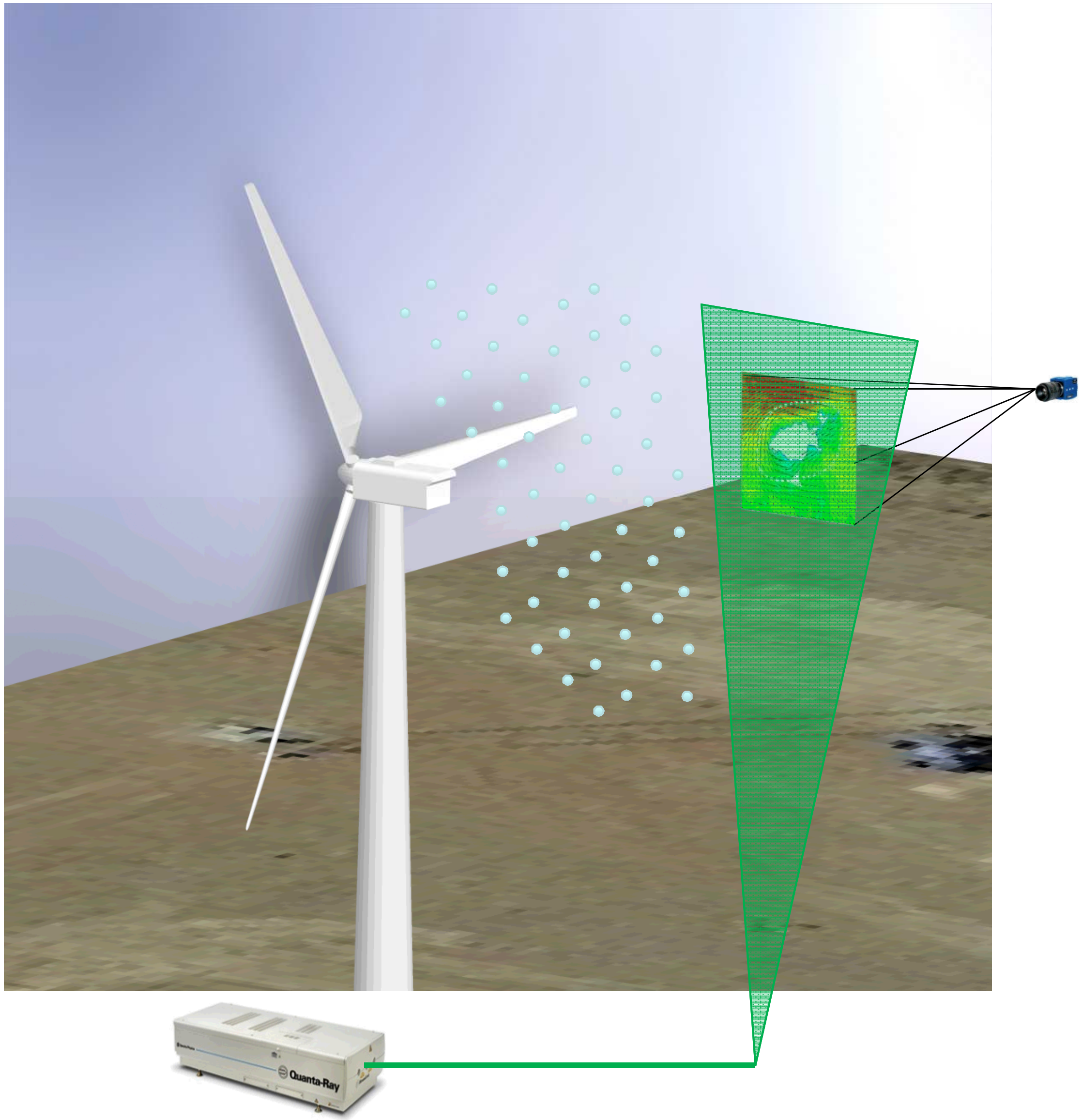


Effects of Averaging





PIV System Requirements



Limiting factor for PIV:

- Light scattered from particles
- Increased laser power/seeding diameter

Drawbacks:

- Very high-powered laser
- Large seeding particles (worse flow tracking)
- Shorter working distance for camera (camera positioned near viewing region)
- Slower data sampling