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Estimating Bias Uncertainties in PIV Data Using Complementary Measurements

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National Nuclear Security Administration

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Motivation

Measure something once ⟶ You have data

Measure something twice ⟶ You have error

Bias uncertainties may not be identifiable by repeated measurements.

- Bias uncertainties usually are dominant.
- We need to take a more reasoned approach to estimating biases.

Uncertainty quantification often is partly or fully neglected.

- Difficult to devote facility time, labor time, or budget.
- Uncertainty quantification methods only are reliable if we can make reasonable estimates of the bias errors.

This work uses complementary and redundant measurements to provide estimates of the bias uncertainties.

Sources of Bias Uncertainty

- perspective distortion
- laser flare
- particle response
- light refraction
- image aberration
- particle dropout
- spatial resolution
- calibration error
- vector validation
- sampling error
- registration error
- velocity gradients
- correlation error
- pixel locking

This is an incomplete list of "known unknowns."

But what about "unknown unknowns?"

What the Uncertainty is *NOT*

It is *NOT* 2σ of a few repeated data points.

It is *NOT* 0.1 pixels of displacement.

It is *NOT* the uncertainty of some previous measurement.

(usually)

But, it is *NOT* realistic to analyze any and all possible errors that could affect the PIV measurement.

Instead, use complementary measurements to estimate the uncertainty found in the actual data.

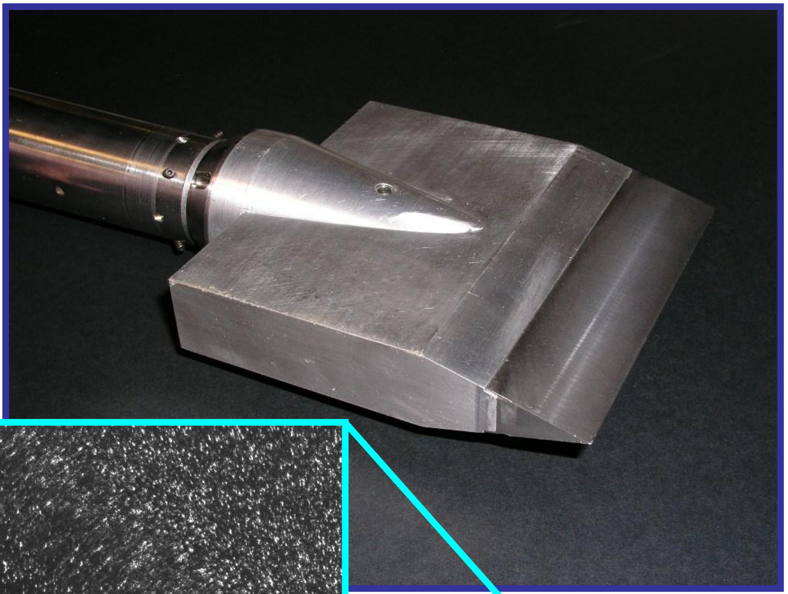
Particle Response

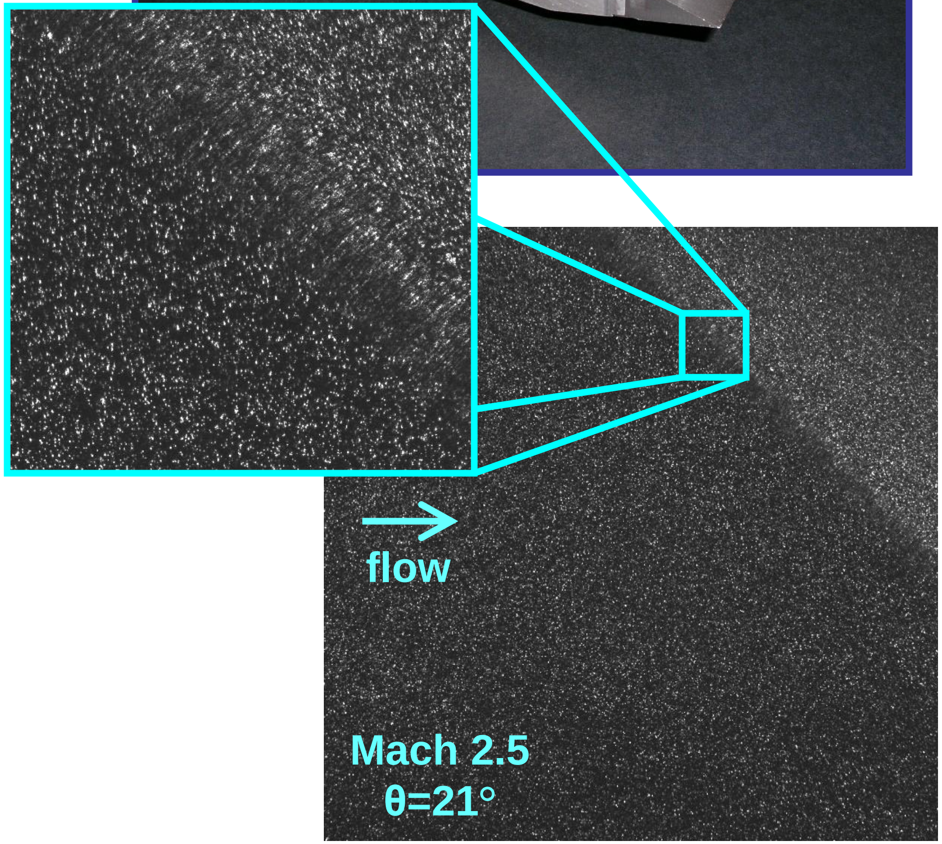
How much PIV uncertainty due to the particle response to velocity gradients?

Is the particle diameter 0.2 – 0.3 µm as specified by the manufacturer?

Test the particle response across a shock generated by a 15° wedge.

- Machs 1.5, 2, and 2.5
- Pitch wedge to get different shock angle θ

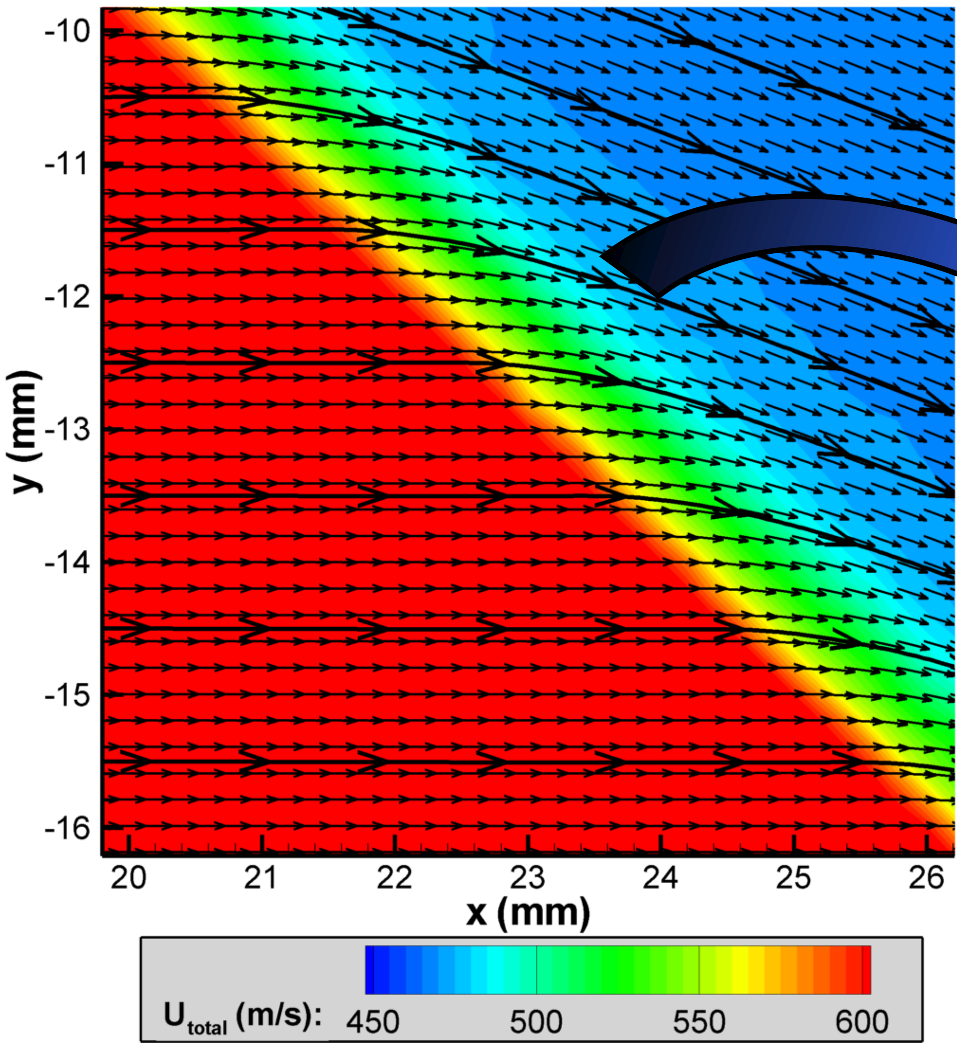




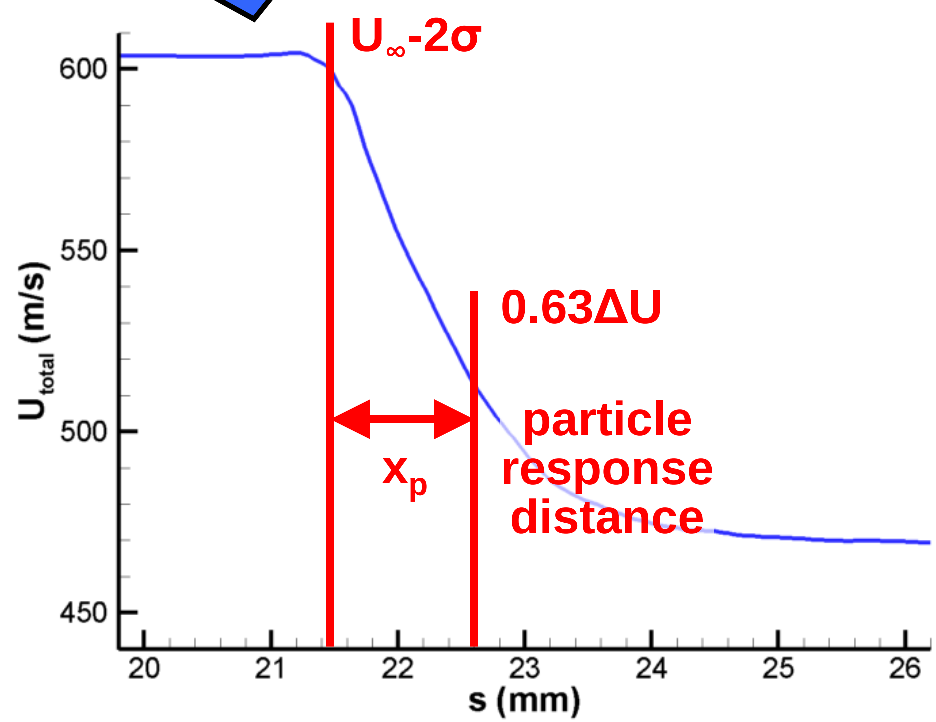
Particle Response

Particle characteristics:

x_p = 1.1 mm
τ_p = 2.0 μs
d_p = 0.76 μm



Extract velocities along a streamline



Particle Response

Over a range of Machs and shock angles:

τ_p = 1 - 2 µs

d_p = 0.7 – 0.8 µm

Particle diameter is larger than the manufacturer specification.

- Probably due to agglomeration when the smoke is ducted to the stagnation chamber.

Is this particle size and response time good enough?

What is a typical turbulent velocity gradient?

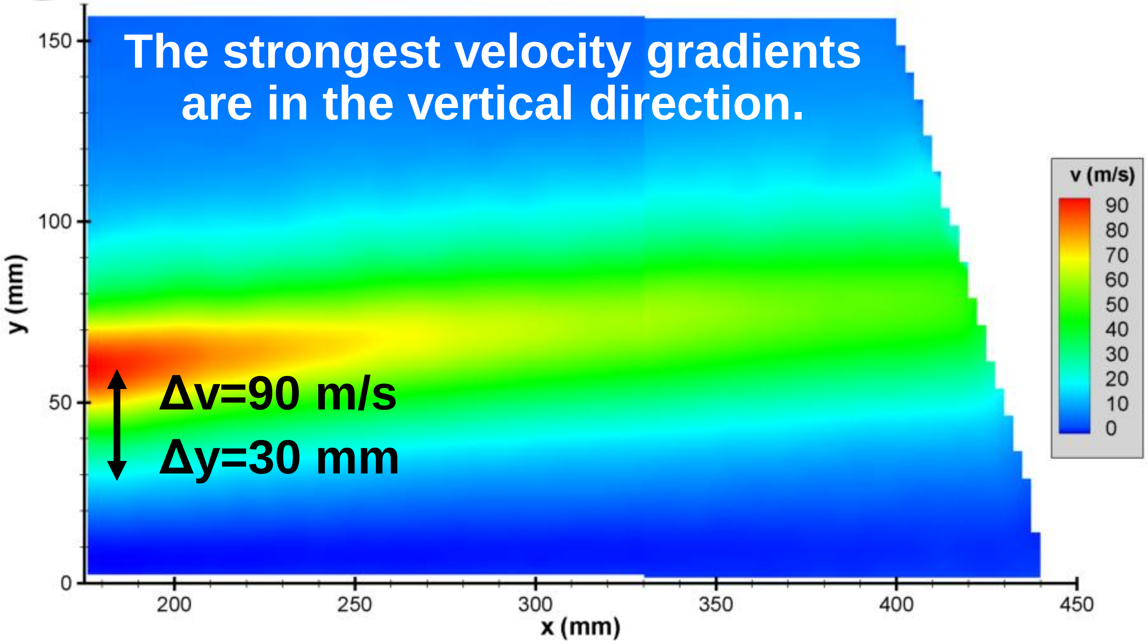
- $(du/dx)_{max} \approx$ 3% of the interrogation window
- At Mach 2.5, this yields **τ_f = 50 µs**

Stokes Number = τ_p / τ_f = 0.04

- $\tau_p / \tau_f < 1$ is acceptable (~1% error)
- $\tau_p / \tau_f < 0.1$ is very good (~0.2% error)

particle response is excellent

What is the Velocity Gradient in a Real Experiment?



Typical approach:

- **Find Δv and Δy from the mean velocity field.**
- **Yields τ_f = 330 μs and $\tau_p / \tau_f < 0.01$.**

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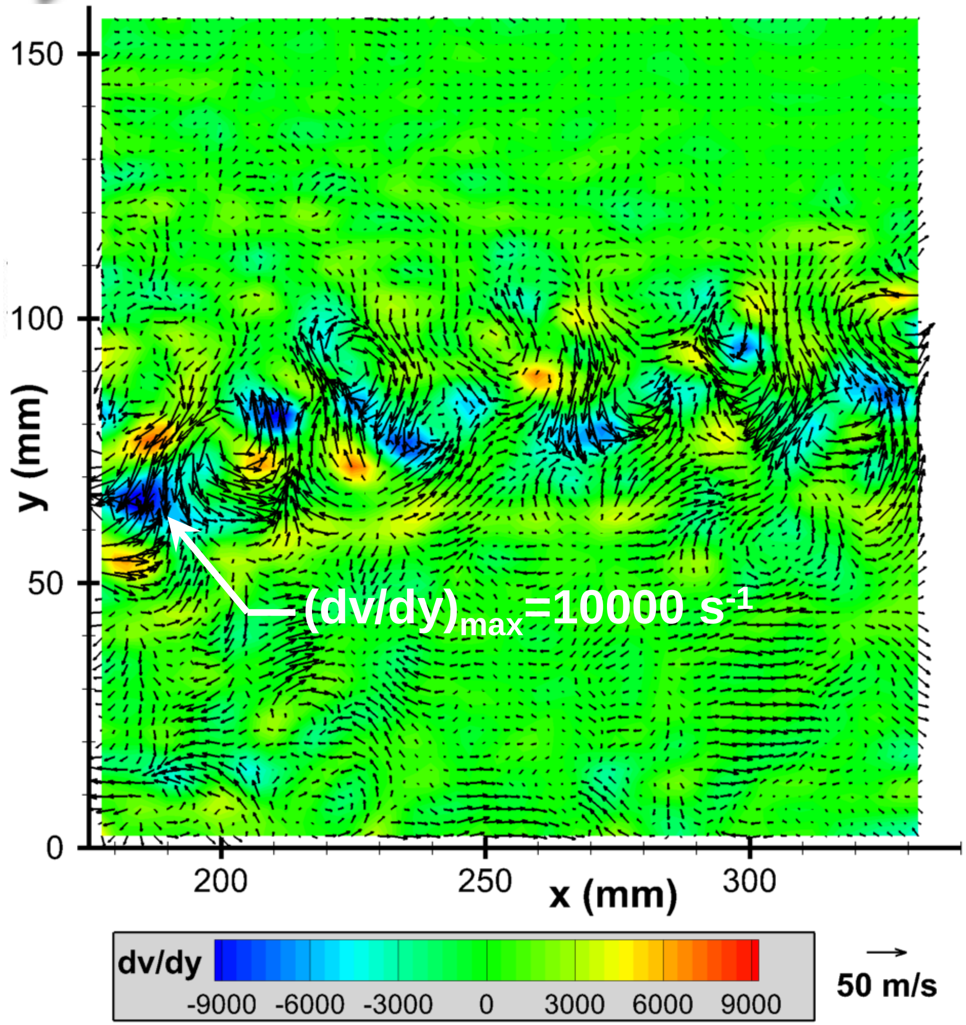
What is the Velocity Gradient in a Real Experiment?



Typical approach:

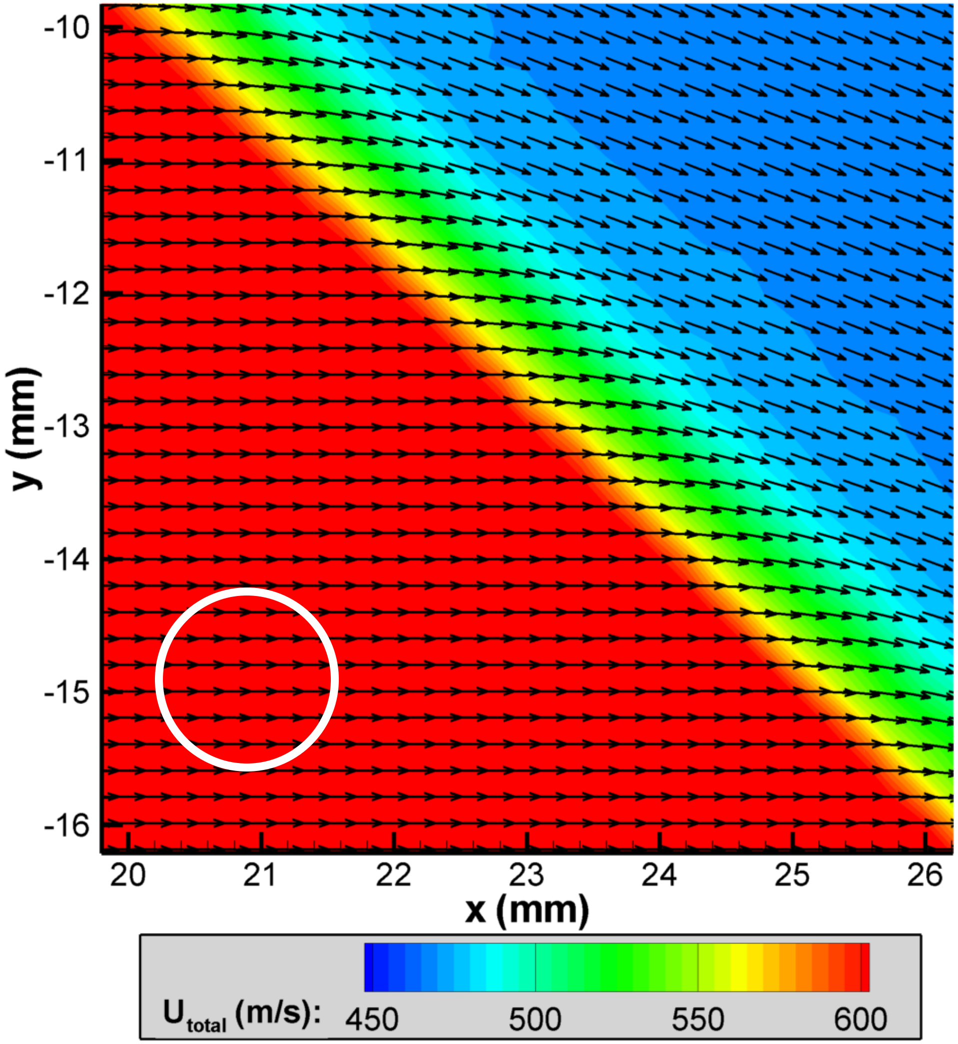
- **Find Δv and Δy from the mean velocity field.**
- **Yields τ_f = 330 μs and $\tau_p / \tau_f < 0.01$.**

But PIV correlates on instantaneous fields, not mean fields.

- **Maximum velocity gradient due to turbulent eddies is about 3-4 times larger.**
- **Yields τ_f = 100 μs and $\tau_p / \tau_f = 0.02$.**

Still excellent in this case, but other experiments that appear to be marginally acceptable may actually have significant bias.

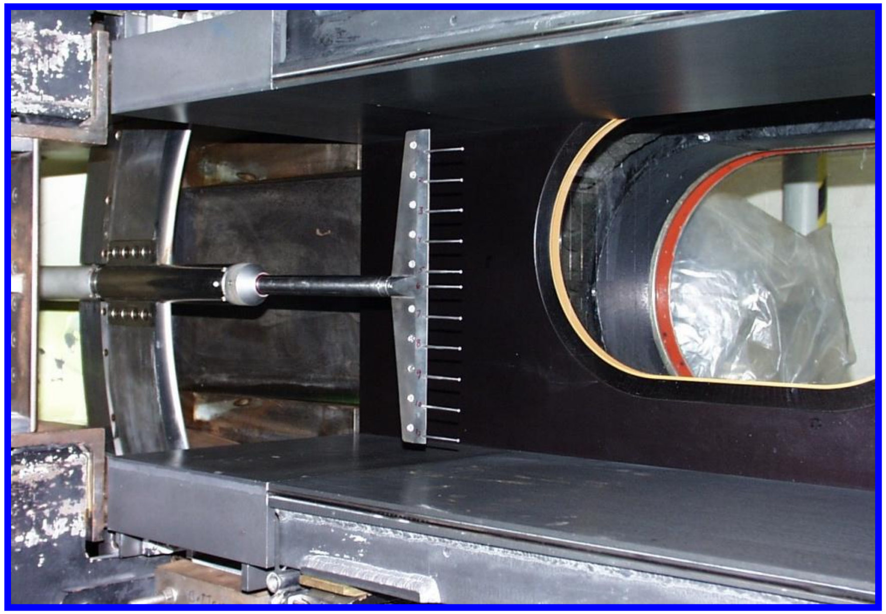
Mean Velocity Accuracy



Bonus: compare the freestream velocities with previous Pitot probe measurements.

- Error < 1% for all Mach numbers.
- Shock angles and velocities within 0.3% of isentropic theory.

More error in Pitot probe than PIV!



Calibration Error

What complementary measurements can assess the calibration error?

Calibration error **: error due to camera mapping process.**

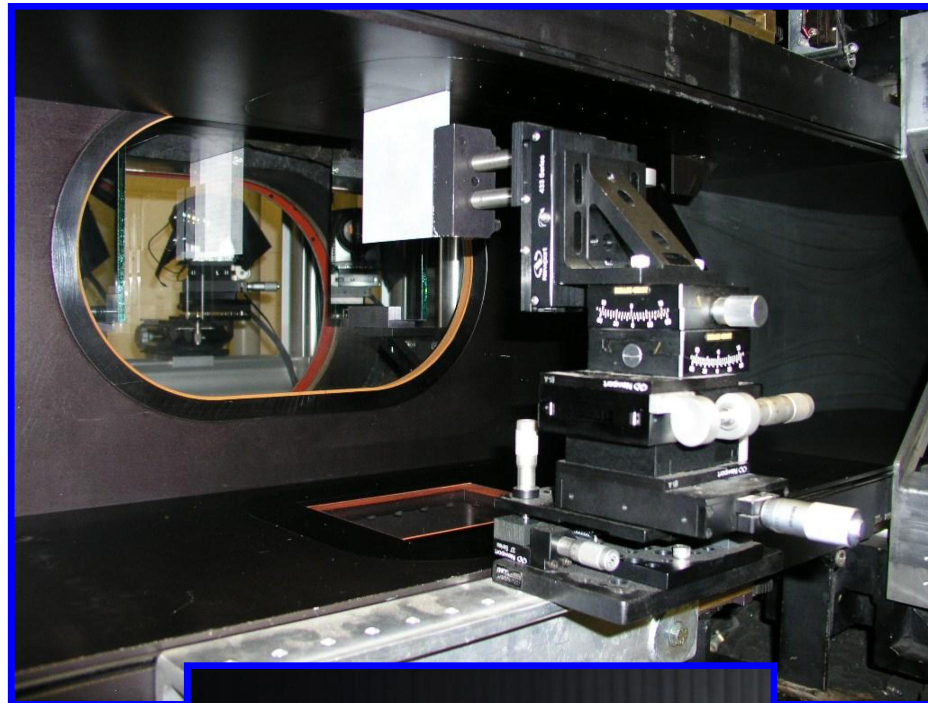
Registration error **: error due to misalignment between imaging plane and laser sheet.**

For two-component PIV, this usually is trivial:

- **Simply image a ruler to obtain a mm-to-pixel conversion.**
- **Uncertainty generally is small.**

For stereoscopic PIV, the calibration error is more likely to be significant.

- **We can assess the error with clever use of our calibration target.**



Calibration Error

We calibrate by traversing a target through the imaging volume.

- **Typically image 7 planes.**

Target consists of a grid of dots on a bead-blasted plate.

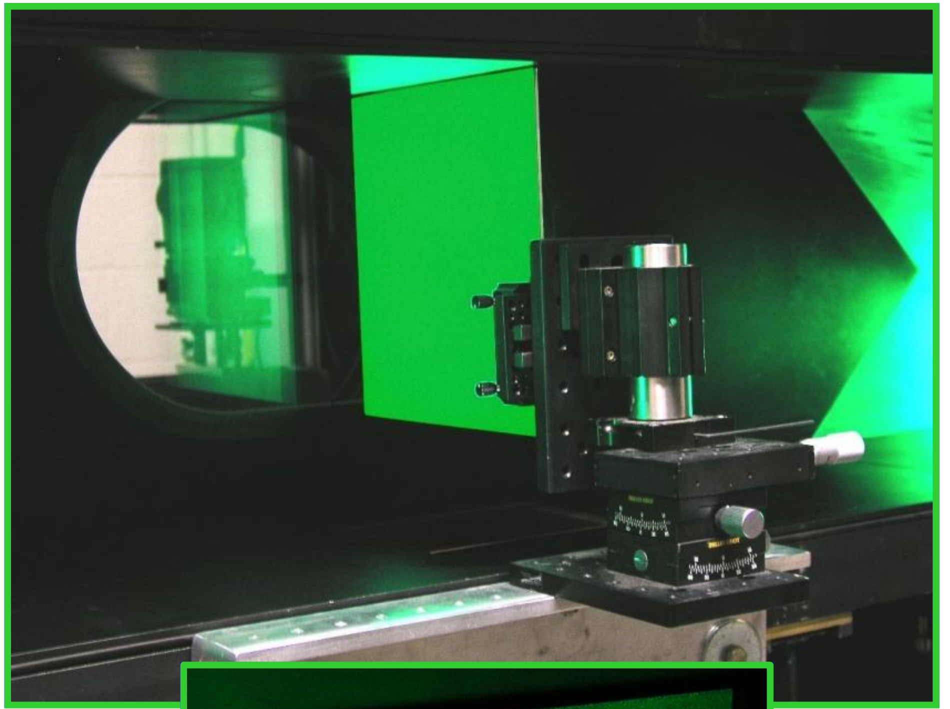
- **Creates a speckle pattern upon which PIV software can correlate.**

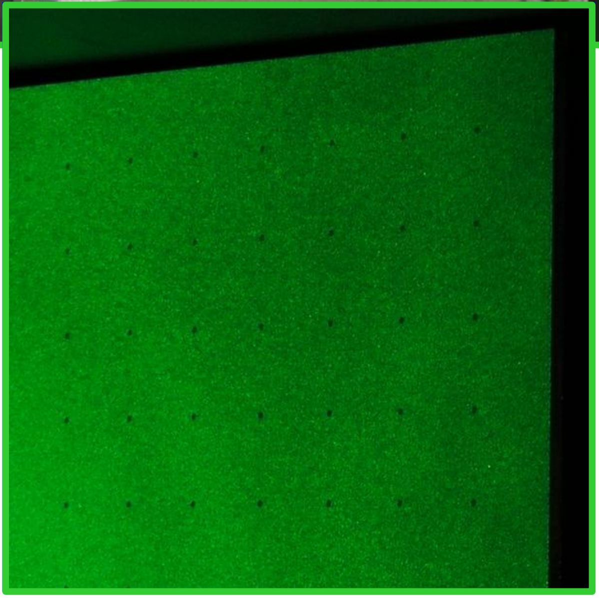
After calibration, leave the target in place.

- **It remains perfectly aligned to the calibration plane…**
- **…but not necessarily to the laser sheet.**

Translate the target according to the expected particle displacement.

- **Process the speckle images as if PIV data and compare.**



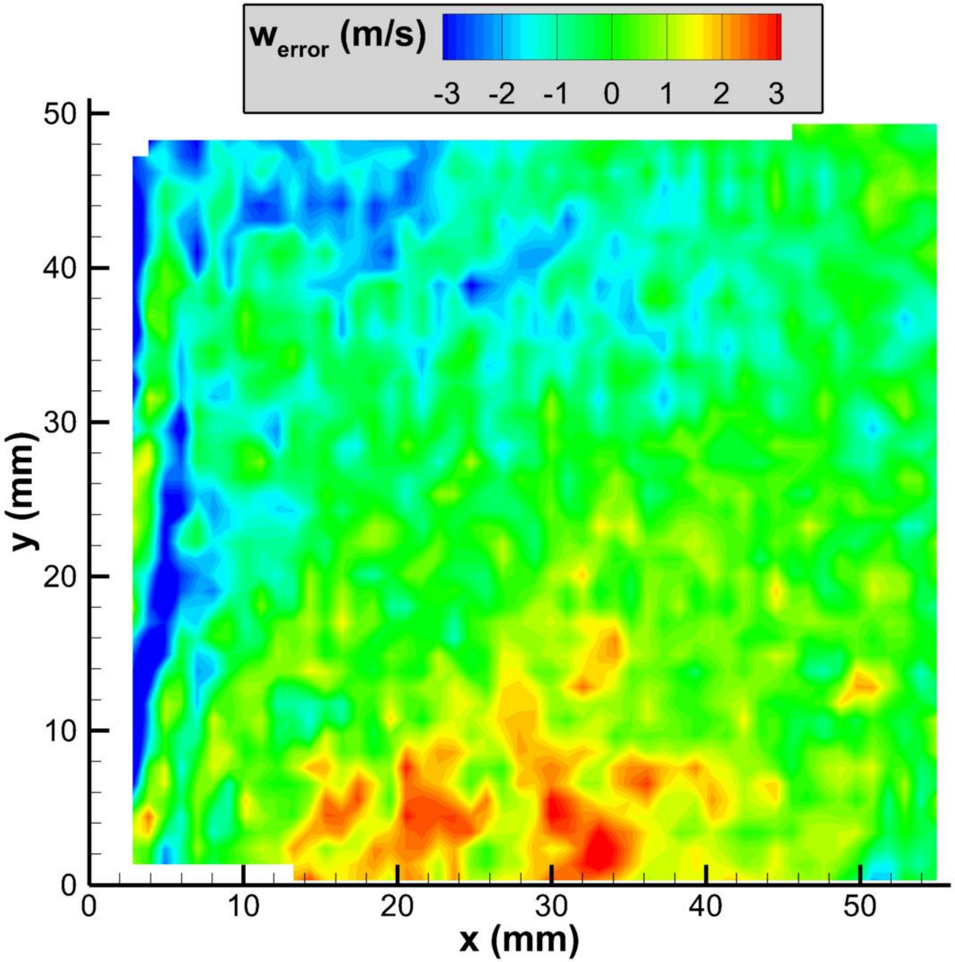


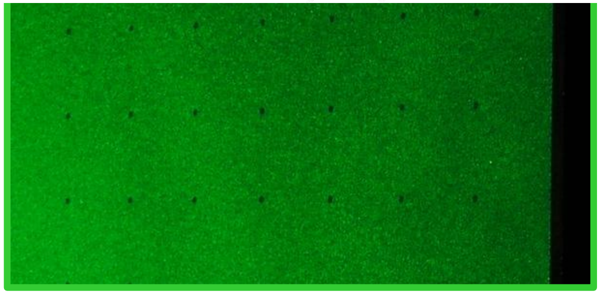
Calibration Error

An example from a streamwise plane calibration:

- **Maximum error in *u* is 3.2 m/s.**
- **Maximum error in *v* is 2.8 m/s.**
- **Maximum error in *w* is 4.1 m/s.**

For this experiment, U_∞ = 450-600 m/s.
(< 1% uncertainty)





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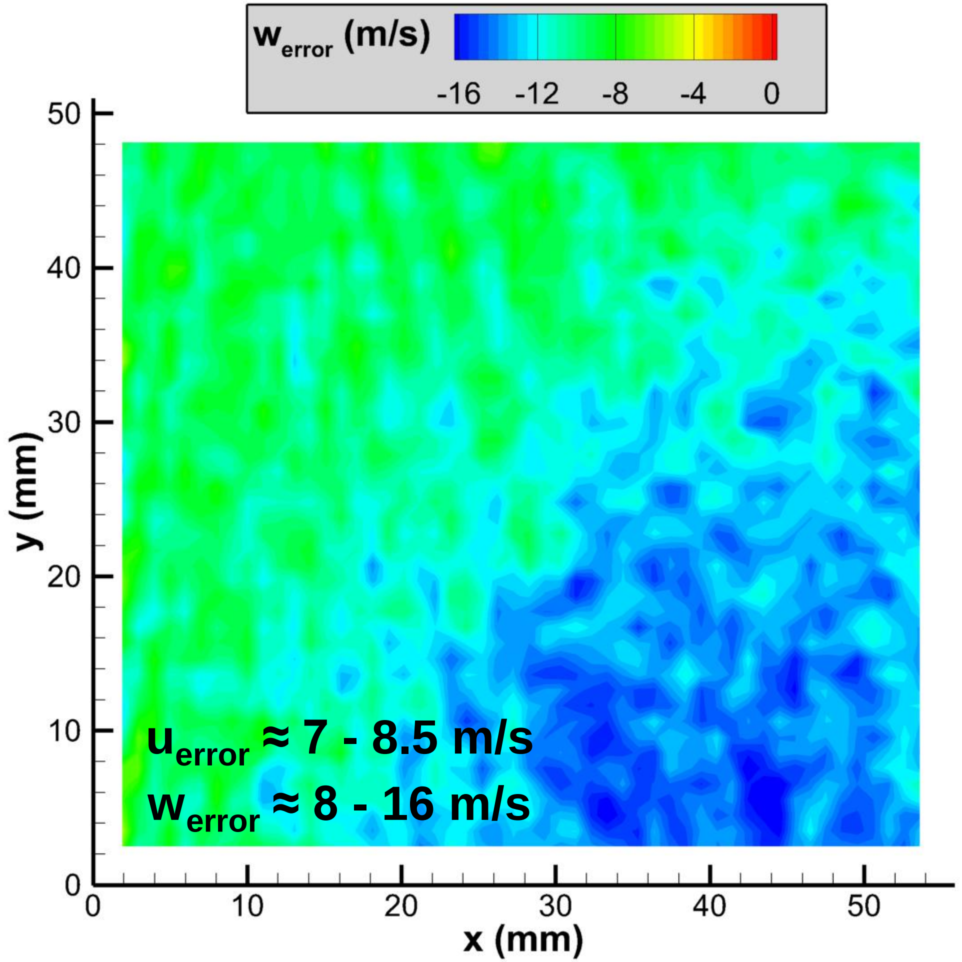
Calibrations do not always work out so well.

- Errors as large as 16 m/s in this poor example (3% uncertainty).

Some error in this procedure comes from the calibration check.

- Uncertainty in translation stages is equivalent to 1-2 m/s.
- Some uncertainty from correlating on speckle pattern.



This is helpful for identifying bad calibrations and bounding the calibration uncertainty.

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Registration Error

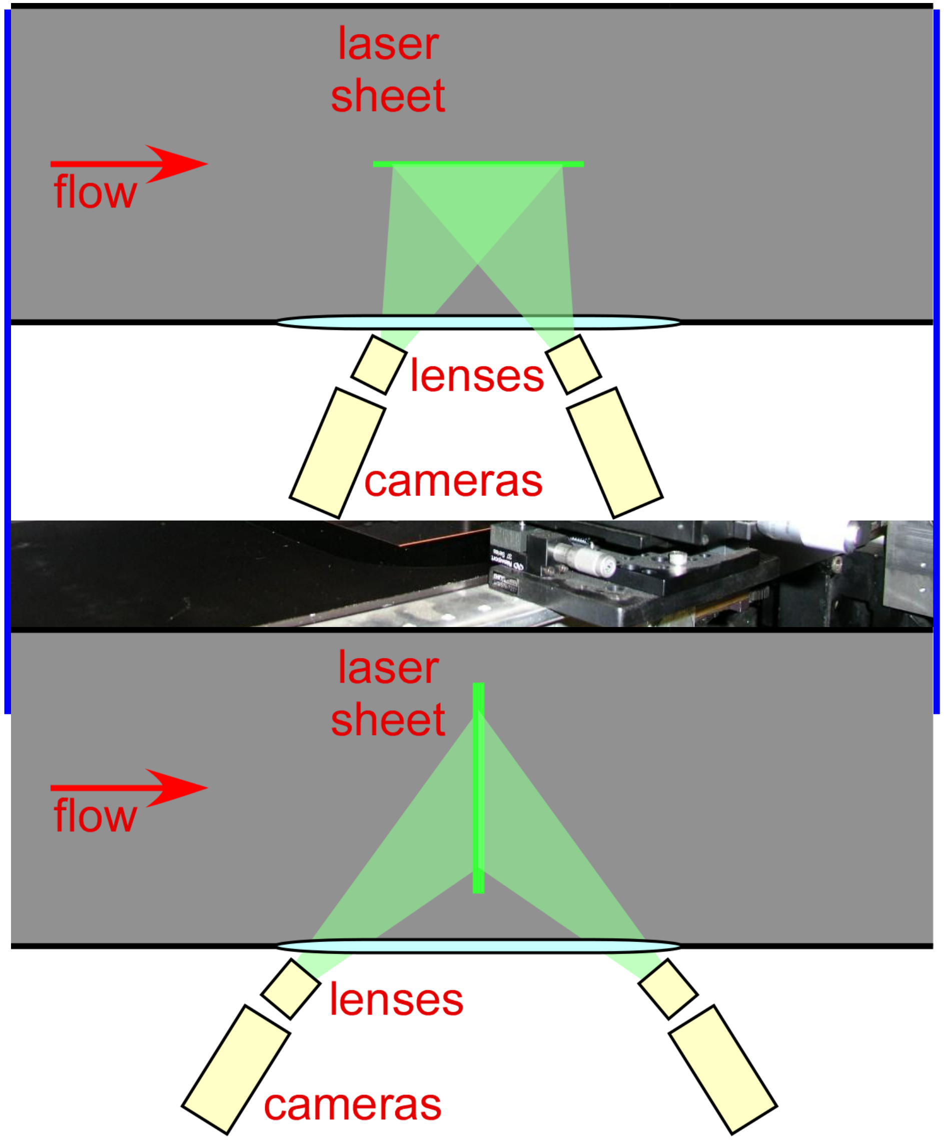
What complementary measurements can assess the registration error?

Alignment horror stories!

- If your target is rotated by 0.5°, errors on the order of 10%.
- If you are careful and thorough, these errors aren't so big.

Stereoscopic self-calibration

- It can be effective for thin sheets and shallow camera angles.
- Otherwise, not so much.
- Even when successful, it introduces errors of its own.



Registration Error

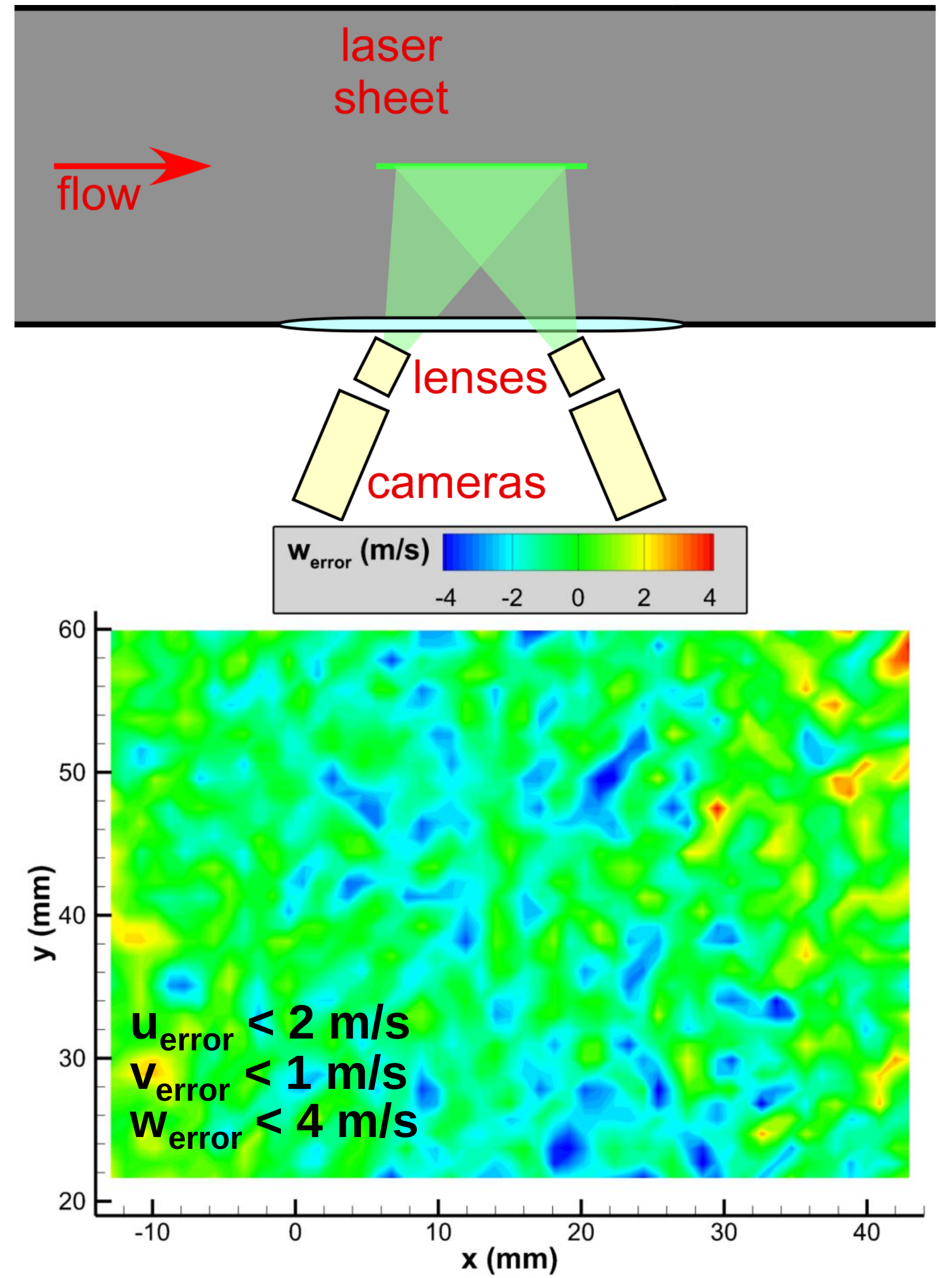
What complementary measurements can assess the registration error?

Remove the model and acquire freestream data.

- **Compare to wind tunnel calibrations (U_∞=270 m/s).**
- **No self-calibration.**

Streamwise configuration:

- **Errors < 0.7% in *u* and *v*.**
- **Errors < 1.5% in *w*.**



Registration Error

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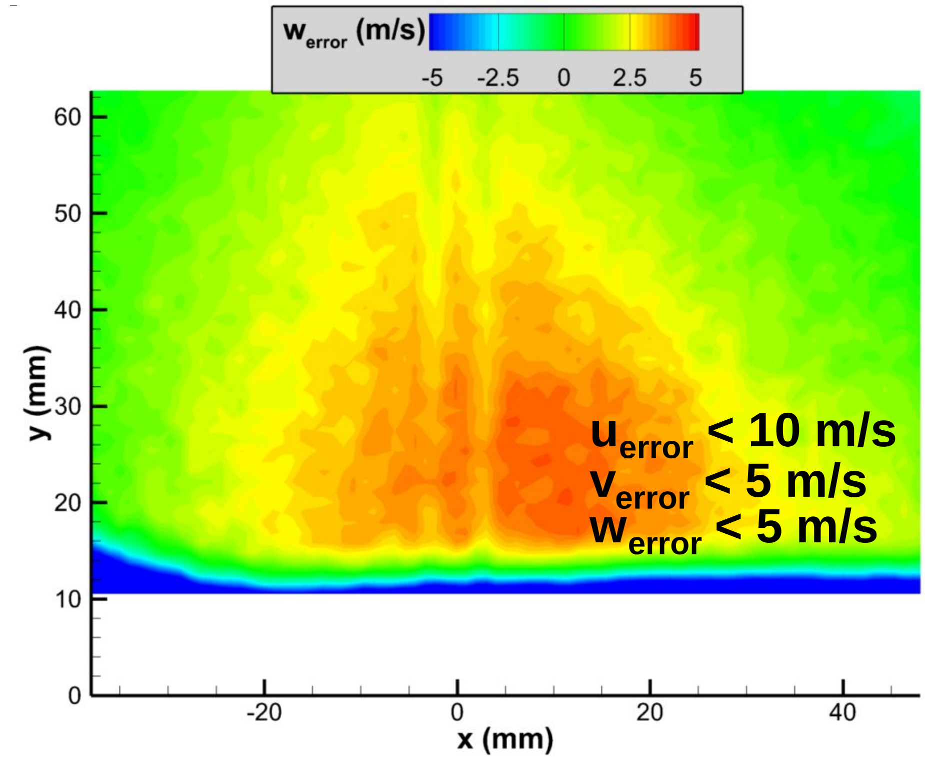
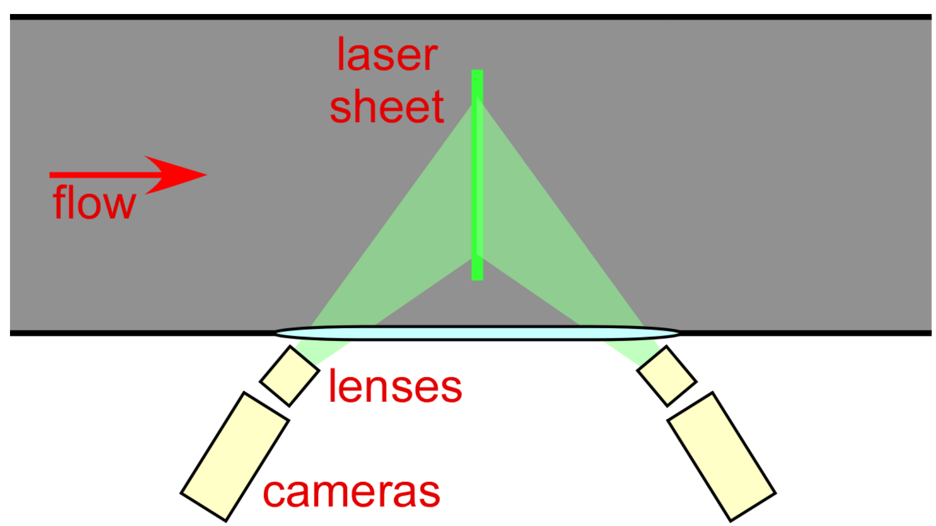
Streamwise configuration:

- **Errors < 0.7% in *u* and *v*.**
- **Errors < 1.5% in *w*.**

Crossplane configuration:

- **Errors are more like 1-3%.**





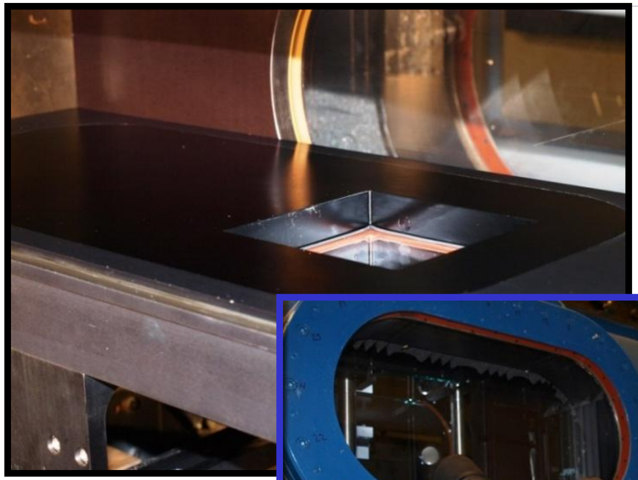
Registration Error

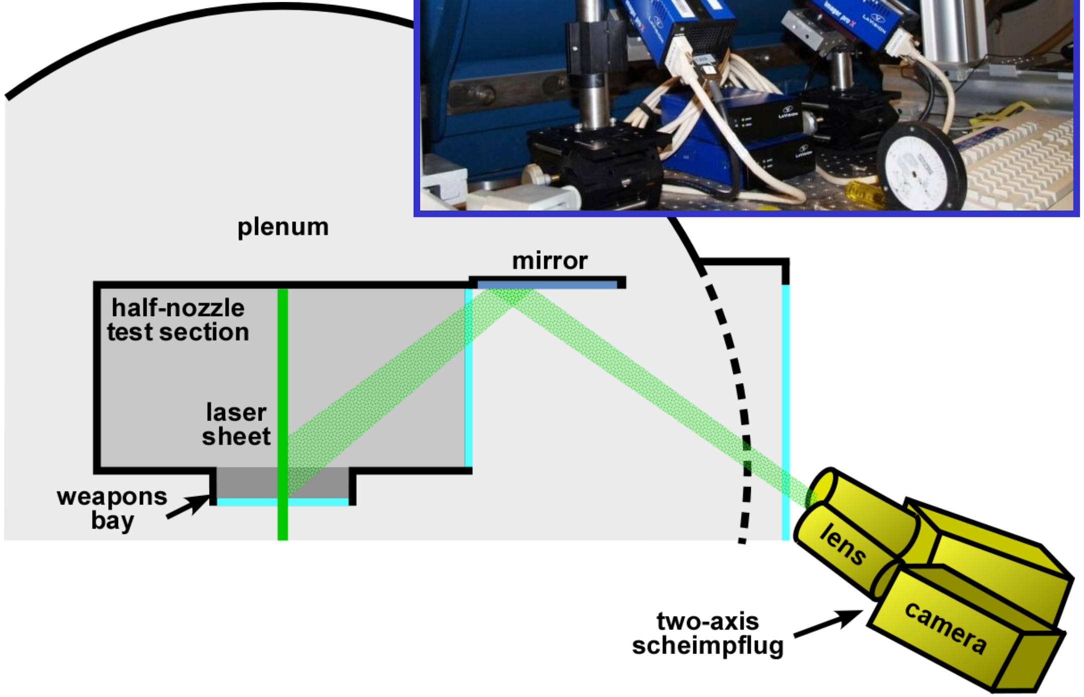
What complementary measurements can assess the registration error?

This procedure has some limitations.

- **For a spatially uniform freestream, we will not detect pure translational misalignment.**
- **In some experiments, we cannot simply remove the model and measure the freestream.**

These sorts of complementary measurements are helpful, but can only take us so far.





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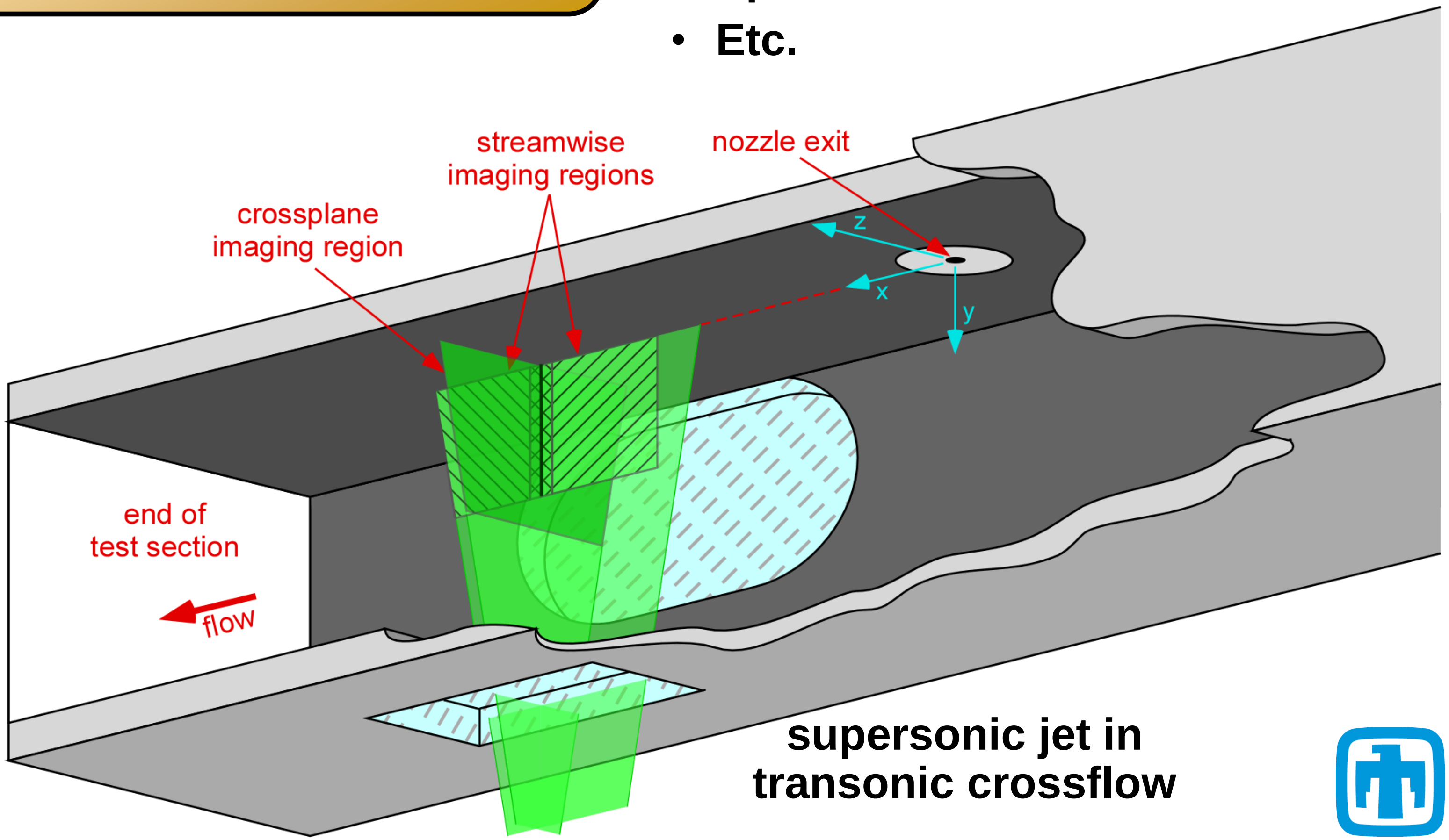
The Value of Redundant Measurements

Ultimately, the best approach is to measure the same data in multiple, differing experiments.

Unfortunately, this is expensive and time consuming.

If we configure PIV in different ways, we may change our sensitivity to biases and can detect them.

- **2-C vs stereo**
- **Light sheet orientation**
- **Spatial resolution**
- **Etc.**



supersonic jet in transonic crossflow

The Value of Redundant Measurements

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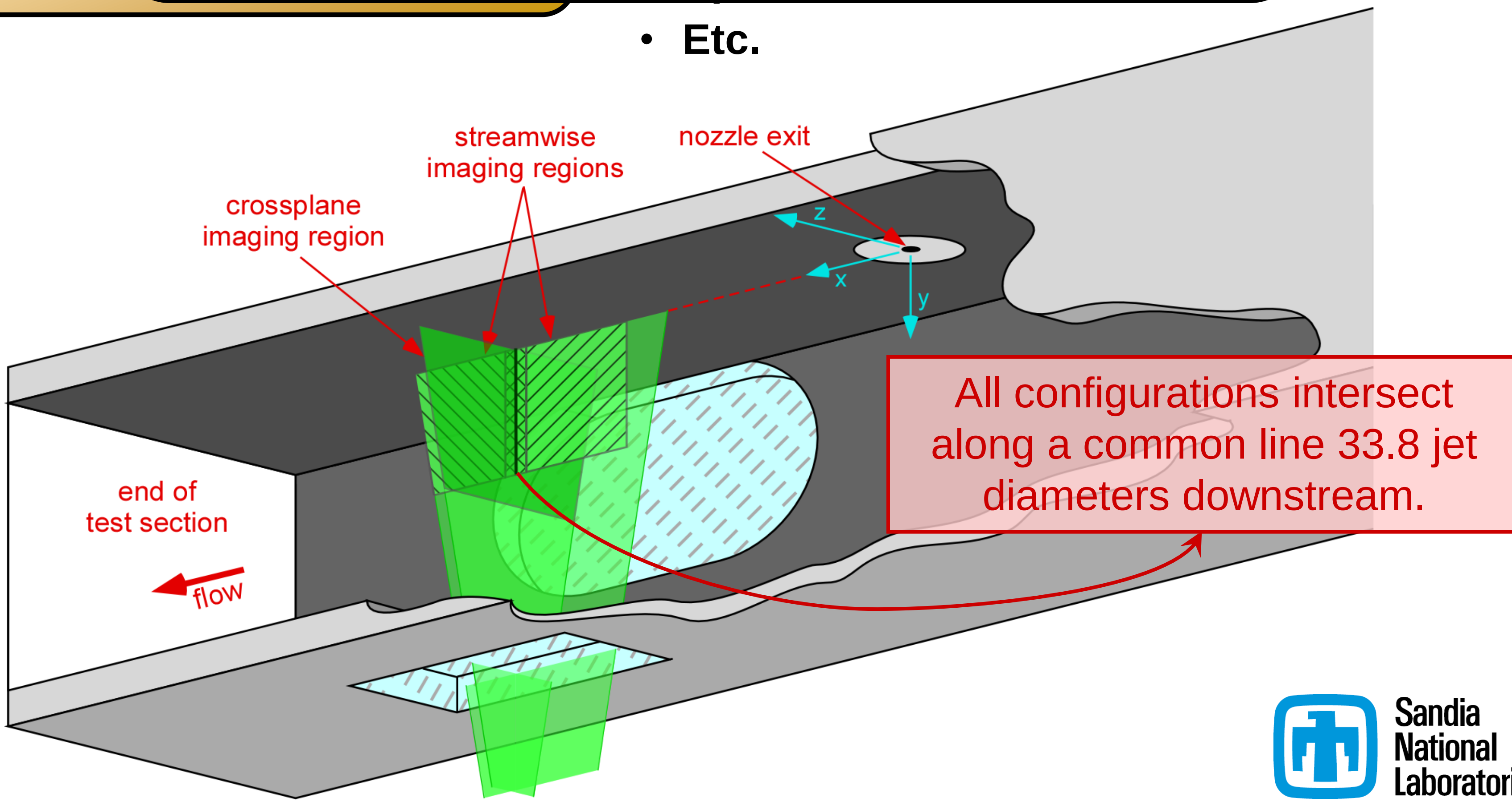
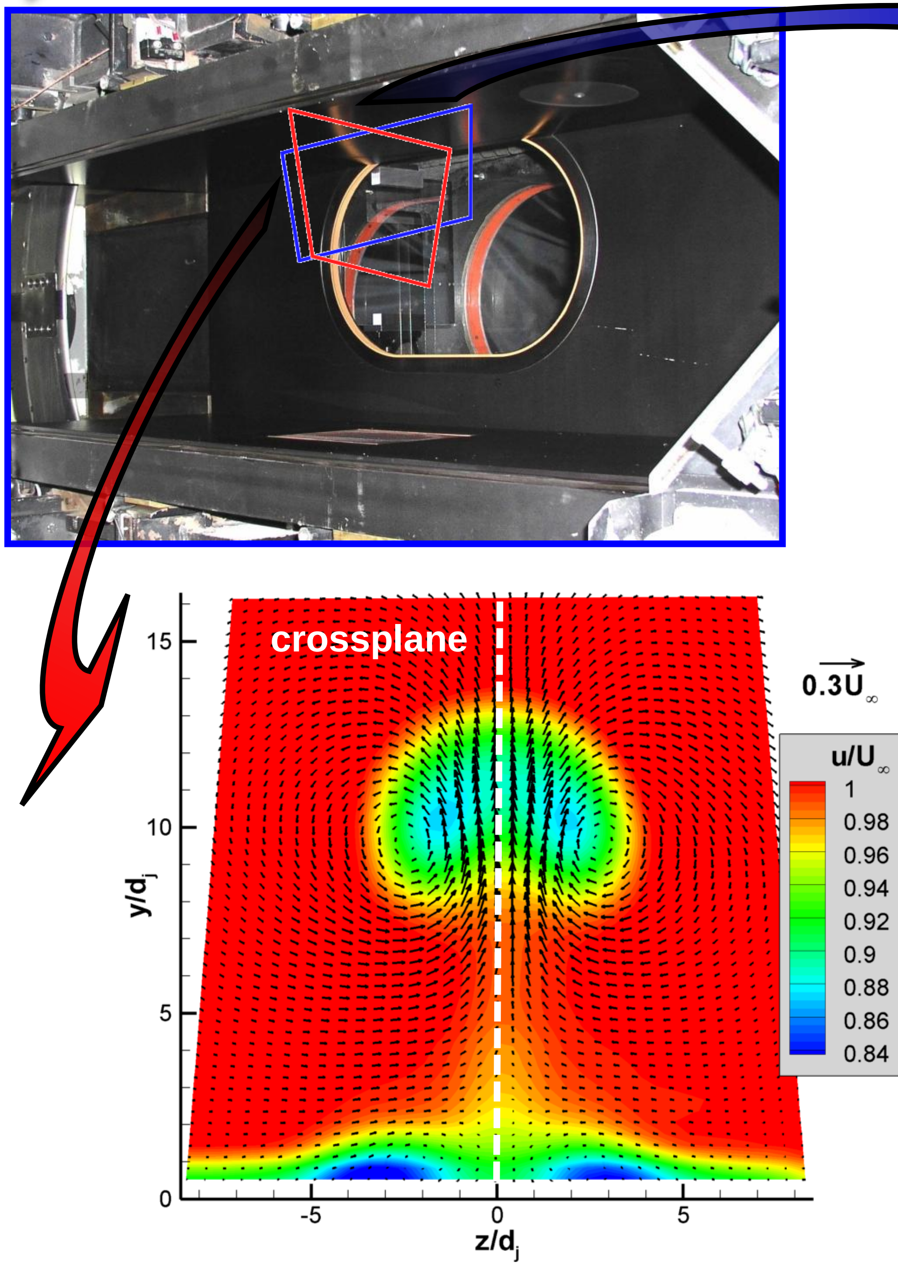
Three PIV Configurations

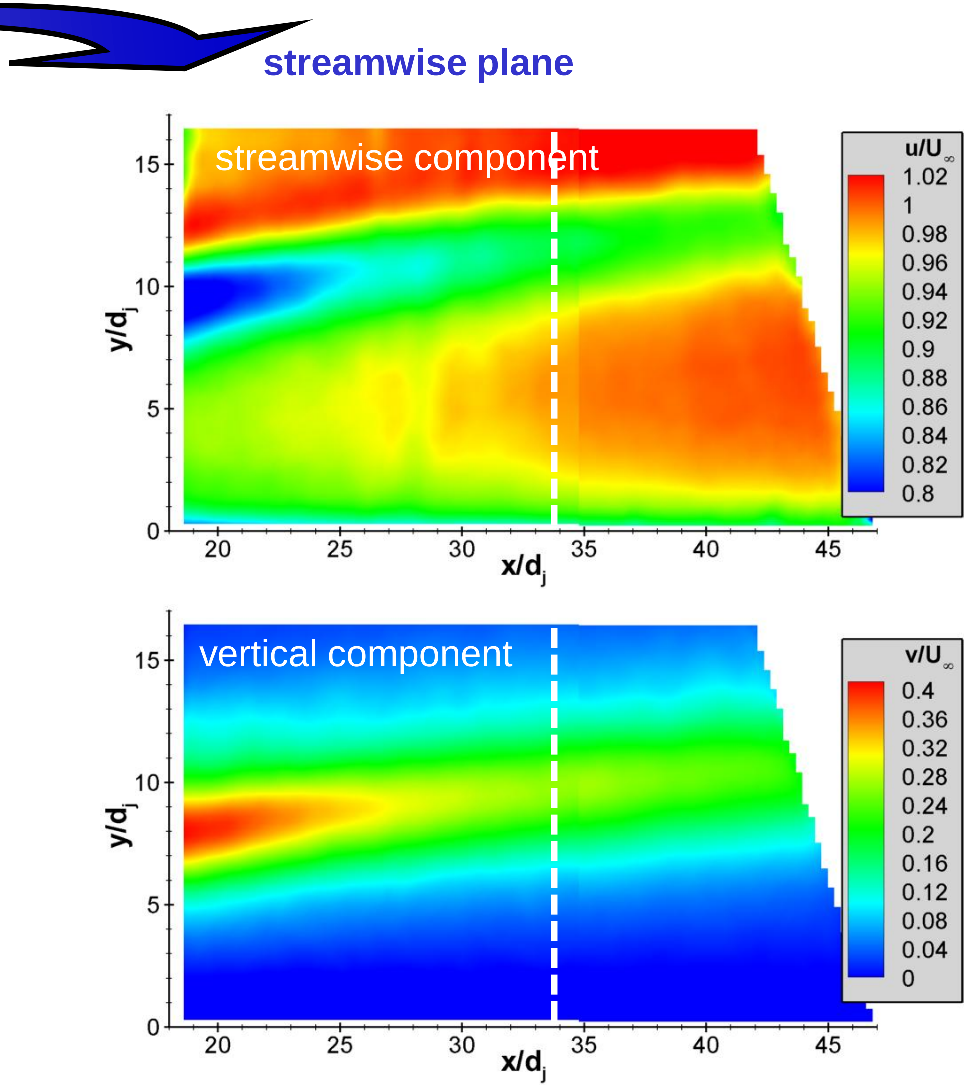
- Two-component (2-C) PIV in the streamwise plane
  - Upstream and downstream stations
- Stereoscopic PIV (3-C) in the streamwise plane
- Stereoscopic PIV (3-C) in the crossplane

- **Etc.**



Jet-in-Crossflow Experimental Results

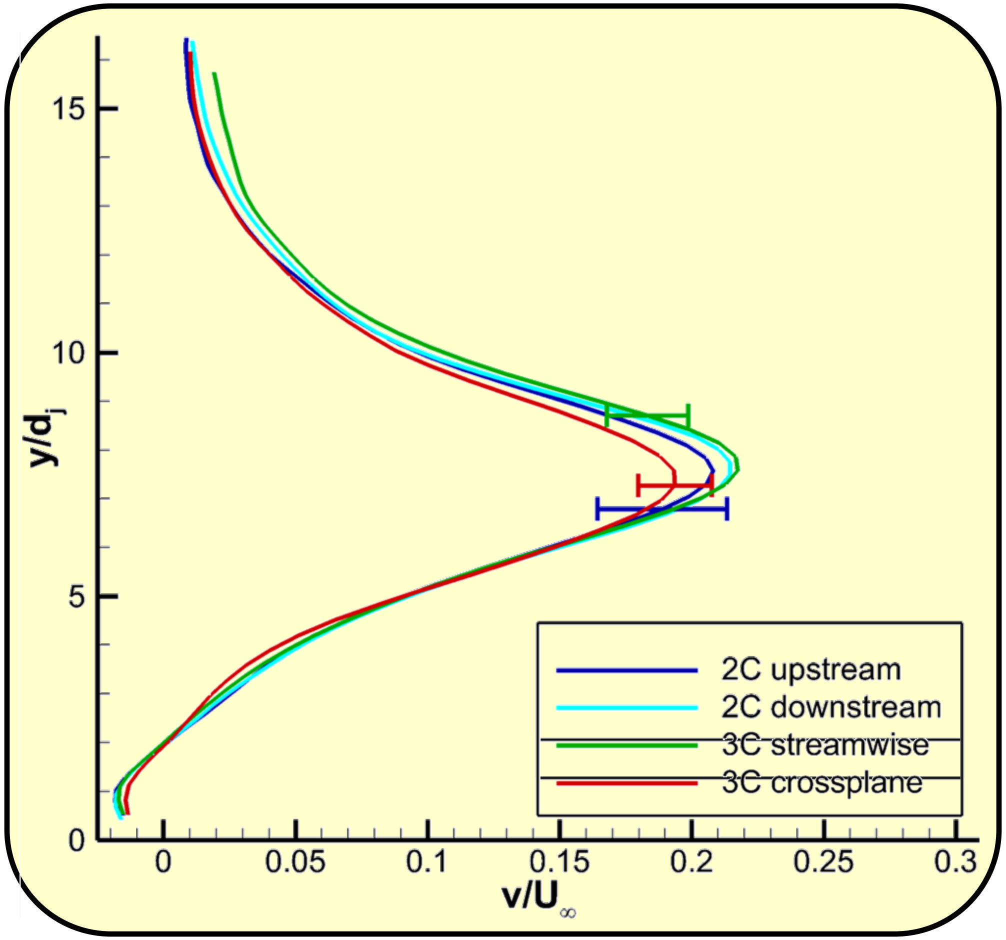




We'll focus on the *v* component.

- **Effects are most evident.**

Comparison of Mean Velocities



Streamwise data agree to within the uncertainty.

Crossplane data magnitude lower than streamwise; most evident in *v*.

This reduced crossplane velocity in *v* lies slightly beyond the uncertainty.

Uncertainty estimates based on PIV precision, repeatability of flow conditions, and calibration and registration bias.

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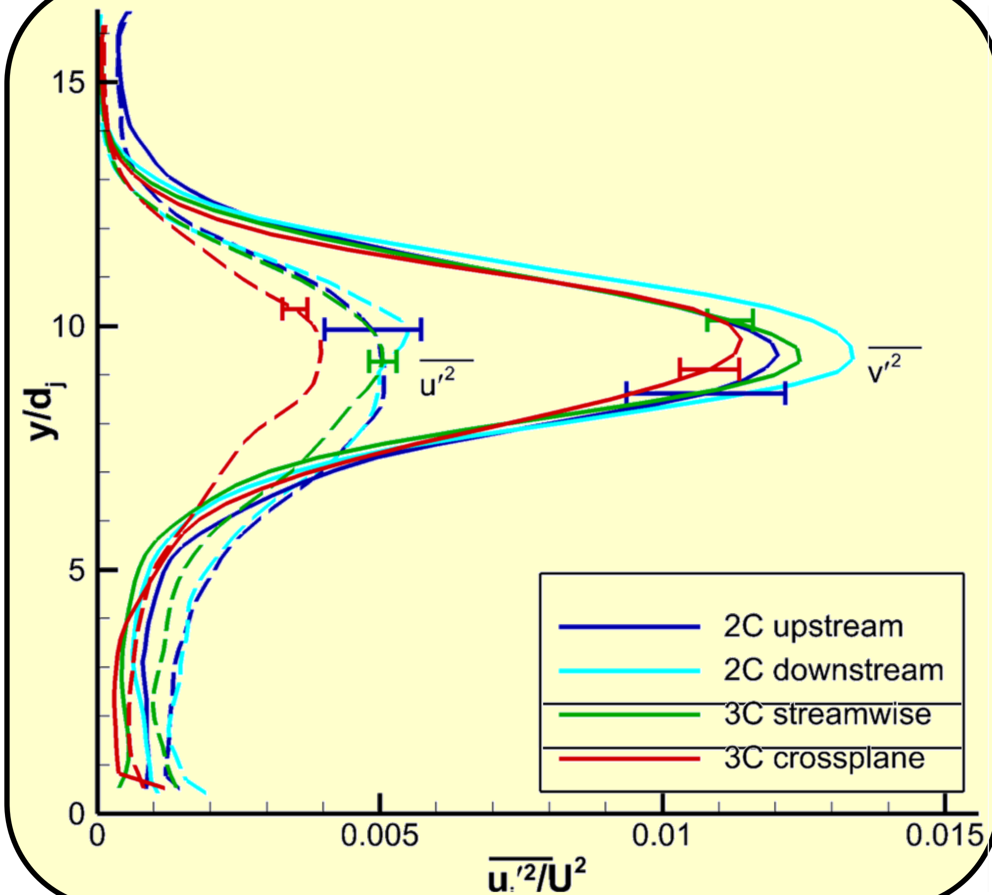
Comparison of Turbulent Stresses



Again, streamwise data agree to within the uncertainty.

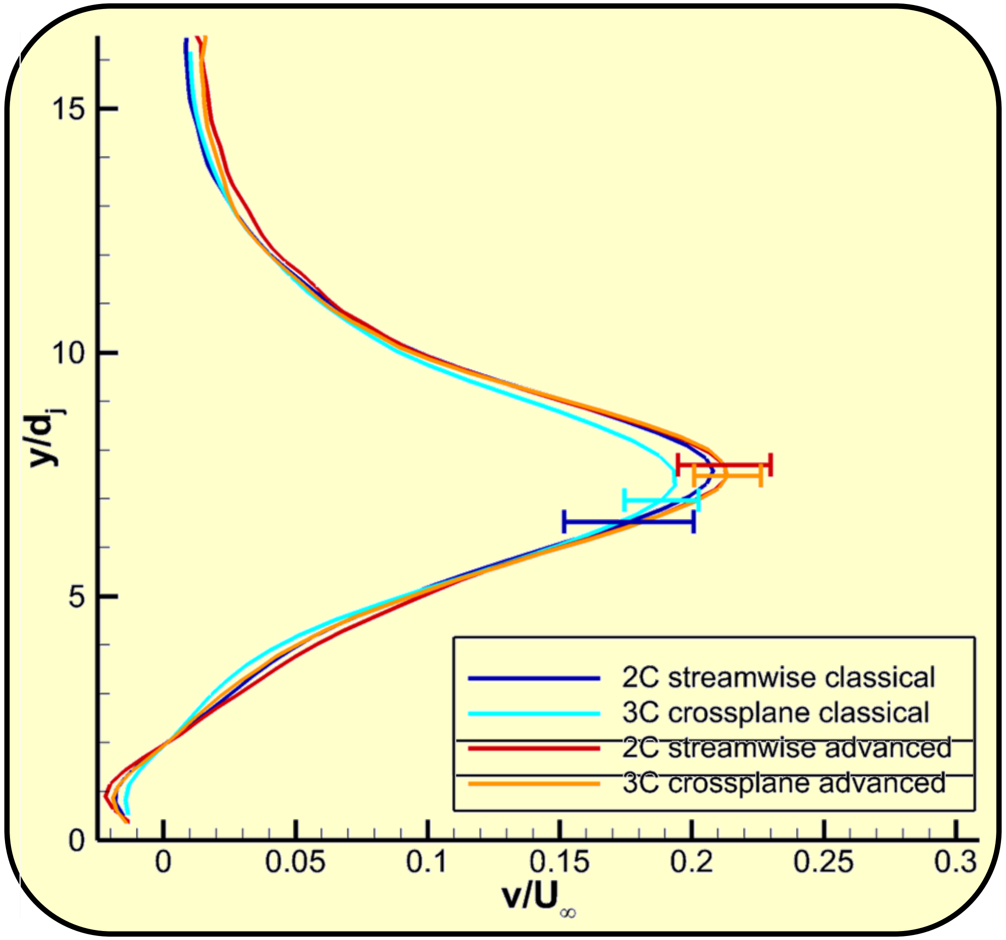
Again, crossplane data magnitude generally lower than streamwise, exceeding the uncertainty.

These results are consistent across repeated experiments, flow conditions, and repeated laser and camera alignments.

These data were acquired in 2003 and processed using classical PIV software (IDT ProVision).

In 2007, we re-processed using advanced software, including image deformation (LaVision DaVis).

Comparison of Processing Algorithms



Omit downstream 2-C station and streamwise 3-C data to reduce clutter.

The advanced algorithm agrees with the classical in the streamwise plane.

The advanced algorithm returns crossplane data in agreement with the streamwise, unlike classical.

With respect to the uncertainty, the advanced algorithm results show better self-consistency.

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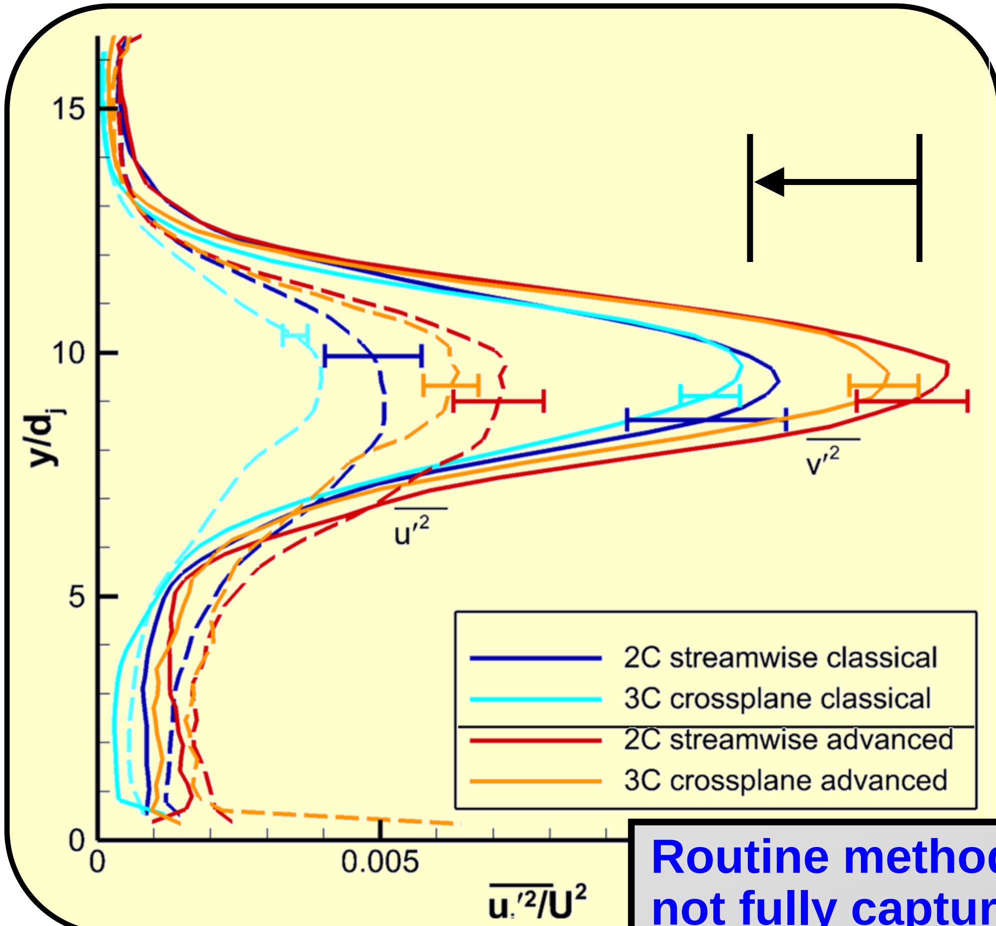
Comparison of Processing Algorithms



Very alarming: The advanced turbulent stresses are much larger than those measured by classical.

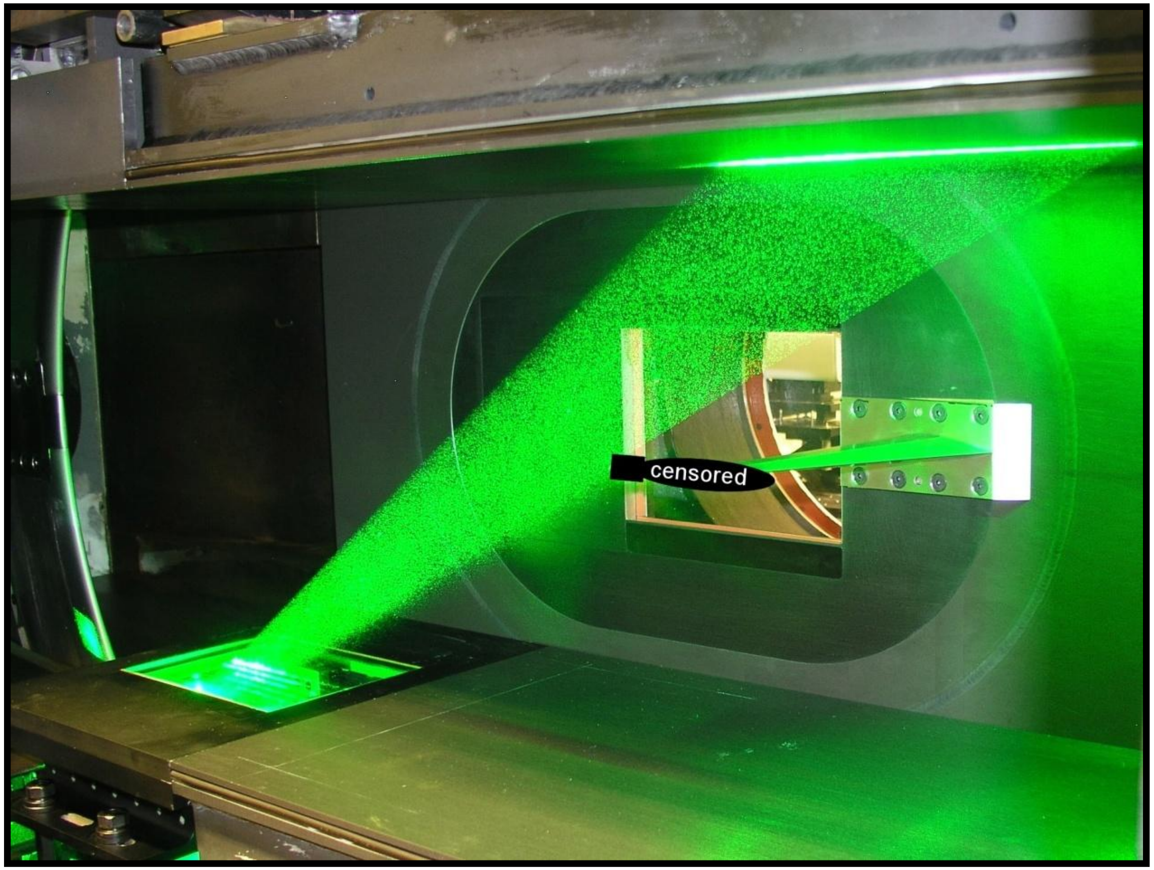
We eventually traced the discrepancy to the use of image deformation in advanced algorithms.

- **Reduces correlation error due to velocity gradients.**
- **Occurs even for velocity gradients within recommended limits:** $(du/dx)_{max} \approx 0.03\ d_I$.

Routine methods of uncertainty quantification may not fully capture the true error sources.

- **Dominant bias errors often are nontrivial to predict beforehand.**
- **Redundant measurements (and data processing) can reveal the "unknown unknowns."**

Another Example of Redundant Measurements



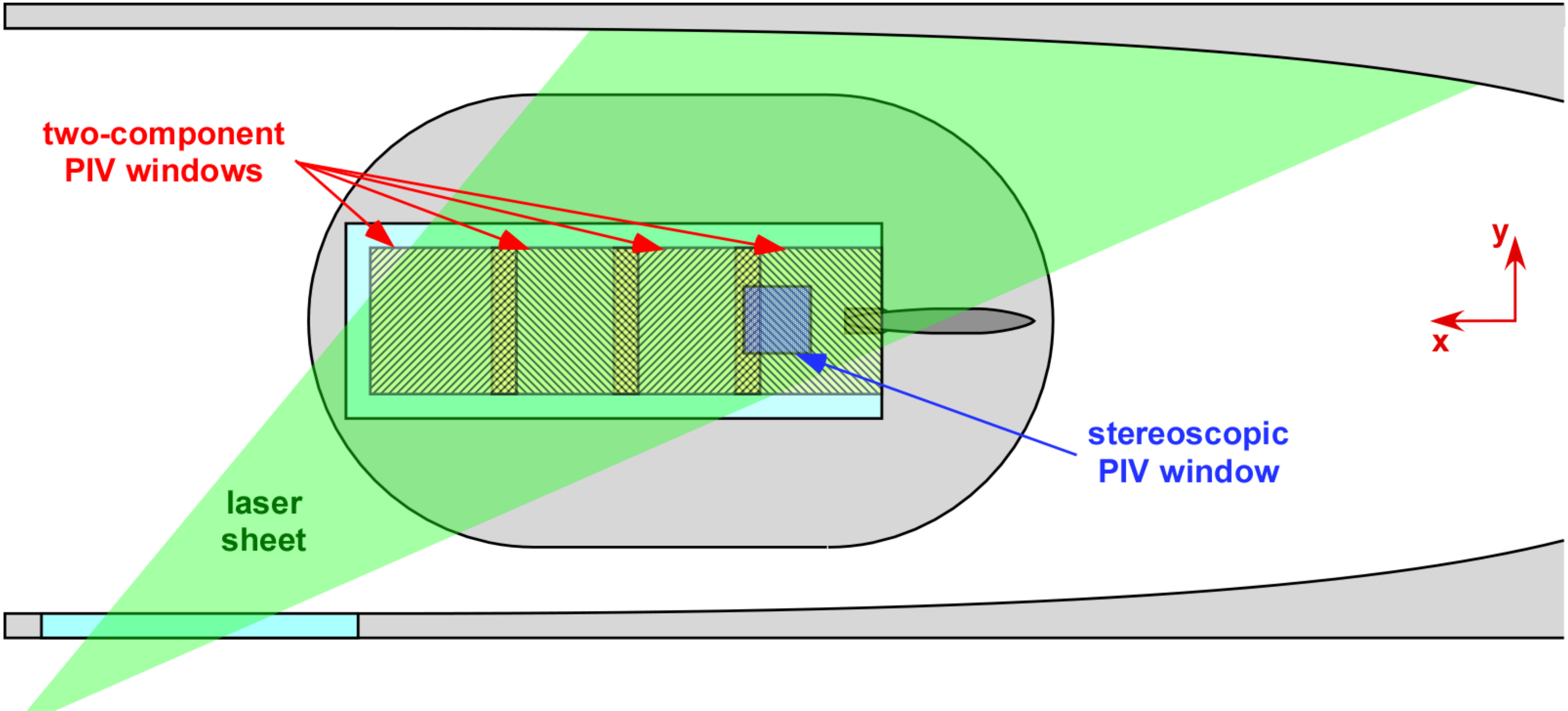
We took a similar approach for a study of wake growth and turbulence of a finned axisymmetric vehicle.

Model mounts on a strut protruding from one side wall.

The laser sheet is aligned with, and parallel to, the model body axis.

The laser sheet clips the edges of some views, which is visible in the following contour plots.

PIV Configuration



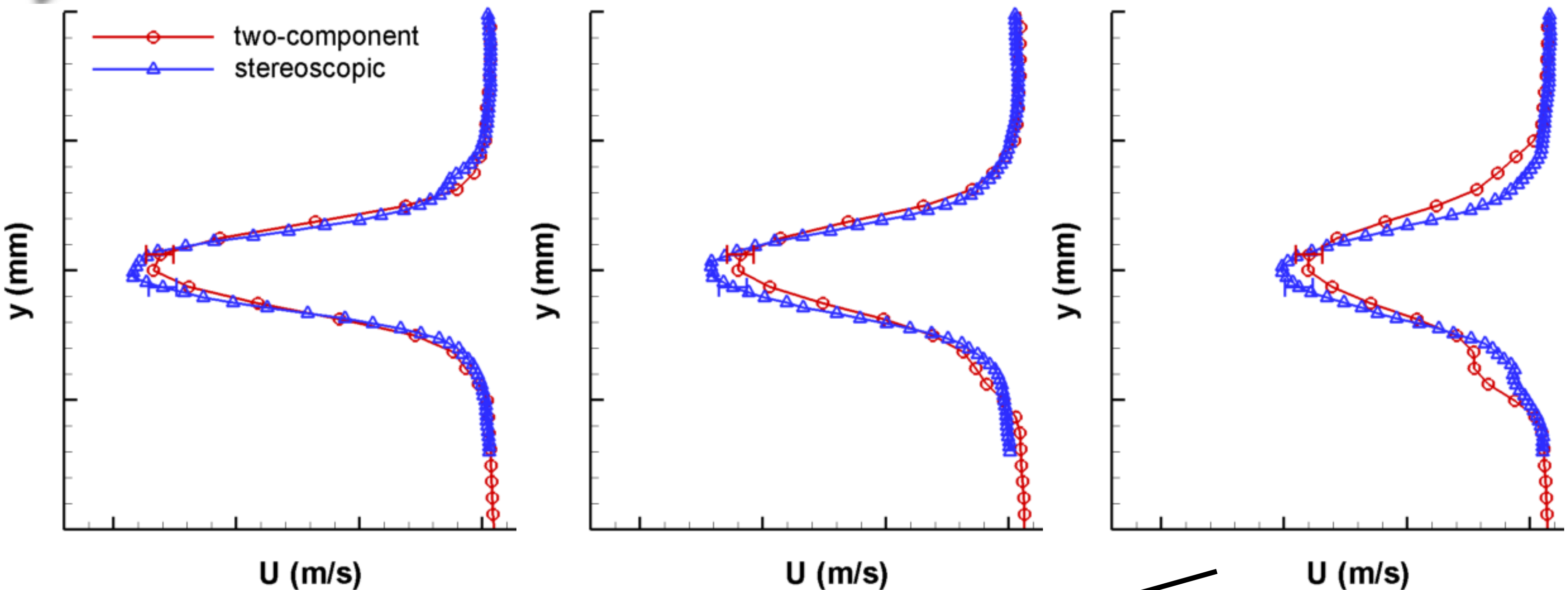
Capture the greatest extent of the wake by using four large imaging regions (two passes of two cameras operating simultaneously) to survey the wake.

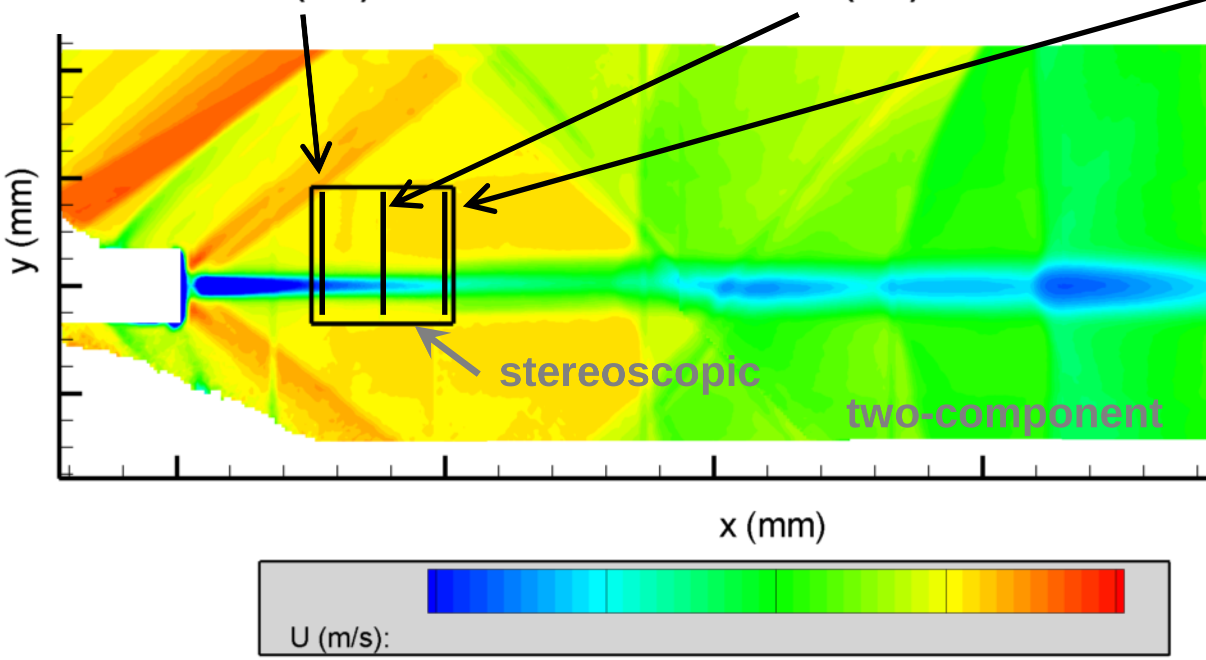
- **This uses *two-component PIV*.**

In a third pass, capture a smaller extent of the wake by using only one imaging region, but perform *stereoscopic PIV*.

All data in the streamwise plane.

Stereoscopic PIV

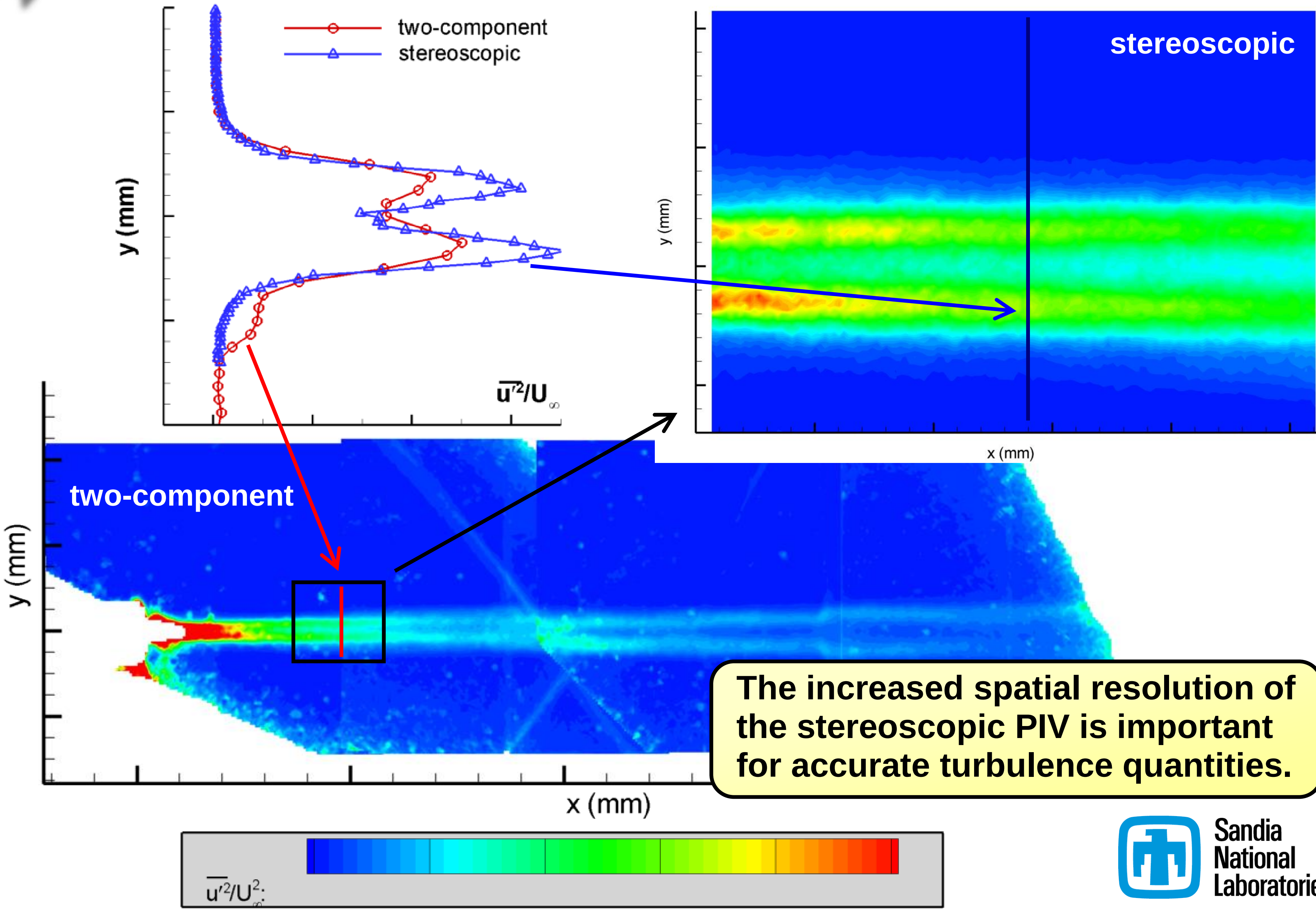




Stereoscopic results are superposed on the two-component results, and are in close agreement.

The lower stereoscopic velocities in the wake are due to the superior spatial resolution and are more likely to be correct.

Streamwise Turbulence Intensity



The increased spatial resolution of the stereoscopic PIV is important for accurate turbulence quantities.

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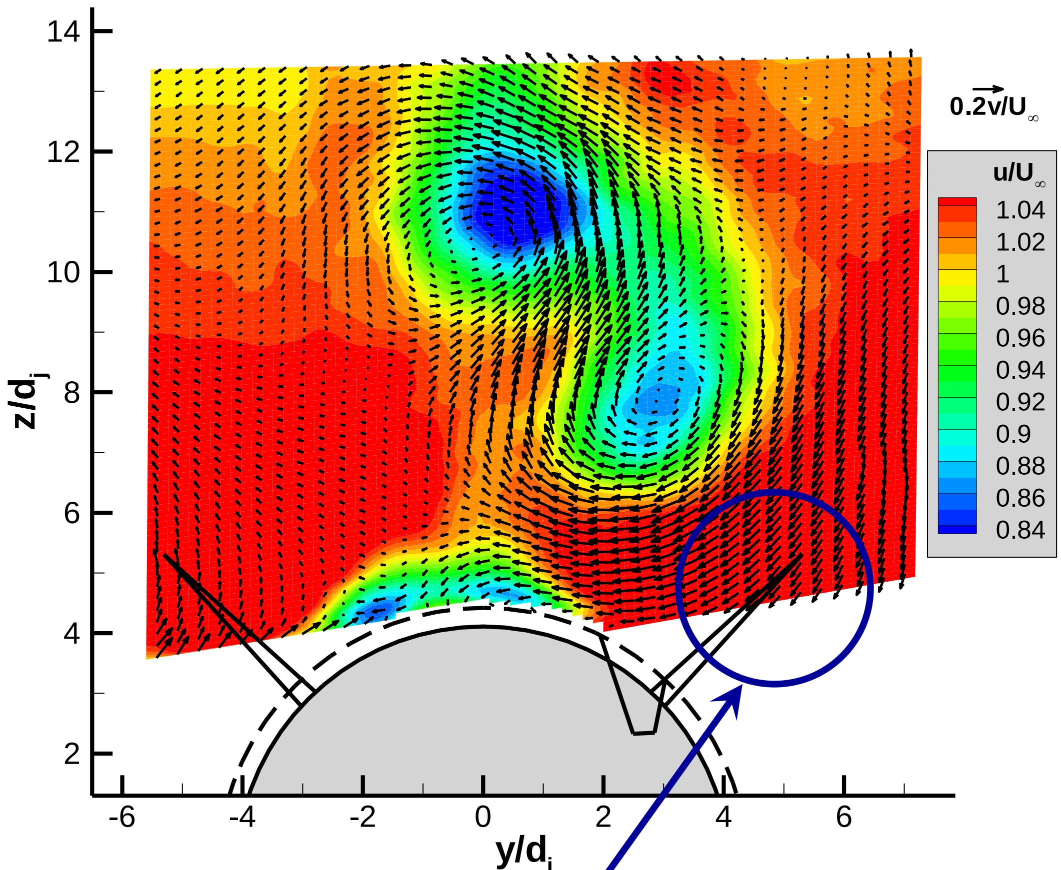
Which Bias Uncertainties Are Important?

Test conducted in the NASA Ames 11-Foot Unitary Tunnel.

Use PIV to measure the vortices responsible for jet/fin interaction.

Stereoscopic images acquired in the crossplane just upstream of the fins.



The vortex-induced motion induces an angle of attack on this fin.

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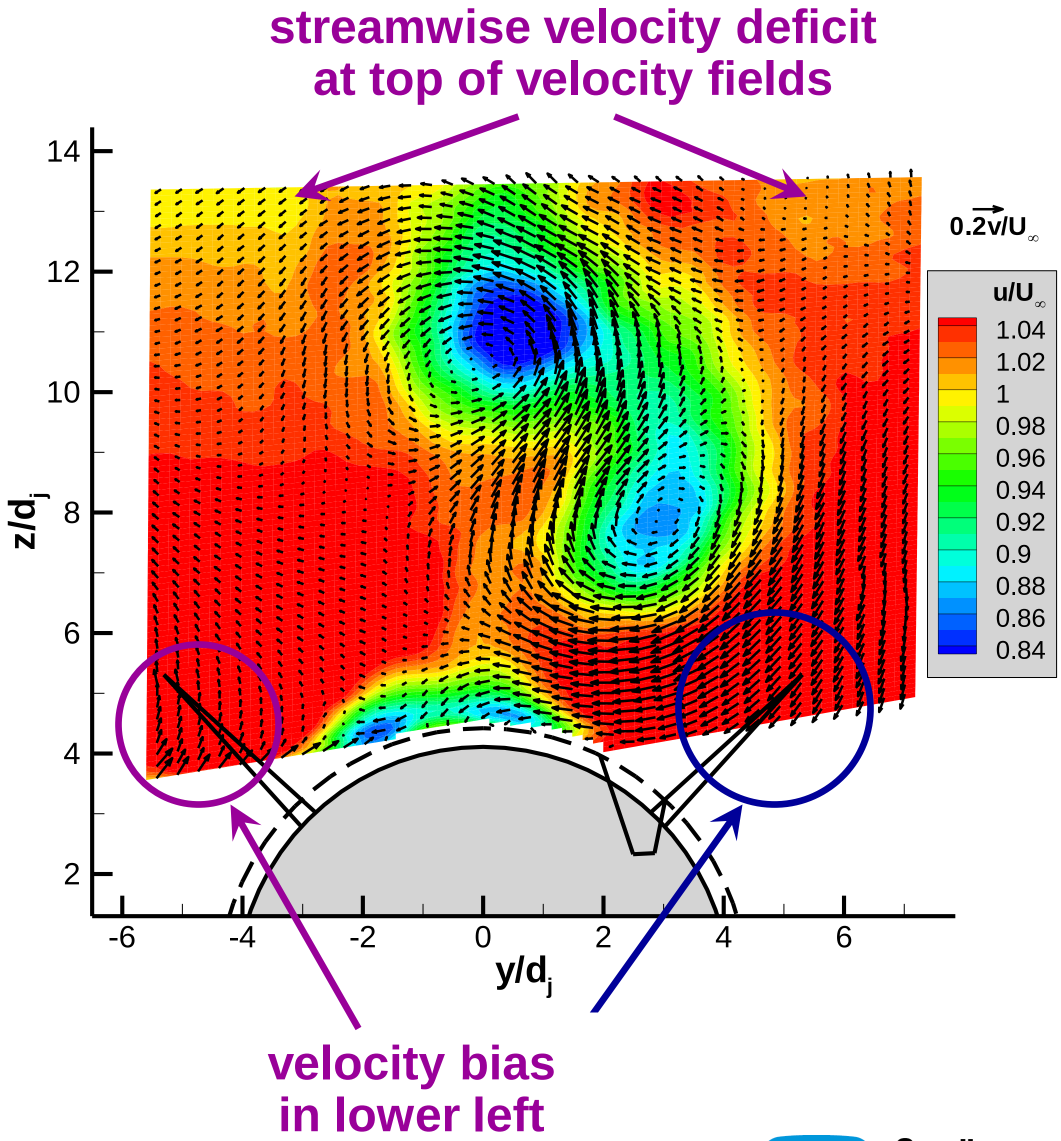
Identifying the Measurement Biases

Unfortunately, the data contain a number of bias errors.

- Identifiable by comparison with freestream data.



Identifying the Measurement Biases

Unfortunately, the data contain a number of bias errors.

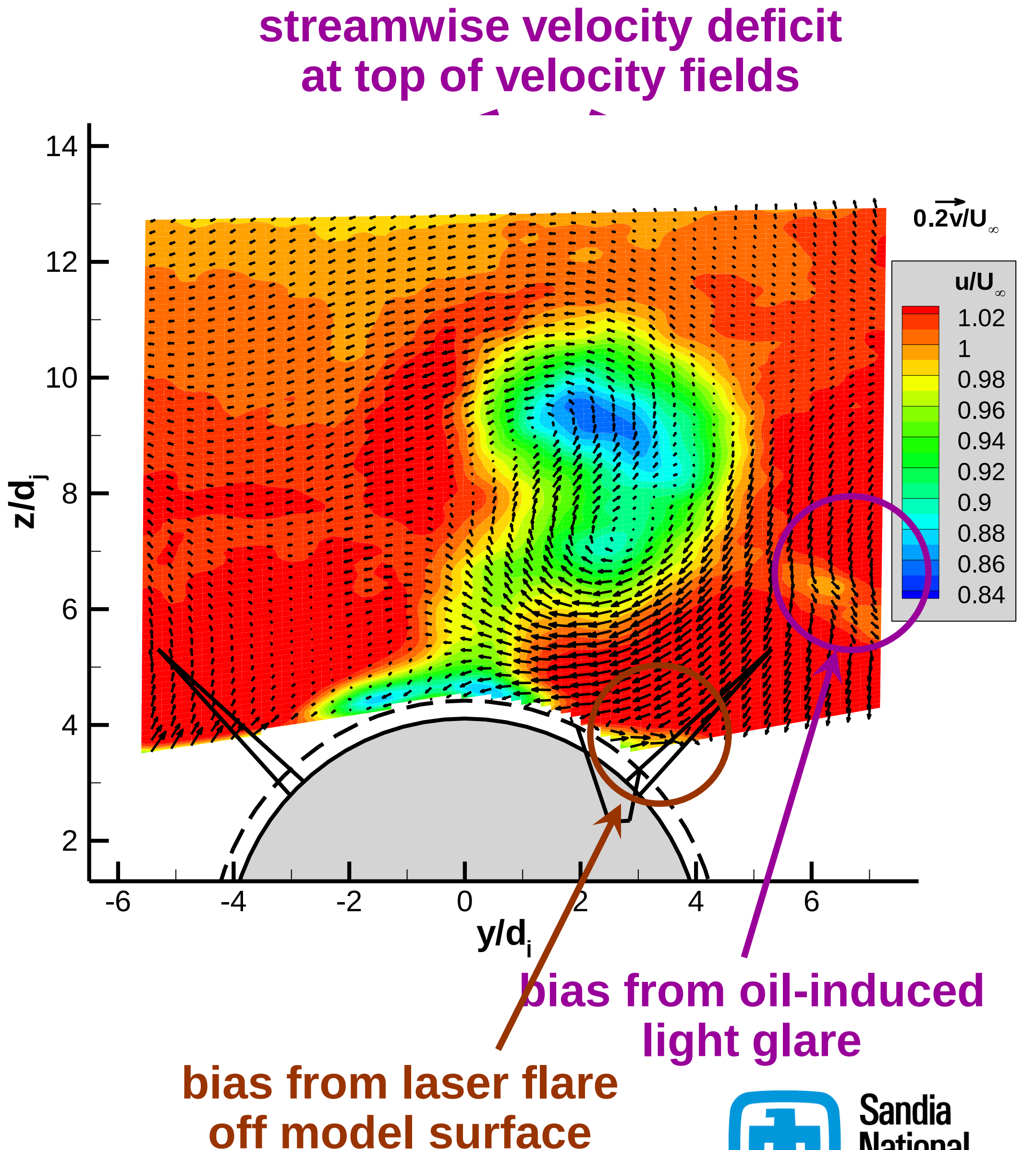
- Identifiable by comparison with freestream data.
- Some biases vary with time.

Oil Accumulation

- Oil residue from the smoke builds up on the windows over time.
- Creates a light glare in specific locations that induce biases.

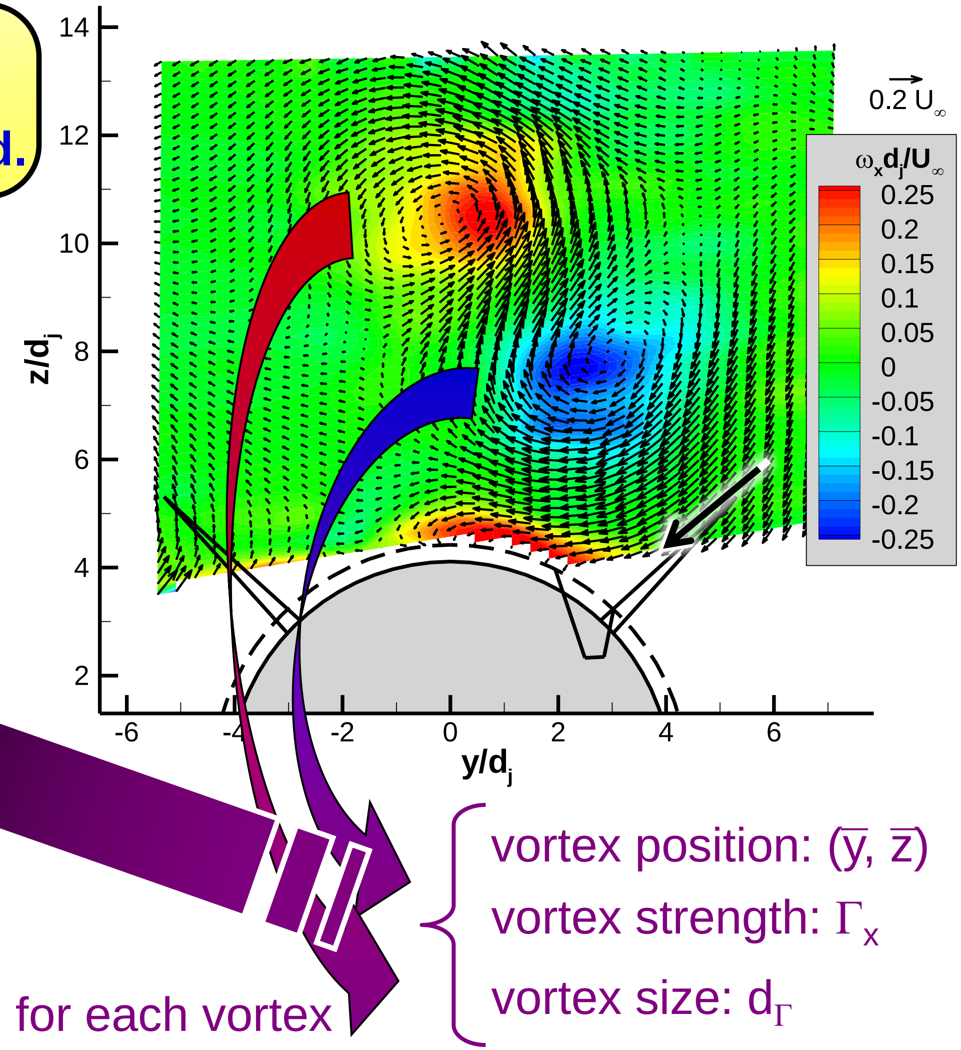
Laser Flare from Model Surface

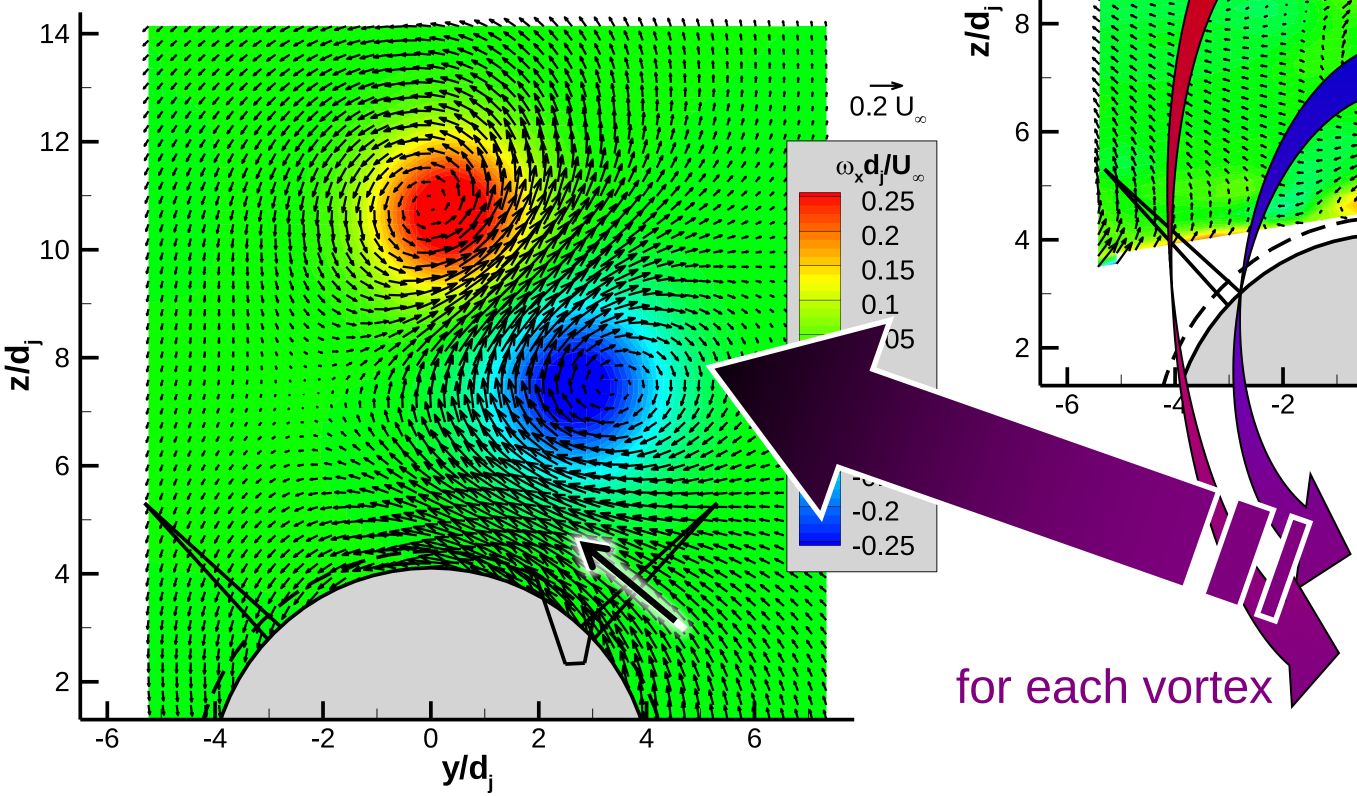
- Creates a velocity bias exactly where jet/fin interaction must be measured.
- But the vortices are well defined.



Vortex Modeling

We can generate a new velocity field using a model based on vortex parameters found from the vorticity field.





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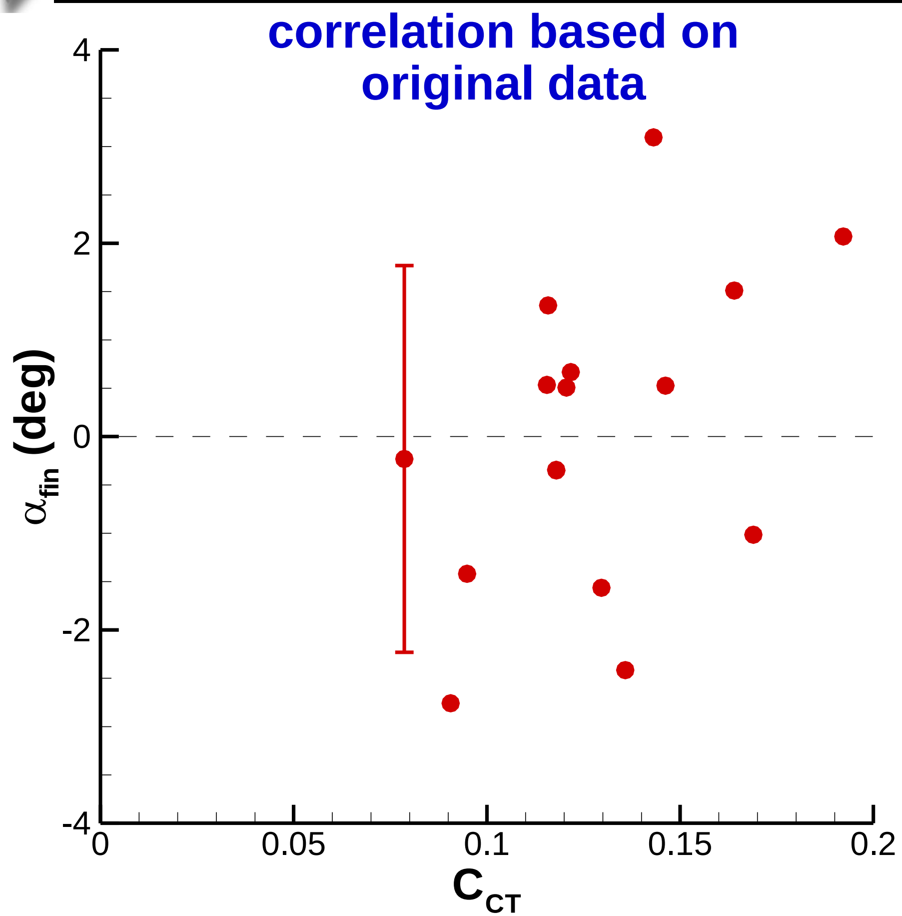
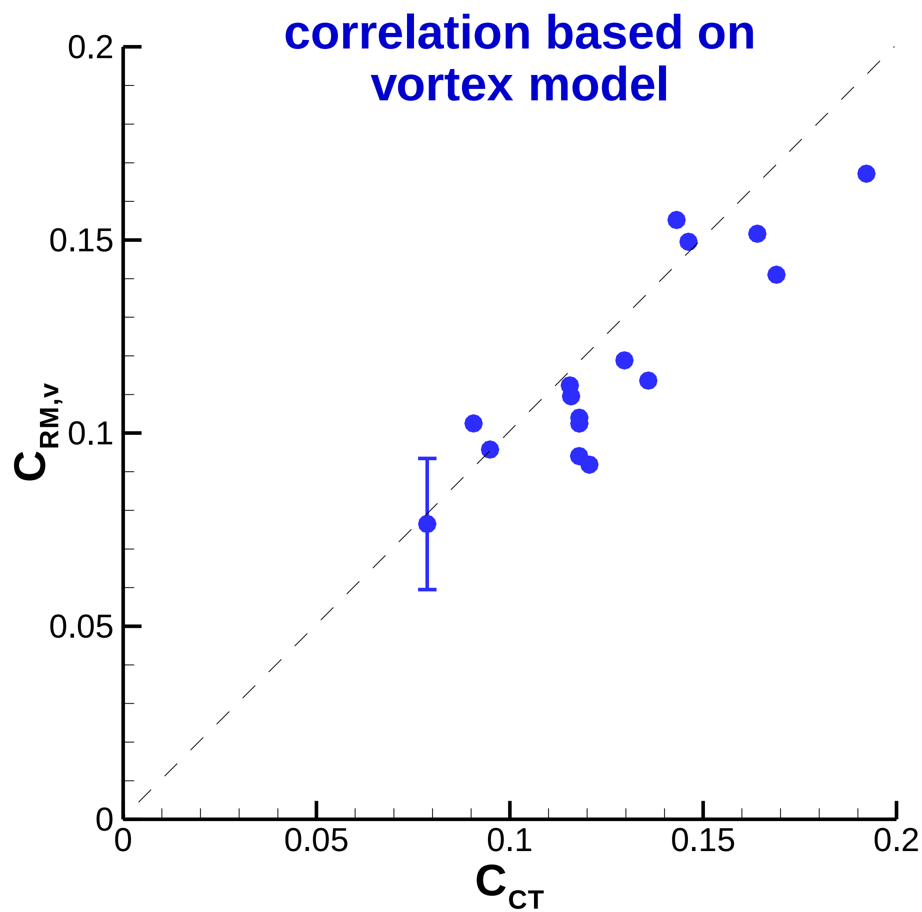
An Improved Result

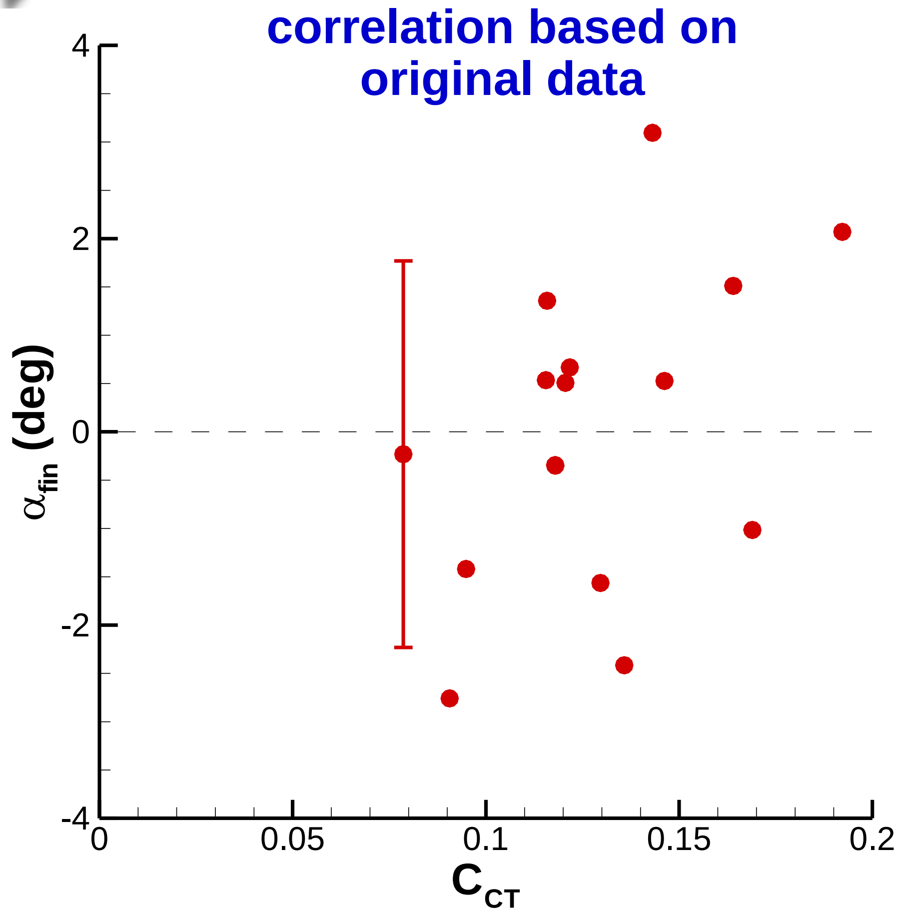


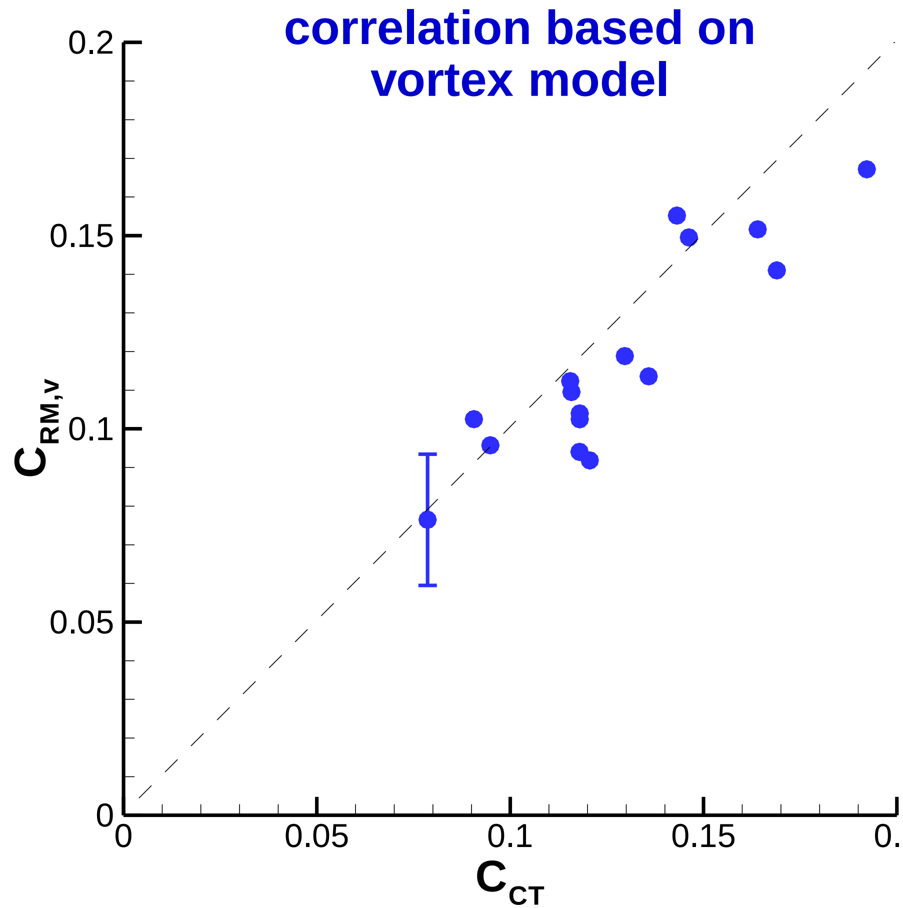


This is effective because:

- Calibration and registration uncertainties typically are of low spatial frequency.
  - *Biases tend to cancel when differentiating to find vorticity.*
- Localized biases are distant from the vortex cores.

An Improved Result

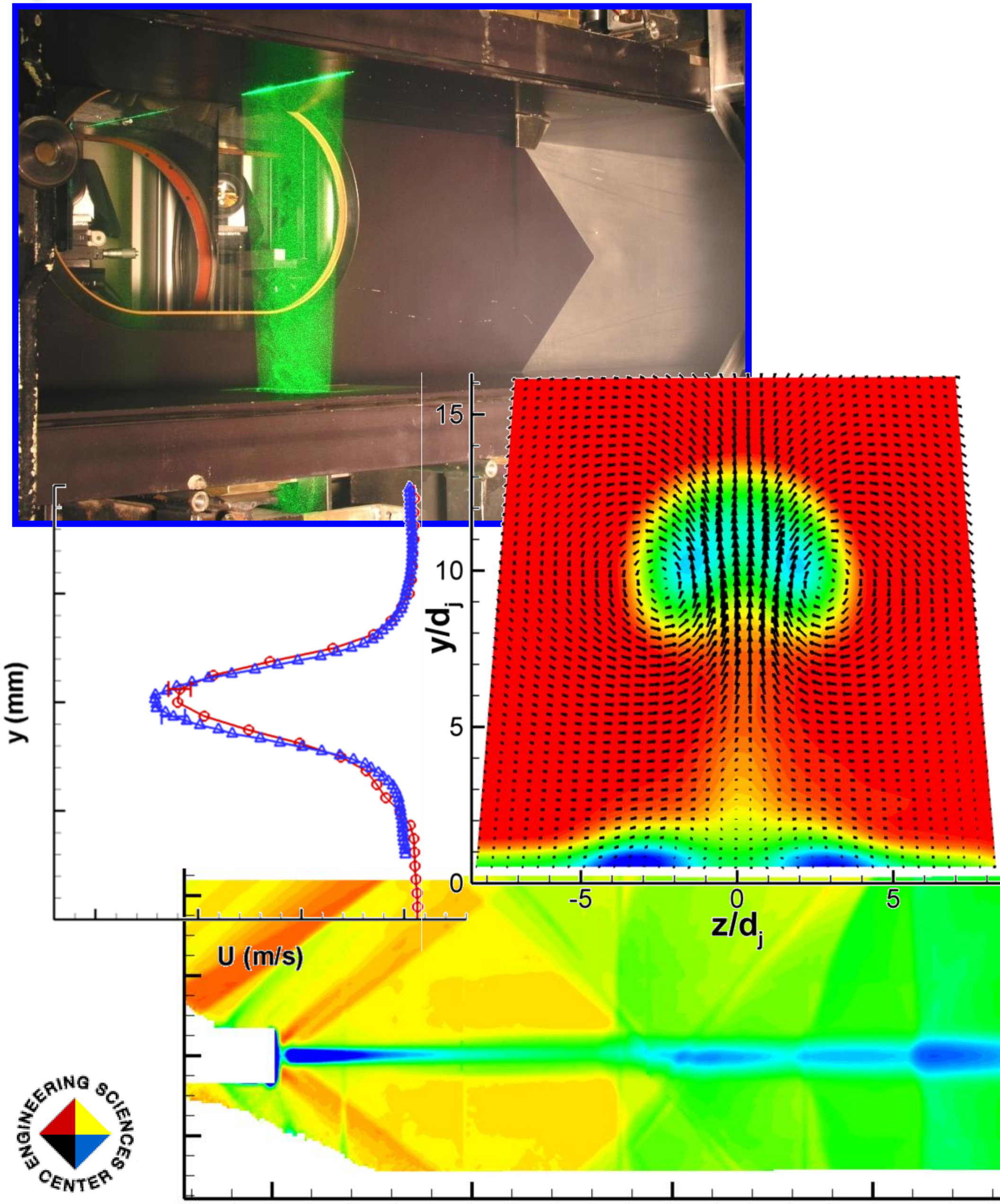




The goals of each experiment determine which uncertainties are important.

An understanding of the nature of the biases may inspire a means of overcoming them.

A Few Concluding Thoughts



A daunting list of bias errors may be present in PIV data.

- They affect different experiments in varied ways.

We have used complementary measurements to identify bias errors.

- But we've learned little about using them to quantify the uncertainties.

Even long established and well understood measurement techniques have many potential biases.