SAND2014-2603P

Improving Data Quality in Particle Image Velocimetry Experiments in a High-Speed Wind Tunnel

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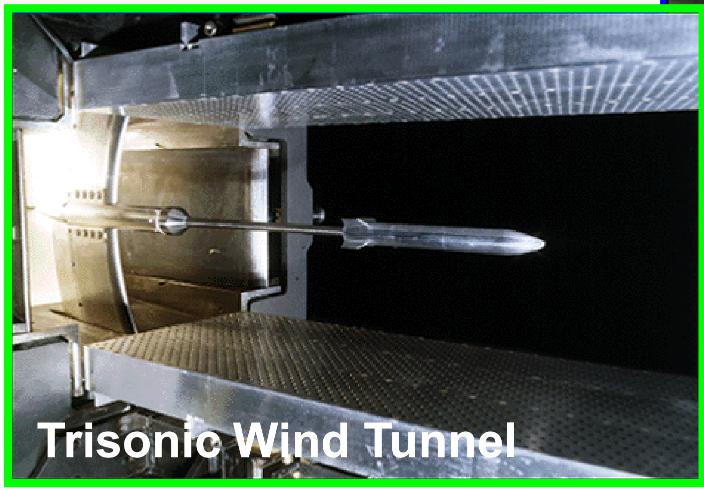
Sandia National Laboratories
Albuquerque, NM

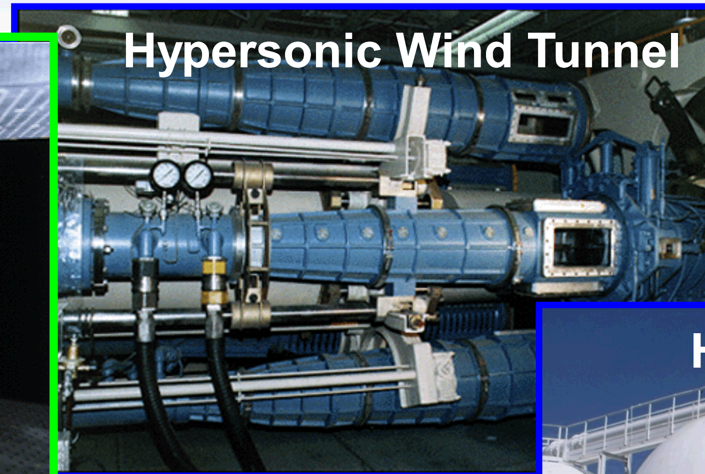
Purdue University Seminar
March 31, 2014
West Lafayette, IN

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.

SOMETIMES I FEEL THAT THE PURPOSE OF MY LIFE
IS ONLY TO SERVE AS A WARNING TO OTHERS.

Experimental Aerosciences Facility





Trisonic Wind Tunnel (TWT)
- Mach 0.5 – 3
- Gravity bombs, missiles

Hypersonic Wind Tunnel (HWT)
- Mach 5, 8, 14
- Re-entry vehicles, rockets

High-Altitude Chamber (HAC)
- Satellite components

Multi-Phase Shock Tube (MST)
- Explosives research

PIV is well-suited to use in the TWT

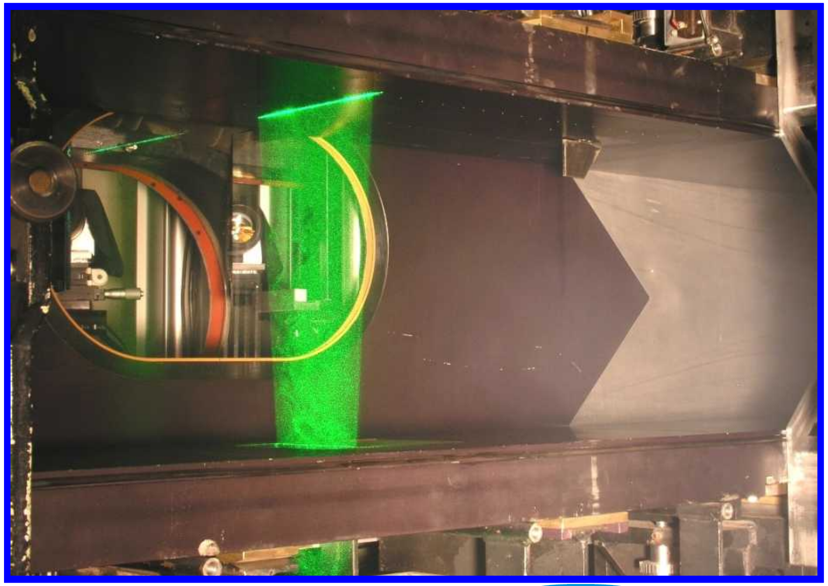
Trisonic Wind Tunnel (TWT)

Technical Characteristics

- Blowdown to atmosphere
- M_∞ = 0.5 - 1.3, 1.5, 2.0, 2.5, 3.0
- Re = 3 - 20 × 10^6 /ft
- Run times: 20 - 120 seconds at 20 - 30 minute intervals
- 12 × 12 inch test section
- ~1 inch diameter model size

Transonic Test Section

- Multiple configurations
  - 4 porous walls
  - 3 porous & 1 solid wall (half-body models)
  - 2 porous walls, 2 solid walls (imaging)
  - 4 solid walls — **PIV Configuration**
- Test section enclosed in pressurized plenum



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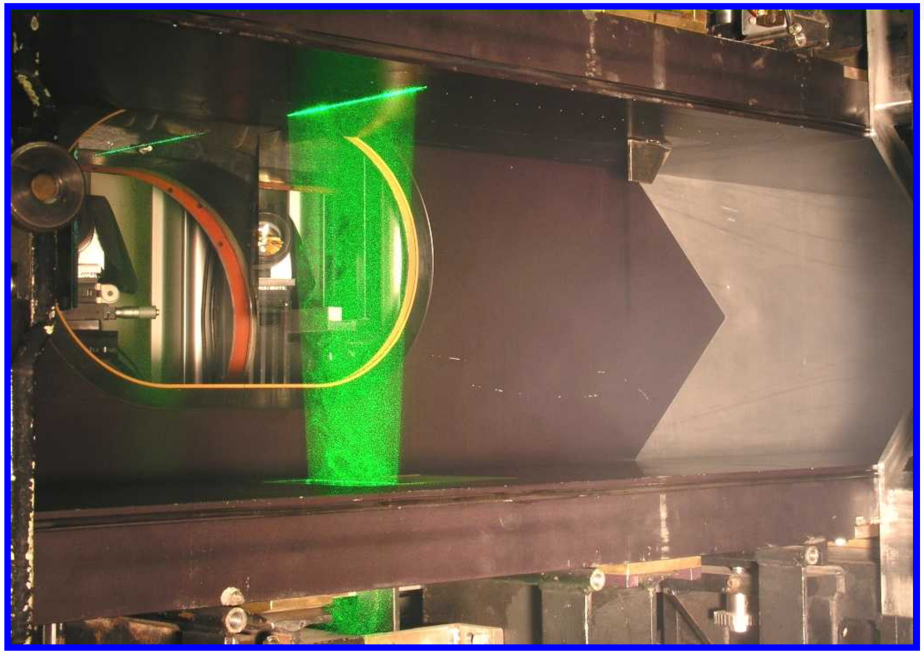
Much of our focus in our laboratory is on advanced diagnostics.

Data acquisition ~1950



Data acquisition ~21st century

Experimental data are necessary to develop and validate Sandia's modeling and simulation capability.

- Provide scientific discovery as well as validation data.

High-fidelity flowfield data are needed, not just aerodynamic coefficients and surface measurements.

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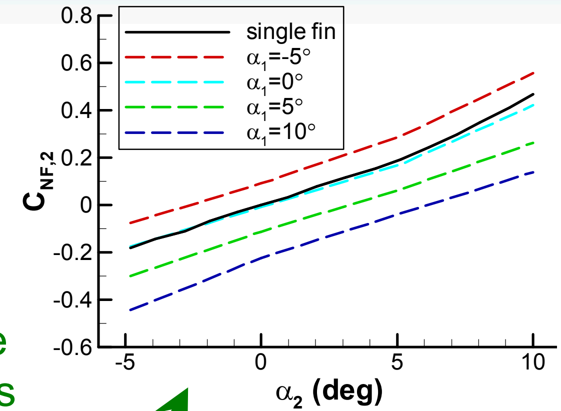
We have used PIV to study the interaction between a trailing vortex and a downstream fin.

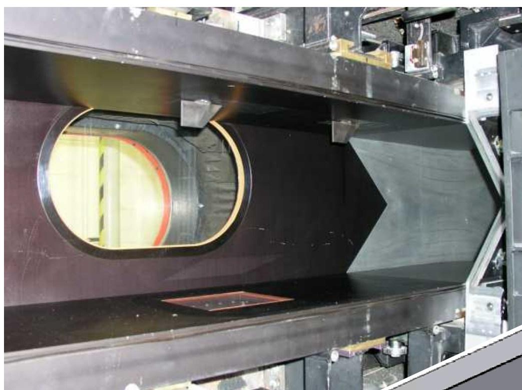
Many modern precision guided weapons use two sets of control surfaces.

Trailing vortices shed from the upstream fins can interact with downstream fins and dramatically alter aerodynamic control.

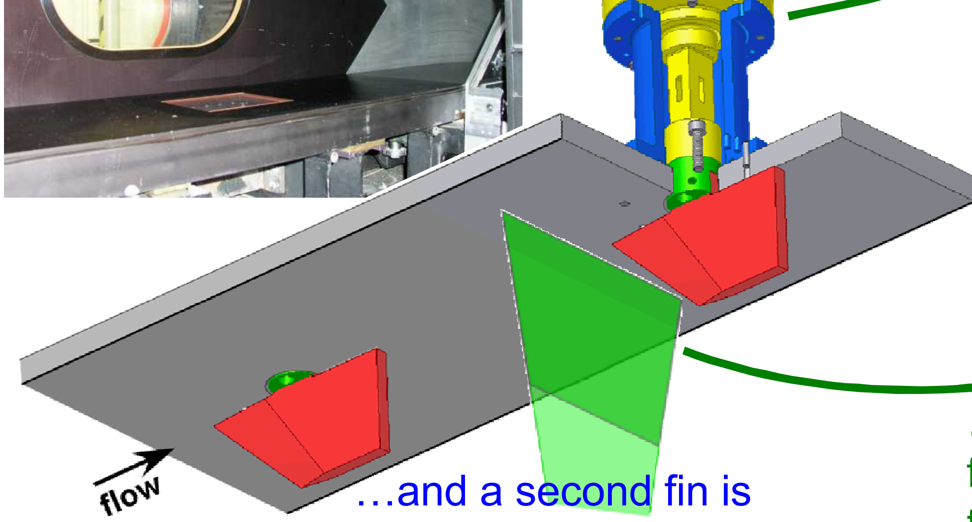
We have conducted a sub-scale experiment in which one wall of the wind tunnel represents the vehicle surface.



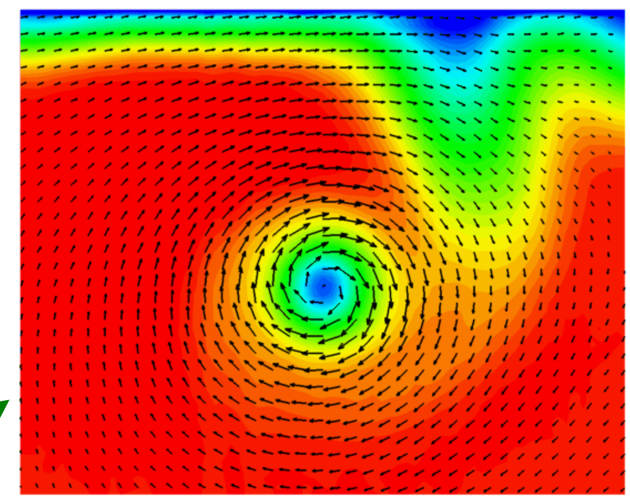
The balance measures the aerodynamics of the interaction...



A fin balance is behind one test section wall…

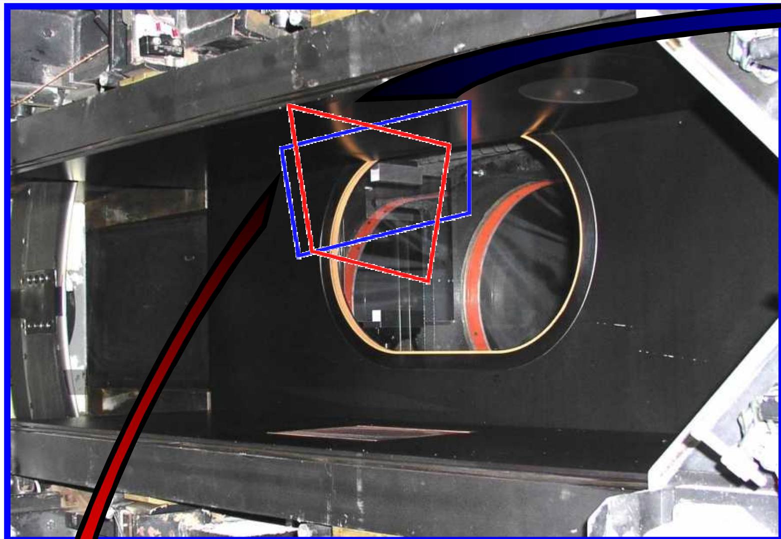


…and a second fin is mounted upstream.

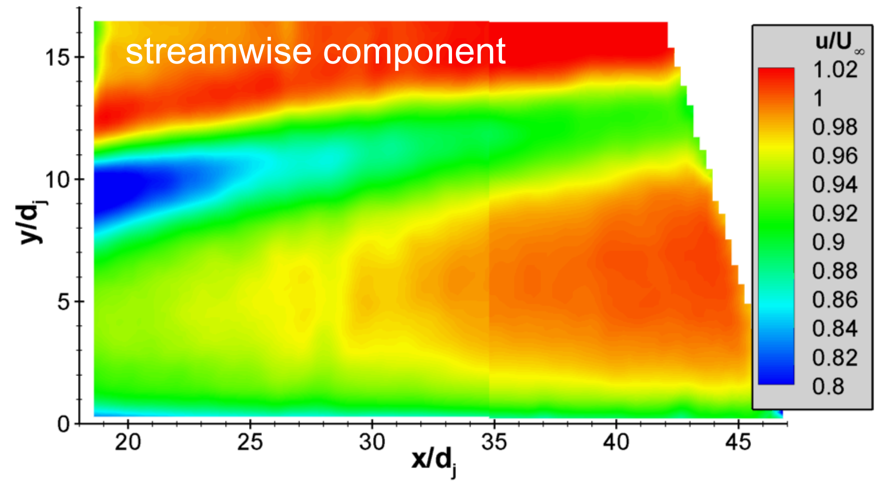


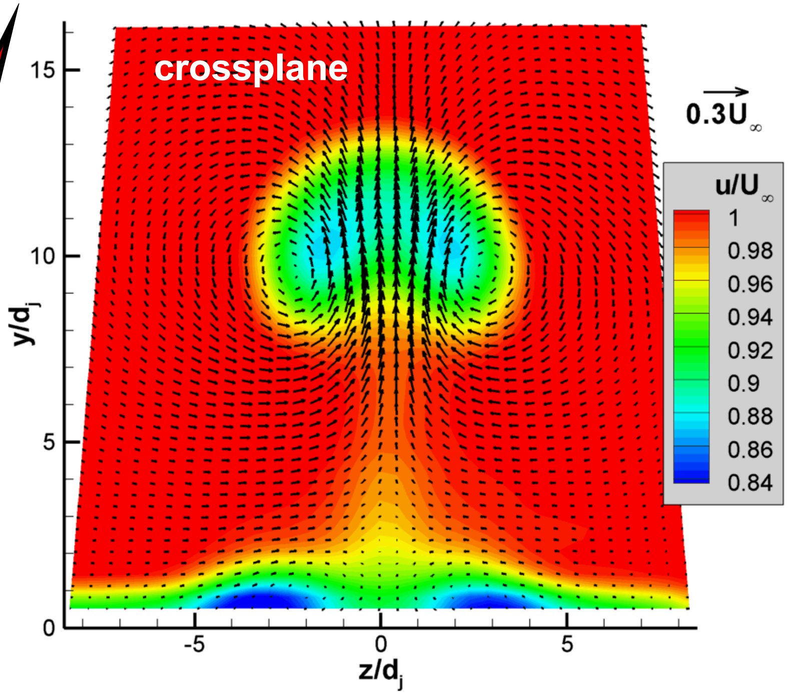
…and PIV measures the fin tip vortex responsible for the altered aerodynamics.

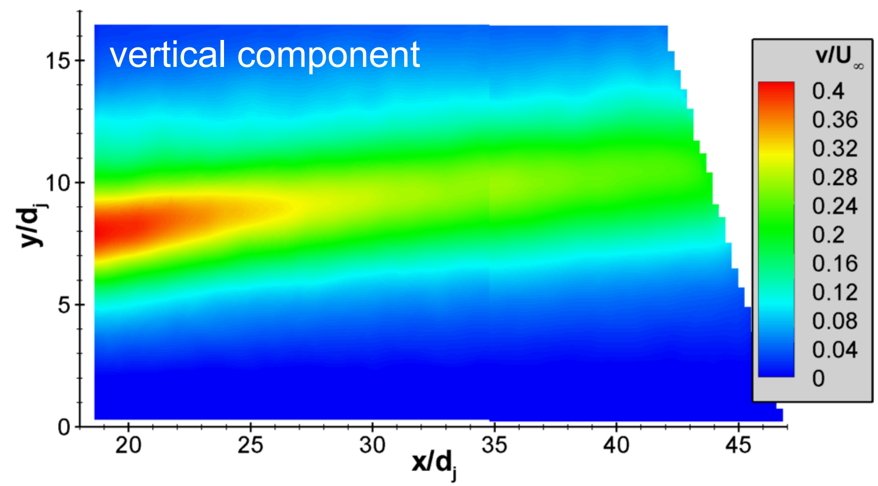
We have used PIV for a jet-in-crossflow experiment in support of a maneuvering rocket design.



streamwise plane







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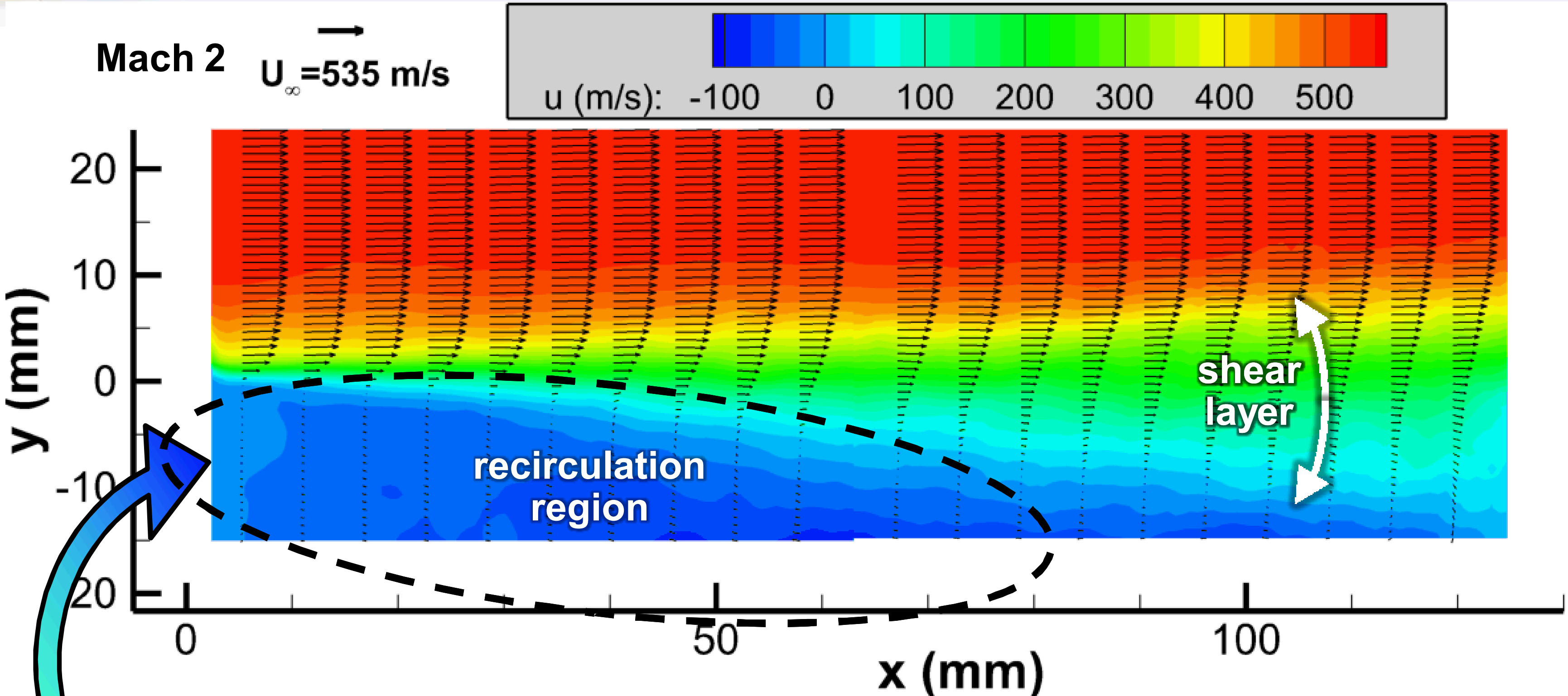
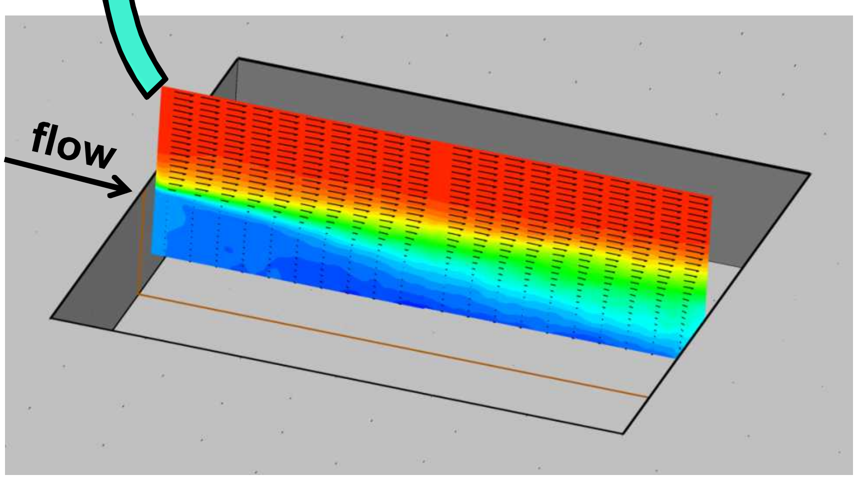
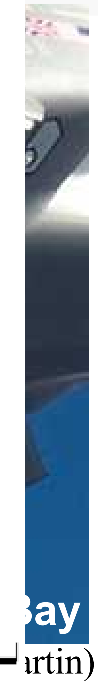
PIV measures the flow a store flies through as it is released from a weapons bay.



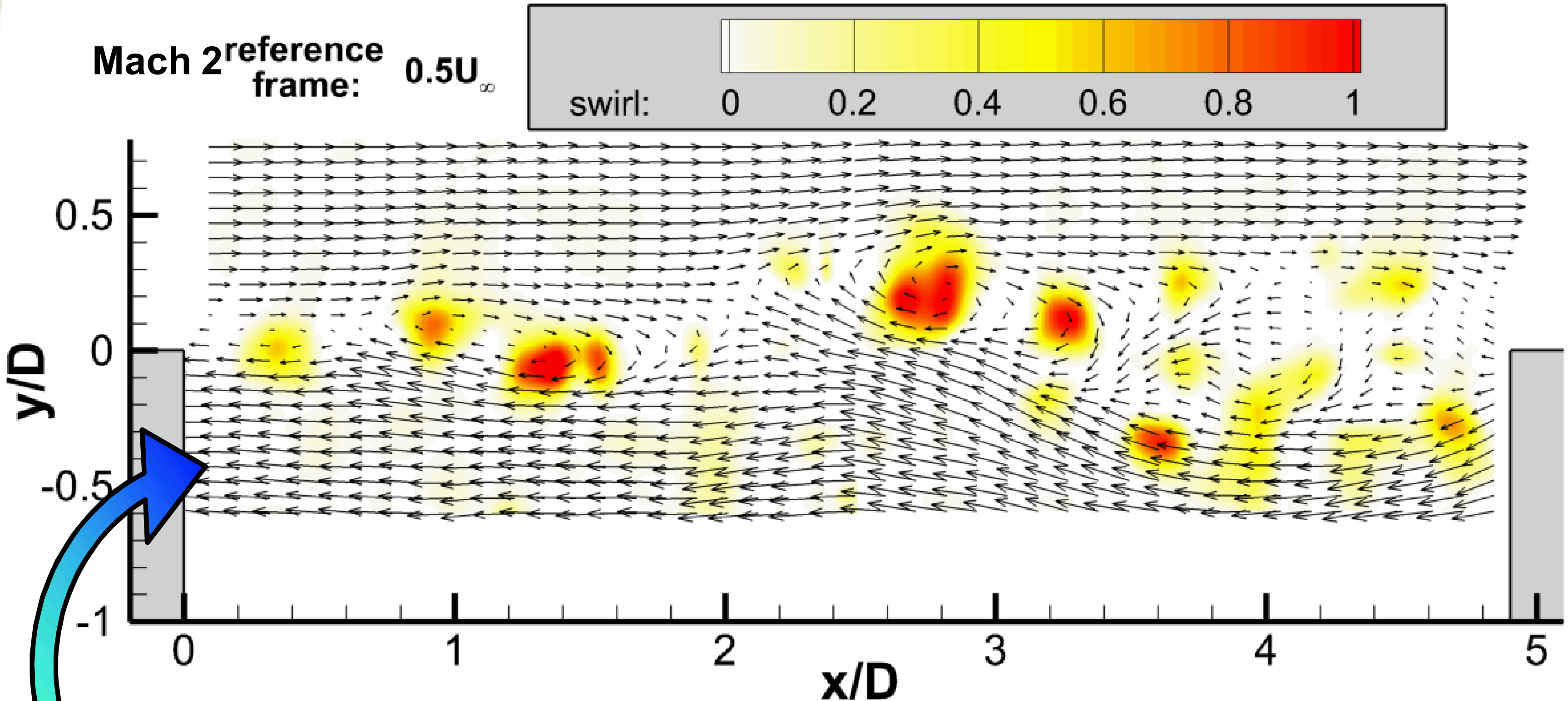


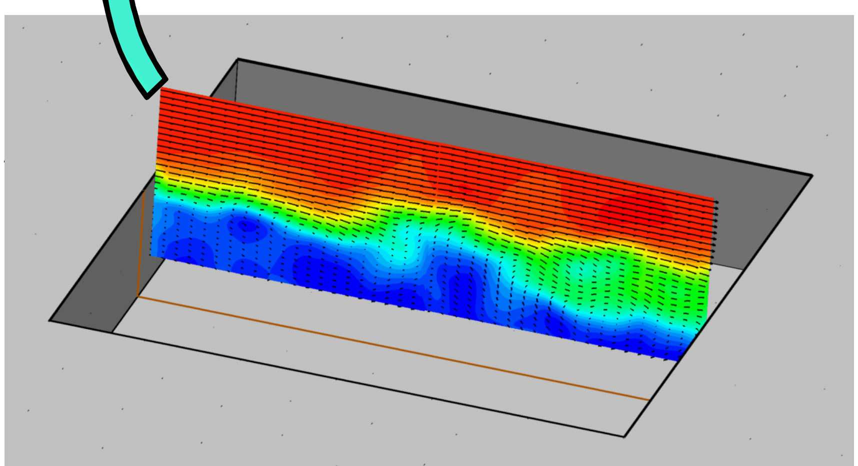


The shear layer that forms over the weapons bay tends to cause a store to pitch up into the aircraft on release.

These data help us predict store separation and design weapons bay geometries with reduced impact on the store trajectory.

PIV measures the flow a store flies through as it is released from a weapons bay.



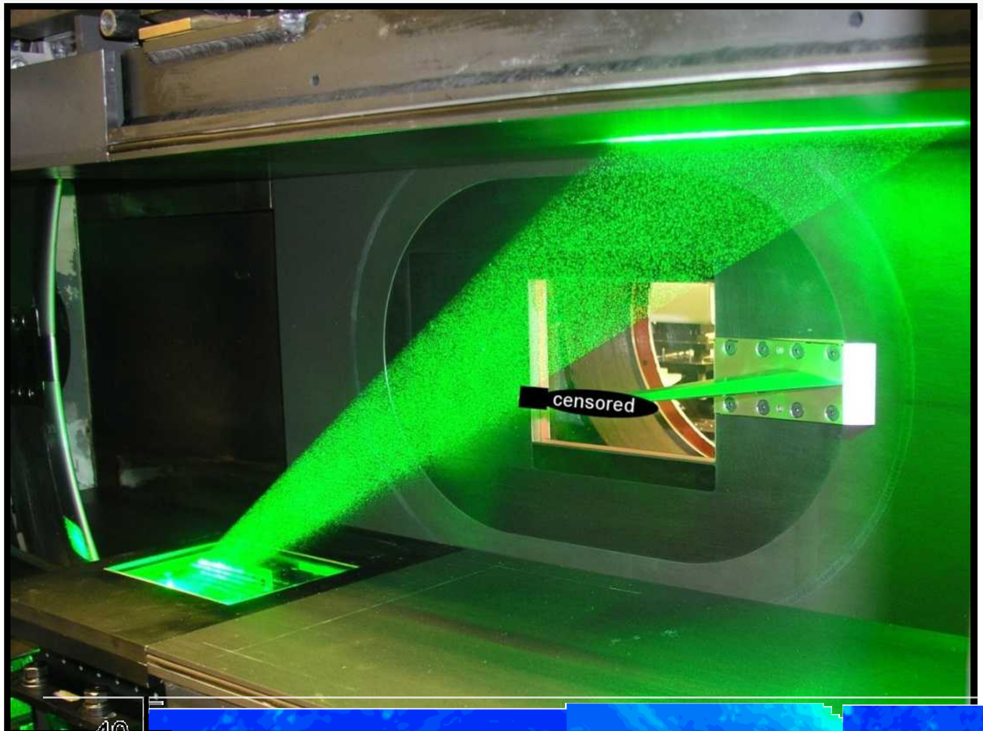


We also can view a snapshot of the instantaneous velocity field.

With some additional data processing, we can identify turbulent eddies responsible for store vibration and acoustic loading.

geometries with reduced impact on the store trajectory.

We have used PIV for aero-optical applications as well.



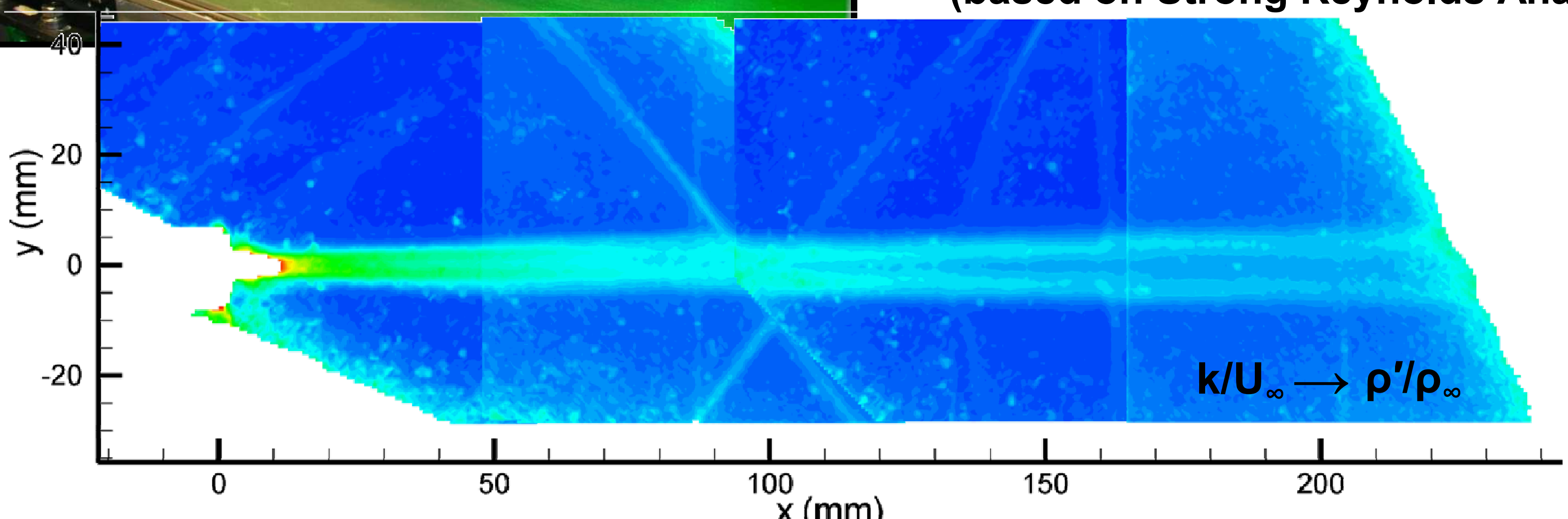
Use PIV to measure the wake growth and turbulence of a missile body.

An optical link is designed between the missile aft body and the release aircraft.

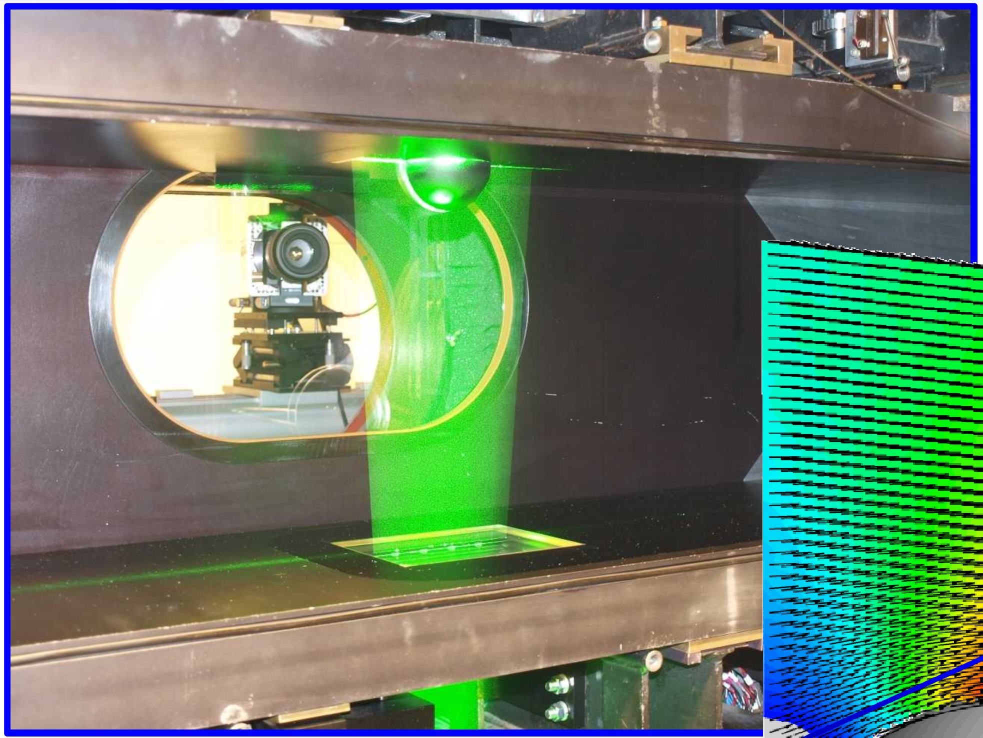
Beam dispersion due to the turbulent wake of the missile.

PIV provides turbulent kinetic energy, which can be converted to density gradients.

(based on Strong Reynolds Analogy)

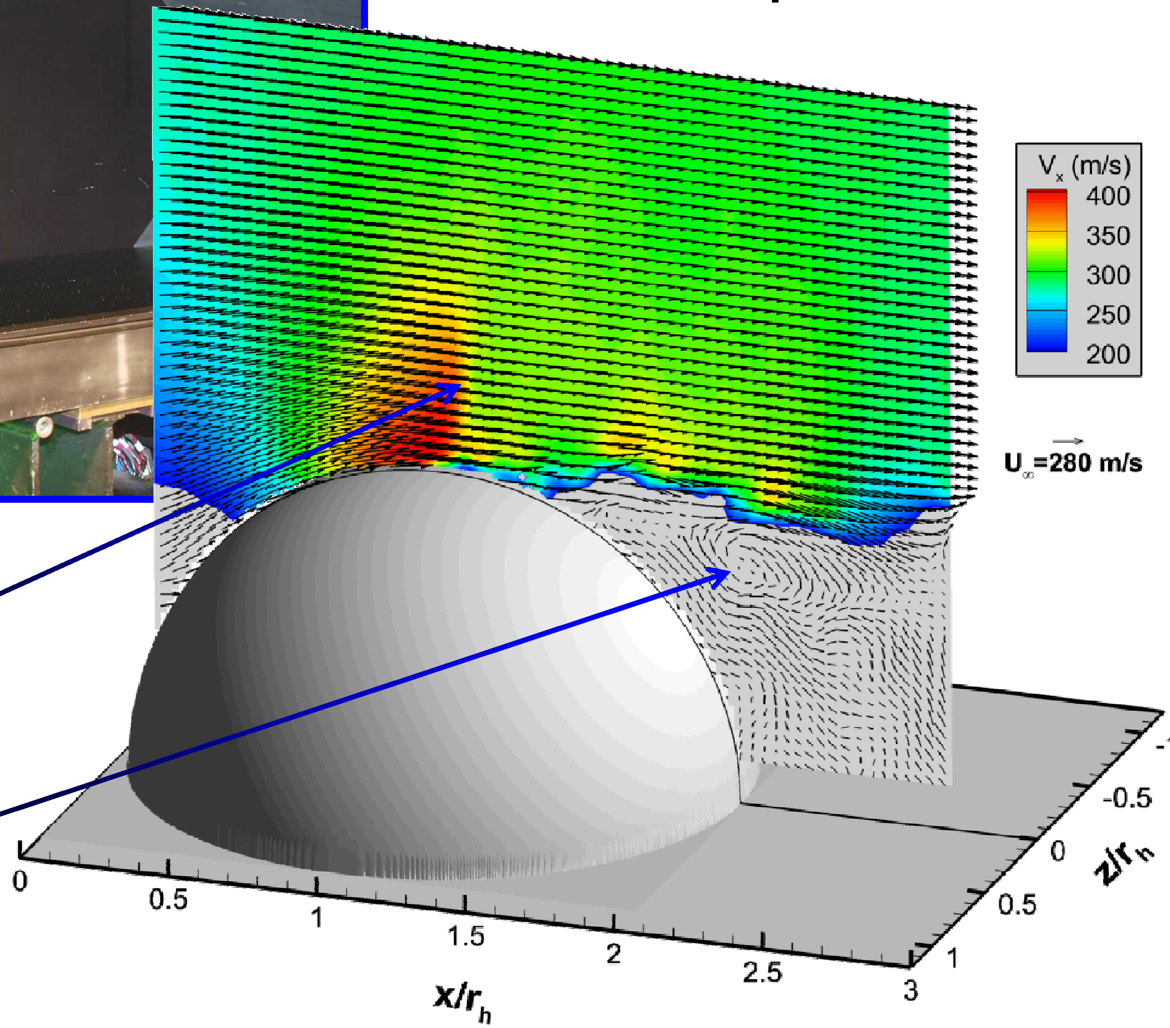


The same approach can be used for an aero-optical turret.



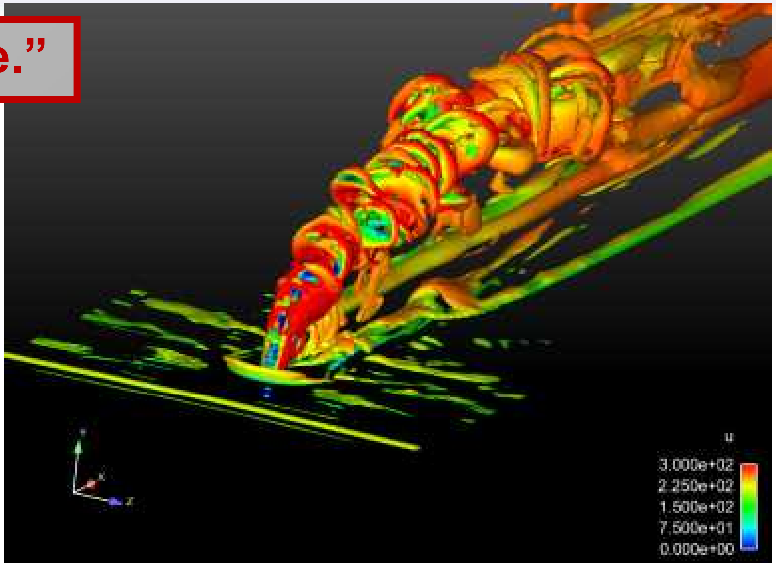
Shown here is a simple hemispherical representation of a turret.

Data can help design complex turrets to reduce aero-optical distortion.



PIV Data for CFD Validation

"Without validation, CFD is just a video game."



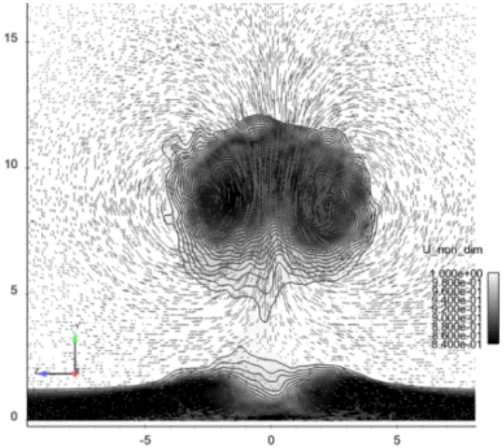
The physical models in our CFD codes must be shown to produce accurate results before we may use them to design flight vehicles.

Our PIV experiments provide key validation data.

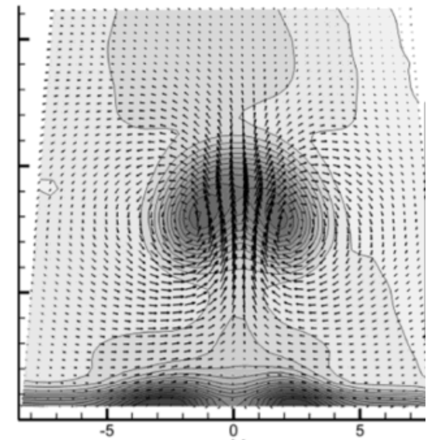
Validation data requires uncertainty quantification.

How can we be confident in the accuracy of our PIV data?

Our ability to make complicated PIV measurements has outpaced our ability to quantify their uncertainty.



Hybrid RANS-LES / DES of Jet-in-Crossflow



PIV data of Jet-in-Crossflow

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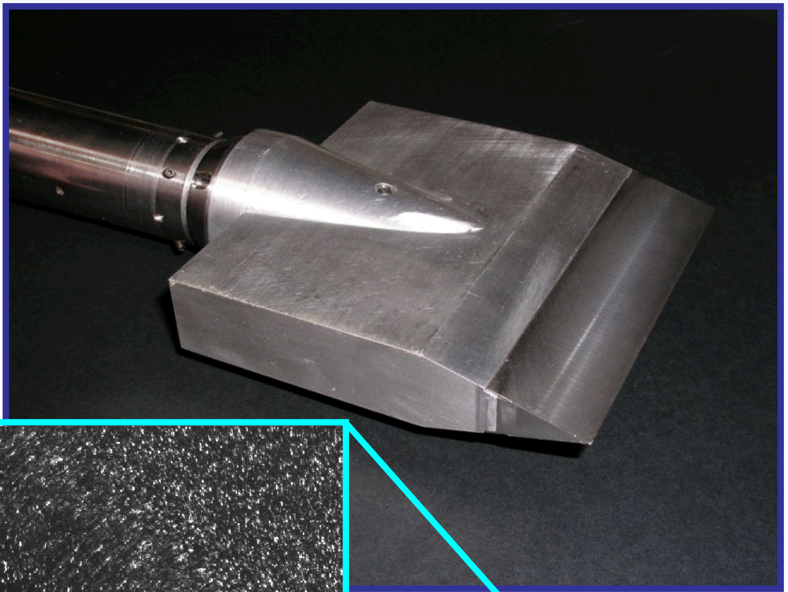
How quickly do the particles respond to velocity gradients?

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

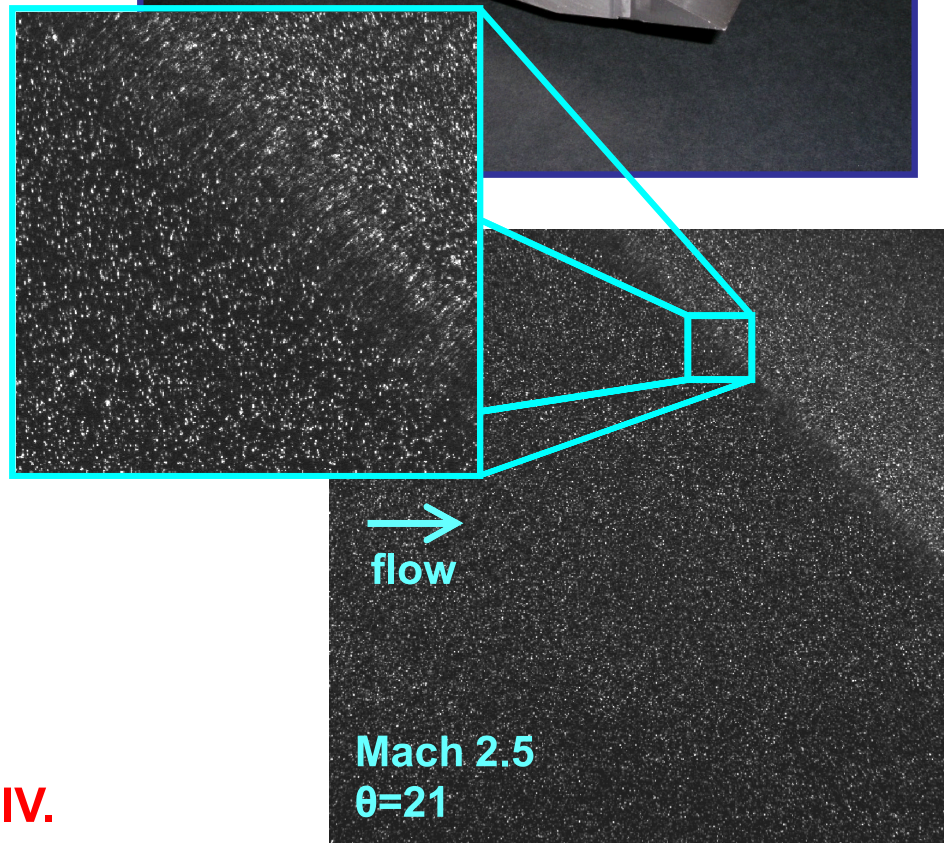
Stokes' drag applies to small particles:

$$\tau_p = \frac{d_p^2 \rho_p}{18\mu}$$

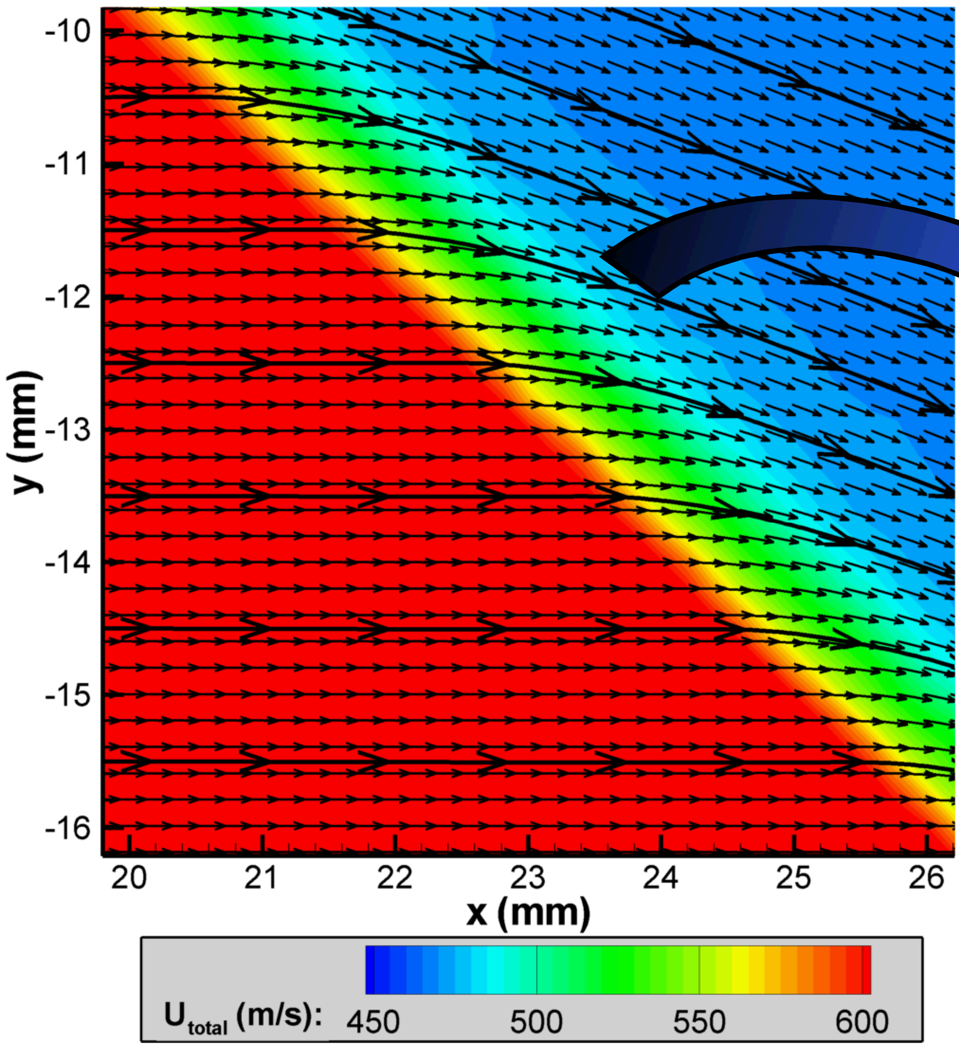
$$x_p = \tau_p \left[u_1 - u_p(t) - u_2 \ln\left(\frac{u_p(t) - u_2}{u_1 - u_2} \right) \right]$$

τ_p defined where $u_p(t)$ reaches 63% of Δu

These all are measured by PIV.



Particle Response



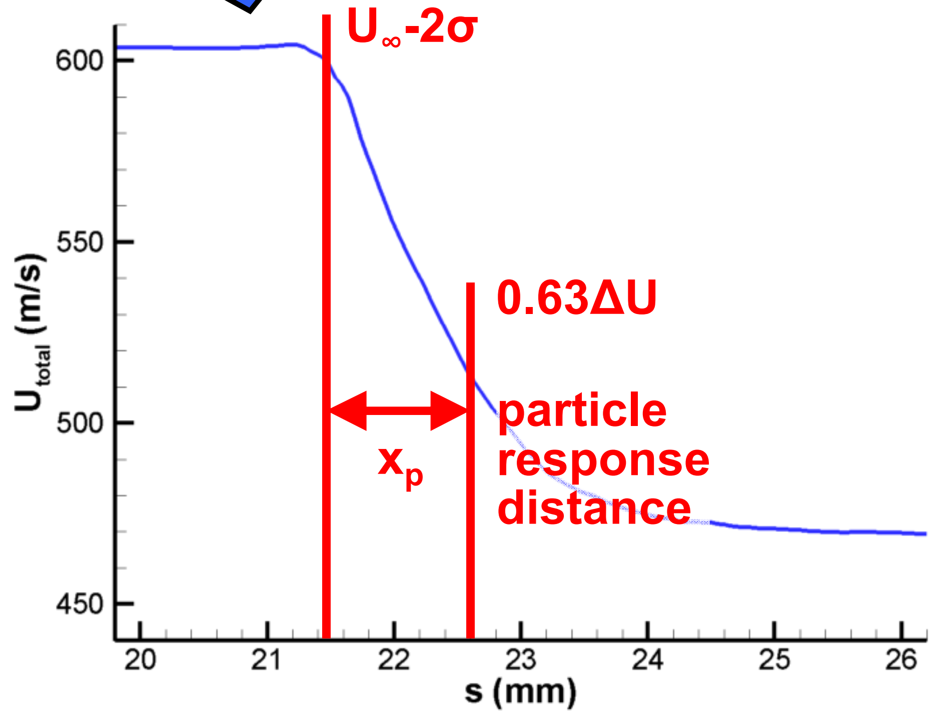
Particle characteristics:

x_p = 1.1 mm

τ_p = 2.0 μs

d_p = 0.76 μm

Extract velocities along a streamline



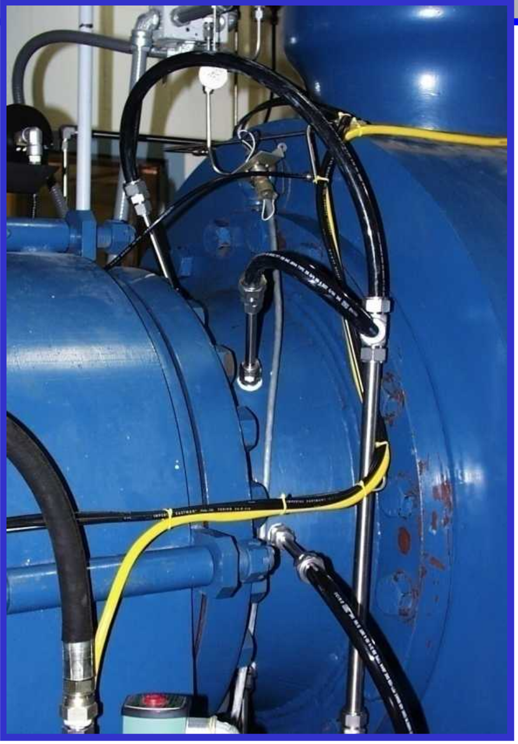
Over a range of Machs and shock angles:

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.

But what is du/dx really?

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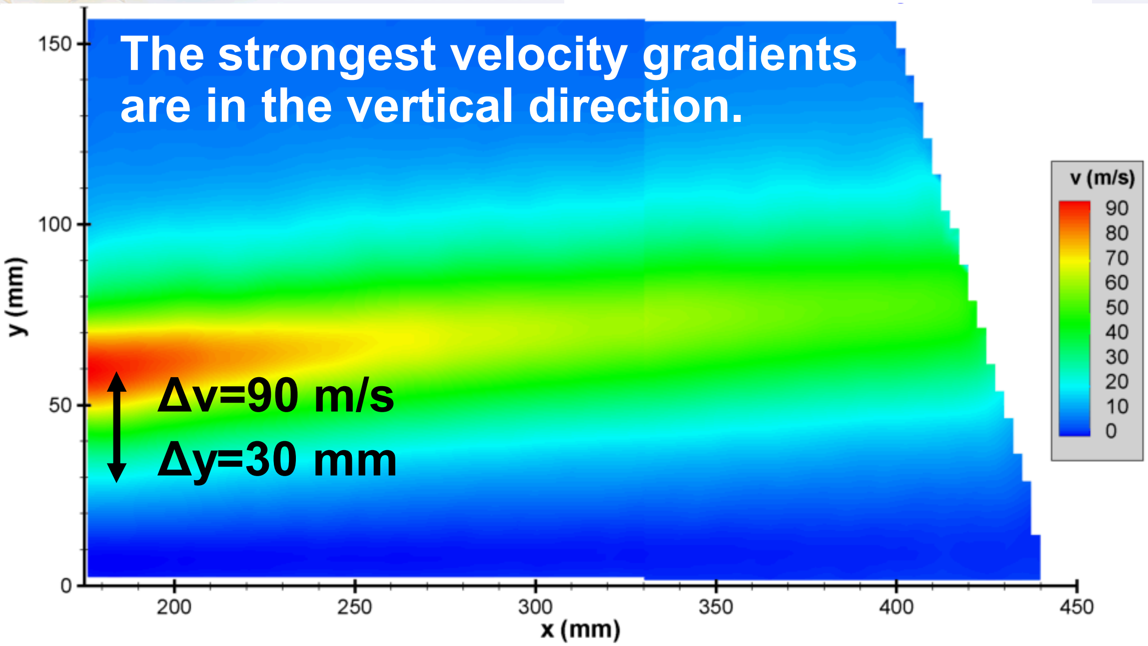
What is the Velocity Gradient in a Real Experiment?



Typical approach:

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

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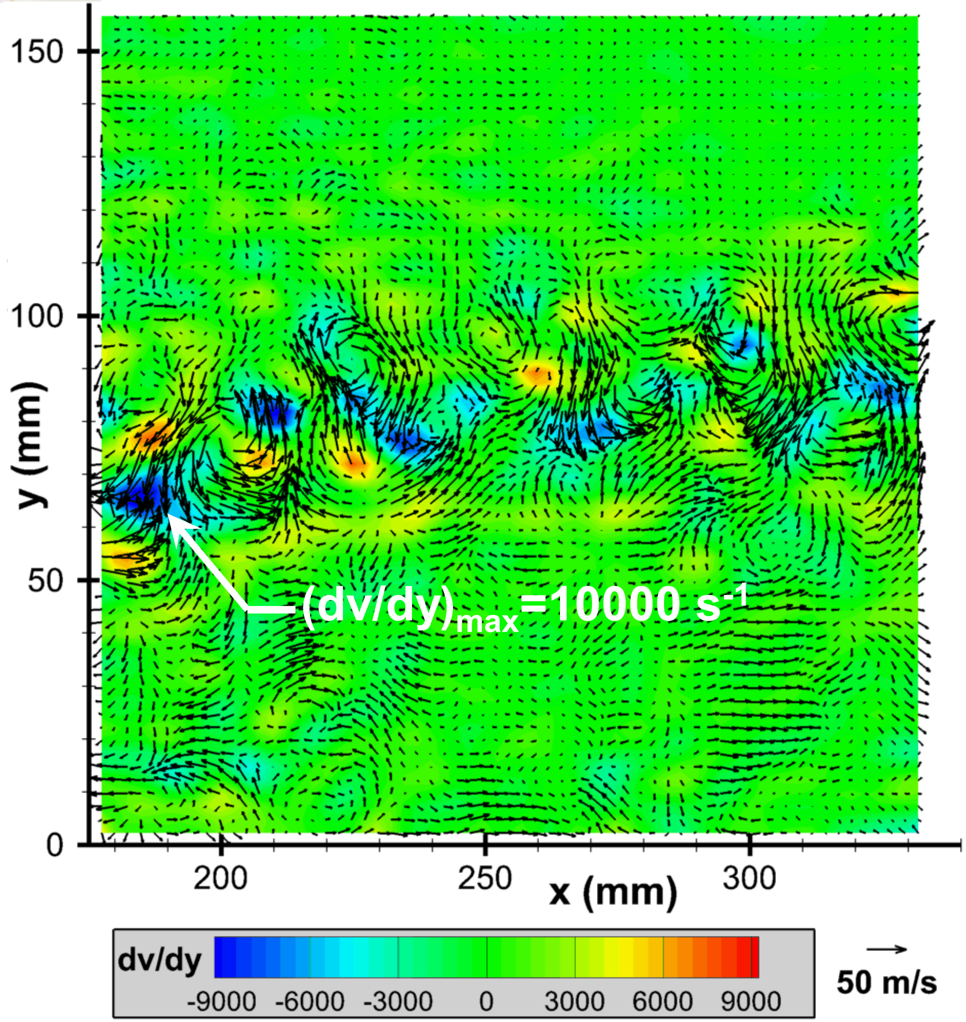
What is the Velocity Gradient in a Real Experiment?



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.

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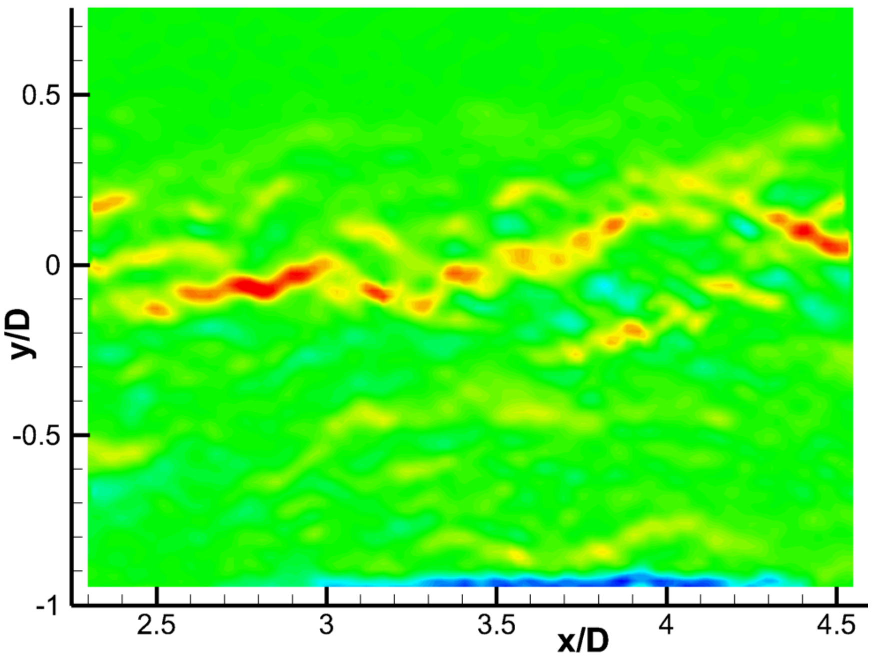
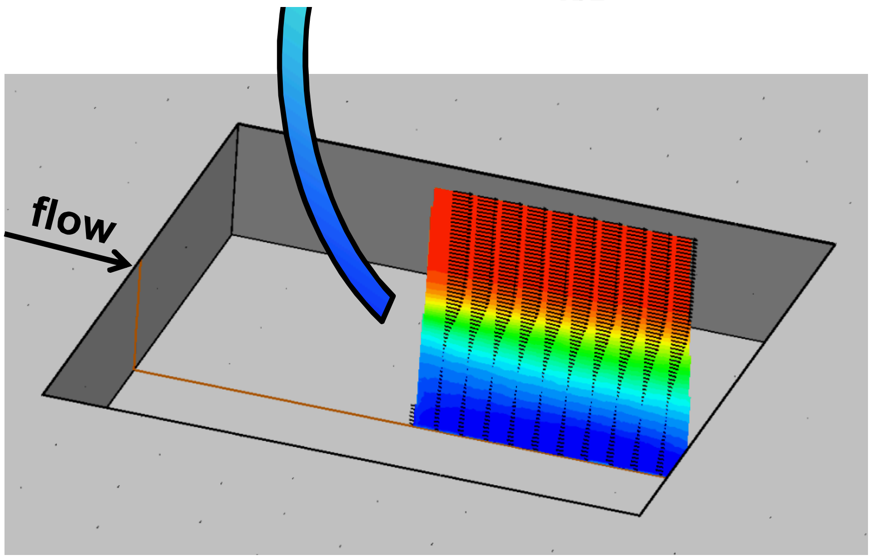
A Tougher Seeding Challenge





From the mean velocity field:

Δu = 730 m/s

Δy = 20 mm

→ Yields τ_f = 30 μs and τ_p / τ_f = 0.07.

Growing, but still good.

From the instantaneous data:

$(du/dy)_{max}$ = 350000 s^{-1}

→ Yields τ_f = 3 μs and τ_p / τ_f = 0.7.

Now particle lag error nears 1%.

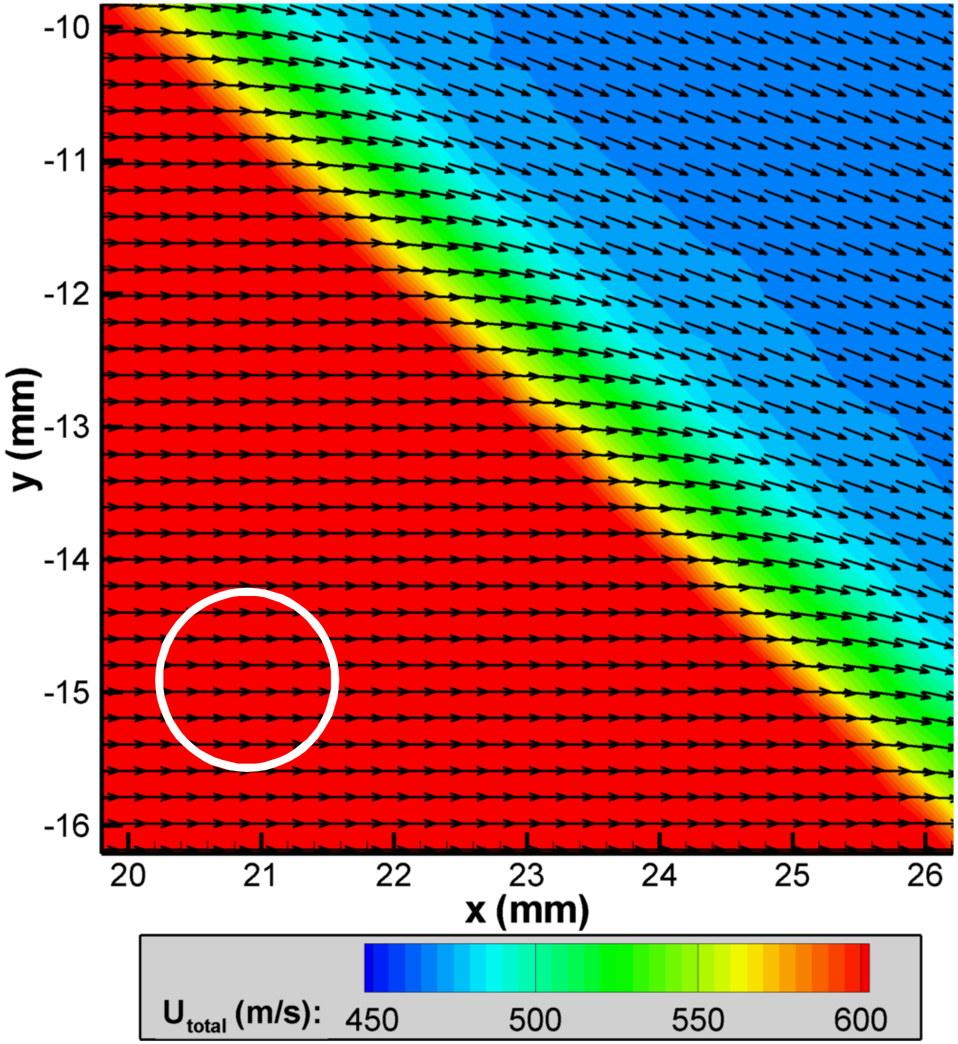
What if we were using solid particles rather than oil?

- Four times as dense

→ Yields τ_p / τ_f = 2 - 3.

This may be a problem.

Velocity Accuracy



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

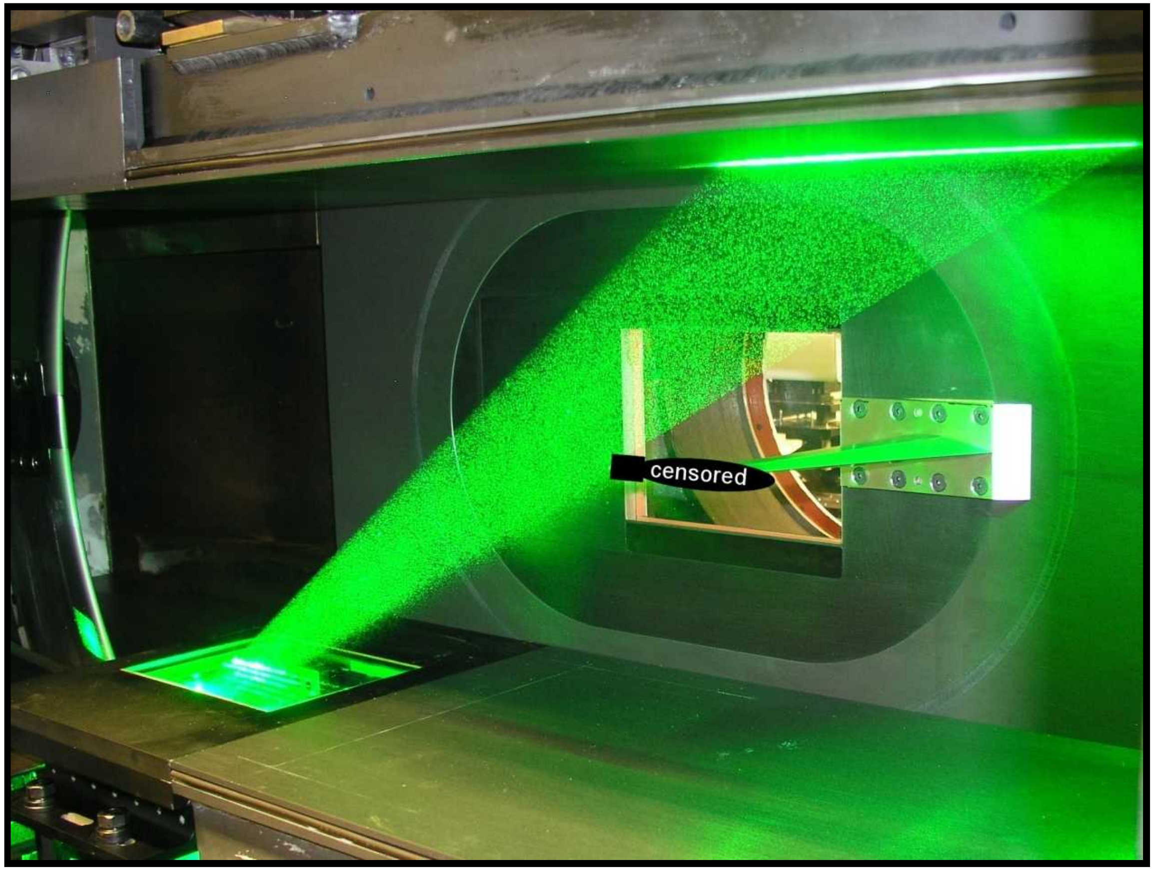
- Error < 1% for all Mach numbers.
- Shock angles and velocities within 0.3% of isentropic theory.

More error in Pitot probe than PIV!

Spatial Resolution of PIV

All measurements are subject to error due to spatial resolution limits.

How does this affect PIV data?



A good example can be found in 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.

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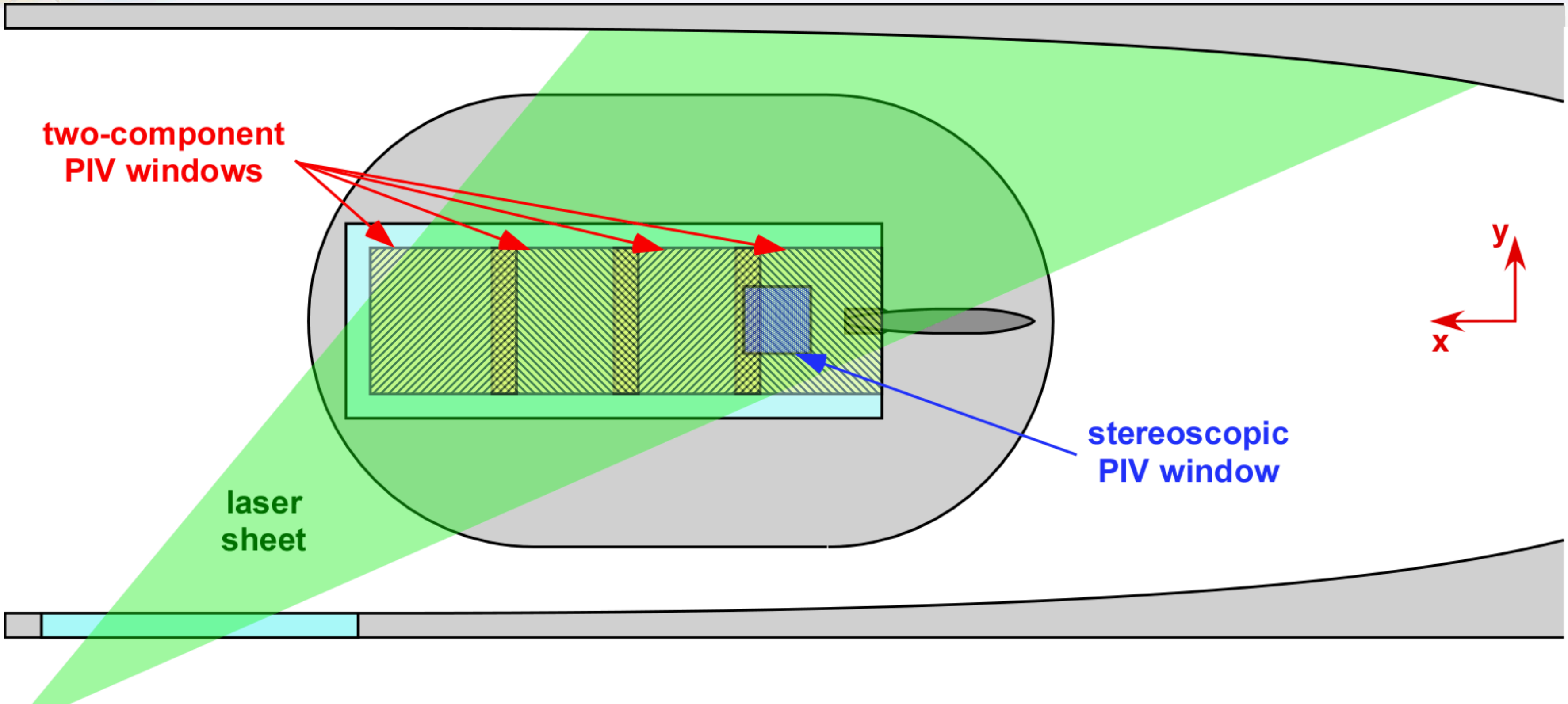
PIV Configuration

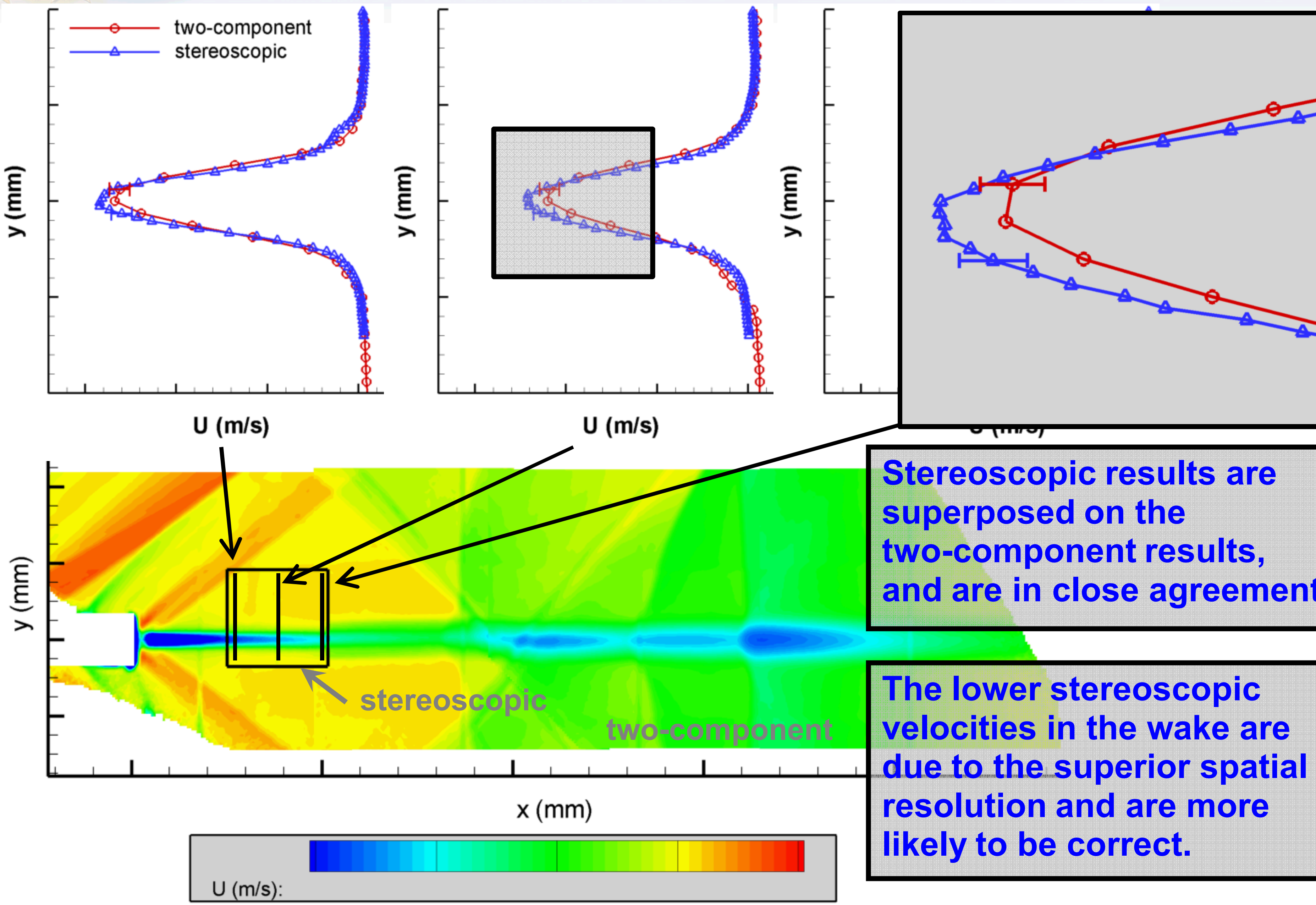


Capture the greatest extent of the wake by using four large imaging regions (two passes of two cameras operating simultaneously) to survey the wake.

- **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*.

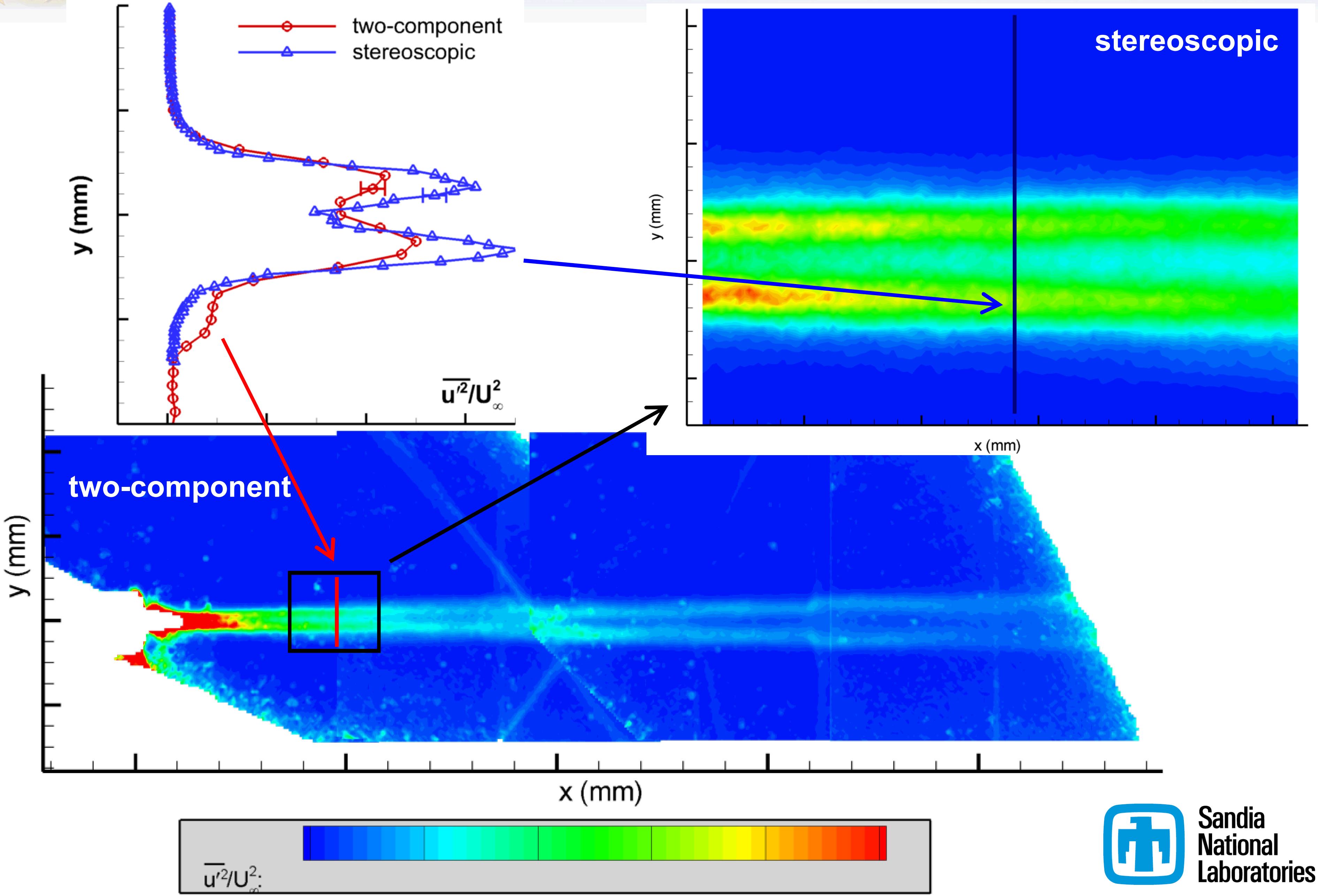
Spatial Resolution: Mean Velocity



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.

Spatial Resolution: Turbulence Intensity



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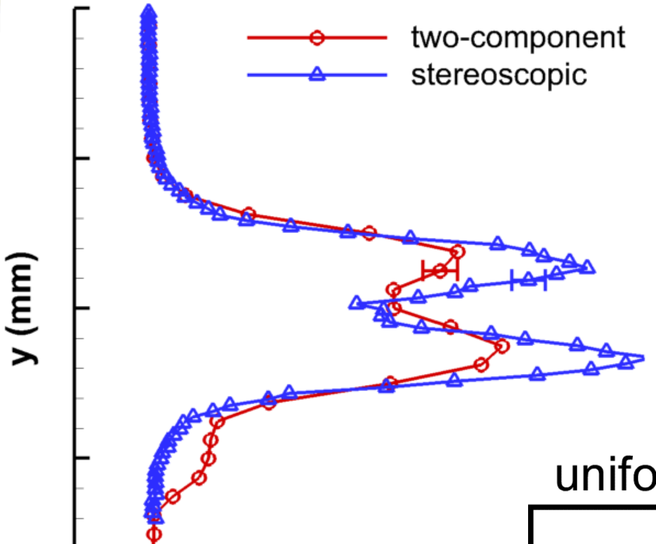
Spatial Resolution / Uncertainty in Turbulence Intensity



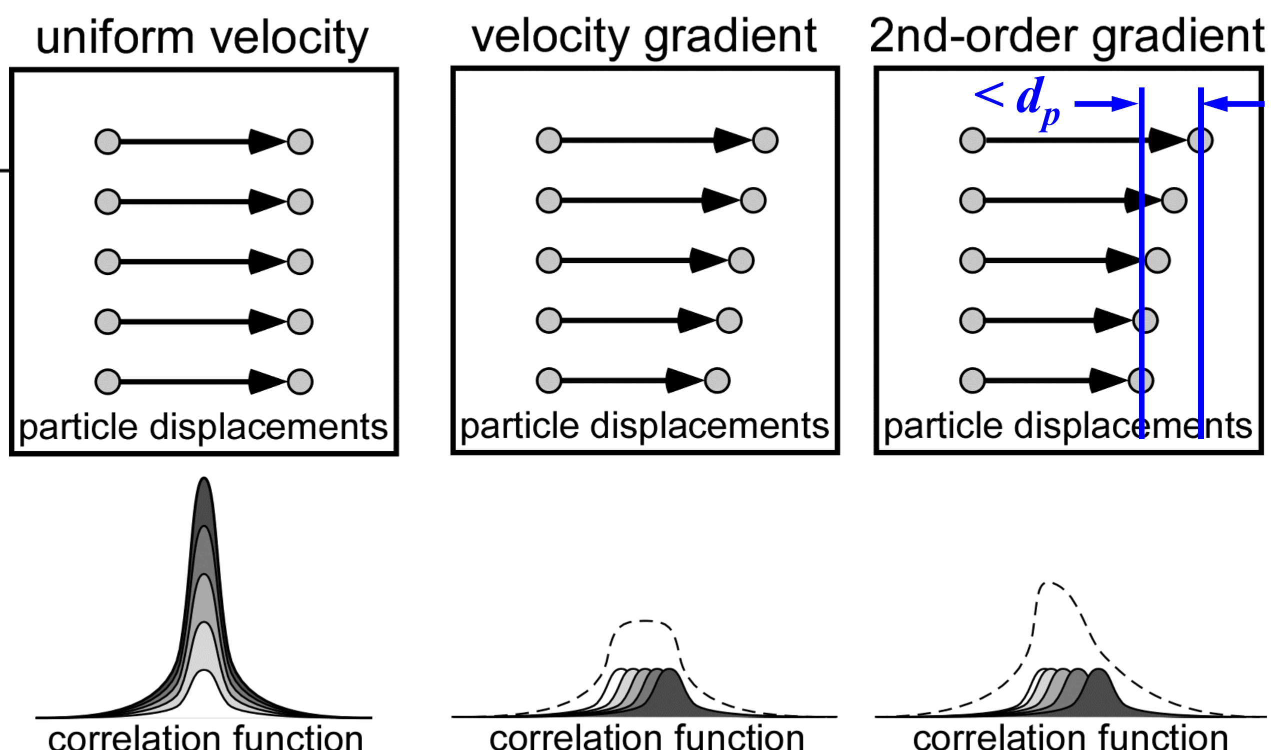
Poor spatial resolution suppresses turbulence intensity:

- Low-pass filtering the turbulence spectrum.
- PIV bias error by the group locking phenomenon.
  - Or, due to second-order velocity gradients.

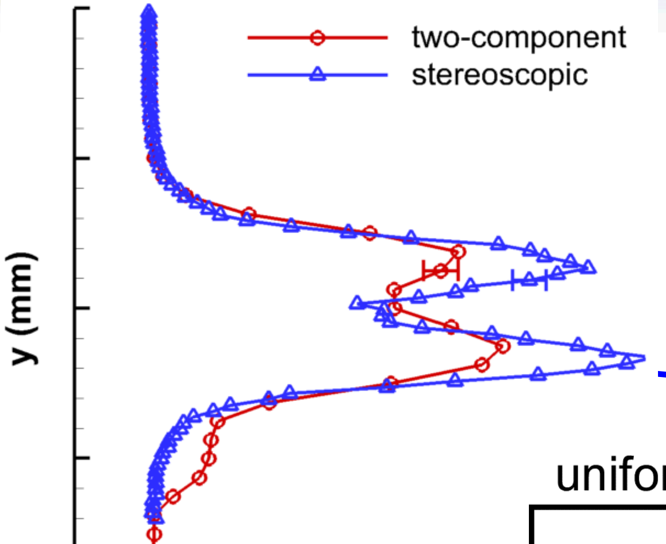
Advanced algorithms incorporating image deformation perform well treating velocity gradients.

Less successful for second-order velocity gradients.

Choose gradient less than particle image diameter.



Uncertainty in Turbulence Intensity



Poor spatial resolution suppresses turbulence intensity:

- Low-pass filtering the turbulence spectrum.
- PIV bias error by the group locking phenomenon.
  - Or, due to second-order velocity gradients.

Some bias error still remains in the superior spatial resolution of the stereo data.

- How do we estimate this?

Advanced algorithms incorporating image

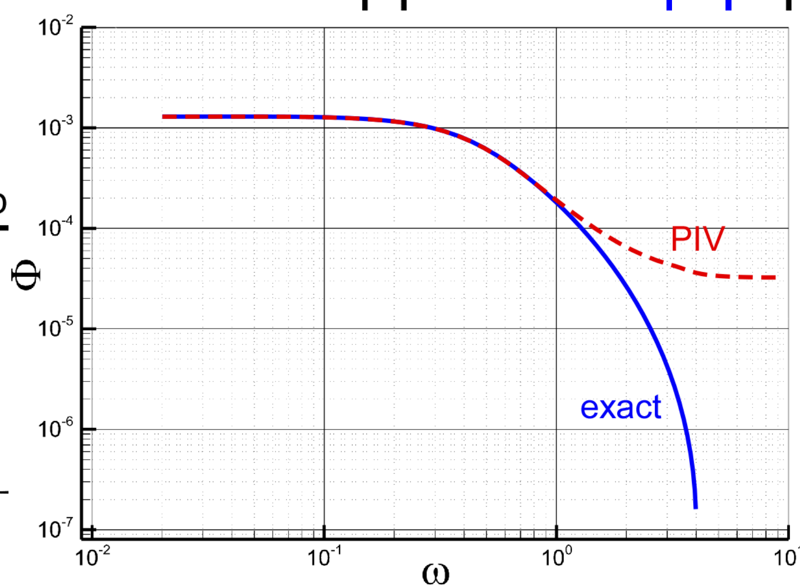
second-order

PIV spatial resolution limited to ~25 pixels.

- Regardless of size of interrogation window.
- Due to image warping and filtering algorithms.

Low-pass spatial filtering is unavoidable and unrecoverable.

- Must consider this in data analysis and comparison to computations.



Stereoscopic Calibration Uncertainty

For two-component PIV, this usually is trivial:

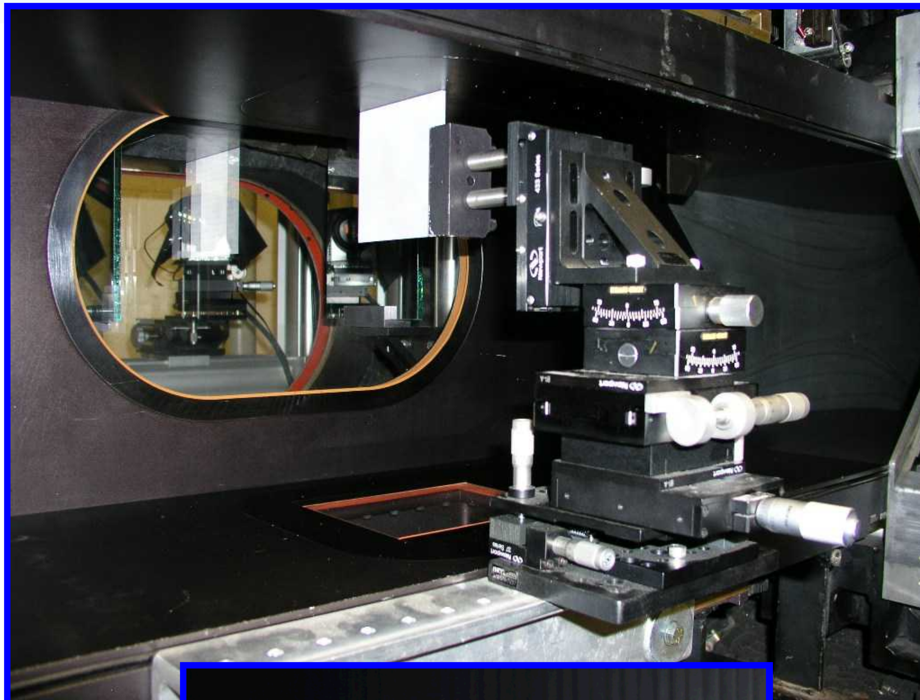
- **Simply image a ruler to obtain a mm-to-pixel conversion.**
- **Uncertainty generally is small.**

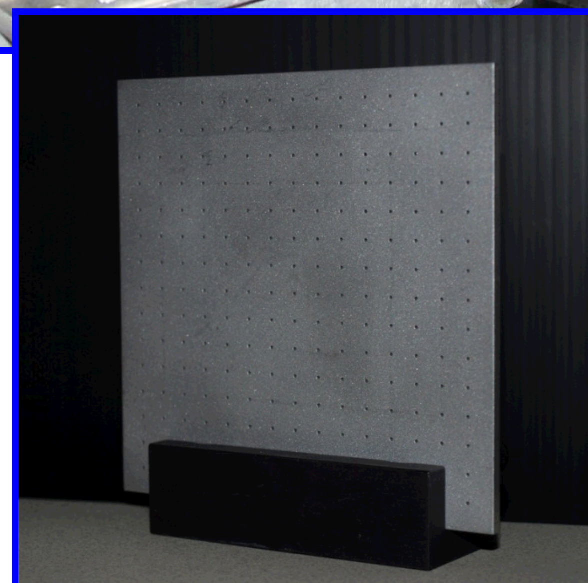
The chief source of stereo calibration error is widely believed to be image registration.

Studies claim target misalignment of 1 mm translation or 0.5 deg rotation cause *velocity errors exceeding 10%*.

Other experiences show that a careful alignment yields velocity errors of about 1-2%.

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





Stereoscopic Calibration Uncertainty

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

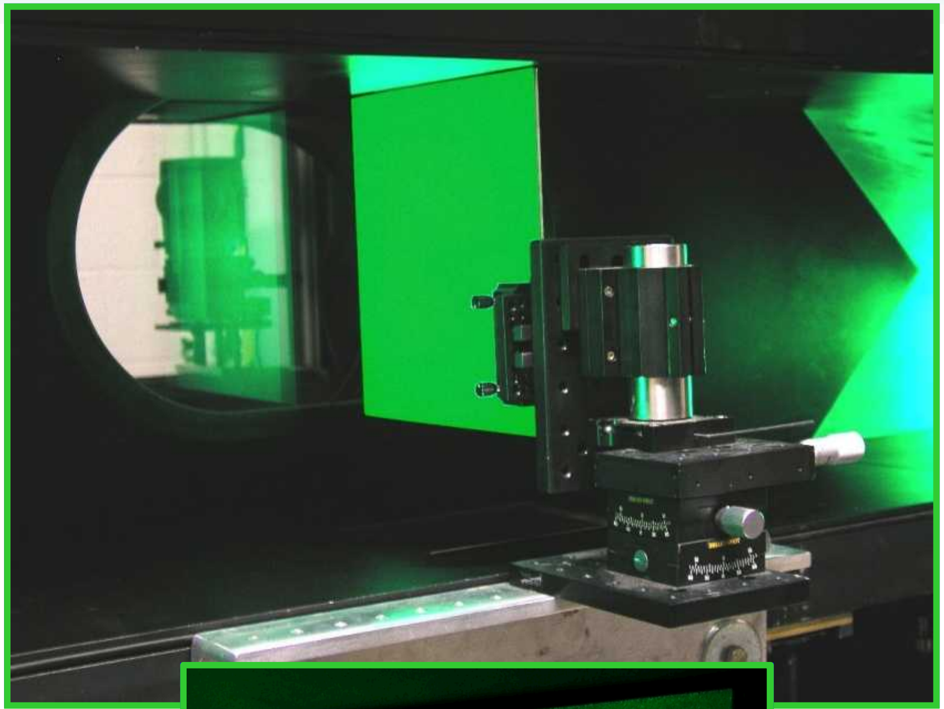
- Creates a speckle pattern upon which PIV software can correlate.

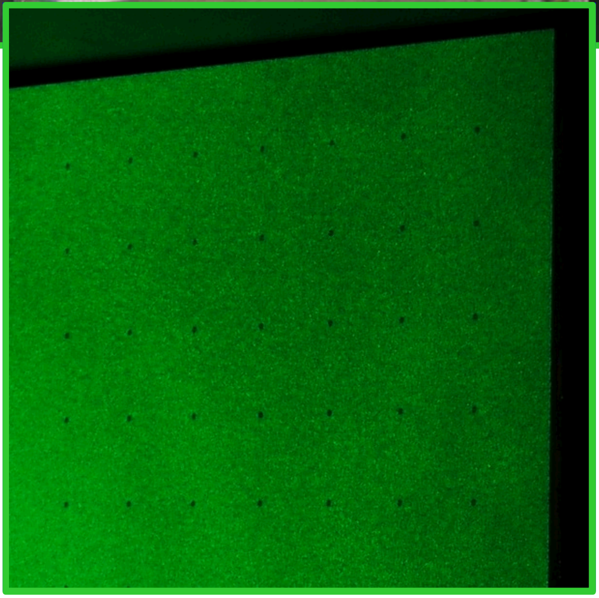
After calibration, leave the target in place.

- 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.



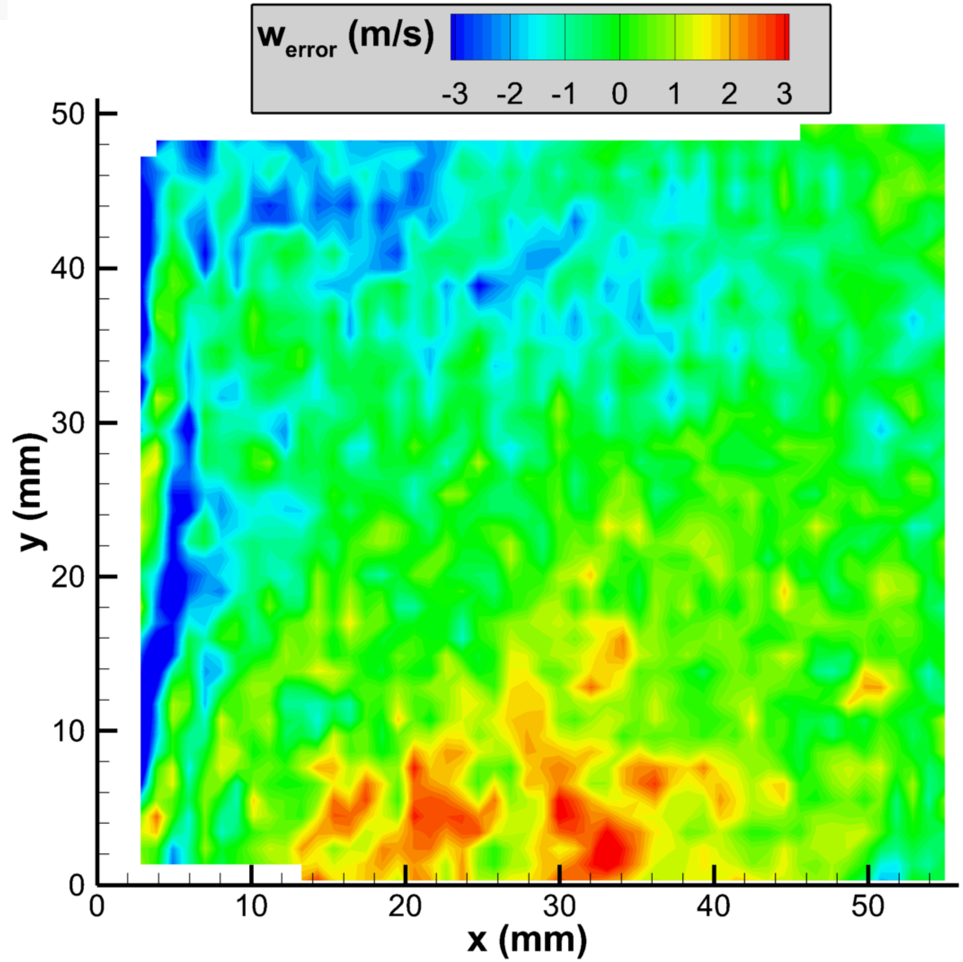


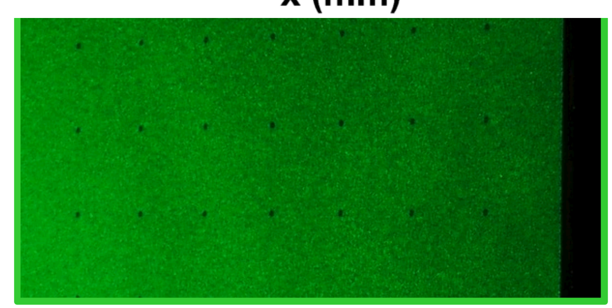
Stereoscopic Calibration Uncertainty

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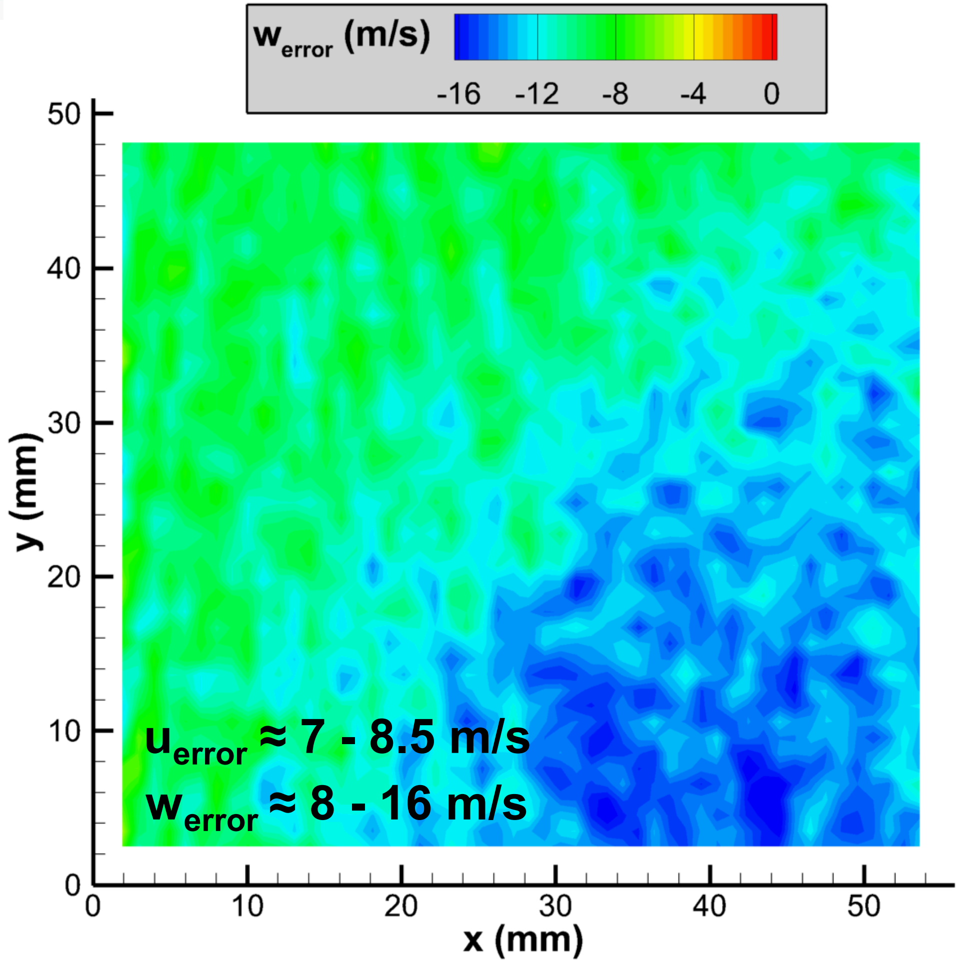
For this experiment, U_∞ = 450 m/s.
(< 1% uncertainty)

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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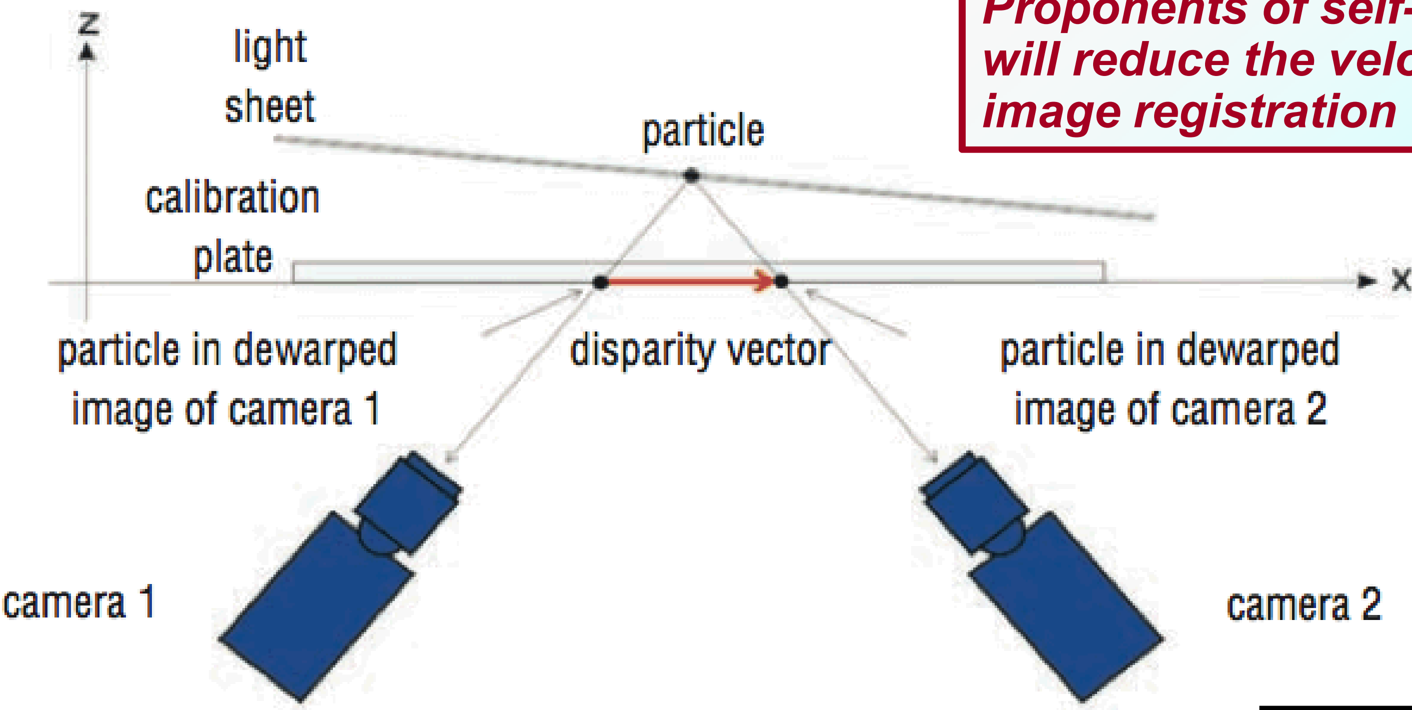
Stereo Self-Calibration

Proponents of self-calibration claim it will reduce the velocity error due to image registration to nearly zero.



Self-calibration corrects:

- Disparity in the camera registration.
- Misalignment between the imaging plane and the laser sheet.

Functions by correlating images at the same time between cameras.

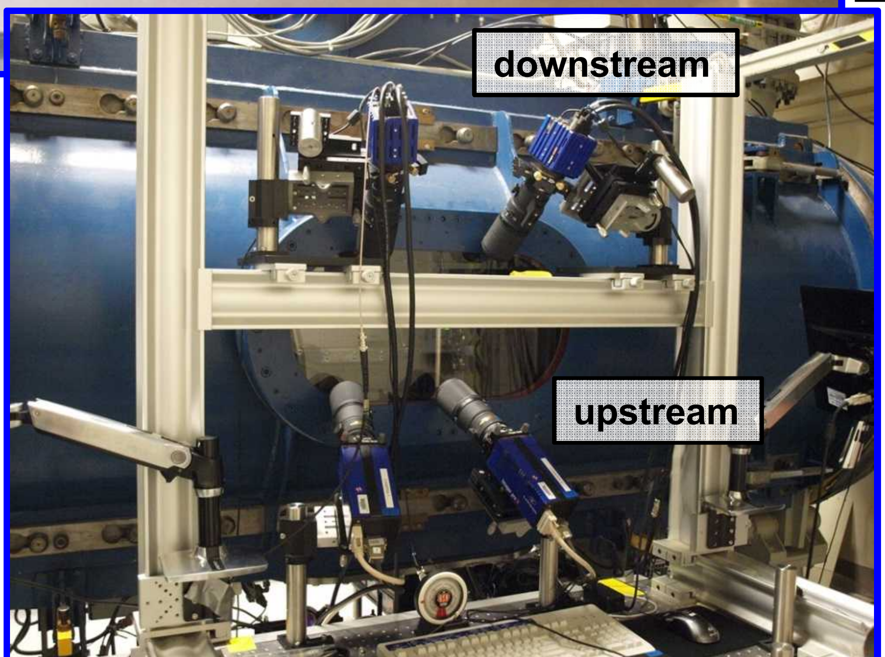
- Sum over many images

***Disparity*: each camera is mapped to a different point in space.**

Does calibration error become negligible?

Is self-calibration always successful?

Transonic Cavity Flow



Return to our weapons bay experiments.

Cavity mounted in ceiling of transonic test section.

Two stereo views for the entire cavity length & to maximize spatial resolution.

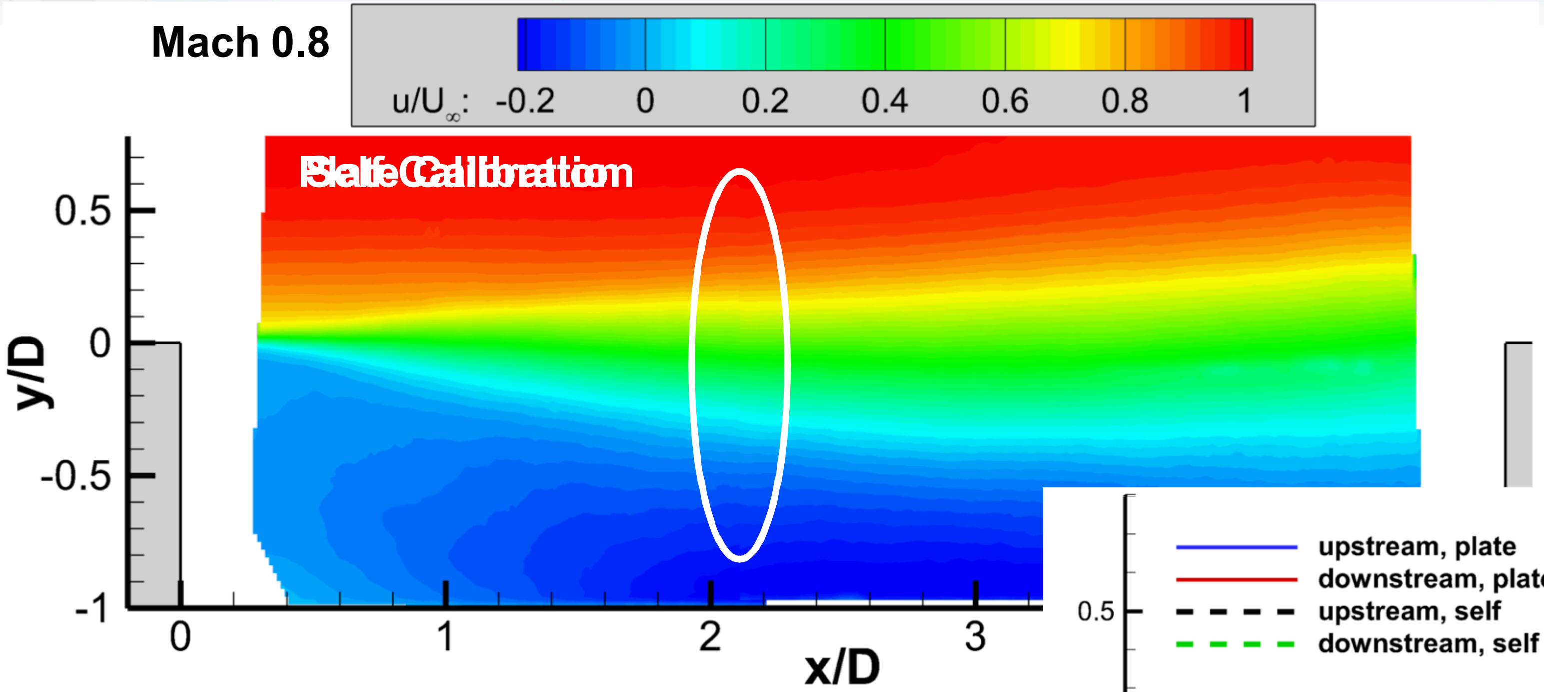
- Upstream cameras angled to peer into cavity.
- Downstream cameras see cavity with a mirror to allow a greater view depth.

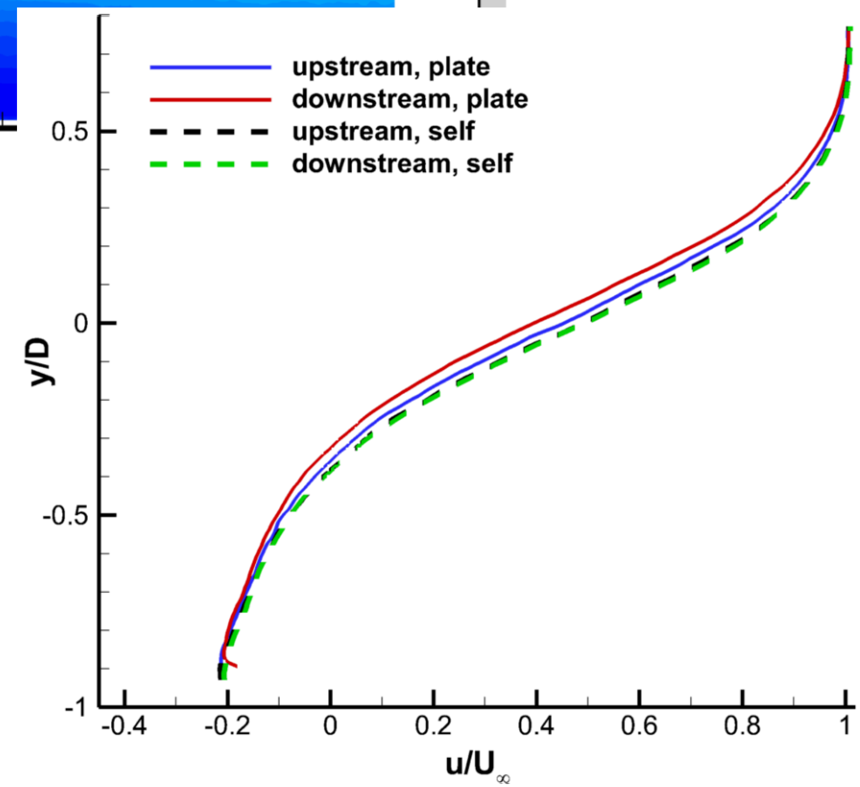
This is an opportunity to compare measurements where the two views overlap.

Use two calibrations:

- **Plate calibration (the basic target calibration)**
- **Plate plus self-calibration**

Transonic Cavity Flow





The plate calibration leaves a clear spatial misalignment between the two stereo systems.

Self-calibration corrects this spatial misalignment.

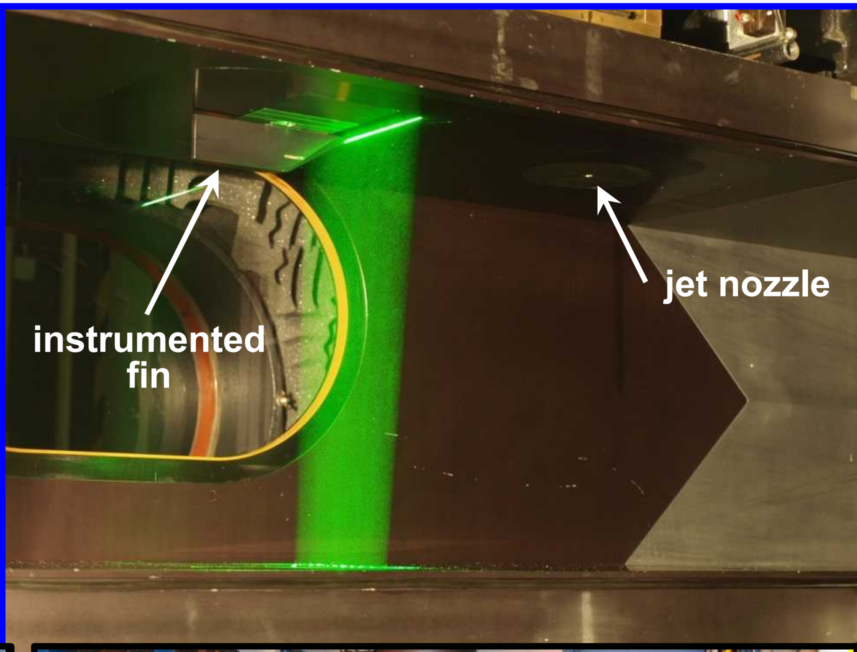
What is the role self-calibration should play in our experiments?

Jet Interaction

Our most recent PIV experiment grew much more complicated.

The need to see around the fin and window locations limited optical access.

- Place one camera on each side of the wind tunnel.
- Each camera views the laser sheet from a very different angle.



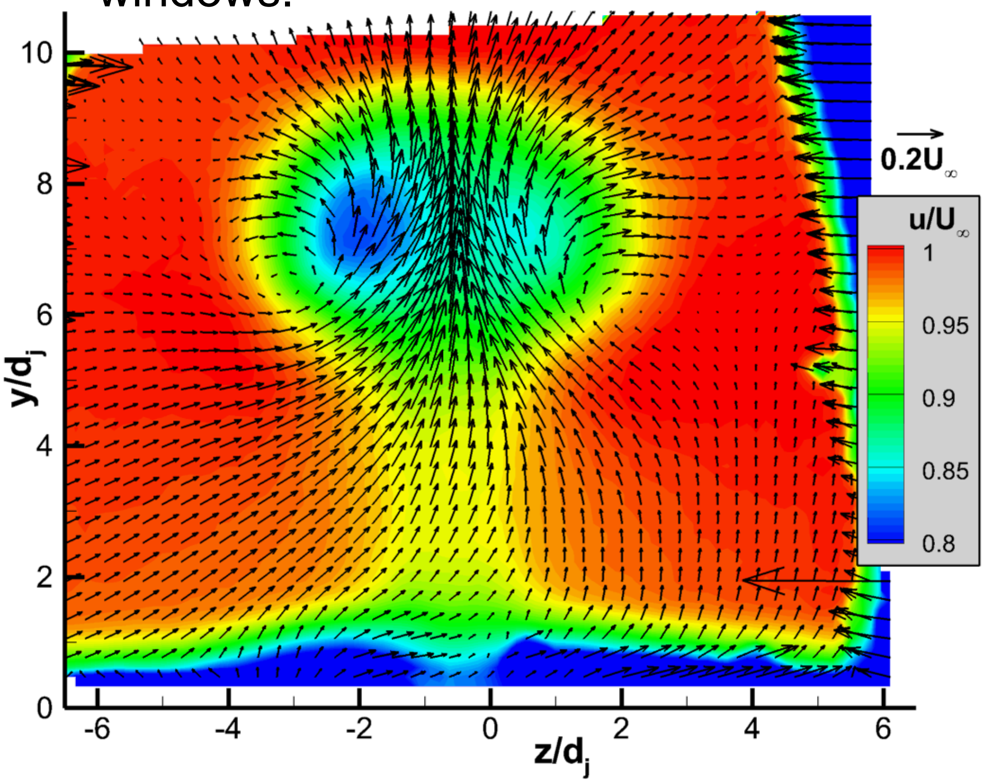
How do we calibrate this?

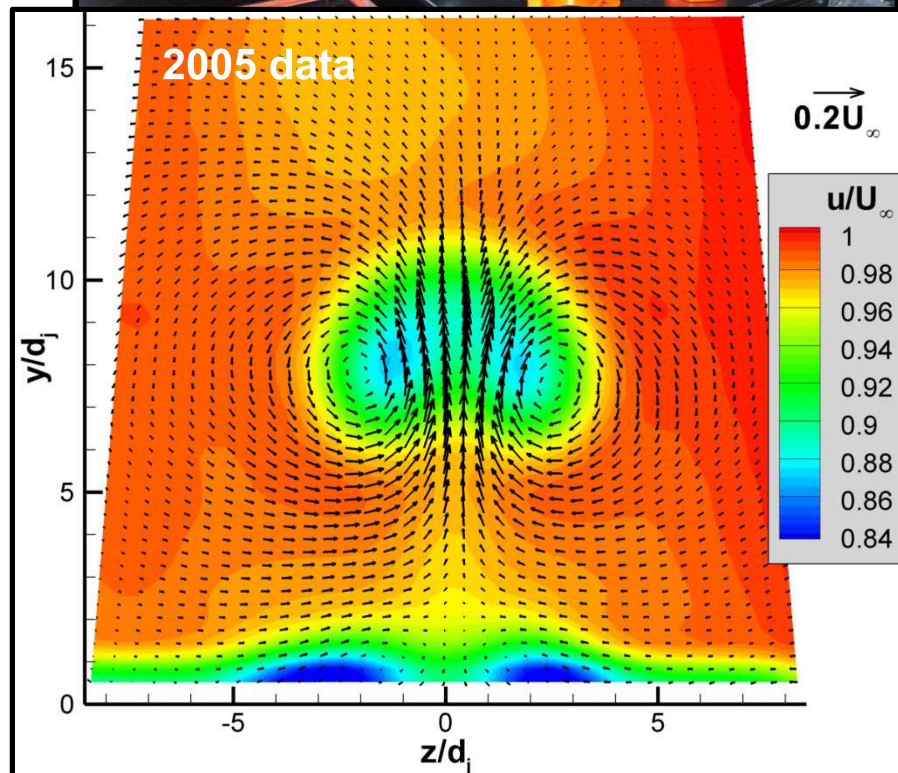
We image the calibration target at seven planes through the laser sheet thickness.

It is time consuming to open and close the test section to adjust the target.

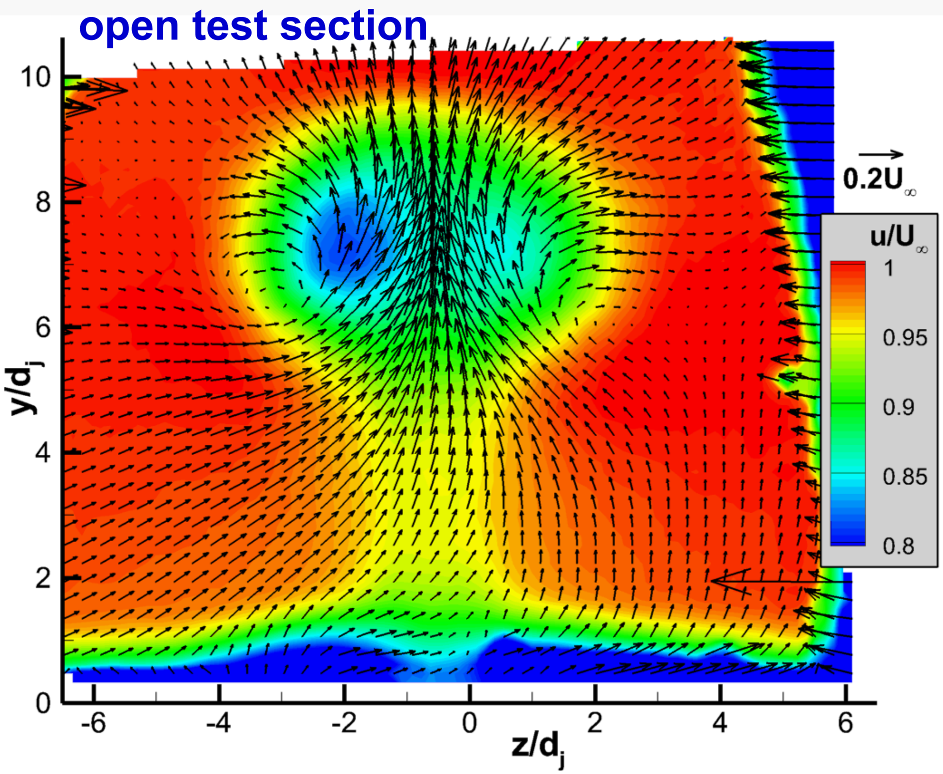
Bad idea: **Calibrate with the test section open.**

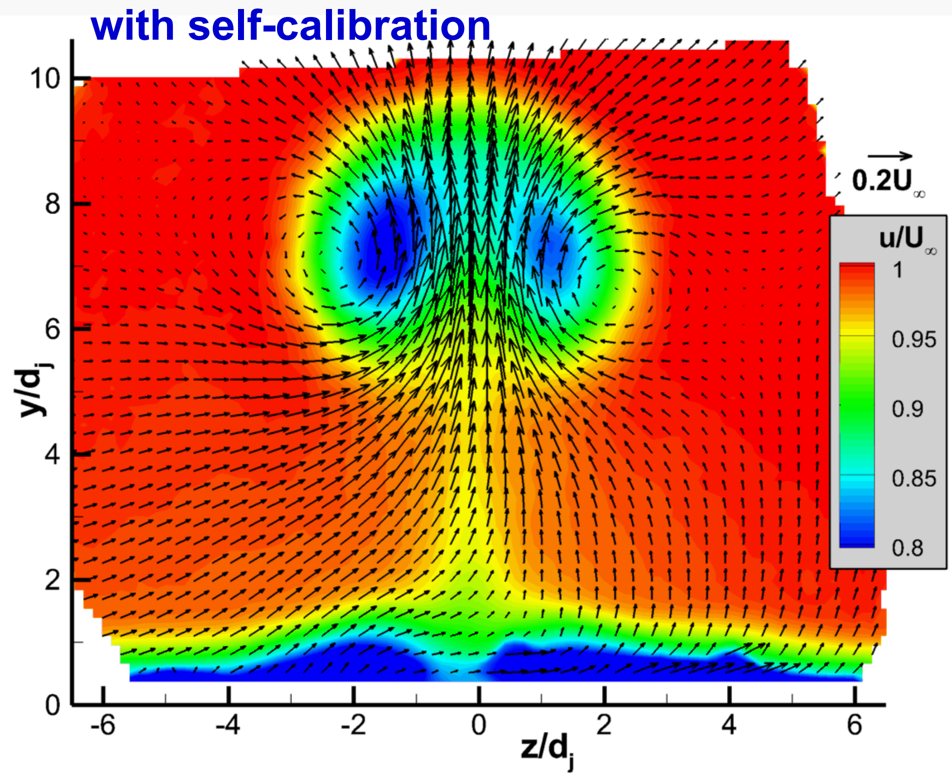
Misrepresents refraction through the windows.





Can self-calibration rescue this bad idea?





Data are clearly wrong.

- Vortices are clearly misshapen.
- Bad vectors at edges.

Better, but is this good enough?

- Vortices are asymmetric.
- Suggests freestream nonuniformity.

How do we know when our calibration is correct and the data are accurate?

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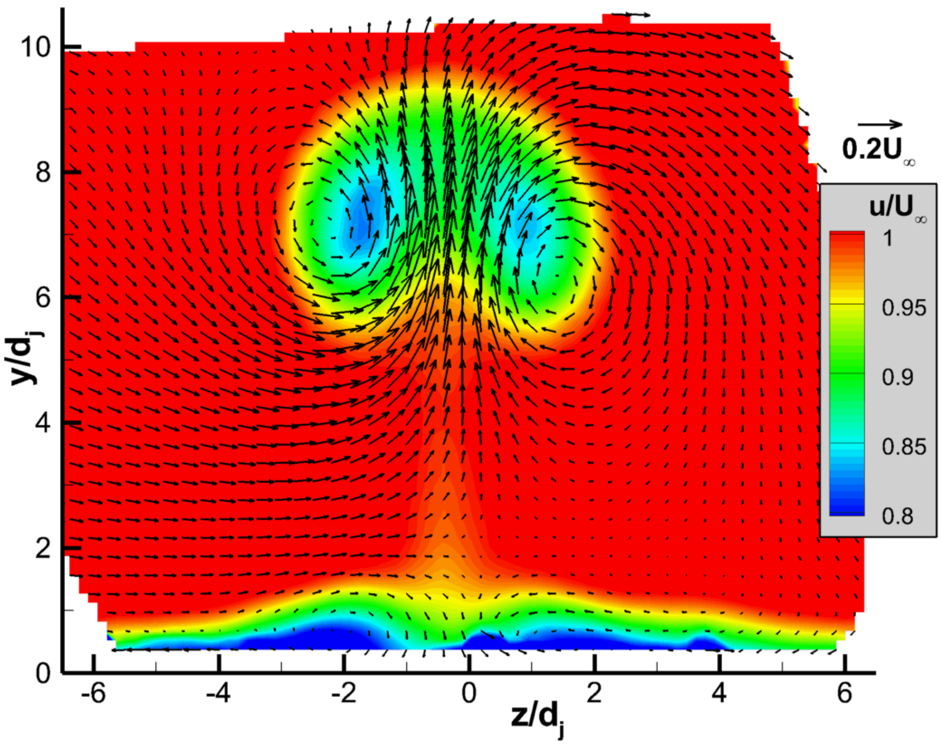
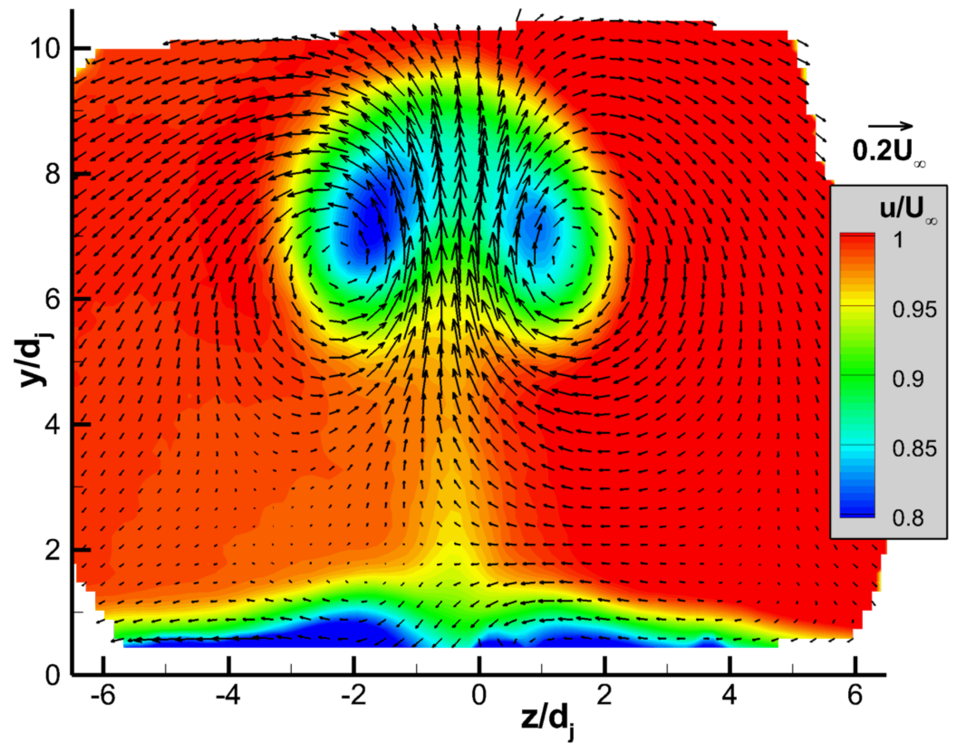
Let's try a smarter calibration.

It's time consuming, but let's seal the test section after every move of the calibration target.

Add self-calibration to this.





This still exhibits suspect data.

- Vortices are asymmetric.
- Freestream nonuniformity.

This is better.

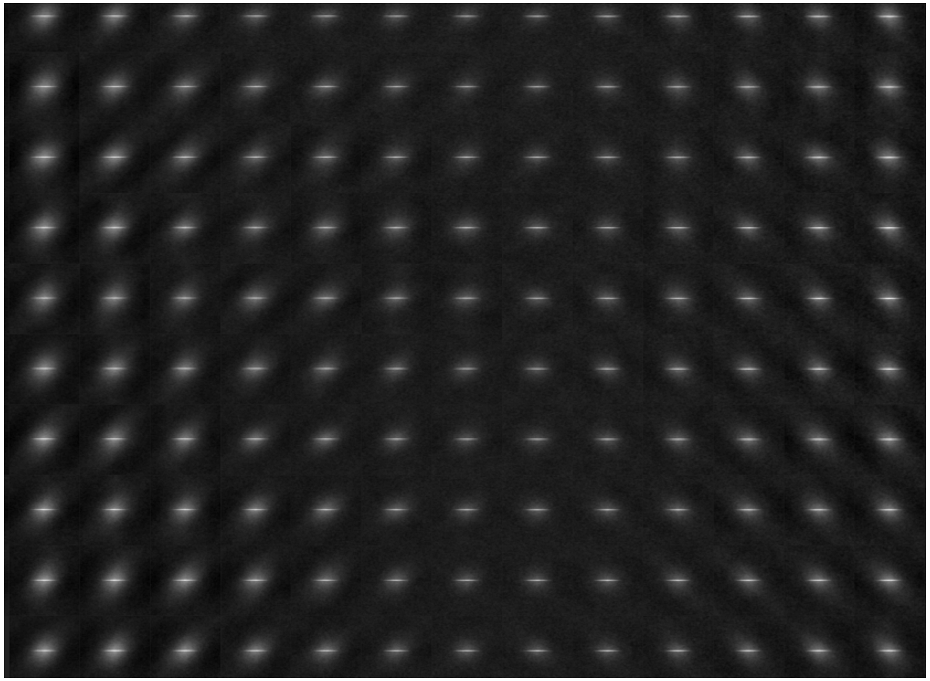
- Vortices appear symmetric.
- Less freestream nonuniformity.

Is this good enough? How can we tell?

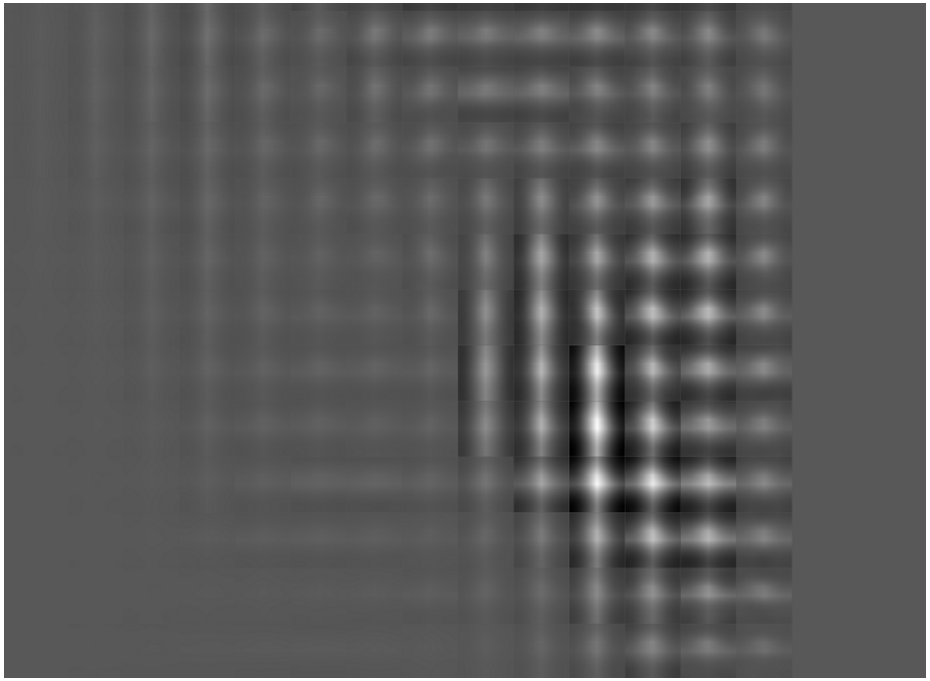
How good is a self-calibration?

The quality of a self-calibration can be judged by its correlation field.

This is a good self-calibration correlation field.



This is not.



We also can track the convergence of the self-calibration over several iterations.

Based on both criteria, the self-calibration for this data set is suspect.

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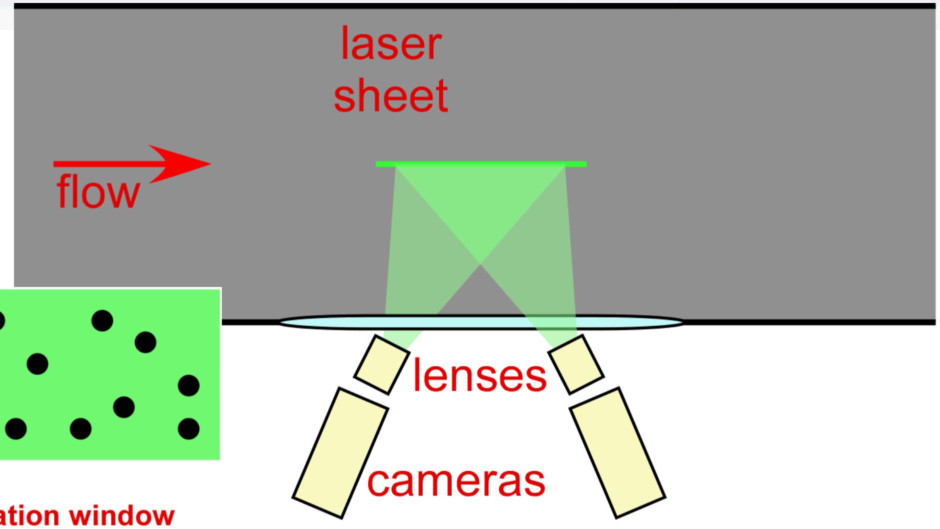
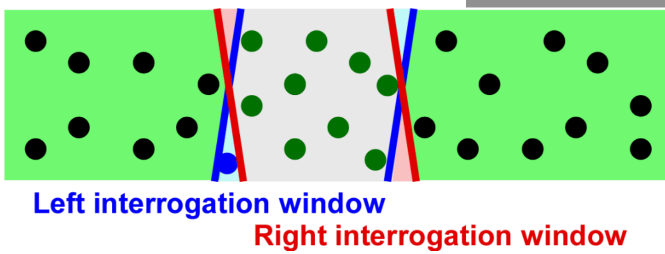
Why does self-calibration struggle in this case?

Good situation:

- Thin laser sheet
- Shallow camera angles

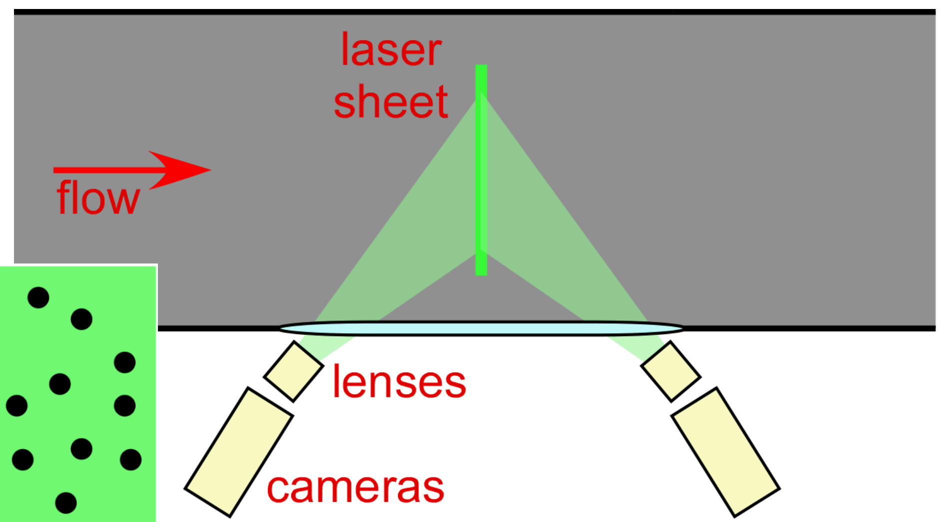


Almost all particles are found in both cameras.

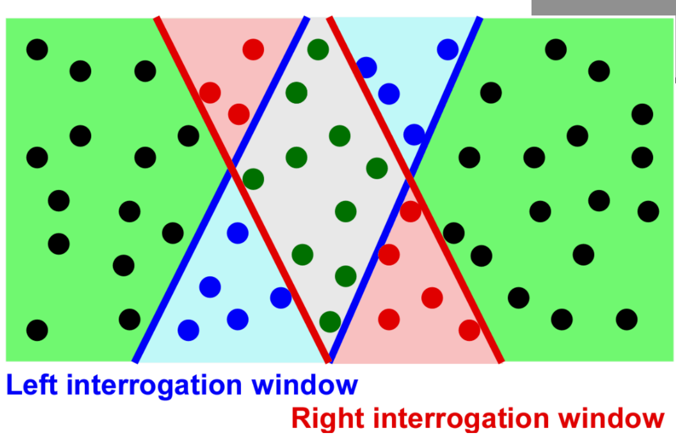


Challenging situation:

- Thick laser sheet
- Large camera angles



Many particles do not match between cameras.



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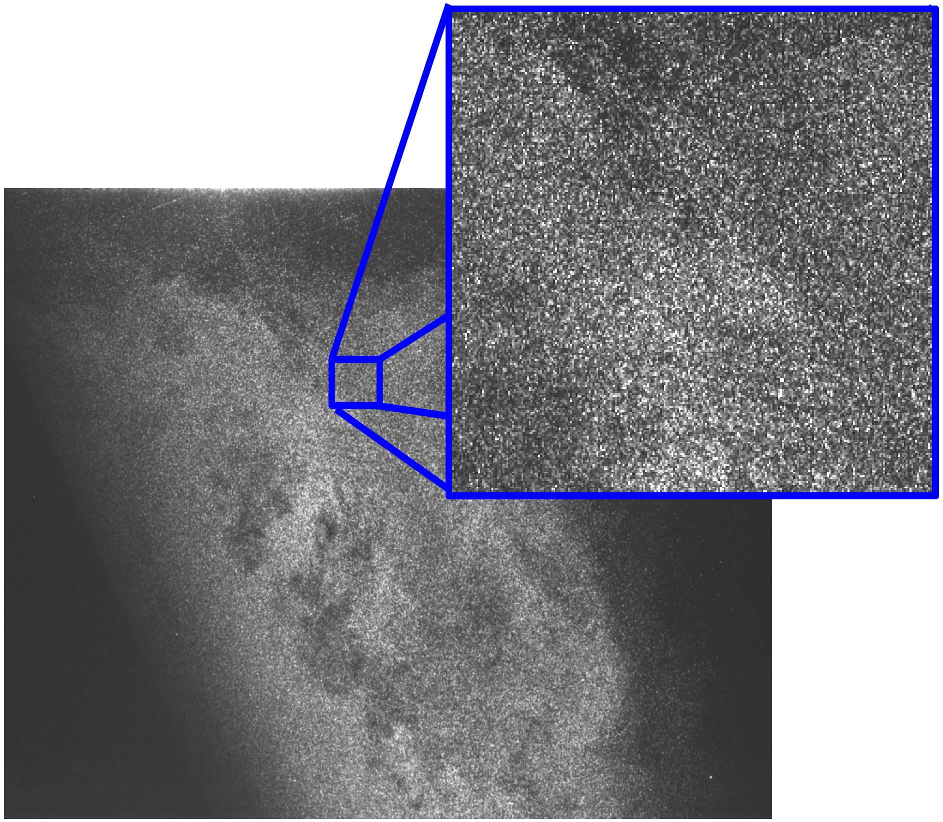
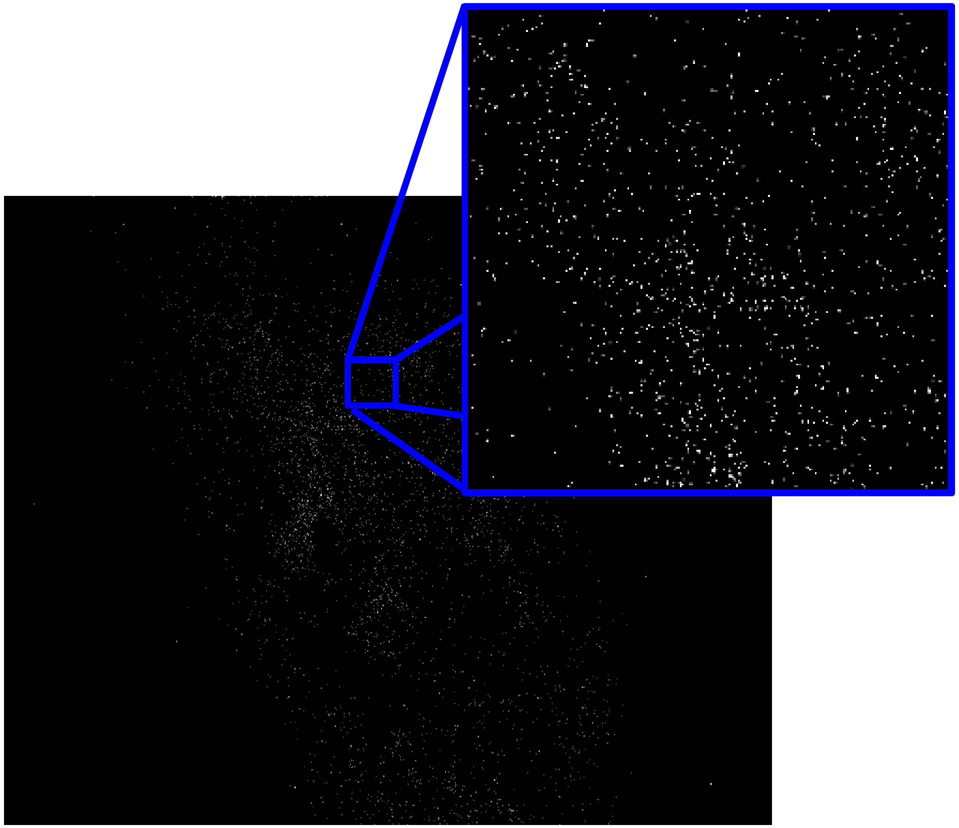
Techniques to improve self-calibration

Threshold the images to correlate only upon the brightest particles, which are most likely to be seen similarly by both cameras.

Raw particle field.



Thresholded particle field.



We also performed wind tunnel runs with the jet off and a light seeding density, specifically for self-calibration.

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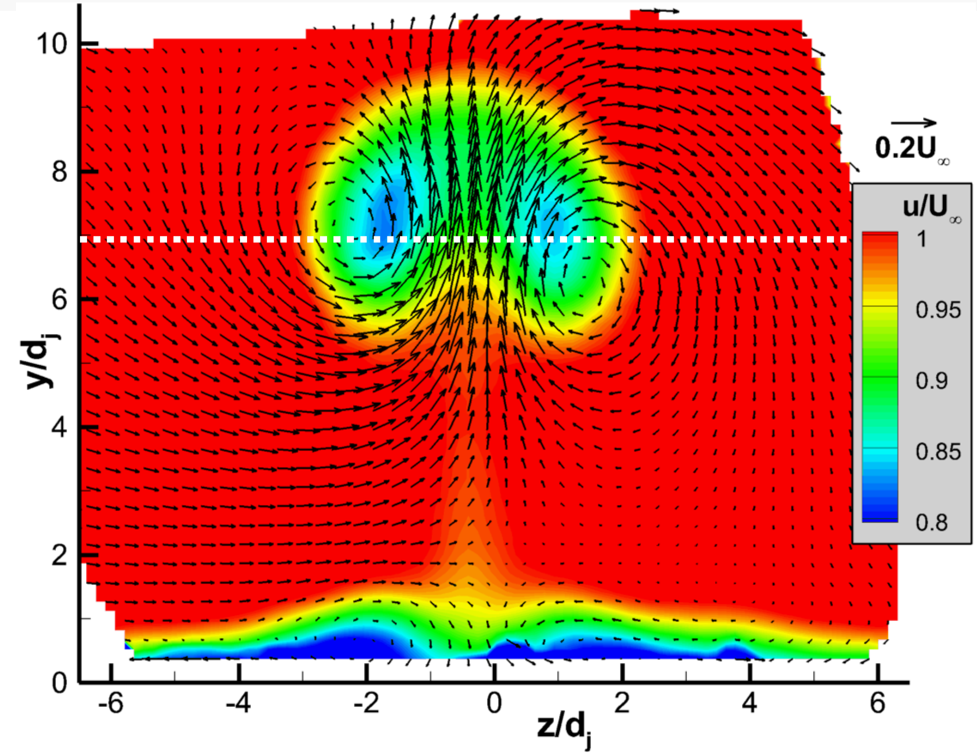
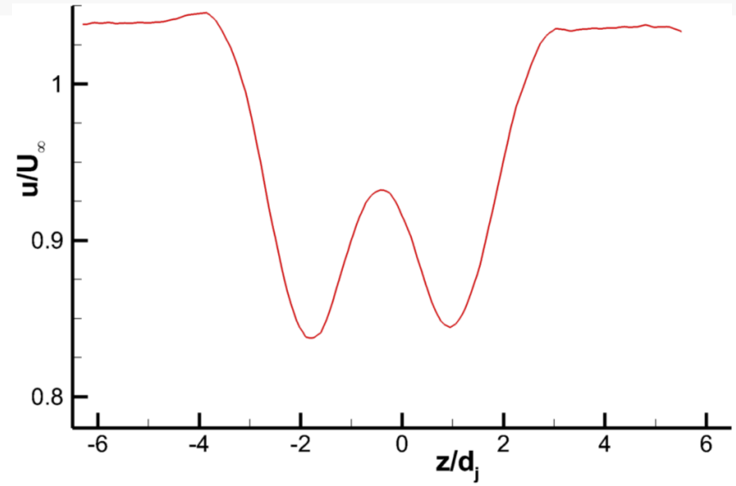
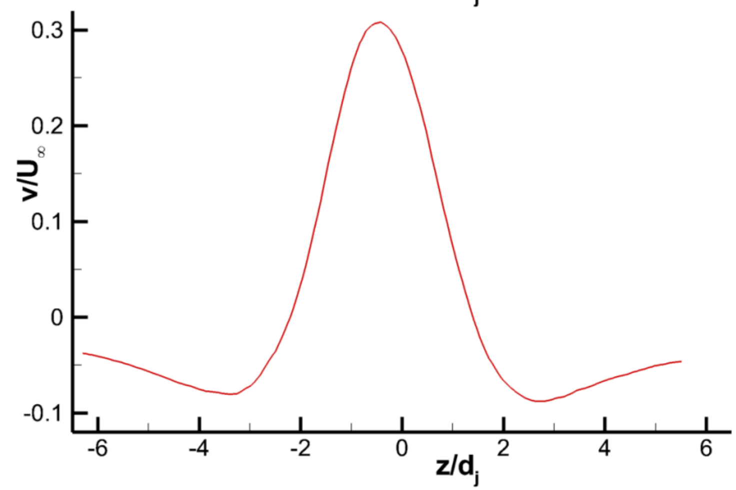
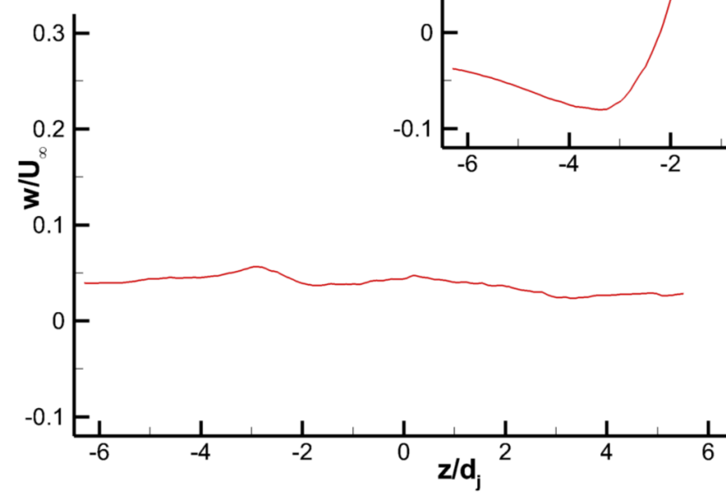
Let’s try a few different self-calibrations.







No self-calibration



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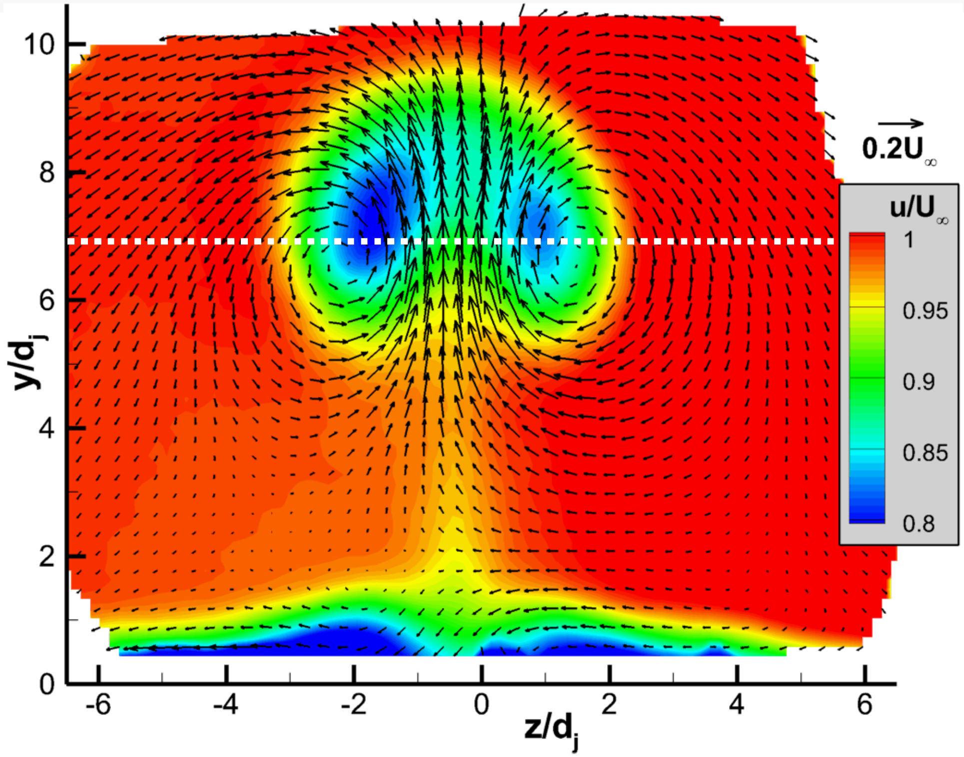
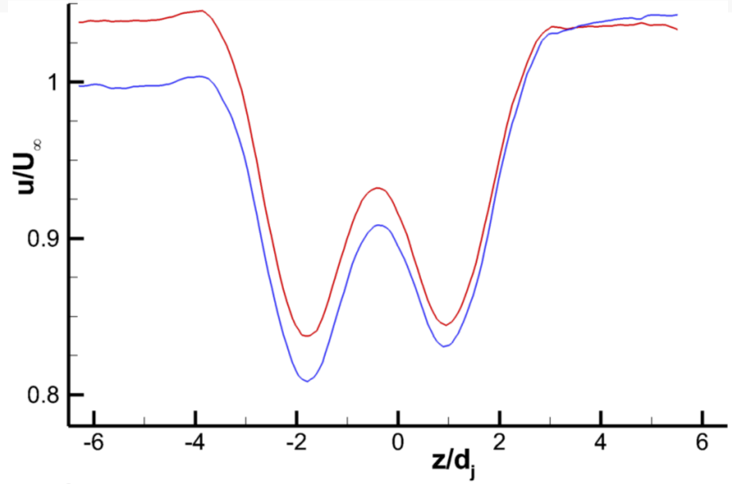
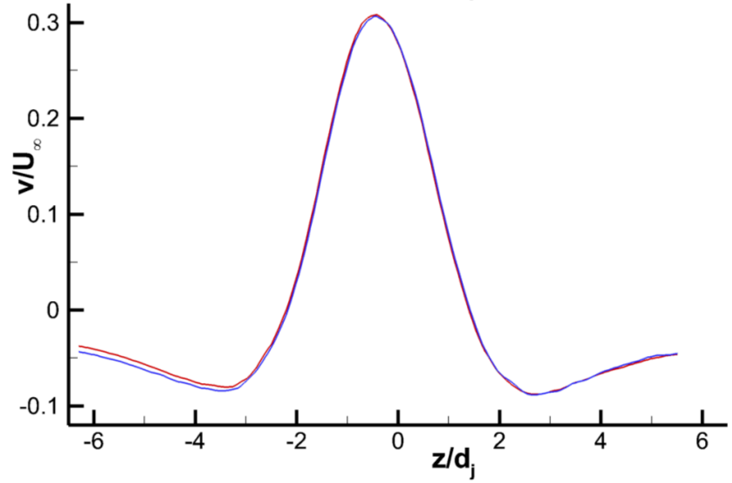
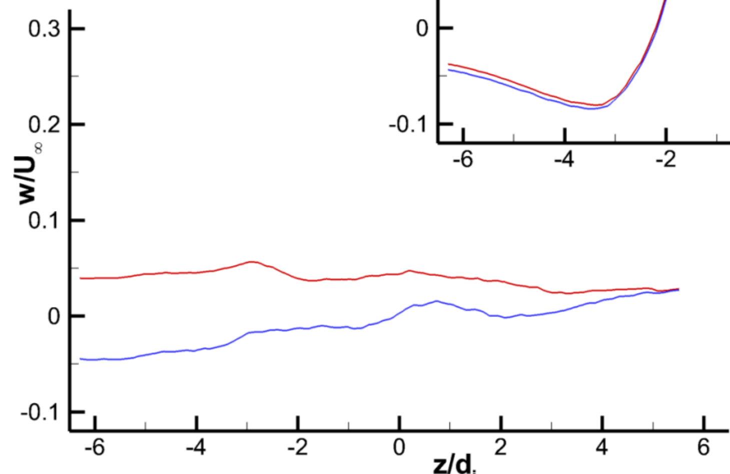
Let's try a few different self-calibrations.



With self-calibration







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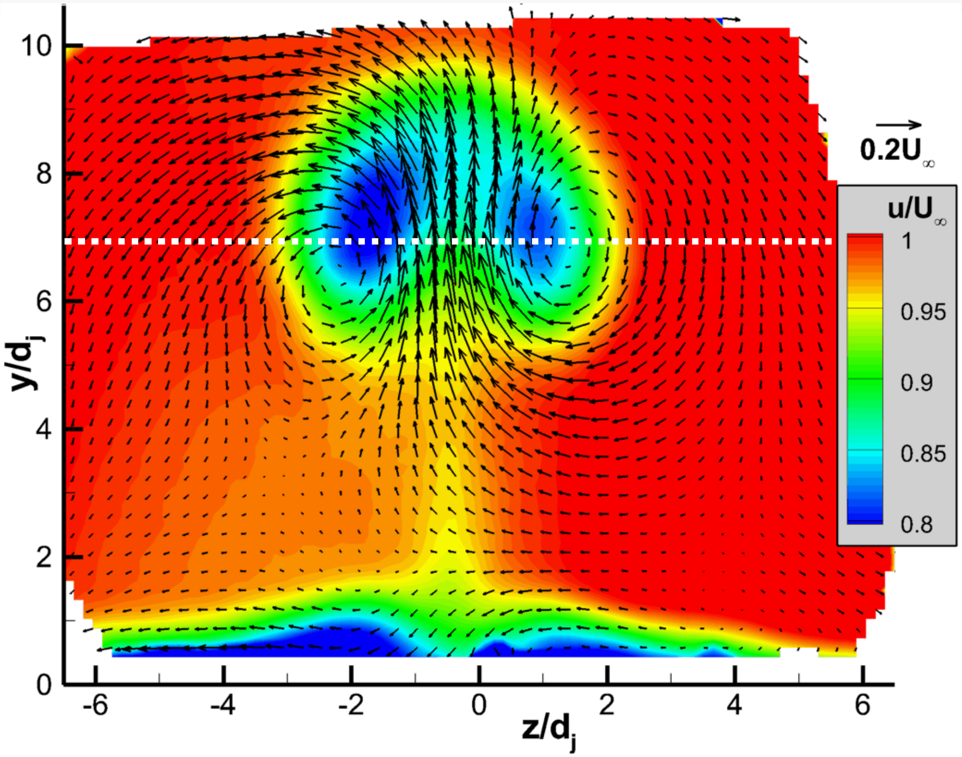
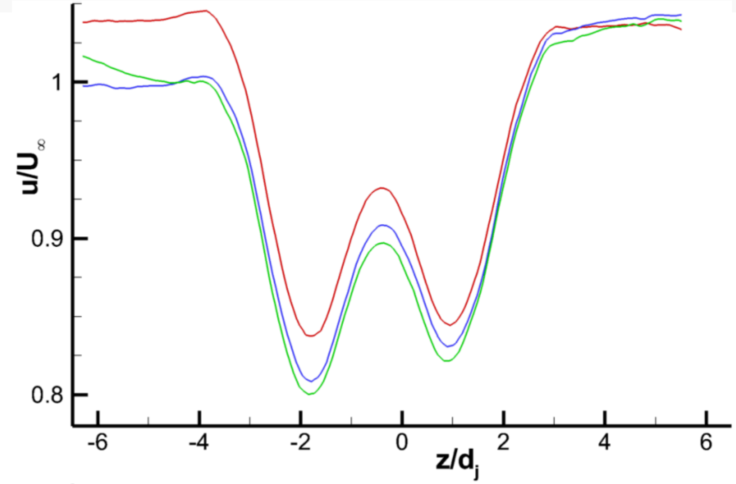
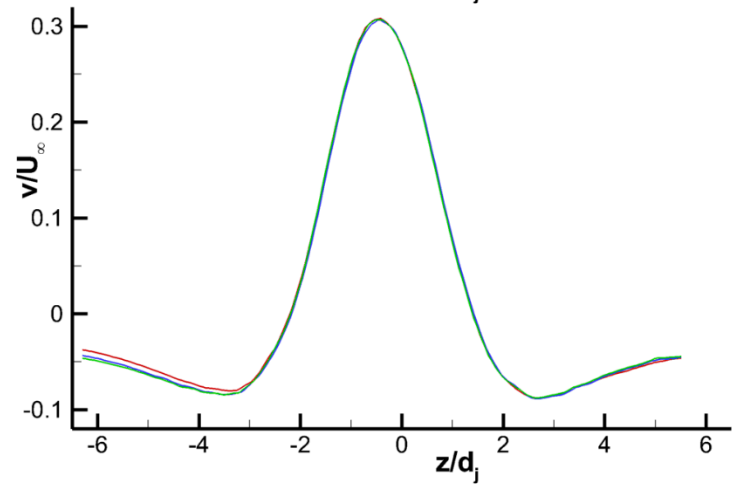
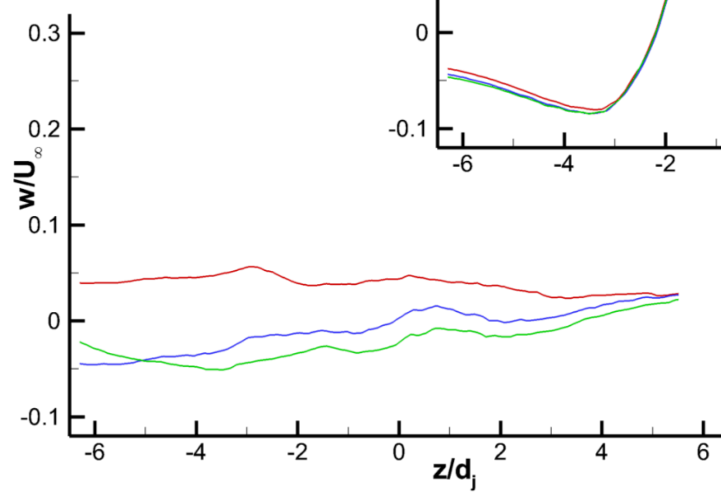
Let's try a few different self-calibrations.







With self-calibration and threshold #1



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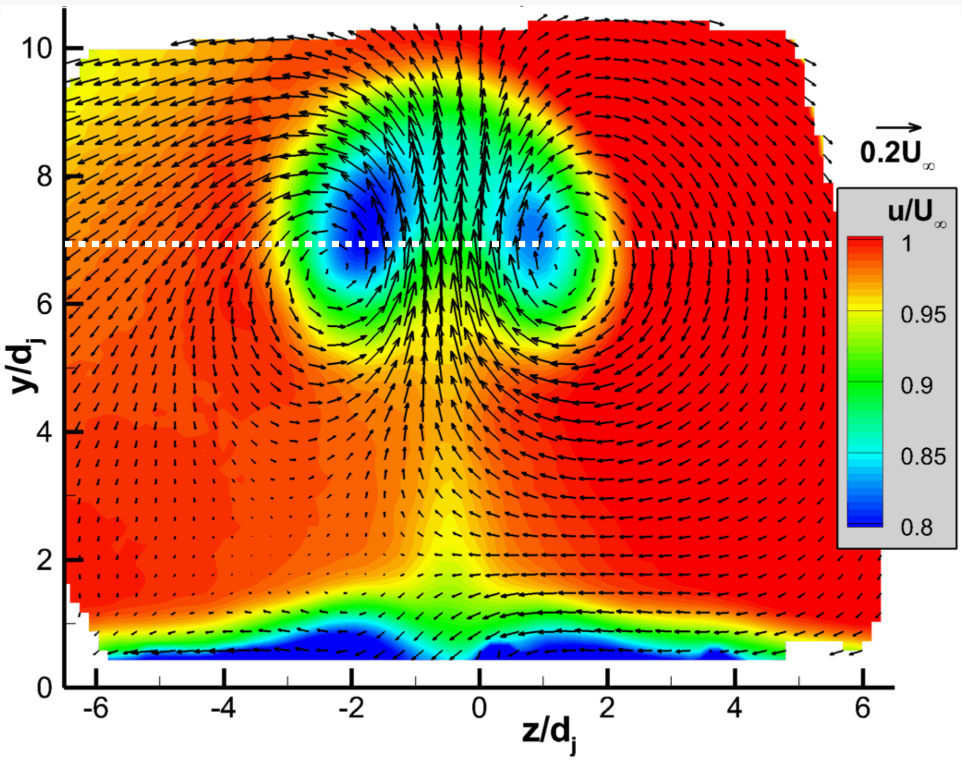
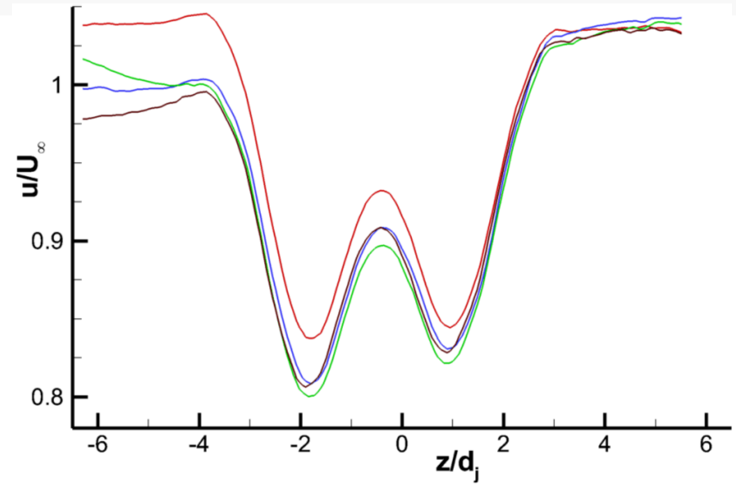
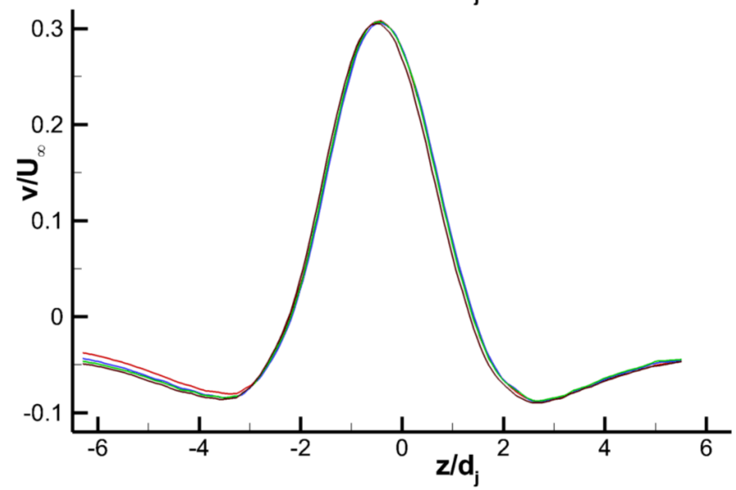
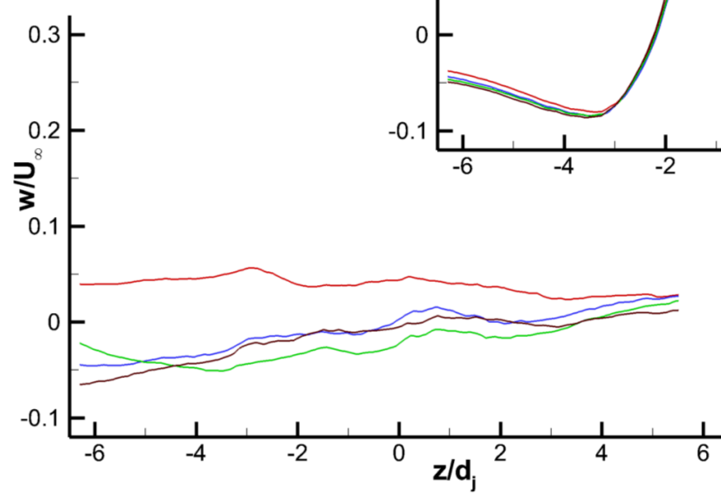
Let's try a few different self-calibrations.







With self-calibration and threshold #2



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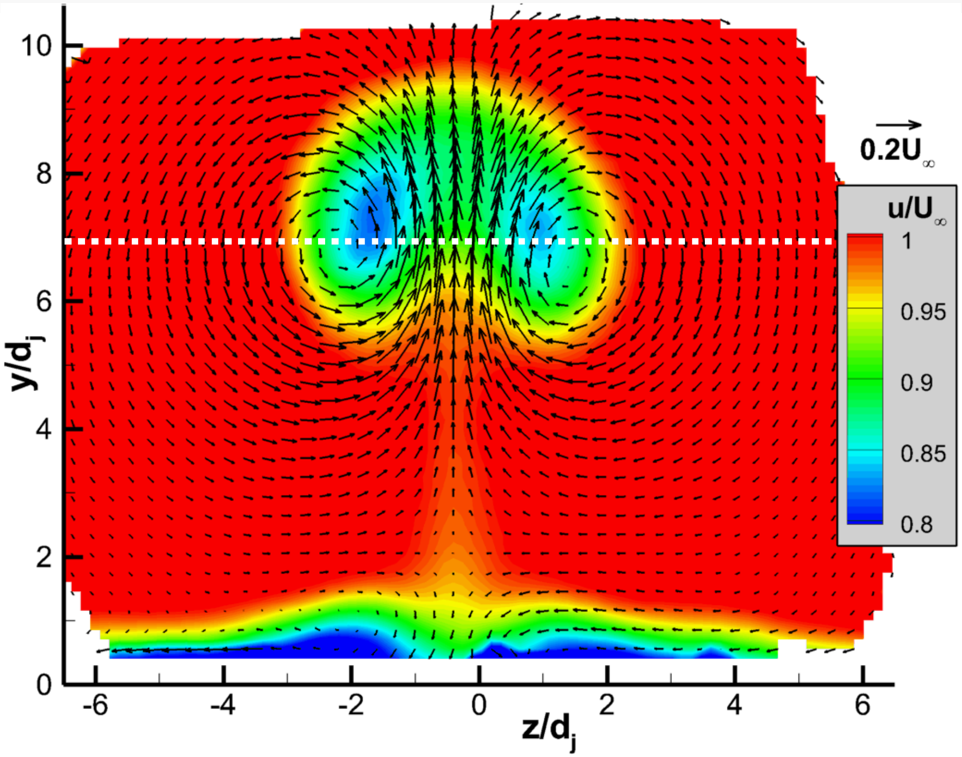
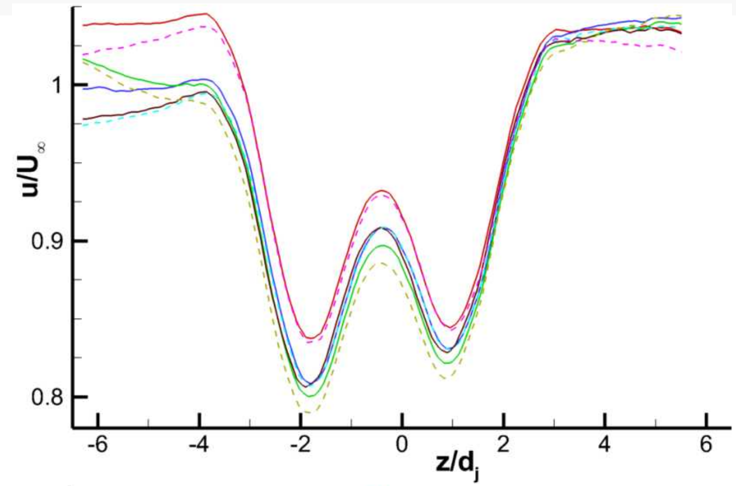
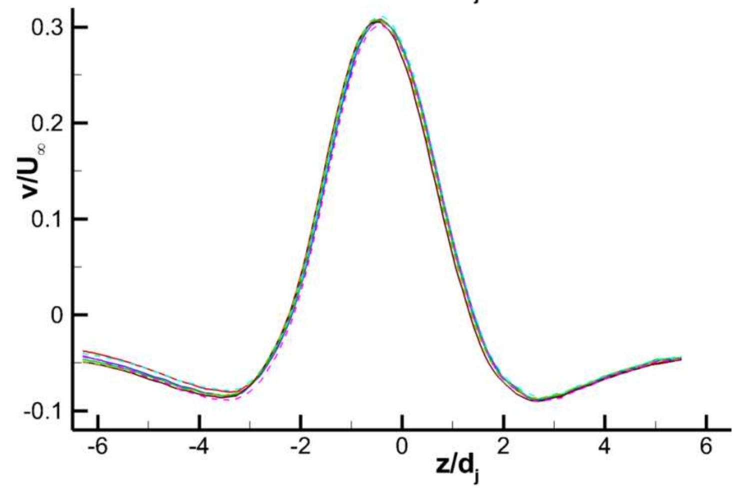
Let’s try a few different self-calibrations.

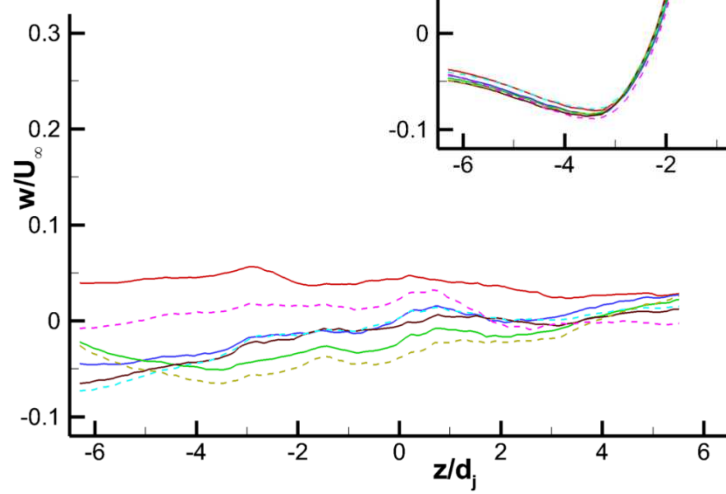






With self-calibration using freestream data

Little error in the v component because the stereo angle is in the x-z plane.



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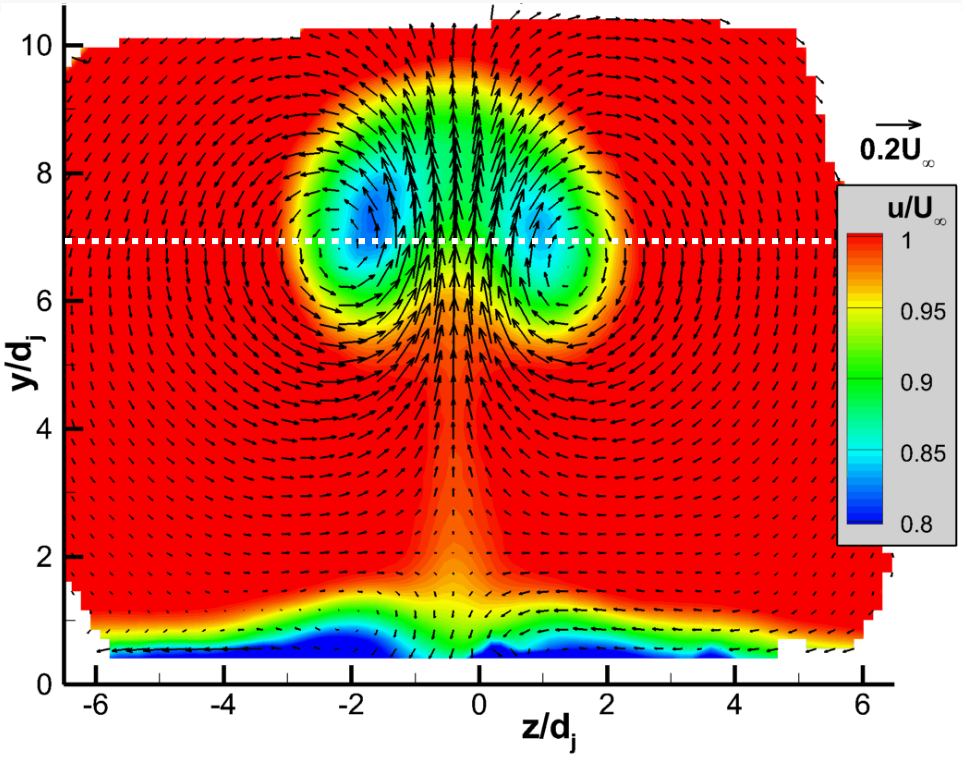
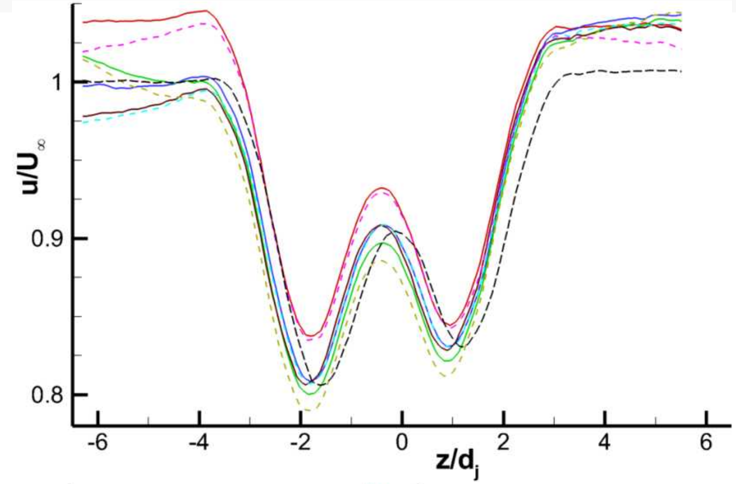
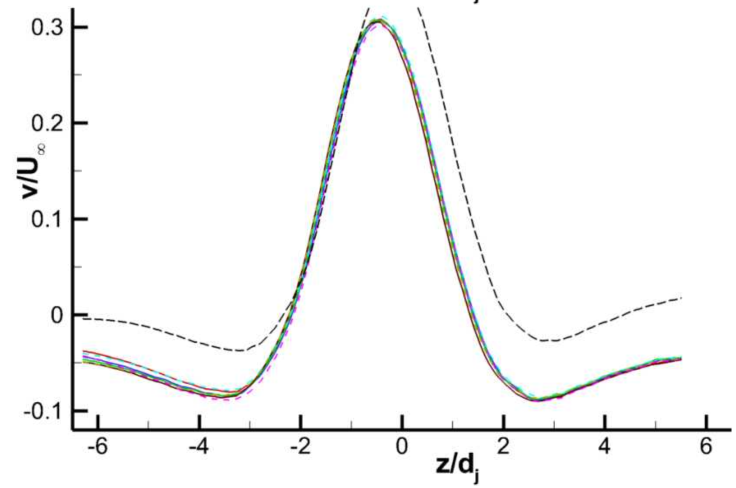
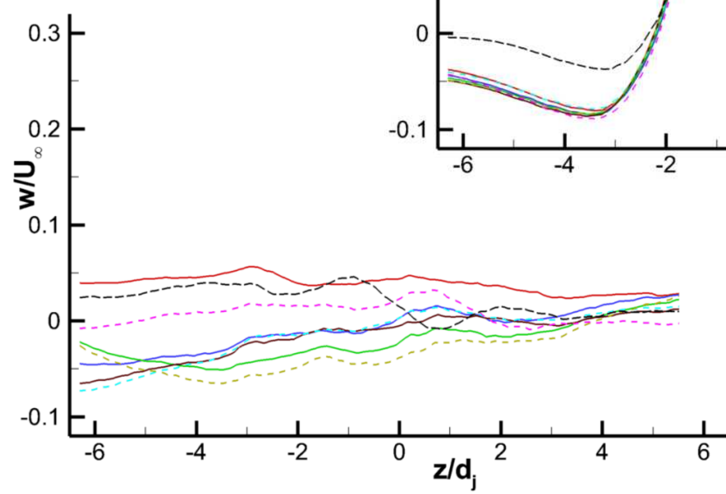
Let's try a few different self-calibrations.







With self-calibration
using freestream data



Self-calibration cannot correct the tunnel-open calibration.

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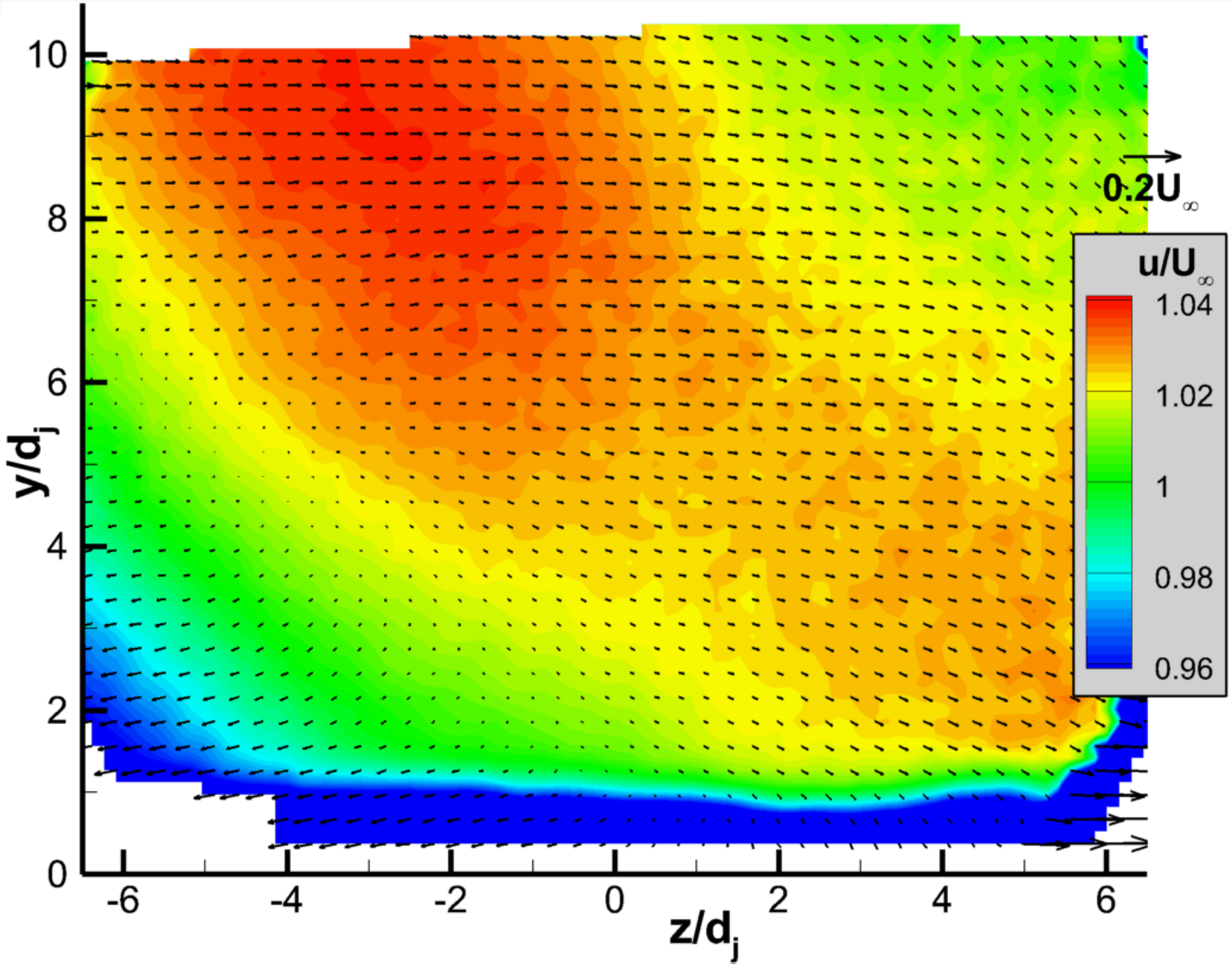
Self-calibration difficulties are most evident if we measure the freestream velocity field



None of these is correct.

Clearly, we need to learn better how to perform self-calibration.

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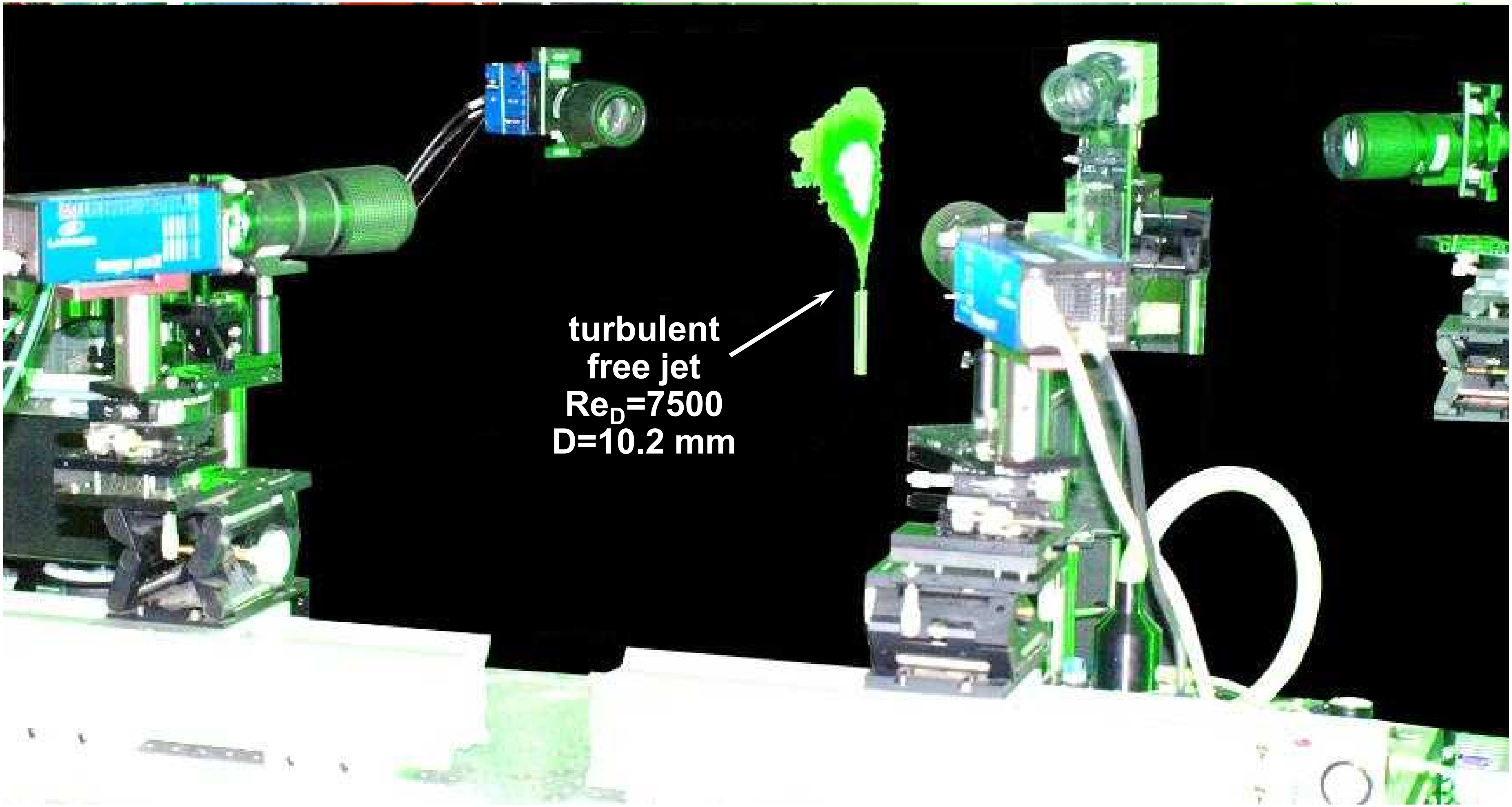
A Benchtop Experiment on a Turbulent Free Jet

Use a simpler environment to study stereo calibration error.



Investigate stereo bias errors by comparing *simultaneous* measurements from three PIV systems.

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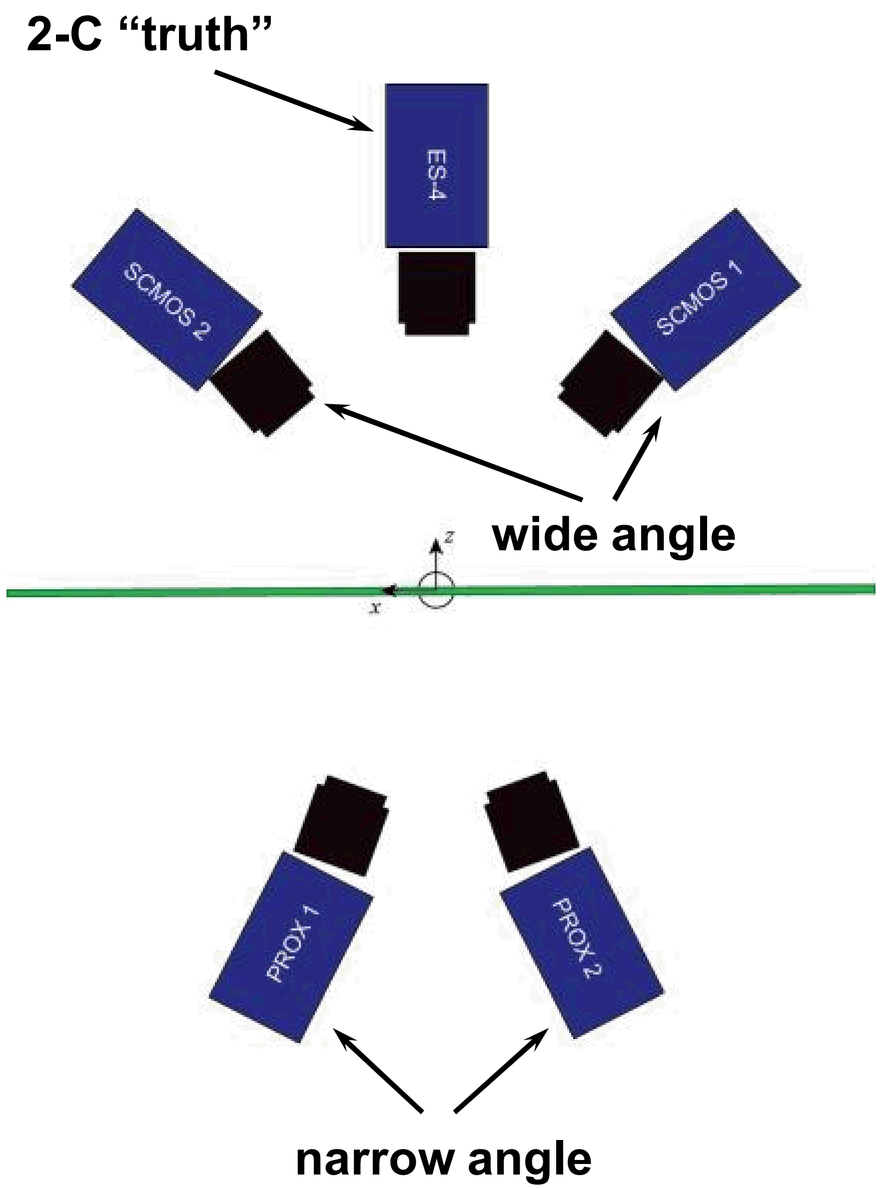
Camera Configuration



ProX "narrow angle" stereo:
- 30 deg from laser sheet normal

sCMOS "wide angle" stereo:
- 60 deg from laser sheet normal

ES-4 two-component:
- Normal to laser sheet
- 360 mm lens and a long standoff
  - Minimize perspective bias
  - No contamination from *w*

→ Consider this measurement to be "truth"

All three systems calibrated simultaneously.

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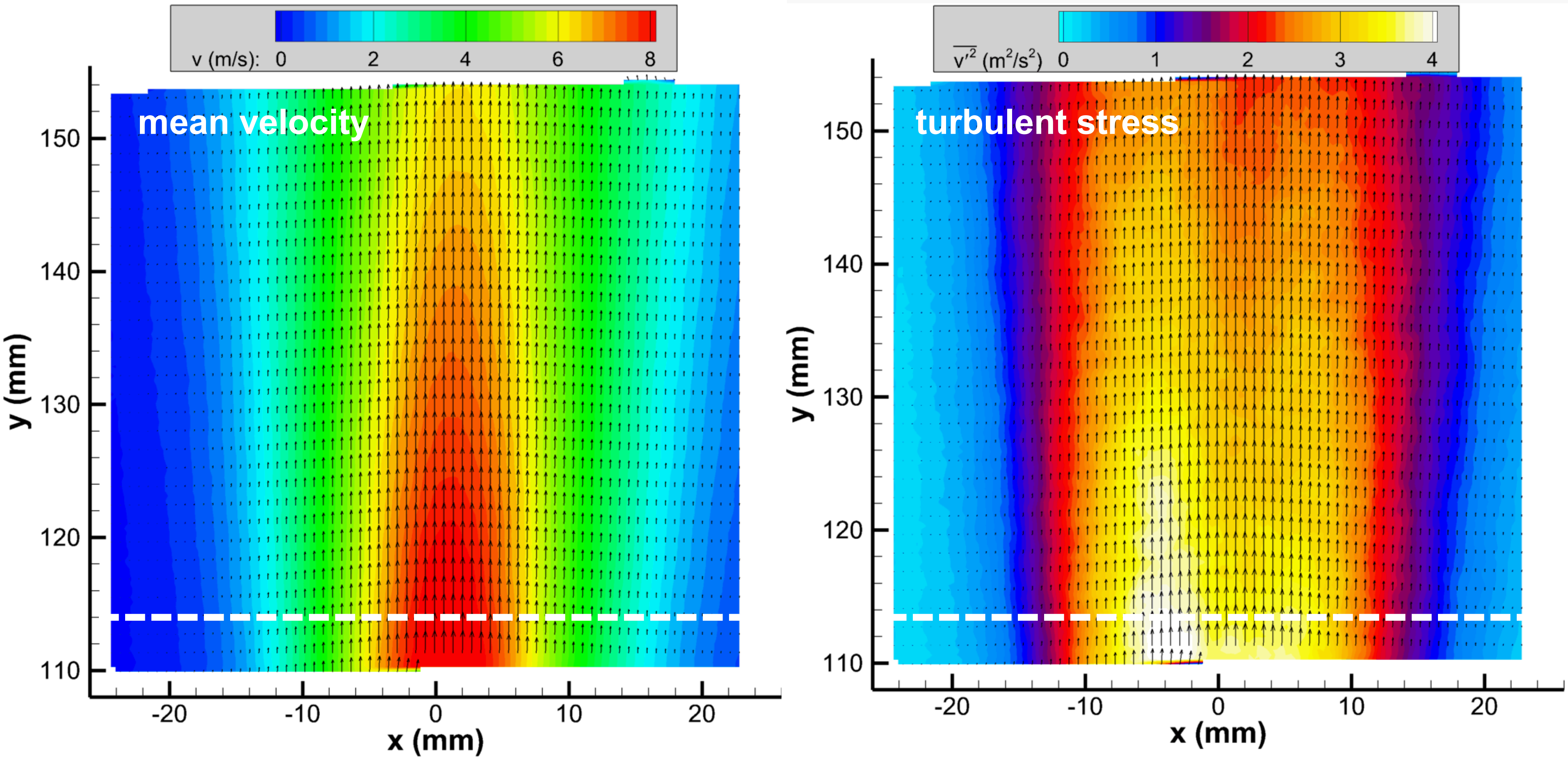
Result: An Unremarkable Free Jet



Some asymmetry is observed, which was real and not a measurement artifact.

Also some variation in time.

But these are irrelevant to an investigation of uncertainty using simultaneous measurements.

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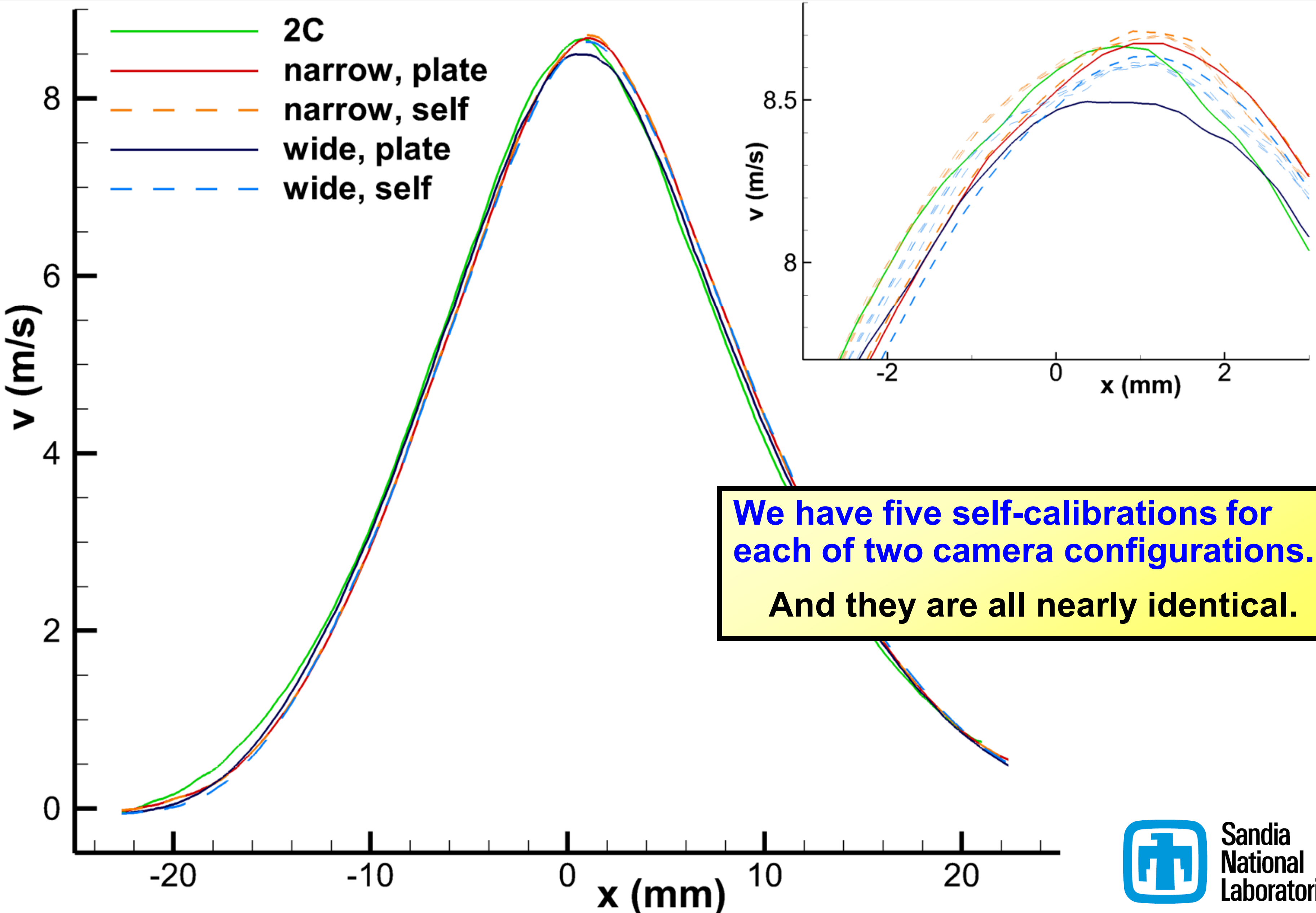
Repeatability of the Self-Calibration



We have five self-calibrations for each of two camera configurations.

And they are all nearly identical.

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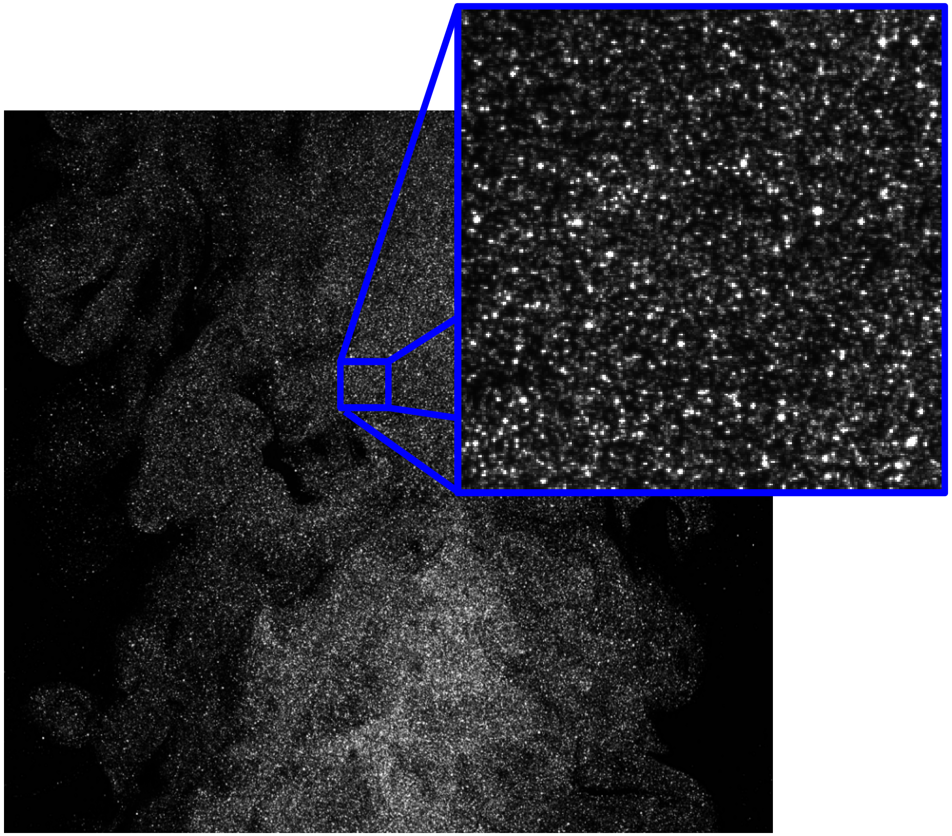
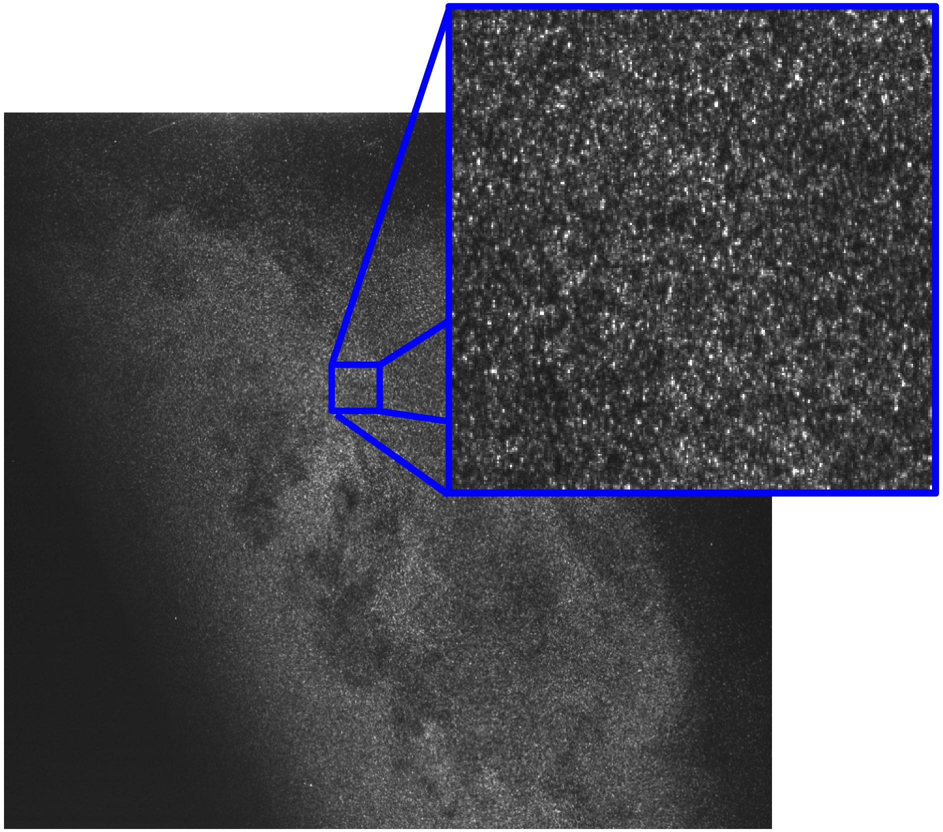
Why is self-calibration more robust for the free jet than for the TWT jet?

Camera angles and laser sheet thickness are in a similar range.





Free jet:

A nearly ideal particle field.

TWT jet-in-crossflow:

Smaller particle images, higher density.

Creates more interference that differs for each camera.

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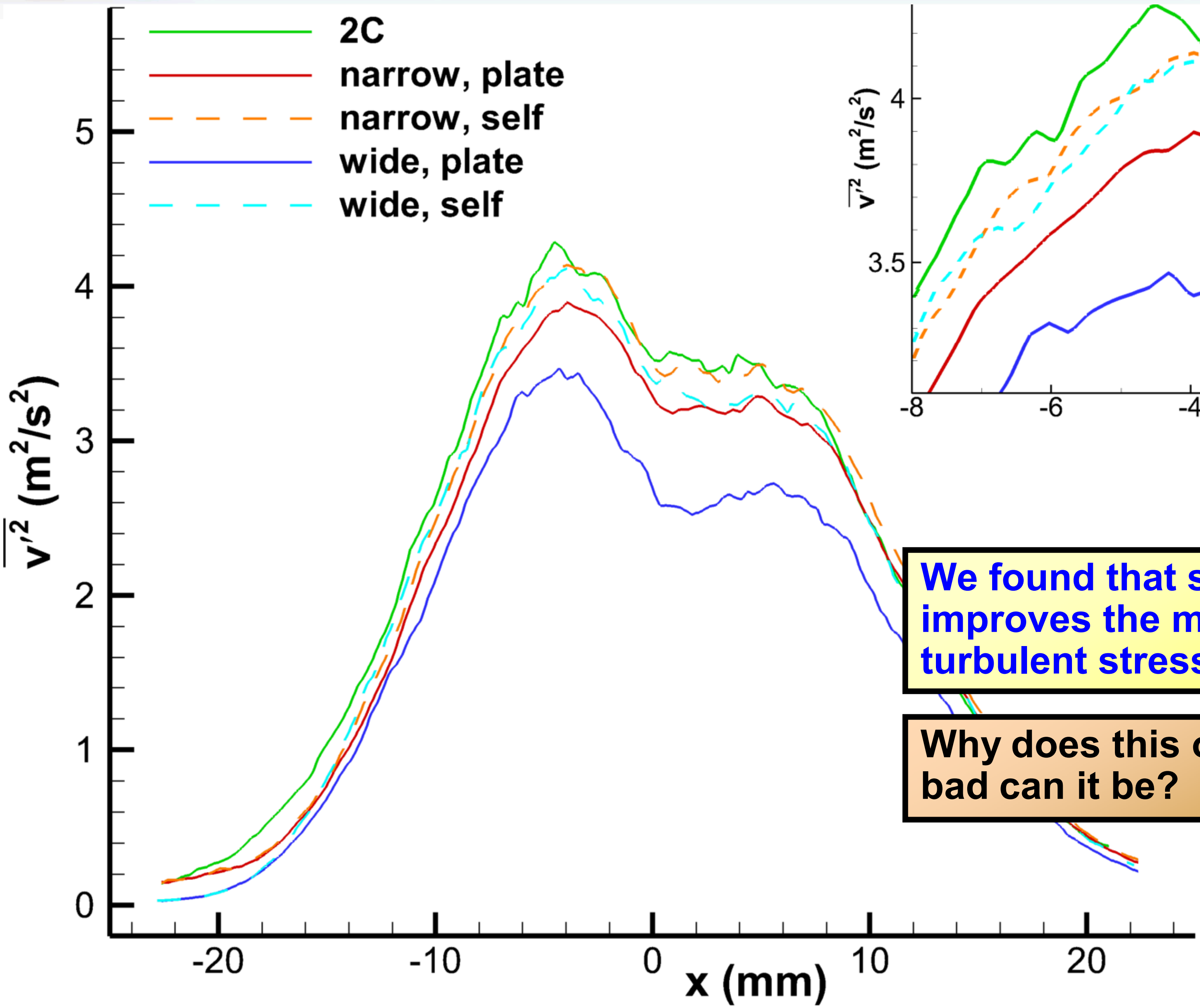
Spatial Error Affects Turbulent Stress



We found that self-calibration improves the measurement of turbulent stress.

Why does this occur, and how bad can it be?

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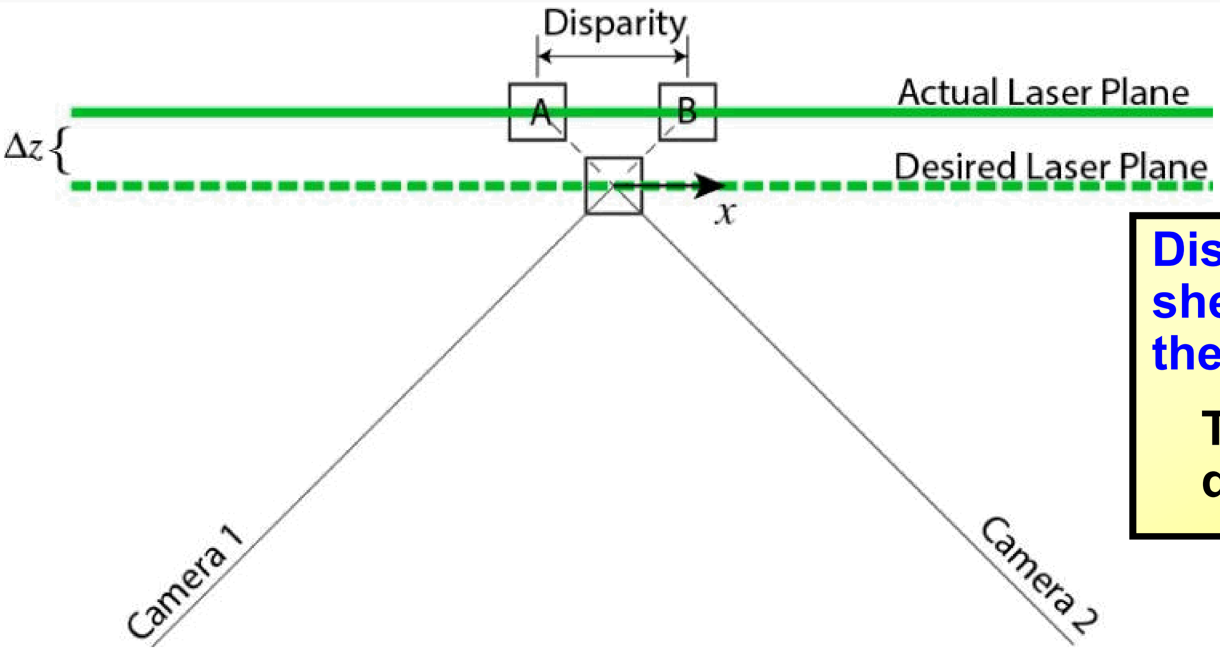
Camera Disparity is Responsible



Disparity occurs when the laser sheet is not located exactly at the calibration target.

This maps each camera to a different point in space.

Trust me with a little math:

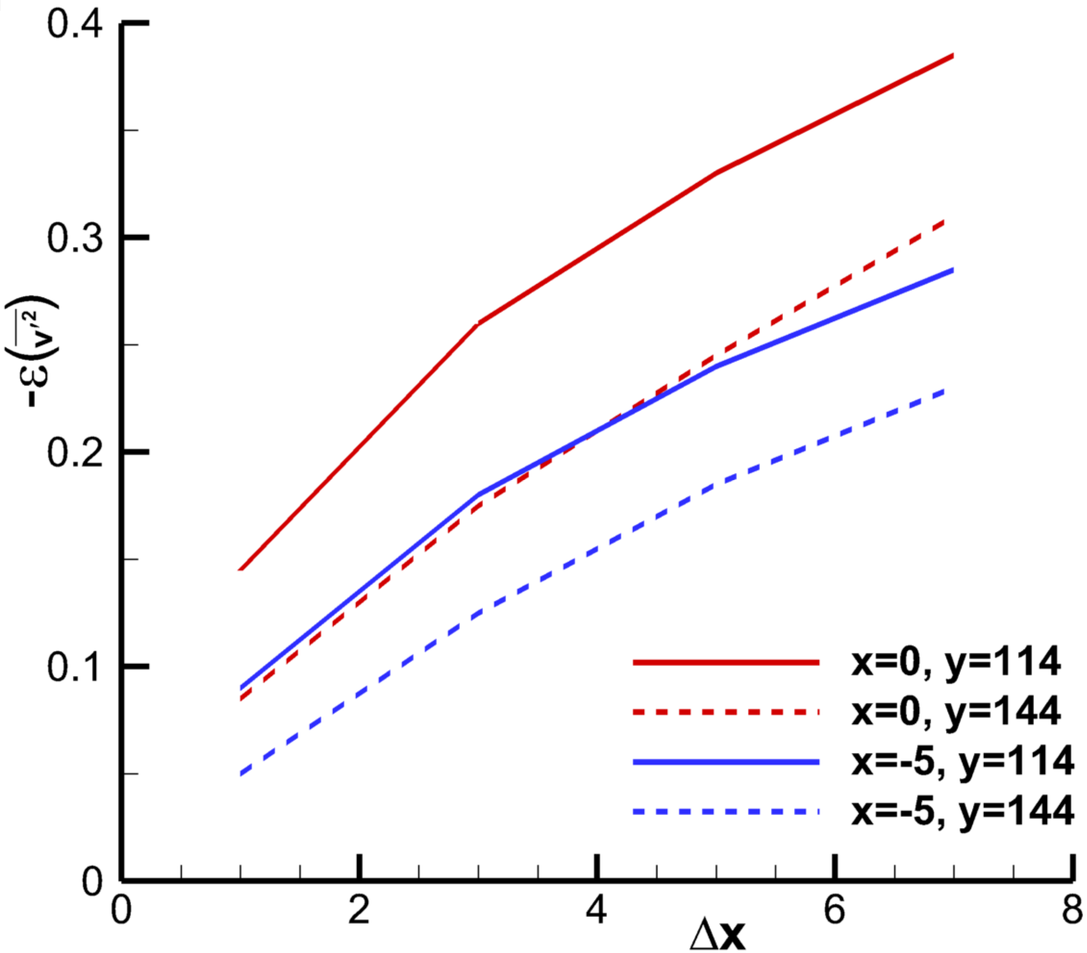
$$\overline{v'v'} = \frac{\sigma_{V_A}^2}{2}(1+\rho) \qquad \rho = \frac{\sigma_{V_A V_B}^2}{\sigma_{V_A}\sigma_{V_B}}$$

ρ: covariance coefficient.

ρ = 1 for perfect registration.

Falls off as disparity increases.

Camera Disparity is Responsible



The bias error in turbulent stress can be as high as 40%.

Even for a disparity of only one vector, error is still 5-15%.

sheet is not located exactly at the calibration target.

This maps each camera to a different point in space.

$$\overline{v'v'} = \frac{\sigma_{V_A}^2}{2}\left(1+\rho\right) \qquad \rho = \frac{\sigma_{V_A V_B}^2}{\sigma_{V_A}\sigma_{V_B}}$$

ρ: covariance coefficient.

ρ = 1 for perfect registration.

Falls off as disparity increases.

A verdict on self-calibration.

We have substantial evidence that a successful self-calibration reduces error compared to just a target calibration.

- Better spatial alignment
- More accurate measurement of mean velocities
- Removes possible bias error in turbulent stress

But self-calibration is not as robust as desired and is prone to sub-optimal results in difficult experiments.

- Sharp camera angle, thick laser sheet
- Small particle images, high particle density

It should not be assumed that self-calibration will render negligible all stereoscopic calibration error!

How do we actually quantify an uncertainty?

- Well, that's still a work in progress….

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Conclusions

SOMETIMES I FEEL THAT THE PURPOSE OF MY LIFE IS ONLY TO SERVE AS A WARNING TO OTHERS.

A Final Thought

Our ability to make complicated PIV measurements has outpaced our ability to quantify their uncertainty.

The many bells and whistles in PIV image acquisition and data processing interact in ways we don't well understand.

Nevertheless, we are slowly learning much about best practices for PIV even if we still struggle to meaningfully quantify the uncertainty.