Background-Oriented Schlieren Applications in NASA Glenn Research Center's Ground Test Facilities

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Outline

Recent BOS developments & applications:

- Brief BOS Overview
- BOS and flow visualization techniques implemented to investigate screech in an open jet rig
- BOS implemented in the Jet Surface Interaction Tests
- 8x6 SWT BOS Demonstration
- 10x10 SWT BOS Implementation
- Engine ground test implementation
- Future work/objectives

Brief Overview – Background Oriented Schlieren (BOS)

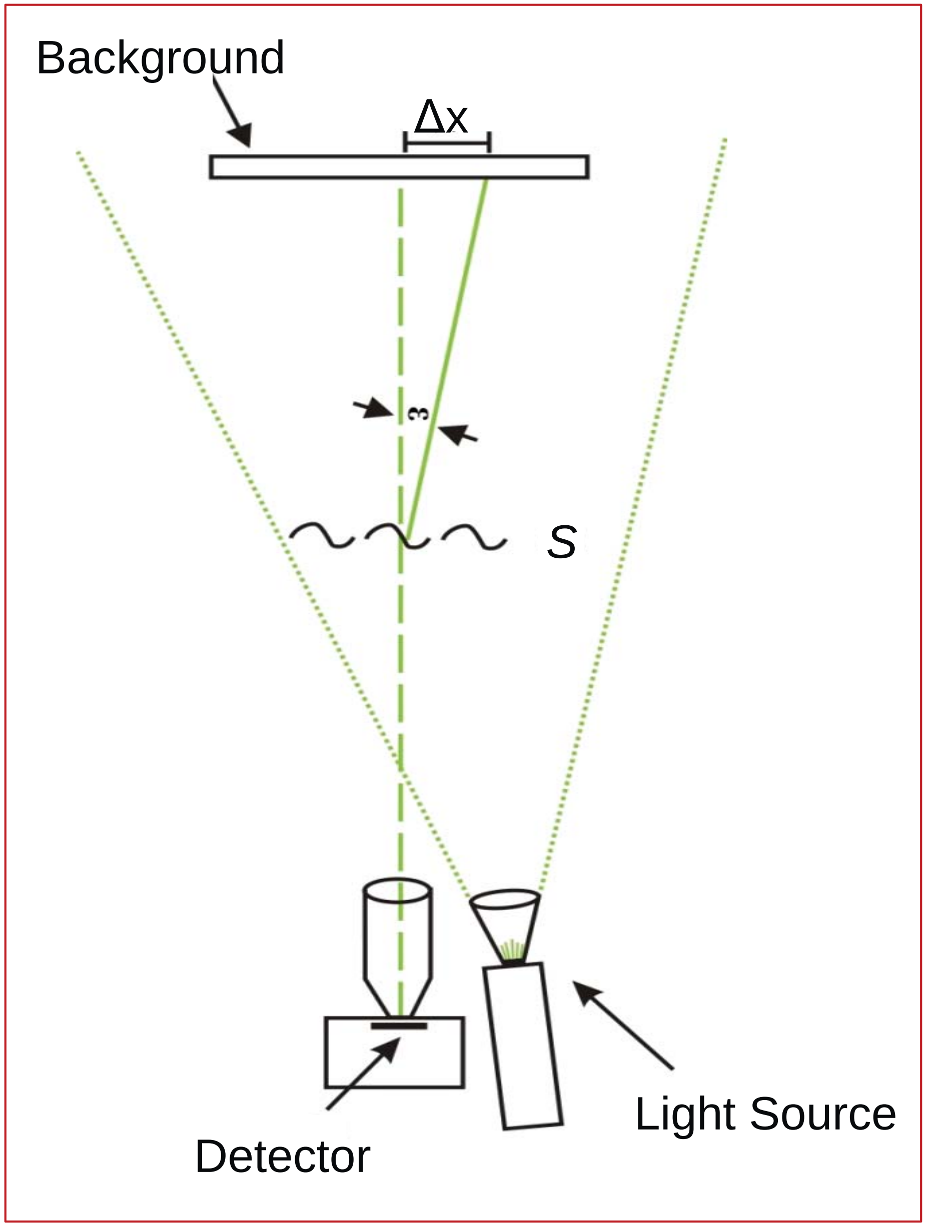
- BOS is a more recent development of the schlieren and shadowgraph techniques used to non-intrusively visualize density gradients.

- Based on an apparent movement of the background when imaged through a density field onto a detector plane.

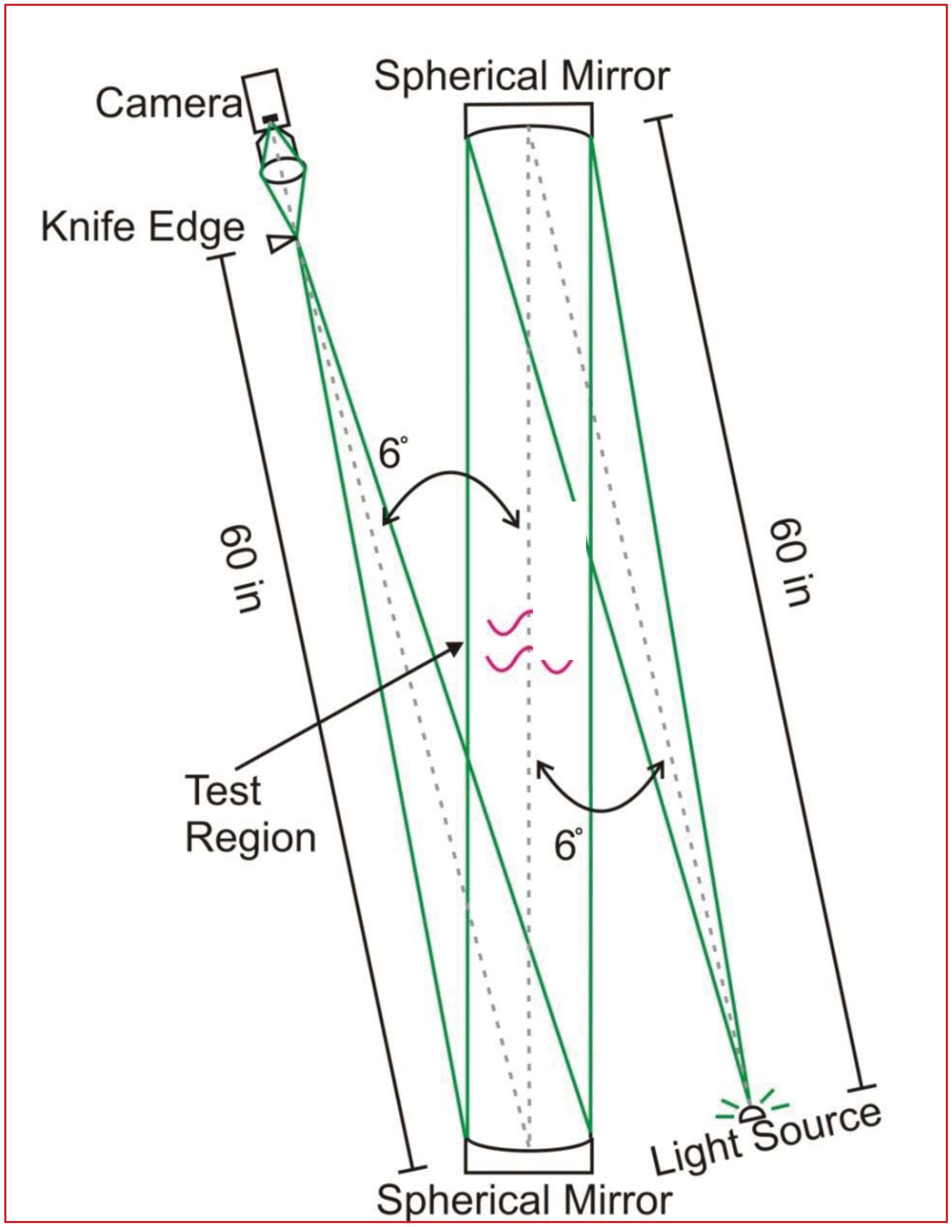
- Schlieren and shadowgraph techniques can be difficult, time consuming, and costly due to large mirrors/lenses and precise alignment.

- BOS captures the density field but only requires a CCD camera, light source, and a high-contrast background.

BOS vs. Classical Schlieren



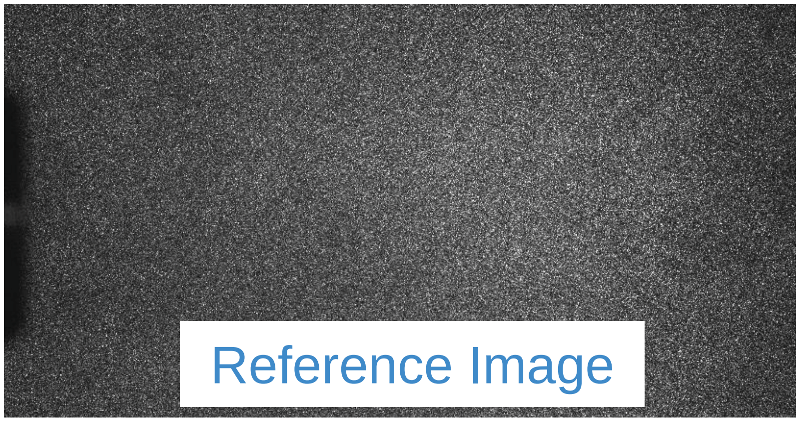
BOS

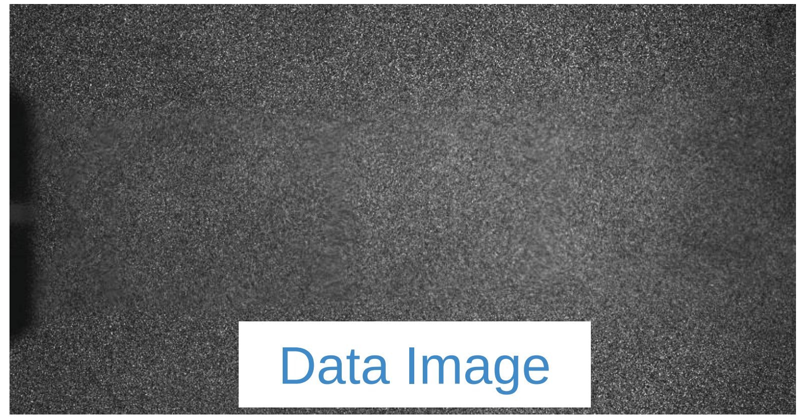


Classical Z-type Schlieren

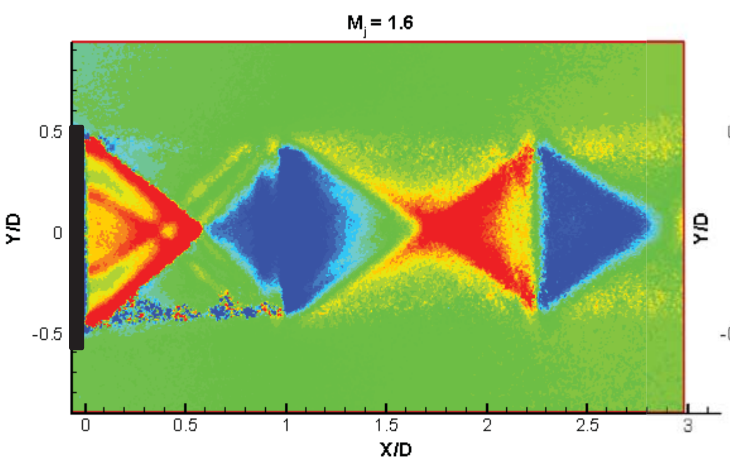
Sample BOS Data

- It is necessary to take **two** images when acquiring BOS data
- Shift between the two images can be calculated by correlation methods (PIV)

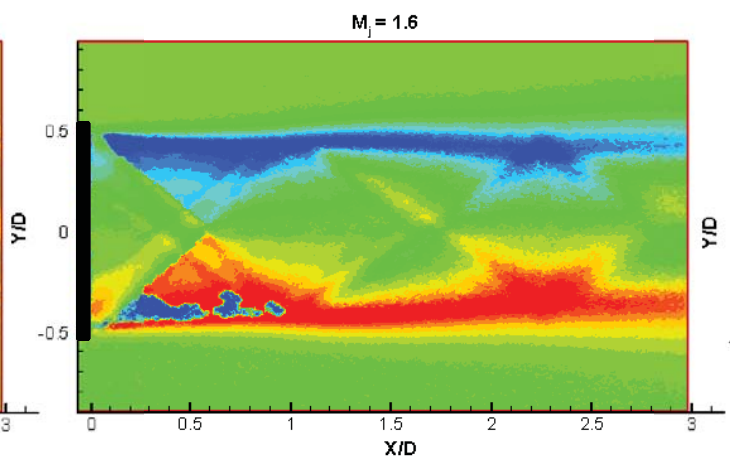




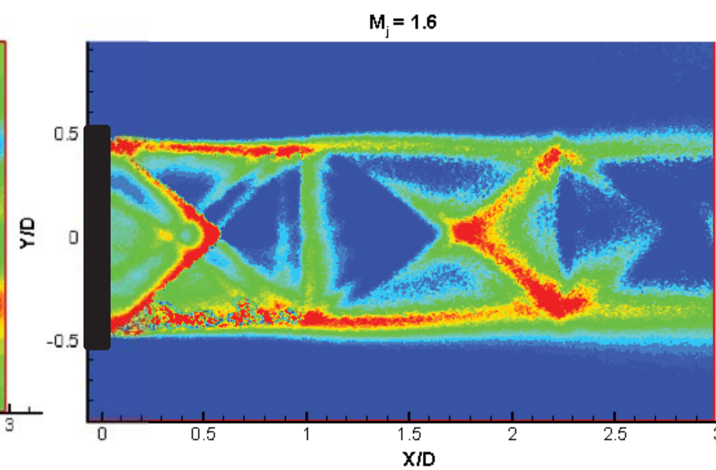
- BOS has the unique ability to distinguish the density gradient as a vector quantity



Axial (x) gradient



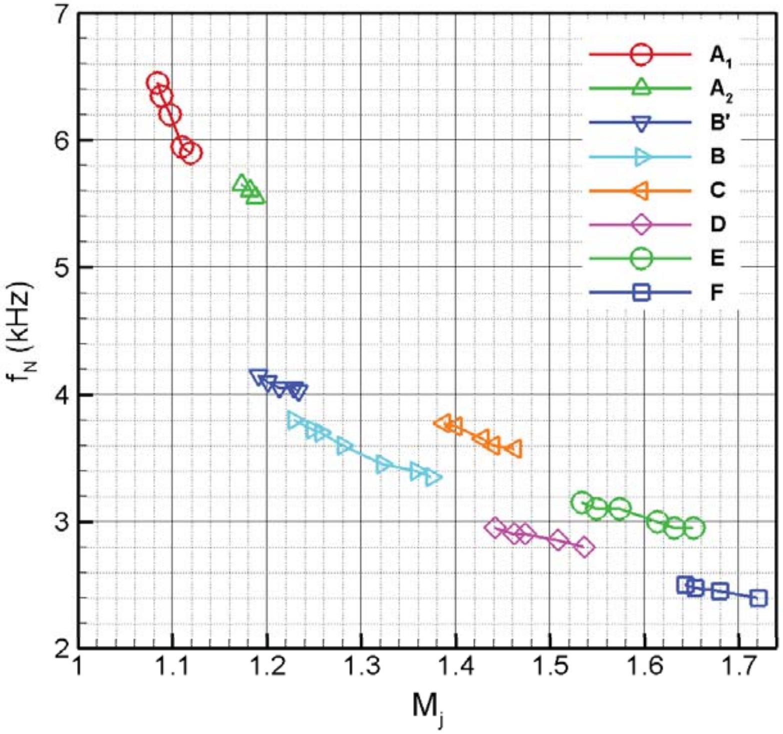
Radial (y) gradient

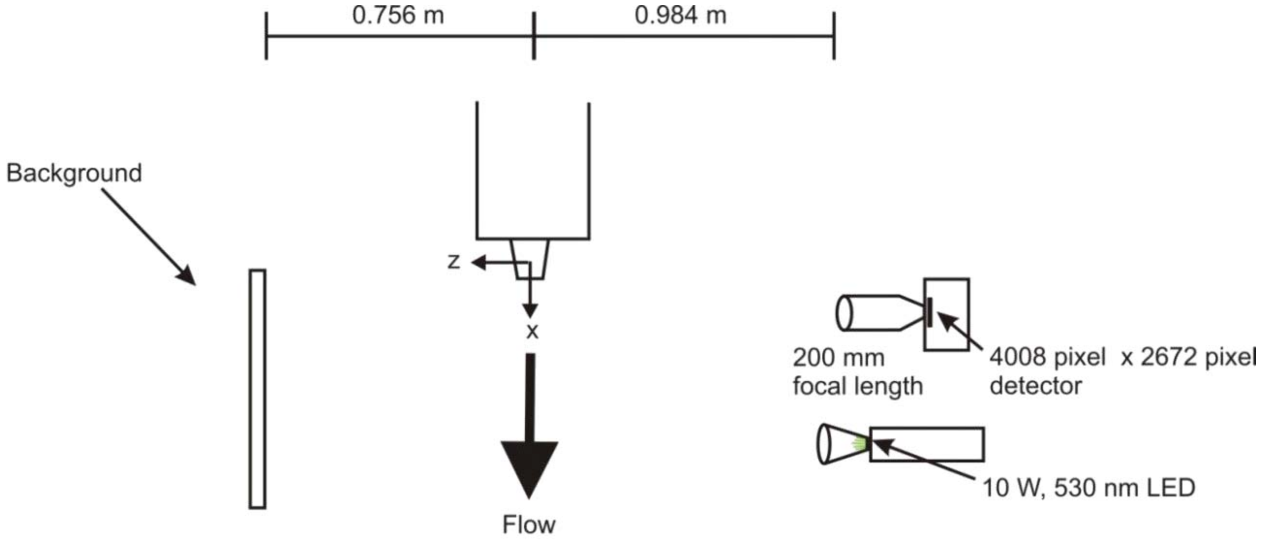


Resultant Magnitude

BOS Implemented to Investigate Screech

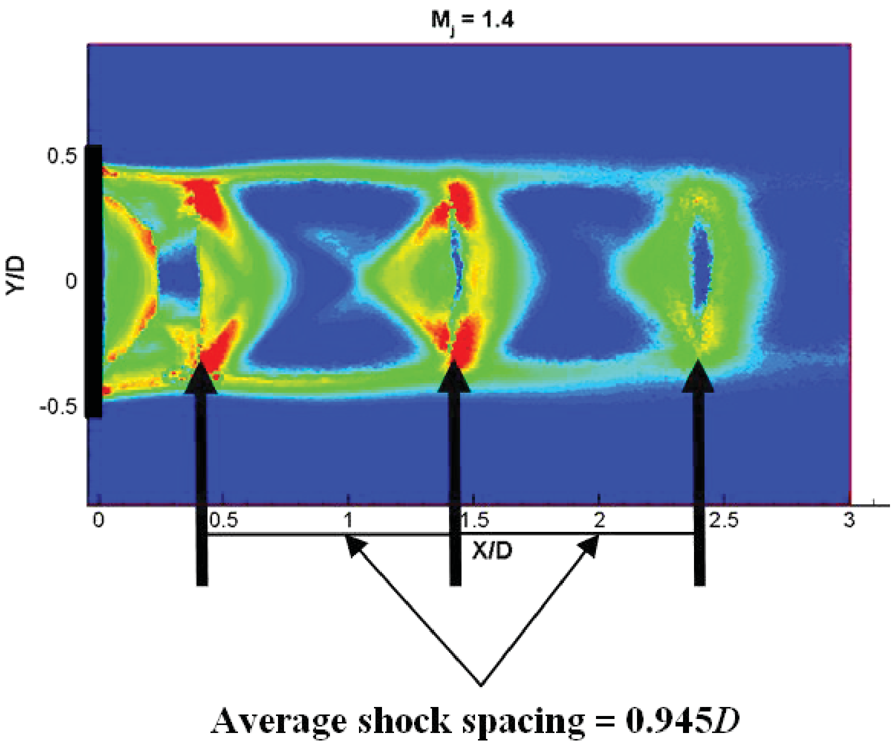
Objective: Use BOS to investigate the stage-jumping behavior of screech in an open jet rig

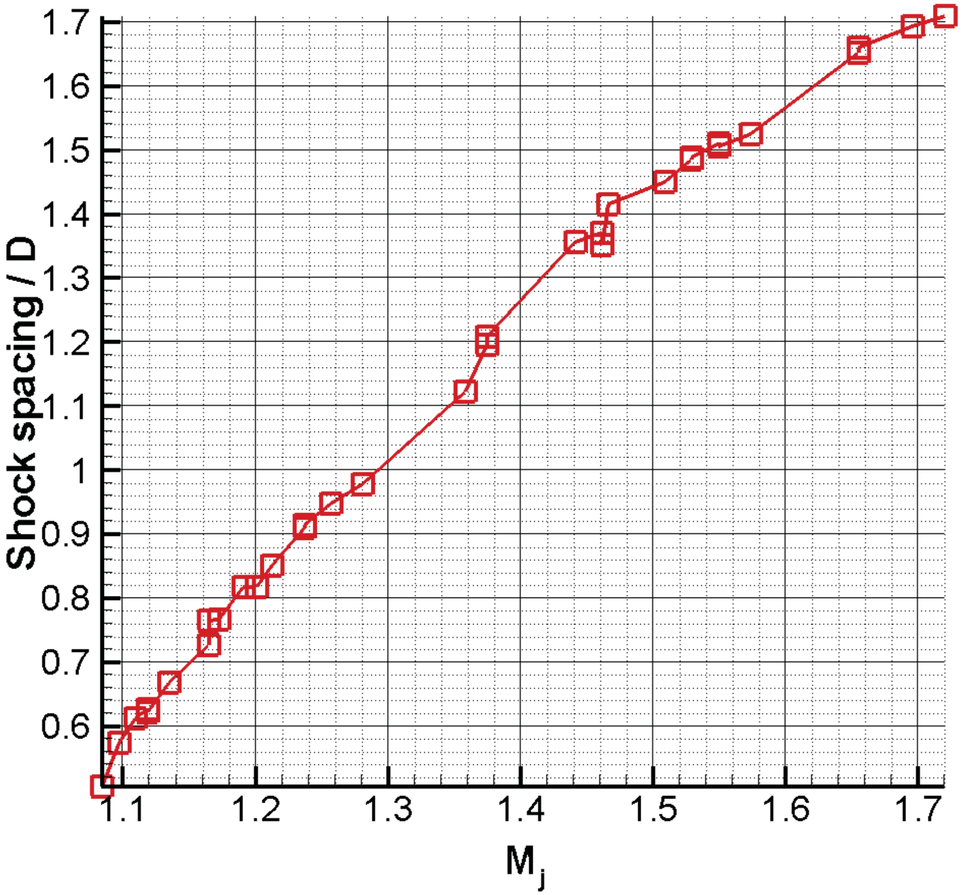




Screech tones are a component of noise generated by supersonic jets operating at imperfectly expanded conditions

BOS Implemented to Investigate Screech



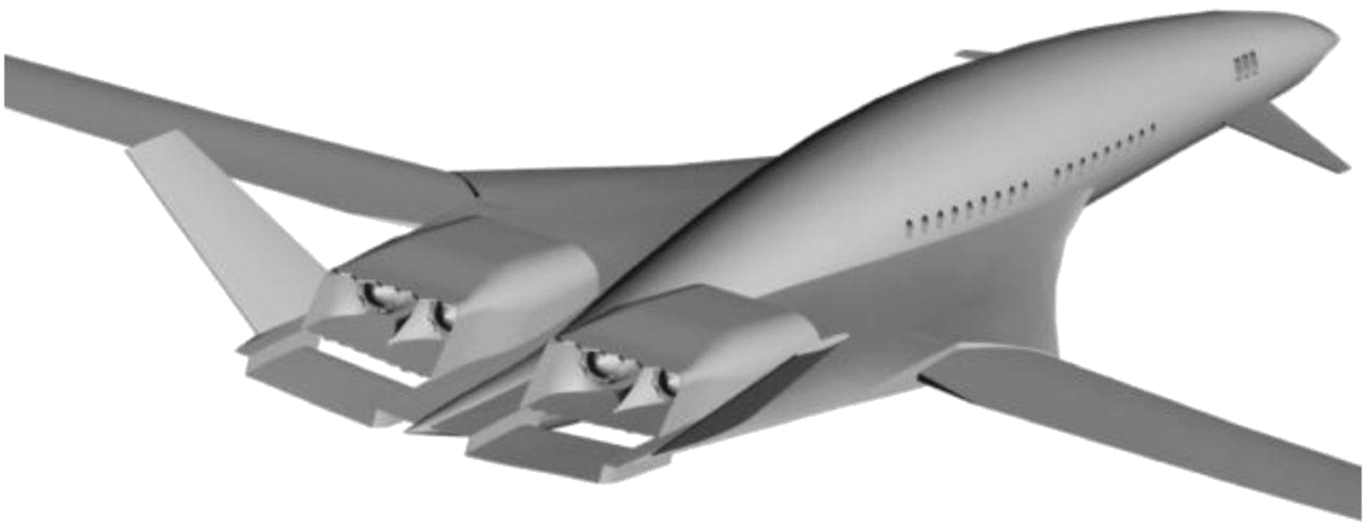


- Shock spacing follows the expected monotonic trend – no large departures
- Does NOT display and abrupt change for overlapping stages at the M_j where hysteresis occurred

BOS to Study Jet-Surface Interaction Noise

Objective: Use BOS to investigate jet-surface noise in an environment not suitable for conventional flow vis

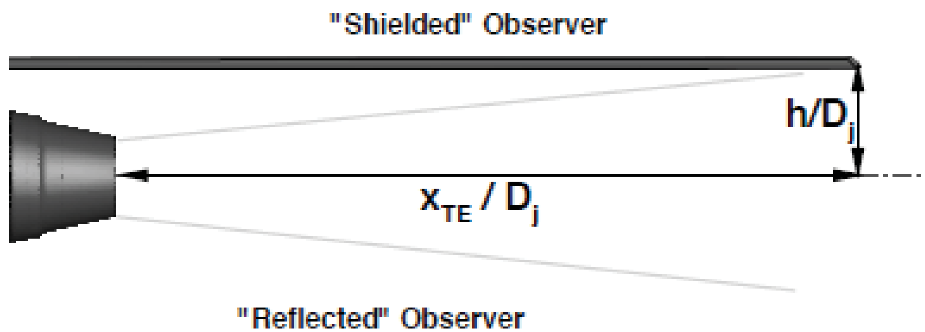
Jet-surface interaction noise - Noise created by the high-speed engine exhaust striking/passing near a solid surface

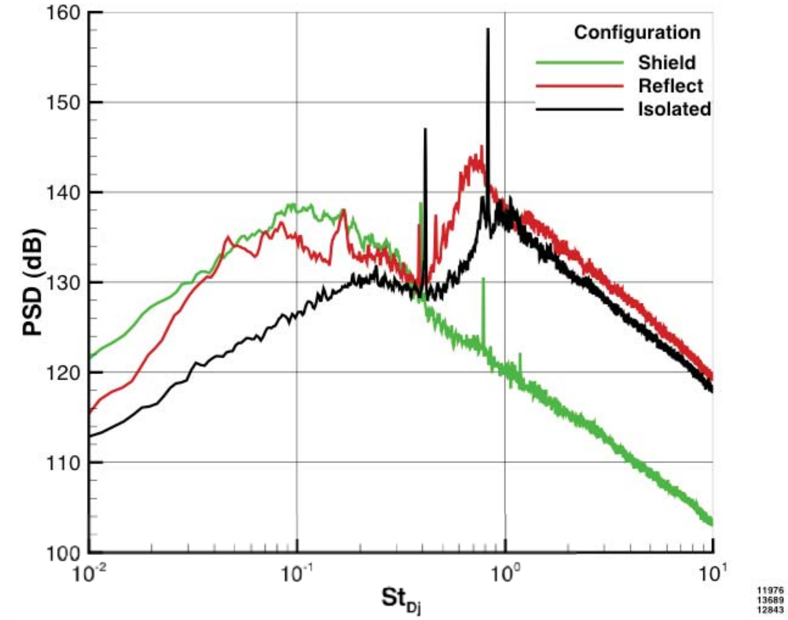


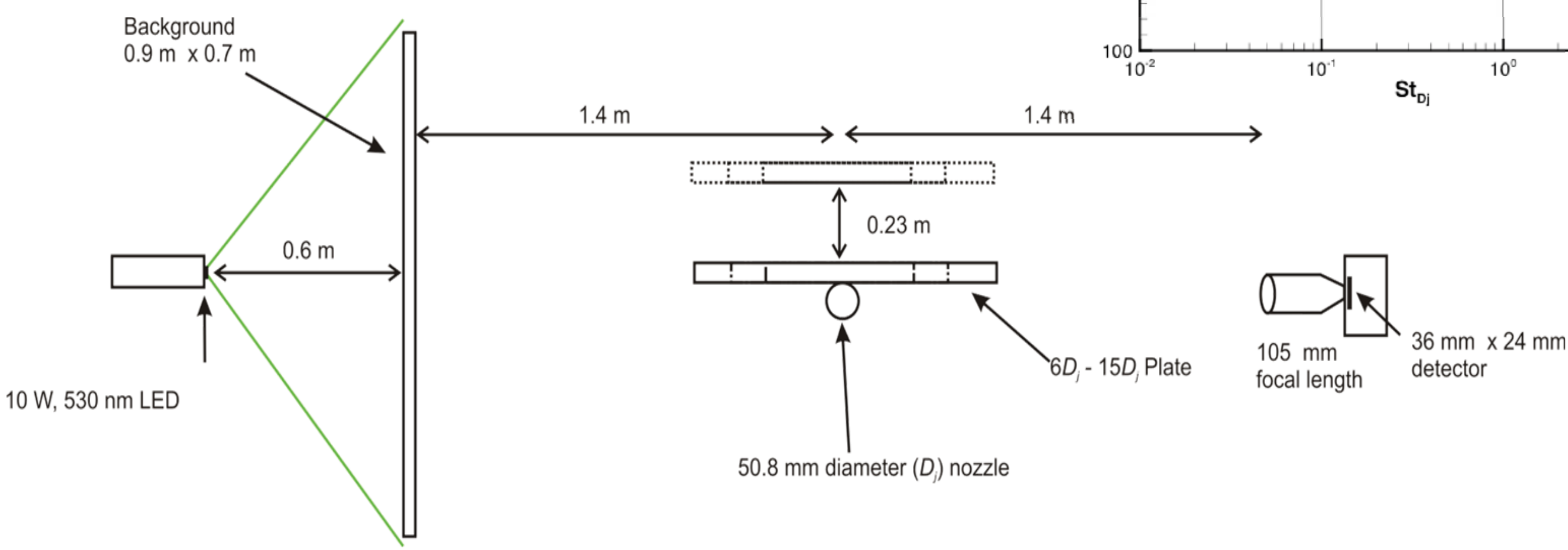
- The current generation of noise prediction tools / methods are not well equipped for the tight engine & airframe designs

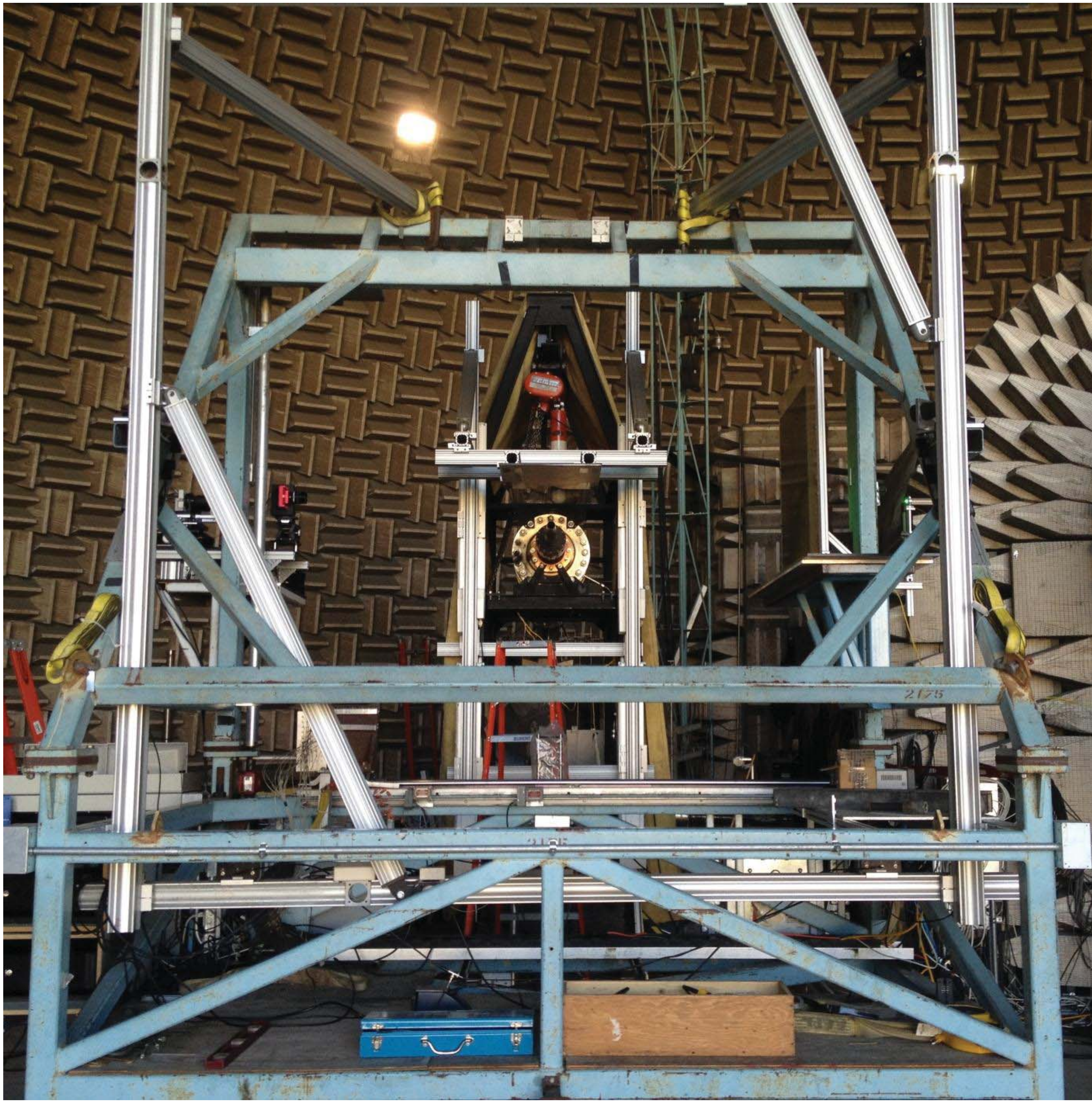
BOS to Study Jet-Surface Interaction Noise

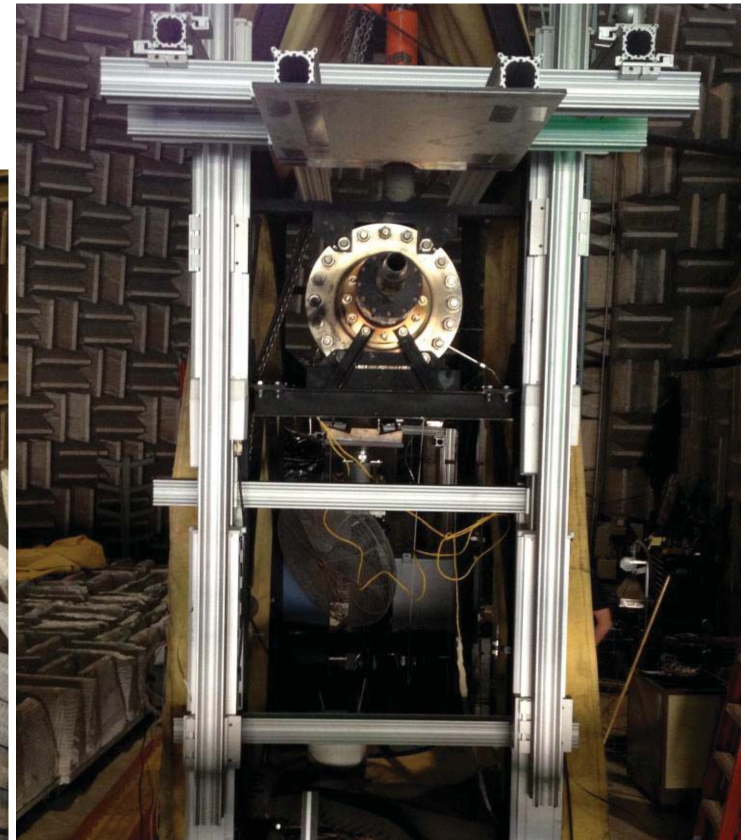
Challenge: Unclear if surface provides shielding effect or interacts with shock cells to decrease broadband shock noise (BBSN)



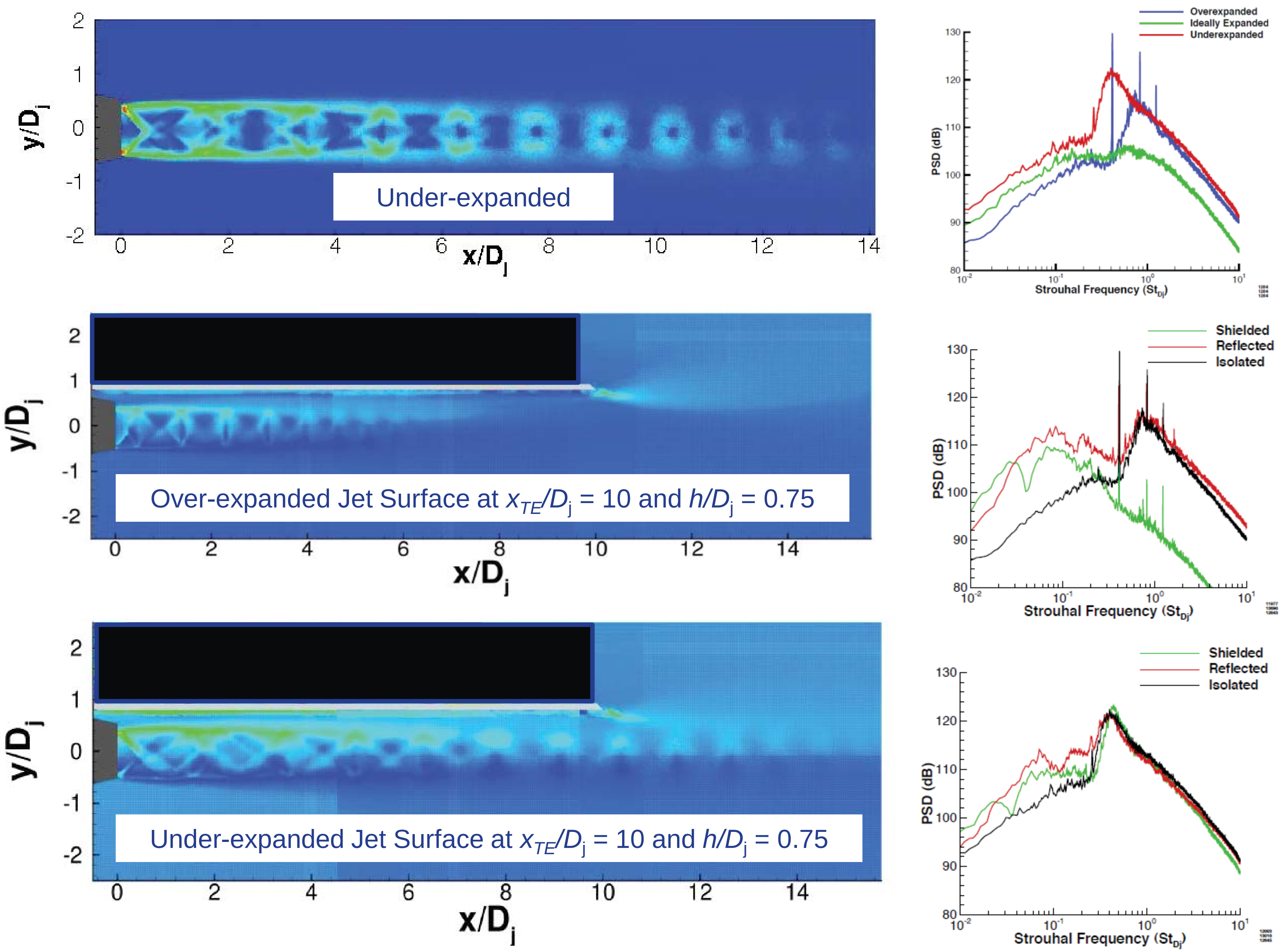






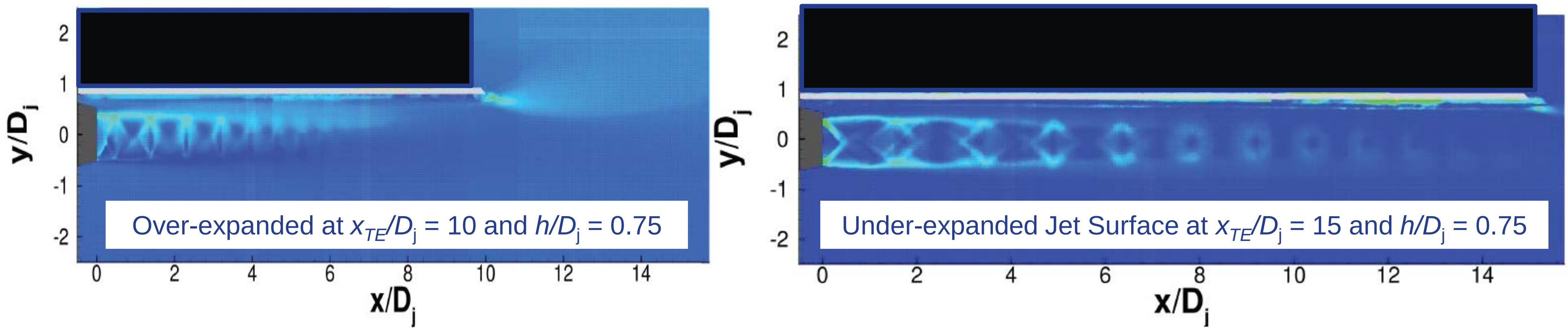


BOS to Study Jet-Surface Interaction Noise

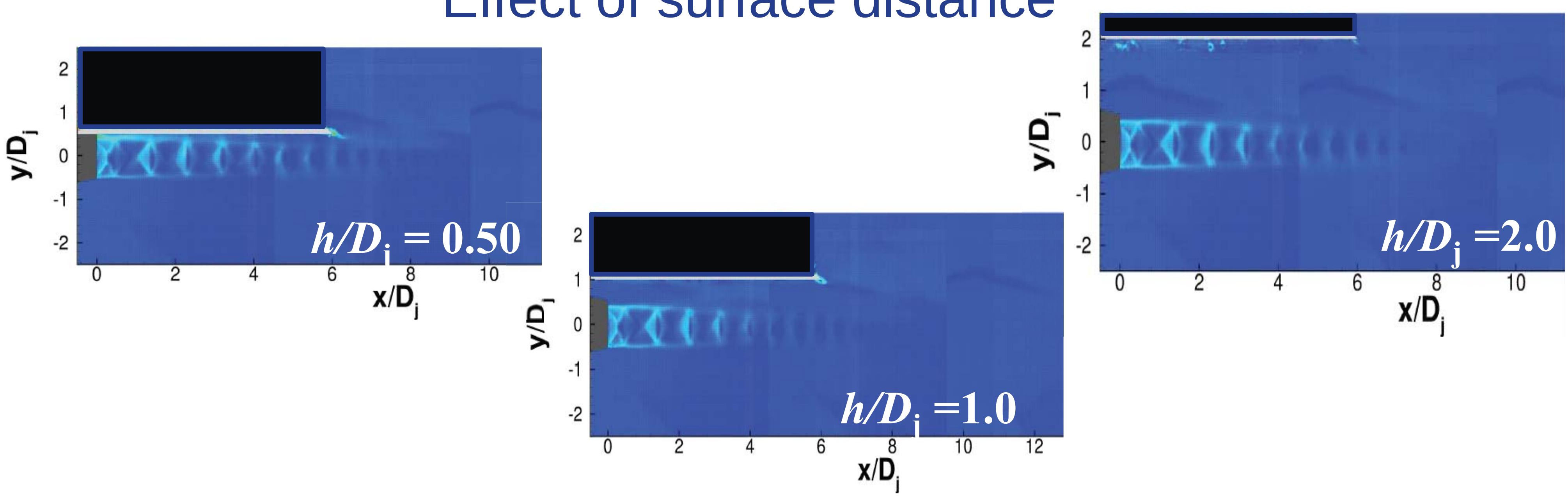


BOS to Study Jet-Surface Interaction Noise

Effect of surface length

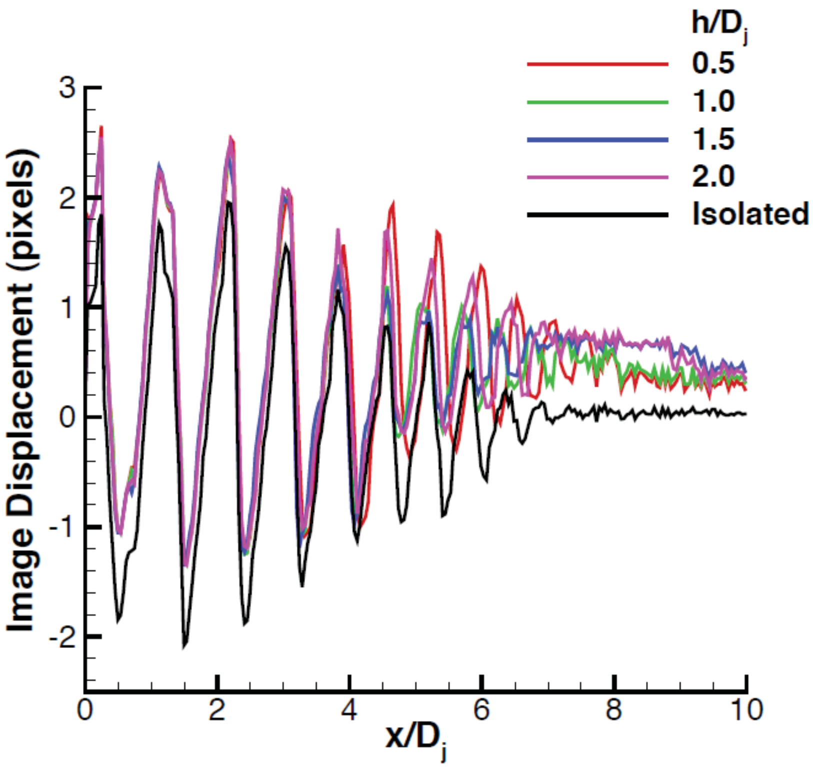


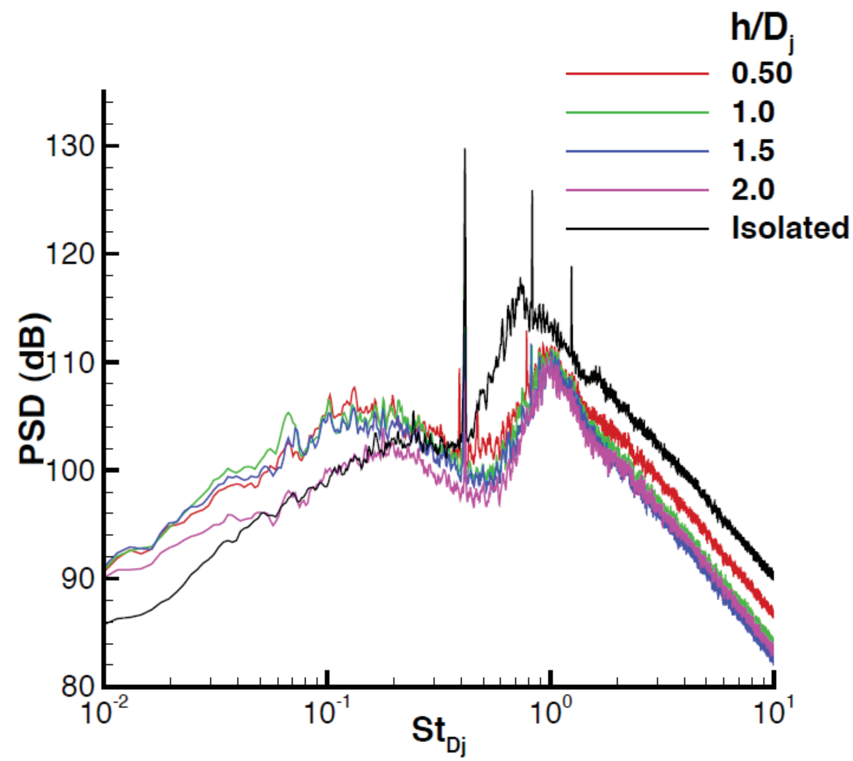
Effect of surface distance



BOS to Study Jet-Surface Interaction Noise

Status: It was determined that changes to the shock cell structure due to the nearby surface have a smaller impact on the BBSN compared to the surface shielding effect. BBSN may be shielded by surfaces close to the jet if those surfaces are sufficiently longer than the shock cell train. Results published in the *AIAA Journal of Aircraft.*



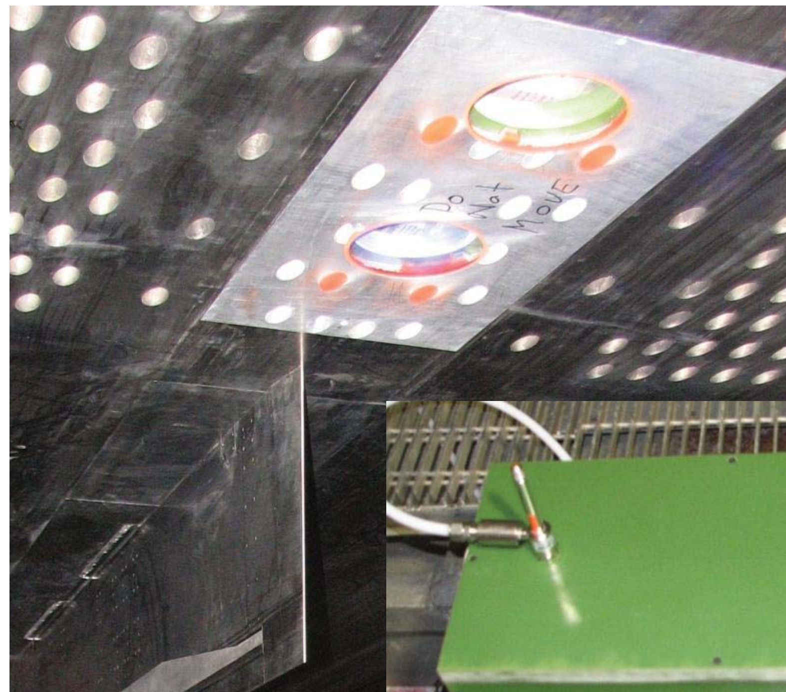


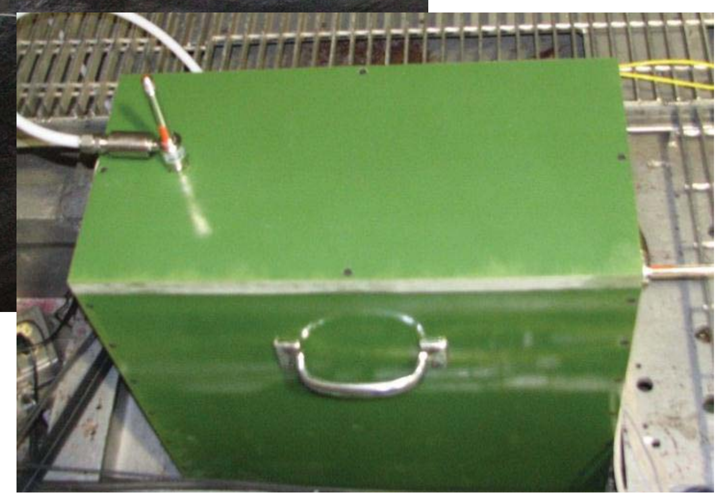
Over-expanded jet for surface at x_{TE}/D_j = 6 and h/D_j = 0.5, 1.0, 1.5, and 2.0

8x6 SWT BOS Demonstration

Near term objective: **Use BOS in the 8x6 to demonstrate its capabilities and further refine its usage for future wind tunnel applications**

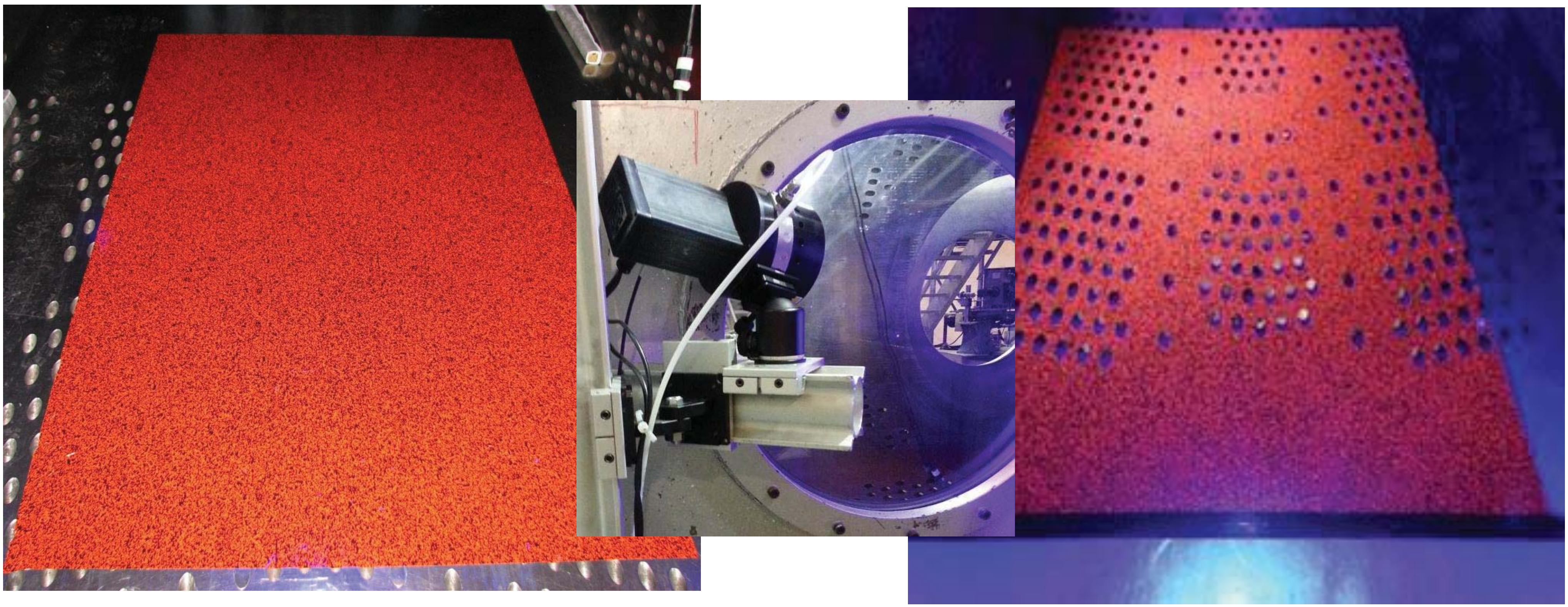
Challenging Environment: **The BOS background had to withstand flow conditions up to M=2 and temperatures up 200˚ F. The camera and requisite lighting all had to survive the ~200˚ F and vibrational environment of the 8x6 balance chamber**





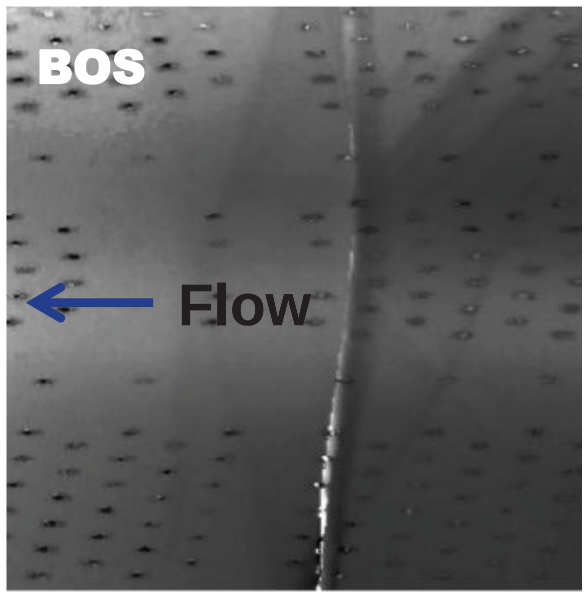
8x6 SWT BOS Demonstration

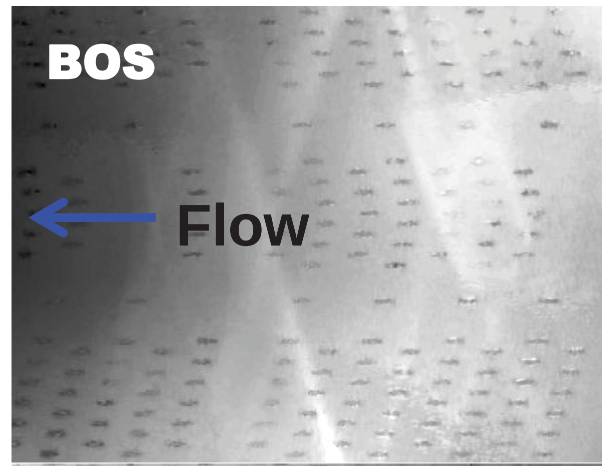
Description: **A fluorescent adhesive background was designed and installed onto the tunnel floor and was shown to survive the harsh conditions.** ***The fluorescent background allows lighting to be applied at any angle as opposed to being nearly perpendicular as required by traditional retro-reflective backgrounds.***

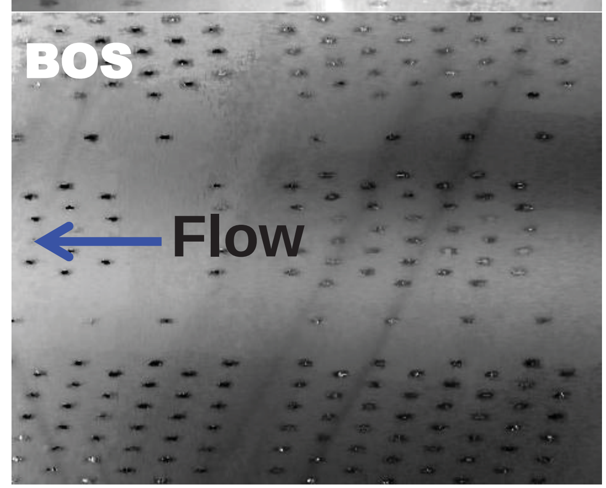


8x6 SWT BOS Demonstration

Status: Data was successfully acquired at conditions up to M=2. ***This is a significant GRC development as this is the first time BOS has been implemented in a GRC wind tunnel***. In addition, flow visualization has never been performed in the top-down direction at the 8x6 wind tunnel. ***This development will allow imaging in locations previously not achievable with conventional Schlieren.***



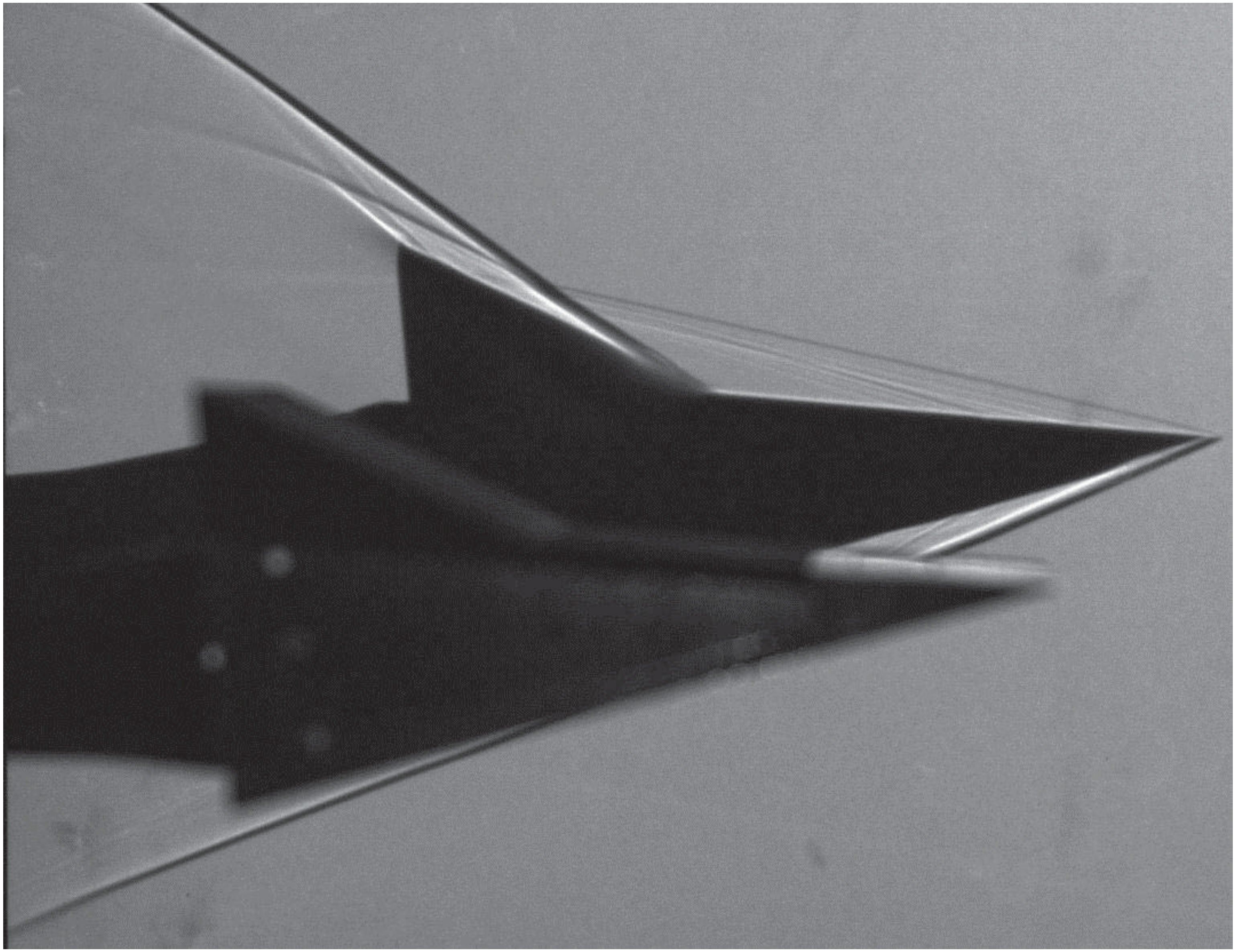




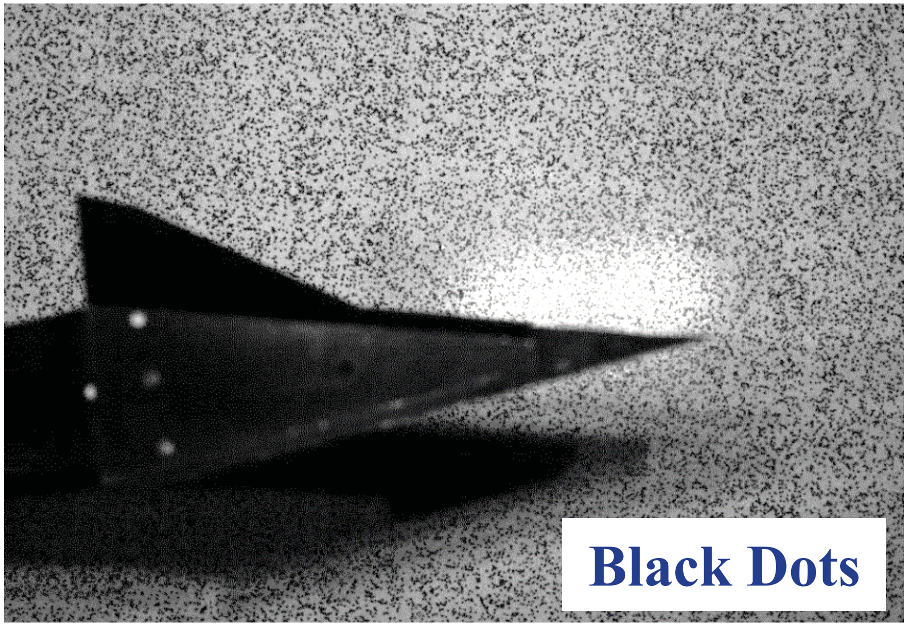
BOS and Conventional Schlieren at same condition. Different views: BOS from top and conventional from side

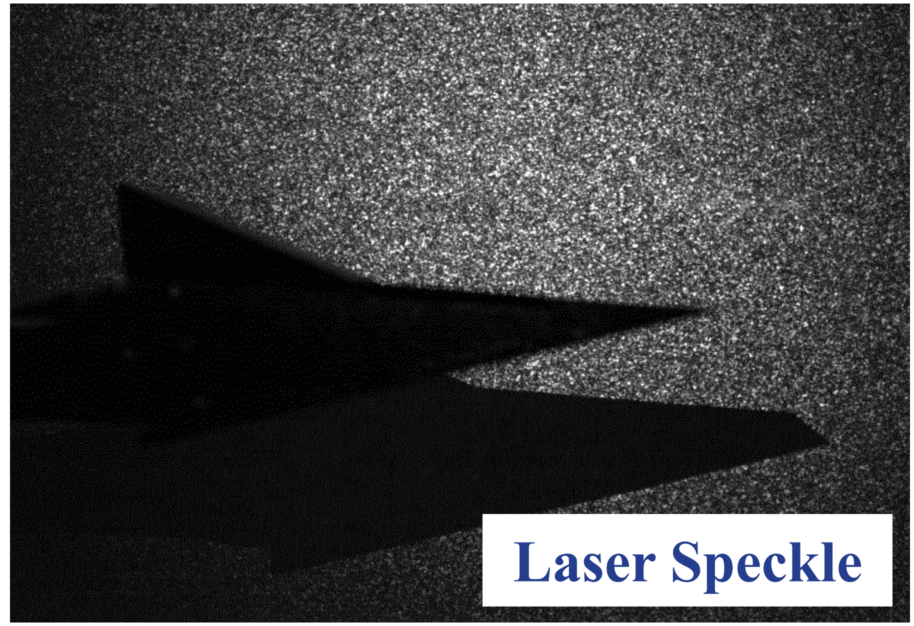
LaRC Collaboration
15-Inch Mach 6 High-Temperature Air Tunnel

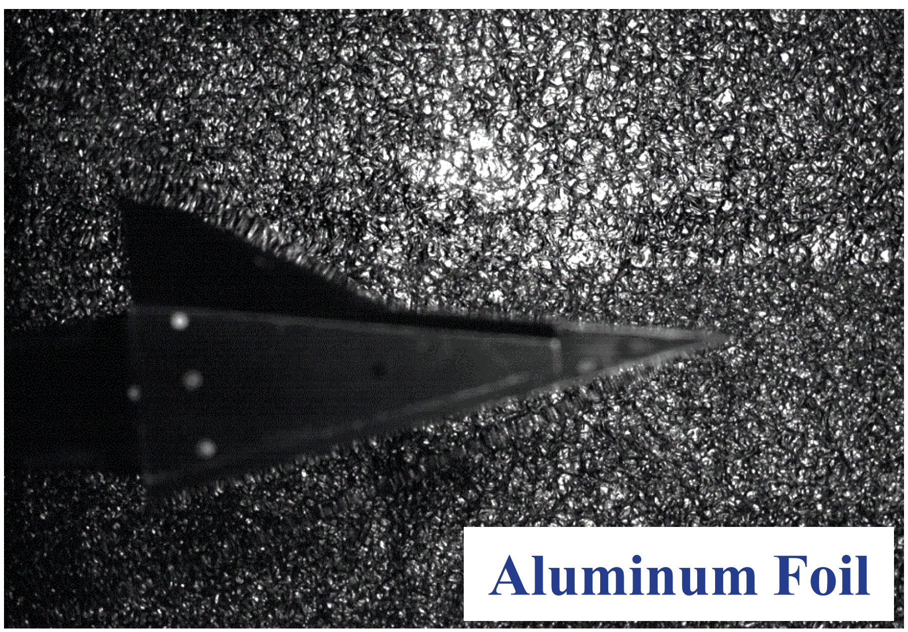
Shadowgraph Reference for BOS Comparison

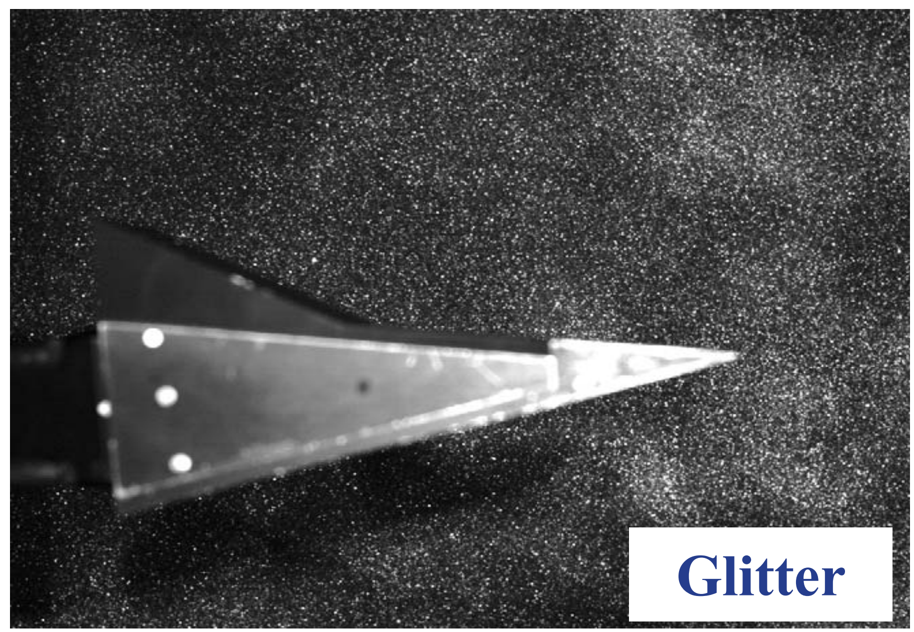


Background Comparison

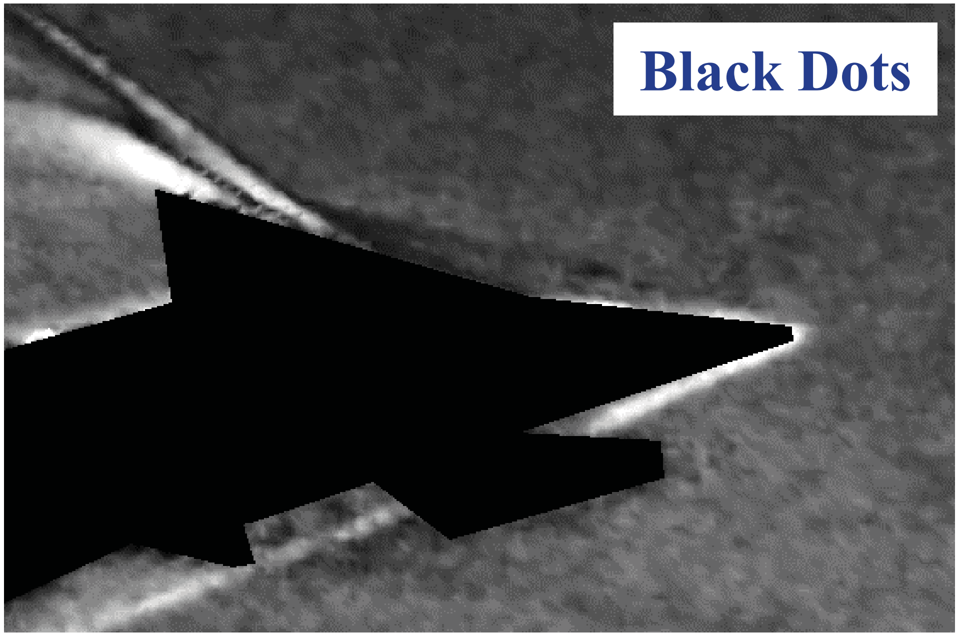


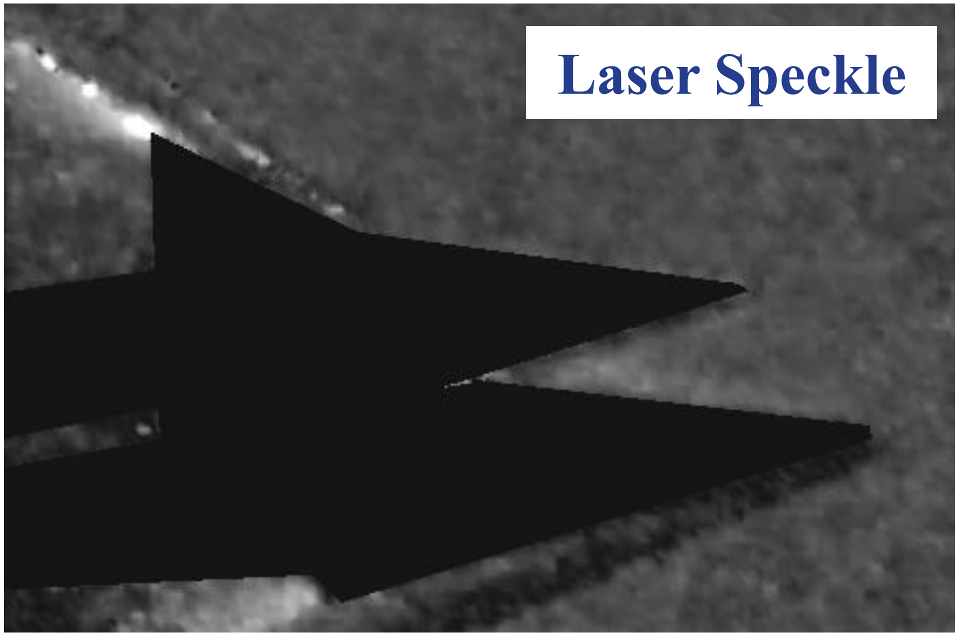


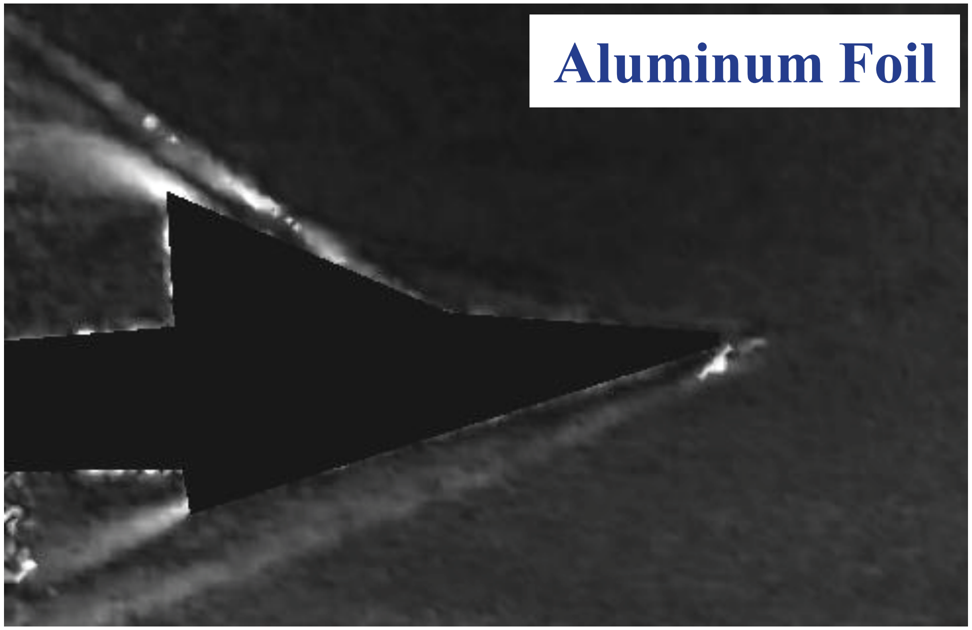


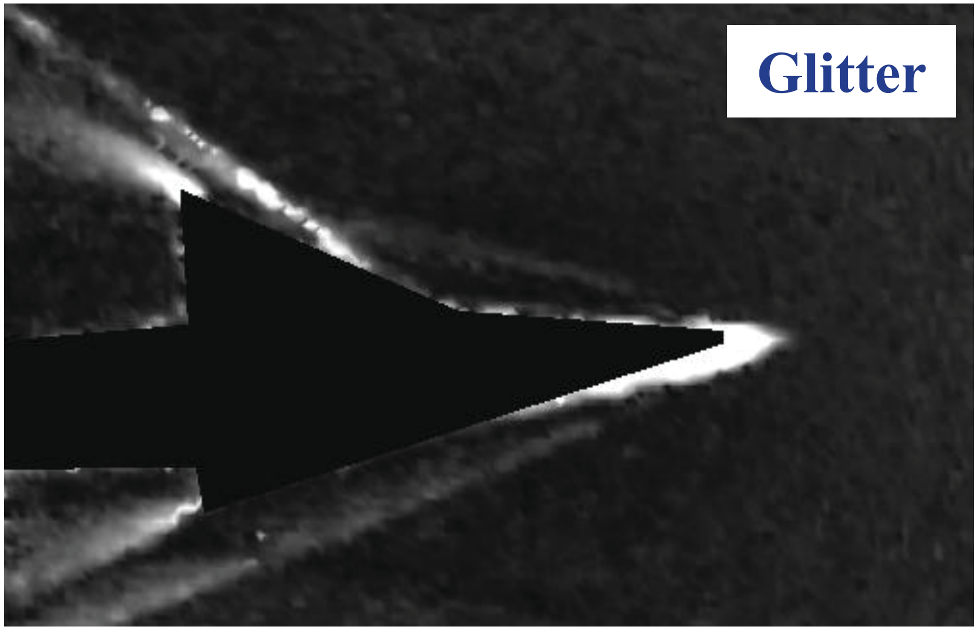


Background Comparison Cont’d

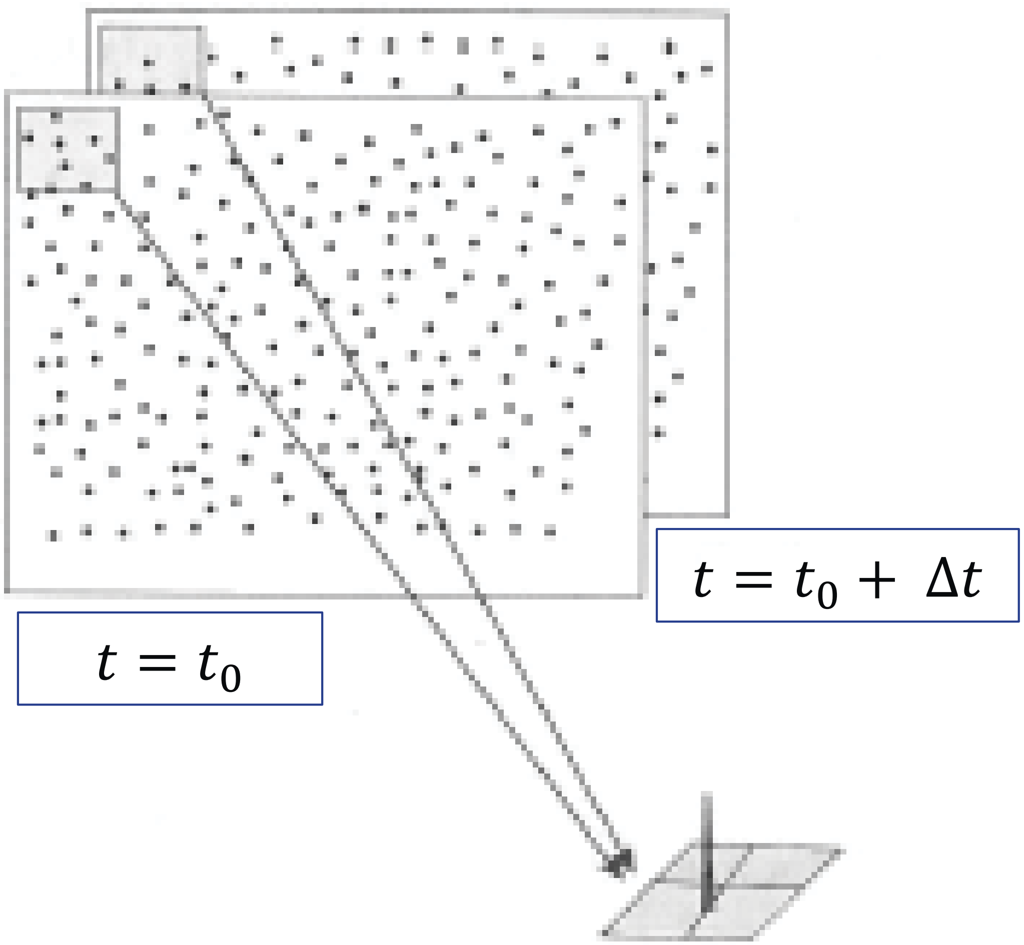






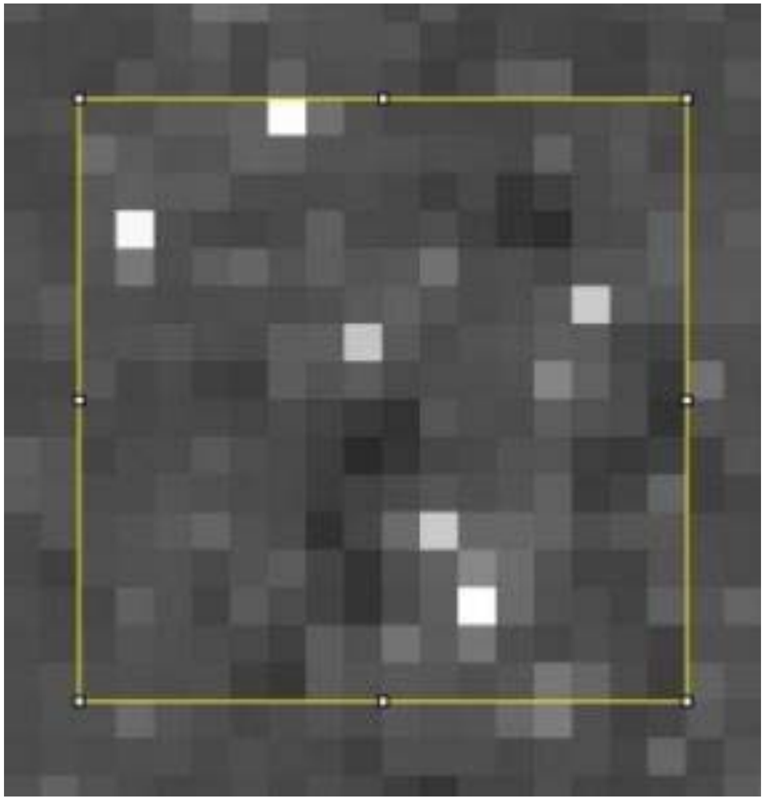


Theory: Cross-Correlation Processing



- Each image is divided into small sub-regions (1 & 2)
- Sub-reg 1 is cross-correlated with corresponding sub-reg 2
- Correlation plane peak gives the resulting displacement vector
- Process is repeated over the entire image
- Results in spatially averaged displacement vectors

Theory: PIV Optimization Guidelines

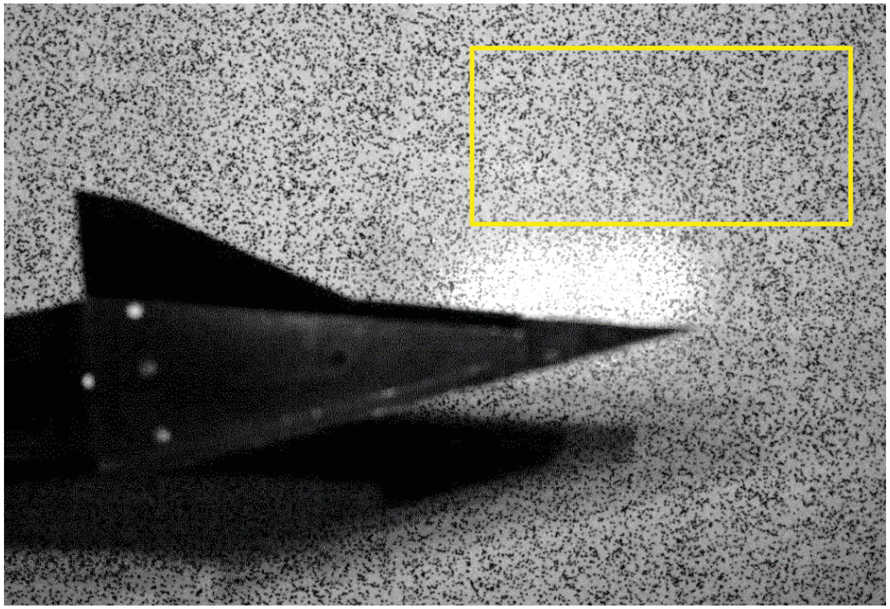


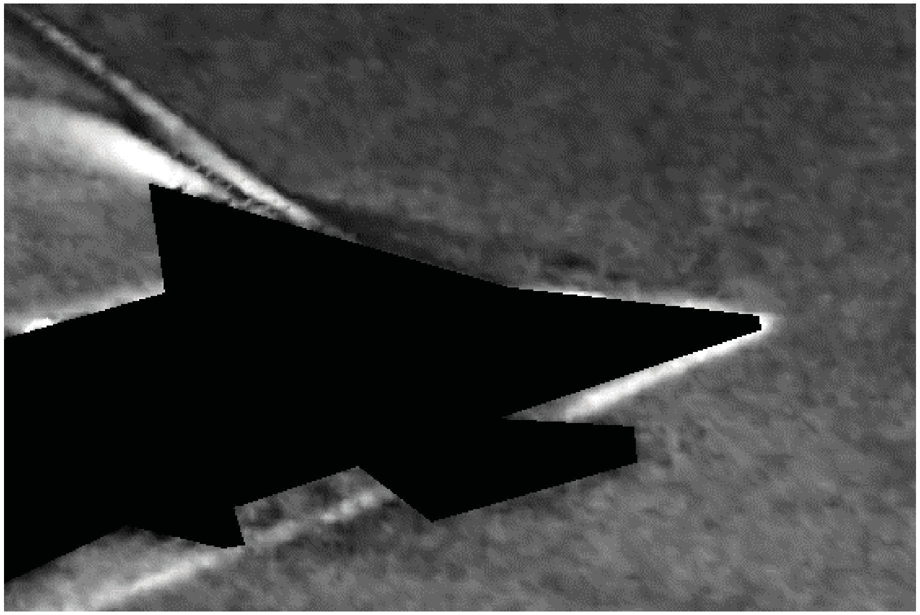
1. Imaged particle diameter spans 1-2 pixels
2. Nominally 10 particles per sub-region
3. Particle displacement should be less than 1/4th sub-region size

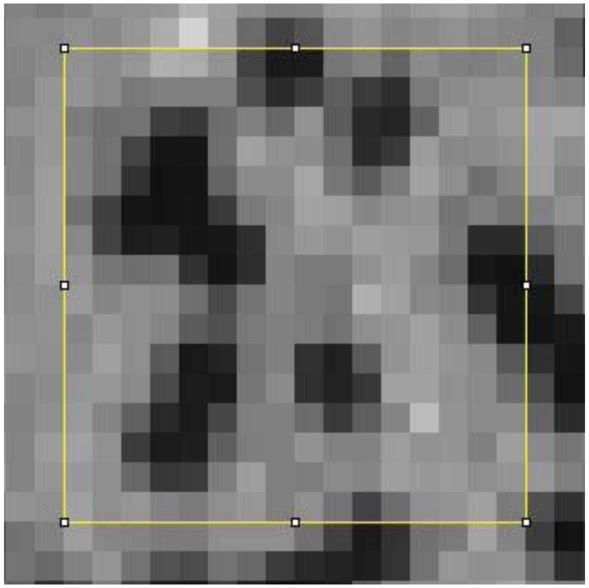
Nominal value of correlation peak error, $\sigma_D = 0.1$ pixel

Nominal sub-pixel accuracy of 0.1 pixel

“Conventional” Random Dot Pattern



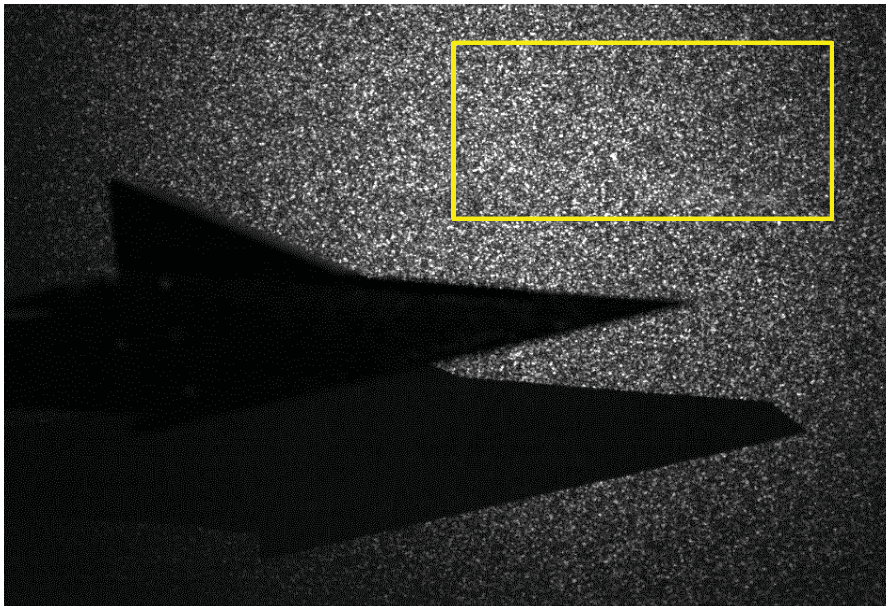


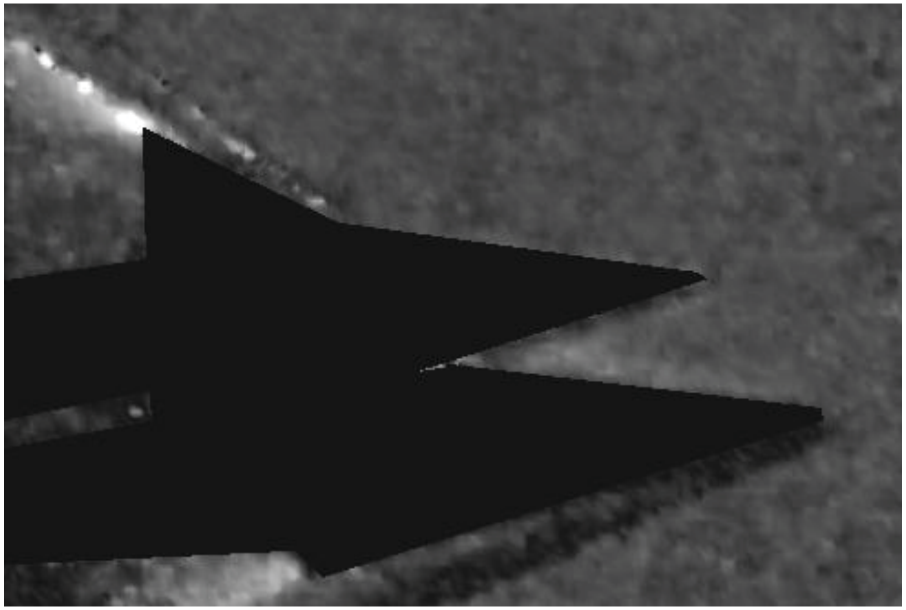


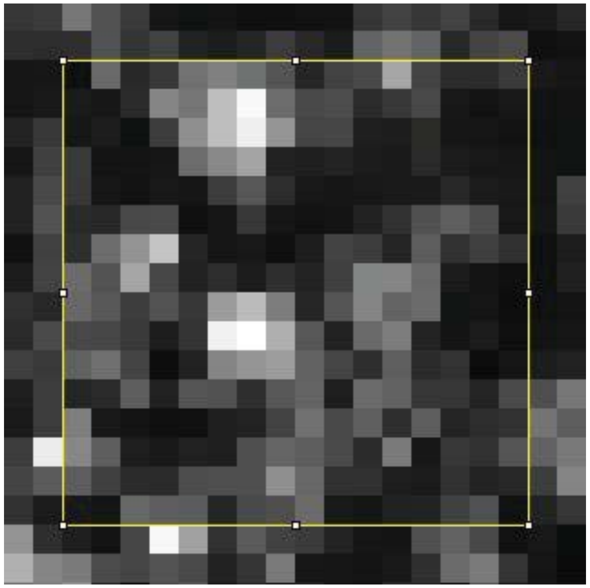
Nominal value of correlation peak error
$\sigma_D = 0.1$ pixel

$\sigma_D = 0.09\ pixels$

Laser Speckle Background

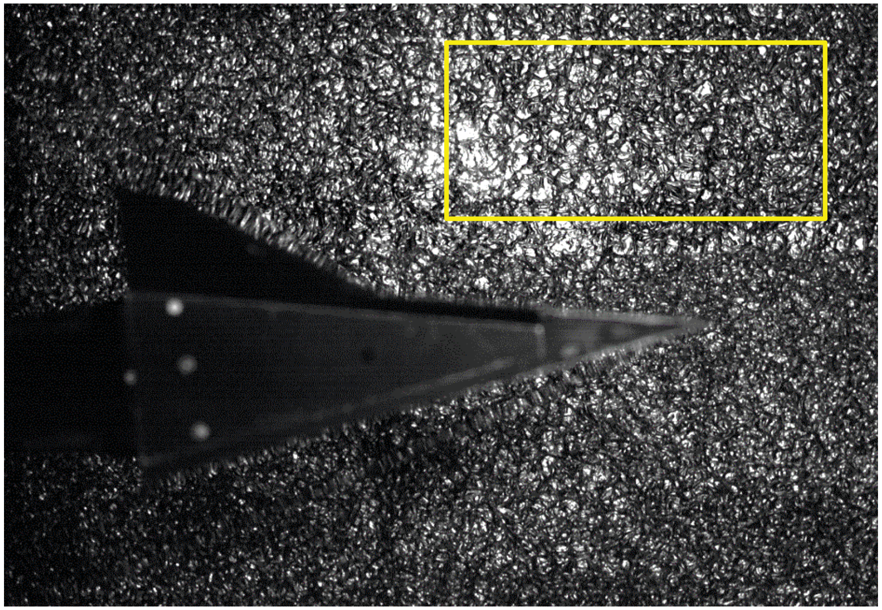


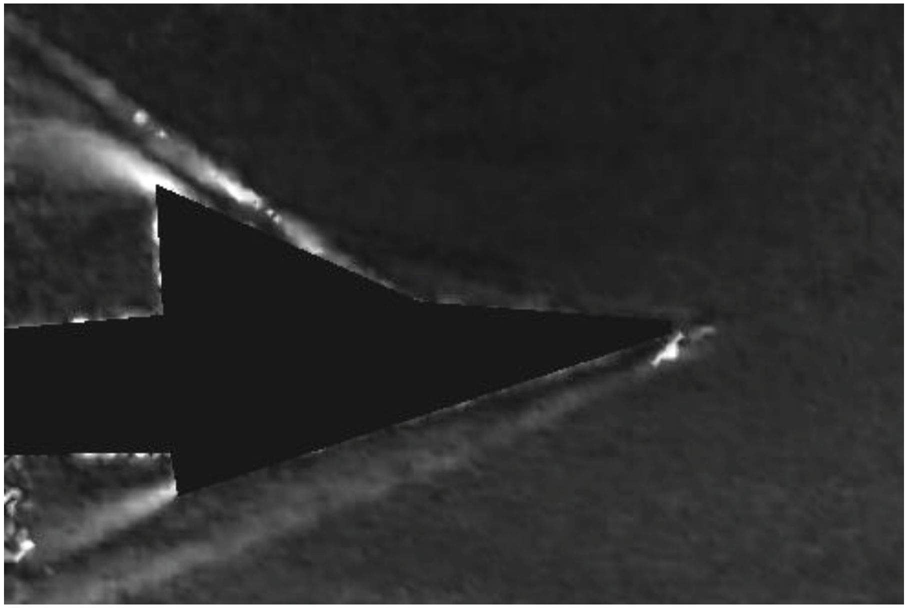


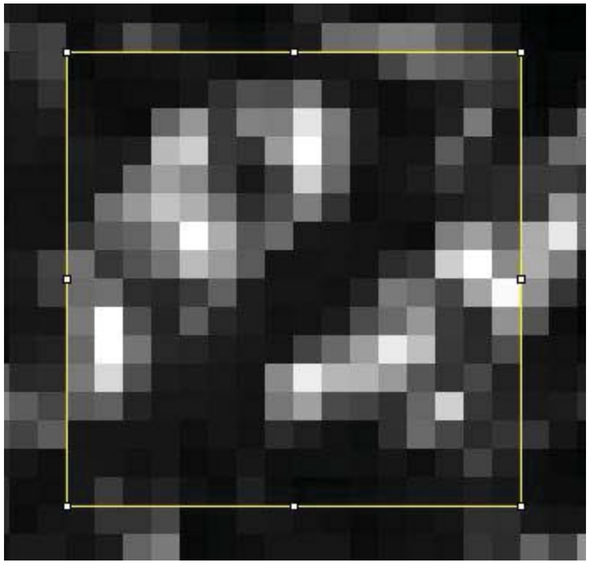


$$\sigma_{mag} = 0.38\, pixels$$

Aluminum Foil Background

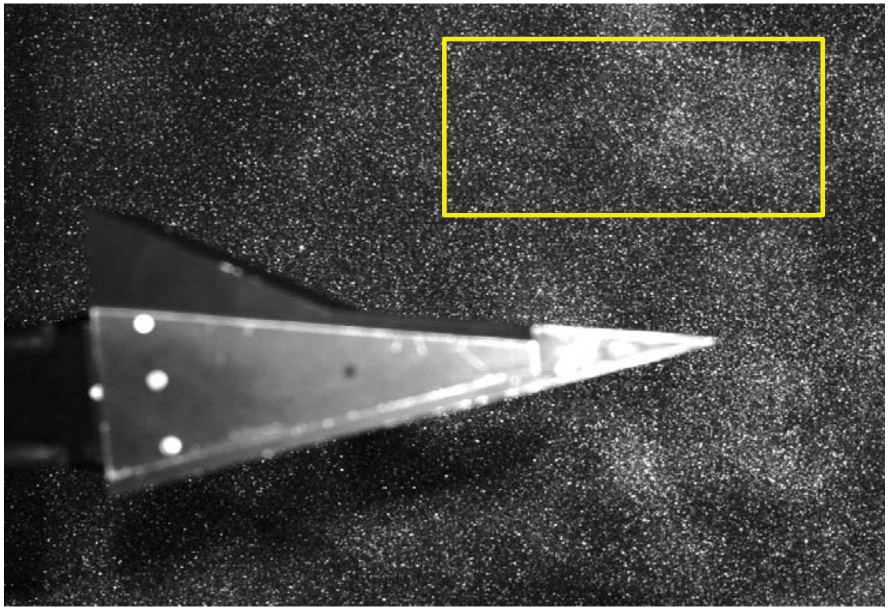


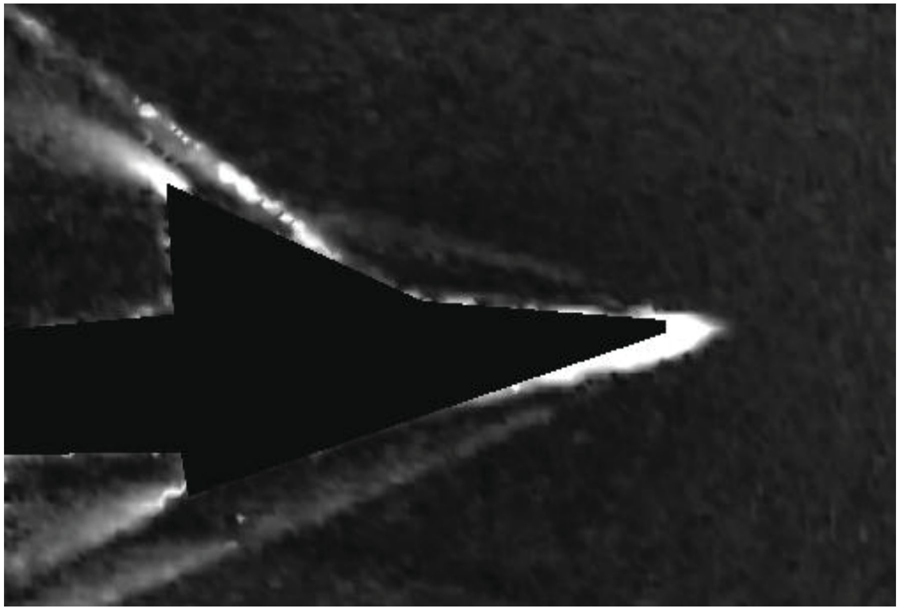


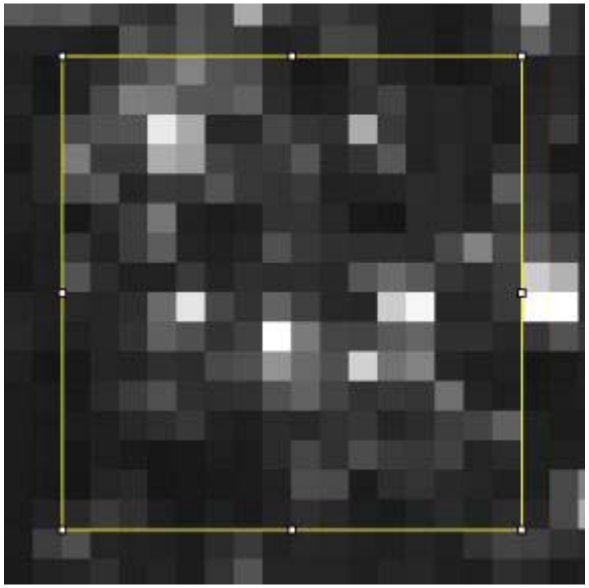


$$\sigma_{mag} = 0.42\ pixels$$

Glitter Background

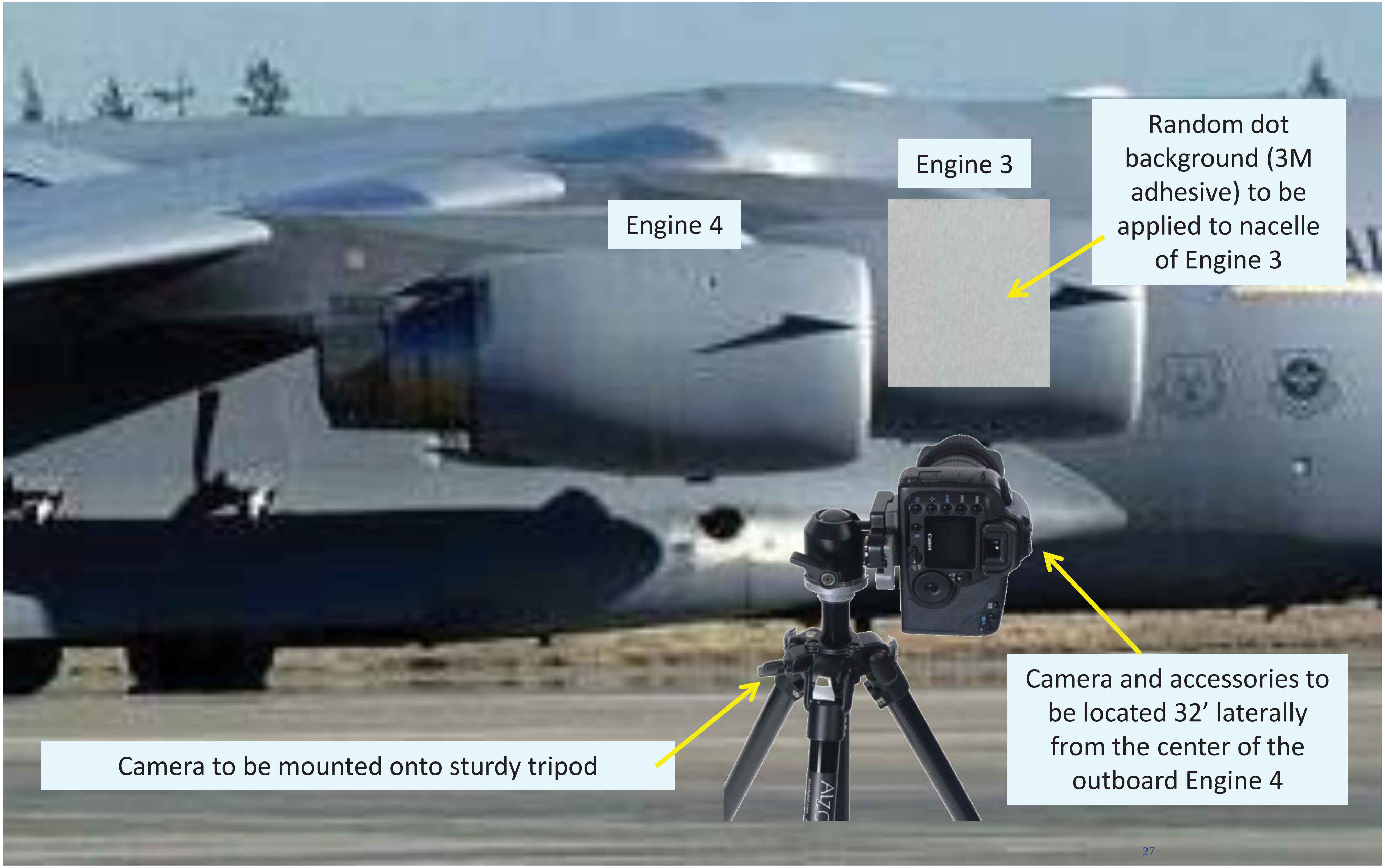






$$\sigma_{mag} = 0.39\ pixels$$

Vehicle Integrated Propulsion Project (VIPR)



NASA GRC 10-ft x 10-ft SWT

- BOS will be used for flow visualization for the Large scale Combined Cycle Inlet Test
- Model blocks the standard schlieren system; very limited optical access
- Researchers would like to see the shocks entering the inlet
- 1st time use of BOS in the 10x10 SWT
  - 305°F, Mach 3.5
  - Forward facing step < 1-2 mil
- BOS at a significant angle

https://facilities.grc.nasa.gov/10x10/gallery.html (from publically available website)

Near Future Work/Objectives

- Implement BOS in VIPR Ground Test
- 10x10 BOS Implementation
- Work with current software to see if it is possible to further refine grid and resolve smaller flow features
- Continue exploring alternative processing algorithms
  - Ed Schair's code
  - LaVision
  - Digital Image Correlation
- Investigate alternative background materials
  - Increase the light being returned
  - Additional retro-reflective materials
  - Fluorescent materials
- Simple quantitative BOS experiments

Acknowledgements

- Thank you to Mark Wernet for his PIV processing code
- NASA Transformational Tools & Technology (T3) Project
- NASA Aeronautics Evaluation & Test Capability (AETC) Project

Thank you for your time!

Questions?