Background Oriented Schlieren (BOS) and other Flow Visualization Developments & Applications at GRC

Michelle Clem

(michelle.m.clem@nasa.gov)

Mark Woike

(mark.r.woike@nasa.gov)

Optical Instrumentation and NDE Branch
NASA Glenn Research Center, Cleveland, OH

Advanced Schlieren Working Group

21-22 November 2013

BOS and Other Flow Vis Developments & Applications

BOS, shadowgraph, schlieren, focusing schlieren

Recent developments, applications & continuations:

- **Investigate screech in an open jet rig**
  - Initial study performed with BOS
  - Continued on with multiple flow vis techniques / comparative study
- **Investigate BBSN in the Jet Surface Interaction Tests**
  - BOS implemented in the Aero Acoustic Propulsion Lab
  - Parametric study carried out in an open jet rig
  - Comparative study
- **Investigate miscellaneous topics of interest**

Brief Overview – Background Oriented Schlieren (BOS)

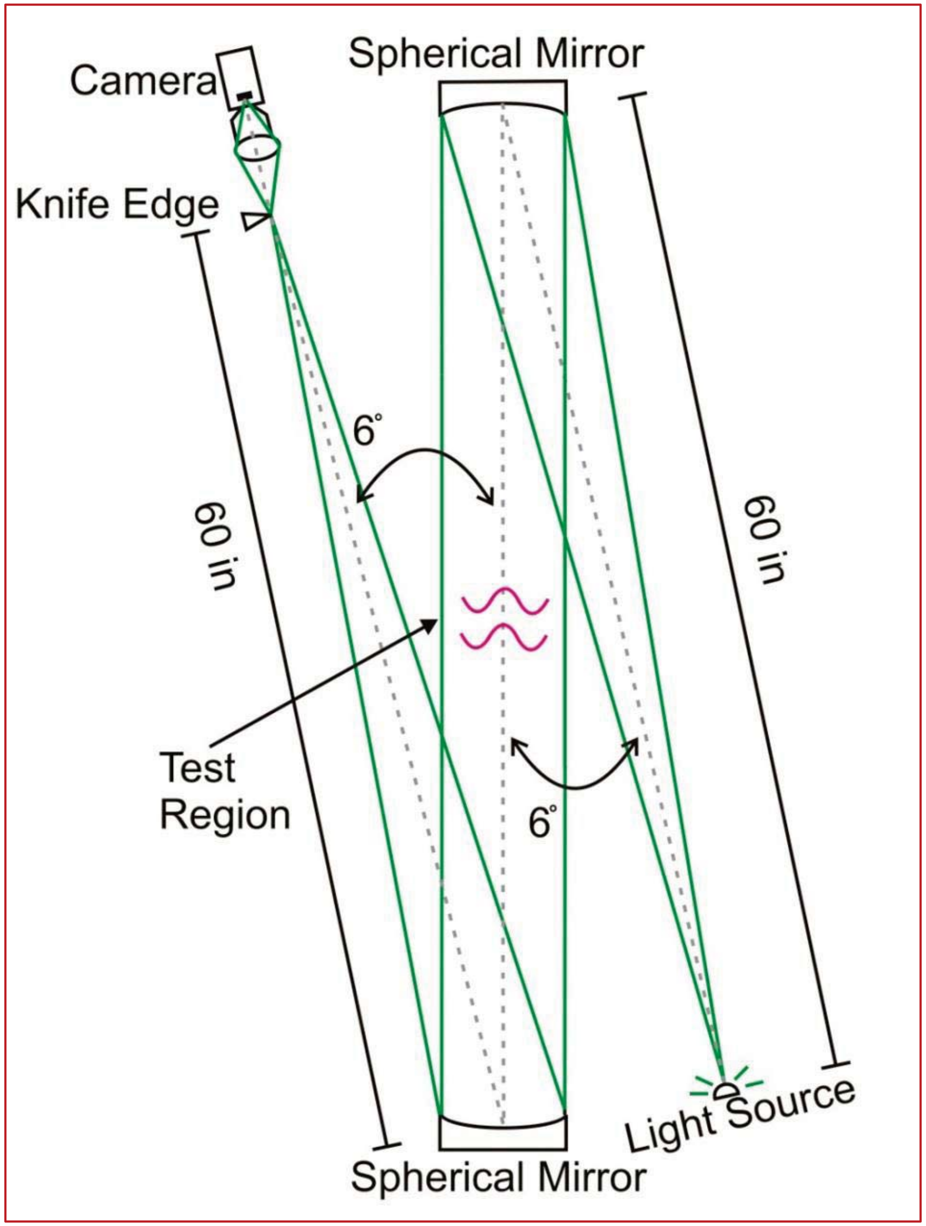
- BOS is a more recent development of the schlieren and shadowgraph techniques used to non-intrusively visualize density gradients.

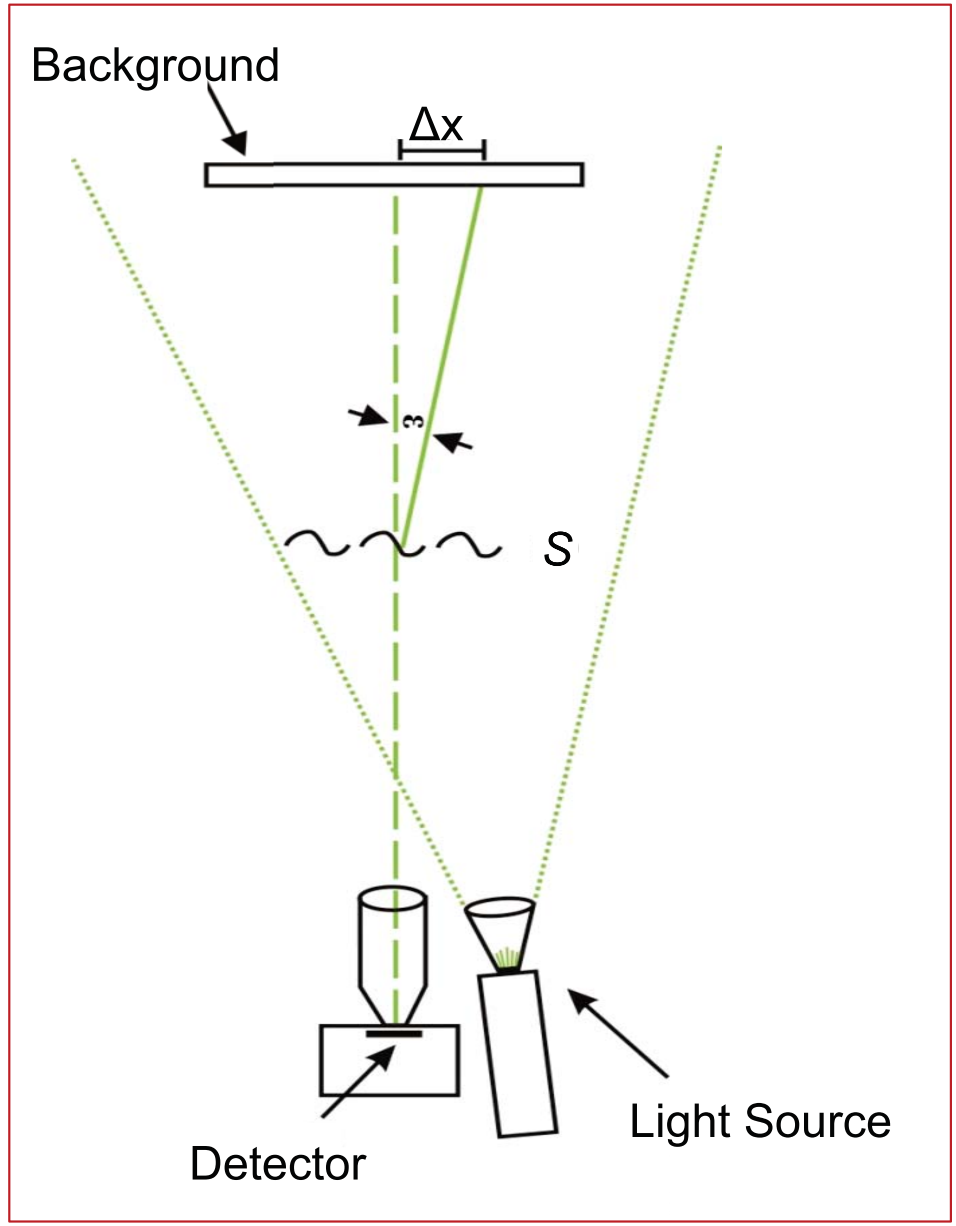
- Based on an apparent movement of the background when imaged through a density field onto a detector plane.

- 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.

Classical Schlieren vs. BOS



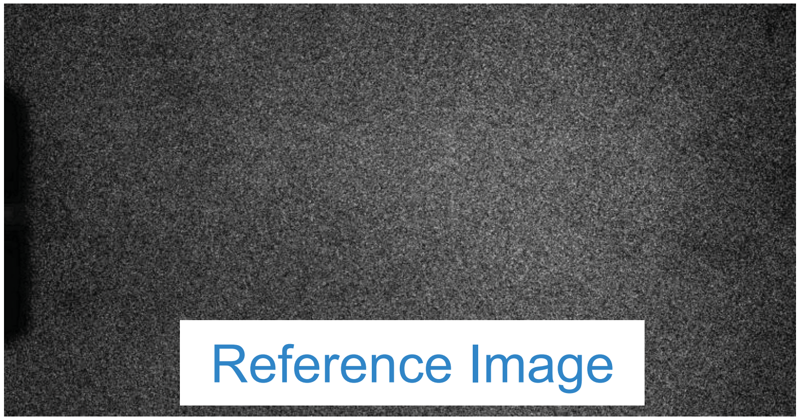


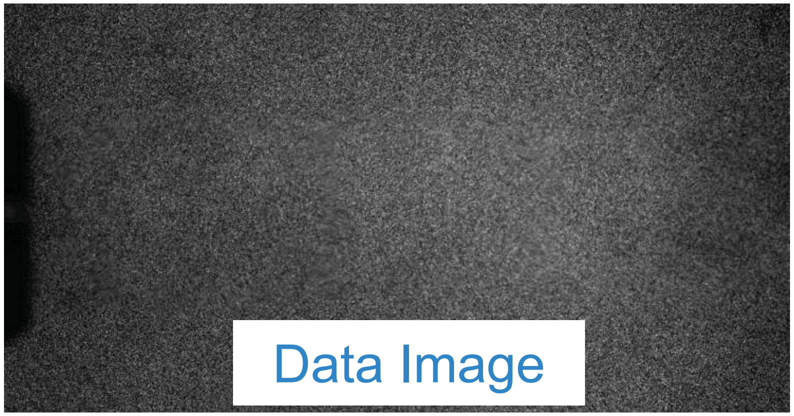
Classical Z-type Schlieren

BOS

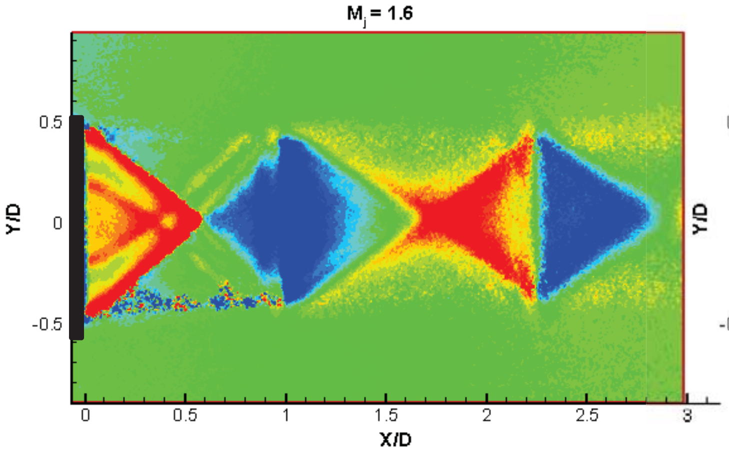
Sample BOS Data

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

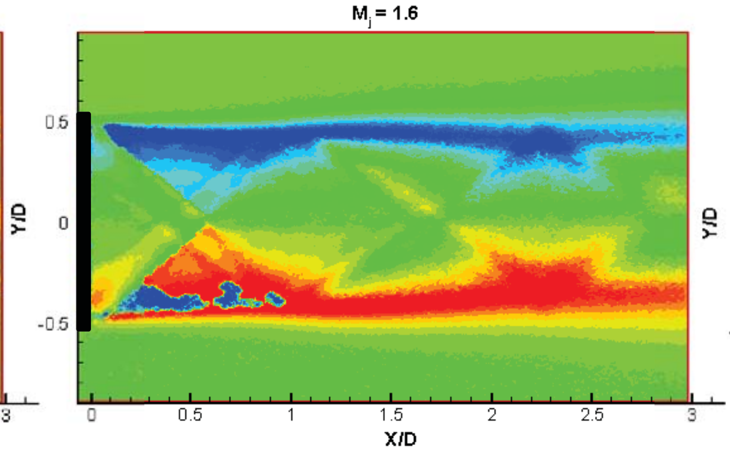




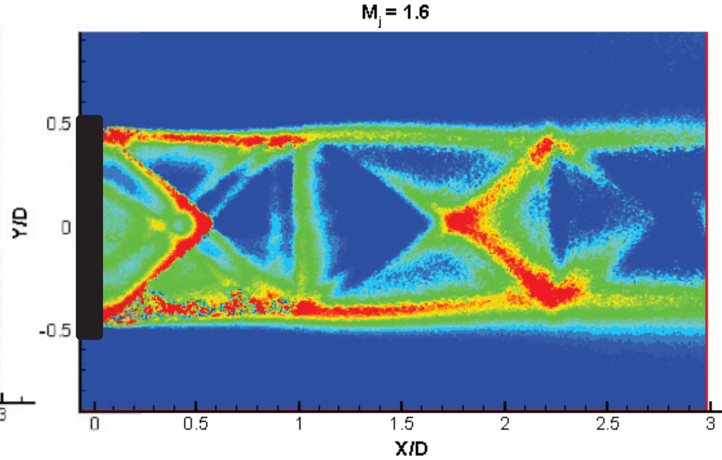
- BOS has the unique ability to distinguish the density gradient as a vector quantity



Axial (x) gradient



Radial (y) gradient



Resultant Magnitude

Particle Size – PIV Optimization

3 guidelines to follow to optimize correlation peak results:

1. Nominally 10 particles per sub-region
2. Maximum expected displacement Δx_{max} < 1/4th sub-region size
3. Imaged particle diameter d_e spans 1-2 pixels

$$d_{diff} = (2.44(1+M)\lambda f\#)^2 \longrightarrow d_e = \sqrt{(d_p M)^2 + (2.44(1+M)\lambda f\#)^2}$$

Correlation peak estimation error

$$\sigma_{\Delta x} = \frac{d}{N} = \frac{\sqrt{2}d_e}{N}$$

Nominally $\sigma_{\Delta x}$ = 0.1 pixel

Full scale error

$$\sigma_u = \frac{\sigma_{\Delta x}}{\frac{1}{4}N}$$

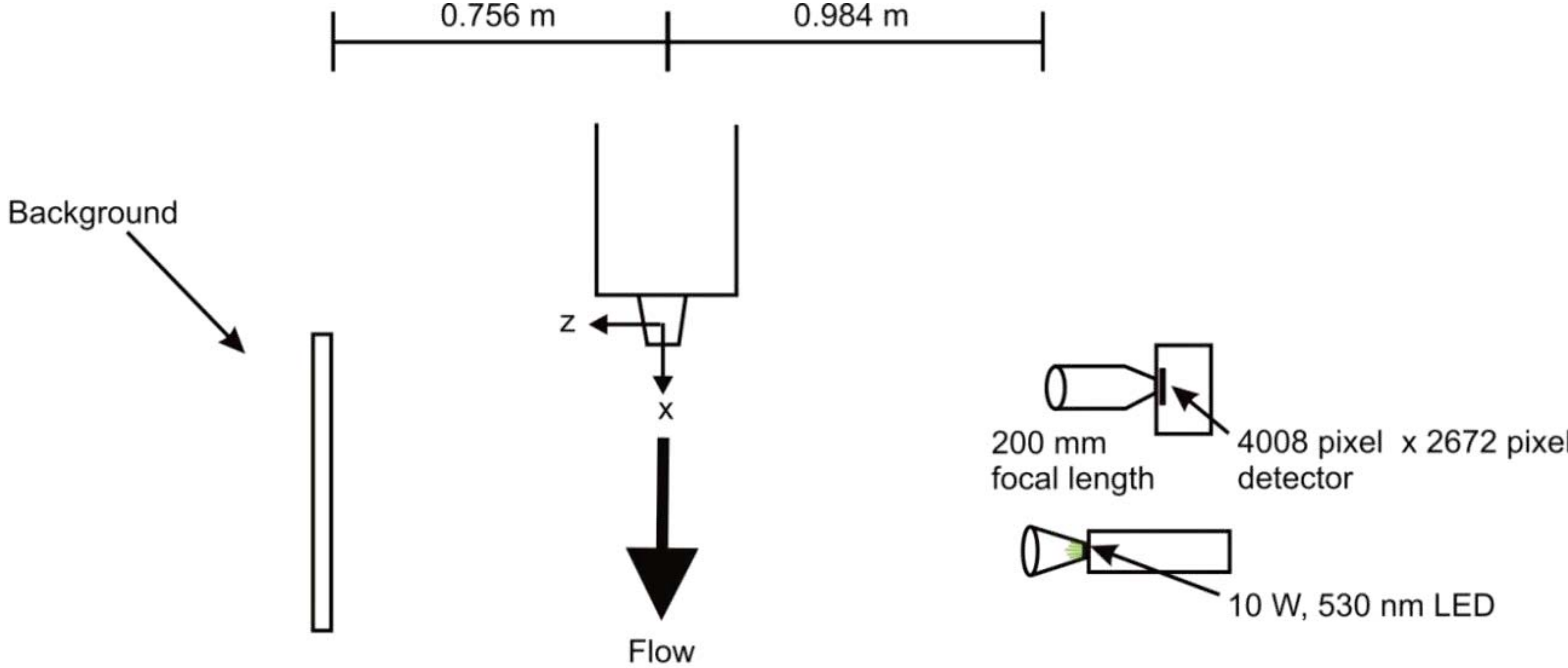
Nominally σ_u = 1%

BOS used in an initial study to investigate screech in an open jet rig

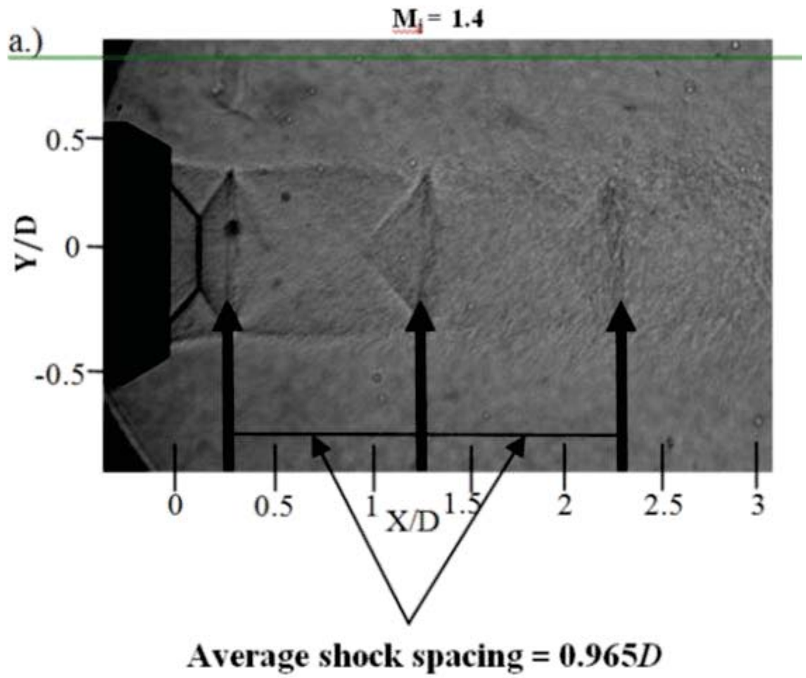
BOS and Screech

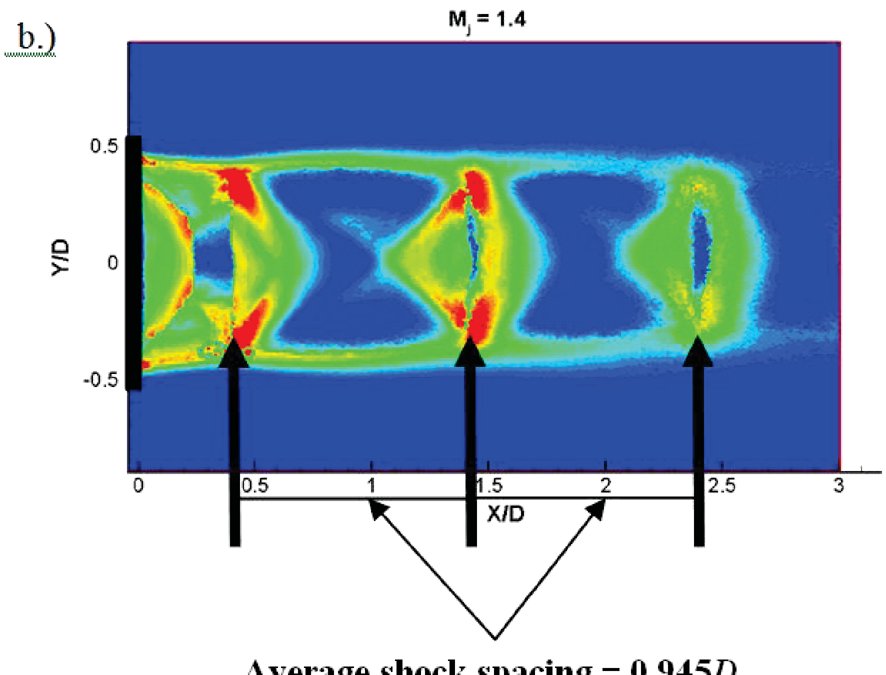
- Screech tones are a component of noise generated by supersonic jets operating at imperfectly expanded conditions
  - Dominant screech tone goes through mode-switching or stage-jumps as the Jet Mach number (M_j) is increased
- Screech is not completely understood
  - Does the shock spacing adjust to accommodate a new wavelength during the stage jump?
  - If so, we theorized the shock spacing would display an abrupt change during the stage jump
- Goal to measure the shock spacing across various screech stage jumps to determine its behavior using a flow visualization technique
  - BOS is good choice
  - In order to validate the shock spacing measurement using BOS it is compared to previously acquired shadowgraph data

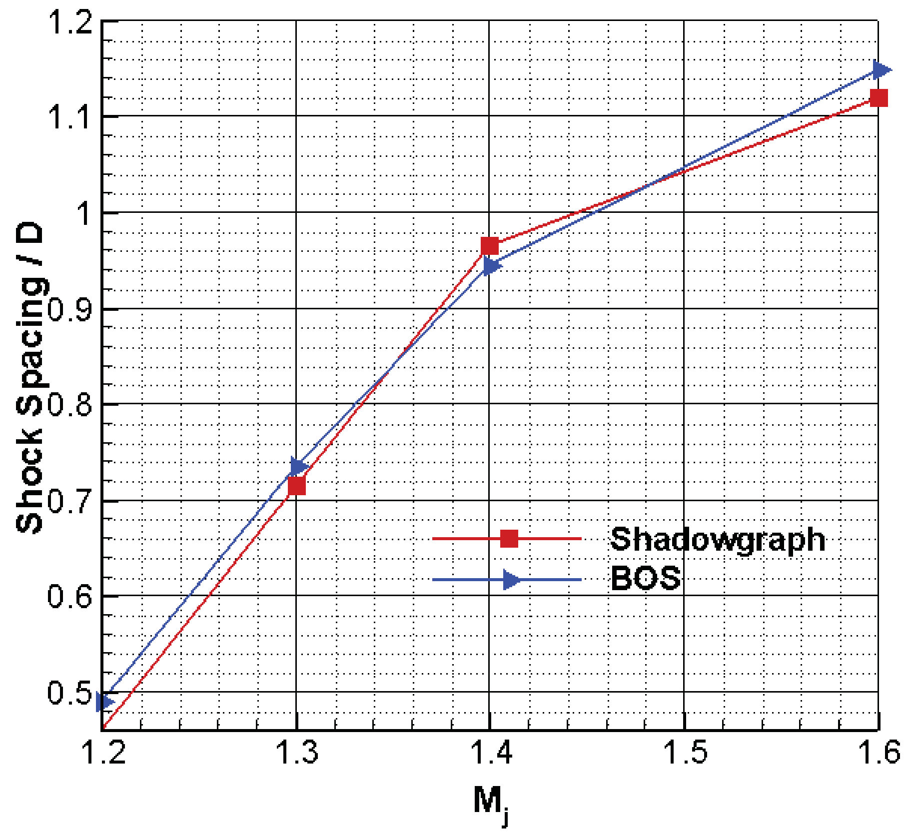
Experimental Setup and Procedure



Results: Shock Spacing Measurement Using BOS



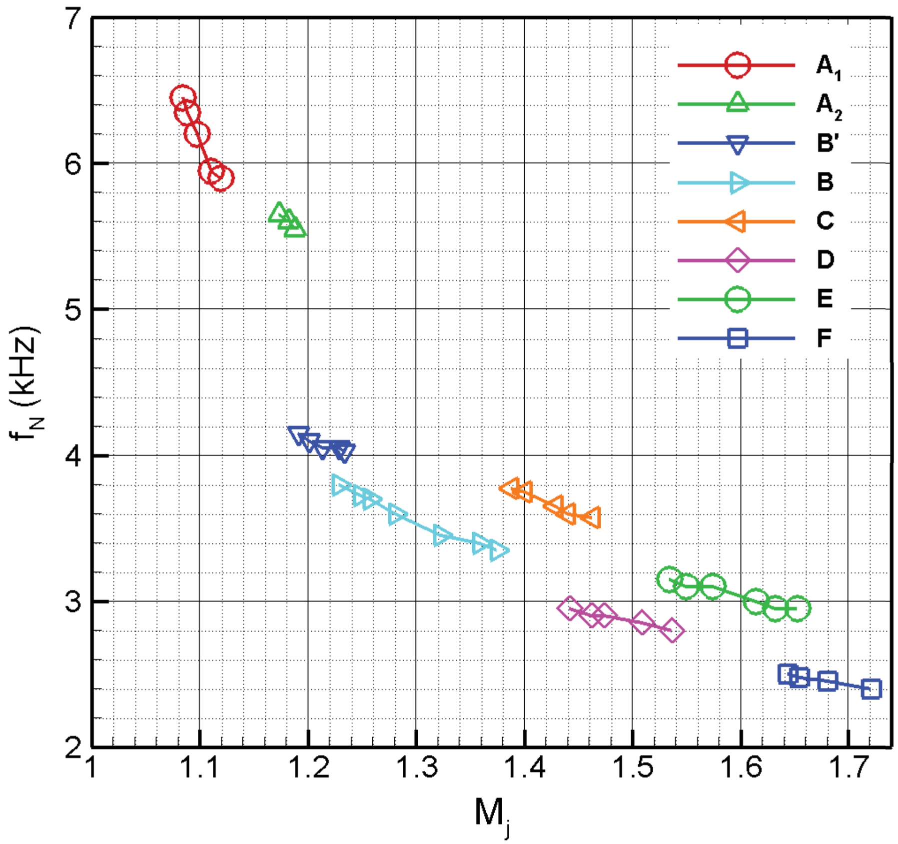


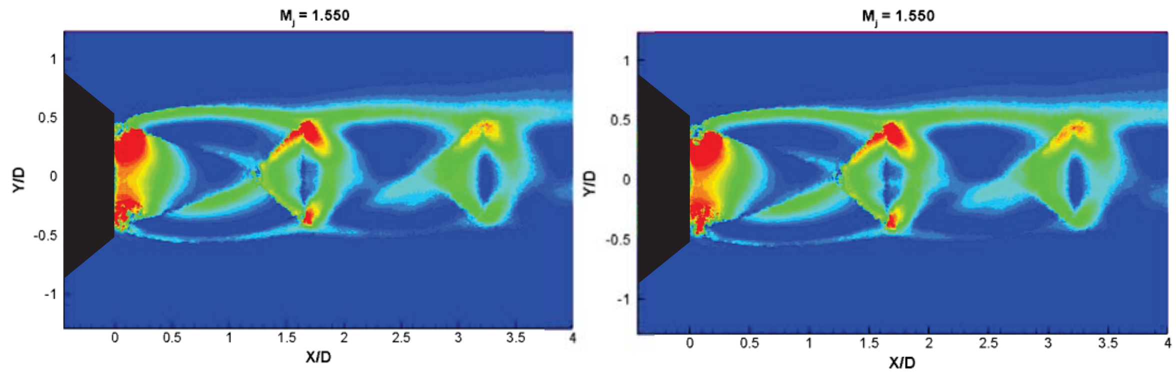


- 50.8 mm nozzle, M_D=1.8
- Flow and shock boundaries are sharper in the shadowgraph
- The overall agreement is good, particularly the inferred shock spacing

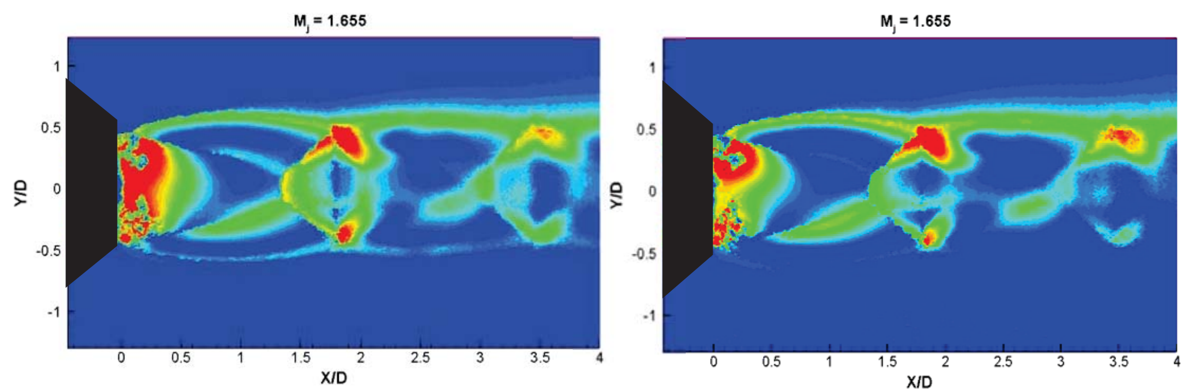
Results: Screech Frequency versus M_j

37.6 mm Circular Convergent Nozzle





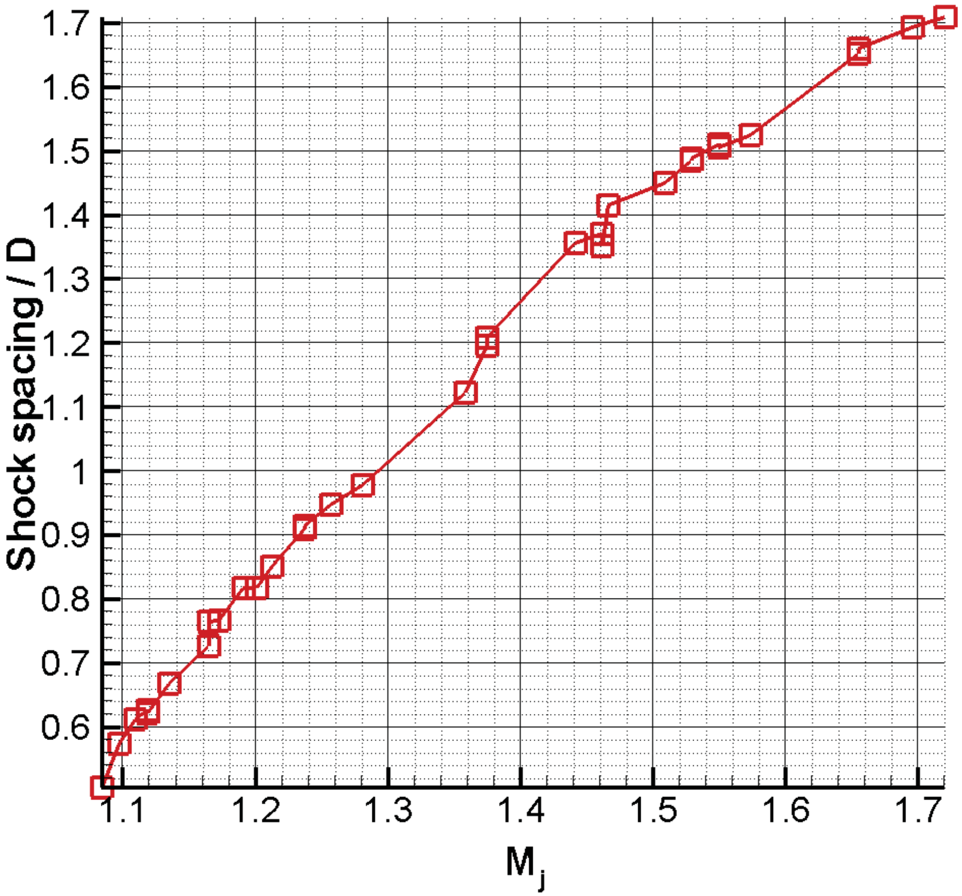
M_j = 1.550 - overlapping stage jump region D and E



M_j = 1.655 - overlapping stage jump region E and F

Hysteresis: stage jump occurs at a different location depending on whether M_j is increased or decreased

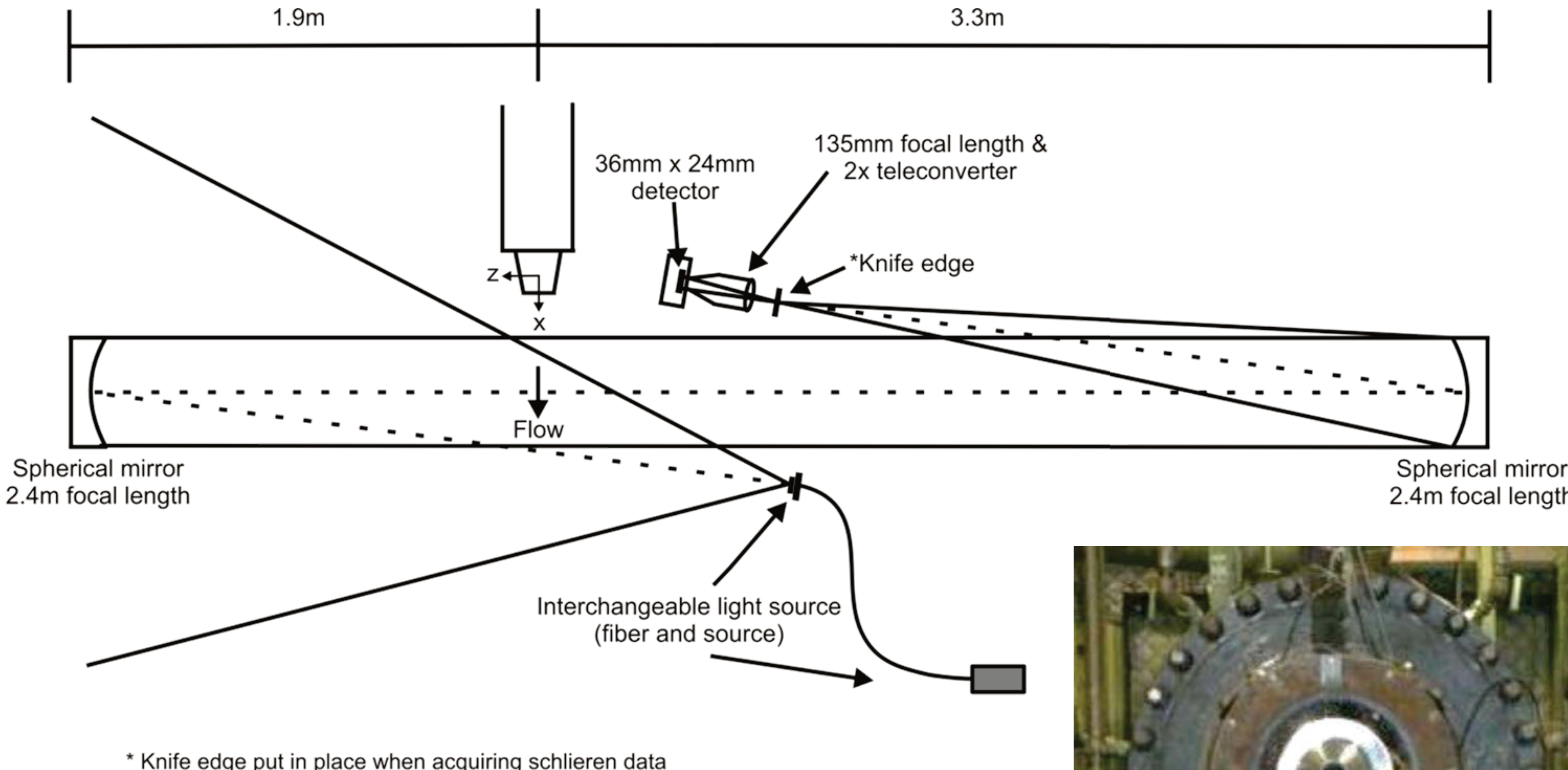
Results: BOS Shock Spacing Measurements



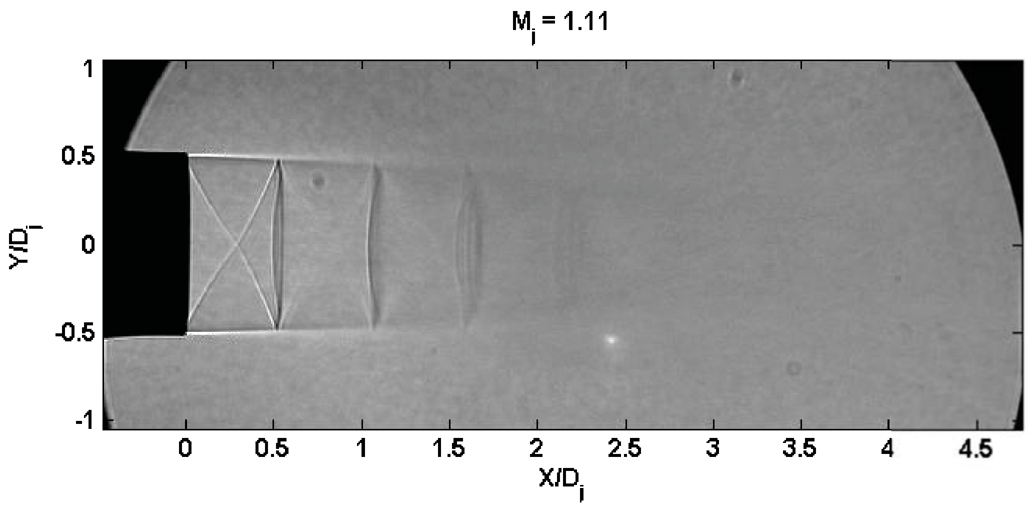
- Shock spacing follows the expected monotonic trend – no large departures
- Does NOT display and abrupt change for overlapping stages at the M_j where hysteresis occurred
- Therefore inferred shock spacing is NOT the parameter that adjusts to accommodate a new frequency when a stage jump occurs

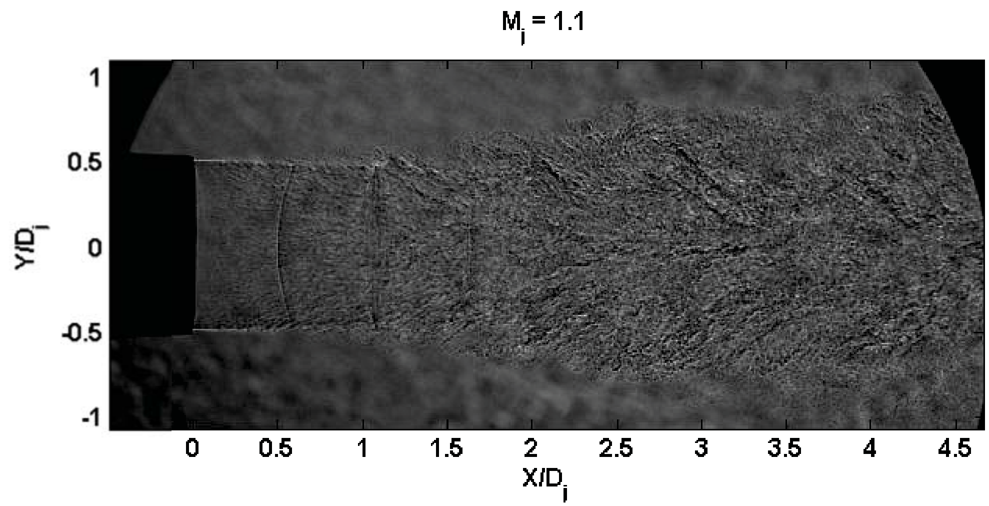
Continuation of screech study with other flow vis techniques

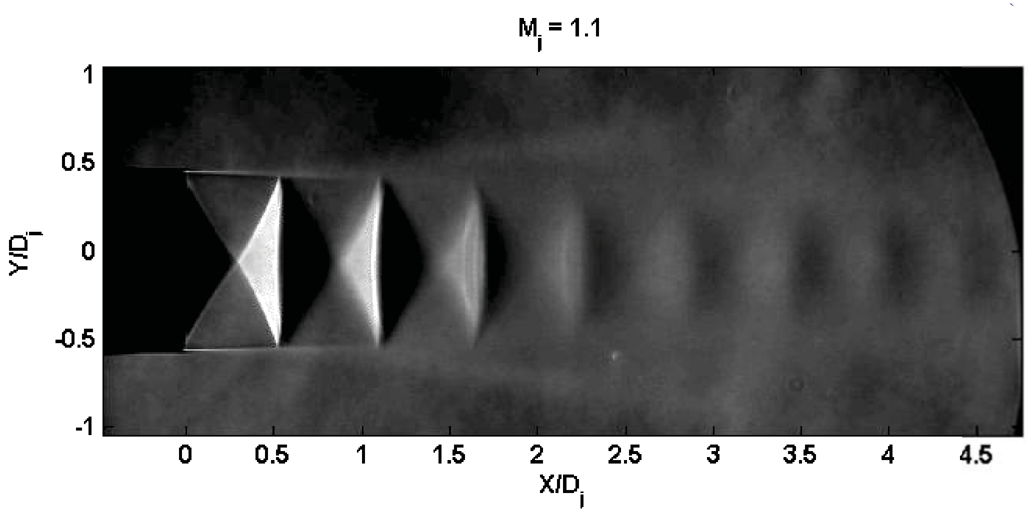
2nd look: Multiple Flow Vis Techniques

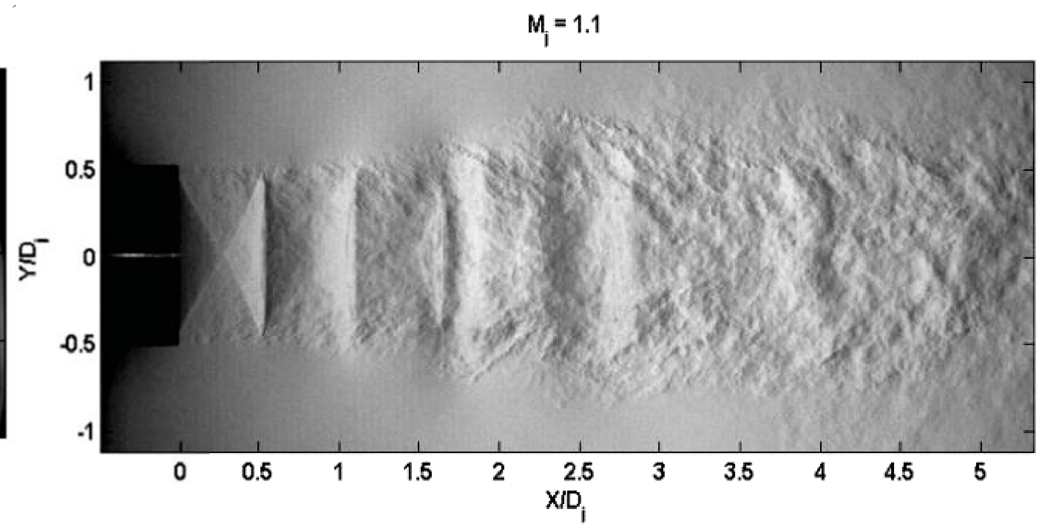


2nd look: Multiple Flow Vis Techniques

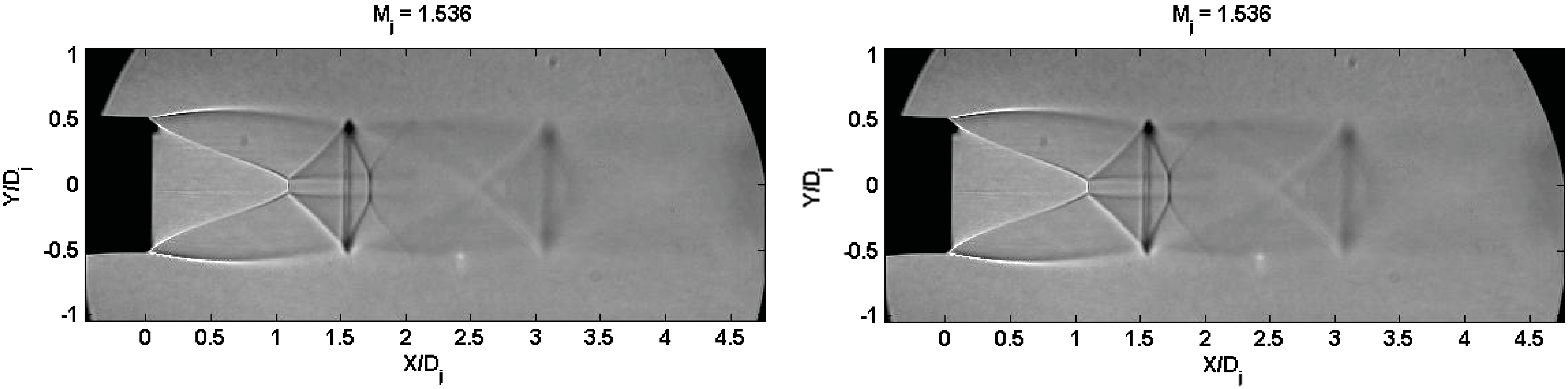




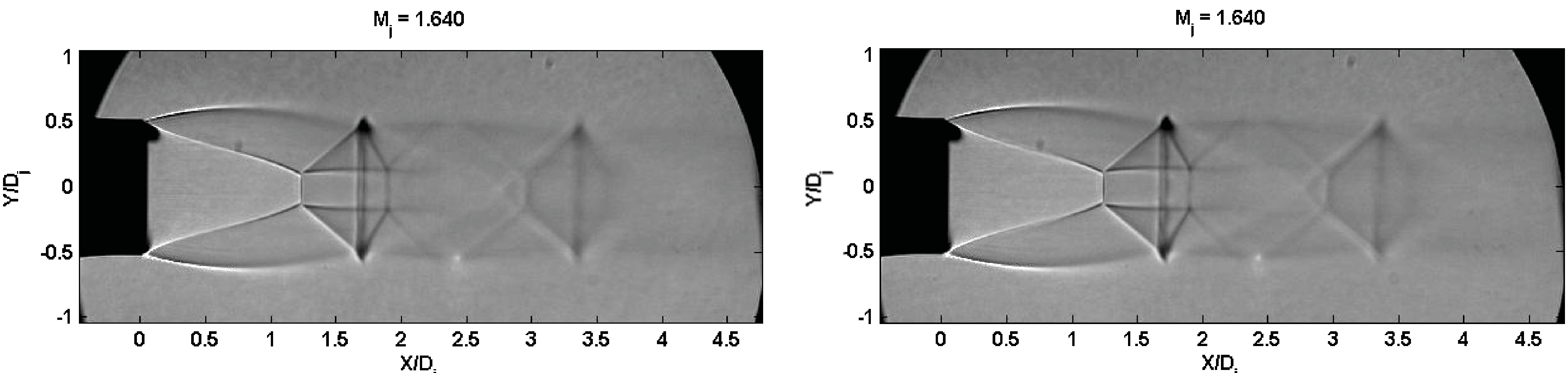




Results: Screech Frequency versus M_j



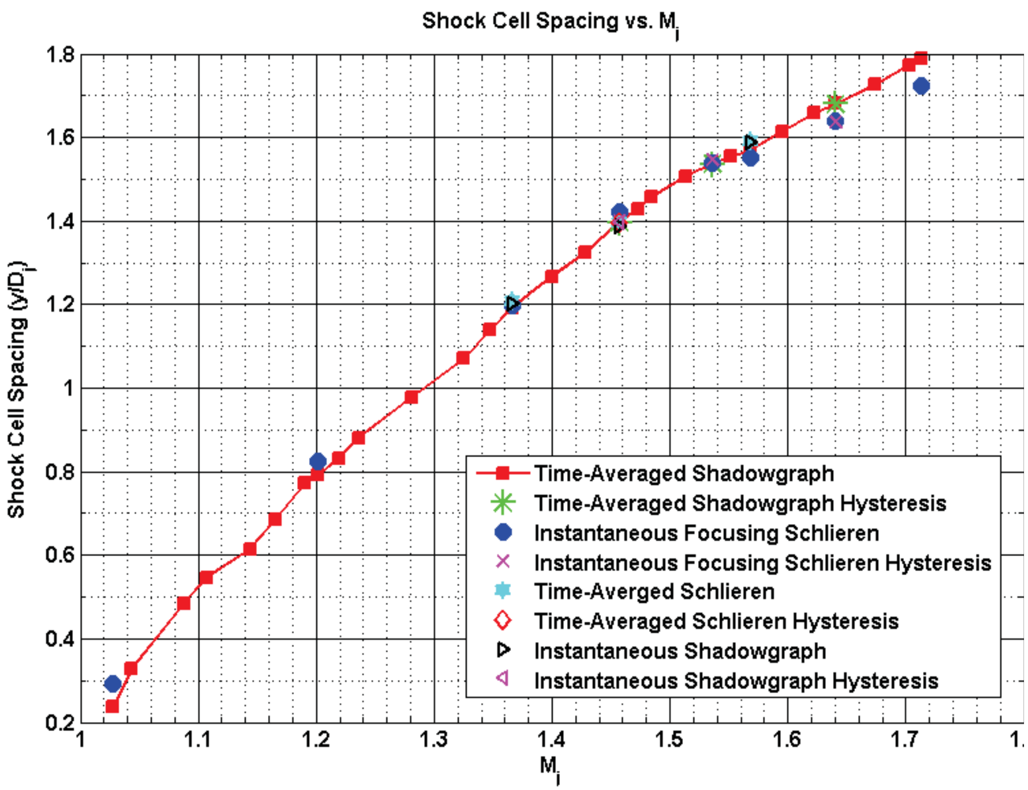
M_j = 1.536 - overlapping stage jump region D and E

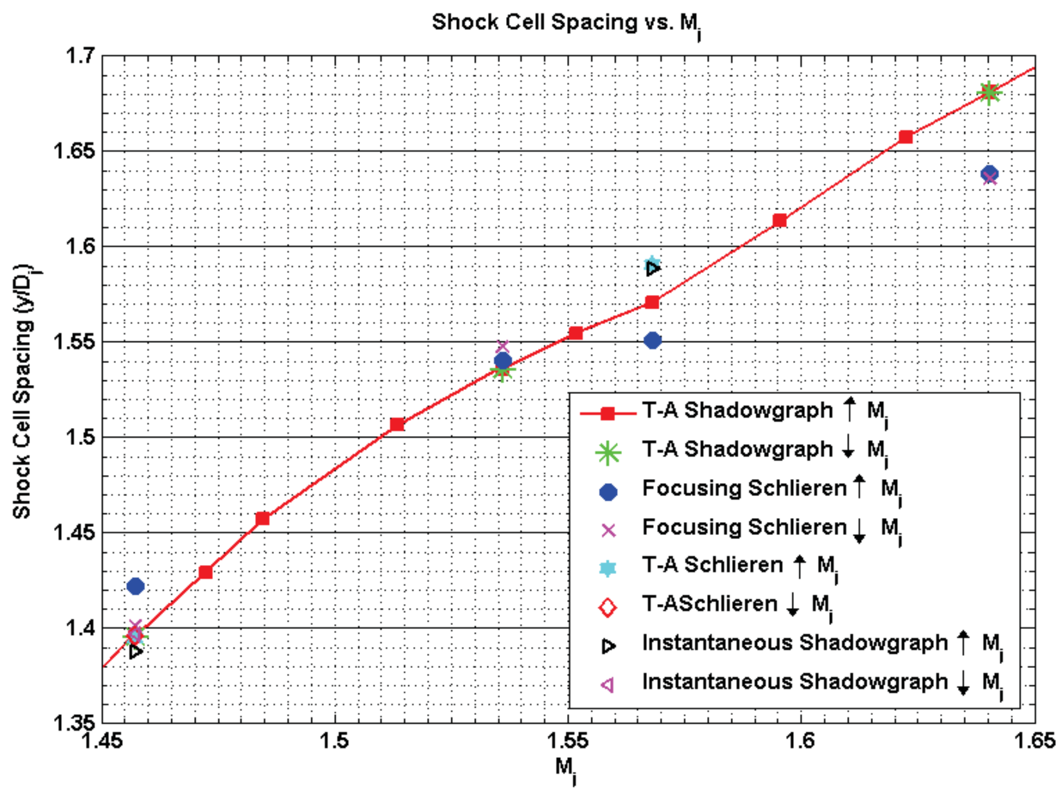


M_j = 1.640 - overlapping stage jump region E and F

Hysteresis: stage jump occurs at a different location depending on whether M_j is increased or decreased

Results: Flow Vis Shock Spacing Measurements





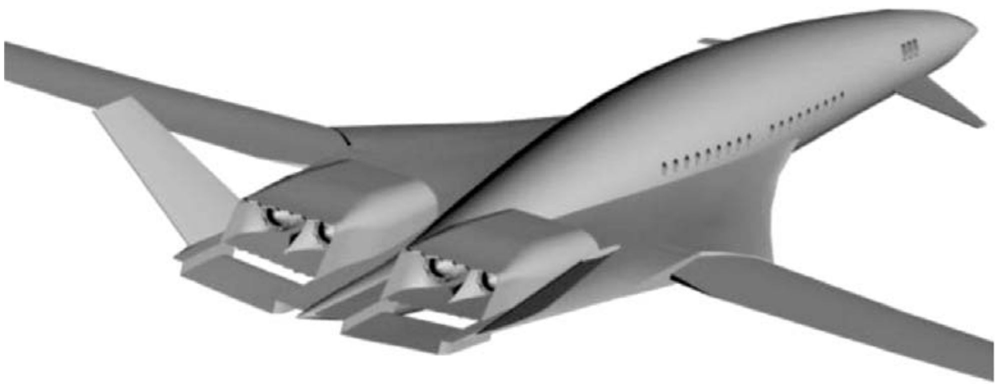
- Repeatable results - Shock spacing follows the monotonic trend
- Reiterates results that inferred shock spacing is NOT the parameter that adjusts to accommodate a new frequency when a stage jump occurs

BOS used in the Jet-Surface Interaction Tests (JSIT)

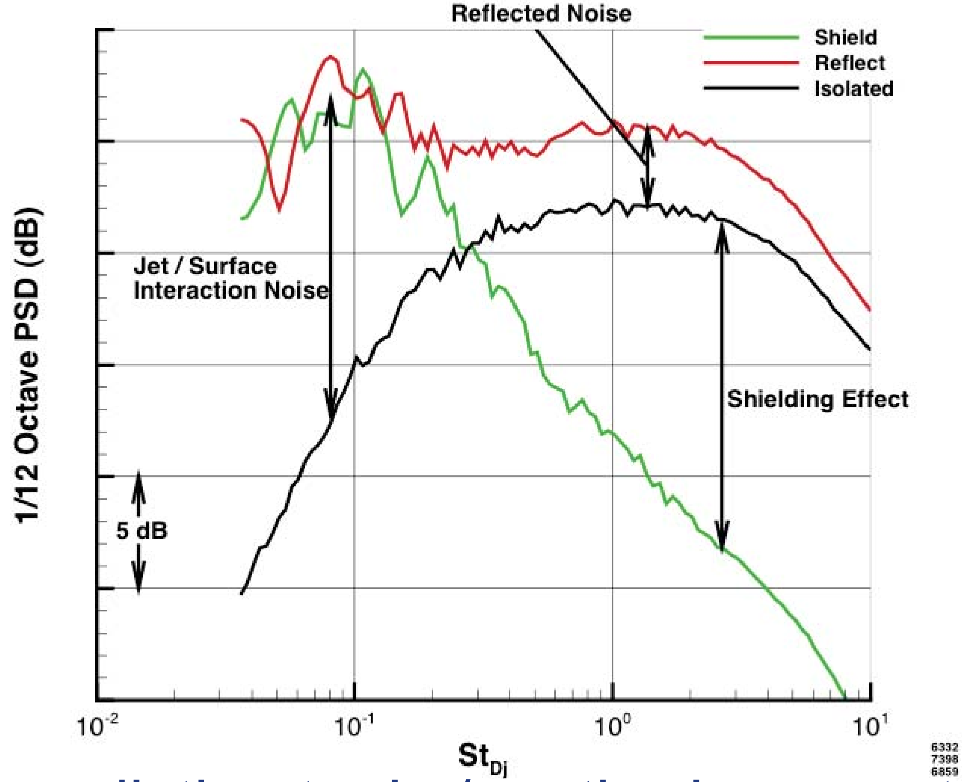
Jet-Surface Interaction Noise

- Many current and future generation aircraft designs incorporate airframe surfaces near the engine exhaust

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



NASA Supersonic Iconic Vehicle

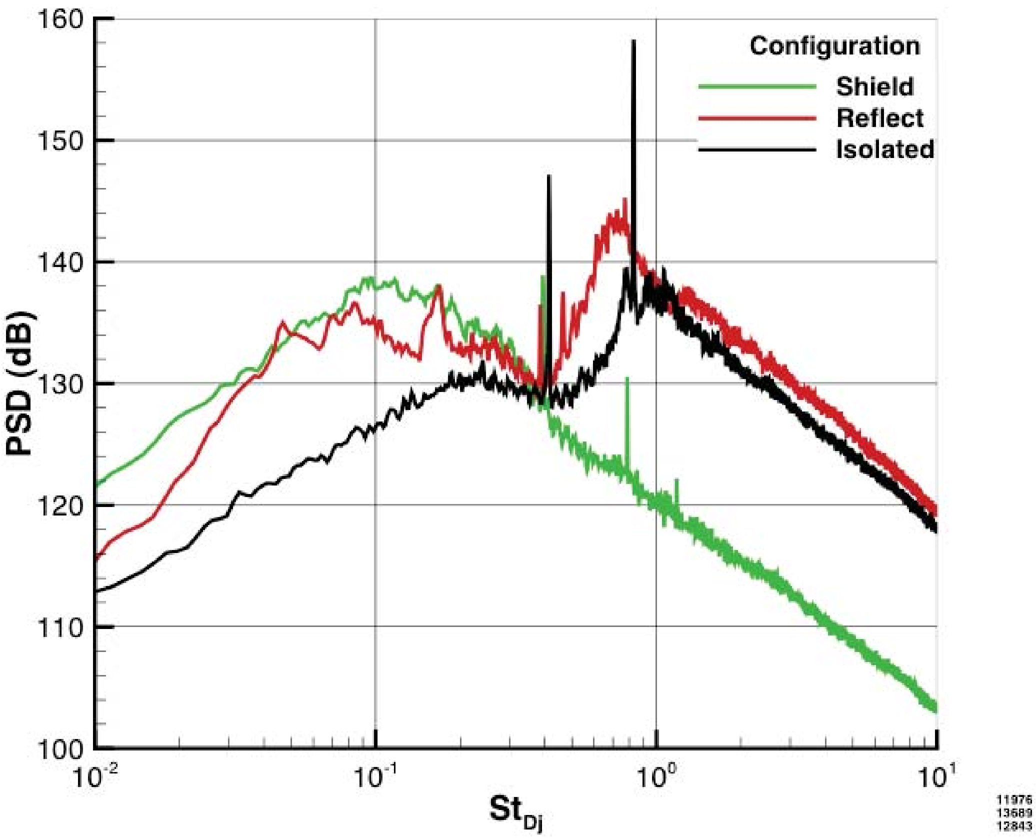


- The current generation of noise prediction tools / methods are not well equipped for the tight engine & airframe designs

Motivation - BBSN

Jet-Surface Interaction Tests were conducted to supply experimental data to support the development/validation of new noise prediction codes and methods that include the affect of nearby surfaces

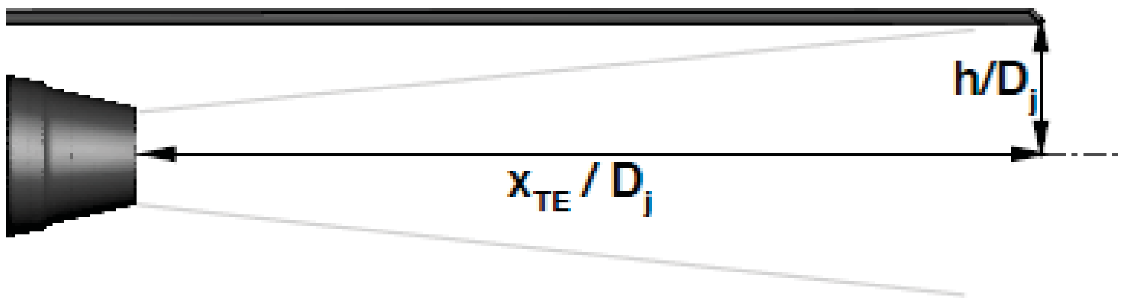
Phase 1: Far-field acoustic data showed that the BBSN was greatly reduced by the surface when the jet was over-expanded



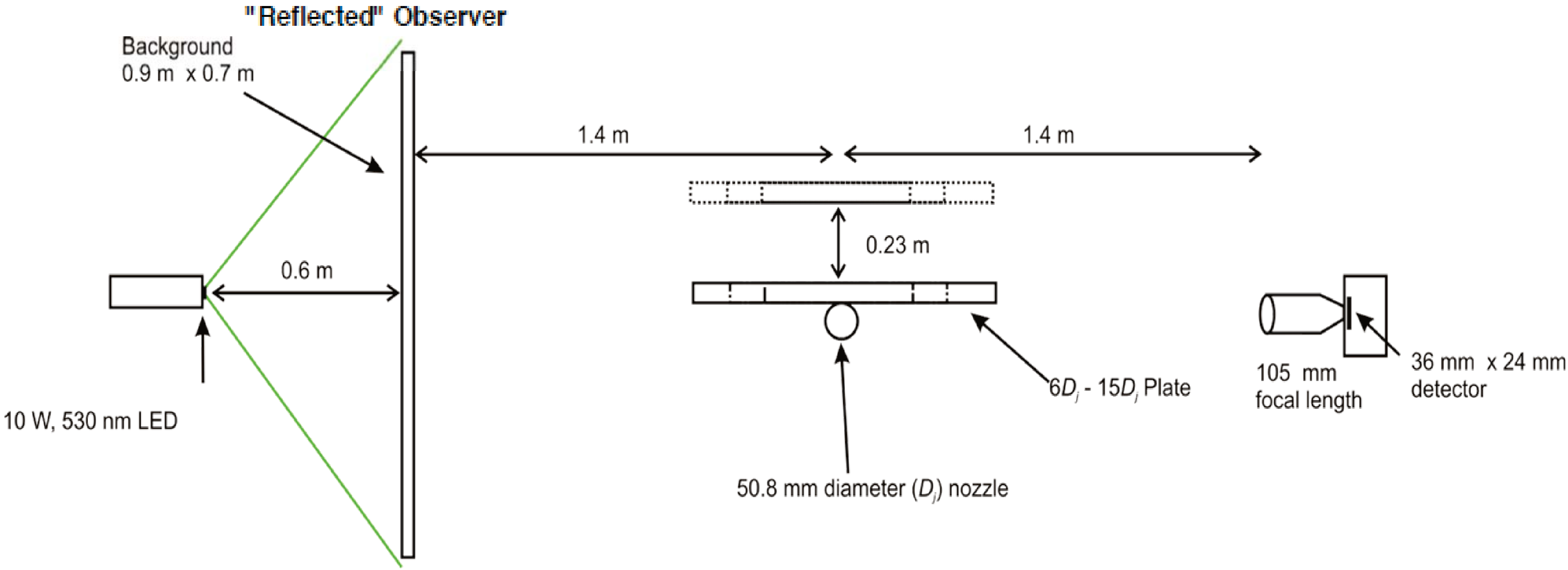
- The amplitude and frequency characteristics of BBSN are a function of the strength, number, and location of the shock cells
- It is still unclear how (or if) a surface affects the shock cells, and, thereby, reduces the BBSN
- Is it a surface shielding effect or is the surface interacting with the shock cell structures?

BOS Experimental Setup

- The jet-surface interaction configuration was formed using a flat planar surface (plate) and a round convergent-divergent nozzle (M_d=1.5)

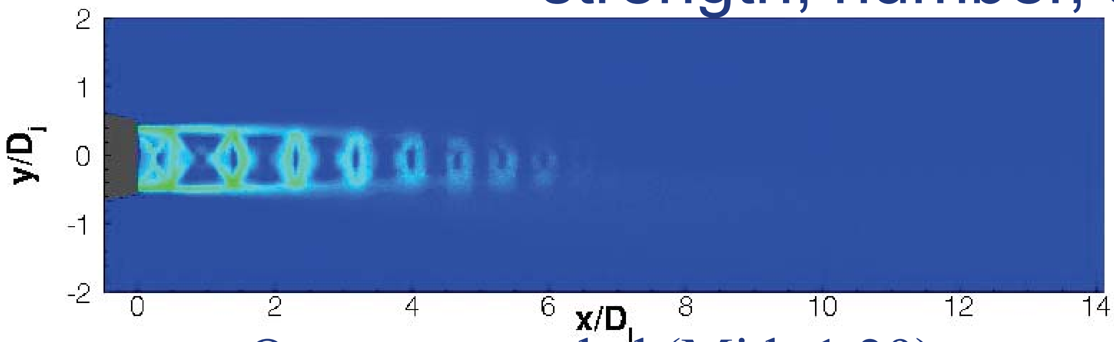


3 plate lengths were tested: x_{TE} = $6D_j$, $10D_j$, and $15D_j$

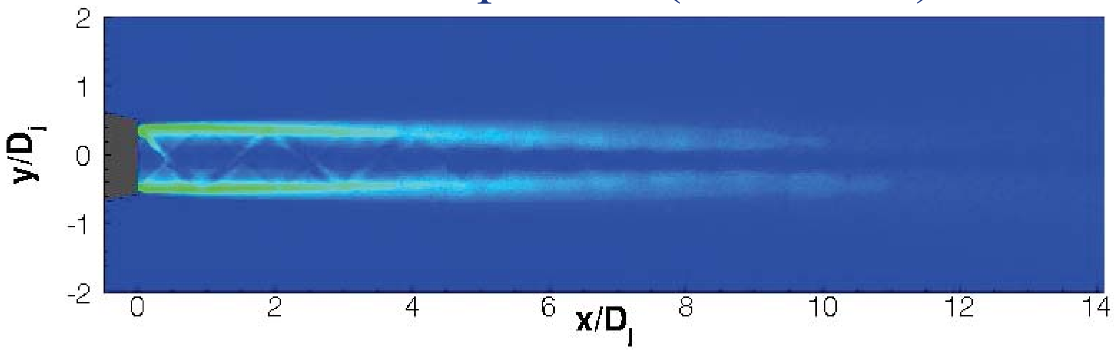


Isolated Supersonic Jet

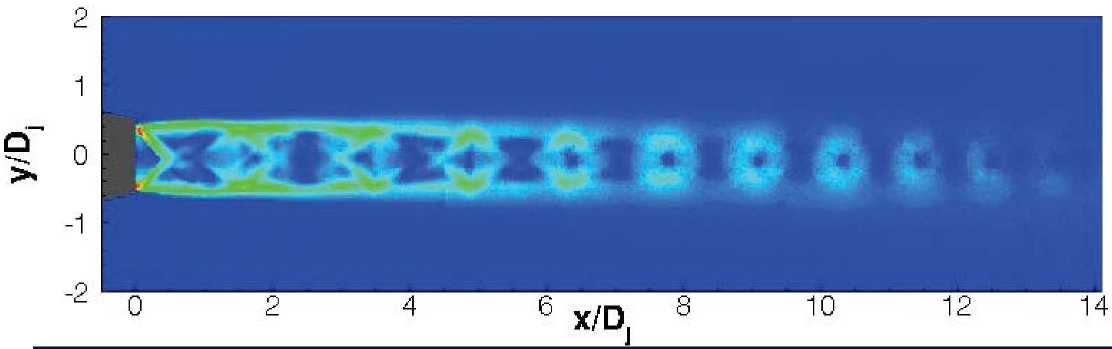
BBSN spectral characteristics are a function of shock cell strength, number, and spacing



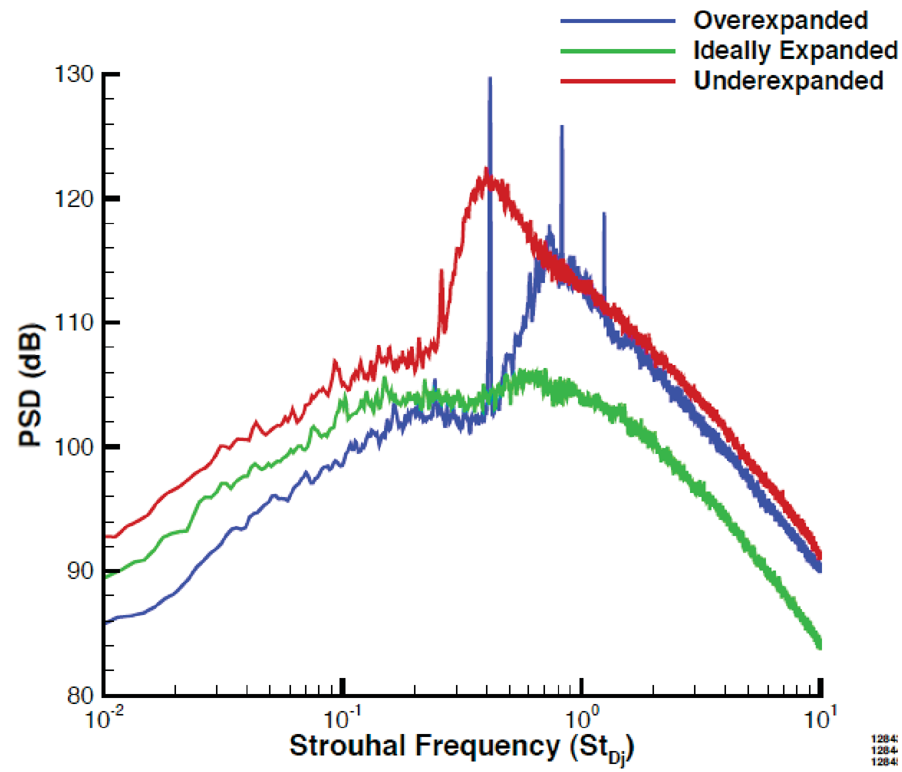
Over – expanded (Mid=1.29)



Ideally expanded (Mid=1.48)



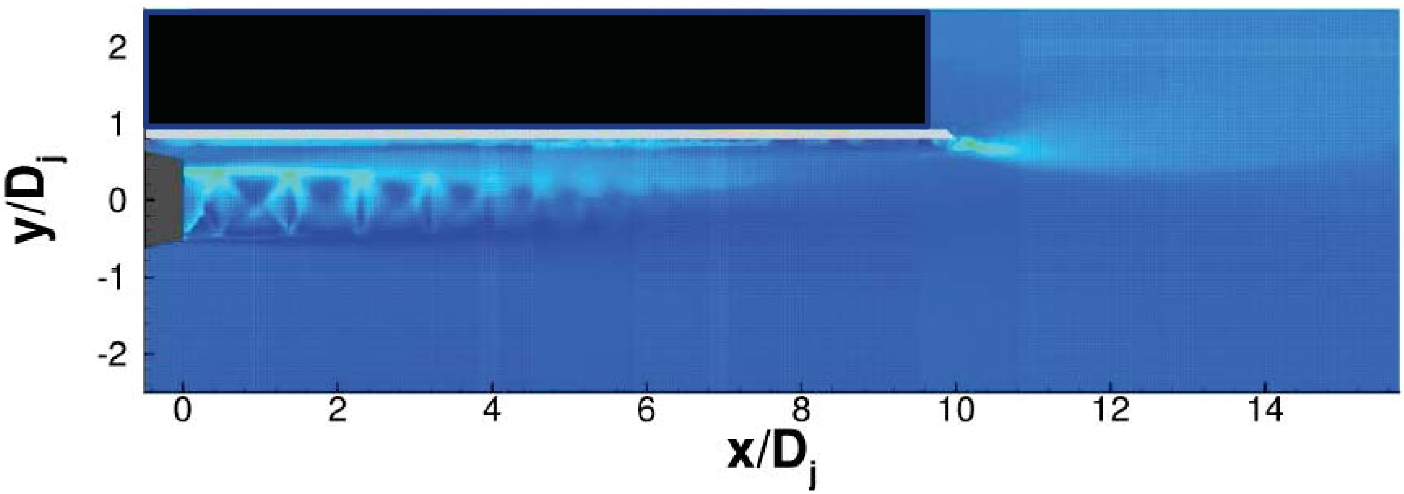
Under – expanded (Mid=1.61)

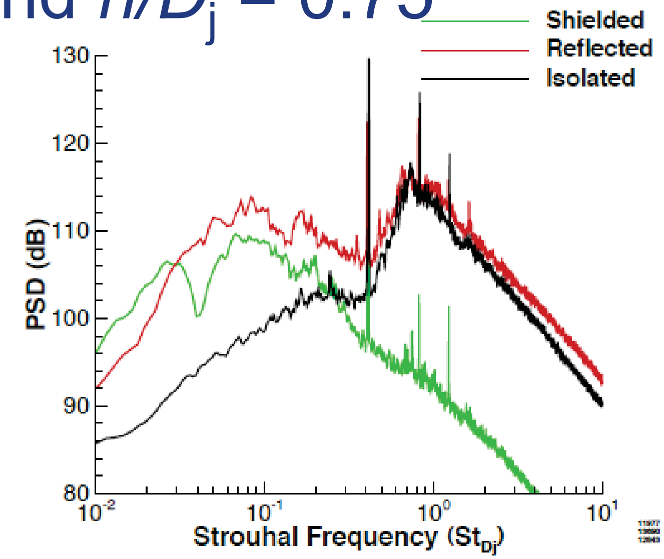


$\theta = 60°$

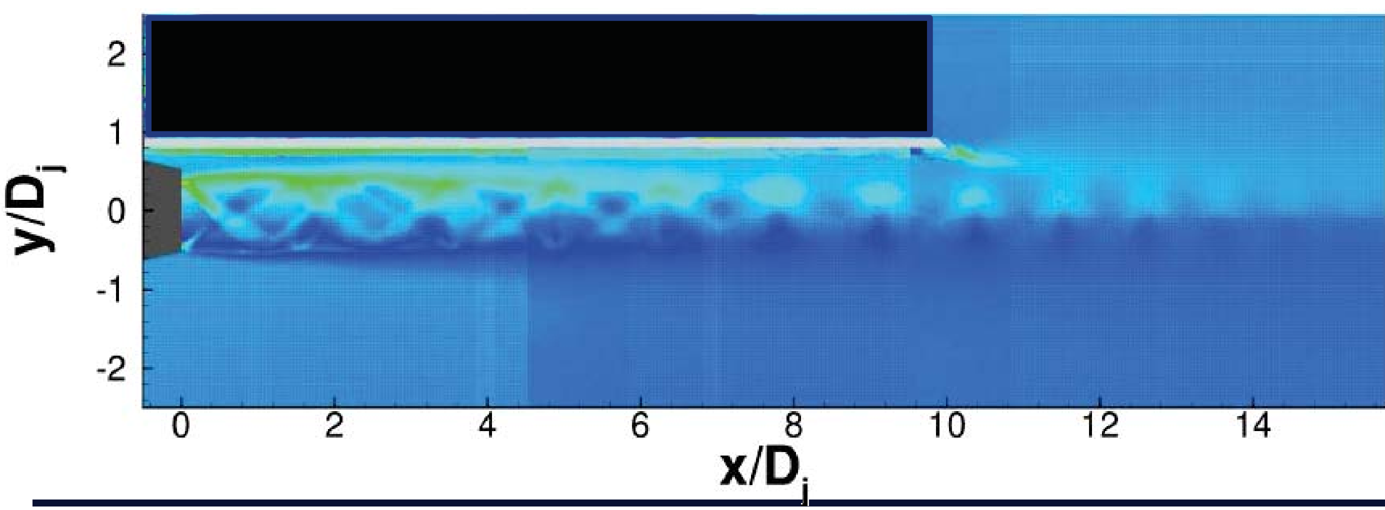
Results: Jet Near a Surface

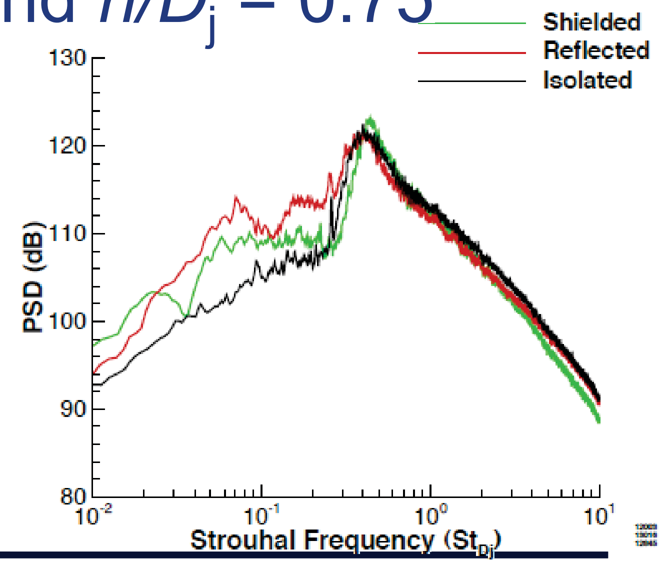
Over-expanded Jet Surface at x_{TE}/D_j = 10 and h/D_j = 0.75





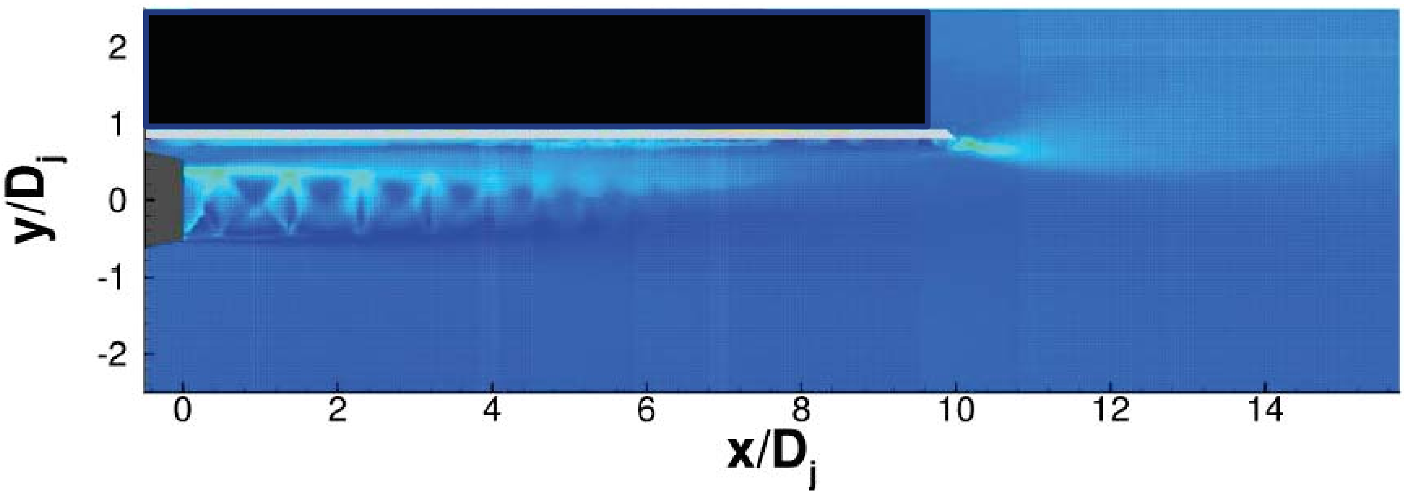
Under-expanded Jet Surface at x_{TE}/D_j = 10 and h/D_j = 0.75

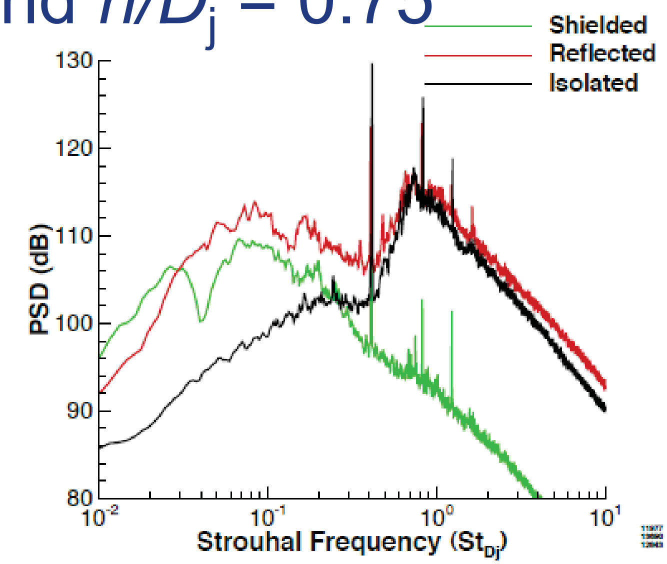




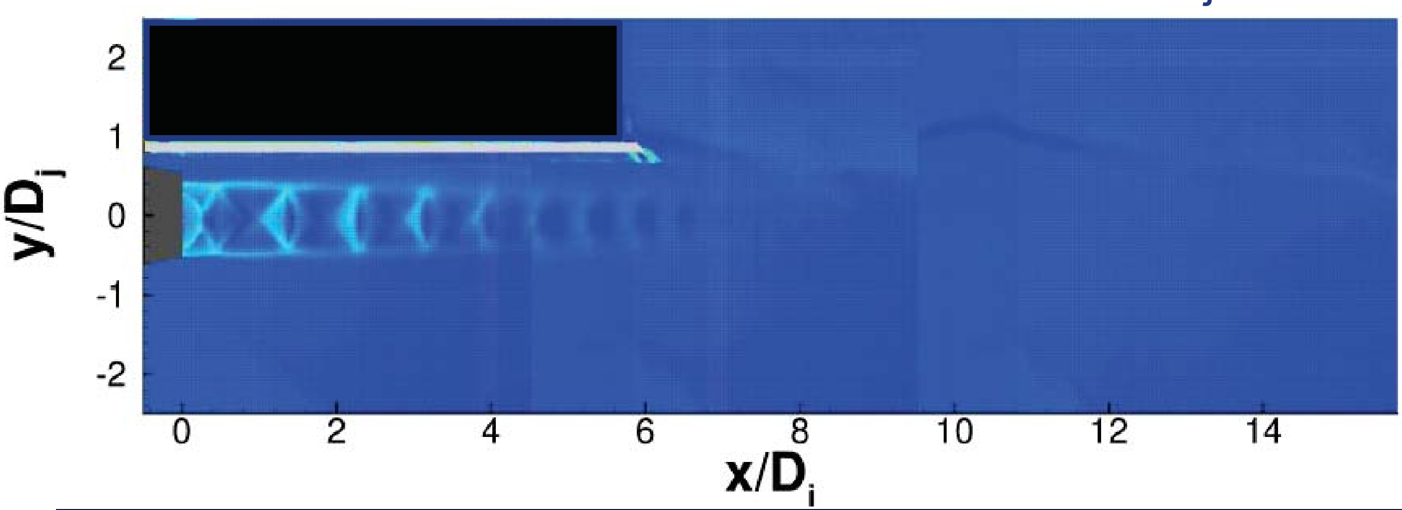
Results: Effect of Surface Length

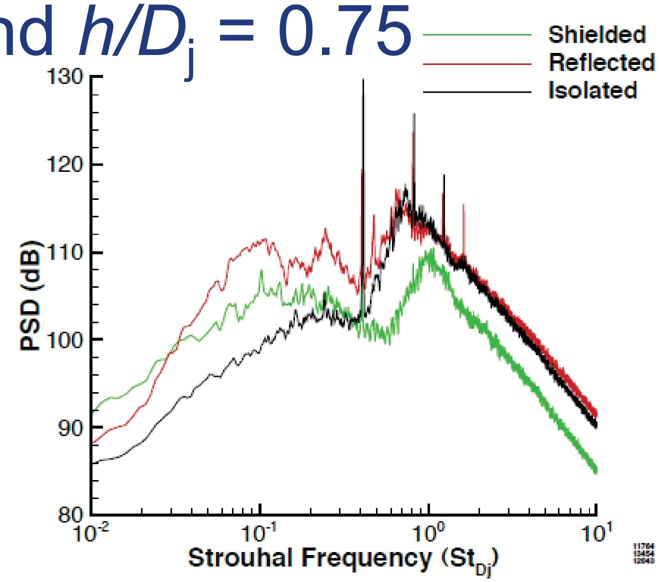
Over-expanded Jet Surface at x_{TE}/D_j = 10 and h/D_j = 0.75





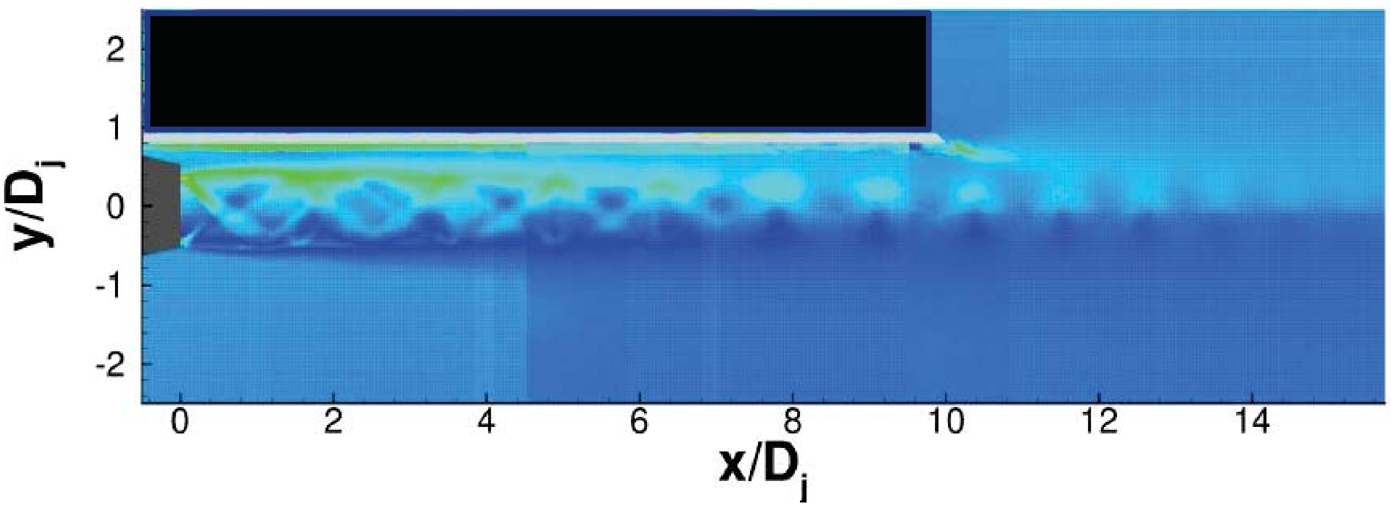
Over-expanded Jet Surface at x_{TE}/D_j = 6 and h/D_j = 0.75

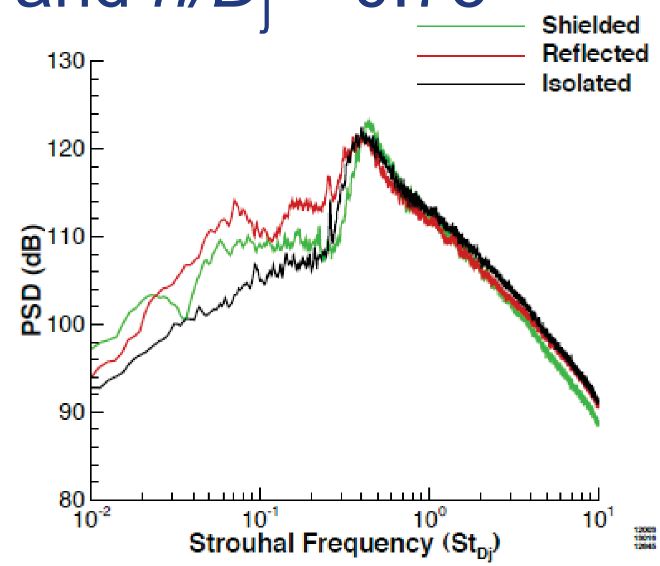




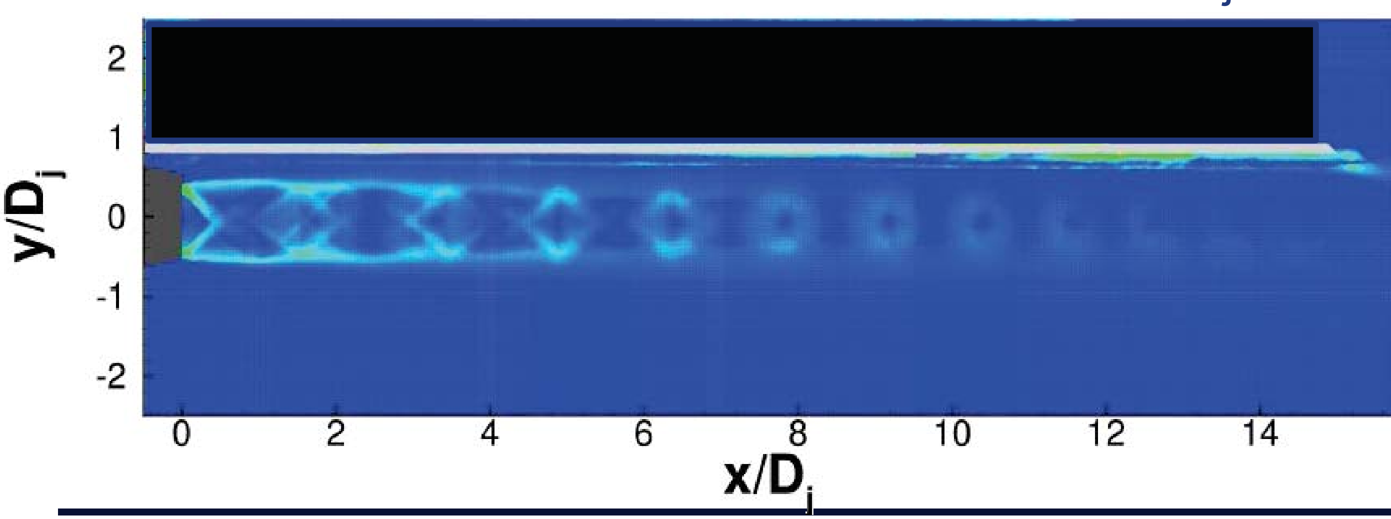
Results: Effect of Surface Length

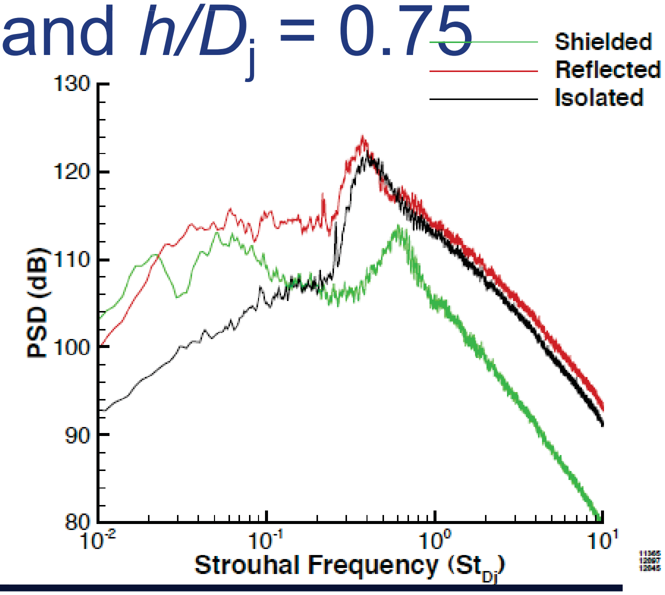
Under–expanded Jet Surface at x_{TE}/D_j = 10 and h/D_j = 0.75





Under–expanded Jet Surface at x_{TE}/D_j = 15 and h/D_j = 0.75

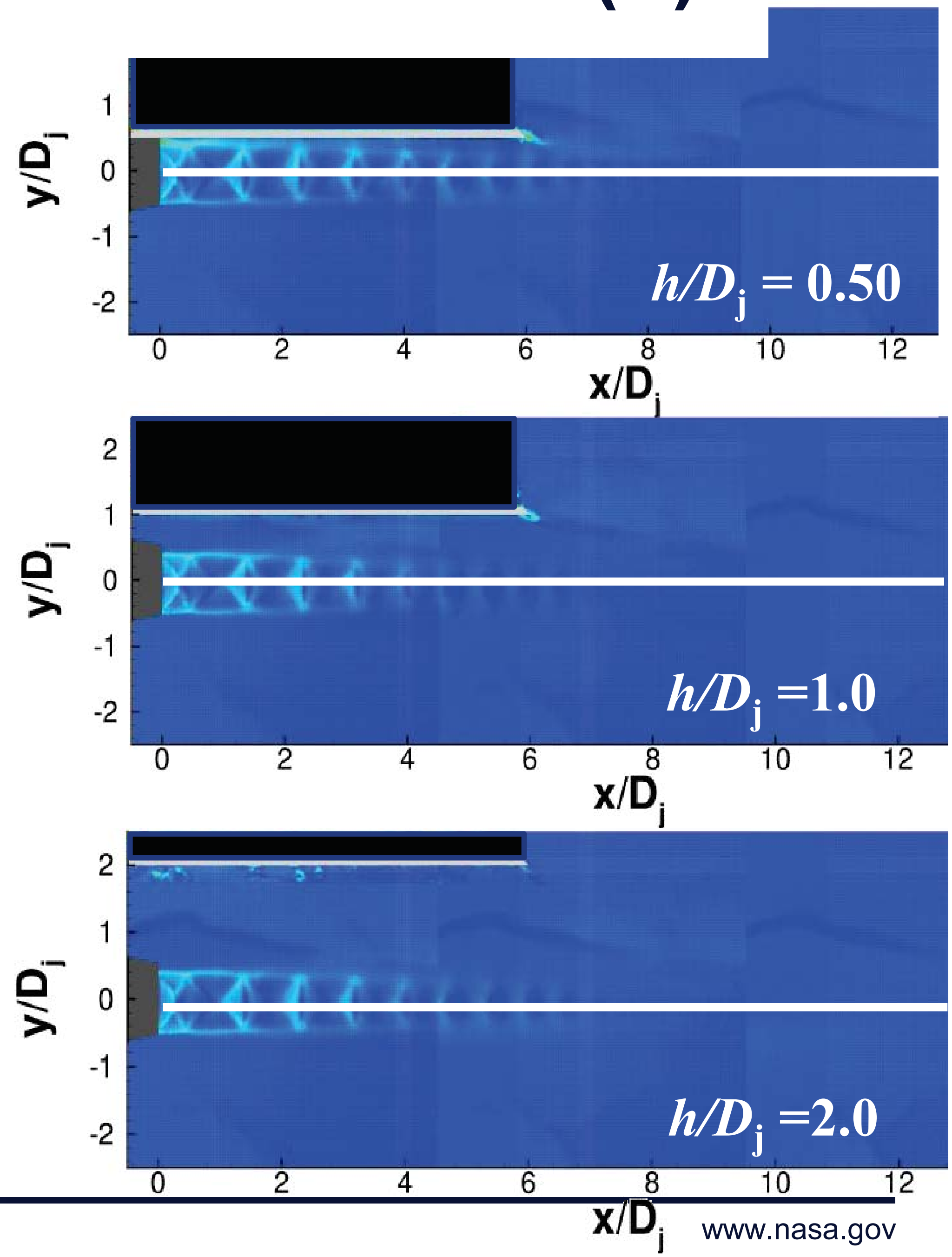




Results: Effect of Surface Distance (h)

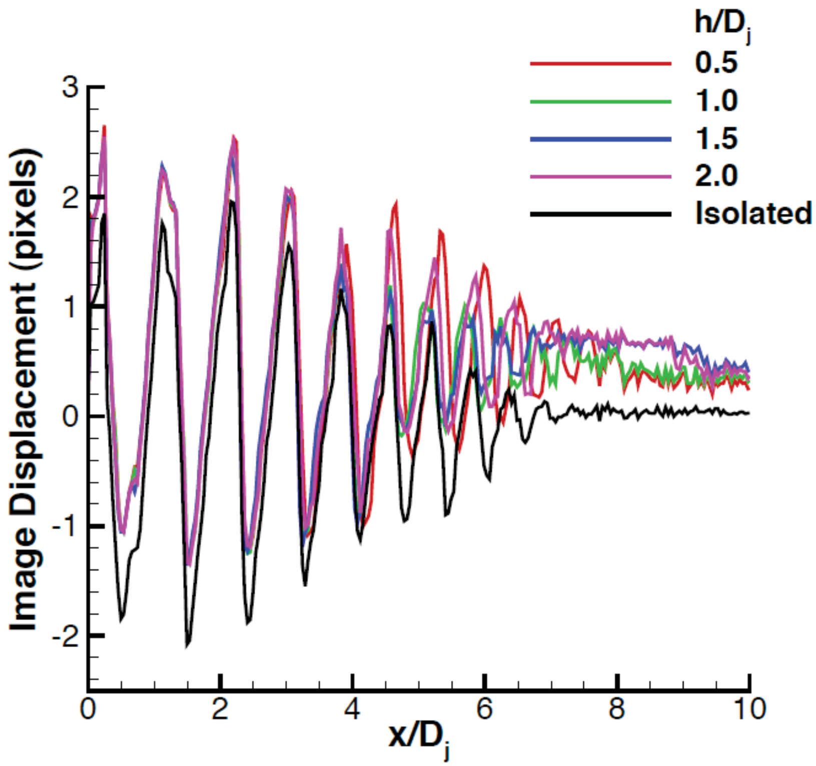
- Over-expanded jet with surface at $x_{TE}/D_j=6$, $h/D_j=0.5$, 1.0, 2.0
- Shock cells appear to behave independent of surface distance
- Shock cells near trailing edge are sufficiently weak and hard to detect amongst the background
- <u>It is difficult to make firm conclusions based on inspection</u>

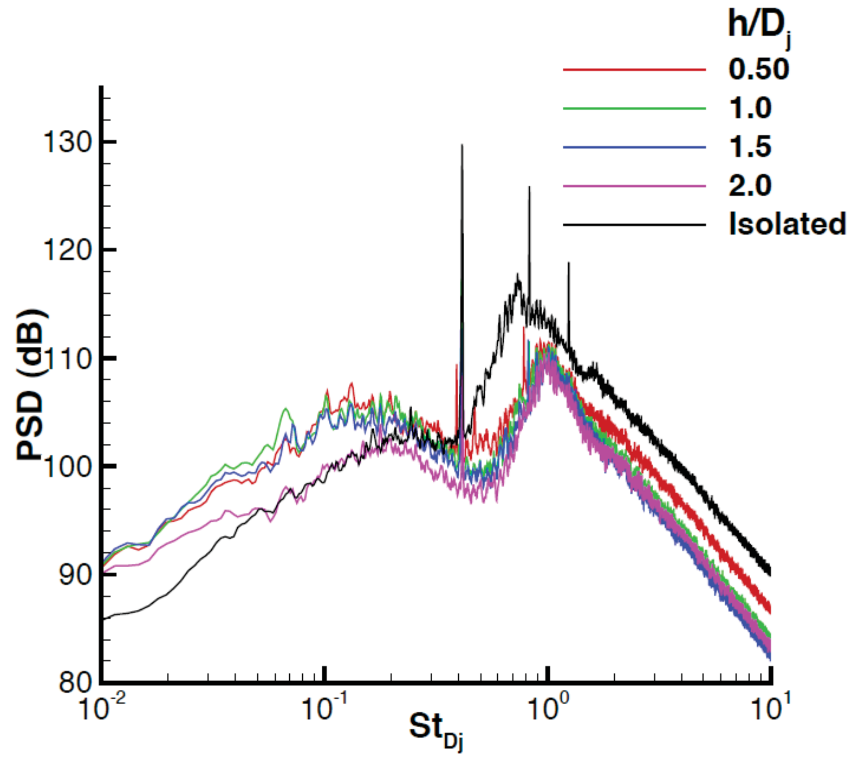
Extract axial image displacements along the nozzle centerline to display shock cell spacing and amplitude information



Results: Effect of Surface Distance

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





- Surface has minimal impact upstream of the trailing edge distance $x/D_j \leq 4$
- Around trailing edge shock cells appear to change amplitude and spacing but have small effect on the BBSN
- BBSN reduction is due to noise shielding rather than changes in shock cells

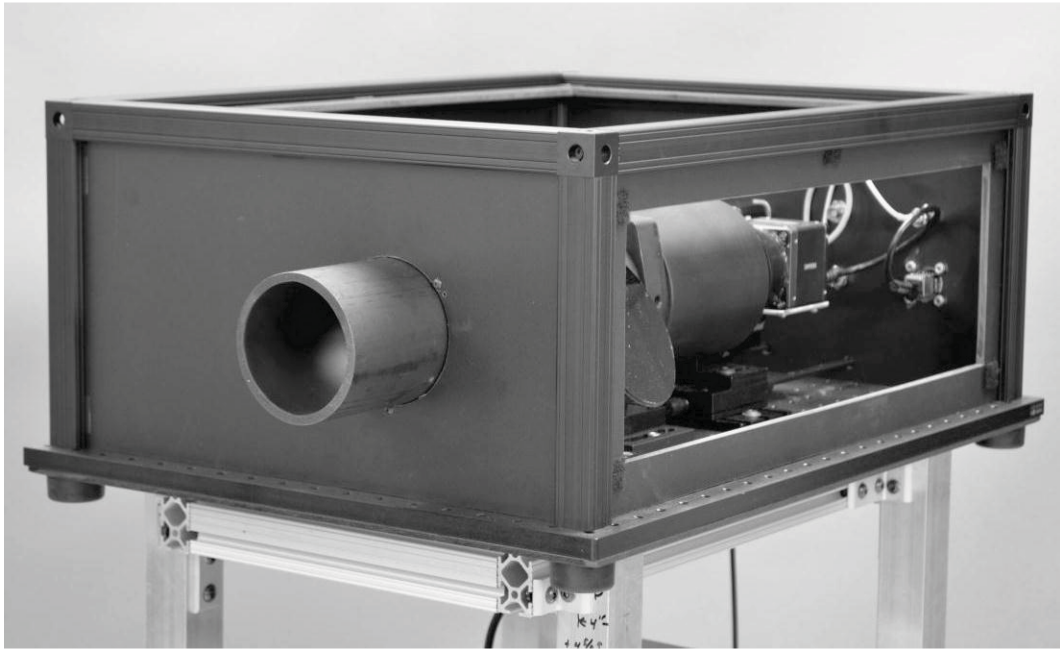
Conclusions: - JSIT

- BOS data were analyzed and compared to corresponding far-field acoustic data to study how the shock cell structure and BBSN are affected by a nearby surface.
- The following observations were made:
    1. Changes to the shock cell structure have a smaller impact on the BBSN compared to the surface shielding effect
    2. BBSN may be shielded by surfaces close to the jet if those surfaces are sufficiently longer than the shock cell train
- Data will aid in the design of future aircraft and the development of supersonic engine exhaust noise prediction tools

Miscellaneous topics of interest

- Focusing Schlieren
- JSIT Parametric Study
- Phase Knife
- Comparative study

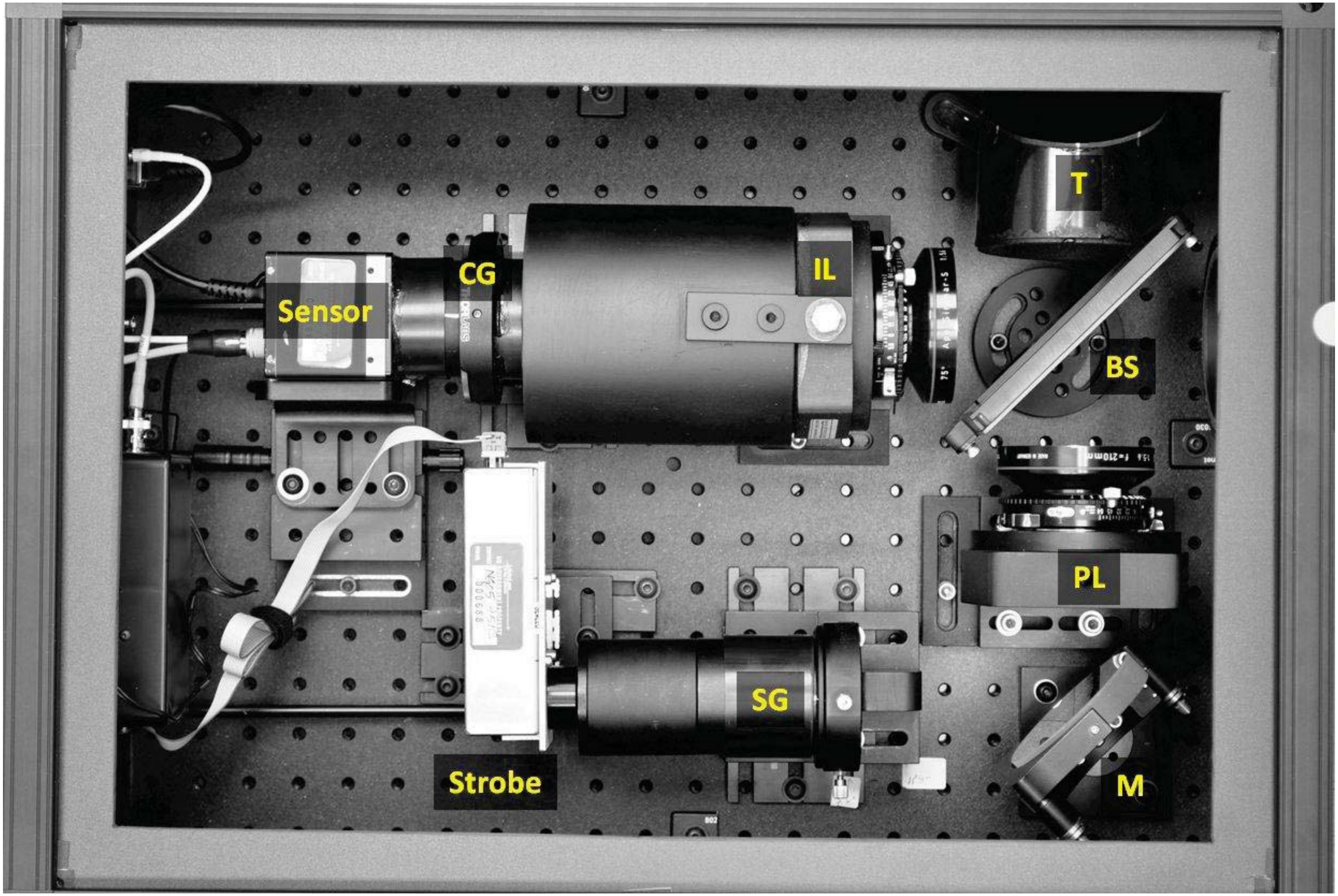
Brief Overview – Focusing Schlieren



SBIR – Metrolaser
COTR - Amy Fagan
Goal: Develop a robust, portable schlieren system, with variable FOV

- Schlierenscope – Focusing schlieren system
  - Dual grid projection system
  - All critical controls are contained within the instrument housing
  - Utilizes a Xenon strobe (1 μs) that freezes motion and captures images with a scientific CCD camera
  - Alignment between the screen and the camera is not critical, which simplifies the setup

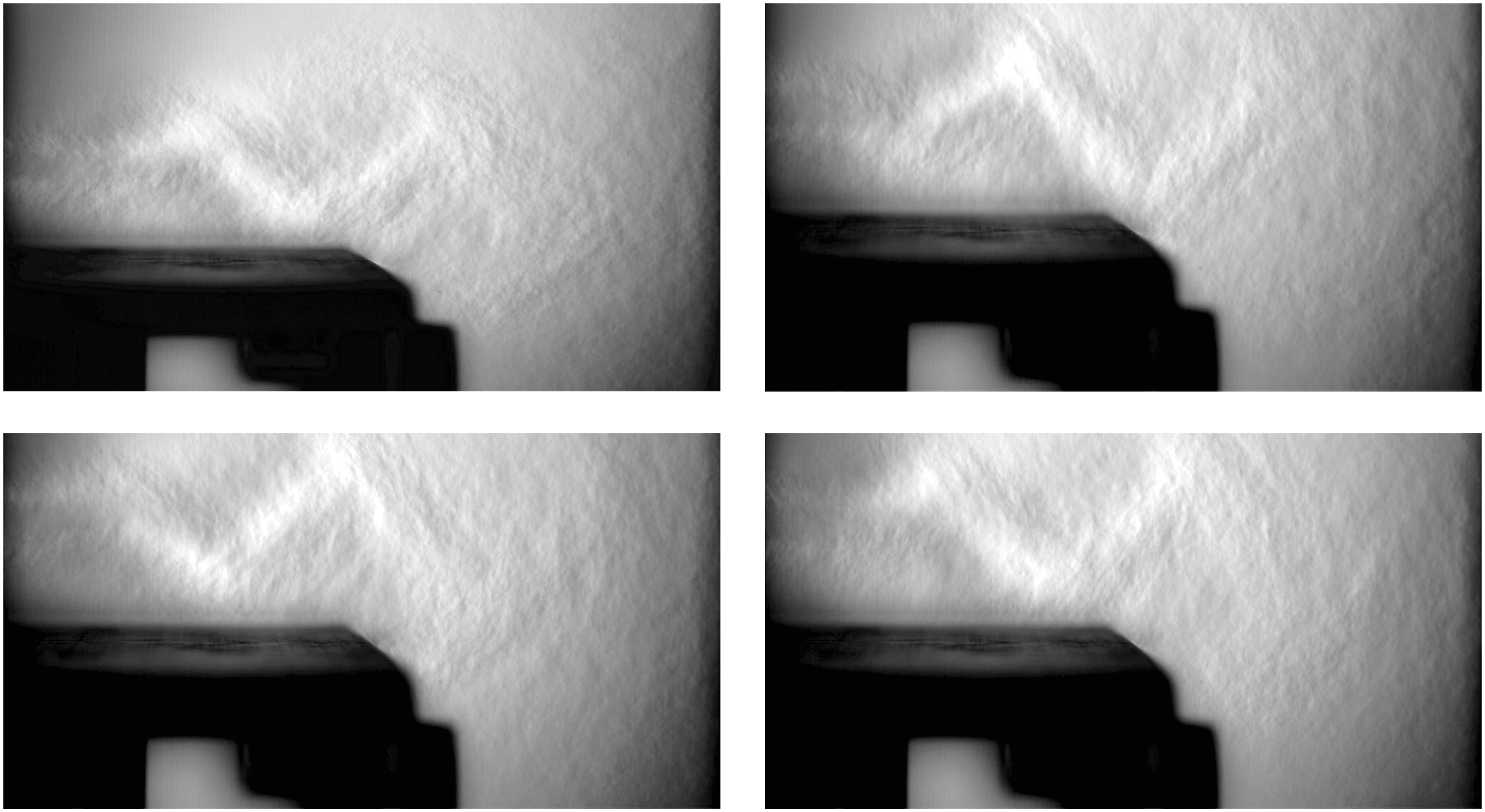
Brief Overview – Focusing Schlieren



Continuation – JSIT Parametric Study

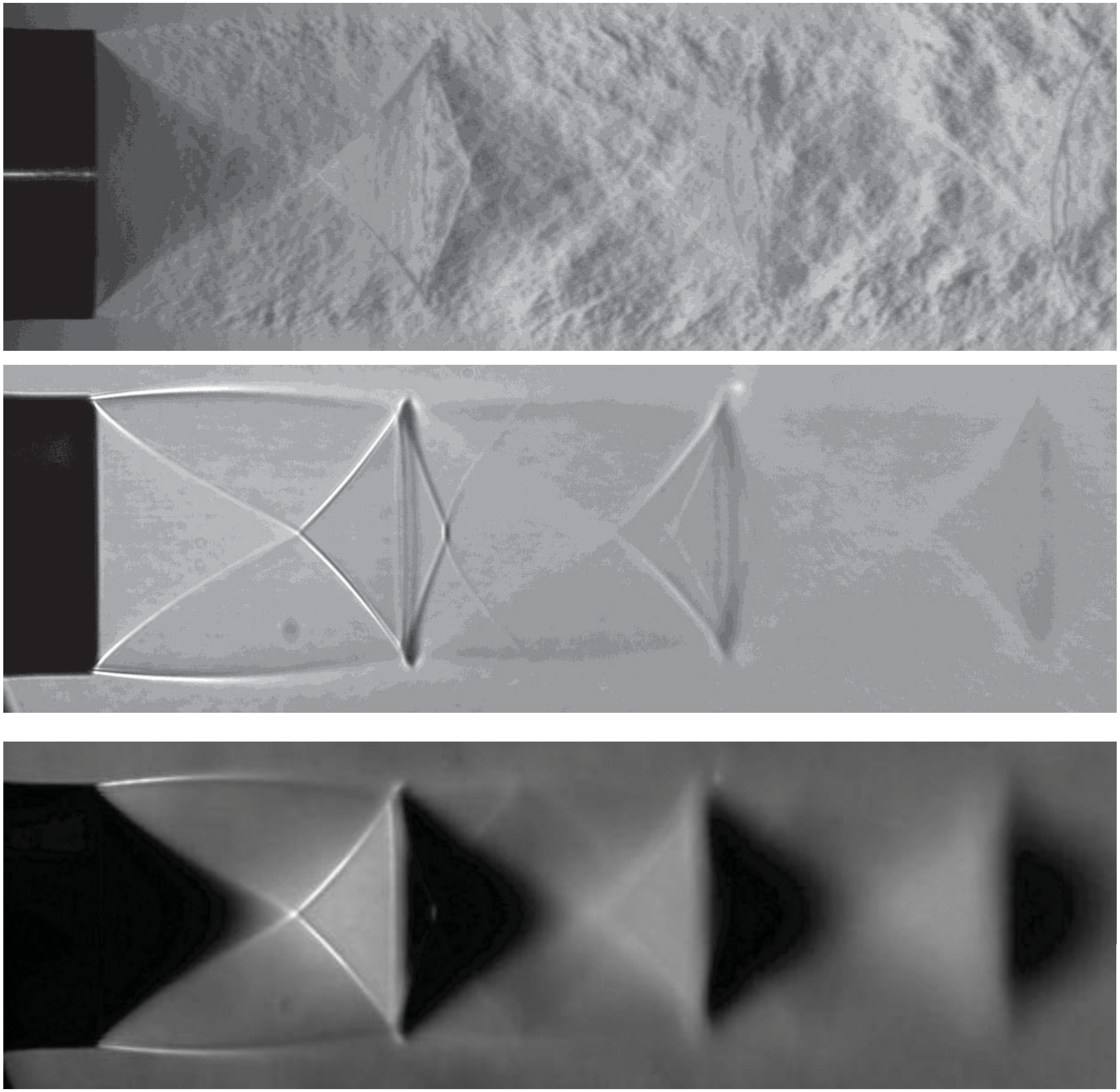
Continuation – JSIT Parametric Study

Plate length: 8 in., **T.E. distance**: 8.5 in., **stand off distance**: 1.35 in., M_j = 0.96



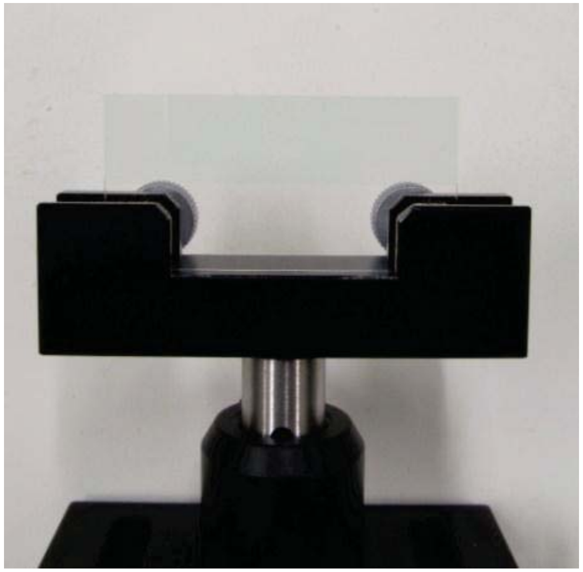
Use tone frequency to trigger/capture schlieren images in 1 period

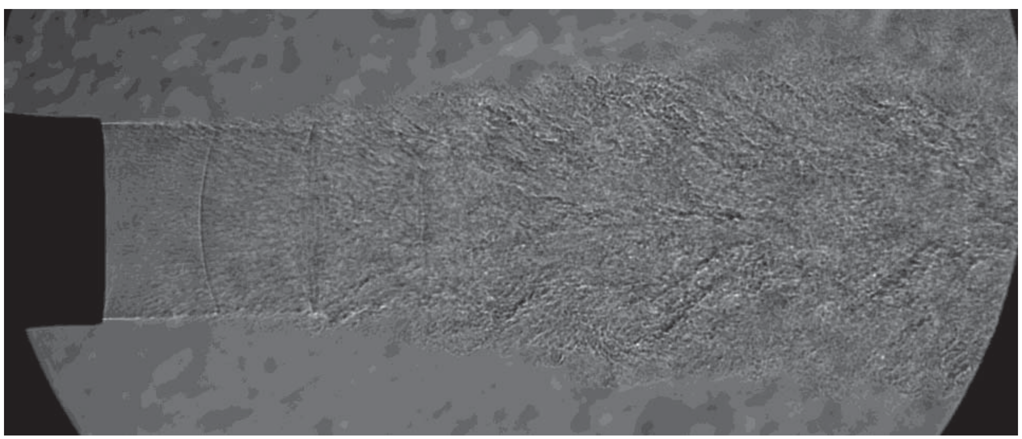
Continuation: Comprehensive Comparative Study



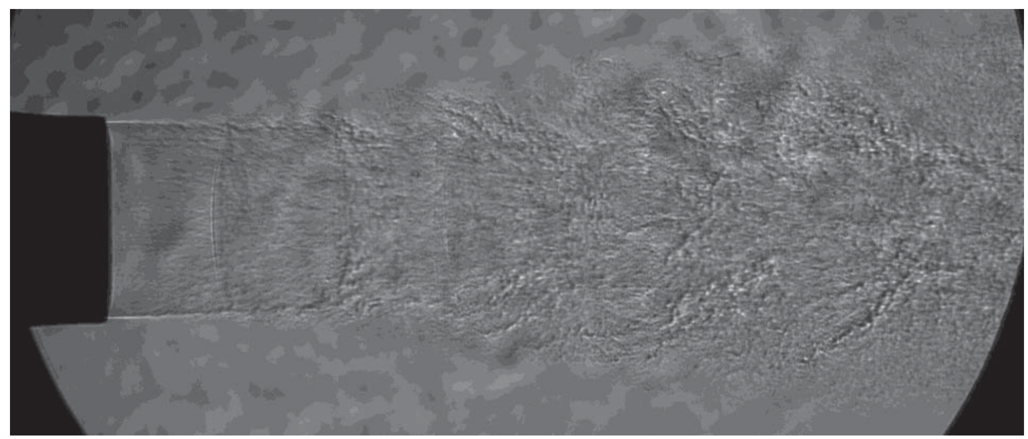
- Better characterize and enhance each technique
- Being used to further investigate the aeroacoustic screech phenomena
- Determine shock spacing

Further Investigate Phase Knife



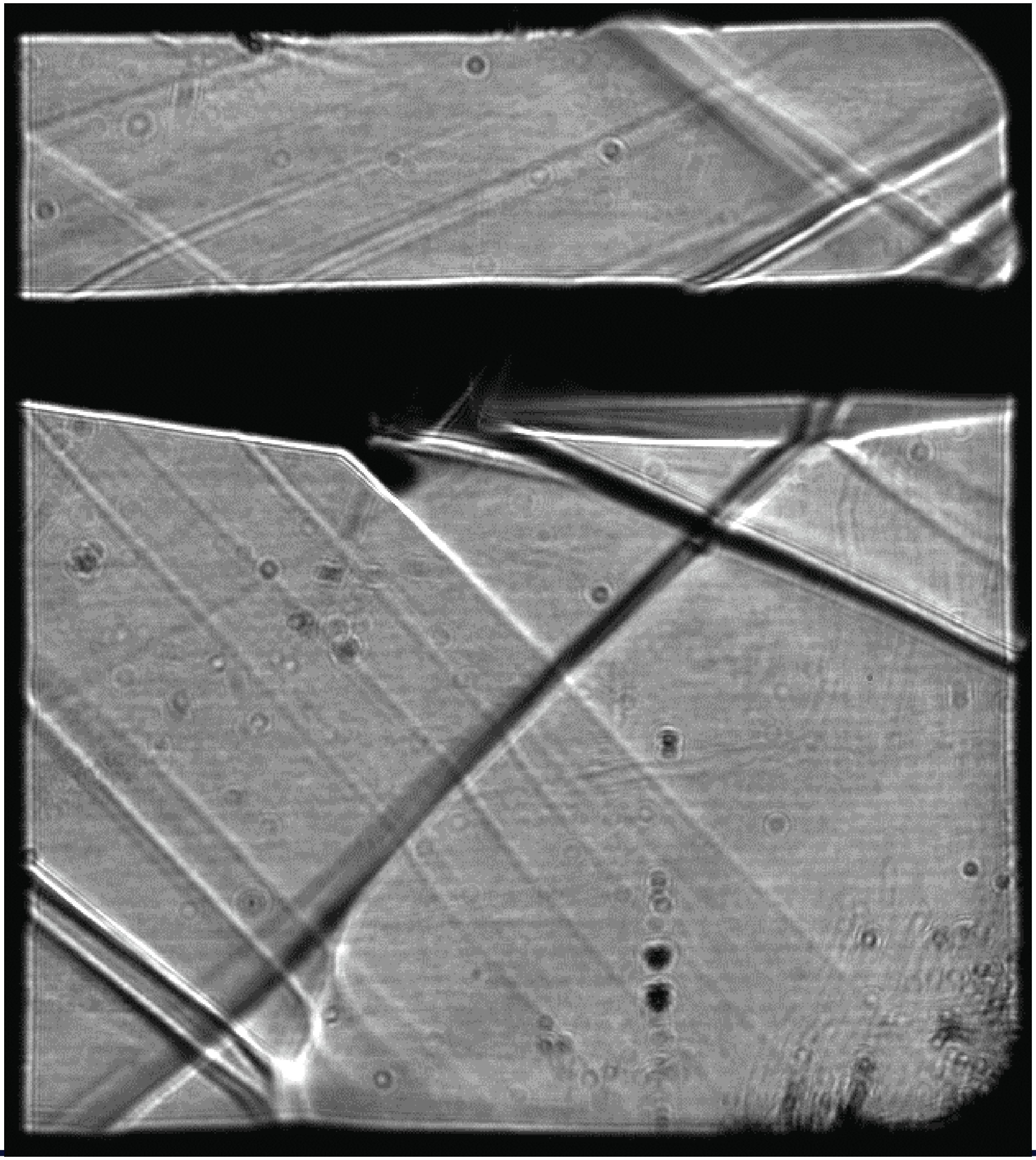


Shadowgraph – No phase knife



Schlieren - phase knife in place

Further Investigate Common Issues



VIPR 1

Thank you for your time!

Questions?