Computational and Experimental Study of Supersonic Nozzle Flow and Shock Interactions

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Outline

- Introduction
- Experimental Study
- Computational Study
- Results
- Summary

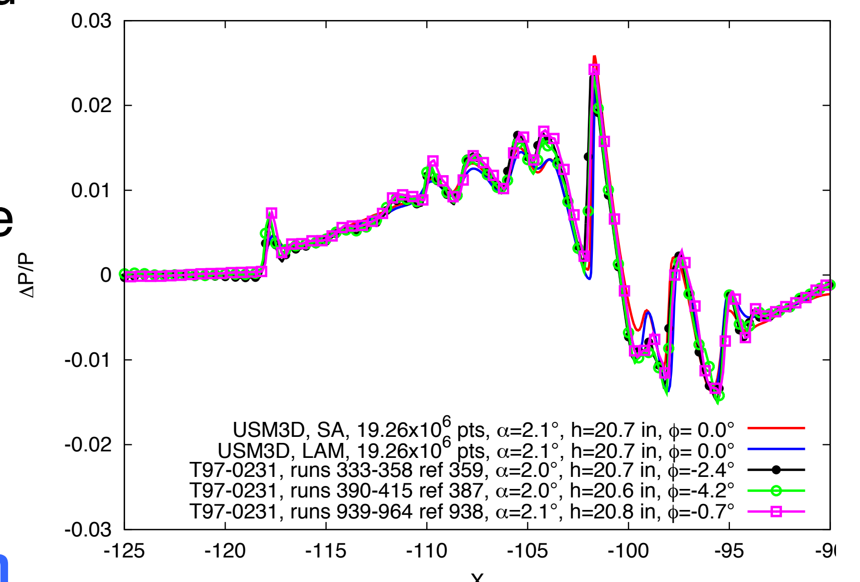
Introduction

- NASA High Speed Project is focusing on technologies to enable future civilian aircraft to fly efficiently with reduced sonic boom, engine and aircraft noise, and emissions.

- Improvement of both computational and experimental capabilities for design and analysis of low boom aircraft.

- How does the engine's plume affect the boom signature.

- **The focus of this study is to assess capability of USM3D to accurately predict the shock / plume interaction**



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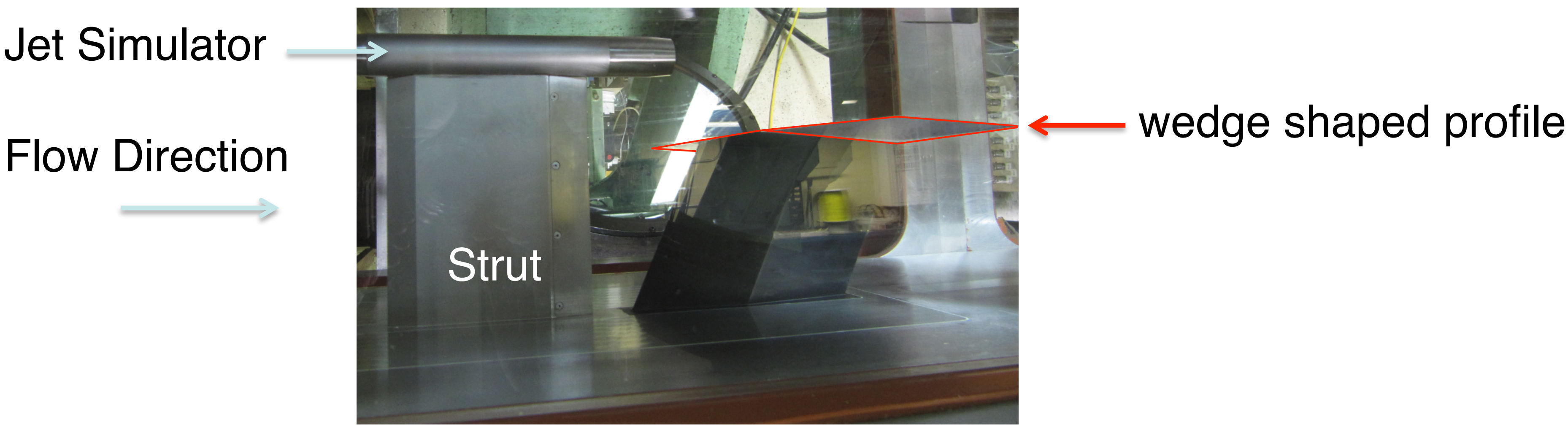
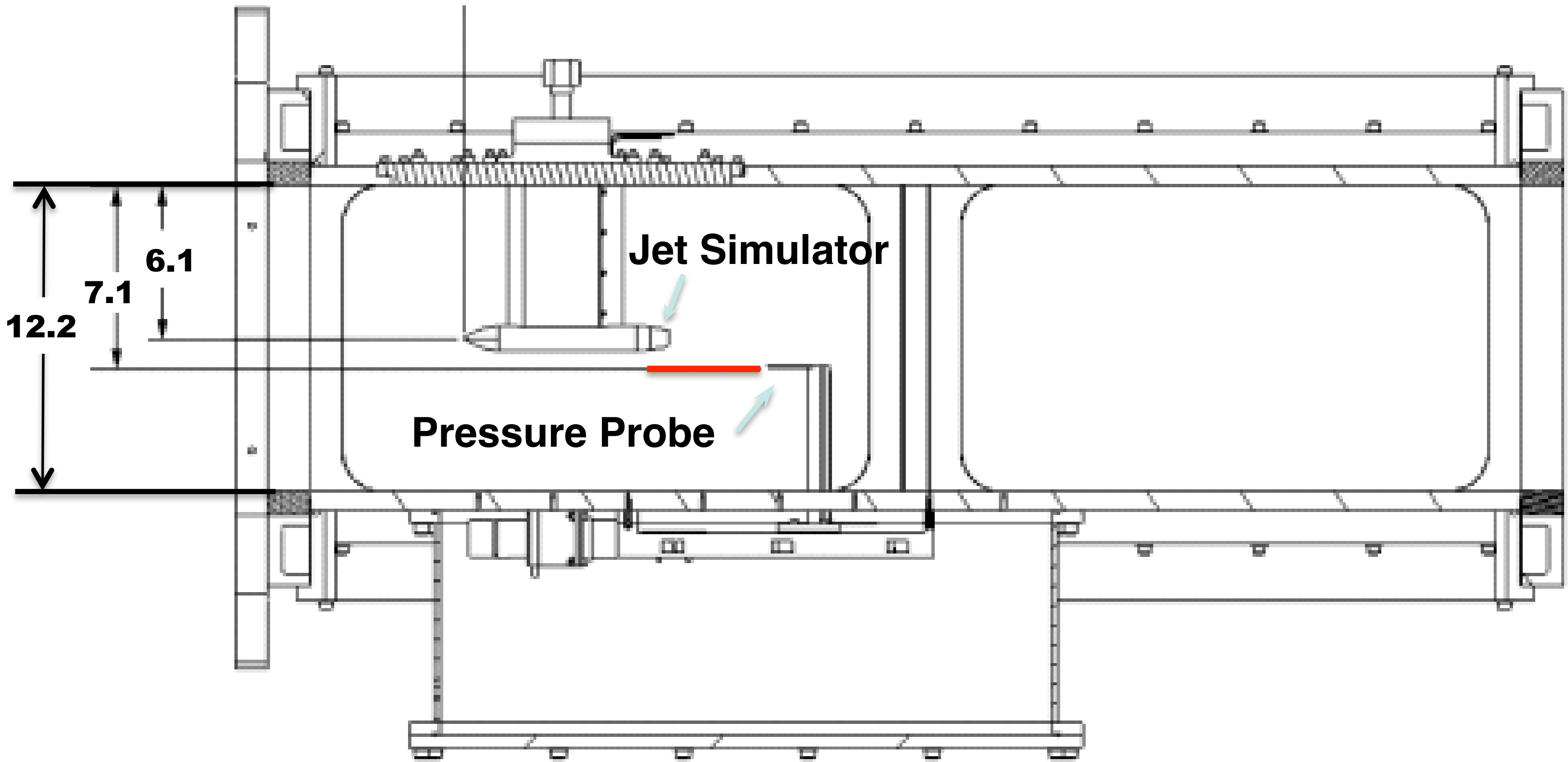
Experimental Study

- Wind tunnel test was conducted at the NASA Glenn Research Center 1-foot by 1-foot supersonic wind tunnel (GRC 1x1 SWT) to:
  - Study the interaction of a shock with an engine's plume
  - Collect data for CFD validation



Raymond Castner, Susan Cliff, Alaa Elmiligui, and Courtney Winski, "Plume and Shock Interaction Effects on Sonic Boom in the 1-foot by 1-foot Supersonic Wind Tunnel."

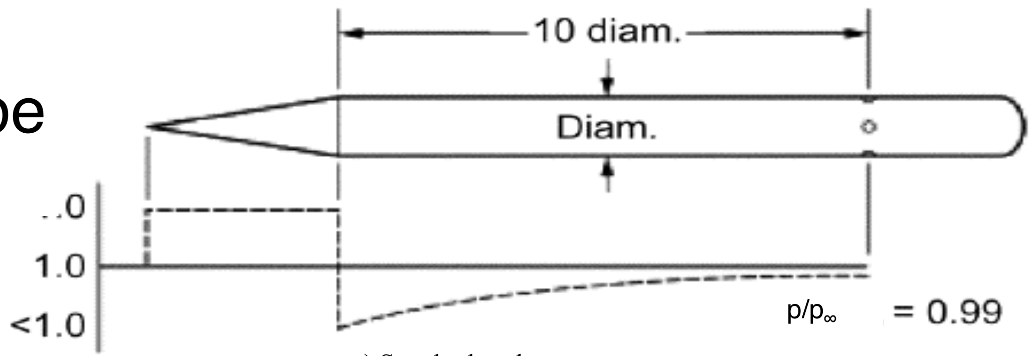
1X1 Supersonic Wind Tunnel Test Section



Test Section is 12-inches by 12.2-inches by 53.25-inches long

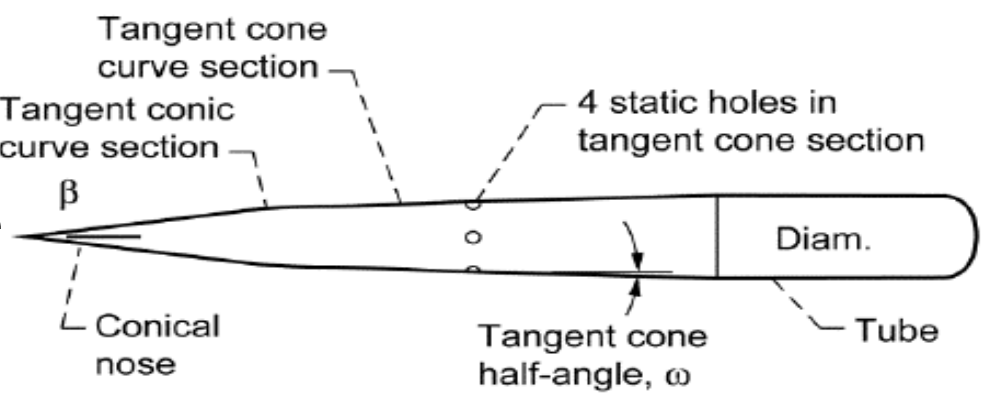
Pressure Probes

Standard probe



a) Standard probe

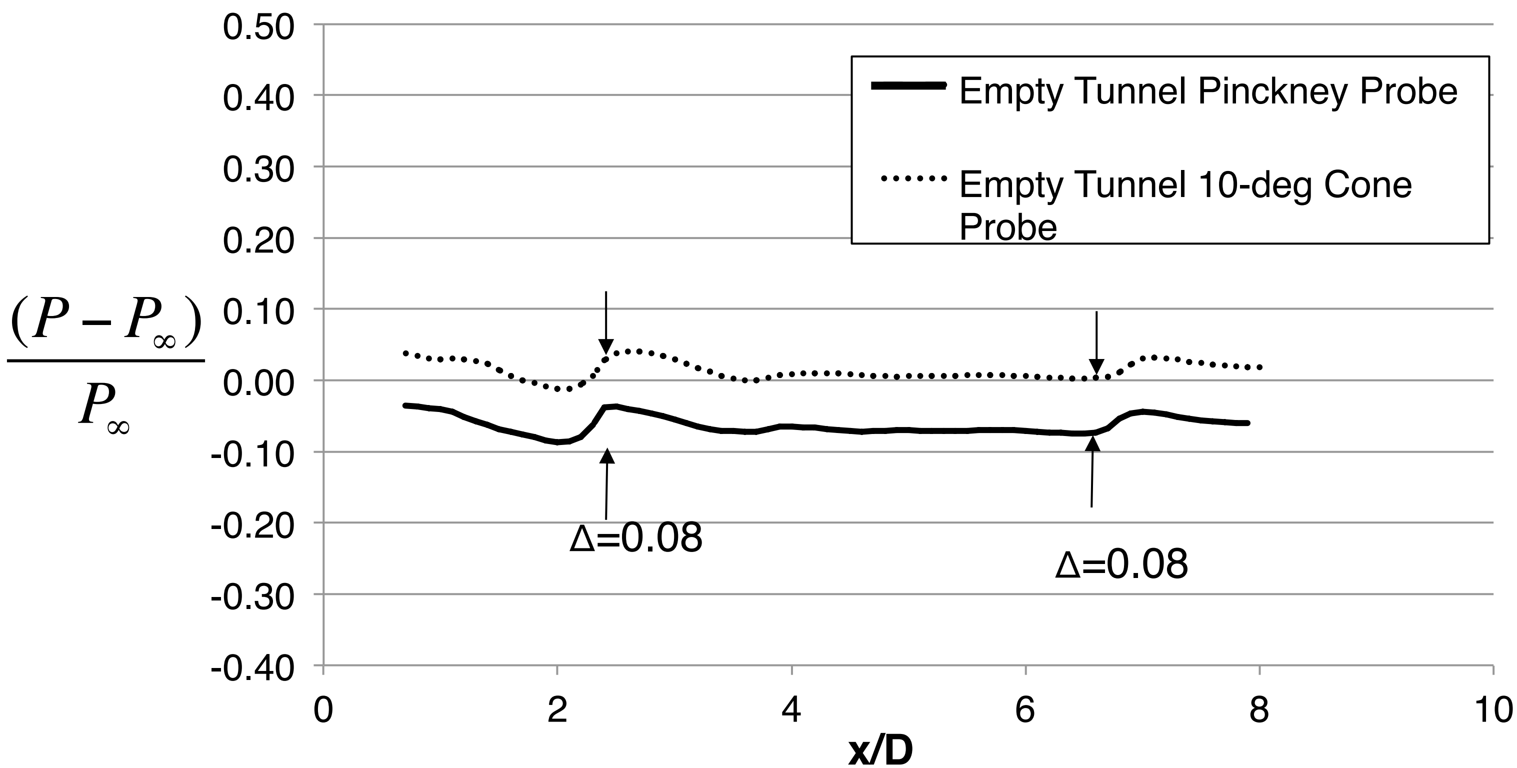
Pinckney probe



Two static pressure probes were built, a 10-degree cone probe and a probe based on the design of Pinckney probe.

Pressure Probes

1x1 SWT Shock and Plume Interaction RUN 44
Empty Tunnel



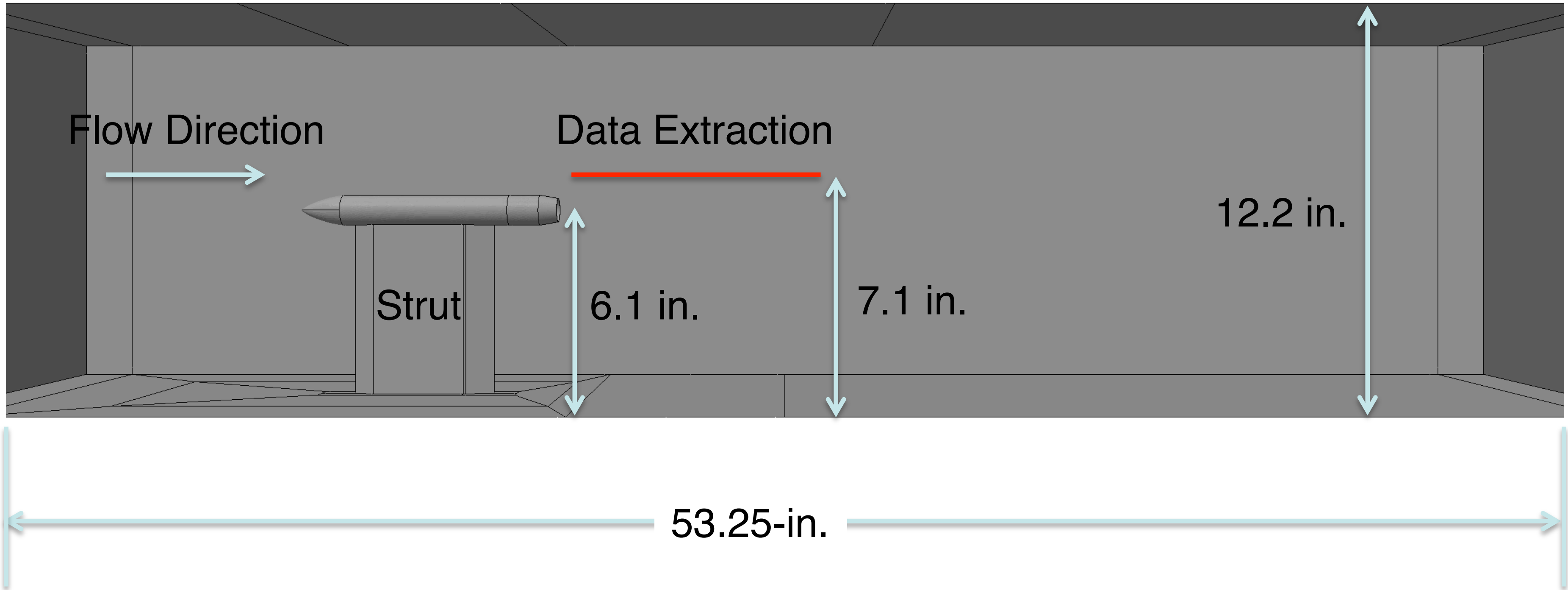
Static pressure data collected with the Pinckney probe demonstrated an offset in ΔP/P of -0.08

Configurations Tested in Wind Tunnel

Total of 8 configurations were tested:

- Empty Tunnel
- 1.5 inch wedge shock generator
- 6 inch wedge shock generator
- Jet and 1.5 inch wedge shock generator
- Jet and 6 inch wedge shock generator

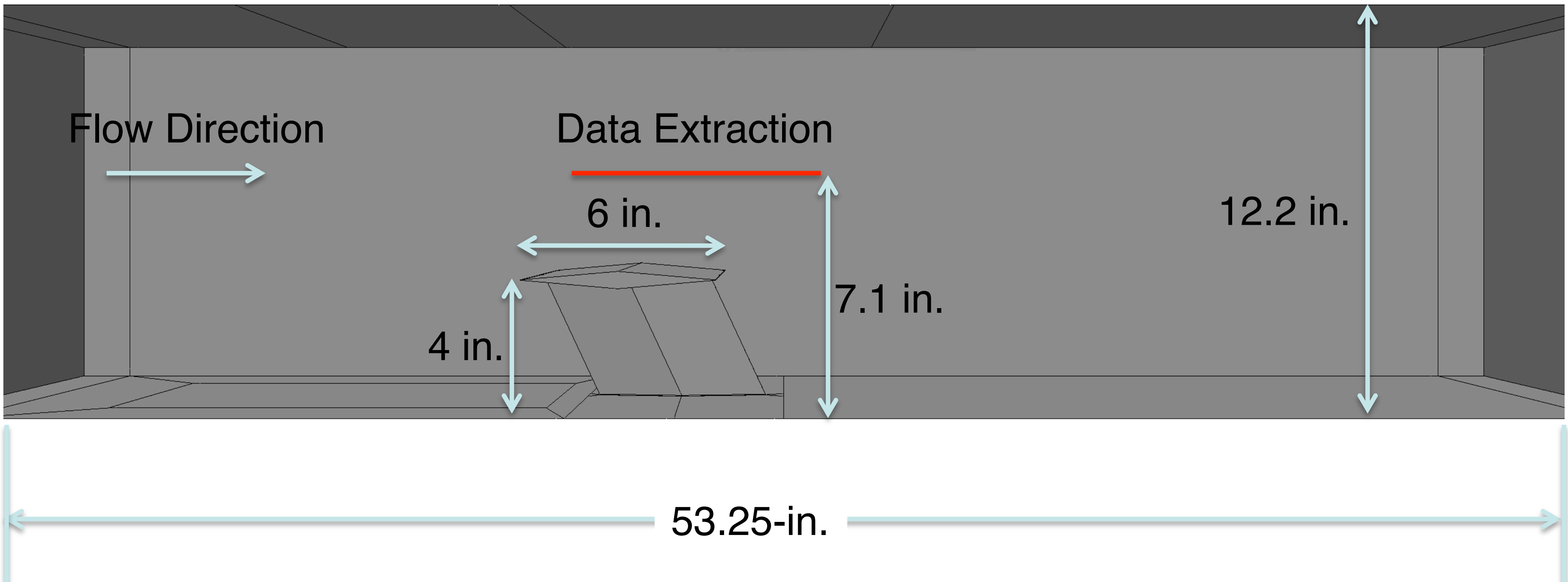
Jet in GRC 1x1 SWT Test Section



Test section is 12-inches X 12.2-inches X 53.25-inches long

Line extractions taken at 1 inch above nozzle centerline

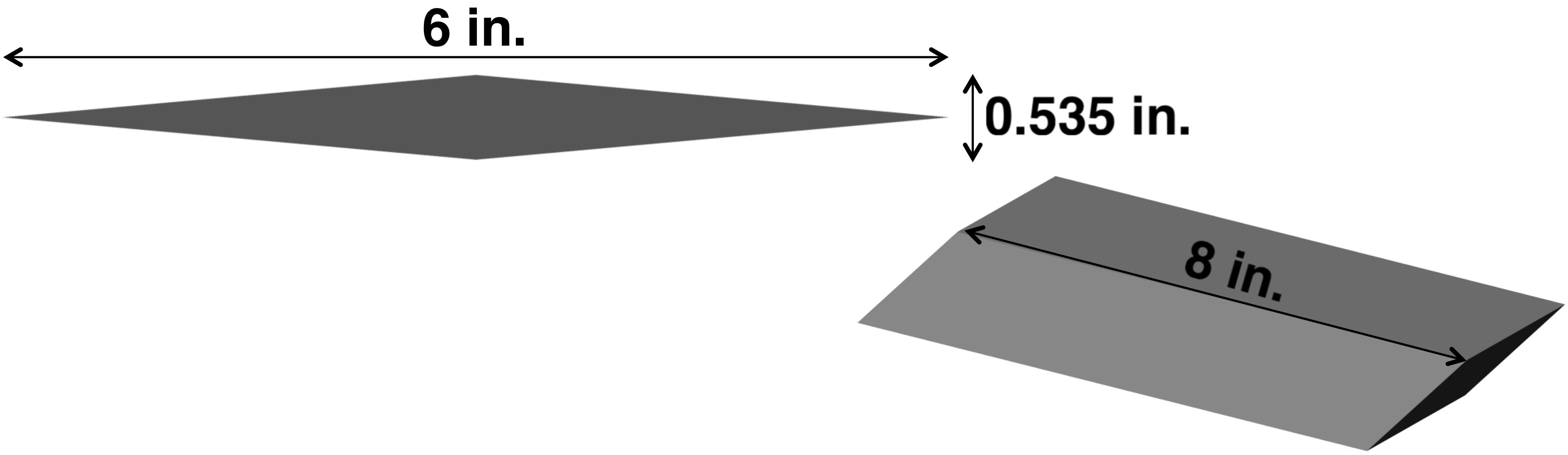
6 inch Wedge



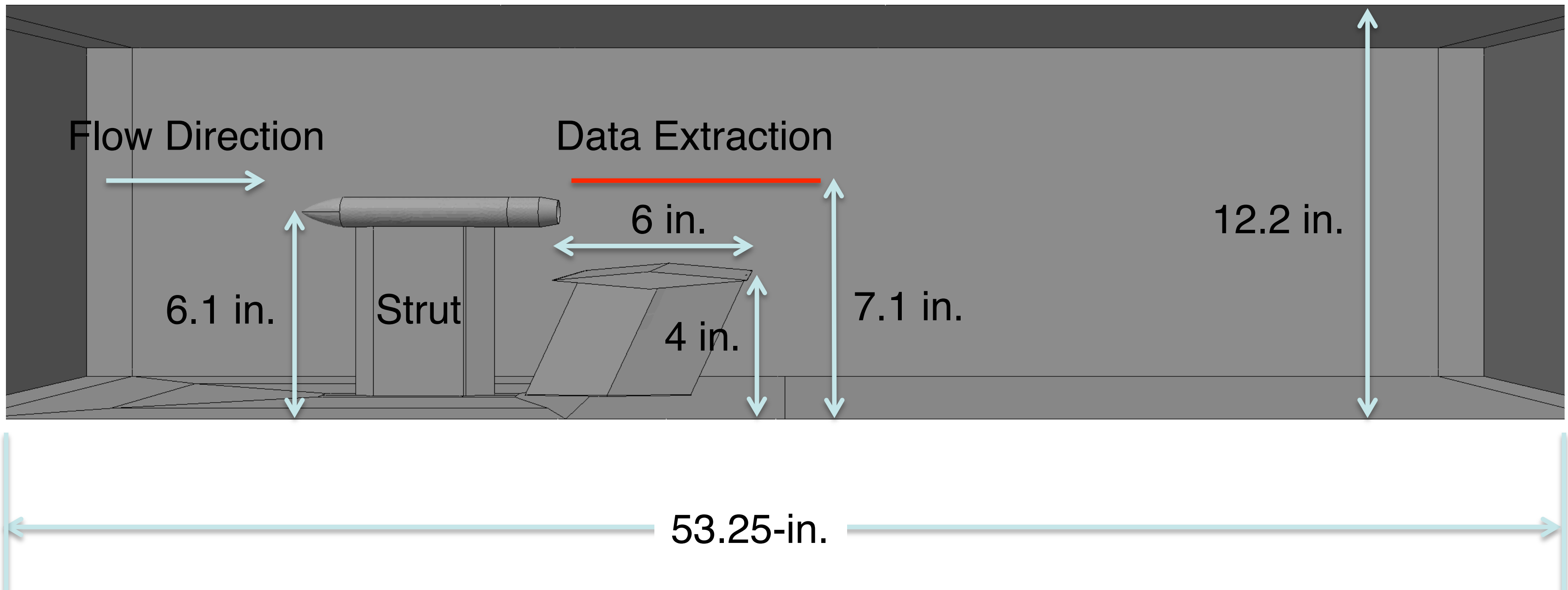
Test section is 12-inches X 12.2-inches X 53.25-inches long

Line extractions taken at 1 inch above nozzle centerline

6 inch Wedge



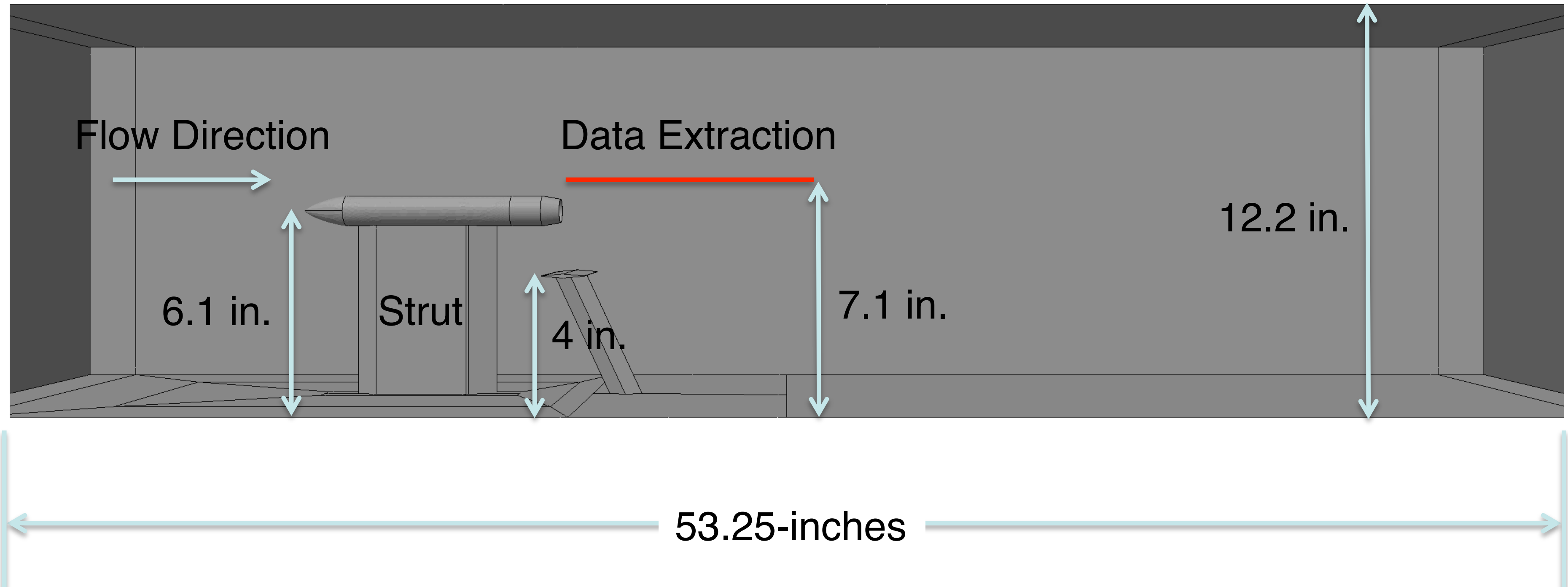
Jet and 6 inch Wedge



Test section is 12-inches X 12.2-inches X 53.25-inches long

Line extractions taken at 1 inch above nozzle centerline

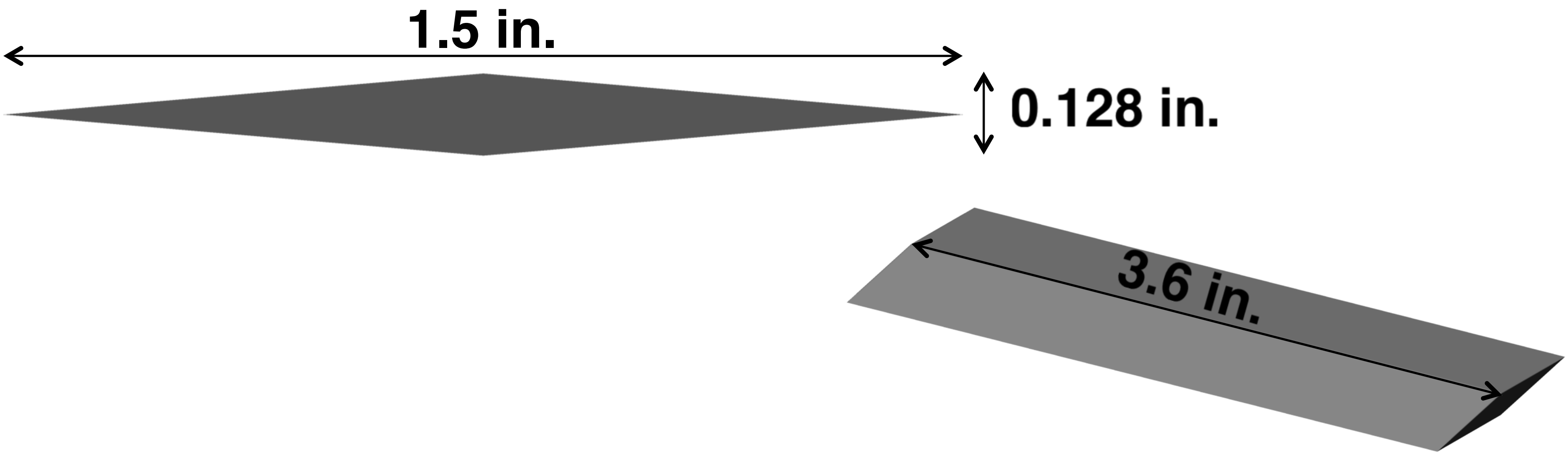
Jet and 1.5 inch Wedge



Test section is 12-inches X 12.2-inches X 53.25-inches long

Line extractions taken at 1 inch above nozzle centerline

1.5 inch Wedge



Wind Tunnel Flow Conditions

Reference Conditions

- **Mach: 1.96**
- **Nominal Reynolds Number: 271,526**
- Temperature: 168.9 K
- Pressure: 1.68 psia

Tunnel Inlet

- Stagnation Temperature: 298.3 K
- Stagnation Pressure: 12.35 psia

Nozzle Inlet

- Stagnation Temperature: 294.4 K
- Stagnation Pressure
  - Po = 69.5, 92.7, 115.8, 139.0, 162.1 kPa
  - **NPR = 6, 8, 10, 12, 14**

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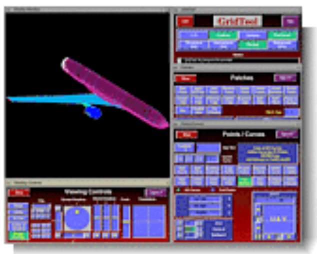
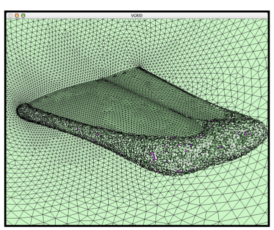
TetrUSS Tetrahedral Unstructured Software System

A proven, stable, and reliable multi-platform system for unstructured Euler and Navier-Stokes CFD analysis



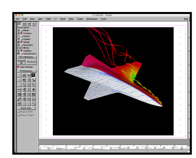
Geometry Setup
GridTool

- *Complete flow analysis system*
- *Well developed infrastructure*
- *In-house experts*
- *Broad outside collaborations*
- *Design via. CDISC/SUSIE*
- *Workhorse system with large experience/confidence base*

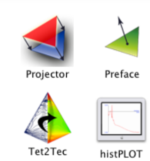


Grid Generation
VGRID OpenGL

Flow Solver
USM3D



Visualization
SimpleView
(Commercial Packages)



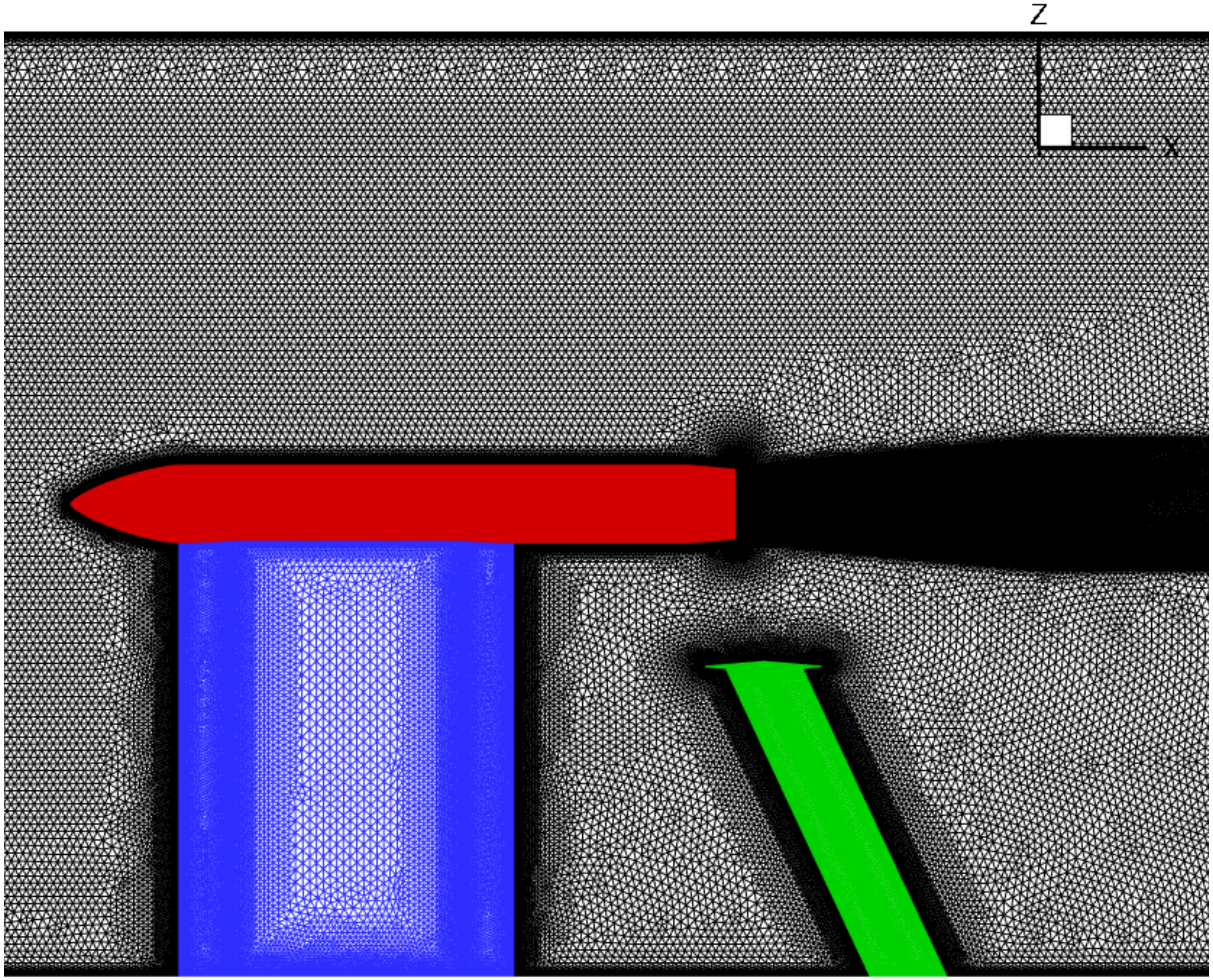
Tools & Utilities

Neal.T.Frink@nasa.gov

USM3D Tetrahedral Flow Solver

- Tetrahedral Cell-Centered, Finite Volume
- Euler and Navier-Stokes
- Time Integration
  – LTS and 2nd order time stepping
- Upwind Spatial Discretization
  – FDS, AUSM, HLLC, LDFSS, FVS
  – Min-mod limiter
- Standard and Special BC's
- Turbulence Models SA, SST, k-ε Sarkar Pressure Dilatation

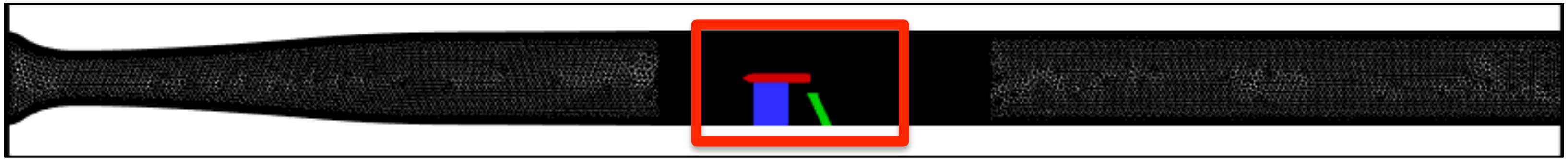
Computational Grids



Test Section:

1. Empty test section
2. 6 inch wedge
3. 1.5 inch wedge
4. Jet & 6 inch wedge
5. Jet & 1.5 wedge

- $y^+ \leq 1$
- Full Tunnel



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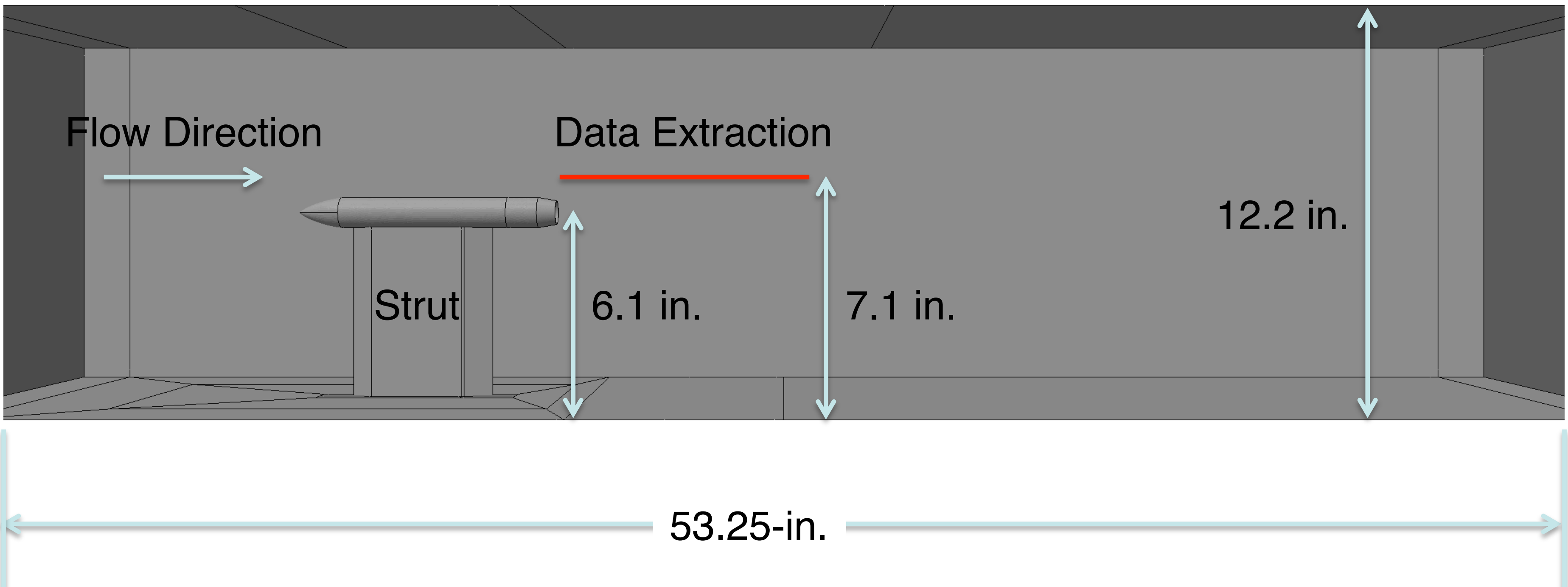
- Results
    - *Mach = 1.96, Re = 271,526*
    - *Jet NPR = 6, 8, 10, 12, 14*
- Summary

Jet in GRC 1x1 SWT Test Section

Mach = 1.96, NPR = 8, Re = 271,526

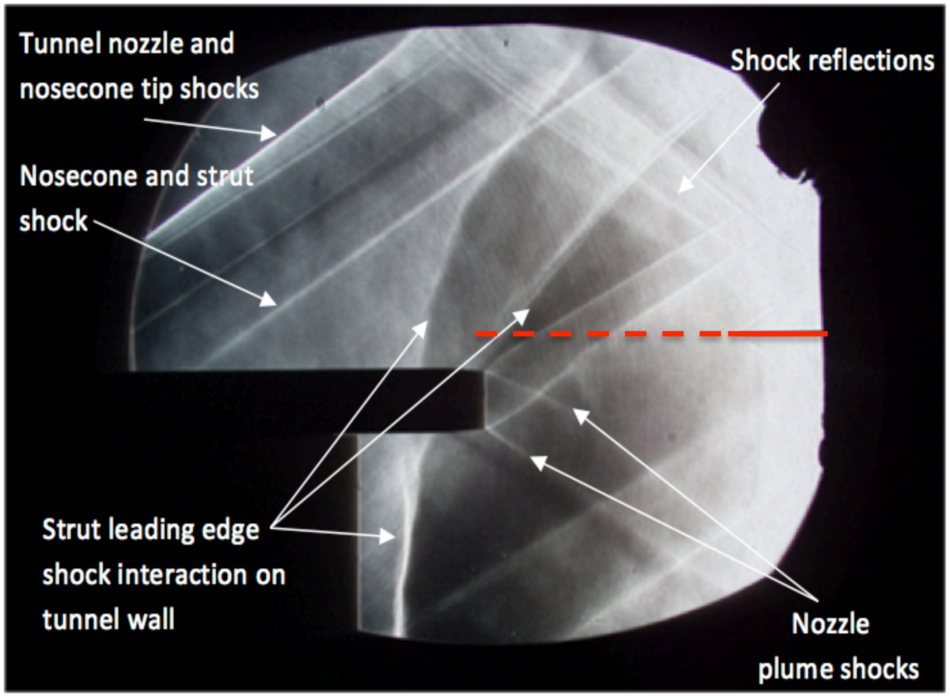


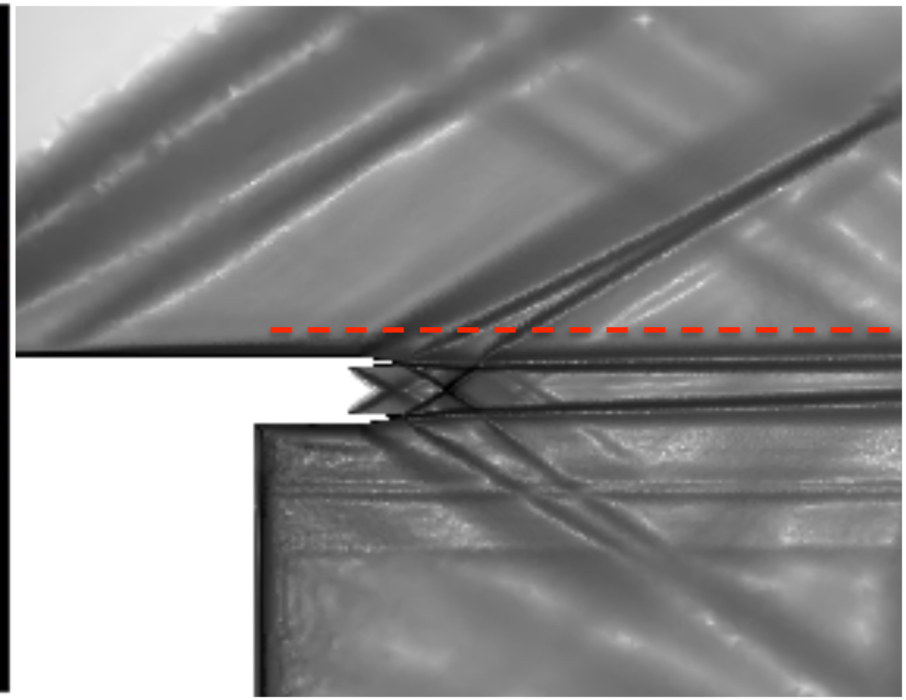
Grid size 37.4 million cells

Line extractions taken at 1 inch above nozzle centerline

Tunnel Shock Structure

Mach = 1.96, NPR = 8, Re = 271,526



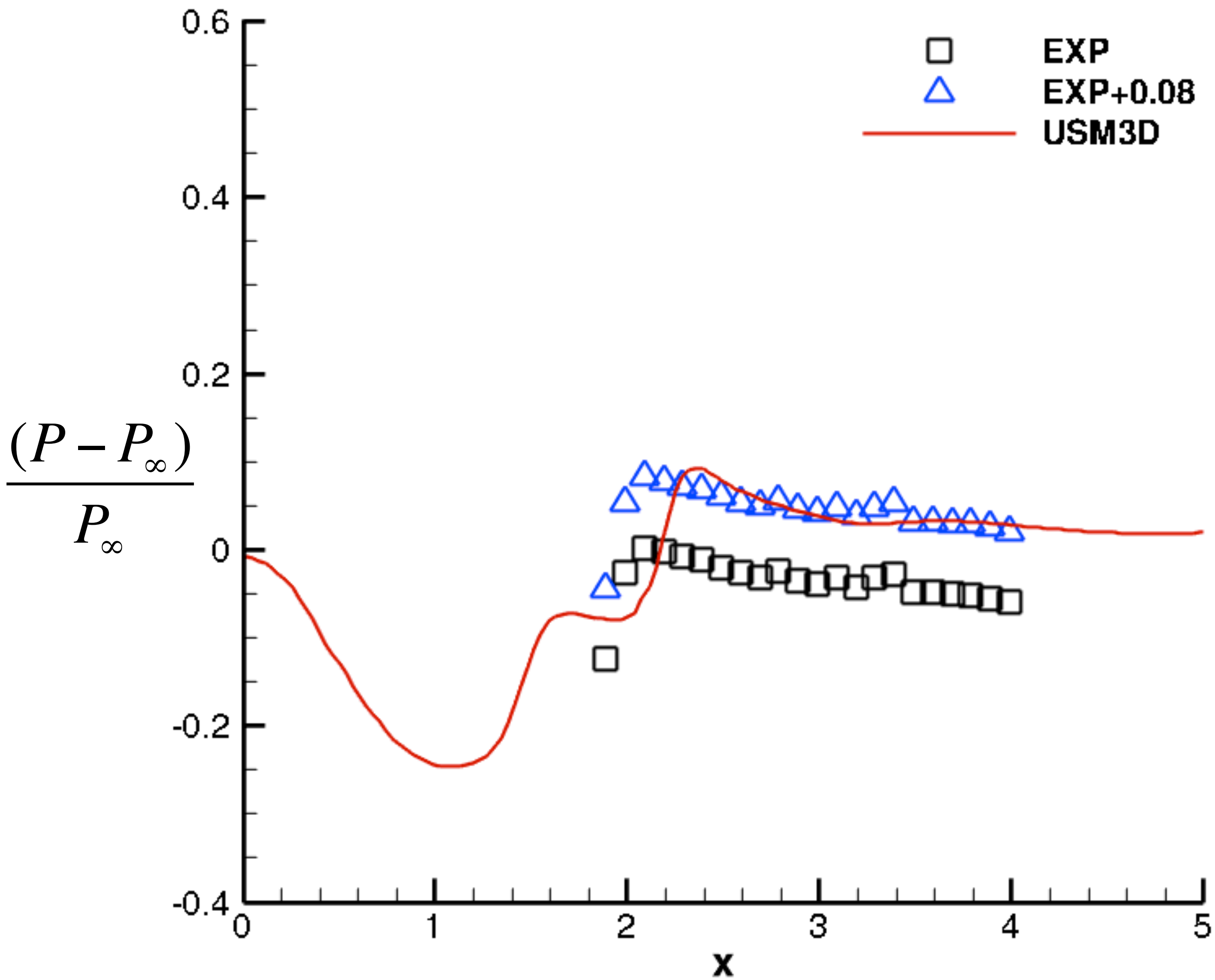


Schlieren Image

Computed Density Gradient

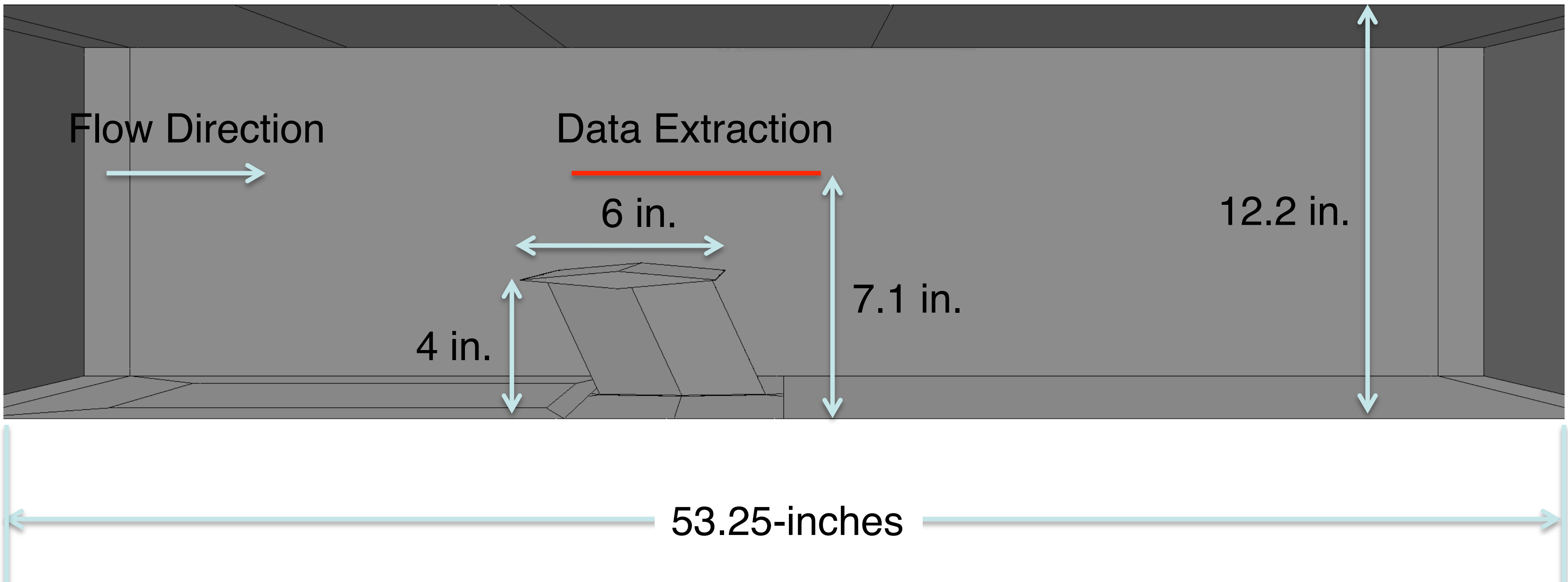
Comparison of Computed Pressure Profiles and Experimental Data

Mach = 1.96, NPR = 8, Re = 271,526



6 inch Wedge

Mach = 1.96, NPR = 8, Re = 271,526

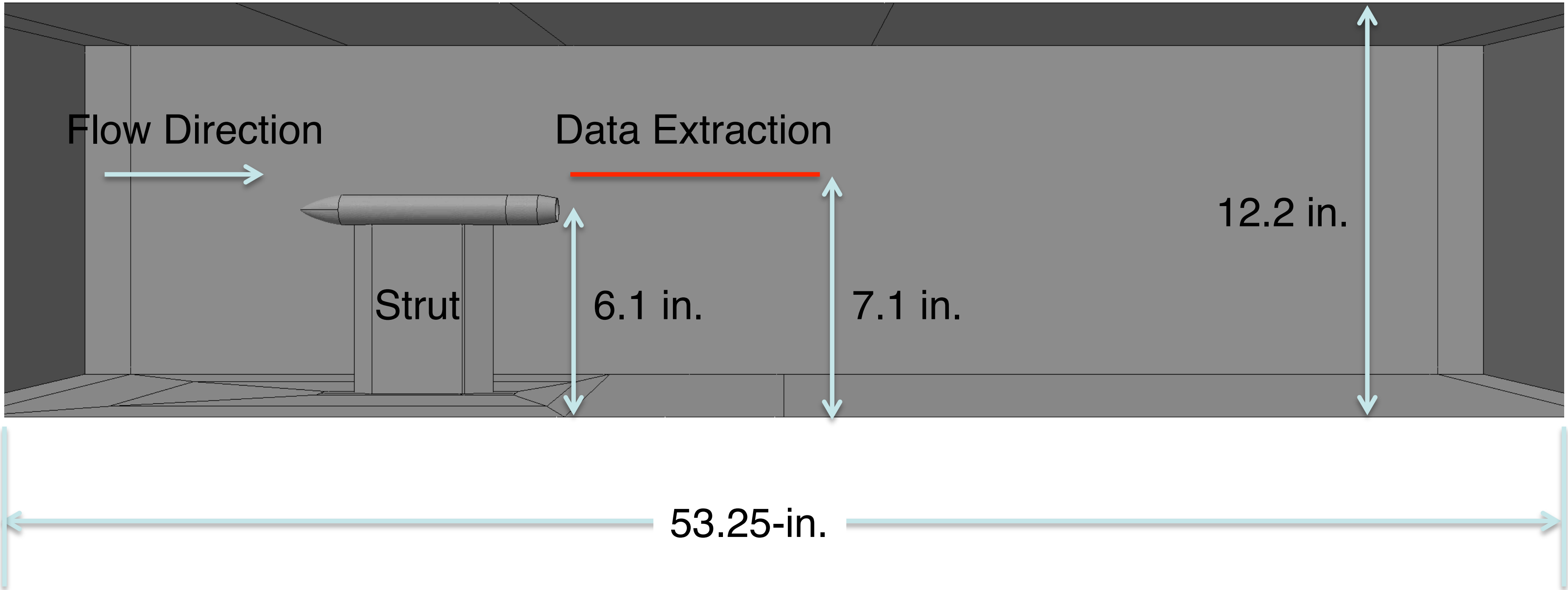


Grid Size 26.6 million cells

Line extractions taken at 1 inch above nozzle centerline

Jet in GRC 1x1 SWT Test Section

Mach = 1.96, NPR = 8, Re = 271,526

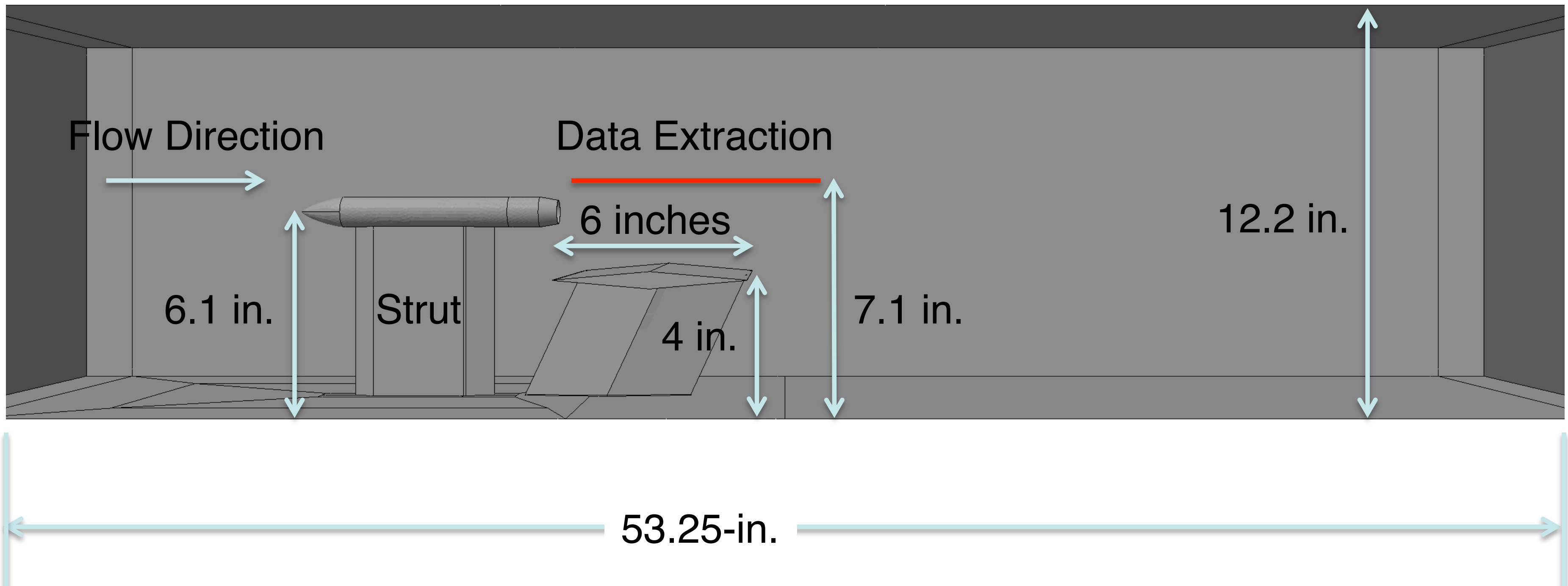


Grid Size 37.4 million cells

Line extractions taken at 1 inch above nozzle centerline

Jet and 6 inch Wedge

Mach = 1.96, NPR = 8, Re = 271,526

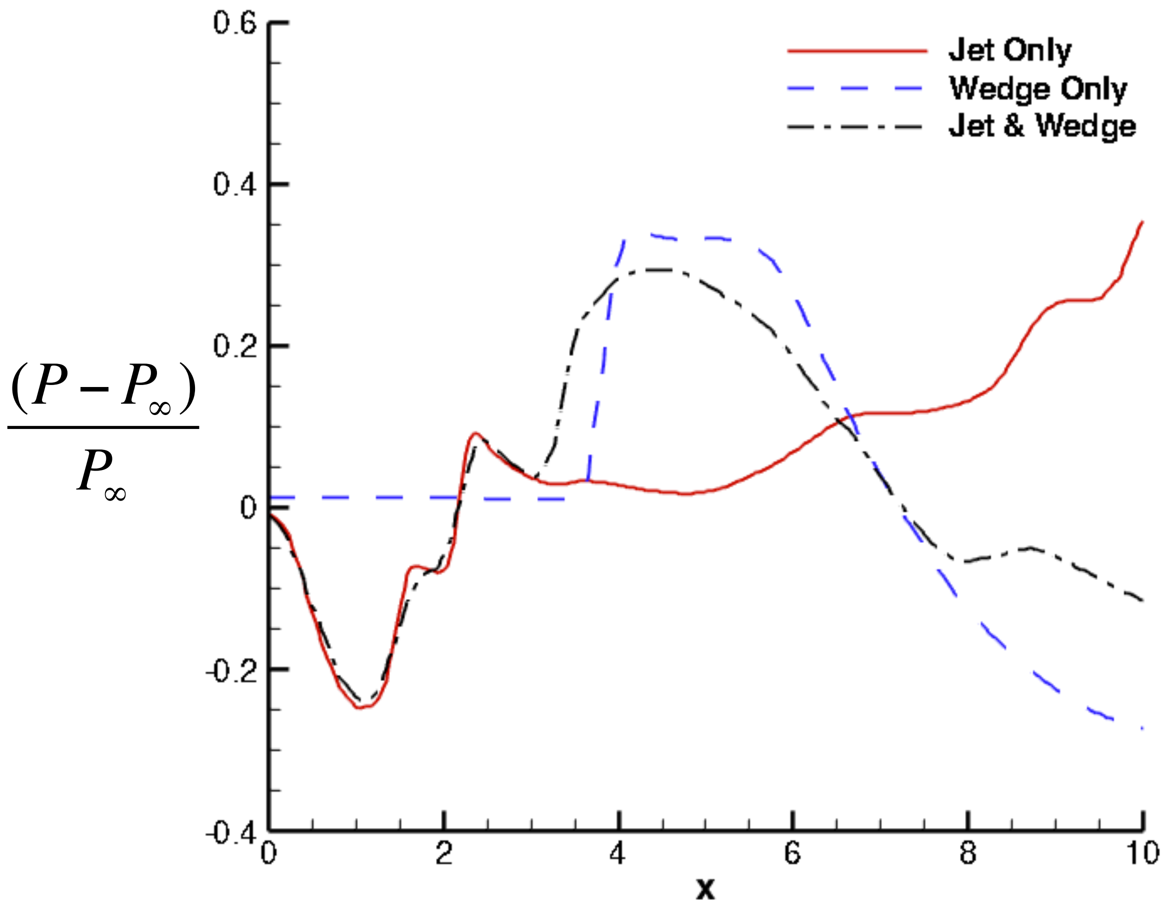


Grid Size 33.9 million cells

Line extractions taken at 1 inch above nozzle centerline

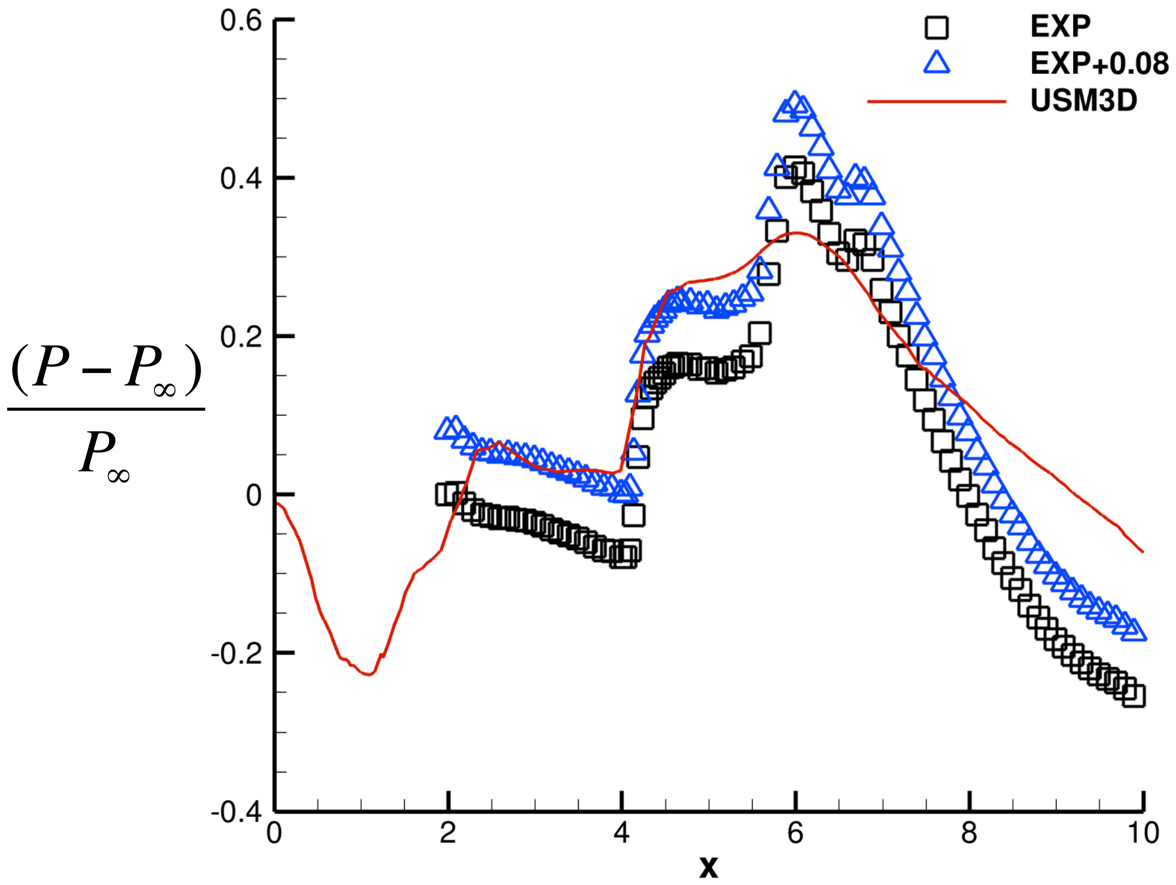
Predicted Pressure Signature of Jet Alone, Wedge Alone and Jet & Wedge

Mach = 1.96, NPR = 8, Re = 271,526



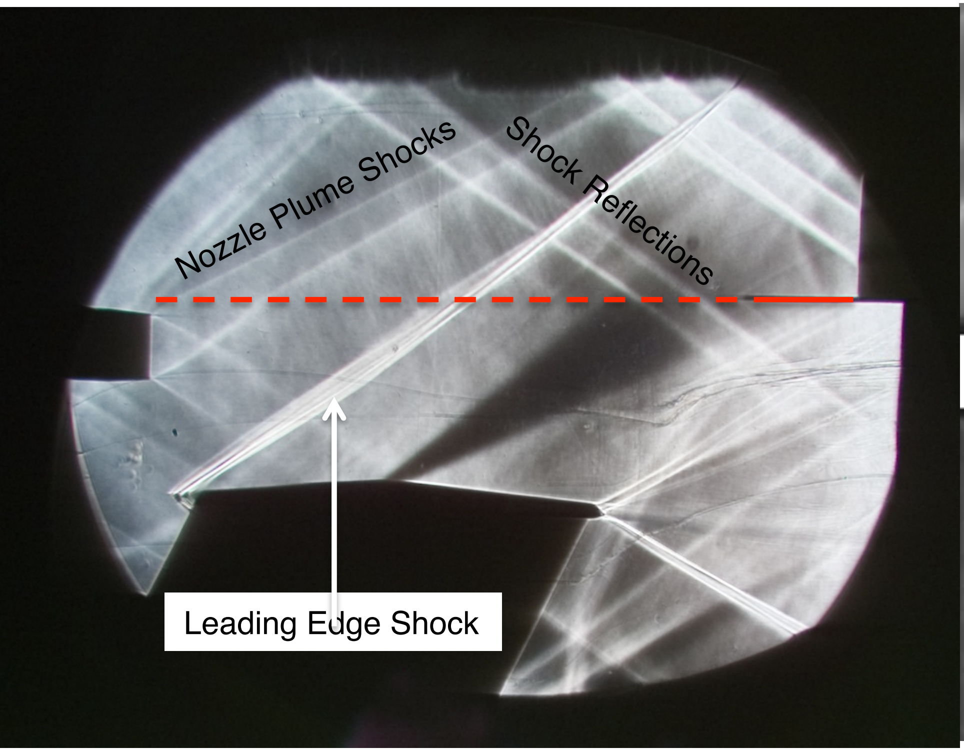
Pressure Signature for Jet and 6 inch Wedge

Mach = 1.96, NPR = 8, Re = 271,526

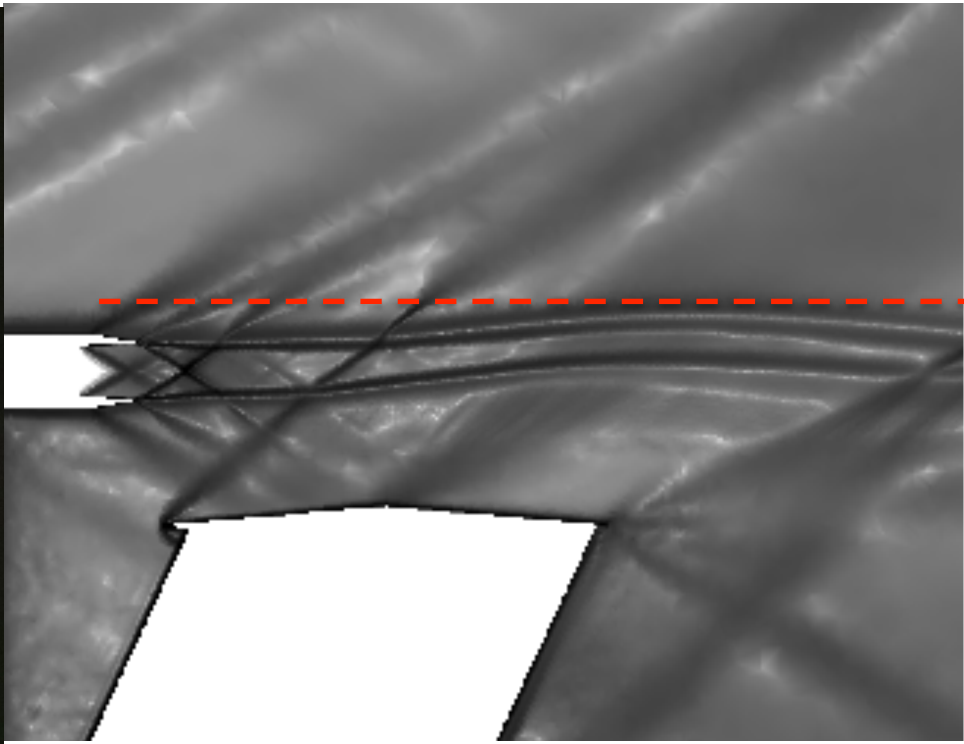


Tunnel Shock Structure for Jet and 6 inch Wedge

Mach = 1.96, NPR = 8, Re = 271,526



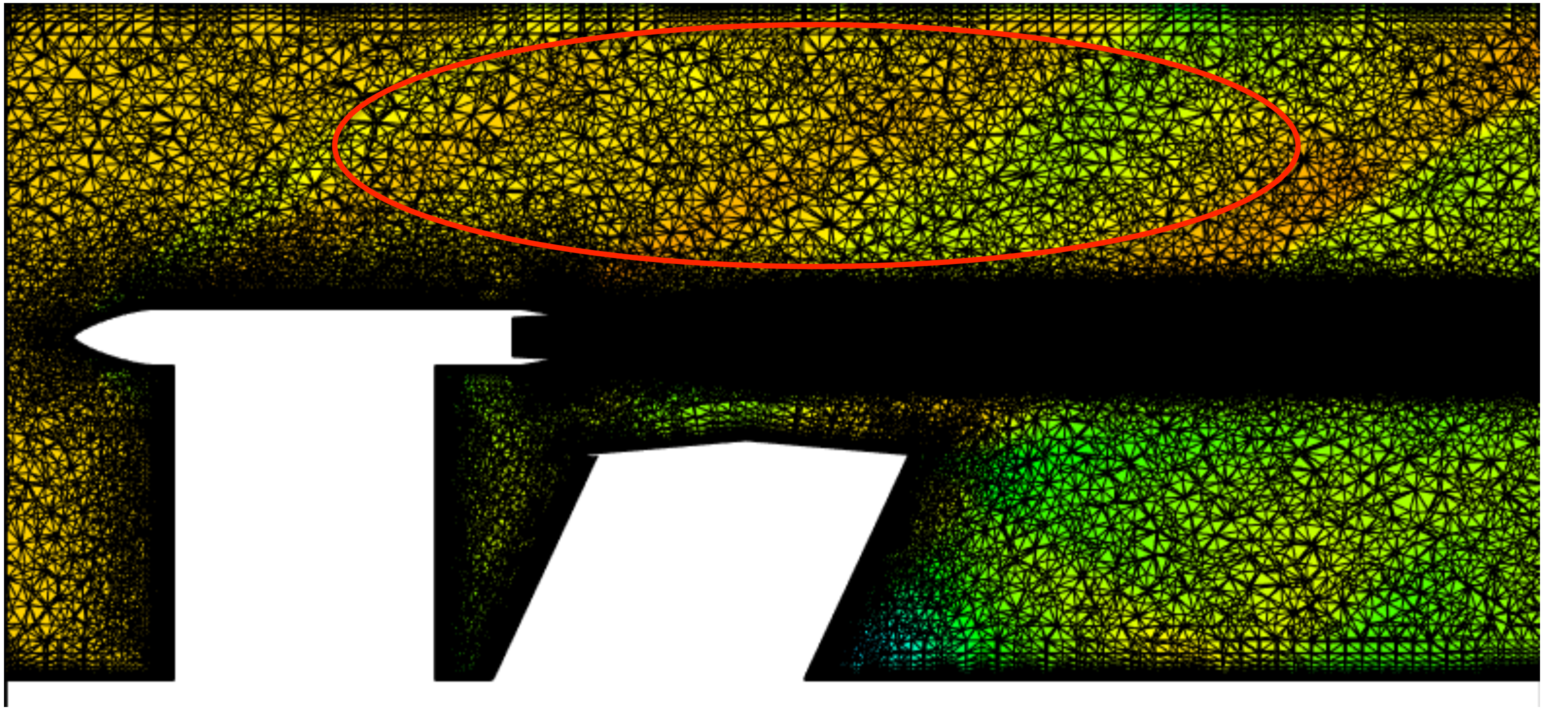
Schlieren Image



Computed Density Gradient

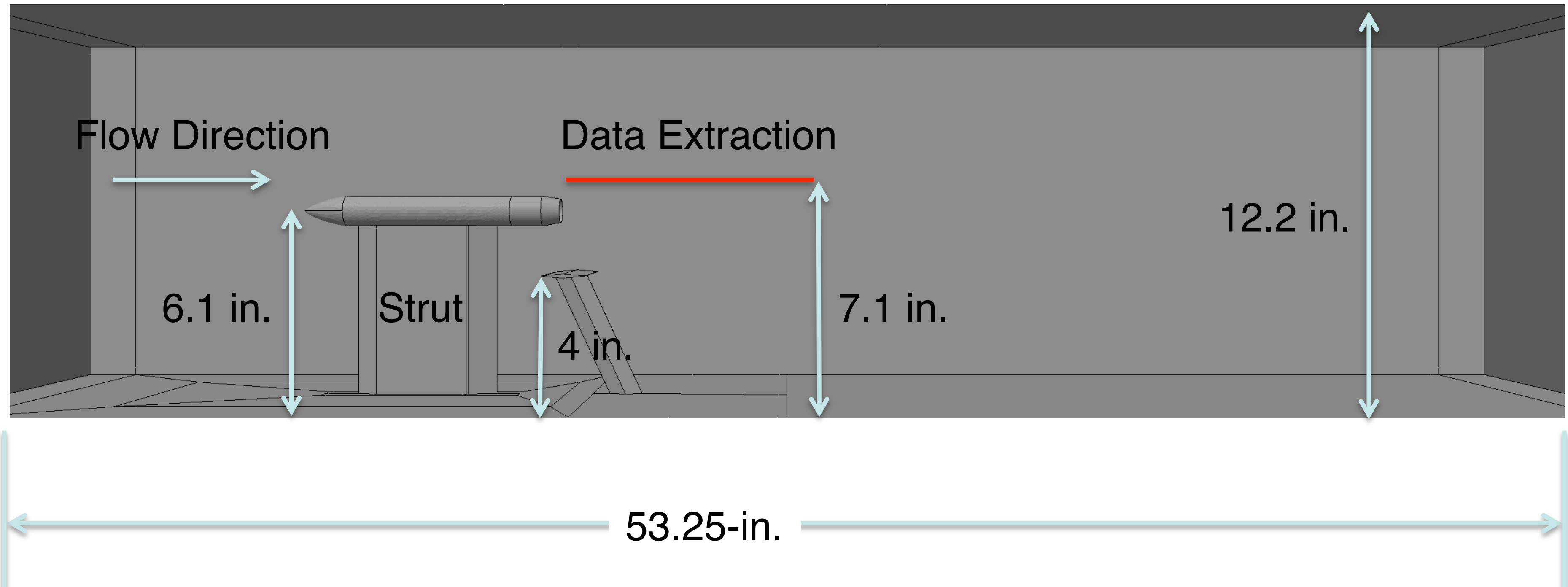
Computational Grid for 6 inch Wedge and Jet

Mach = 1.96, NPR = 8, Re = 271,526



Jet and 1.5 inch Wedge

Mach = 1.96, NPR = 8, Re = 271,526

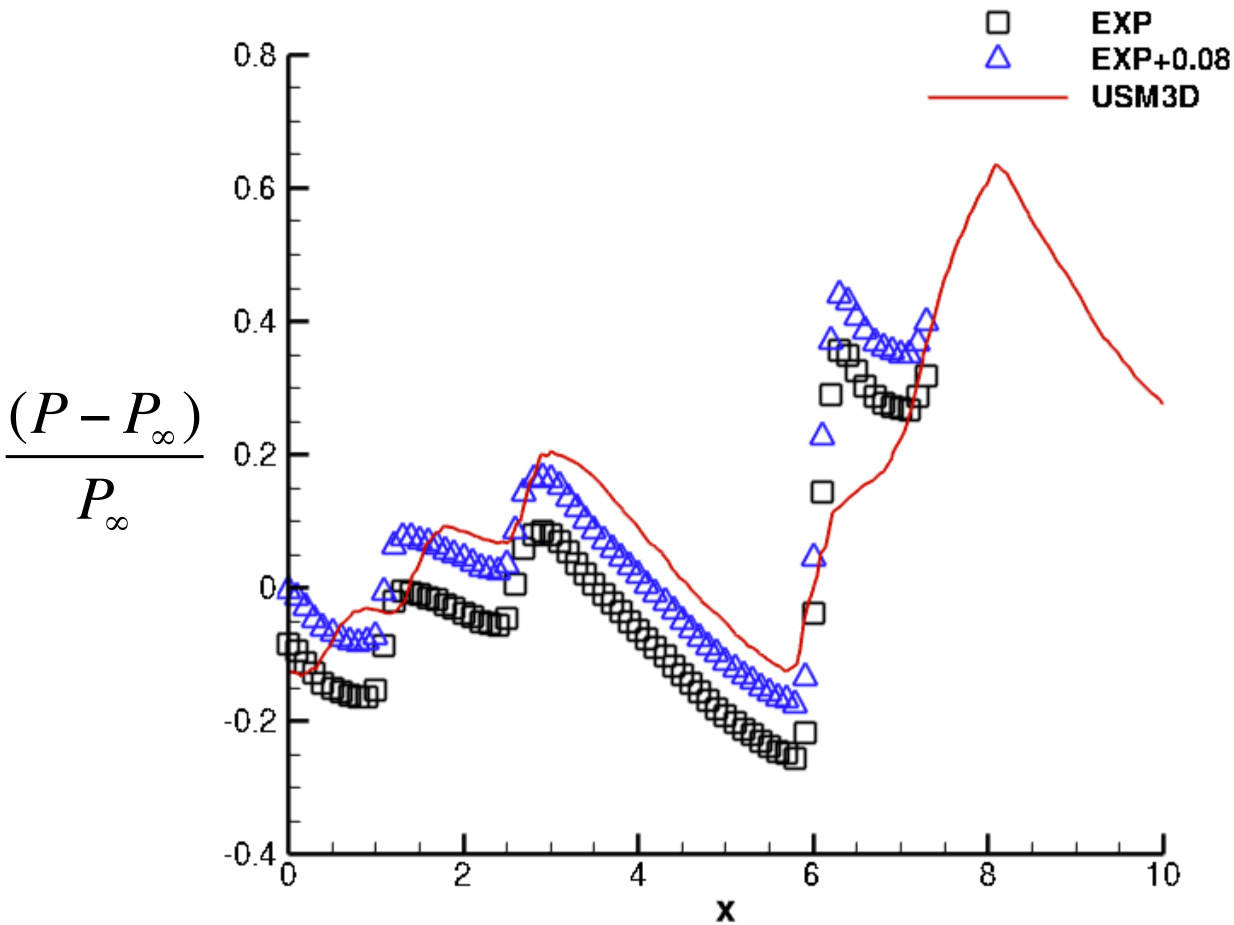


Grid Size 52.3 million cells

Line extractions taken at 1 inch above nozzle centerline

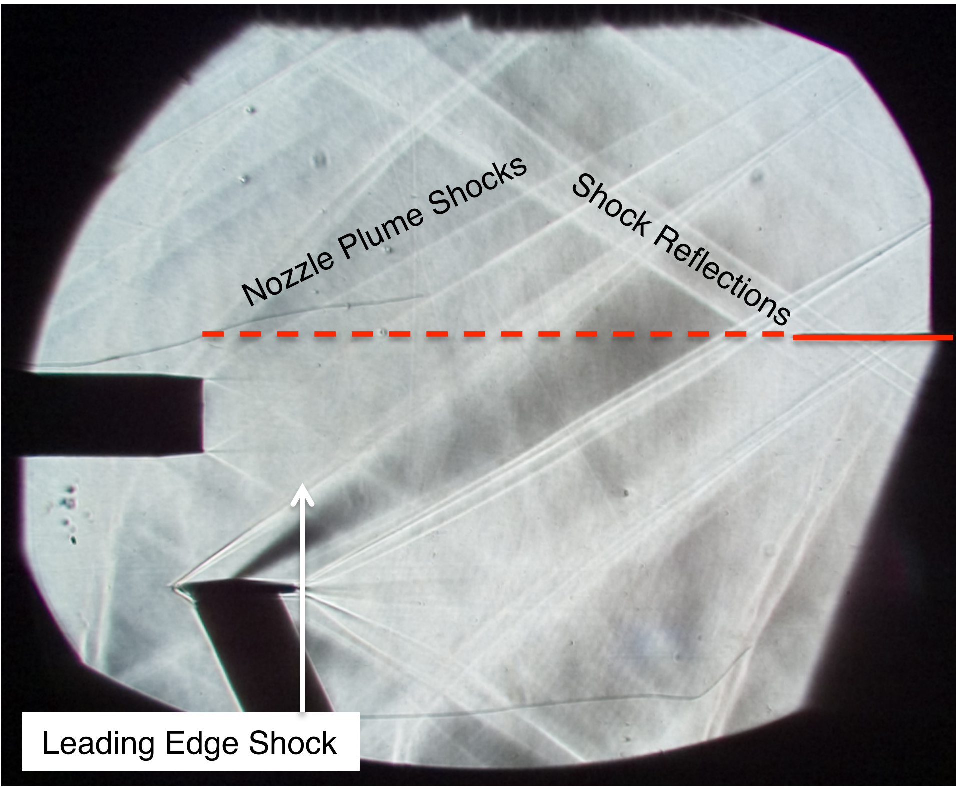
Pressure Signature for Jet and 1.5 inch Wedge

Mach = 1.96, NPR = 8, Re = 271,526

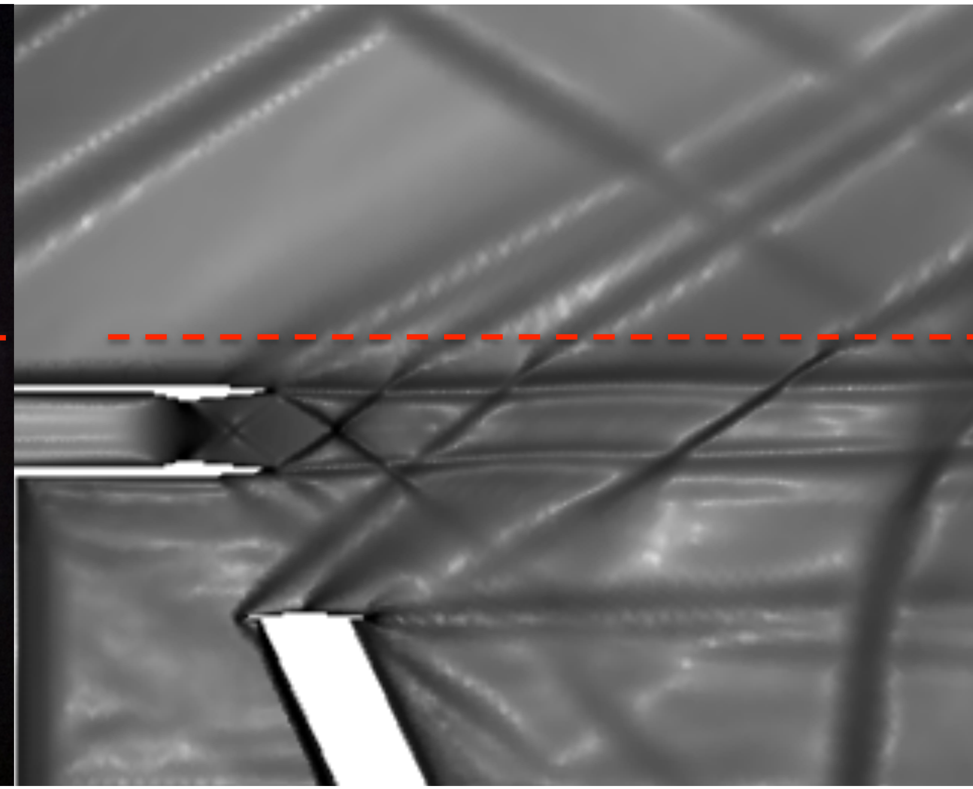


Tunnel Shock Structure for Jet and 1.5 inch Wedge

Mach = 1.96, NPR = 8, Re = 271,526



Schlieren Image



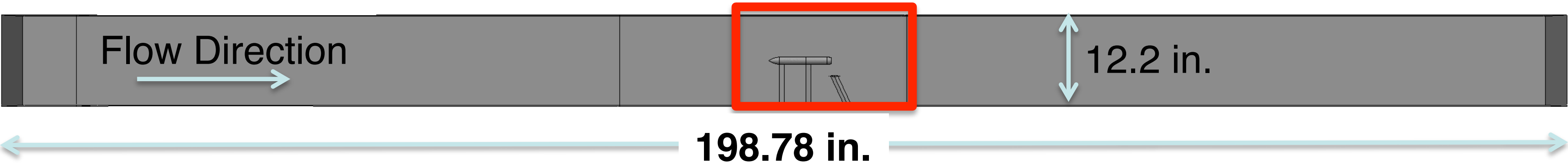
Computed Density Gradient

Jet and 1.5 inch Wedge Modeled in GRC 1x1 SWT Wind Tunnel

Mach = 1.96, NPR = 8, Re = 271,526

Top view

Side view

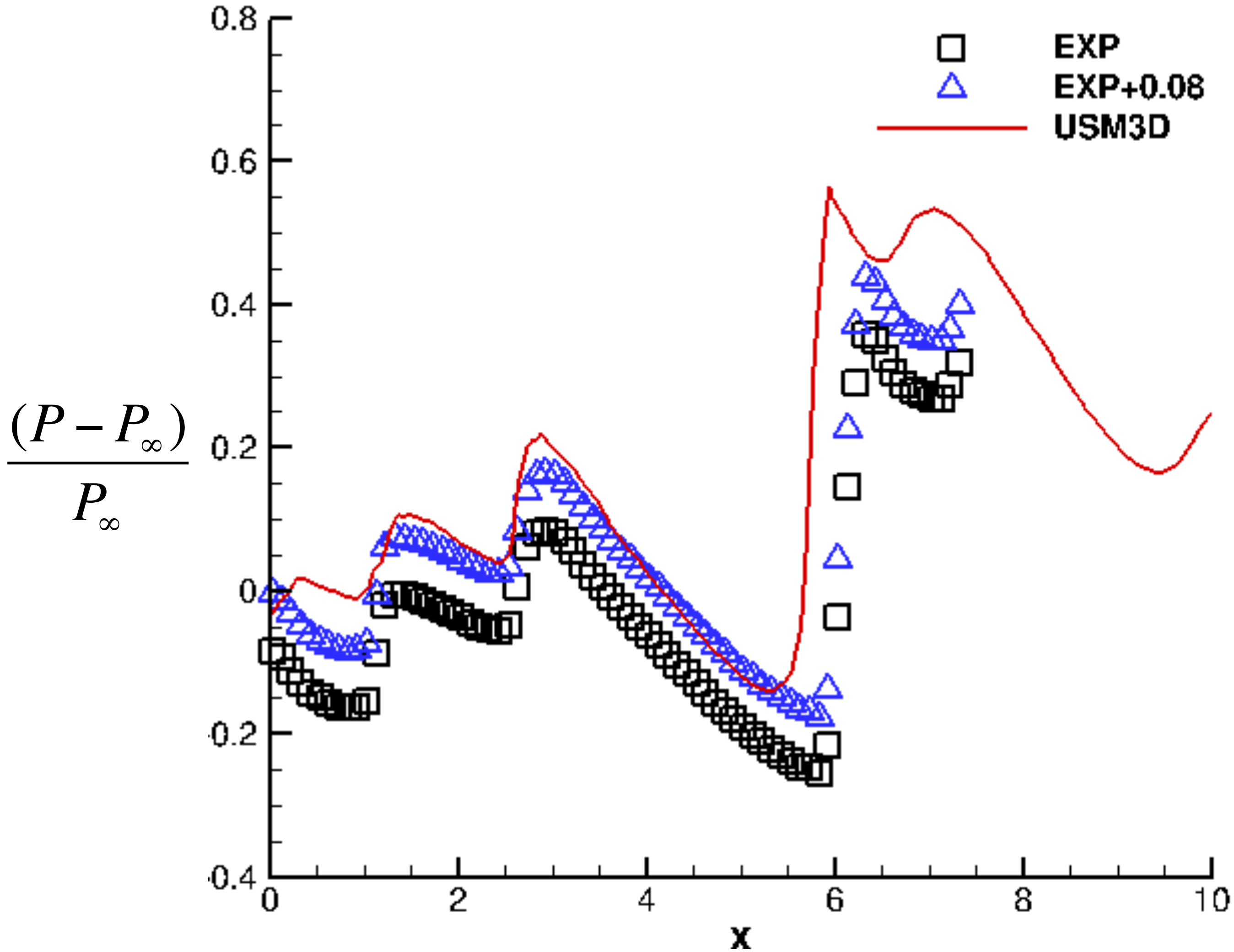


Grid Size 52.6 million cells

Test section is 12-inches by 12.2-inches by 53.25-inches long

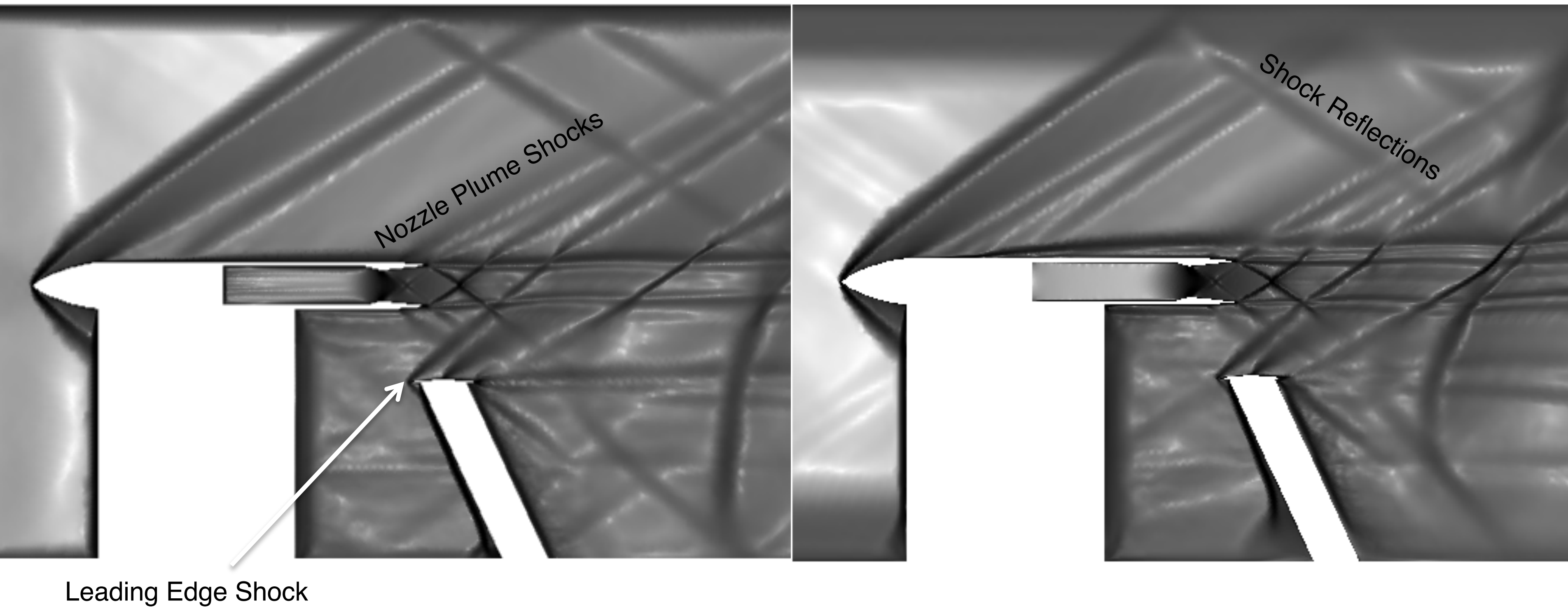
Pressure Signature for Jet and 1.5 inch Wedge

Mach = 1.96, NPR = 8, Re = 271,526



Tunnel Shock Structure for Jet and 1.5 inch Wedge, NPR = 8

Mach = 1.96, NPR = 8, Re = 271,526



Test Section Only

Full Tunnel Modeled

Summary

- Testing was completed in the GRC 1x1 SWT Wind Tunnel:
  - To study the interaction of a shock with an engine's plume
  - To collect data for CFD validation where a nozzle plume is passing through the shock generated from wedge

- USM3D was used to model the test section of the GRC 1x1 SWT with the jet and wedge installed.
  - Isolated nozzle
  - Isolated wedge (1.5 and 6 inch wedges)
  - Jet and wedge (1.5 and 6 inch wedges)
  - *Mach = 1.96, Re = 271,526, NPR= 6, 8, 10, 12, 14*

- Grid sourcing feature of VGRID provided USM3D with the capability to resolve the jet's plume shear layer and internal shock structure.

Summary

- Computational study only attempted to match experimental results from x=2 to approximately x=6.
- Overall reasonable agreement between CFD results and experimental data. CFD signature peaks being slightly higher.
- The computational study shows that engine plume flow affects the shock signature by moving it slightly forward and dampening the pressure peak of the shock.
- The wedge shock bends the jet plume flow upwards.
- Good qualitative agreement between Schlieren images and the computed density gradient.

Acknowledgment

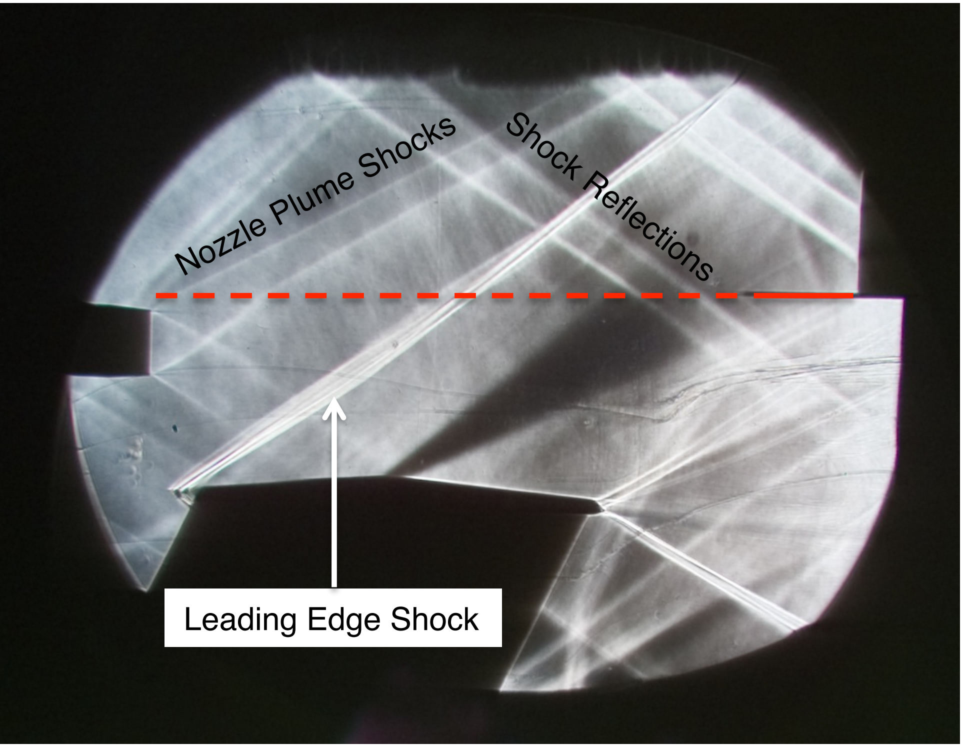
- The research reported in this study was sponsored by the NASA Fundamental Aeronautics Program High Speed Project.

- High Fidelity Validation Team
  - Linda Bangert
  - Susan Cliff
  - Courtney Winski

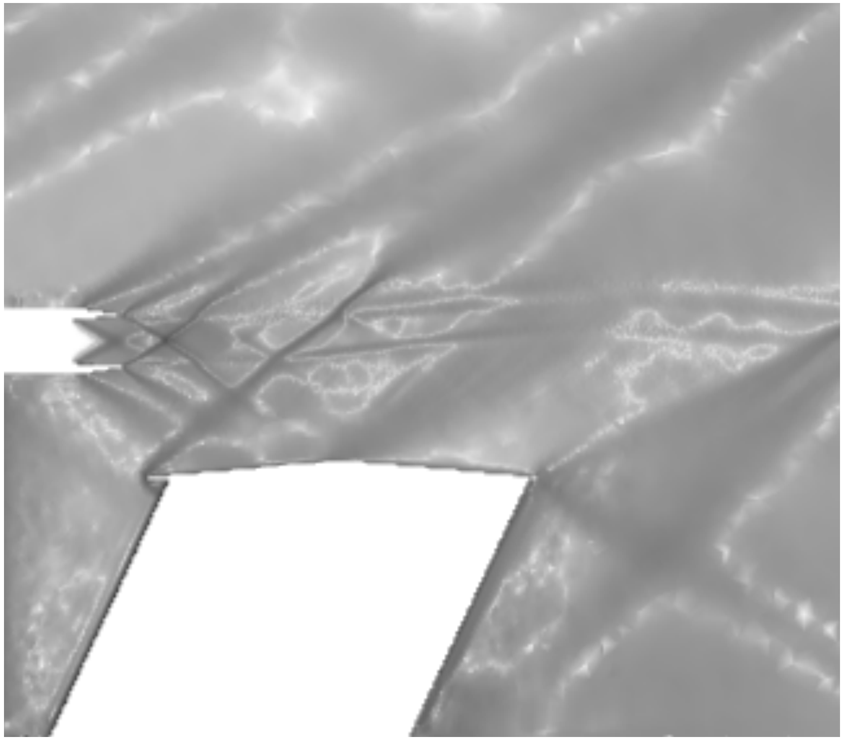

Questions ?

Tunnel Shock Structure for Jet and 6 inch Wedge

Mach = 1.96, NPR = 8, Re = 271,526



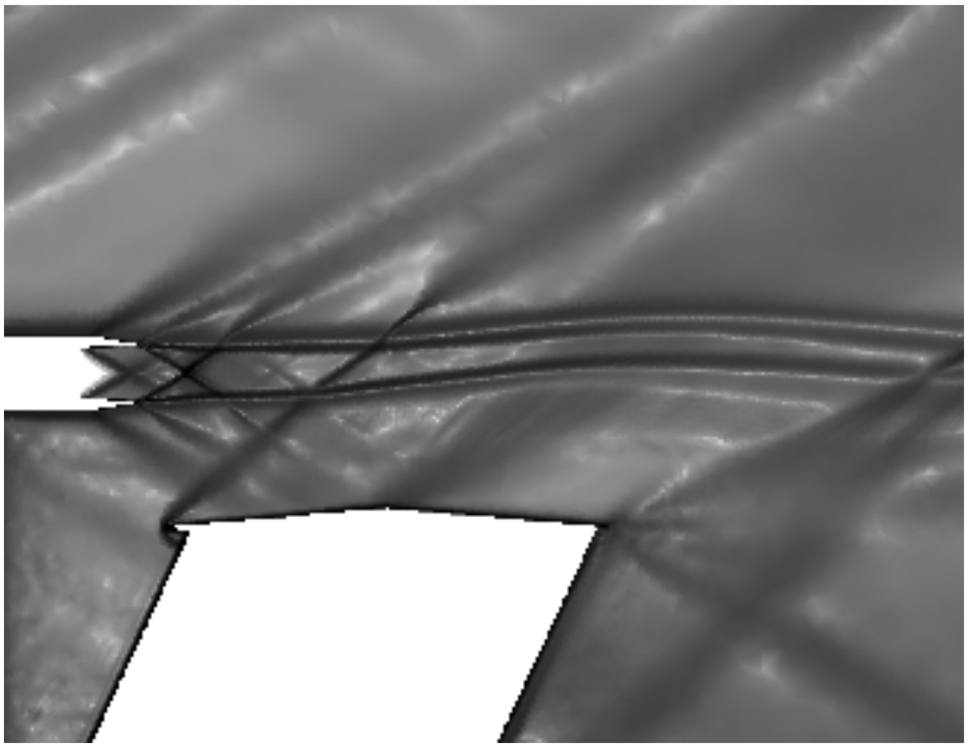
Schlieren Image



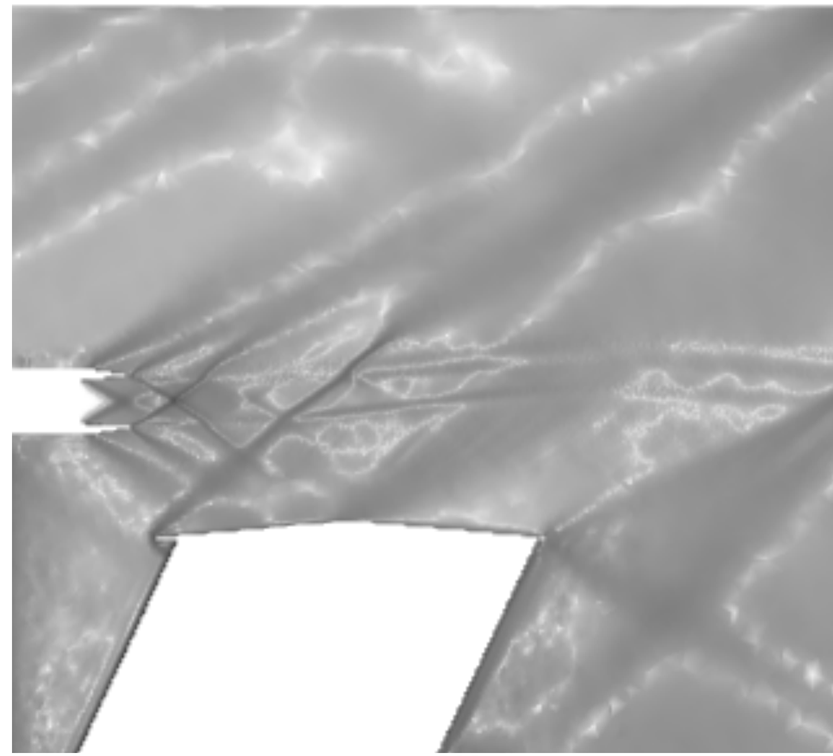
Computed Density Gradient

Tunnel Shock Structure, NPR=8

Mach = 1.96, NPR = 8, Re = 271,526



Computed Density Gradient
in All Three Direction



Computed Density Gradient
in Two Directions