Computational Studies for Sonic Boom Prediction

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AIAA 2014-2008: J. Housman, E. Sozer, S. Moini-Yekta, and C. Kiris

Outline

- Introduction
- Launch Ascent and Vehicle Aerodynamics (LAVA) Framework
- 1st AIAA Sonic Boom Prediction Workshop
- Oblique Shock/Plume Interaction
- Summary

This work has been funded by the NASA Fundamental Aeronautics Program High-Speed Project

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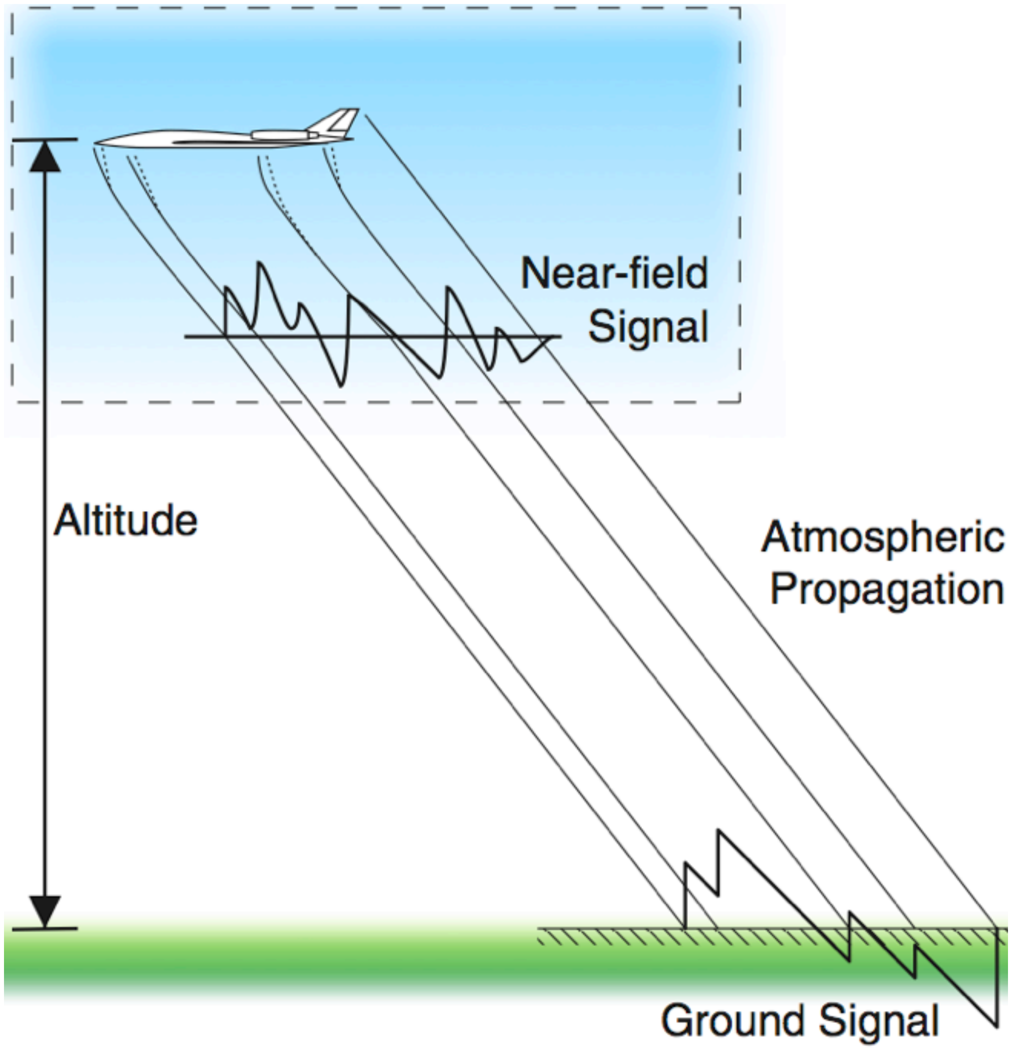
The Sonic Boom Problem

Supersonic Civilian Aircraft



Aftosmis and Nemec, AIAA 2014-0558

- **No civilian supersonic aircraft since retirement of Concorde in 2003**
- **Renewed interest in sonic boom minimization over last decade**
- **CFD can be a useful tool in the design process**
- **Accuracy of CFD prediction must be assessed**

CFD Validation Study

1st AIAA Sonic Boom Prediction Workshop

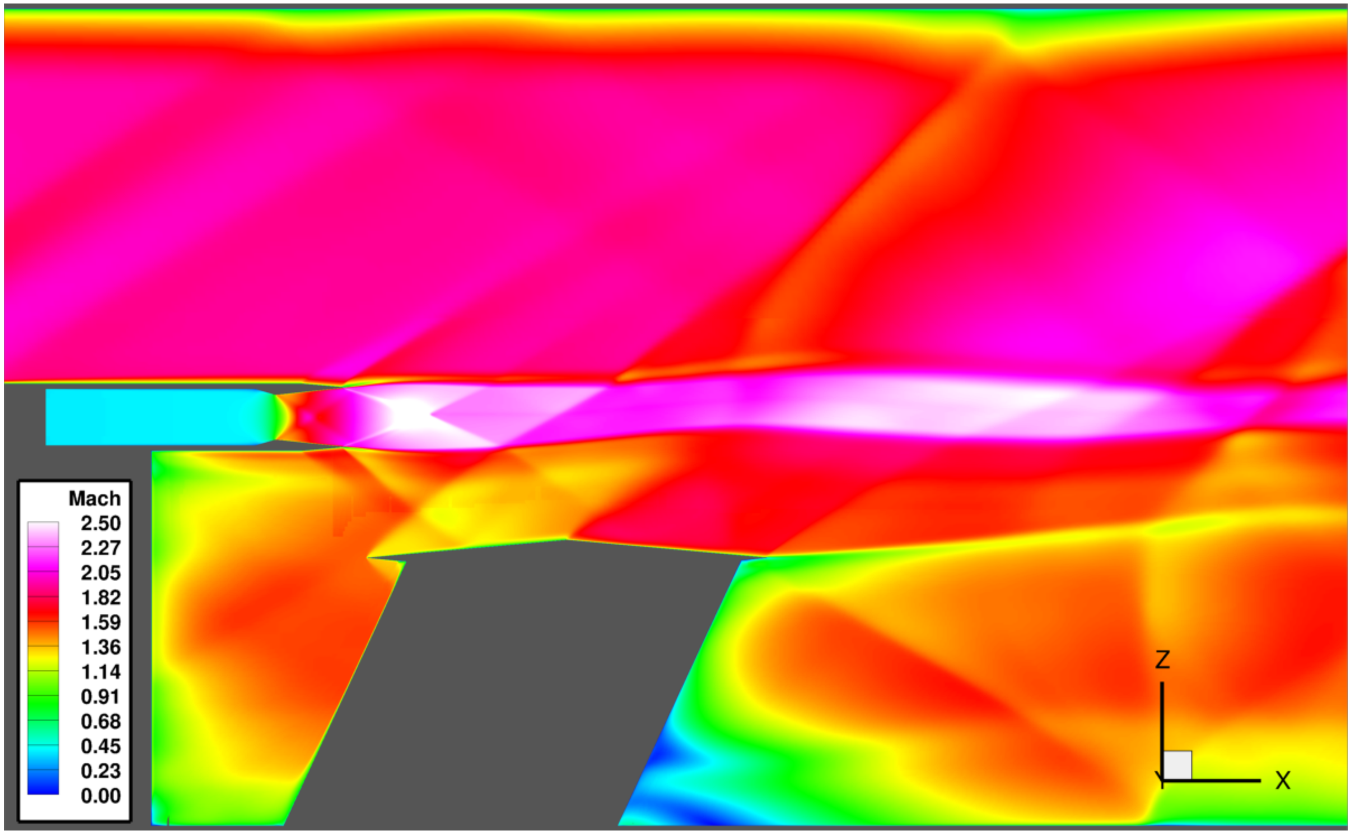
- Workshop is designed to assess the state-of-the-art in CFD simulation capabilities for sonic boom prediction
- Three models of increasing geometric complexity are included in the study
  - SEEB-ALR
  - 69º Degree Delta-Wing Body
  - Lockheed Martin 1021 model
- LAVA results using structured and unstructured grids were submitted to the workshop

Lockheed Martin 1021 model

CFD Validation for Shock/Plume Interaction

Oblique Shock/Plume Interaction Wind Tunnel Test

- Shock waves generated by tail surfaces or engine installation geometry may travel through the exhaust jet changing angle
- Refraction effects must be included in the design process to ensure low boom
- Wind tunnel experiments have been performed at the 1x1 SWT at GRC
- Data from these tests are being used in a validation effort for CFD



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LAVA Framework

*Launch Ascent and Vehicle Aerodynamics Framework**

- **Computational Fluid Dynamics (CFD) Solver**
  - **Cartesian, Curvilinear, and Unstructured Grid Types**
  - **Overset Grid and Immersed Boundary Methods**
  - **Reynolds Averaged Navier-Stokes and Detached Eddy Simulation Capabilities**

Meshing	Convective Flux Discretization	Turbulence Model	Linear Solvers
Structured Overset	Modified Roe and Central	Spalart-Allmaras	Alt. Line Jacobi
Unstructured Polyhedral	AUSMPW+	Spalart-Allmaras	GMRES

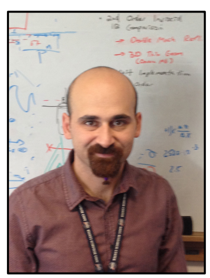
Development Team

AMS Seminar for LAVA
http://www.nas.nasa.gov/publications/ams/2014/06-10-14.html

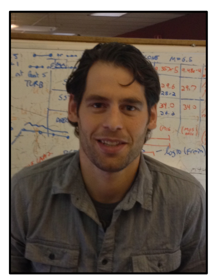
Cetin Kiris

Jeffrey Housman

Michael Barad



Emre Sozer



Christoph Brehm

Shayan Moini-Yekta

*Kiris et. al. AIAA-2014-0070

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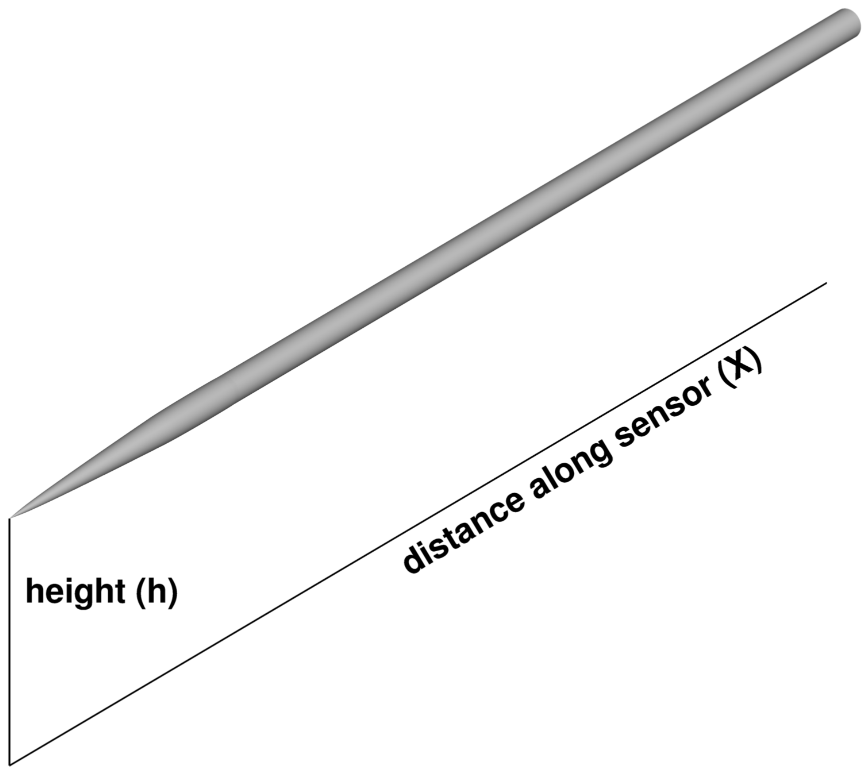
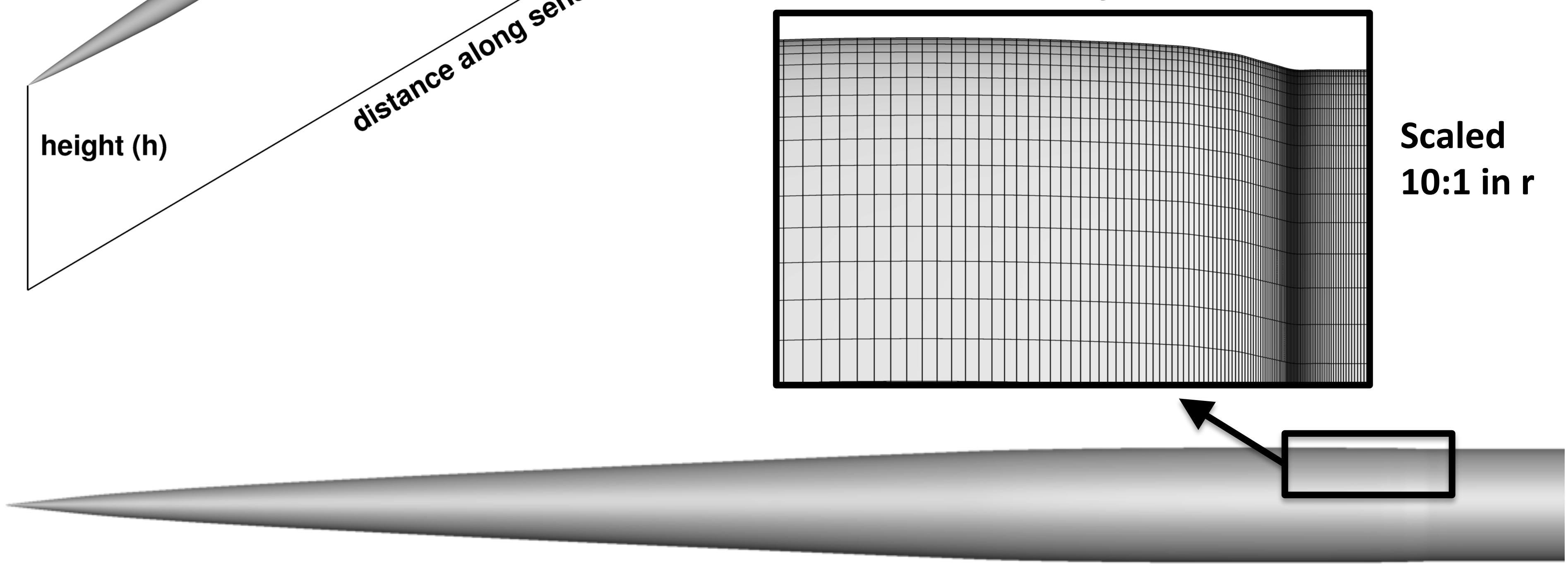
Geometric Model

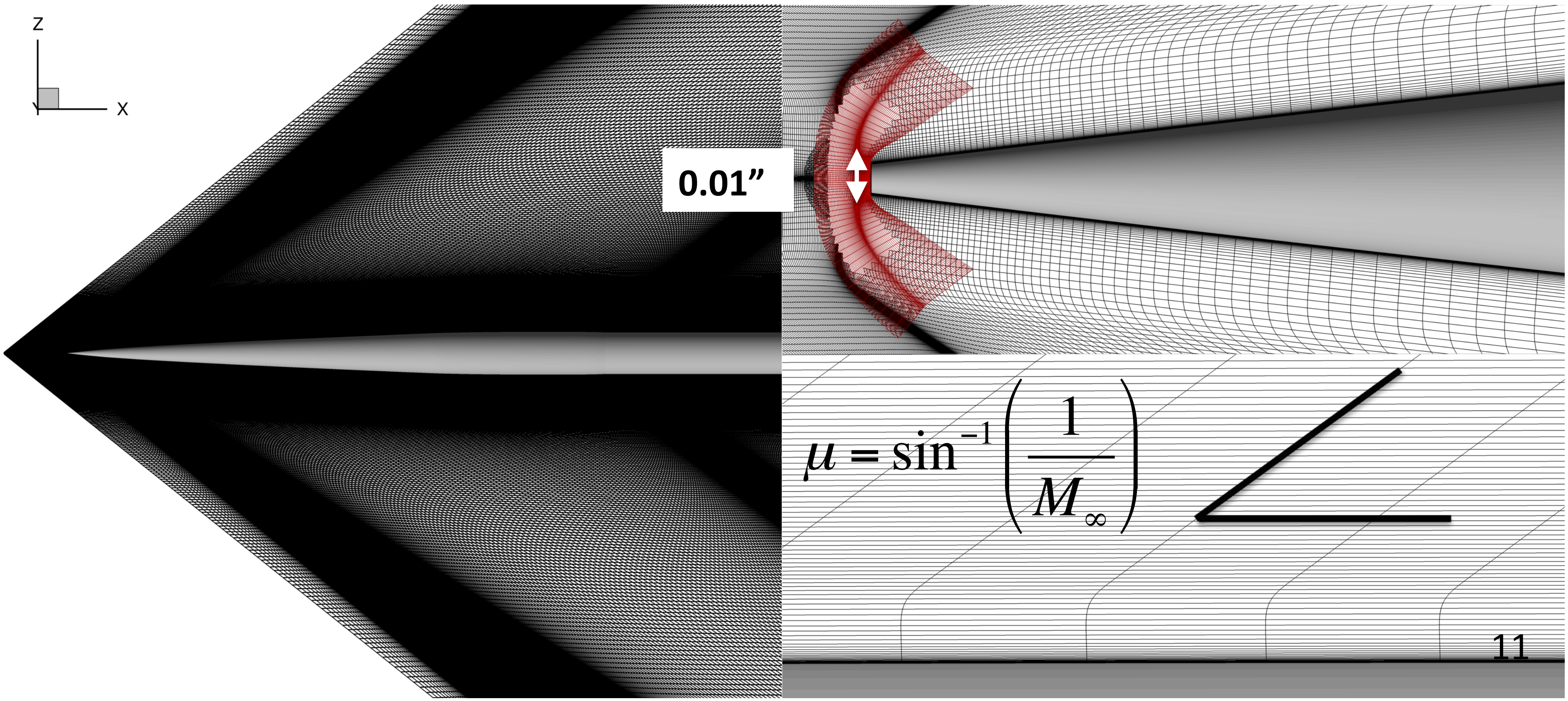


- Axisymmetric model designed for low boom and low drag
- Seeb model modified downstream of shoulder (ALR)
- Model Length: 17.67 inches
- Computation Model: 68.3 inches
- Inviscid Analysis: Mach = 1.6



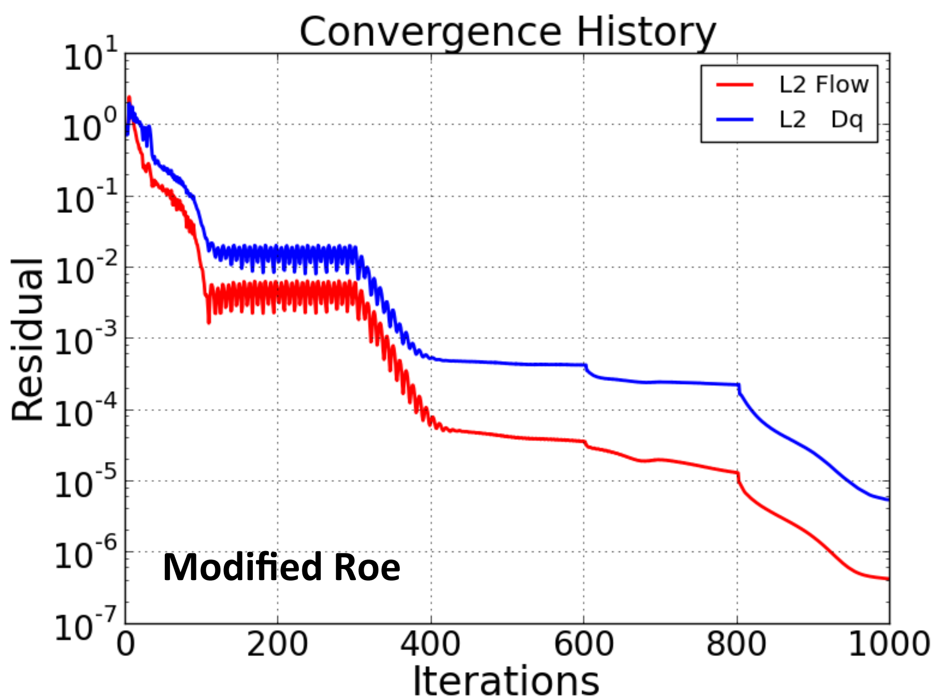
Computational Grid

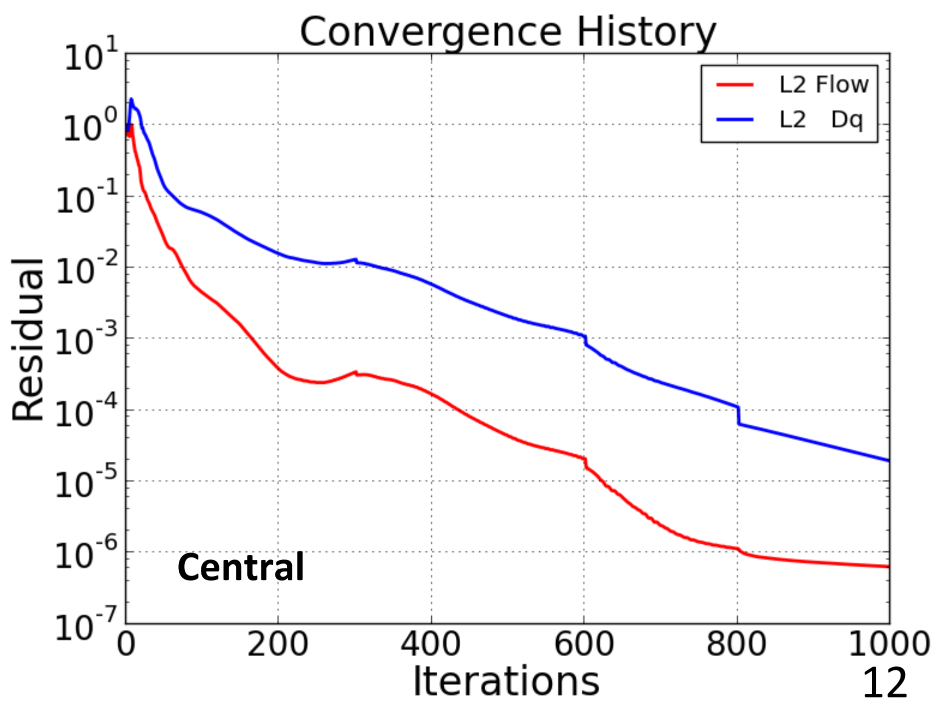
- 4 zones and 21.7 million grid points
- Near-body marched normal to surface then turned to Mach-angle aligned mesh
- Local bow shock capturing grid near blunt nose



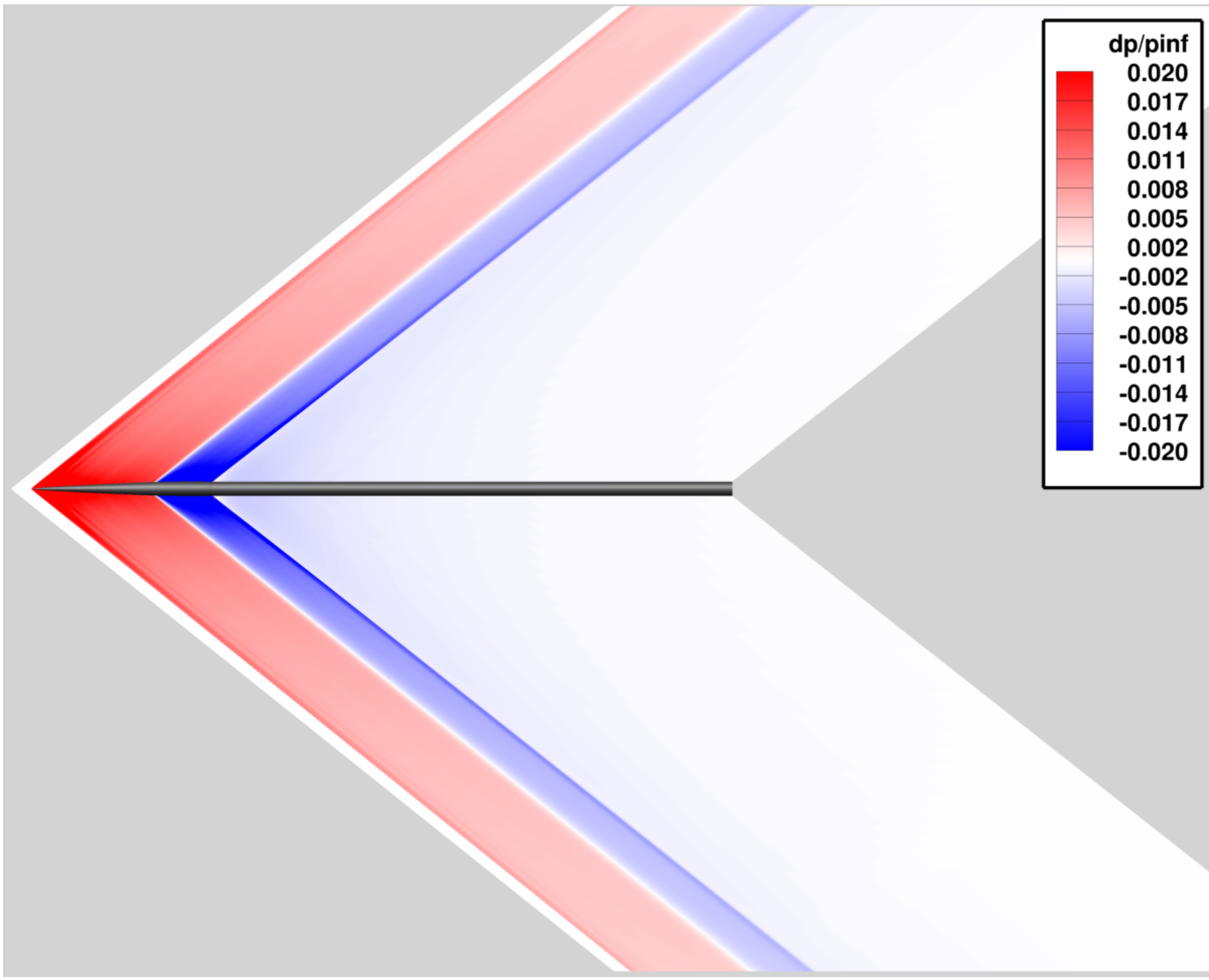
Computational Requirements

Flux	CPU Type	Cores	Walltime	Total Core Hours
Modified Roe	Westmere	48	1 hr. 30 min.	72.0
Central	Westmere	48	1 hr. 18 min.	62.4





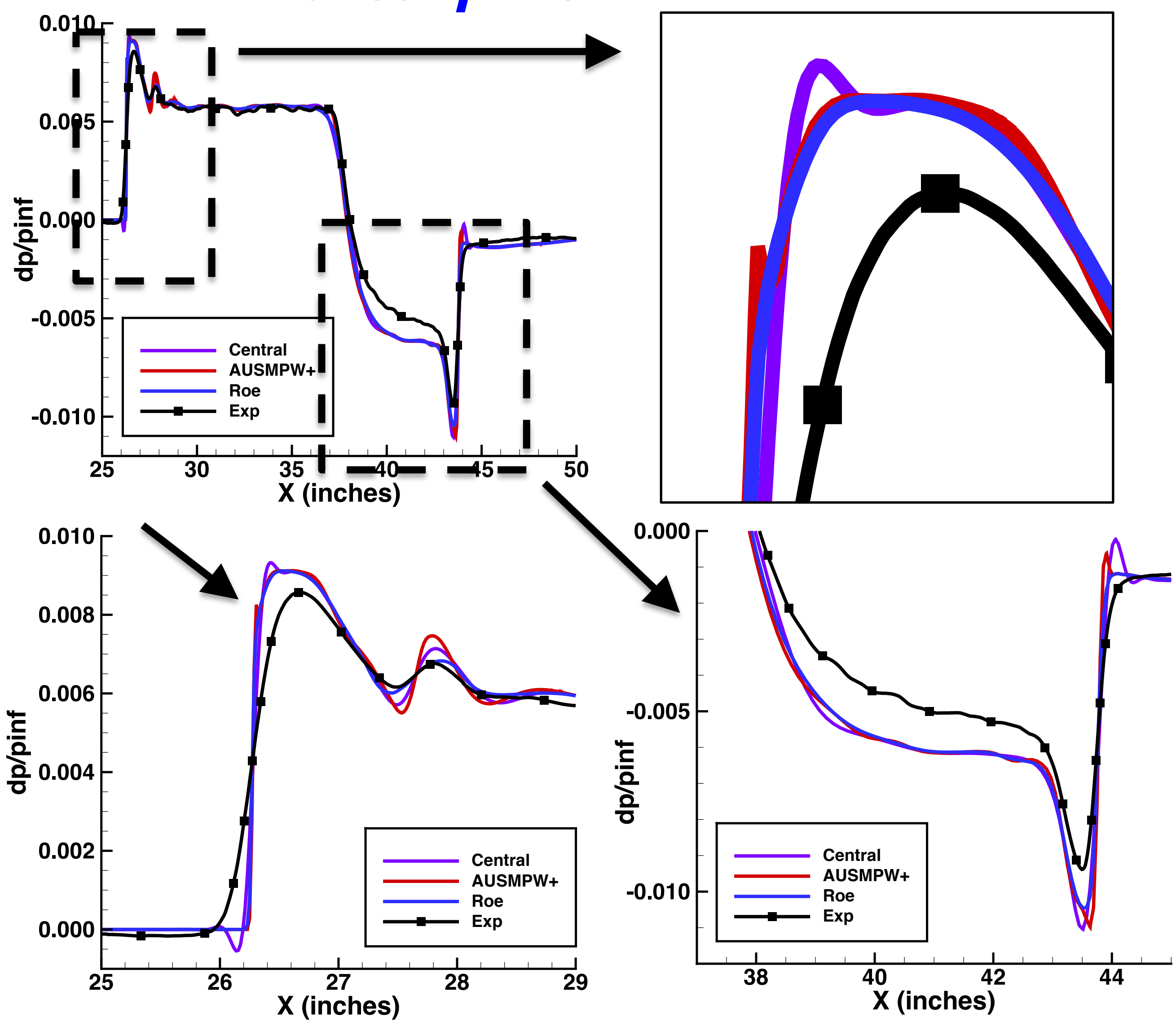
Flow-Field Visualization



- **Bow shock forms at blunt nose of the model**
- **Secondary shock is generated from small slope change near the nose**
- **Rarefaction wave develops downstream of the shoulder**

Results and Comparison

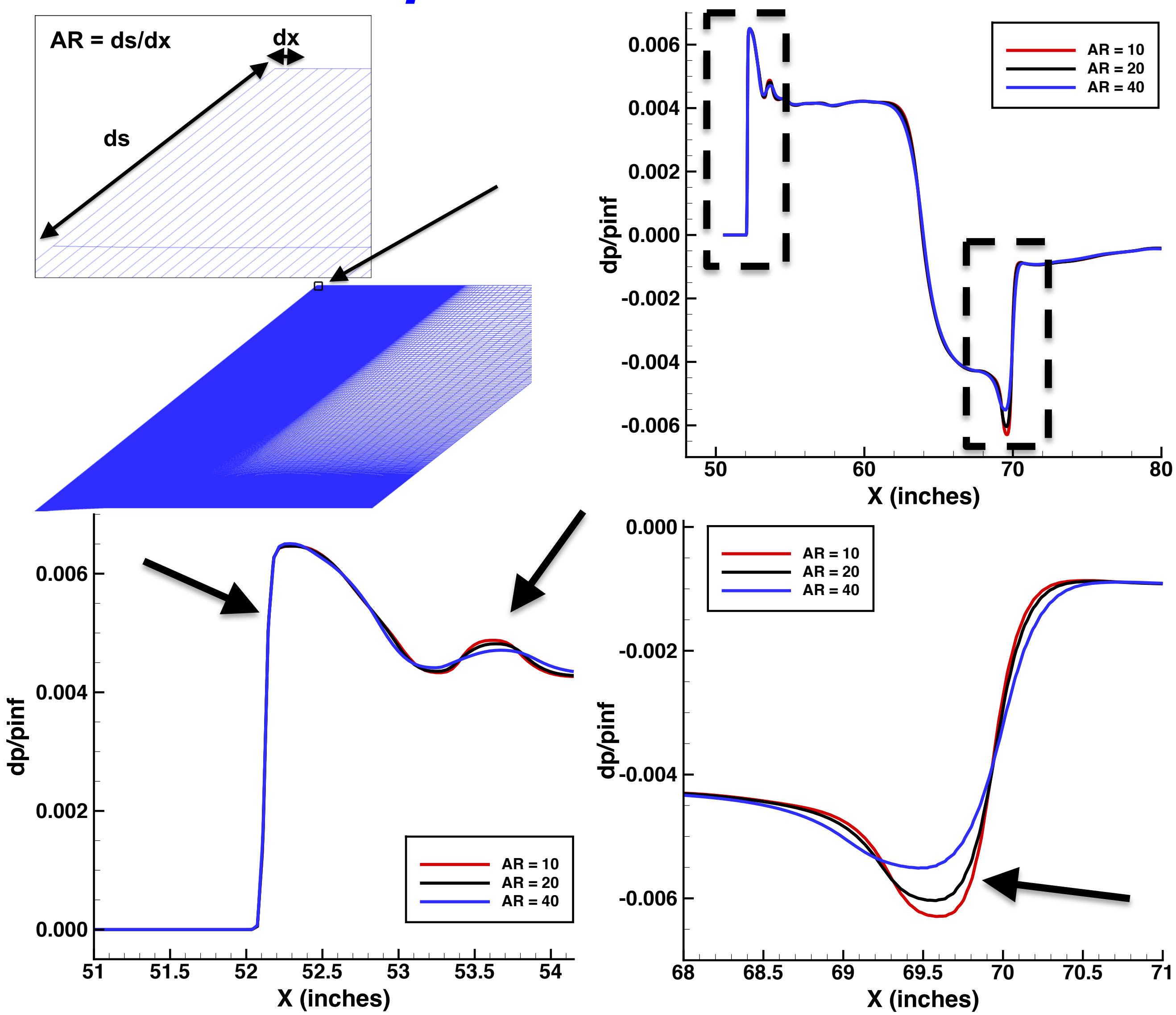
h = 21.2 inches ϕ = 0 °



- Good comparison observed over most of the signal
- Bow shock and secondary shock well-captured by CFD
- Experimental result shows a smoother primary shock
- Oscillations observed using Central and AUSMPW+ on bow shock
- CFD over-predicts the pressure decrease across the expansion

Sensitivity Analysis: Aspect Ratio

h = 42 inches $\phi = 0^{o}$



- Sensitivity to grid Aspect Ratio (AR) at the outer-boundary
- No sensitivity observed in bow shock
- Secondary peak and pre-recovery peak pressures show some sensitivity to AR
- Change in peak decreases with decreasing AR
- AR = 20 submitted to the workshop

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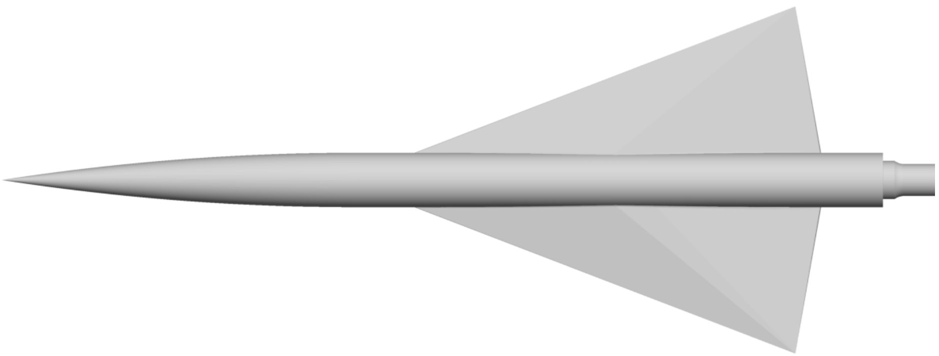
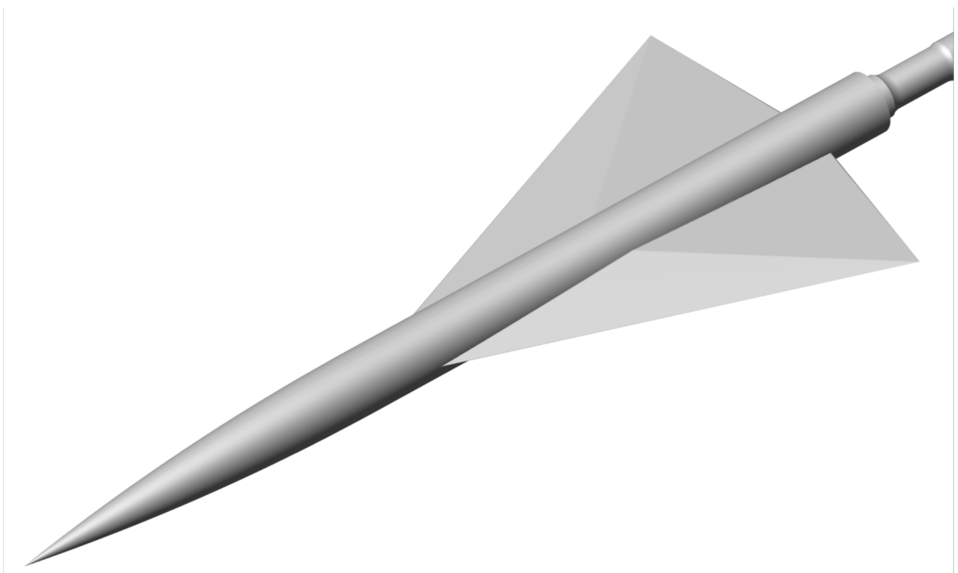
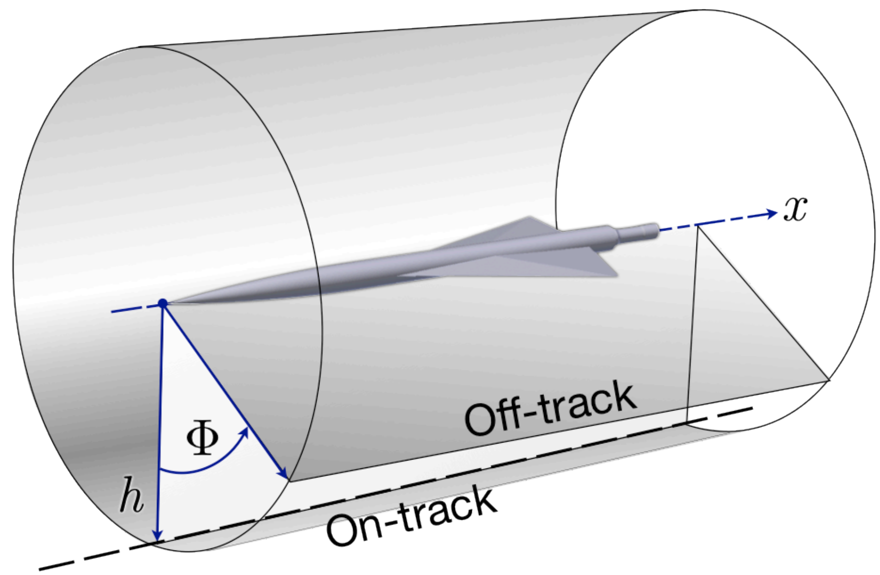
Geometric Model



Model Length = 6.9 inches
Model+Sting Length = 30.4 inches
Span = 2.7 inches

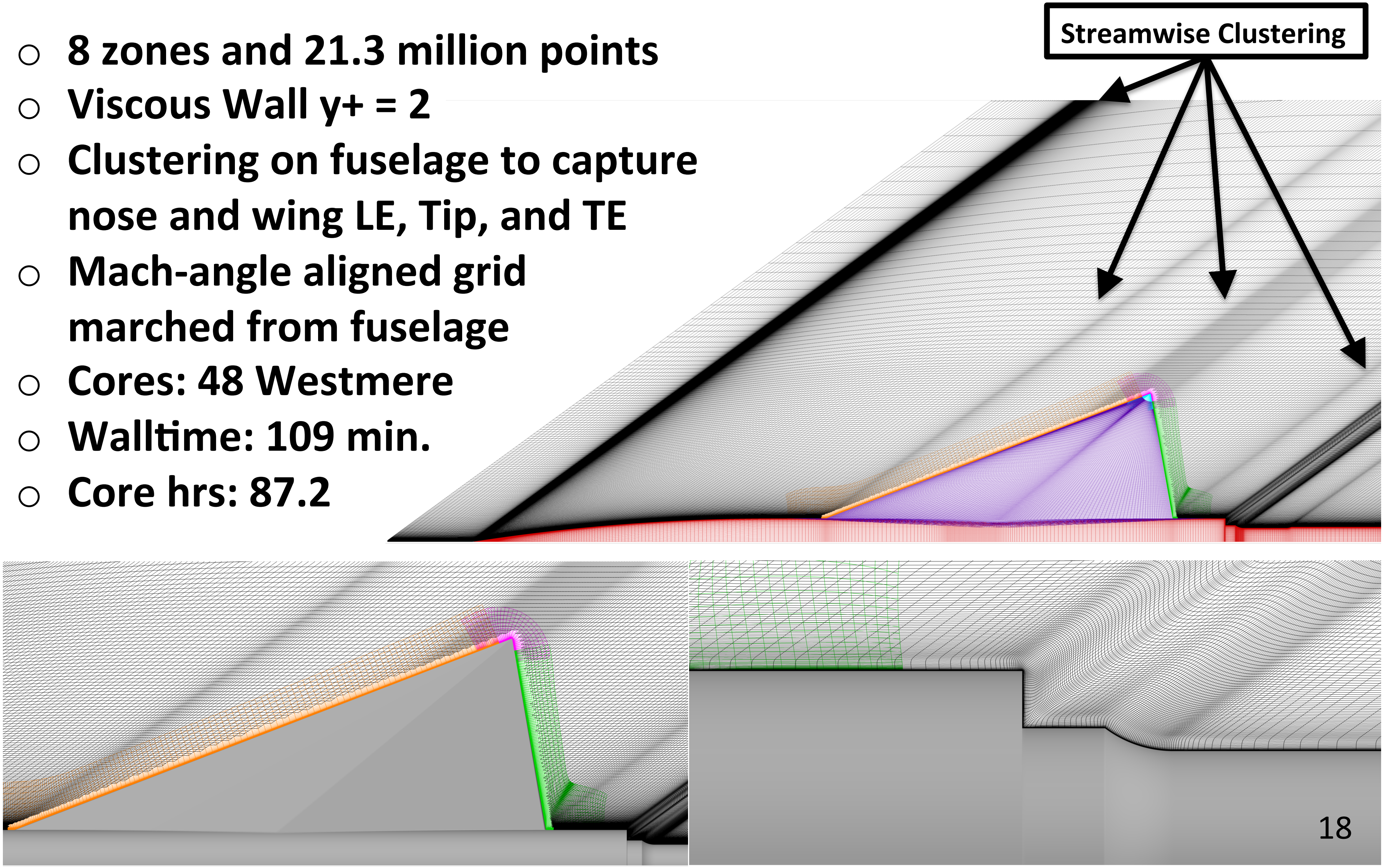




- 69º swept Delta Wing bisecting a cylindrical fuselage attached to an axisymmetric sting
- Mach = 1.7 Reynolds Number = 4.24 M (per ft)

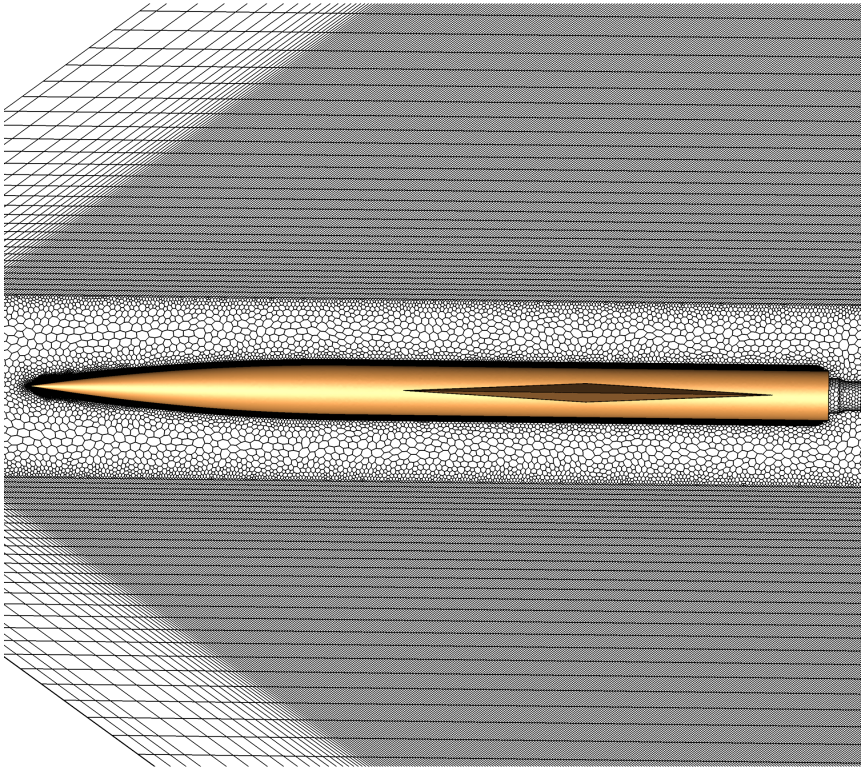
Structured Overset Grid

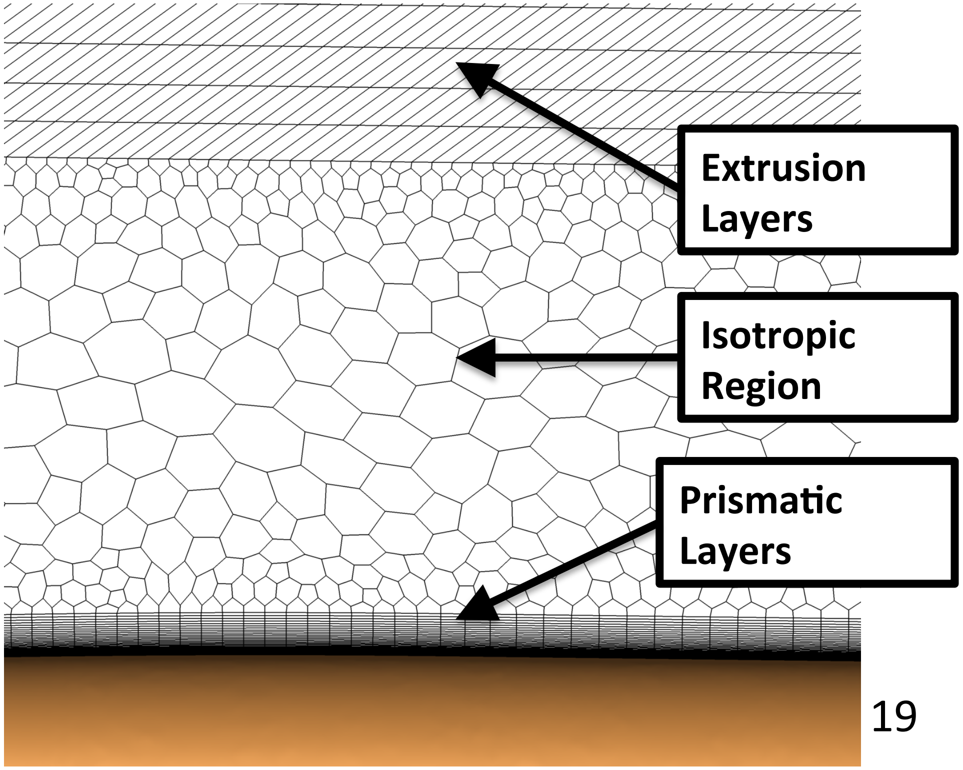
- 8 zones and 21.3 million points
- Viscous Wall y+ = 2
- Clustering on fuselage to capture nose and wing LE, Tip, and TE
- Mach-angle aligned grid marched from fuselage
- Cores: 48 Westmere
- Walltime: 109 min.
- Core hrs: 87.2



Unstructured Polyhedral Grid

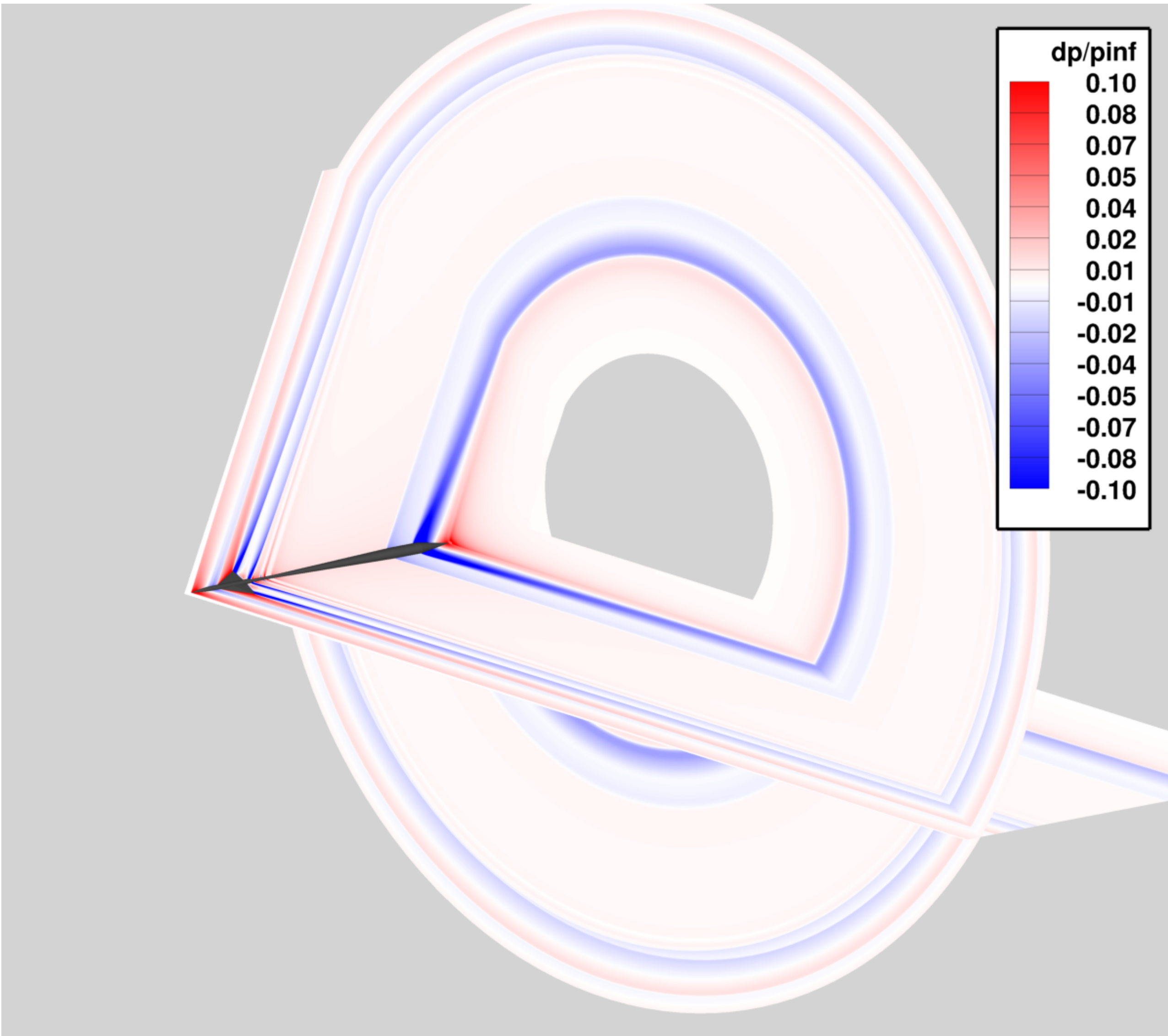
- 12.1 million polyhedral cells
- Anisotropic prismatic layers grown from surface
- Core mesh utilizes nearly isotropic polyhedral cells
- Mach-angle aligned mesh extruded from outer core boundary
- Cores: 320 Sandy Bridge; Walltime: 25 min.; CPU hrs: 133.3





Flow-Field Visualization

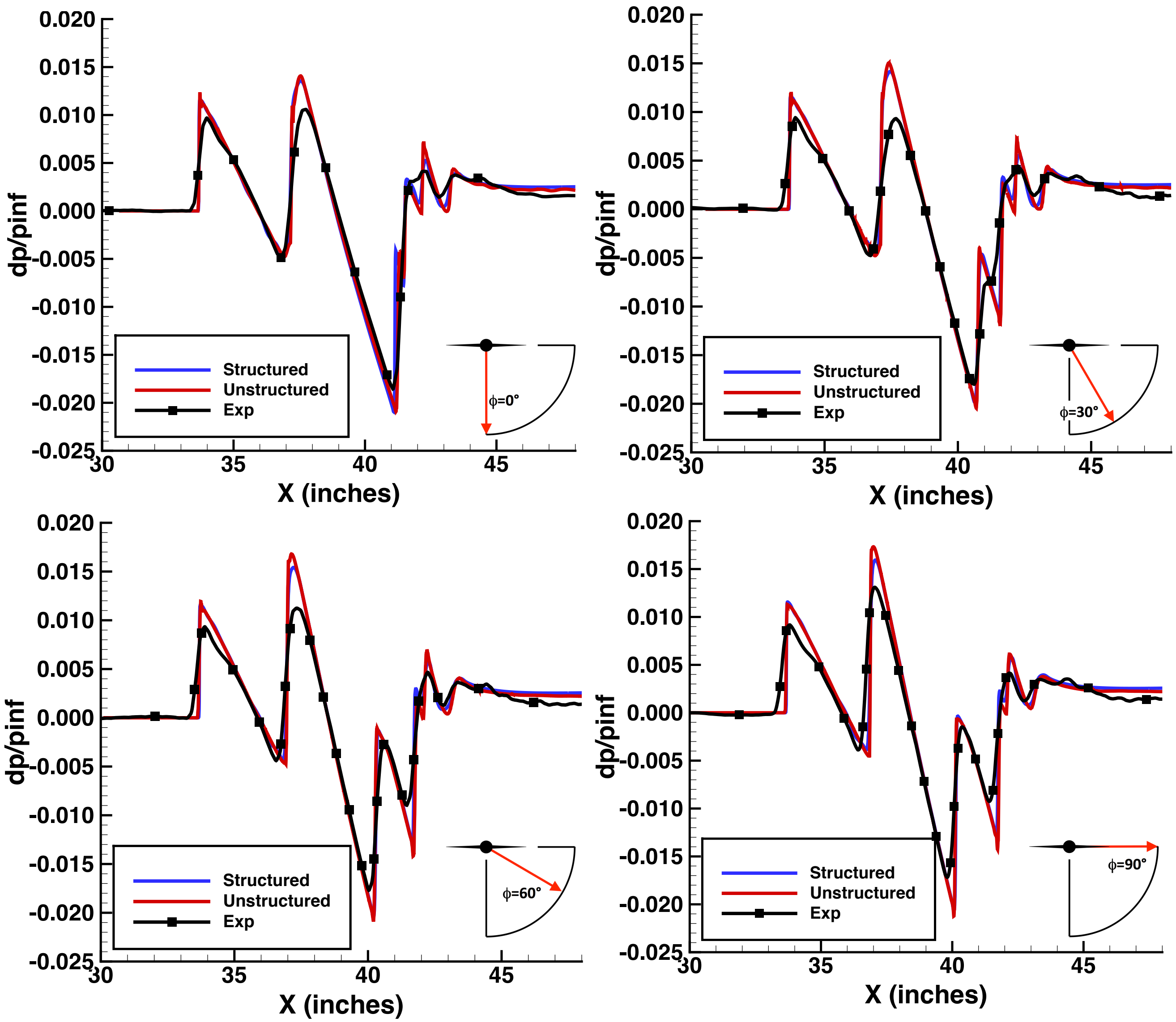
Flow Field Visualization



- **Amplitude of pressure waves decay with radial distance (energy)**
- **Delta wing disturbs the symmetric signal generated by the fuselage**
- **Signal will eventually regain symmetry with increased radial distance (equivalent area)**

Results and Comparison

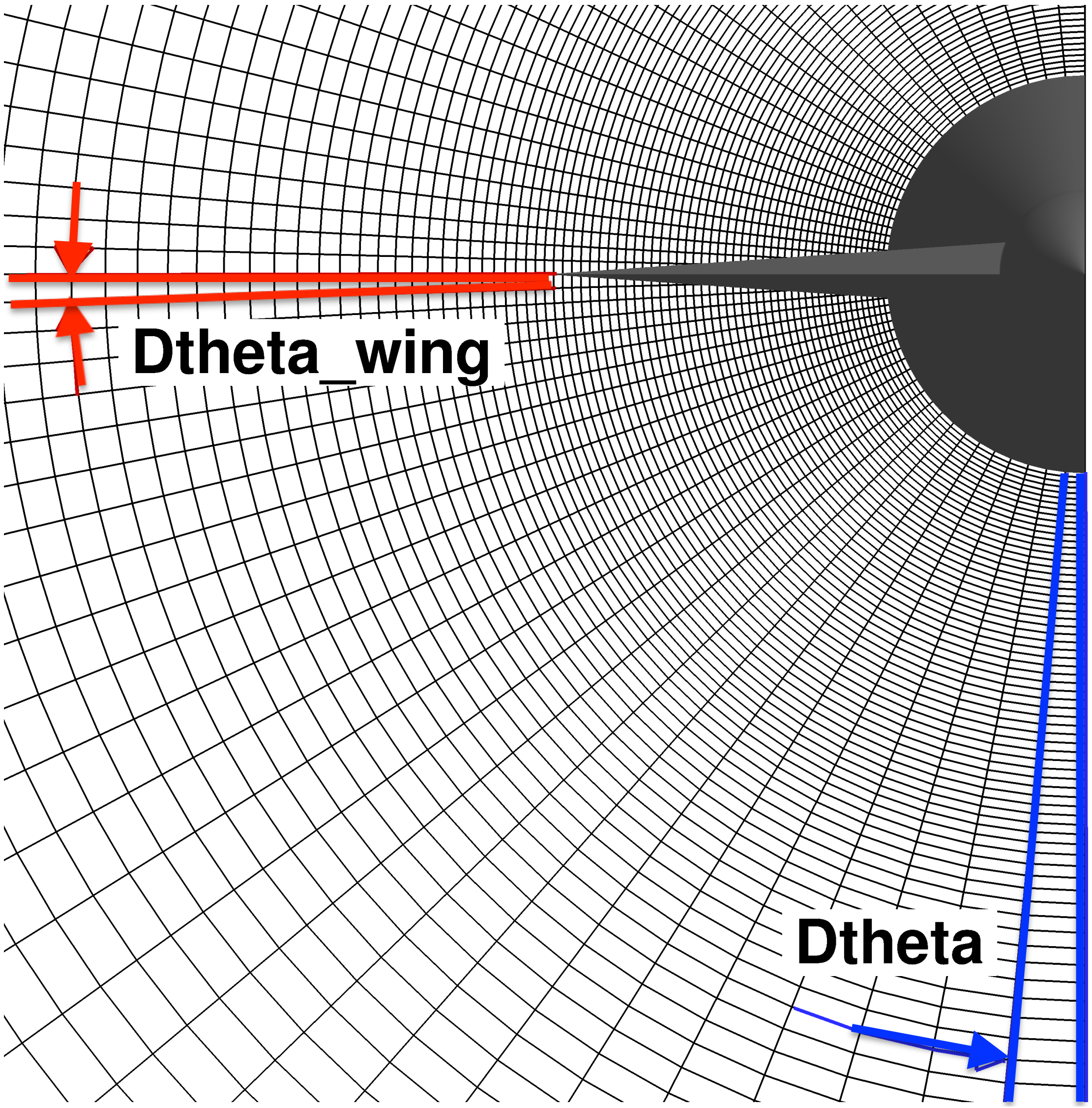
h = 24.8 inches

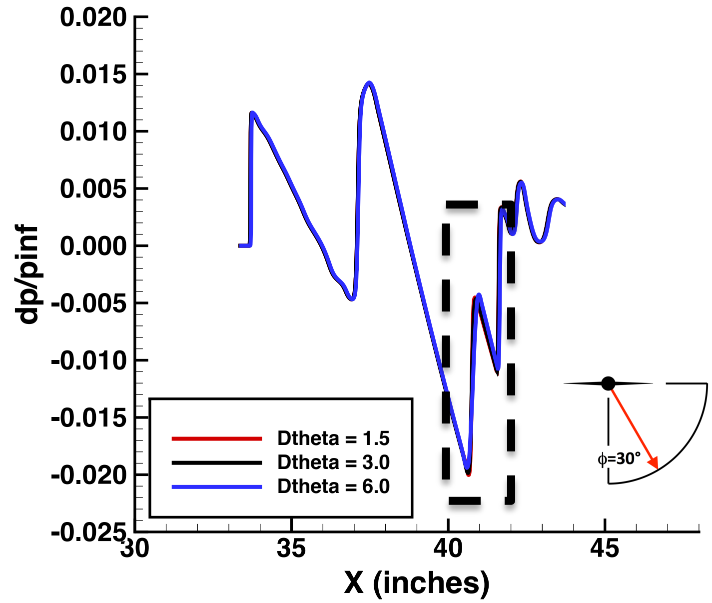


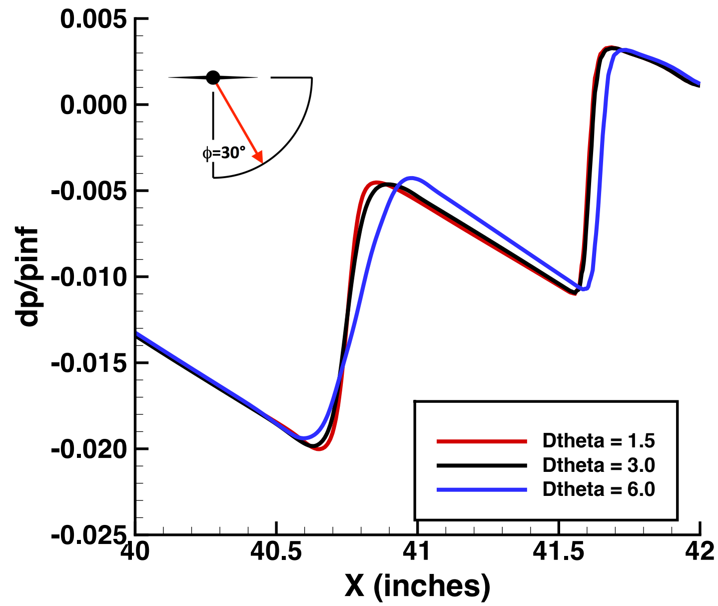
- Pressure peaks are more smooth in Experimental data
- Slope of rarefaction waves match very well
- Stronger aft wing shock predicted by CFD than Experiment at lower Φ angles

Sensitivity Analysis: Circumferential Spacing

h = 24.8 inches ϕ = 30 º







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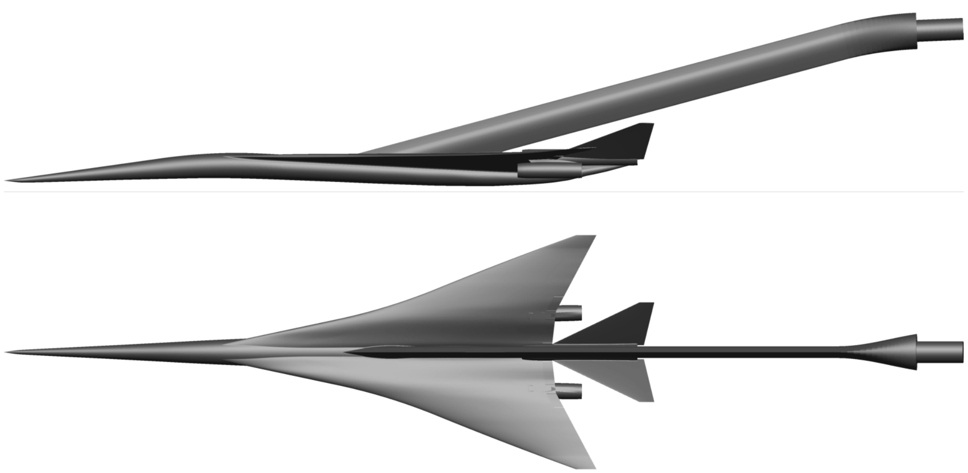
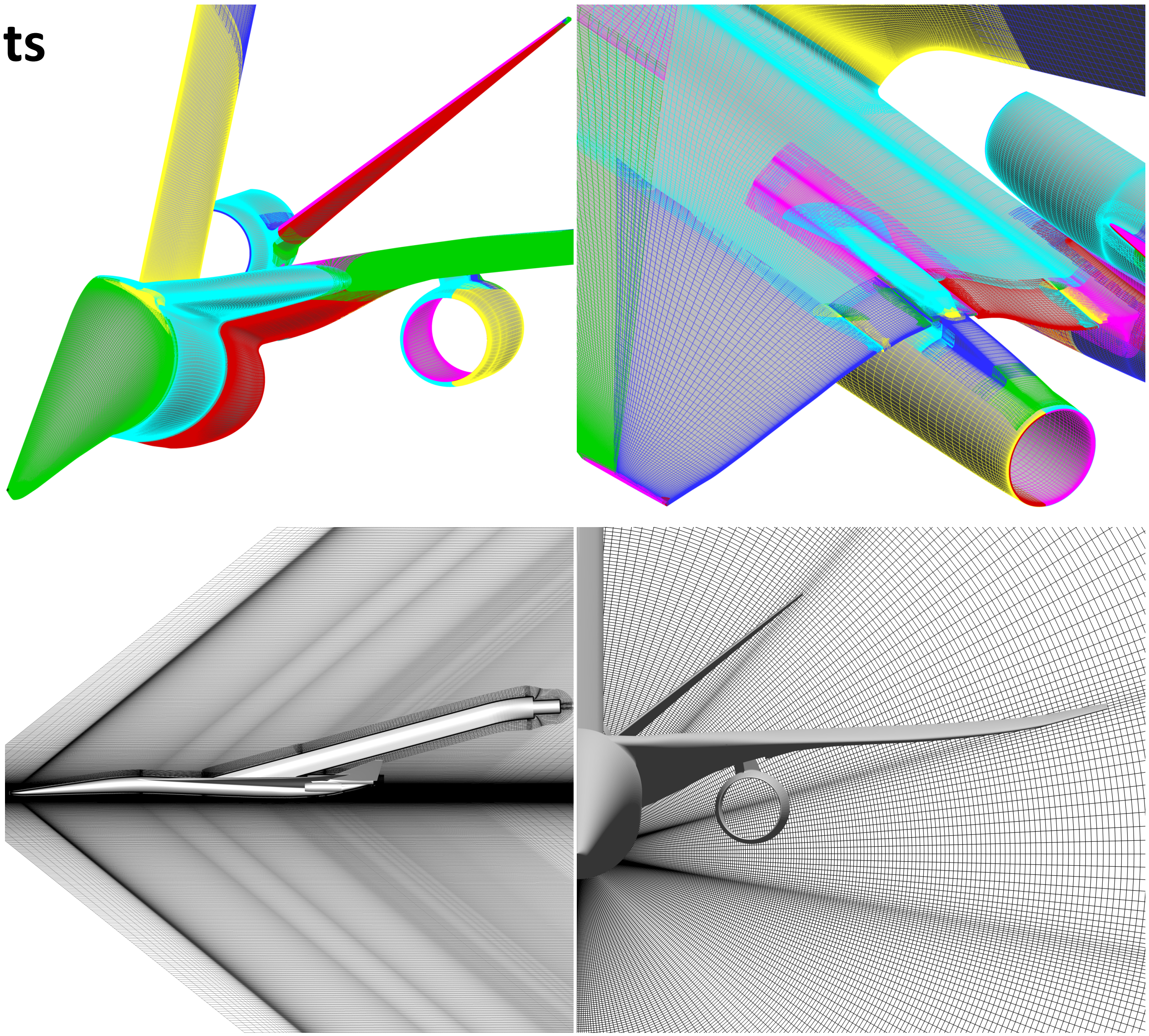
Geometric Model

- Lockheed Martin Phase I low sonic boom model
- Mach = 1.6, Reynolds number 4.36 M (per ft.), $\alpha = 2.1^{o}$
- Designed for low boom on-track and reduced pressure up to 20^{o}
- Model length 22.4 inches representing 0.8 % scale (1:125)
- Swept blade strut designed to minimize interference
- Trip disks added near wing leading edge to force transition



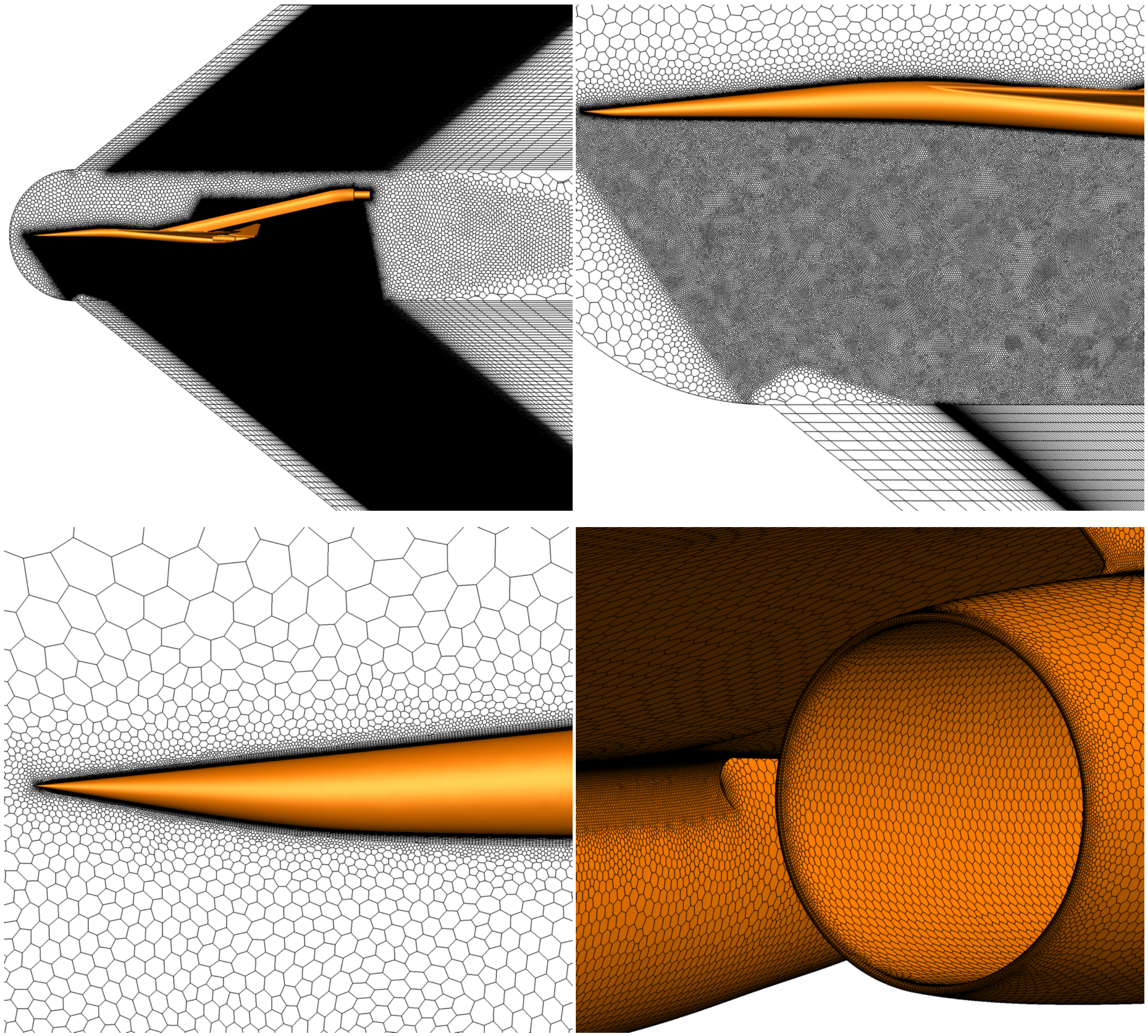
Structured Overset Grid

- 97 zones
- 72.7 million grid points
- Wall y+ = 1.2
- Mach-angle aligned grid detached from fuselage
- Clustering in streamwise and circumferential directions
- Cores: 180 Ivy Bridge
- Walltime: 90 min.
- Core hours: 270

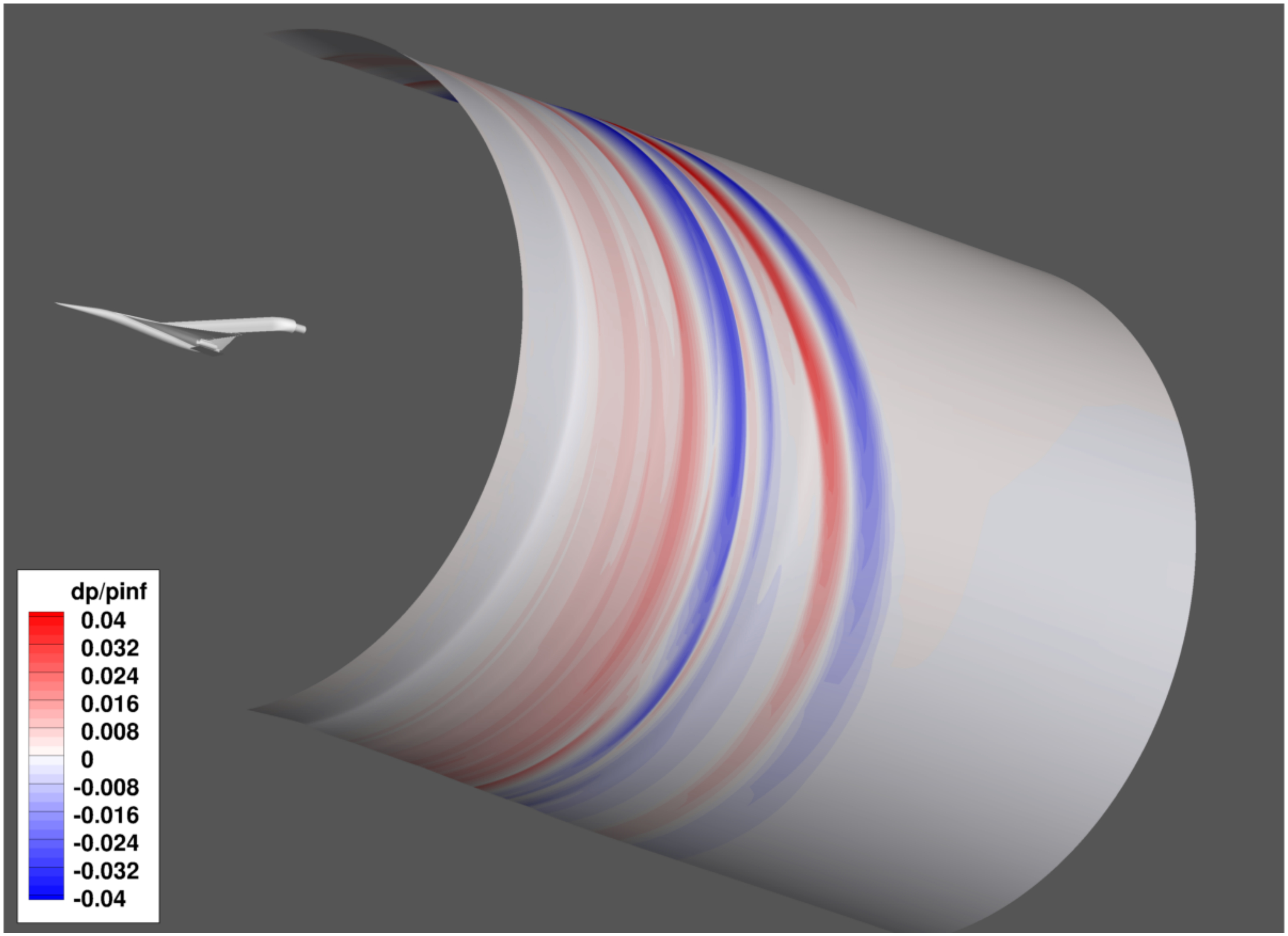


Unstructured Polyhedral Grid

- 65.5 million polyhedral cells
- Surface cell size specification used on symmetry plane for improved on track accuracy
- Fine surface mesh resolution with clustering near sharp geometric features
- Cores: 2000
- Walltime: 45 min.
- Core hours: 1500



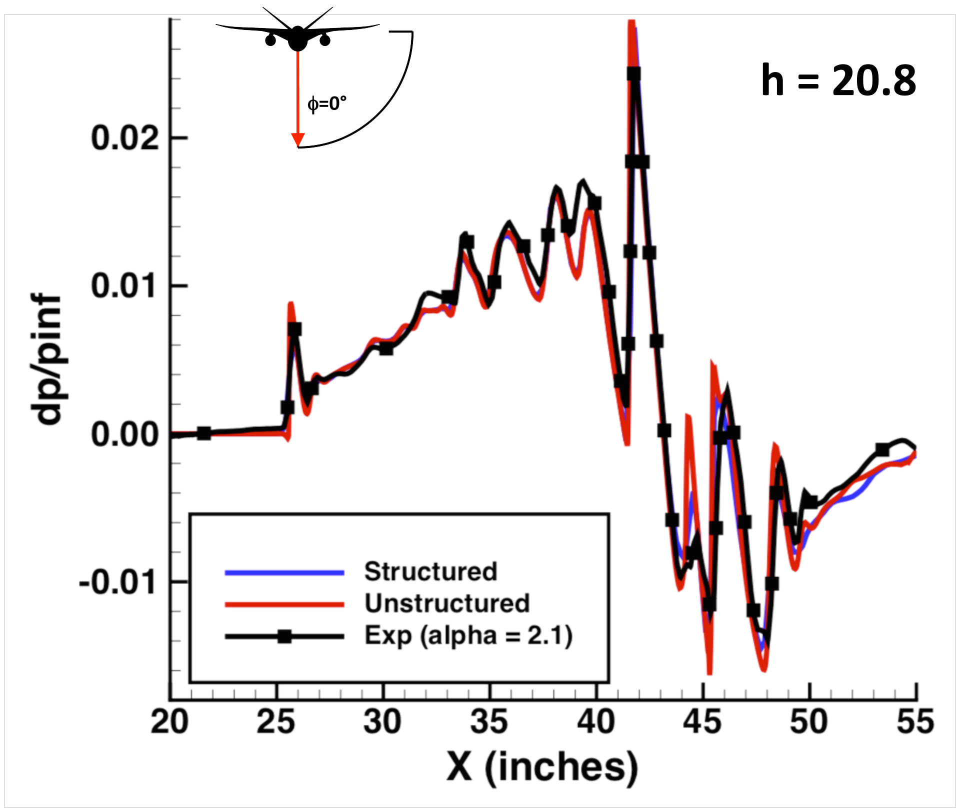
Flow Field Visualization

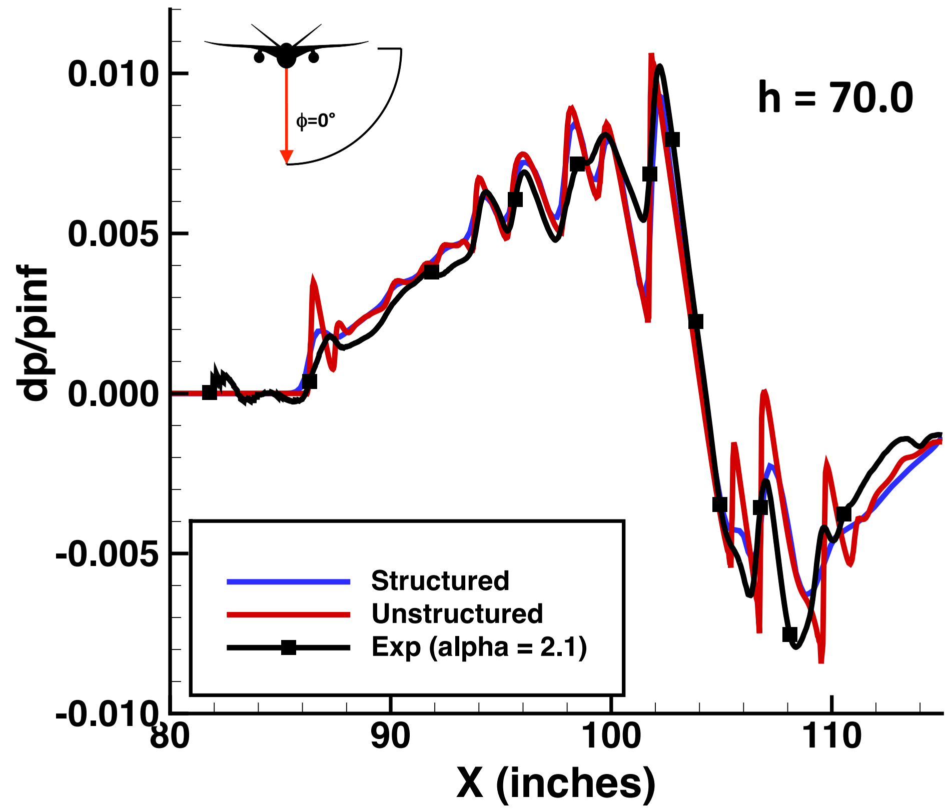


- **Complex wave pattern generated by the model**
- **Magnitude of peaks decay radially**
- **Shape of vehicle is designed to help reduce the on-track sonic boom**

Results and Comparison

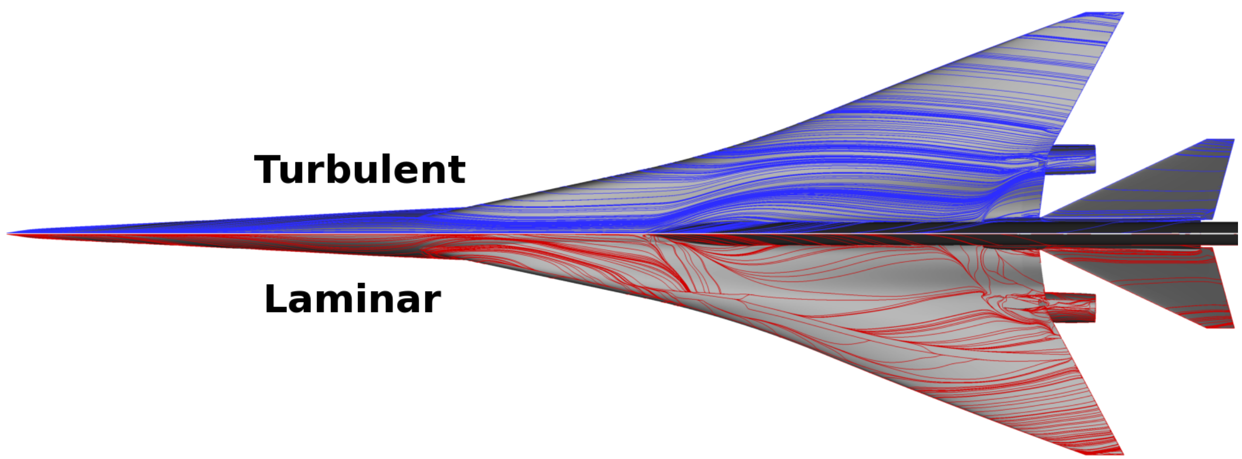
On-Track



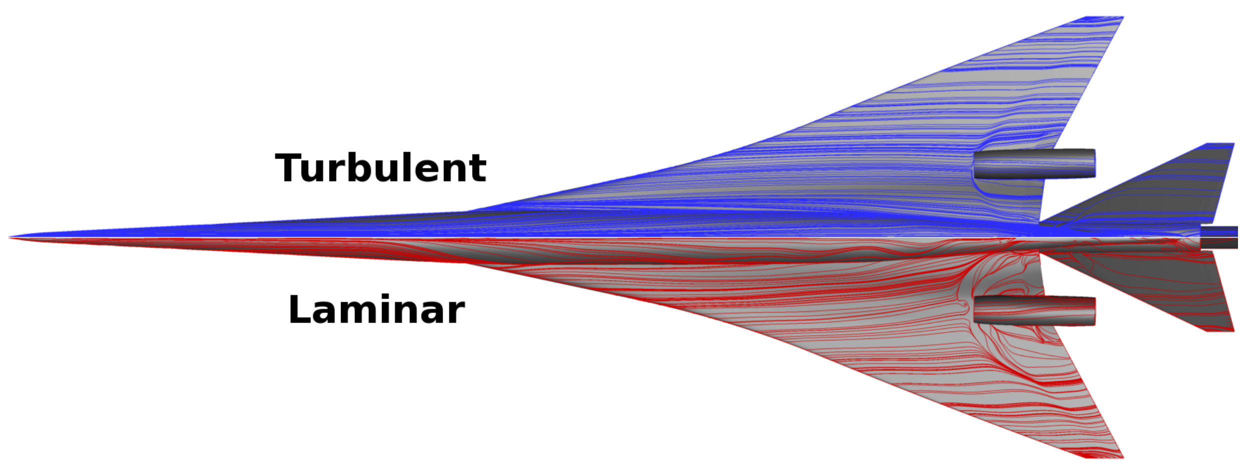


- At h = 20.8 the structured and unstructured solutions match well until X = 43.5
- At h = 70 stronger peaks are observed in the unstructured results (AUSMPW+)
- Both approaches match the experimental data well

Viscous Sensitivity Analysis



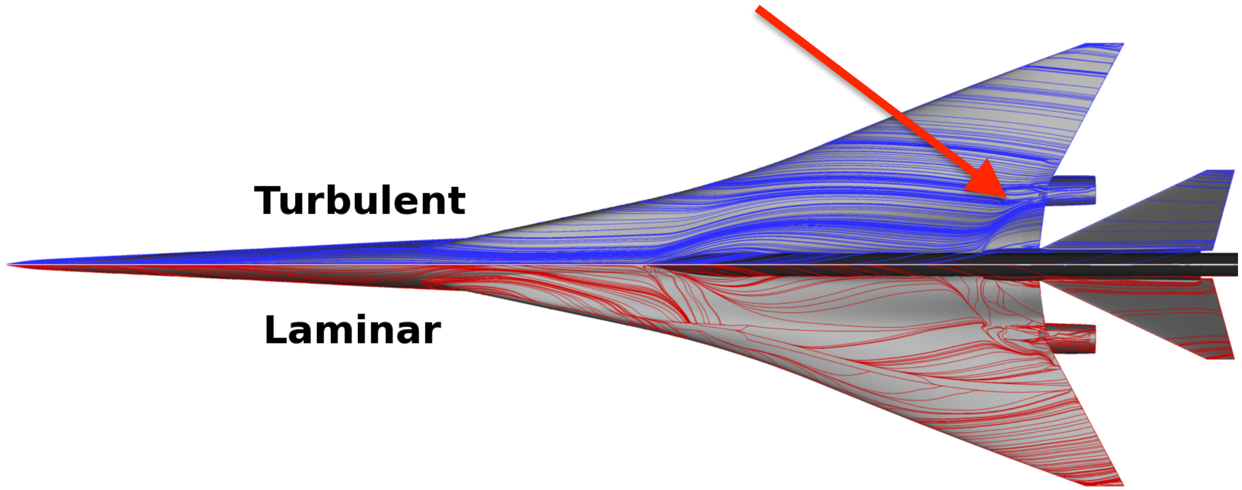
Top Surface



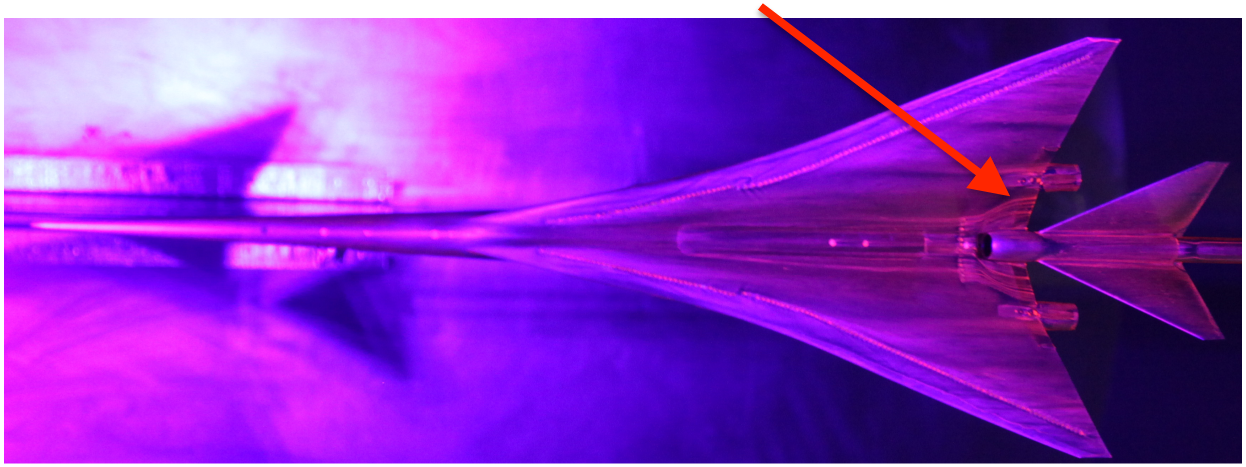
Bottom Surface

- Larger differences observed in surface oil flow
- Shock wave generated by the blade causes laminar flow separation near the leading edge of the top wing surface
- Strength of separation generated from under-wing nacelle is larger using Laminar flow assumption

Viscous Sensitivity Analysis



CFD



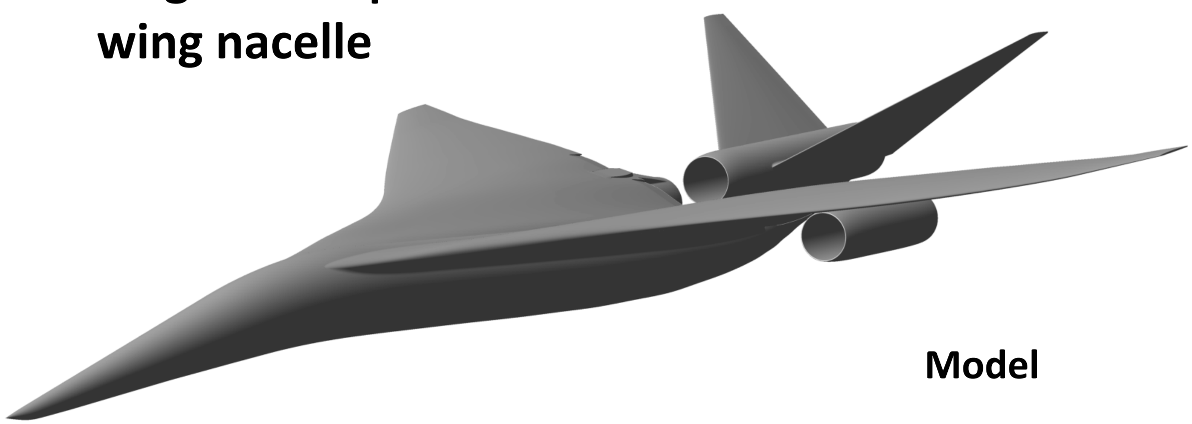
Experiment

- Oil flow comparison between CFD and experiment on top surface
- Turbulent flow patterns match experiment better than laminar flow assumption
- Flow turning at the aft end of the wing between the sting and wing-nacelle attachment hardware is well-captured

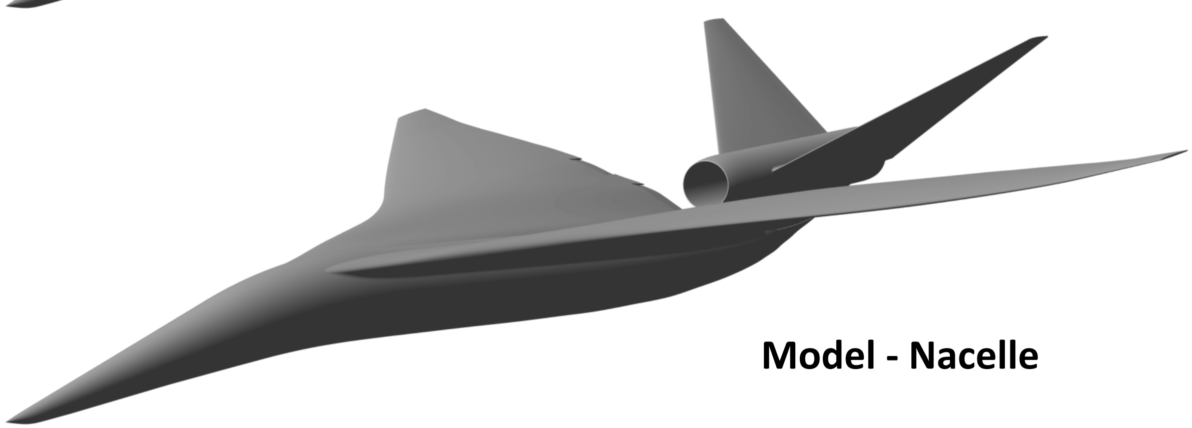
Lockheed Martin 1021

Geometric Sensitivity Analysis

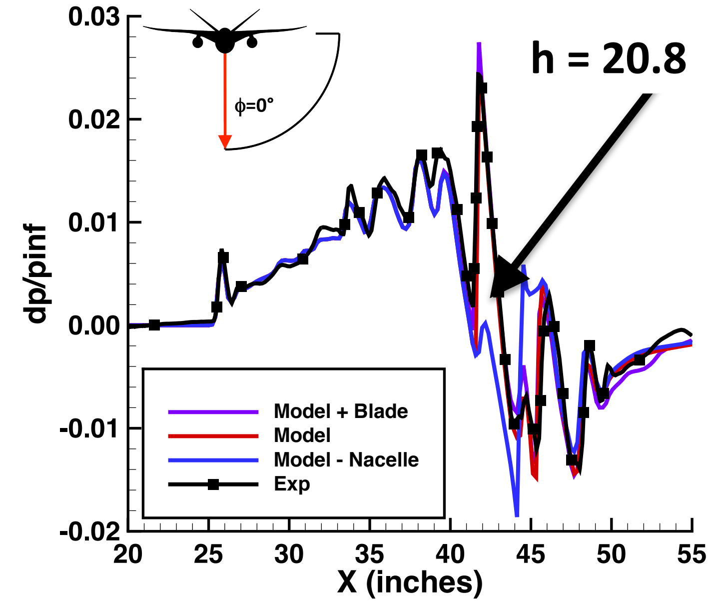
- Two additional configurations performed to assess geometric sensitivity
- Almost no difference excluding the blade
- Largest overpressure attributed to the under-wing nacelle

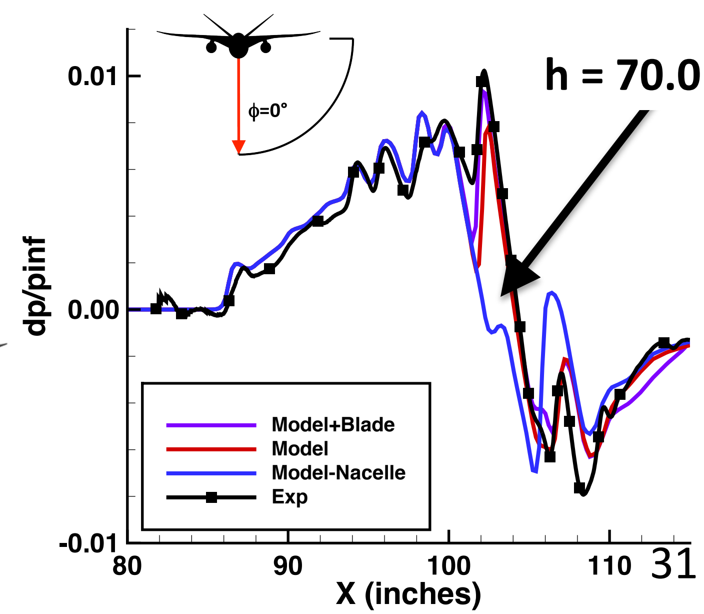


Model



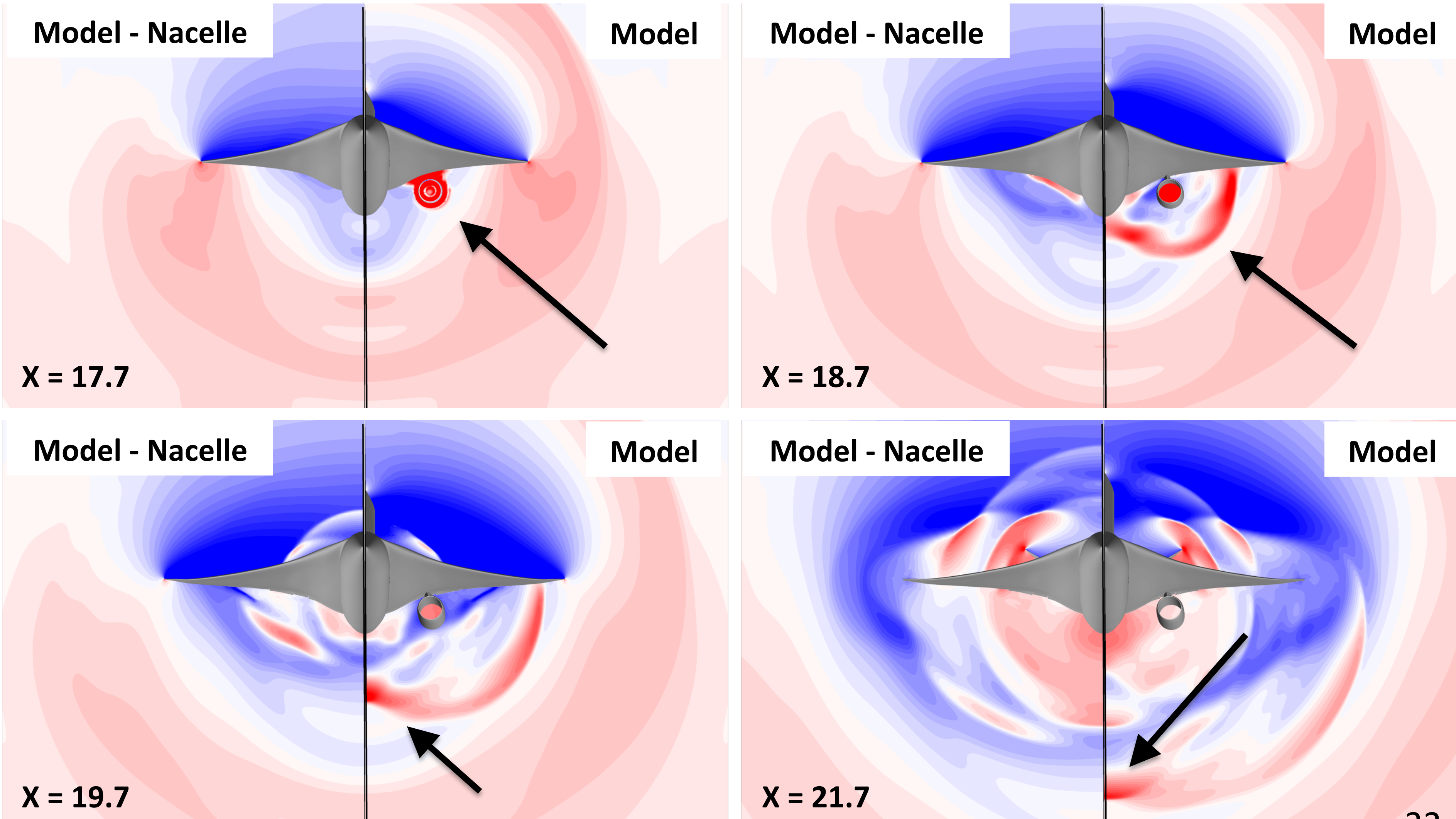
Model - Nacelle





Lockheed Martin 1021

Geometric Sensitivity Analysis



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Oblique Shock/Plume Interaction

Objectives

- Assess the accuracy in RANS CFD prediction capabilities for oblique shock/plume interaction
- Explain differences between inviscid and viscous analysis assumptions and wind tunnel data*
- Assist in analyzing current wind tunnel data quality and potential probe measurement errors

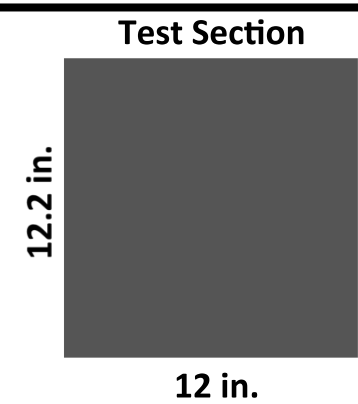
Approach

- Perform both RANS and inviscid CFD analysis using the LAVA code
- Compare CFD results with 1x1 SWT data on several configurations:
  - Empty tunnel
  - Isolated nozzle in tunnel
  - Isolated wedge in tunnel (1.5 and 6 inch wedges)
  - Complete configuration (1.5 and 6 inch wedges)
- Line extractions taken at 1 inch above nozzle centerline unless stated otherwise

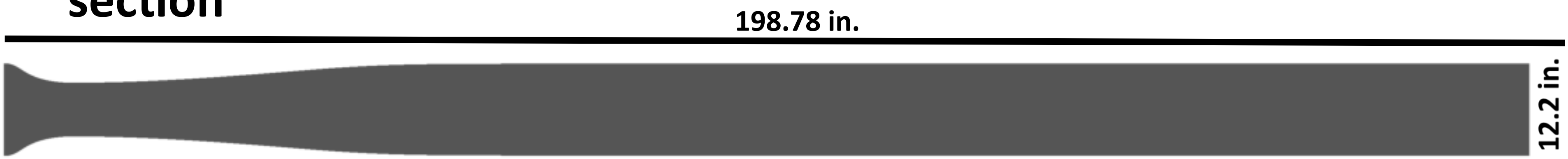
** All WT measurements reported here were performed at NASA GRC, POC: Ray Castner*

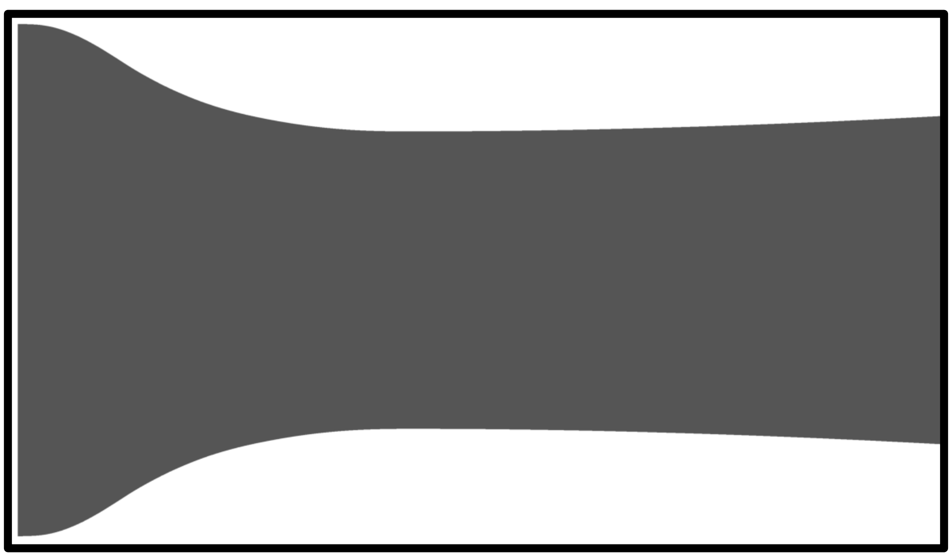
Geometric Model

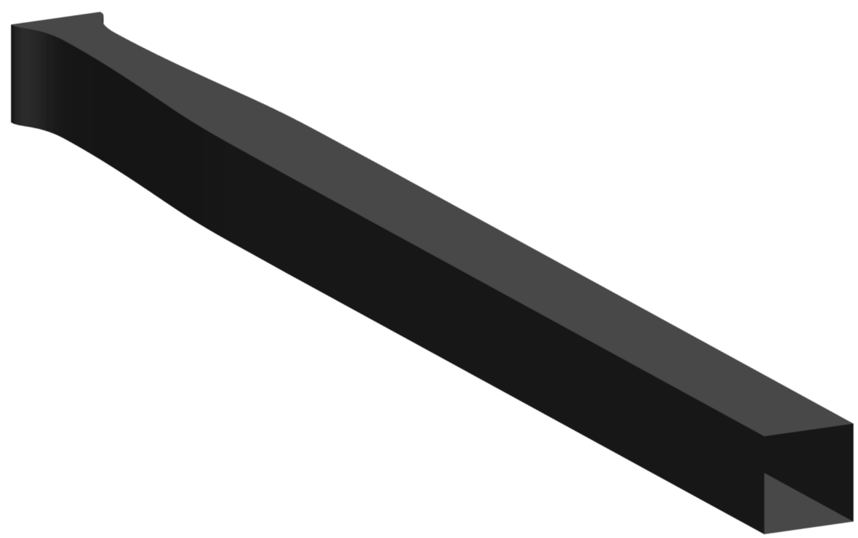
Wind Tunnel



- 1x1 Supersonic WT at NASA Glenn (GRC)
- 12 x 12.2 inch test section
- 1.723 Area Ratio
- Approx. 126 inches of straight tunnel after diverging section



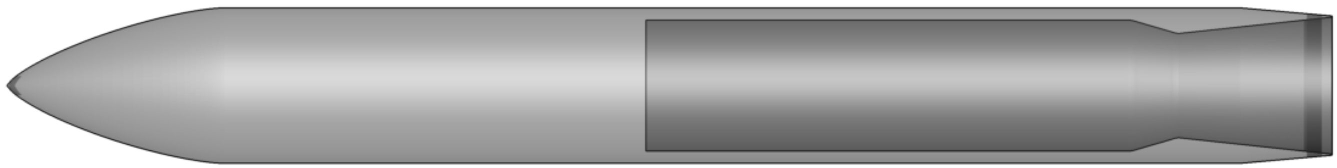




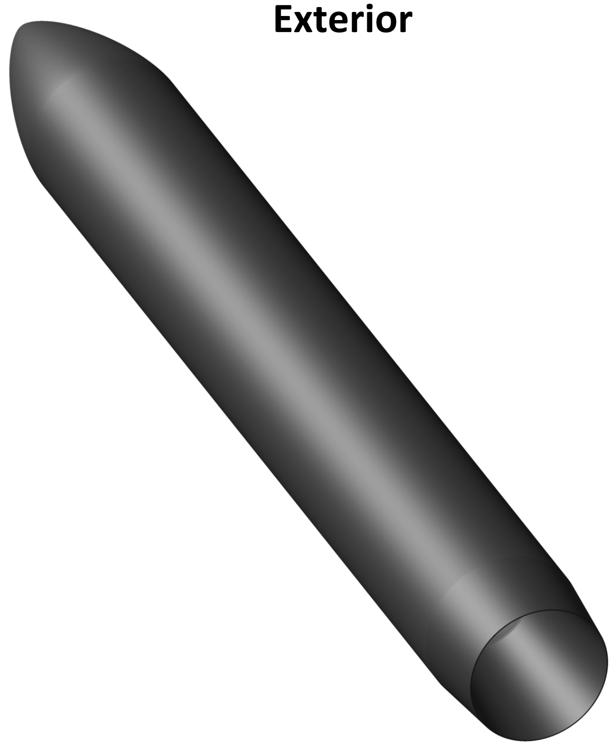
Geometric Model

Nozzle

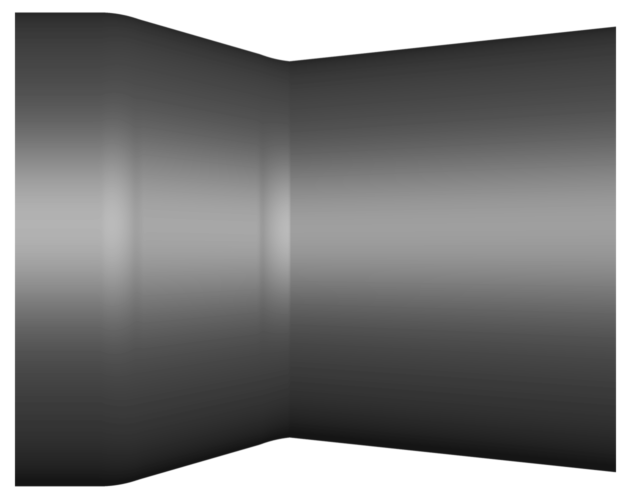
- Exterior Length 8.56 inch
- Interior Length 4.43 inch
- Inner Diameter 0.88 inch
- Outer Diameter 1.0 inch
- Lip Thickness 0.0075 inch
- Area Ratio 1.726



Exterior



Interior

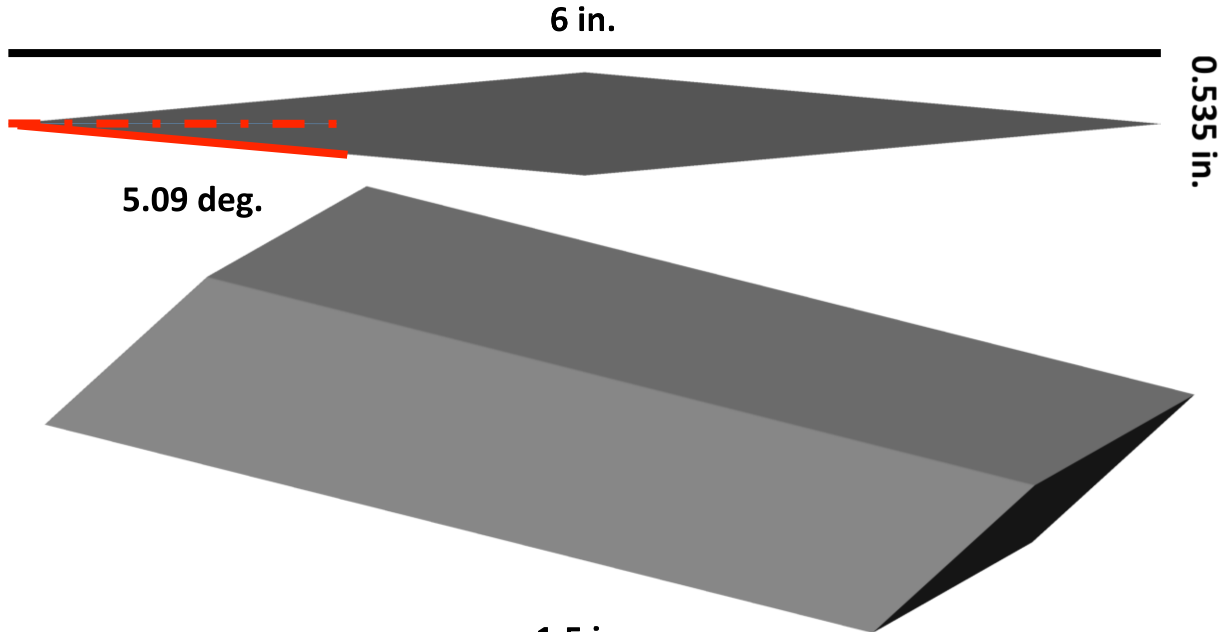


Throat Section

Geometric Model

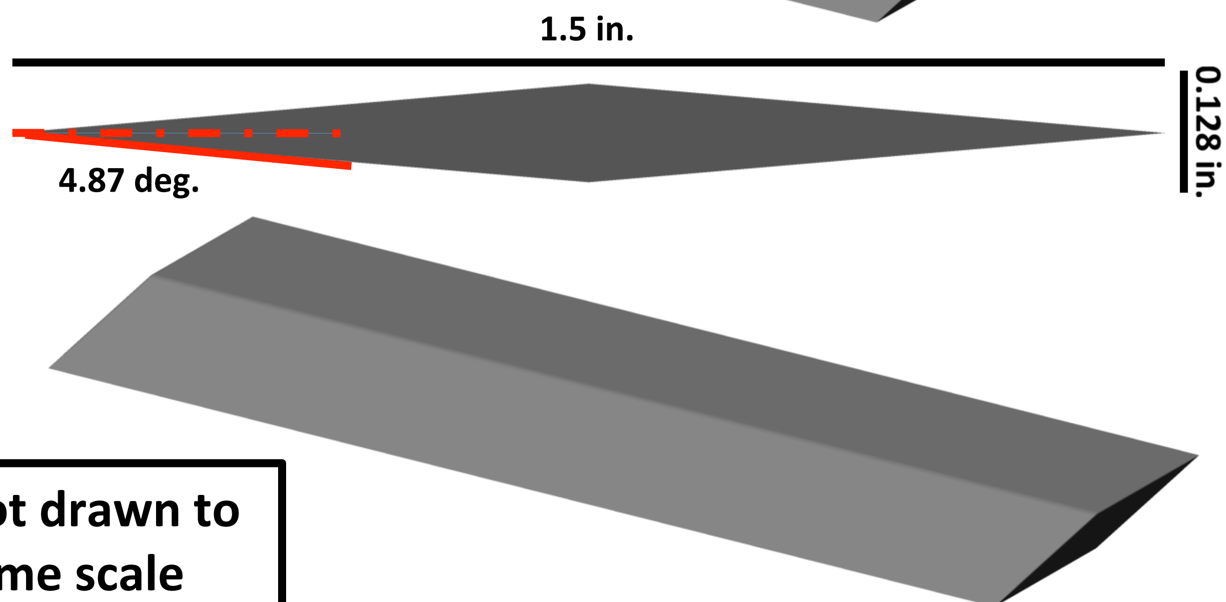
6 inch Wedge

- **Length: 6 inch**
- **Width: 8 inch**
- **Height: 0.535 inch**
- **Angle: 5.09 degrees**



1.5 inch Wedge

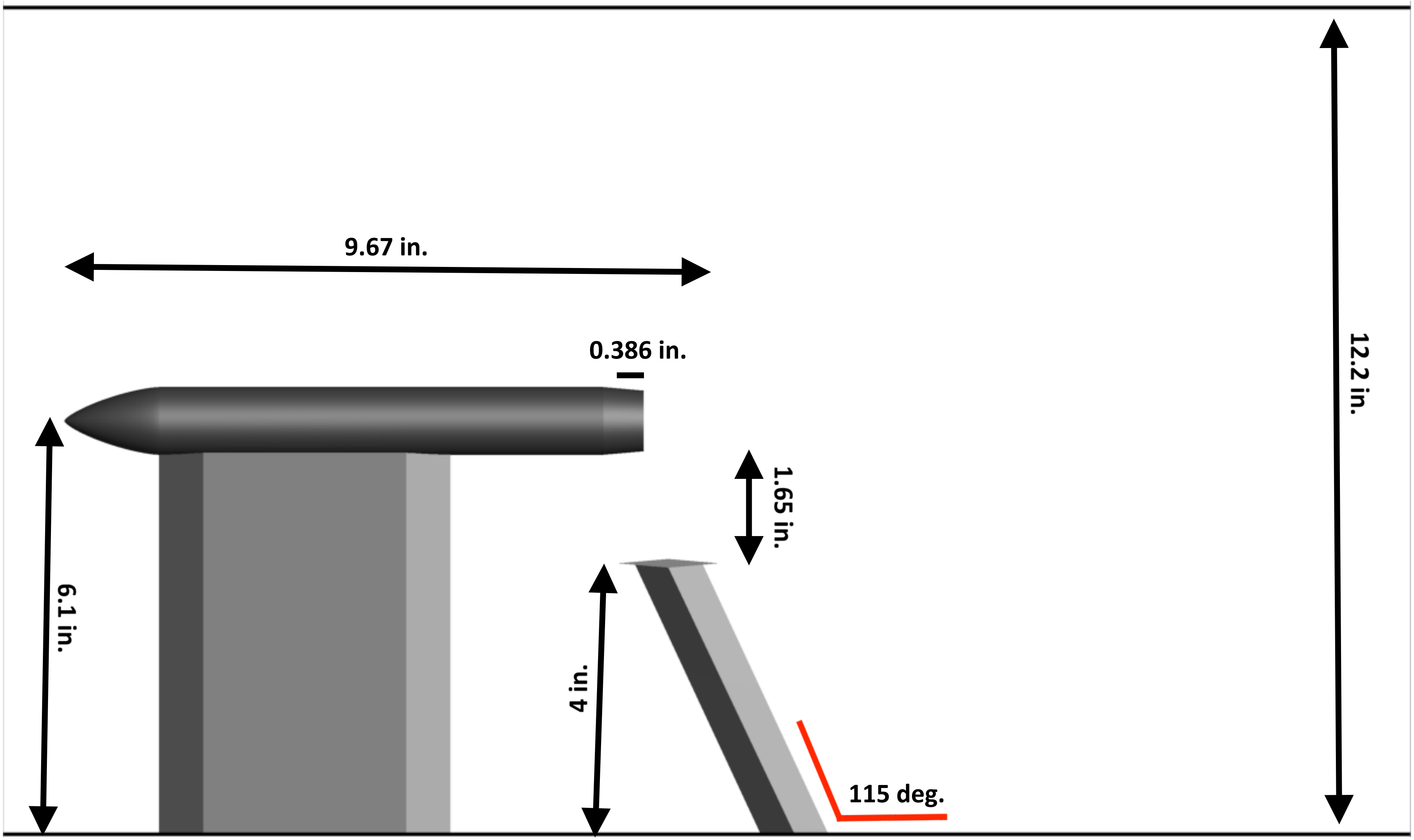
- **Length: 1.5 inch**
- **Width: 3.6 inch**
- **Height: 0.128 inch**
- **Angle: 4.87 degrees**



Not drawn to same scale

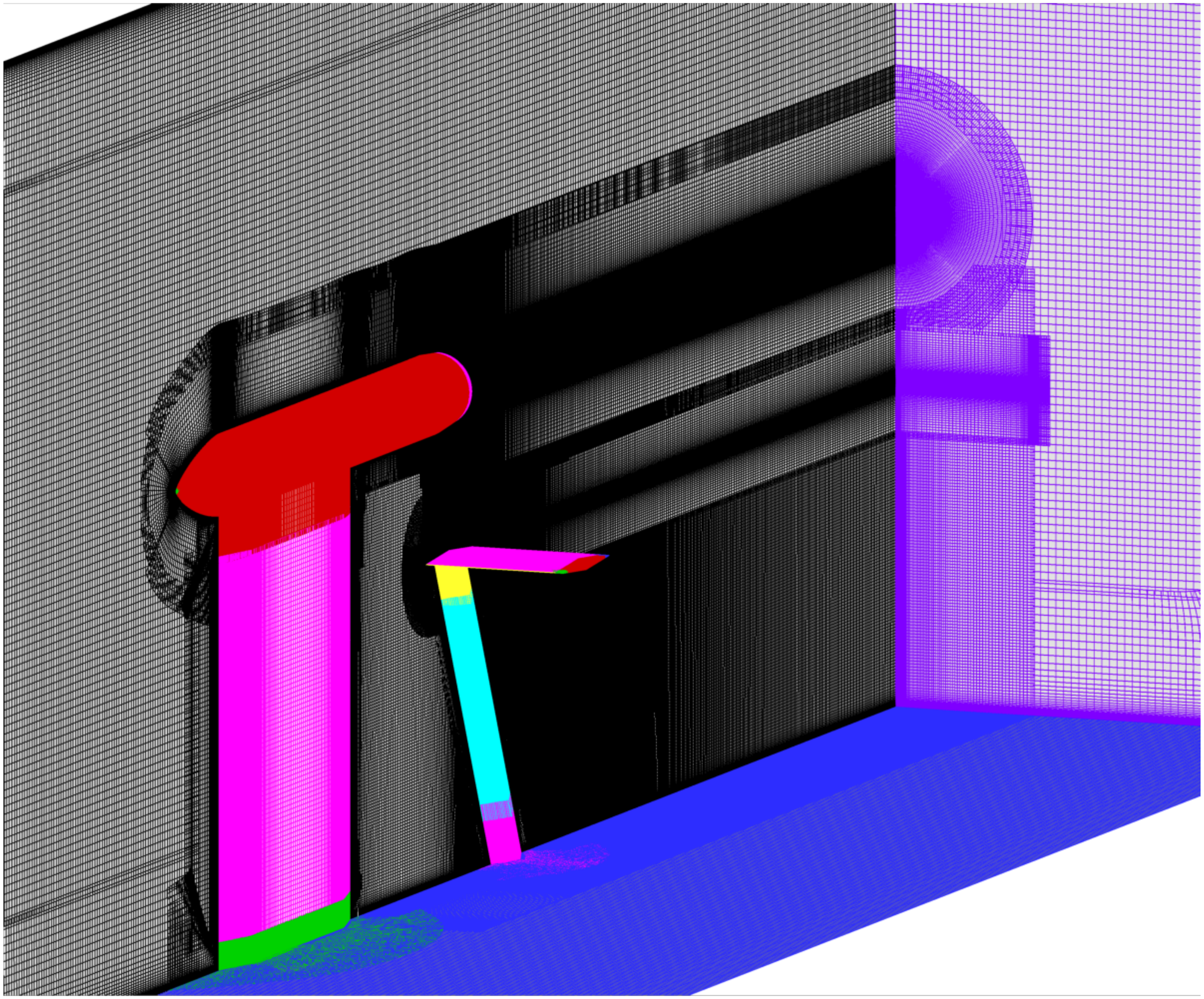
Geometric Model

Installed 1.5 inch Wedge and Nozzle Configuration



Structured Overset Grid

Installed 1.5 inch Wedge and Nozzle Configuration



- **27 zones**
- **108.5 M grid pnts**
- **Triple fringe**
- **Stencil Qual 0.9**
- **0 Orphans**
- **y+ ≈ 1**
- **Grid Breakdown**
  - **Tunnel 49 M**
  - **Nozzle and Plume 29.2 M**
  - **Wedge and Wake 13.7 M**
  - **Nozzle Support and Wake 15.6 M**
  - **Wedge Support 1 M**

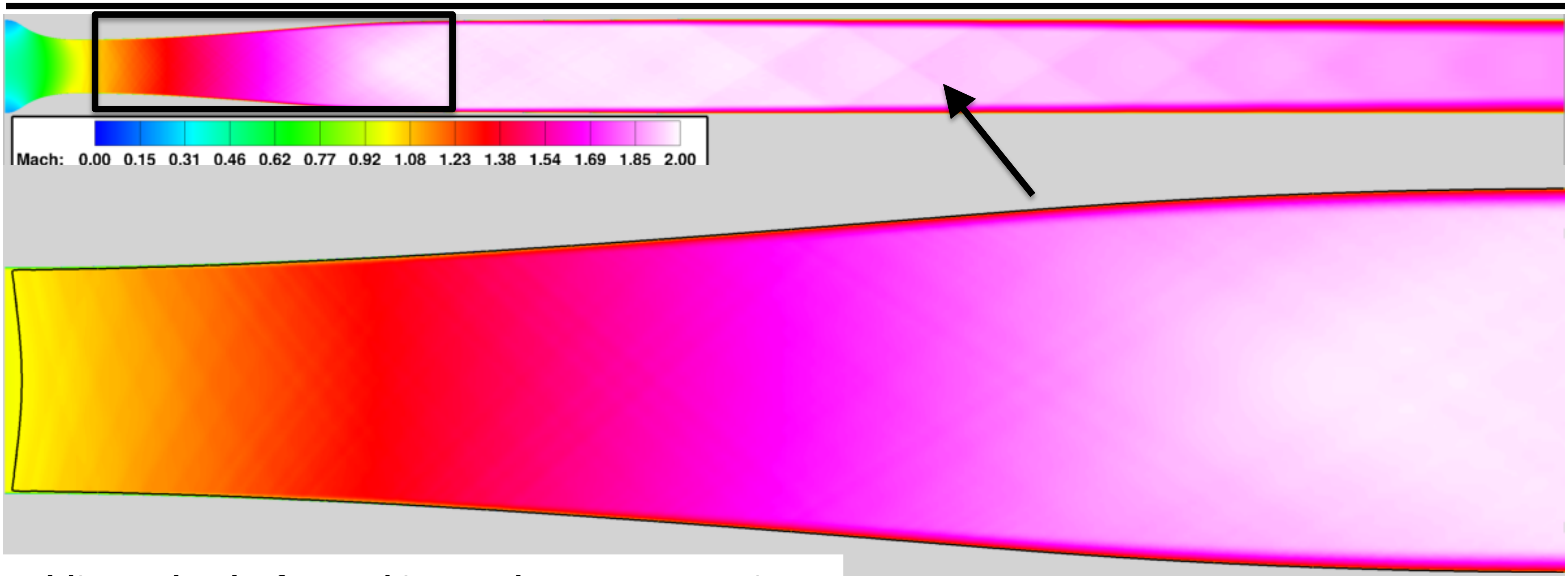
Flow Conditions

- Reference Conditions
  - Mach: 1.96
  - Reynolds Number: 10.69 M/meter
  - Temperature: 168.9 K
  - Pressure: 11.6 kPa (1.68 psia)
- Tunnel Inlet
  - Stagnation Temperature: 298.3 K
  - Stagnation Pressure: 85.15 kPa (12.35 psi)
- Nozzle Inlet
  - Stagnation Temperature: 294.4 K
  - Stagnation Pressure
    - NPR = 6, 69.5 kPa
    - NPR = 8, 92.7 kPa
    - NPR = 10, 115.8 kPa
    - NPR = 12, 139.0 kPa
    - NPR = 14, 162.1 kPa

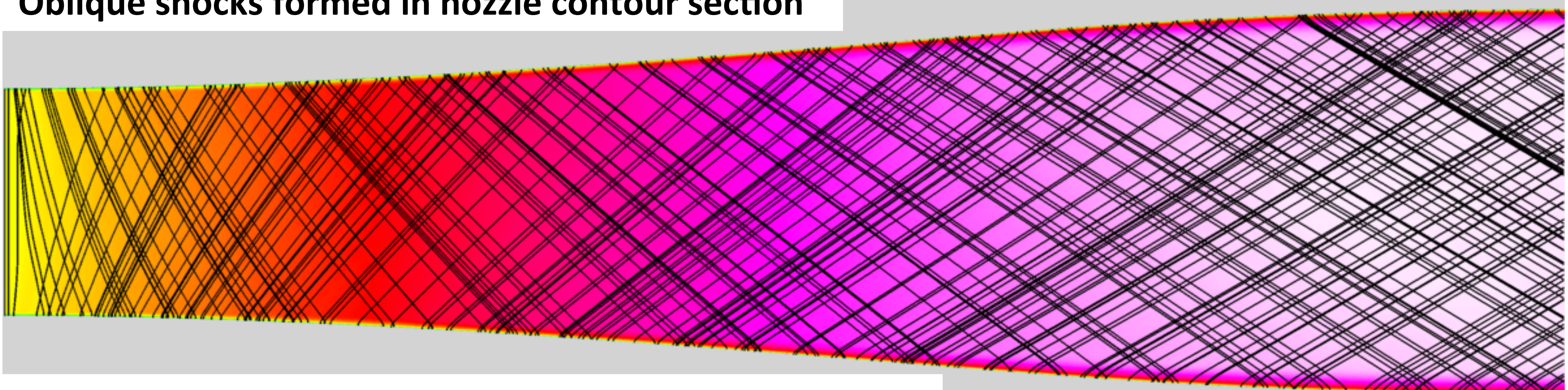
Outline

- ○ Introduction
- ○ Launch Ascent and Vehicle Aerodynamics (LAVA) Framework
- ○ 1st AIAA Sonic Boom Prediction Workshop
- ○ **Oblique Shock/Plume Interaction**
    - **Empty Tunnel**
    - 1.5 inch Wedge in Tunnel
    - 1.5 inch Wedge and Nozzle in Tunnel
- ○ Summary

Flow-Field Visualization



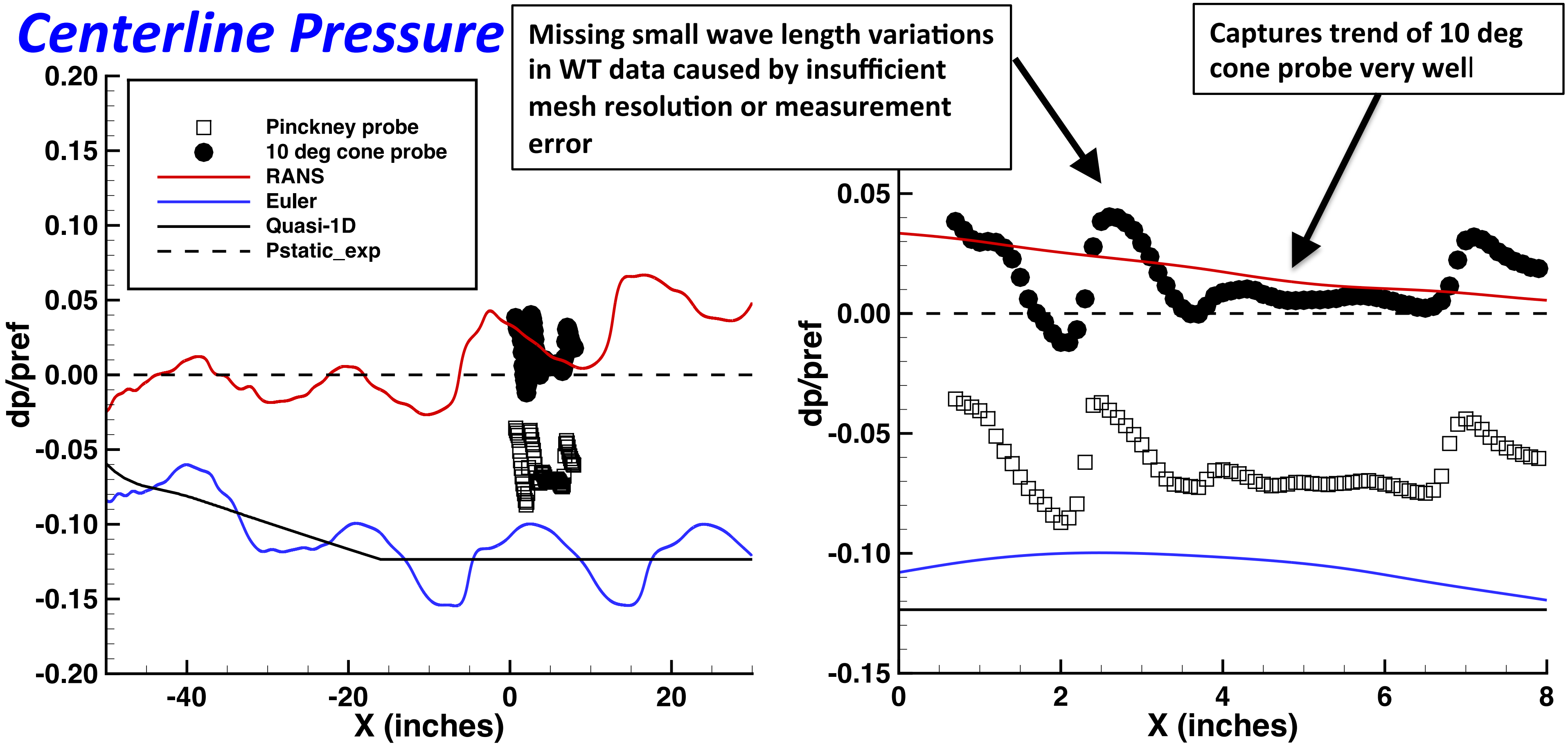
Oblique shocks formed in nozzle contour section



Shocks travel along characteristic lines down the tunnel

Results and Comparison

Centerline Pressure



- Static pressure WT measurement of 1.68 psia is used in non-dimensionalization for all pressure plots
- Quasi-1D, Euler, and Pinckney probe results do not match the static pressure measurement
- RANS and 10 deg. cone probe data match well in magnitude and trend

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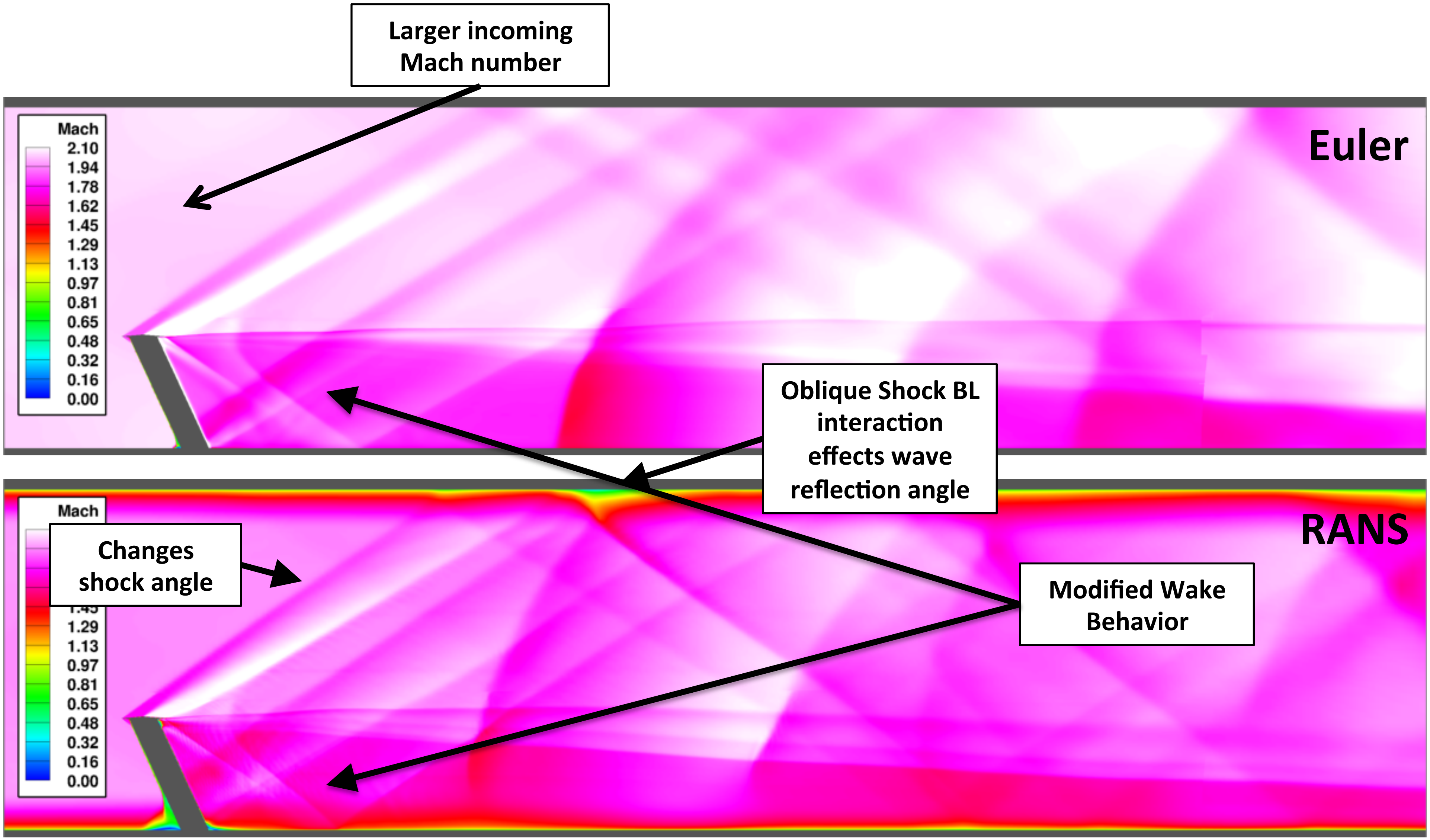
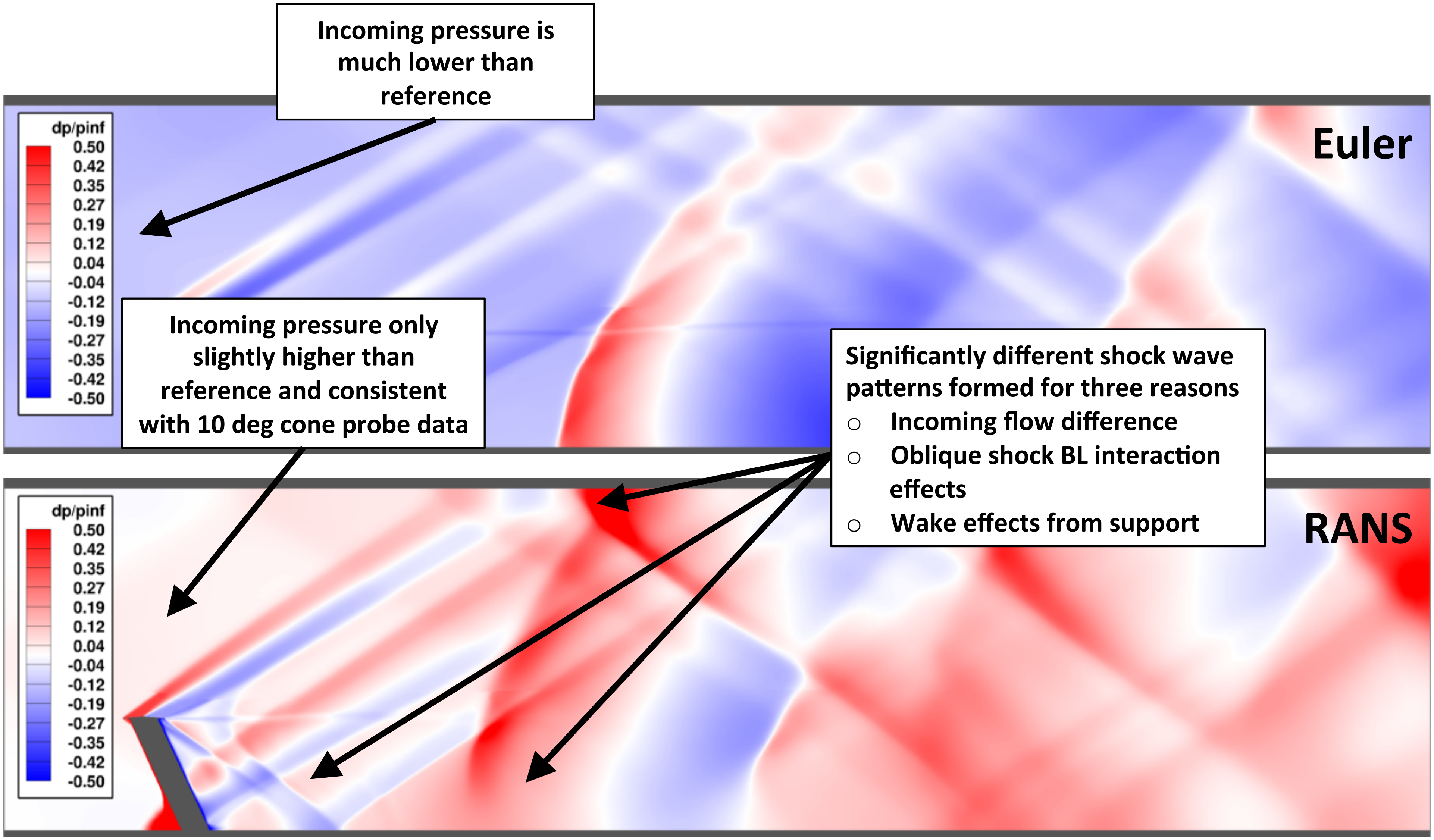
Flow-Field Visualization

Mach Number



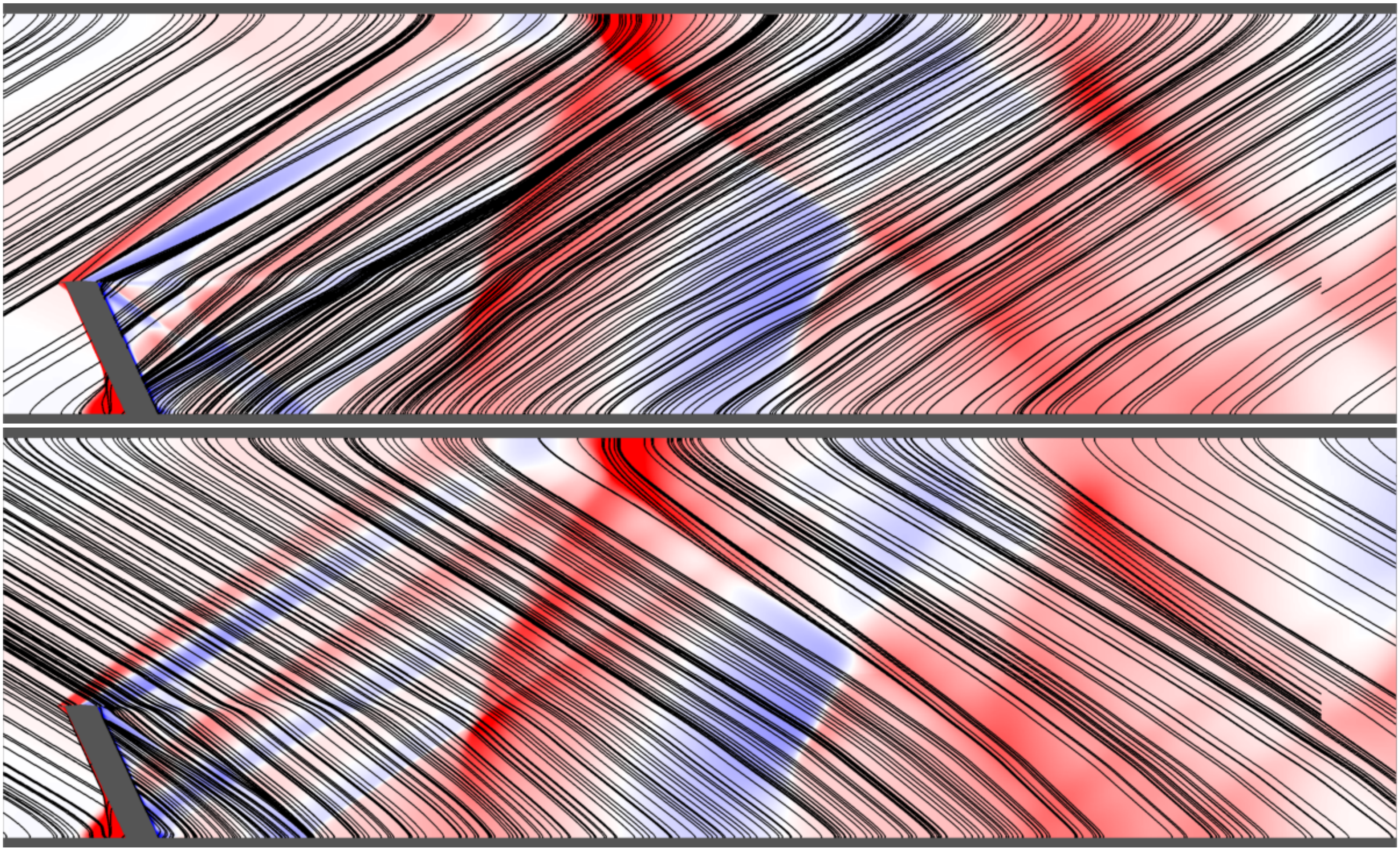
Flow-Field Visualization

Pressure



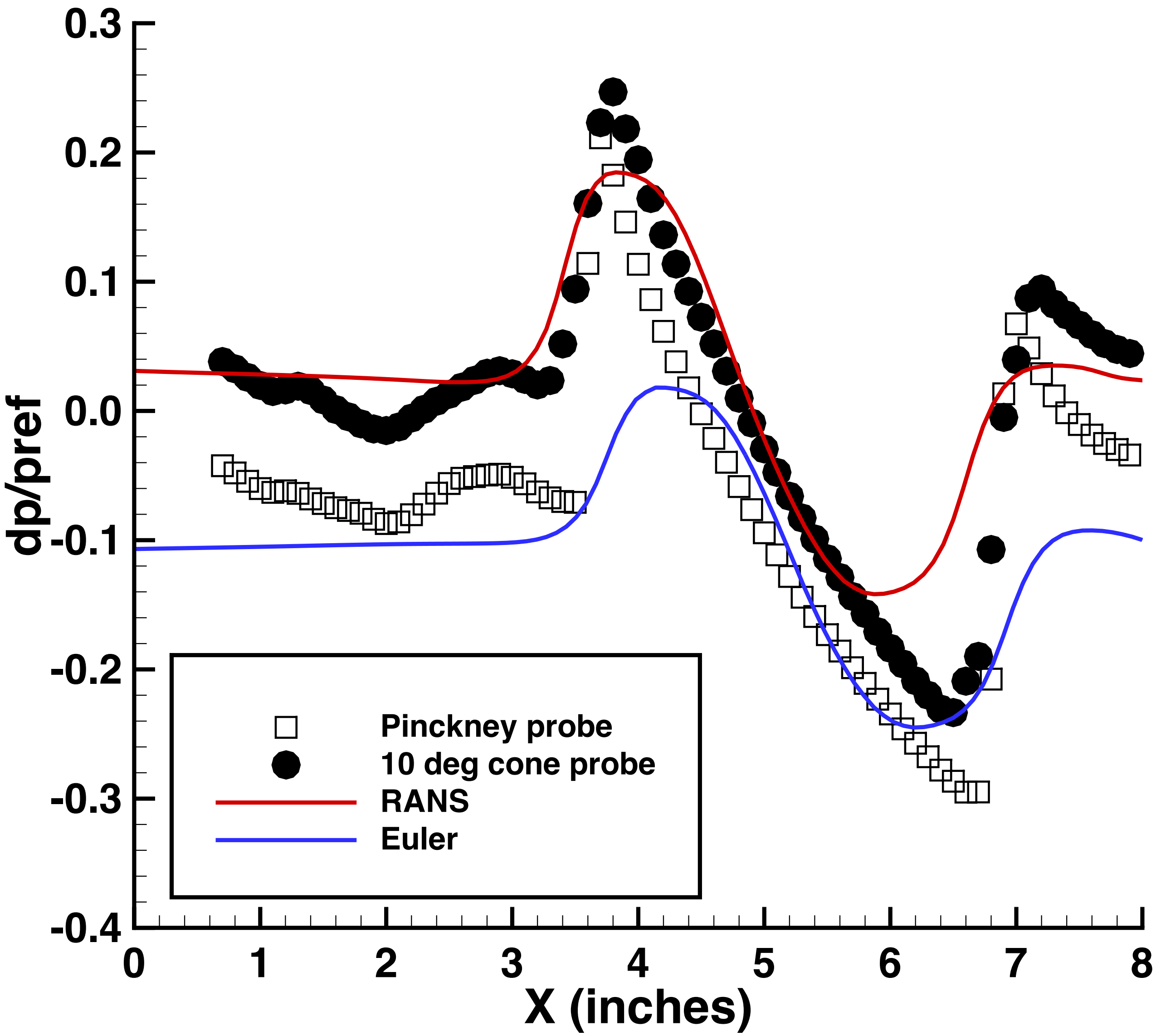
Flow-Field Visualization

Characteristics



Results and Comparison

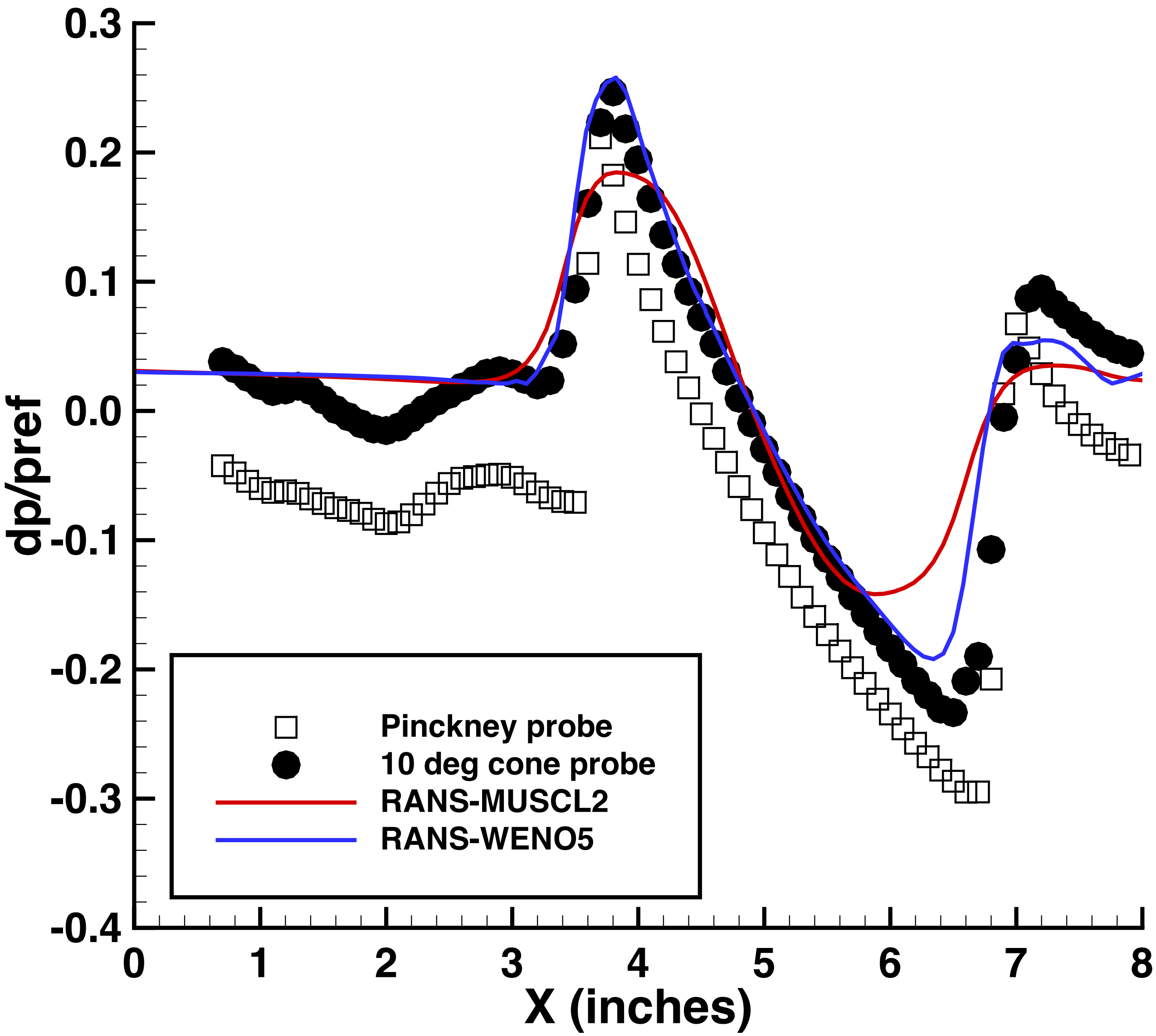
Data Comparison



- Pinckney probe data should be slightly above zero at x = 0 based on 10 deg cone probe and RANS CFD data from empty tunnel
- Shock locations are well-captured using RANS, but shock is smeared.
- Inviscid analysis predicts incorrect shock angle

Results and Comparison

Data Comparison



- **Higher-order accurate WENO based variable reconstruction can be used to recover the peaks observed in the 10 deg. cone probe data.**
- **Additional computational cost of reconstruction is approximately 3% compared to MUSCL reconstruction**

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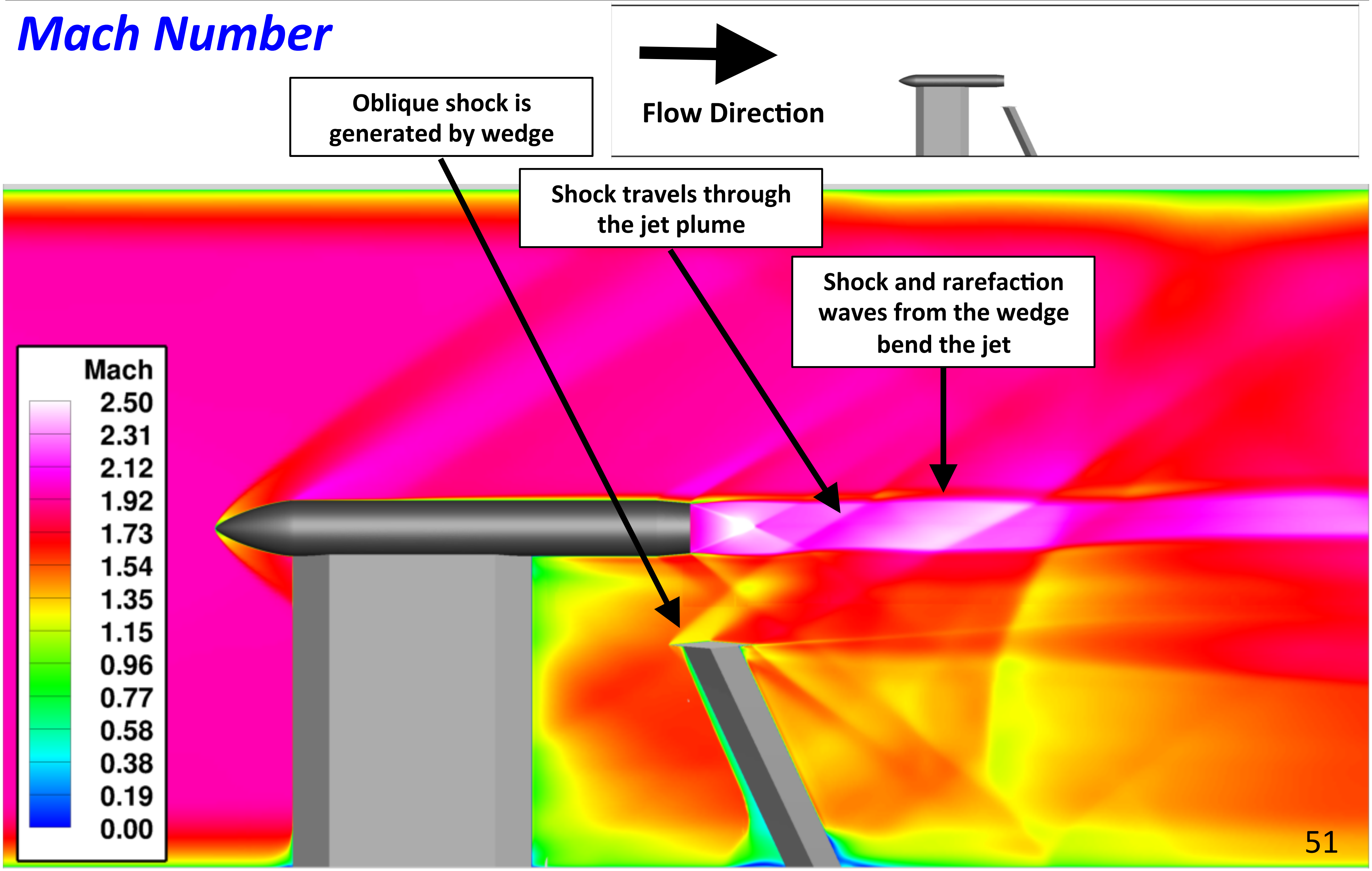
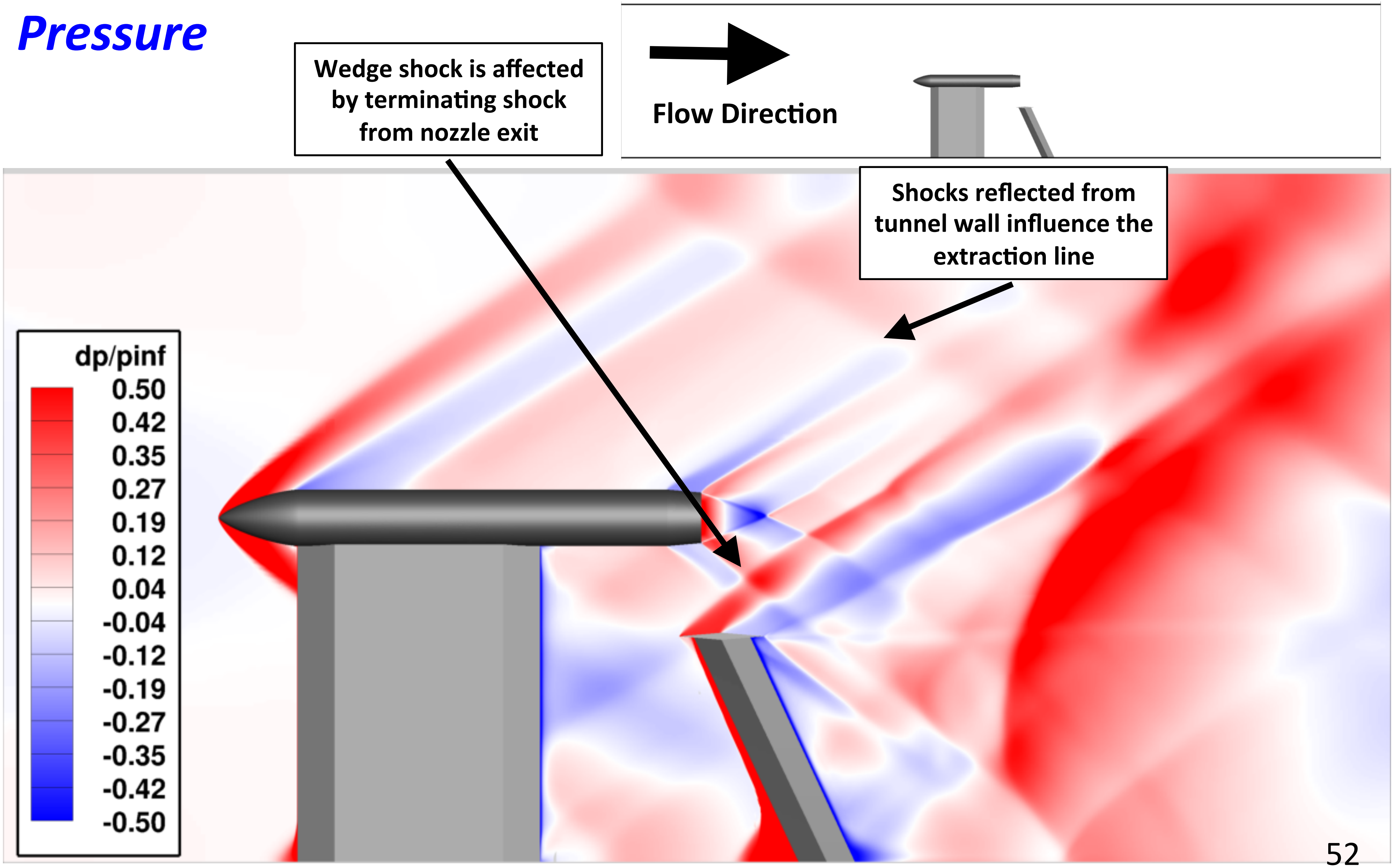
Flow-Field Visualization

Mach Number



Flow-Field Visualization

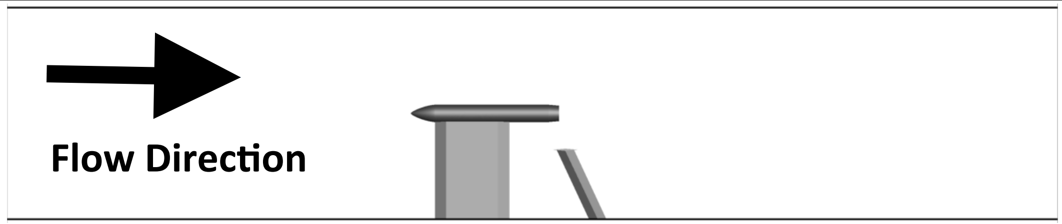
Pressure

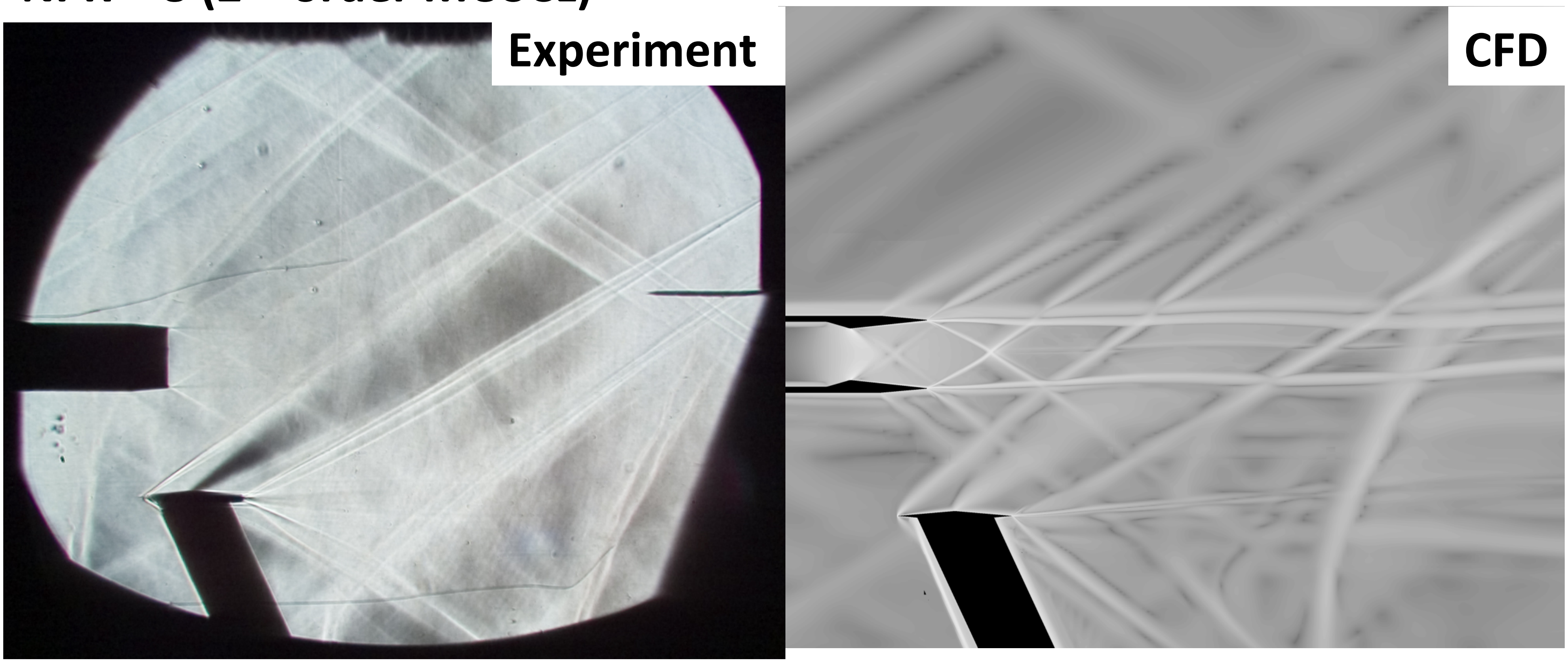


Results and Comparison

Schlieren versus Density Gradient

NPR = 8 (2nd order MUSCL)



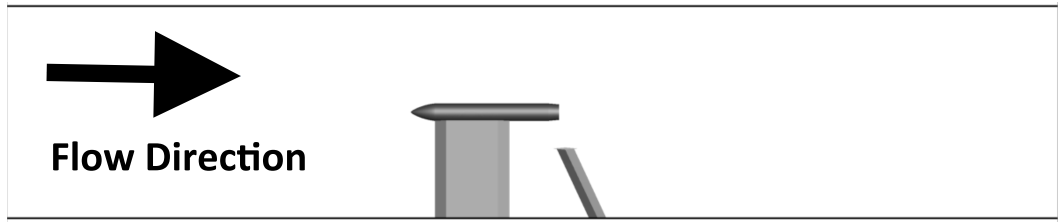


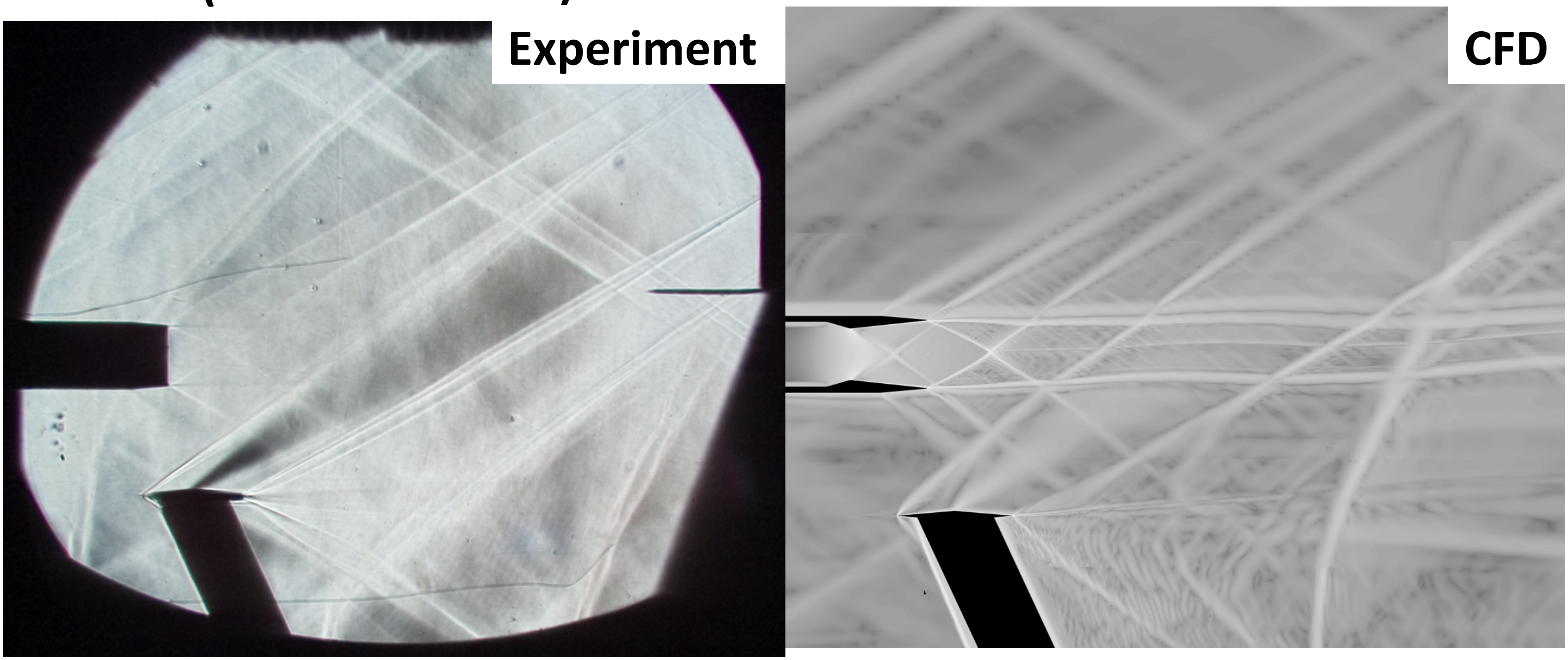
- **Most shocks observed in Schlieren are well-captured by CFD**
- **Bending of the plume is difficult to identify in the Schlieren**

Results and Comparison

Schlieren versus
Density Gradient

NPR = 8 (5th order WENO)



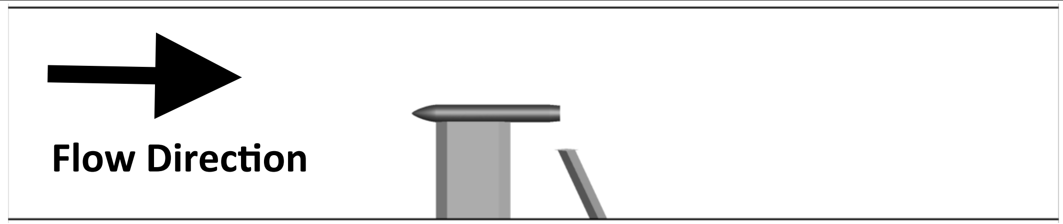


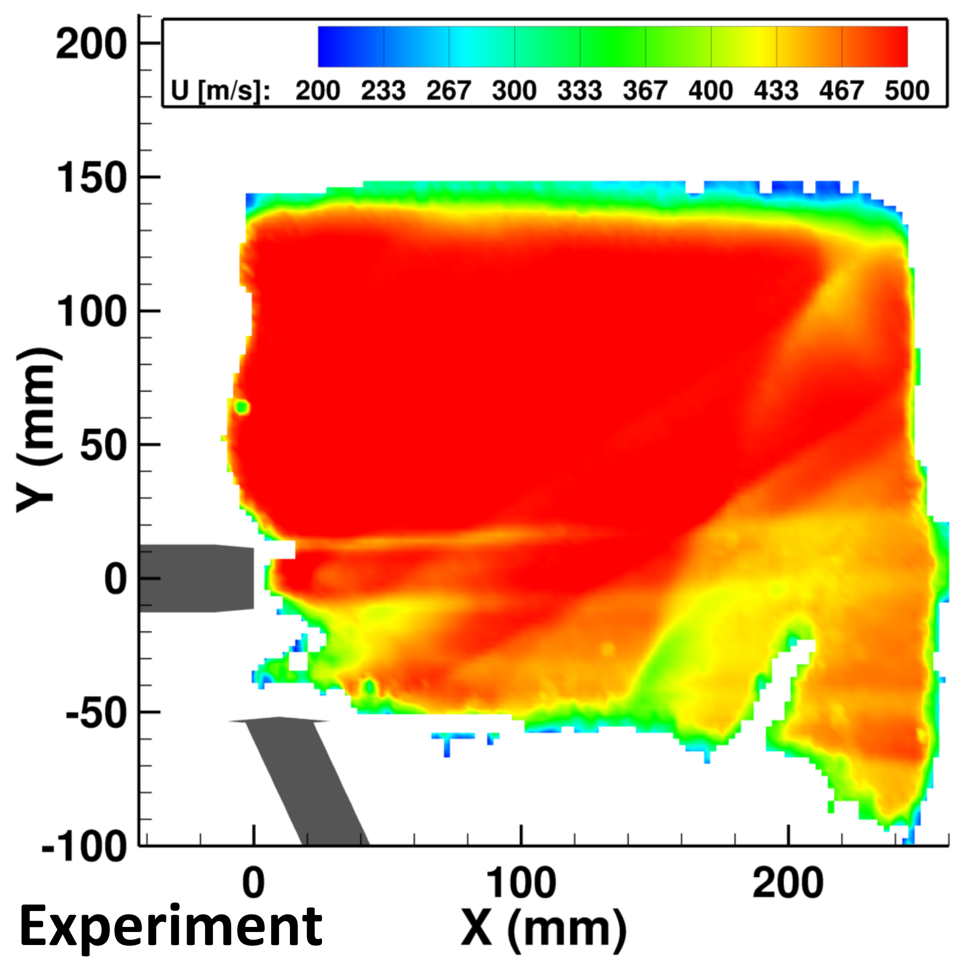
- **Higher-order WENO based variable reconstruction improves the resolution of the CFD solution on the same grid**

Results and Comparison

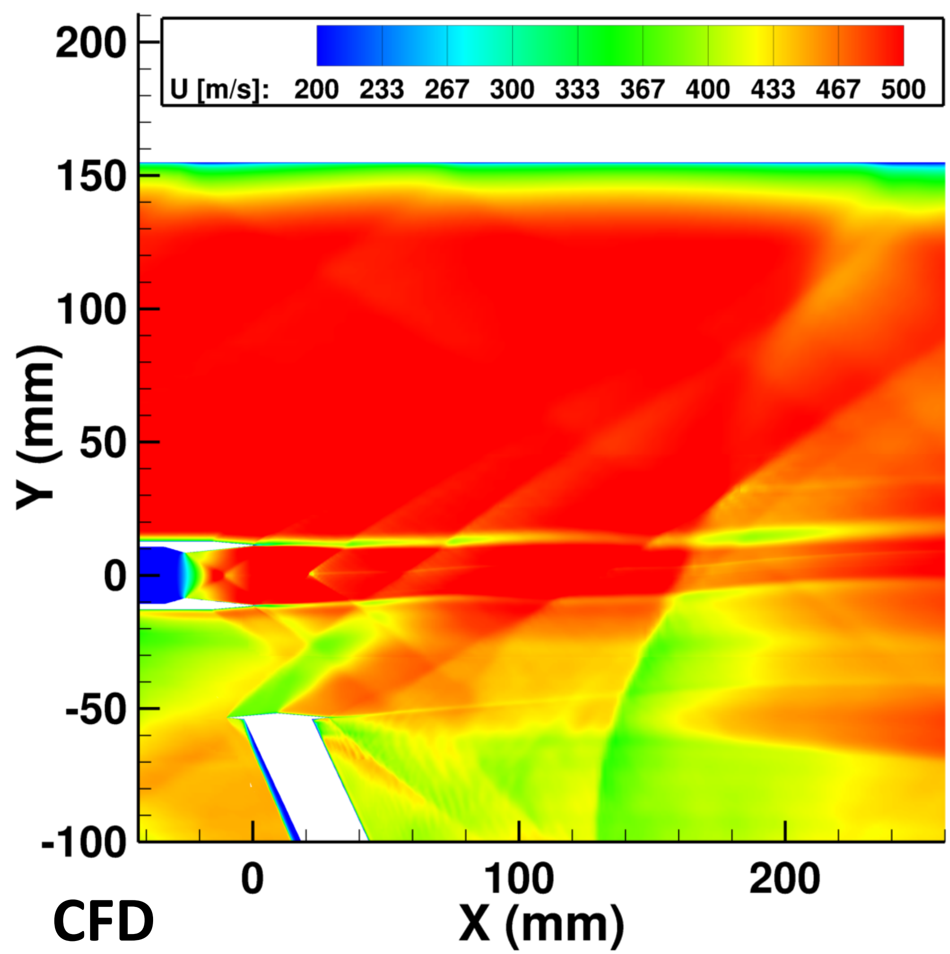
PIV Streamwise Velocity

NPR = 8





Experiment

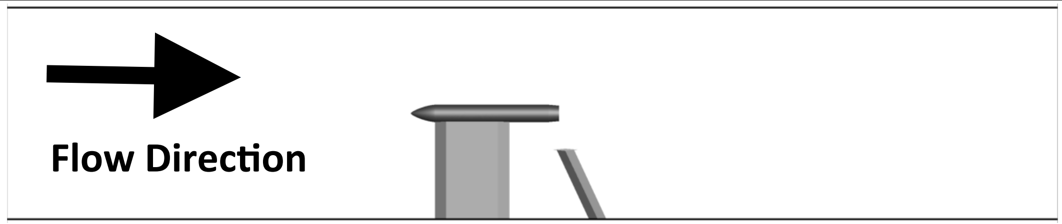


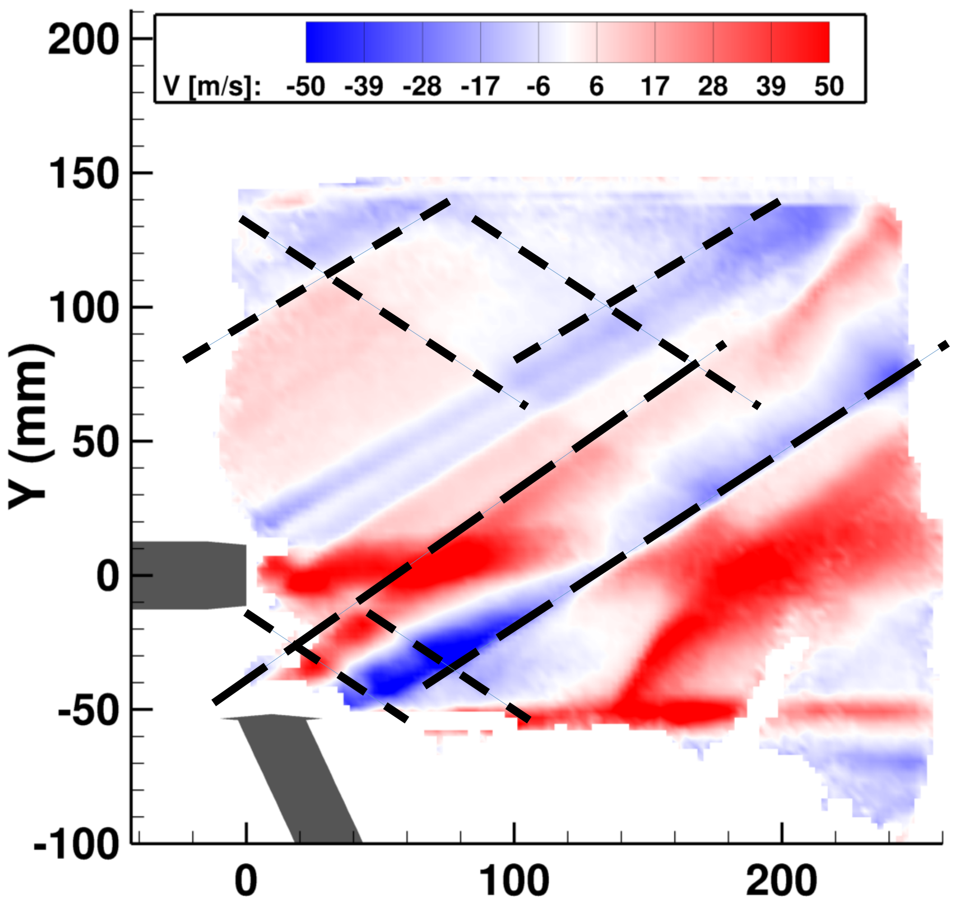
CFD

Results and Comparison

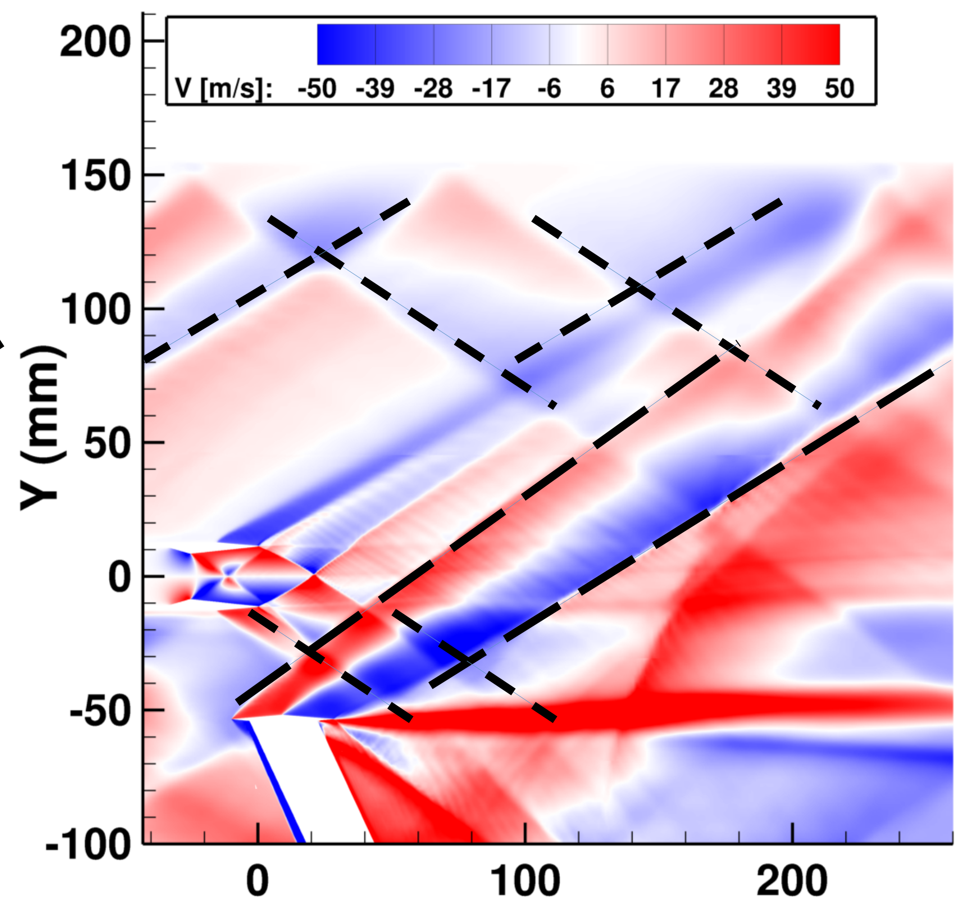
PIV Vertical Velocity

NPR = 8





Experiment

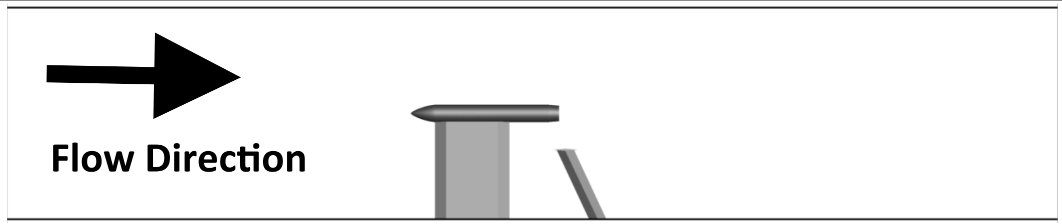


CFD

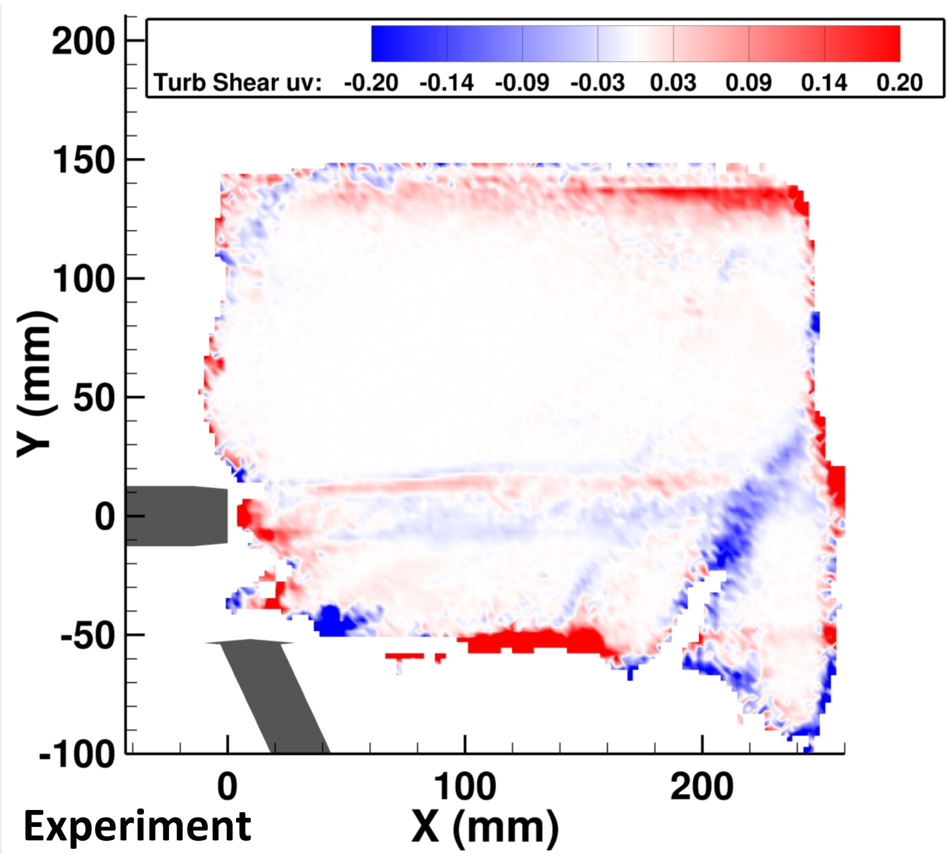
Results and Comparison

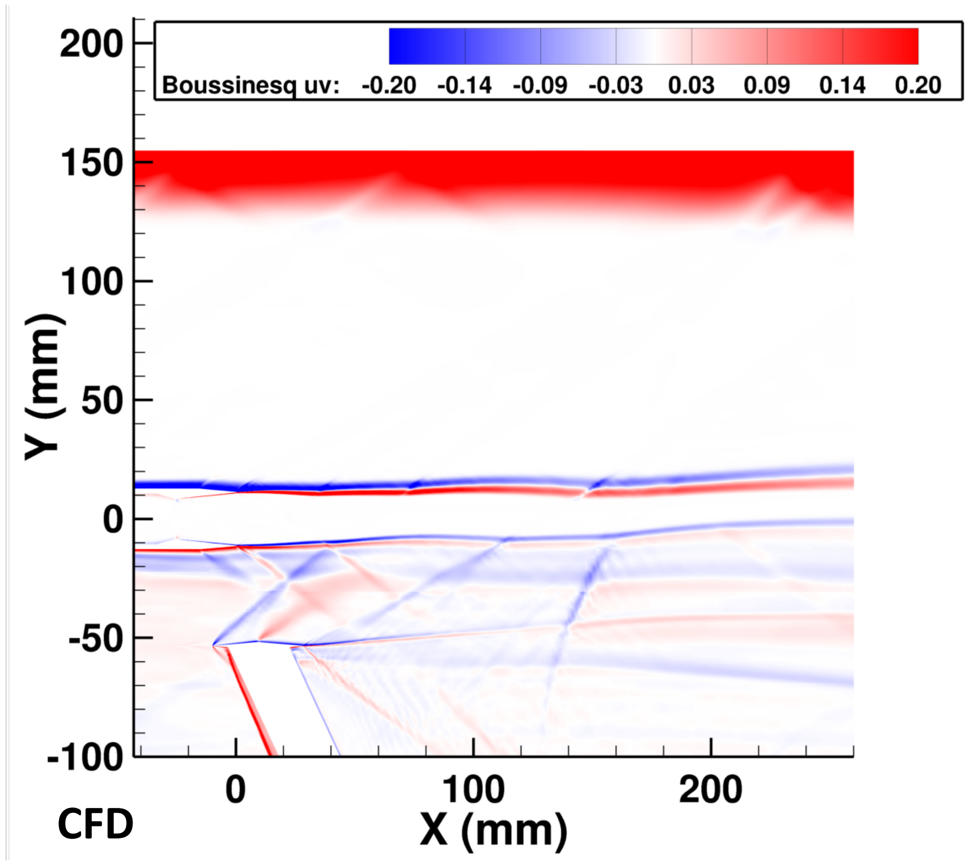
PIV Turbulent Shear

NPR = 8



$$\tau_{xy}^{R} = -\rho\,\overline{u'v'} \approx 2\mu_T \bar{S}_{xy}$$ **(Boussinesq Hypothesis)**

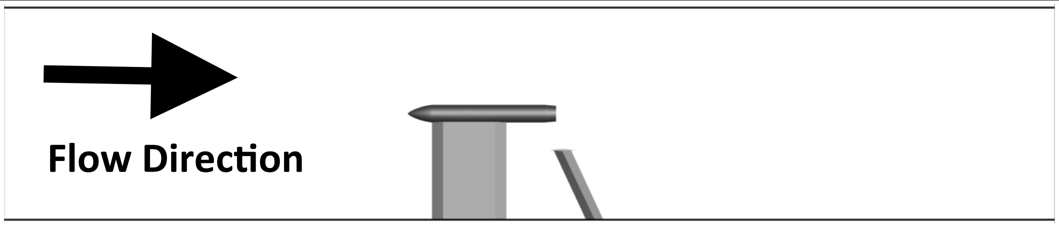


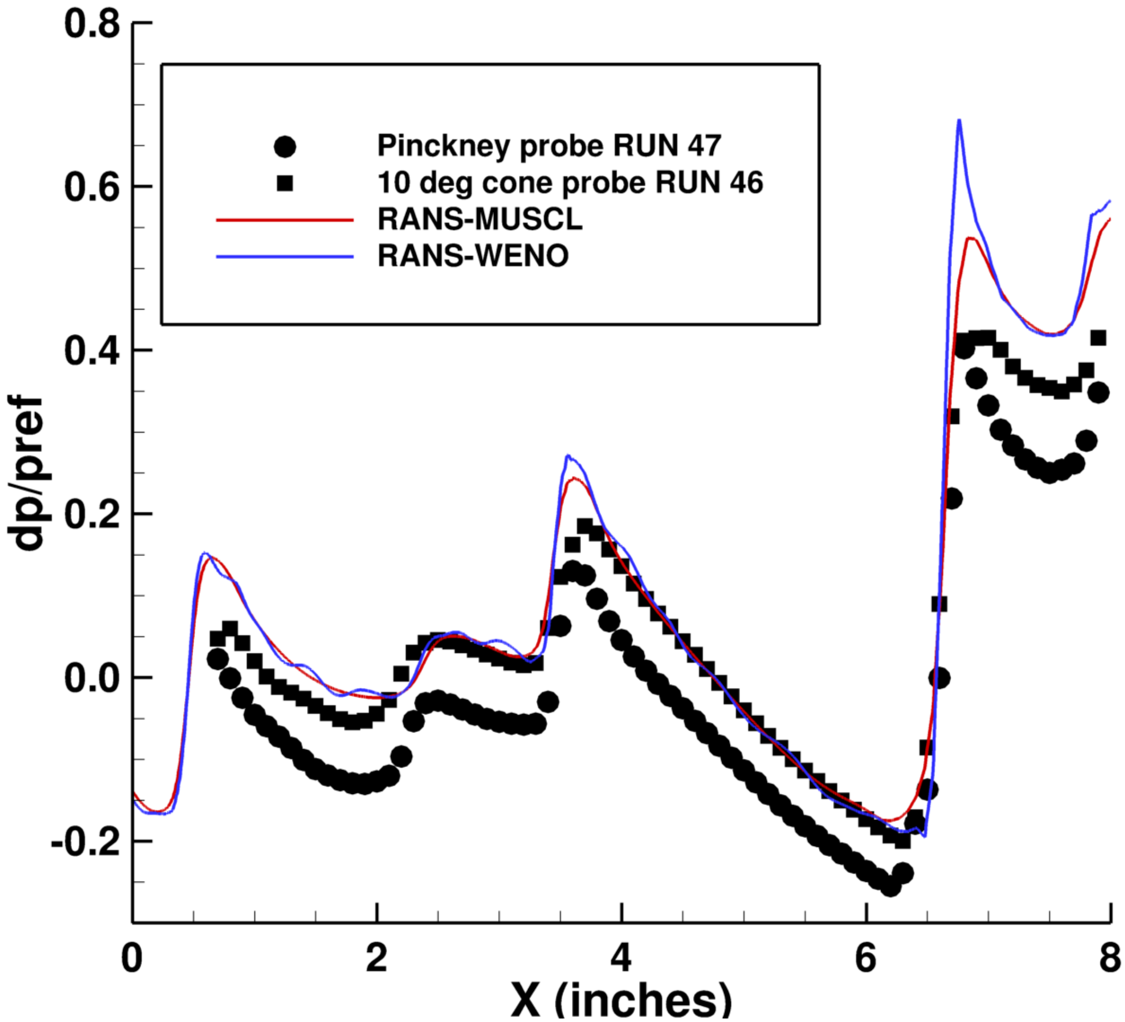


Results and Comparison

Data Comparison

NPR = 12



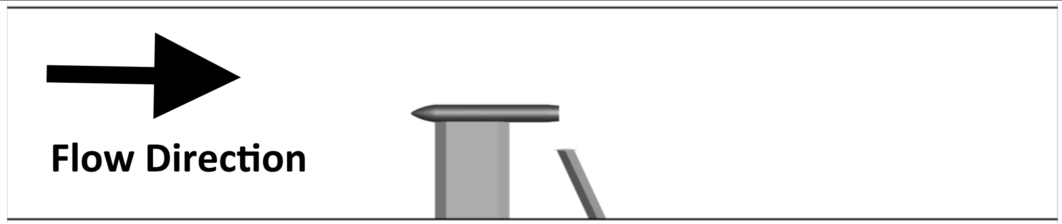


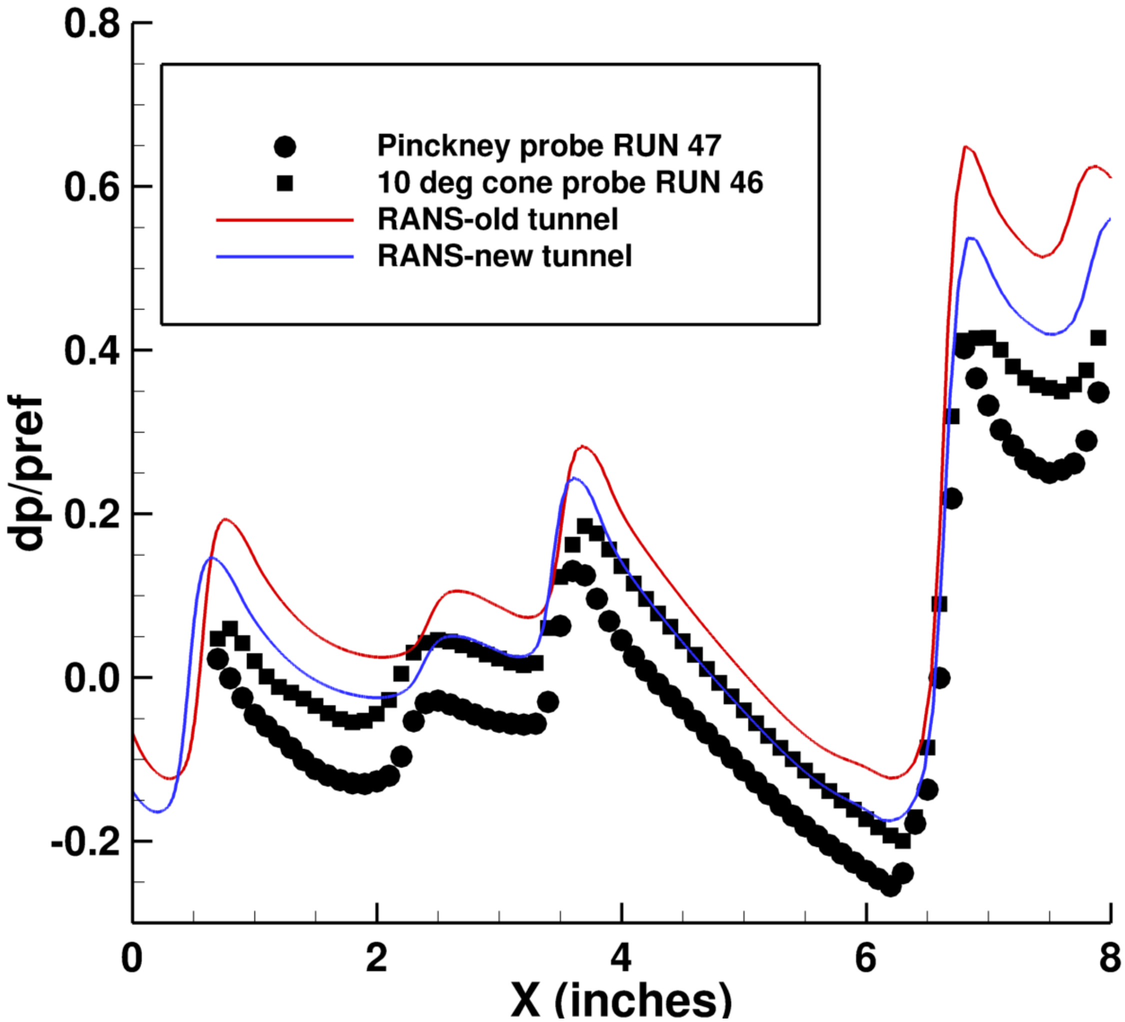
- **10 deg probe data compares very well with RANS CFD data**
- **Addition plume shear layer grid and upstream nozzle support grid improve resolution of MUSCL reconstruction solution**
- **Higher-order WENO reconstruction only provides minor improvement in pressure peaks**

Oblique Shock/Plume Interaction Test

Small Wedge in Tunnel

Data Comparison NPR = 12





- More accurate linear taper between nozzle contour section and straight test section was implemented to improve tunnel geometry representation
- CFD solution is highly sensitive to minor tunnel geometry changes
- Remaining differences between CFD and 10 deg. cone probe data may be attributed to additional differences in modeled geometry, insufficient mesh resolution, and inaccuracy in RANS model

Summary

- LAVA framework has been successfully for:
  - Sonic Boom Prediction Workshop configurations
  - 1x1 SWT with nozzle (NPR = 6 to 14) and 1.5 inch wedge
- Structured and unstructured grid methodologies yield similarly accurate solutions
- Unstructured-grid computational resources are approximately 2 – 5.5 times larger than structured-grid
- Analyses of 1x1 SWT test of Oblique shock/plume interaction shows that:
  - Inviscid analysis is not sufficient (in this WT)
  - RANS analysis matches 10 cone probe well
  - Tunnel geometry and proper meshing are essential to obtain good comparisons

Acknowledgements

- **NASA Fundamental Aeronautics Program High-Speed Project**
- **First AIAA Sonic Boom Prediction Workshop Committee**
- **NASA Advanced Supercomputing (NAS) facility at NASA Ames Research Center**
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- **GRC collaborator:**

  Ray Castner