Computational Studies for Sonic Boom Prediction

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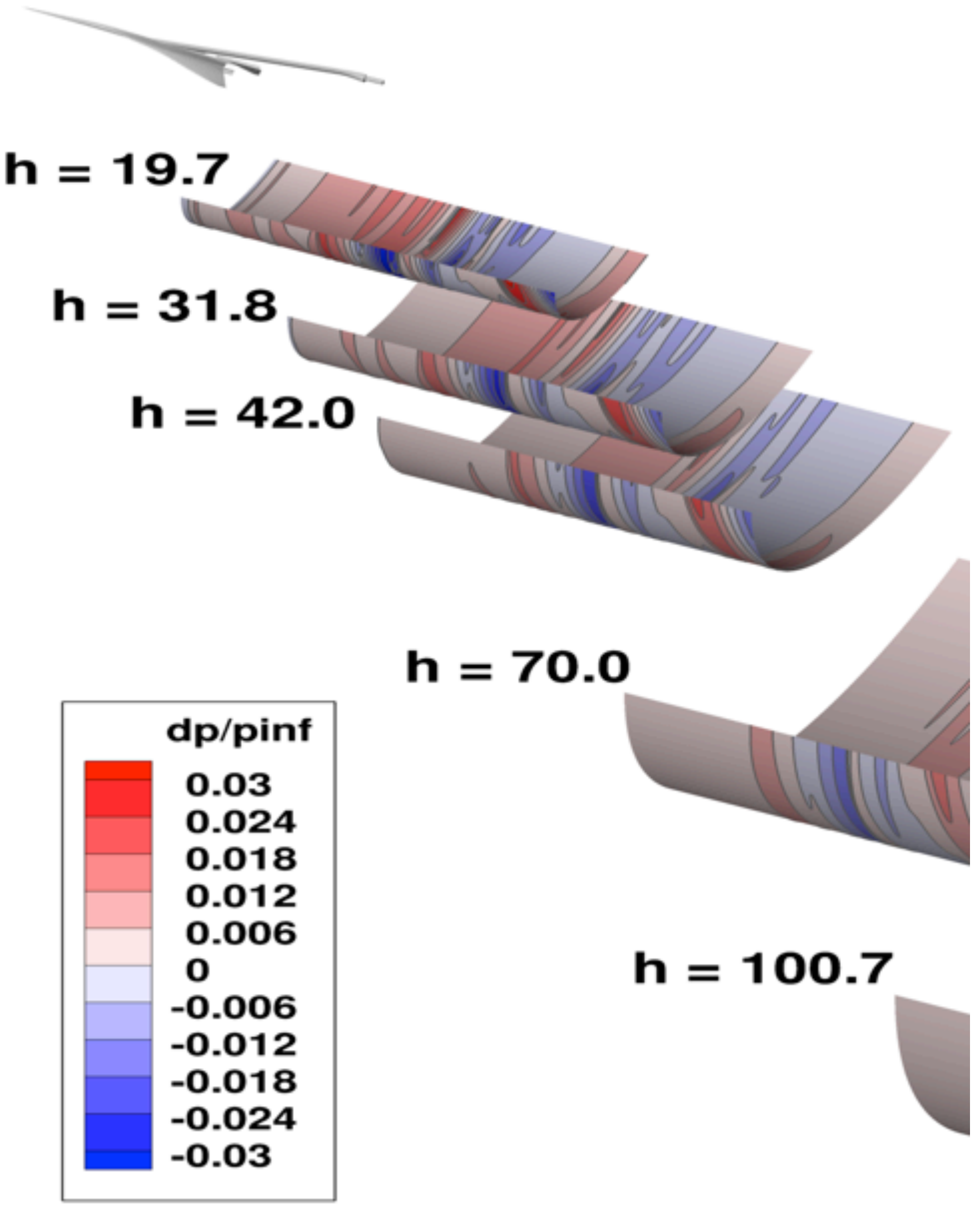
AIAA 2014-2008: J. Housman, E. Sozer, S. Moini-Yekta, and C. Kiris

Outline

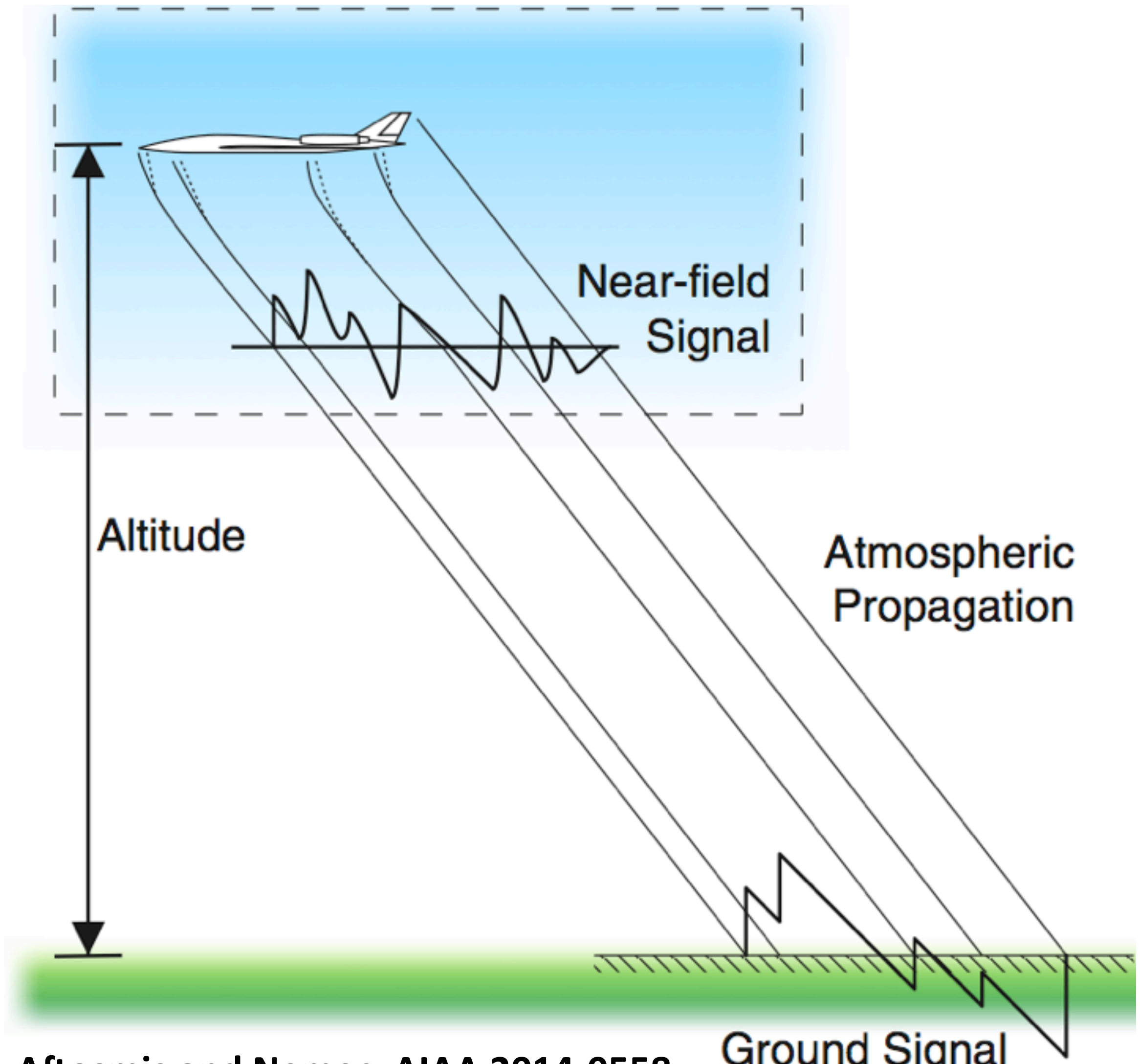


- Introduction
- Launch Ascent and Vehicle Aerodynamics (LAVA) Framework
- 1st AIAA Sonic Boom Prediction Workshop
- Oblique Shock/Plume Interaction
- Summary

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

Introduction

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**

Introduction

1st AIAA Sonic Boom Prediction Workshop

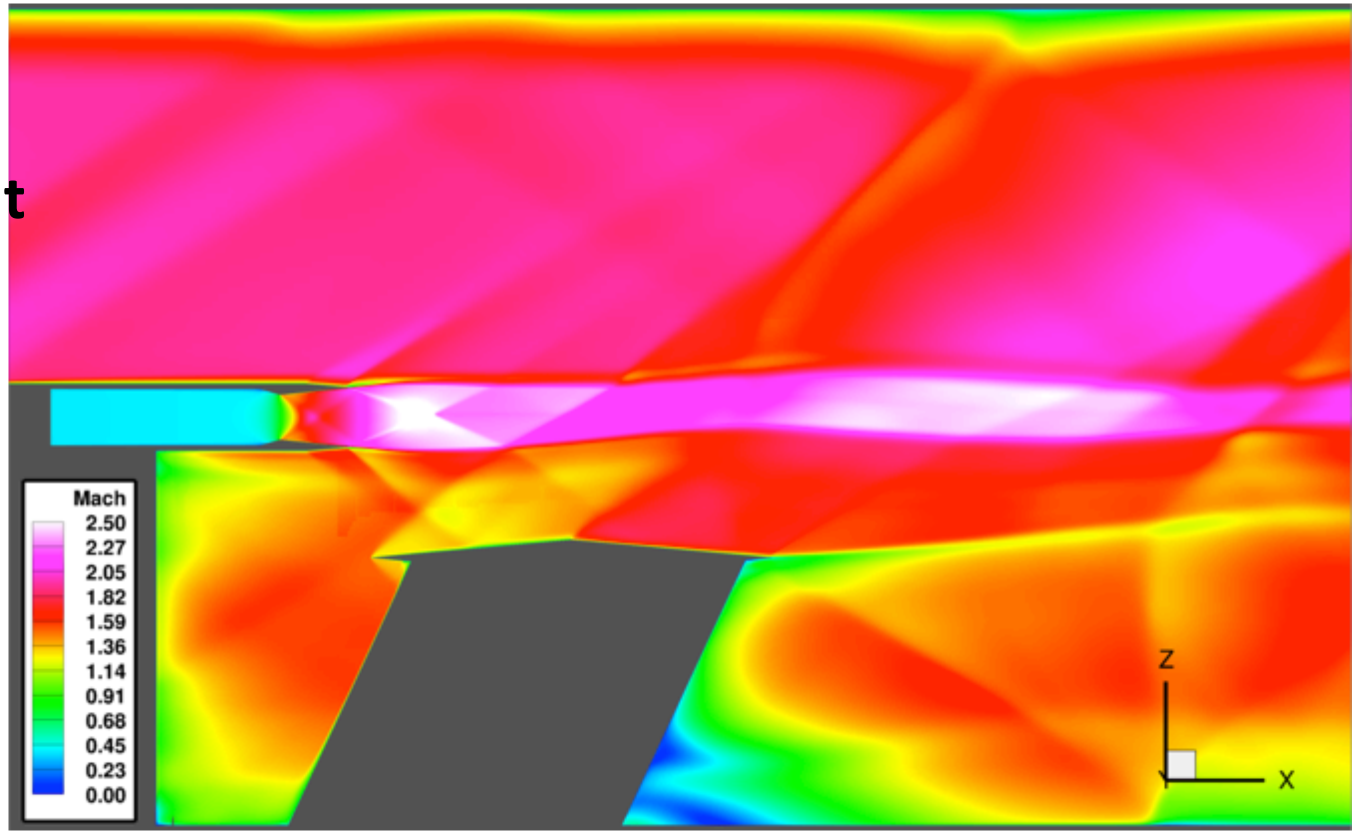
- Workshop is designed to assess the state-of-the-art in CFD simulation capabilities for sonic boom prediction
- Three models of increasing geometric complexity are included in the study
  - SEEB-ALR
  - 69 Degree Delta-Wing Body
  - Lockheed Martin 1021 model
- LAVA results using structured and unstructured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

Lockheed Martin 1021 model

Introduction

Oblique Shock/Plume Interaction Wind Tunnel Test

- Shock waves generated by tail surfaces or engine installation geometry may travel through the exhaust jet and and change 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 test are being used in a validation effort for CFD



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

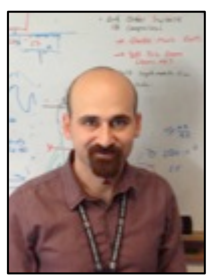
Meshing	Convective Flux Discretization	Turbulence Model	Linear Solvers
Structured Overset	Modified Roe and Central	Spalart-Allmaras	Alt. Line Jacobi
Unstructured Polyhedral	AUSMPW+	Spalart-Allmaras	GMRES

Development Team

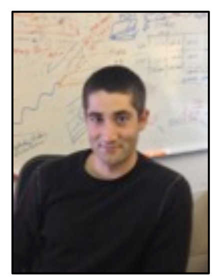

Cetin Kiris


Jeffrey Housman


Michael Barad


Emre Sozer


Christoph Brehm


Shayan Moini-Yekta

*Kiris et. al. AIAA-2014-0070

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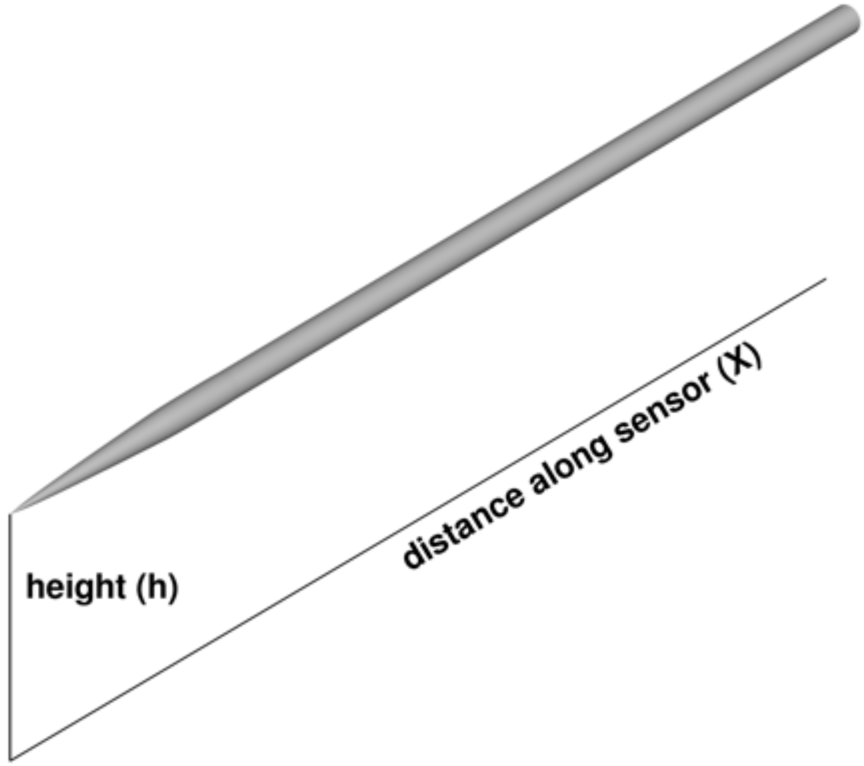
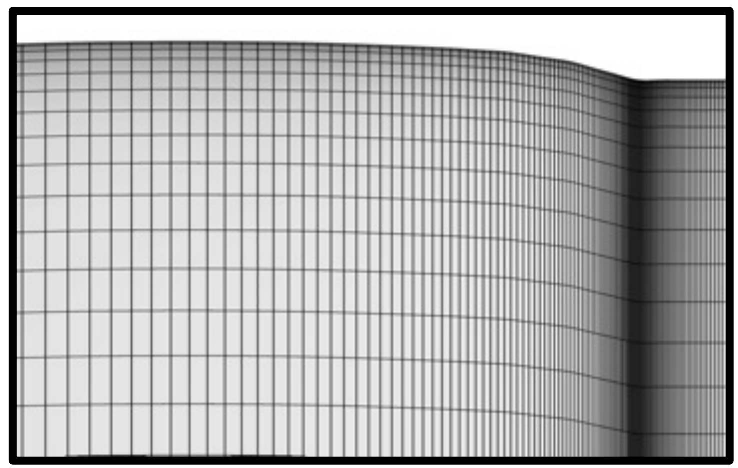
Seeb-ALR

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

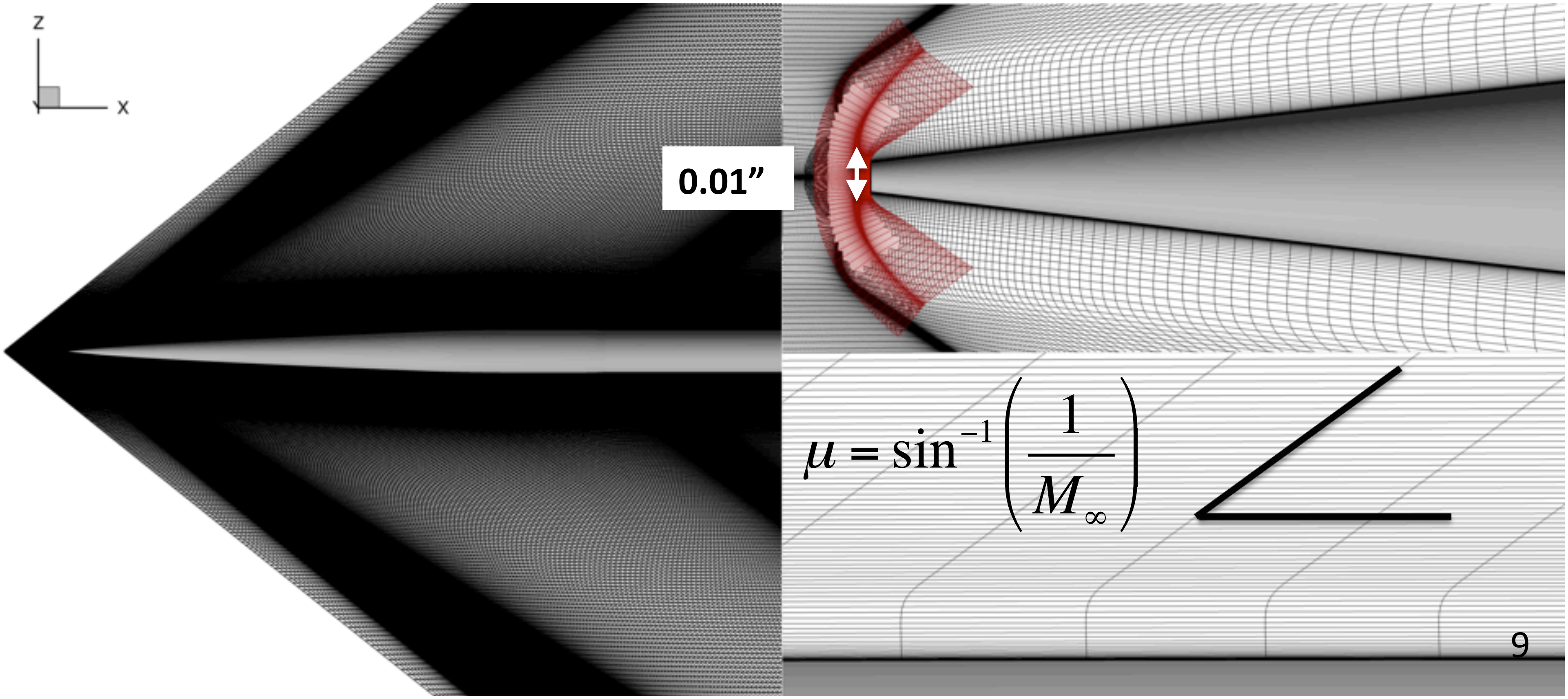


Scaled
10:1 in r

Seeb-ALR

Computational Grid

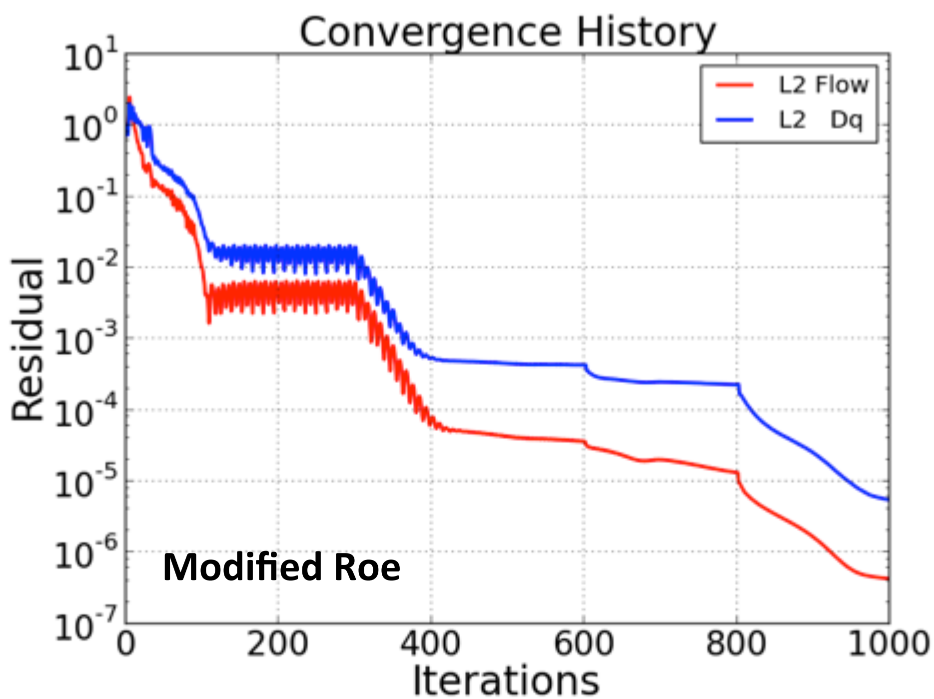
- 4 zones and 21.7 million grid points
- Near-body marched normal to surface then turned to Mach-angle aligned mesh
- Local bow shock capturing grid at near blunt nose

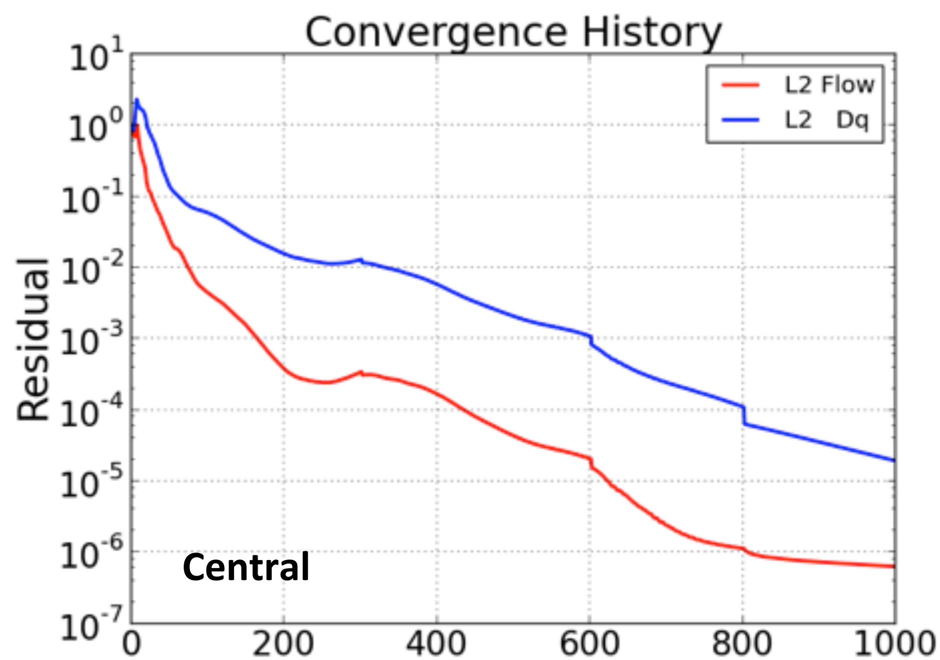


Seeb-ALR

Computational Requirements and Residual Convergence

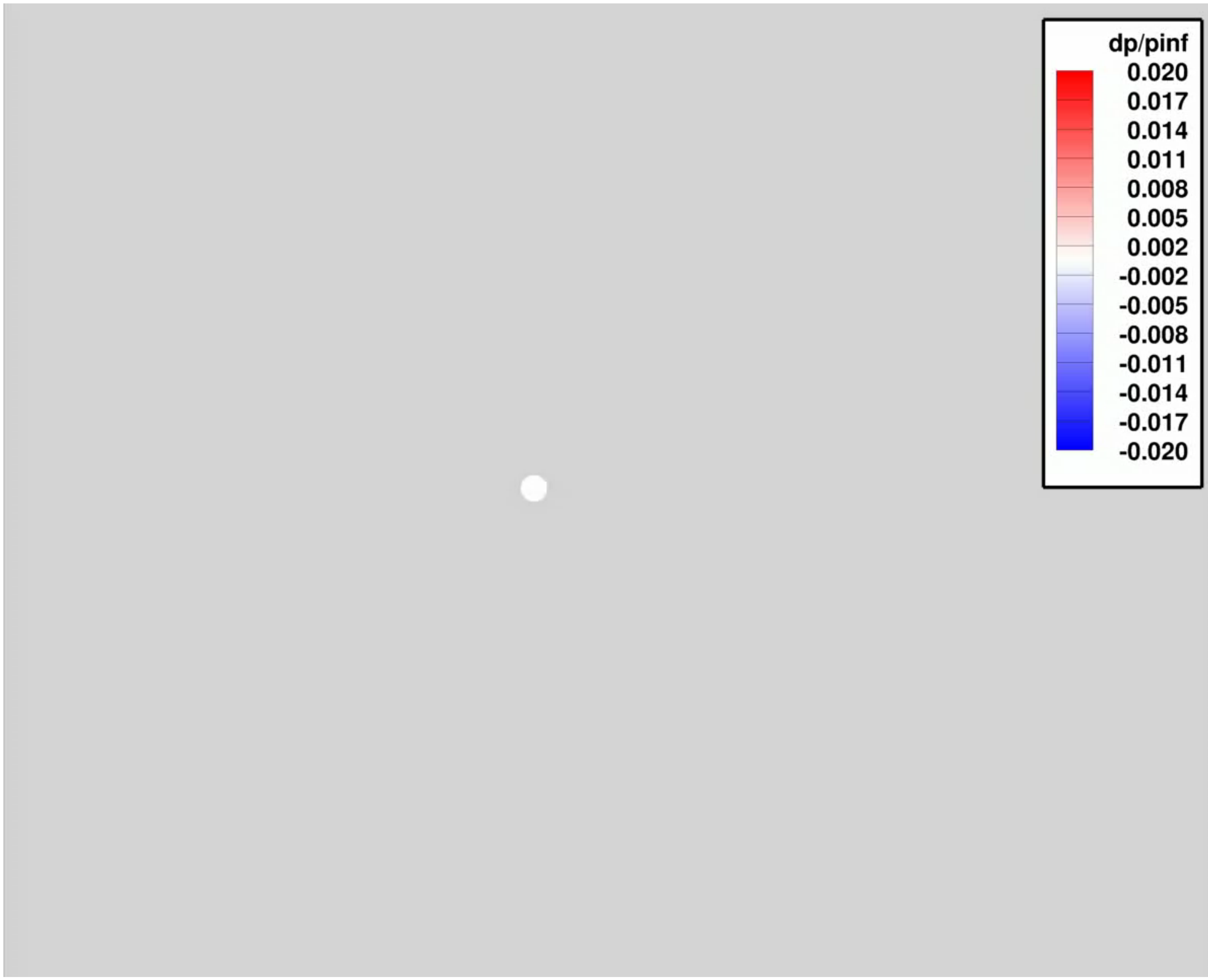
Flux	CPU Type	Cores	Walltime	Total Core Hours
Modified Roe	Westmere	48	1 hr. 30 min.	72.0
Central	Westmere	48	1 hr. 18 min.	62.4





Seeb-ALR

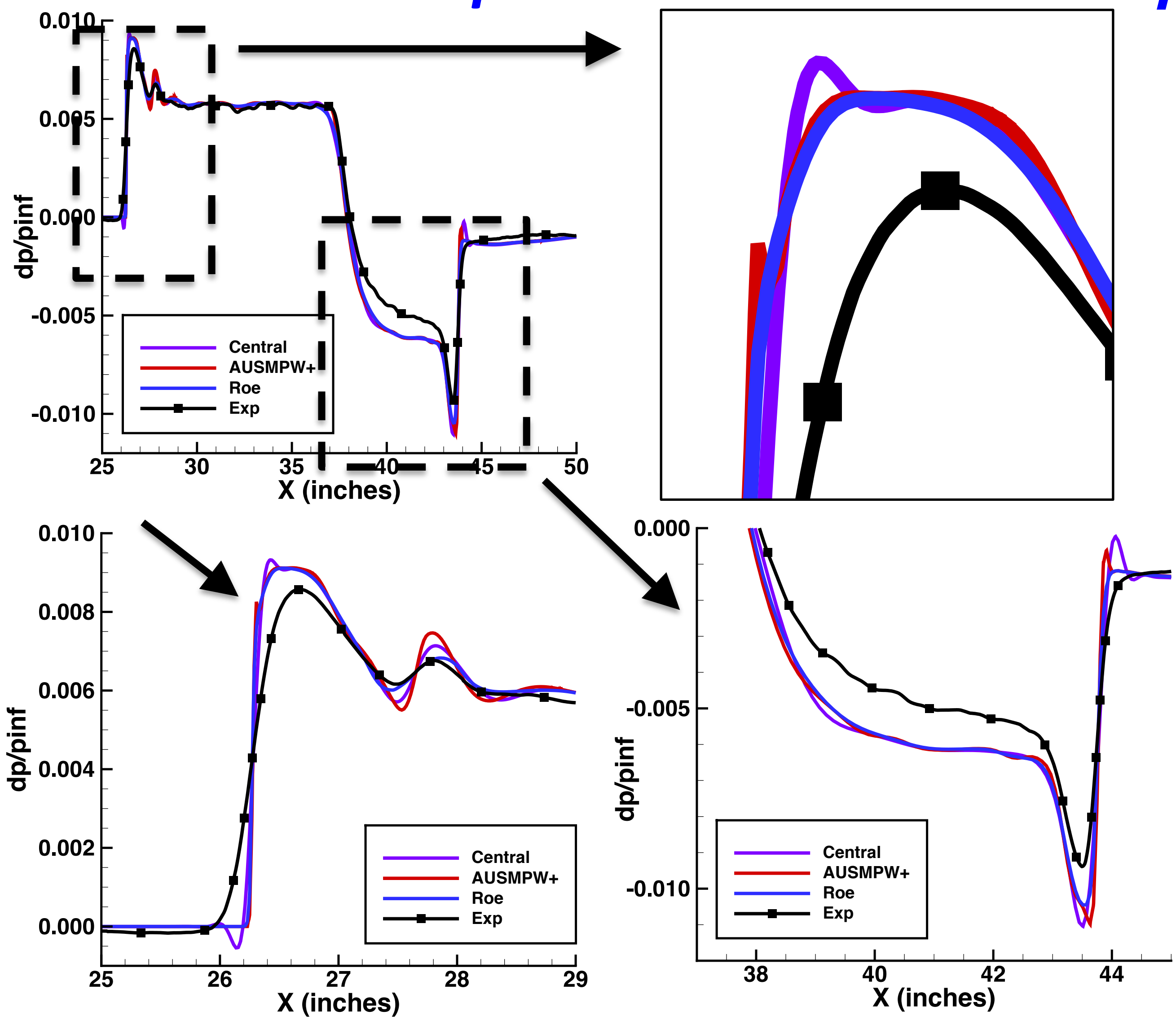
Flow Field Visualization



- **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**

Seeb-ALR

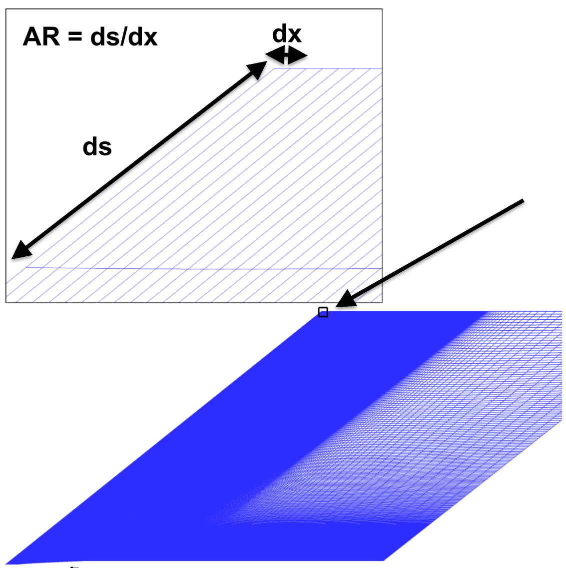
Results and Comparison: h = 21.2 inches ϕ = 0 degrees

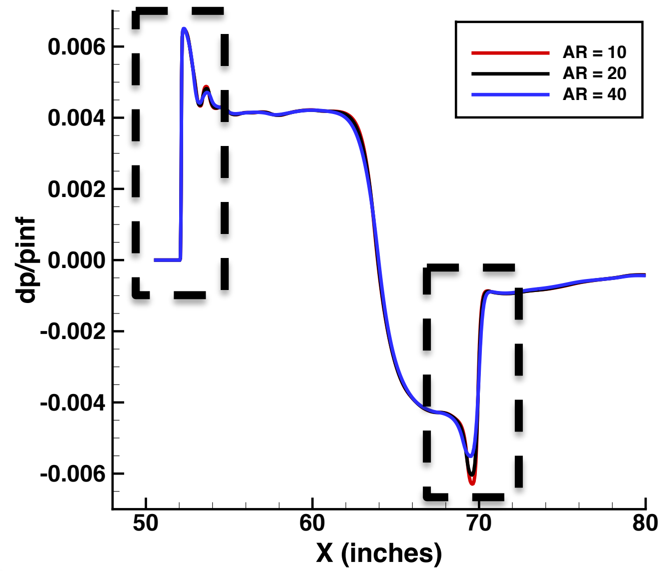


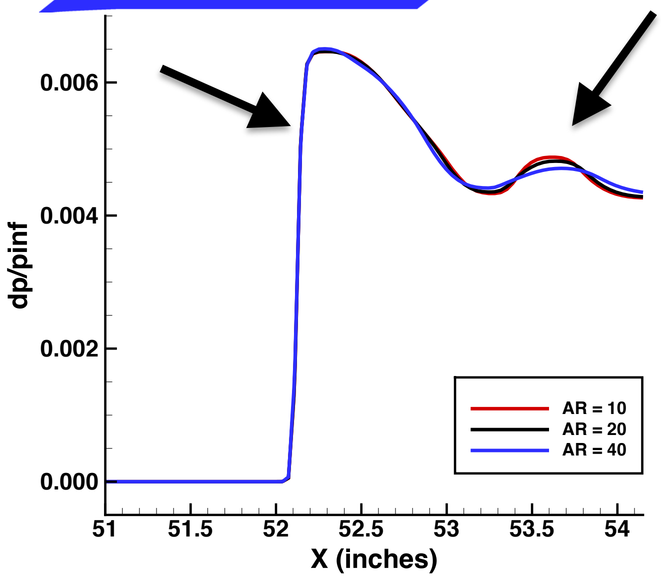
- Good comparison observed over most of the signal
- Bow shock and secondary shock well-captured by CFD
- Experimental result shows a smoother primary shock
- Oscillations observed using Central and AUSMPW+ on bow shock
- CFD over-predicts the pressure decrease across the expansion

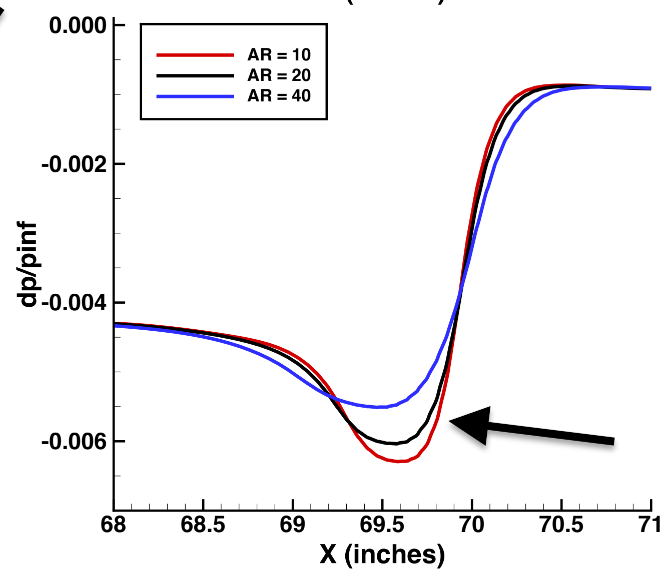
Seeb-ALR

Aspect Ratio Sensitivity Analysis: h = 42 inches $\phi = 0^o$







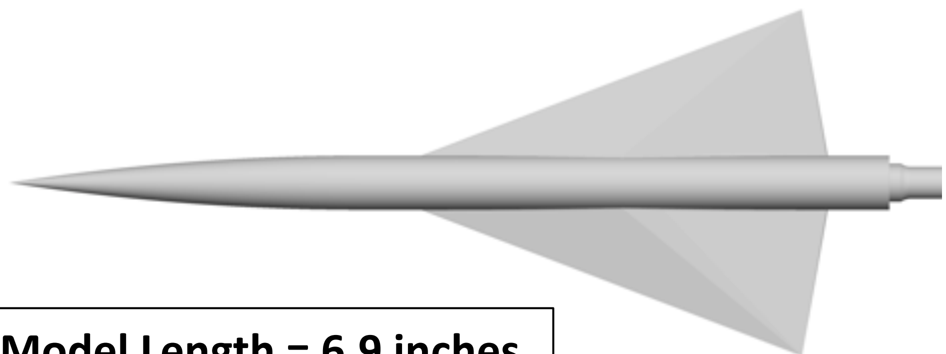


- Sensitivity to grid Aspect Ratio (AR) at the outer-boundary
- No sensitivity observed in bow shock
- Secondary peak and pre-recovery peak pressures show some sensitivity to AR
- Change in peak decreases with decreasing AR
- AR = 20 submitted to the workshop

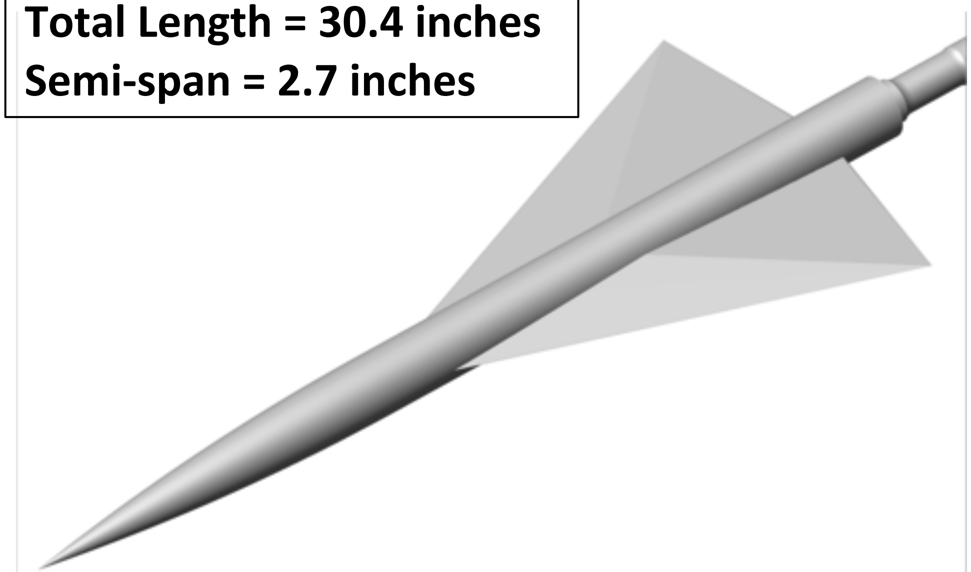
69 Degree Delta Wing Body

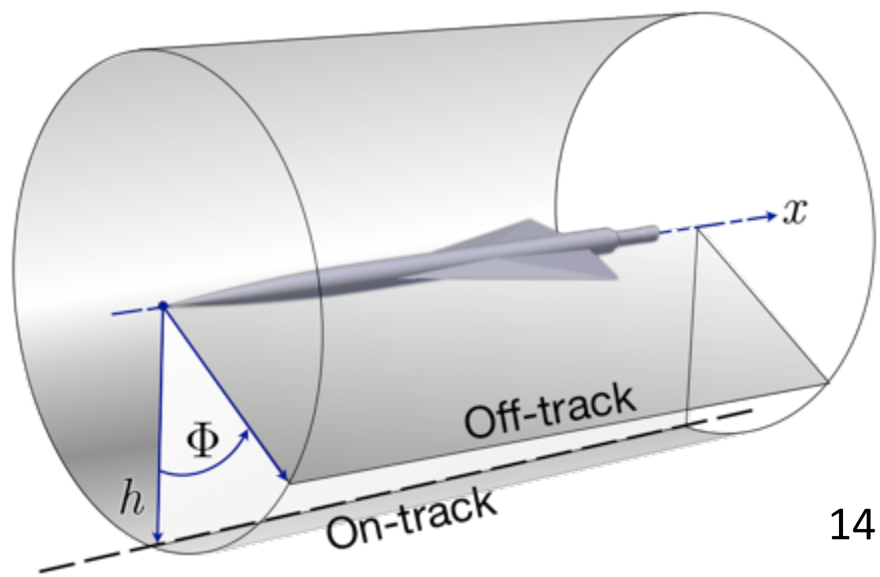
Geometric Model

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



Model Length = 6.9 inches
Total Length = 30.4 inches
Semi-span = 2.7 inches

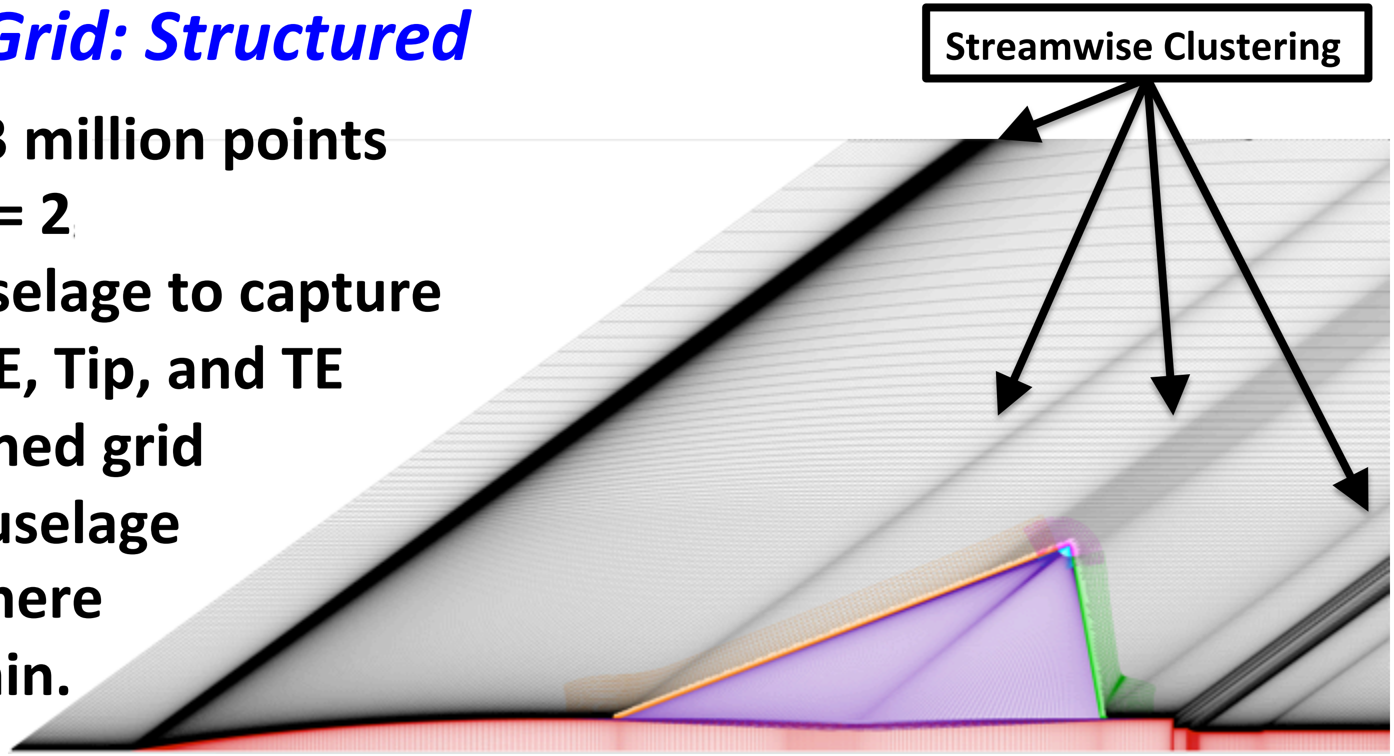


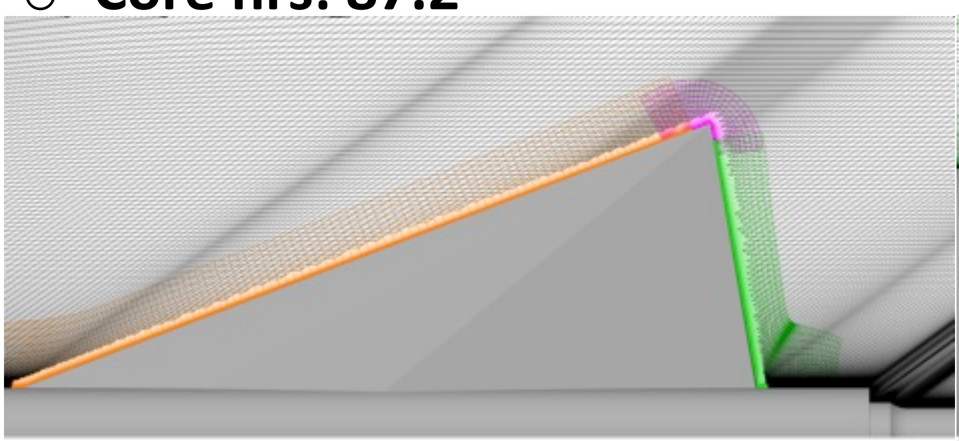


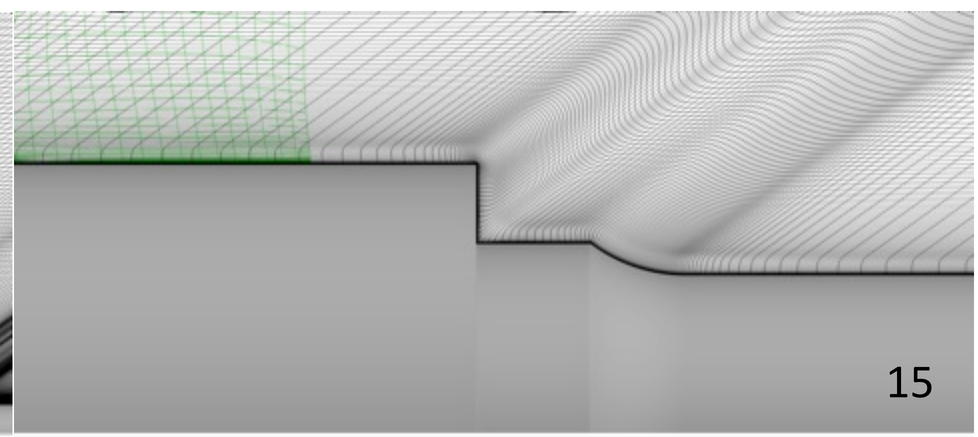
69 Degree Delta Wing Body

Computational Grid: Structured

- 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



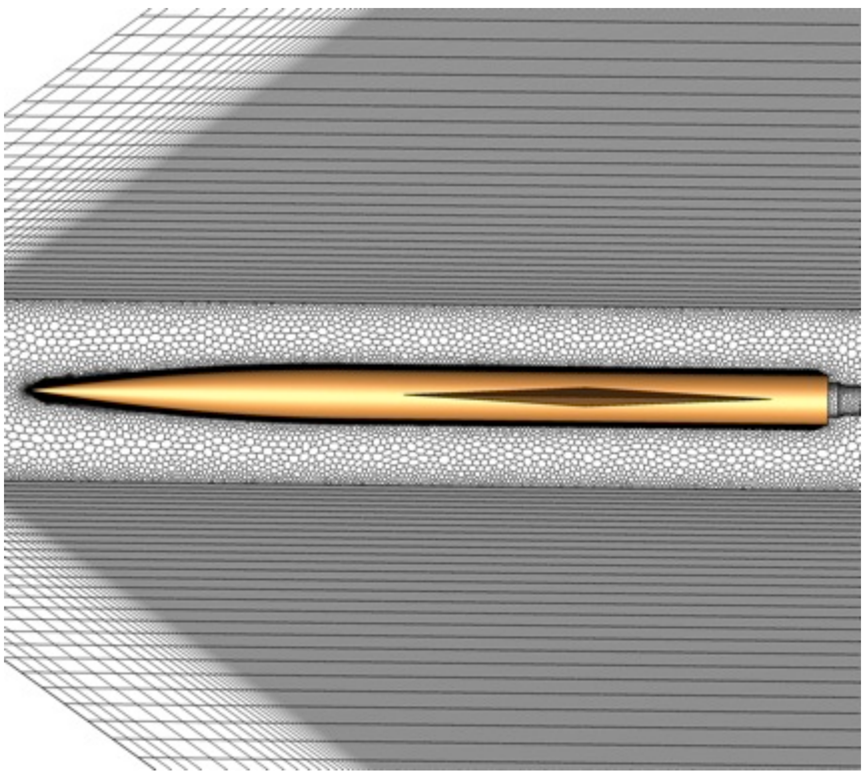


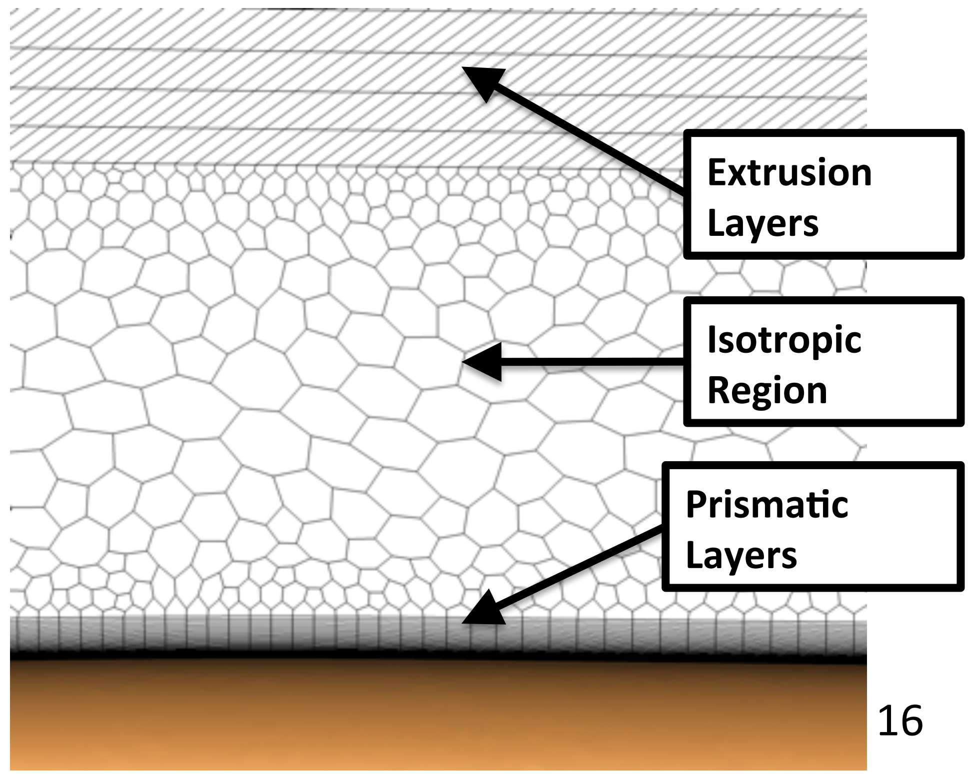


69 Degree Delta Wing Body

Computational Grid: Unstructured

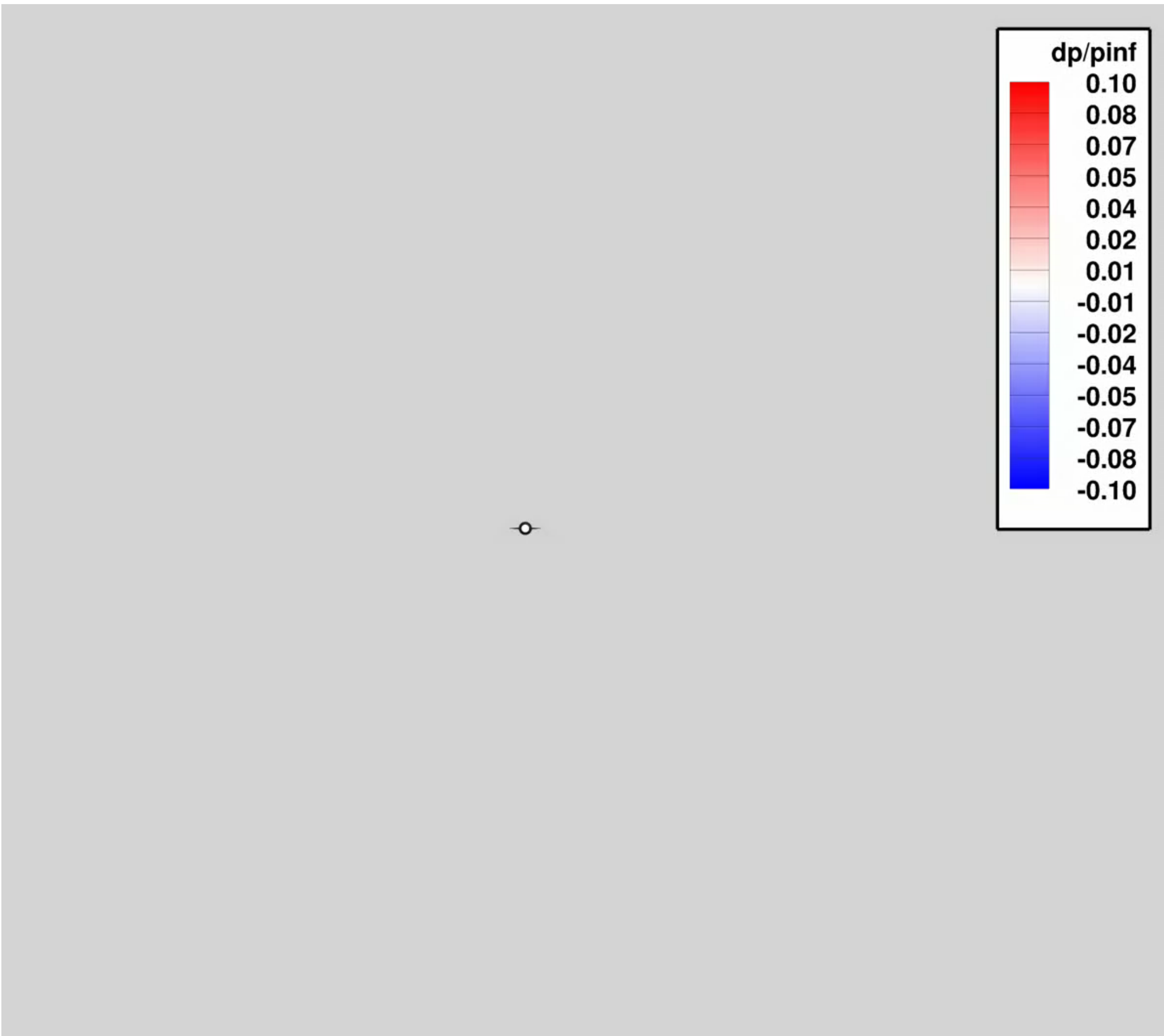
- 12.1 million polyhedral cells
- Anisotropic prismatic layers grown from surface
- Core mesh utilizes nearly isotropic polyhedral cells
- Mach-angle aligned mesh extruded from outer core boundary
- Cores: 320 Sandy Bridge; Walltime: 25 min.; CPU hrs: 133.3





69 Degree Delta Wing Body

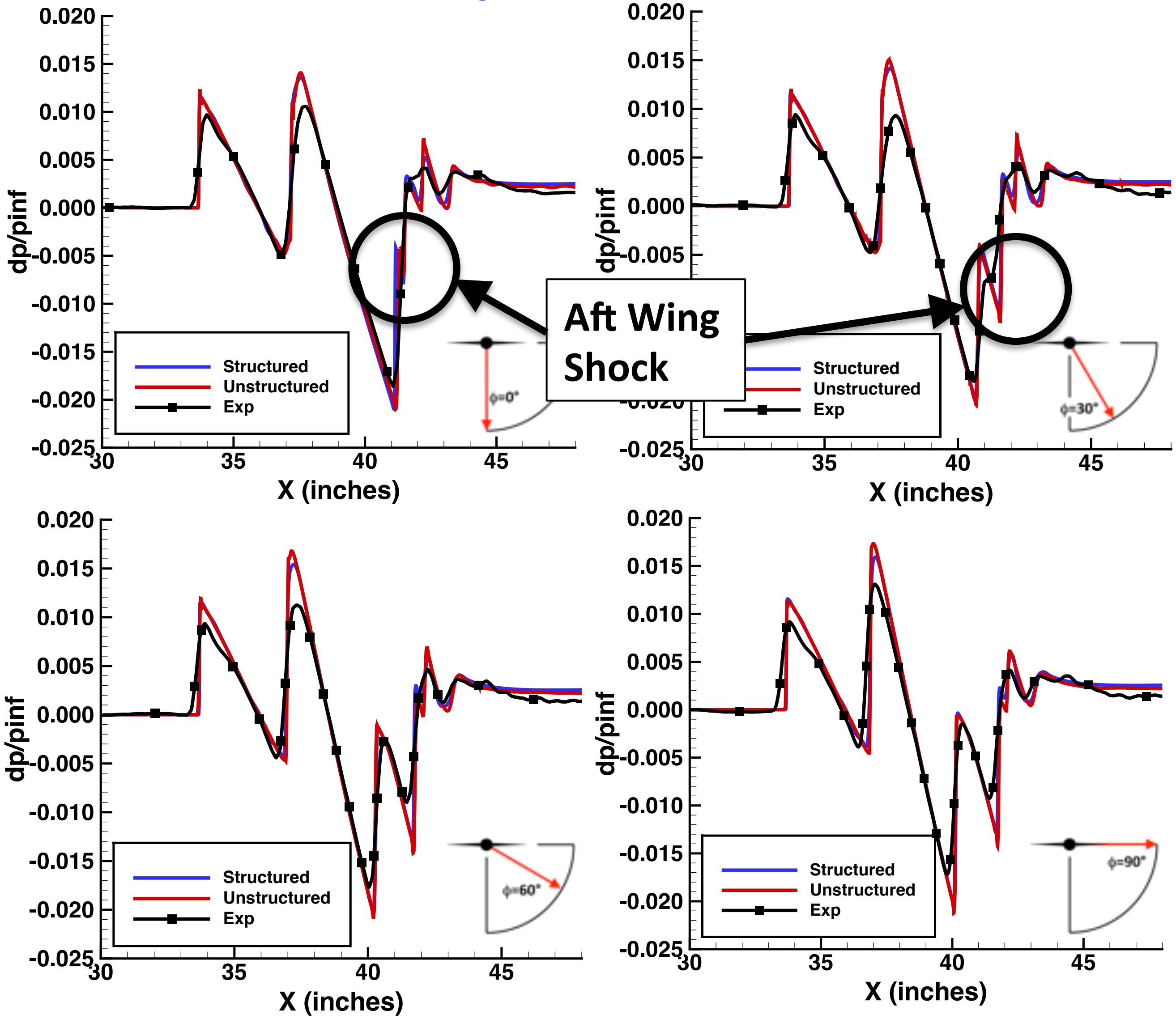
Flow Field Visualization



- 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)

69 Degree Delta Wing Body

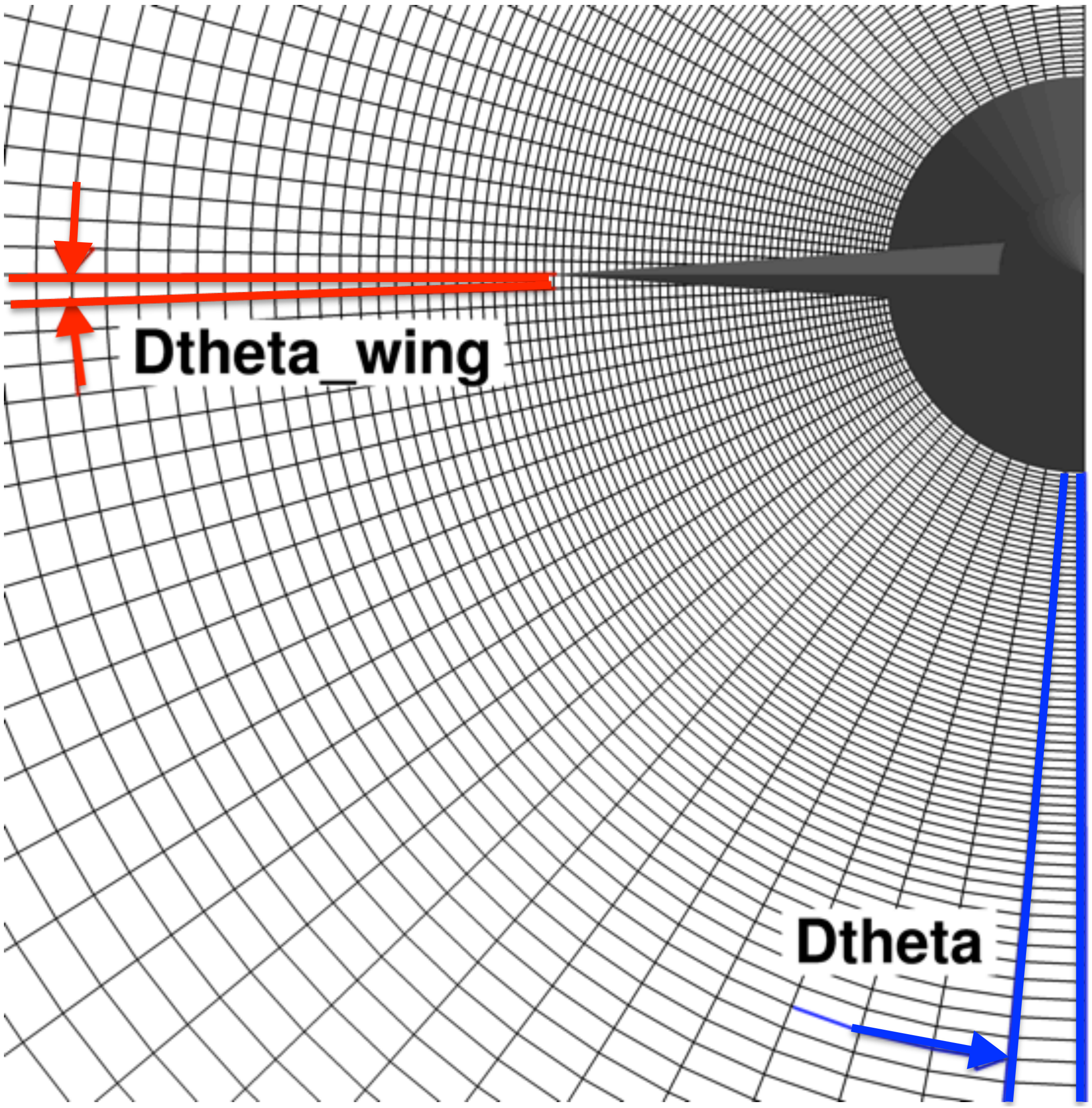
Results and Comparison: h = 24.8 inches

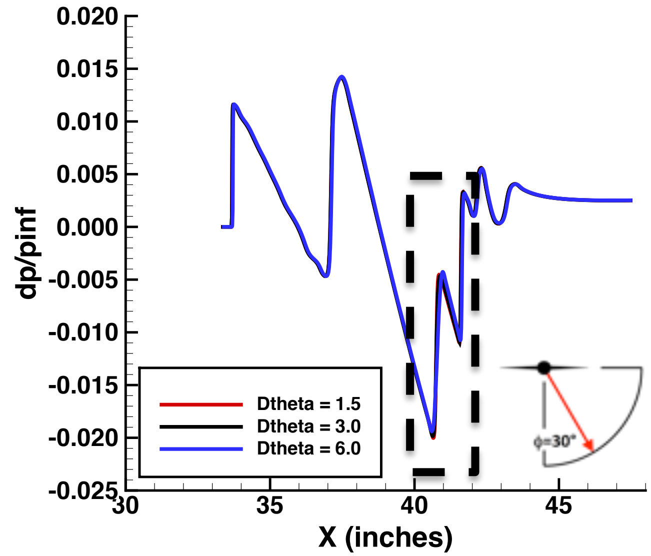


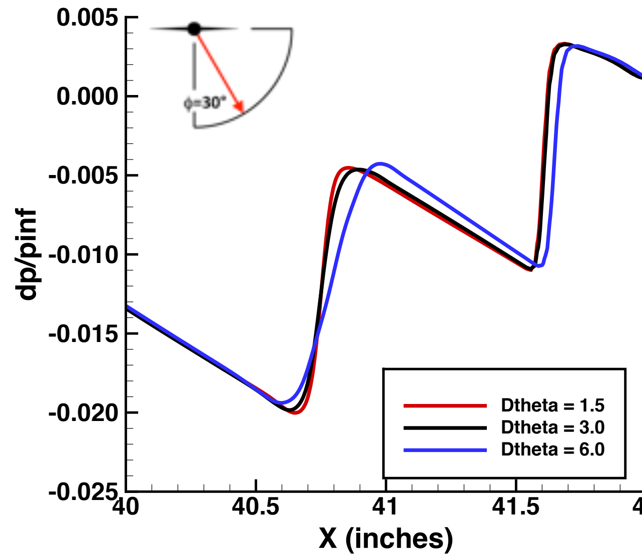
- Pressure peaks are more smooth in Experimental data
- Slope of rarefaction waves match very well
- Stronger aft wing shock predicted by CFD than Experiment at lower Φ angles

69 Degree Delta Wing Body

Circumferential Spacing Sensitivity Analysis: h = 24.8 inches



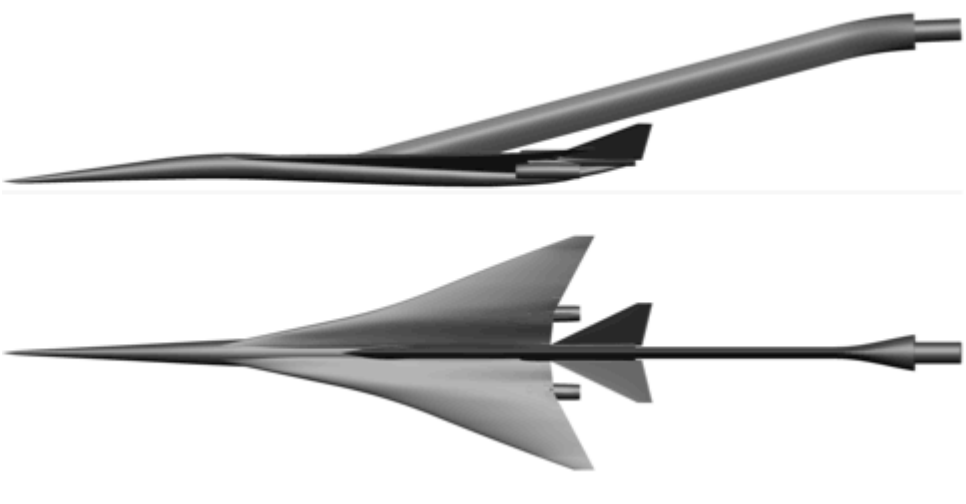




Lockheed Martin 1021

Geometric Model

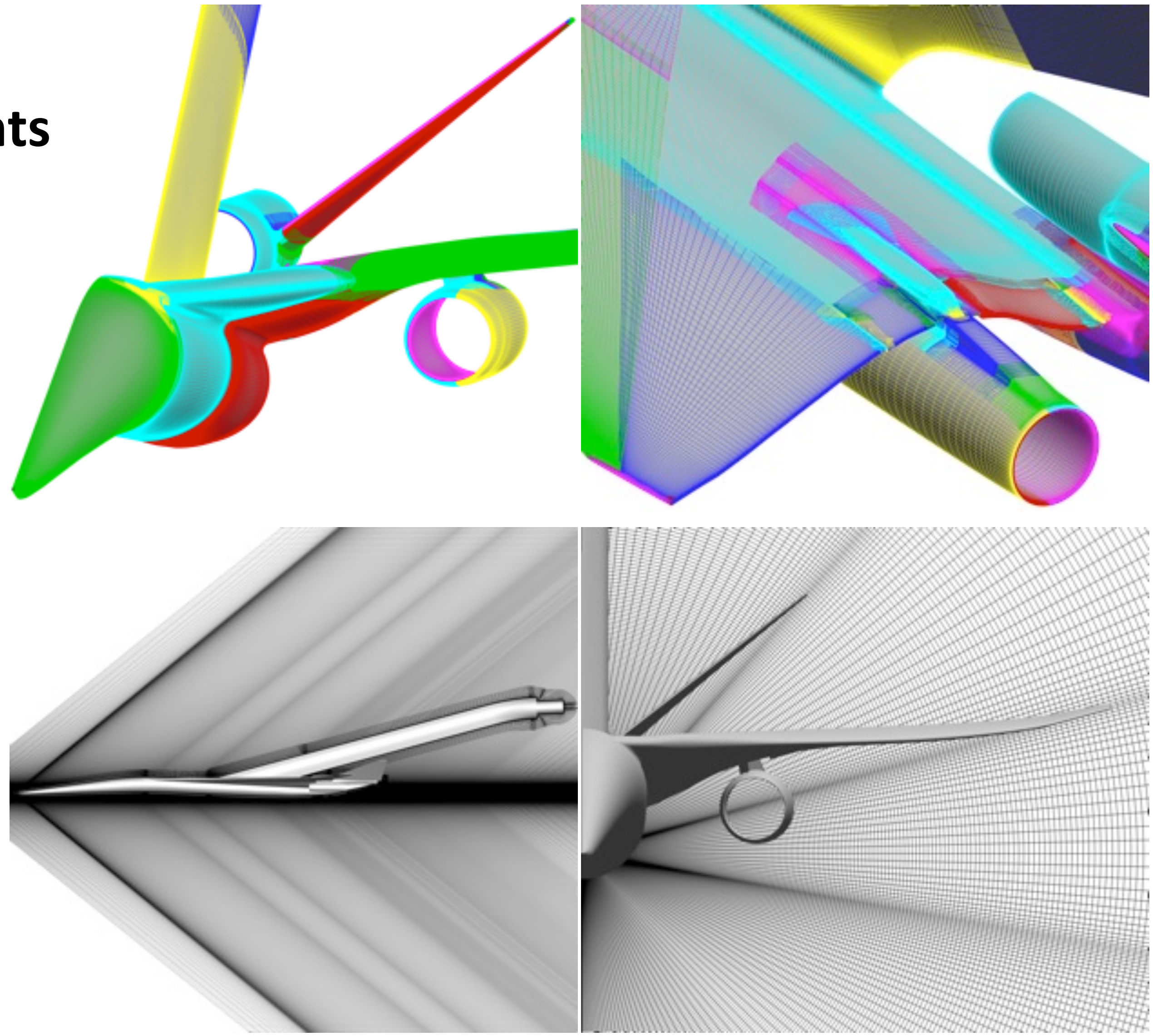
- Lockheed Martin Phase I low sonic boom model
- Mach = 1.6, Reynolds number 4.36 M (per ft.), $\alpha = 2.1^{o}$
- Designed for low boom on-track and reduced pressure up to 20^{o}
- Model length 22.4 inches representing 0.8 % scale (1:125)
- Swept blade strut designed to minimize interference
- Trip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



Lockheed Martin 1021

Computational Grid: Structured

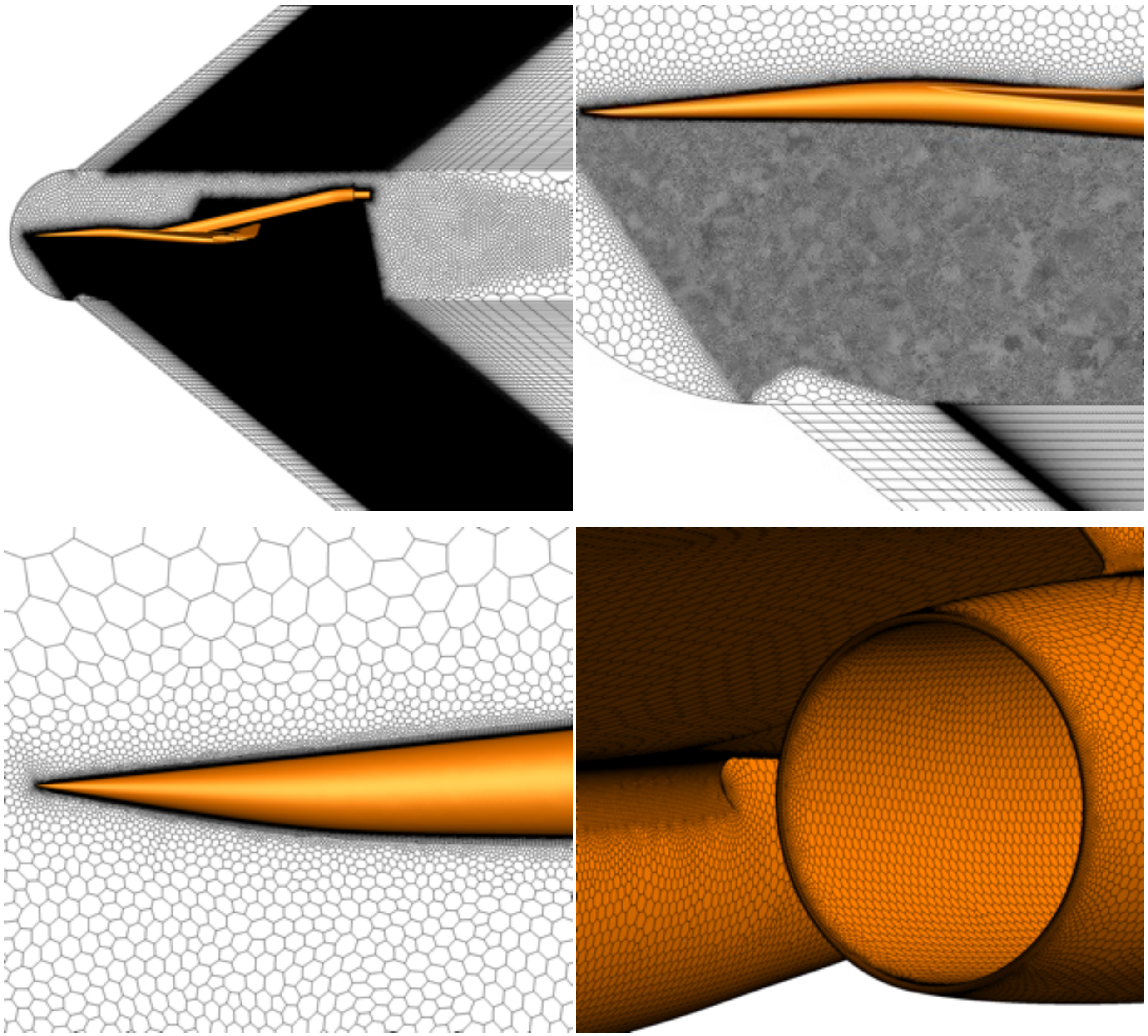
- 97 zones
- 72.7 million grid points
- Wall y+ = 1.2
- Mach-angle aligned grid detached from fuselage
- Clustering in streamwise and circumferential directions
- Cores: 180 Ivy Bridge
- Walltime: 90 min.
- Core hours: 270



Lockheed Martin 1021

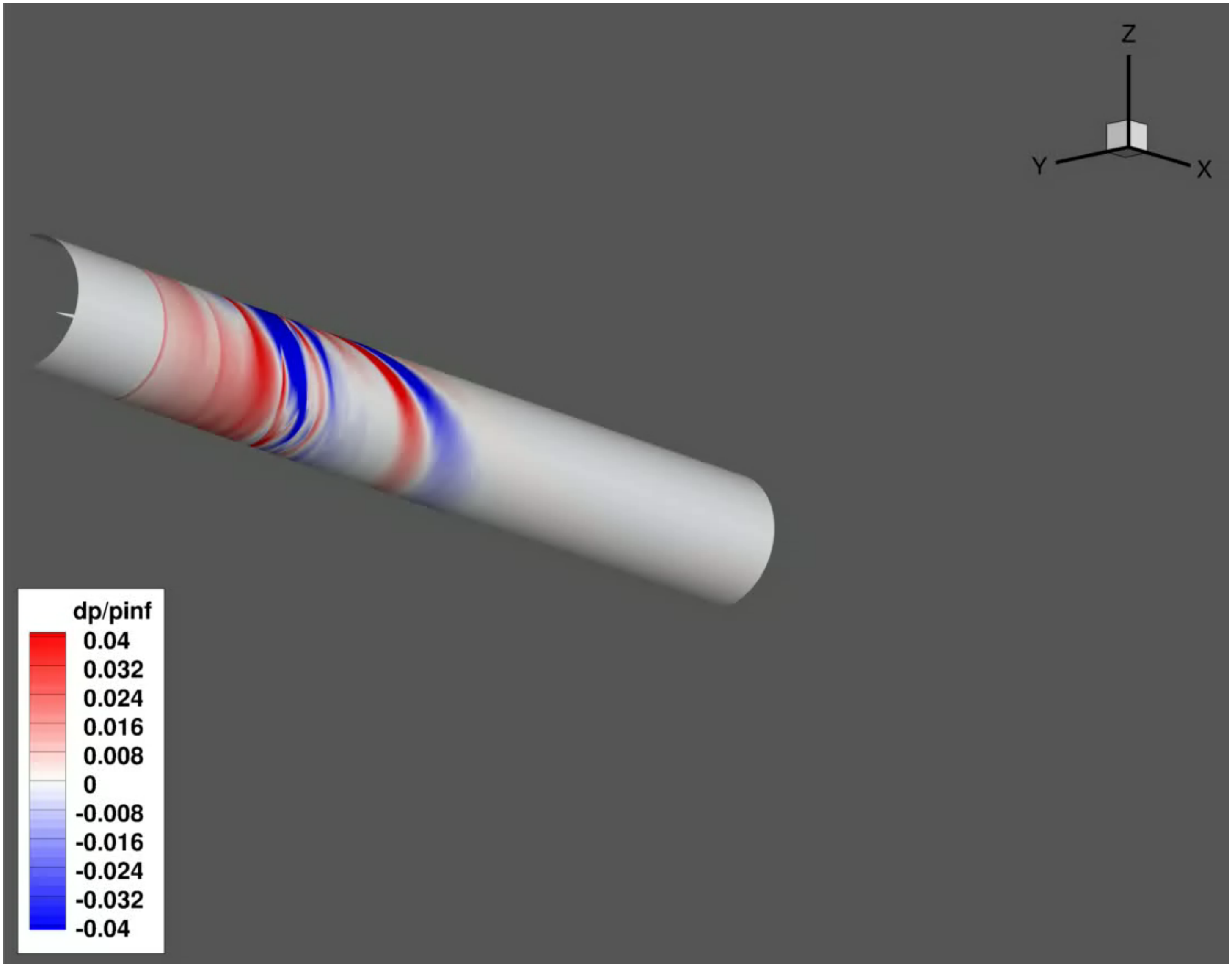
Computational Grid: Unstructured

- 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



Lockheed Martin 1021

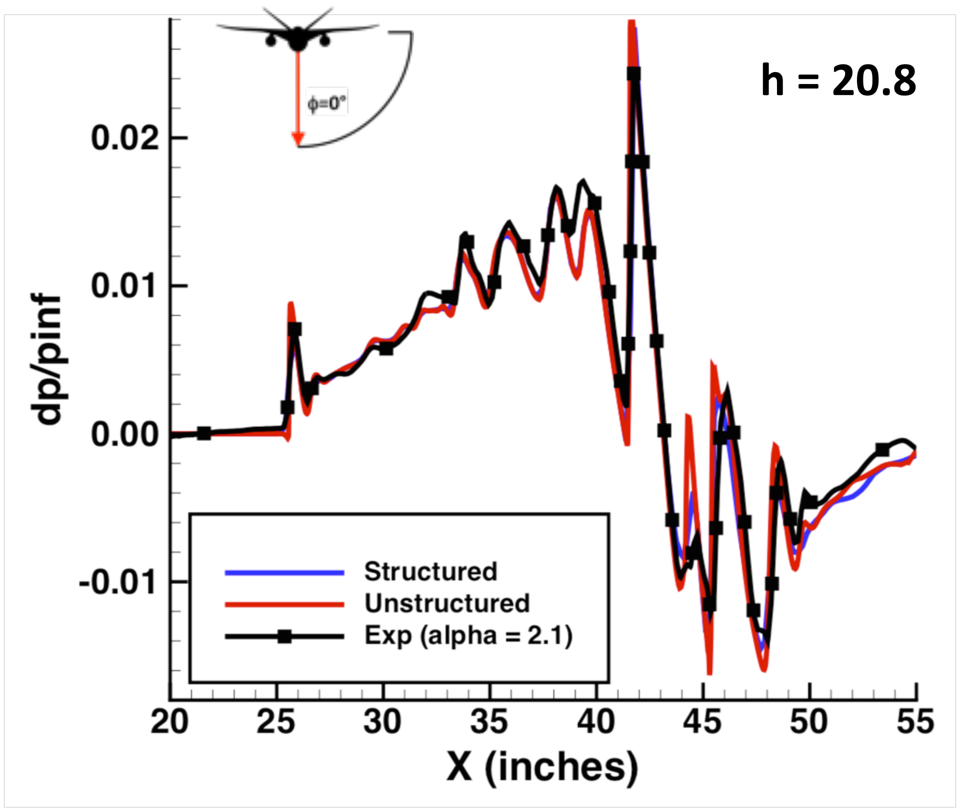
Flow Field Visualization

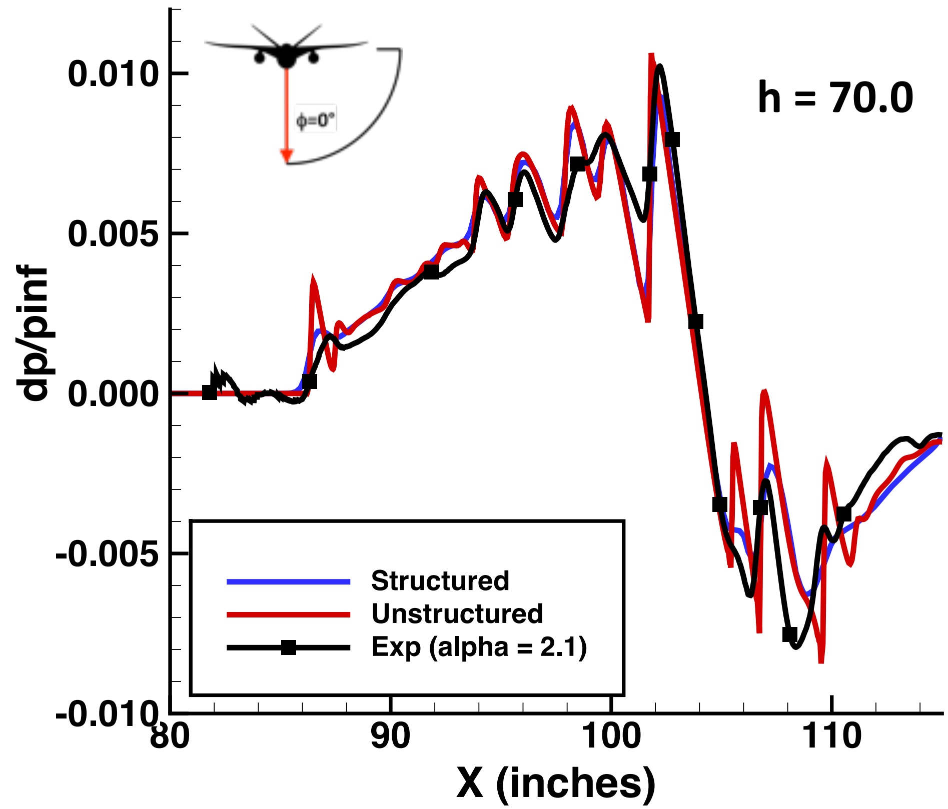


- **Complex wave pattern generated by the model**
- **Magnitude of peaks decay radially**
- **Shape of vehicle is designed to help reduce the on-track sonic boom**

Lockheed Martin 1021

Results and Comparison: On-Track

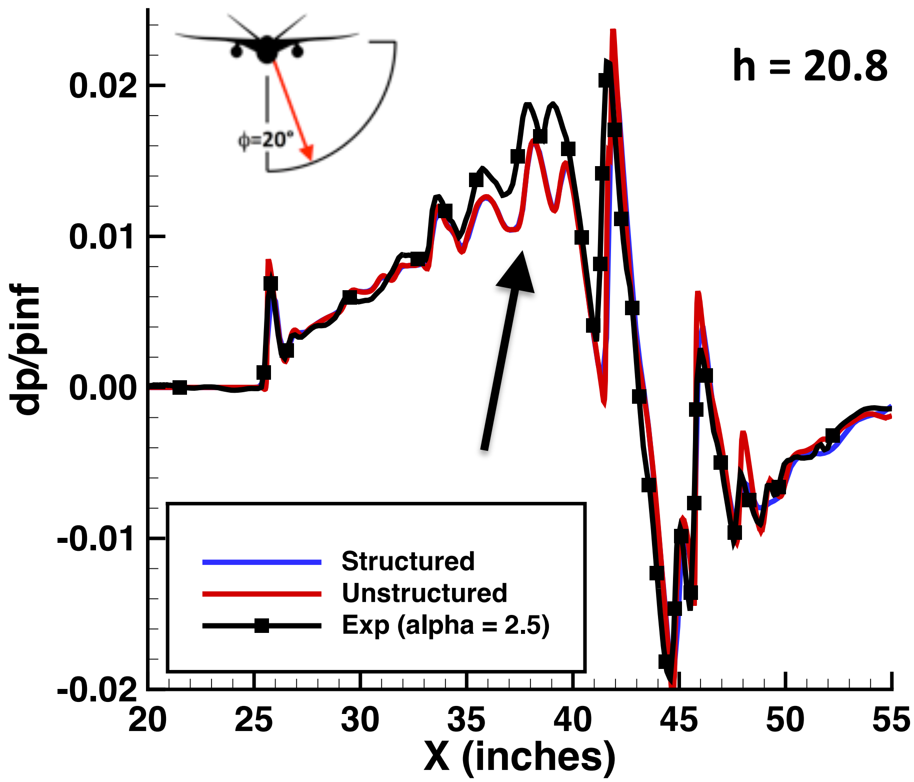


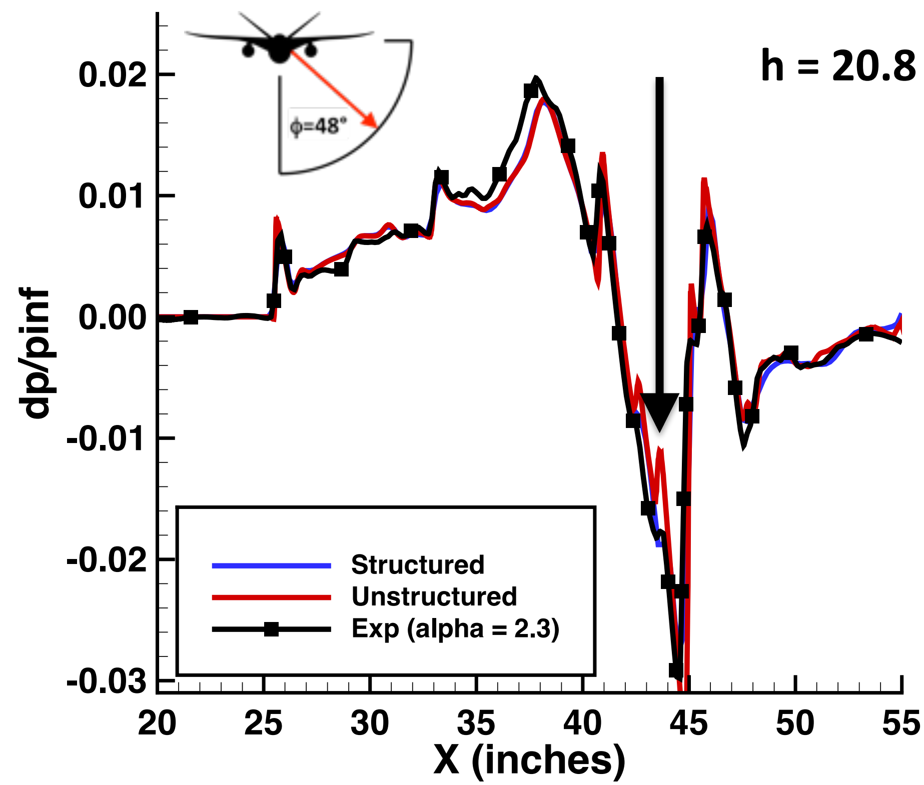


- At h = 20.8 the structured and unstructured solutions match well until X = 43.5
- At h = 70 stronger peaks are observed in the unstructured results (AUSMPW+)
- Both approaches match the experimental data well

Lockheed Martin 1021

Results and Comparison: Off-Track

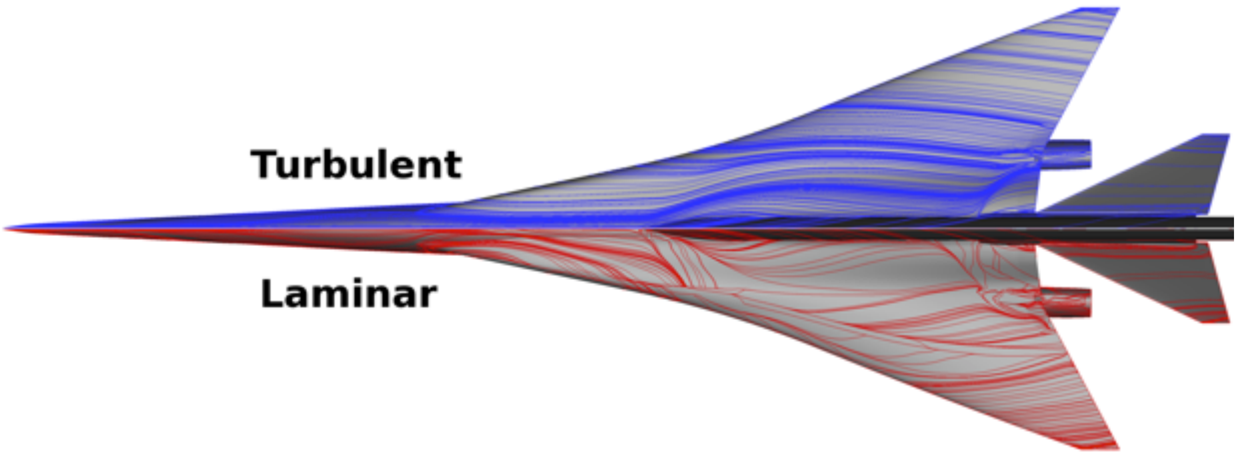




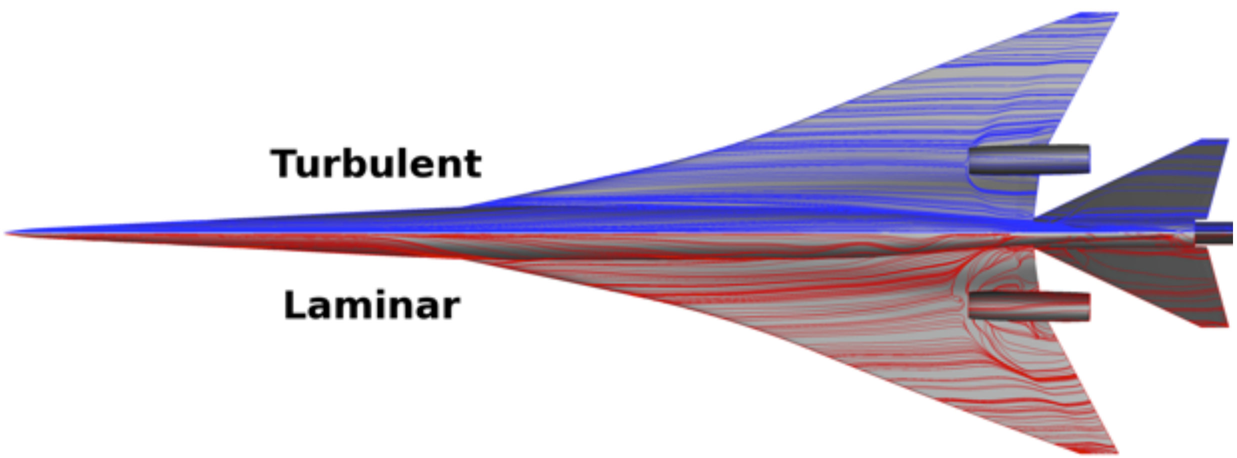
- CFD was solved at α=2.1° while experimental data was only available at near-by α
- At ϕ=20° structured and unstructured solutions match well, discrepancy with experiment from 35 < X < 40 are due to differences in α
- Sharper peaks are generated using the unstructured grid at ϕ=48°

Lockheed Martin 1021

Viscous Sensitivity Analysis



Top Surface



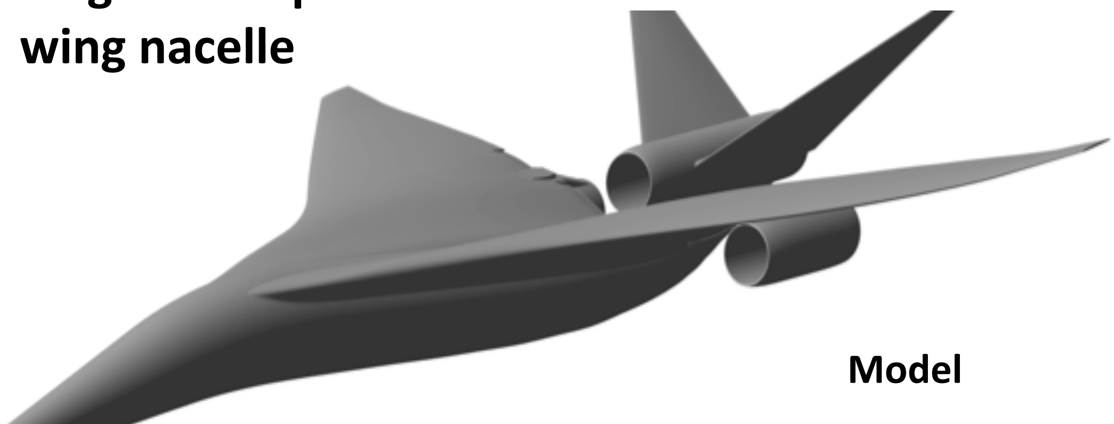
Bottom Surface

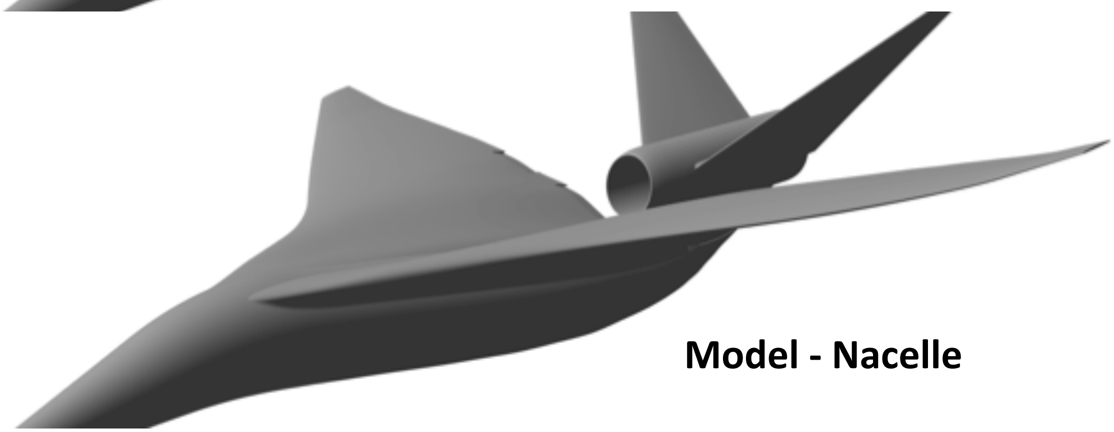
- **Larger differences observed in surface oil flow**
- **Shock wave generated by the blade causes laminar flow separation near the leading edge of the top wing surface**
- **Strength of separation generated from under-wing nacelle is larger using Laminar flow assumption**

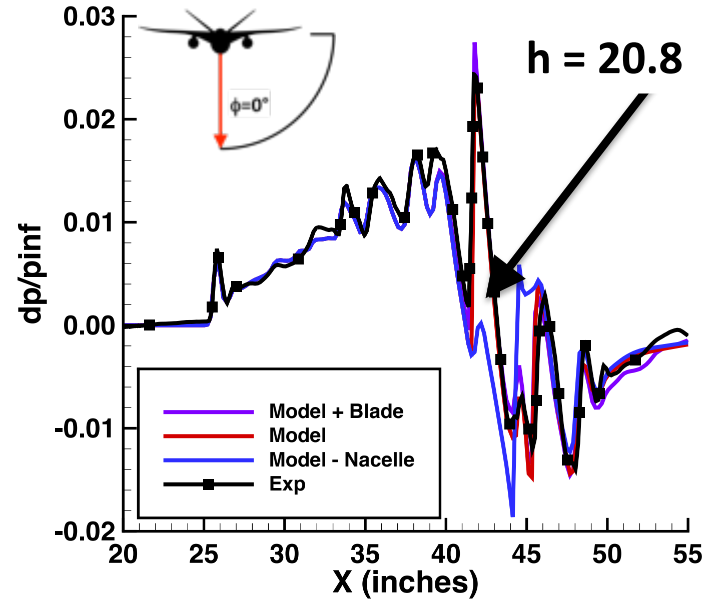
Lockheed Martin 1021

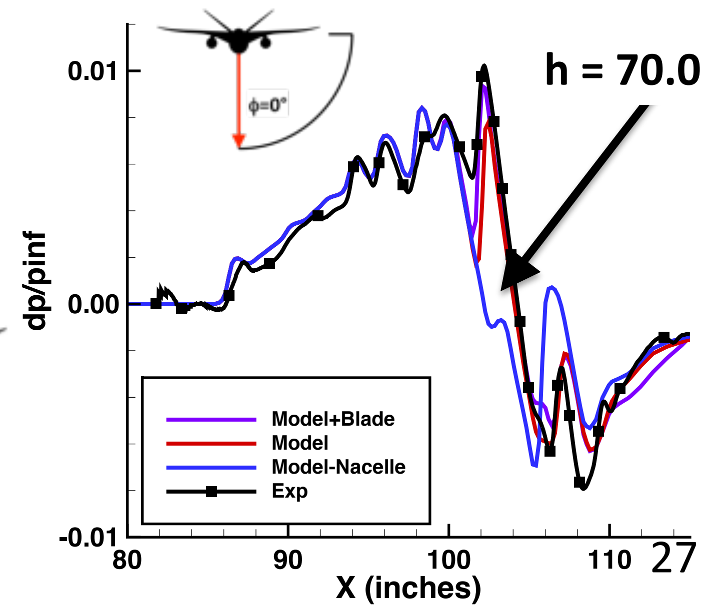
Geometric Sensitivity Analysis

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



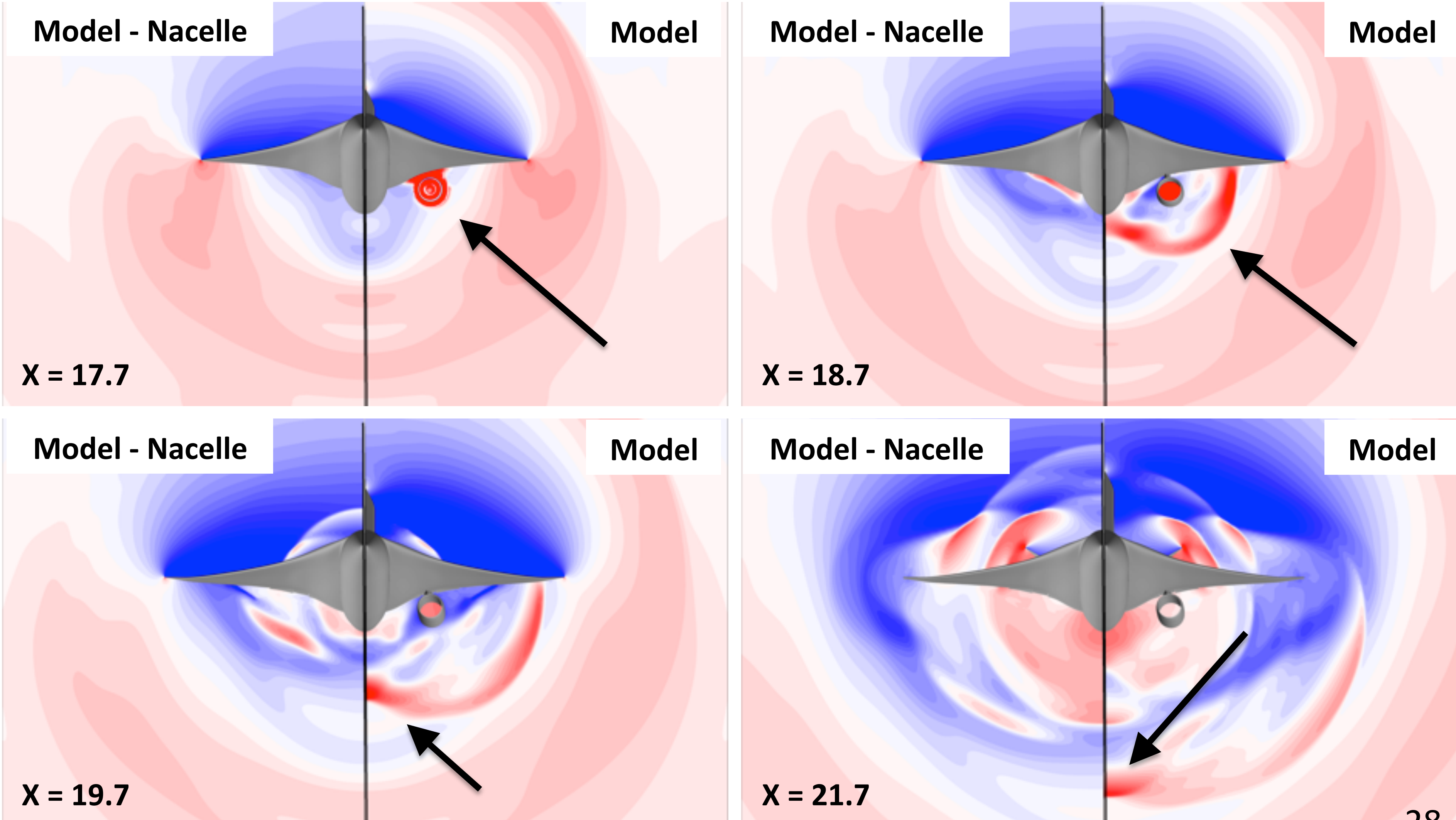






Lockheed Martin 1021

Geometric Sensitivity Analysis



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- **Oblique Shock/Plume Interaction**
- Summary

Oblique Shock/Plume Interaction Test

Objectives

- Assess the accuracy in RANS CFD prediction capabilities for oblique shock plume interactions
- 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

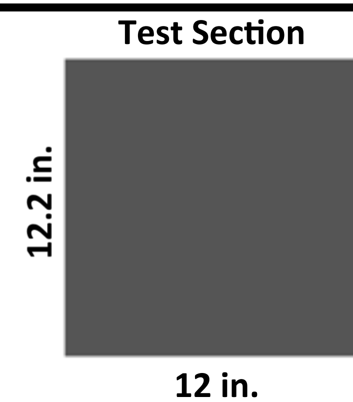
Approach

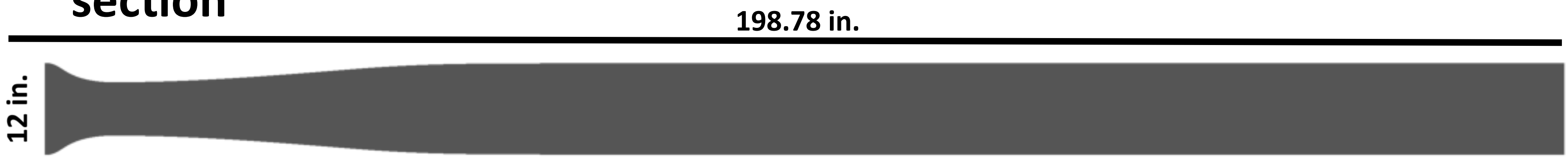
- Perform both RANS and inviscid CFD analysis using the LAVA code
- Compare CFD results with 1x1 WT data on several configurations:
    - Empty tunnel
    - Isolated Wedge in tunnel
    - Isolated Nozzle in tunnel
    - Complete configuration for large and small wedges
- Analyze flow physics and assess influence of tunnel support structures

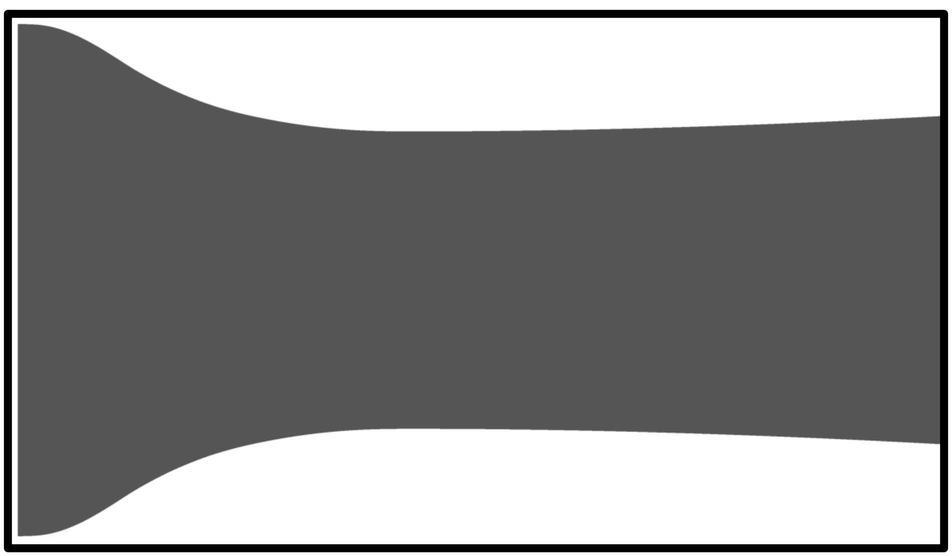
Oblique Shock/Plume Interaction Test

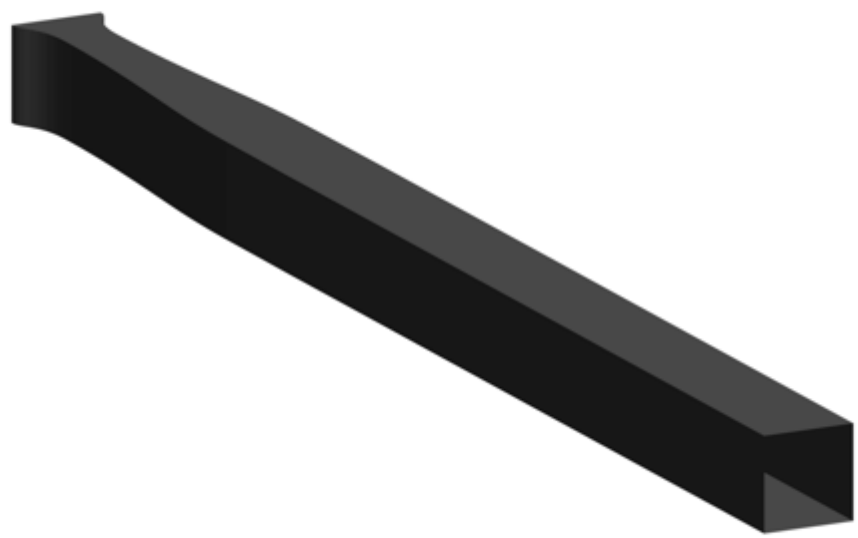
Wind Tunnel

- 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





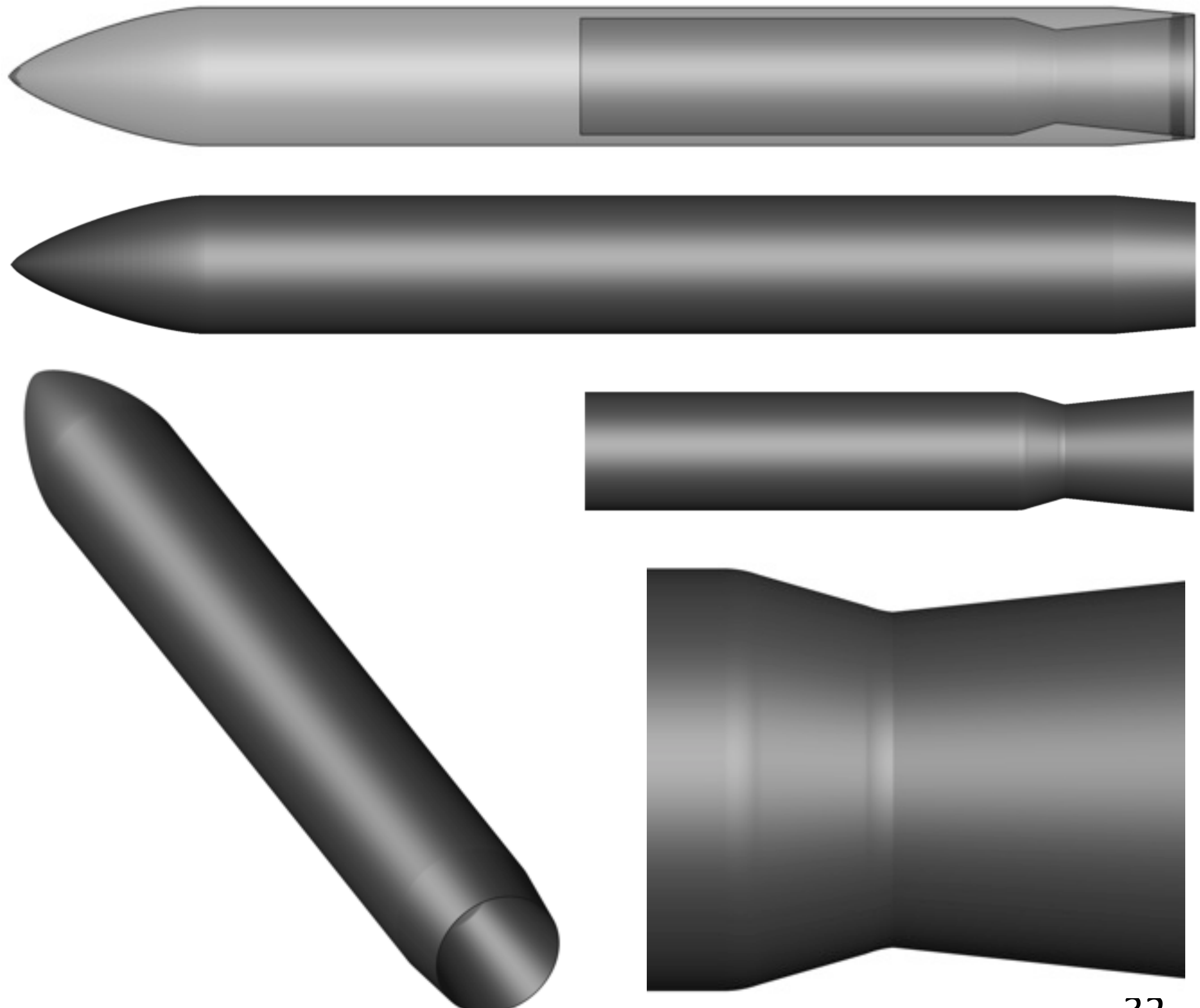




Oblique Shock/Plume Interaction Test

Nozzle

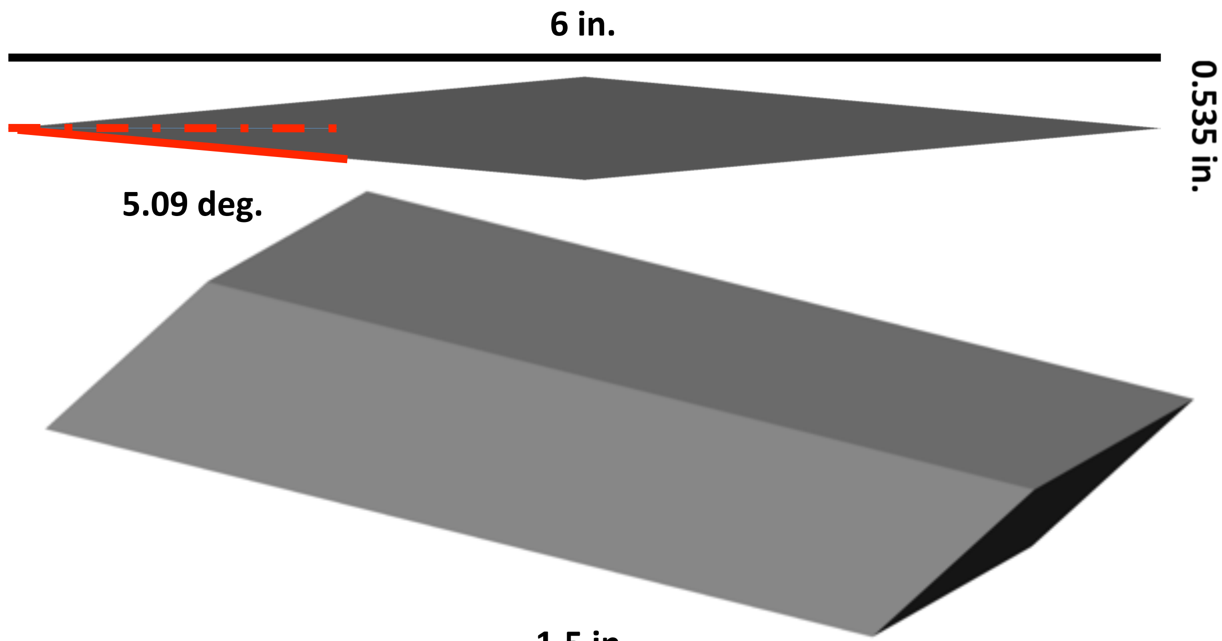
- Exterior Length 8.56 inch
- Interior Length 4.43 inch
- Inner Diameter 0.88 inch
- Outer Diameter 1.0 inch
- Lip Thickness 0.0075 inch
- Area Ratio 1.726



Oblique Shock/Plume Interaction Test

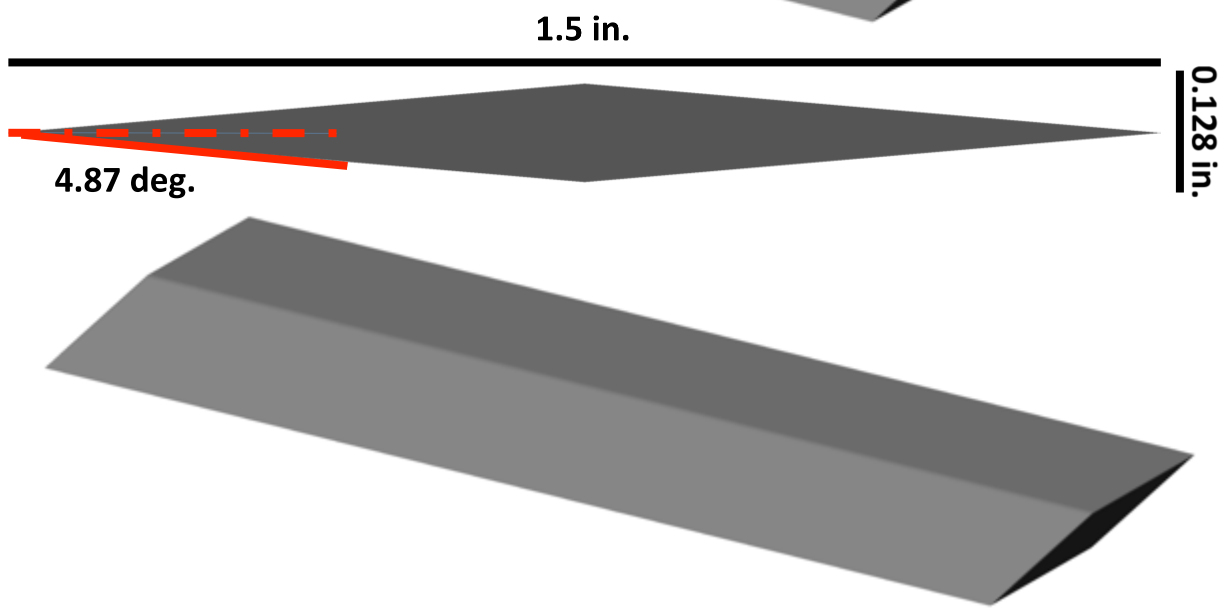
Large Wedge

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



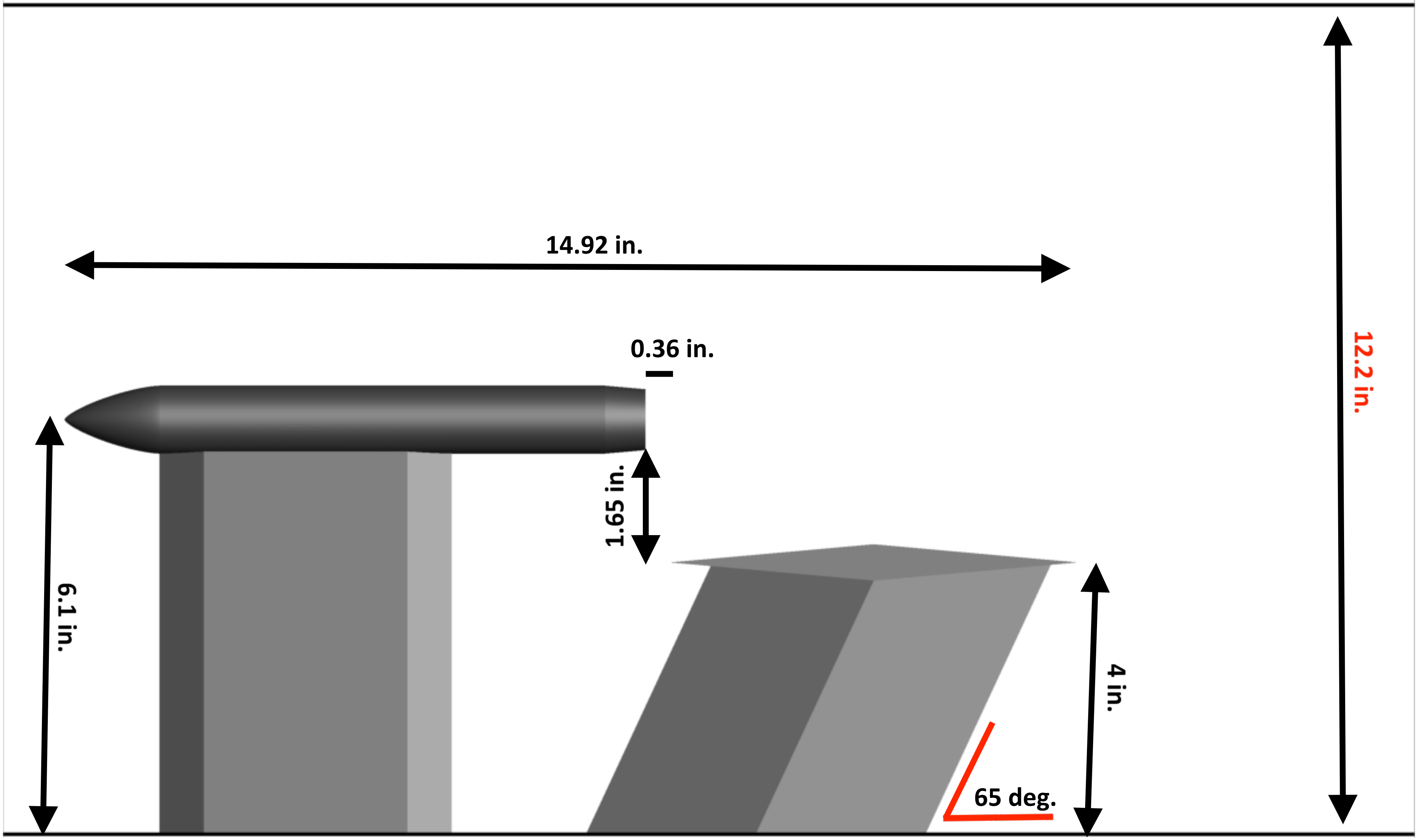
Small Wedge

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



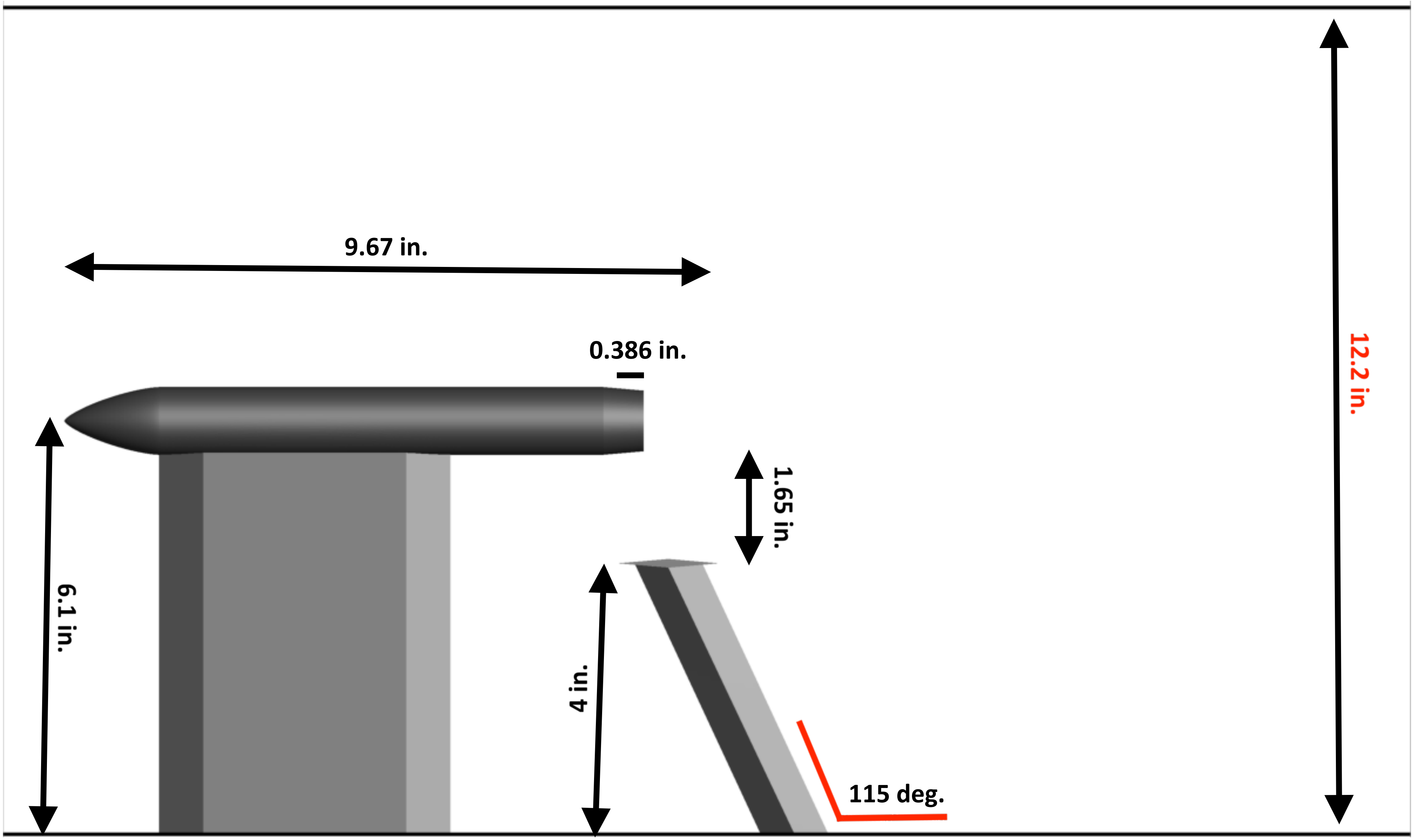
Oblique Shock/Plume Interaction Test

Installed Large Wedge Configuration



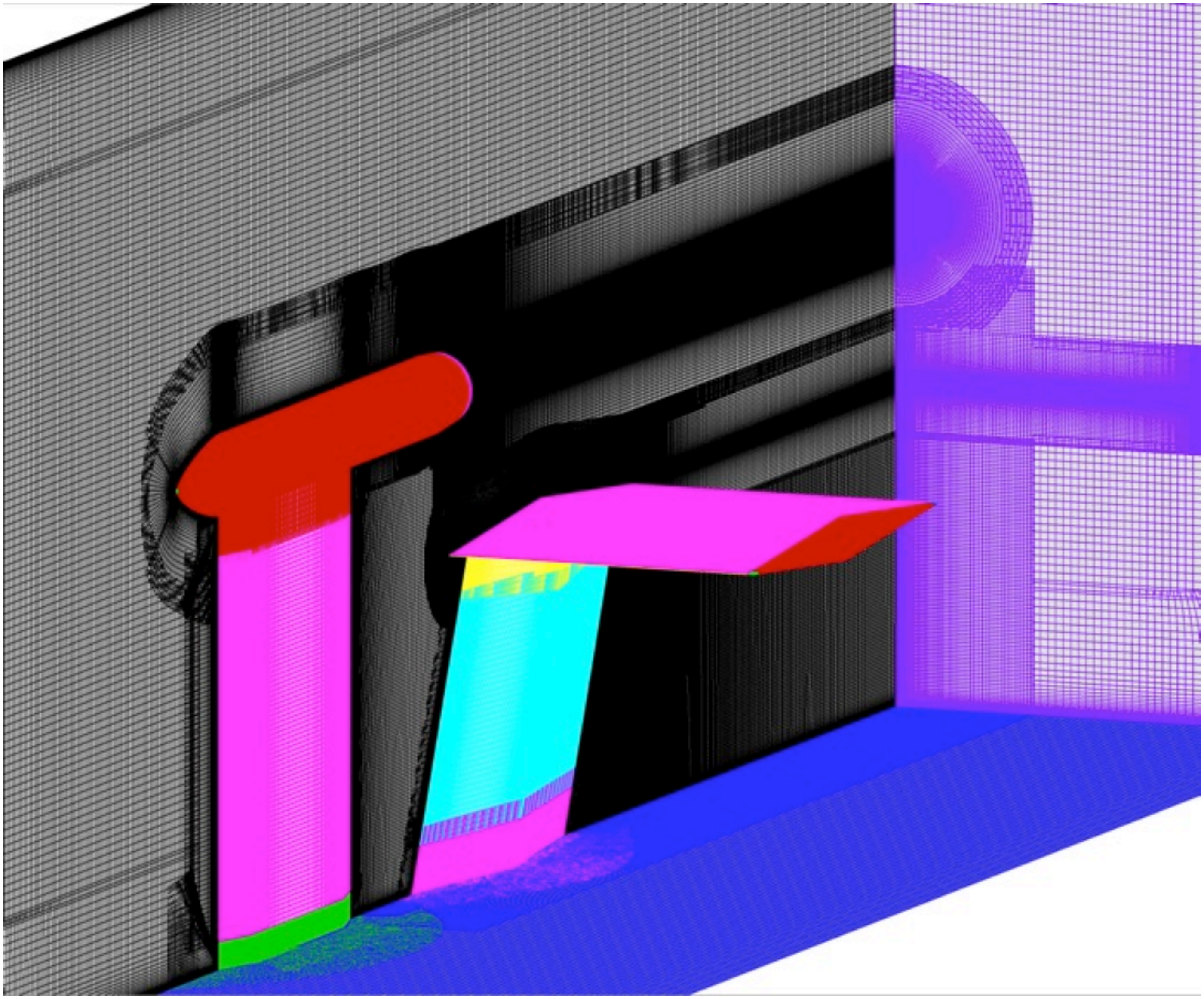
Oblique Shock/Plume Interaction Test

Installed Small Wedge Configuration



Oblique Shock/Plume Interaction Test

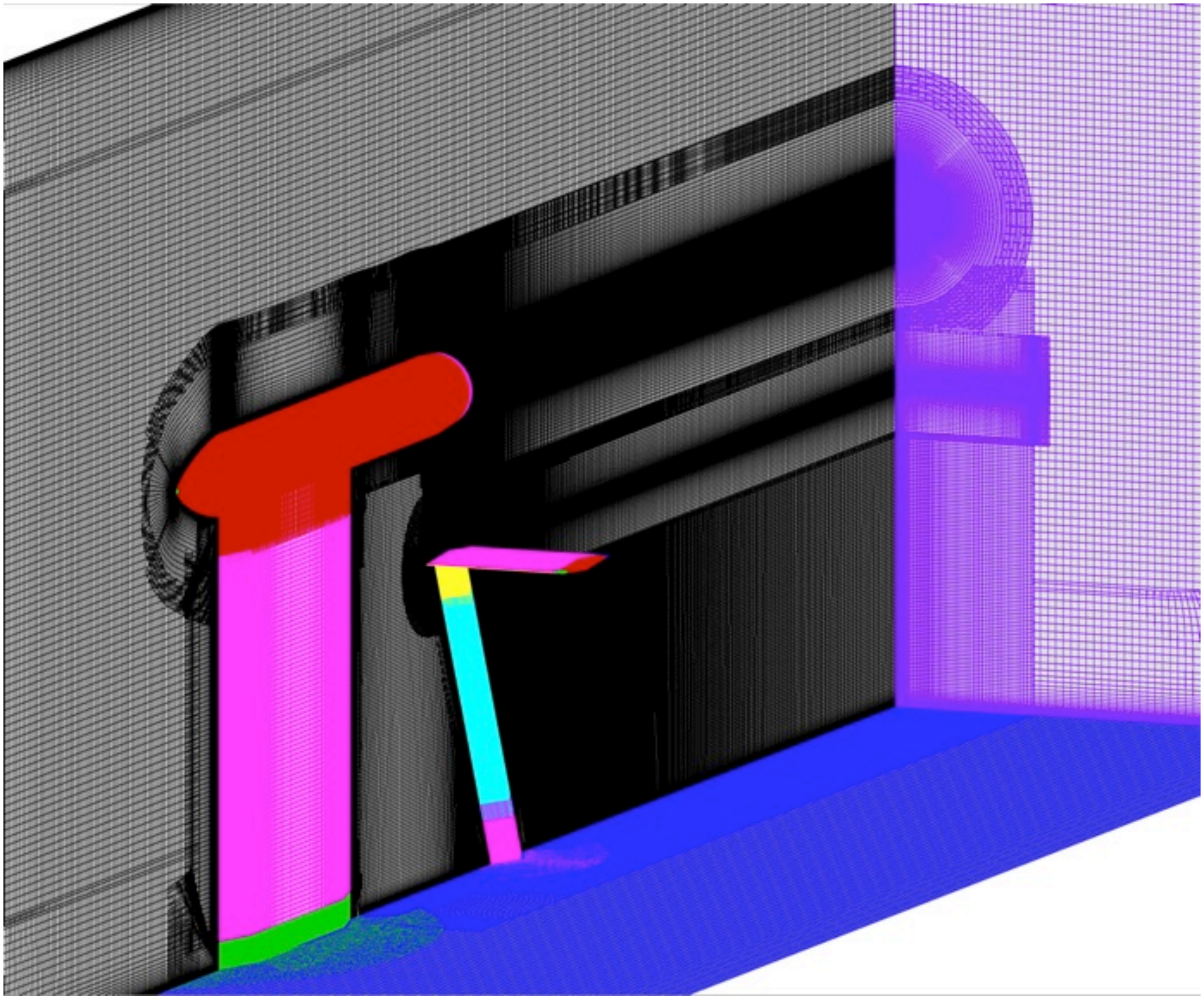
Large Wedge Configuration



- 24 zones
- 95.9 M grid pnts
- Triple fringe
- Stencil Qual 0.9
- 0 Orphans
- y+ ≈ 1
- Grid Breakdown
  - Tunnel 28.1 M
  - Nozzle 9 M
  - Shear Layer 20 M
  - Wedge 12.5 M
  - Wedge Wake 10 M
  - Nozl Suprt 2.4 M
  - Wedg Suprt 1.7 M
  - Suprt Wake 12 M

Oblique Shock/Plume Interaction Test

Small Wedge Configuration



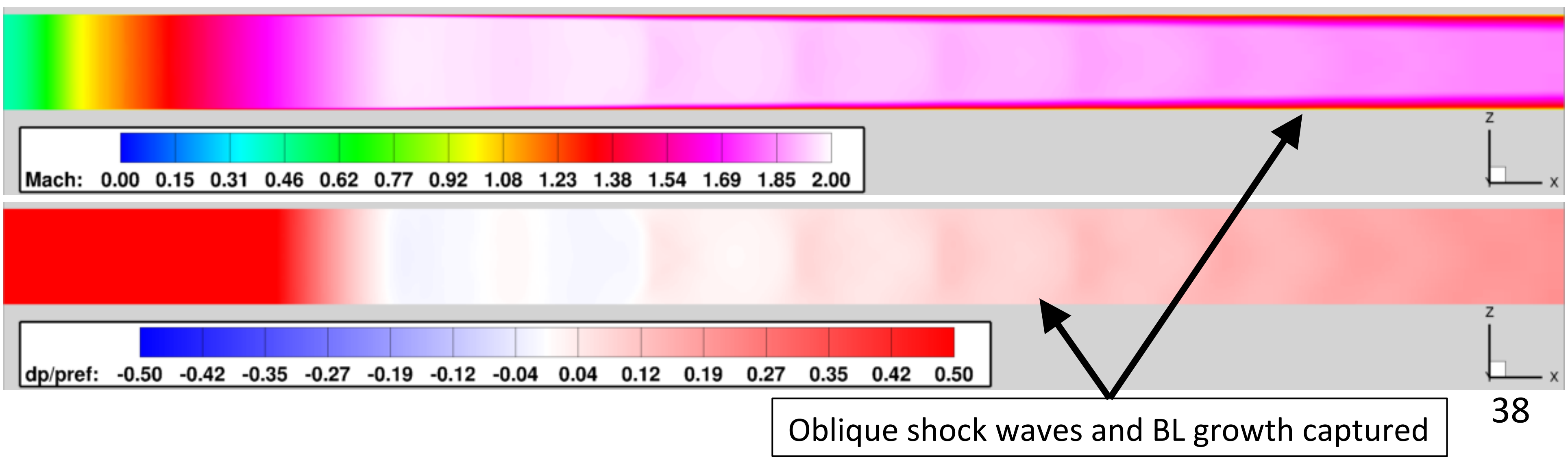
- 24 zones
- 87.0 M grid pnts
- Triple fringe
- Stencil Qual 0.9
- 0 Orphans
- y+ ≈ 1
- Grid Breakdown
  - Tunnel 28.1 M
  - Nozzle 9 M
  - Shear Layer 20 M
  - Wedge 7.1 M
  - Wedge Wake 6.8 M
  - Nozl Suprt 2.4 M
  - Wedg Suprt 1.7 M
  - Suprt Wake 12 M

Oblique Shock/Plume Interaction Test

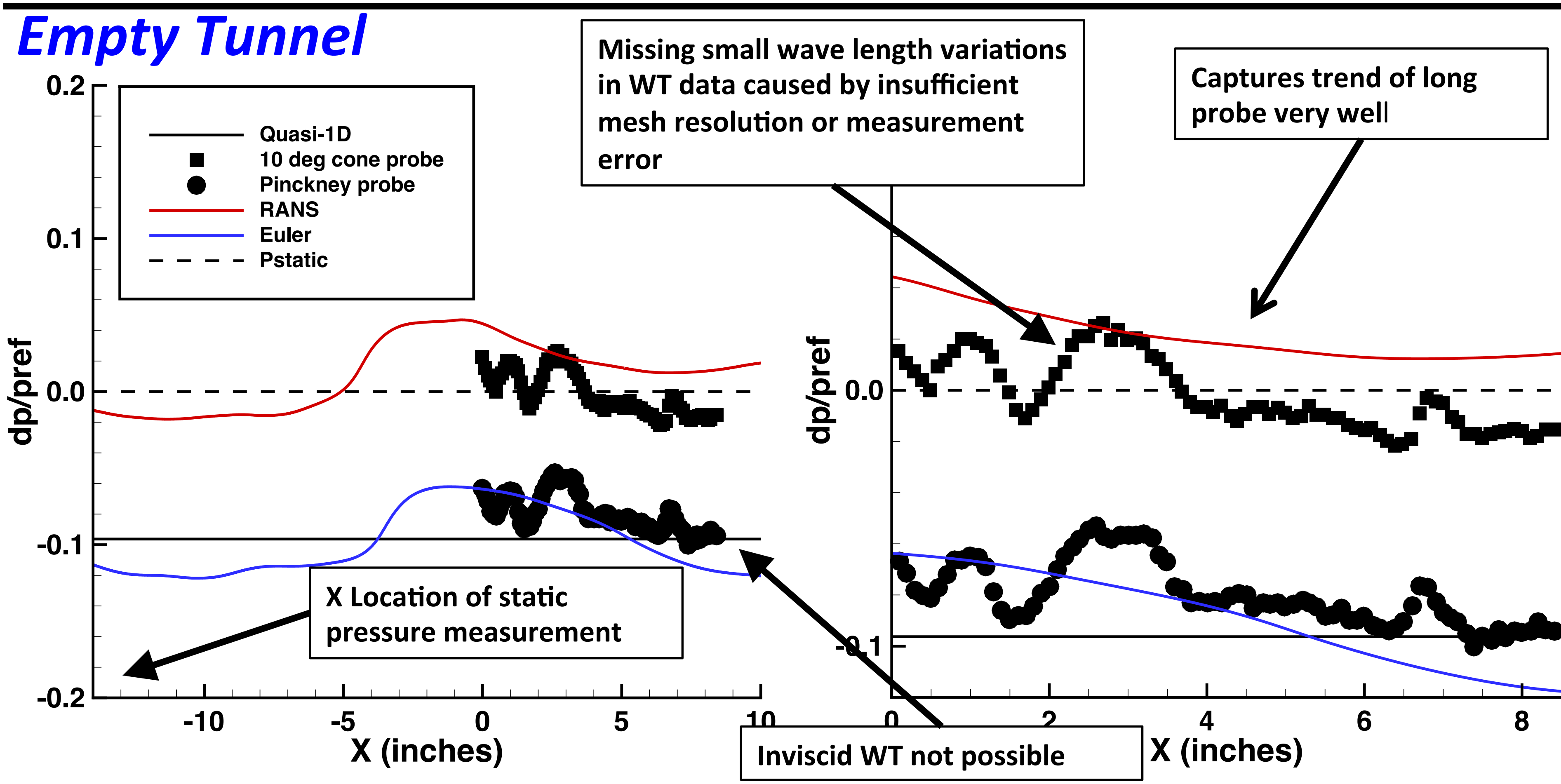
Conditions

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

Based on WT measurements from Ray Castner



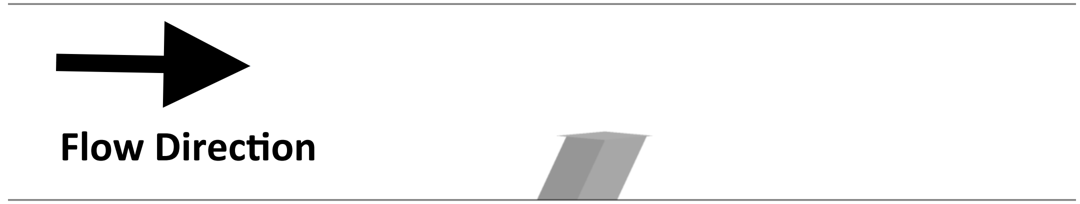
Oblique Shock/Plume Interaction Test



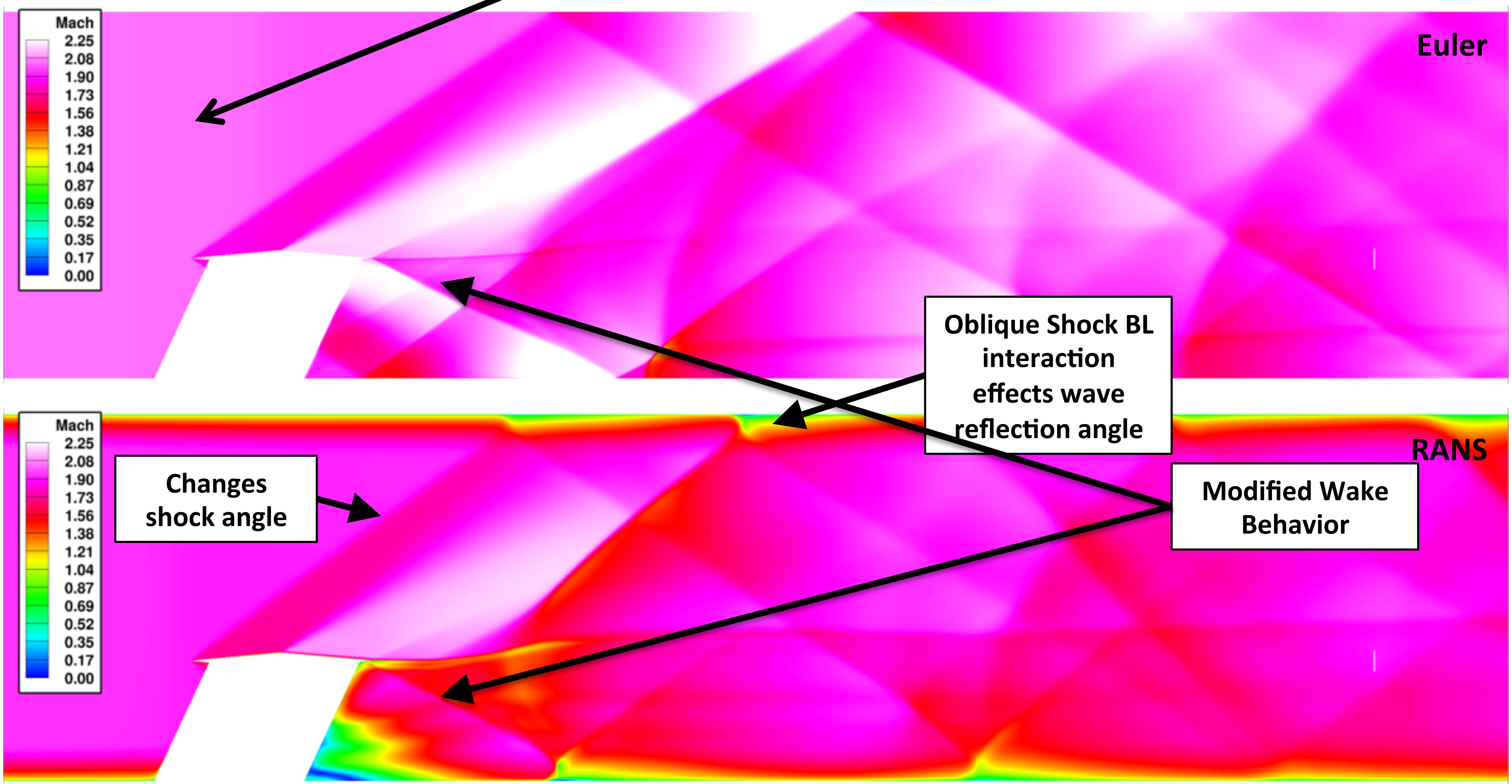
- Static pressure WT measurement of 1.68 psia is used in non-dimensionalization for all pressure plots
- Quasi-1D, Euler, and Short Probe results do not match the physically correct behavior of nearly zero delta pressure
- RANS and Long Probe data match well in magnitude and trend

Oblique Shock/Plume Interaction Test

Large Wedge in Tunnel



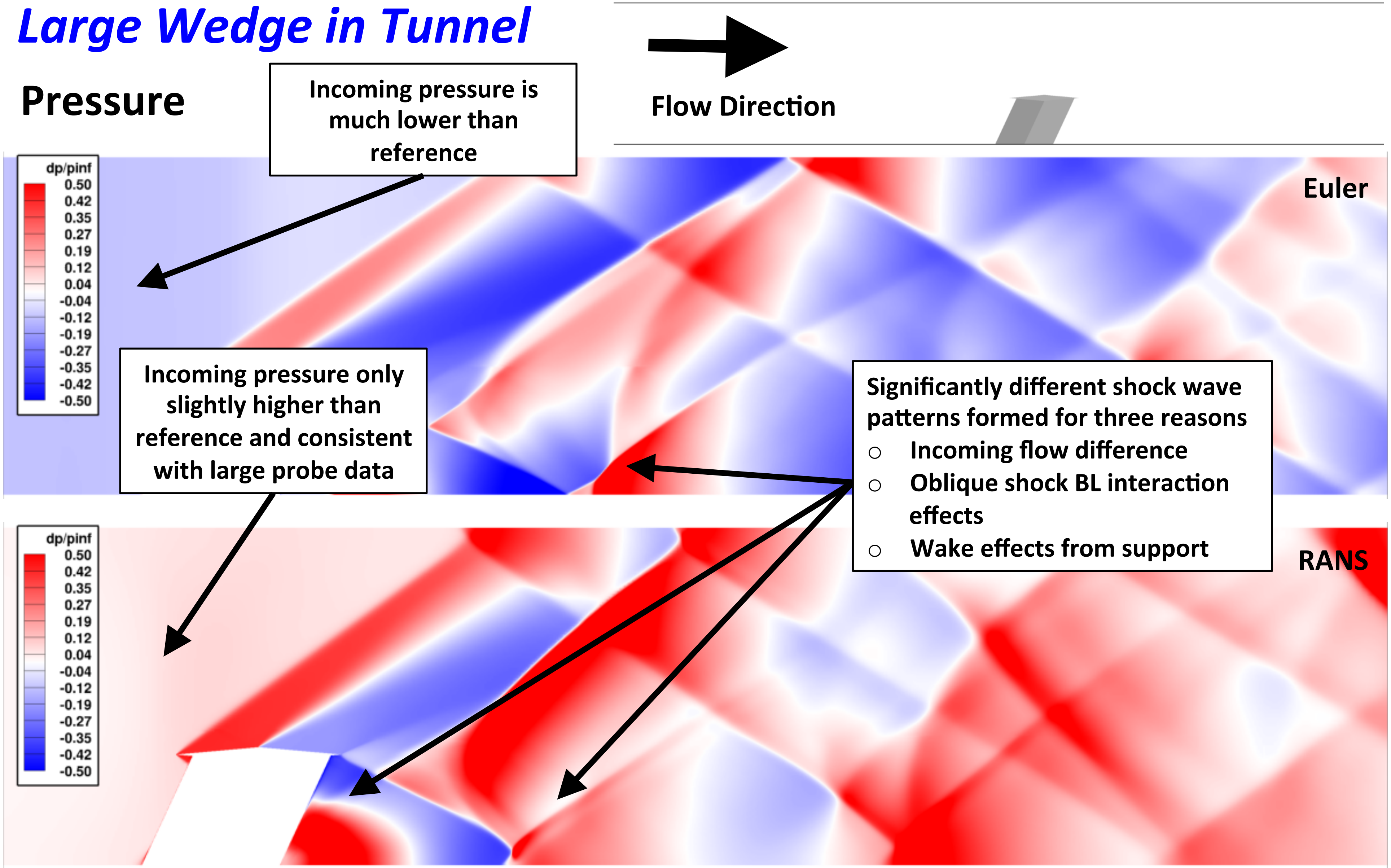
Mach Number



Oblique Shock/Plume Interaction Test

Large Wedge in Tunnel

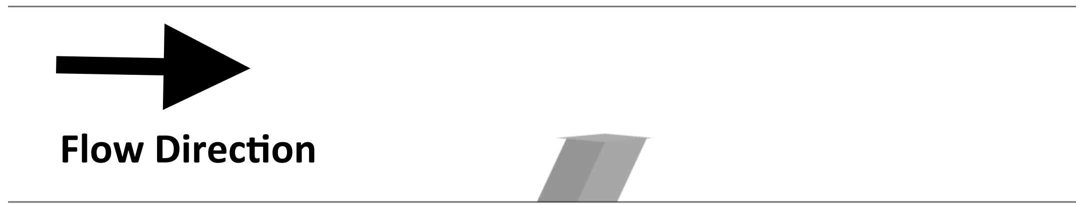
Pressure

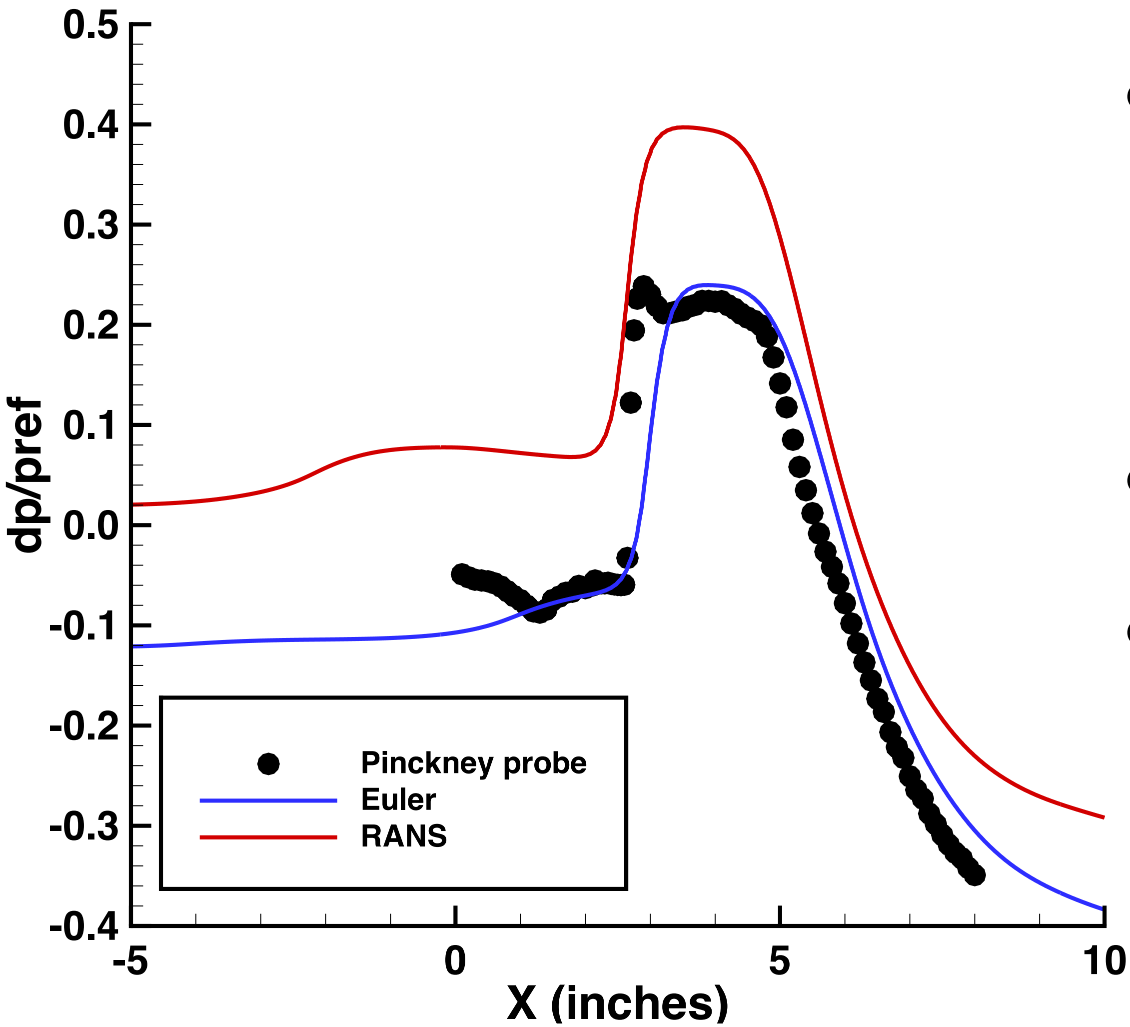


Oblique Shock/Plume Interaction Test

Large Wedge in Tunnel

Data Comparison



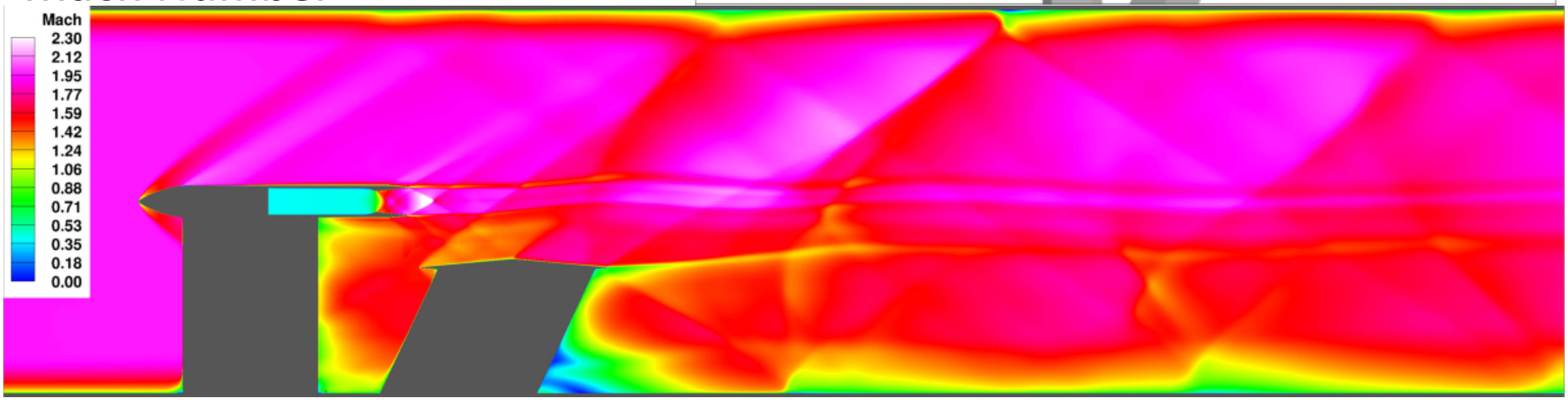


- Short probe data should be slightly above zero at x = 0 based on long probe and RANS CFD data from empty tunnel
- Shock locations are well-captured using RANS.
- Inviscid analysis predicts shock later since shock angle is effected by larger incoming Mach number.

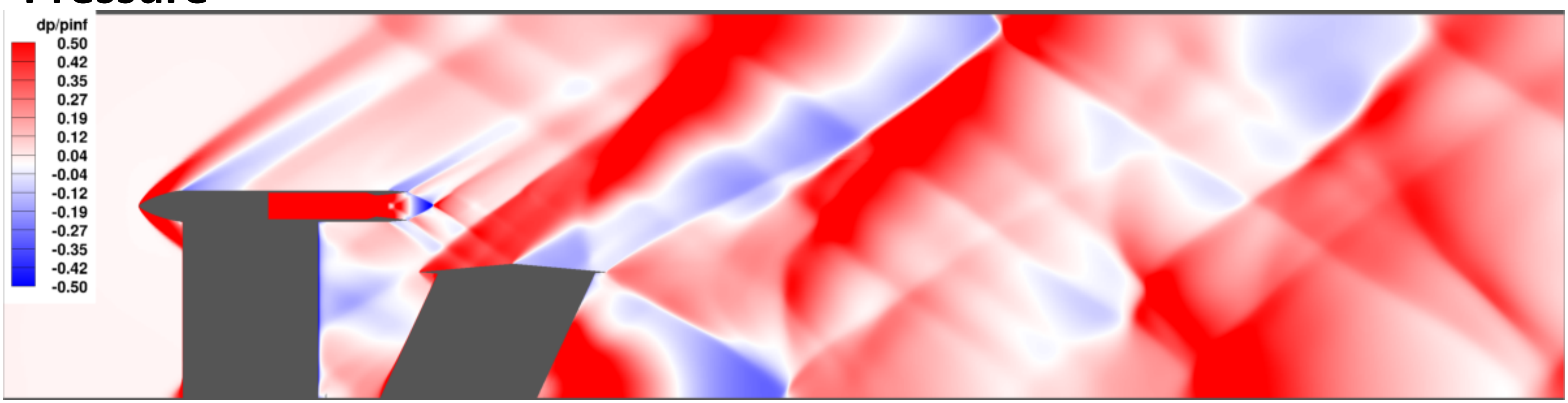
Oblique Shock/Plume Interaction Test

Installed Large Wedge

Mach Number



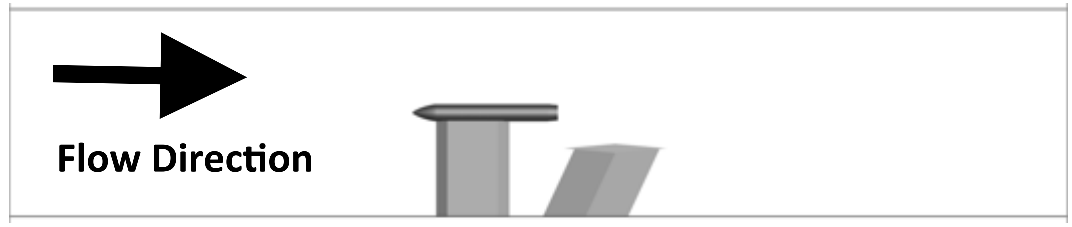
Pressure

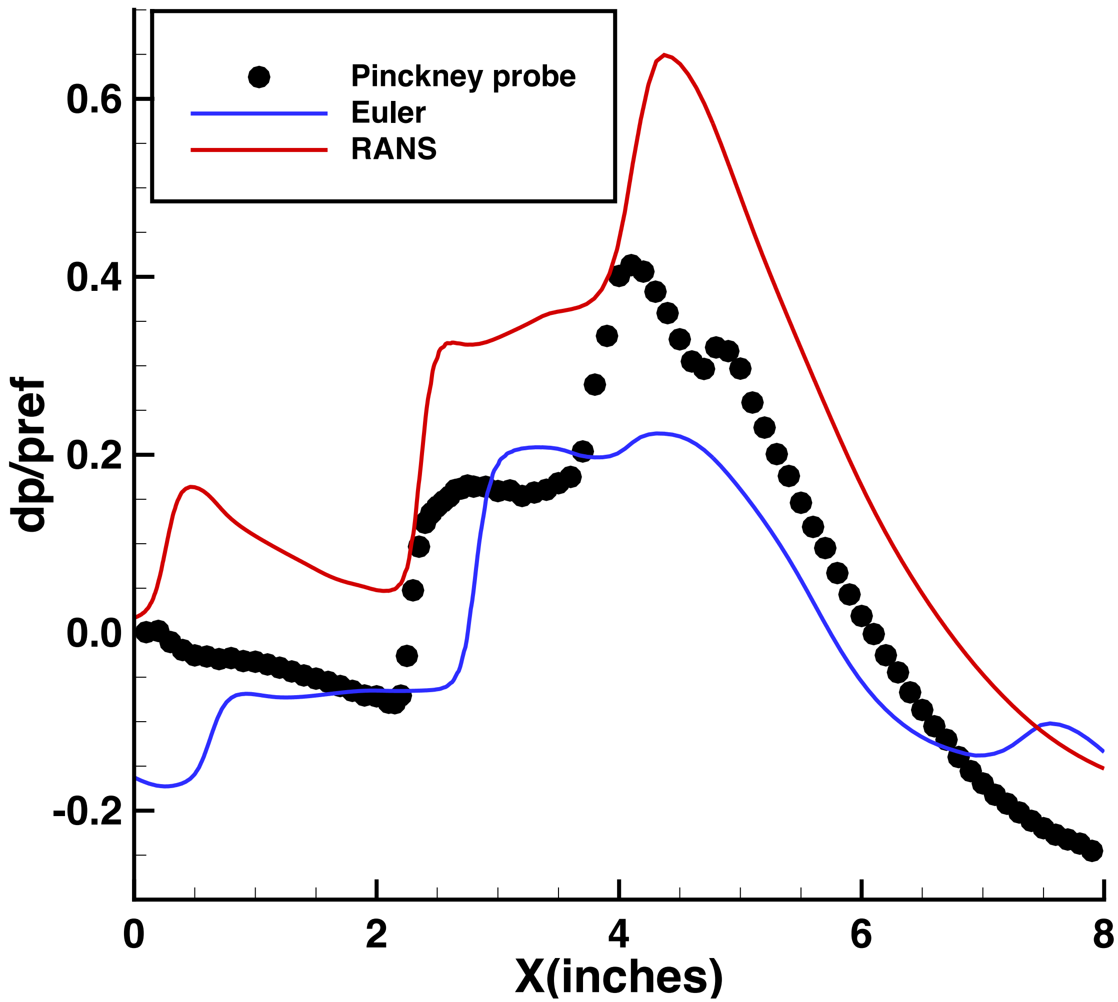


Oblique Shock/Plume Interaction Test

Large Wedge in Tunnel

Data Comparison NPR = 8



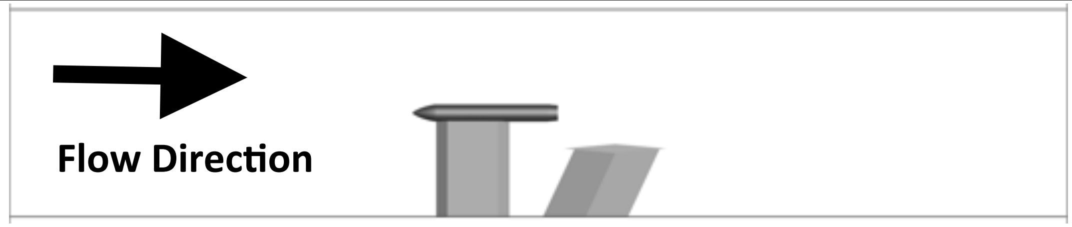


- Shape of the pressure signatures between the short probe data and RANS result compare well
- Location of the shocks and slope of the relaxation match, but magnitude is shifted
- Pinckney probe data may contain offset as demonstrated in empty tunnel and wedge cases
- Inviscid results show similar magnitude to probe, but the shape is incorrect because incoming flow is different

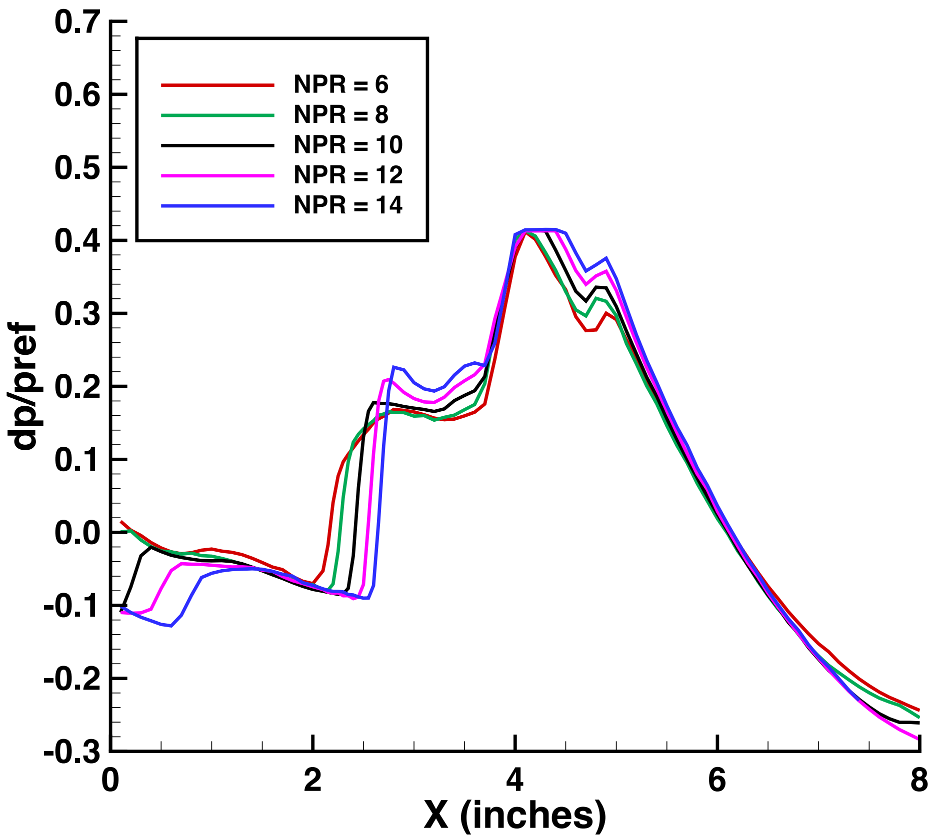
Oblique Shock/Plume Interaction Test

Large Wedge in Tunnel

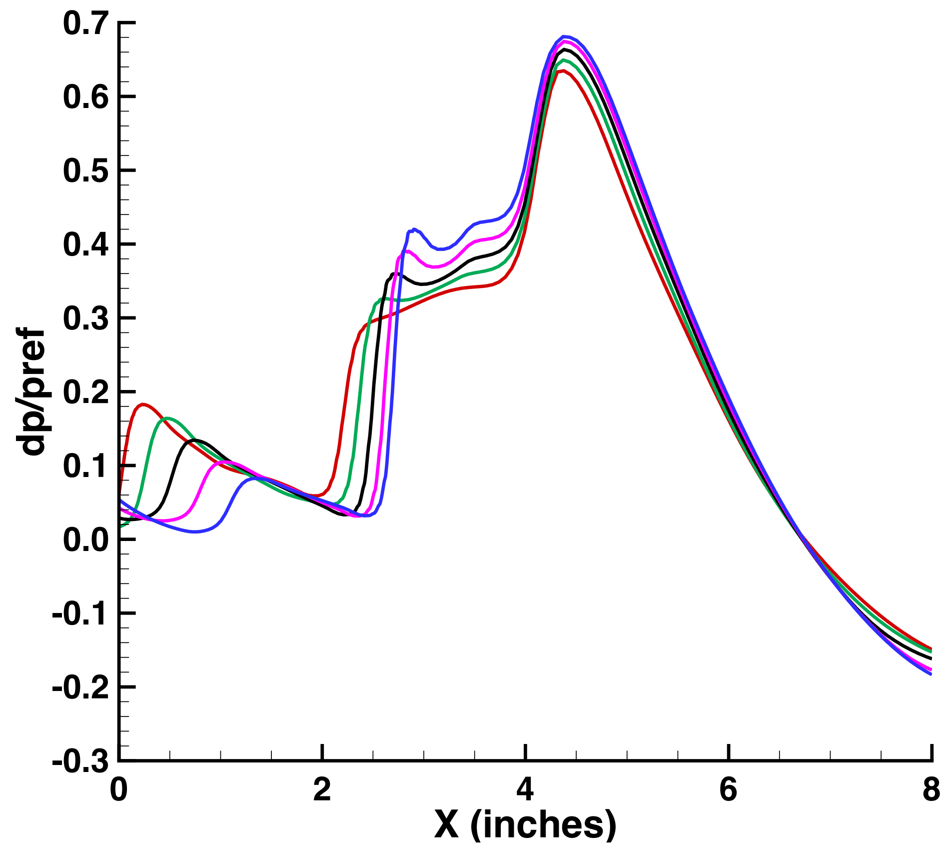
NPR Sensitivity



Pinckney probe data



CFD RANS data



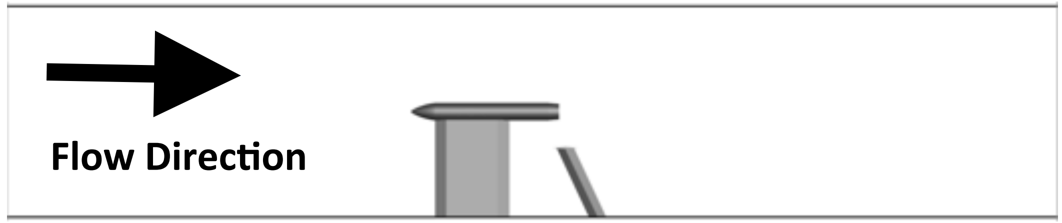
- **Qualitative trends match well but levels appear shifted**

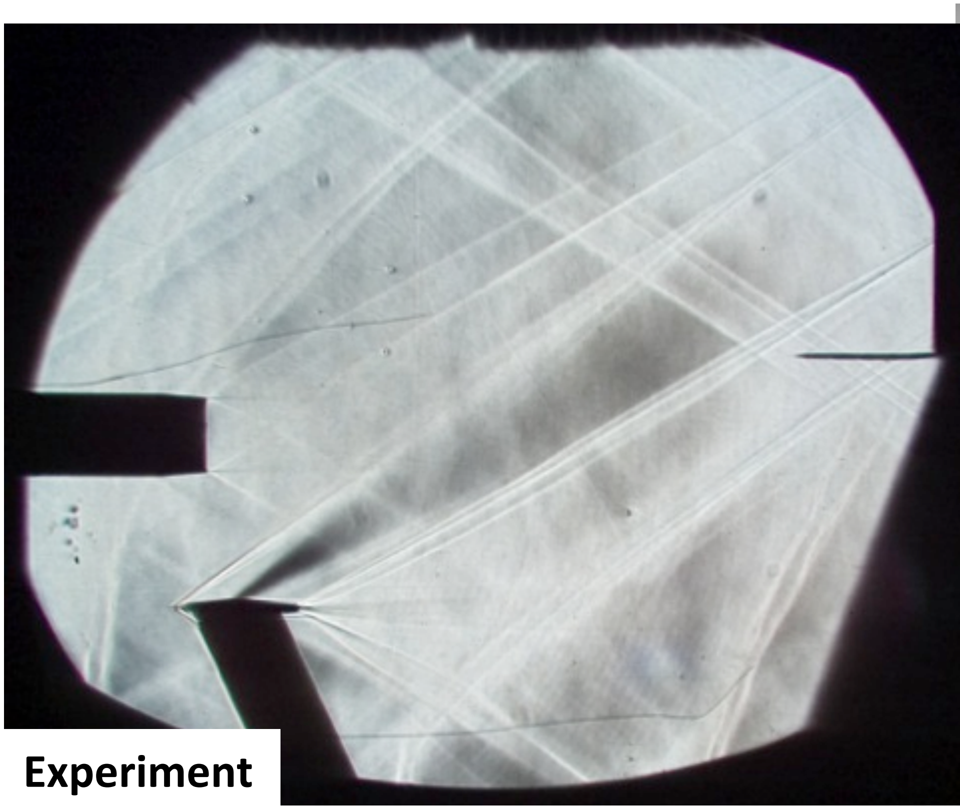
Oblique Shock/Plume Interaction Test

Small Wedge in Tunnel

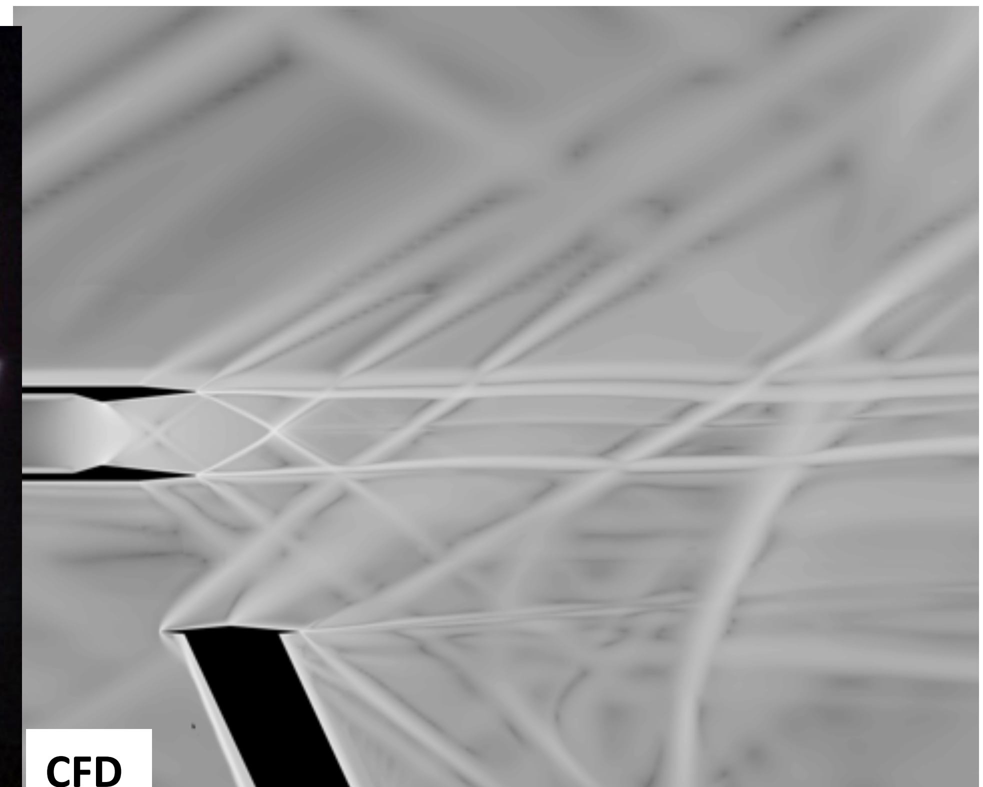
Schlieren Comparison

PR = 8 (2^{nd} order MUSCL)





Experiment



CFD

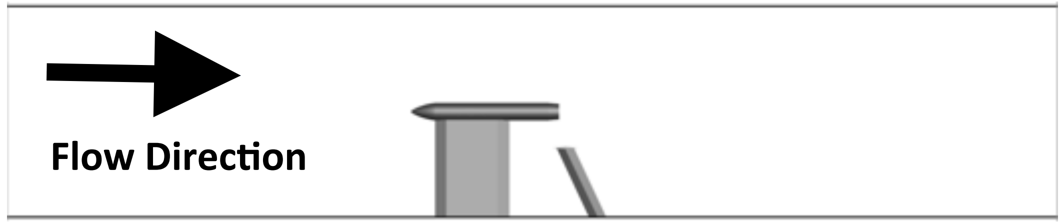
- Here

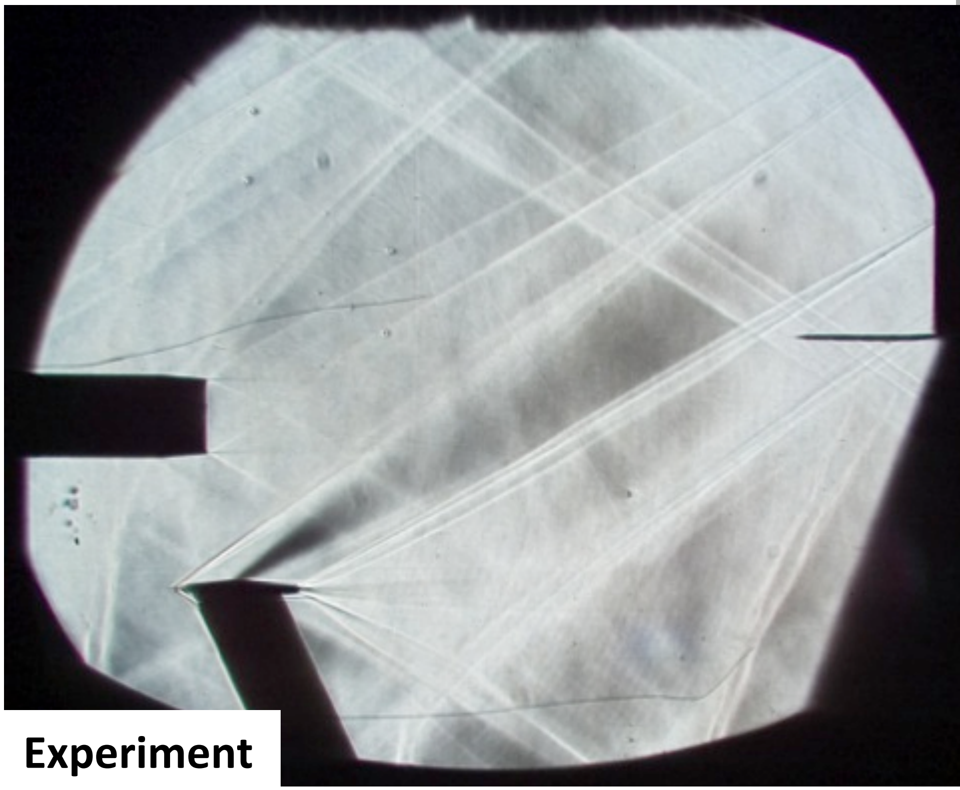
Oblique Shock/Plume Interaction Test

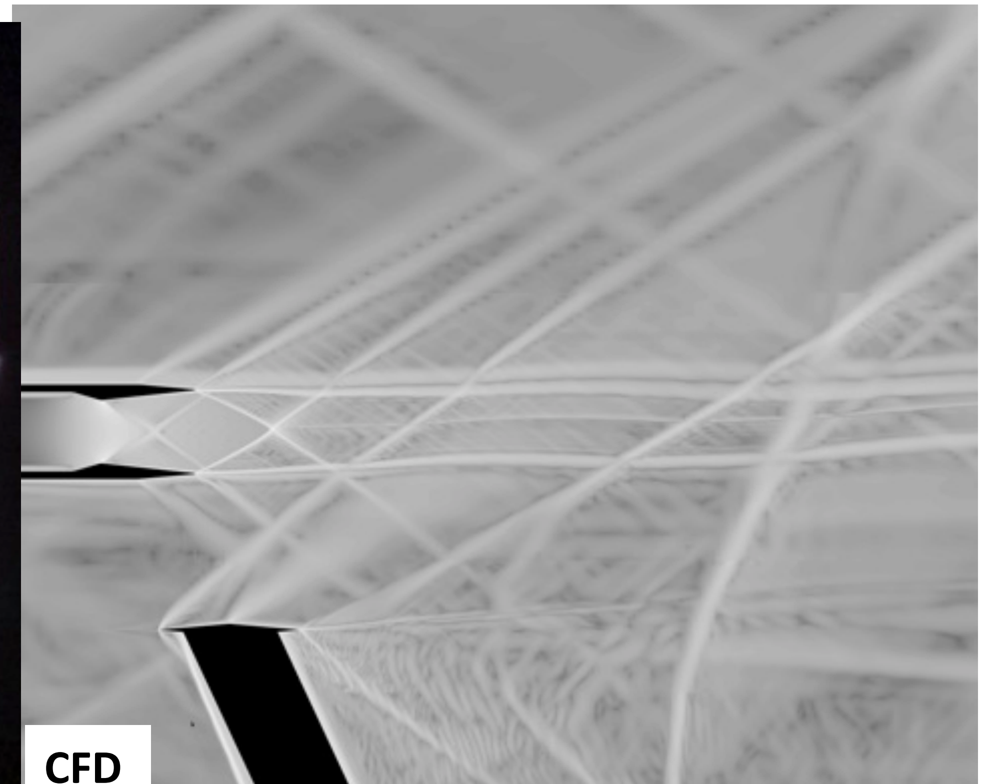
Small Wedge in Tunnel

Schlieren Comparison

PR = 8 (5th order WENO)




Experiment


CFD

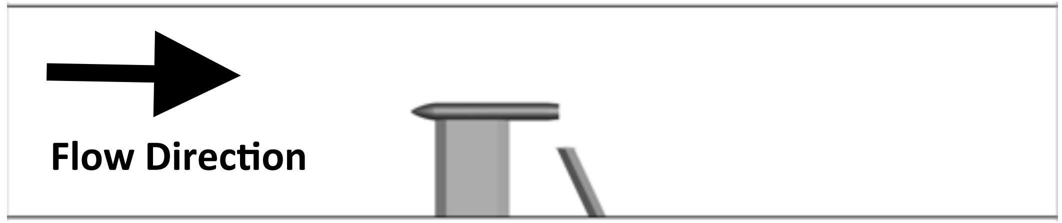
- **Here**

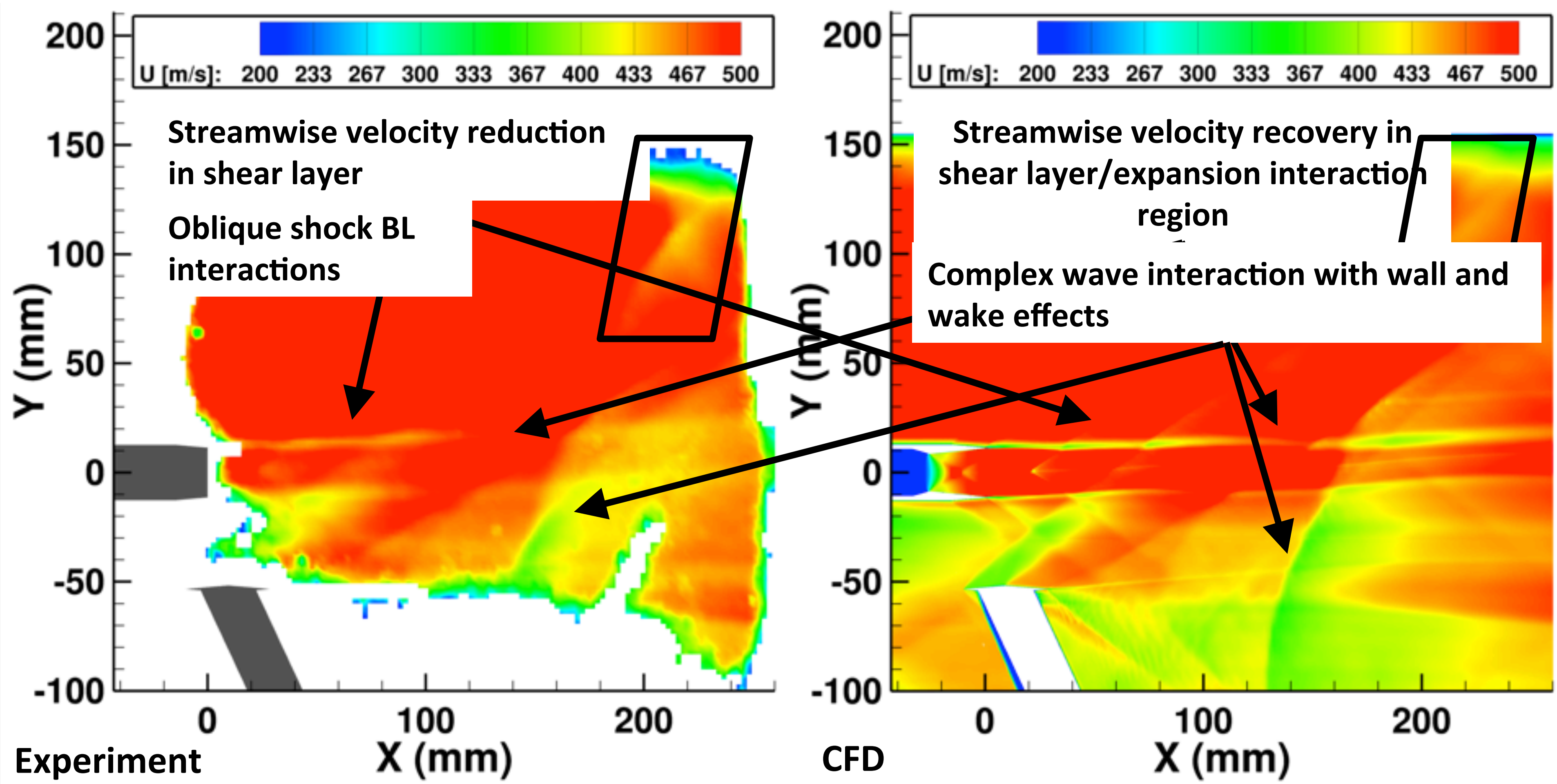
Oblique Shock/Plume Interaction Test

Small Wedge in Tunnel

PIV Comparison PR = 8

Streamwise Velocity



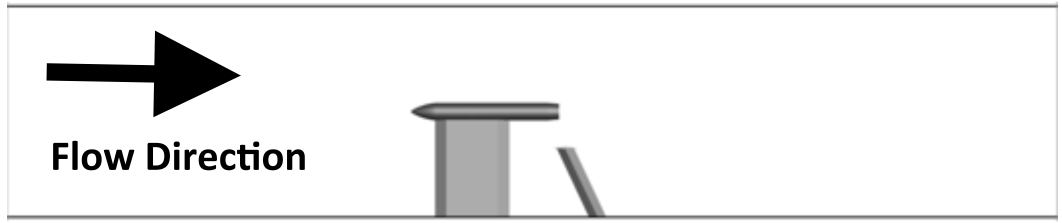


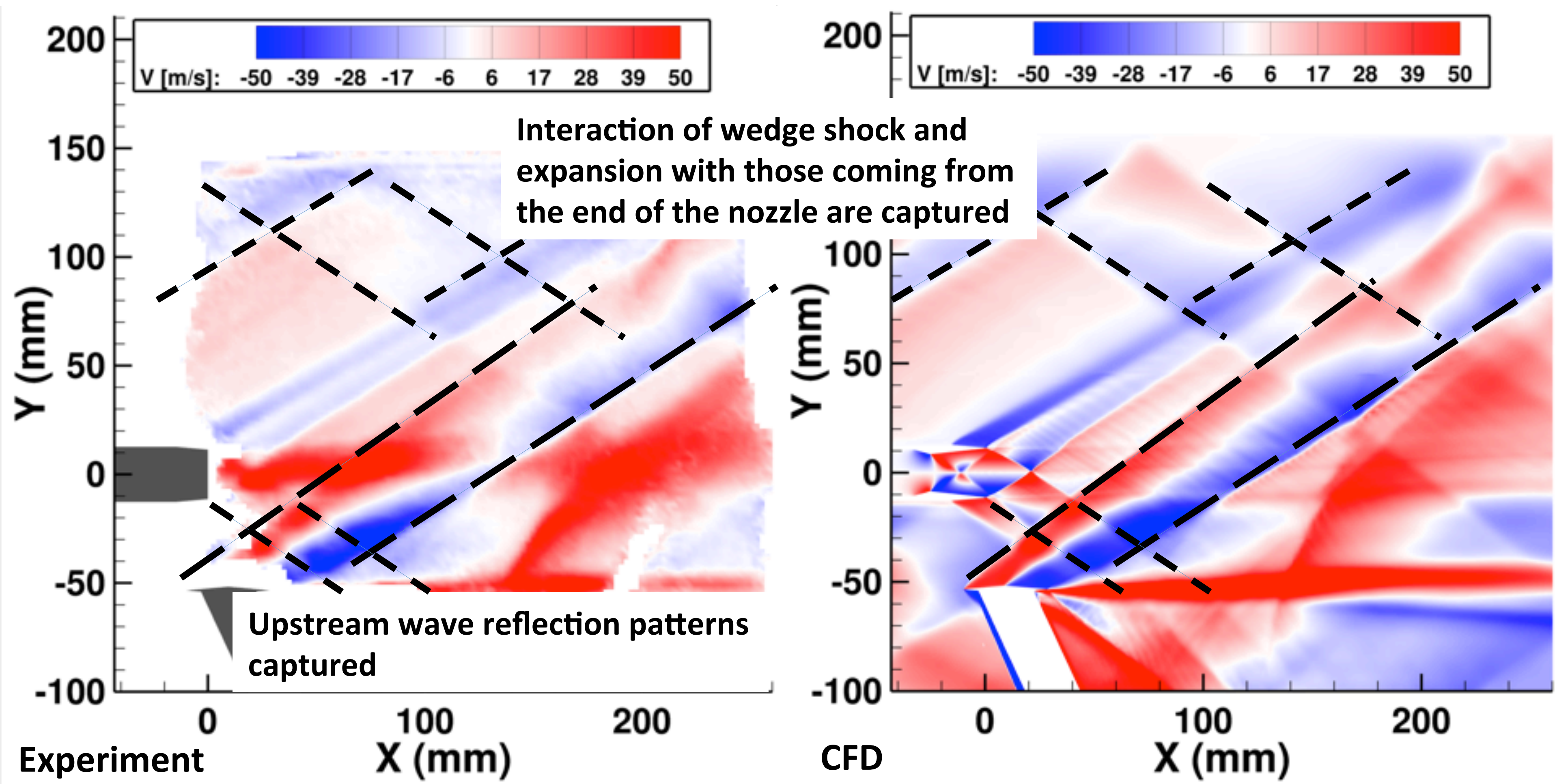
Oblique Shock/Plume Interaction Test

Small Wedge in Tunnel

PIV Comparison PR = 8

Vertical Velocity



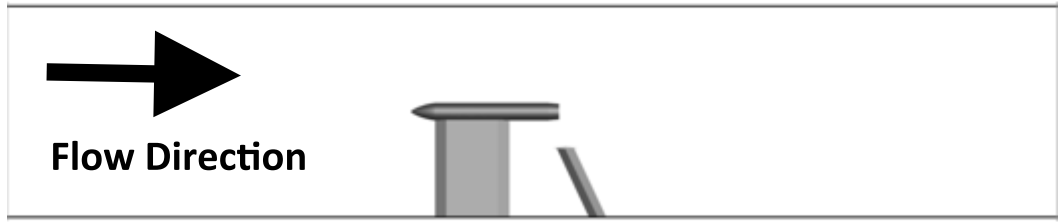


Oblique Shock/Plume Interaction Test

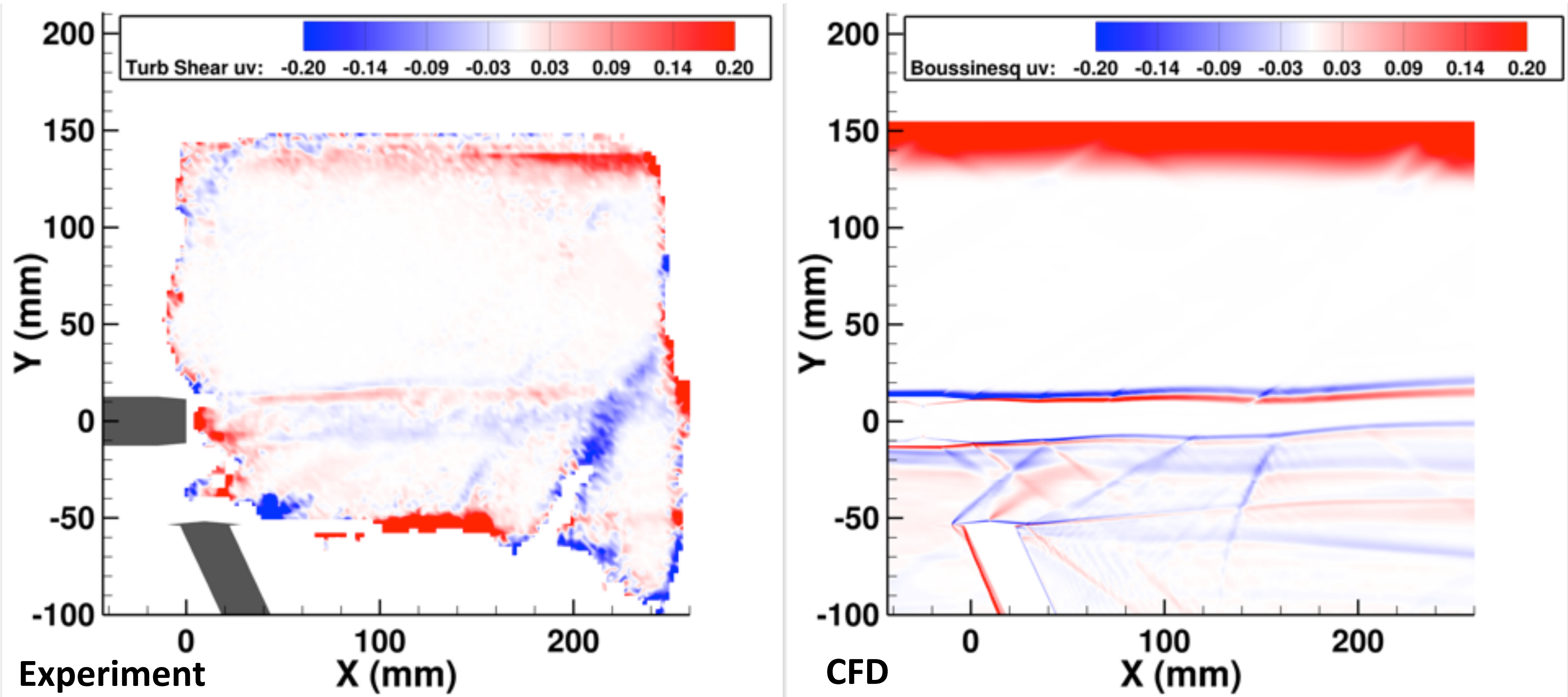
Small Wedge in Tunnel

PIV Comparison PR = 8

Turbulent Shear



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



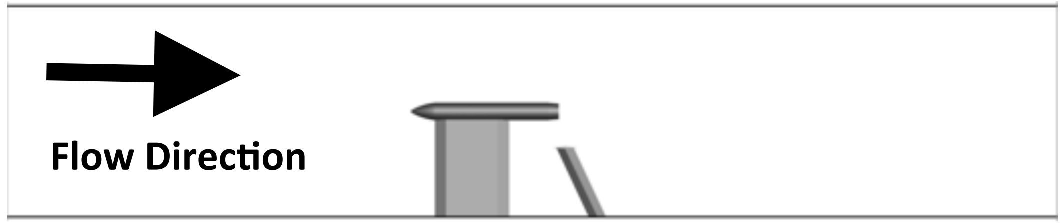
Experiment

CFD

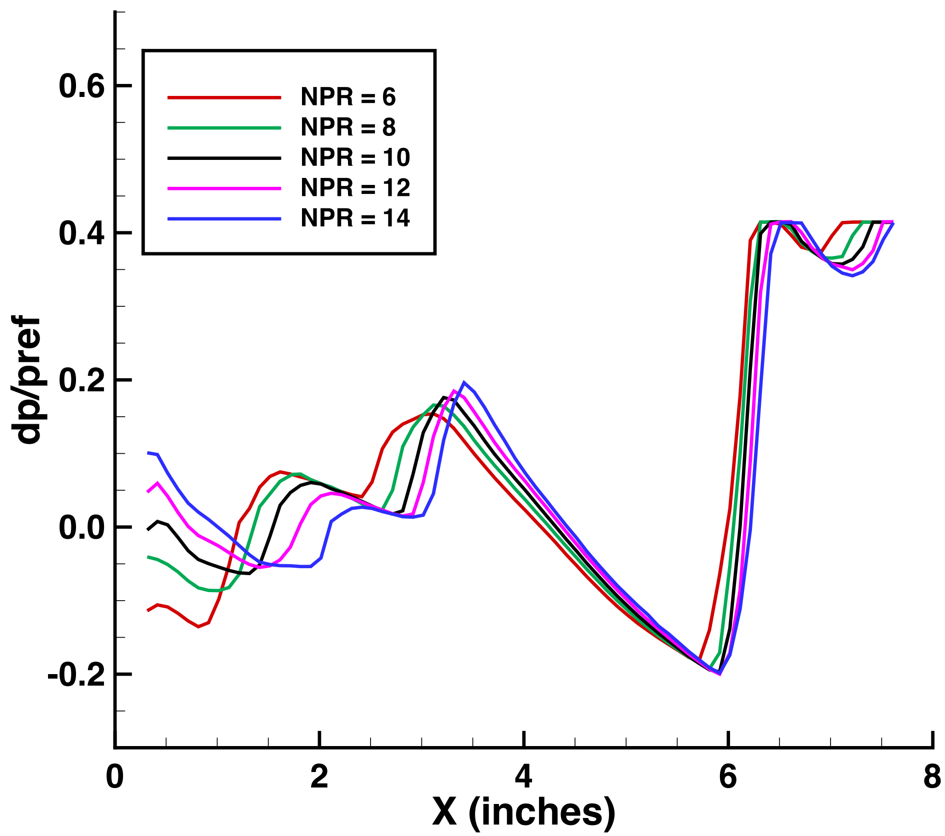
Oblique Shock/Plume Interaction Test

Small Wedge in Tunnel

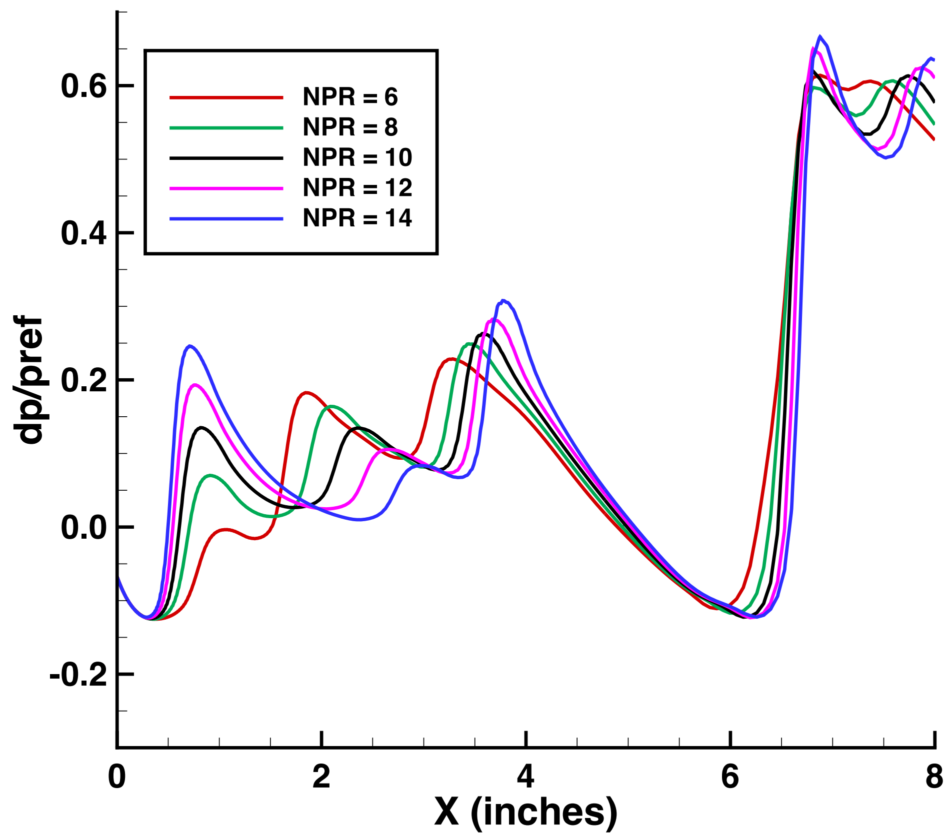
NPR Sensitivity



10 deg cone probe (long) RUN 46



CFD RANS data

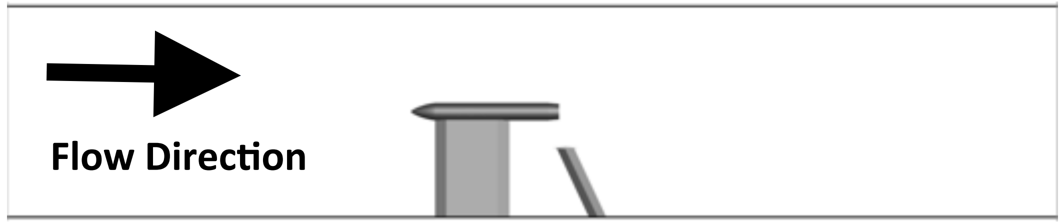


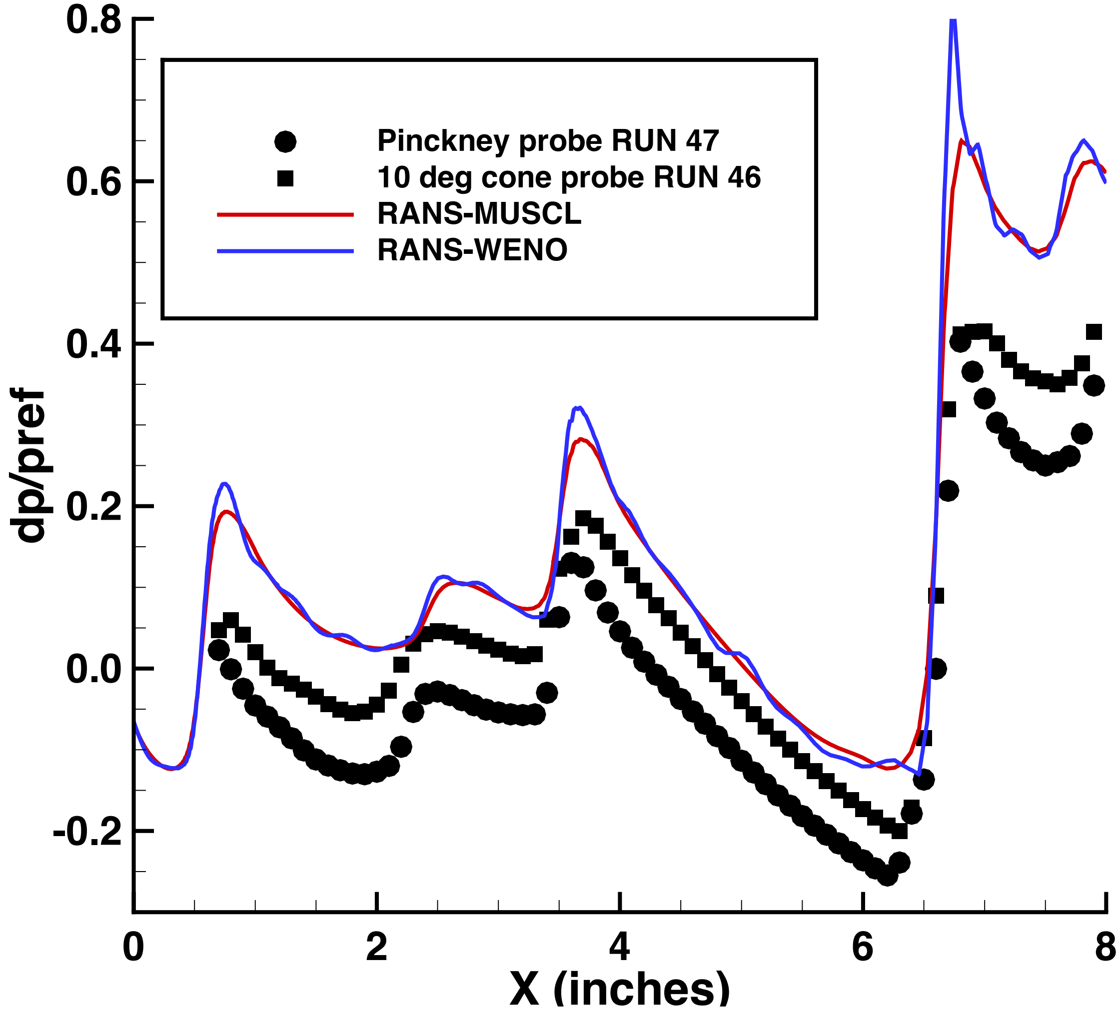
- **Qualitative trends match well but levels appear shifted**

Oblique Shock/Plume Interaction Test

Small Wedge in Tunnel

Data Comparison NPR = 12





- 10 deg cone probe data appears to be shifted 0.07 from the Pinckney probe data towards the CFD
- All shock locations and wave patterns appear consistent between CFD and WT data
- WENO solution contains sharper peaks than MUSCL, but also contains a low level of oscillation which may be spurious
- Remaining increment discrepancy may be attributed to incorrect tunnel orientation in CFD

Summary

- LAVA framework has been successfully applied to the Sonic Boom Prediction workshop test cases.
- Both structured and unstructured grid methodologies have been investigated and similar accuracy demonstrated
- Computational resources are approximately 2 – 5.5 times more using the unstructured approach
- The AUSMPW+ and Modified Roe fluxes performed better than central differencing (fewer spurious oscillations)
- Good comparison achieved with experimental data

Summary

- Viscous and inviscid CFD analysis has been applied to the 1x1 WT test of oblique shock/plume interaction
- Analysis of the empty wind-tunnel demonstrated:
  - Short probe data appears to under-predict the pressure
  - RANS results are consistent with the large probe data
  - Inviscid results are consistent with Quasi-1D nozzle theory
- Analysis of the wedge in tunnel demonstrated:
  - RANS analysis predicts the correct shape and location of the shocks
  - Inviscid analysis predicts incorrect shock location and strength caused by the incorrect conditions upstream of the wedge
  - Although magnitude of the short probe data appears to match inviscid results the upstream portion of the pressure signature is not consistent with the static pressure measurement at the start of the test section.

Summary

- RANS analysis of the plume shock interaction for both the large and small wedge cases show good agreement in terms of signature shape and shock location
- Inviscid analysis shows incorrect wave patterns and magnitudes
- Improvements to inviscid analysis may be obtained by excluding the converging/diverging section of the WT and using WT measured reference conditions at the test section input.
- Comparison of RANS CFD data to PIV and Schlieren images demonstrate good agreement between CFD and experimental results
- Additional wind tunnel runs have been performed using the long probes to help assess the "delta" discrepancy between the short probe data and the CFD

Acknowledgements

- **NASA Fundamental Aeronautics Program High-Speed Project**
- **First AIAA Sonic Boom Prediction Workshop Committee**
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- **GRC collaborator:**
  Ray Castner