



Engineering, Test & Technology
Boeing Research & Technology

BCFD Anisotropic Adaptive Results Sonic Boom Prediction Workshop III

Todd Michal

Technical Fellow

Boeing Research and Technology - St. Louis, MO

AIAA Sonic Boom Prediction Workshop III

January 4-5, 2020, Orlando FL

Outline

- **Tools and Computing Platform**
- **Summary of Cases**
- **Results: Biconvex 9x7 Shock-Plume Interaction Model**
- **Results: C608 Low Boom Flight Demonstration Model**

Flow Solver/Computing Platform

■ **BCFD Flow Solver (Boeing CFD)**

- 2nd order cell centered finite volume discretization (HLLC++)
- TVD Barth Limiter
- All cases run with RANS - SA turbulence model

■ **EPIC (Edge Primitive Insertion and Collapse) Adaptation**

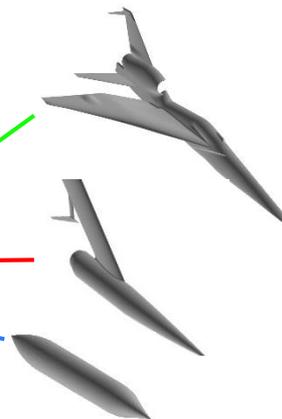
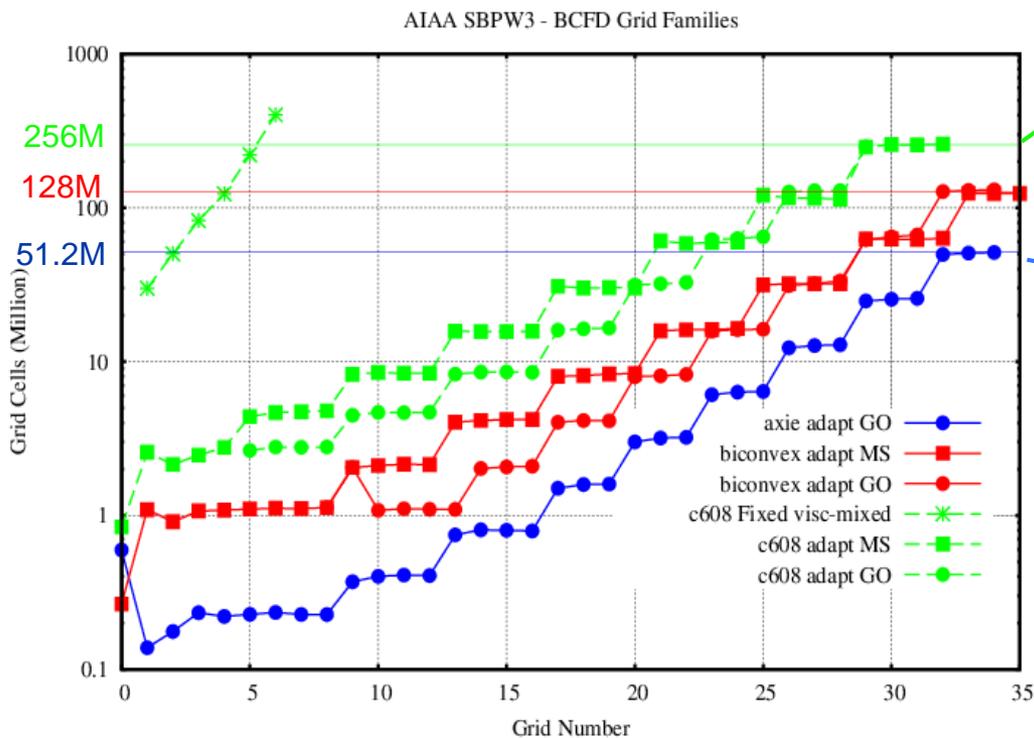
- Coarsen/refines surface and volume mesh to match target metric field
- Sizing metric based on solution error estimate + geometric constraints

■ **Computing Platform**

- MPI parallel (BCFD), MPI+openMP parallel (EPIC)
- Bi-convex – 10 nodes, 32 AMD EPYC 7301 CPUs, 96GB memory
- C608 - 400 cores, UV 3000 with Intel XEON E5-4650 v2 2.4 Ghz CPUs, 1.5TB memory

Summary of Cases/Grids

- Fixed grids provided by workshop (c608 visc-mixed)
- Adapted grids generated with EPIC (prism/tet element)
 - ✓ Very coarse initial grids, < 1M cells, $y^+ \sim 500$
 - ✓ GO – Goal Oriented output error (adjoint-based pressure error on all signature lines)
 - ✓ MS – Multi-scale error (minimize Mach Hessian interpolation error)



Case	Grid Family	Grid Sizes (DOF)
axie	adapt_GO ●	100K – 51.2M
biconvex	adapt_MS ■	1M-128M
	adapt_GO ●	1M-128M
C608	fixed *	30M-401M
	adapt_MS ■	1M-256M
	adapt_GO ●	1M-256M

Geometry Processing

- Started with provided STEP files for all cases
- Processed models in CADfix
 - Convert all surfaces to Nurbs
 - Export IGES plus topology file
- Modifications Performed

➤ Axie

- ✓ Converted model from mm to meters
- ✓ Split model at $y=0$ plane
- ✓ Removed half body



➤ Biconvex

- ✓ Split horizontal tail at leading edge line
- ✓ Split nose cone

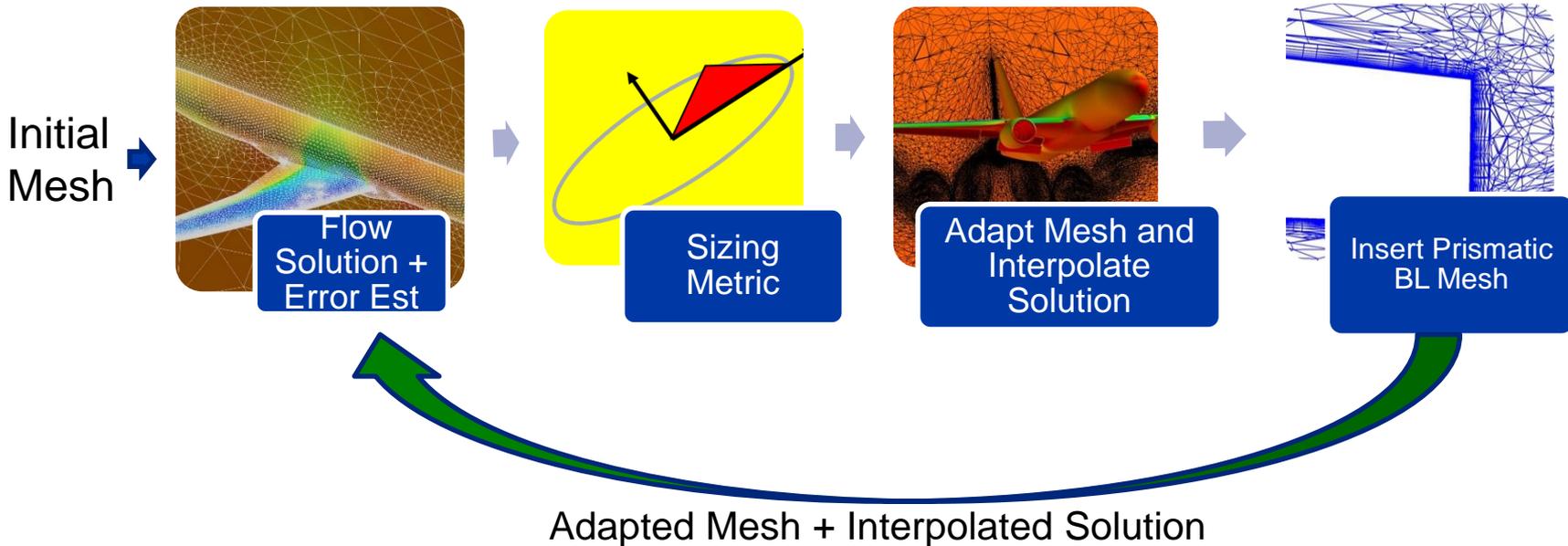


➤ C608

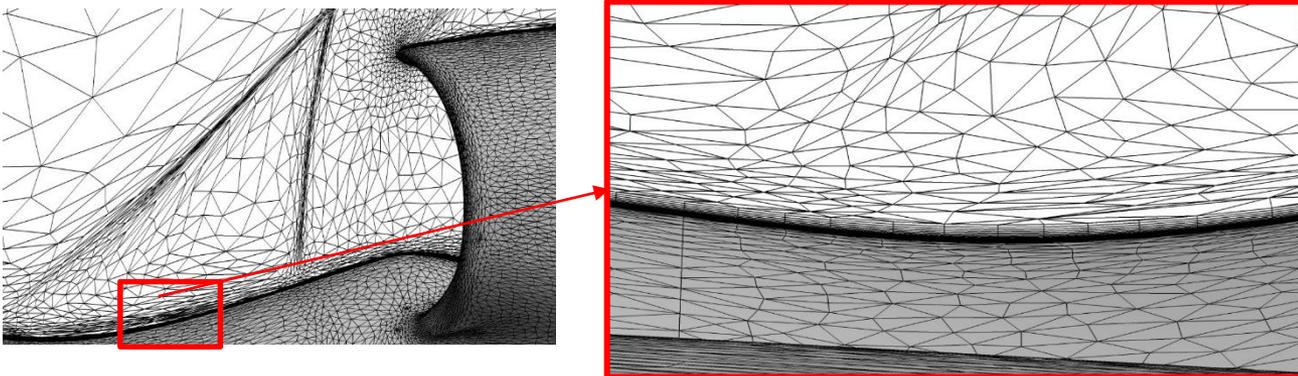
- ✓ No modifications



Adaptive Grid Generation



- Iterative application of solution/adaptation at specified sequence of target cell sizes (complexity)
- This layer of BL elements inserted near wall



- $y^+ = 1$ normal spacing
- $\sim y^+ = 800$ total thickness of prism layers

Adaptive Grids

- **Coarse initial grids created for each configuration**
 - Anisotropic triangular surface mesh (automatically refined to surface curvature)
 - Wall normal spacing $y^+ \sim 500$
 - Prism/Tet elements (600K axie, 265K biconvex, 842K c608)

- **Adapted Using 2 Error Estimates**

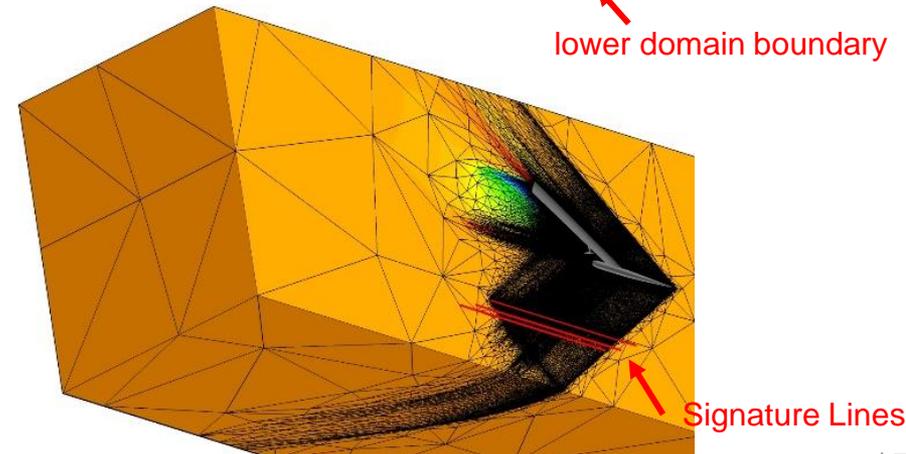
Biconvex Configuration – Adapted Grids

Multiscale Error Estimate

- Minimize L_p interpolation error of Mach Hessian
- Targets adaptation to reduce error globally

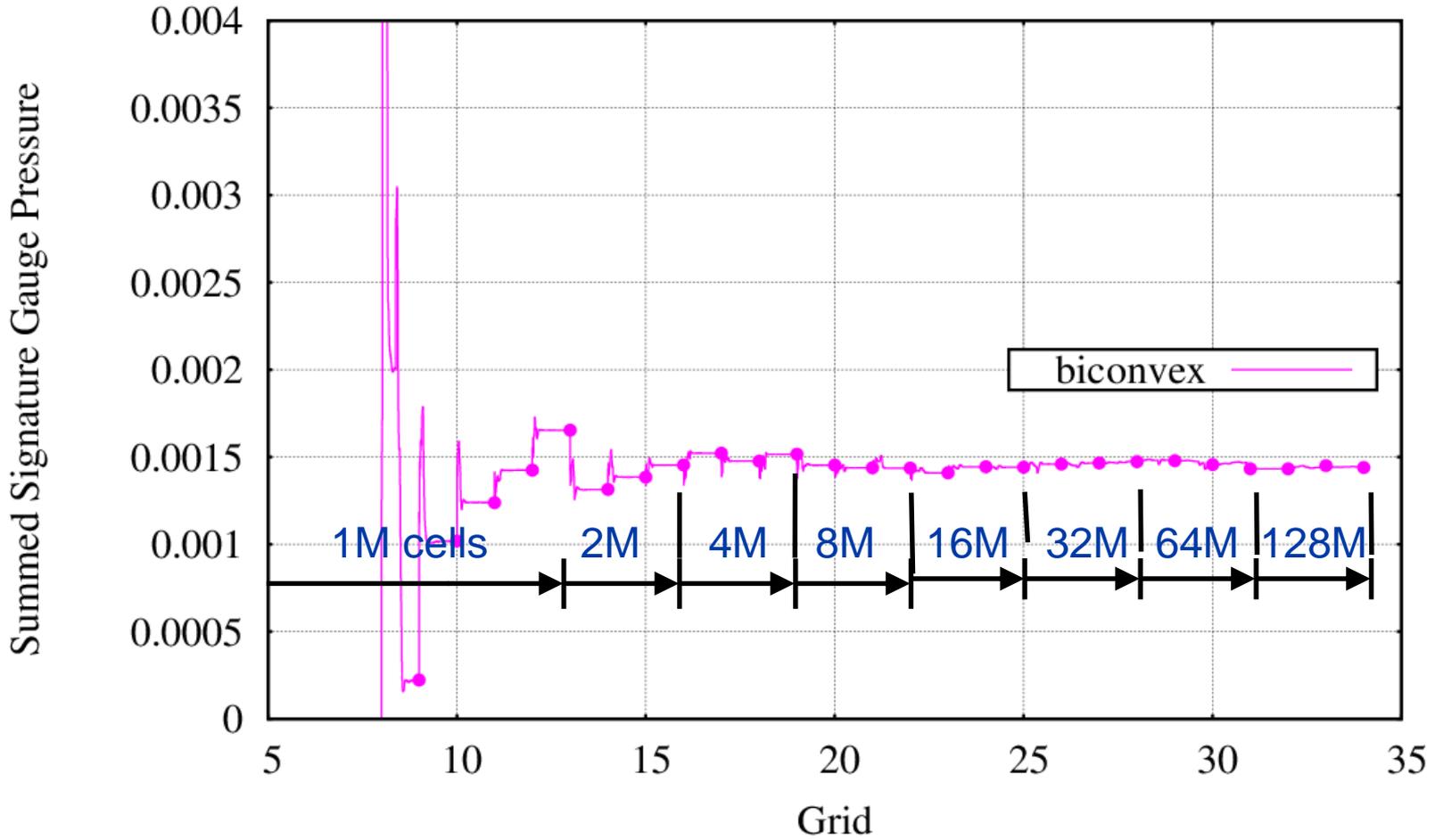
Goal Oriented Error Estimate

- Minimize error in gauge pressure at signature lines
- Only adapts mesh where it impacts solution on signature lines



Sample Output Functional Grid Convergence – Biconvex

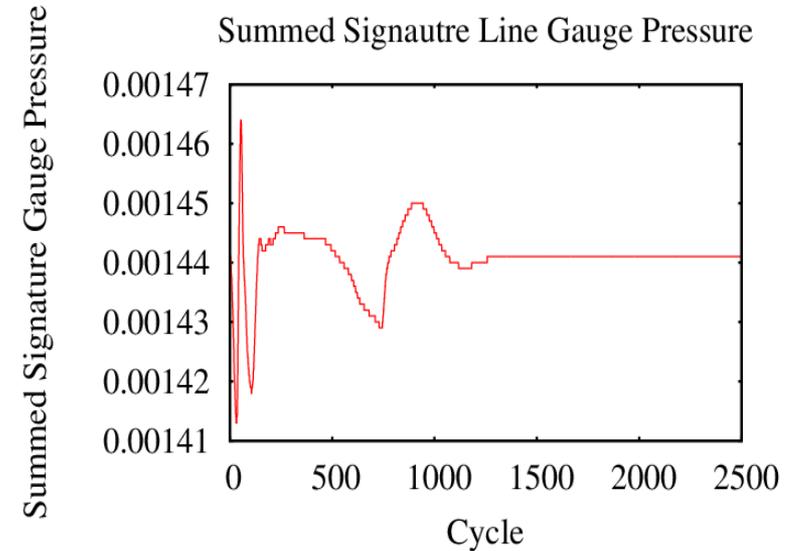
SBPW3
Summed Signature Pressure History



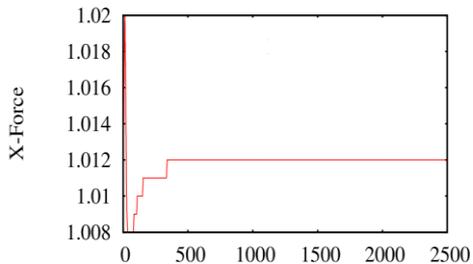
Sample BCFD Solution Convergence

Biconvex 128M Cell - Goal Oriented Adapted Grid

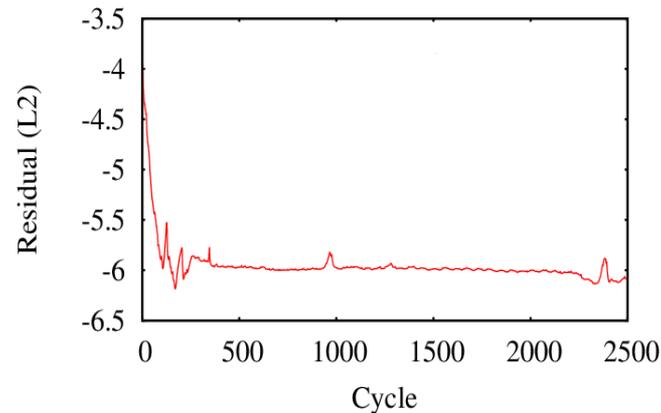
- **Solution convergence determined from residuals, forces, and sum of gauge pressure**
- **Initial solution interpolated from previous grid**
- **Solution convergence comparable with other BCFD adaptive cases**



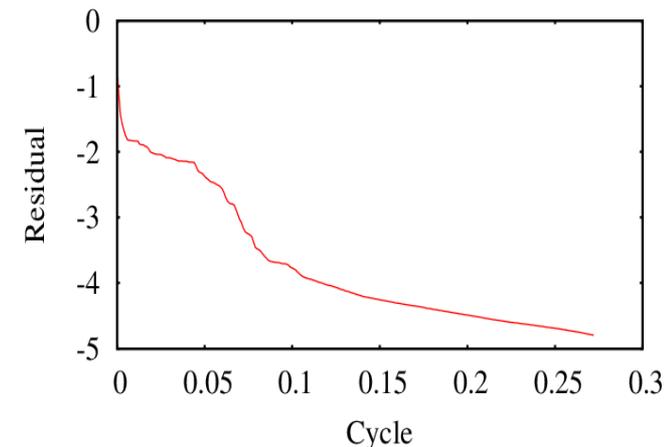
X-Force History



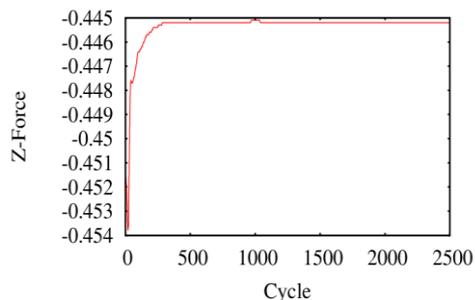
Residual History



Adjoint Residual History



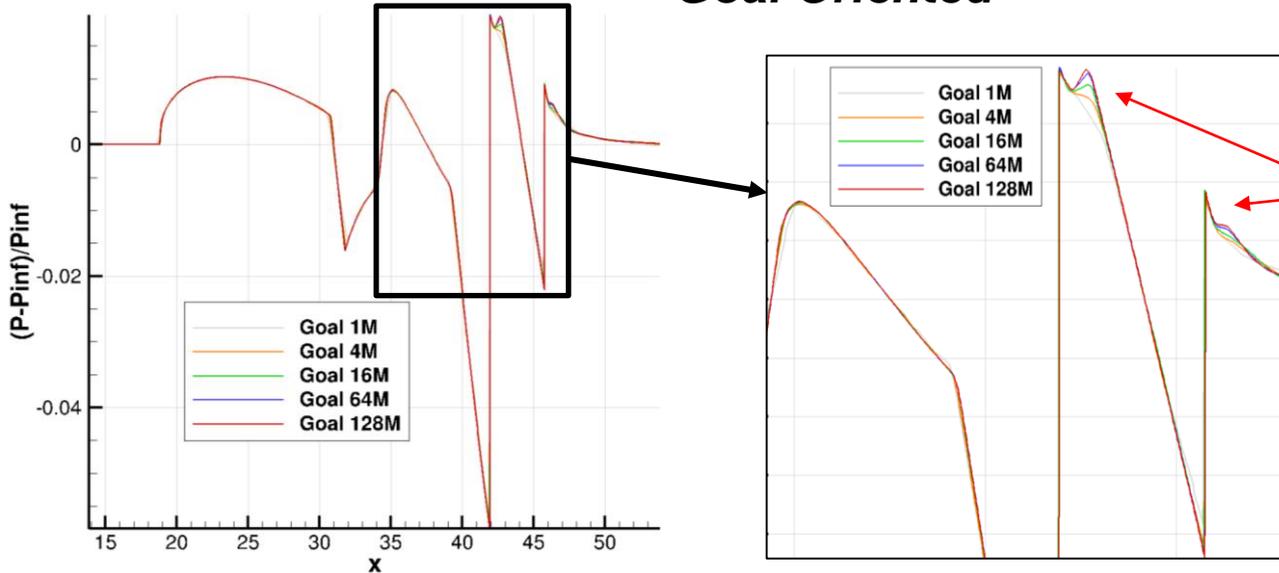
Z-Force History



Adaptive Grid Convergence – Biconvex Model

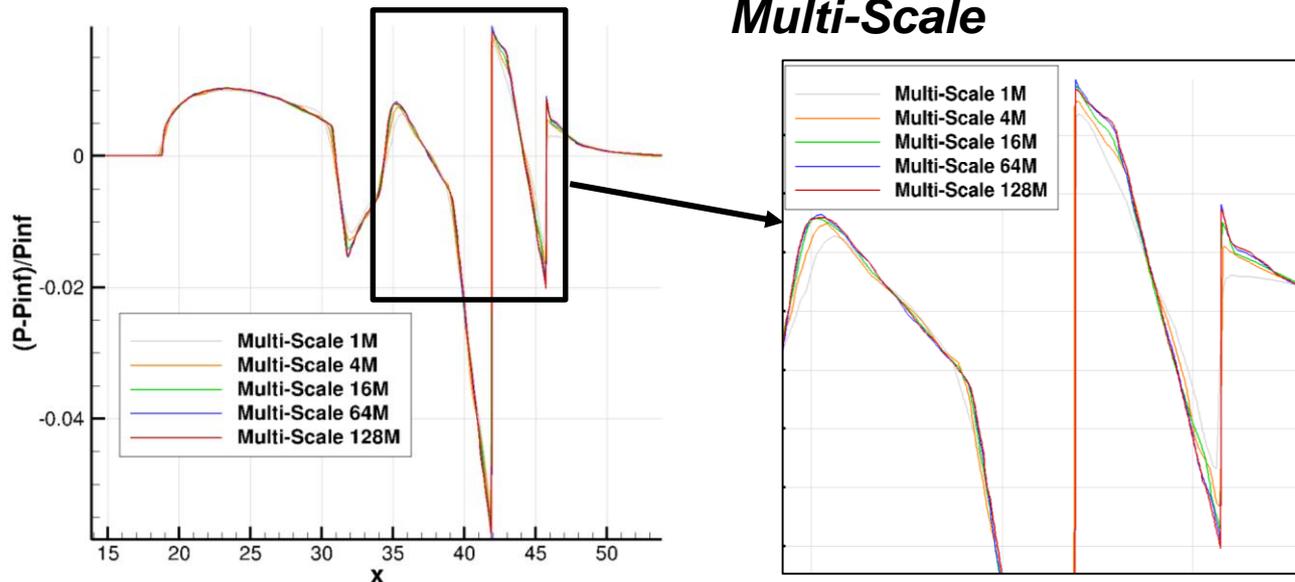


Goal Oriented



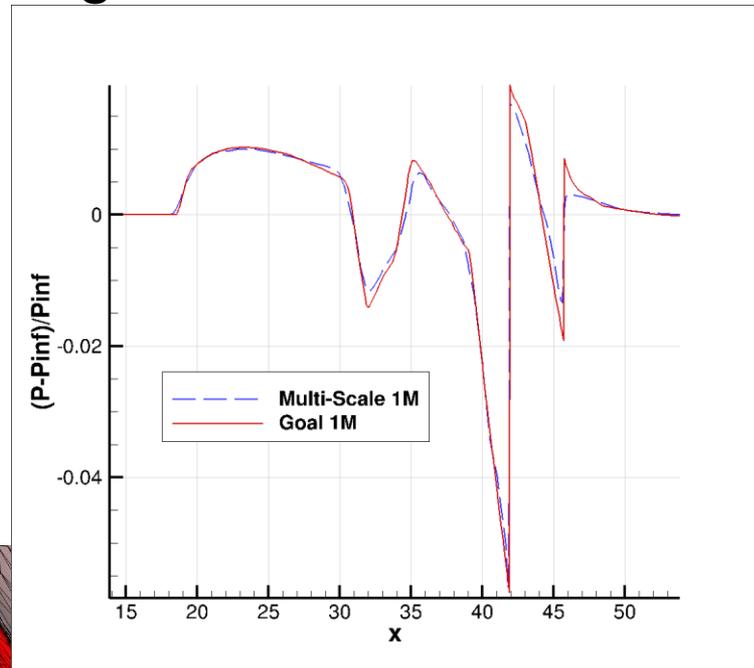
- Body signature well captured at 1M cells
- Secondary compression peaks aft of nozzle slow to converge

Multi-Scale

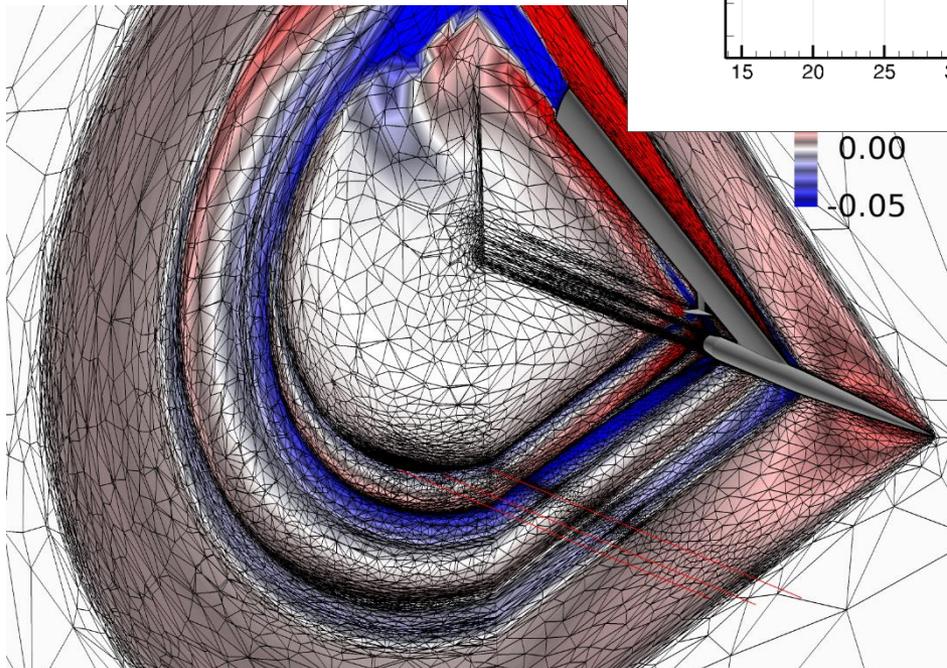


- Body signature captured after 16M cells
- Secondary compression peaks not resolved with 128M cells

Adaptive Grid Convergence – Biconvex Case (1M Cells)

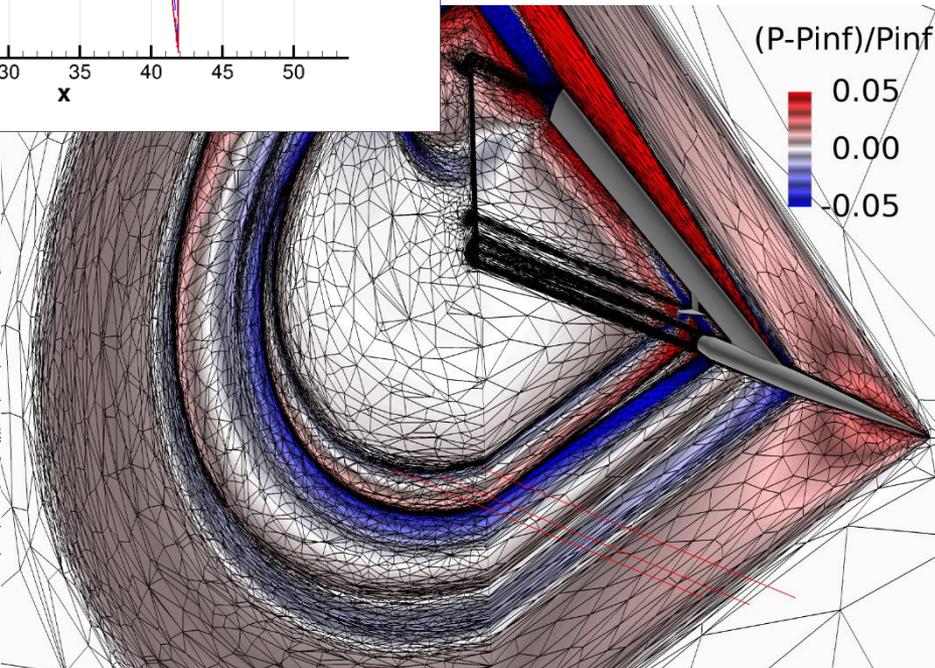


- Signature from body resolved by GO error



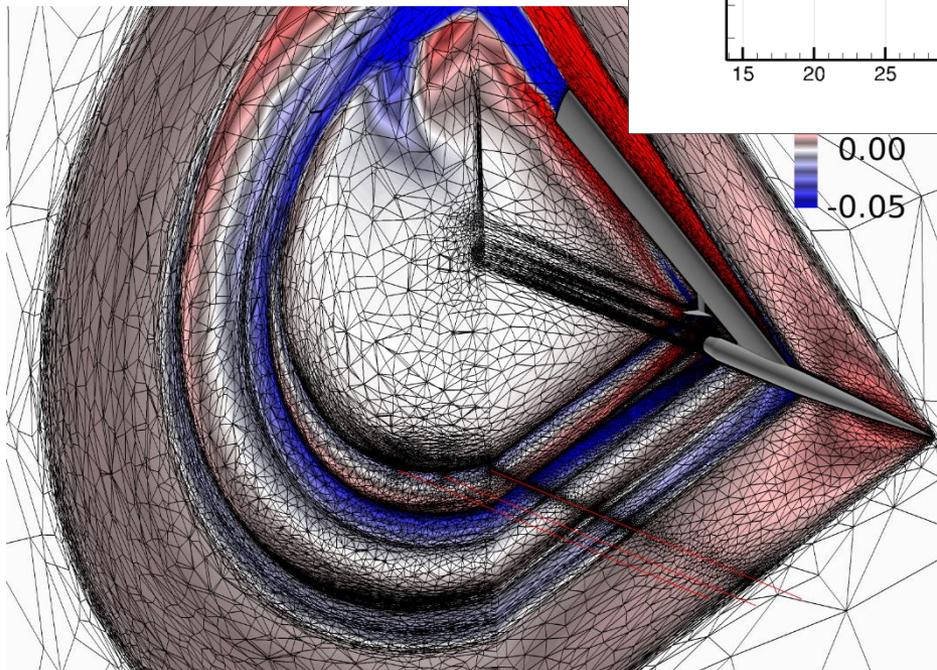
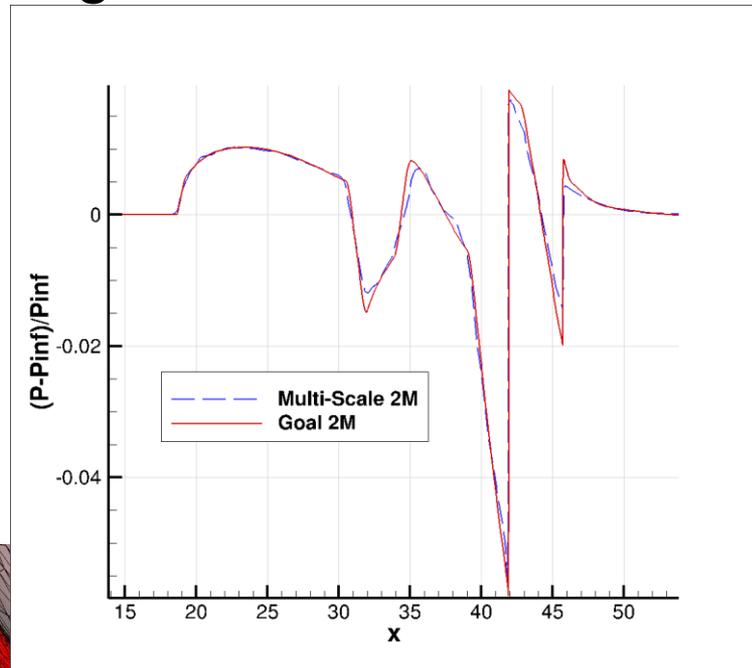
Goal Oriented Adapted Grid

Copyright © 2020 Boeing. All rights reserved.

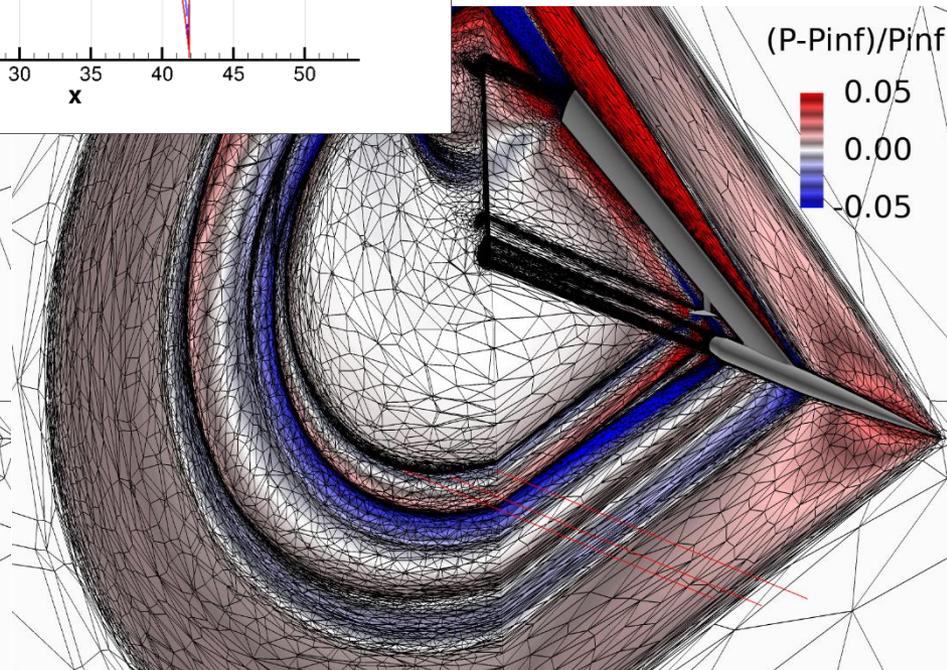


Multi-Scale Adapted Grid

Adaptive Grid Convergence – Biconvex Case (2M Cells)

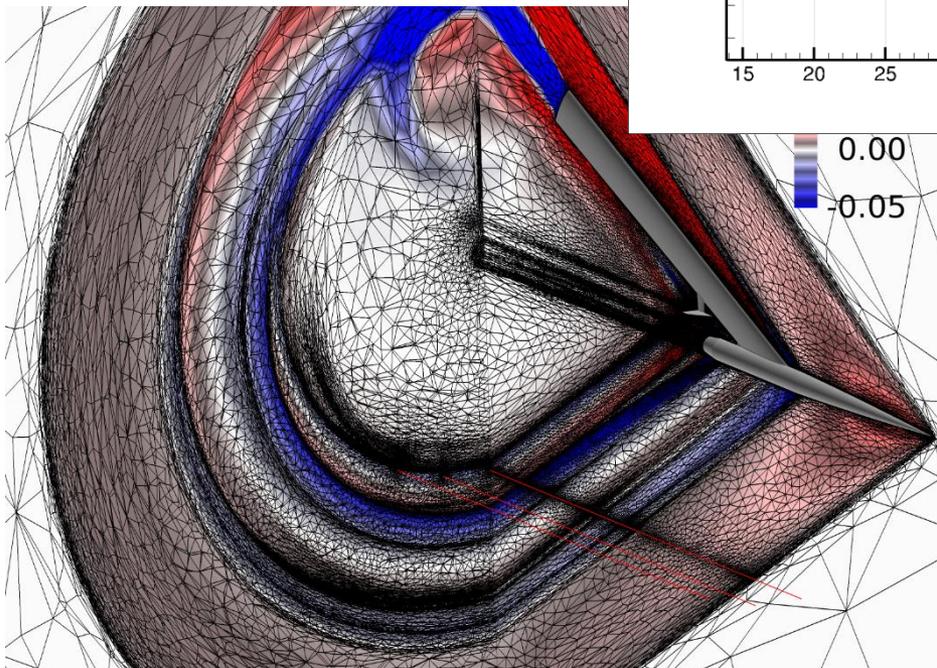
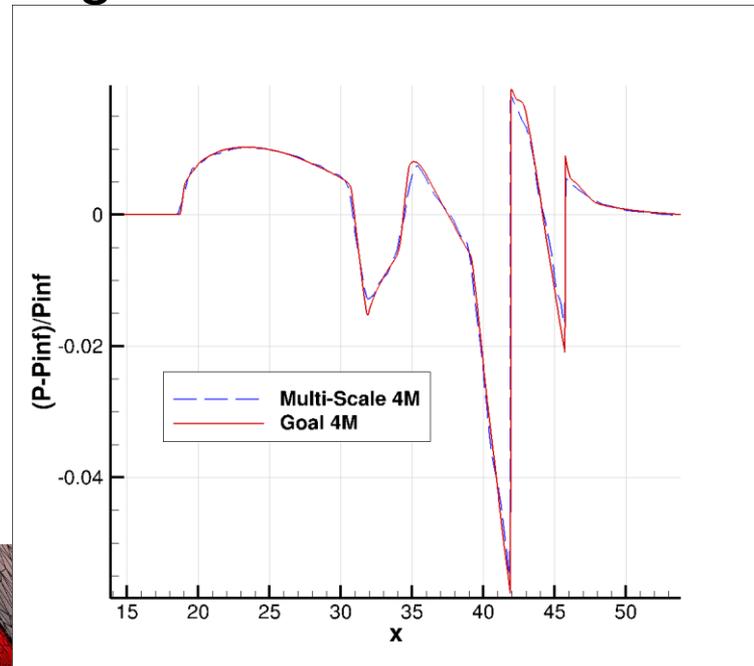
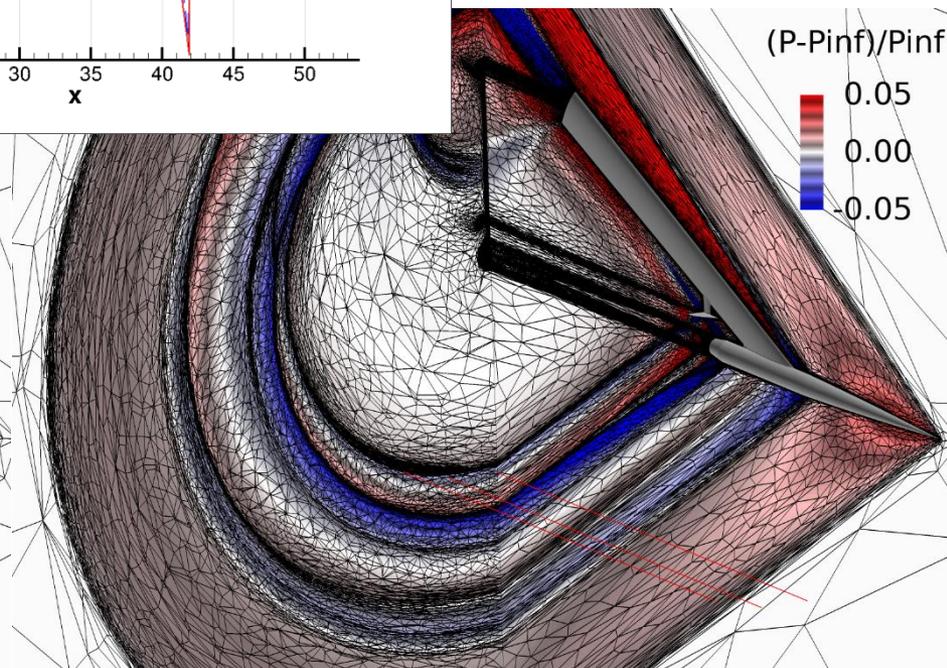


Goal Oriented Adapted Grid

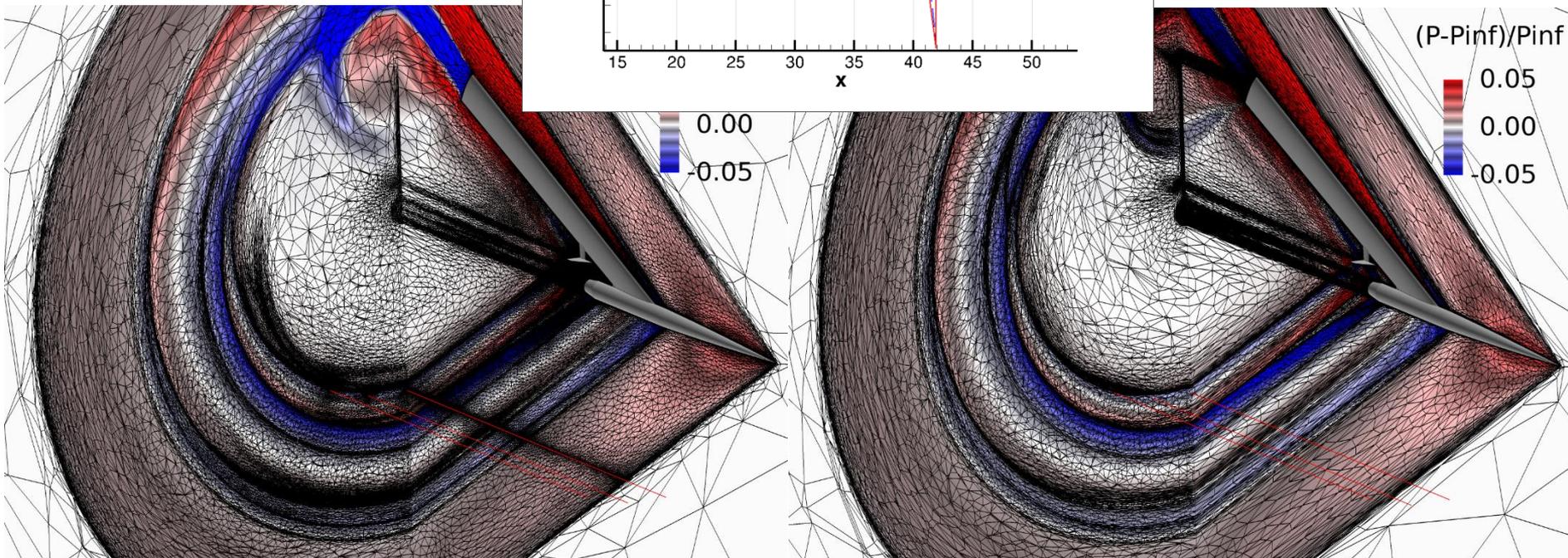
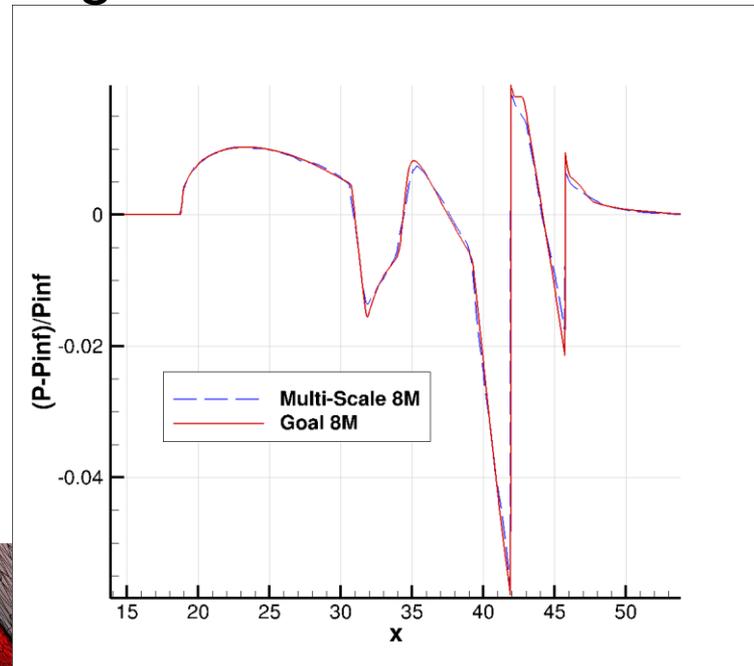


Multi-Scale Adapted Grid

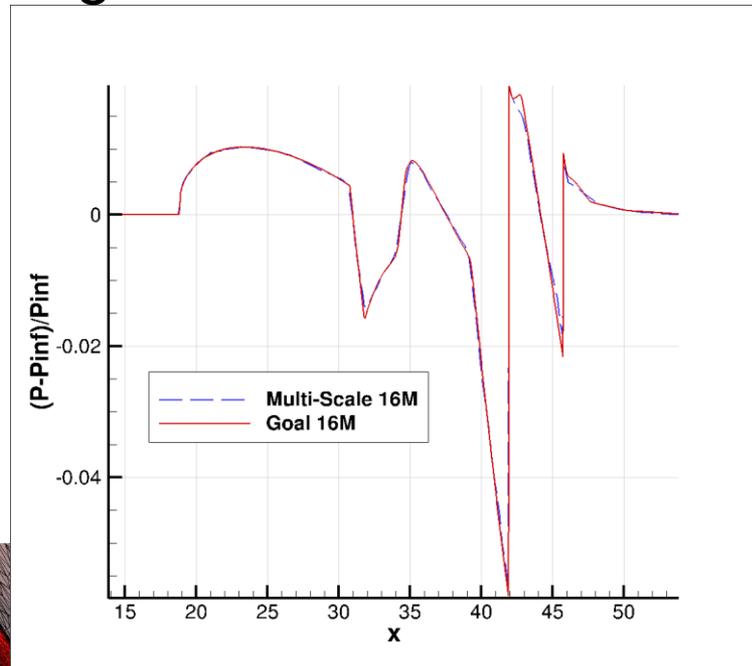
Adaptive Grid Convergence – Biconvex Case (4M Cells)

**Goal Oriented Adapted Grid****Multi-Scale Adapted Grid**

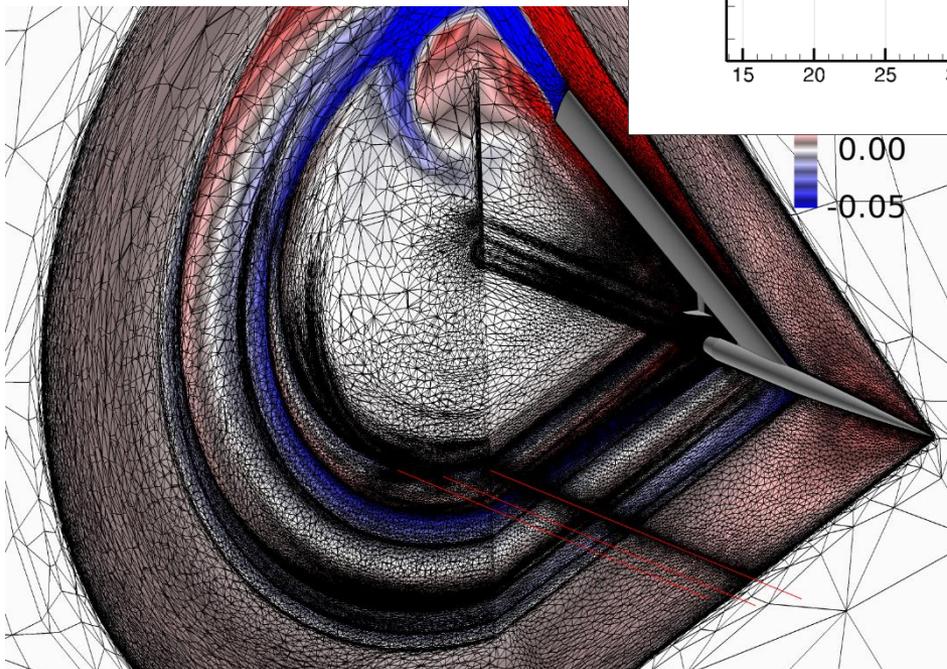
Adaptive Grid Convergence – Biconvex Case (8M Cells)

**Goal Oriented Adapted Grid****Multi-Scale Adapted Grid**

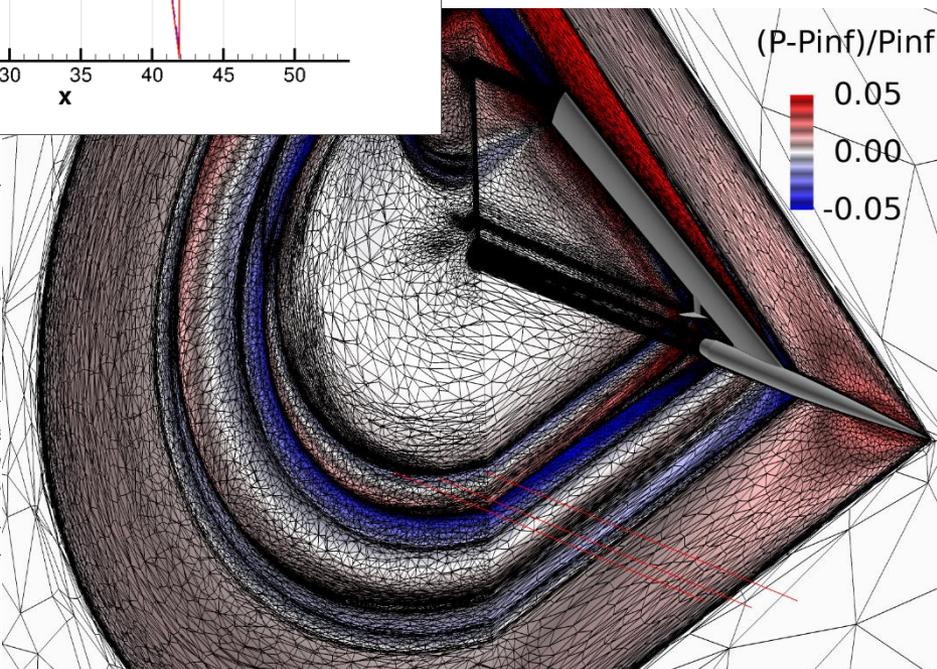
Adaptive Grid Convergence – Biconvex Case (16M Cells)



- Body signature resolved for GO and MS

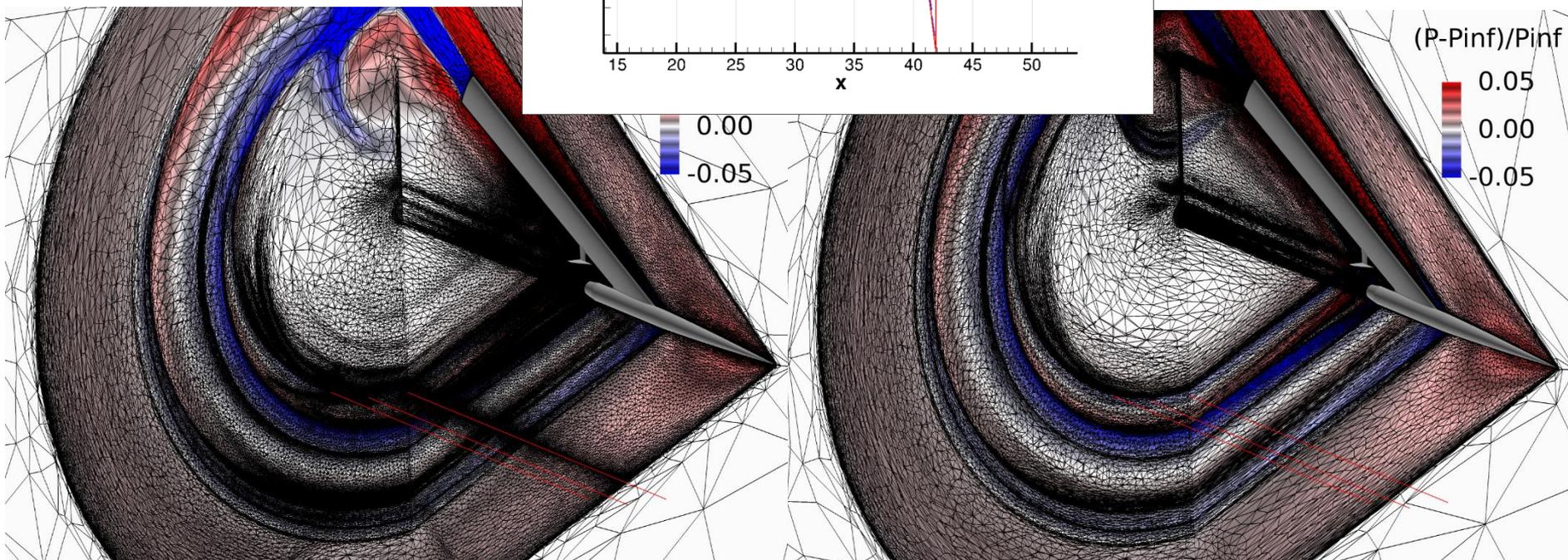
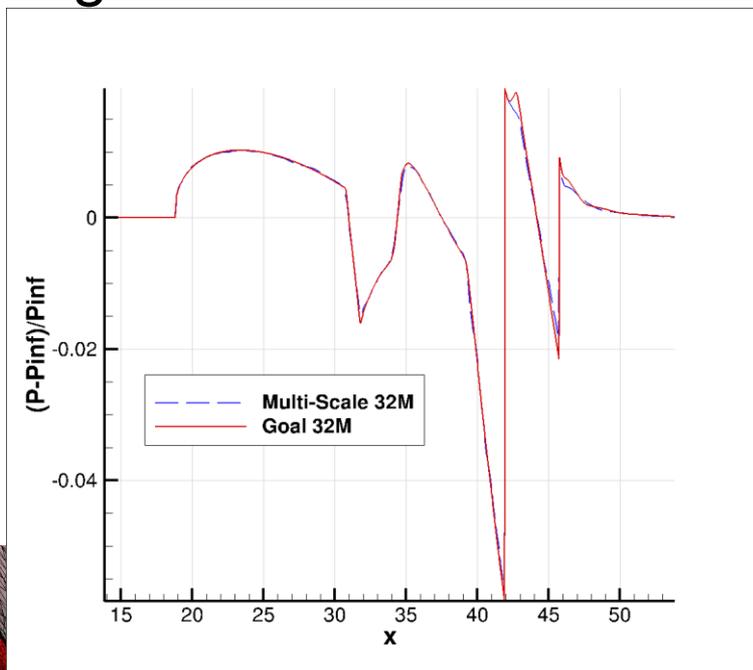


Goal Oriented Adapted Grid



Multi-Scale Adapted Grid

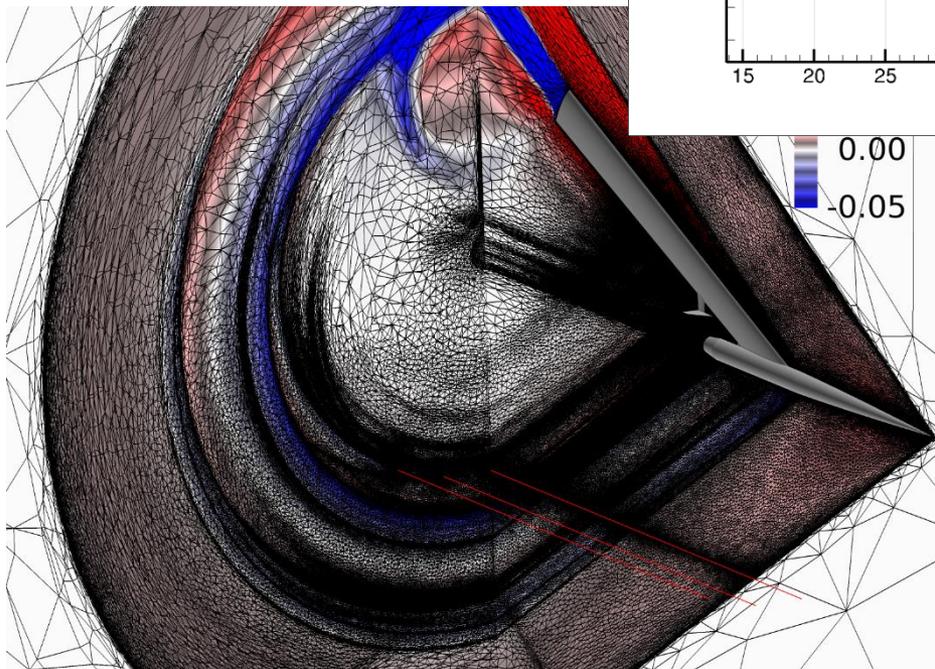
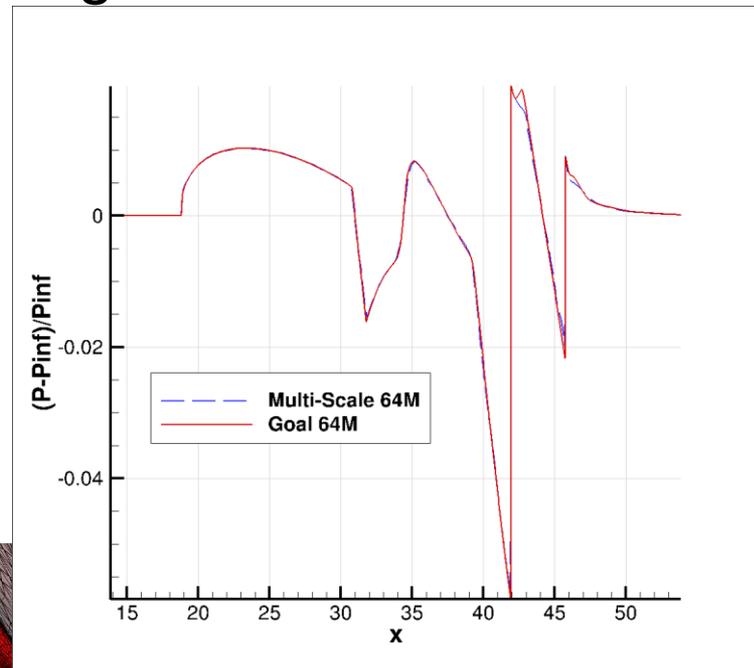
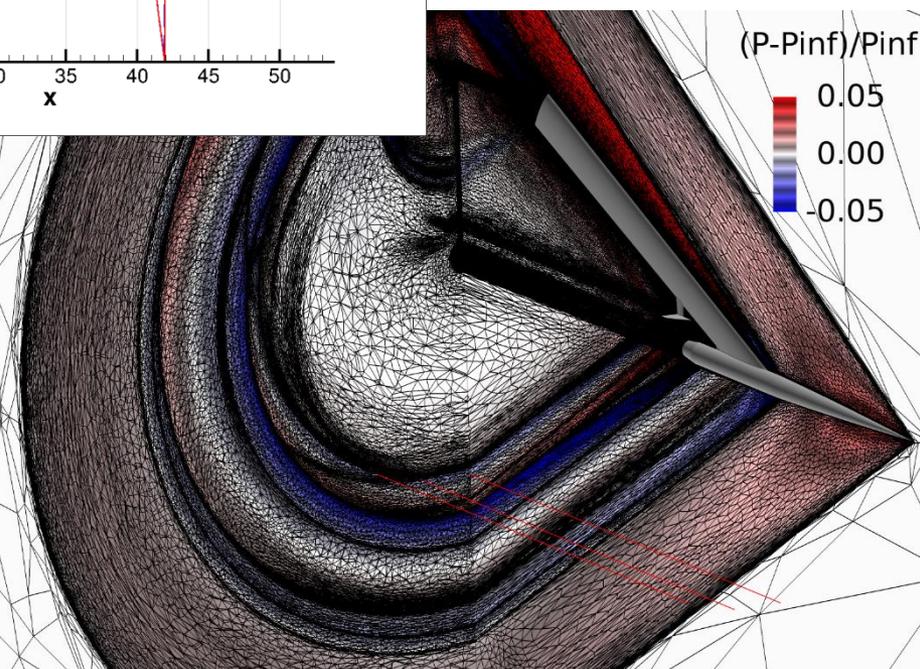
Adaptive Grid Convergence – Biconvex Case (32M Cells)



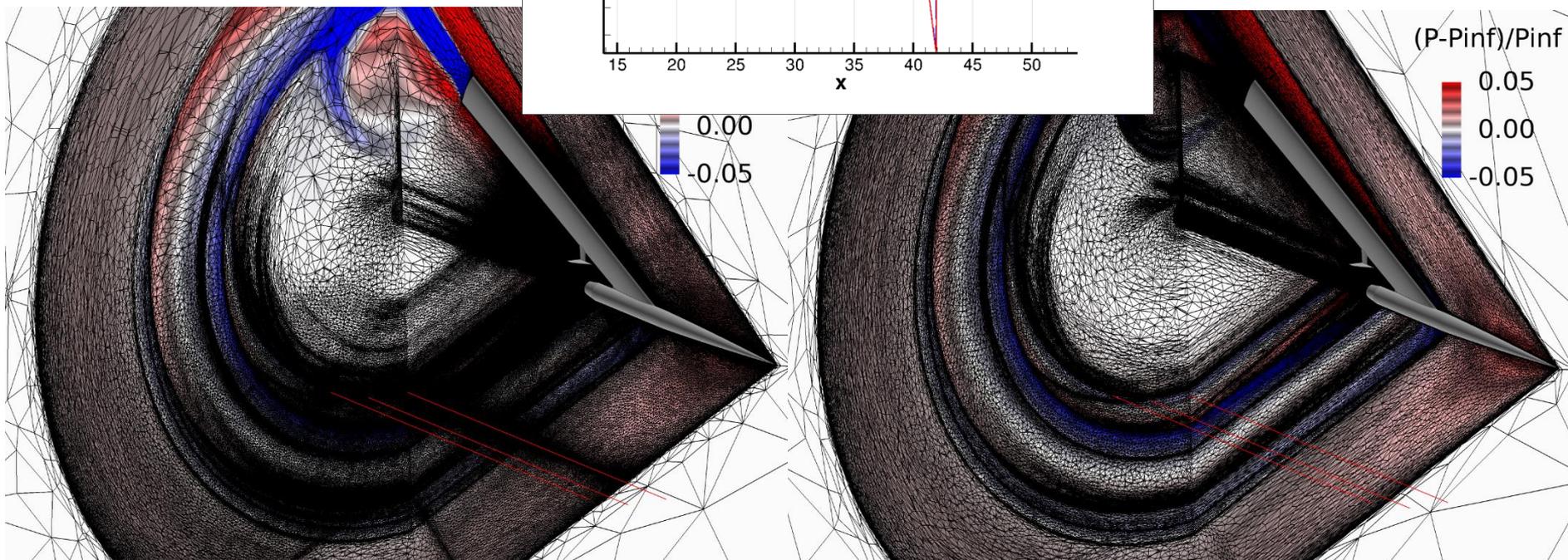
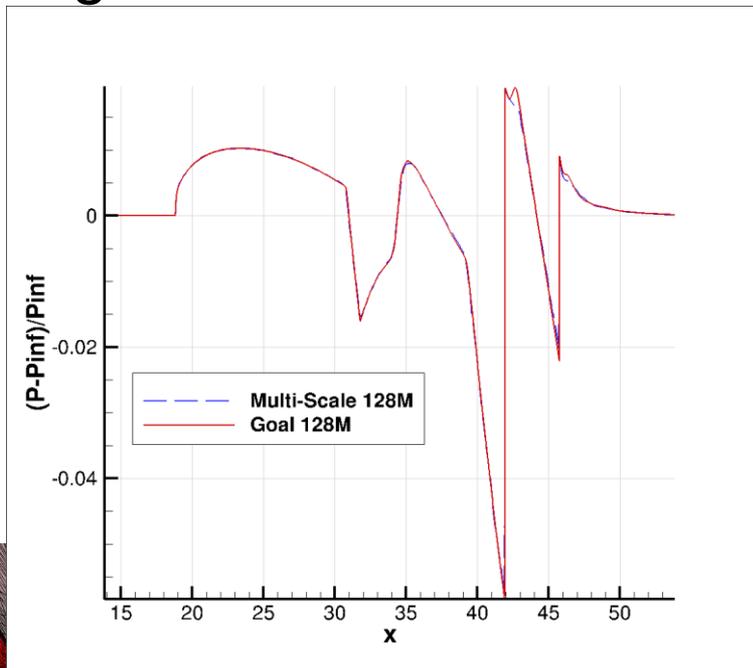
Goal Oriented Adapted Grid

Multi-Scale Adapted Grid

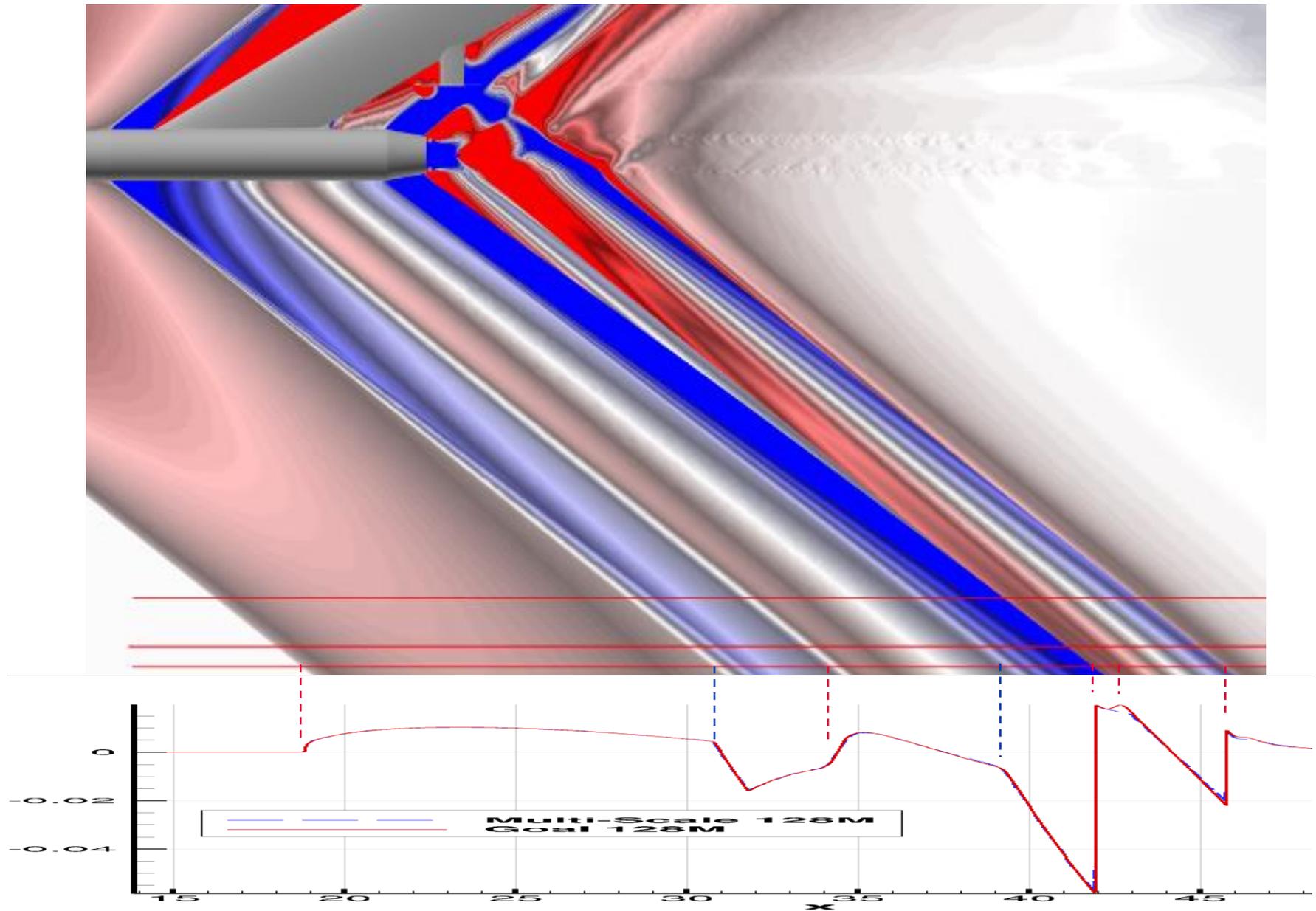
Adaptive Grid Convergence – Biconvex Case (64M Cells)

**Goal Oriented Adapted Grid****Multi-Scale Adapted Grid**

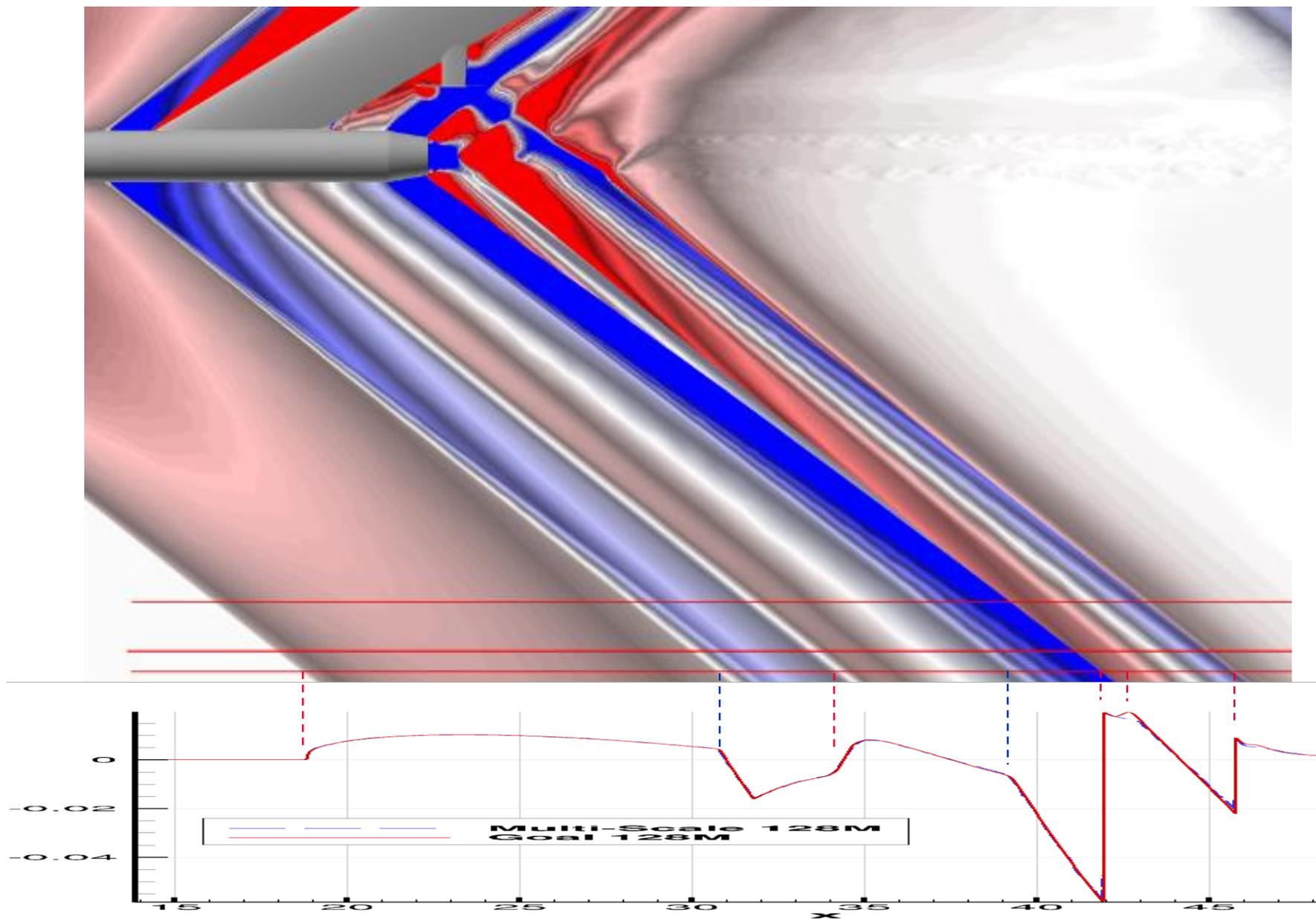
Adaptive Grid Convergence – Biconvex Case (128M Cells)

**Goal Oriented Adapted Grid****Multi-Scale Adapted Grid**

Goal Oriented Error Estimate

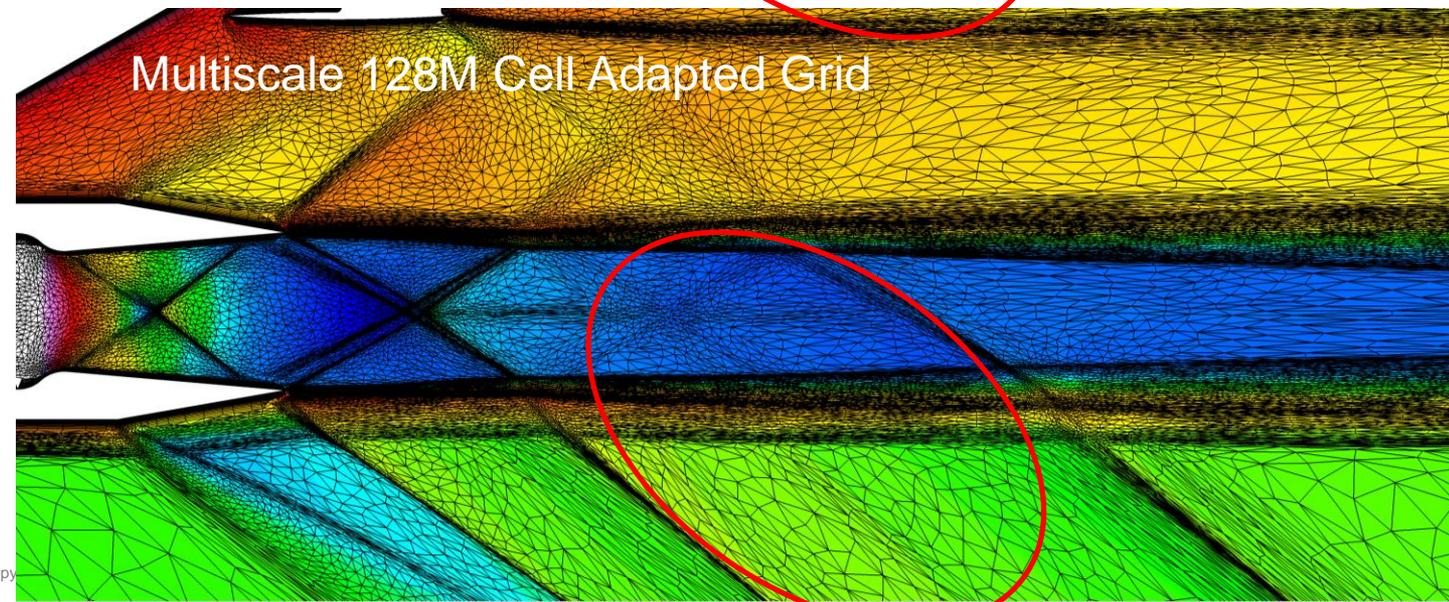
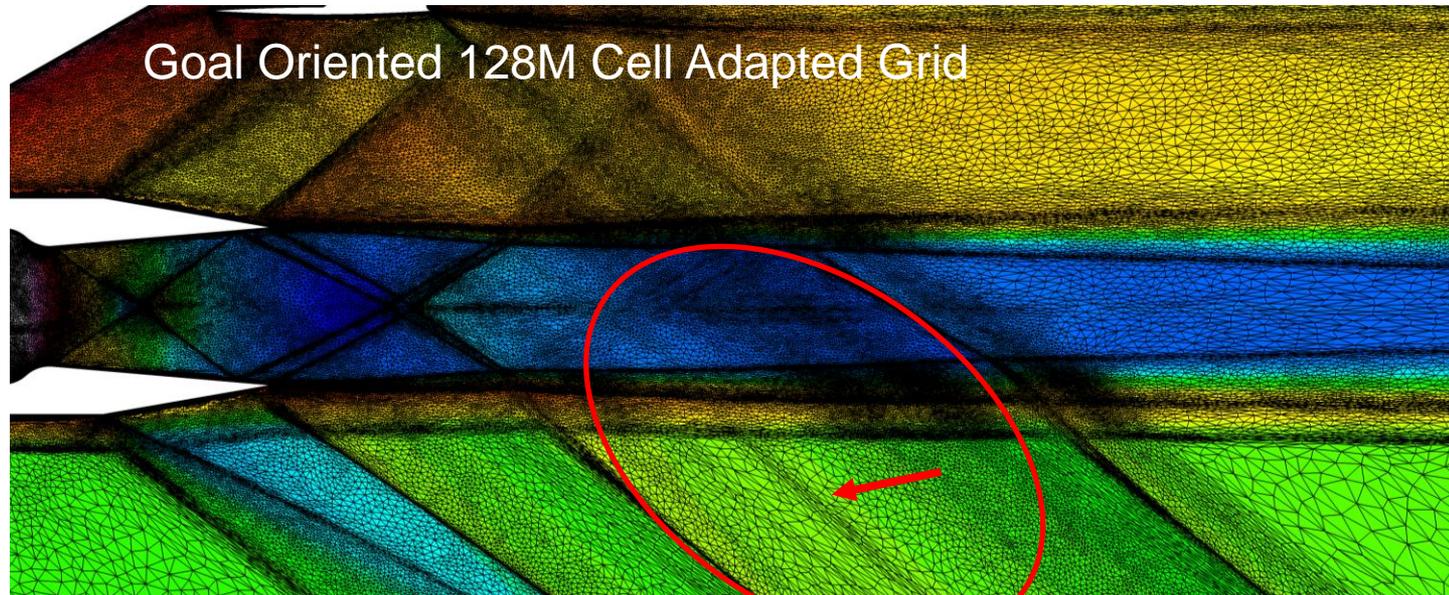


Multiscale Error Estimate

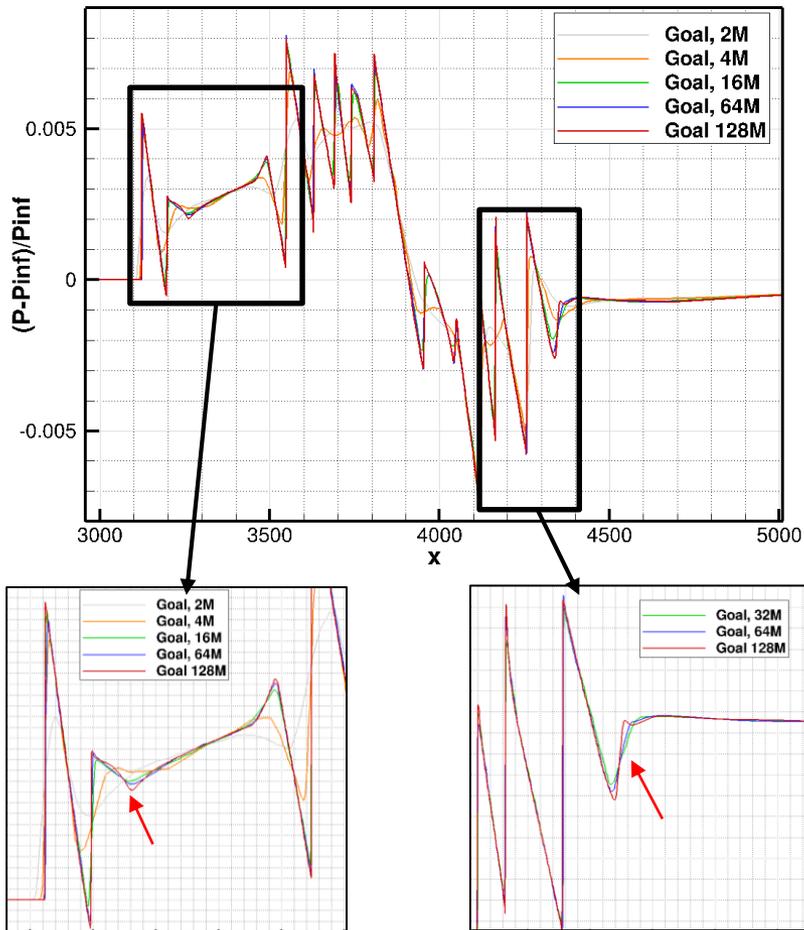


Mach Contour Comparison - Biconvex Nozzle Plume

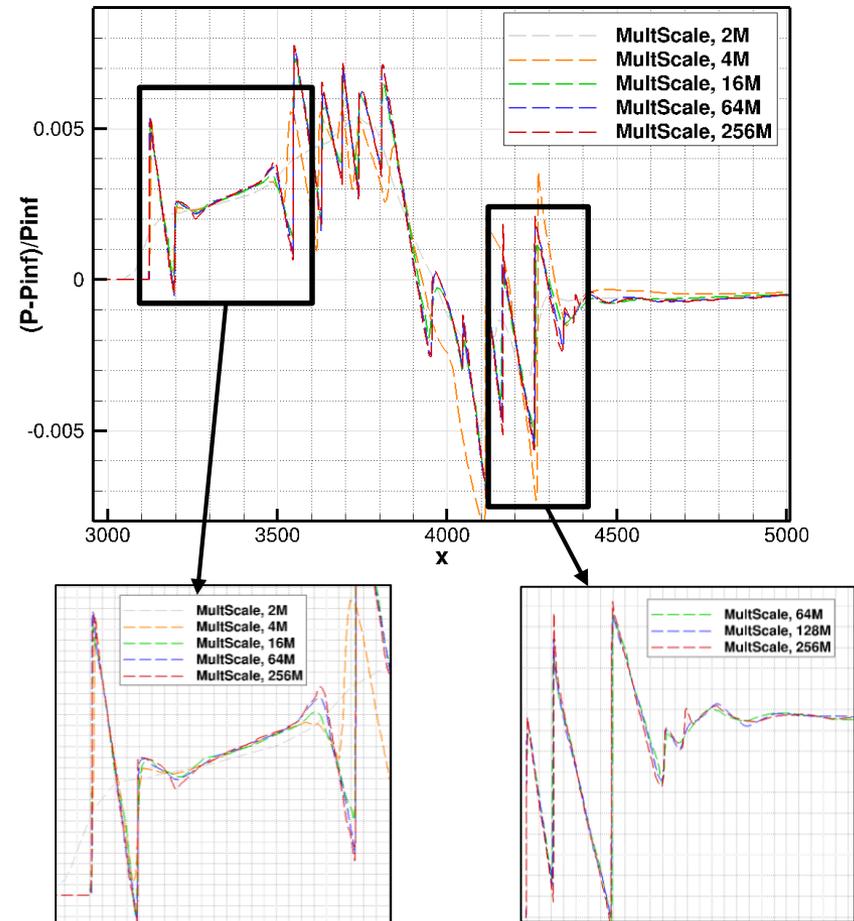
Goal Oriented and Multiscale 128M cell Adapted Grids



Adaptive Grid Convergence C608 Demonstrator

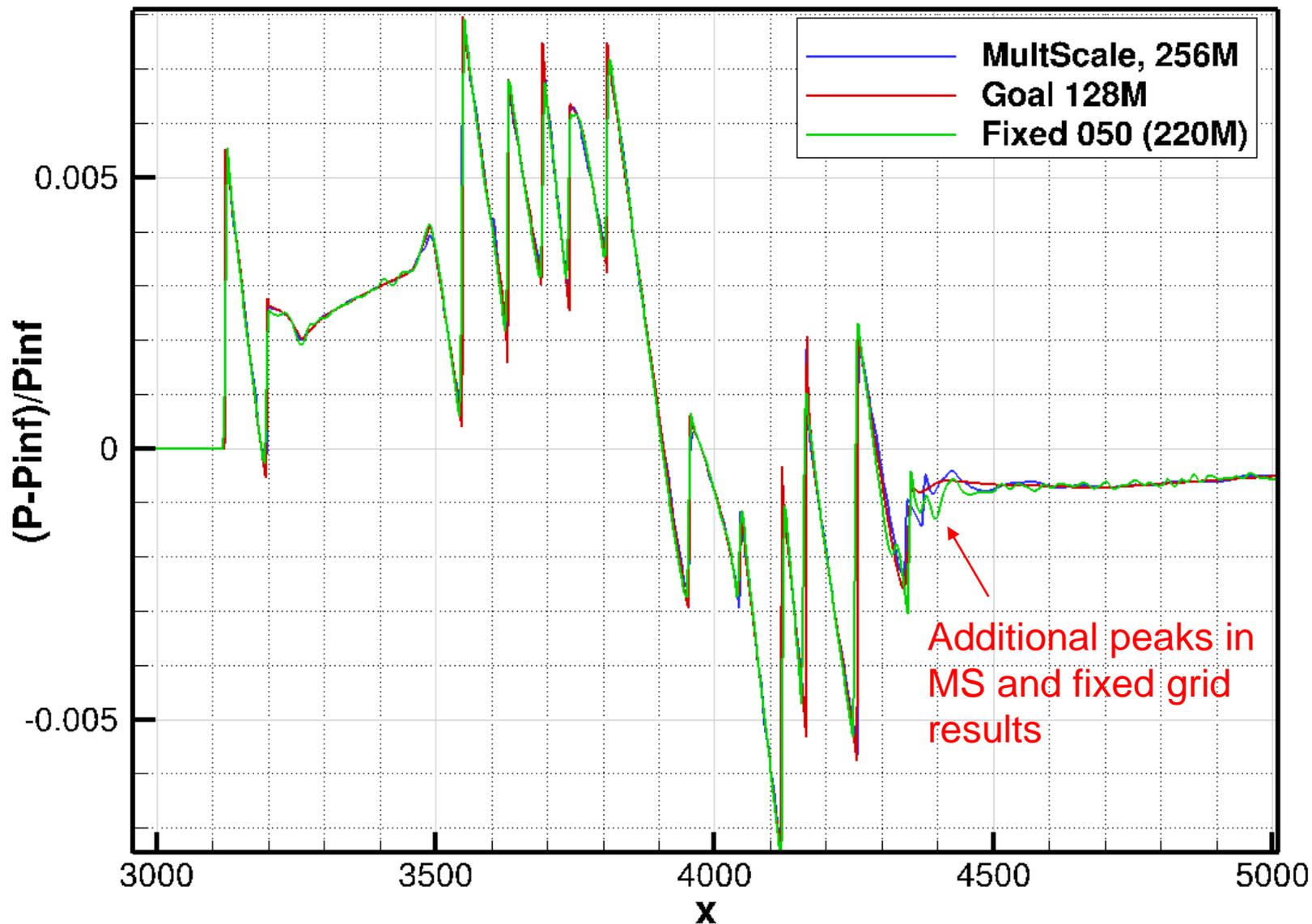
**Goal Oriented**

- Majority of signature captured at 64M cells
- Second nose expansion and nozzle wake interaction slow to converge

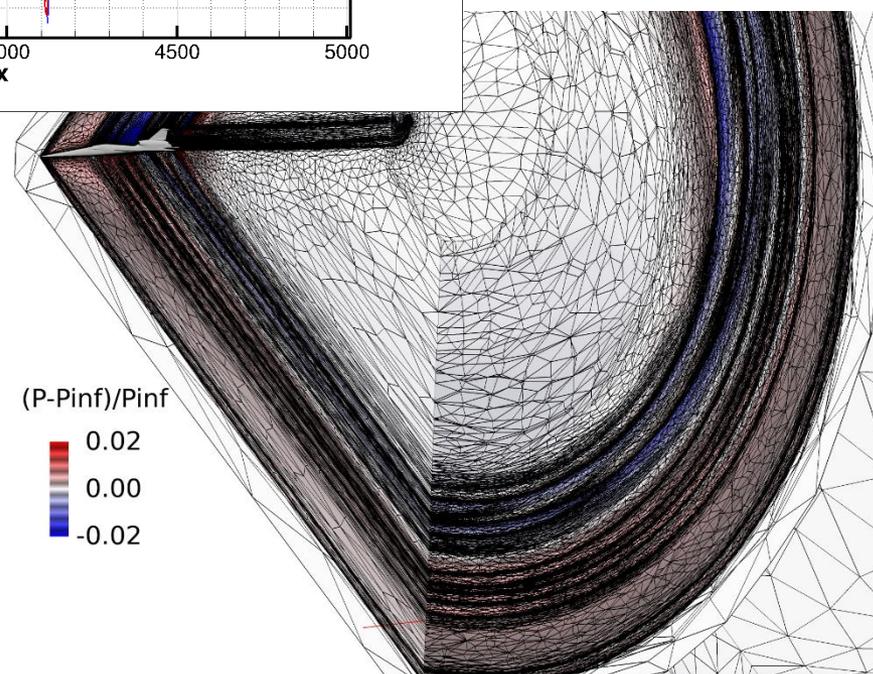
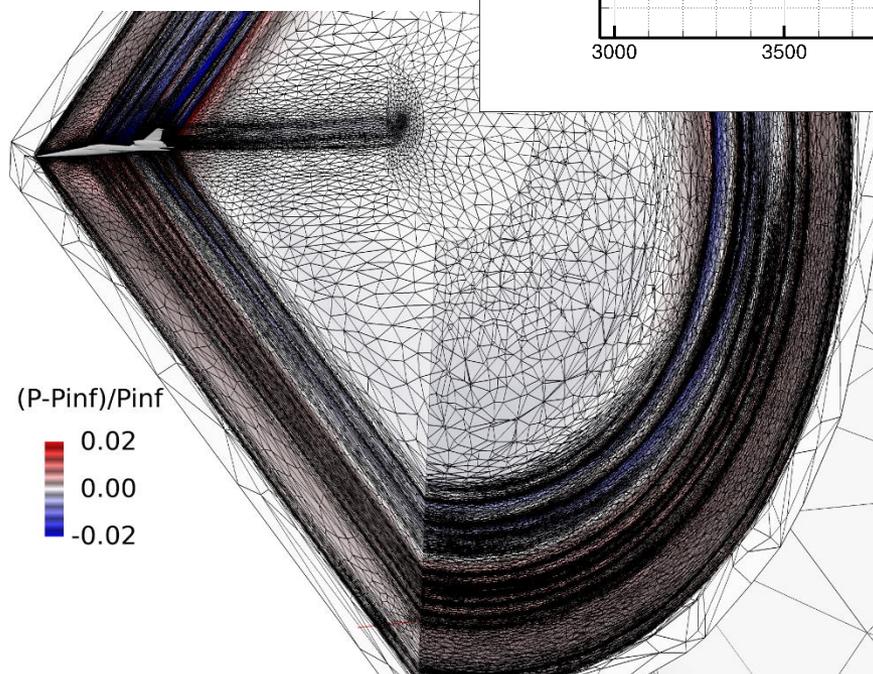
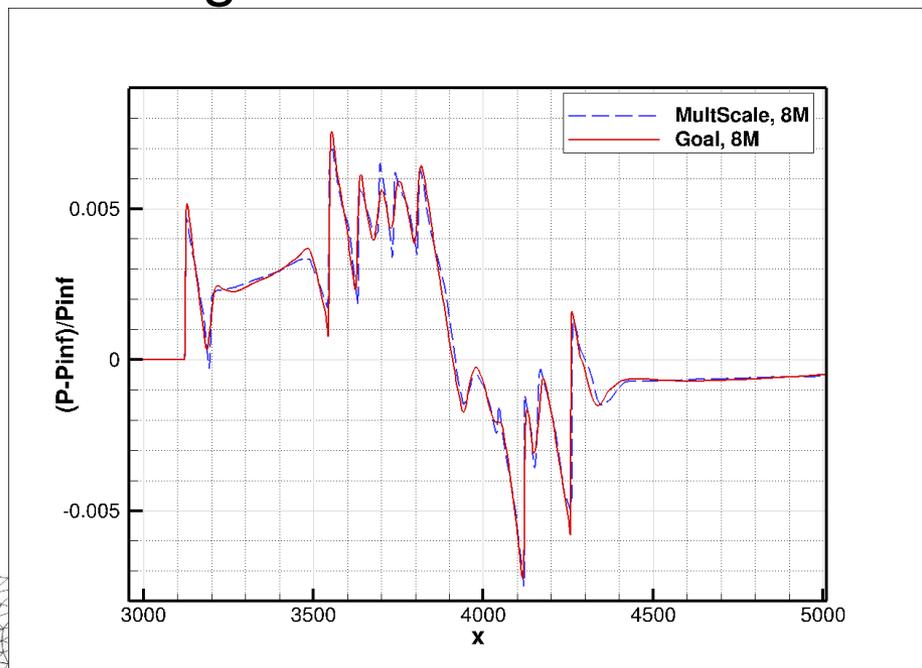
Multi-Scale

- Majority of signature captured at 64M cells
- Additional peaks in signature aft of nozzle

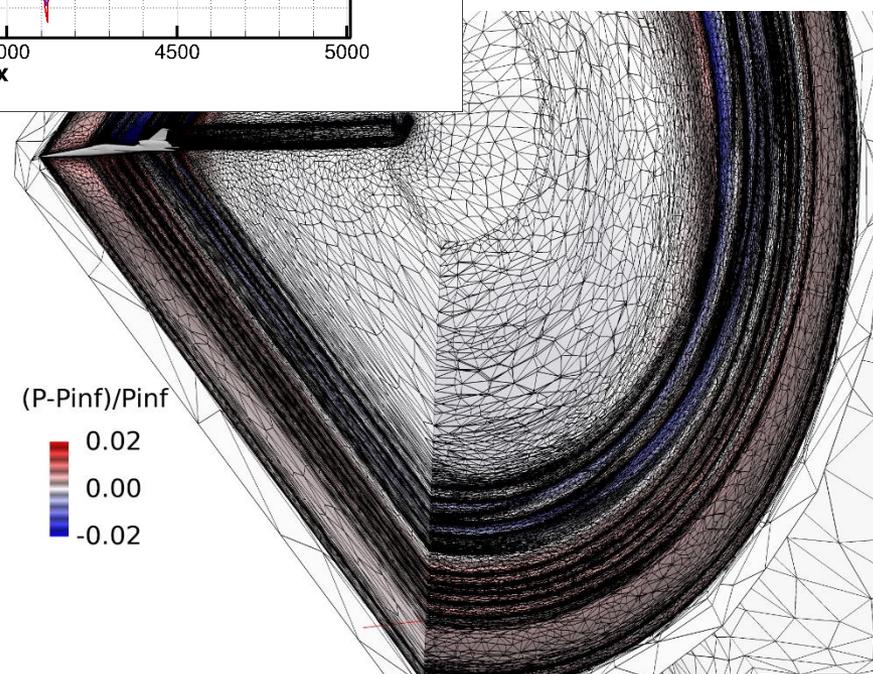
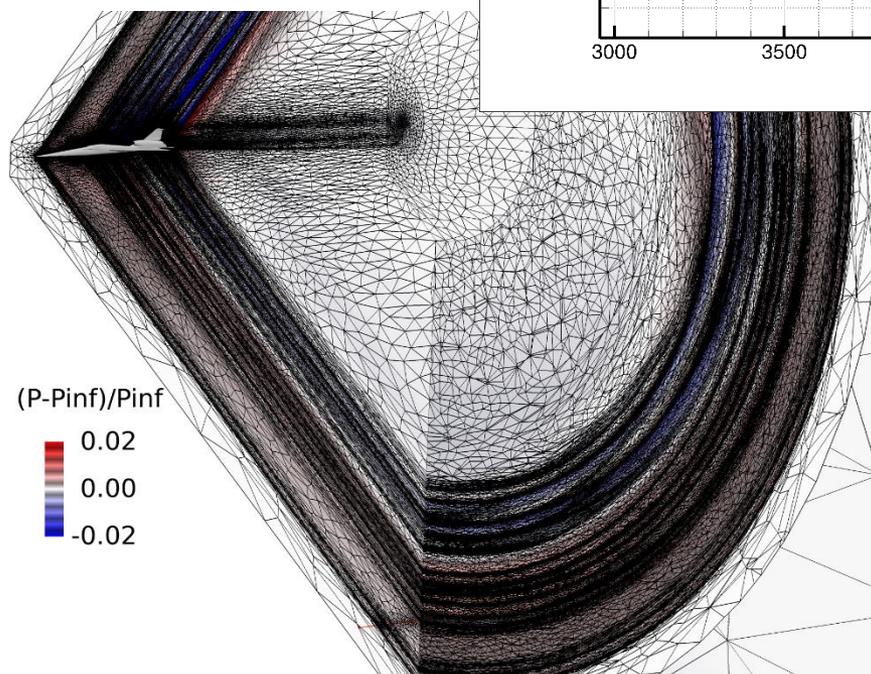
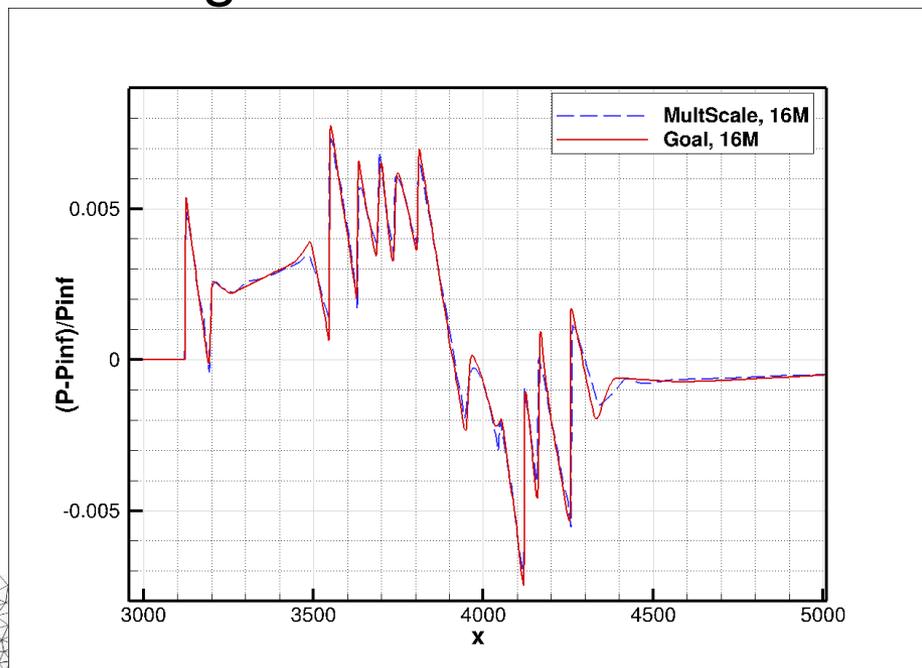
Comparison of c608 Near Field Signature Finest Fixed/Adapted Grids



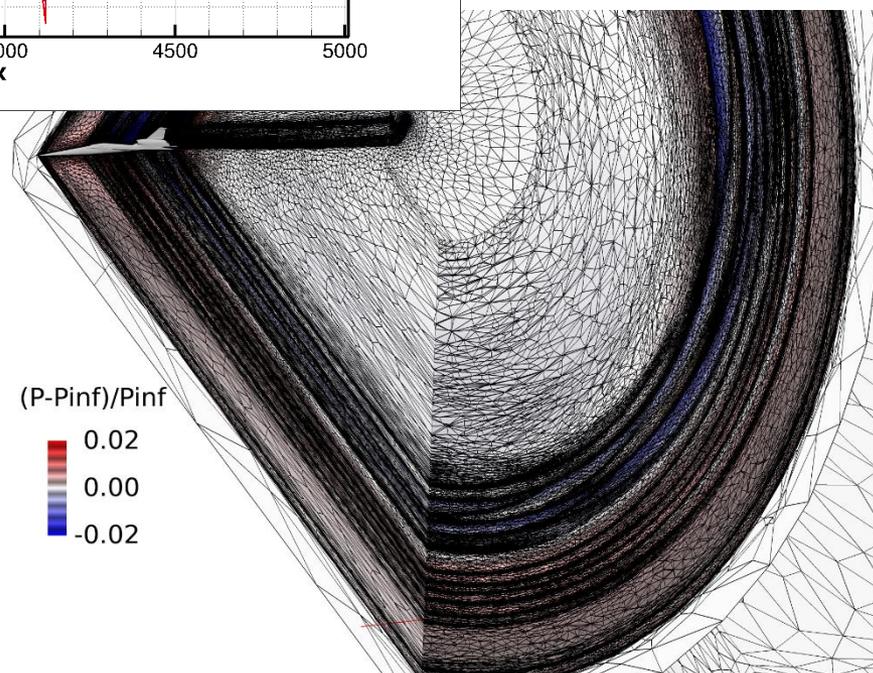
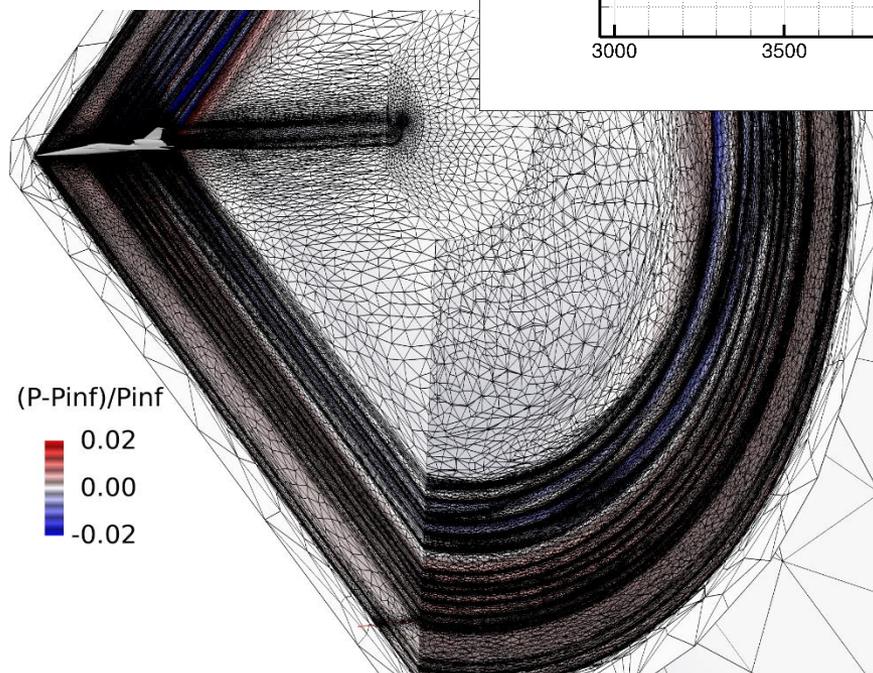
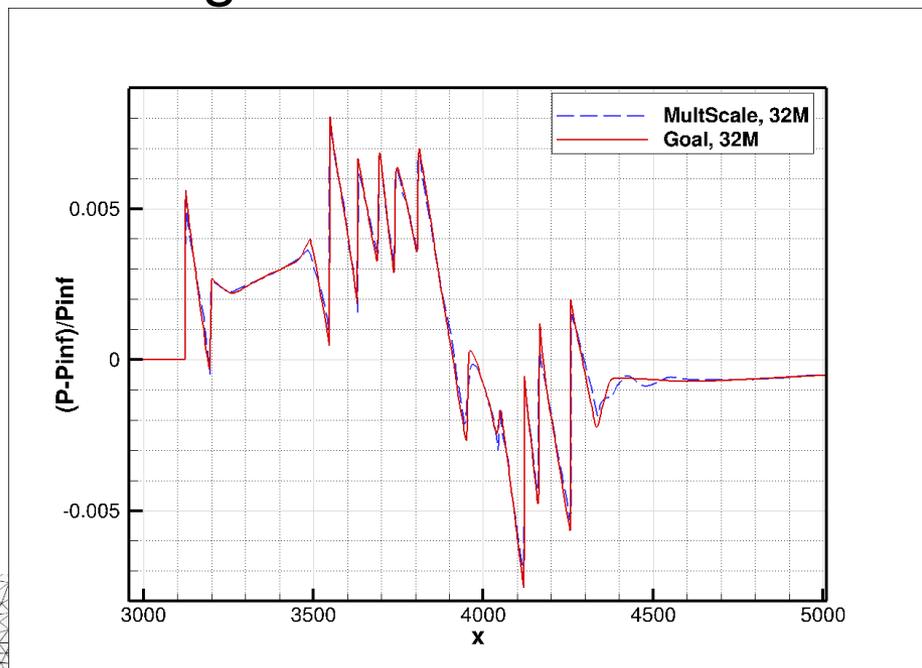
Adaptive Grid Convergence – c608 Case



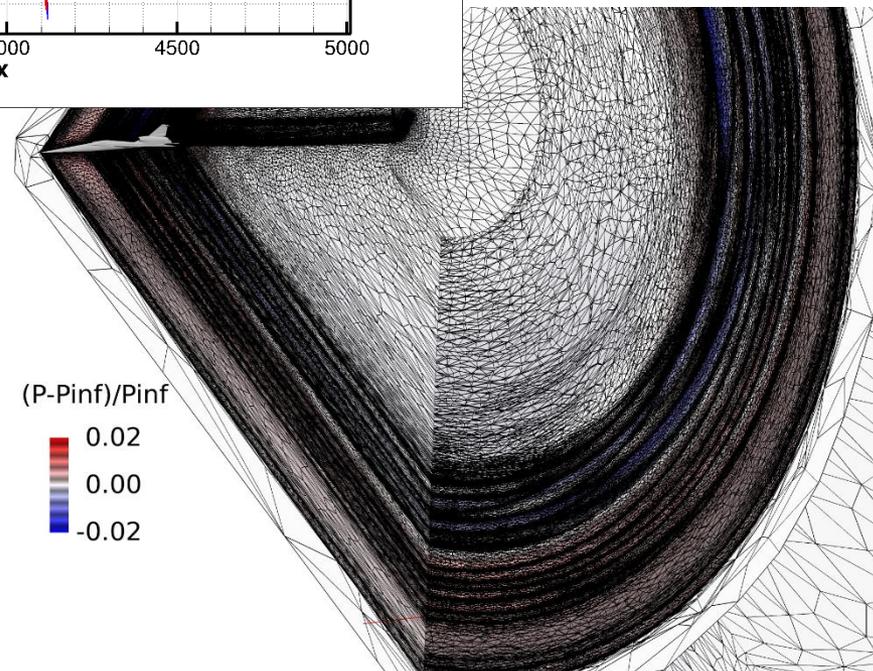
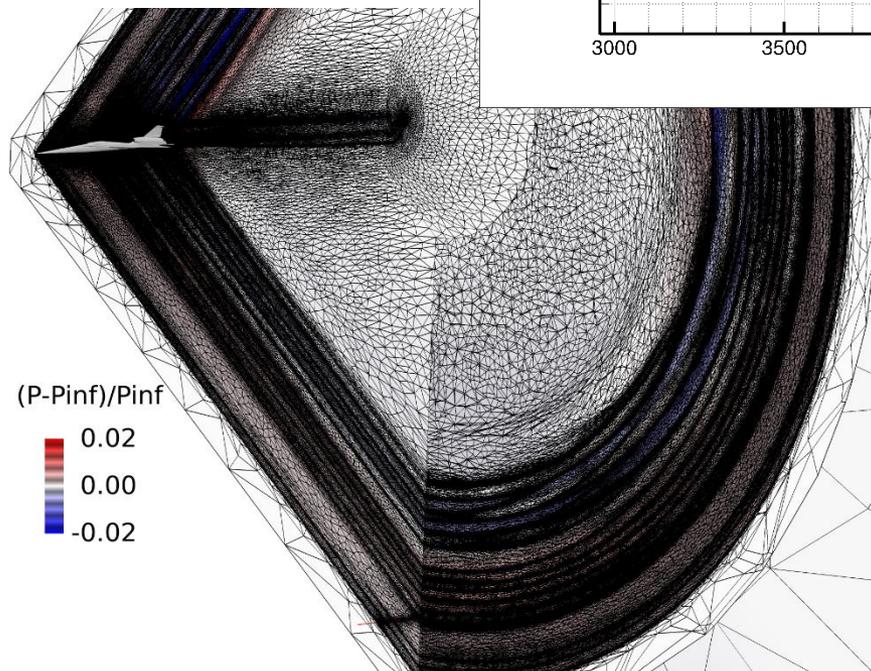
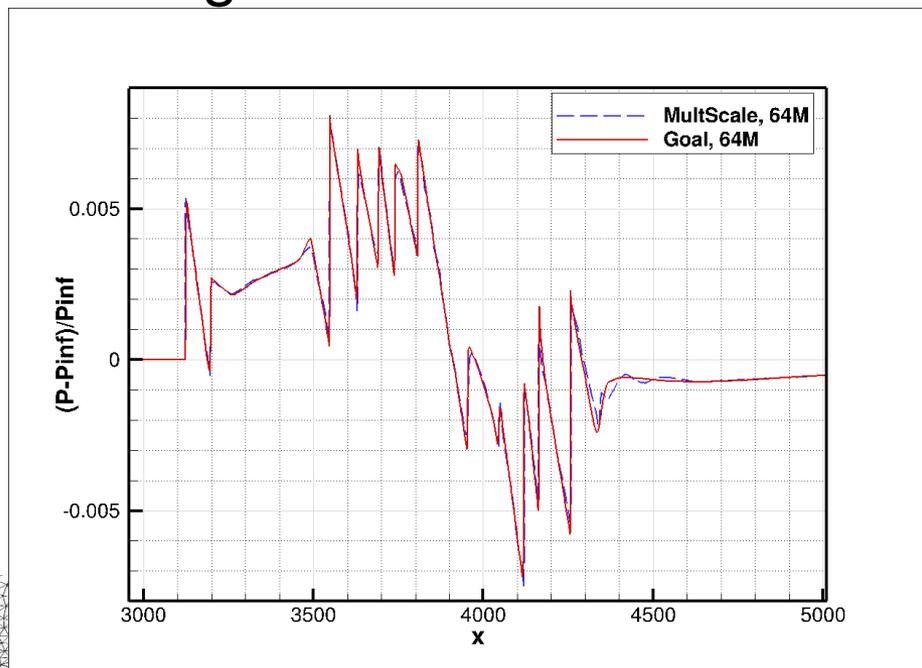
Adaptive Grid Convergence – c608 Case



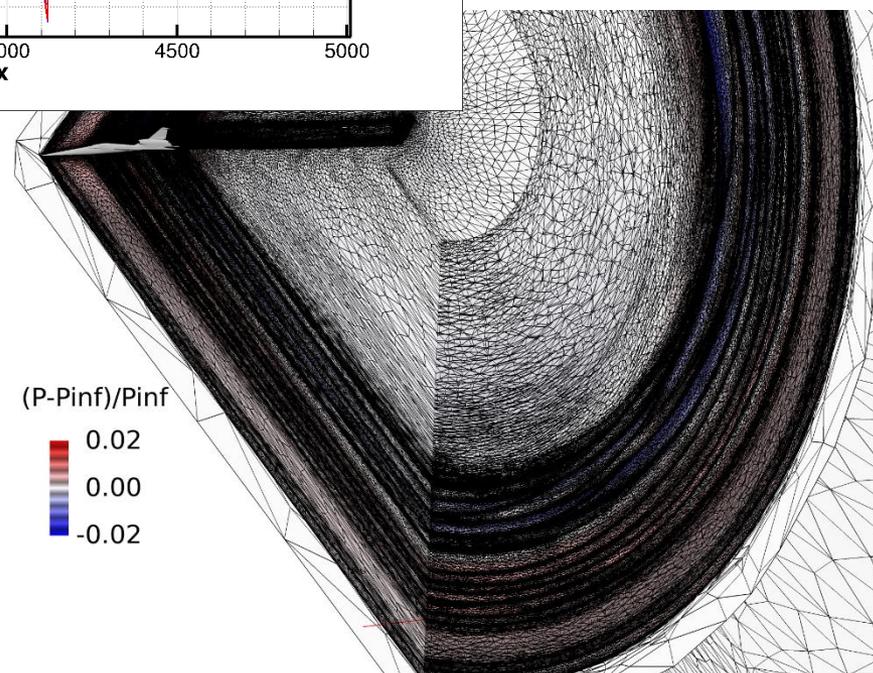
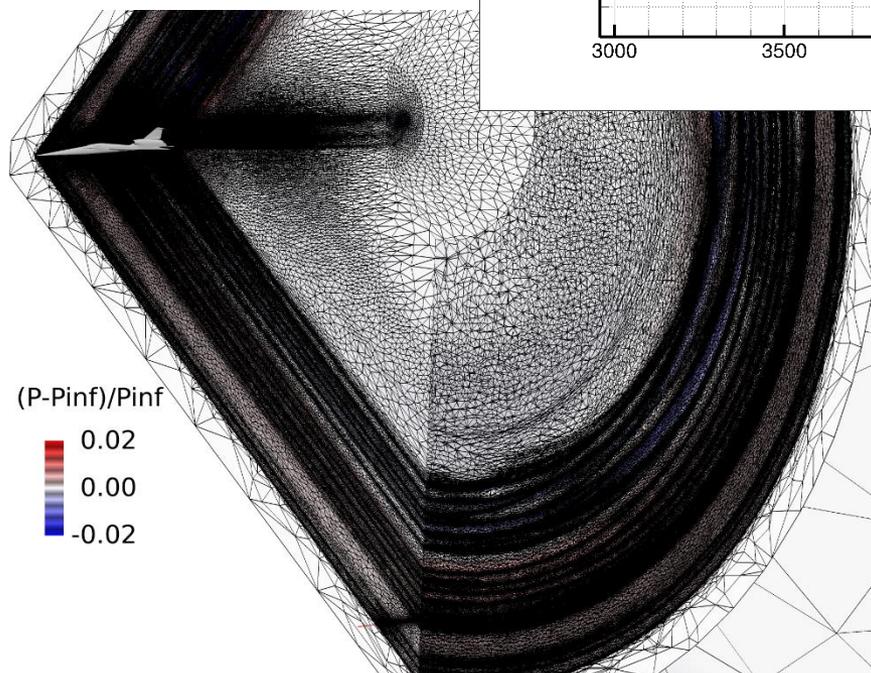
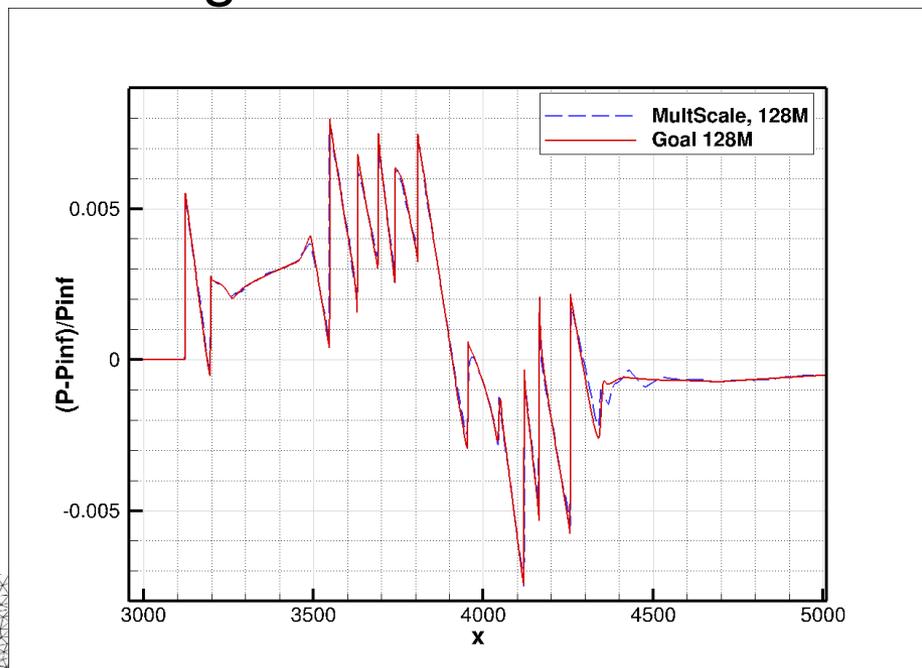
Adaptive Grid Convergence – c608 Case



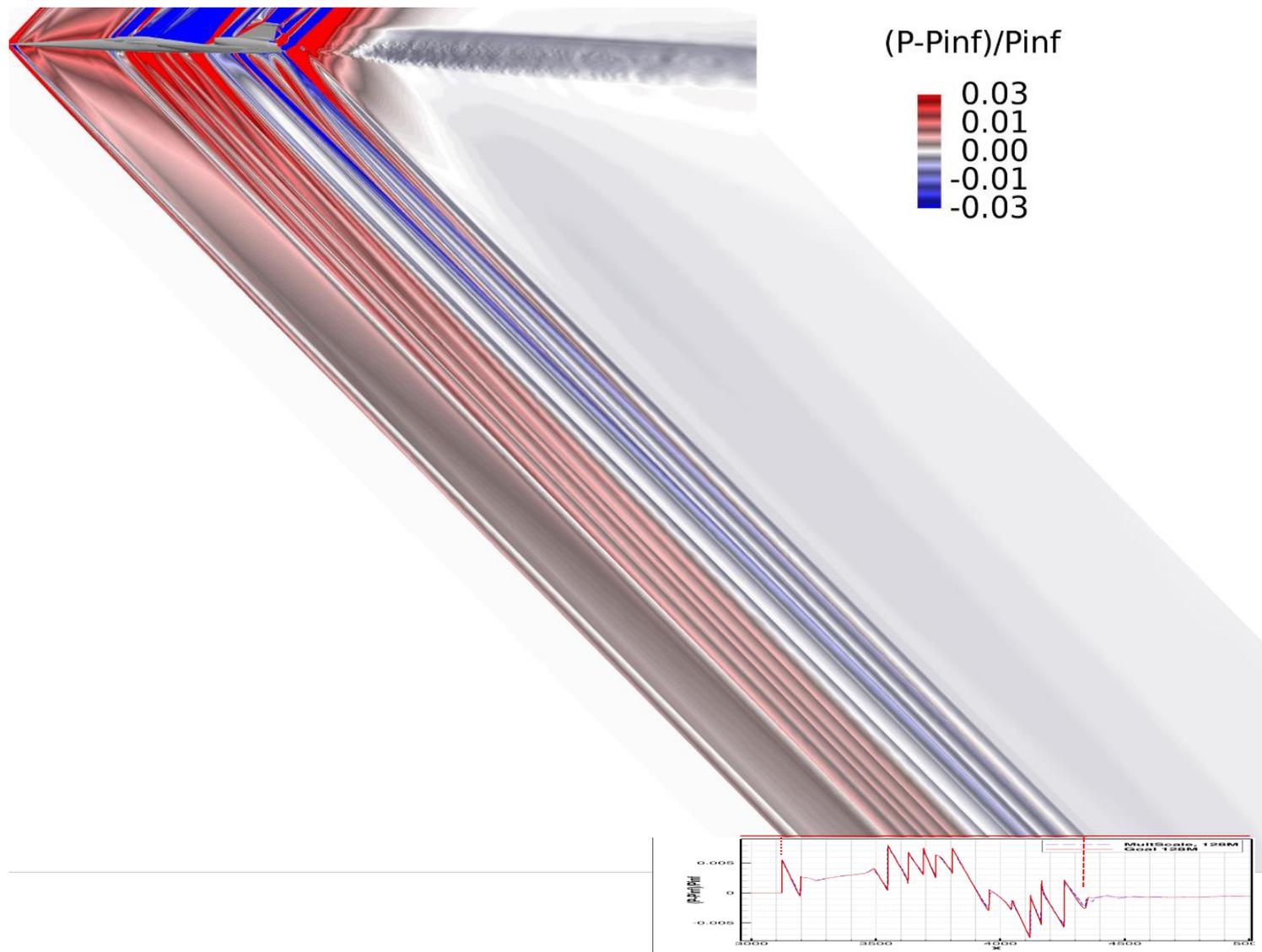
Adaptive Grid Convergence – c608 Case



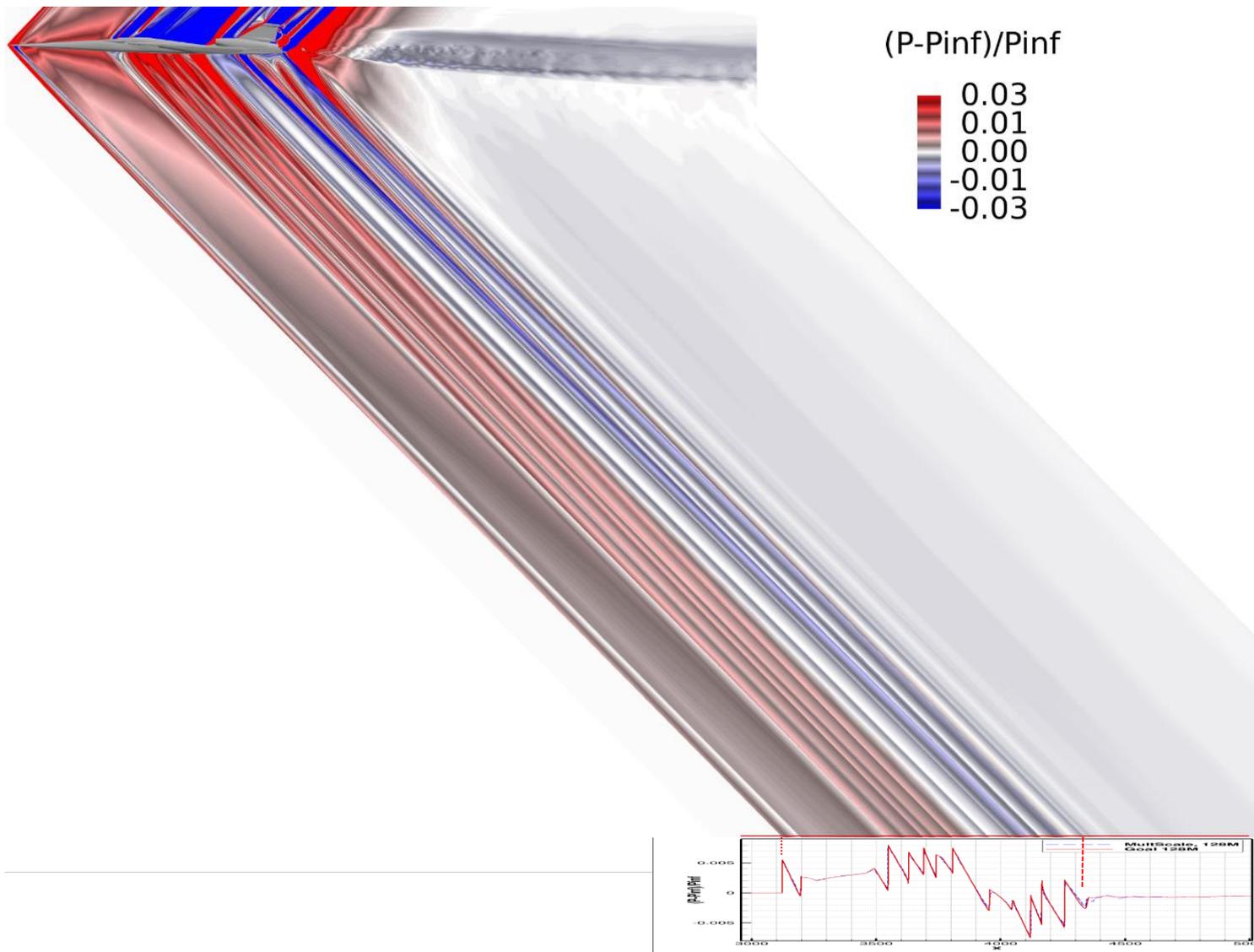
Adaptive Grid Convergence – c608 Case



Goal Oriented



Multiscale



Conclusions

Grid Convergence

- Adaptivity improves mesh convergence over fixed grid (c608 case)
- GO convergences faster than MS for bi-convex and c608 cases
- GO advantage less prominent for c608 due to higher geometry fidelity and additional coverage of signature lines

Nozzle Plume Interaction

- Bi-convex case: secondary compression resolved in GO results
 - better resolution of nozzle plume and h-tail reflected shock interaction
- C608 demonstrator: significant differences in signature aft of nozzle
 - additional signature peaks in MS and fixed grid results

Analysis Challenges

- Tecplot macro failed to run on 401M cell fixed grid
- Primal solution failed to converge for some c608 256M cell grids