Cartesian Mesh Simulations for the 3rd AIAA Sonic Boom Prediction Workshop

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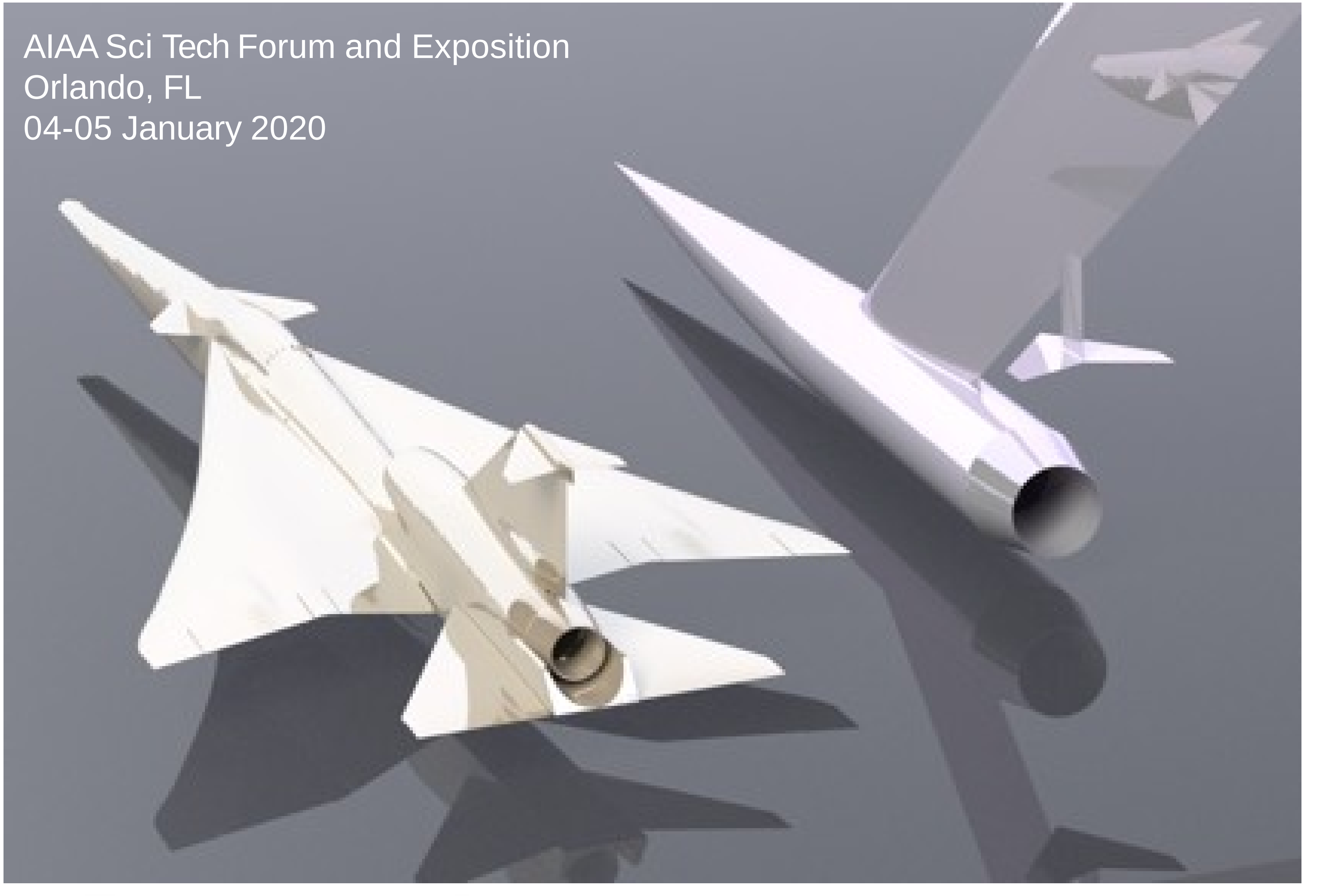

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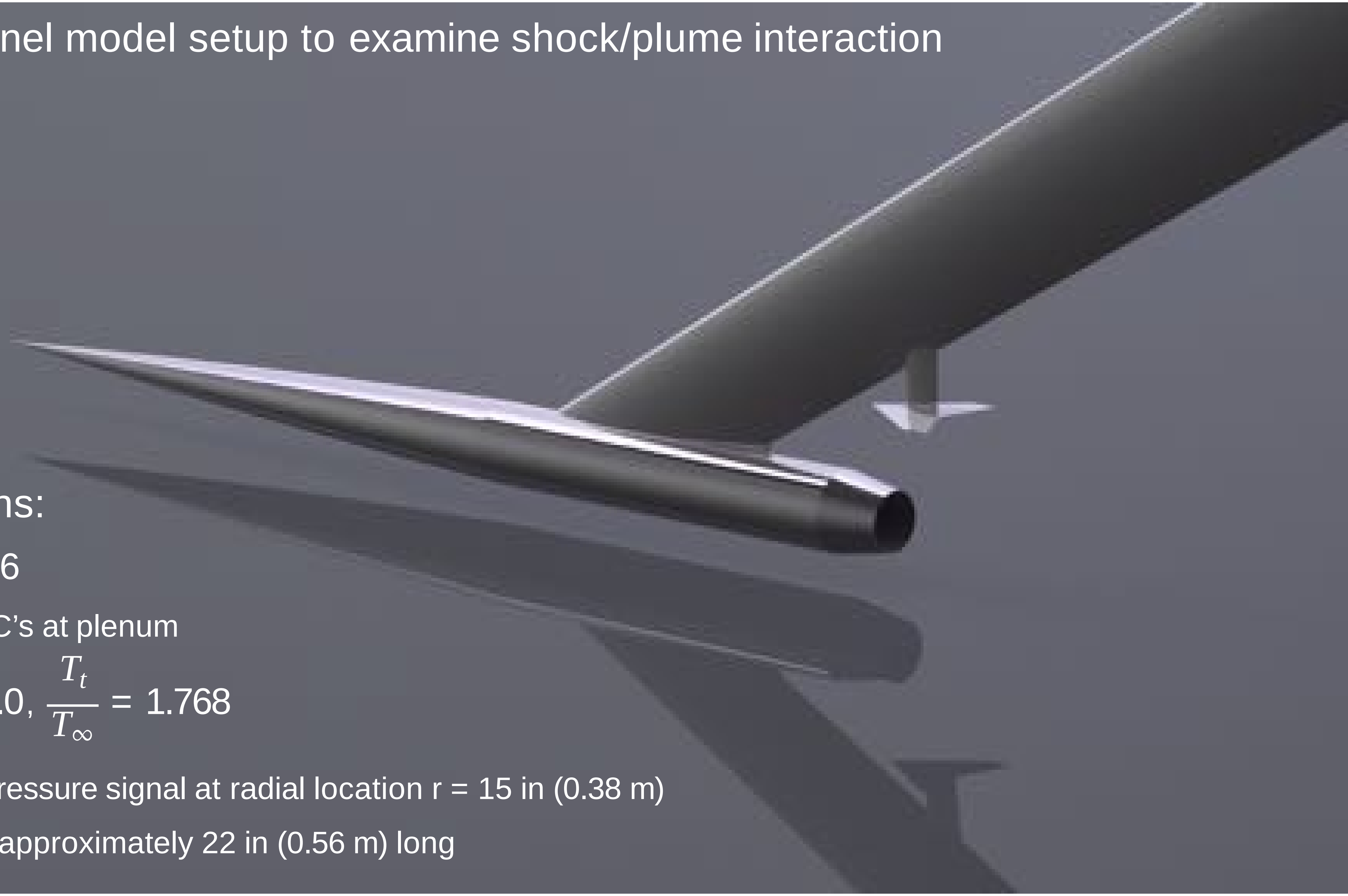
Outline

- Cases
  - Biconvex - shock/plume interaction
  - C608 - full aircraft geometry
- Flow solver & computational resources
- Geometry & grids
- Numerical convergence
- Results
- Challenges
- Conclusions

Biconvex

Wind tunnel model setup to examine shock/plume interaction



Conditions:

- $M_\infty = 1.6$
- Power BC's at plenum
- $\dfrac{p_t}{p_\infty} = 8.0, \dfrac{T_t}{T_\infty} = 1.768$
- Extract pressure signal at radial location r = 15 in (0.38 m)
- Model is approximately 22 in (0.56 m) long

C608

2020.01.04

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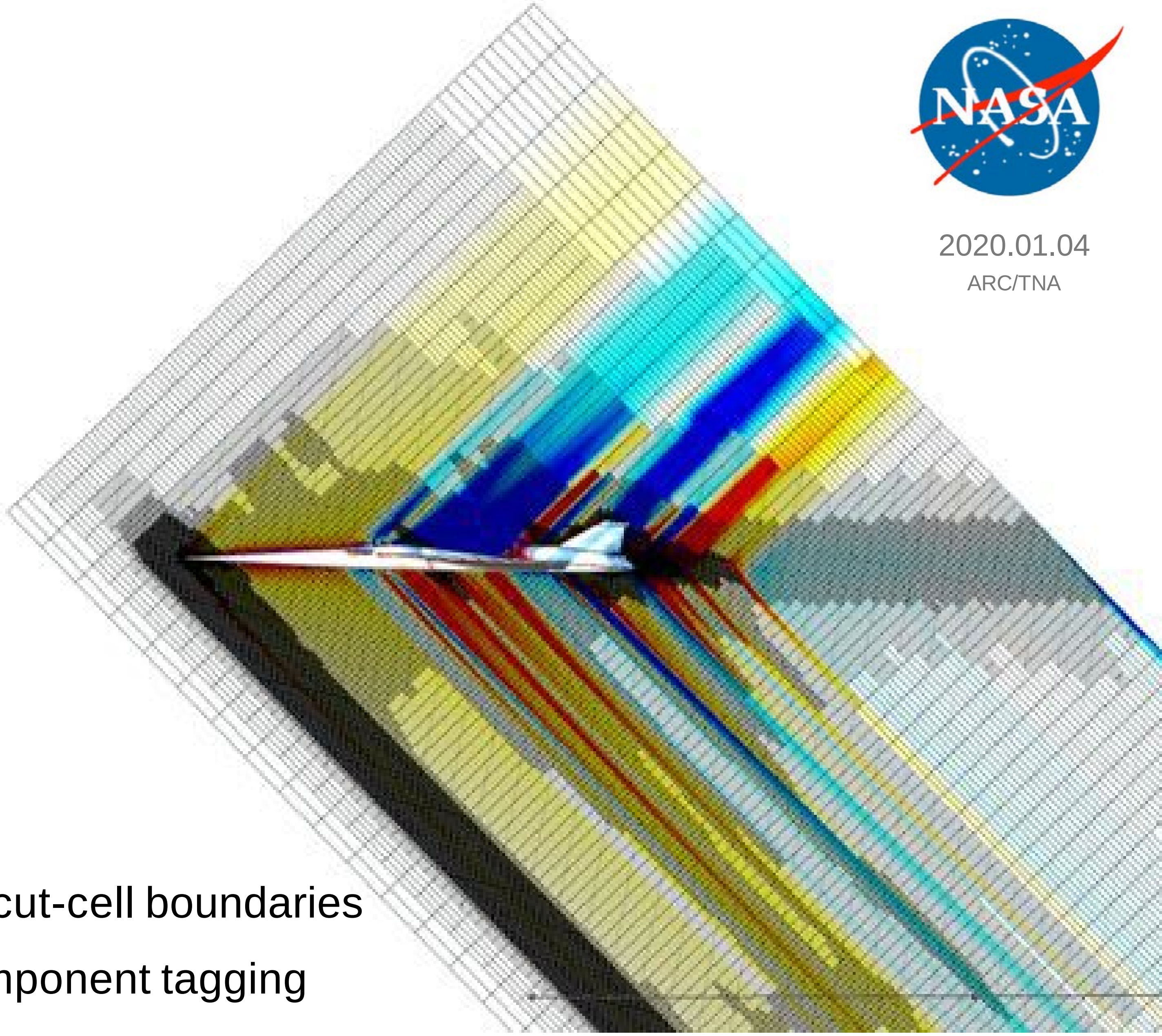
- Modified version of Low Boom Flight Demonstrator design iteration
- Full aircraft, complex geometry, multiple inflow/outflow BC's

Conditions:

- M_∞ = 1.4, Altitude $h = 53{,}200 ft$
- Power BC's at engine nozzle $p_t/p_\infty = 10.0$, $T_t/T_\infty = 7.0$
- Power BC's at bypass nozzle $p_t/p_\infty = 2.4$, $T_t/T_\infty = 2.0$
- Engine fan inlet $p_b/p_\infty = 2.6$ (desired Mach 0.4 flow at engine fan face)
- Environmental Control System vent inlets $p_b/p_\infty = 1.4$ (desired Mach 0.35 flow at ECS inlets)
- Extract pressure signal at radial location L
- Model is approximately 1080 in (27.43 m) long

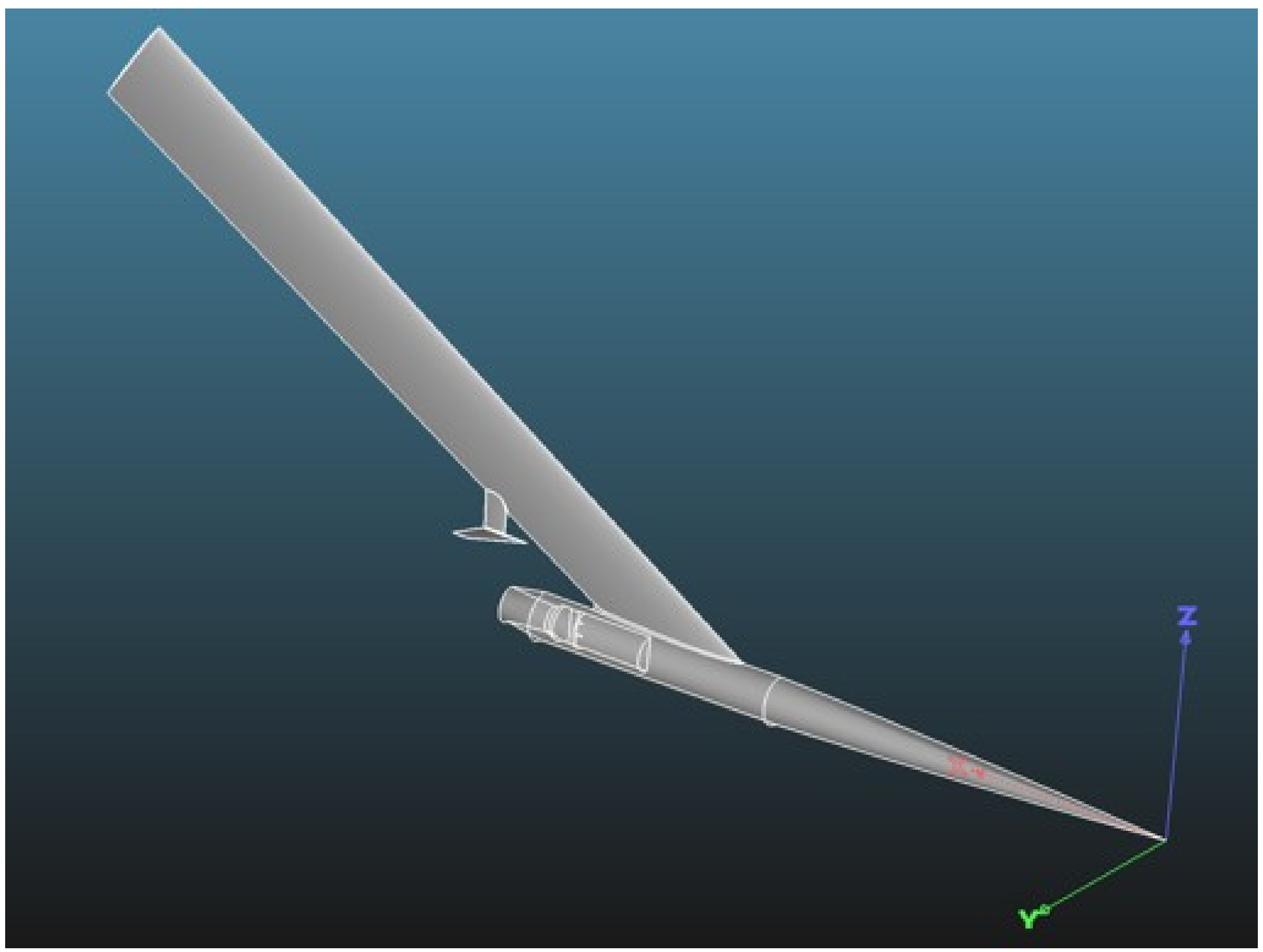
Cart3D Software

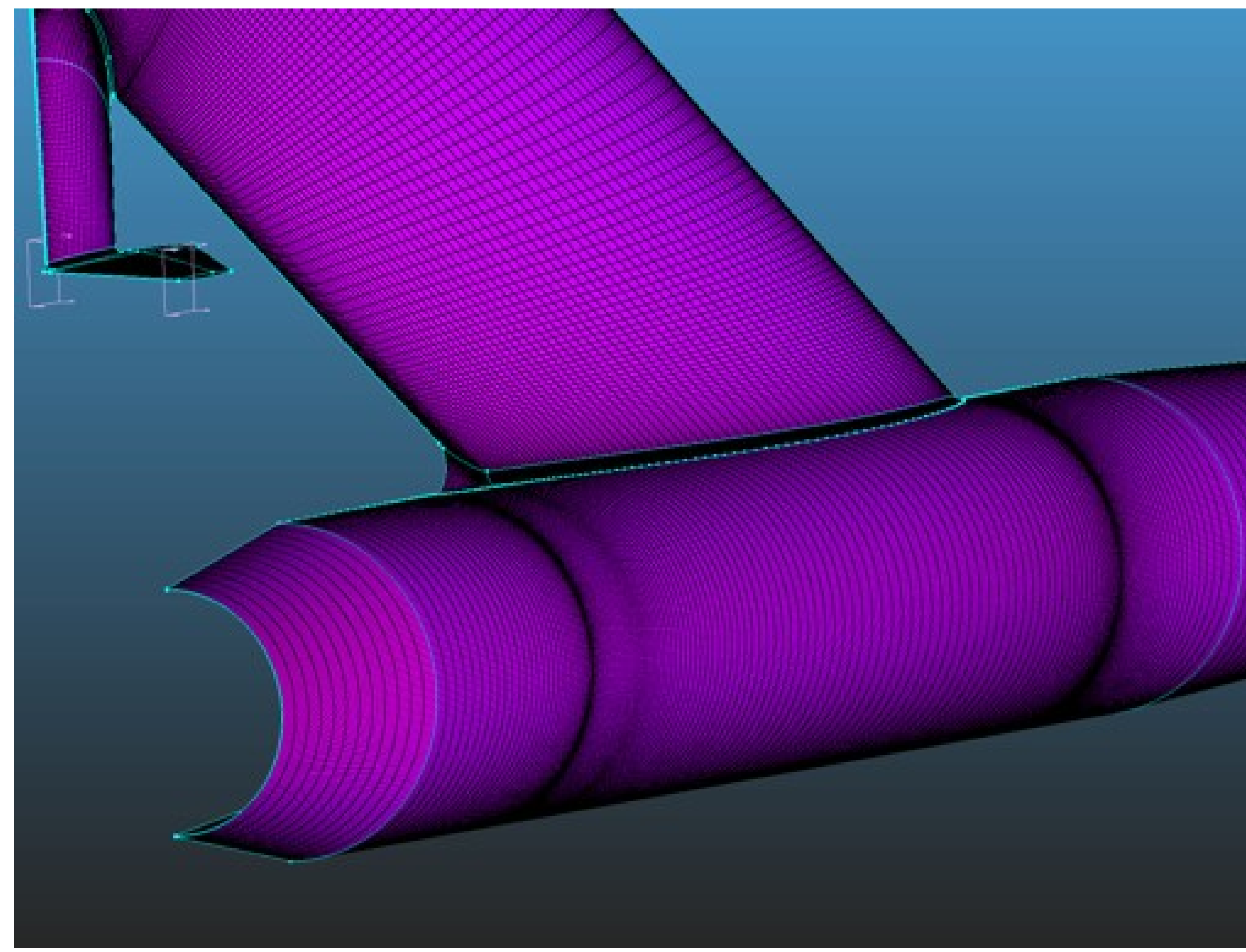


- Flow solver: Cart3D v1.5.5.3
  - Steady, inviscid Euler equation solver
  - Second-order upwind method
  - Domain decomposition, highly scalable
  - Multigrid acceleration (4 MG levels)
  - 5-stage RK scheme, van Leer limiter
- Automatic meshing
  - Multilevel Cartesian mesh with embedded cut-cell boundaries
  - Unstructured surface triangulation with component tagging
- Output-driven mesh refinement
  - Discrete adjoint solution and local error estimate
  - Several different adjoint functionals, including pressure signal Δp
- Computing platform
  - NASA ARC Electra, 1 Skylake node (40 cores, Intel Xeon Gold 6148)
  - Biconvex: 19.9 M cells, 40 min final flow solve, 32 min adaptive meshing (x3 sim's)
  - C608: 29.6 M cells, 60 min final flow solve, 53 min adaptive meshing (x19 sim's)

Geometry

- Biconvex
  - Created surface triangulation from STP and IGS files
  - Diagonalized structured grid where possible
  - Filled in planar and irregularly shaped areas with unstructured cells





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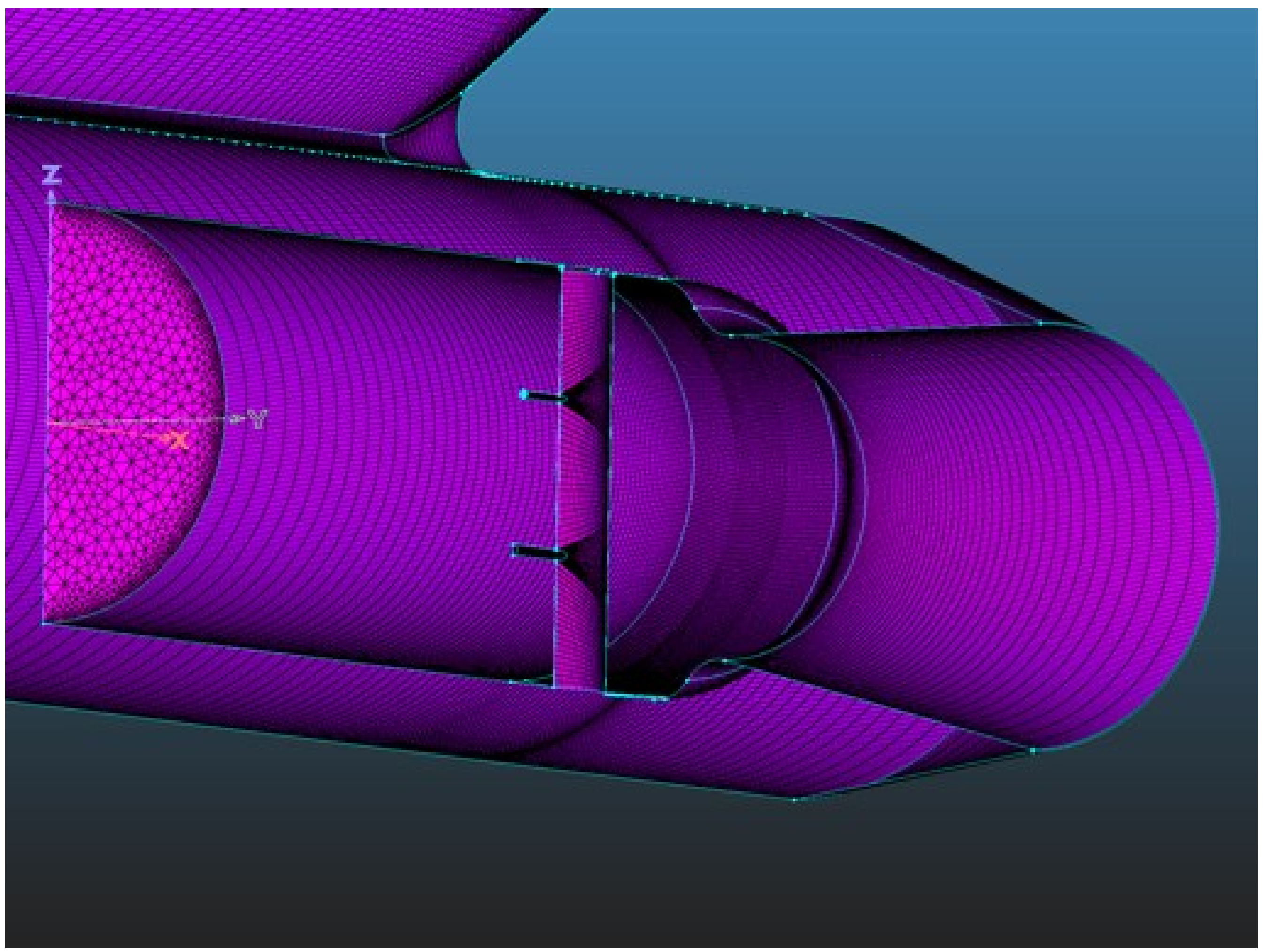

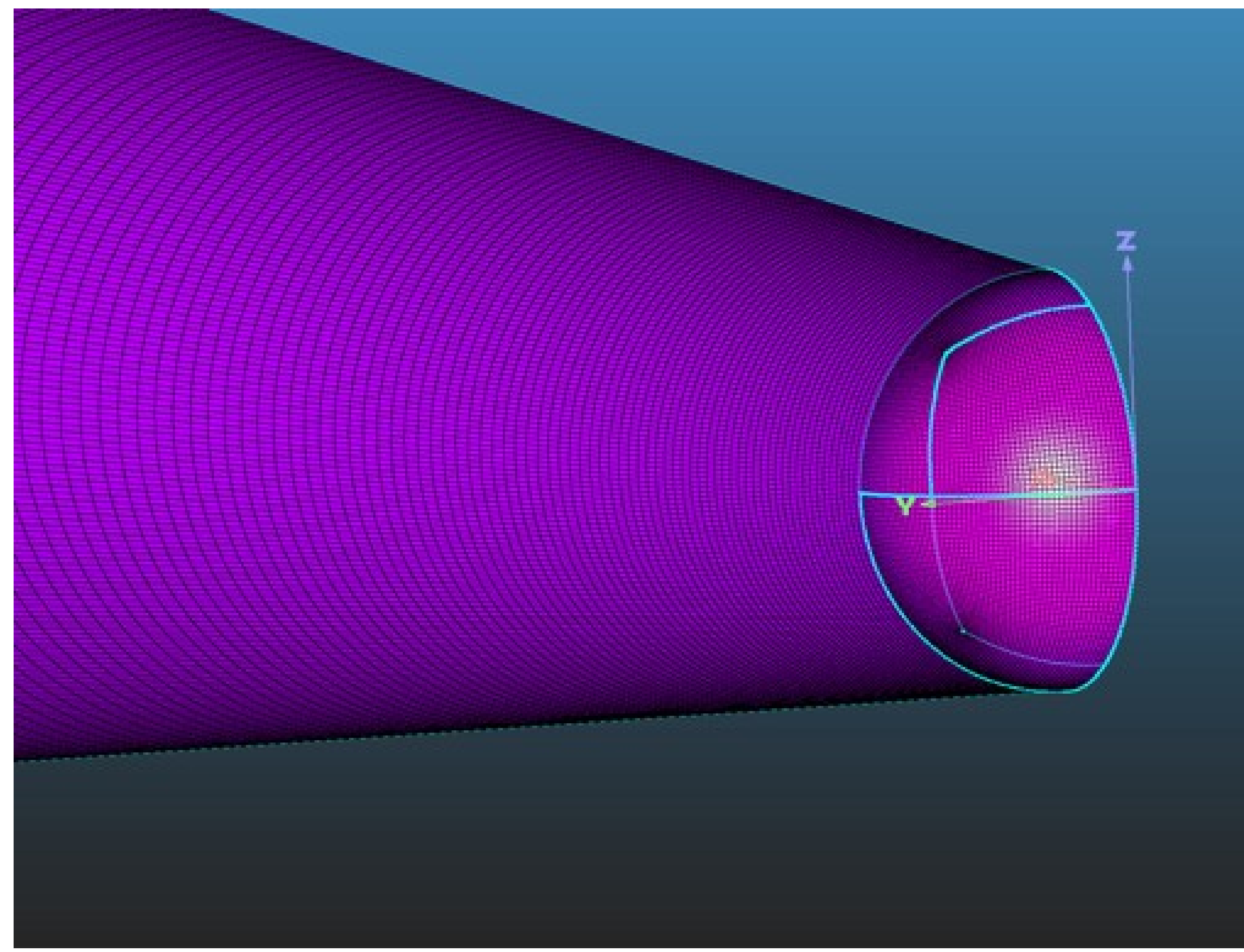

Geometry

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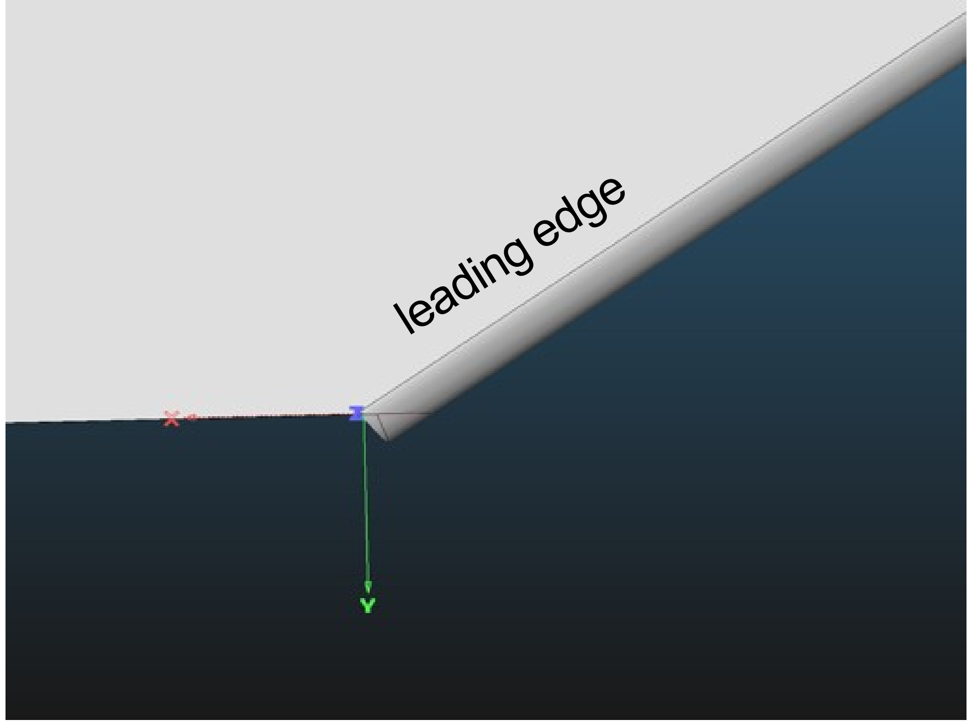
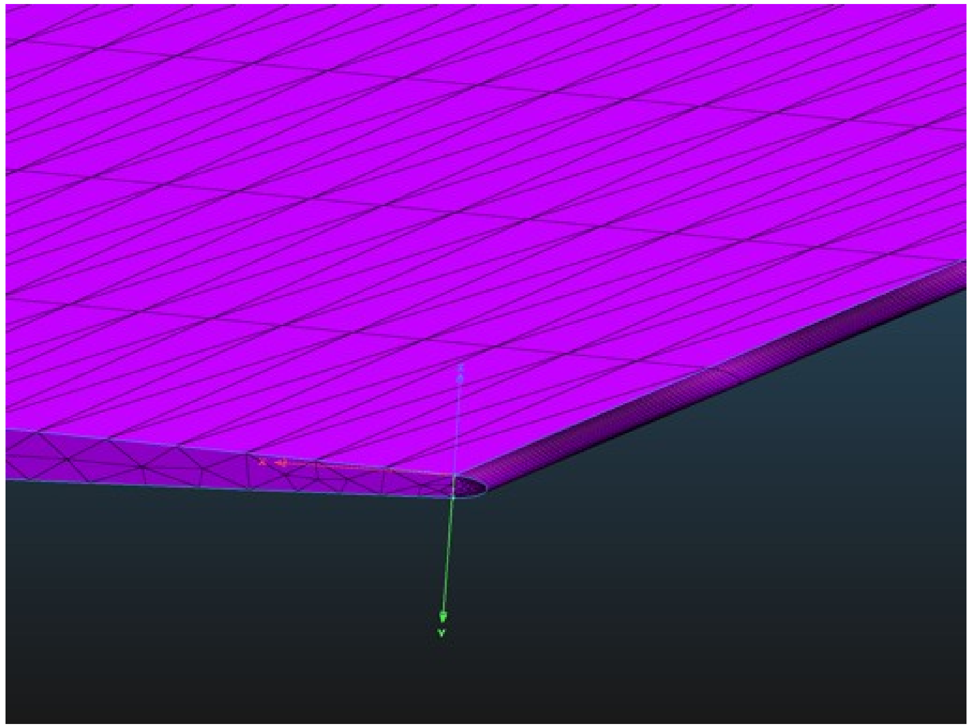
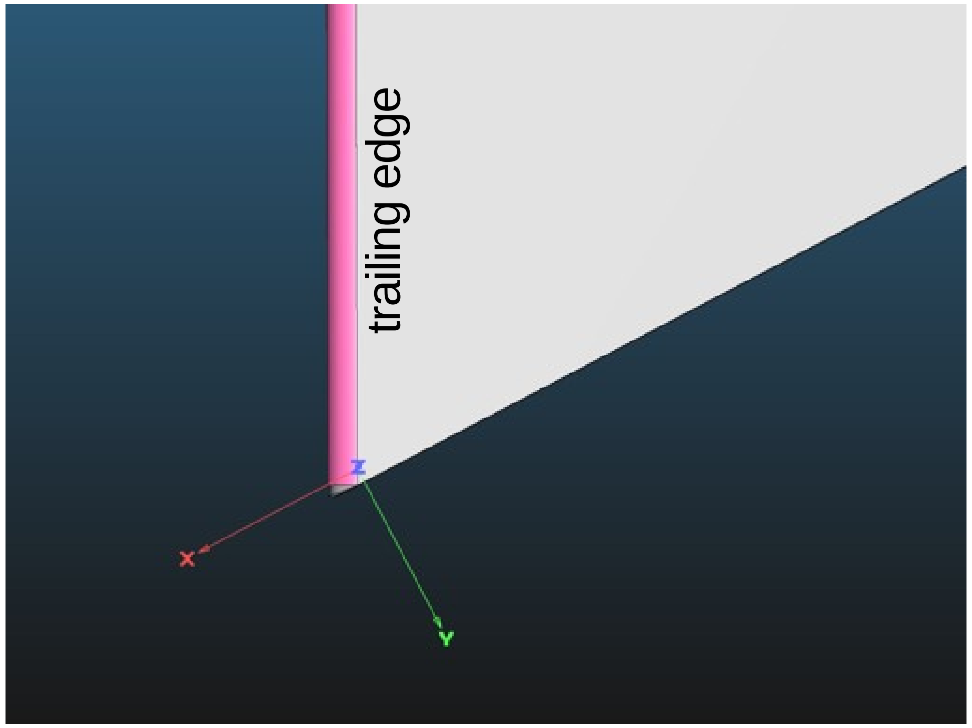
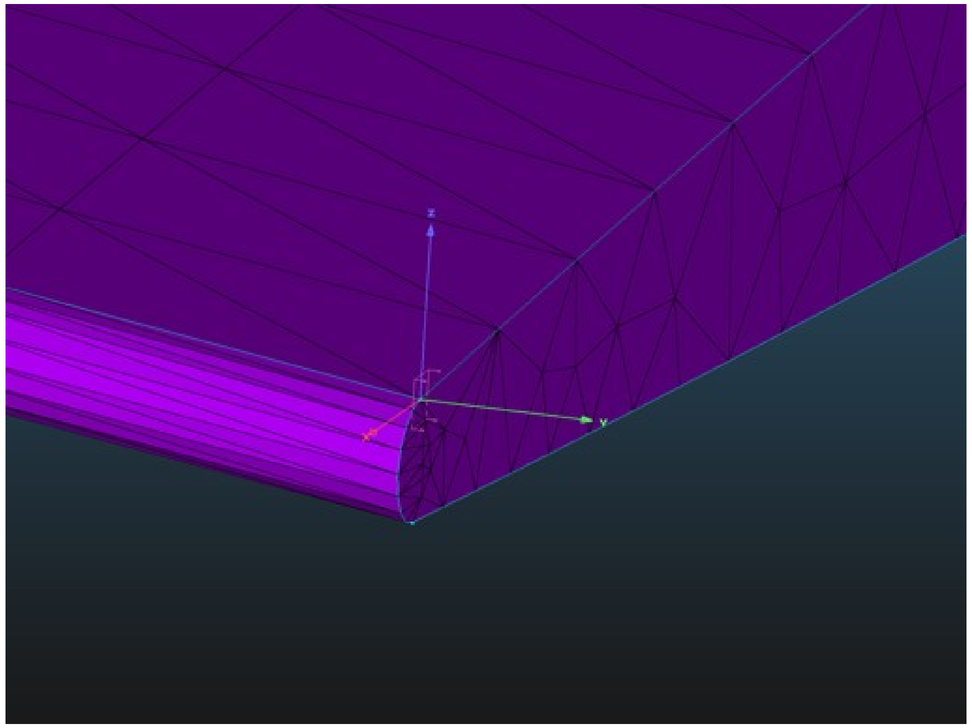
- Issues with leading edge and trailing edge at tip of airfoil
- Cleaned up geometry by projecting LE and TE onto plane of wing tip









Geometry

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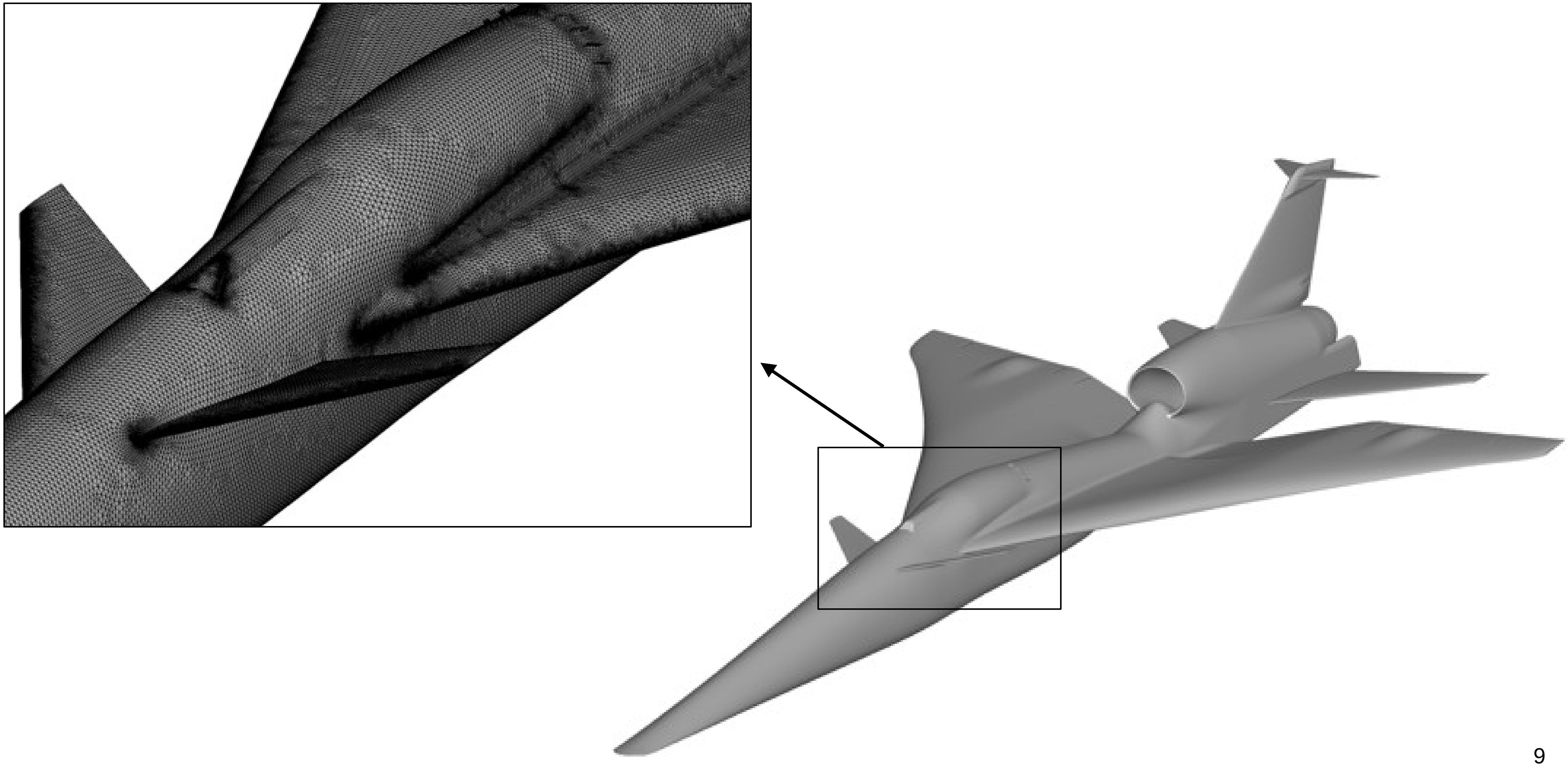
- C608
  - Received unstructured surface triangulation from J. Jensen (NASA ARC)
  - 494 k vertices, 987 k triangles

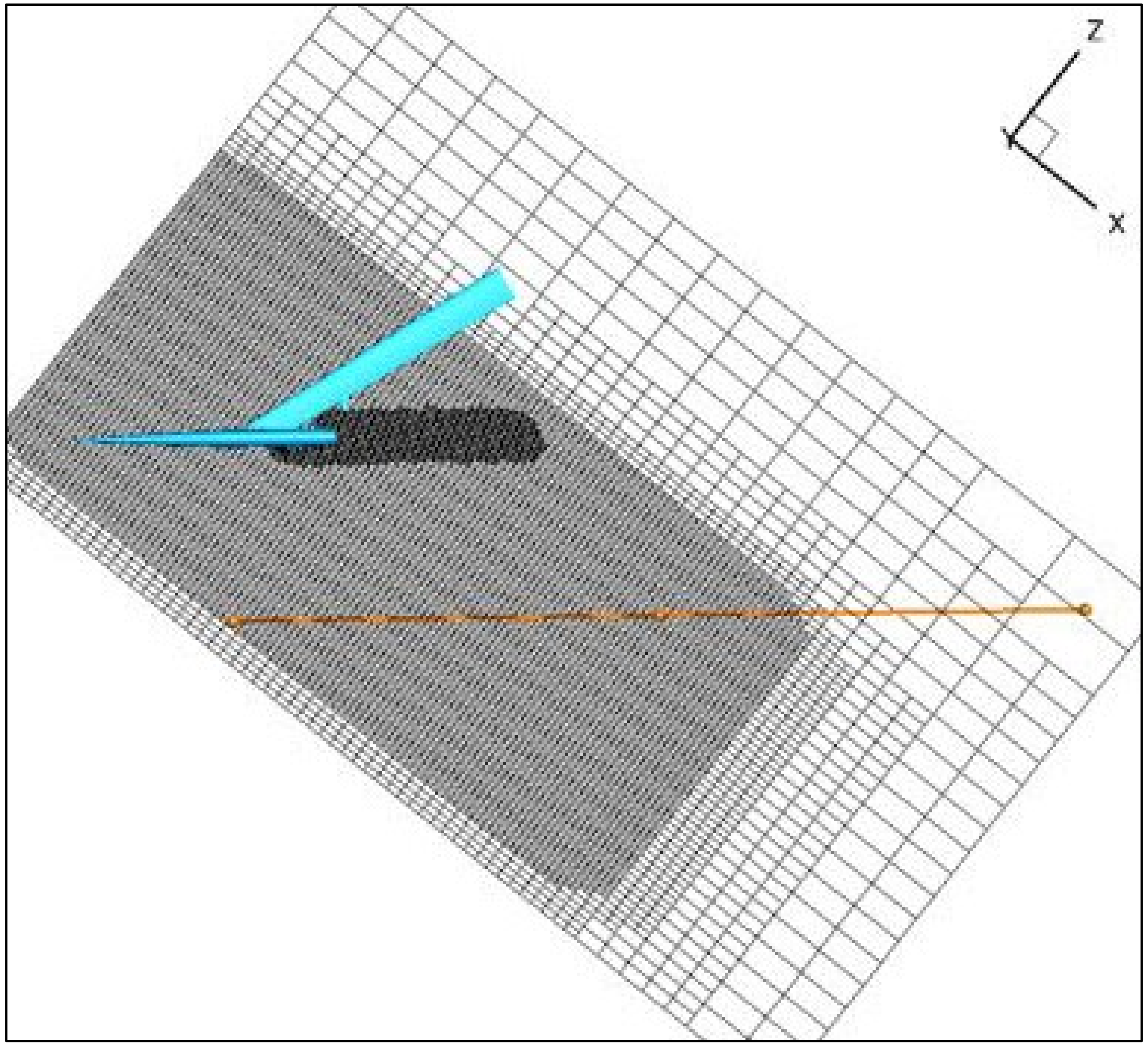


Volume Mesh

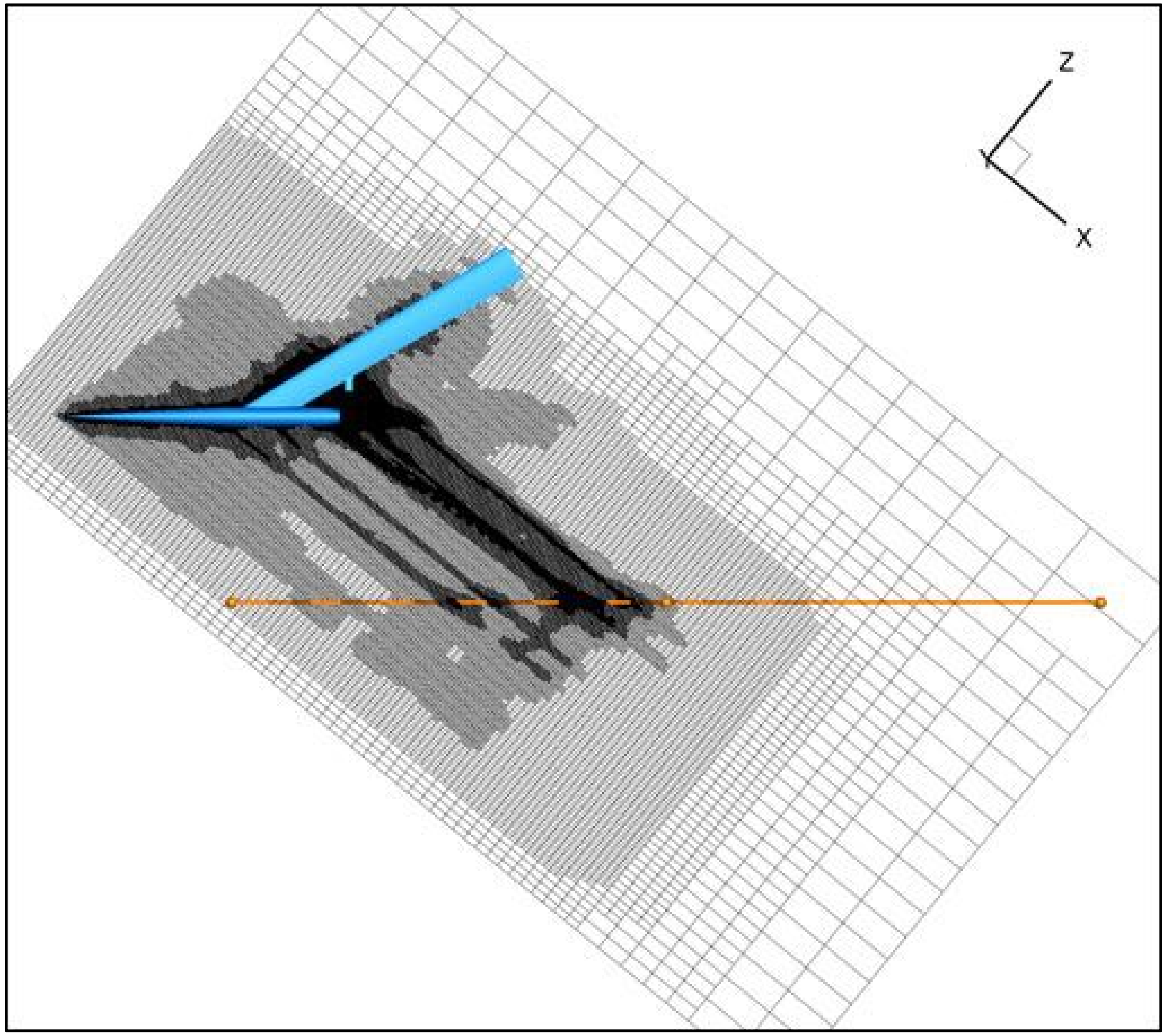
- Cartesian cut-cell volume mesh for inviscid flow solver
- Cart3D autoBoom - previous SBPW2 work
  - Aligned with Mach angle (with tiny offset to avoid sonic glitch)
  - Roll the model geometry for different off-track ϕ angles
  - Separate simulation for each off-track ϕ on 1 node, can be run simultaneously
  - Tested different cell aspect ratios in the propagation and spanwise directions
- Adjoint-driven mesh adaptation
  - Line sensor at multiple body lengths away
  - Objective function is integrated pressure $\Delta p/p_\infty$
- Final grid sizes for data submittal
  - Biconvex: 4.5, 8.9, 19.9 million cells for coarse, medium, fine
  - C608: 7.1, 14.2, 29.6 million cells for coarse, medium, fine

Volume Mesh

- Adjoint-driven mesh adaptation
  - Line sensor at multiple body lengths away
  - Objective function is weighted integral of $\Delta p/p_{\infty}$



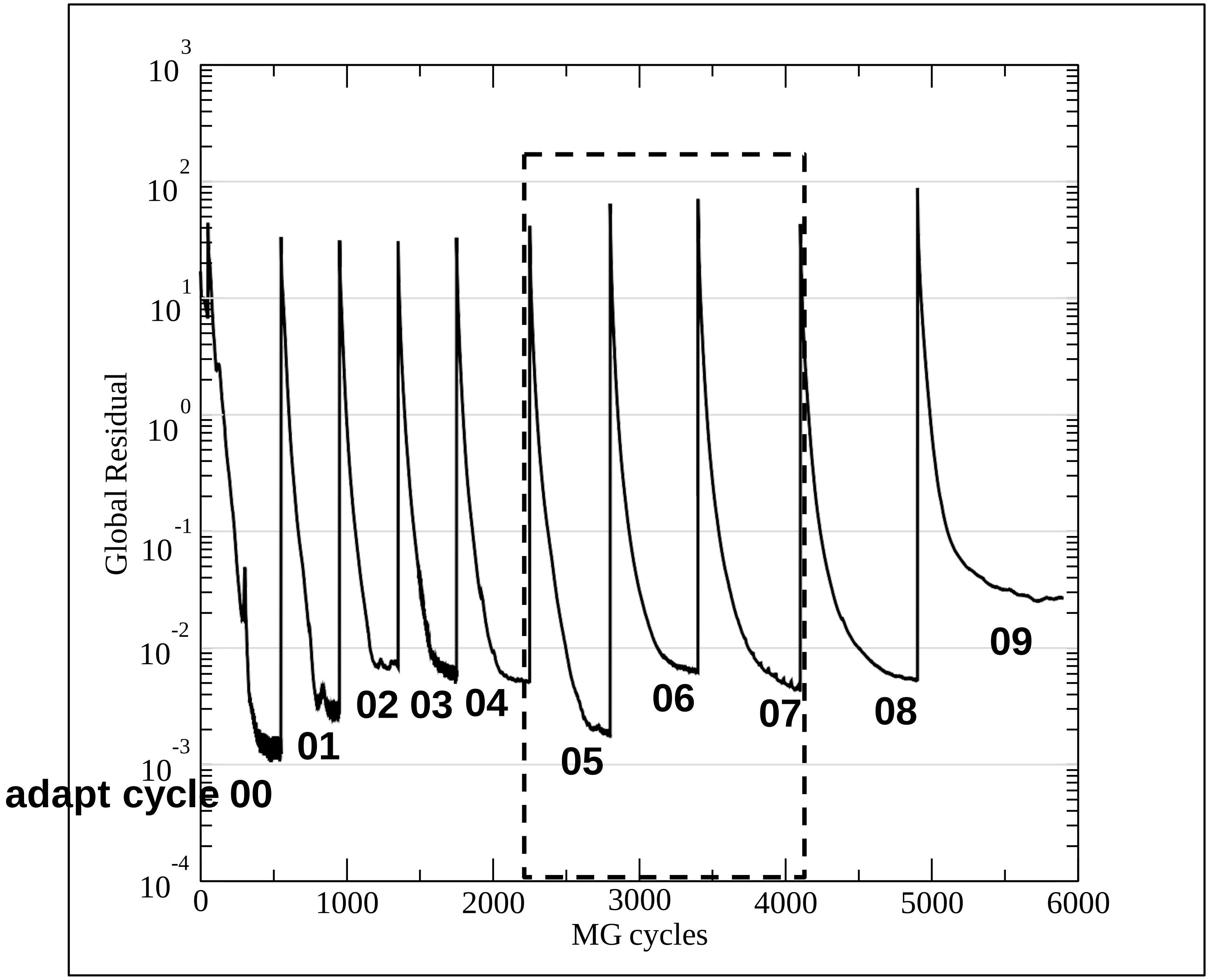
Initial mesh



Mesh after adaptation (coarse mesh)

Numerical Convergence

- Biconvex
  - 550, 600, 700 iterations on coarse, medium, fine grids
  - Submitted adapt cycles 05, 06, 07 (ran 2 more out to 09 to check)



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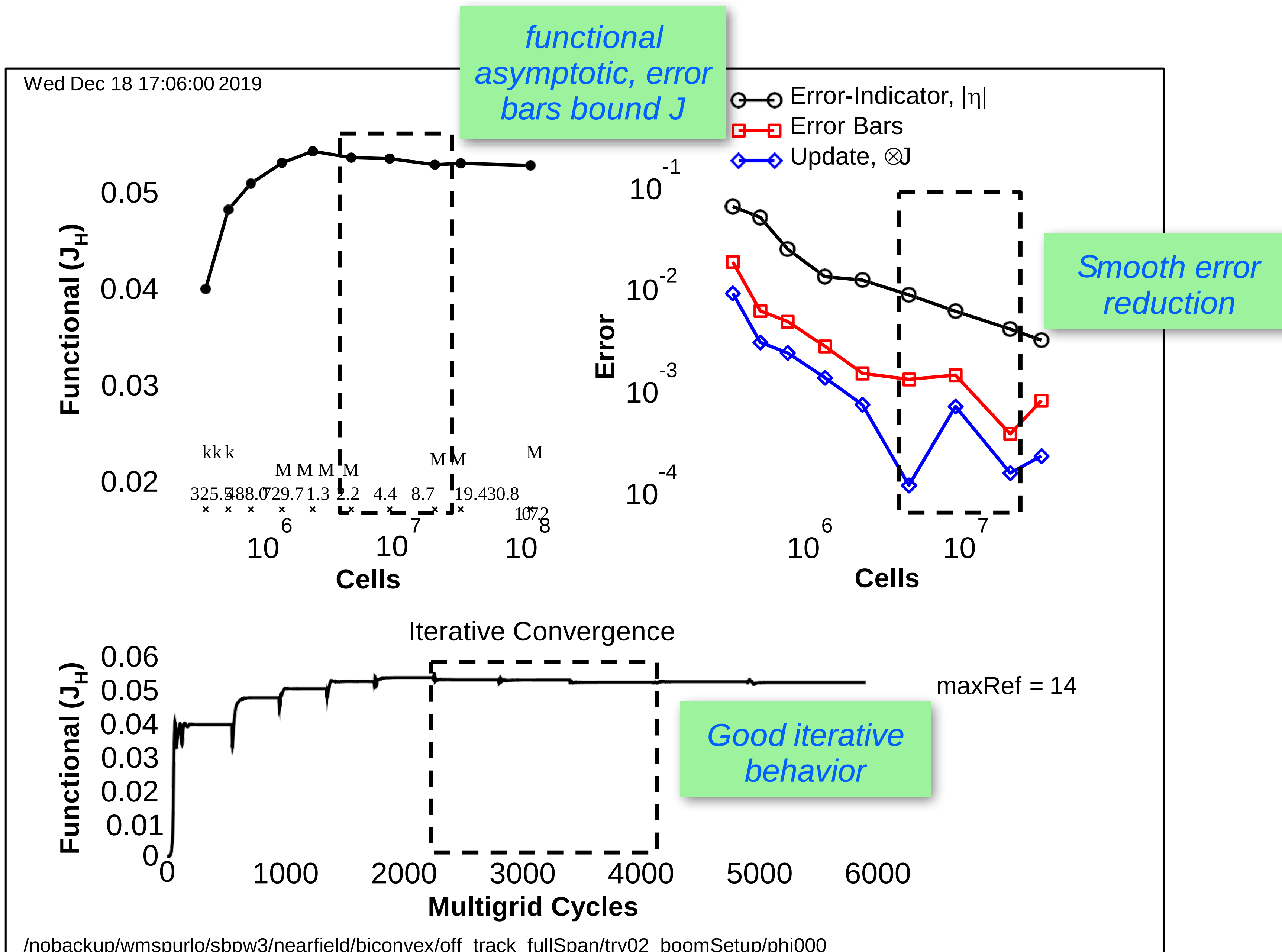
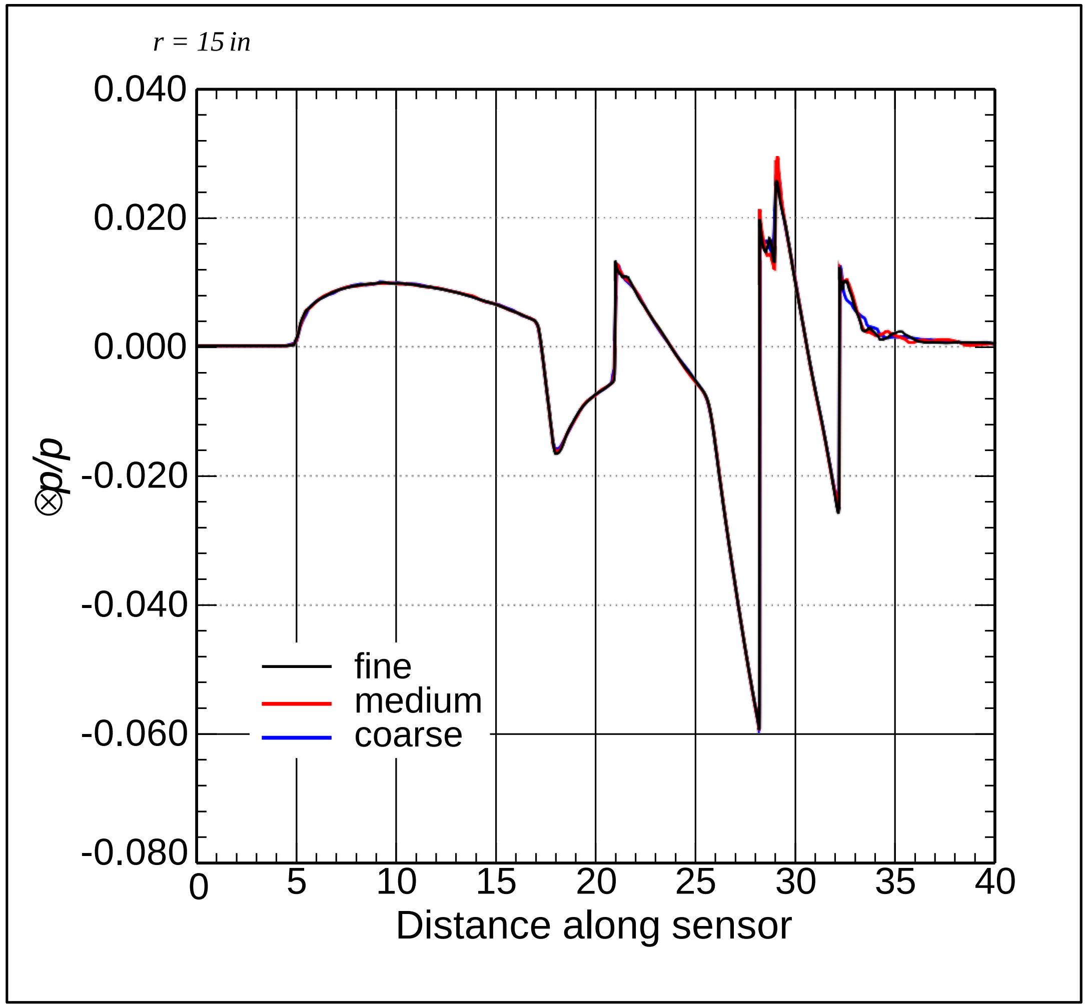
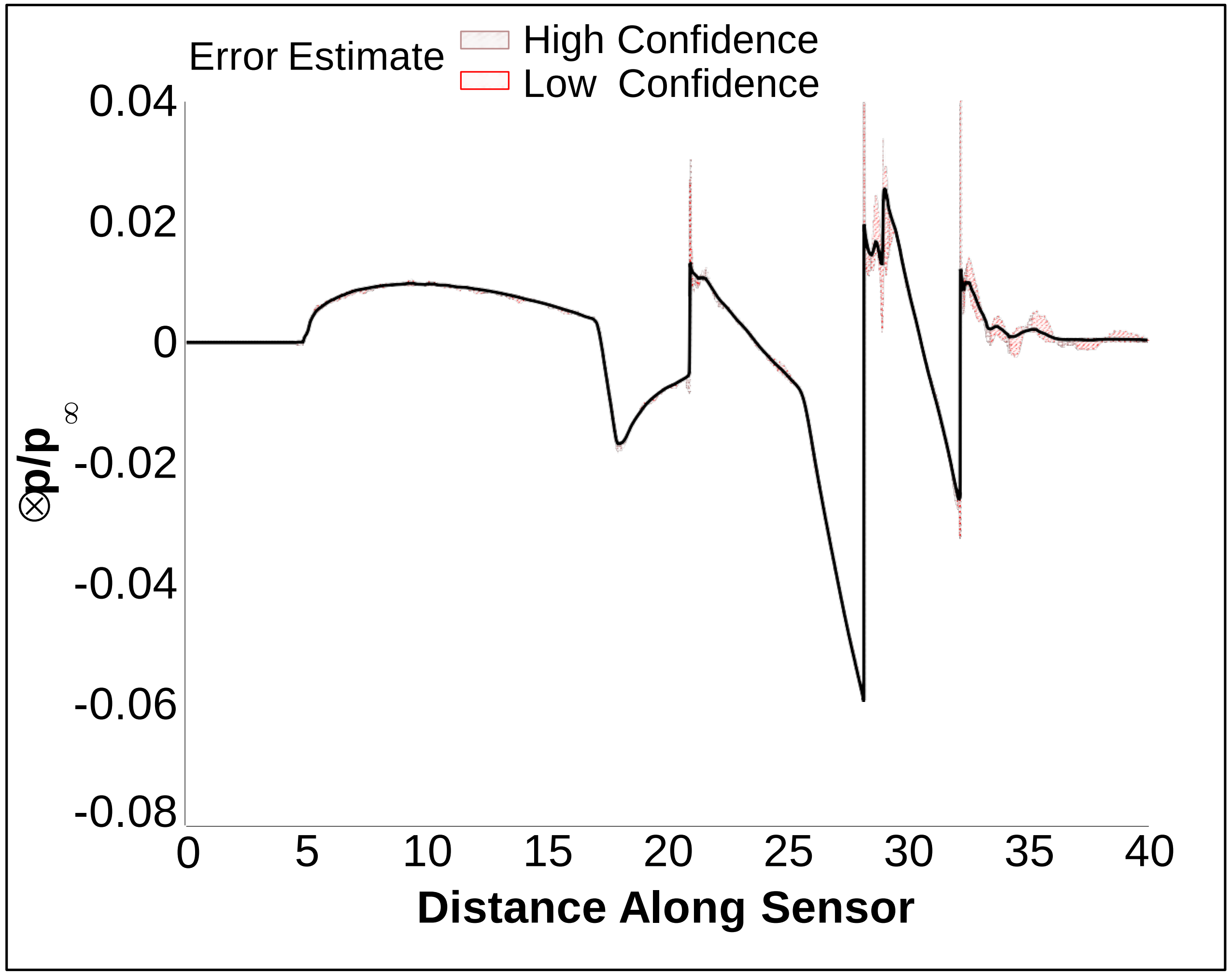


Numerical Convergence

- Biconvex
  - 550, 600, 700 iterations on coarse, medium, fine grids
  - Solutions are well converged by adapt 05, 06, 07 cycles
  - Richardson extrapolation used for error estimate





Numerical Convergence

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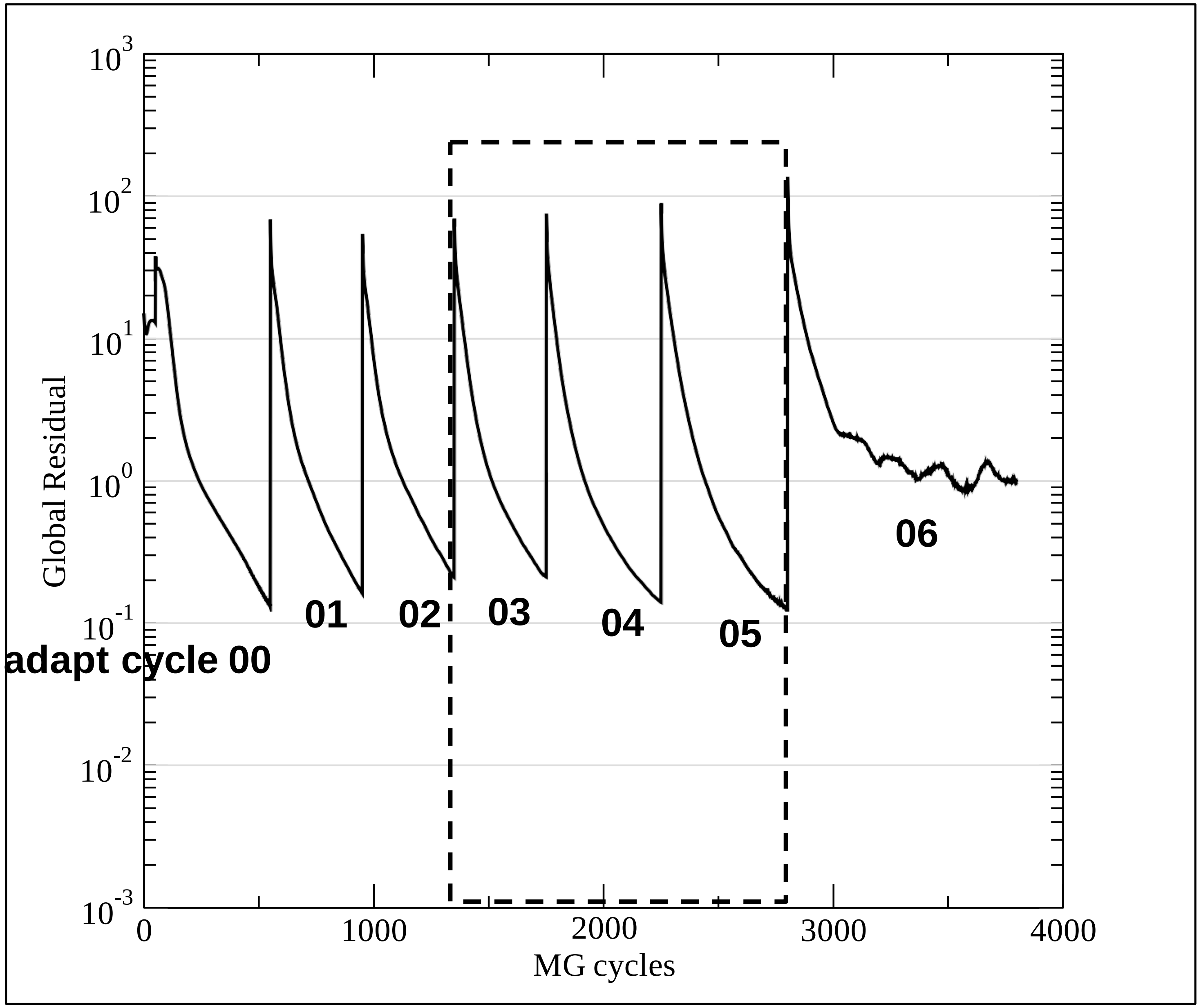
- C608
  - 400, 500, 550 iterations on coarse, medium, fine grids
  - Submitted adapt cycles 03, 04, 05 (ran 1 more out to 06 to check)

$\phi = 0°$



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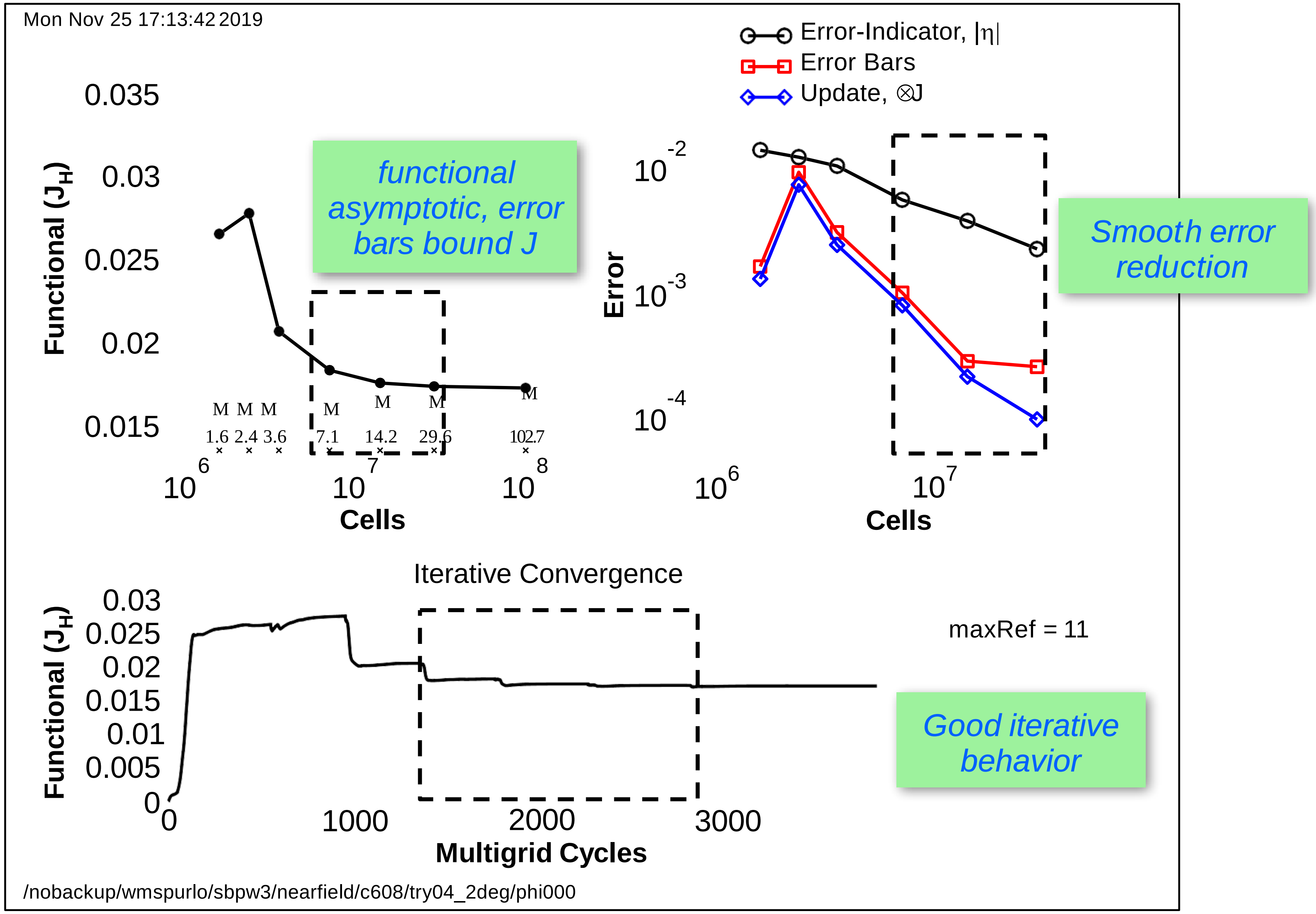

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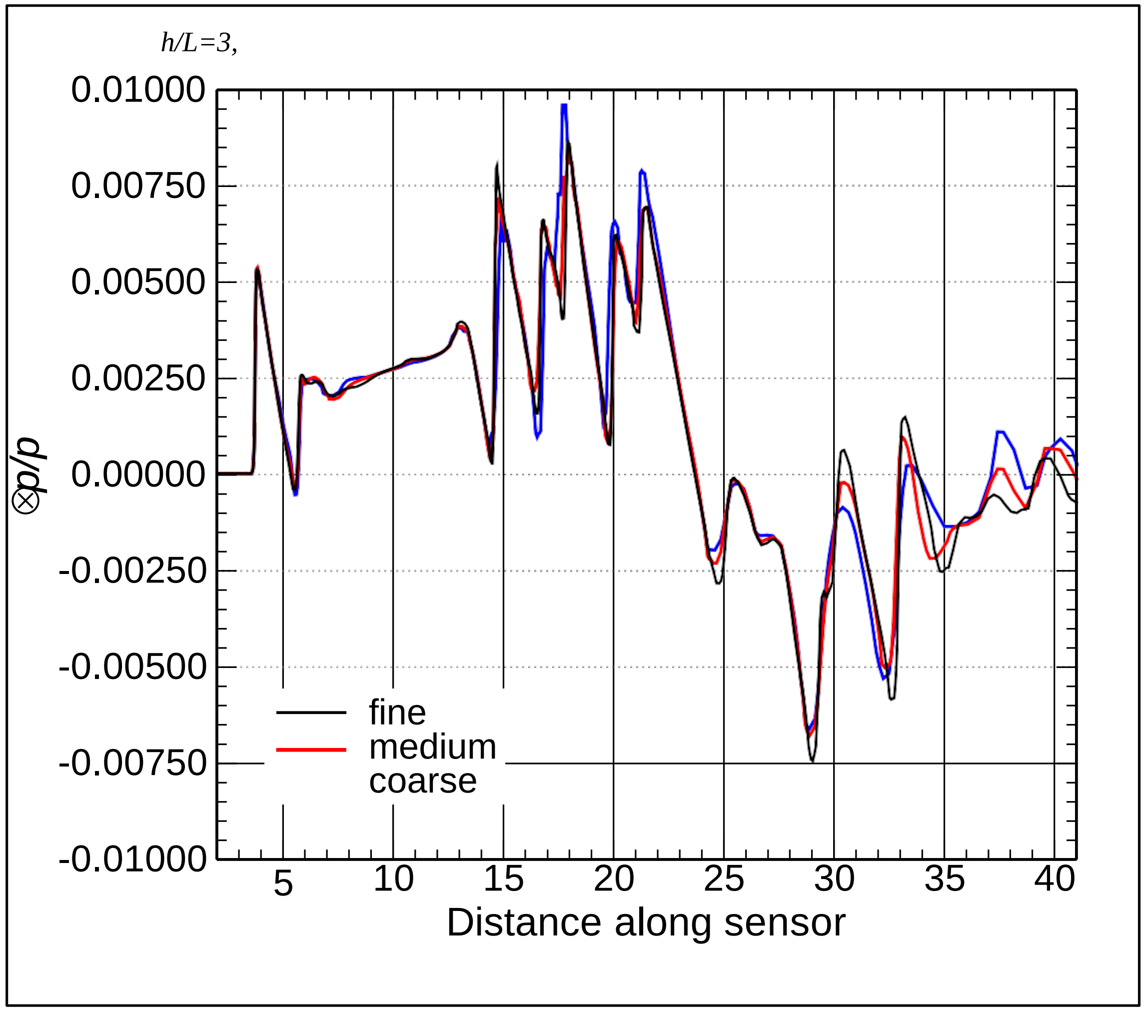

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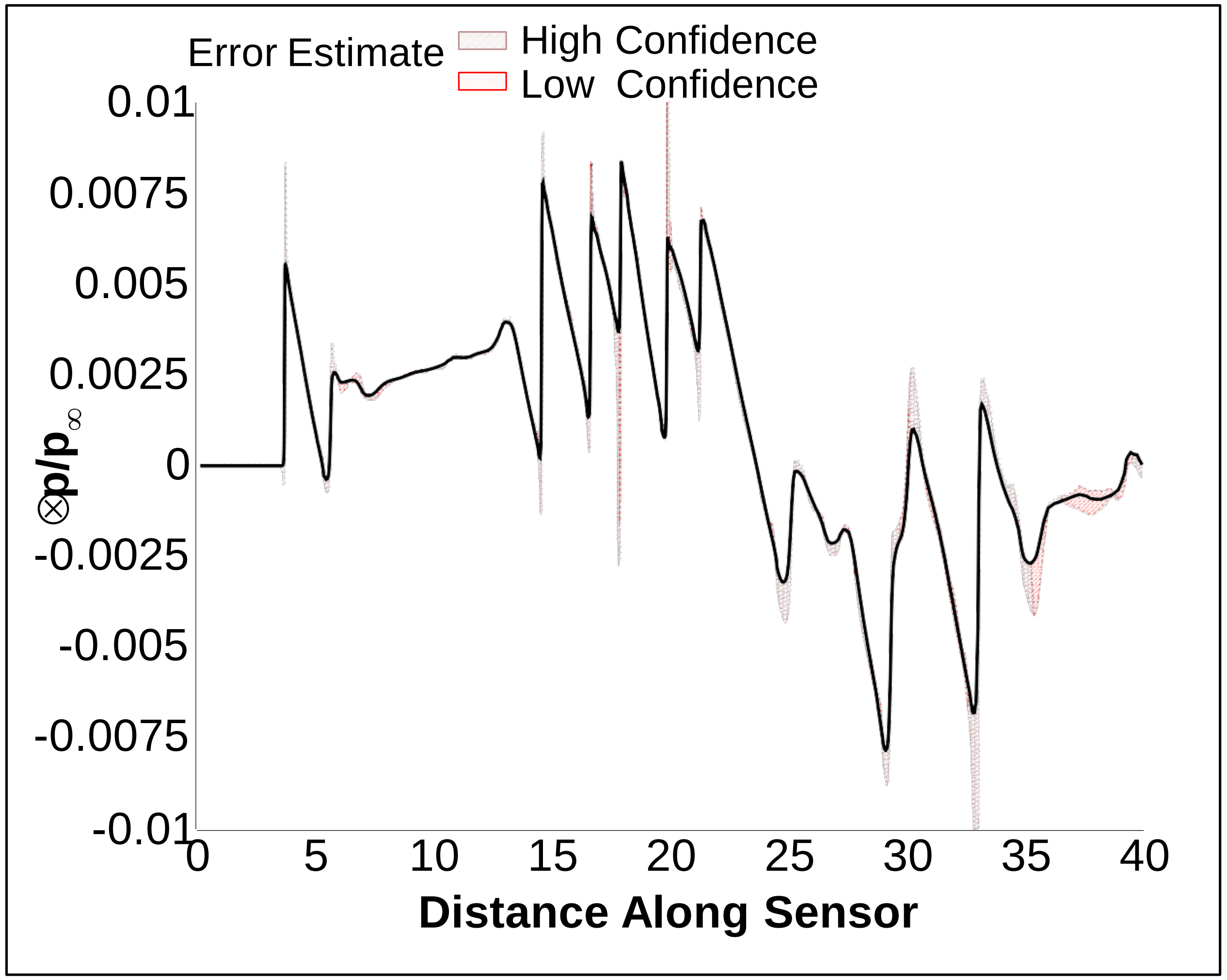
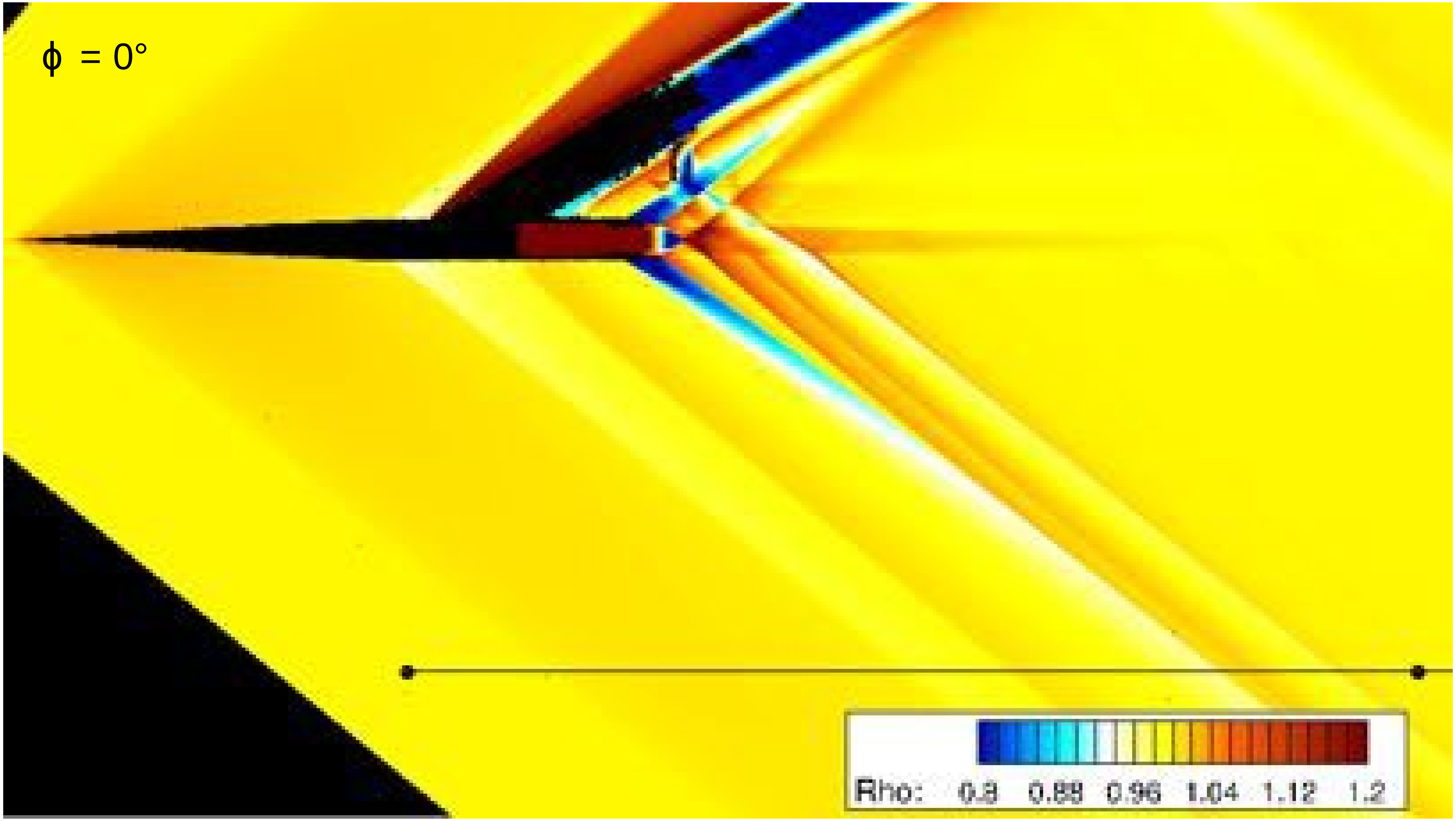


Results: Biconvex

- Density contours



Results: Biconvex

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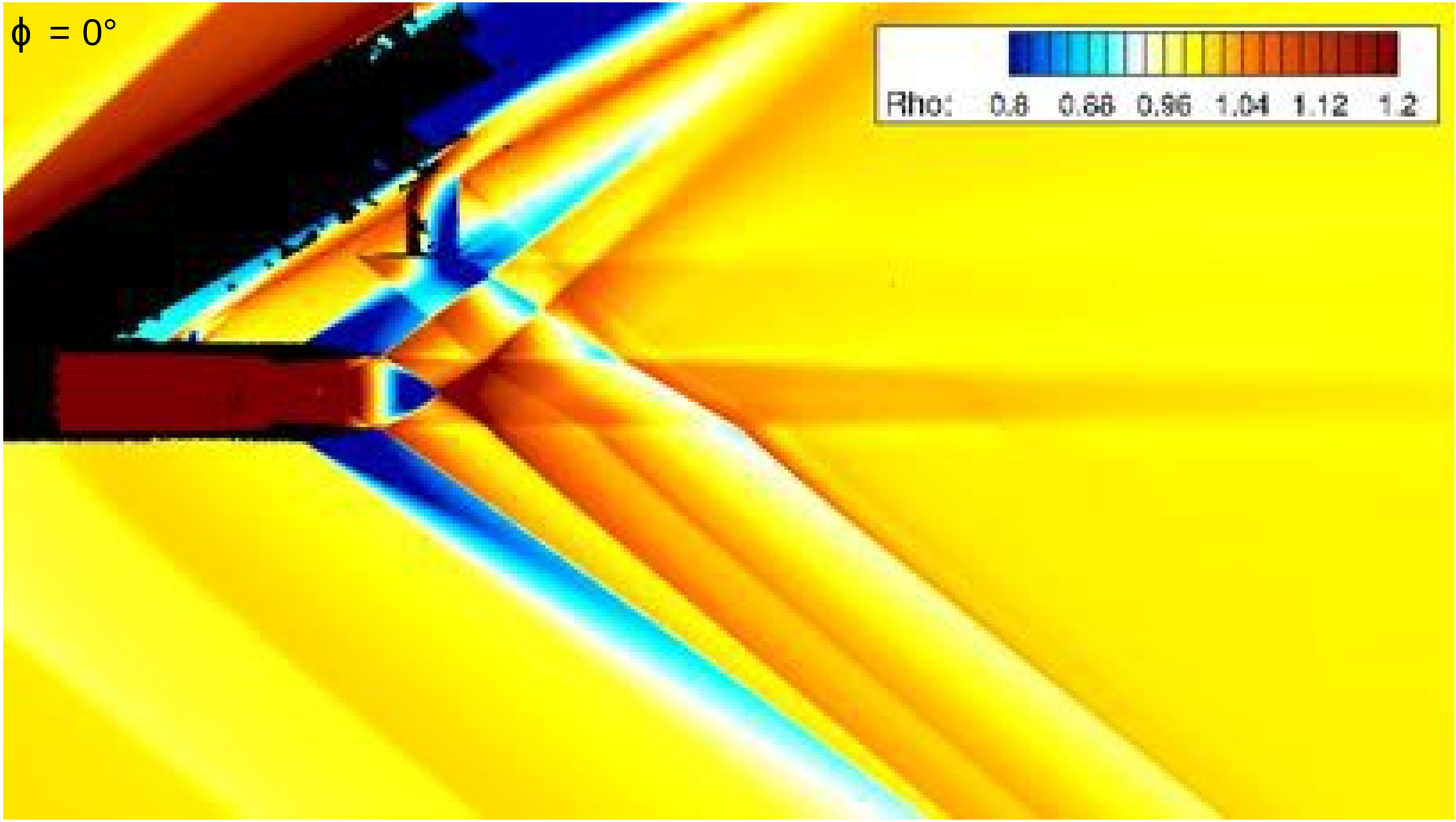
- Density contours (zoomed in on plume-shock interaction region)



Results: Biconvex

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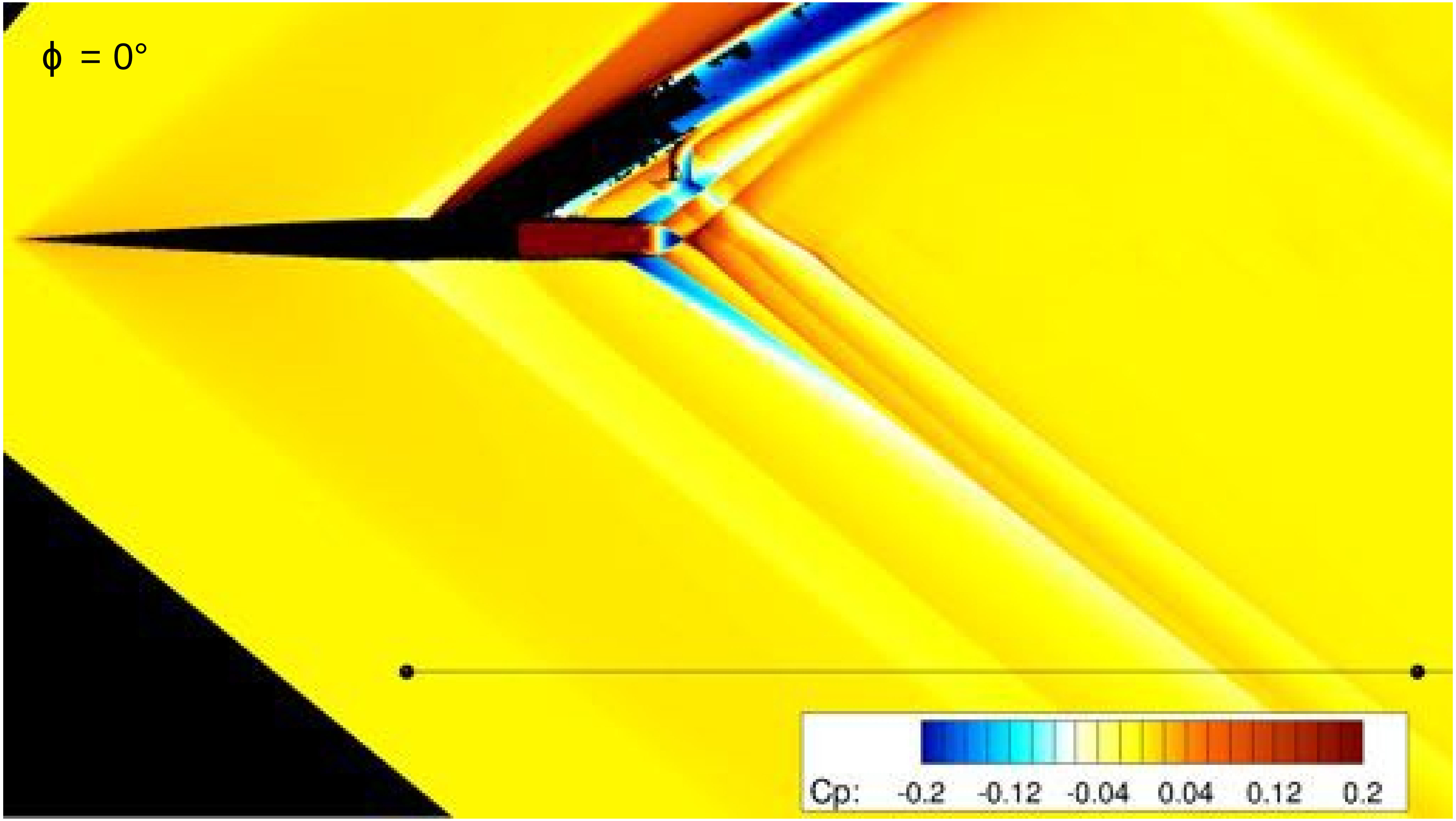
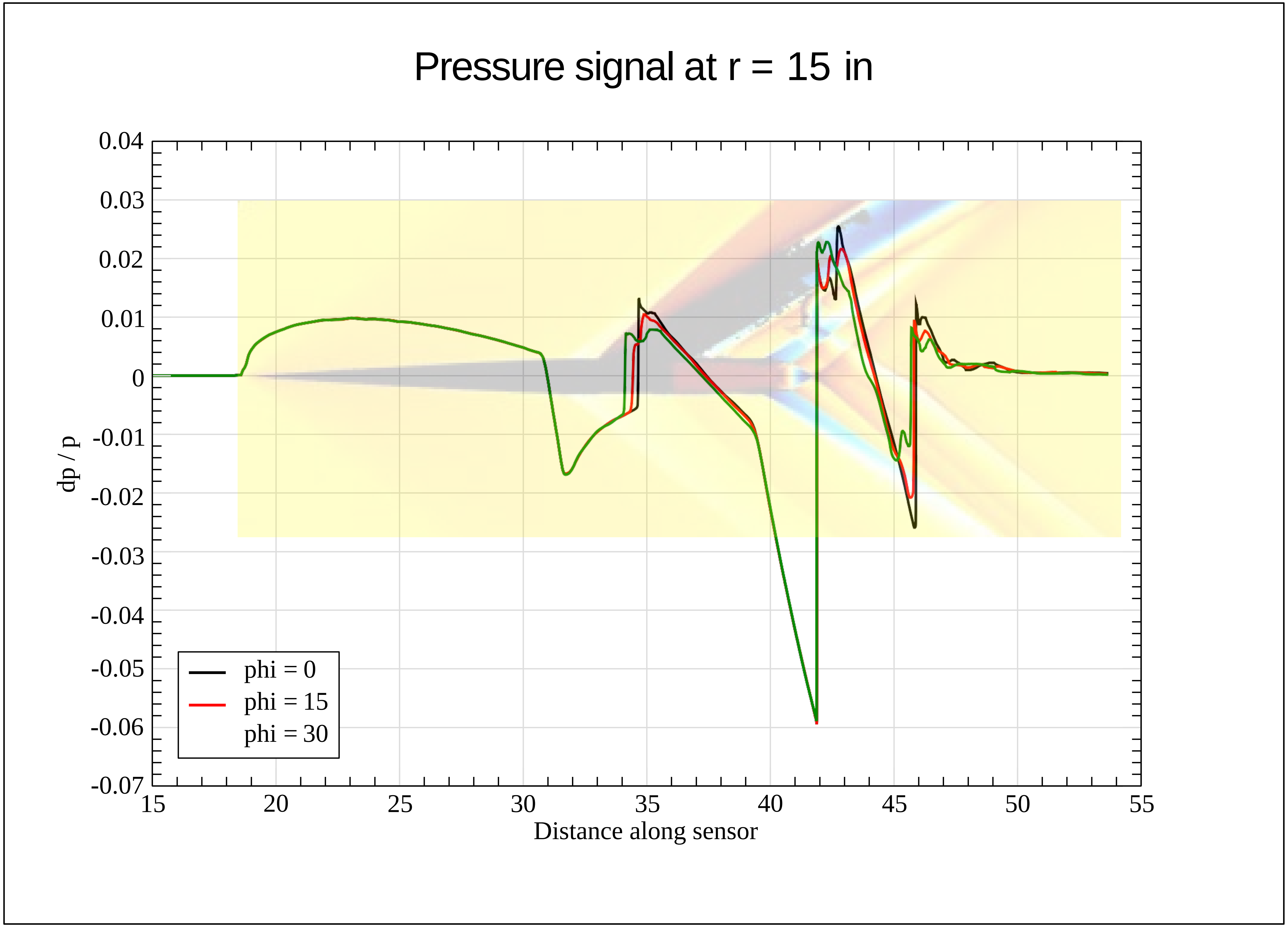
- Pressure coefficient contours

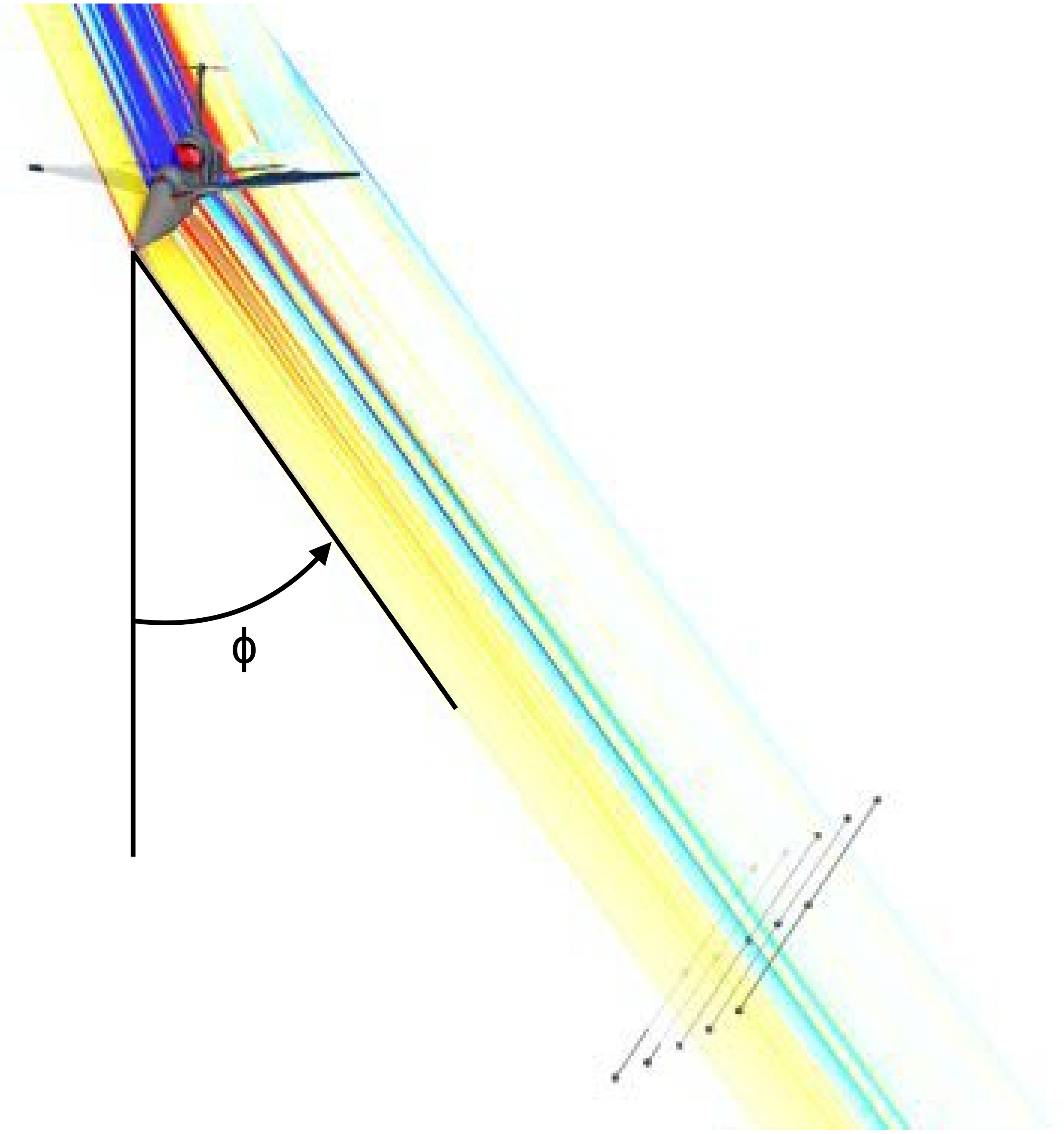


Results: Biconvex



Results: C608

- Separate simulation run at off-track ϕ every 10° (19 total)
- Five line sensors at offsets of Δϕ = [-4, -2, 0, +2, +4]
- Covers full half-cylinder 0 ≤ ϕ ≤ 180° in increments of 2°



Results: C608

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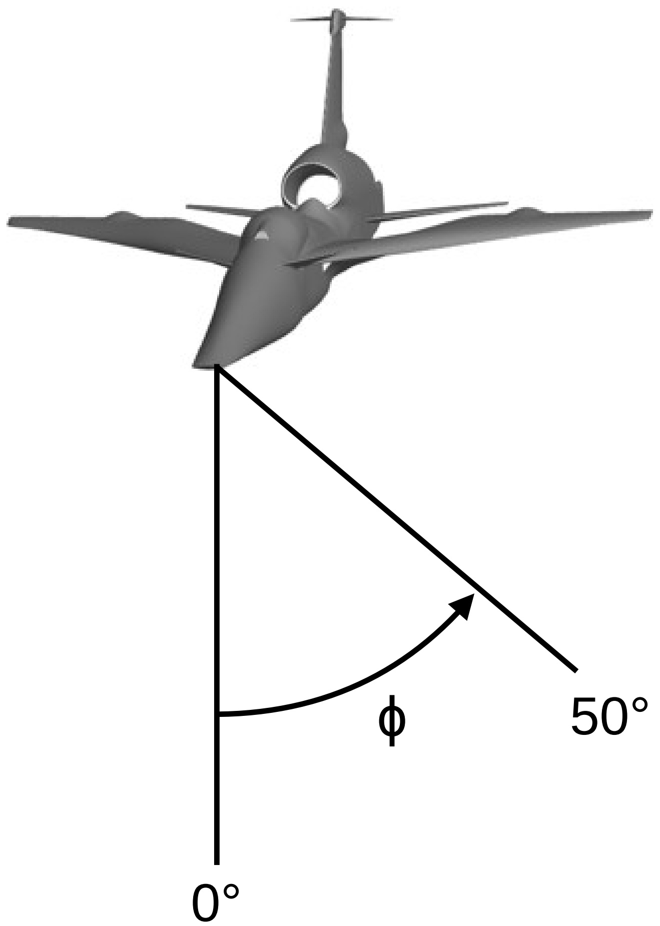

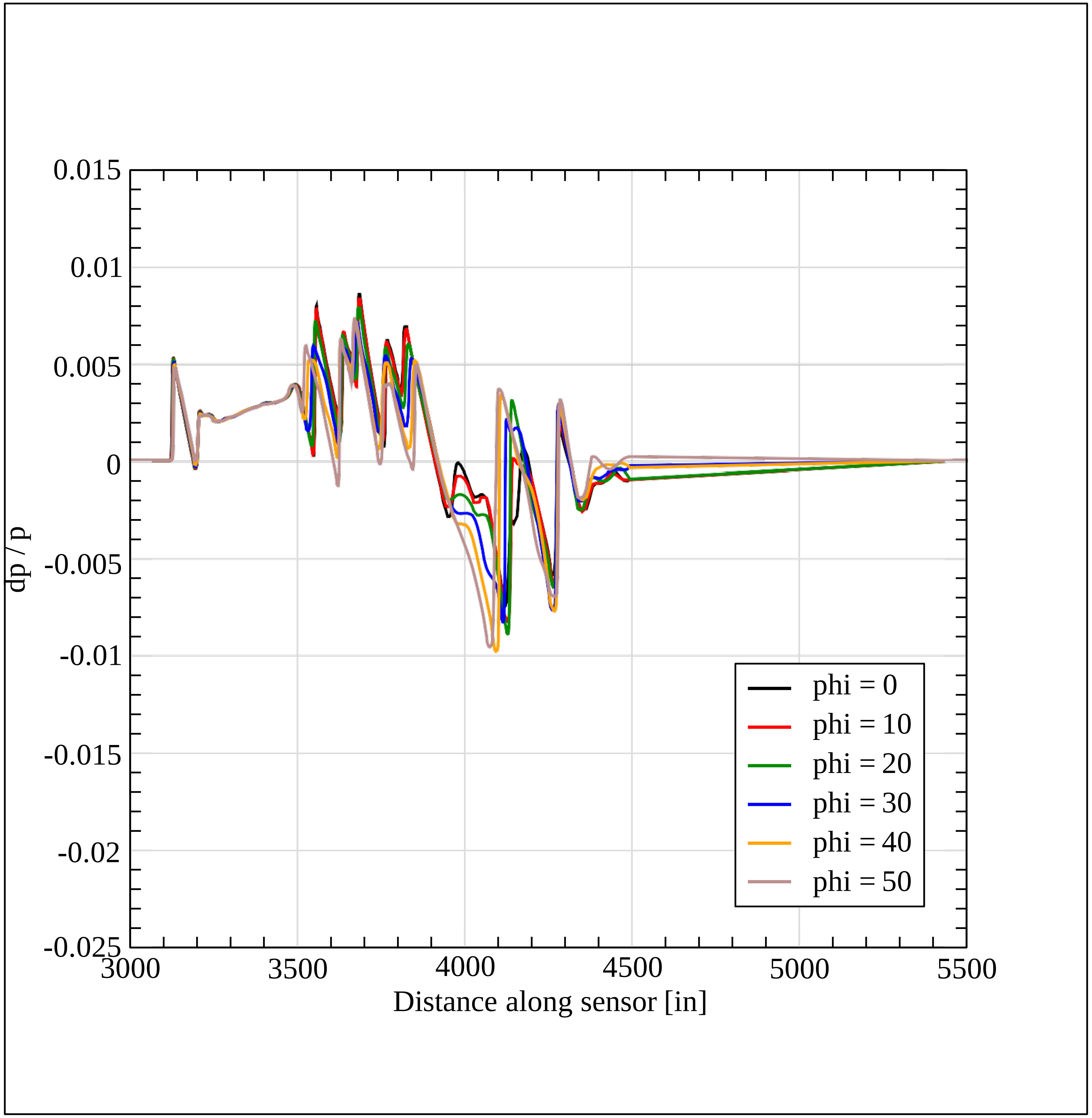

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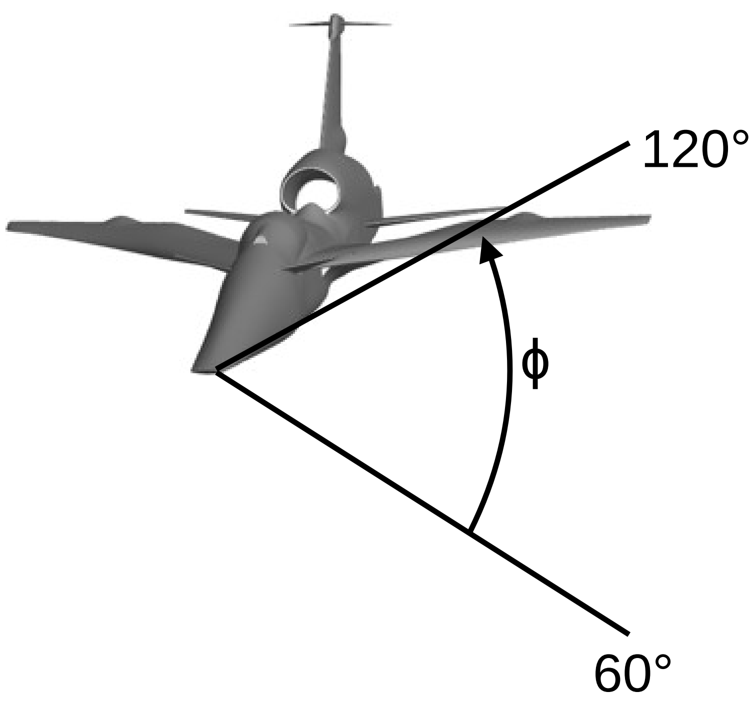

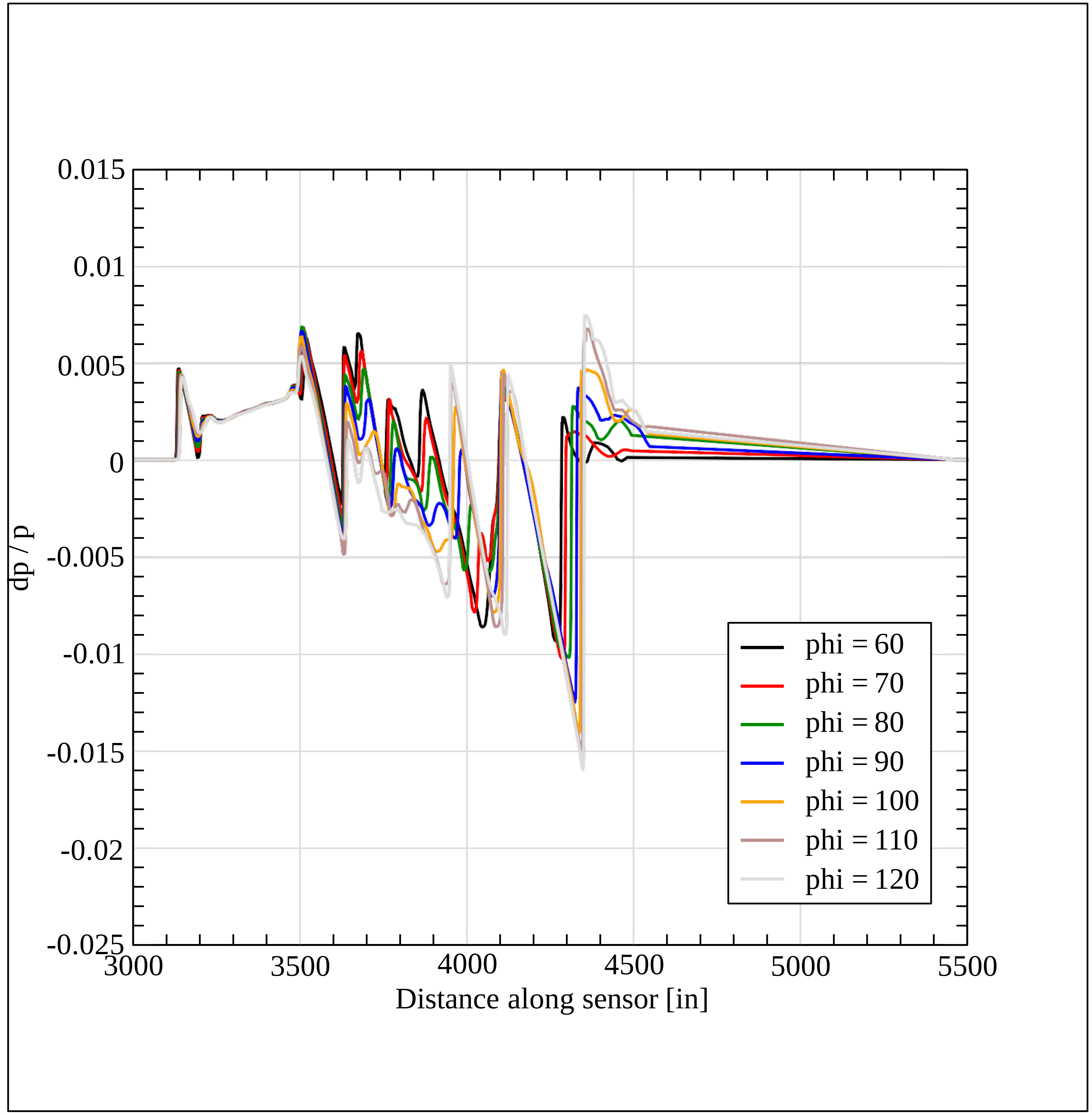

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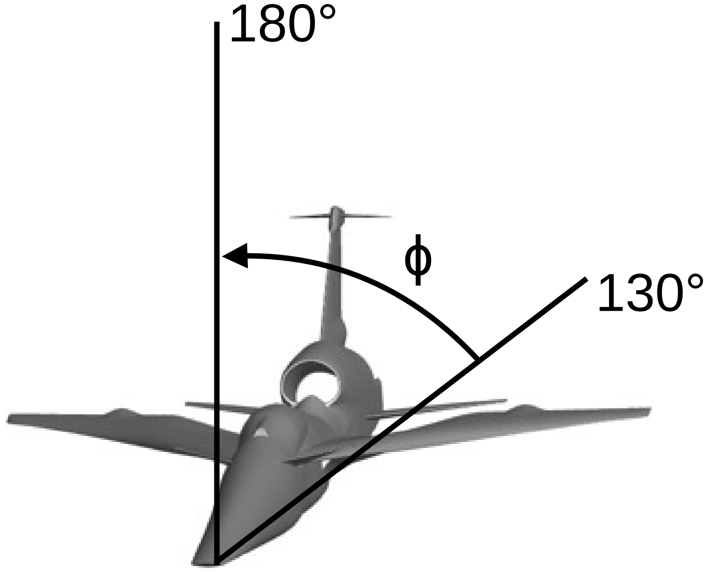

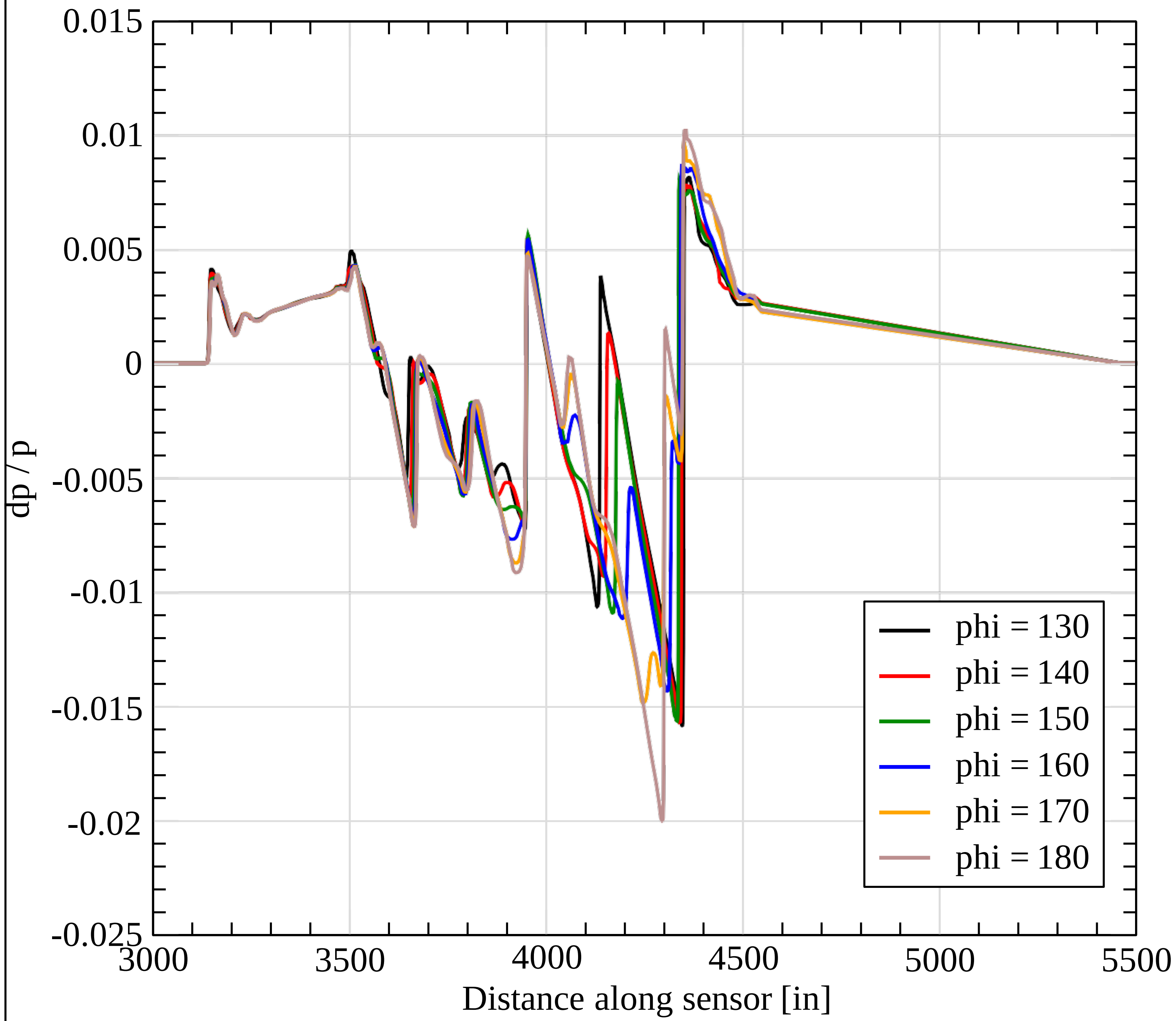

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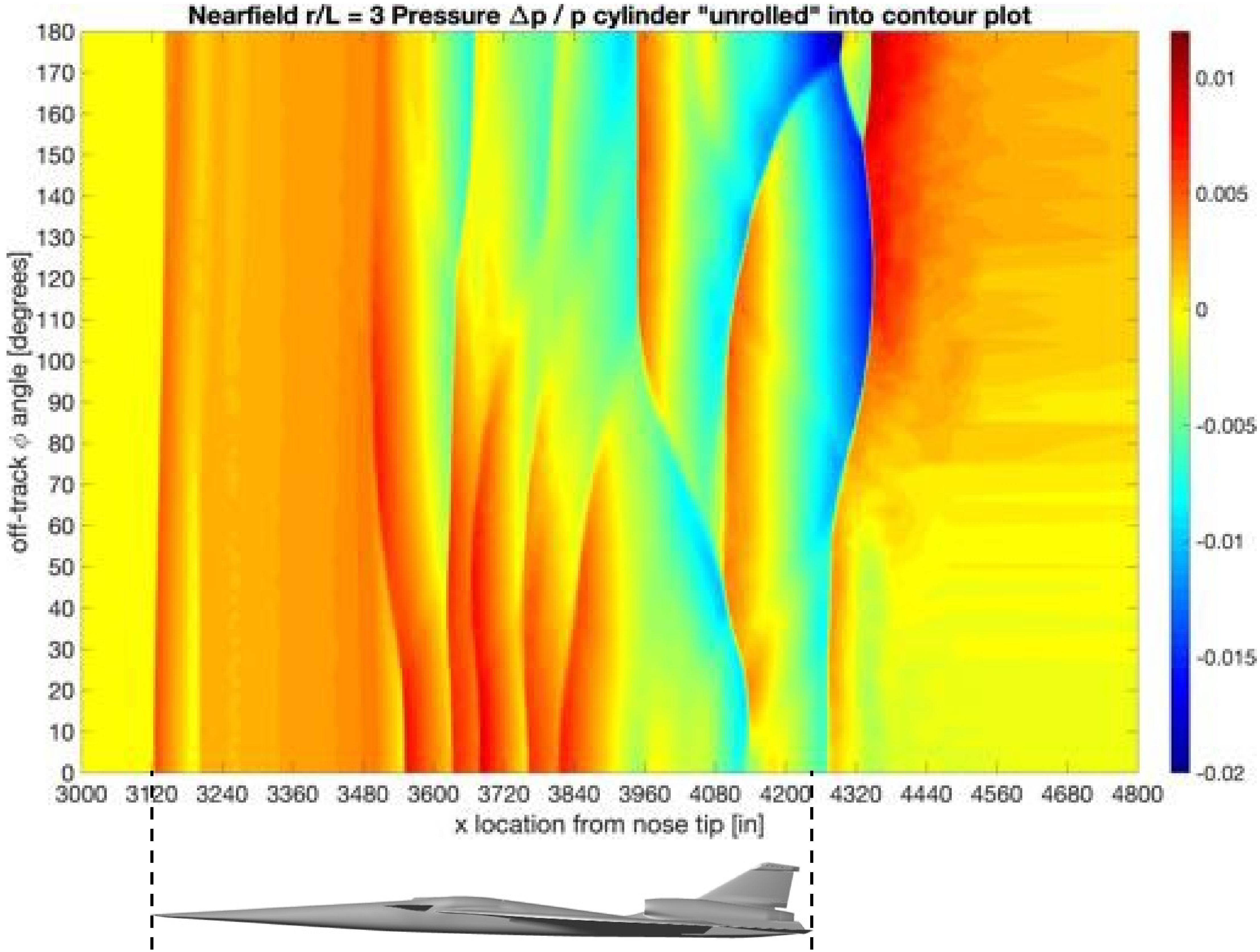

Challenges

- C608
  - Getting outflow BC's to correct desired Mach number
    - Adjusted the back pressure
      - Engine inlet from suggested 2.6 to 2.75
      - ECS inlets from suggested 1.4 to 2.70
  - Consistent closeouts are challenging
    - Plume/shock is difficult to capture
    - Mesh coarsening farther back in plume can create spurious artifacts in pressure signal

Conclusions

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- Complex geometry increases computational cost
  - More features to resolve
  - Must take pressure signal farther from body
- Adaptive meshing refines based on solution error and objective function
- Must routinely check for solution quality
  - Numerical convergence and adjoint performance
  - Grid sequencing with coarse, medium, fine grid pressure signal
  - Comparison metrics for multiple off-track ϕ sim's: mass flow through inflow/outflow boundaries, force & moment coefficients
- Richardson extrapolation shows highest uncertainty in aft portion of signal, which is particularly challenging with propulsion and plumes
- Inviscid simulation can effectively capture supersonic flow features of shocks, expansions, and coalescence

Acknowledgements

- James Jensen for workshop C608 geometry
- Melissa Carter and Mike Park for organizing the workshop and for their correspondence on the nearfield cases
- ARMD Commercial Supersonic Technology Project for supporting this work
- NASA Advanced Supercomputing Division for computational resources

Questions?

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