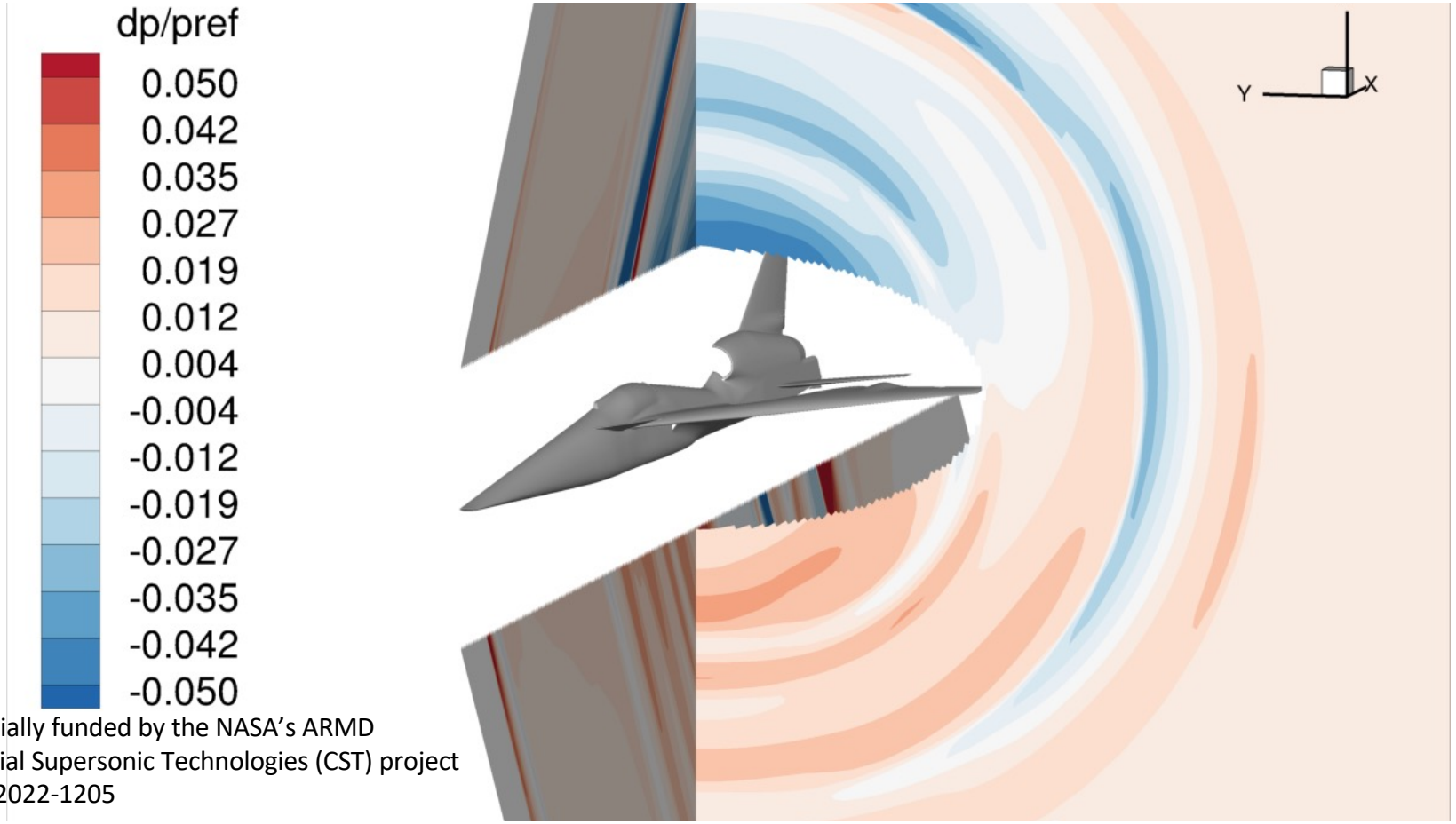
# Algorithmic Improvements to a High-Order Space Marching Method for Sonic Boom Propagation




work partially funded by the NASA's ARMD Commercial Supersonic Technologies (CST) project
ICCFD11-2022-1205

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Computational Aerosciences Branch
NASA Ames Research Center

Advanced Modeling & Simulation (AMS) Seminar
Thursday July 21, 2022

# Outline

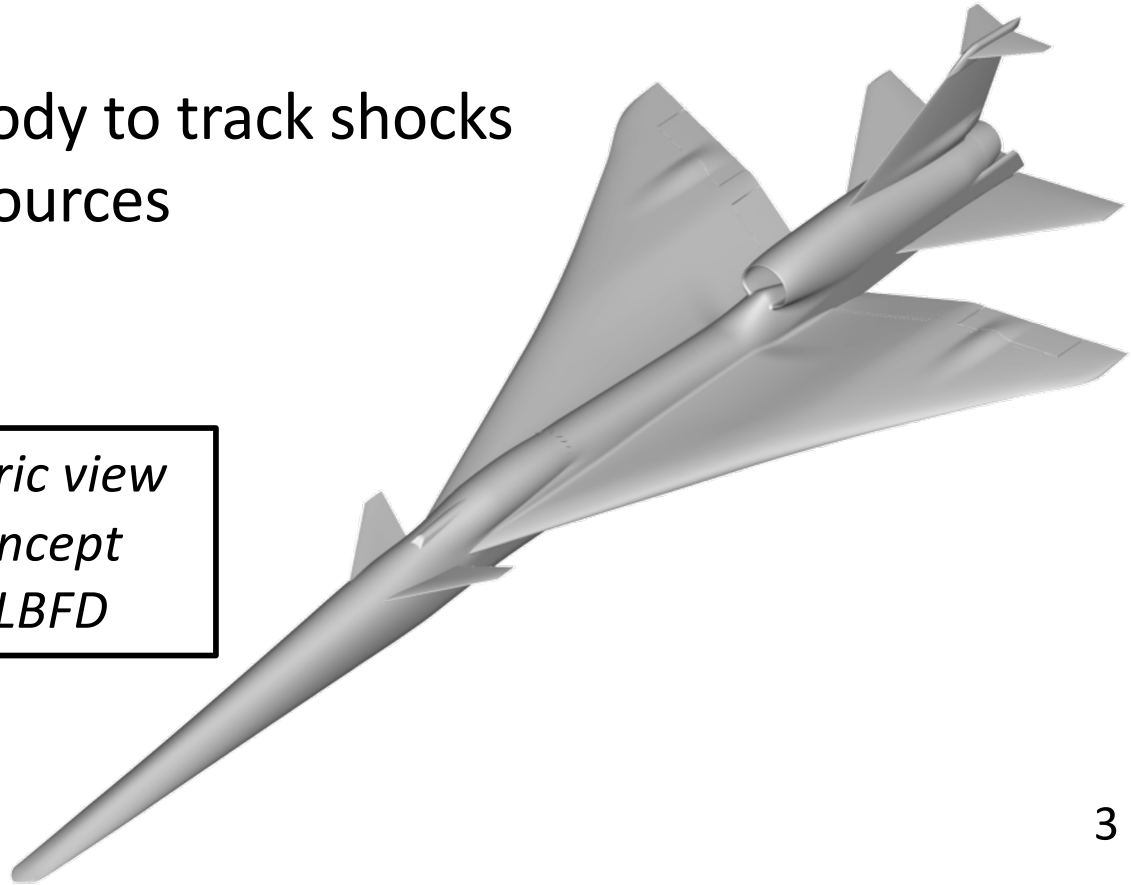



- Introduction
- Computational Methodology
  - Mach-cone Aligned Space Marching Grid
  - Numerical Discretization
- Results
  - CFD Domain Reduction
  - Unstructured Solver Coupling
  - CFD Accuracy Enhancement
  - Near-Field Difference Propagation
  - Local Error Analysis
- Summary

# Introduction

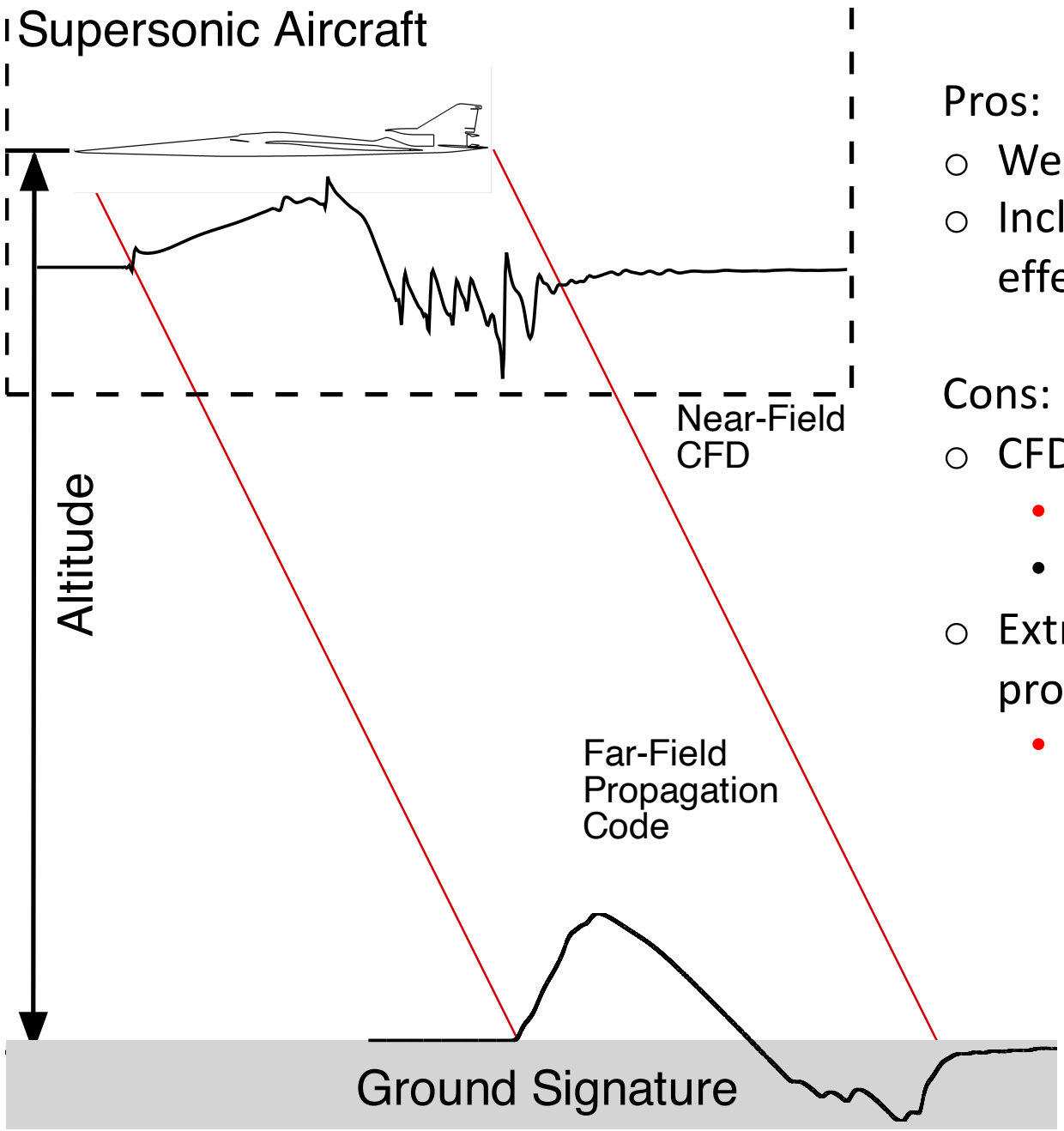
NASA's Low-Boom Flight Demonstration (LBFD) project

- Primary goal is to demonstrate feasibility of supersonic over-land flight at reduced loudness levels
- X-59 Quiet Supersonic Technology (QueSST) airplane
- Mission planning requires large database consisting of *O*(1000)-*O*(10,000) solutions
  - Fine mesh away from body to track shocks
  - High computational resources
  - Must be accurate
  - Must be automated



*Iso-parametric view of early concept design of LBFD*

# Previous 2-Step Ground Level Noise Prediction




Pros:

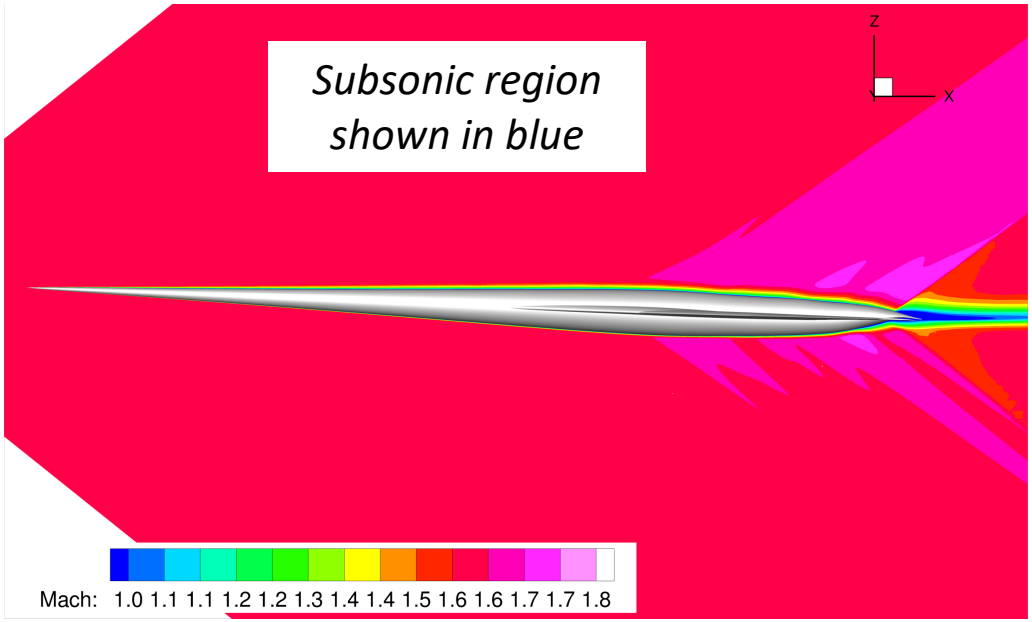
- Well established procedure
- Includes important atmospheric effects

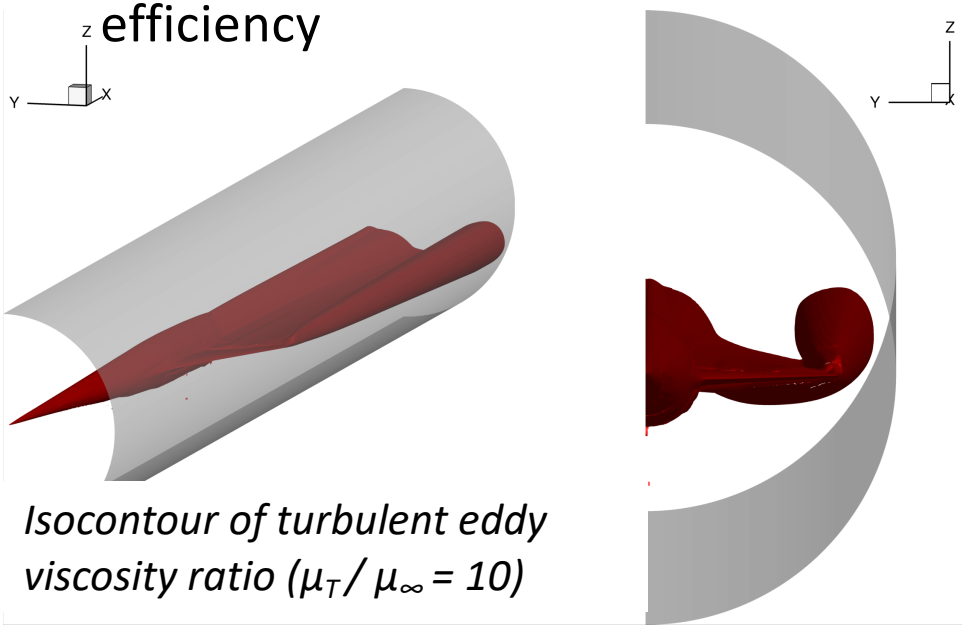
Cons:

- CFD domain is relatively large
  - High Computational Cost
  - Accuracy (2nd order)
- Extraction radius for far-field propagation relatively small
  - Ignores potentially important azimuthal effects

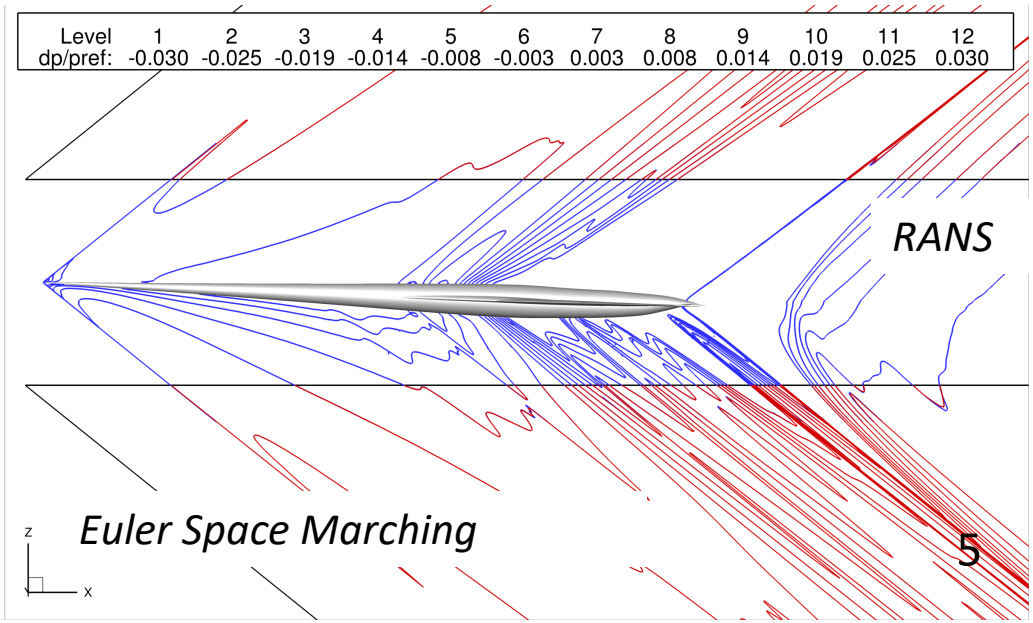
# Special Features of Supersonic Flow

- All information travels in a common "time-like" direction along characteristic surfaces
- Viscous effects are only important near the walls of the aircraft
- Space marching is a special discretization/solution strategy which uses these features for computational efficiency

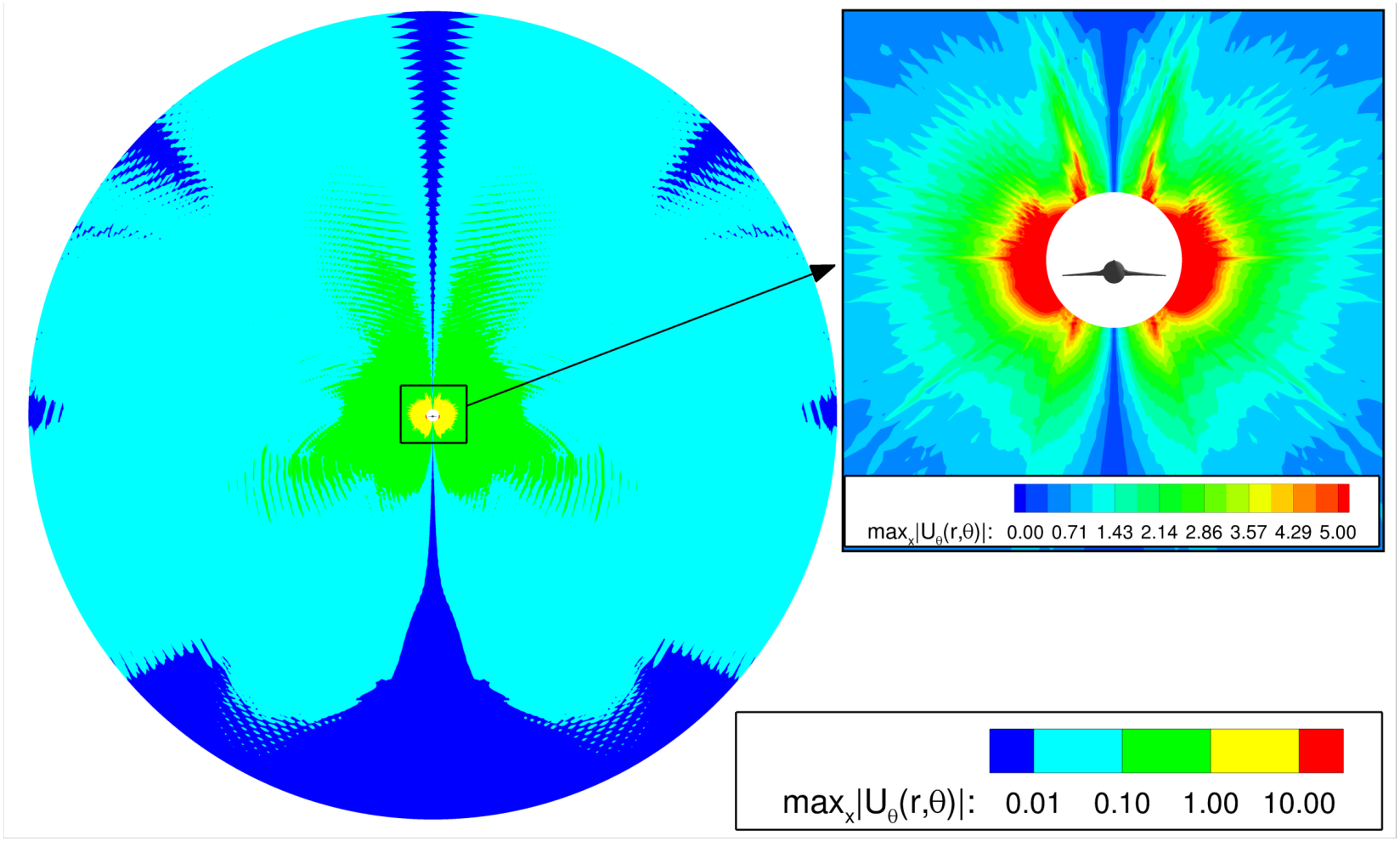



*Isocontour of turbulent eddy viscosity ratio ($\mu_T / \mu_\infty = 10$)*



# Azimuthal Dependence on Ground Level Noise

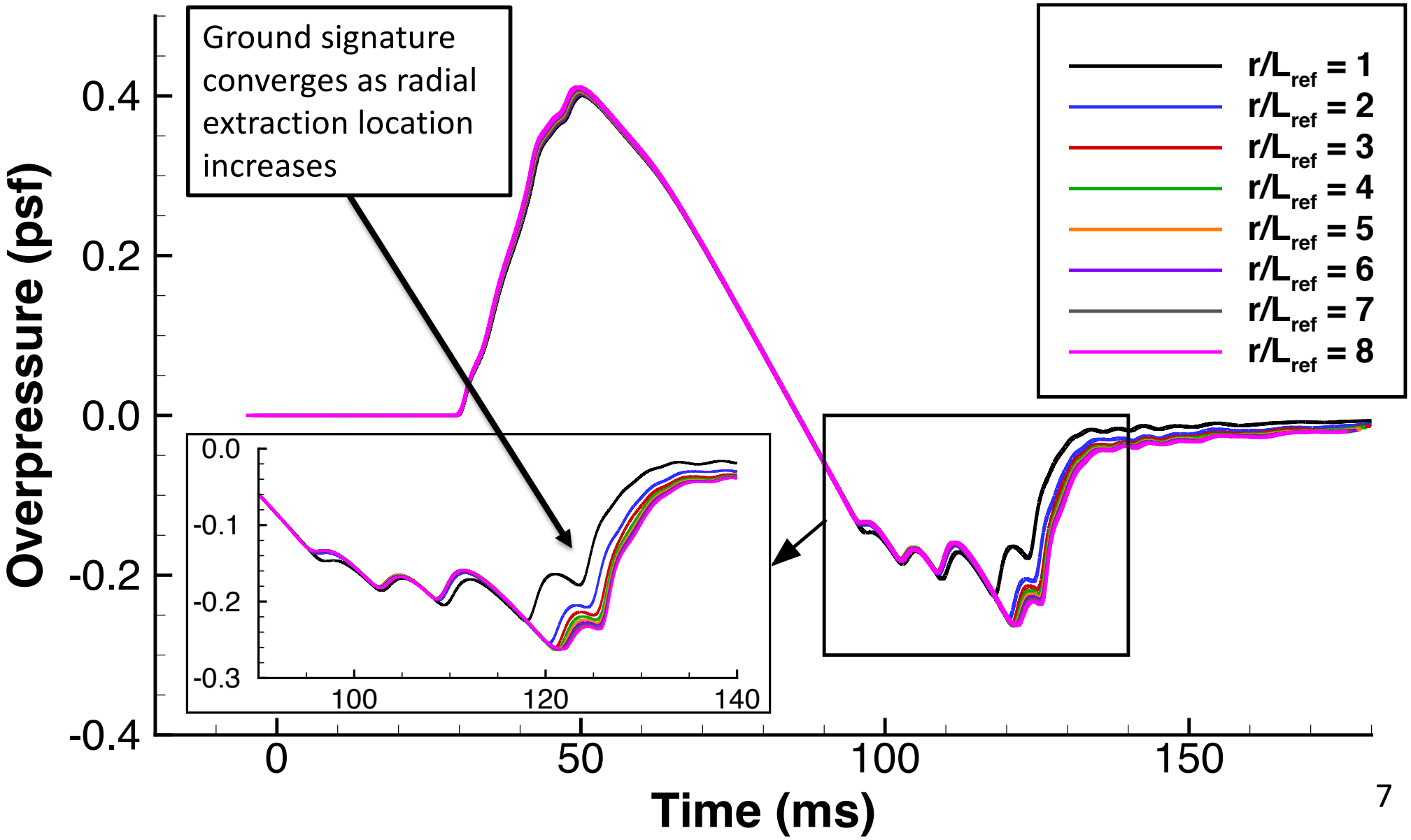



- Non-zero azimuthal velocity observed past 10 body lengths from aircraft showing large radial extent of azimuthal effects
- Dipole shape of azimuthal velocity field indicates lift as dominate mechanism
- Confirms earlier work by George

George, A., "Reduction of Sonic Boom by Azimuthal Redistribution of Overpressure," AIAA J., Vol. 15, No. 5, 1977

# Azimuthal Dependence on Ground Level Noise

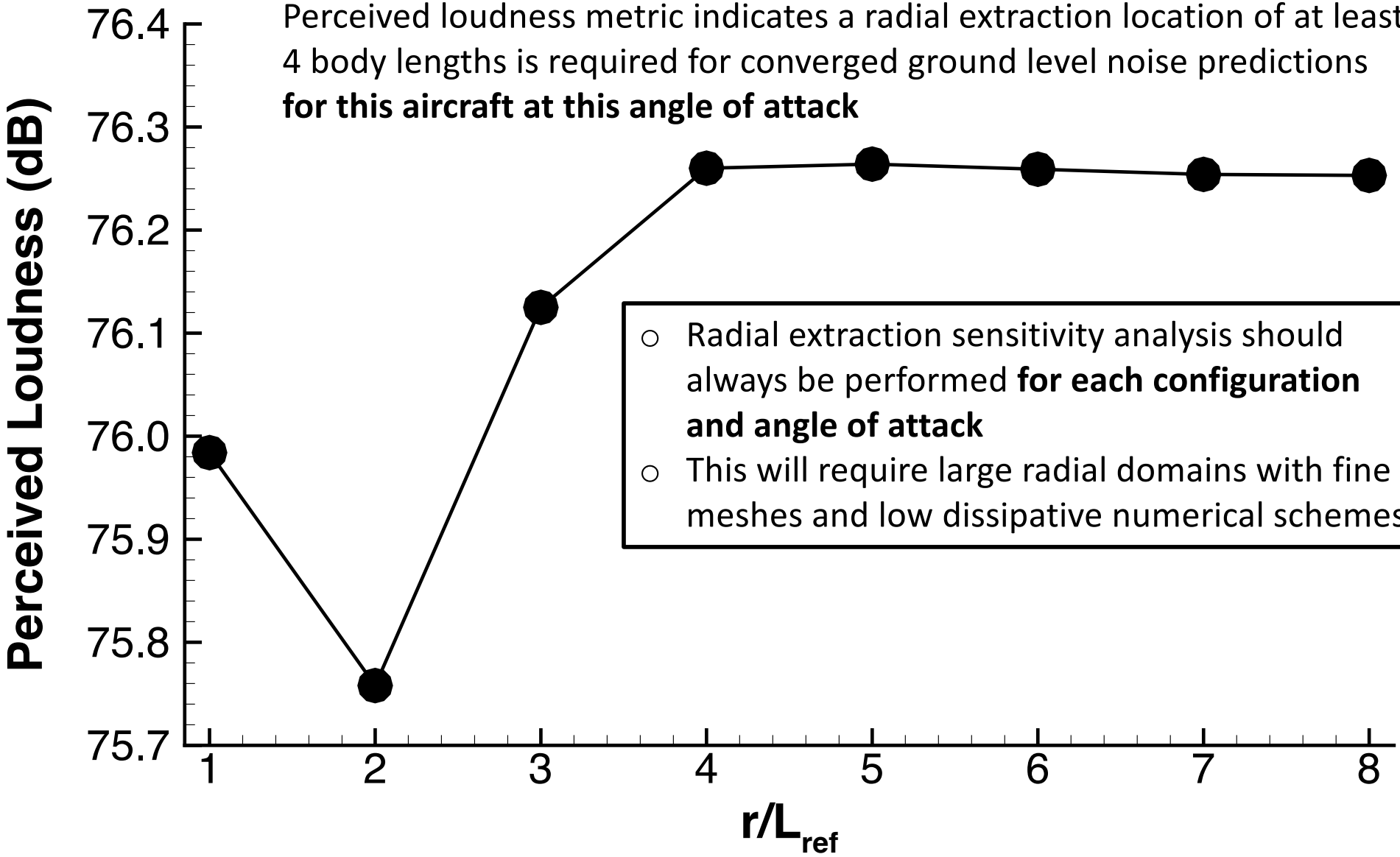
Overpressure ground signatures propagated with sBOOM from each radial extraction



# Azimuthal Dependence on Ground Level Noise

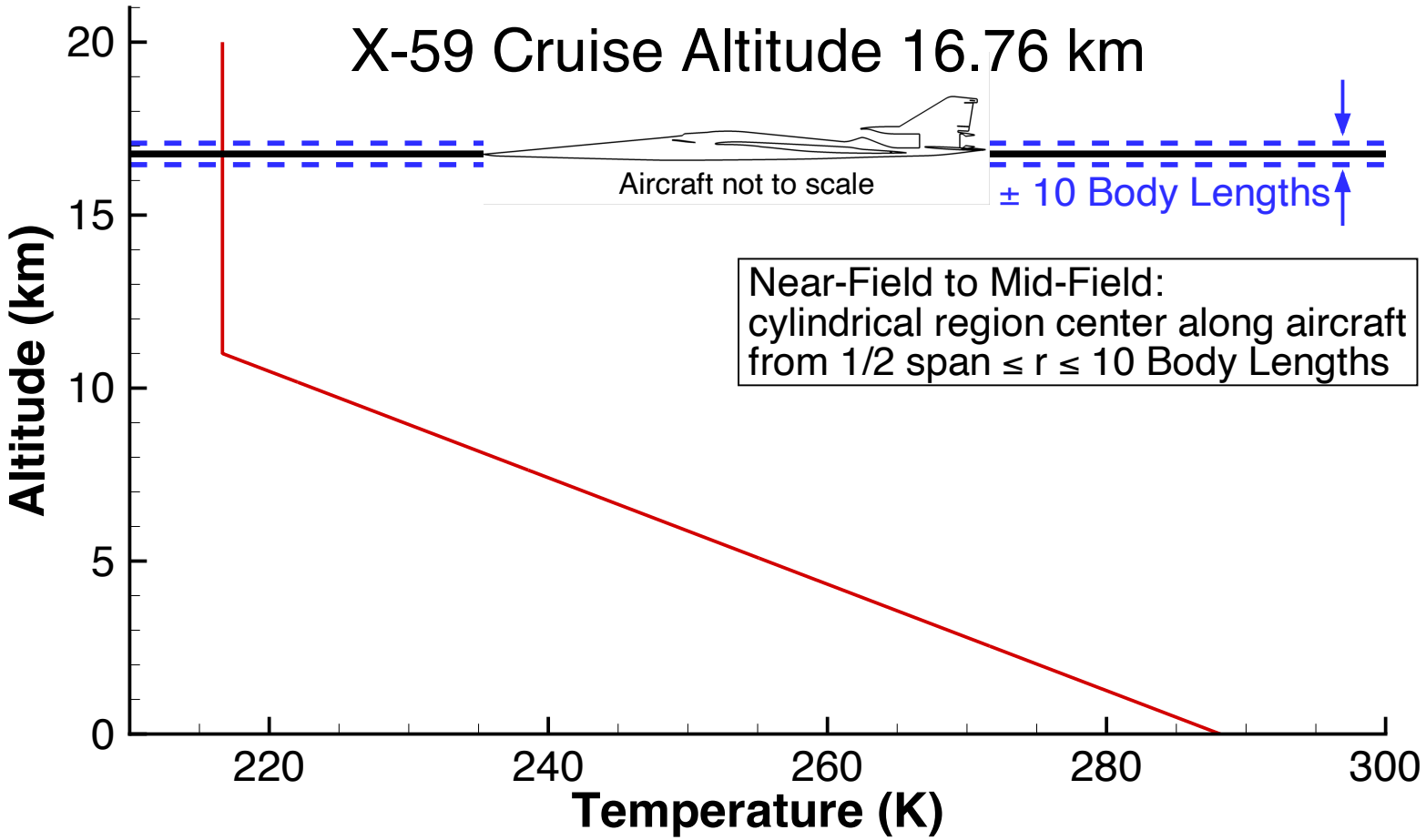
Perceived loudness on the ground as a function of radial extraction location

Perceived loudness metric indicates a radial extraction location of at least 4 body lengths is required for converged ground level noise predictions **for this aircraft at this angle of attack**



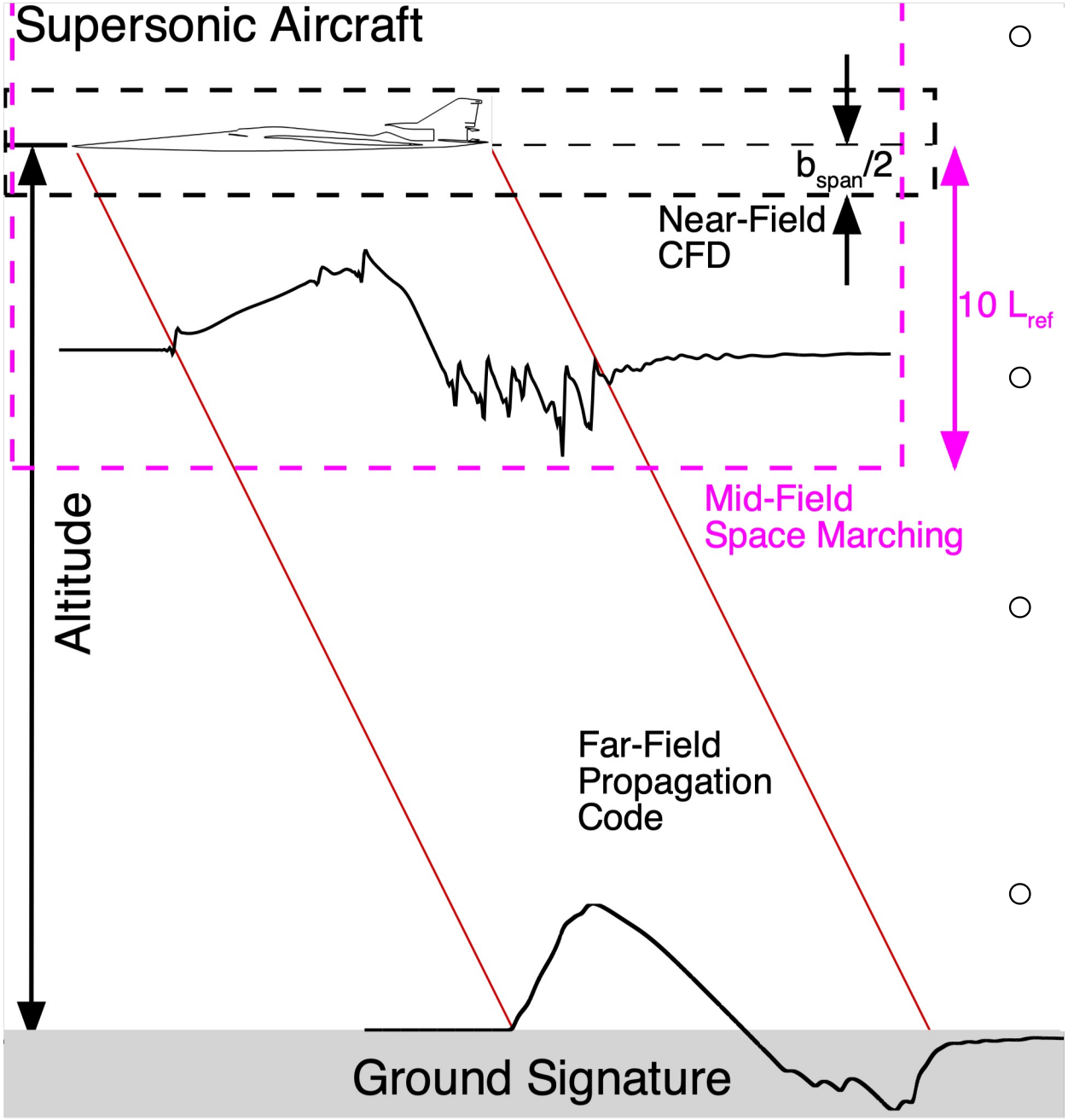

- Radial extraction sensitivity analysis should always be performed **for each configuration and angle of attack**
- This will require large radial domains with fine meshes and low dissipative numerical schemes

# Definition of Near-Field to Mid-Field



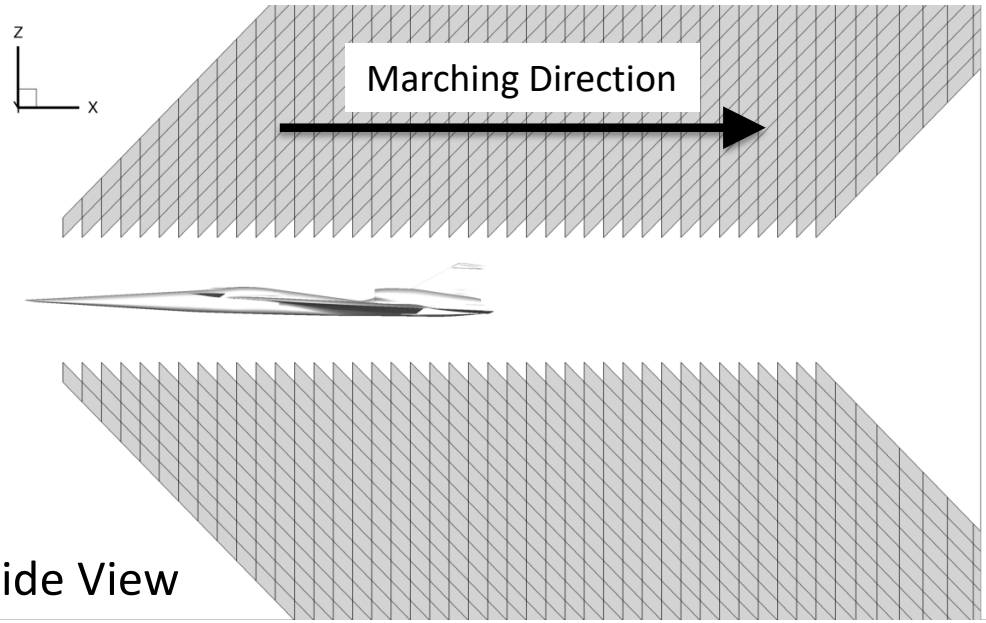

- Plot of altitude versus ICAO standard atmospheric temperature
- No variation in temperature within 10+ body lengths of the aircraft
- Atmospheric effects are currently neglected in the near-field to mid-field
  - examples: wind variation, molecular relaxation, and humidity

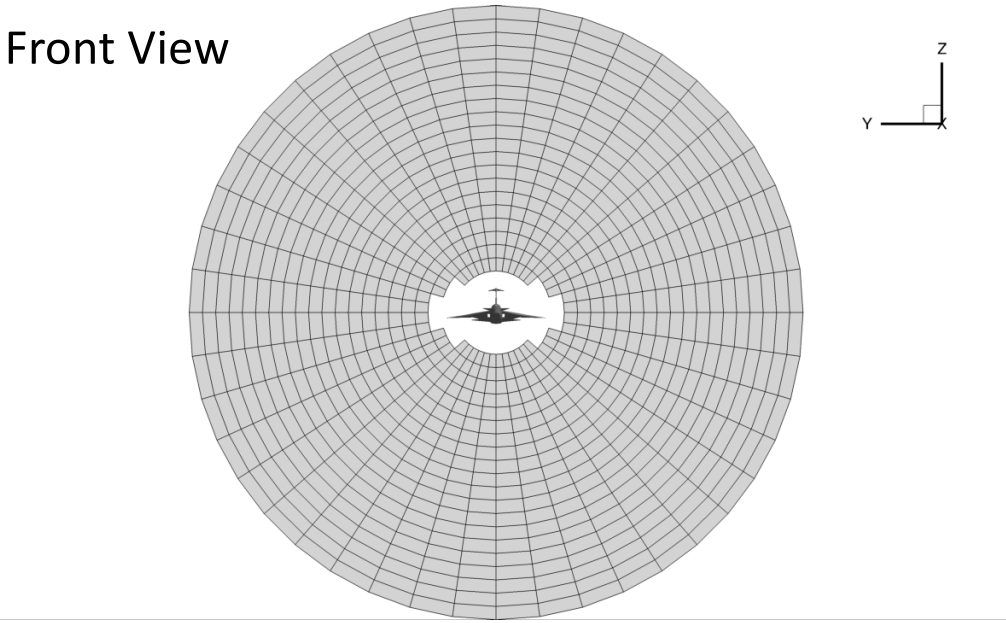
# 3-Step Ground Level Noise Prediction

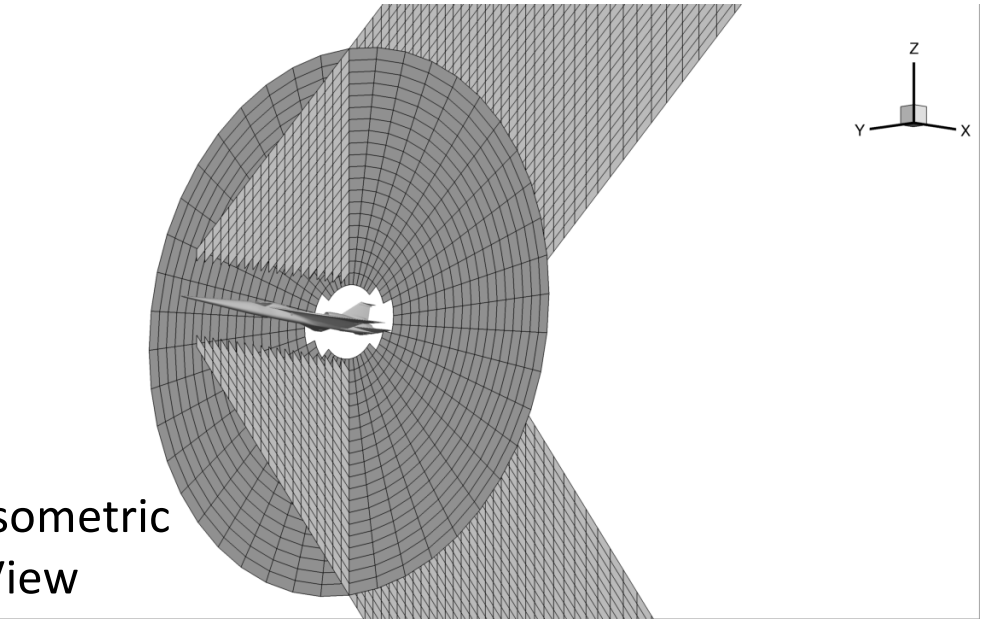



- Pros:
  - Reduced CFD domain
  - Space marching procedure:
    - Automated grid generation
    - Runs on workstation in minutes
    - Includes all relevant azimuthal effects
    - Changes from 3D steady into 2D "unsteady-like"
  - More than 50% reduction in total time
  - Same level of accuracy for ground level noise
- Cons:
  - Introduces additional step in process

# Mach-cone Aligned Space Marching Grid



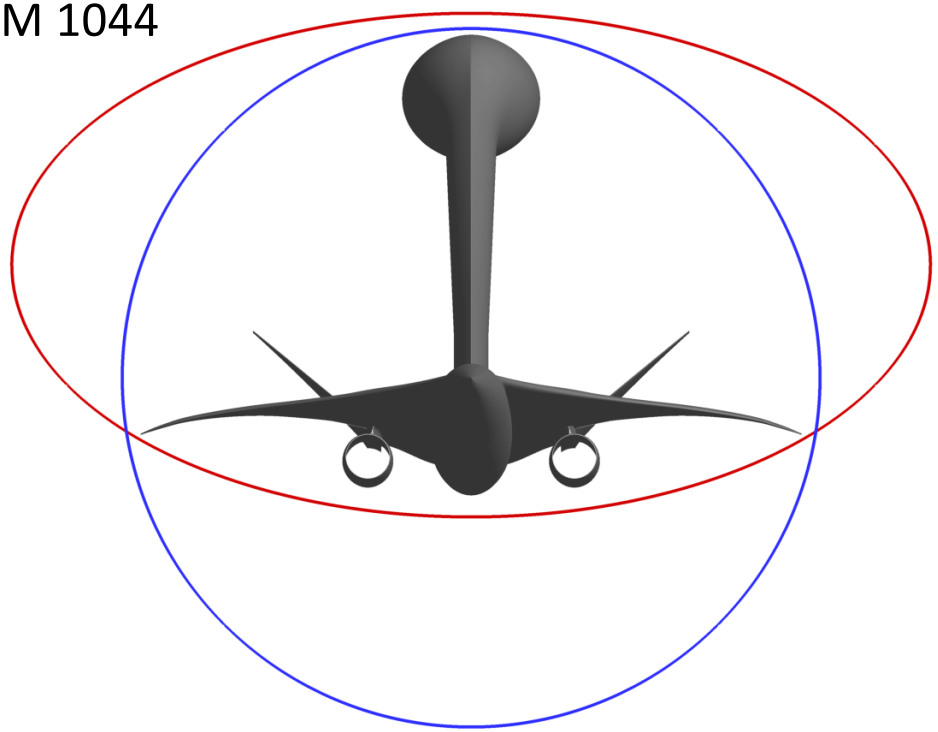



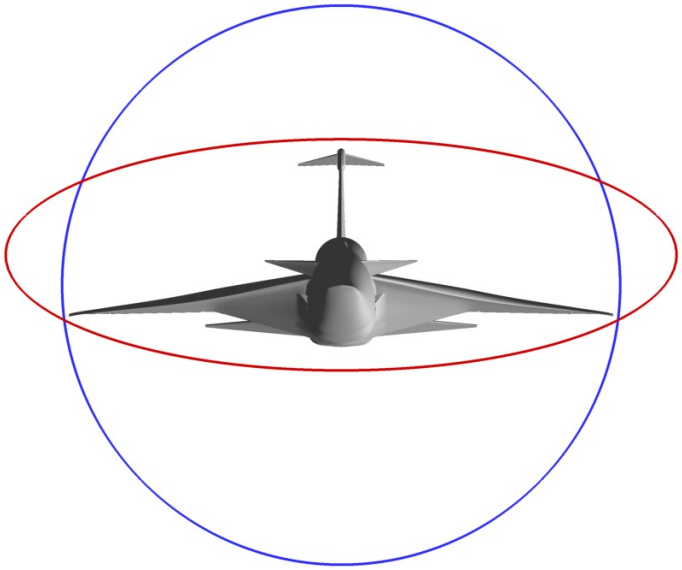

- Grid design inspired by Siclari and Darden AIAA-1990-4000
- Space marching direction aligned with freestream flow direction to guarantee valid space march as local Mach number approach unity
- Mach-cone aligned to reduce effect of artificial dissipation
- Automatically generates O(10)-O(1000) million grid points meshes in seconds on a workstation

# Elliptic Hole Cutting Procedure

LM 1044



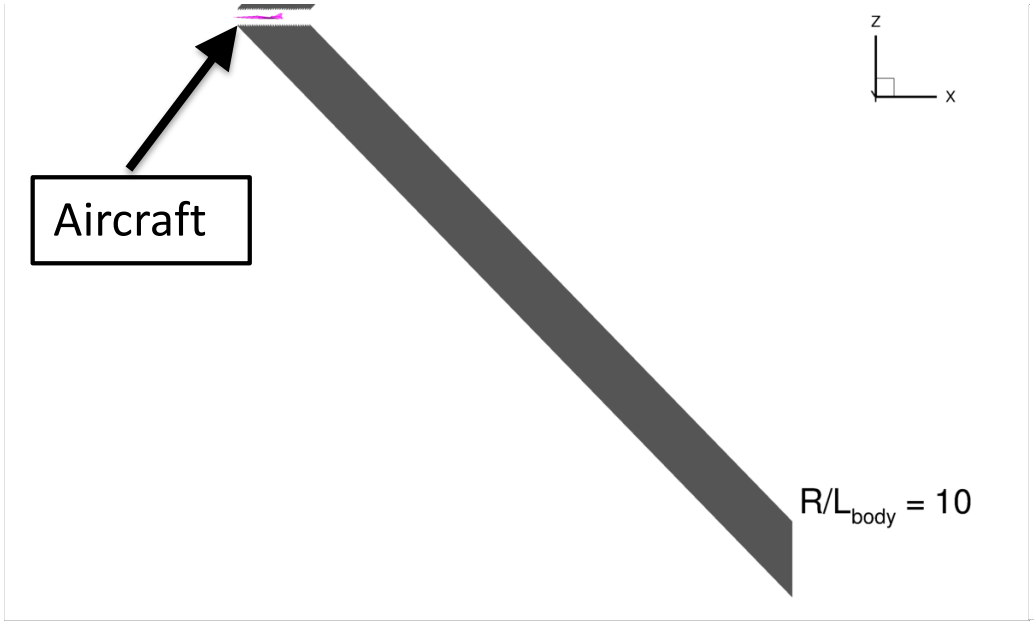
C608

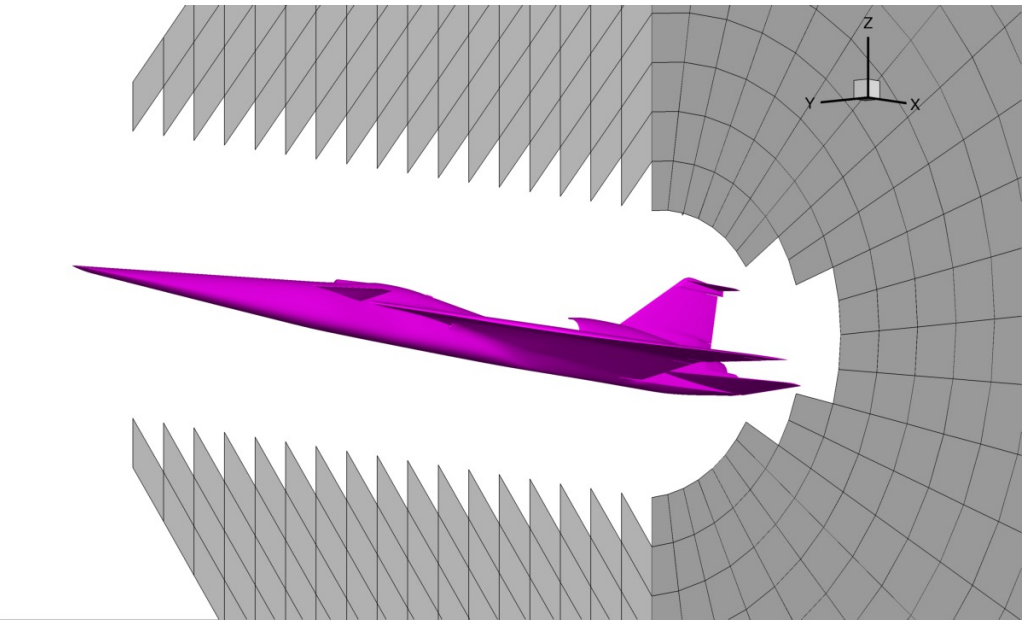


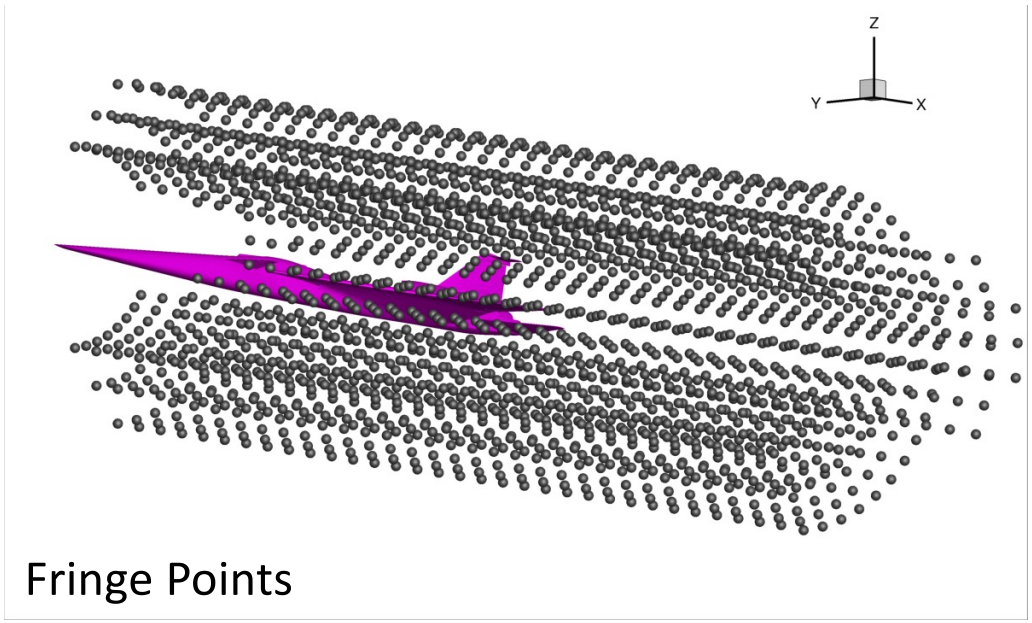
- The original cylindrical hole cutting procedure has been replaced with an elliptic hole cutting procedure
  - Remains geometrically simple for easy user placement*
  - Enables closer coupling to the aircraft
  - Reduces CFD meshing requirements away from aircraft body

*An automated multi-ellipsoidal procedure is currently being developed

# CFD/Space Marching Coupling

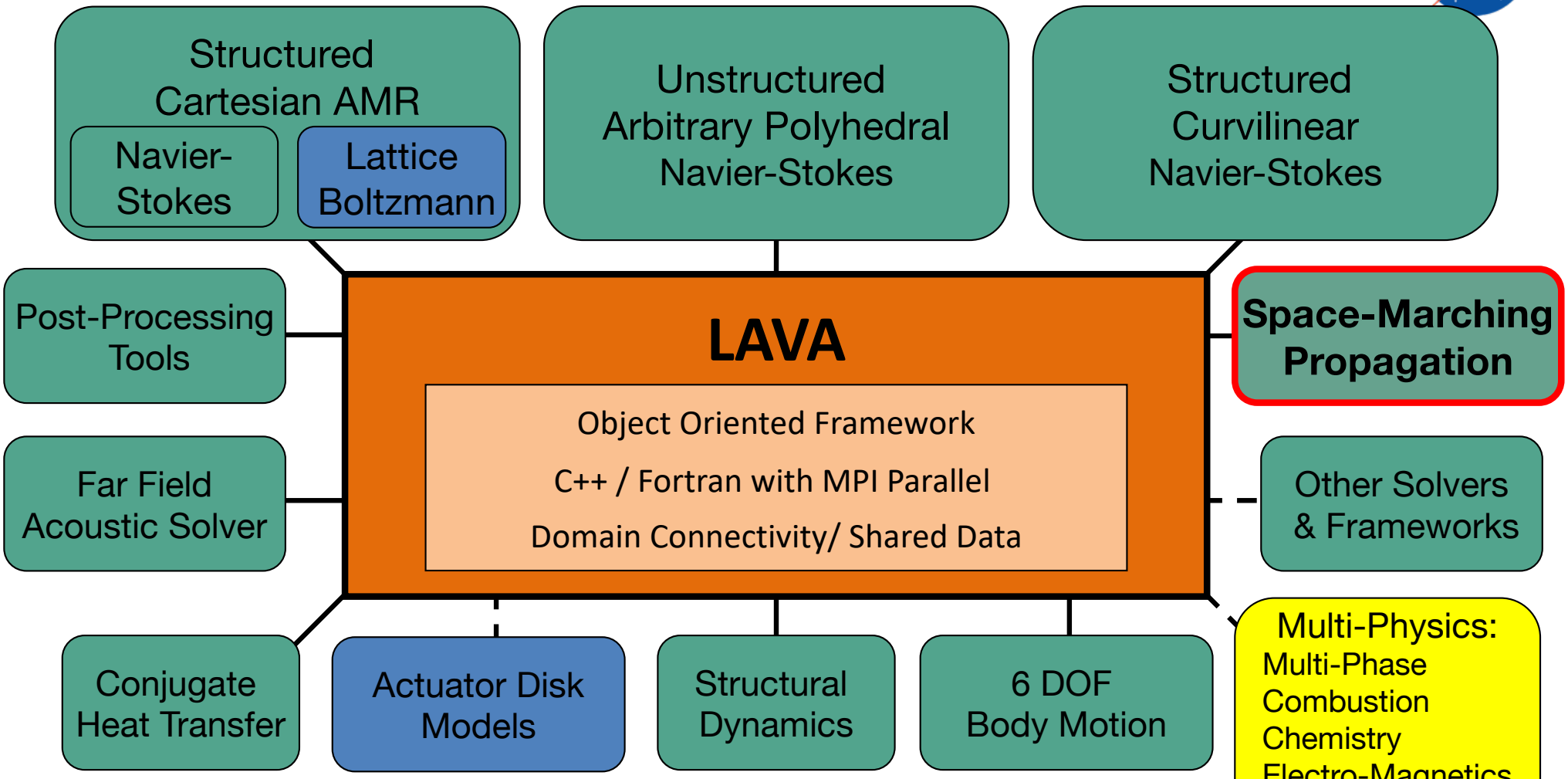


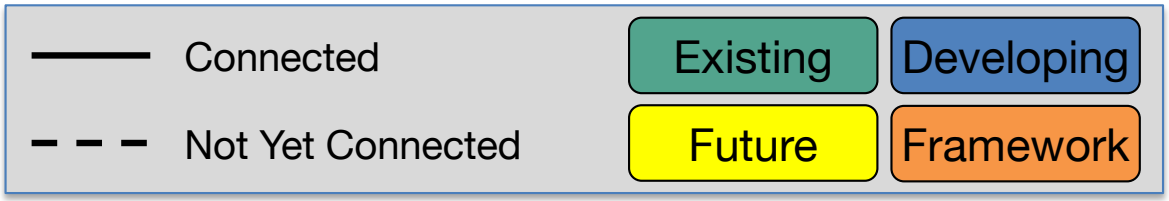

- Coarse space marching grid shown to illustrate procedure
  - Grid is automatically generated to user specified radial extent
  - Elliptic hole cut is performed
  - Fringe points are marked and CFD solution interpolated
  - Space marching is performed

# LAVA Framework




***Other Development Efforts***

- Higher order and low dissipation
- Curvilinear grid generation
- Wall modeling
- LES/DES/ILES Turbulence
- HEC (optimizations, accelerators, etc)




*Kiris at al. AIAA-2014-0070 & AST-2016*

# Numerical Discretization




- Governing equations are the steady-state 3D Euler equations transformed to a general curvilinear coordinate system in strong conservation law form
- Second-order BDF2 is used in the space marching direction (BDF1 and BDF3 options are available)
- High-order Hybrid Weighted Compact Nonlinear Scheme (HWCNS) is used in the two non-space marching coordinate directions
  - Interface (half-point) fluxes are evaluated with Roe-like scheme
  - Left/right interface states use $3^{rd}$ or $5^{th}$ order WENO interpolation
  - $4^{th}$ order centered finite difference using a combination of fluxes at the grid points and the half-points used for flux derivatives
- Identical finite-difference operators (BDF2 and HWCNS) are used in metric term evaluation for free-stream preservation
- 2D nonlinear system is solved at each space marching station using an alternating line Jacobi relaxation procedure

See paper for details: ICCFD11-2022-1205

# Computational Results

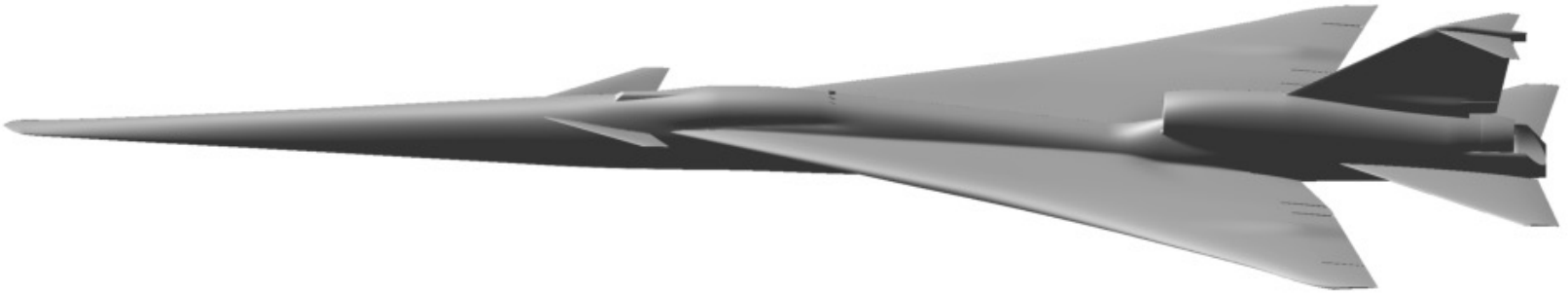


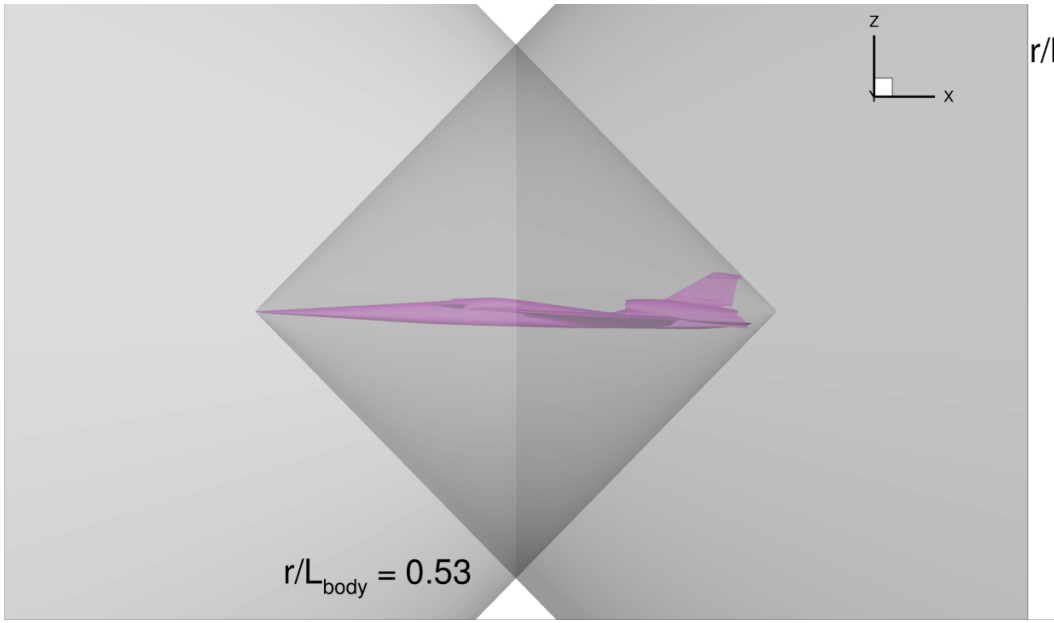

- CFD Domain Reduction
  - Domain of dependence
  - Comparison of 2-step and 3-step (space marching) procedures
- Unstructured Solver Coupling
  - Example of USM3D + LAVA space marching
- CFD Accuracy Enhancement
  - HALO3D coarse mesh improvement demonstration
- Near-field Difference Propagation
  - Application to LM1021
- Local Error Analysis
  - Application to JAXA Wing Body (JWB)

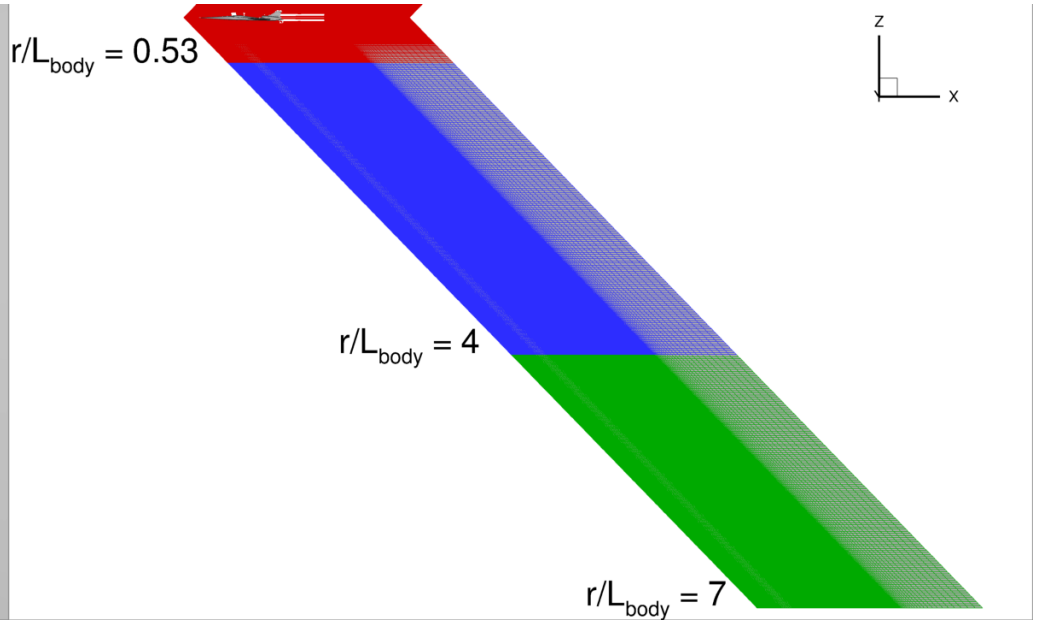
# CFD Domain of Dependence

**C608**

Mach 1.4
Re/m 4.3 million
Altitude 16.2 km
Length 27.432 m

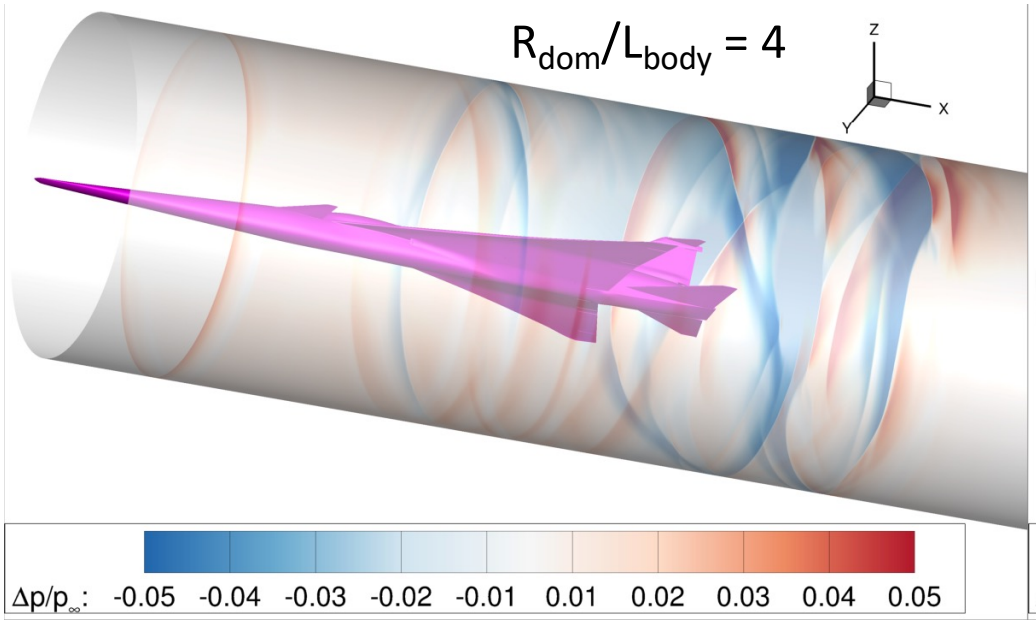


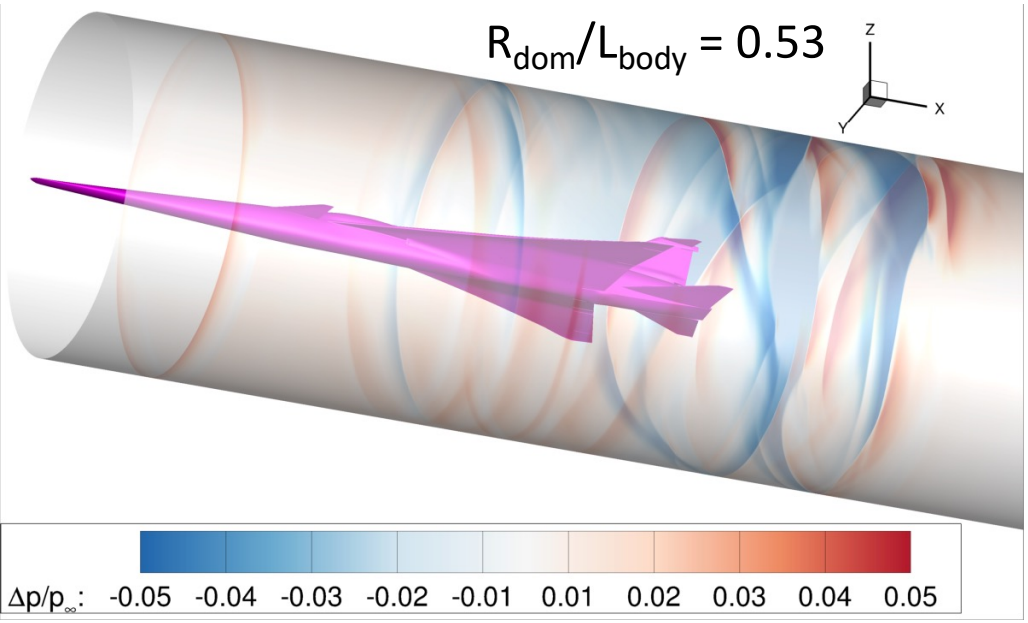


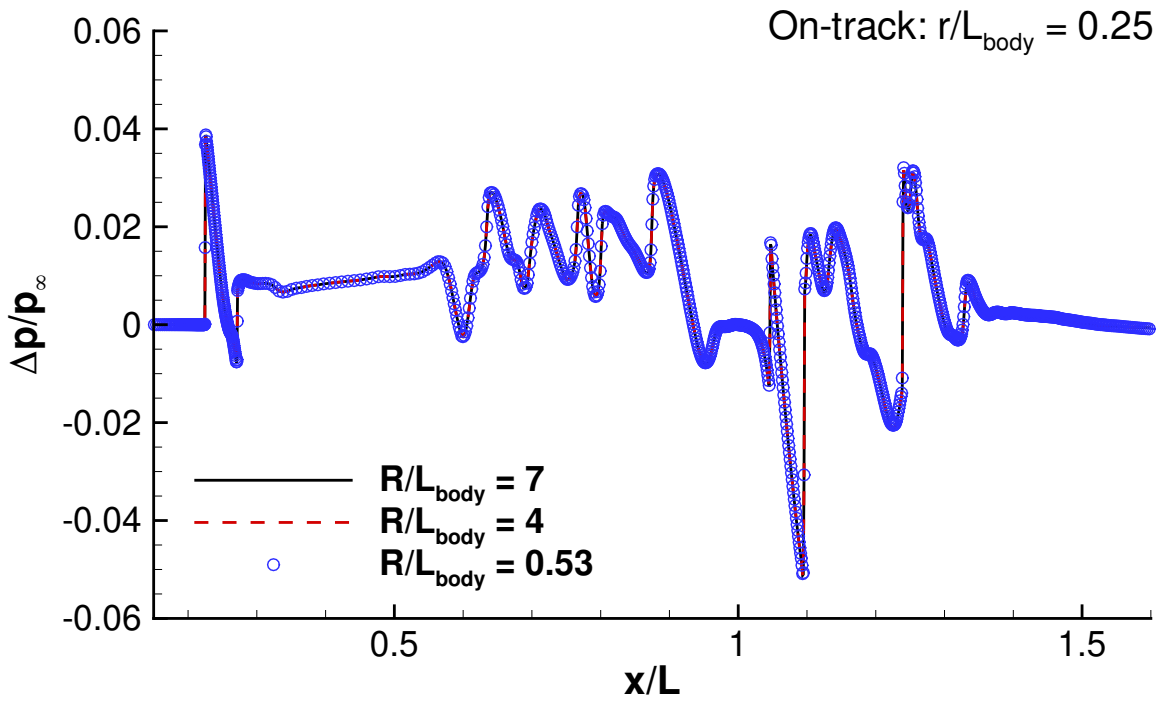




- Intersecting two Mach cones which encapsulate the aircraft provides an approximate domain of dependence
- Sensitivity to radial domain extent is assessed using CFD

# CFD Domain of Dependence

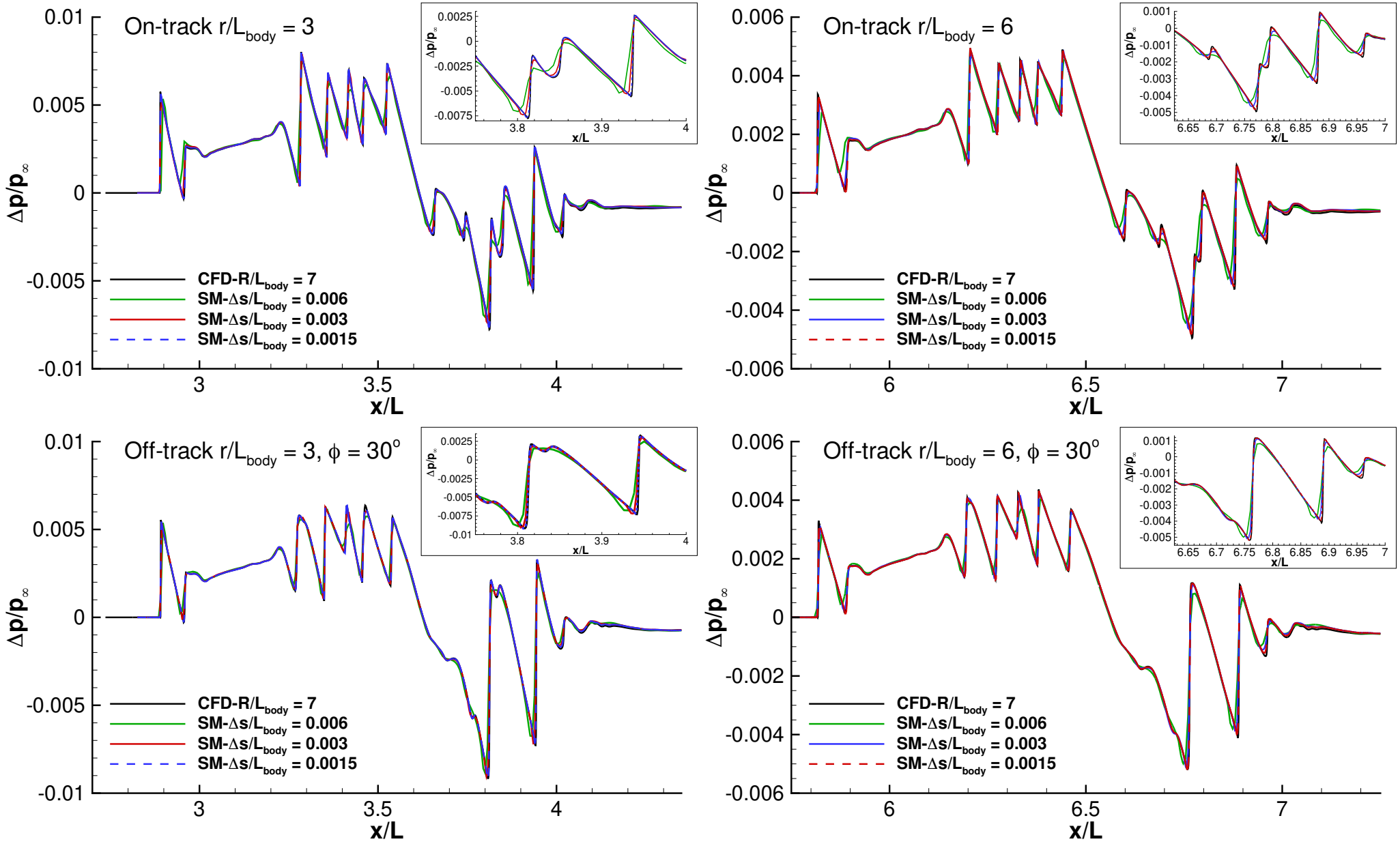


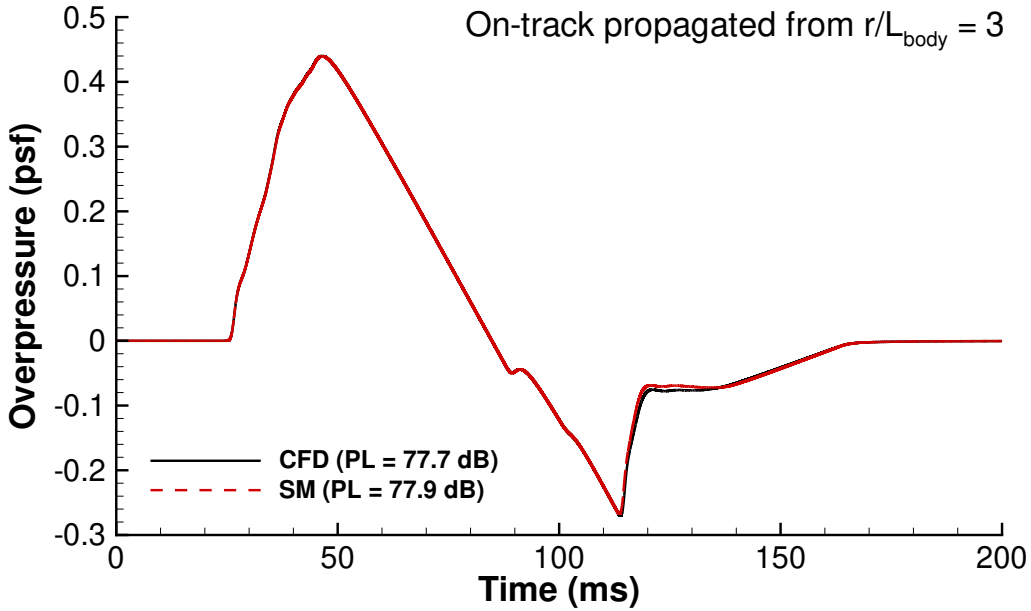

- Contour plots of pressure on a cylindrical surface at $r/L_{body}$ = ¼ using CFD radial domain lengths of 4 and 0.53
- No sensitivity is observed near the CFD/space marching coupling location

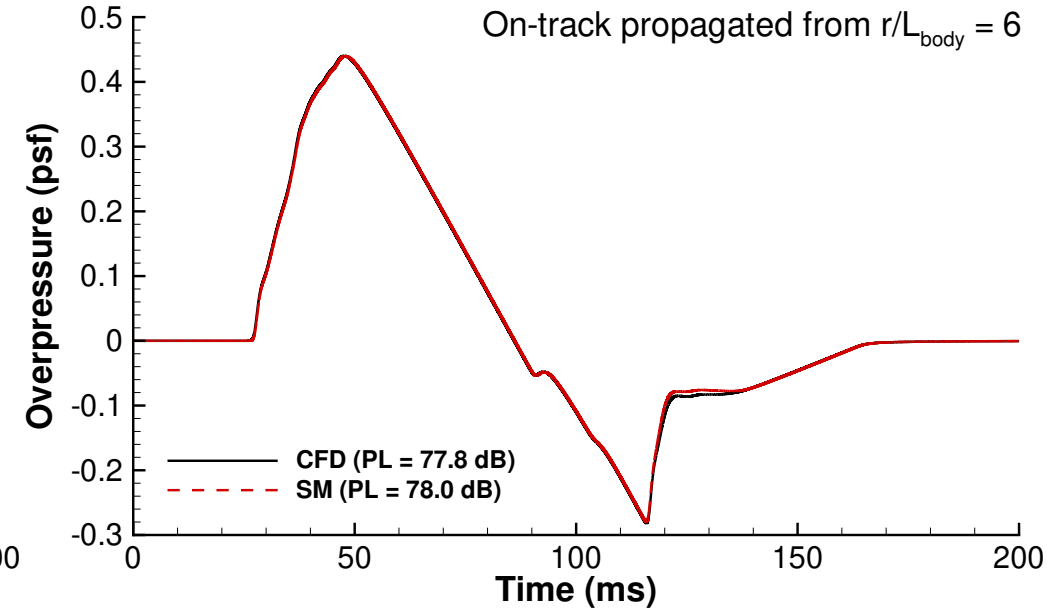
# Comparison of 2-step and 3-step procedures




Medium grid spacing of $\Delta s/L_{body} = 0.003$ is sufficient for maintaining accuracy of original CFD

# Comparison of 2-step and 3-step procedures



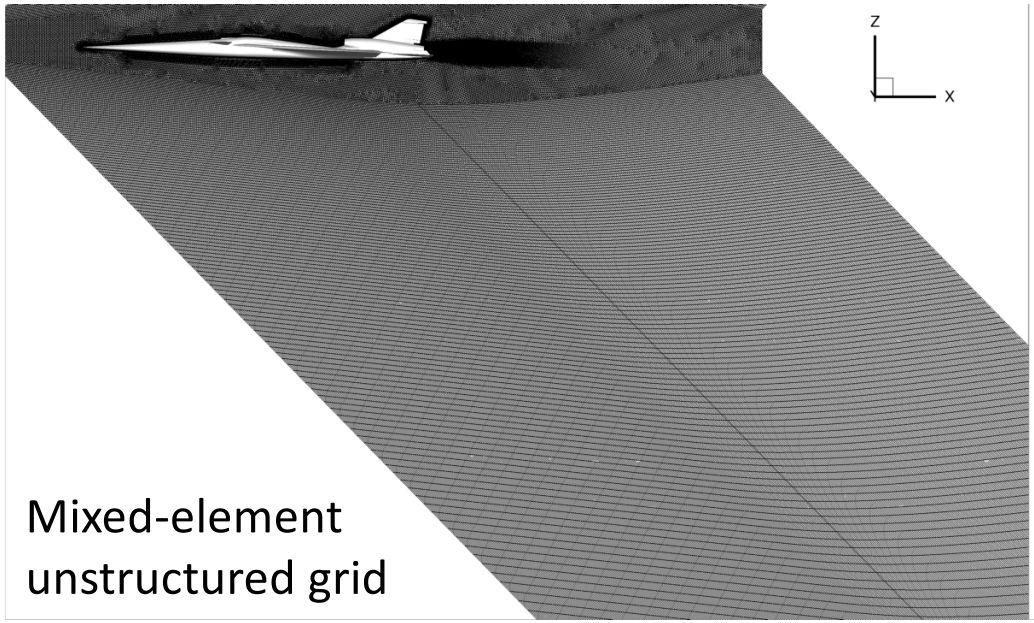

- Comparison of ground level noise between 2-step and 3-step procedures
  - Perceived loudness levels within 0.2 dB of each other at both interface locations to the far-field acoustic propagation code
  - Minor discrepancy in recovery portion between 120-130 ms

| Grid | $\Delta s/L_{body}$ | N (million) | Time (s) |
|---|---|---|---|
| Coarse | 0.006 | 18.9 | 44 |
| Medium | 0.003 | 72.3 | 139 |
| Fine | 0.0015 | 285.4 | 440 |

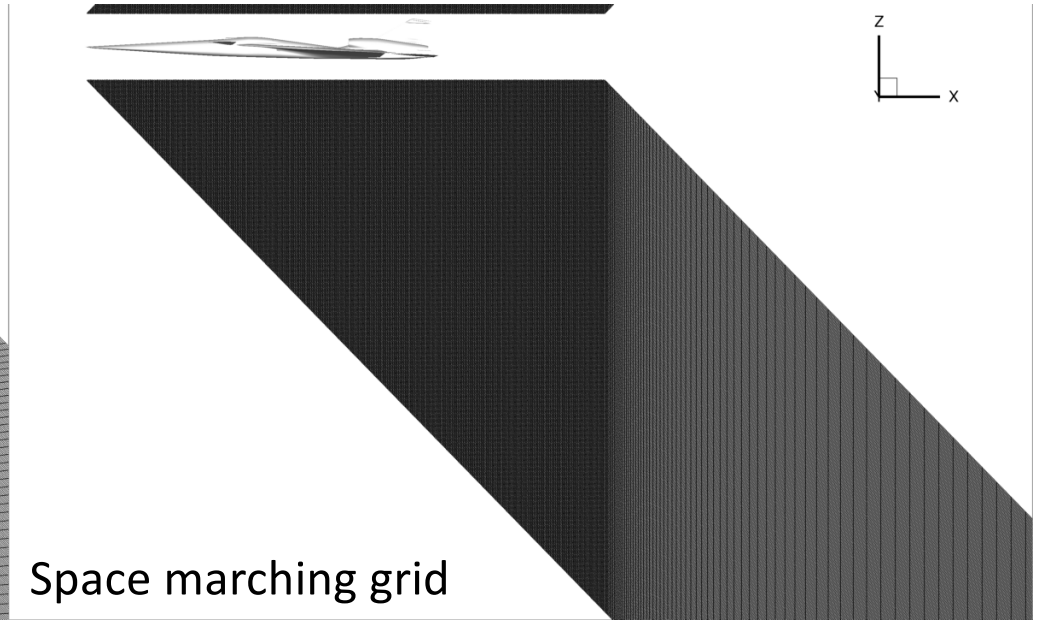
## Computational Benefits

1) CFD domain size reduction factor of 13.2
2) Number of CFD grid points cut in half
3) Computational resources also half
4) SM-Medium 2 minutes 19 seconds

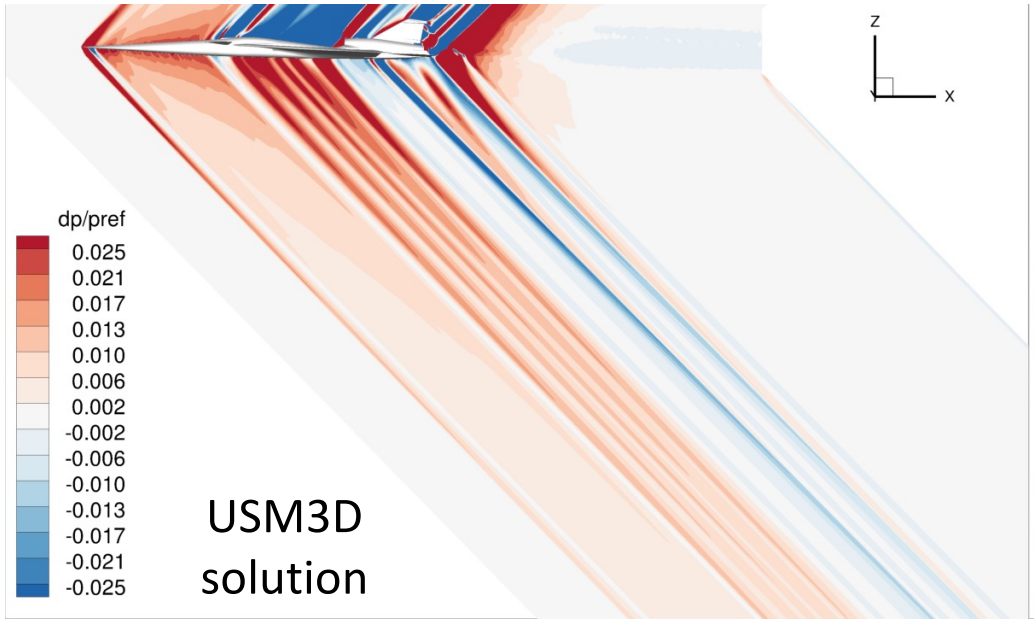
# Unstructured Solver Coupling



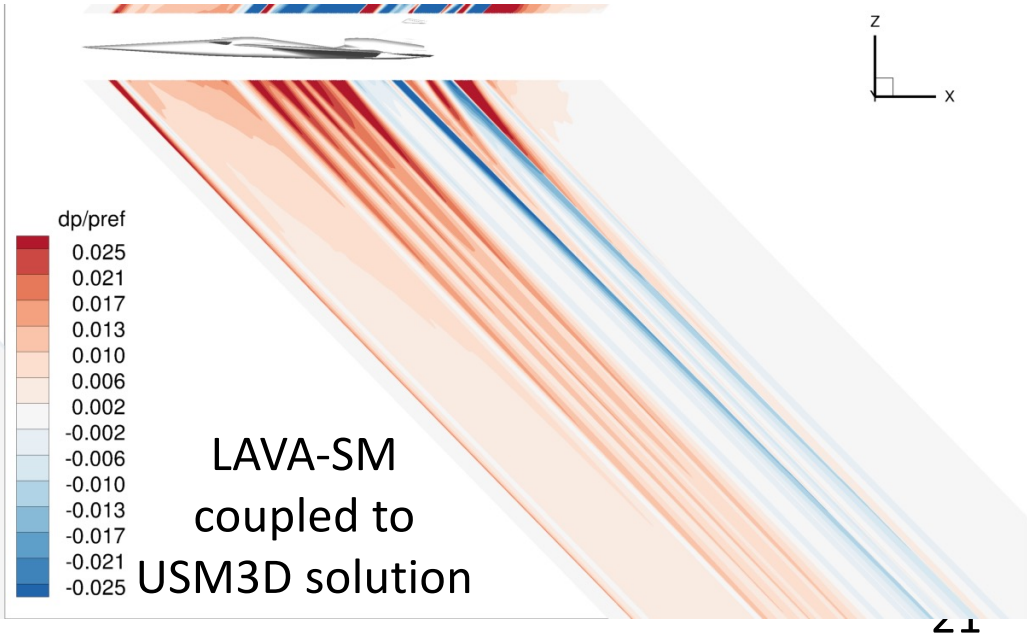

Mixed-element unstructured grid




Space marching grid



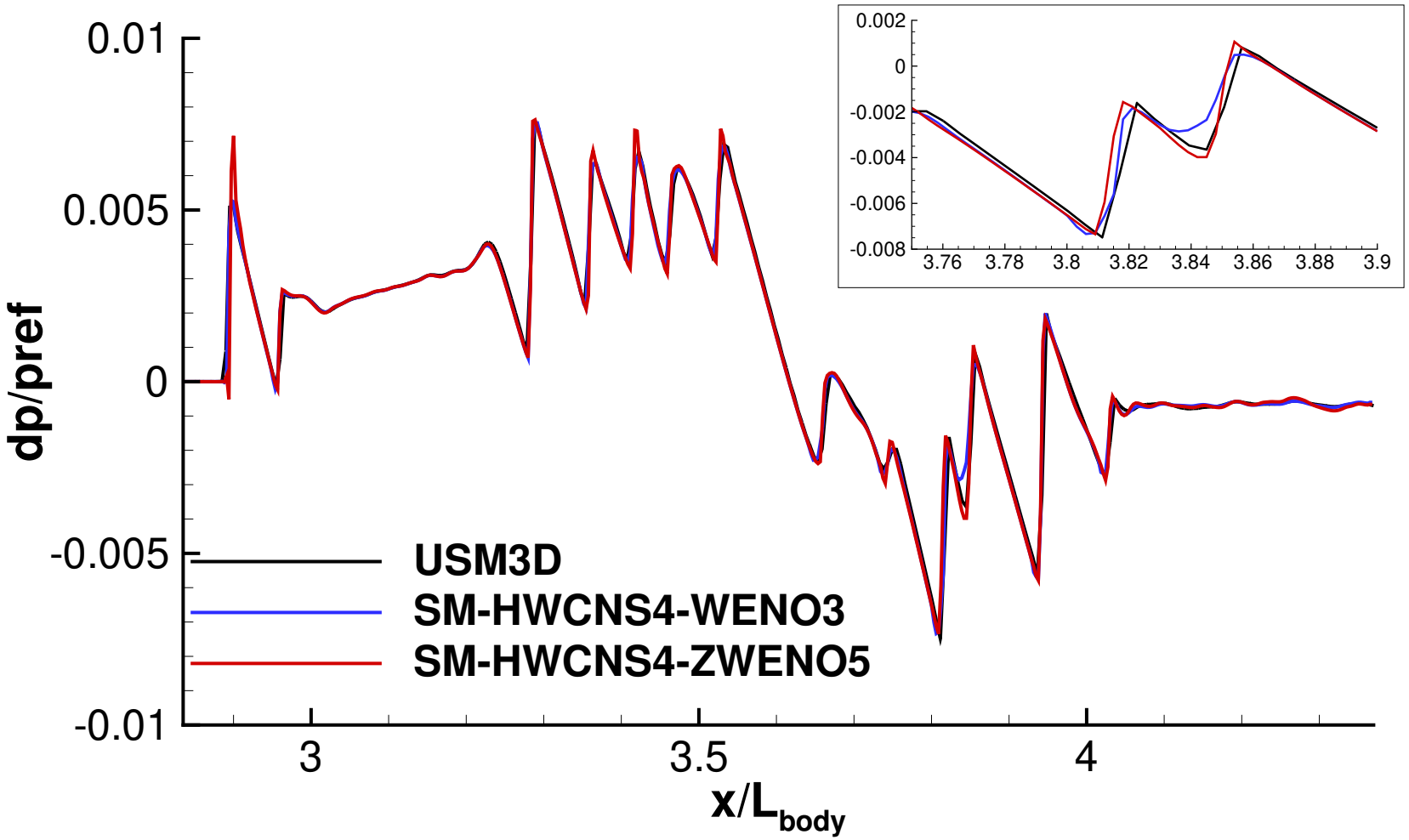

USM3D solution




LAVA-SM coupled to USM3D solution

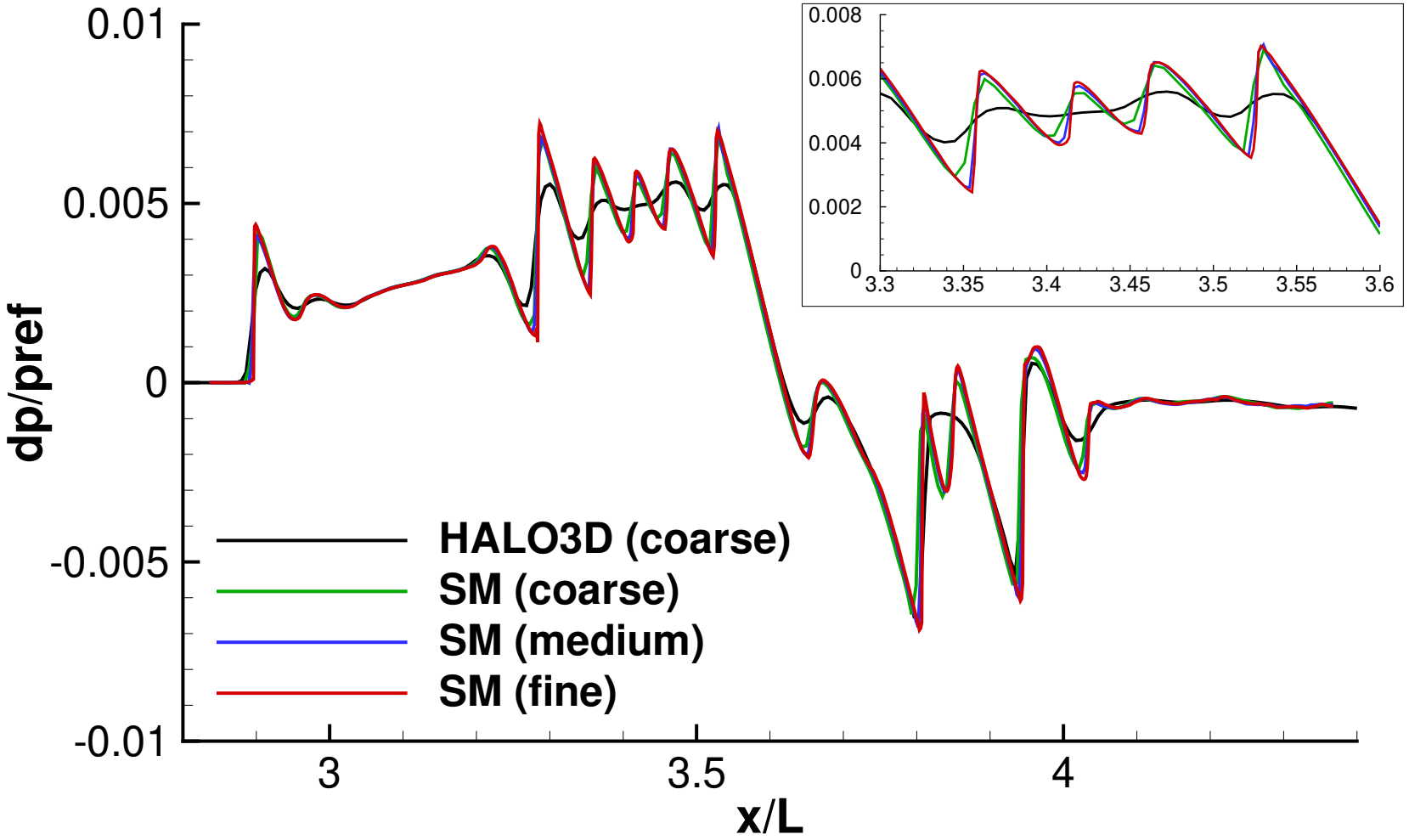
# Unstructured Solver Coupling

- On-track comparison of pressure at $r/L_{body}$ = 3 between USM3D and LAVA space marching coupled with USM3D using two different numerical flux options
- Both numerical schemes match USM3D very well over most of the signature
- Minor discrepancy at $x/L_{body}$ = 3.85 reduced with higher-order scheme
- Space marching time of 138.3 and 144 seconds respectively (72 M grid points)

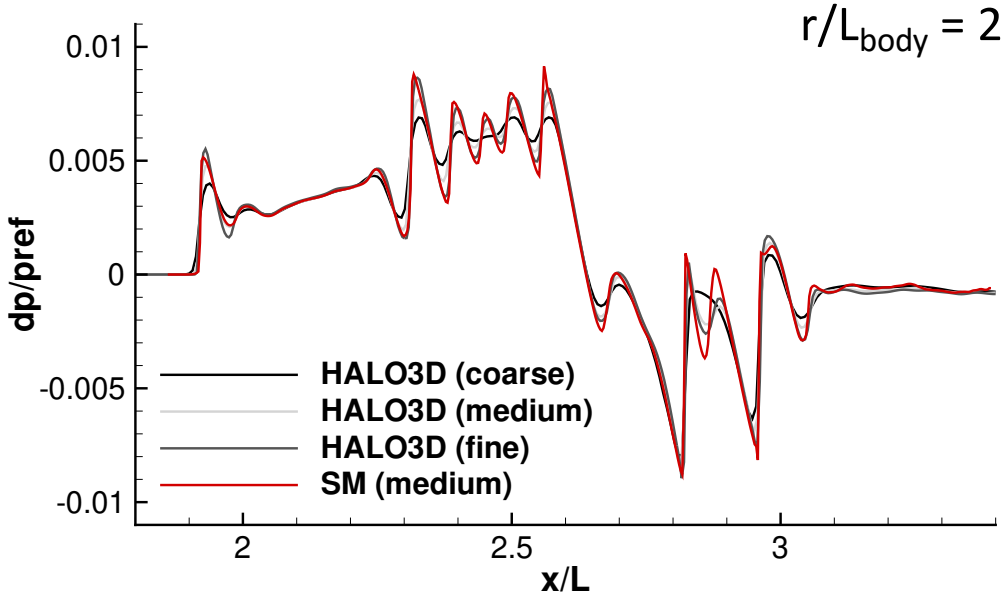


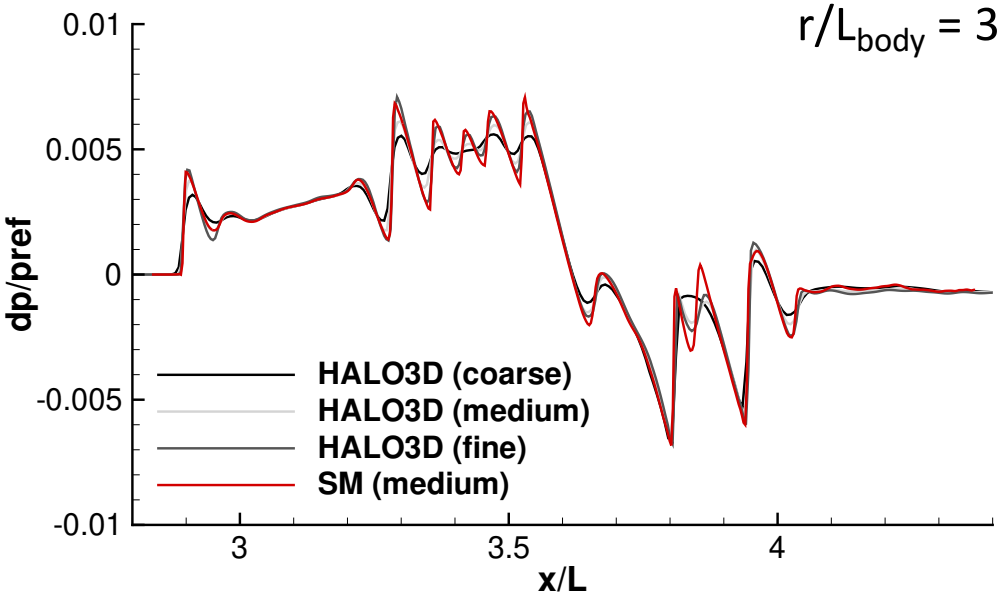
# Accuracy Enhancement

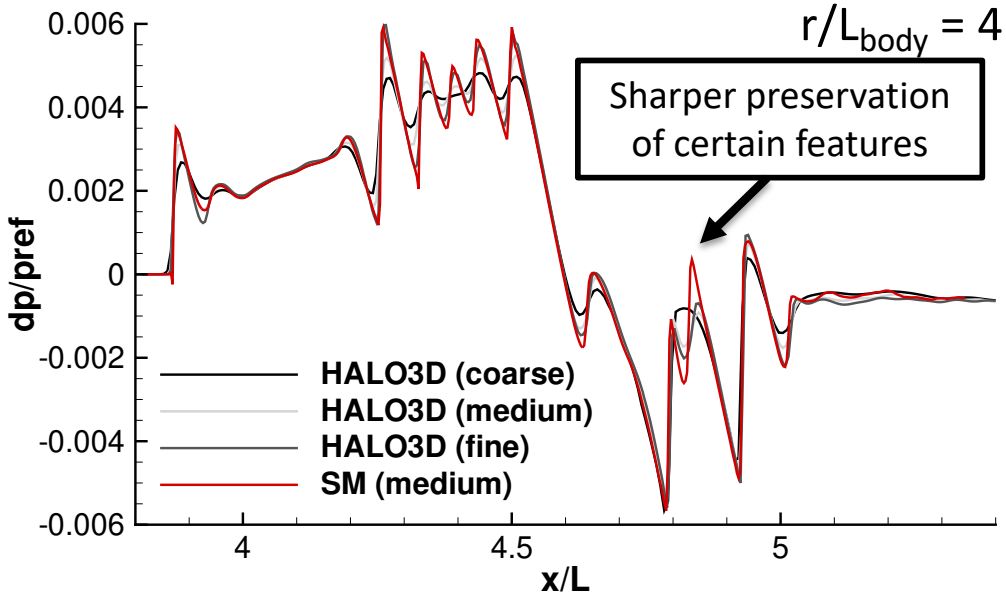
- HALO3D solutions on the coarse, medium, and fine committee mixed-element unstructured grids were provided by the ANSYS Canada team
- A space marching mesh sensitivity study was performed using the coarse HALO3D solution
- Medium space marching grid is observed to be sufficient (72 M grid points)

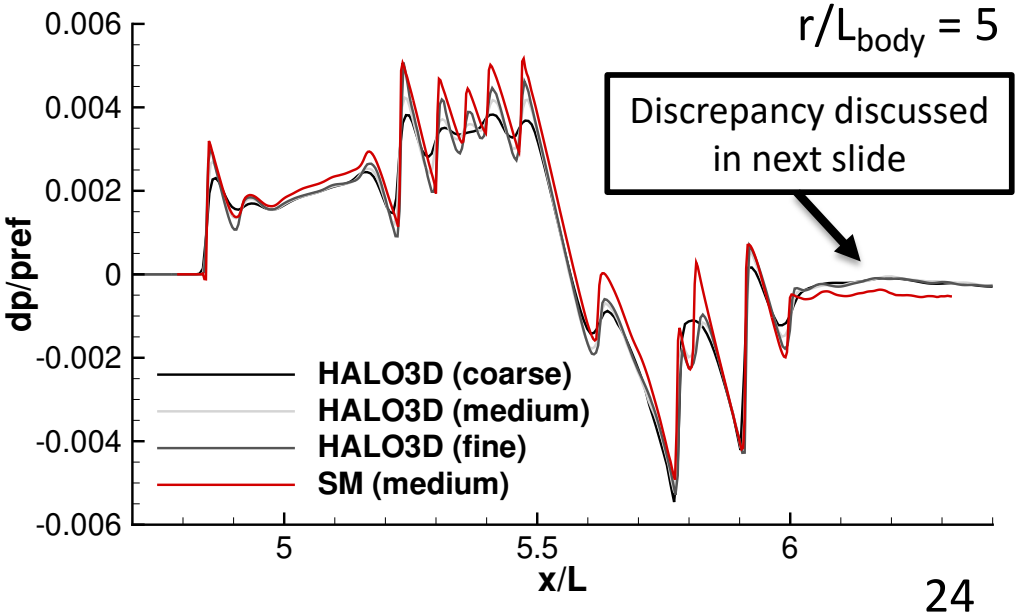


# Accuracy Enhancement



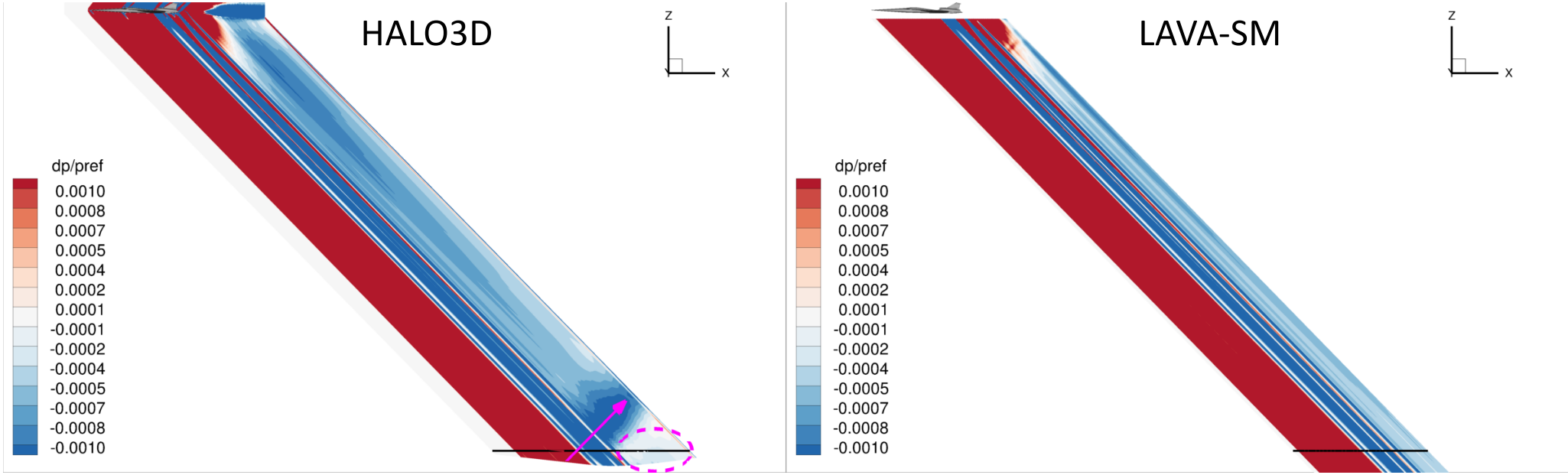




Medium grid spacing space marching improves coarse grid HALO3D solution to fine grid level (cost 2 minutes 37 seconds)

# Accuracy Enhancement

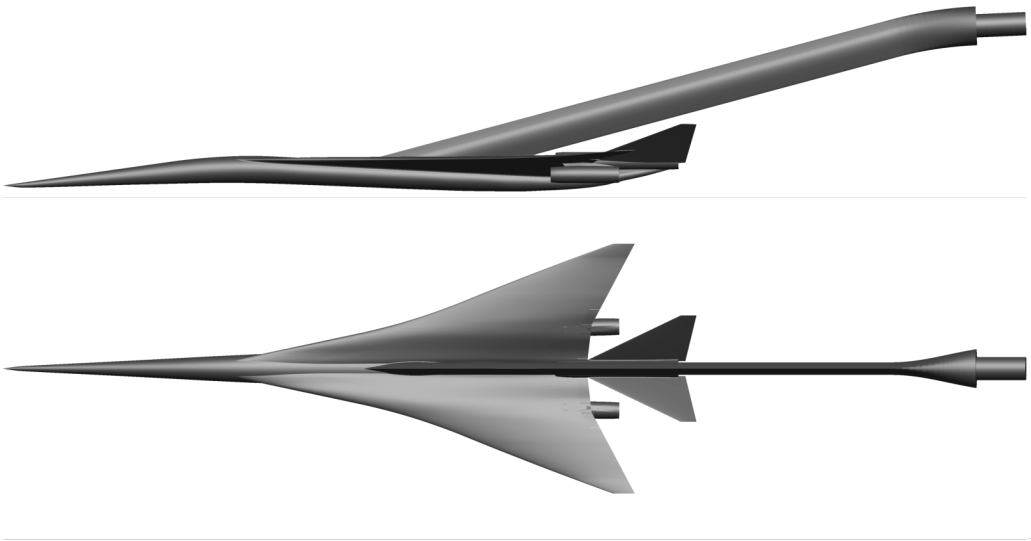



- HALO3D shows spurious reflection at exterior radial boundary, not observed in space marching solution
- Space marching coupled with coarse grid HALO3D solution is as accurate as fine grid HALO3D solution at $r/L_{body}$ = 2 and 3
- LAVA-SM shows improved resolution over fine grid HALO3D at $r/L_{body}$ = 4 and 5
- Mesh size difference between coarse and fine mixed-element grids is factor of 3
- Cost of space marching coupled to coarse grid HALO3D solution is 2 minutes 37 seconds (negligible compared to CFD cost)

# Near-Field Distance Propagation: LM1021

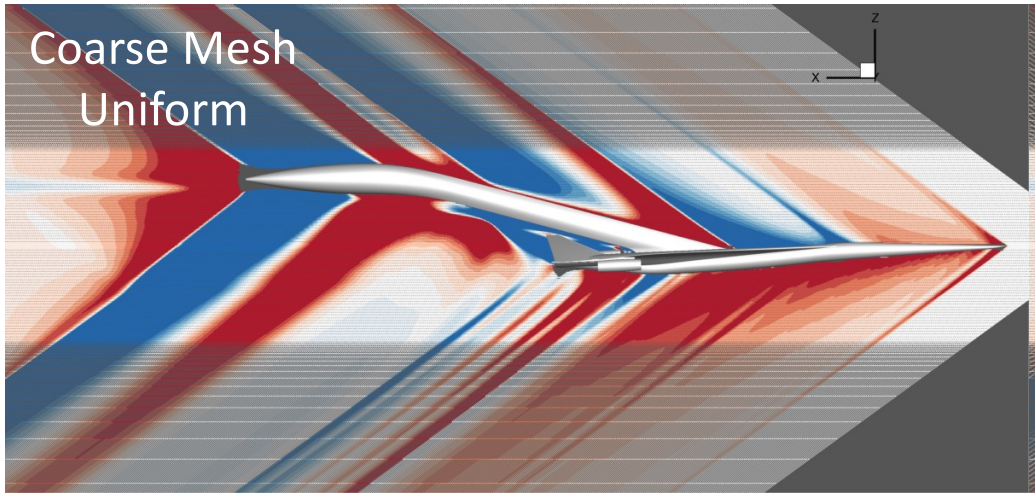
Lockheed Martin Phase I low boom model from 1st AIAA Sonic Boom Workshop (LM1021)

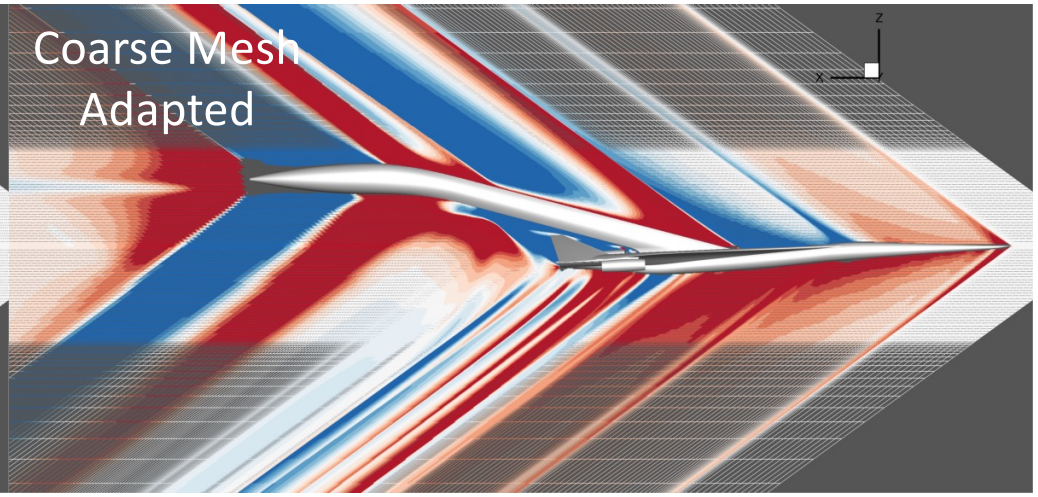
- Designed to achieve low boom on-track signatures
- Reference length: $L_{ref}$ = 22.365 inch (0.568 m) 0.008 percent scale
- Mach = 1.6, Re/m = 4.36 million, and $\alpha = 2.1^{o}$
- Experimental data reported in *Cliff et. al.* (AIAA-2014-0560)
- Near-field CFD results using LAVA reported in *Housman et. al.* (AIAA-2014-2008)

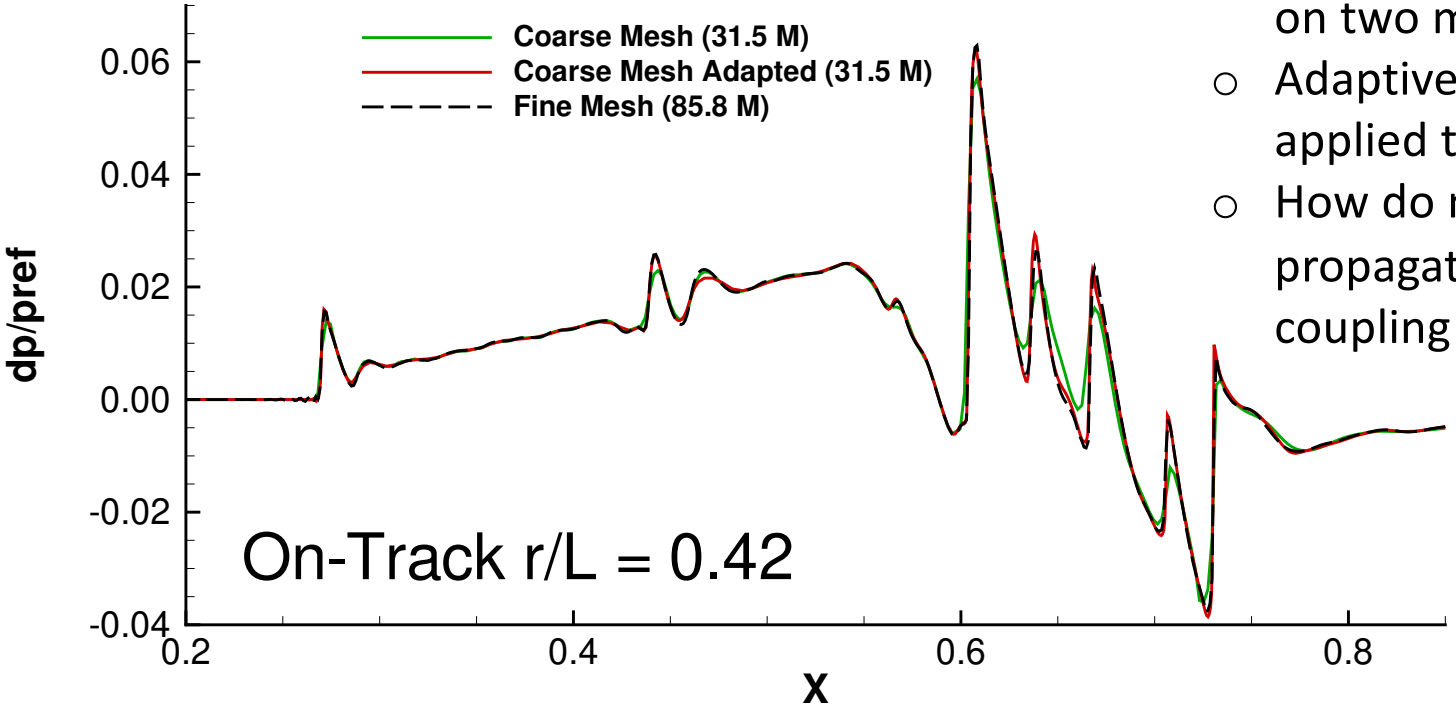




# Near-Field Distance Propagation: LM1021

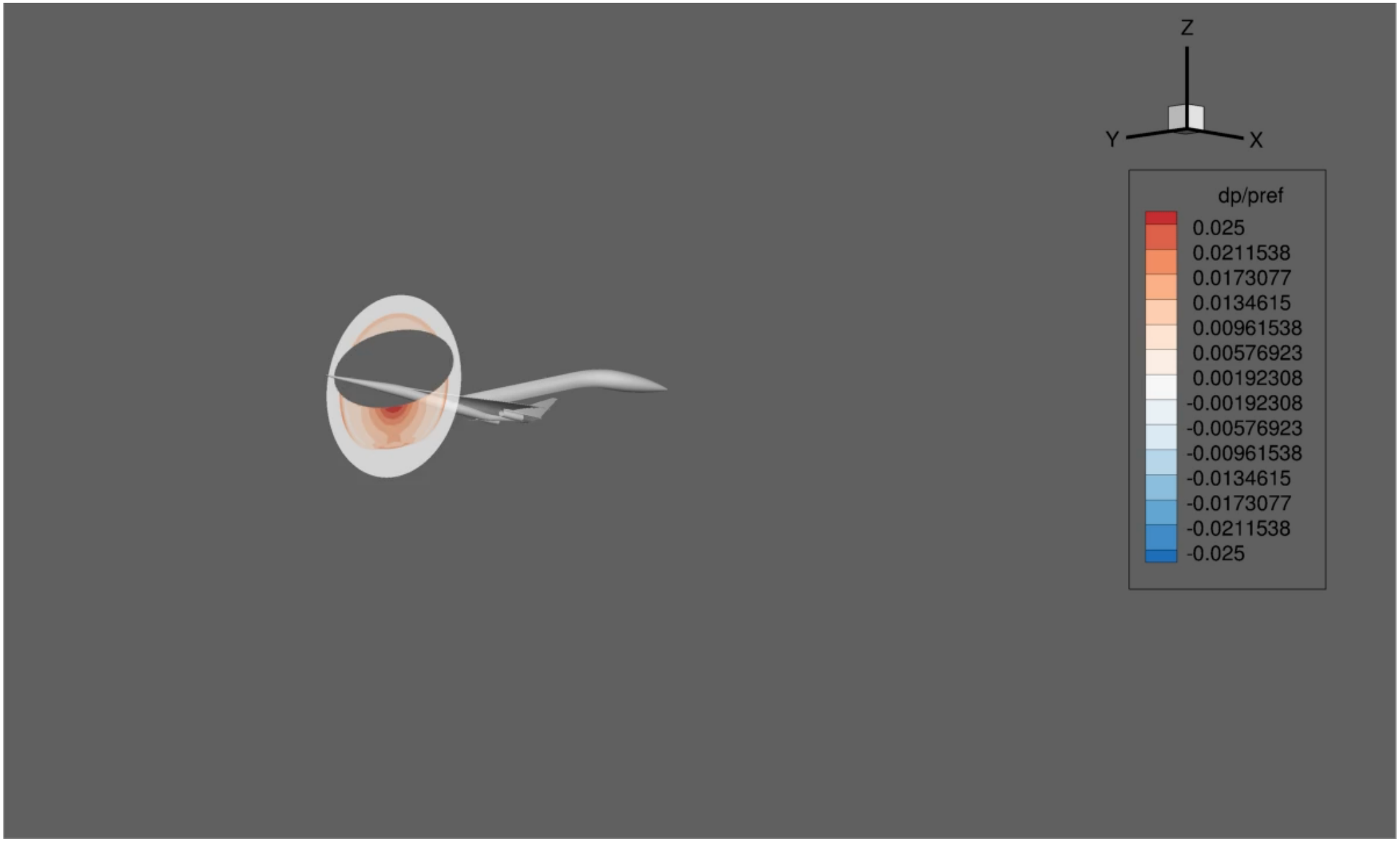


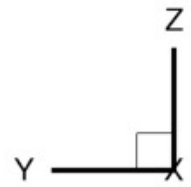




- Near-field CFD analysis performed on two mesh resolutions
- Adaptive mesh redistribution applied to coarse grid (C. Ashby)
- How do near-field differences propagate to the far-field radial coupling location?

# Near-Field Distance Propagation: LM1021



# Near-Field Distance Propagation: LM1021









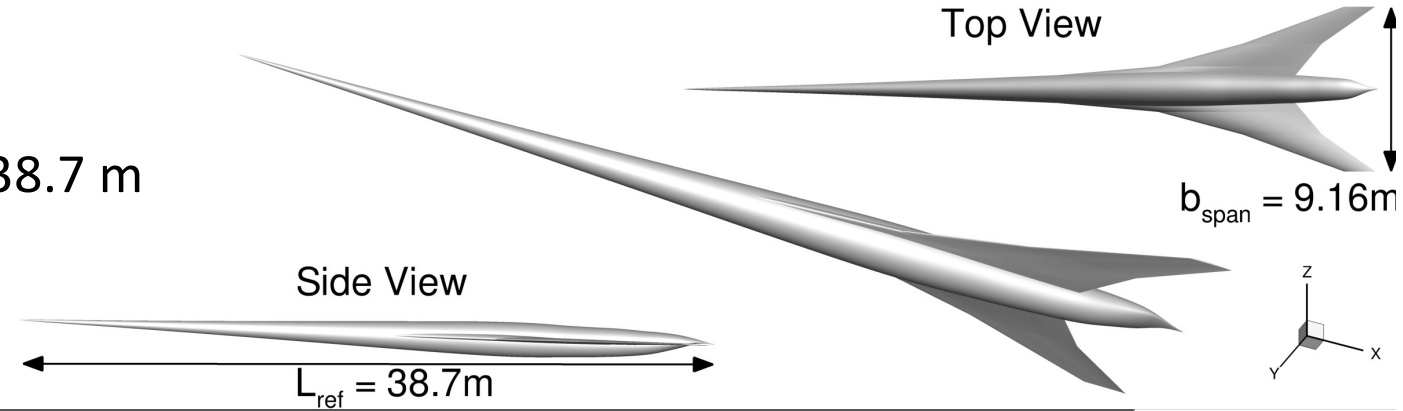
Coarse Mesh
Adapted

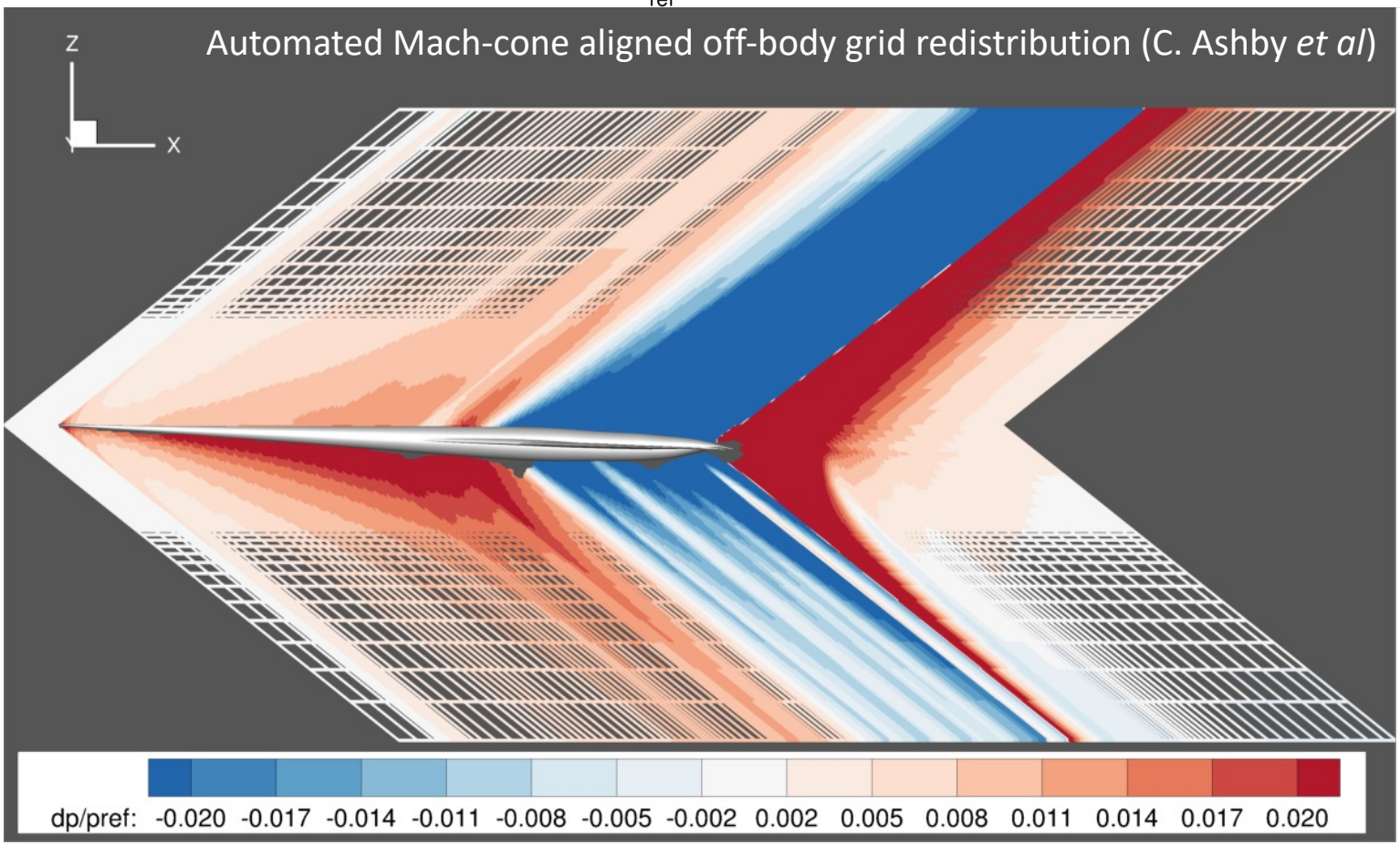
Coarse Mesh
Uniform

# Local Error Analysis: JAXA Wing Body

## JAXA Wing Body (JWB)

- Reference length: $L_{ref}$ = 38.7 m
- Mach = 1.6, Re/m = 5.7 million, and $\alpha$ = 2.3°

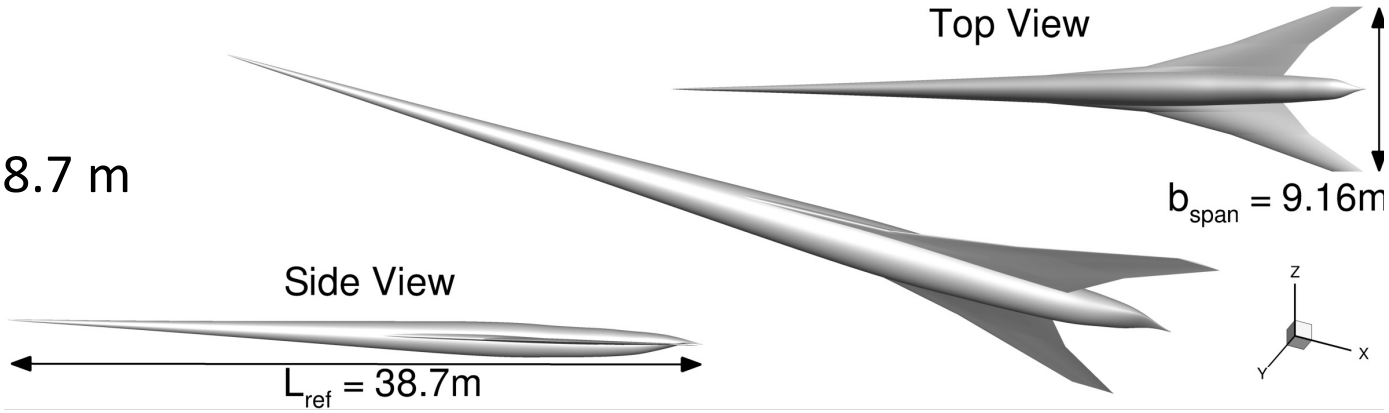


# Local Error Analysis: JAXA Wing Body

JAXA Wing Body (JWB)

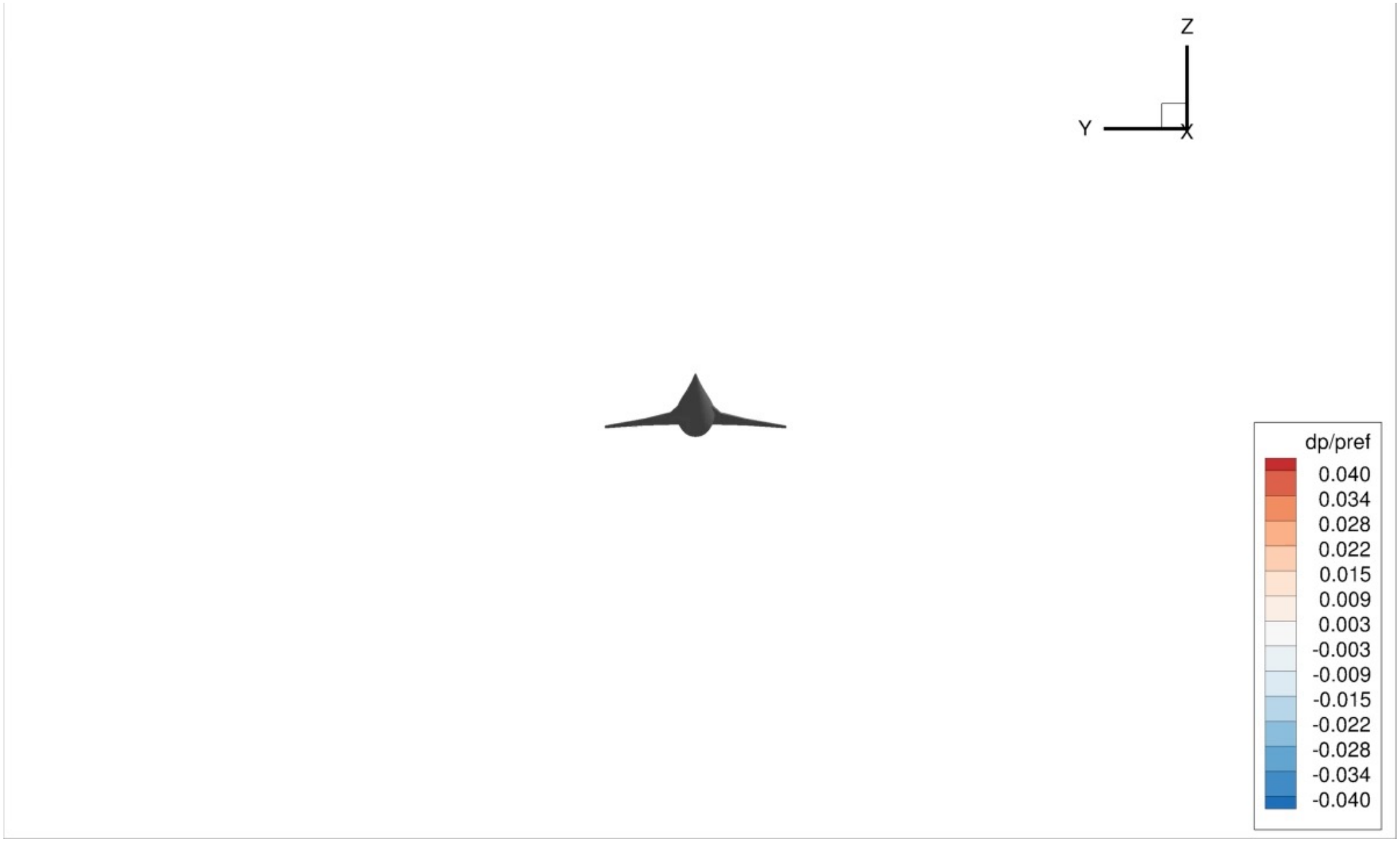
- Reference length: $L_{ref}$ = 38.7 m
- Mach = 1.6, Re/m = 5.7 million, and $\alpha$ = 2.3°



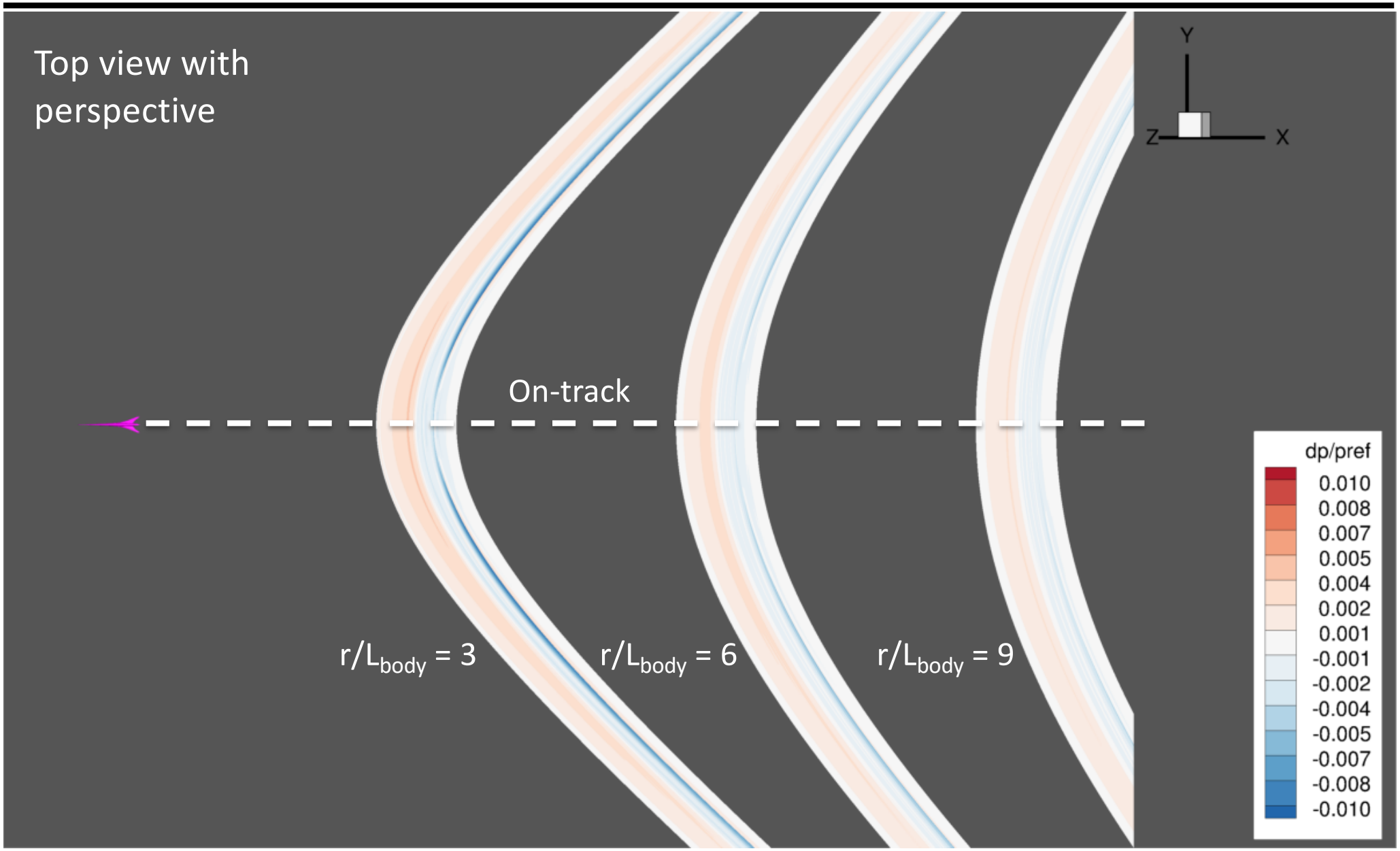

| Mesh | Number of grid points (millions) | Time (seconds) |
|---|---|---|
| Coarse | 22.7 | 53.1 |
| Medium | 87.4 | 189.1 |
| Fine | 342.7 | 752.3 |
| Reference | 1,356.6 | 3366* |

*Space marching solution of 1.3 billion grid points in under 1 hour on a modern workstation using 80 threads

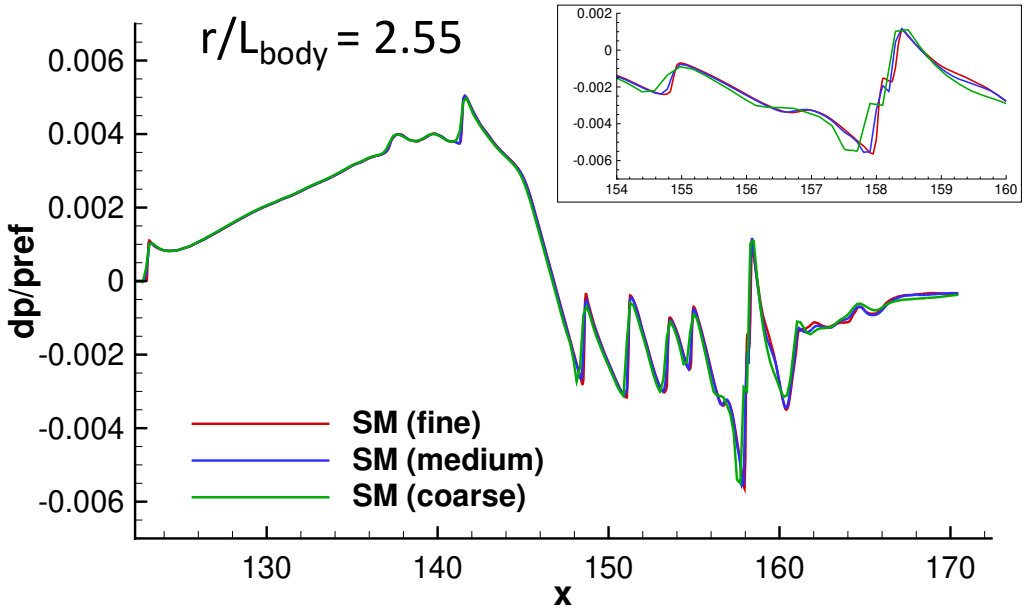
# Local Error Analysis: JAXA Wing Body

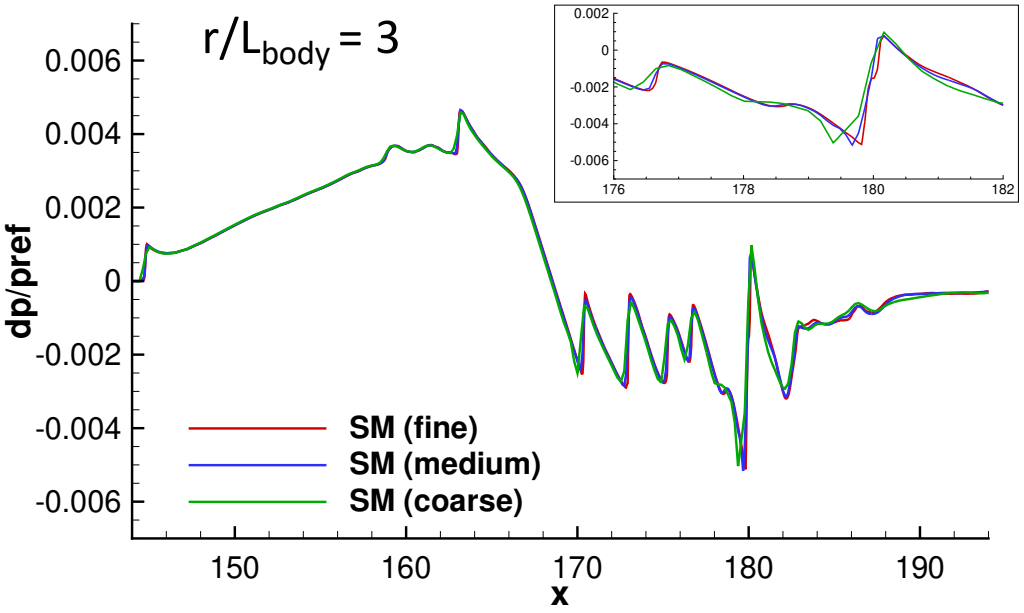


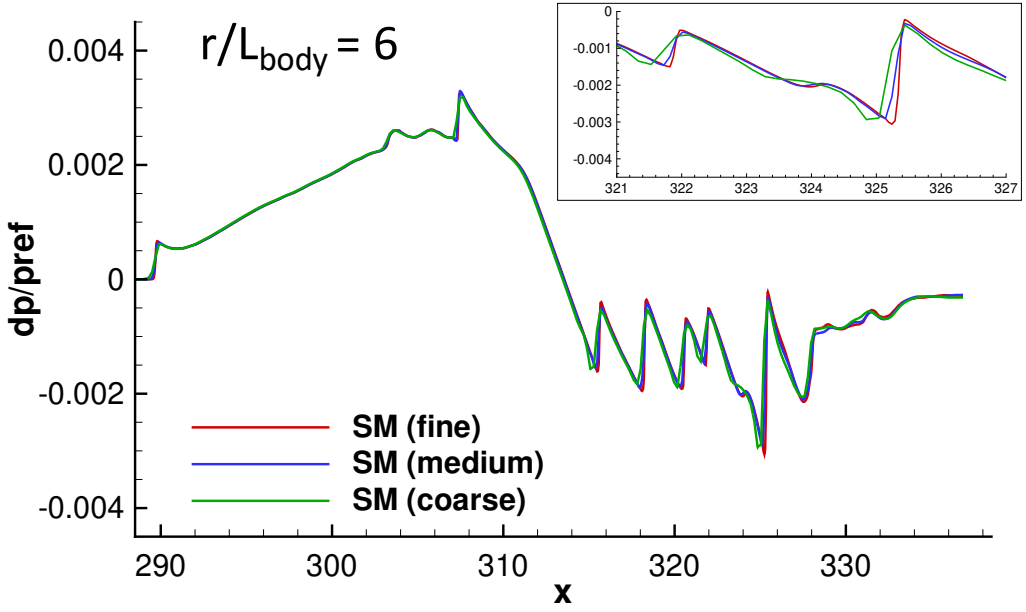
# Local Error Analysis: JAXA Wing Body

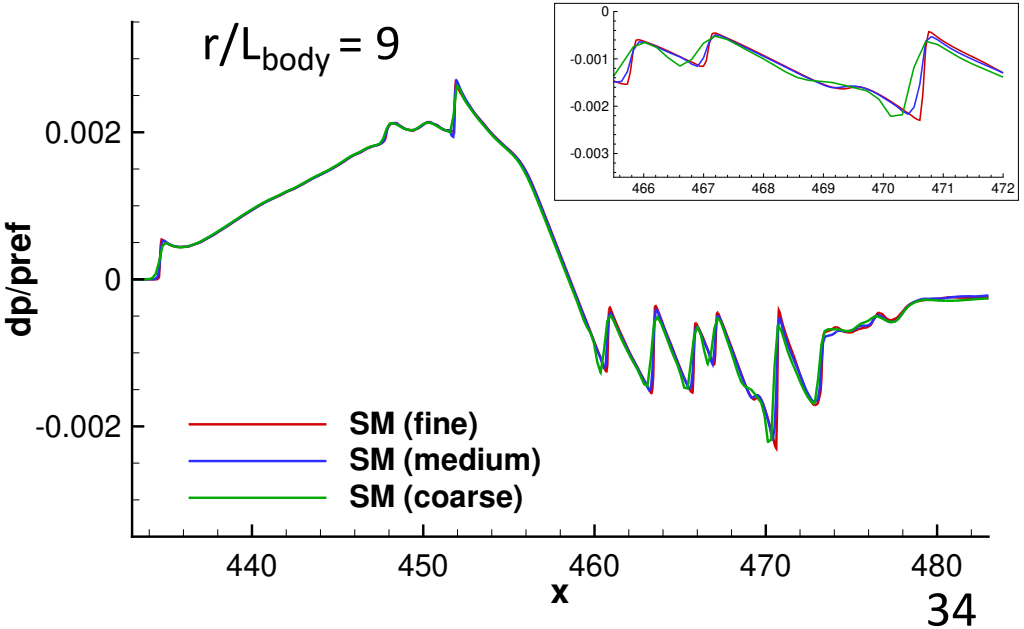


# Local Error Analysis: JAXA Wing Body

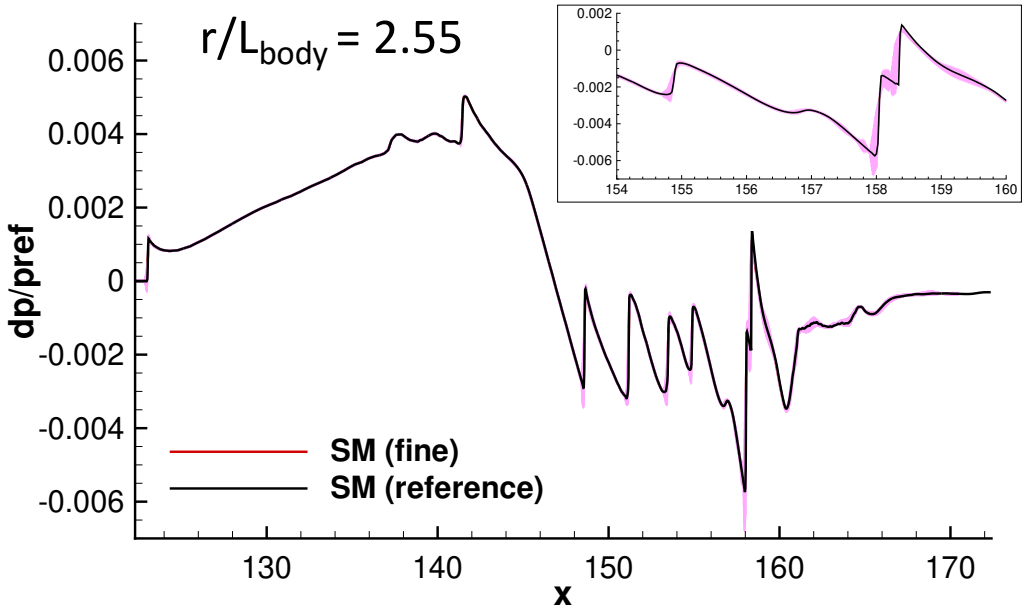


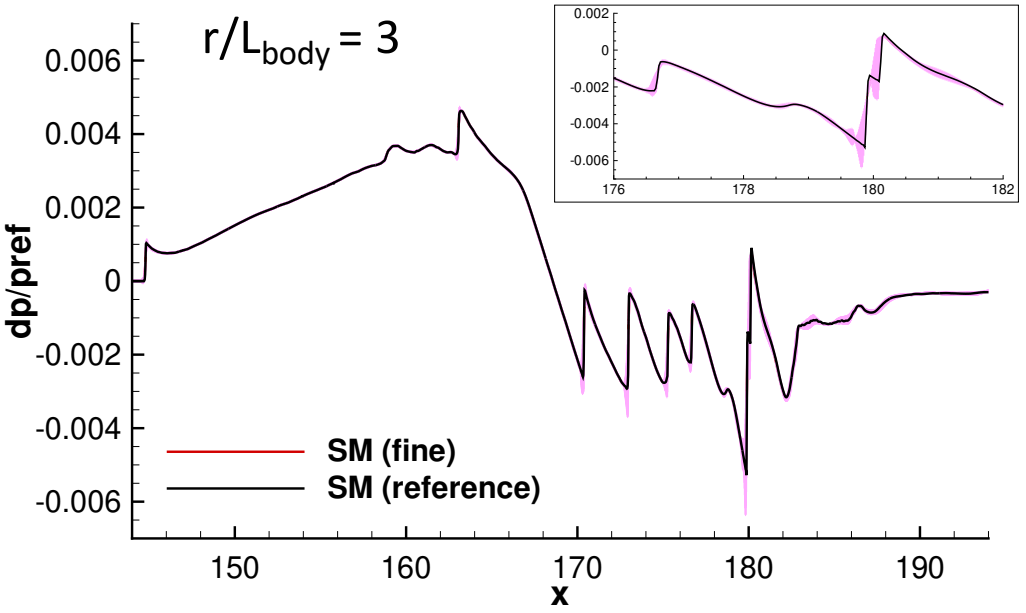



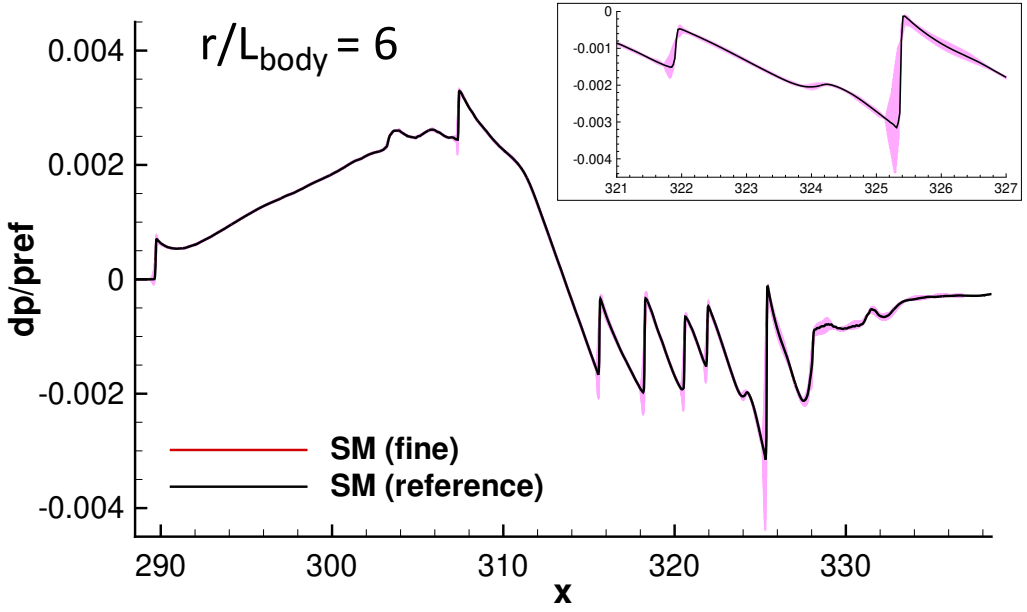



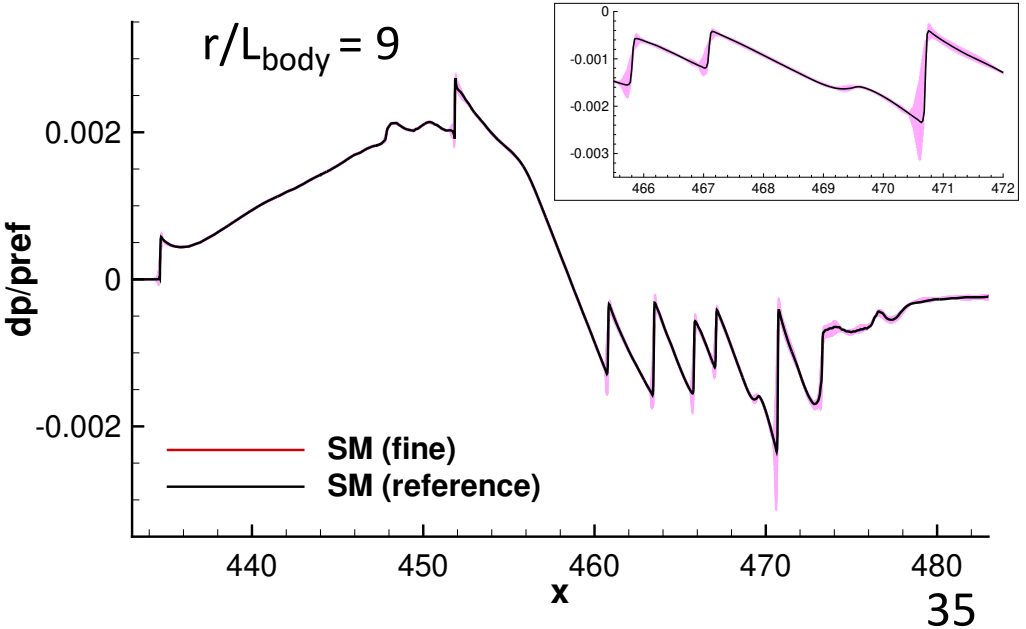



# Local Error Analysis: JAXA Wing Body






Local error analysis procedure developed in Anderson, Aftosmis, and Nemec (J. Aircraft 2019)

# Summary

- Algorithmic improvements to the high-order space marching method in LAVA have been presented
  - Alignment of space marching coordinate direction to the freestream direction
  - An elliptic hole cutting procedure to reduce near-field CFD accuracy requirements
  - Extension of overset interpolation routines for coupling with other (non-LAVA) solvers
- Demonstration of success of 3-step method on powered C608 configuration
  - Reduction of CFD radial domain based on domain of dependence
  - Reduction in computational cost compared to 2-step procedure
  - Equivalent results to ground level noise predictions to 2-step method
- Examples of coupling to unstructured grid solutions
  - Successful coupling with USM3D
  - Accuracy enhancement of HALO3D solutions
- Application of near-field difference propagation via space marching
- Evaluation of space marching grid resolution uncertainty using a local error analysis procedure

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- We would also like to thank Marian Nemec from the Cart3D team as well as the members of the LAVA team from NASA Ames Research Center for valuable discussions
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