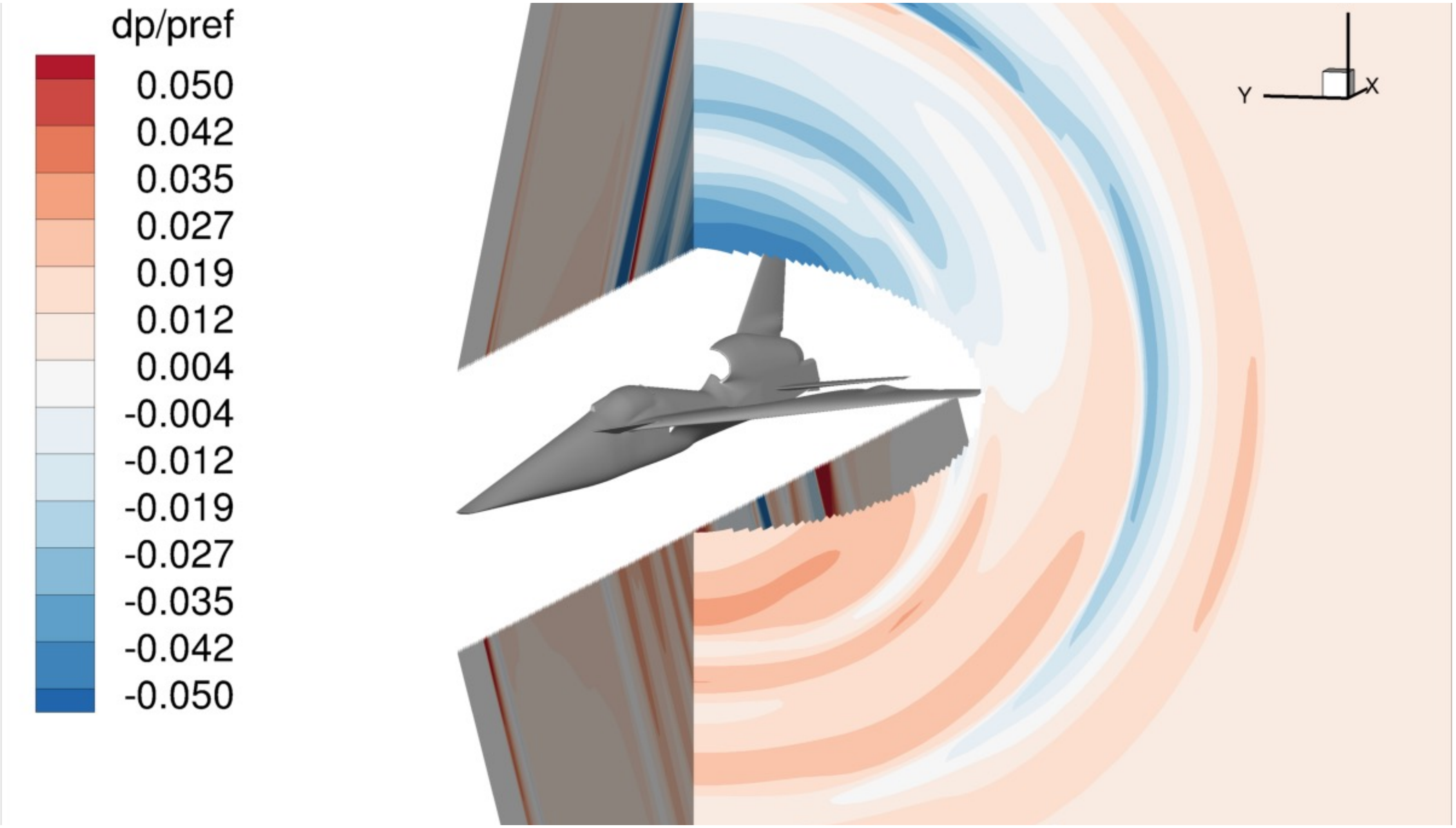
Algorithmic Improvements to a High-Order Space Marching Method for Sonic Boom Propagation



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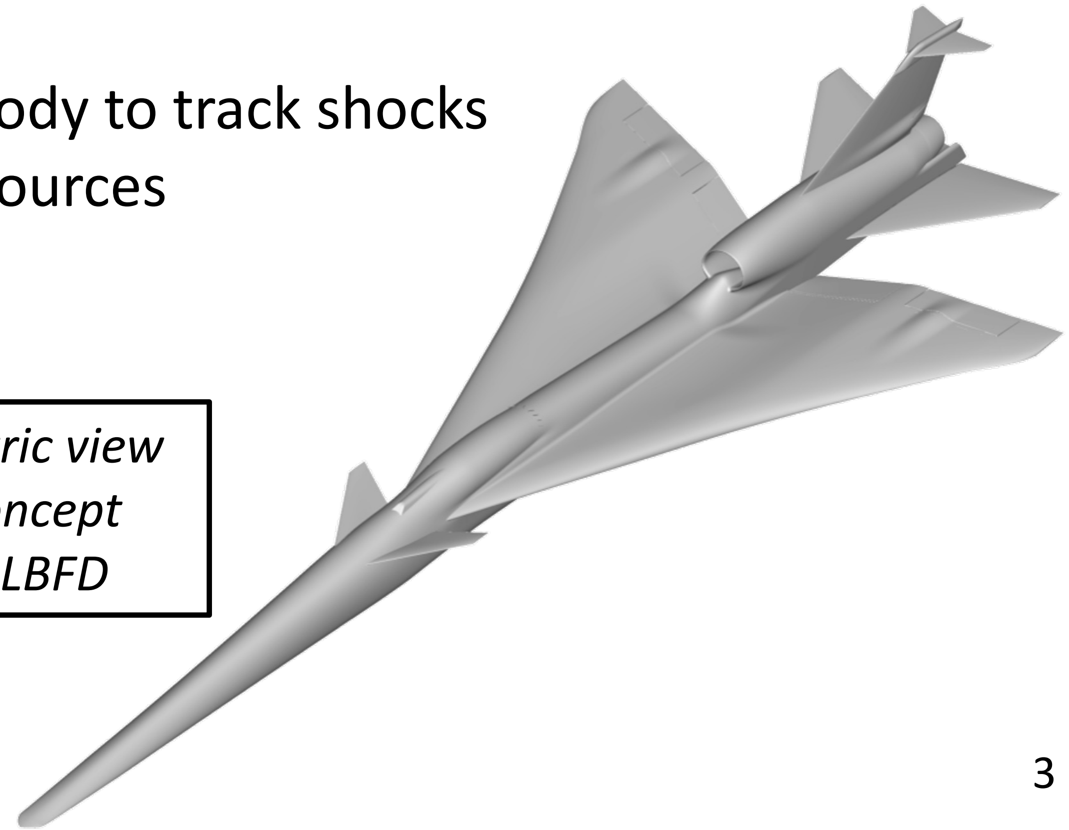
Outline

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

Introduction

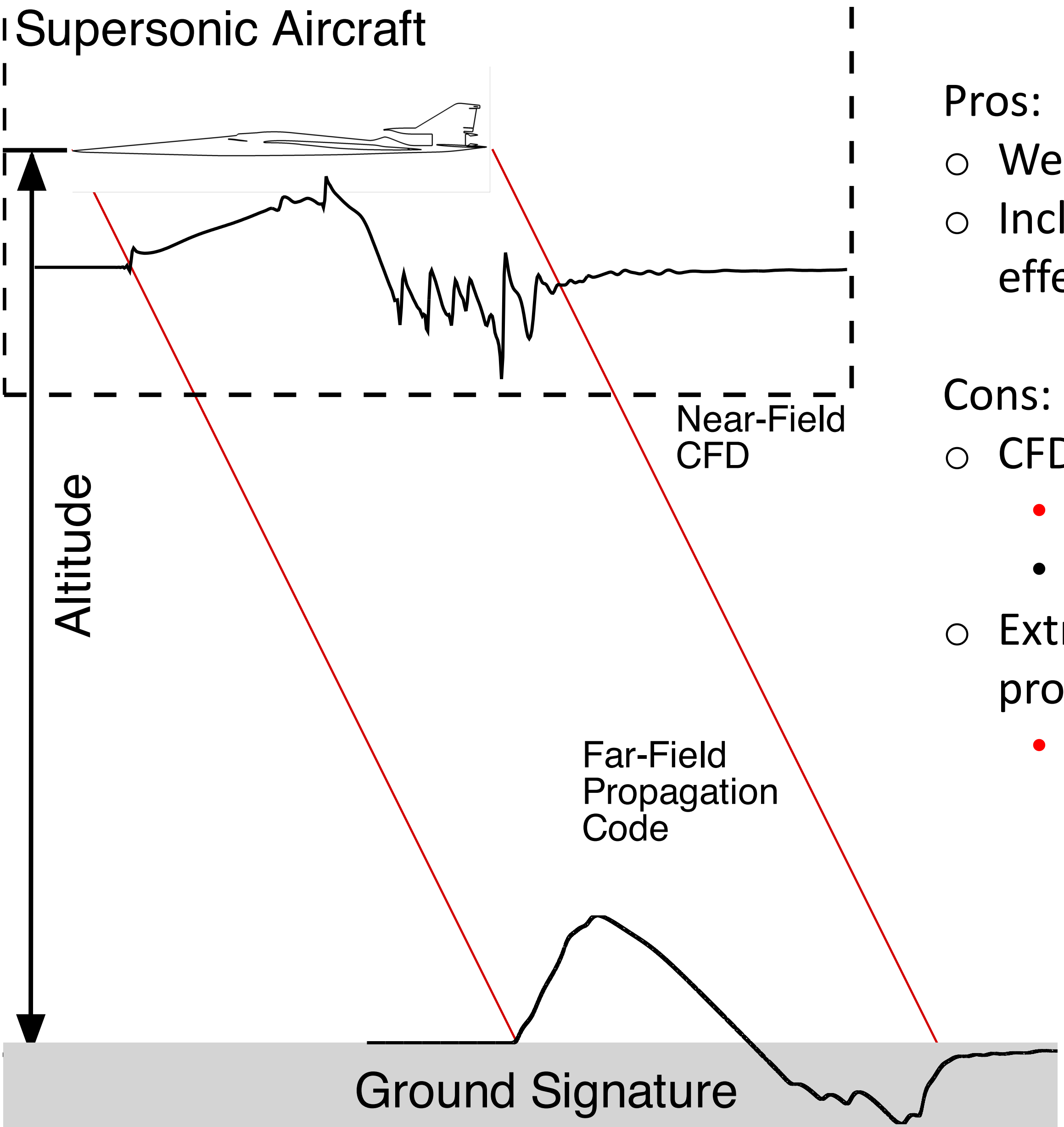
NASA's Low-Boom Flight Demonstration (LBFD) project

- 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:

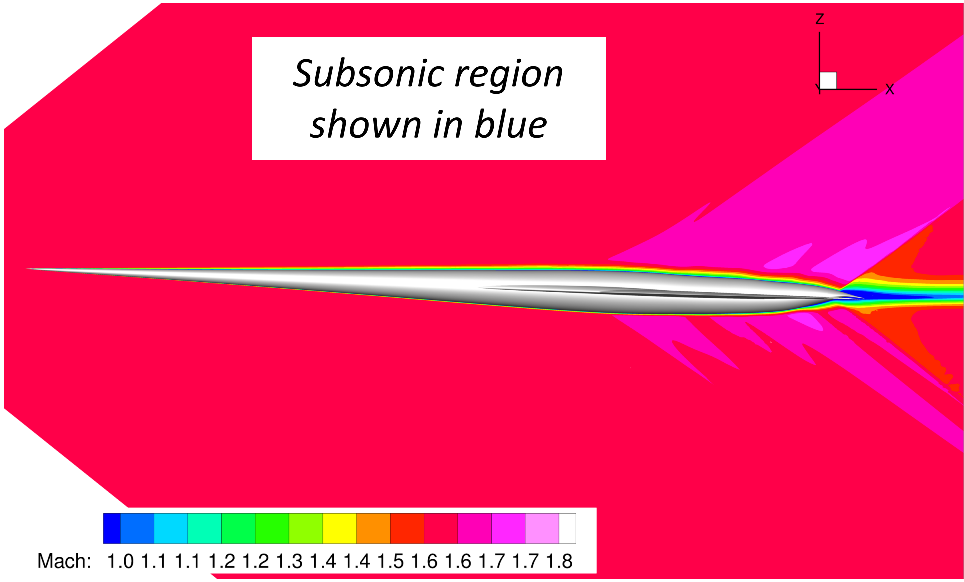
- Well established procedure
- Includes important atmospheric effects

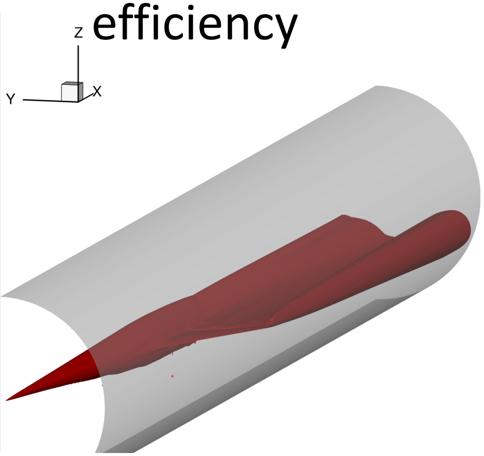
Cons:

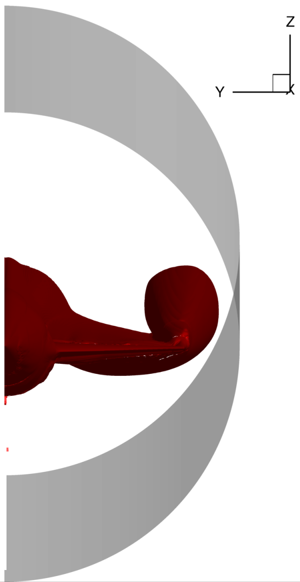
- CFD domain is relatively large
  - High Computational Cost
  - Accuracy (2nd order)
- Extraction radius for far-field propagation relatively small
  - Ignores potentially important azimuthal effects

Special Features of Supersonic Flow

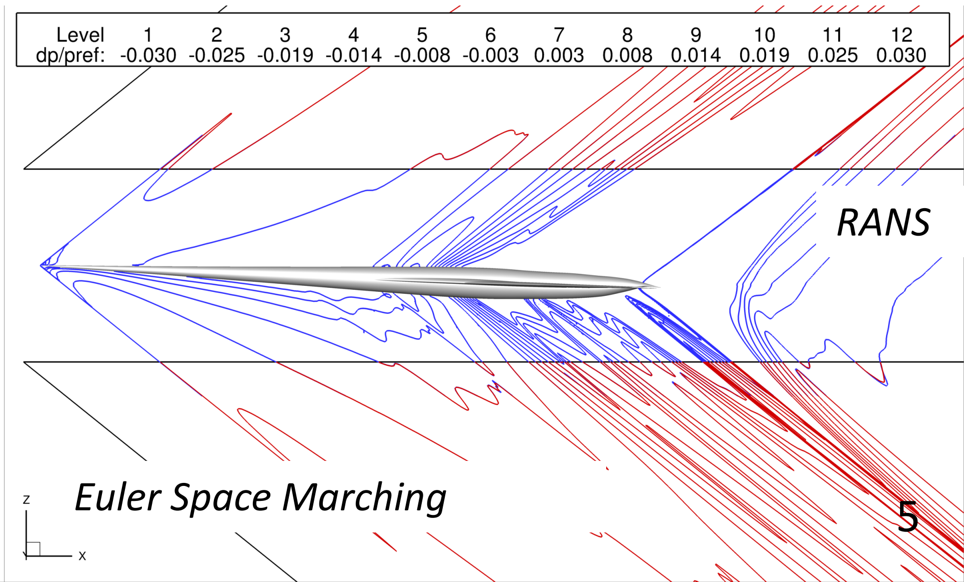
- All information travels in a common "time-like" direction along characteristic surfaces
- Viscous effects are only important near the walls of the aircraft
- Space marching is a special discretization/solution strategy which uses these features for computational efficiency



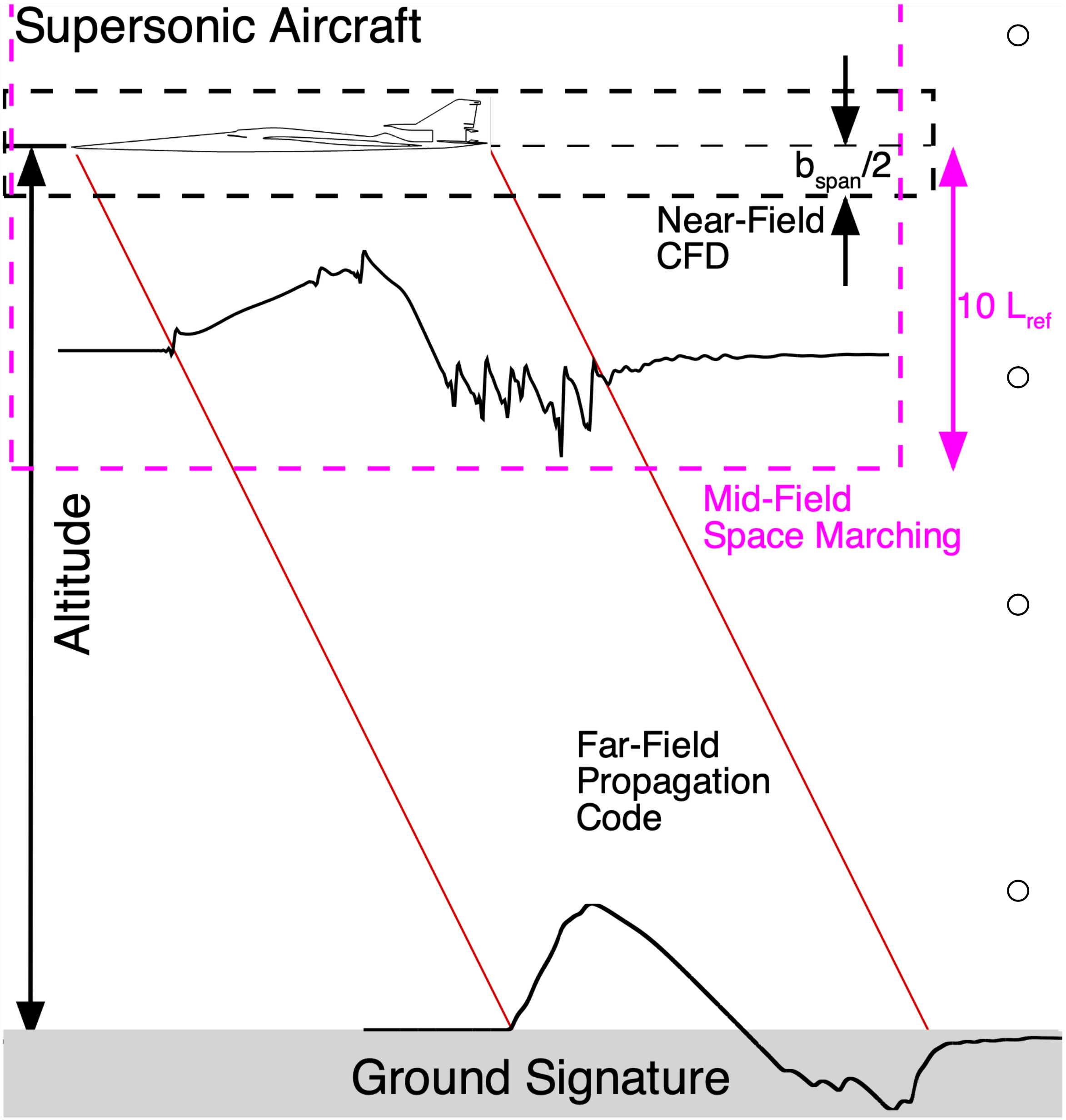




Isocontour of turbulent eddy viscosity ratio ($\mu_T / \mu_\infty = 10$)

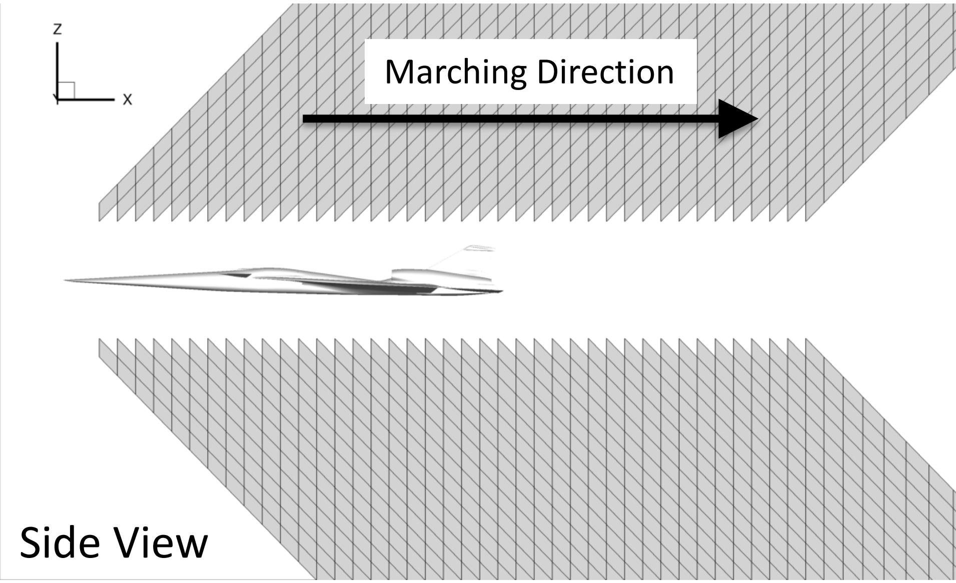


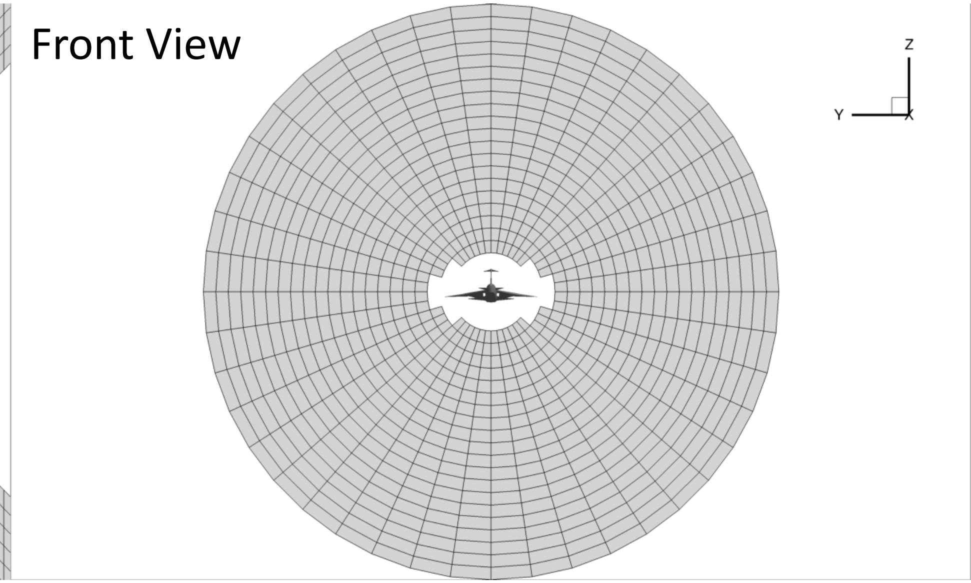
3-Step Ground Level Noise Prediction

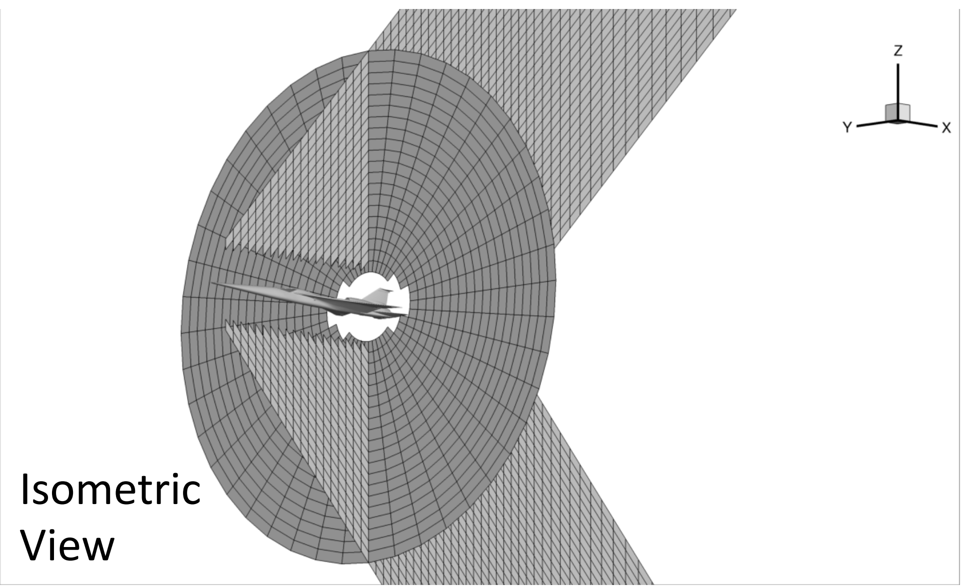


- Pros:
  - Reduced CFD domain
  - Space marching procedure:
    - Automated grid generation
    - Runs on workstation in minutes
    - Includes all relevant azimuthal effects
    - Changes from 3D steady into 2D “unsteady-like”
  - More than 50% reduction in total time
  - Same level of accuracy for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

Mach-cone Aligned Space Marching Grid

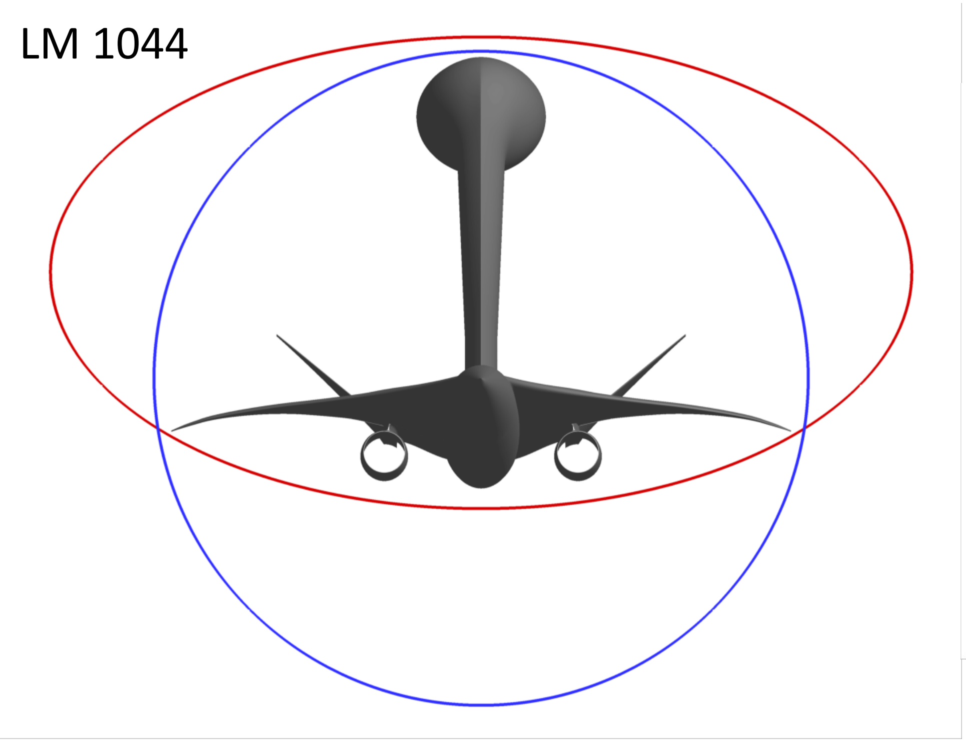


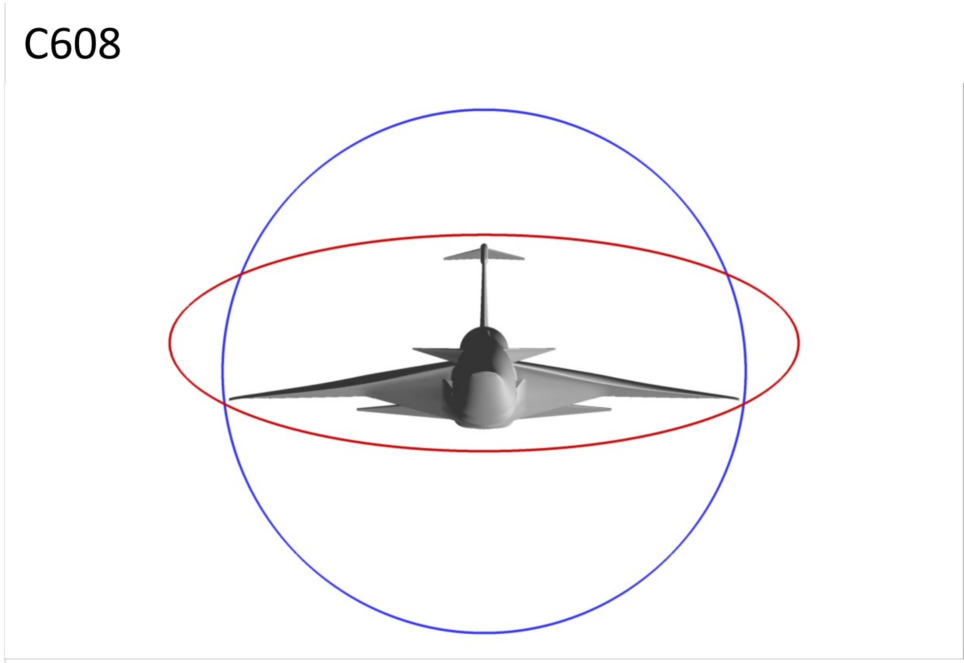




- Grid design inspired by Siclari and Darden AIAA-1990-4000
- Space marching direction aligned with freestream flow direction to guarantee valid space march as local Mach number approach unity
- Mach-cone aligned to reduce effect of artificial dissipation
- Automatically generates O(10)-O(1000) million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

Elliptic Hole Cutting Procedure

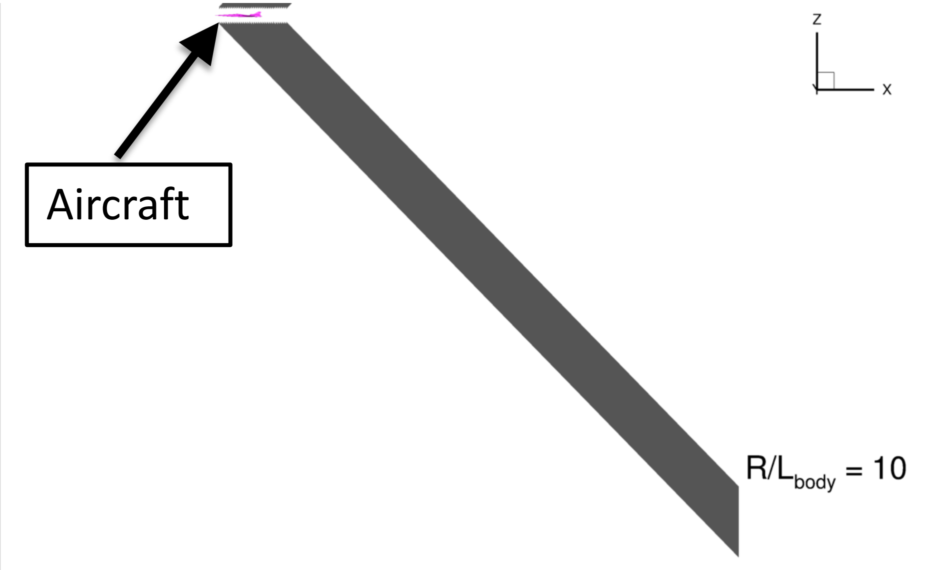


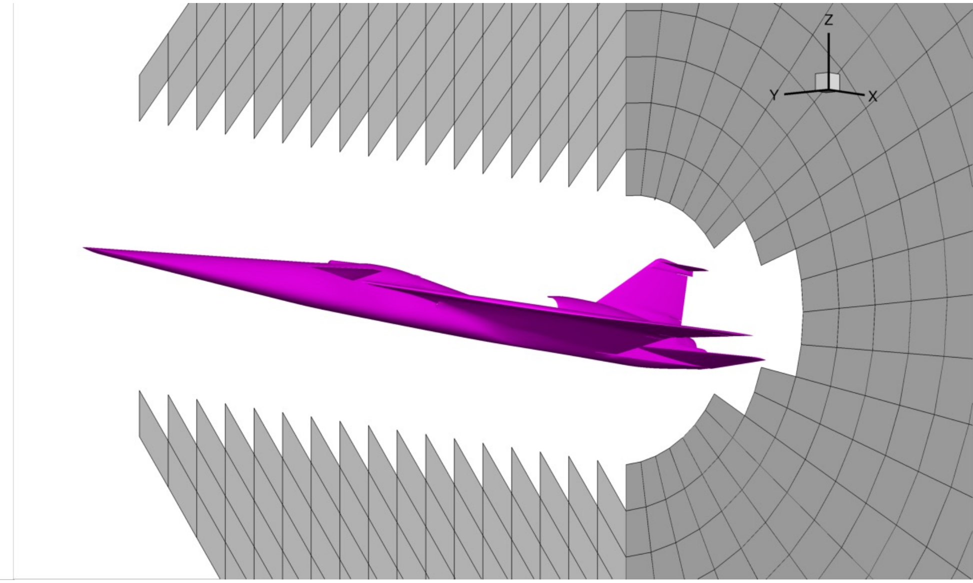


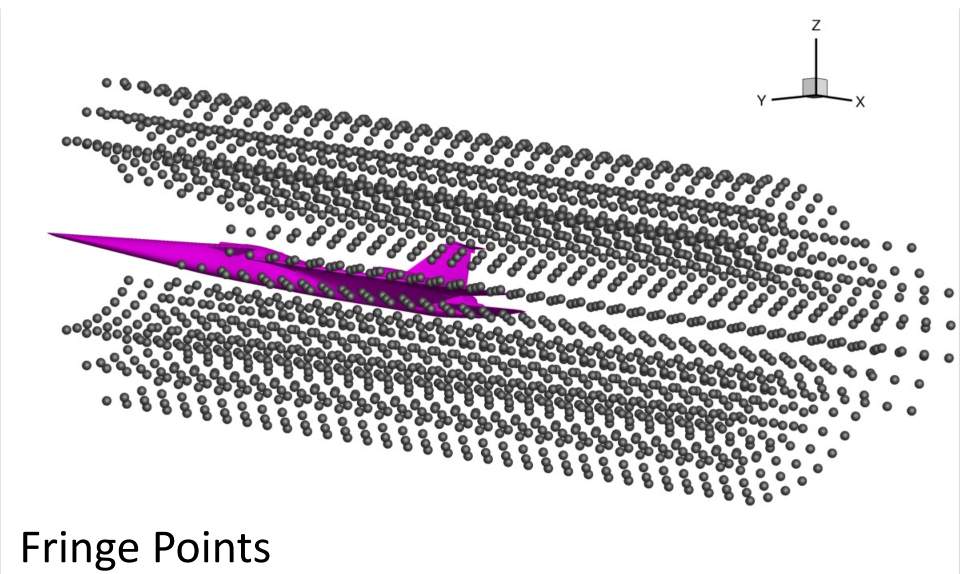
- The original cylindrical hole cutting procedure has been replaced with an elliptic hole cutting procedure
  - Remains geometrically simple for easy user placement*
  - Enables closer coupling to the aircraft
  - Reduces CFD meshing requirements away from aircraft body

*An automated multi-ellipsoidal procedure is currently being developed

CFD/Space Marching Coupling

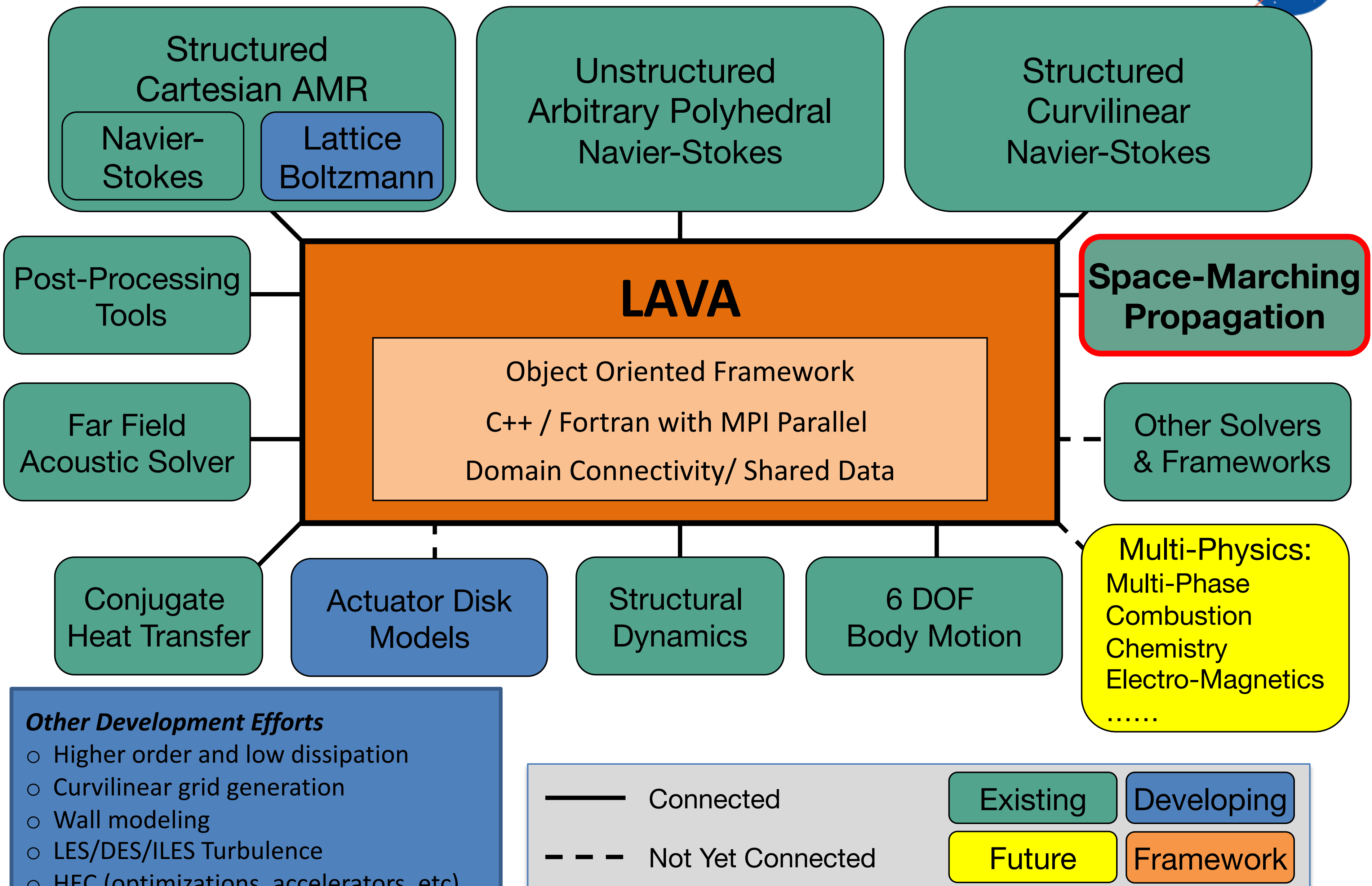






- Coarse space marching grid shown to illustrate procedure
  - Grid is automatically generated to user specified radial extent
  - Elliptic hole cut is performed
  - Fringe points are marked and CFD solution interpolated
  - Space marching is performed

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

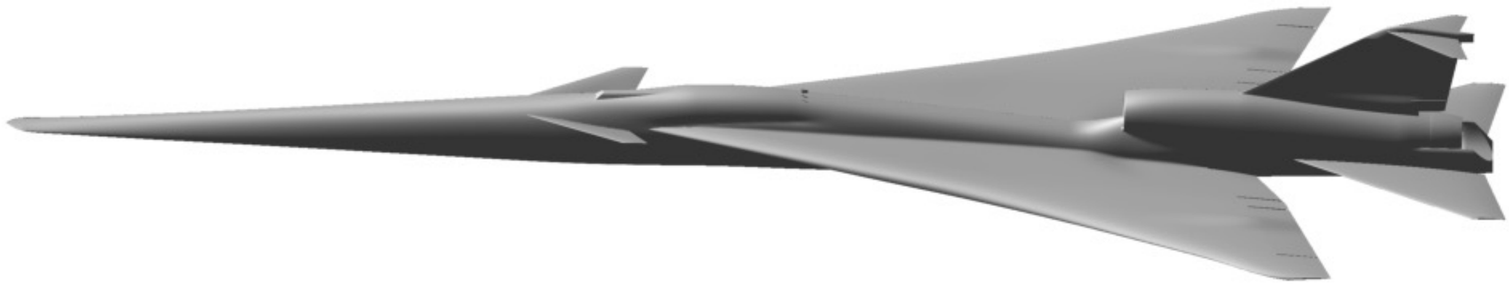
Computational Results

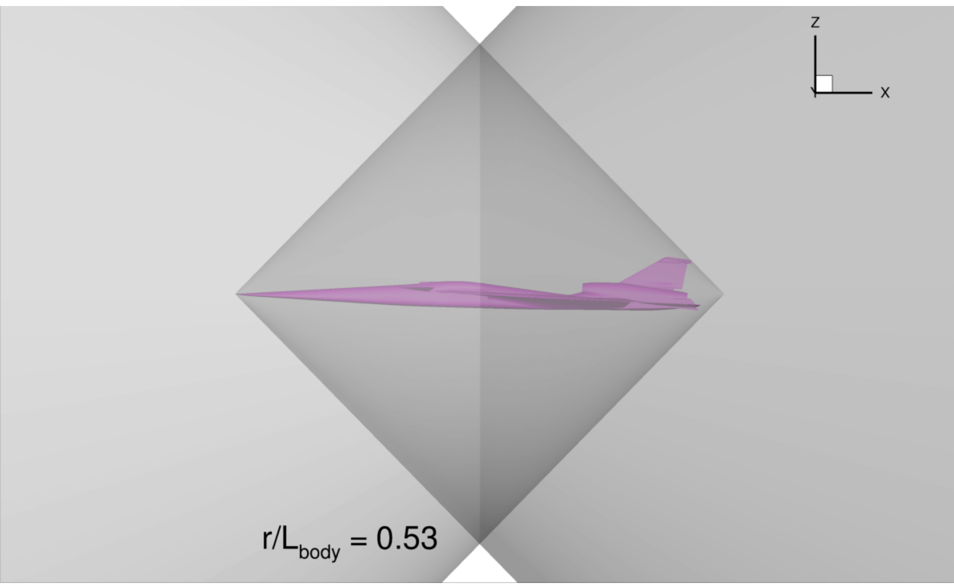
- CFD Domain Reduction
  - Domain of dependence
  - Comparison of 2-step and 3-step (space marching) procedures
- Unstructured Solver Coupling
  - Example of USM3D + LAVA space marching
- CFD Accuracy Enhancement
  - HALO3D coarse mesh improvement demonstration
- Local Error Analysis
  - Application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

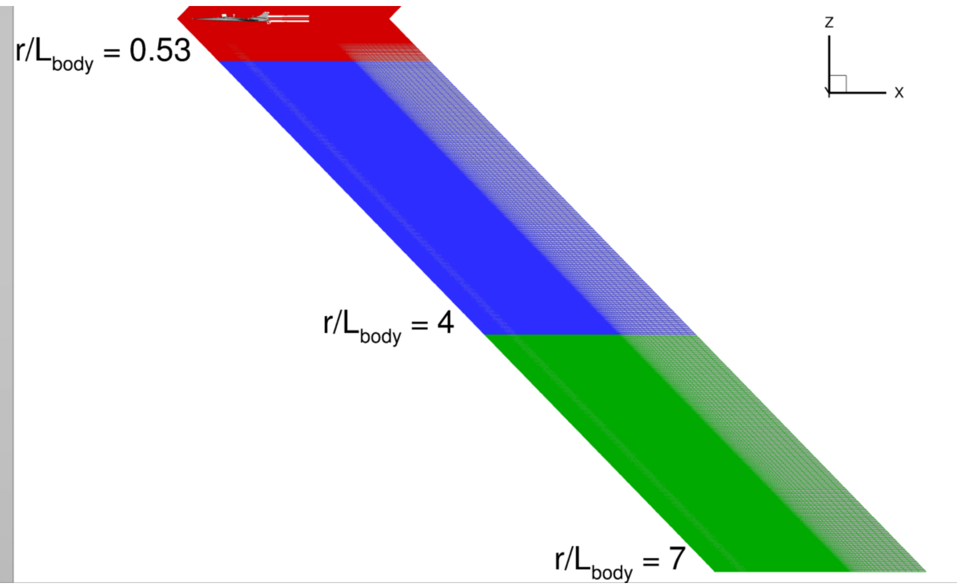
CFD Domain of Dependence

C608

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

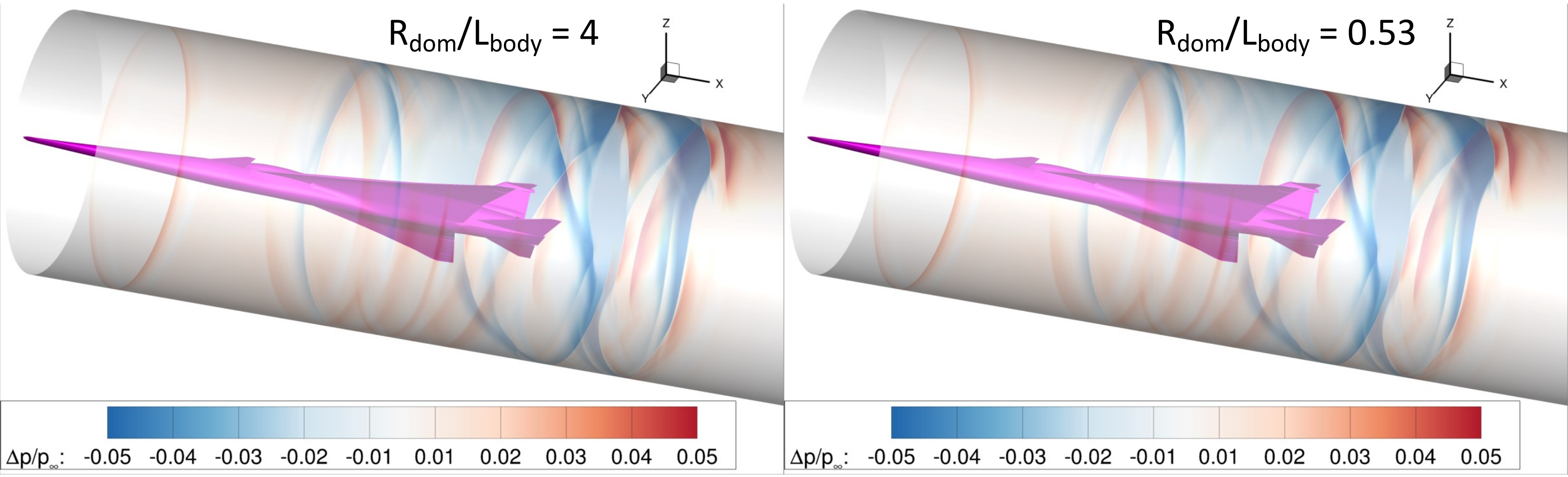


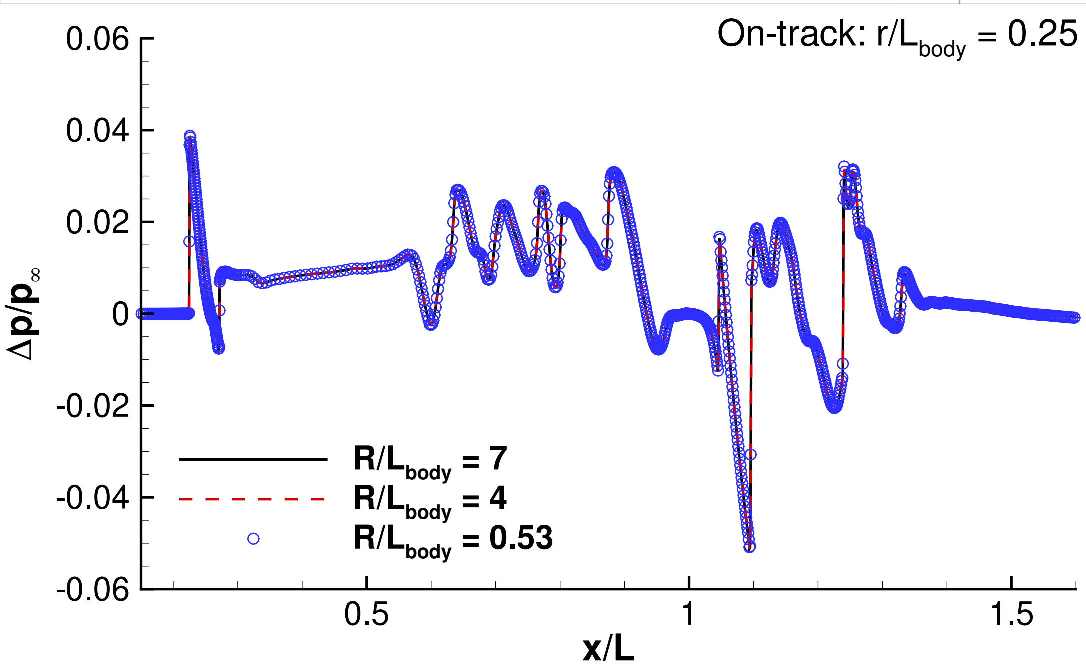




- Intersecting two Mach cones which encapsulate the aircraft provides an approximate domain of dependence
- Sensitivity to radial domain extent is assessed using CFD

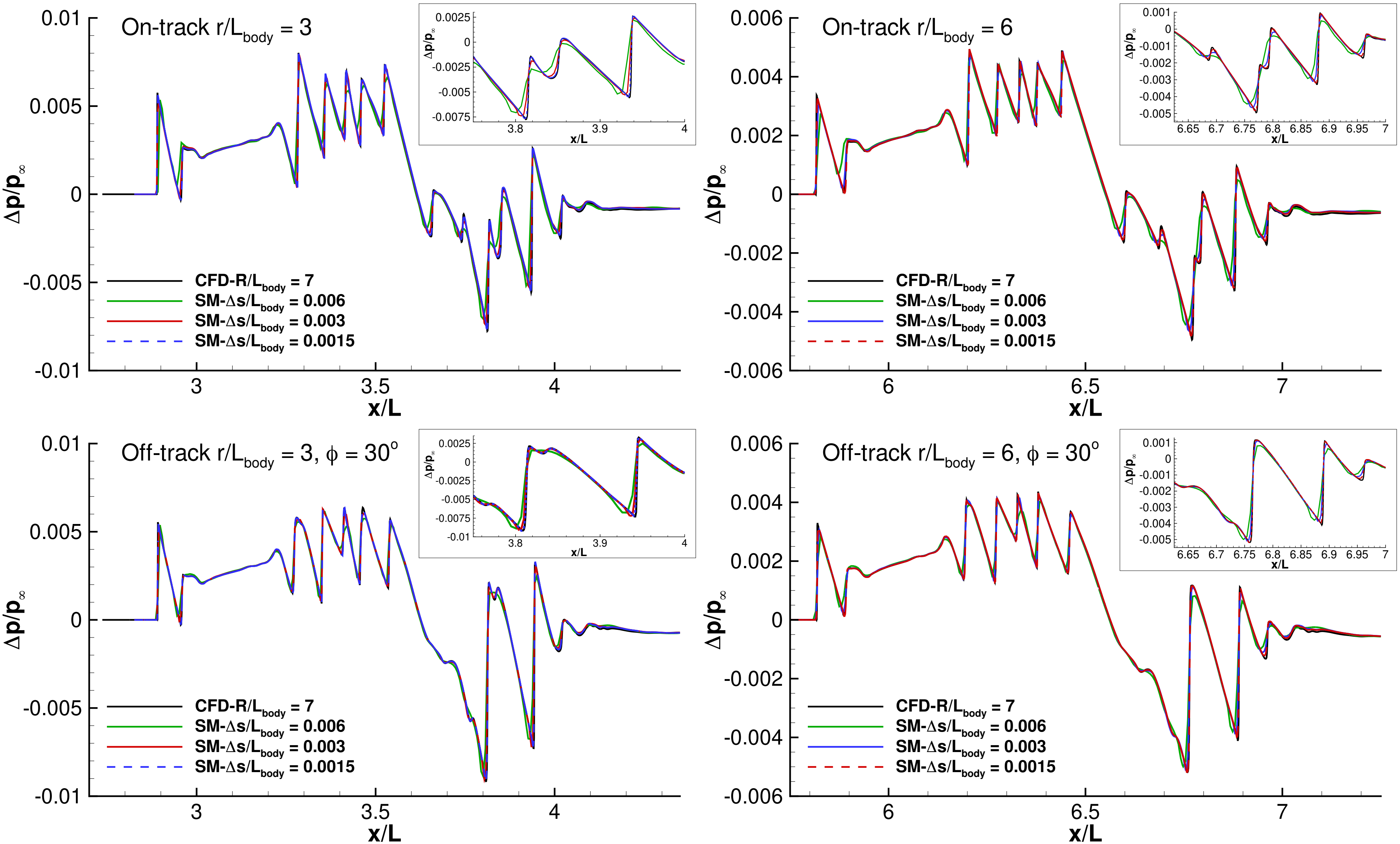
CFD Domain of Dependence





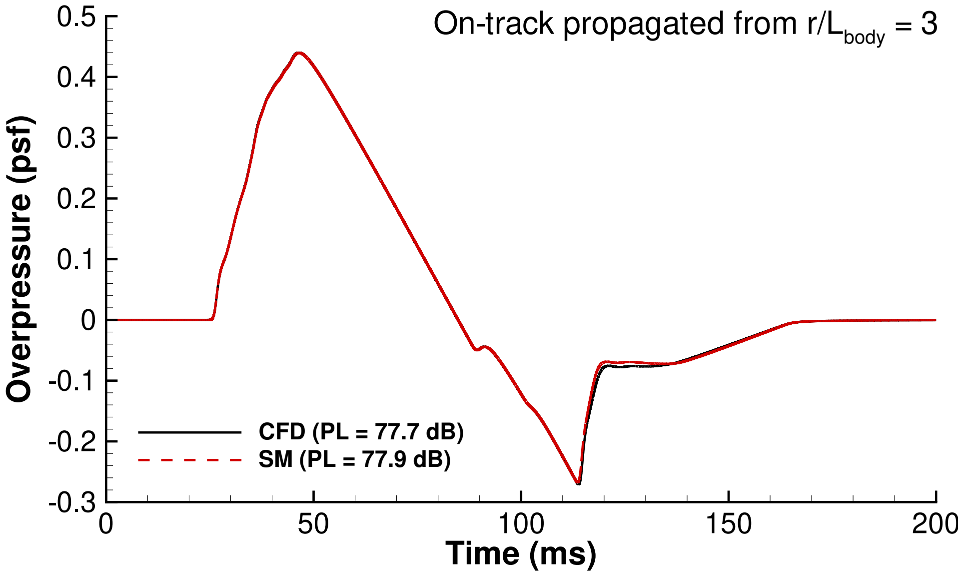
- Contour plots of pressure on a cylindrical surface at r/L_{body} = ¼ using CFD radial domain lengths of 4 and 0.53
- No sensitivity is observed near the CFD/space marching coupling location

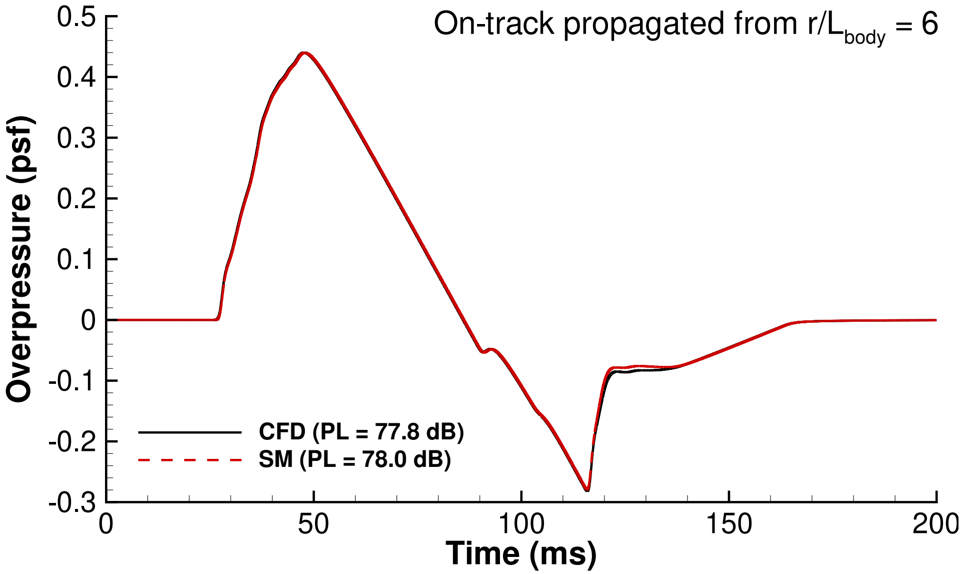
Comparison of 2-step and 3-step procedures



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





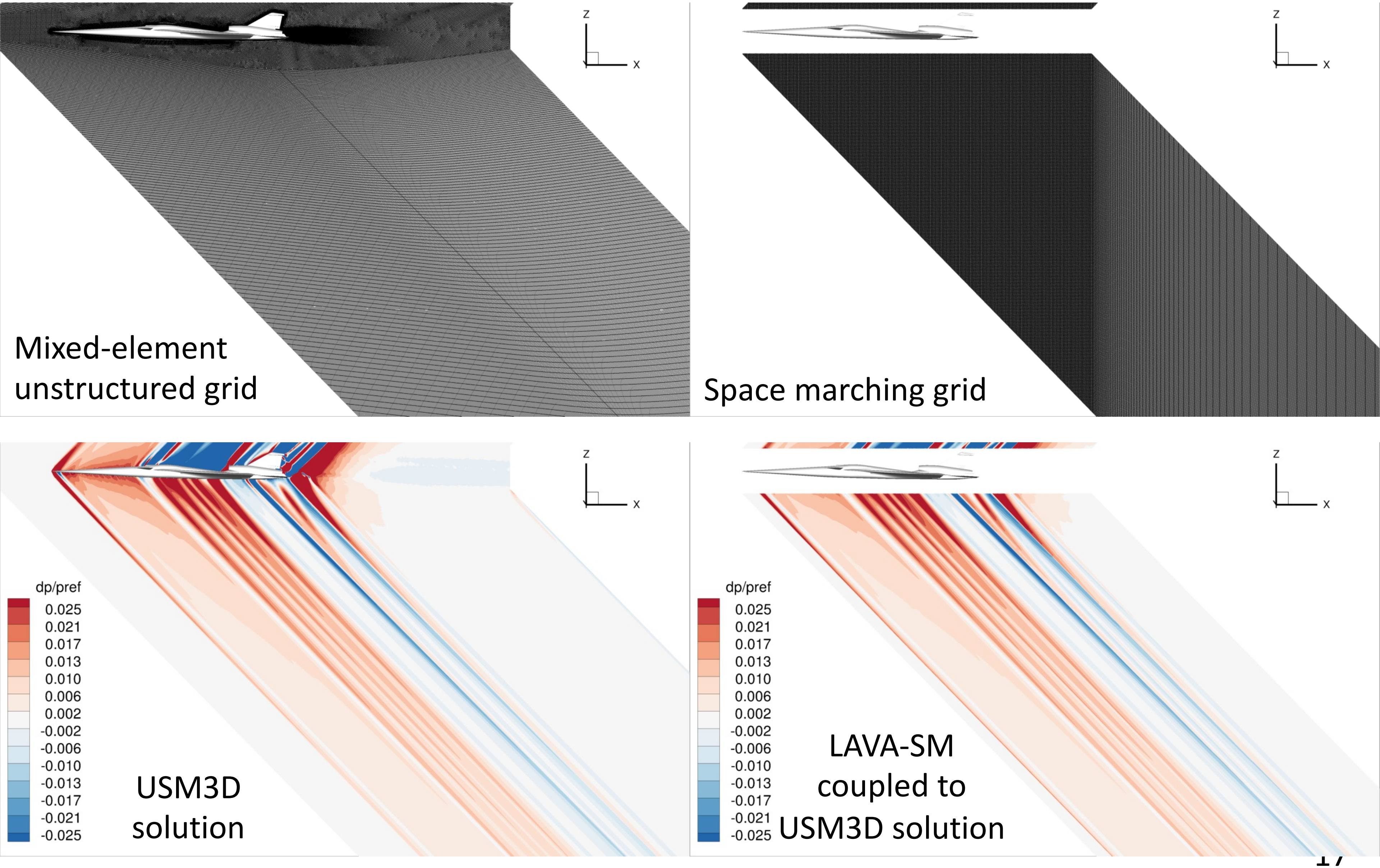
- Comparison of ground level noise between 2-step and 3-step procedures
  - Perceived loudness levels within 0.2 dB of each other at both interface locations to the far-field acoustic propagation code
  - Minor discrepancy in recovery portion between 120-130 ms

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

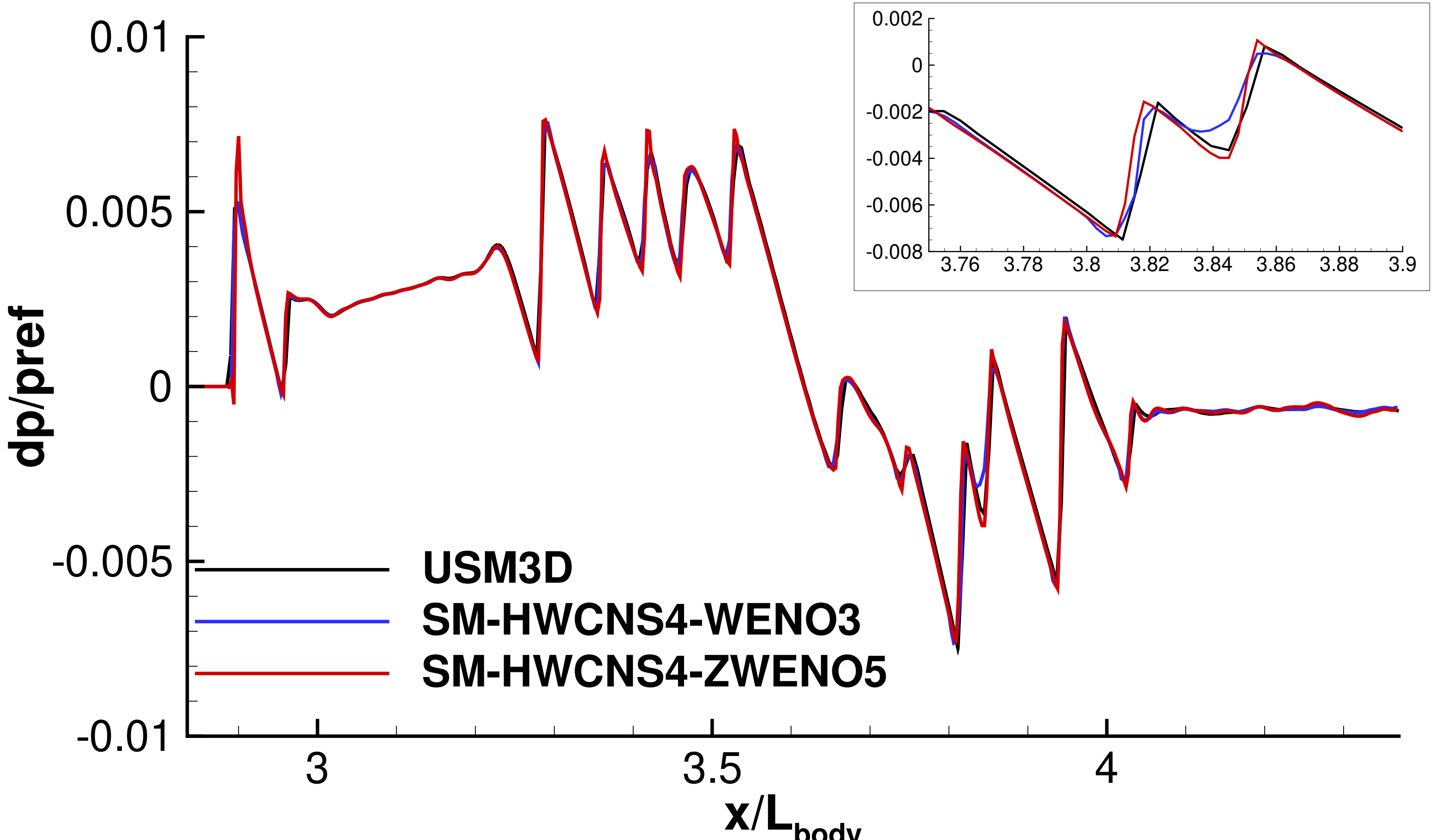
1) CFD domain size reduction factor of 13.2
2) Number of CFD grid points cut in half
3) Computational resources also half
4) SM-Medium 2 minutes 19 seconds

Unstructured Solver Coupling



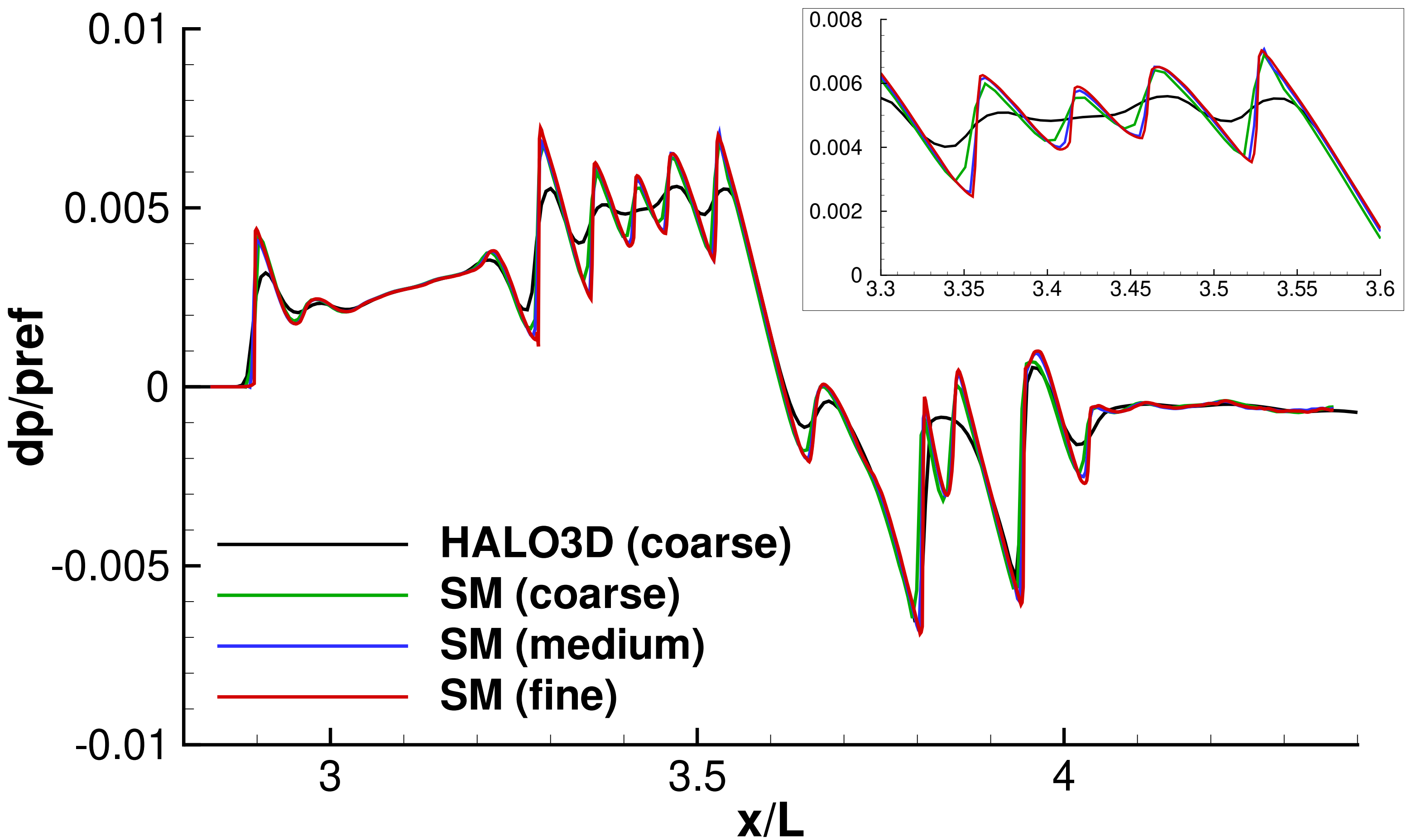
Unstructured Solver Coupling

- 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)

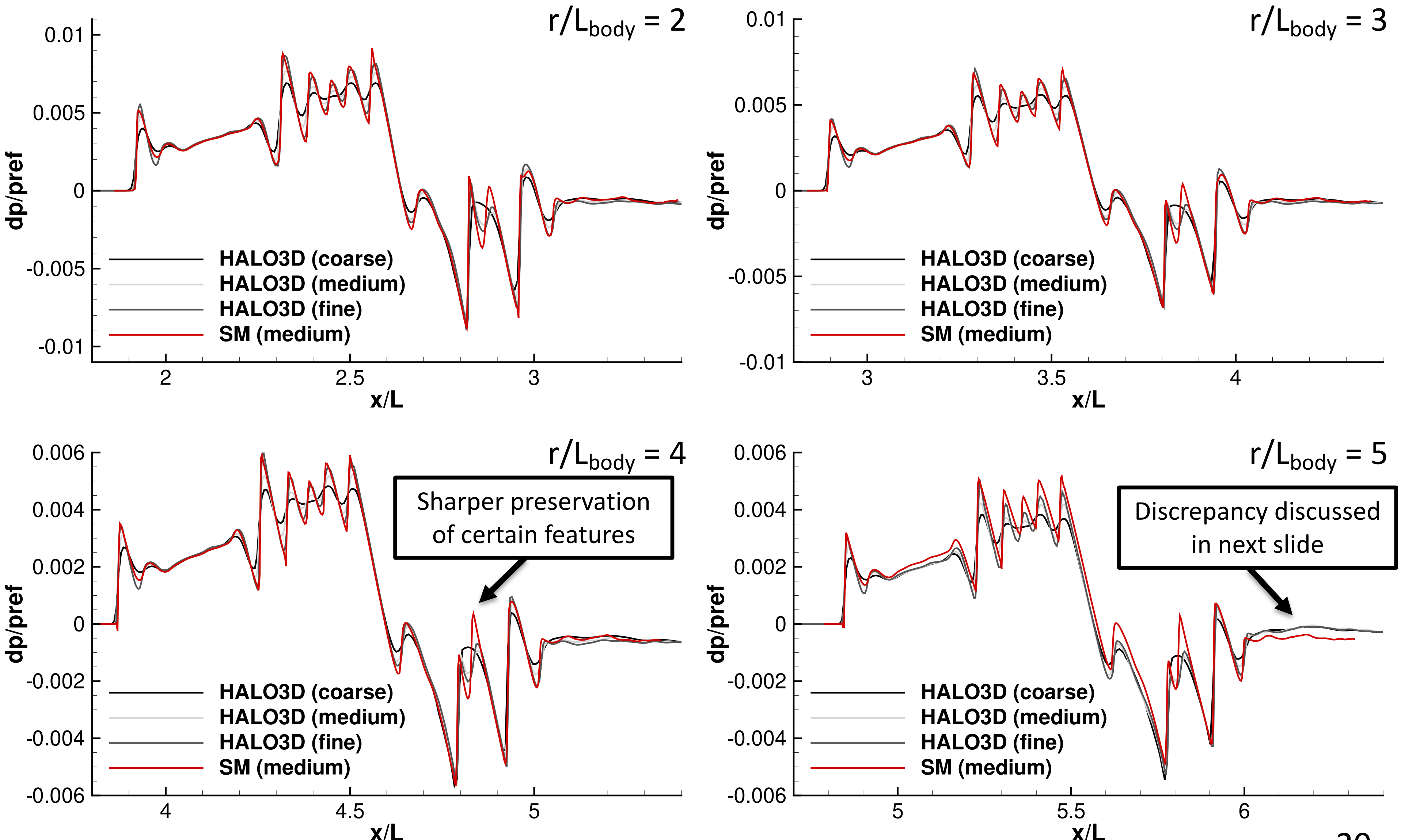


Accuracy Enhancement

- 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)

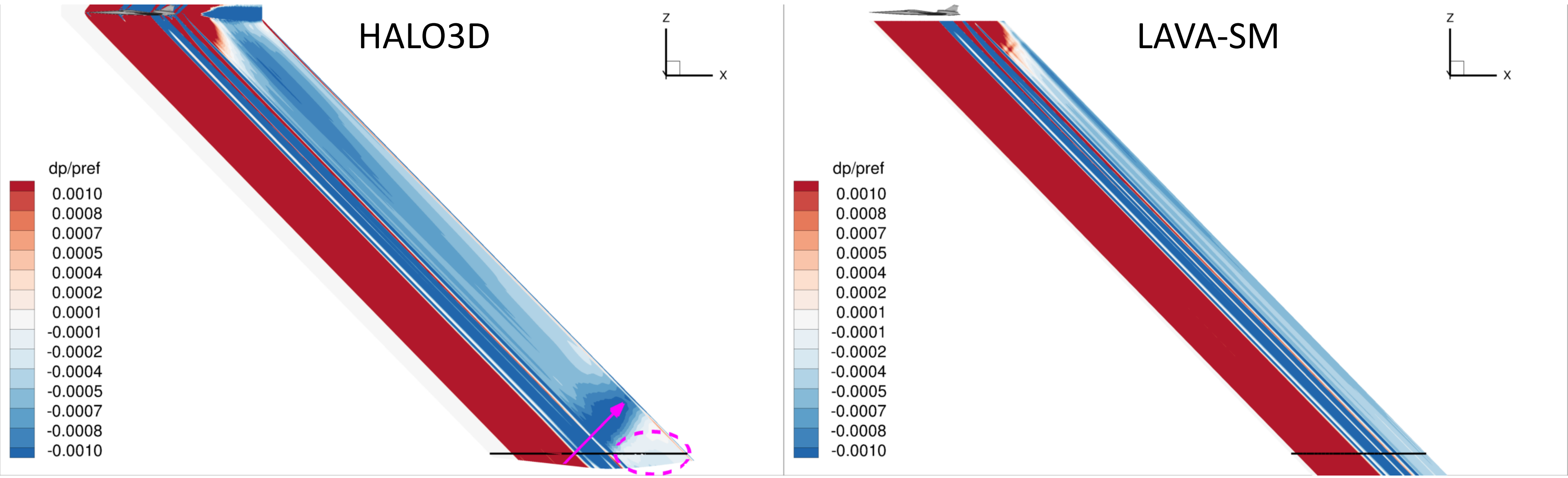


Accuracy Enhancement



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

Accuracy Enhancement

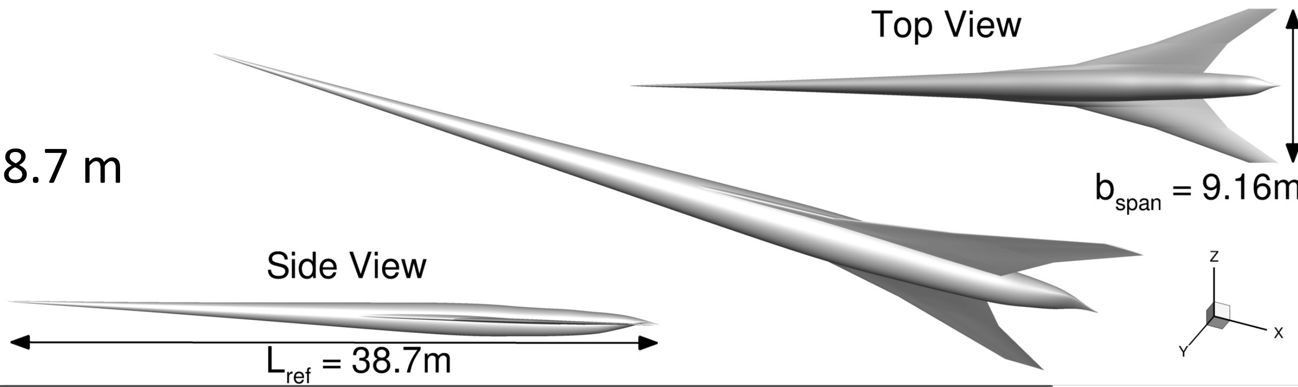


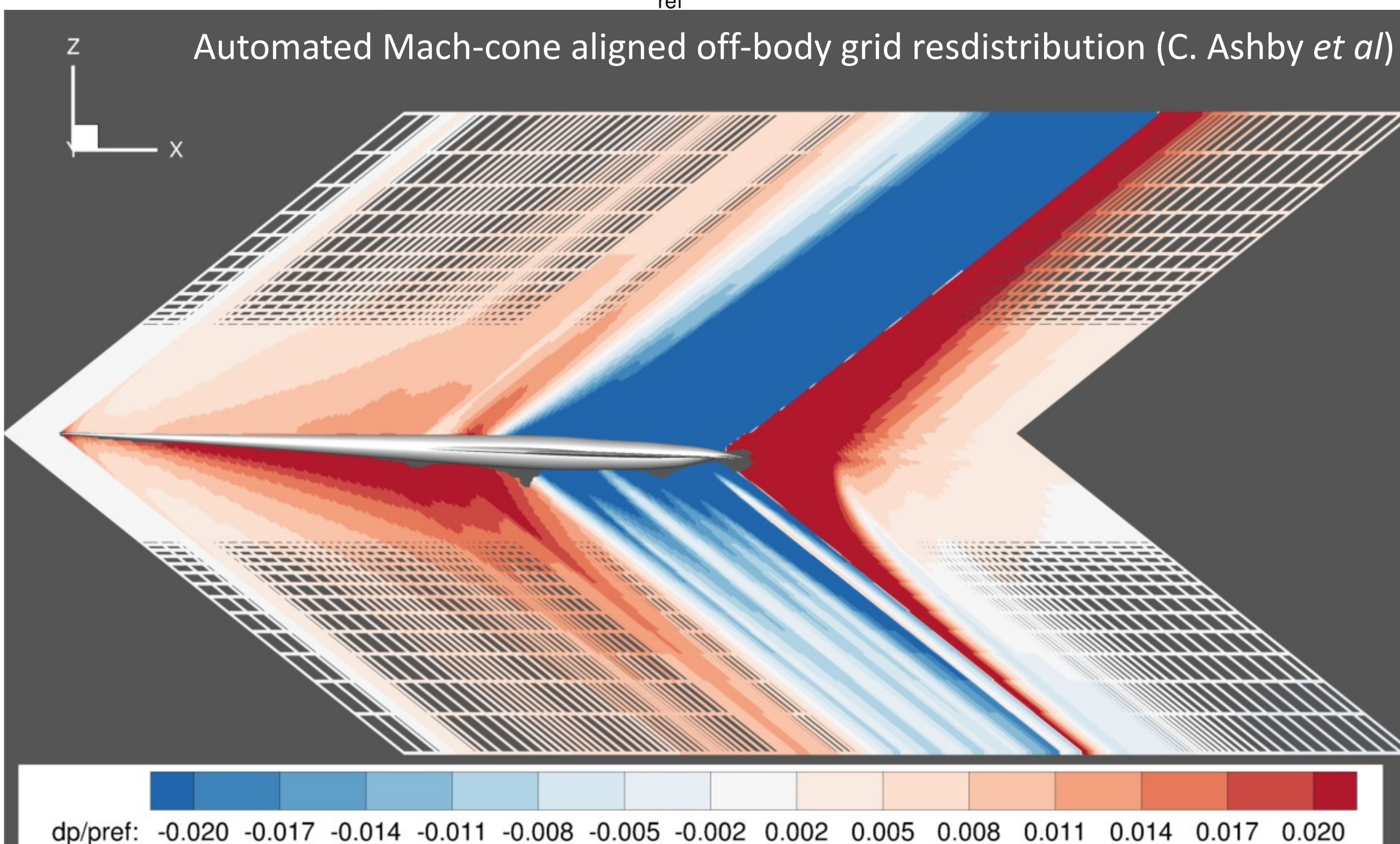
- HALO3D shows spurious reflection at exterior radial boundary, not observed in space marching solution
- Space marching coupled with coarse grid HALO3D solution is as accurate as fine grid HALO3D solution at r/L_{body} = 2 and 3
- LAVA-SM shows improved resolution over fine grid HALO3D at r/L_{body} = 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)

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 α = 2.3°





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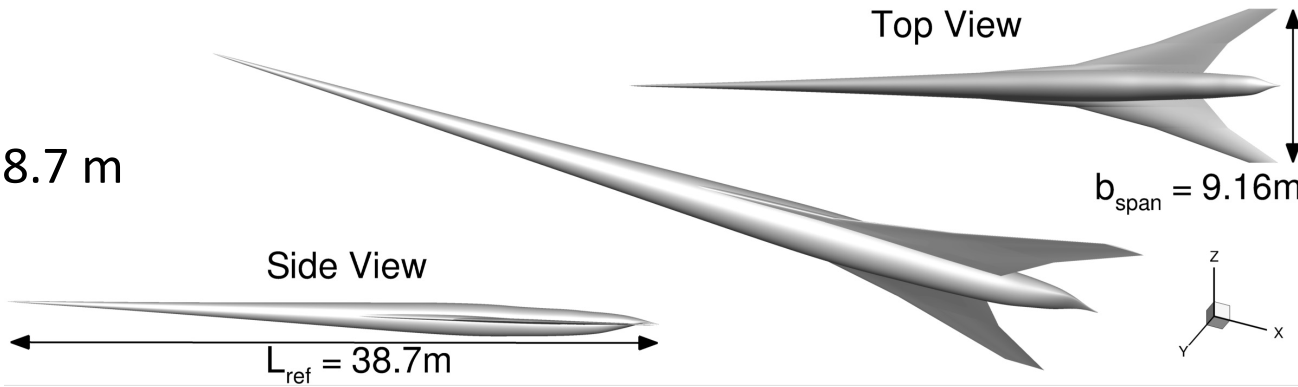
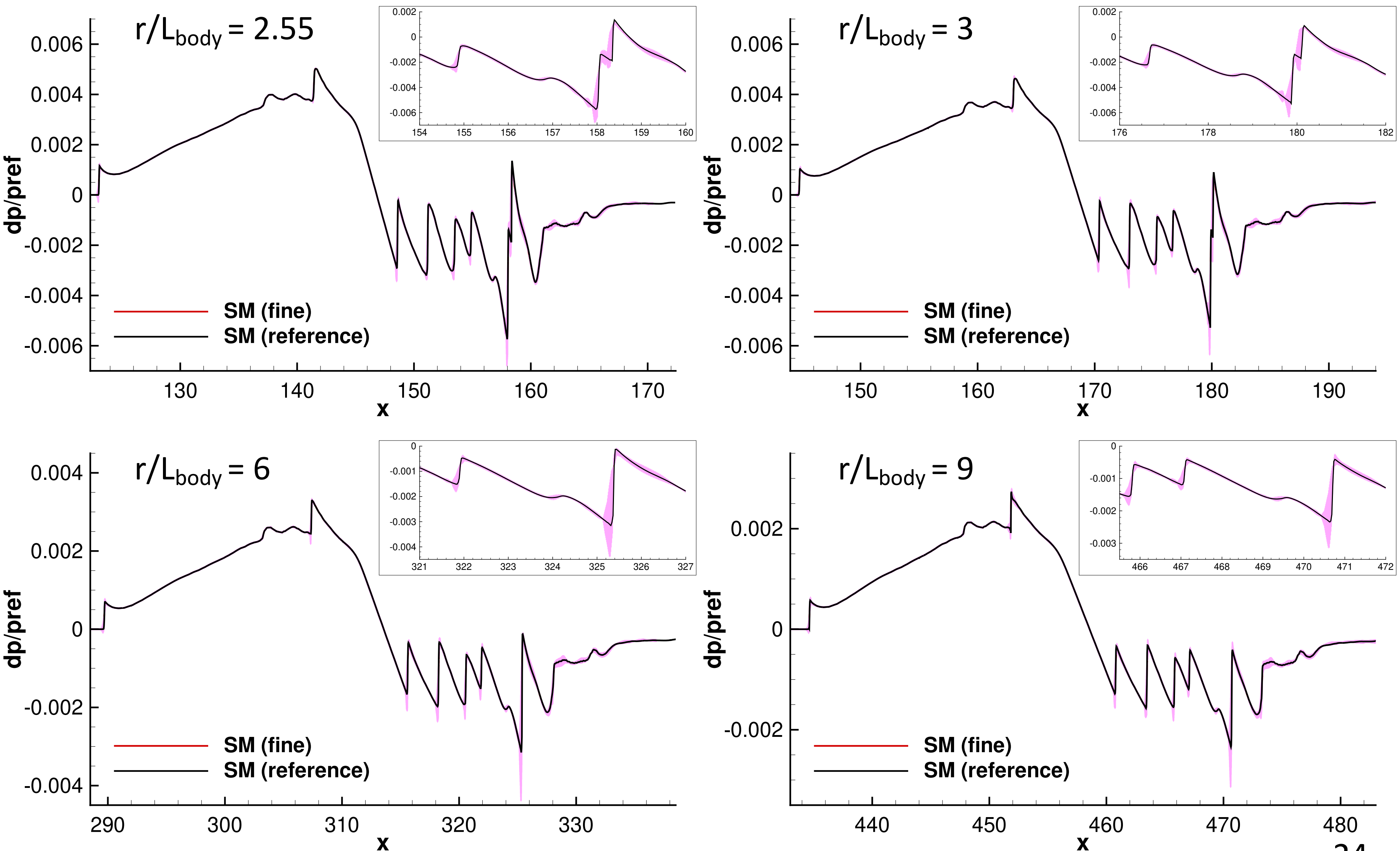


Mesh	Number of grid points (millions)	Time (seconds)
Coarse	22.7	53.1
Medium	87.4	189.1
Fine	342.7	752.3
Reference	1,356.6	3366*

*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 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
- Evaluation of space marching grid resolution uncertainty using a local error analysis procedure

Acknowledgements

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- Computer time has been provided by NASA's Advanced Supercomputing (NAS) at NASA Ames Research Center