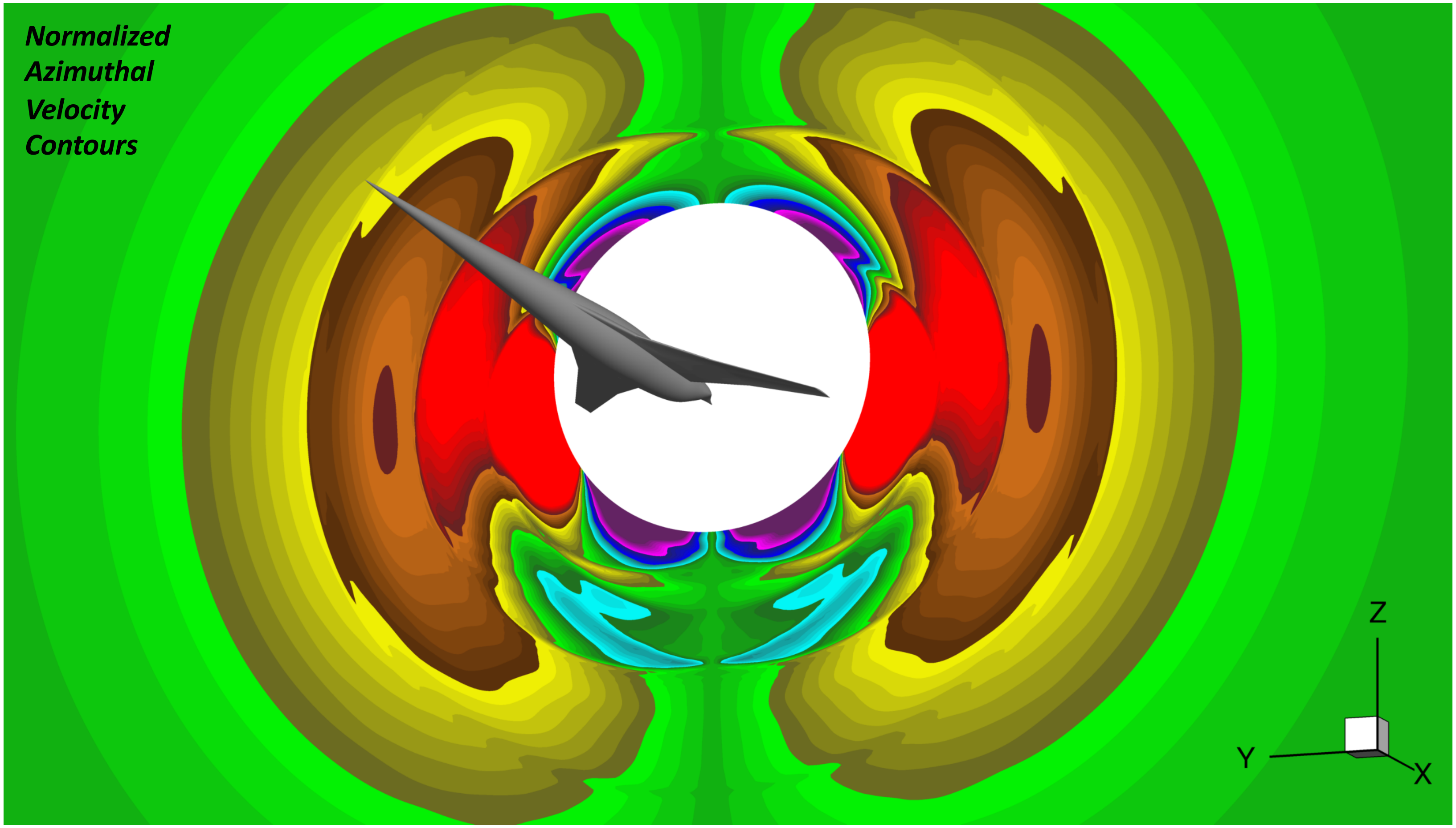
Efficient Near-Field to Mid-Field Sonic Boom Propagation using a High-Order Space Marching Method*



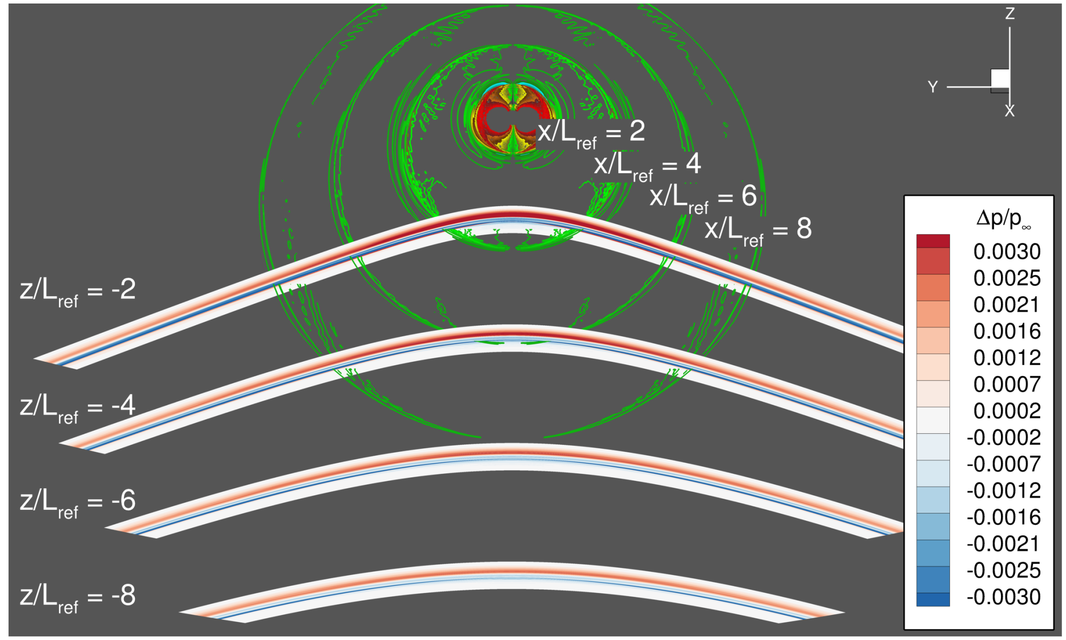
Jeffrey Housman, Gaetan Kenway, James Jensen, and Cetin Kiris
Computational Aerosciences Branch
NASA Ames Research Center

*work funded by the NASA's ARMD
Commercial Supersonic Technologies (CST) project
AIAA-2019-3487

Advanced Modeling & Simulation (AMS) Seminar Series
Tuesday August 12, 2019

Outline

- Introduction
- Computational Methodology
  - Mach-cone Aligned Space Marching Grid
  - Numerical Discretization
  - Near-Field to Mid-Field Procedure



- Results
  - Grid and Solver Sensitivity Studies
  - Azimuthal Dependence of Nonlinear Wave Propagation
  - Low Boom Aircraft Wind Tunnel Model Validation
- Example of Computational Savings
- Summary and Future Work

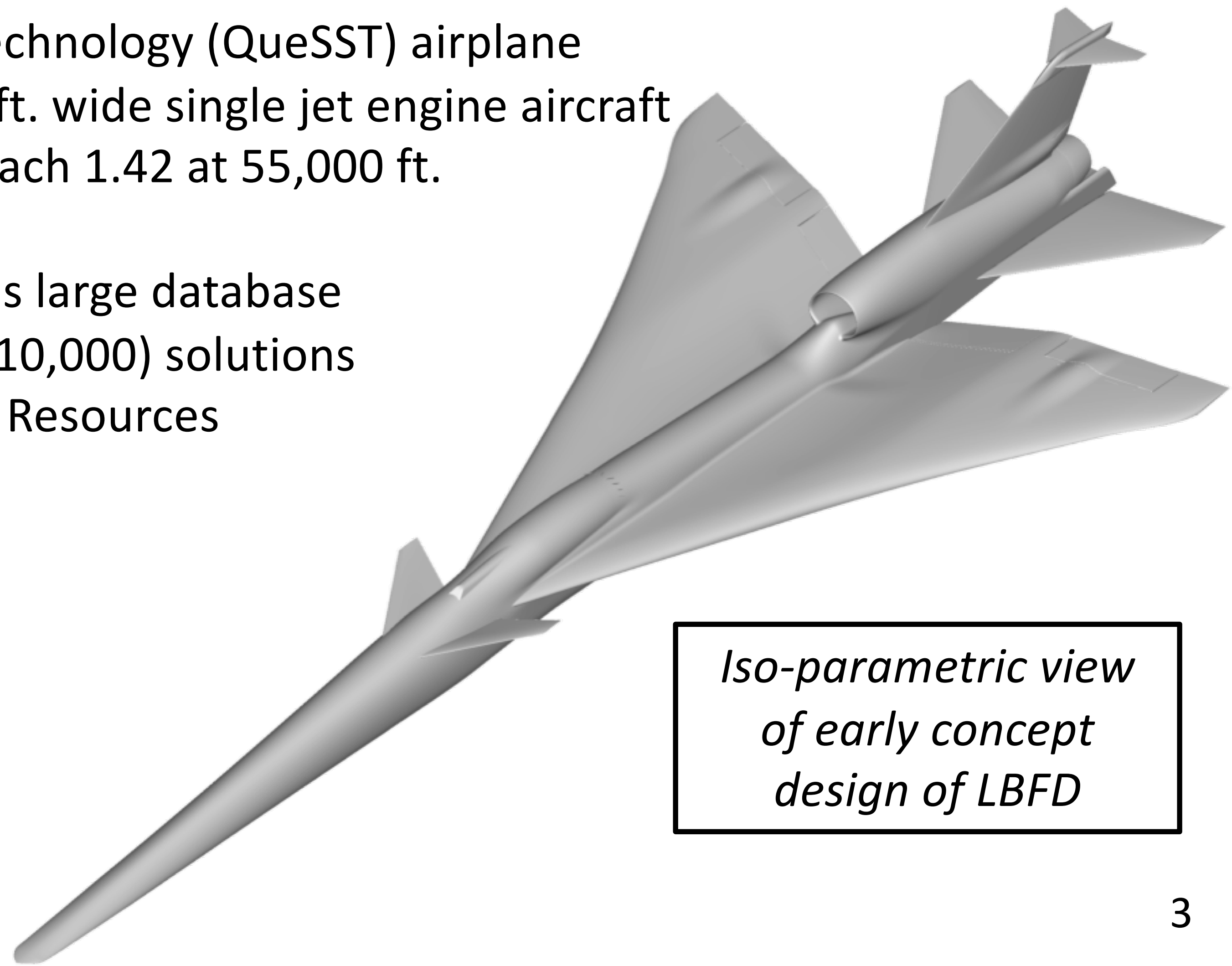
Introduction

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

- Primary goal is to demonstrate feasibility of supersonic over-land flight at reduced loudness levels

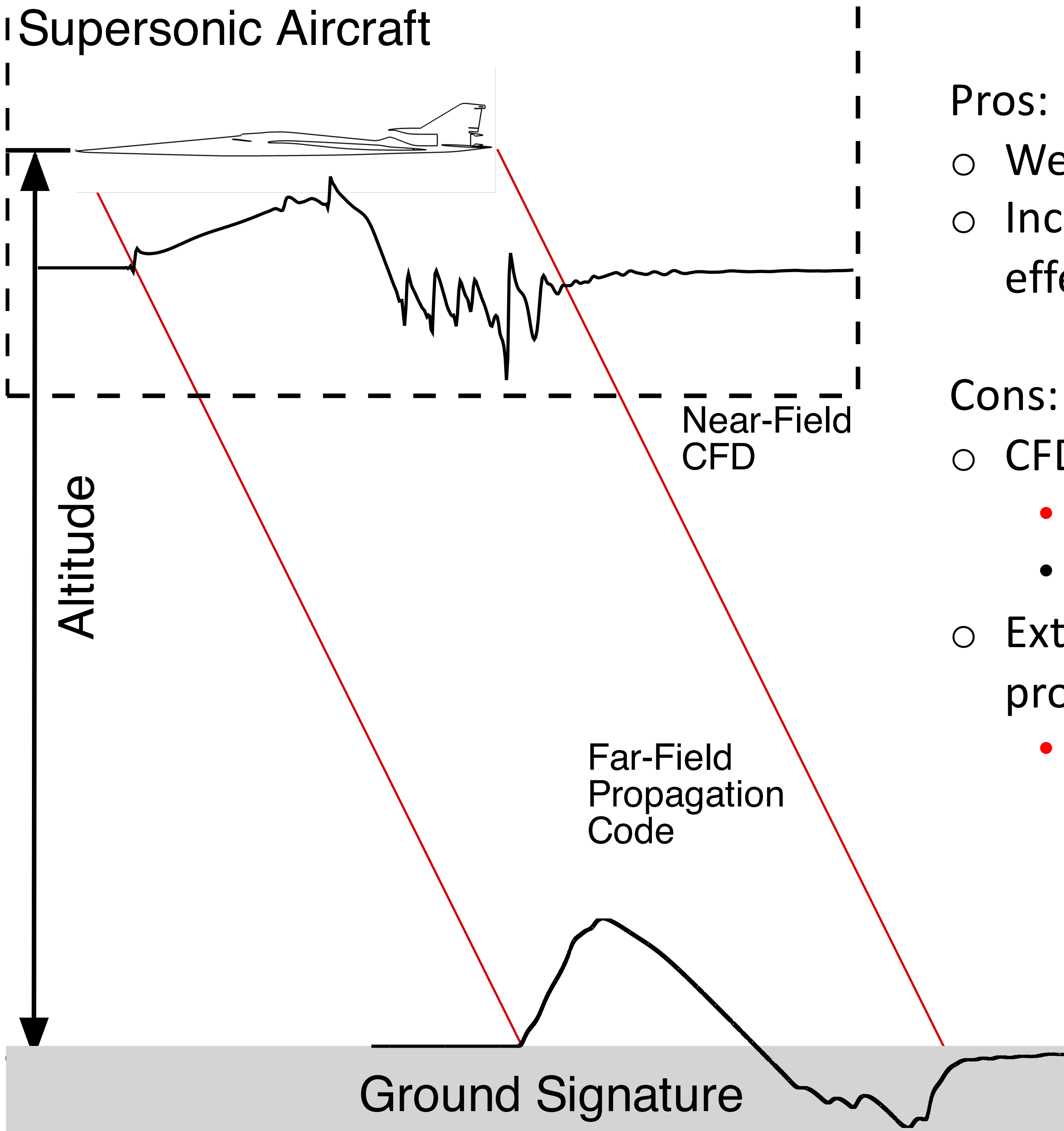
- X-59 Quiet Supersonic Technology (QueSST) airplane
  - 94 ft. long and 29.5 ft. wide single jet engine aircraft
  - Designed to fly at Mach 1.42 at 55,000 ft.

- Mission planning requires large database consisting of *O*(1000)-*O*(10,000) solutions
  - High Computational Resources
  - Must be automated
  - Must be accurate



Iso-parametric view of early concept design of LBFD

Current 2-Step Ground Level Noise Prediction



Pros:

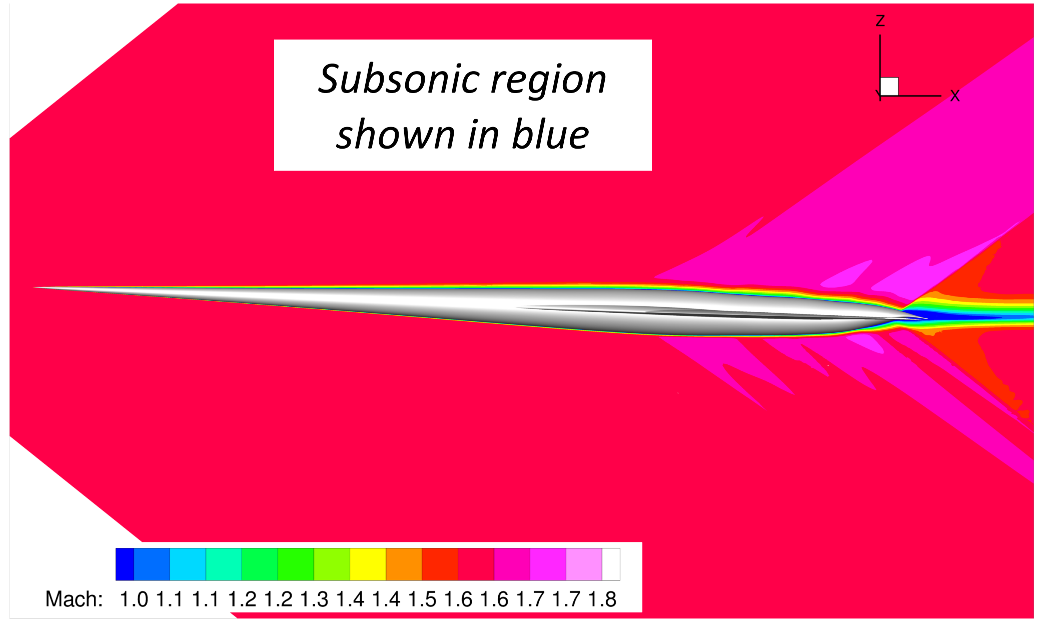
- Well established procedure
- Includes important atmospheric effects

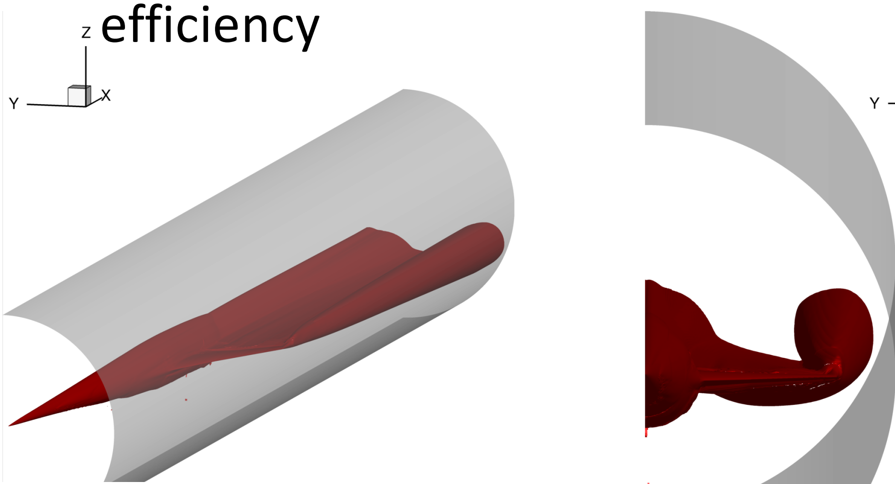
Cons:

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

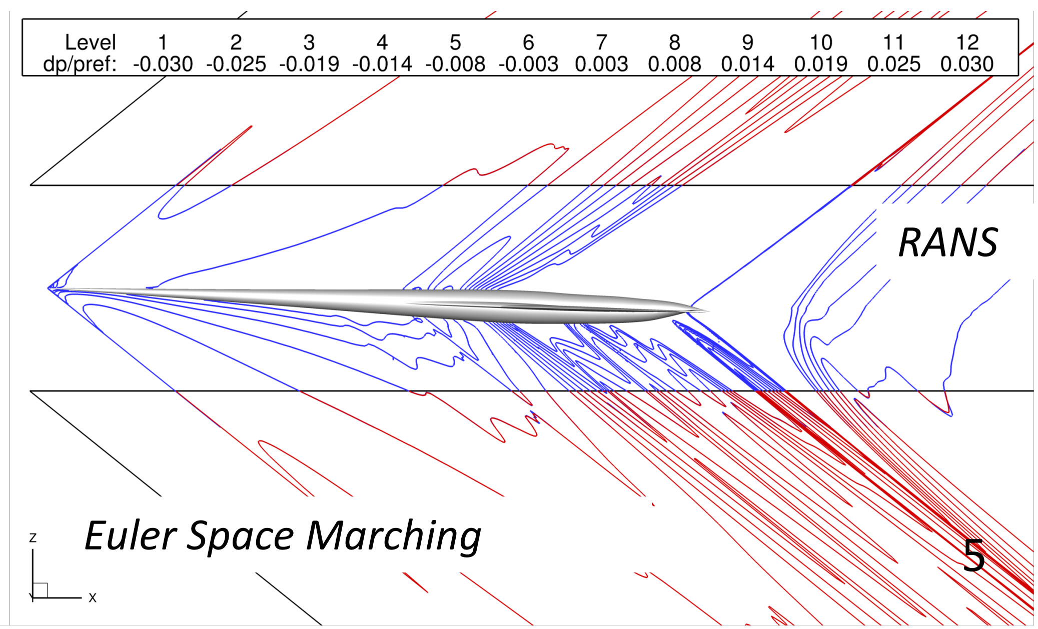
Special Features of Supersonic Flow

- 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

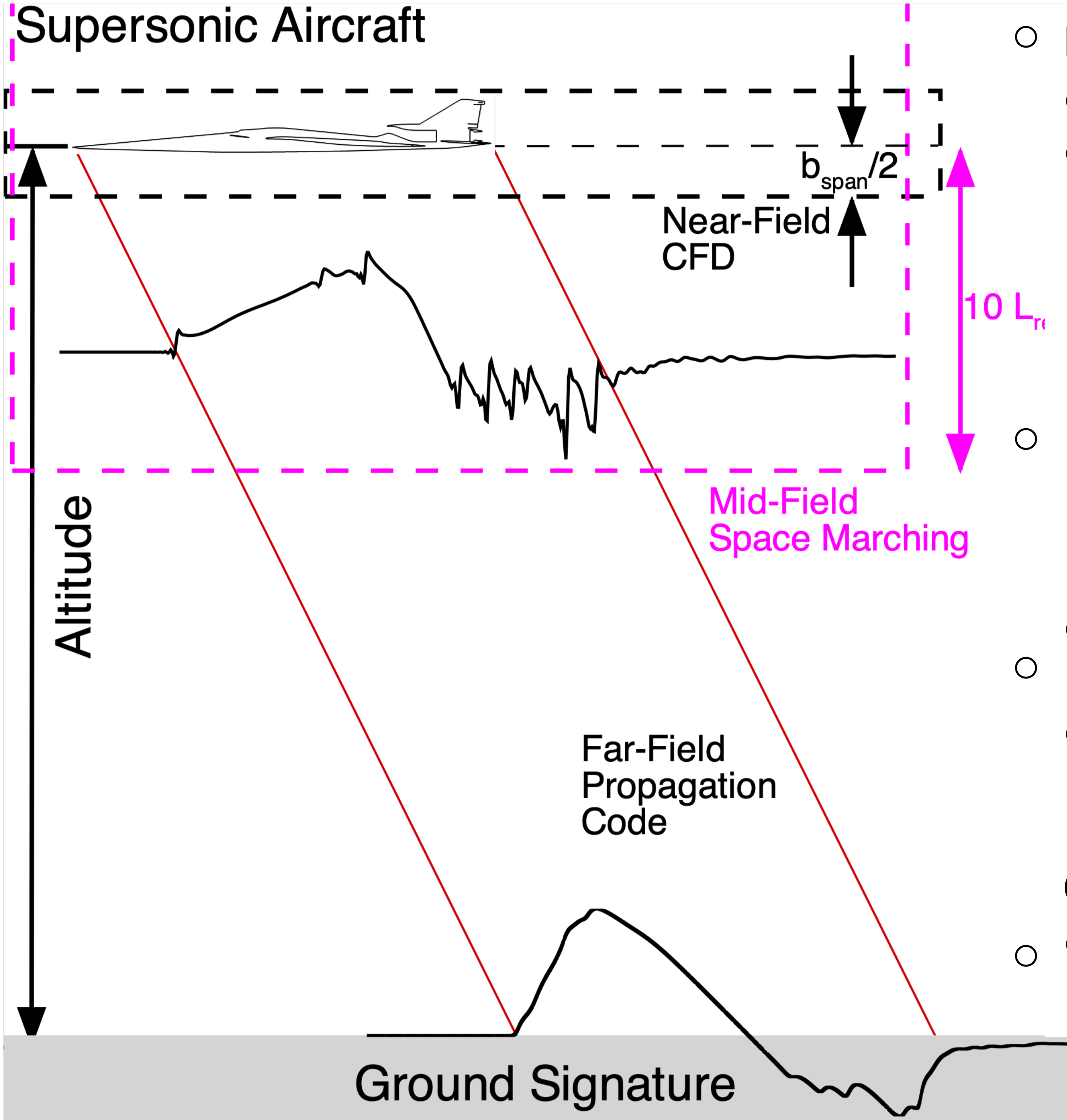




Isocontour of turbulent eddy viscosity ratio (μ_T / μ_∞ = 10)



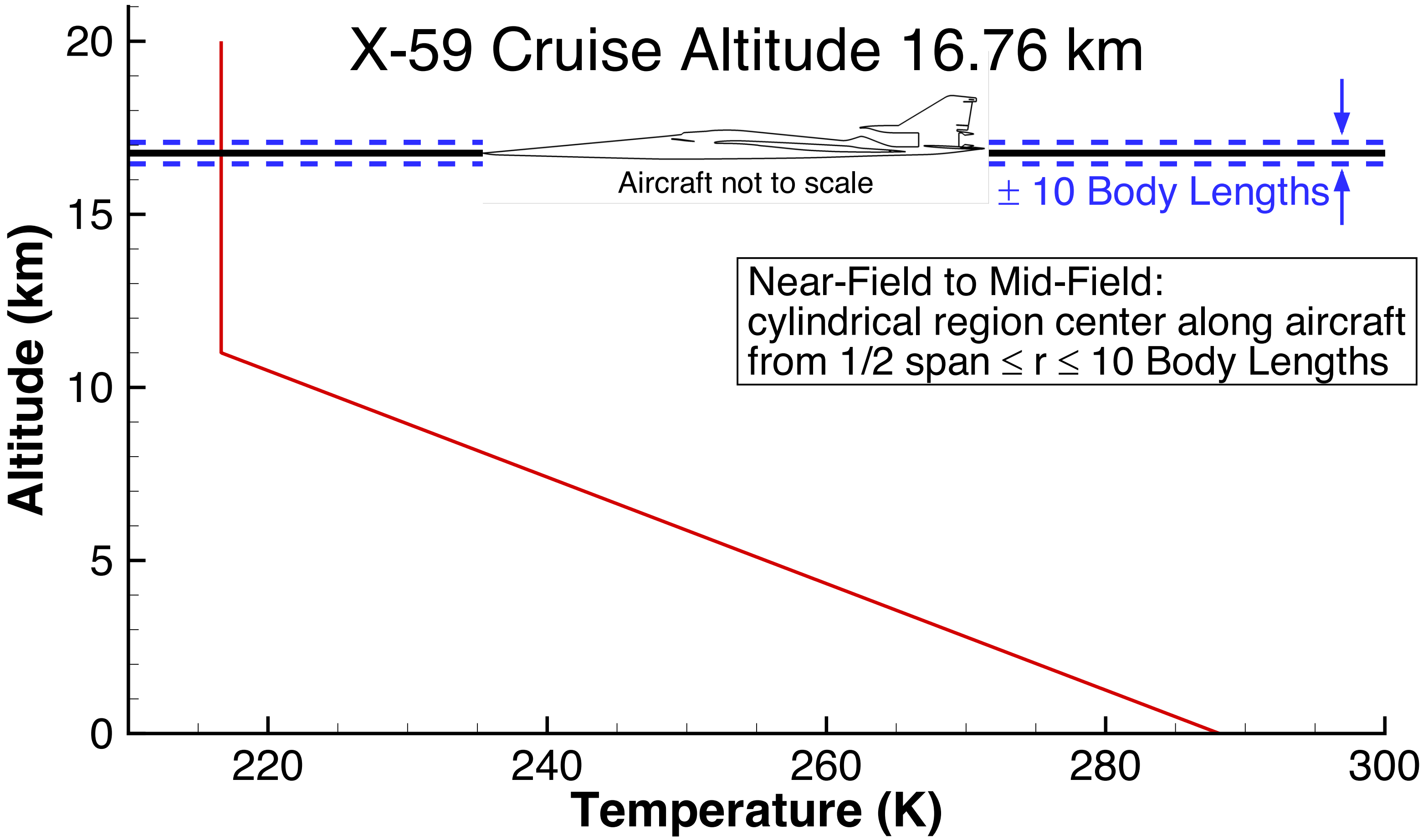
3-Step Ground Level Noise Prediction



- 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
- far-field wave propagation code

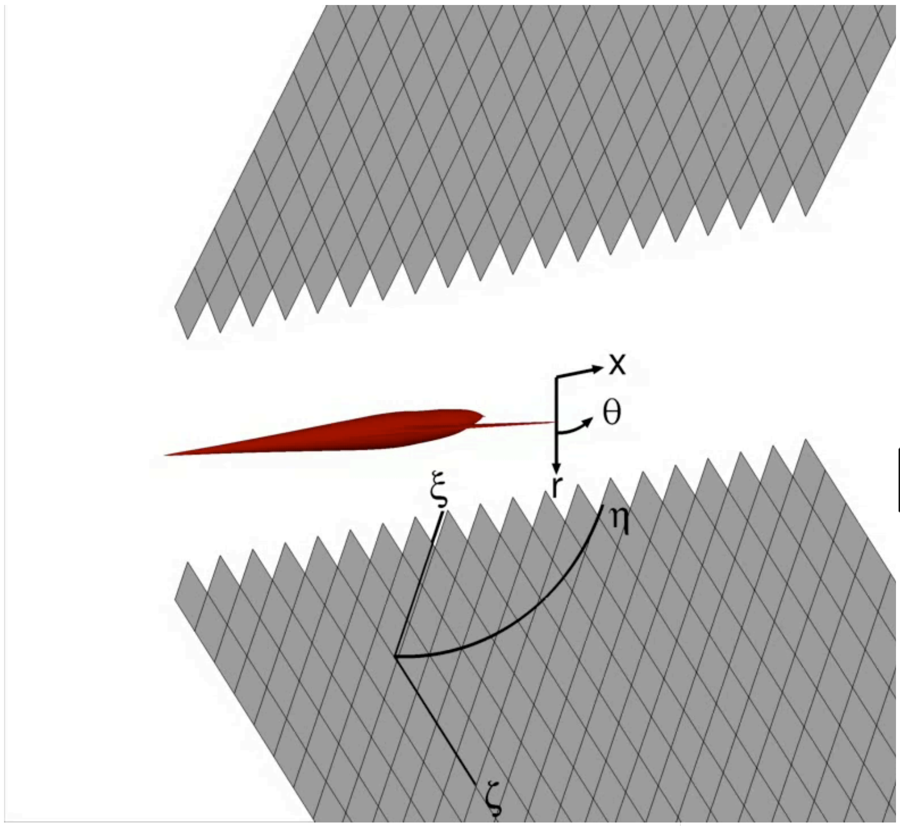
Definition of Near-Field to Mid-Field

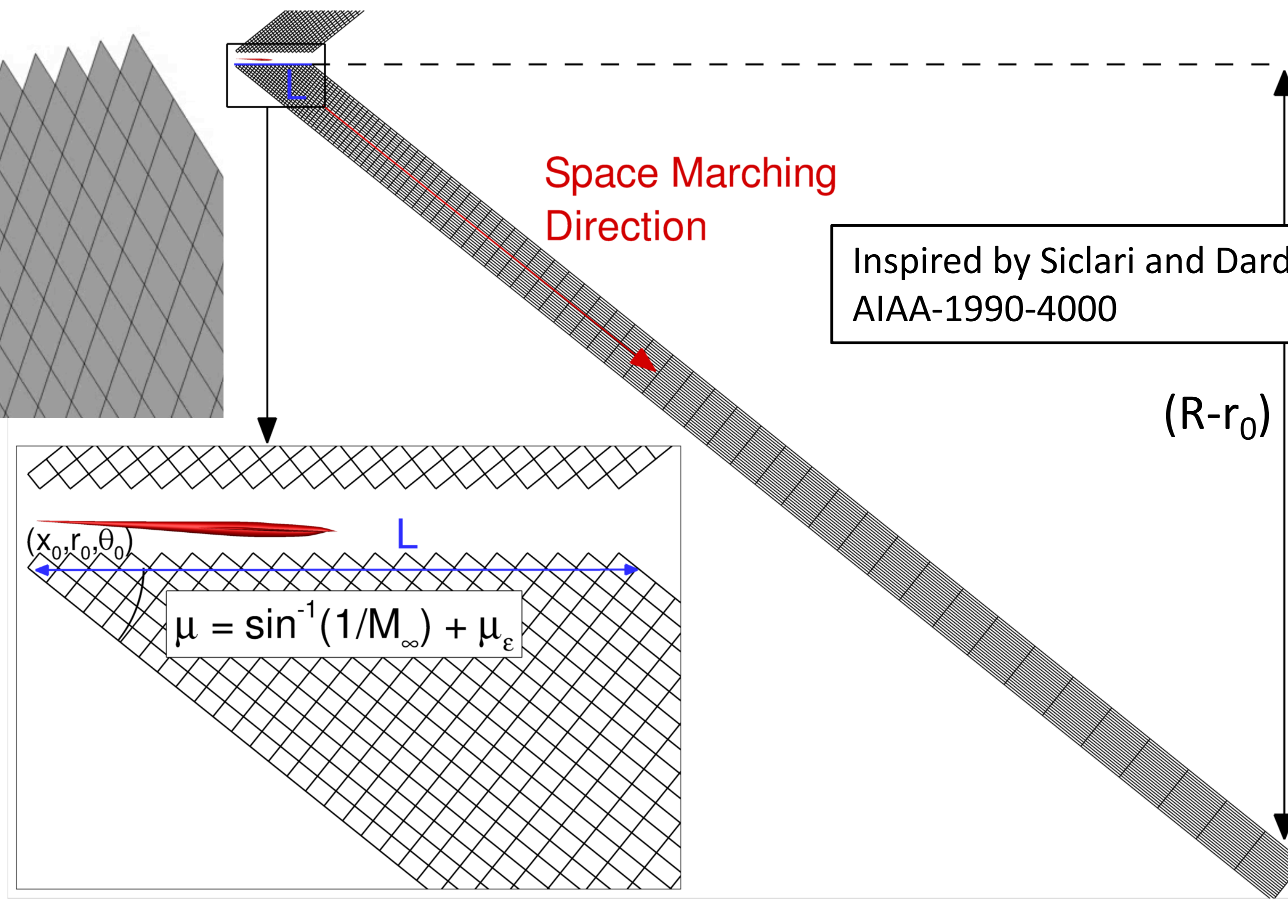


- Plot of altitude versus ICAO standard atmospheric temperature
- No variation in temperature within 10+ body lengths of the aircraft
- Atmospheric effects are currently neglected in the near-field to mid-field
    - examples: wind variation, molecular relaxation, and humidity

Mach-cone Aligned Space Marching Grid

- Mach-cone aligned to reduce effect of artificial dissipation
- Small perturbation in alignment to reduce chance of numerical flux crossing sonic line
- Orthogonal to preserve supersonic Mach number in space marching direction

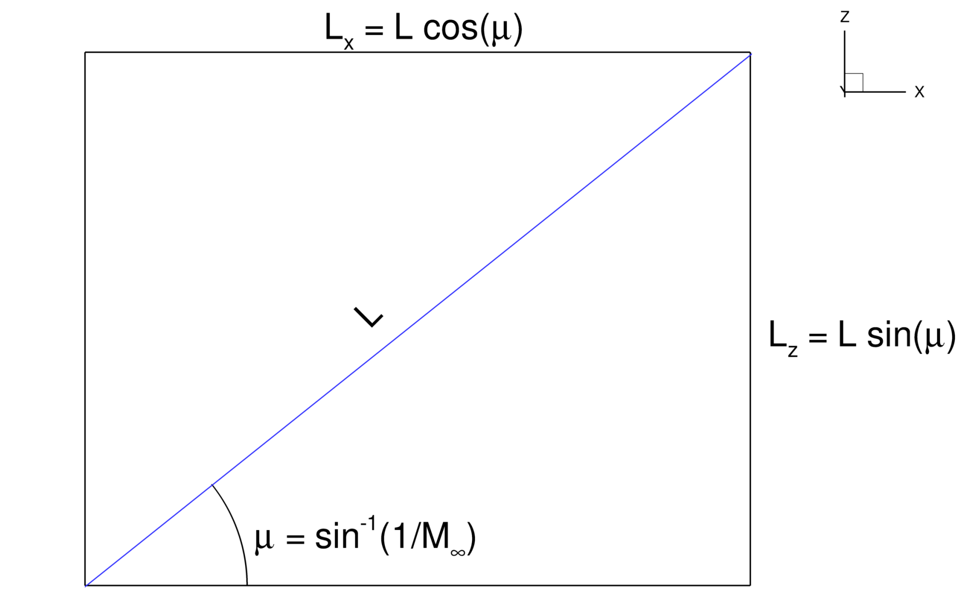




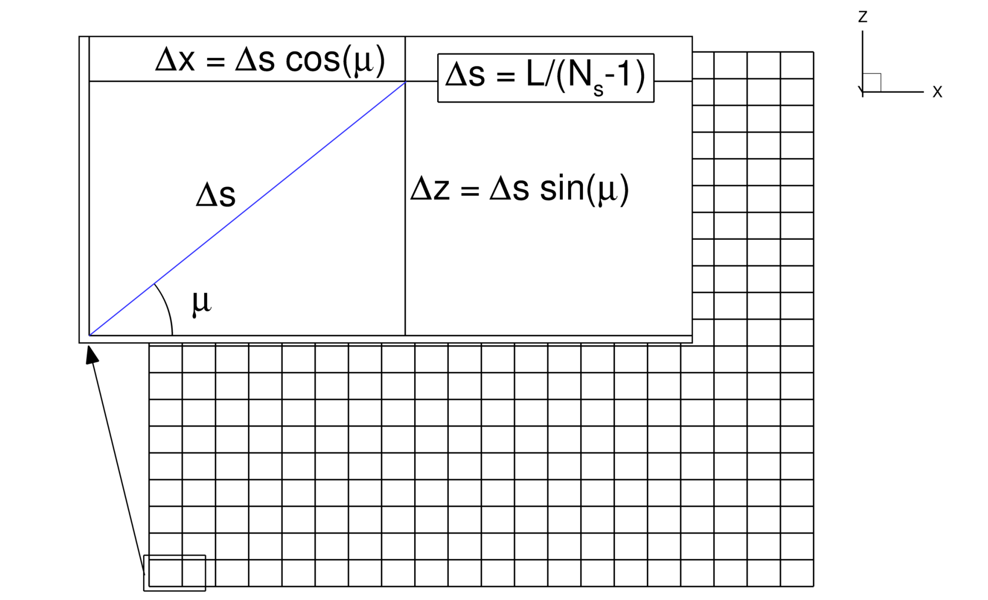
Inspired by Siclari and Darden
AIAA-1990-4000

- Standalone grid generation code with limited input parameters
- Generates *O*(10)-*O*(100) million grid point meshes in seconds on a workstation

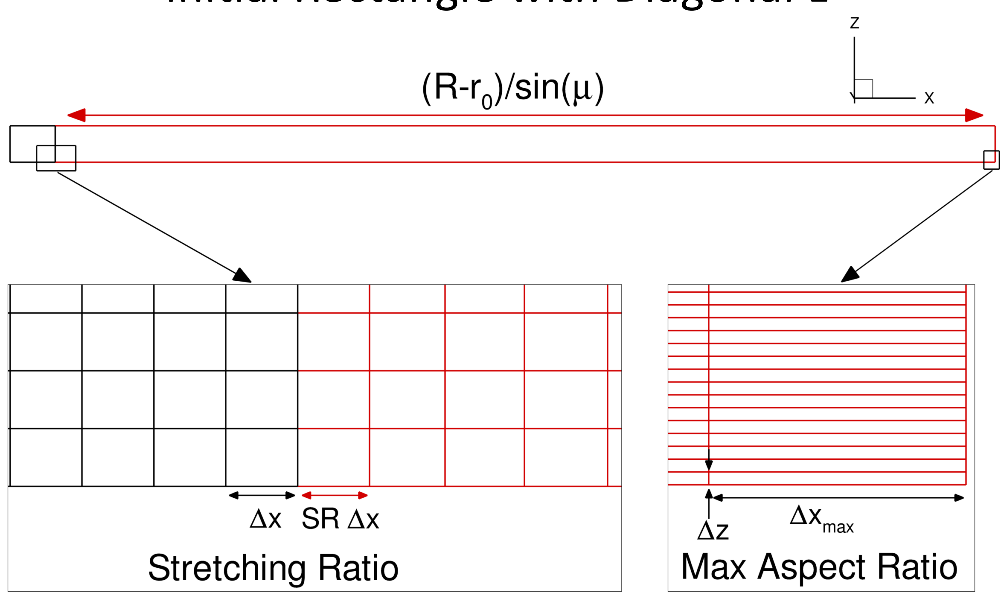
Mach-cone Aligned Space Marching Grid

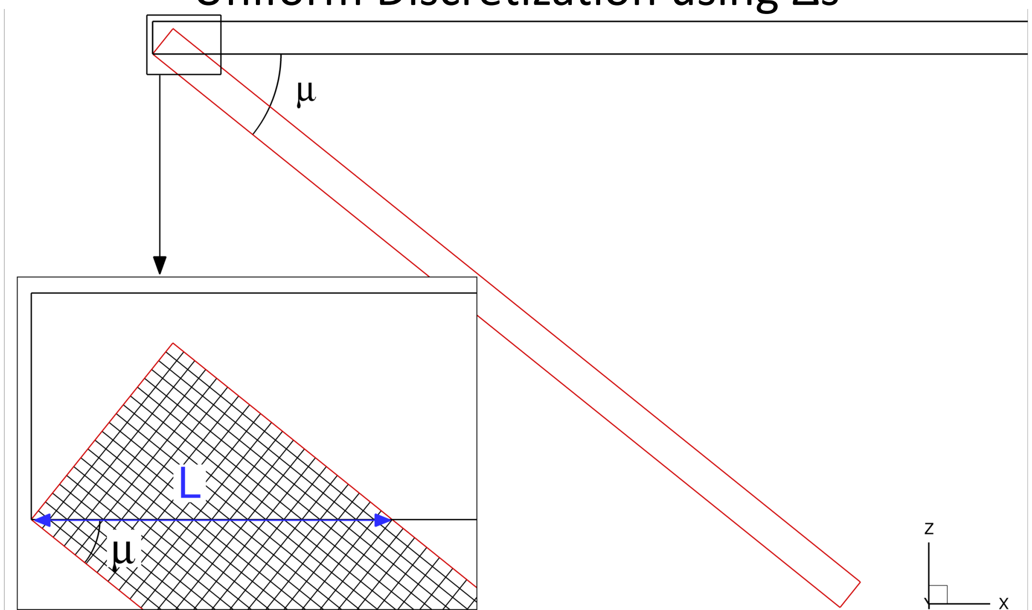


Initial Rectangle with Diagonal L



Uniform Discretization using Δs

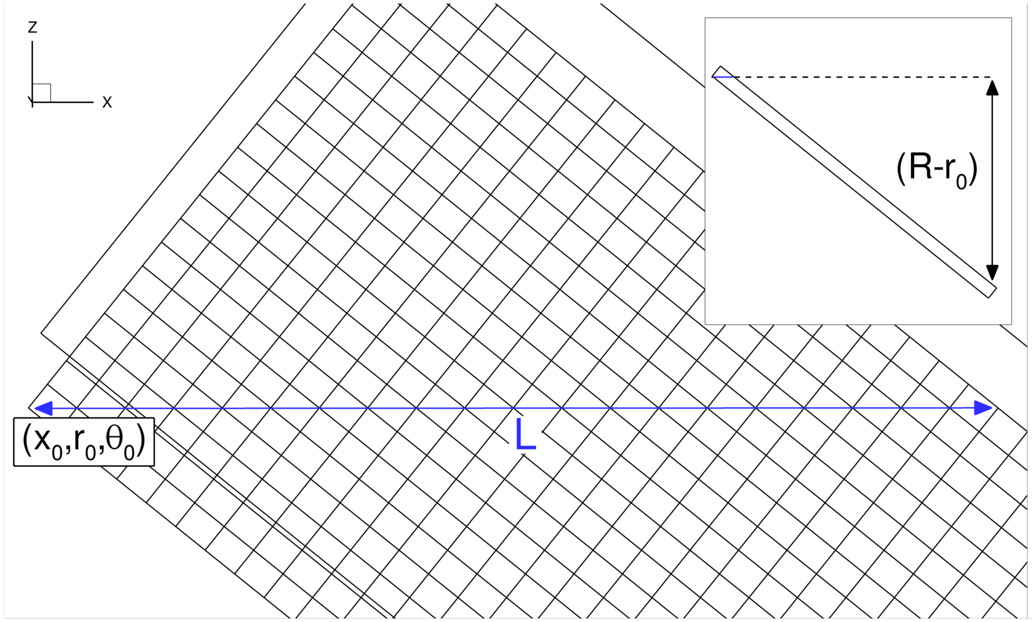




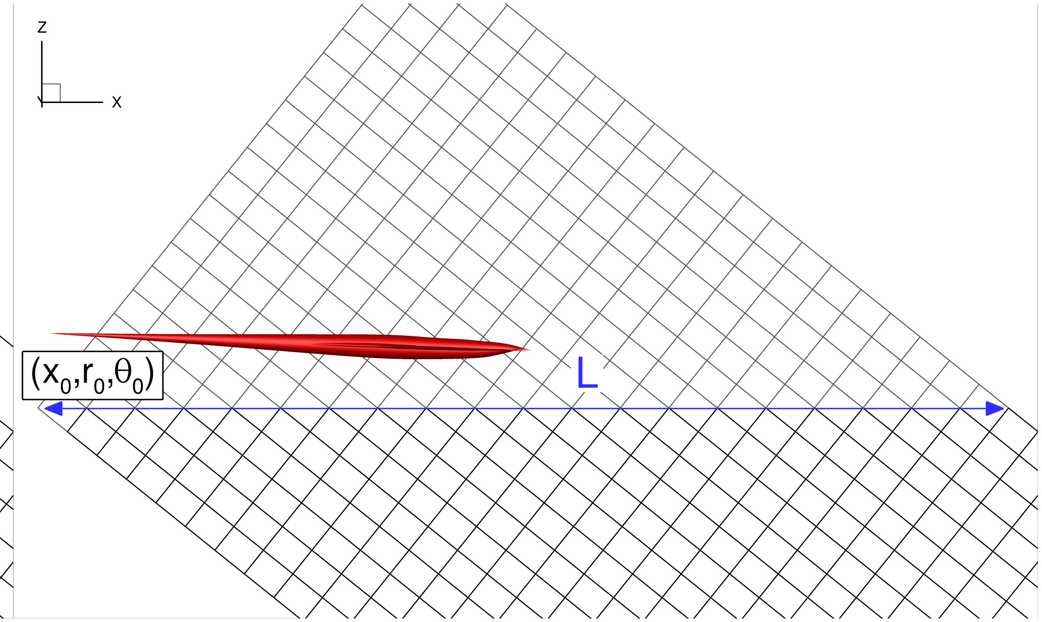
Extend using SR and AR_{max}

Rotate using Mach-cone angle

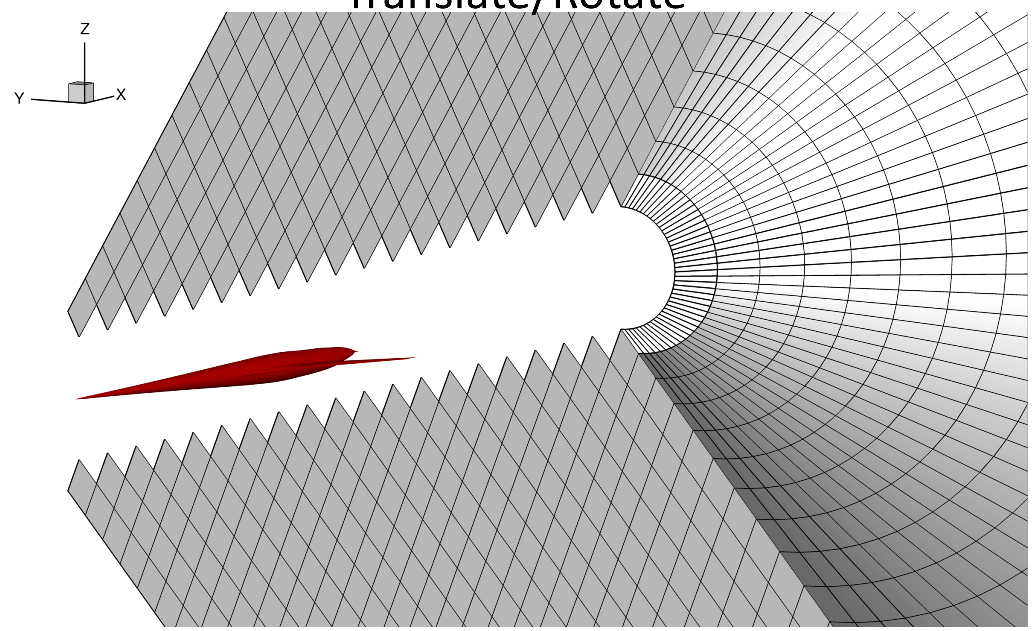
Mach-cone Aligned Space Marching Grid



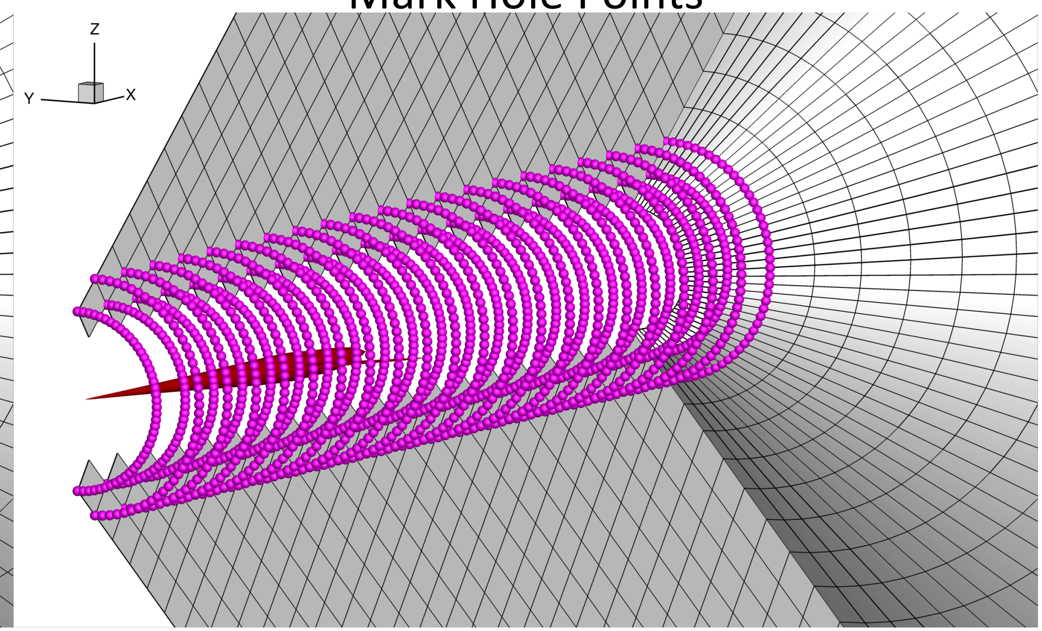
Translate/Rotate



Mark Hole Points



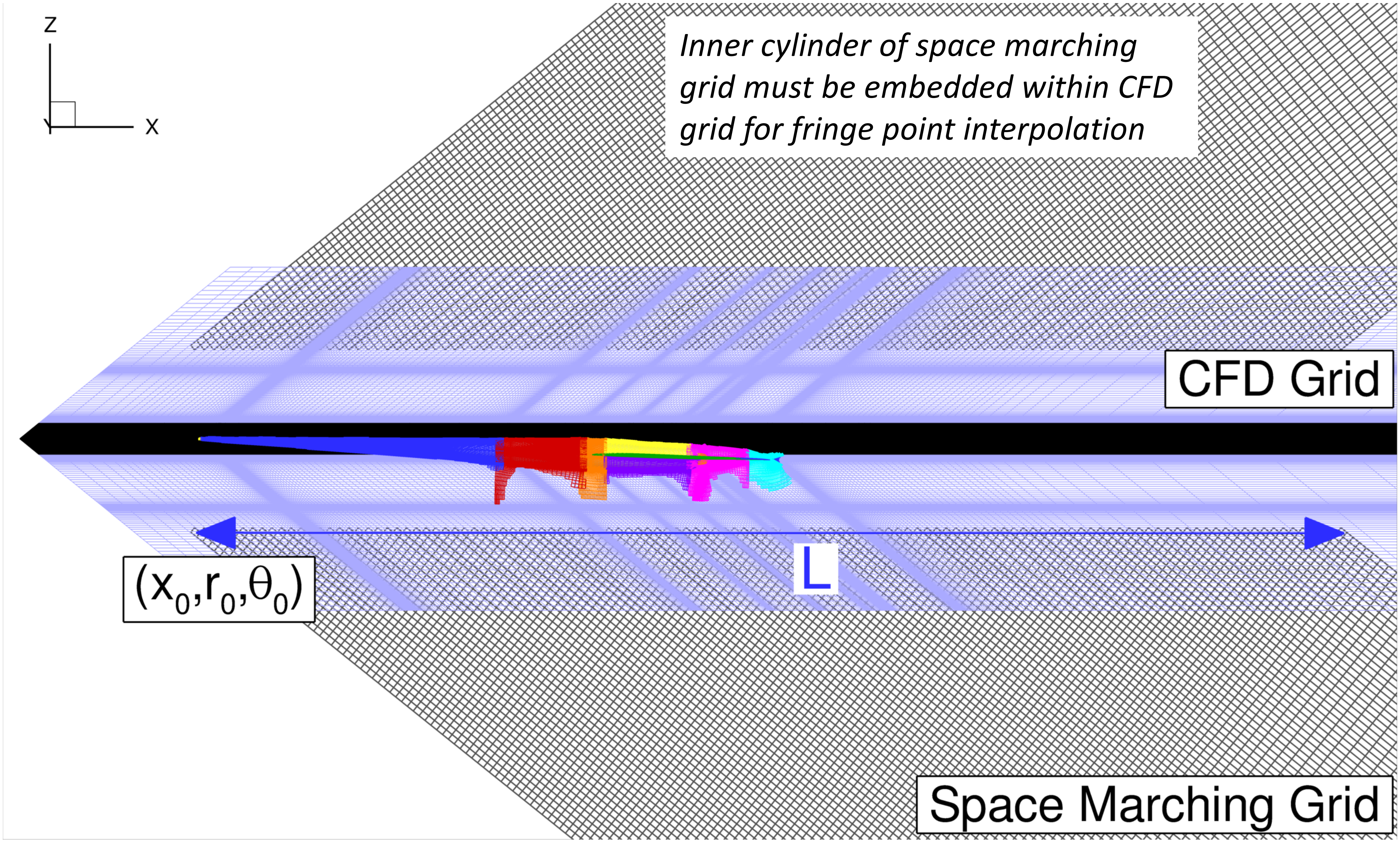
Revolve from θ_0 to θ_{max}



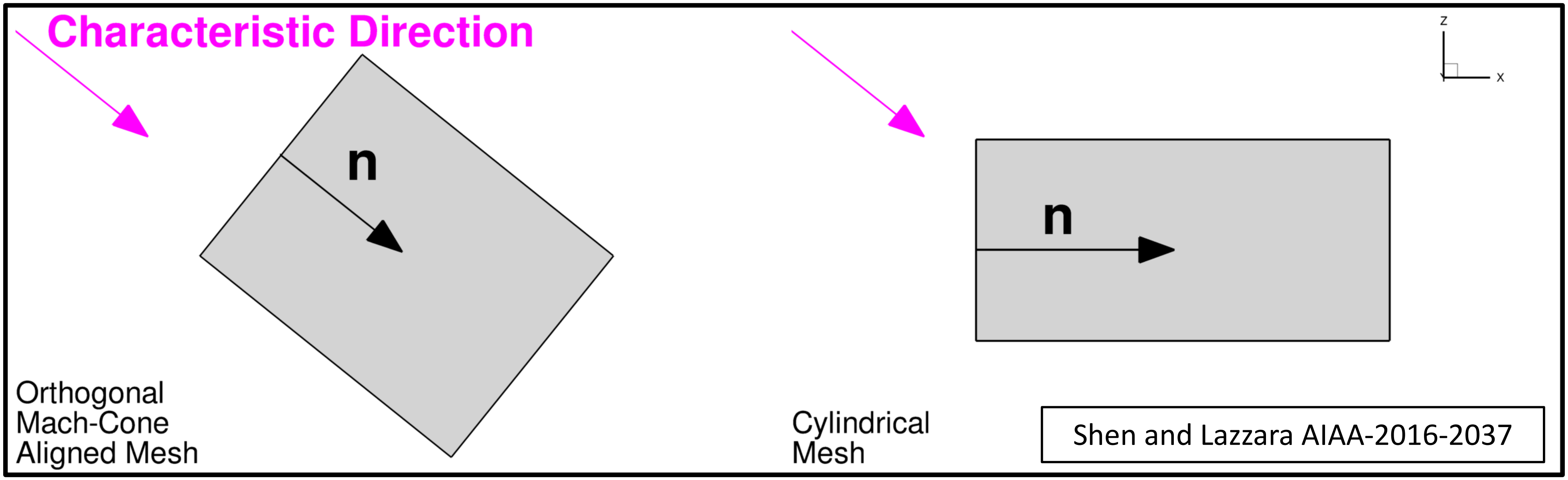
Mark Fringe

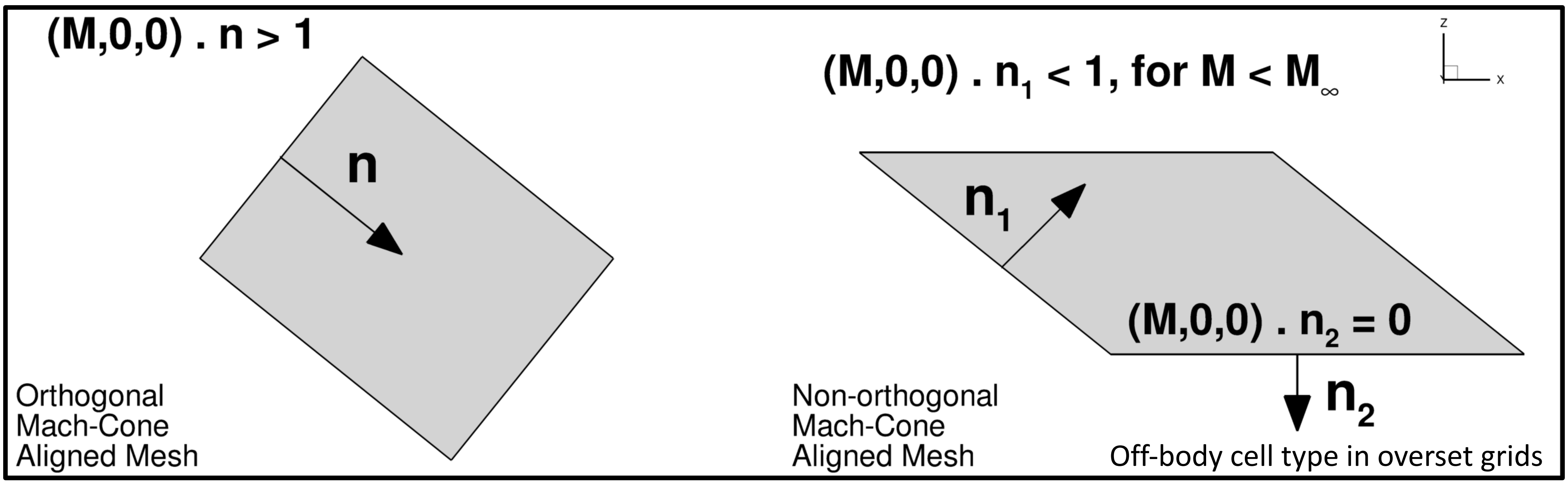
Mach-cone Aligned Space Marching Grid

Symmetry plane view of space marching grid and CFD grid



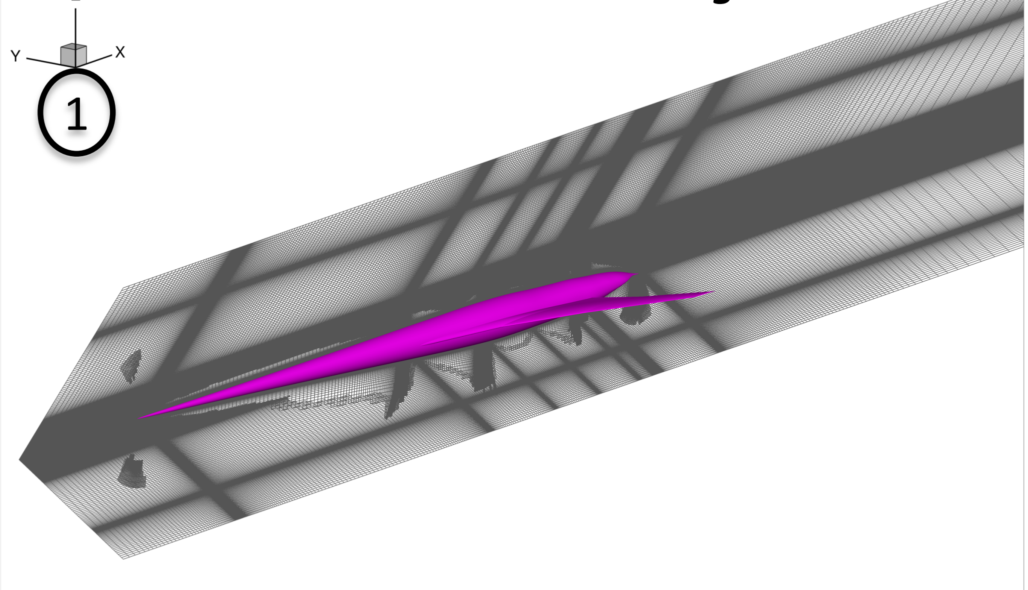
Mach-cone Aligned Space Marching Grid



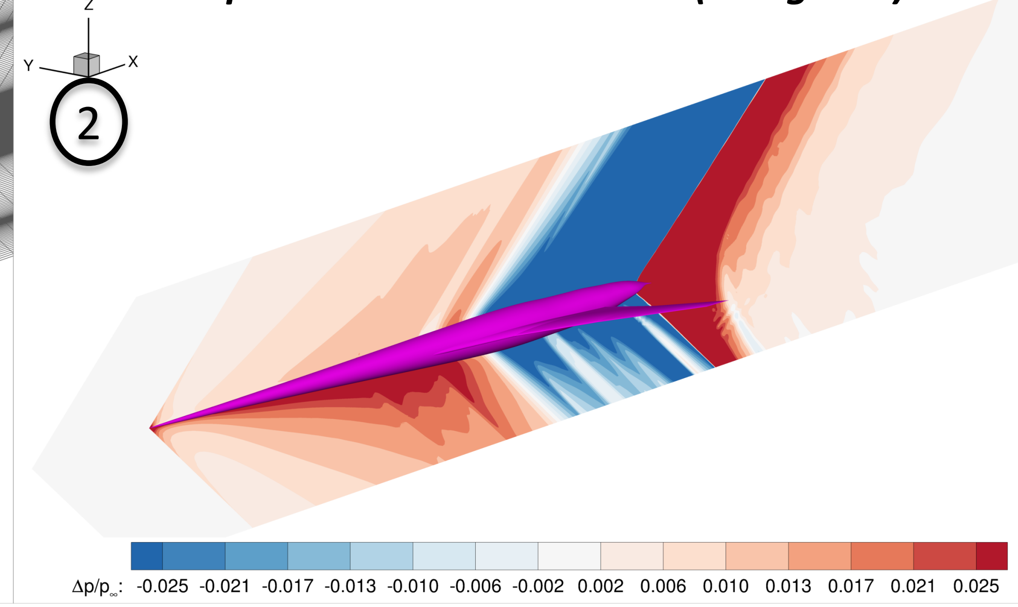


Near-Field to Mid-Field Procedure

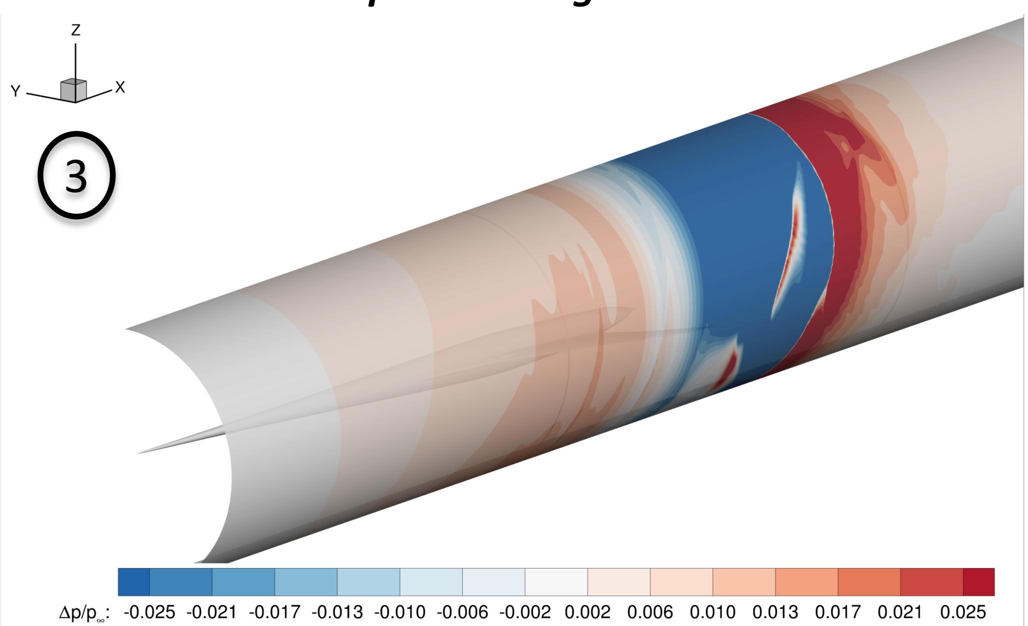
Generate Near-Field CFD grid



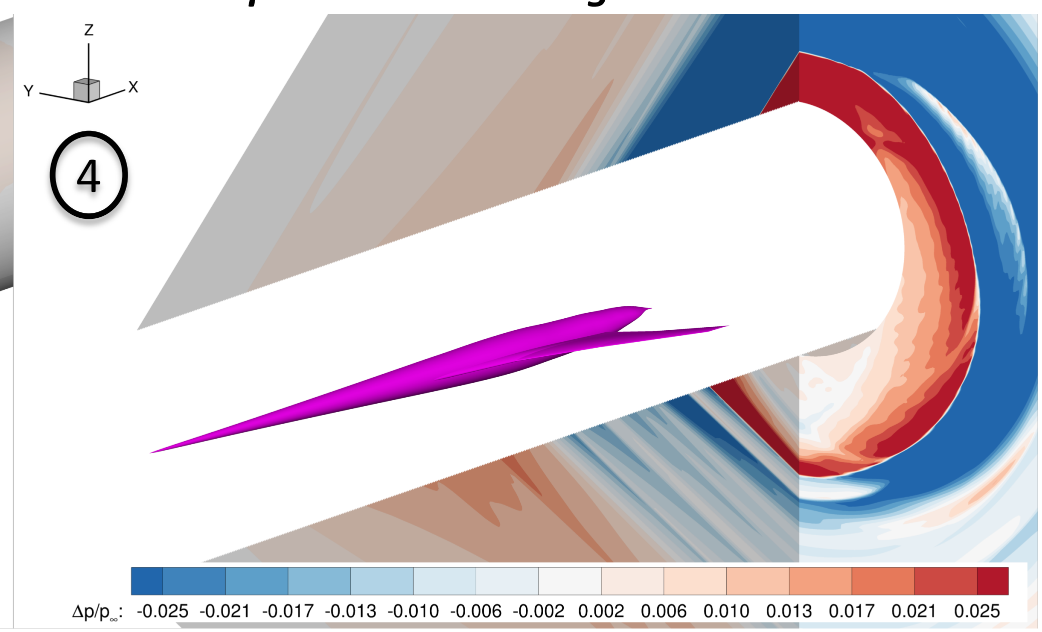
Compute Near-Field Solution (using CFD)



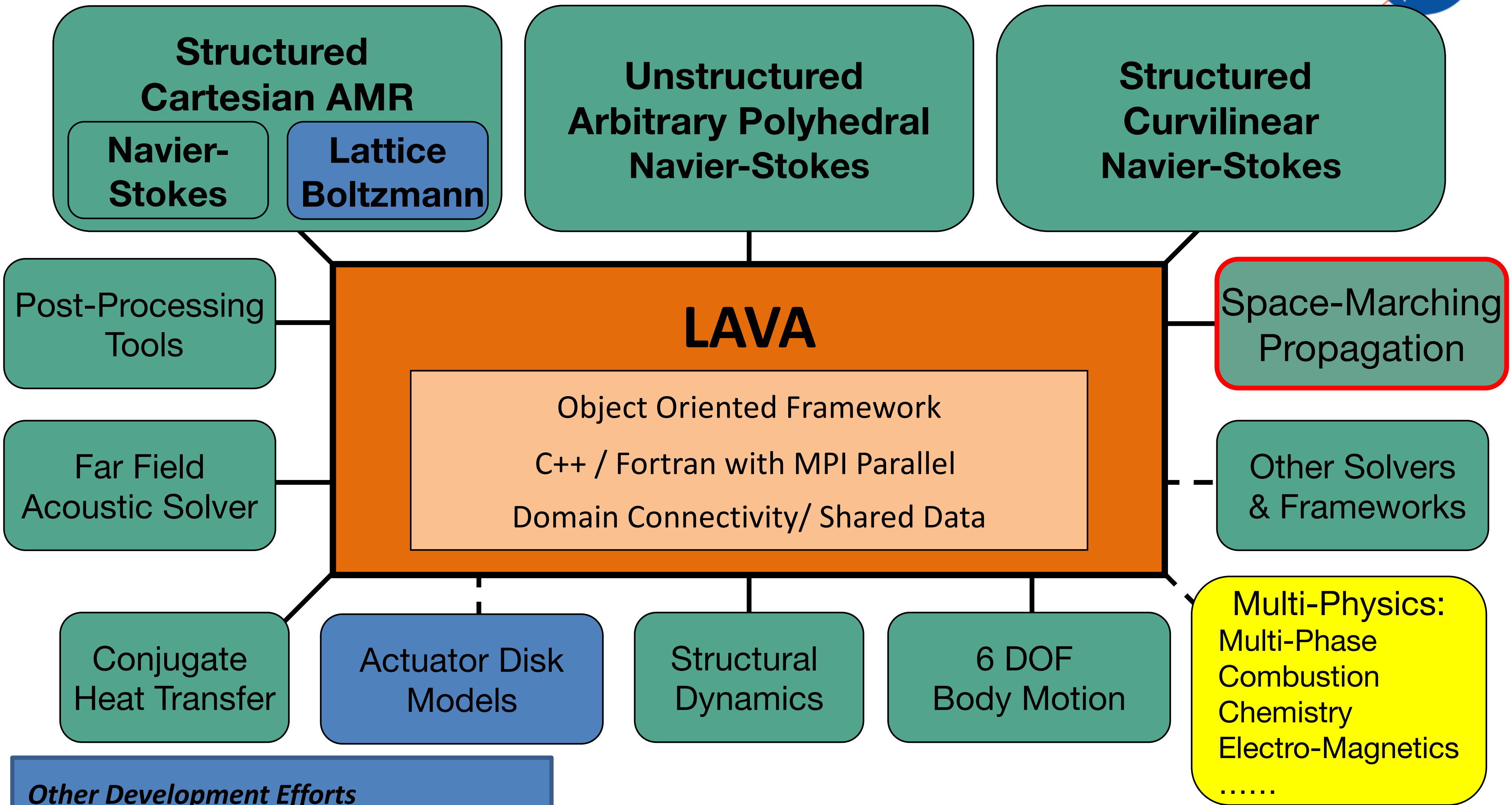
Interpolate Fringe Points



Space March through Mid-Field



LAVA Framework



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

—— Connected

- - - Not Yet Connected

Existing | Developing | Future | Framework

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, BDF2OPT, BDF3)
- High-order Hybrid Weighted Compact Nonlinear Scheme (HWCNS) is used in the other two coordinate directions
  - Interface (half-point) fluxes are evaluated with modified Roe
  - Left/Right interface states use 3rd or 5th order WENO interpolation
  - 4th order centered finite difference using a combination of fluxes at the grid points and the half-points used for flux derivative
- Identical finite-difference operators (BDF2 and HWCNS) 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

See paper for details

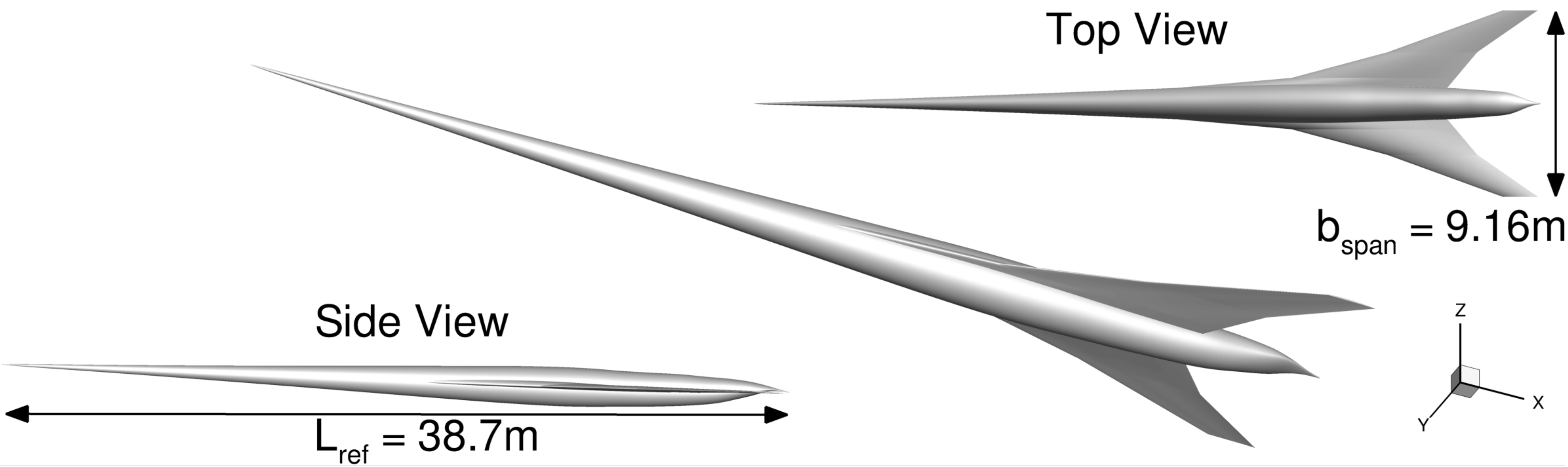
Computational Results

- **JAXA Wing Body**
  - Sensitivity Studies: (see paper for all sensitivity studies)
    - Mach cone perturbation angle
    - Stretching ratio
    - Maximum aspect ratio
    - Streamwise resolution
    - Circumferential resolution
    - Circumferential extent
    - Metric term evaluation
    - Convective flux discretization
    - Nonlinear convergence tolerance
  - Azimuthal Dependence of Nonlinear Wave Propagation
    - Near-Field to Mid-Field
    - Mid-Field to Ground
- **Low Boom Aircraft Wind Tunnel Model**
  - Space Marching Grid and Solution
  - Wind Tunnel Comparison

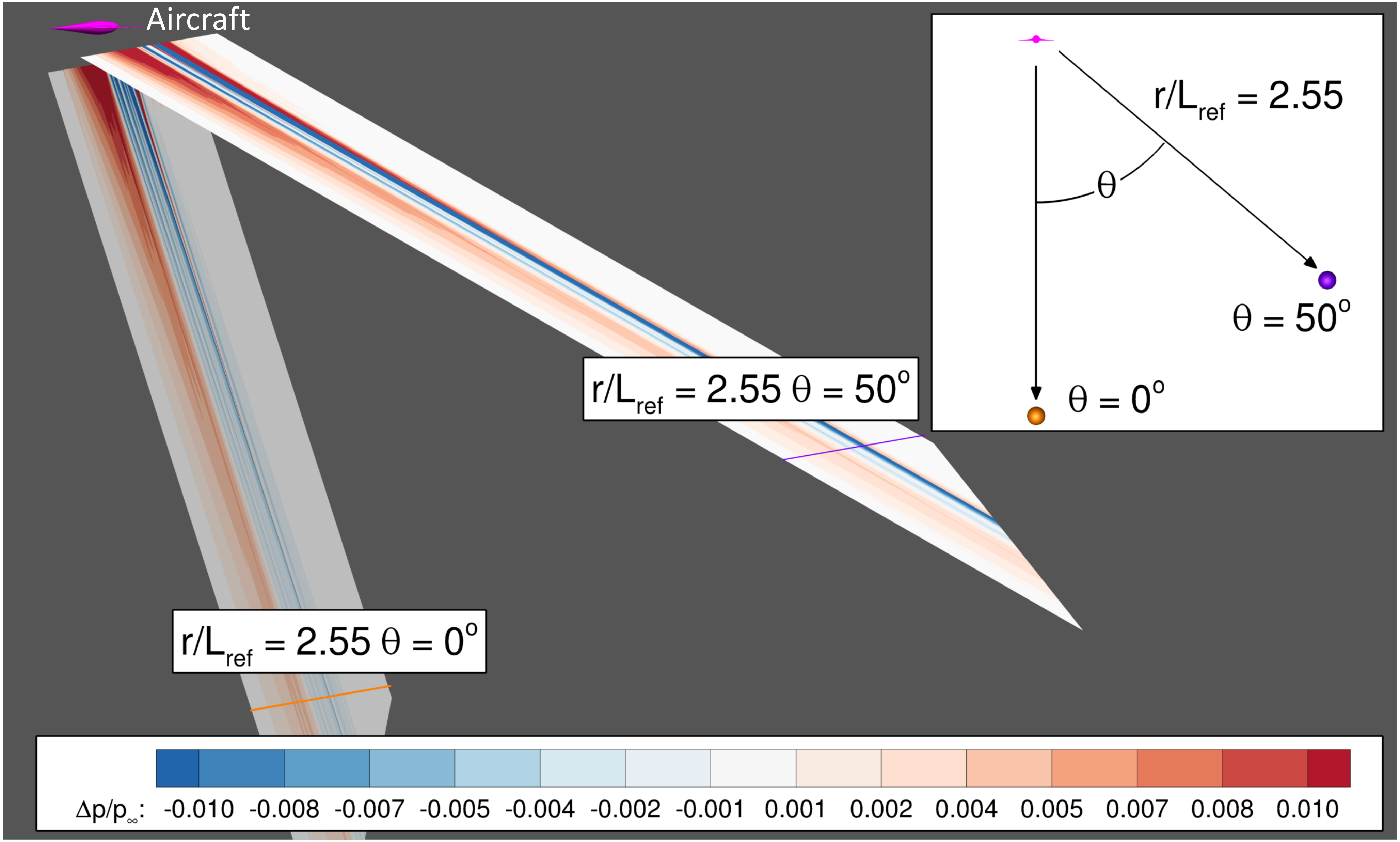
JAXA Wing Body

JAXA Wing Body (JWB) configuration from 2nd AIAA Sonic Boom Workshop (SBPW2)

- Designed to achieve low boom levels
- Reference length: L_{ref} = 38.7 m
- Mach = 1.6, Re/m = 5.7 million, and $\alpha = 2.3^o$
- Near-field CFD results using LAVA reported at SBPW2

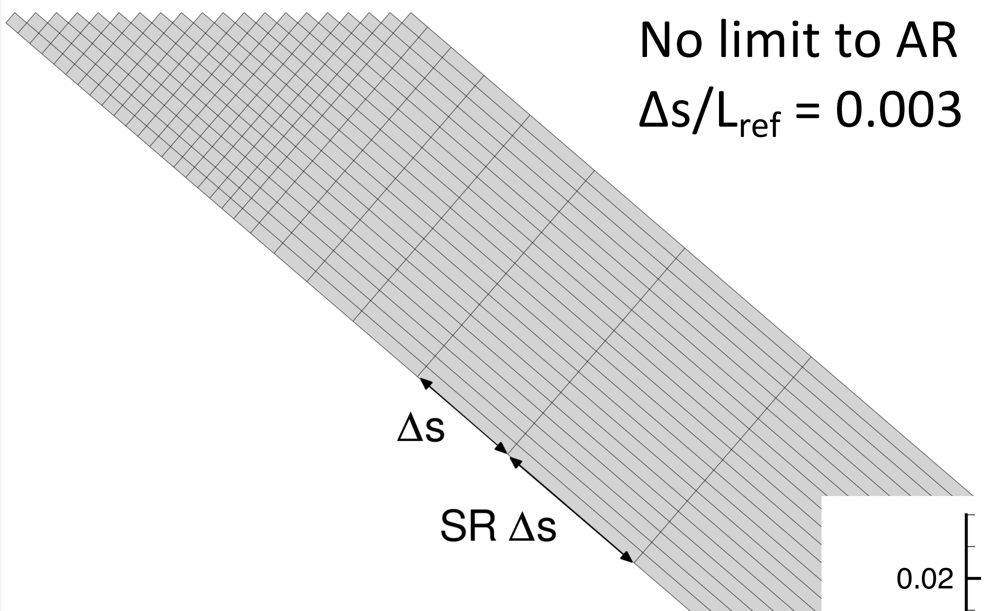


JWB Extraction Locations



Sensitivity Study: Stretching Ratio

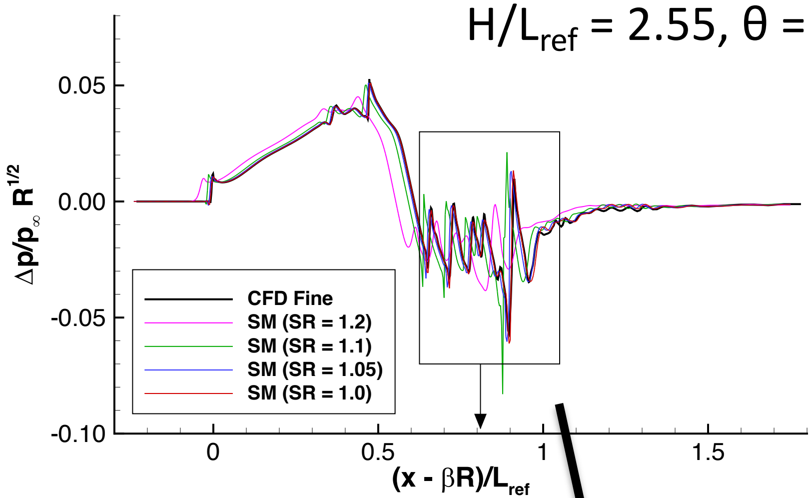
SR = 1.0, 1.05, 1.1, 1.2

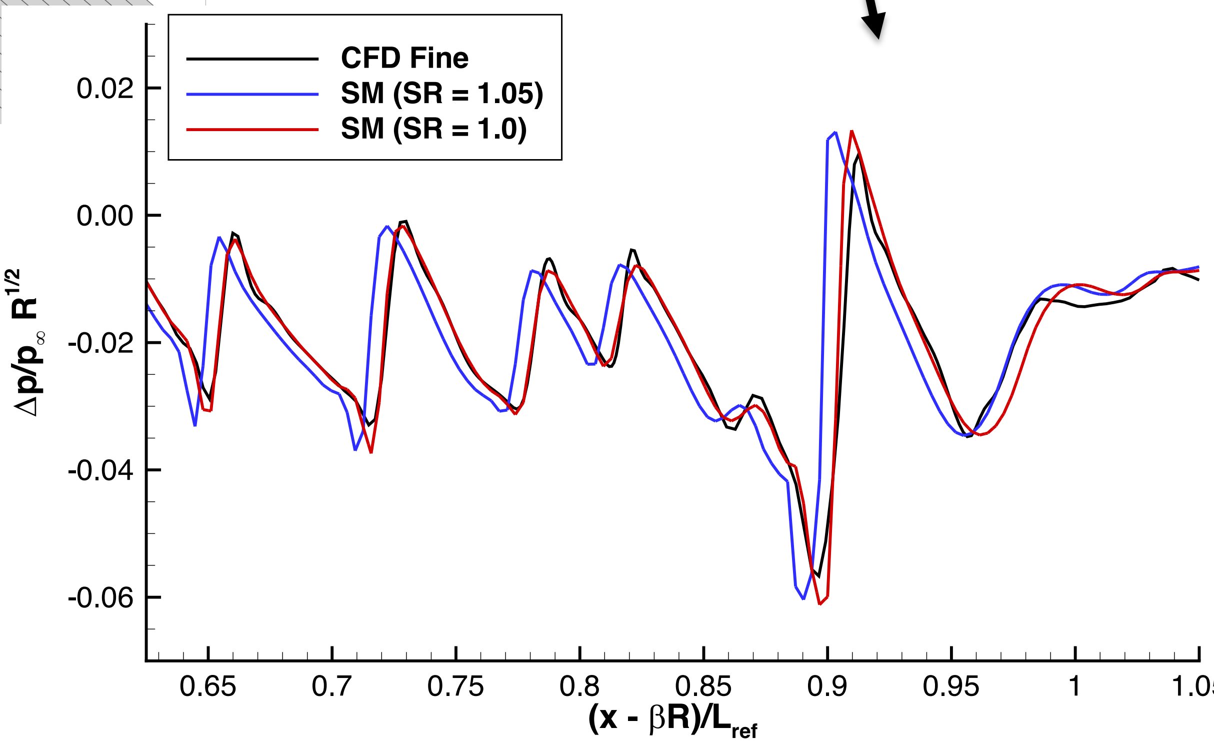


No limit to AR

$\Delta s/L_{ref} = 0.003$

$H/L_{ref} = 2.55$, $\theta = 0^{o}$





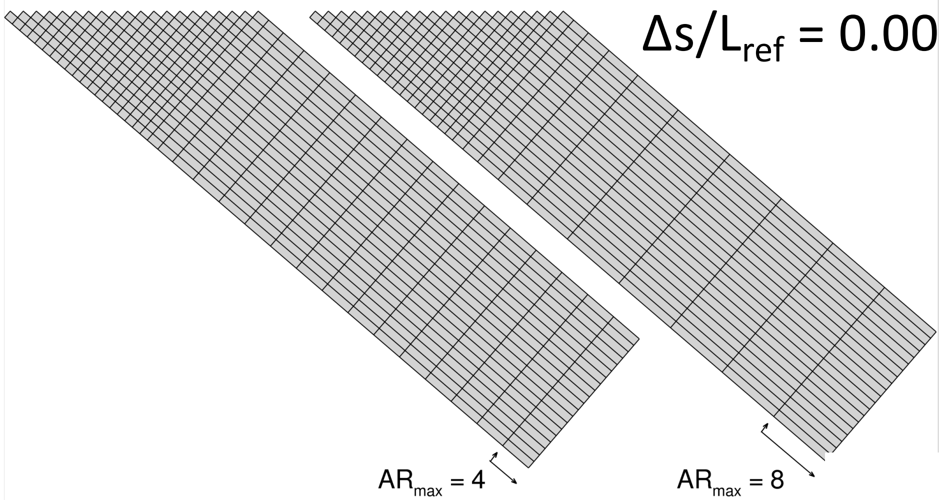
- Generated 4 space marching grids with varying stretching ratios in the space marching direction
- As the SR increases the ”effective phase error” in the extracted signature increases

Sensitivity Study: Max Aspect Ratio

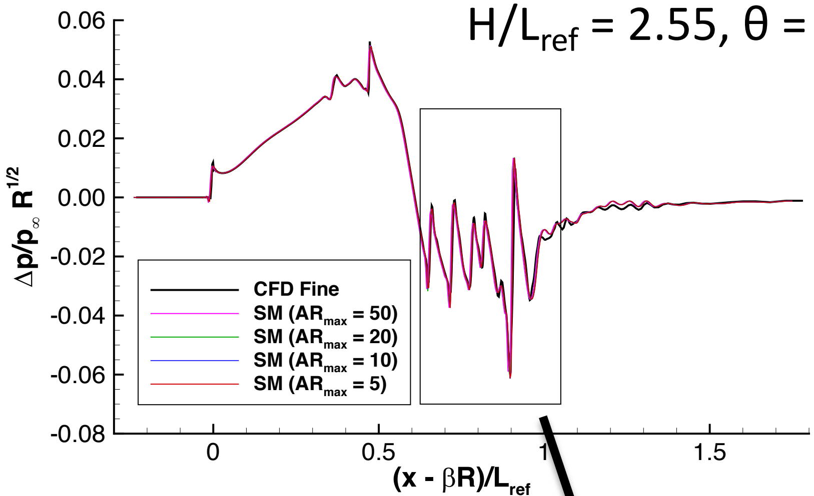
AR_{max} = 5, 10, 20, 50

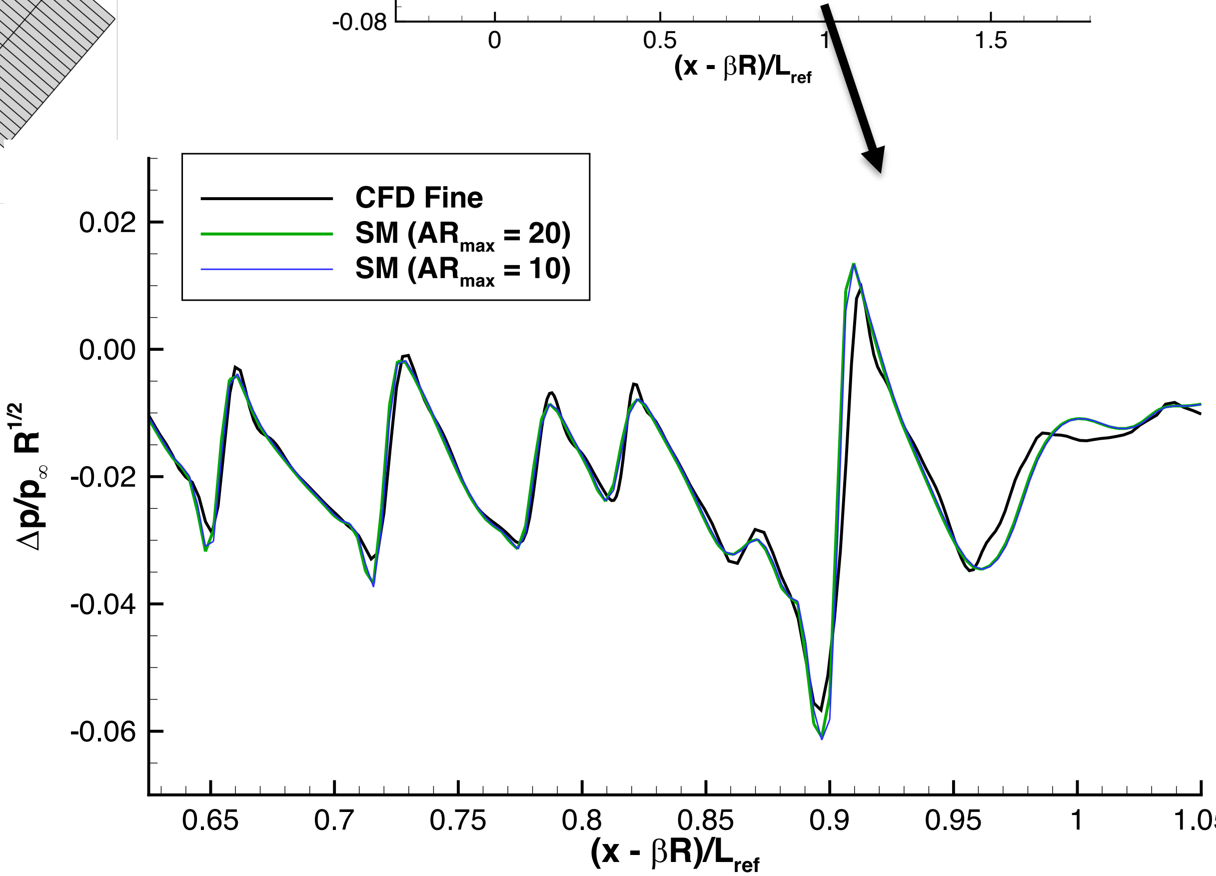
SR = 1.05

$\Delta s/L_{ref}$ = 0.003



H/L_{ref} = 2.55, θ = 0°

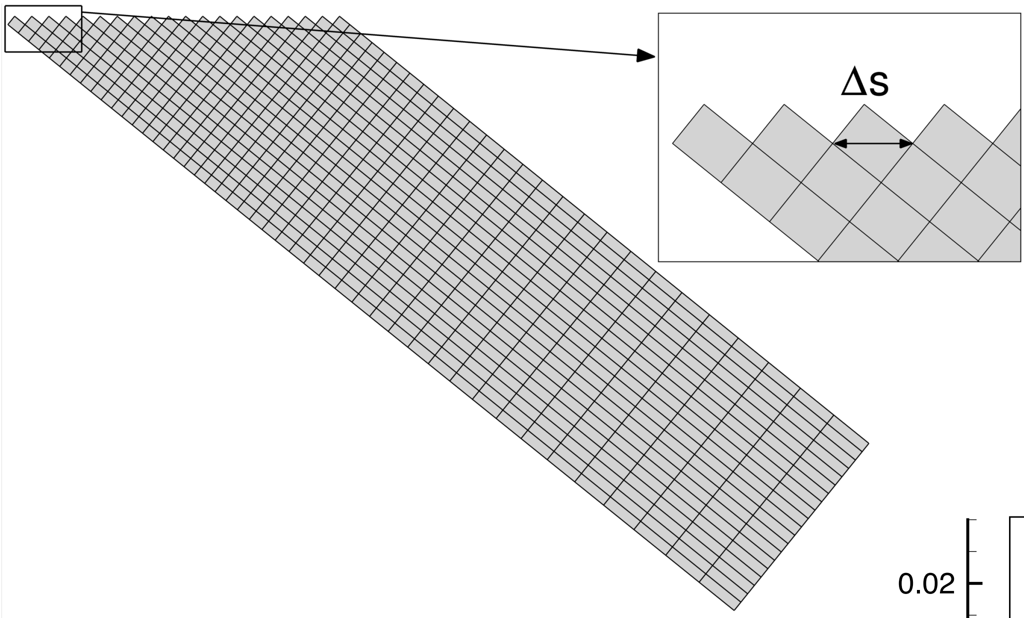




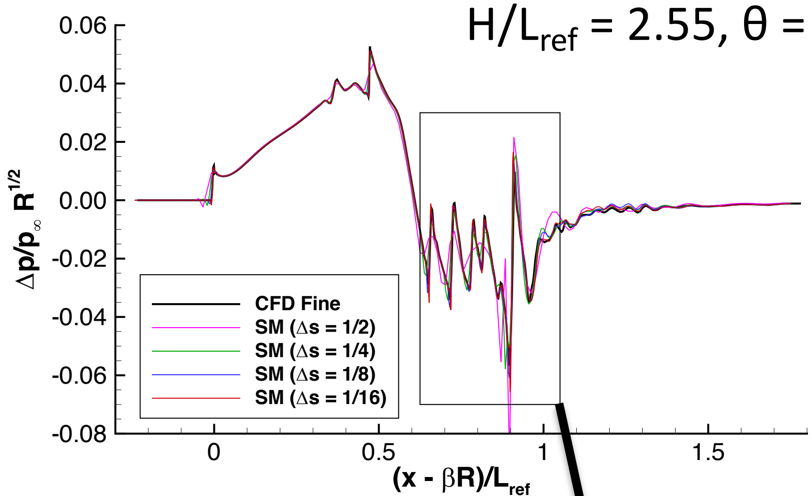
- Generated 4 space marching grids with varying maximum aspect ratio
- The effective phase error caused by SR can be controlled using AR_{max}
- AR_{max} = 20 appears sufficient at this resolution

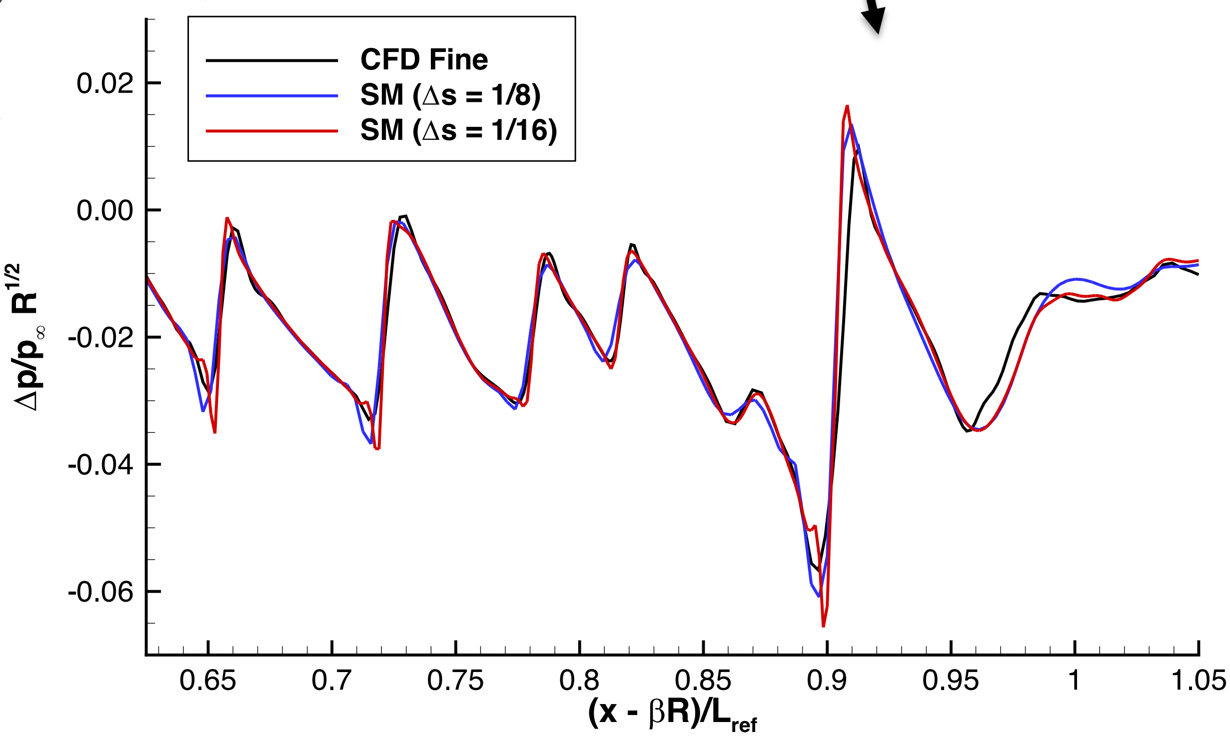
Sensitivity Study: Streamwise Spacing

$\Delta s/Lref$ = 0.012, 0.006, 0.003, 0.0015



$H/L_{ref} = 2.55, \theta = 0^o$

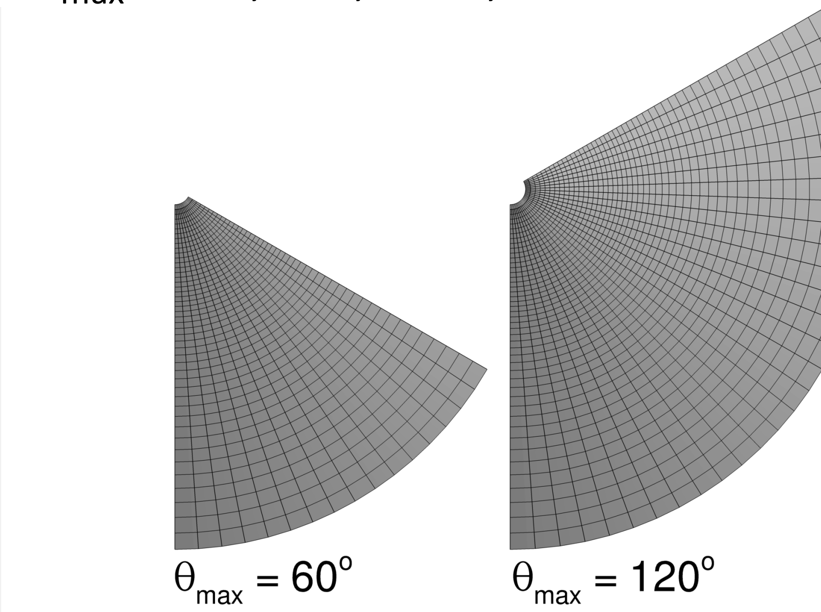


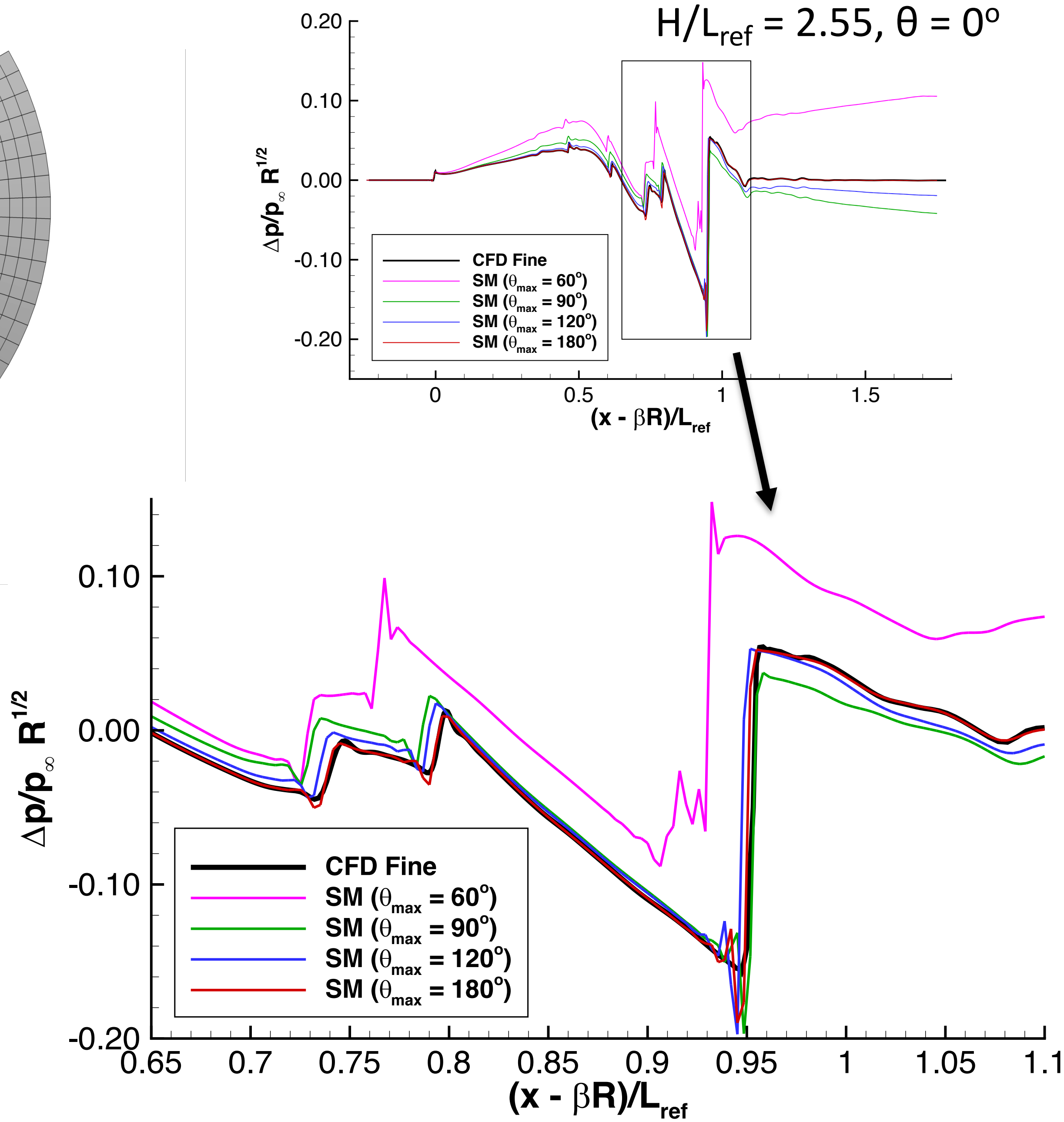


- Generated 4 space marching grids with uniformly refined streamwise spacing
- $\Delta s/Lref$ = 0.003 appears adequate
- Space marching solution converges towards CFD solution

Sensitivity Study: Circumferential Domain

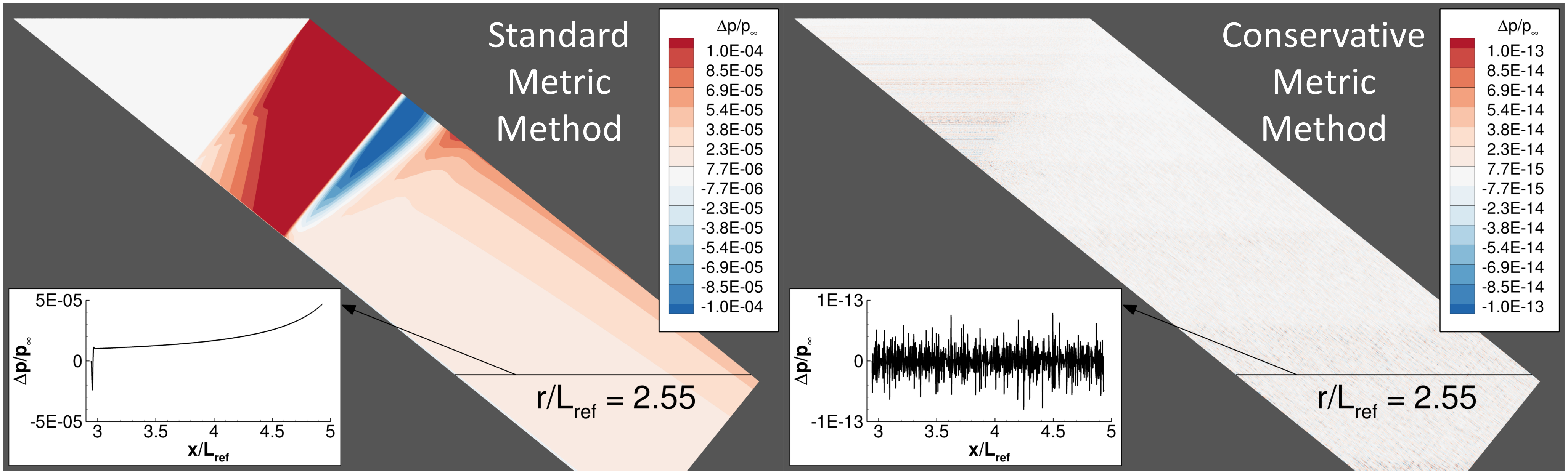
θ_{max} = 60°, 90°, 120°, 180°





- Generated 4 space marching grids with different maximum circumferential domains
- Azimuthal dependence near the aircraft is very large indicating θ_{max} = 180° is required (symmetric body)

Sensitivity Study: Metric Term Evaluation

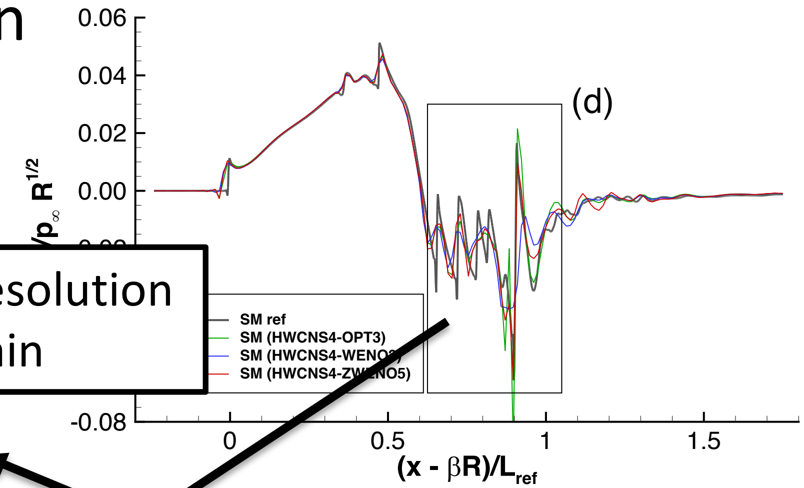


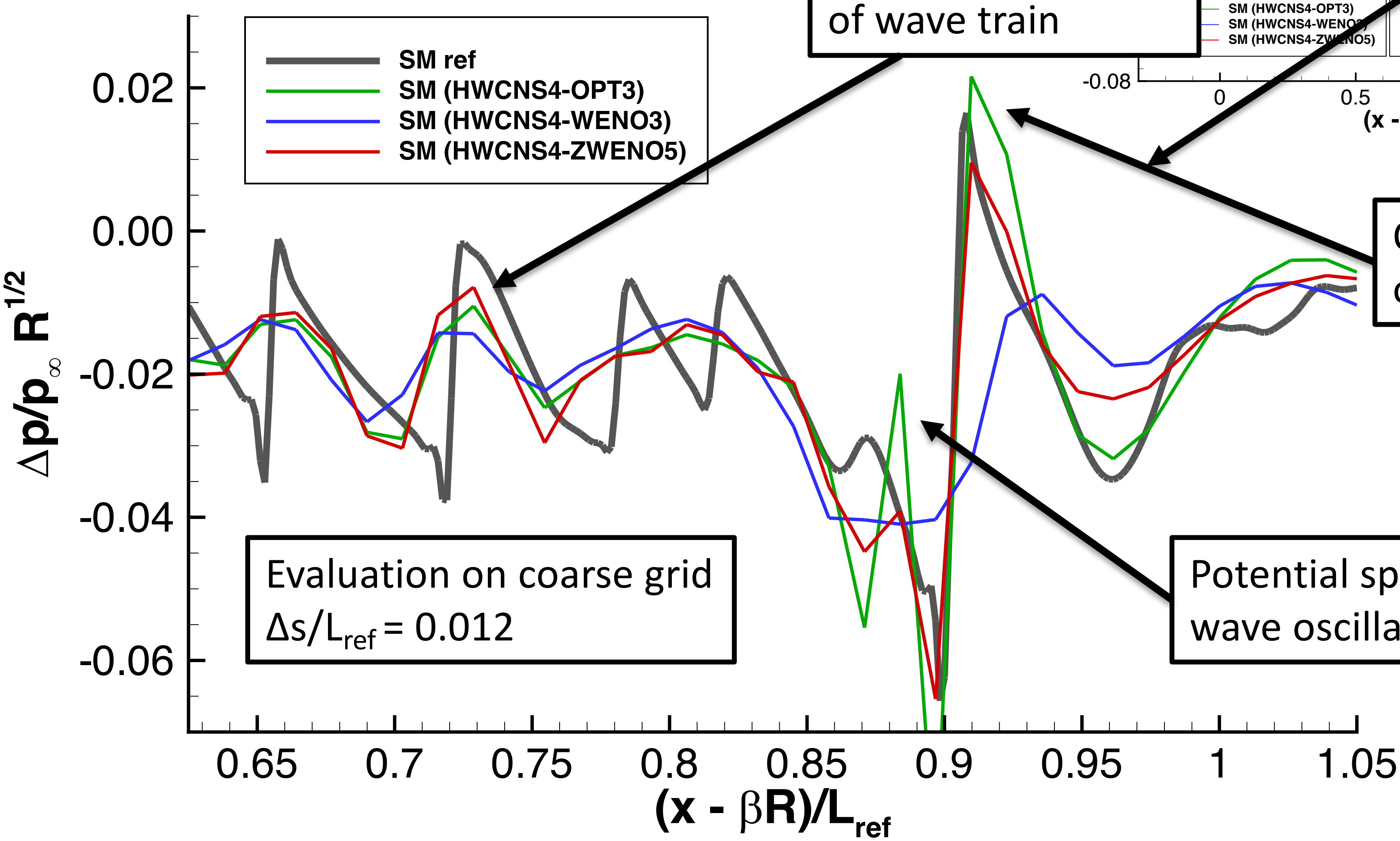
- Evaluation of free-stream conditions using the space marching procedure with standard second order metric terms (left) and the conservative metric method (right)
- Standard metric term evaluation leads to free-stream errors of $O(10^{-5})$ which do not decay with propagation distance
- The conservative metric method results in free-stream errors at machine precision level
- As the nonlinear wave propagates away from the aircraft the amplitude decays and can be overwhelmed by the free-stream error using the standard metric evaluation

Sensitivity Study: Convective Flux Discretization

Comparison of left/right state interpolation

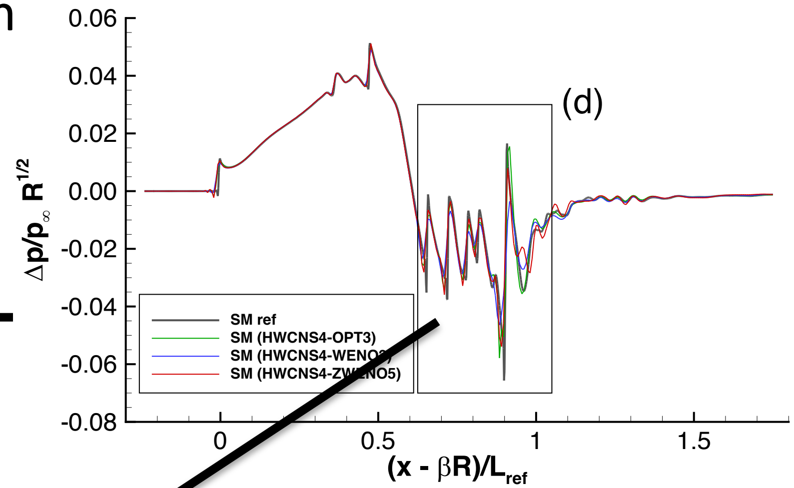
- OPT3 – 3rd order optimal weights
- WENO3 – standard 3rd order WENO
- ZWENO5 – optimized 5th order WENO

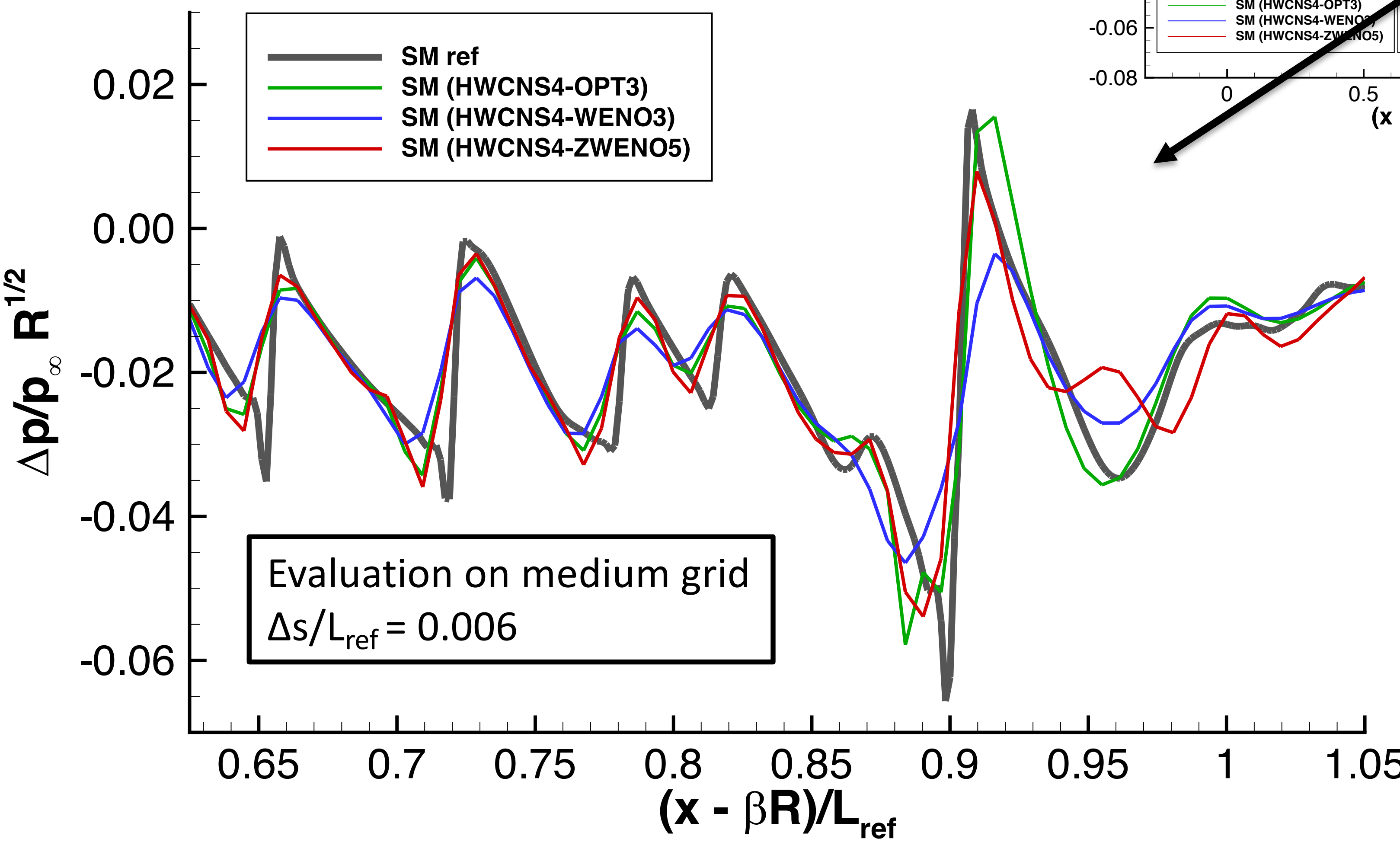




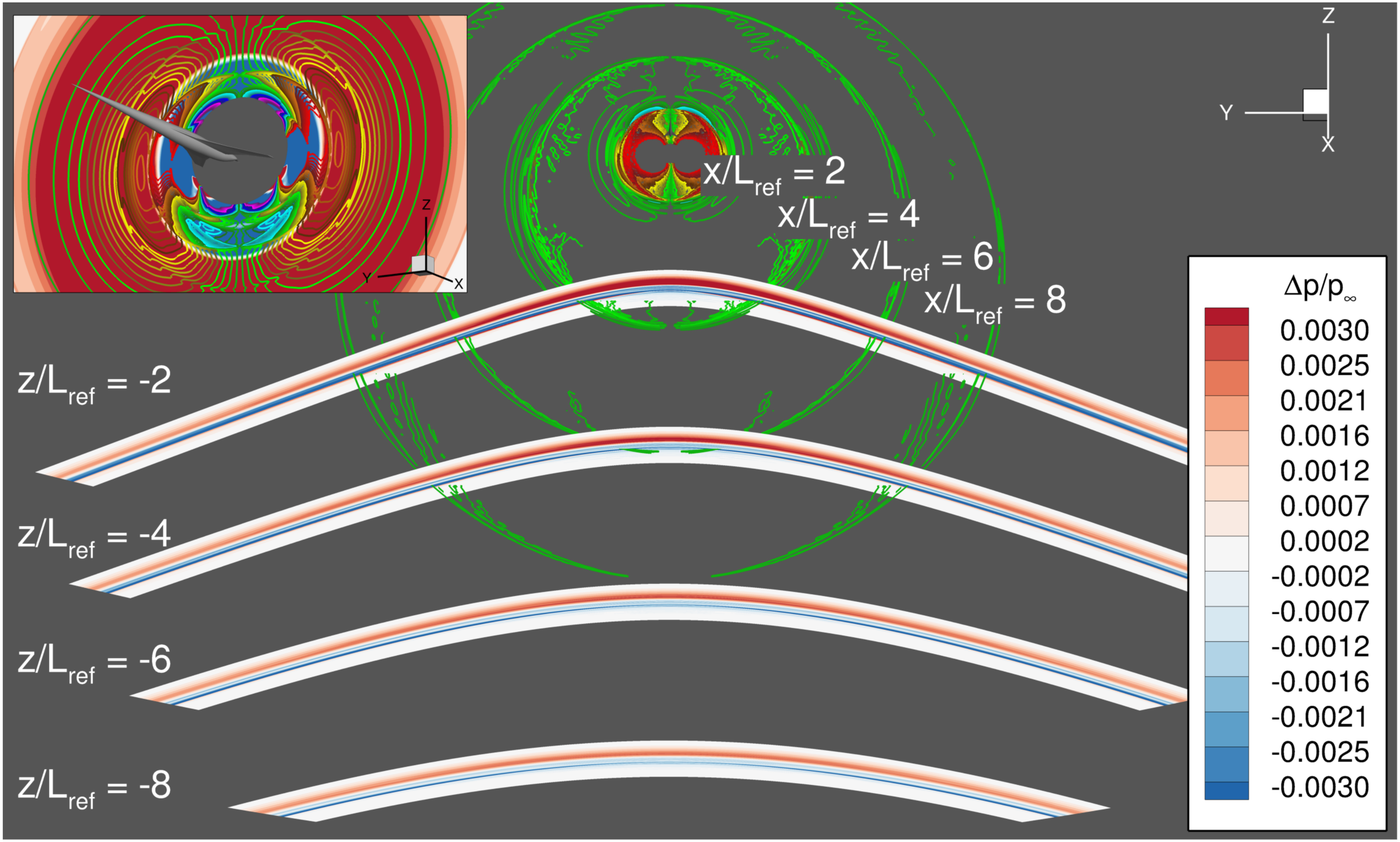
Sensitivity Study (Convective Flux Discretization)

- ZWENO5 interpolation shows superior resolution of the wave train upstream of the wing shock/expansion
- ZWENO5 has reduced spurious wave oscillations



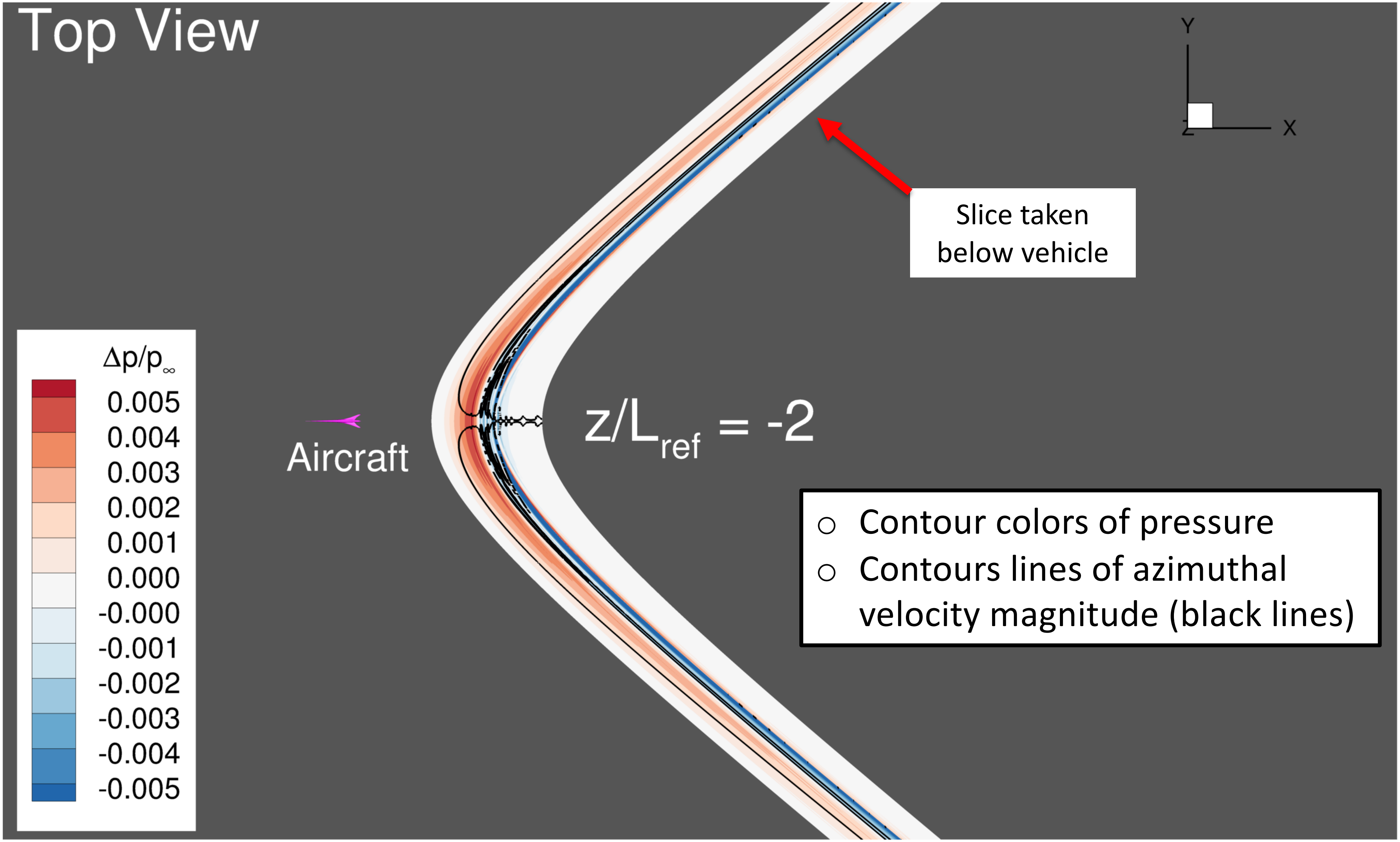


Azimuthal Dependence of Nonlinear Wave Propagation



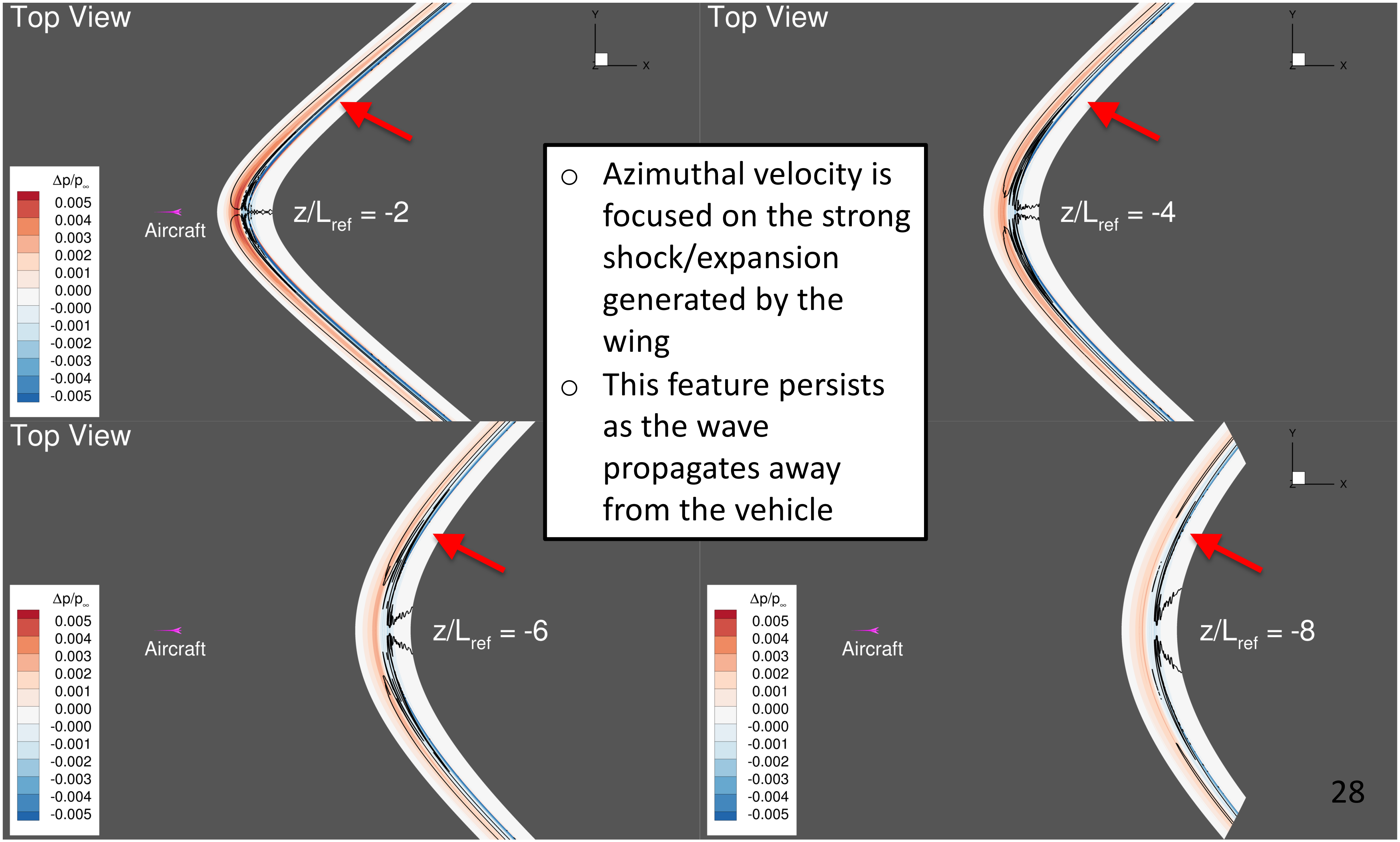
Contour lines of azimuthal velocity with elevation slices of pressure

Azimuthal Dependence of Nonlinear Wave Propagation



Azimuthal Dependence of Nonlinear Wave Propagation

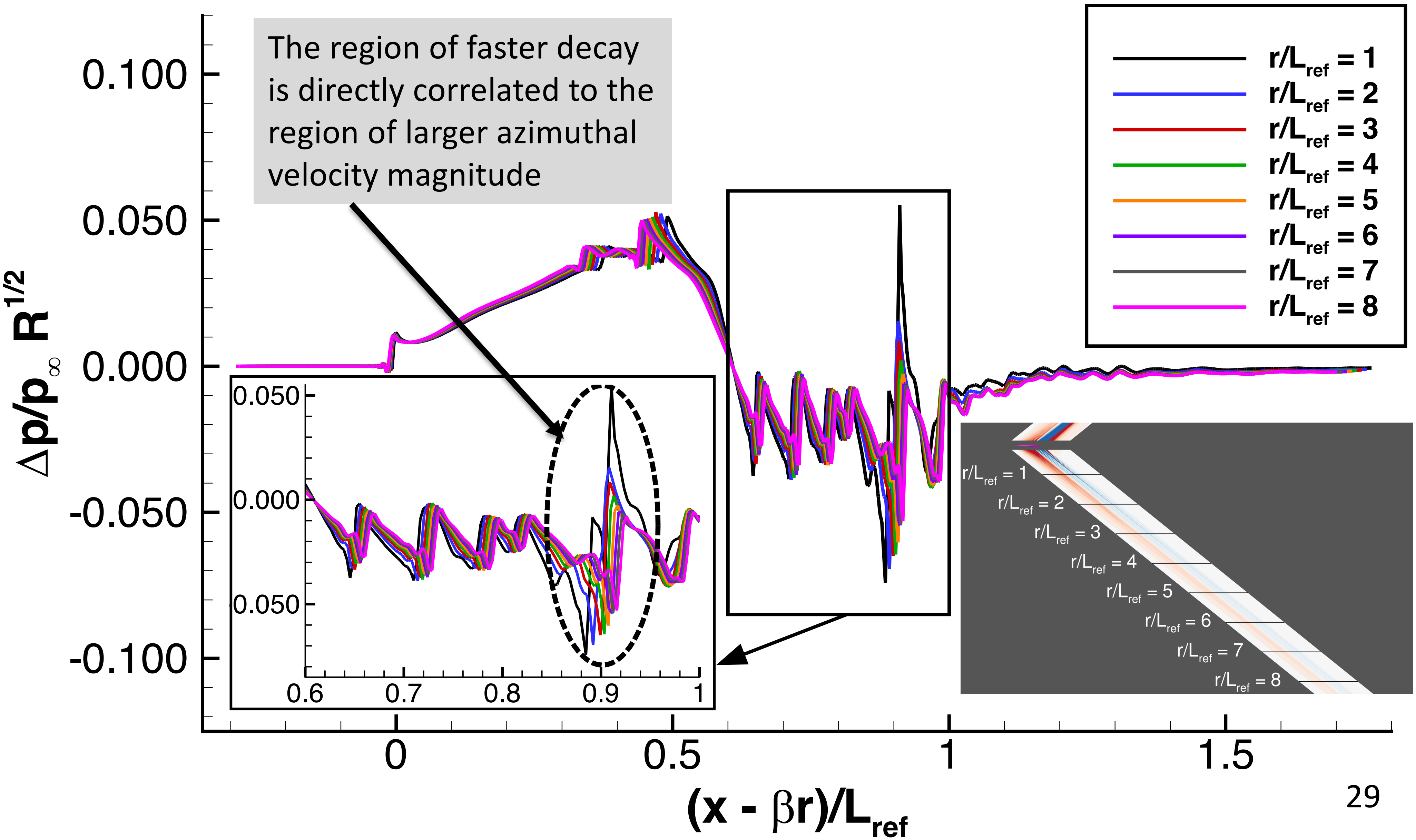
Pressure contour colors with contour lines of azimuthal velocity magnitude



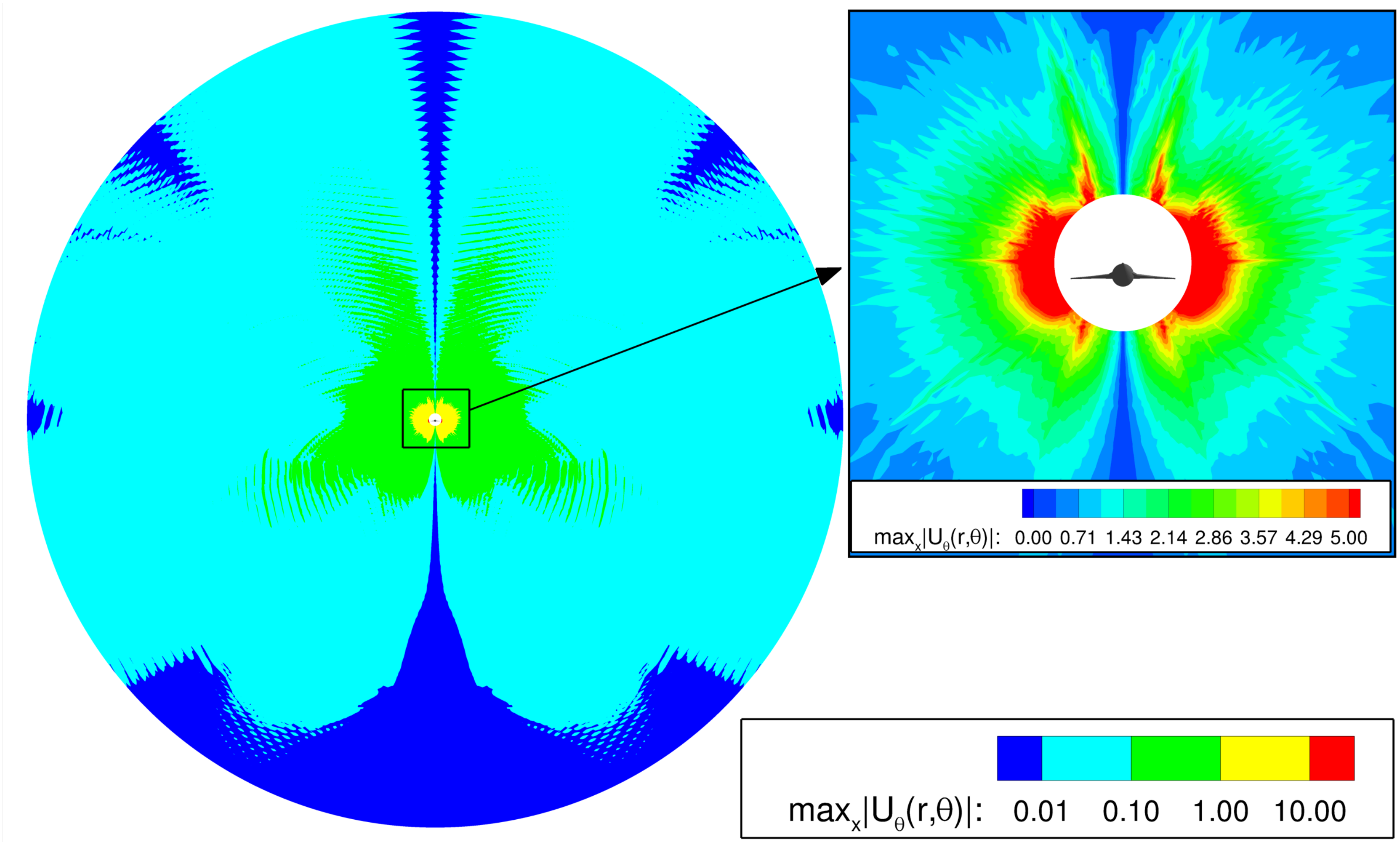
- Azimuthal velocity is focused on the strong shock/expansion generated by the wing
- This feature persists as the wave propagates away from the vehicle

Azimuthal Dependence: Near-Field to Mid-Field

Scaled pressure signatures extracted at 8 different radial locations below the aircraft



Azimuthal Dependence: Near-Field to Mid-Field

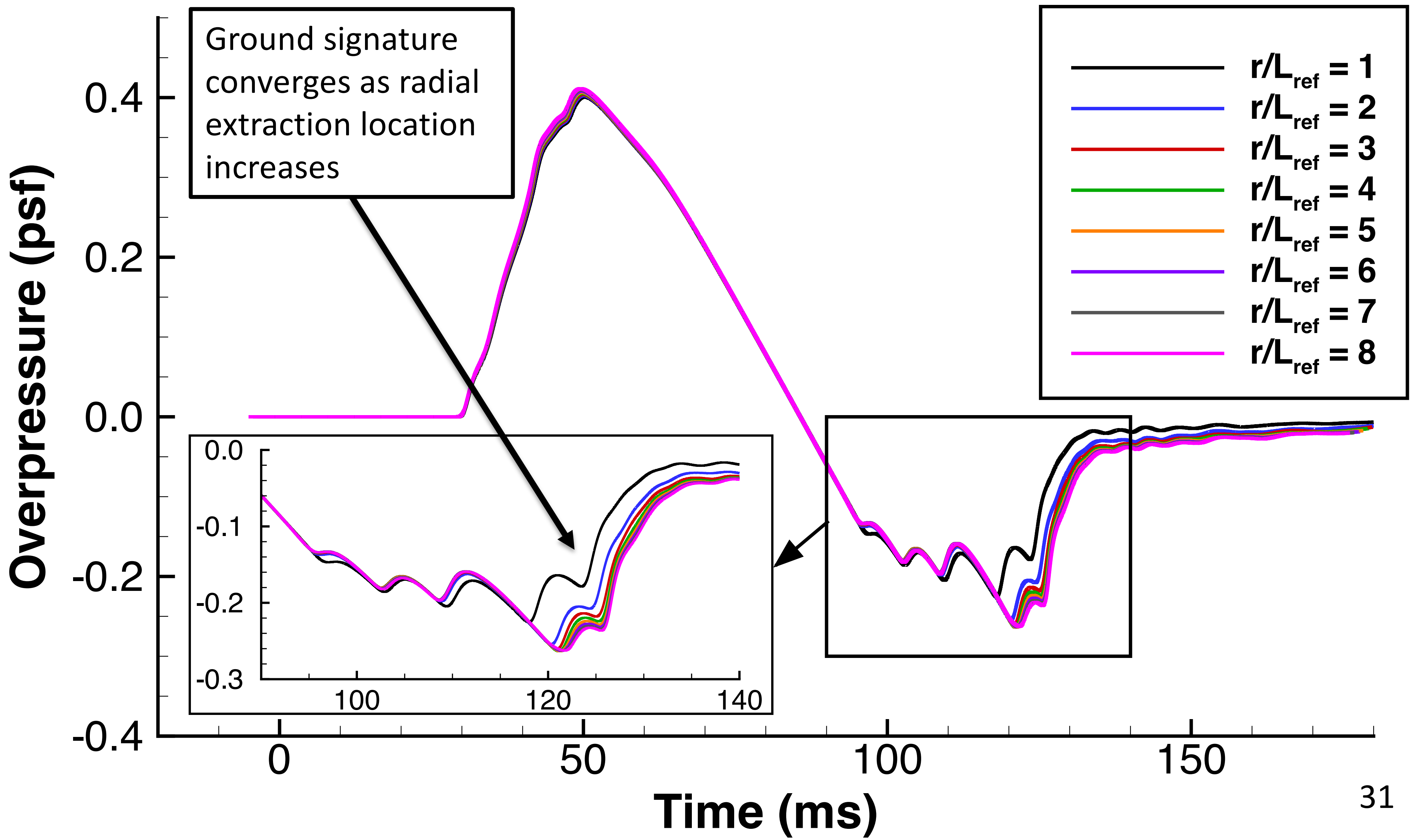


- Non-zero azimuthal velocity observed past 10 body lengths from aircraft showing large radial extent of azimuthal effects
- Dipole shape of azimuthal velocity field indicates lift as dominate mechanism
- Confirms earlier work by George

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

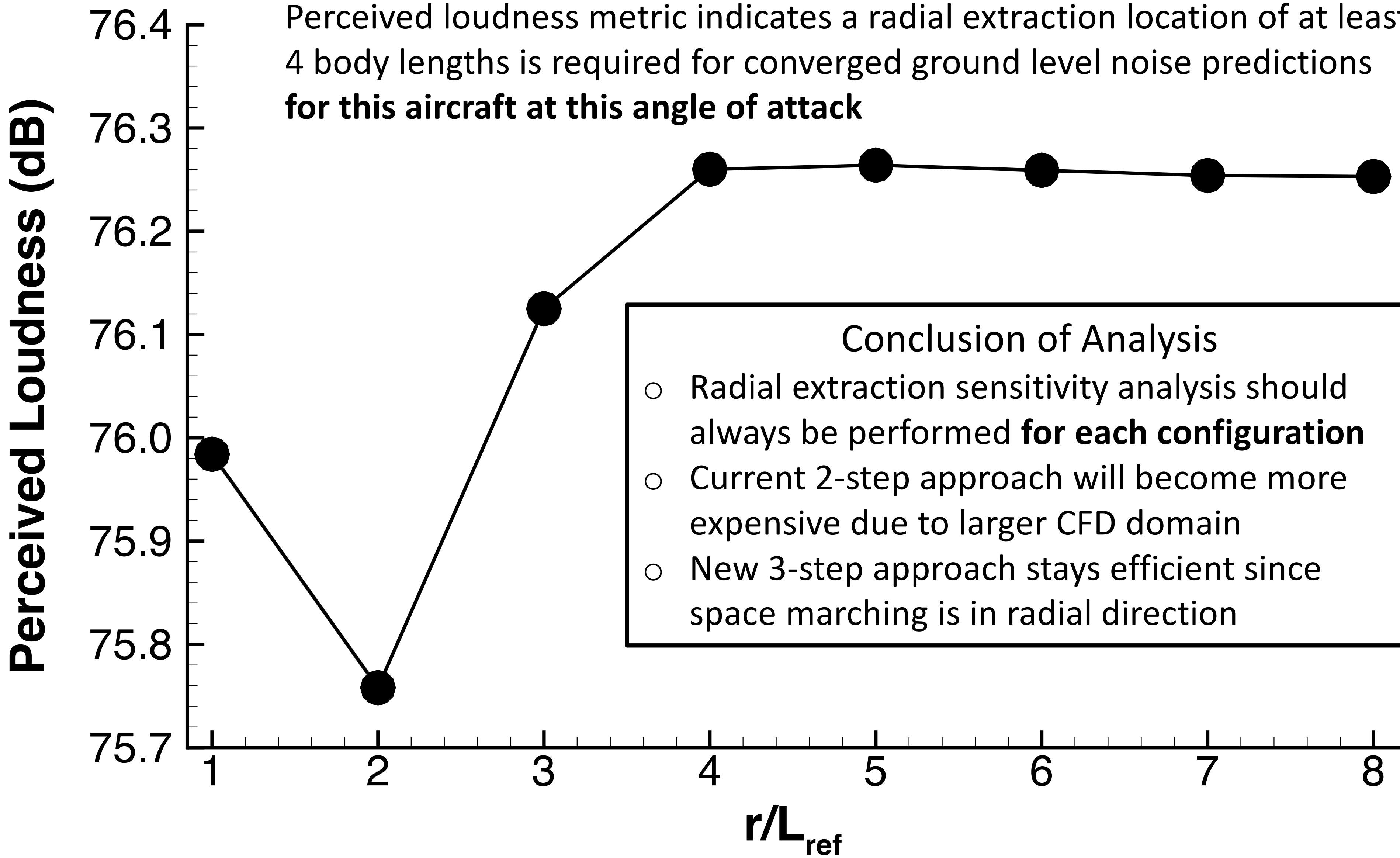
Azimuthal Dependence: Mid-Field to Ground

Overpressure ground signatures propagated with sBOOM from each radial extraction



Azimuthal Dependence: Mid-Field to Ground

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**

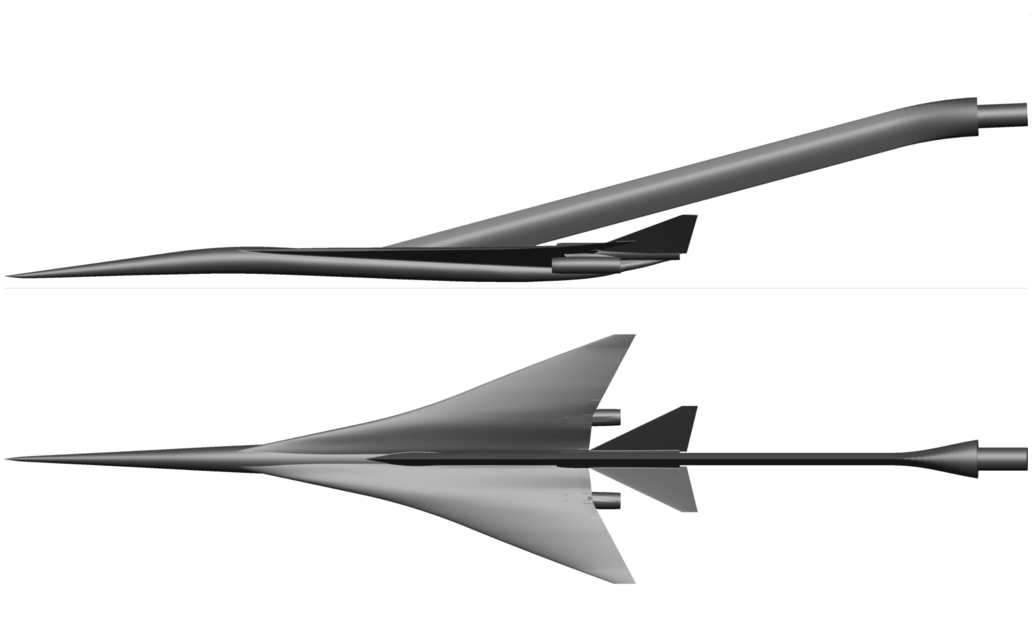
Conclusion of Analysis

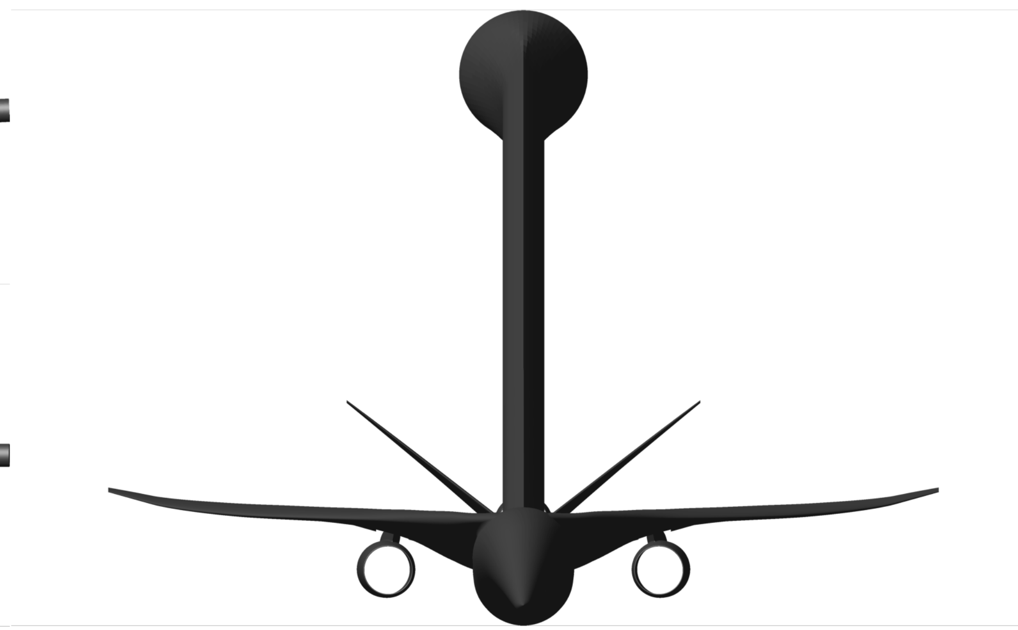
- Radial extraction sensitivity analysis should always be performed **for each configuration**
- Current 2-step approach will become more expensive due to larger CFD domain
- New 3-step approach stays efficient since space marching is in radial direction

Low Boom Aircraft Wind Tunnel Model

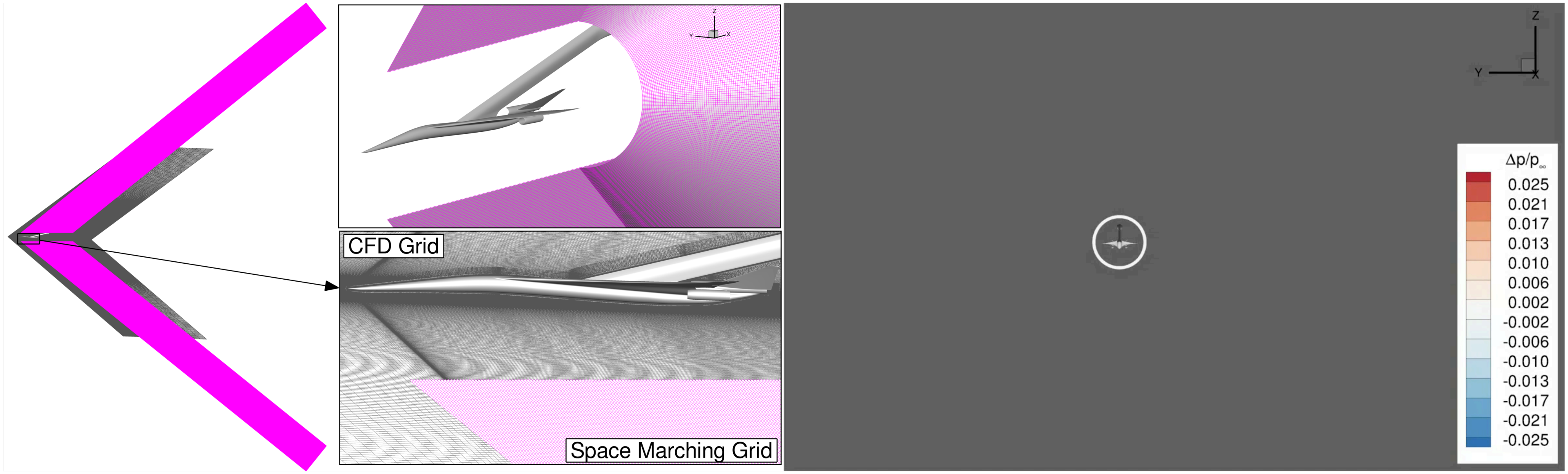
Lockheed Martin Phase I low boom model from 1st AIAA Sonic Boom Workshop (LM1021)

- 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)



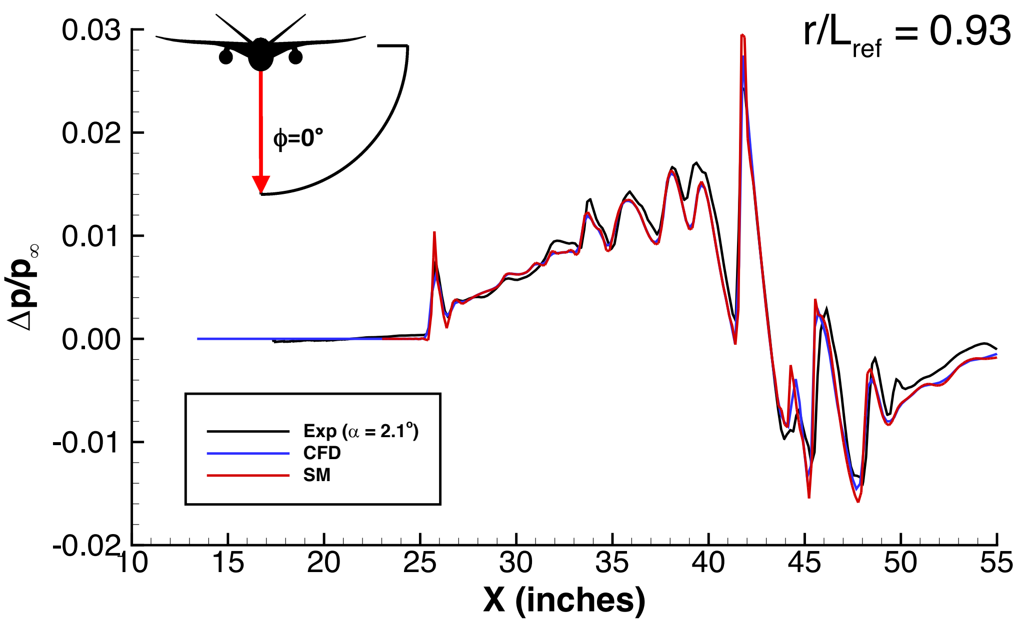


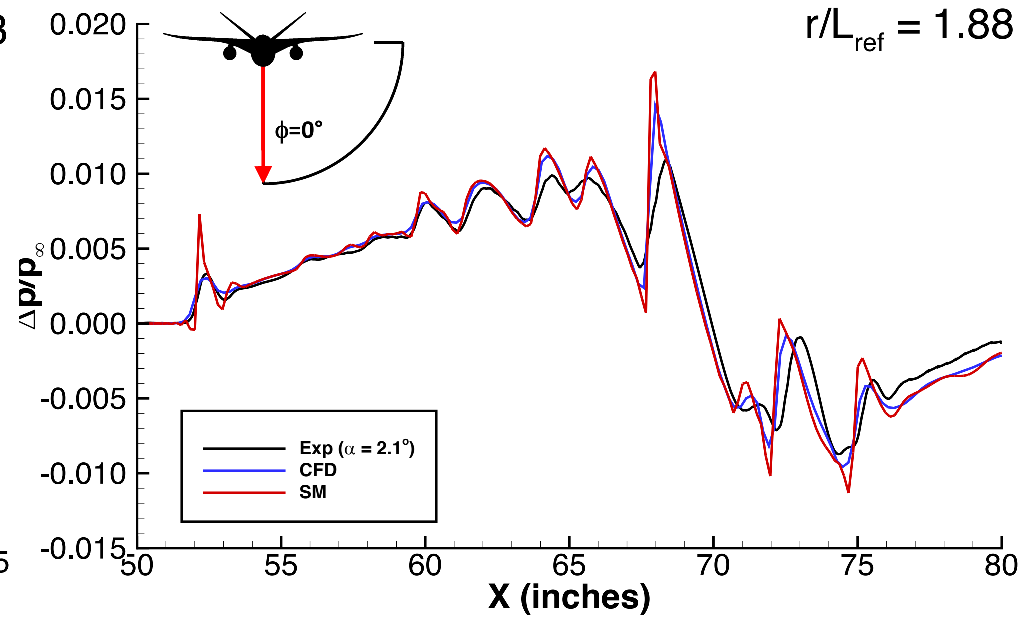
LM1021 Space Marching Grid and Solution

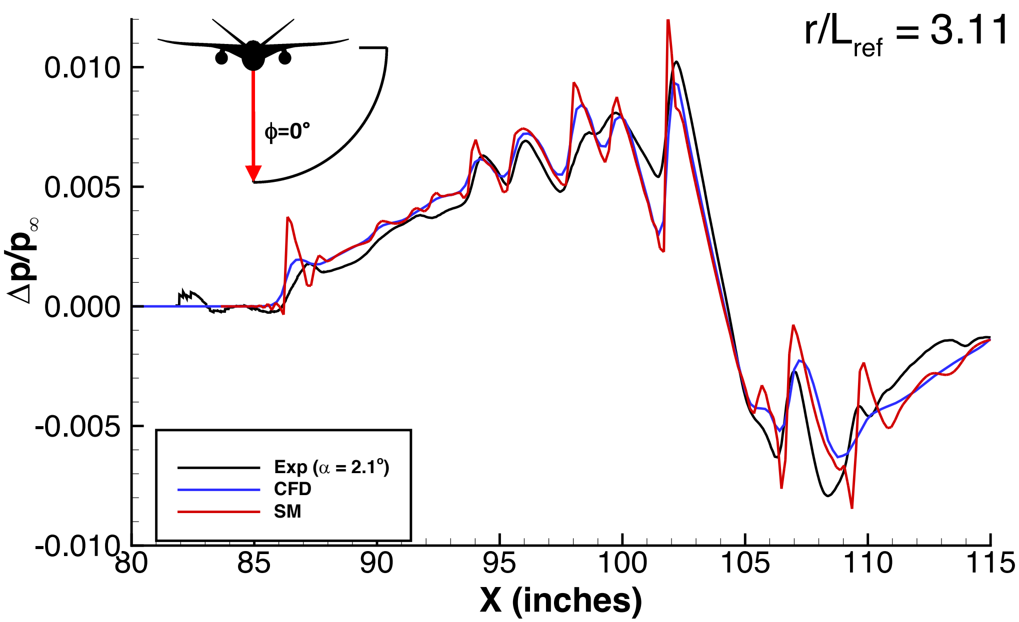


- Inputs for space marching grid generation were taken from grid sensitivity studies (see paper for details)
- SR = 1.05, AR_{max} = 20, $\Delta s/L_{ref}$ = 0.003, $\Delta\theta = 1^o$, $\theta_{max} = 180^o$, R = 10 L_{ref}
- Grid Dimensions: 351 x 181 x 564 (35.8 Million points, 4.2 seconds to generate)
- Inputs for space marching solver parameters were taken from solver sensitivity study (HWCNS4-ZWENO5)
- Space marching wall-clock time 106 seconds using 80 threads on single workstation

LM1021 Wind Tunnel Comparison







- Space marching and CFD solutions match wind tunnel data well at r/L_{ref} = 0.93
- As r/L_{ref} increases pressure peaks in wind tunnel data appear smoothed (averaging procedure see Cliff 2014)
- Space marching and CFD solutions retain sharp peaks at larger r/L_{ref}
- Space marching solution shows higher amplitudes than 2nd order CFD

Computational Savings

Example: JAXA Wing Body (66% reduction)

Measured Time (JWB)	2-Step Approach	3-Step Approach
CFD (RANS)	1920 core hrs. ($R = 7L_{ref}$)	640 core hrs. ($R \sim b/2$)
Space Marching*	NA	3 min. 6 seconds ($R = 10L_{ref}$)
sBOOM (1 azimuth)	~30 seconds	~30 seconds
Total Time	1920 hrs. 30 sec.	640 hrs. 3 min. 36 sec.

- Total time dominated by near-field CFD with both approaches
- Reduction of CFD domain lead to the reduction in total CPU time used
- Space marching approach time is small:
  - Space marching grid generation (116.4 Million points 13.6 sec.)
  - Interpolation of CFD solution onto fringe points (7.5 sec. 40 cores)
  - Space marching solution (164.9 sec. 80 threads)

Summary

A high-order accurate space marching method was developed for efficient near-field to mid-field sonic boom propagation

- A Mach-cone aligned curvilinear grid using *iblanking* technology was developed which is appropriate for space marching
- Thorough grid and solver parameter sensitivity studies reported in paper (AIAA-2019-3487)
- Important azimuthal effects on near-field to mid-field wave propagation and mid-field to ground level noise prediction was demonstrated
- Completed validation of the near-field to mid-field approach on the LM1021 wind tunnel model

Summary

A three-stage process for computing ground level noise from an aircraft was developed

- Reduces CFD domain extent by 40 – 60 %
- Introduces new near-field to mid-field space marching method
    - Space marching grid generated in seconds (automatically)
    - Interpolation from CFD to space marching grid
    - Space marching propagation (up to 10 body lengths) in minutes on a workstation
- Total time reduction of 66% compared to current approach for the JAXA wing body configuration

Future Work

- Given the high-accuracy and low computational cost of the fully 3D space-marching method, we are examining ways to extend the method to propagate directly to the ground

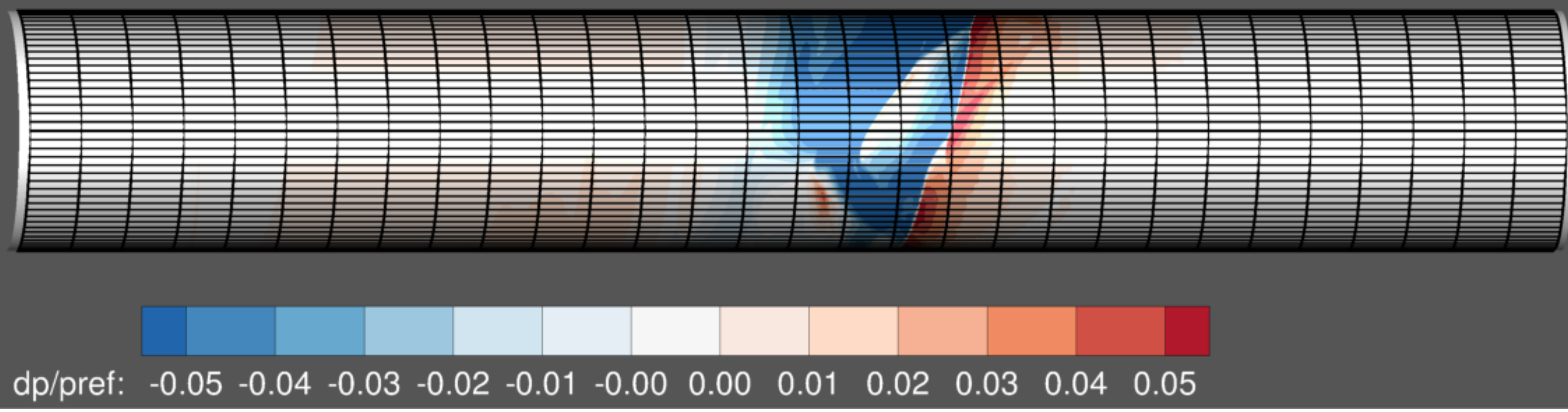
- This will require including important atmospheric effects and hydrostatic effects of gravity

- Similar work using a standard CFD approach has recently been published by Yamashita and Suzuki *(AIAA J. Vol. 54, 2016; J. of Aircraft, Vol. 55, No. 3, 2018)*

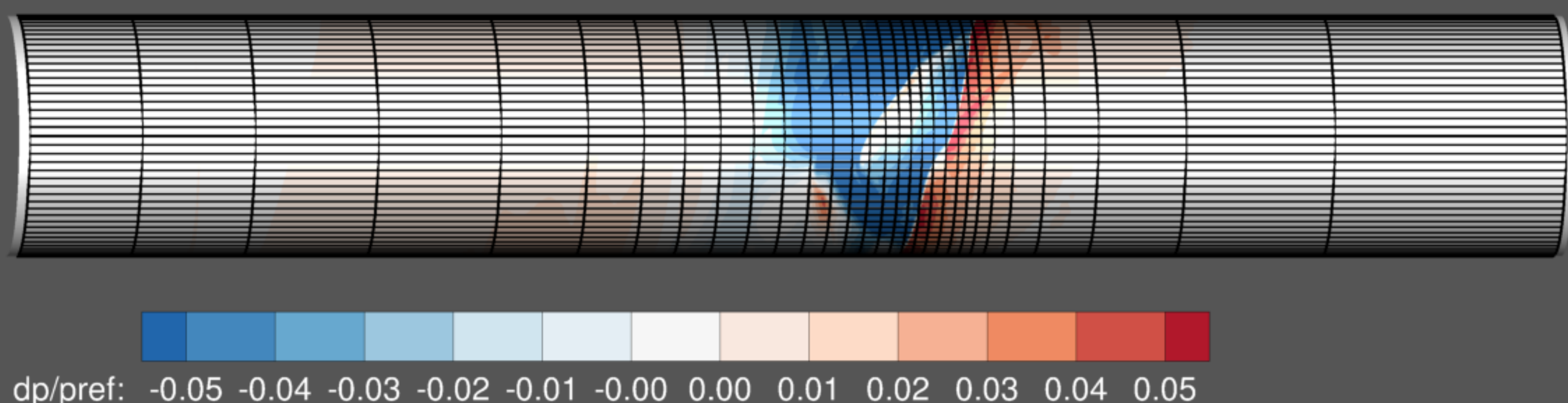
- Adaptive mesh redistribution methods are being explored to reduce the necessary number of grid points while maintaining the accuracy of the method (work being done with recently hired NASA Pathway student Chase Ashby, U. of Kentucky)

Future Work

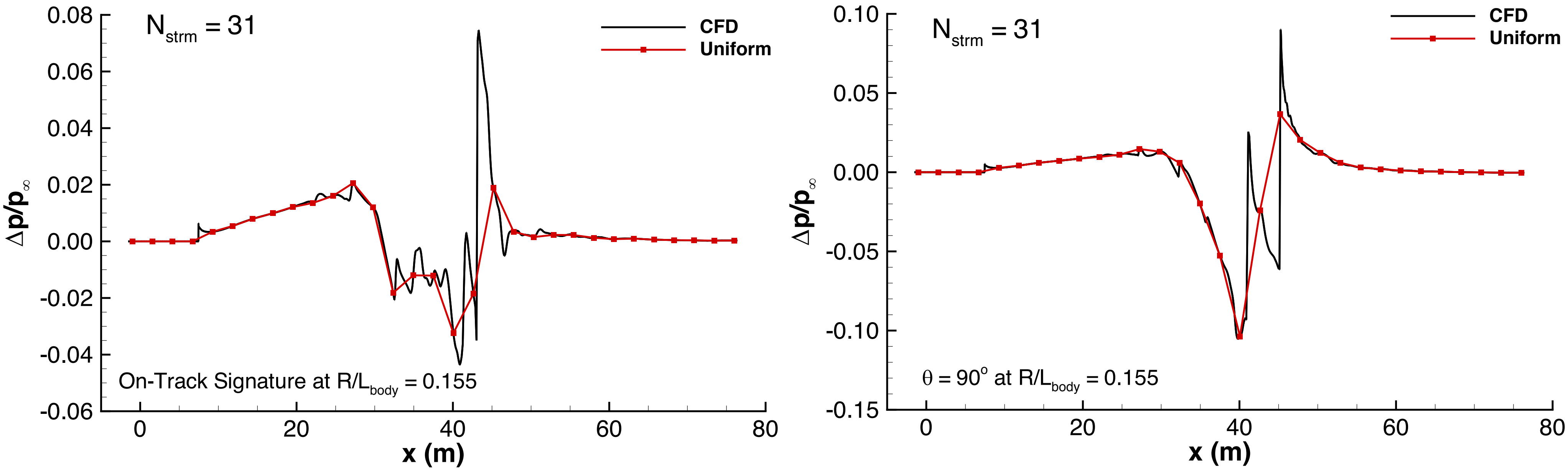
Uniform Mesh N_{strm} = 31



Redistributed Mesh N_{strm} = 31

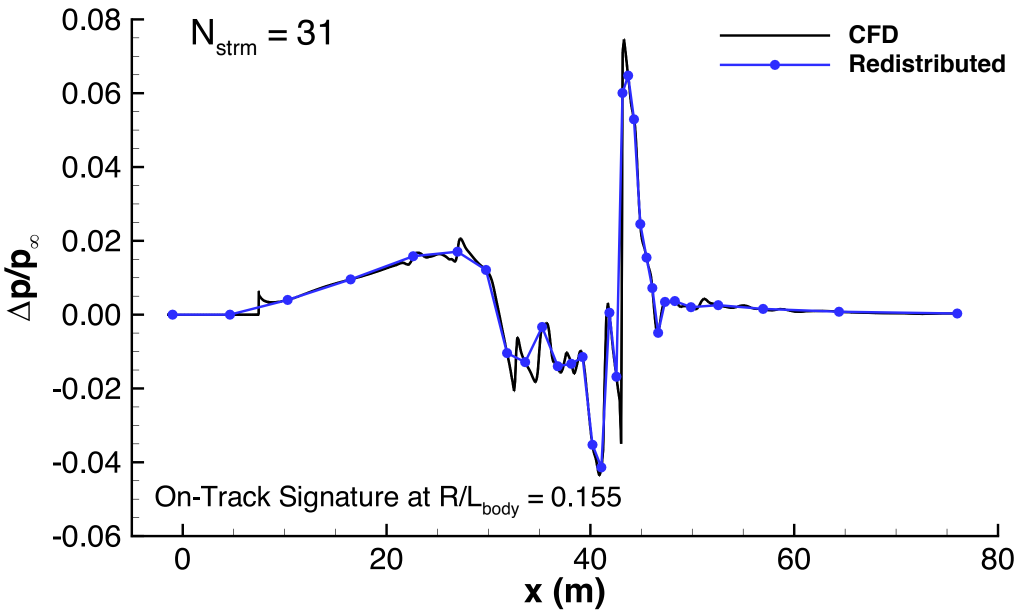


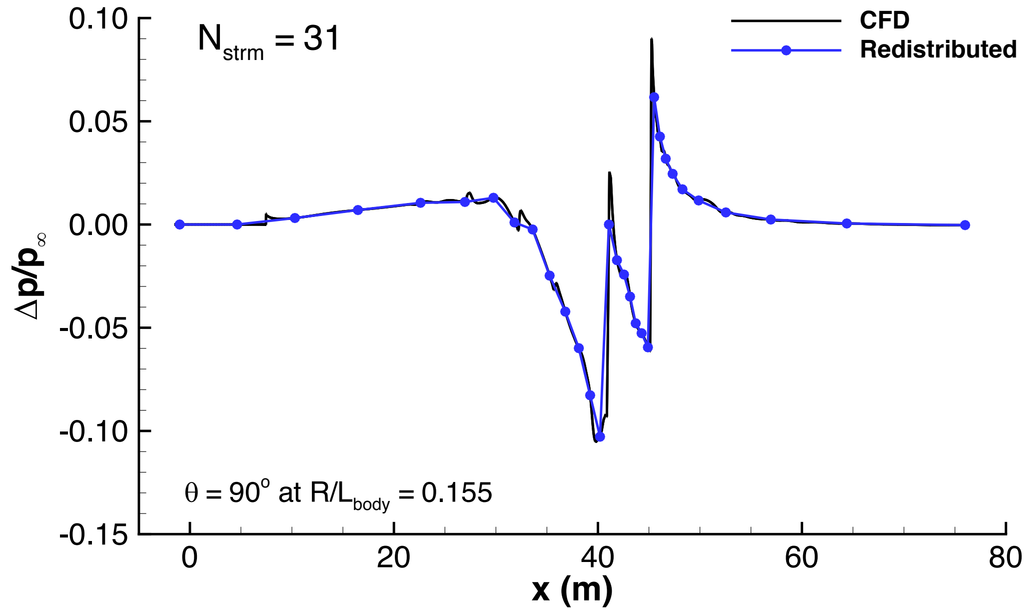
Future Work



- Uniform grid distribution results in lack of resolution of the shock/expansion caused by the wing
- Wave-train observed in the on-track signature is also under-resolved
- The current space-marching grid generation procedure would require adding additional uniformly spaced grid points until each of the important flow features are captured

Future Work





- Redistribution of the grid points in the streamwise direction results in a much better representation of the CFD data with only 31 points
- Using the mesh redistribution procedure we hope to approach a mesh converged mid-field solution with at least of factor of two less streamwise grid points
- This mesh redistribution scheme is also being generalized to 3D for application to the off-body (and eventually near-body) CFD mesh

Acknowledgements

- Work was funded by NASA's ARMD Commercial Supersonic Technologies (CST) project

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