Enhanced Simulation Techniques in Predicting X-59 Sonic Boom Loudness Using CFD

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Commercial Supersonic Technologies (CST) project

ICCFD12, Kobe, Japan
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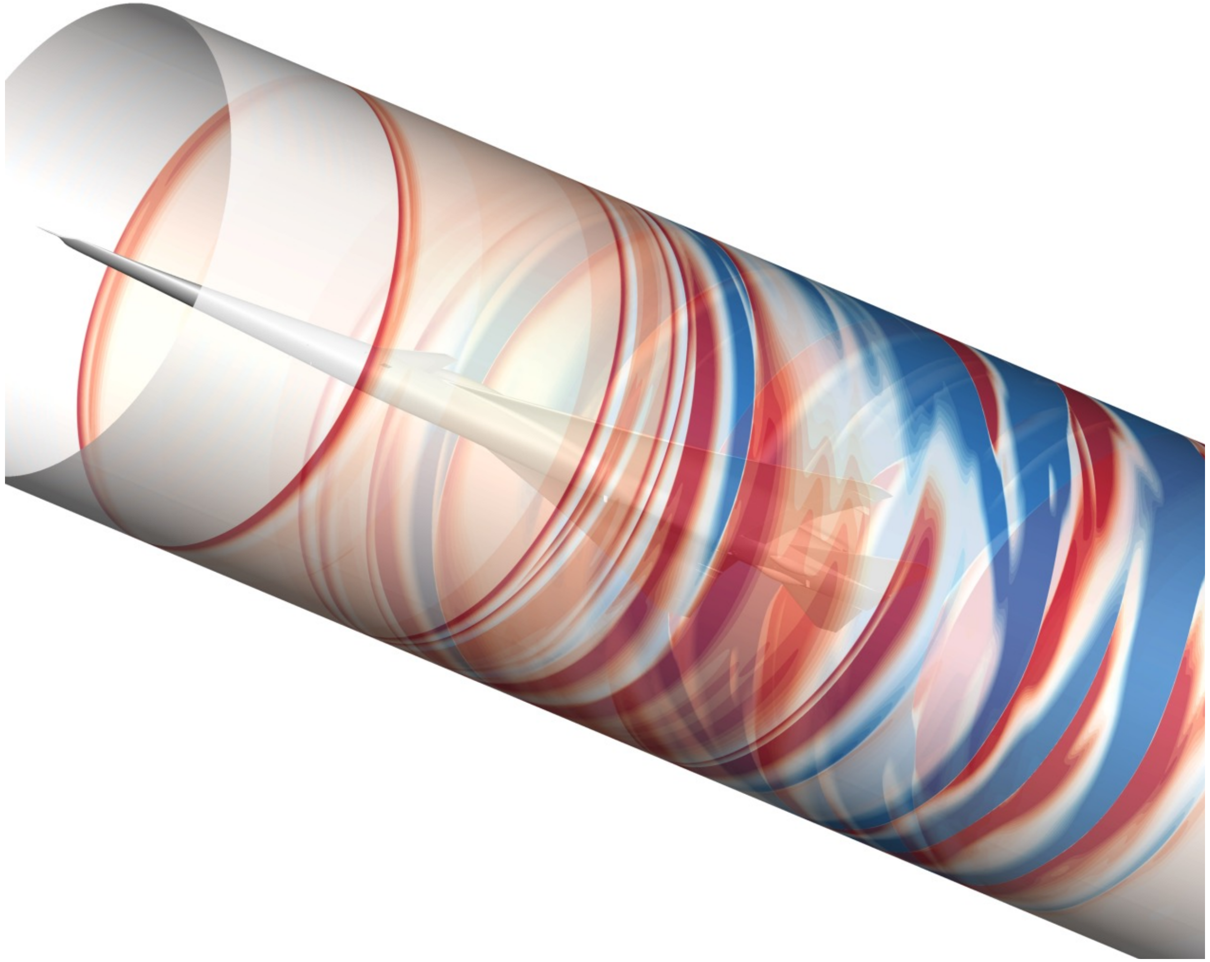
QueSST Mission

- Explore the potential of quiet supersonic flight by building a low boom flight demonstrator aircraft
- Mission phases:
  I. Aircraft Development
  II. Acoustic Validation
  III. Community Testing
- Mission requires fast, robust, and accurate loudness predictions

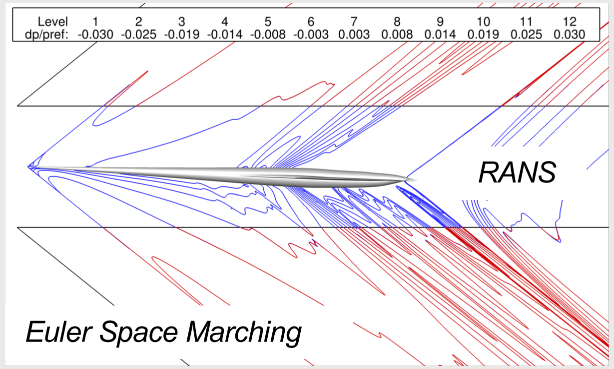


QUESST

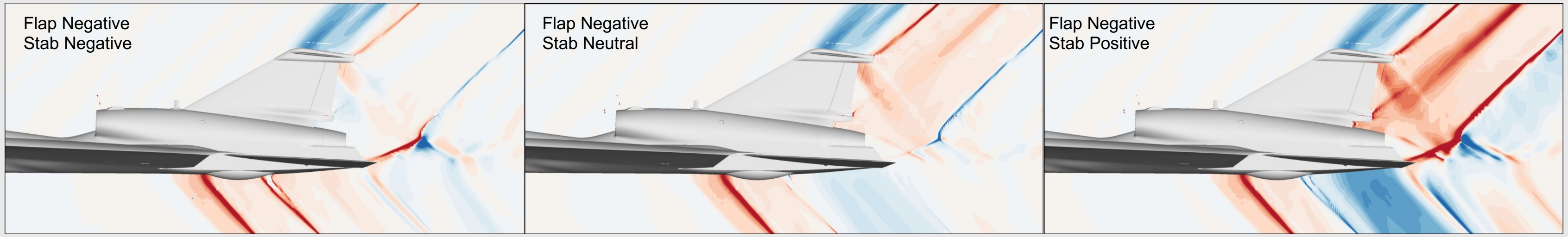
https://www.nasa.gov/mission/quesst/

Advancements on Loudness Prediction Methods

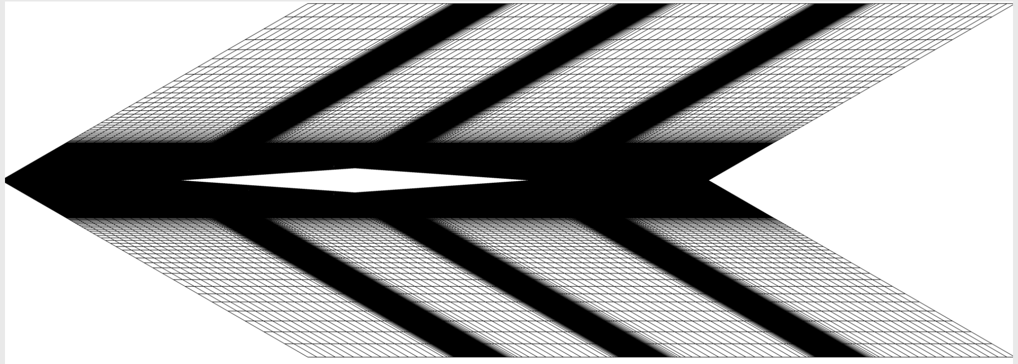
I. Space Marching



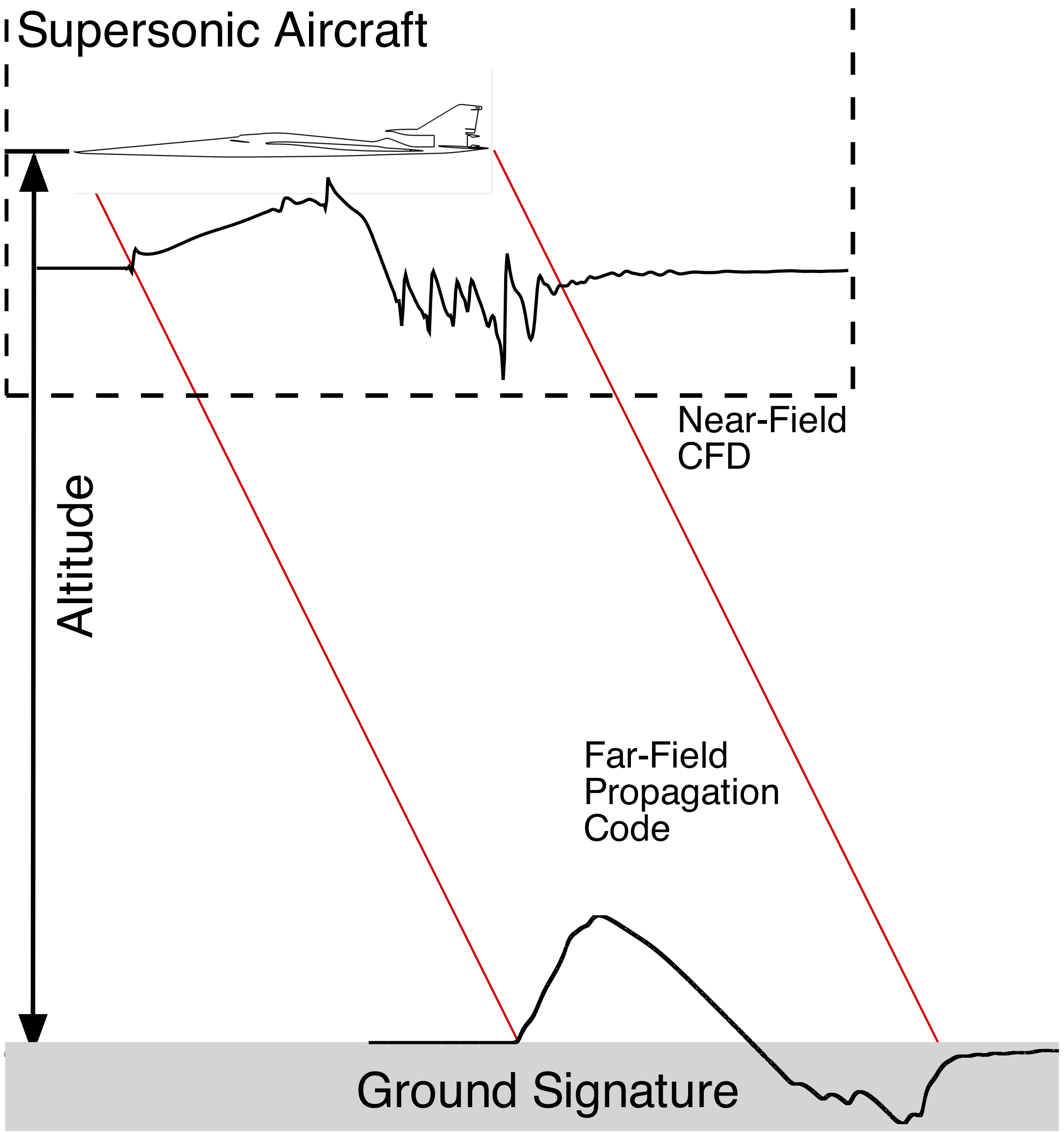
II. Database Scripting



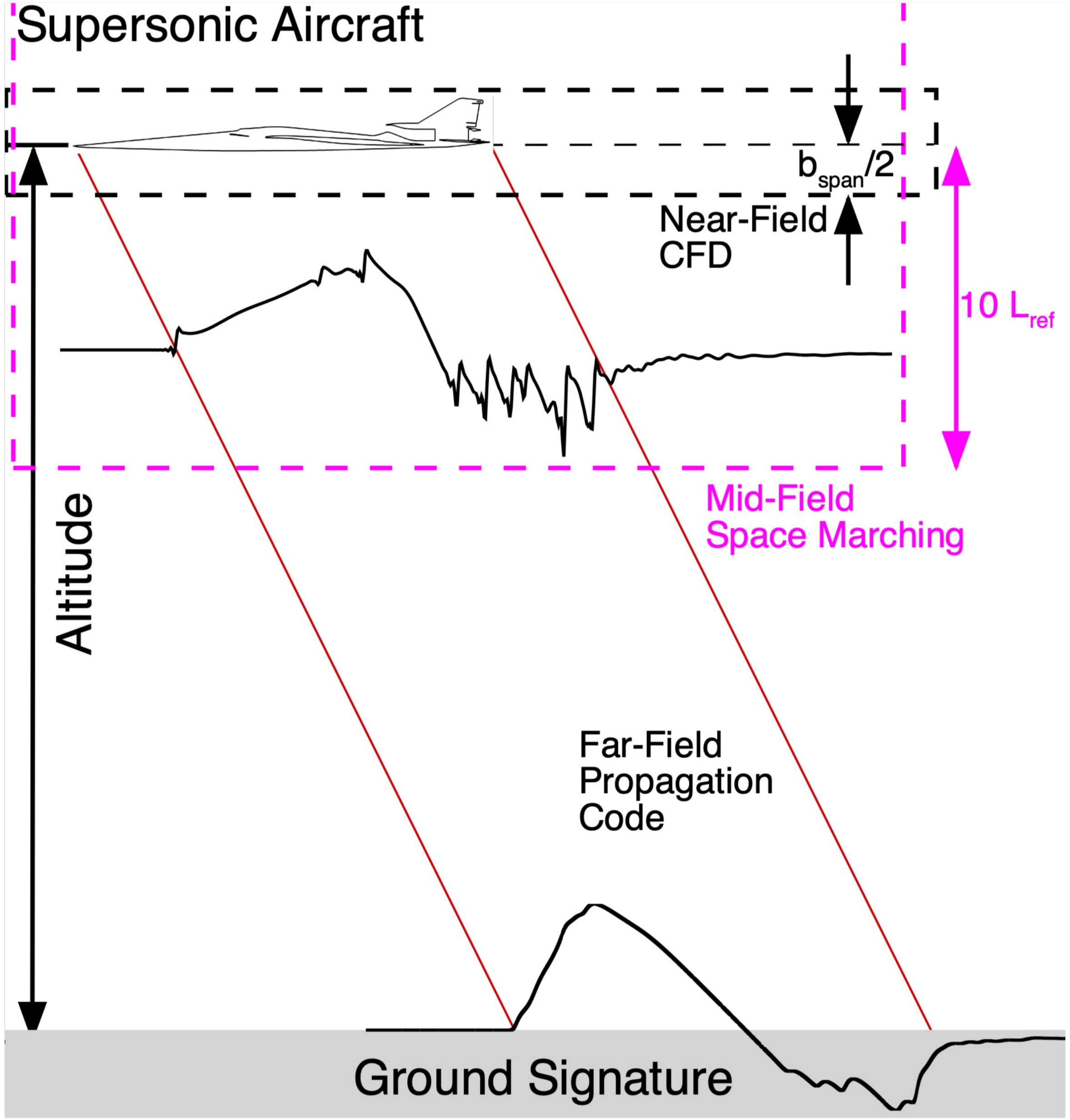
III. Mesh Redistribution



Two Step Loudness Prediction

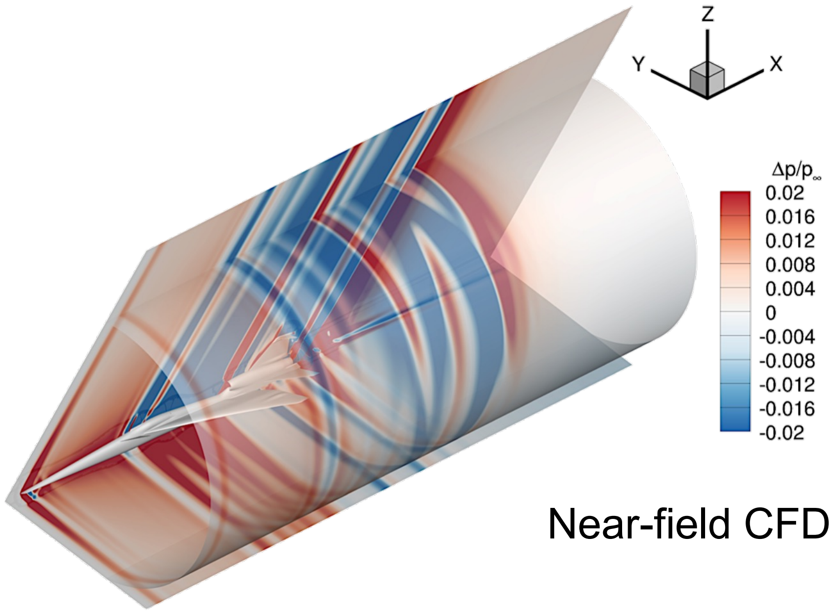


Three Step Loudness Prediction



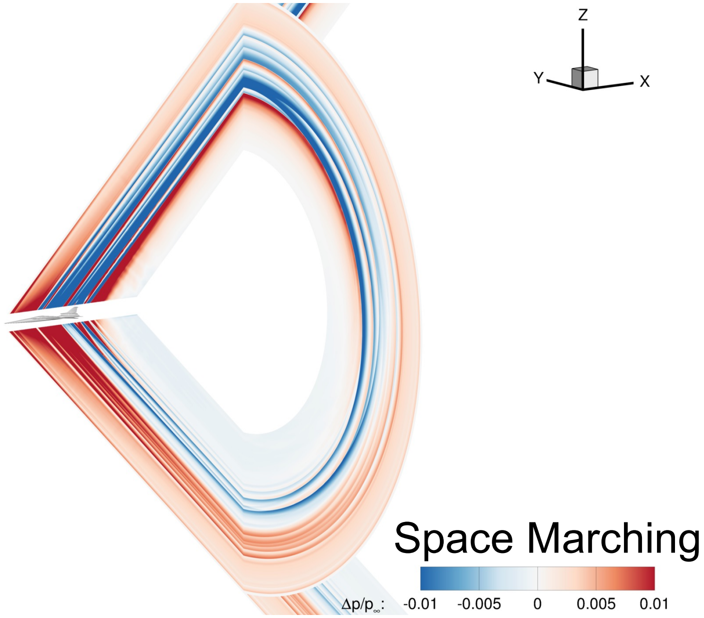
Housman et al. 2022

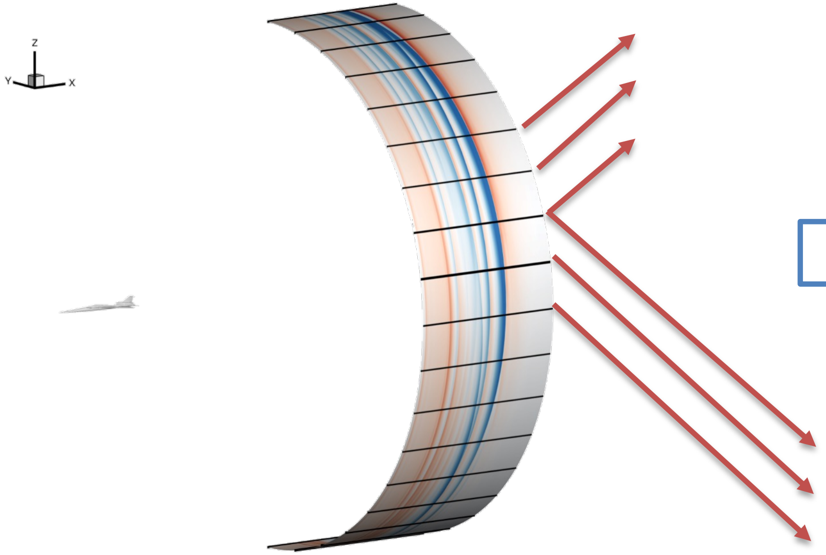
Three Step Simulation Procedure



Near-field CFD

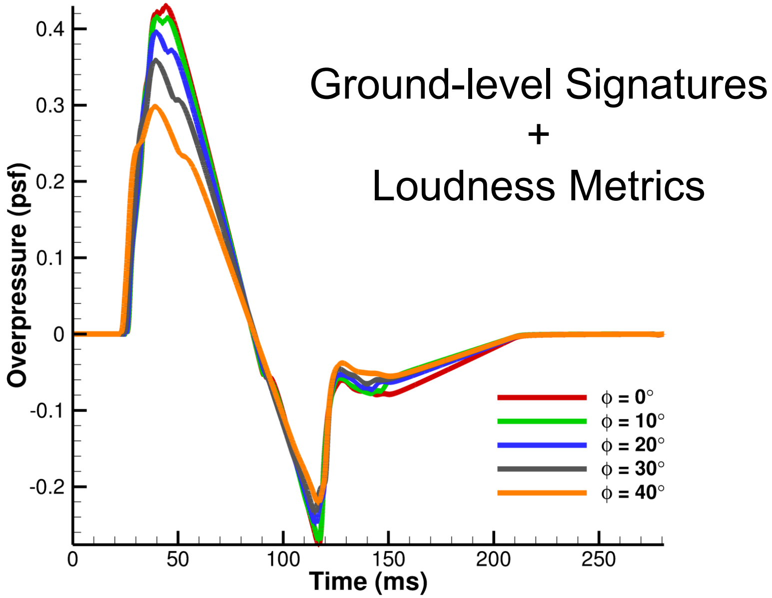
Interpolation
+
Space Marching



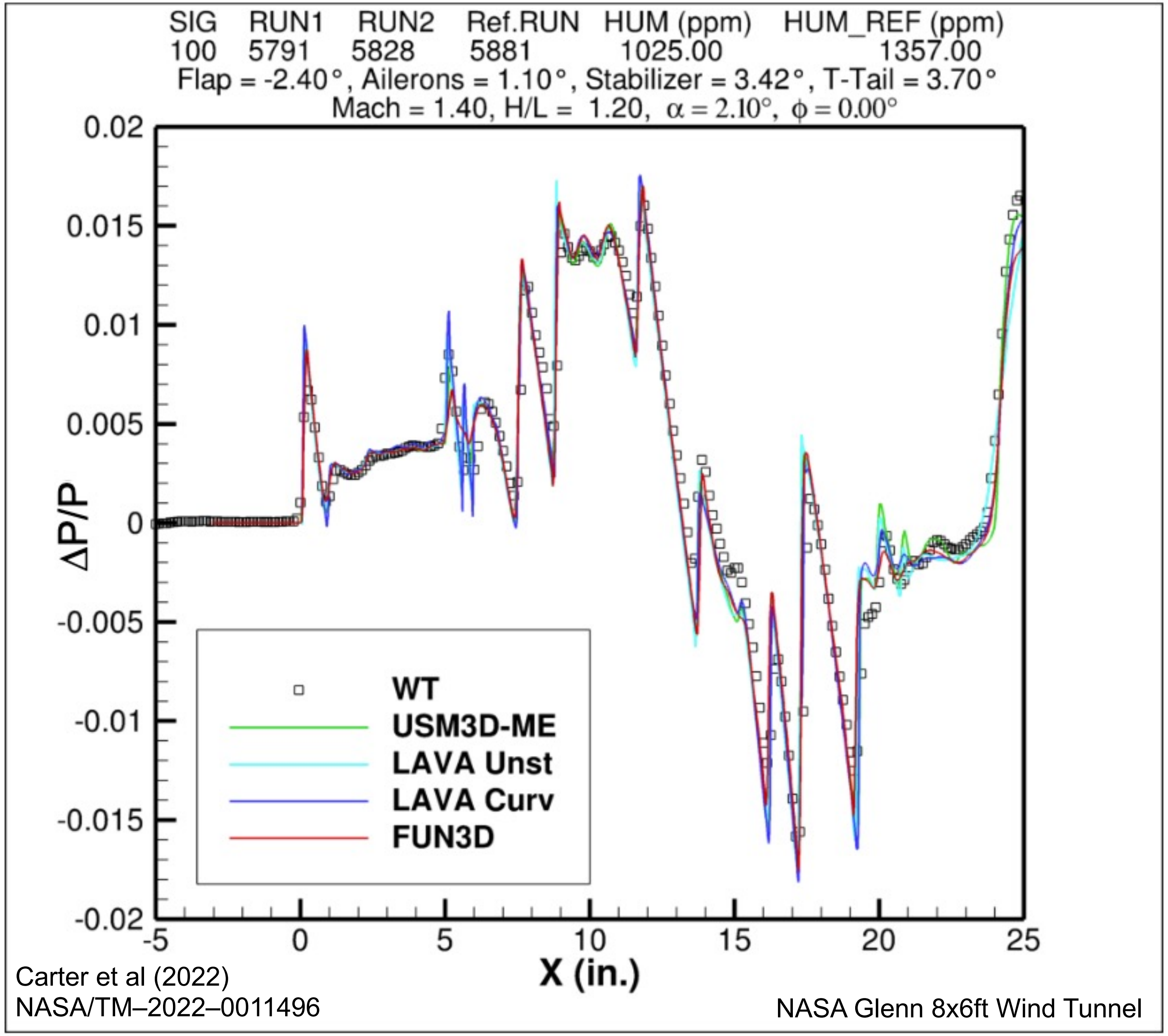


Pressure Cylinder Extraction

Acoustic Propagation



LAVA Curvilinear Validated against Wind Tunnel Test



Representative X-59 Case

Flight Conditions

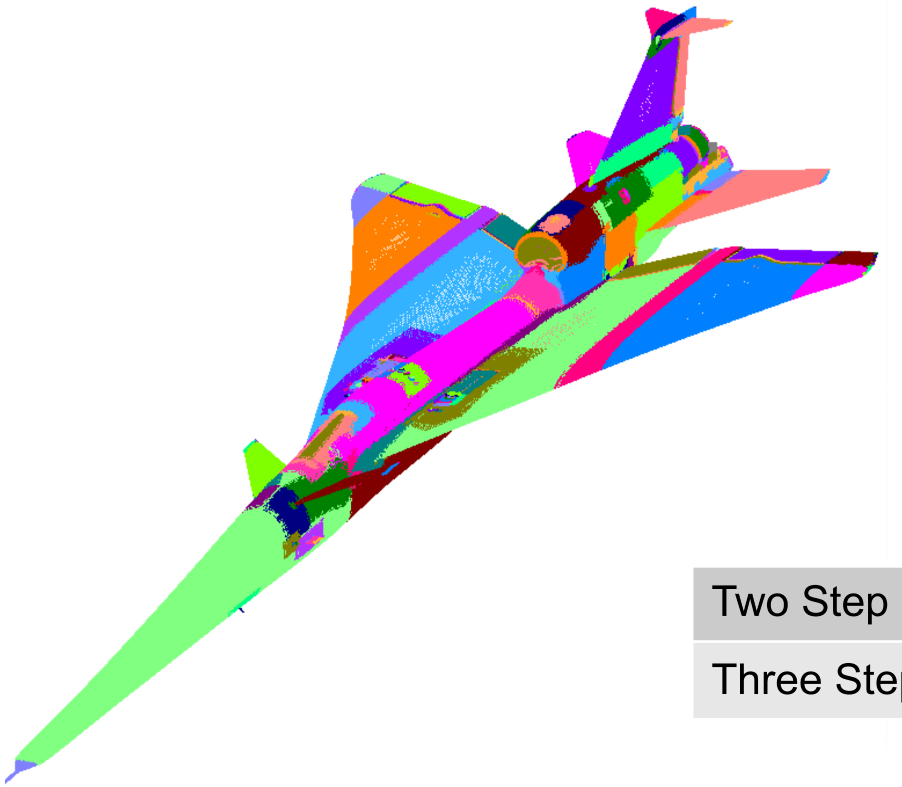
- Mach: 1.4
- Altitude: 53,000 ft
- Pref: 10520 Pa
- Angle of attack: 2.04 degrees
- Length: 27.432 m

LAVA Curvilinear Solver

- Steady RANS with SA turbulence model
- Body conforming structured overset grids

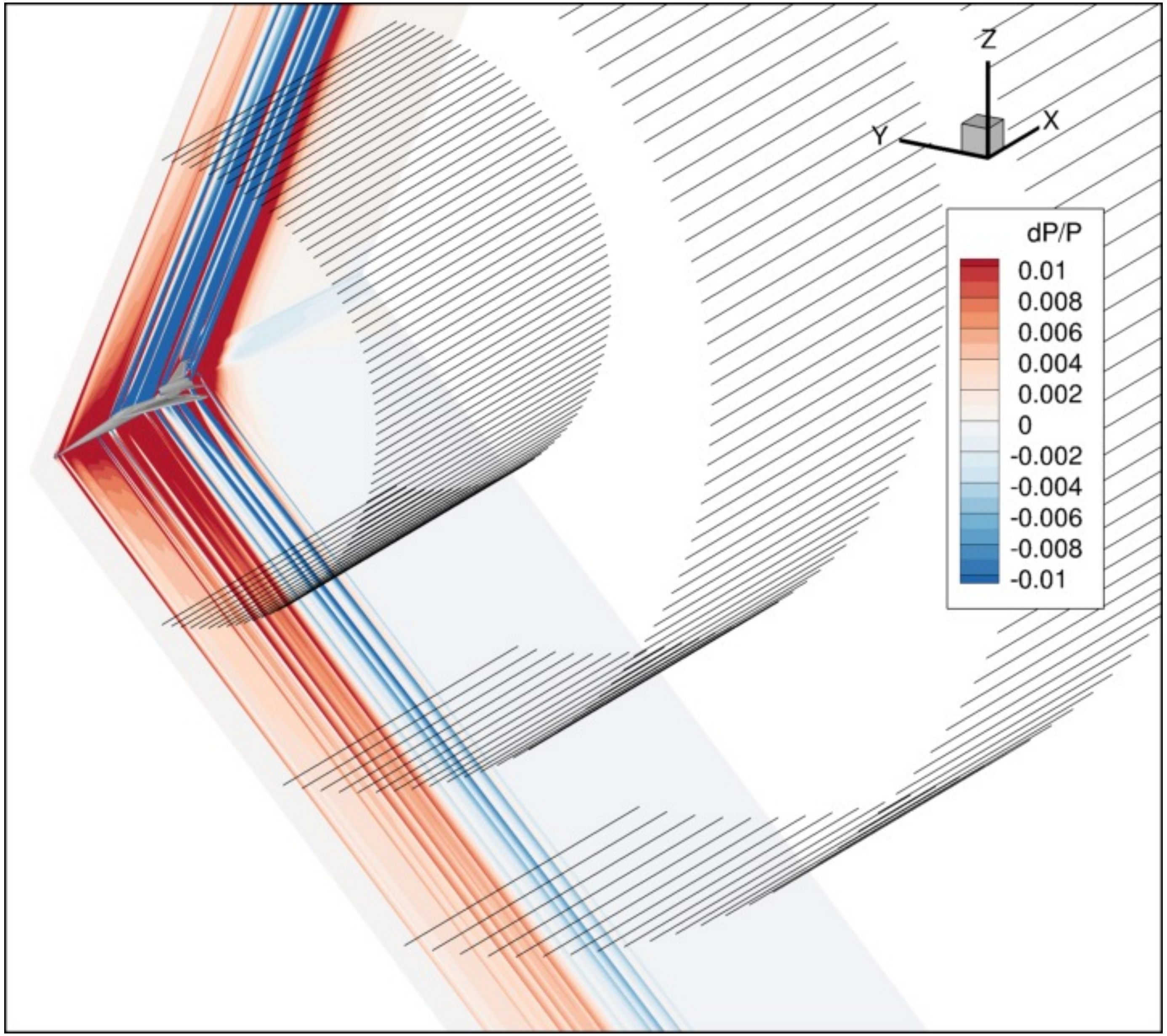
Space Marching

- Steady Euler equations
- HWCNS4-WENO3 for space dimensions
- BDF2 for streamwise (marching) direction

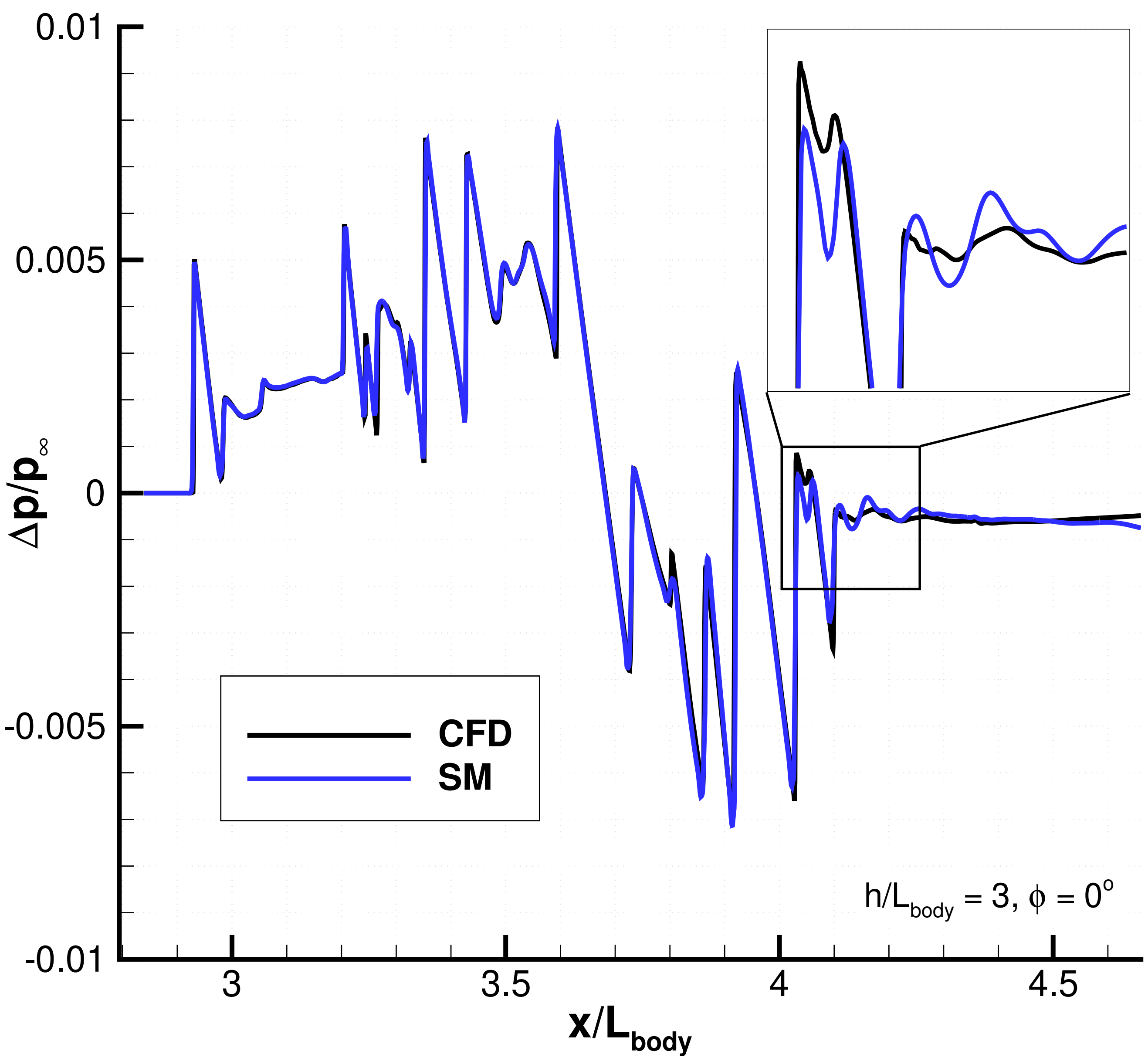


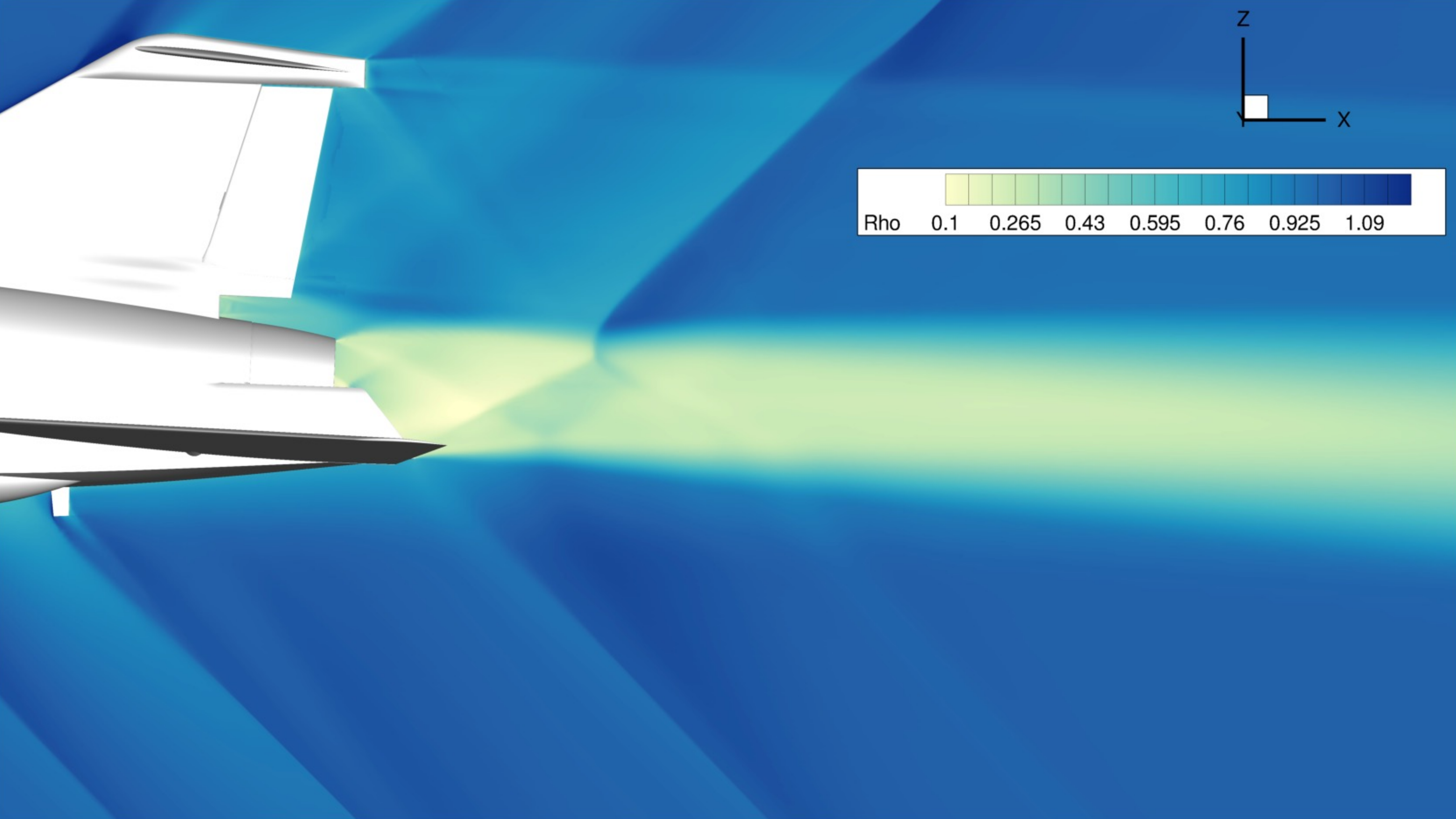
	Prediction Method	Off-body Radial Extent	CFD DoF	Off-body DoF	SM Grid DoF
Two Step	CFD Only	3.1L	545 M	412 M	--
Three Step	CFD + SM	0.6L	273 M	131 M	411 M

Pressure disturbance in the near-field



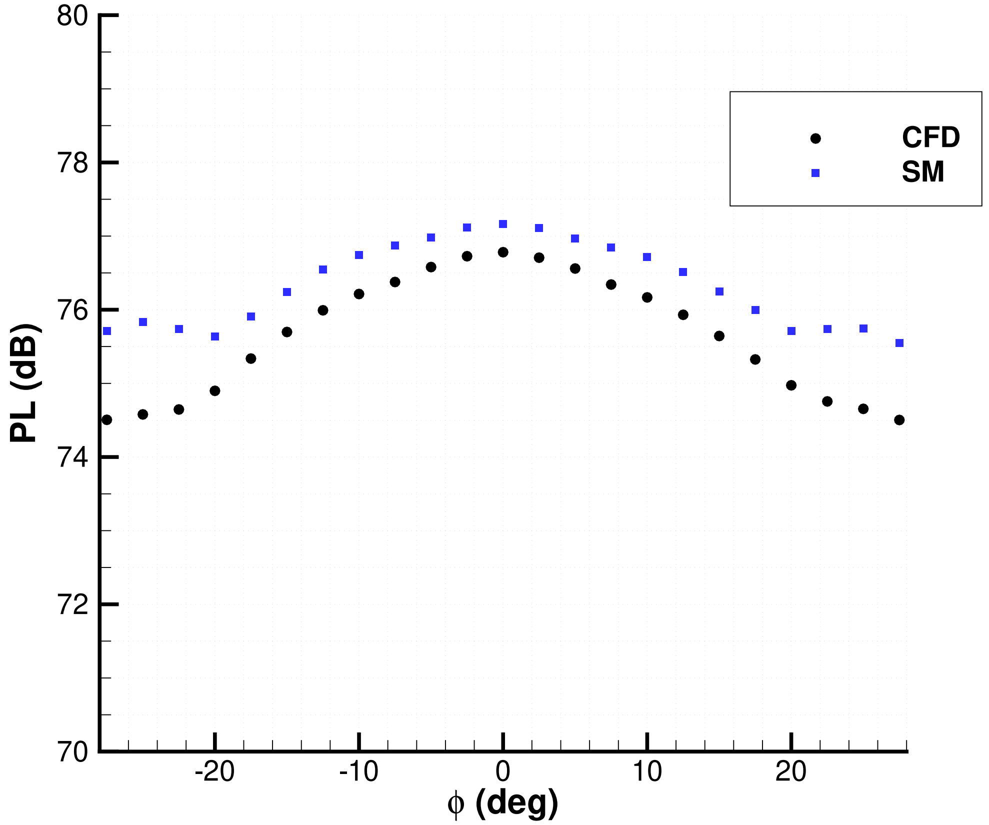
On-track (ϕ=0) pressure signature

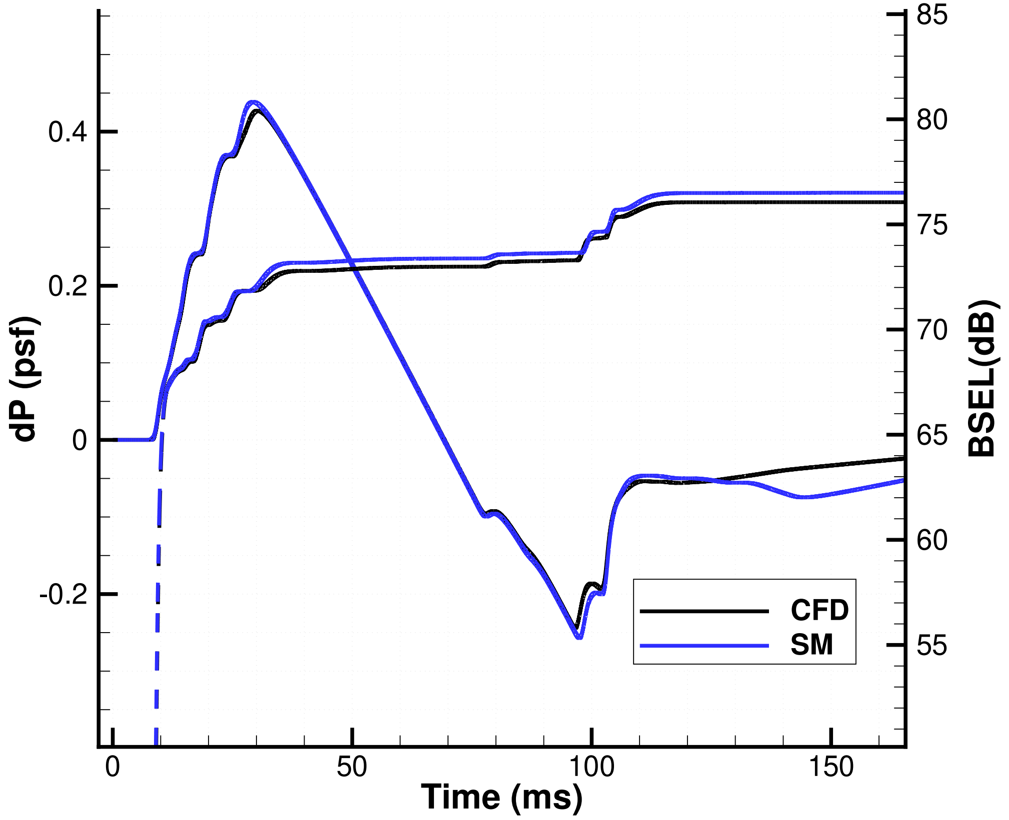




Z
X
Rho
0.1
0.265
0.43
0.595
0.76
0.925
1.09

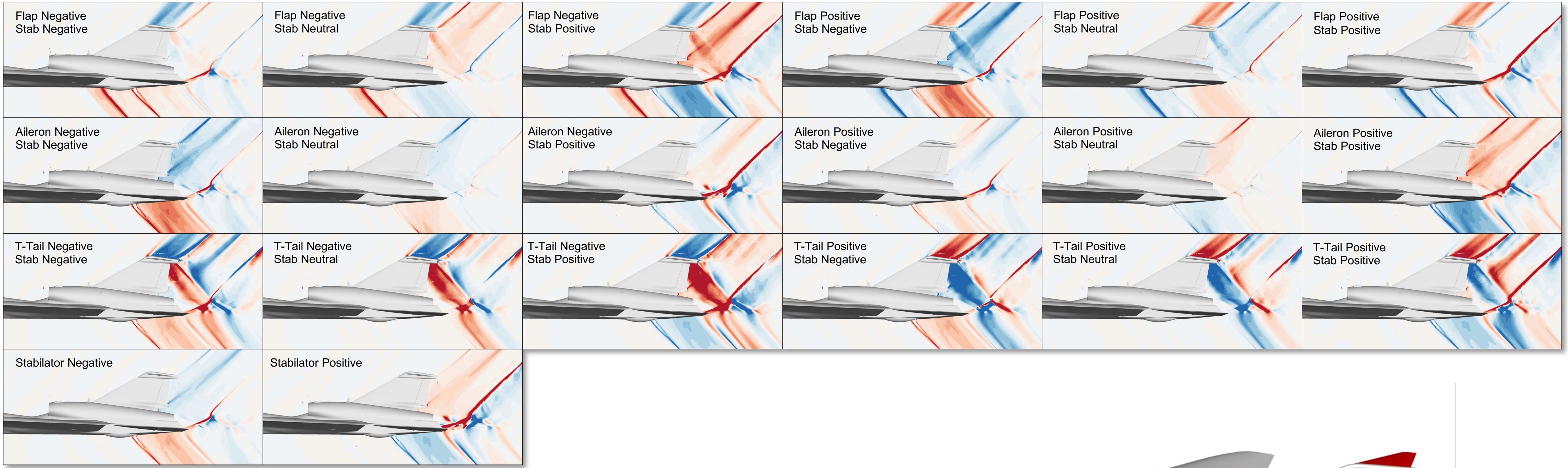
Loudness Predictions from sBOOM



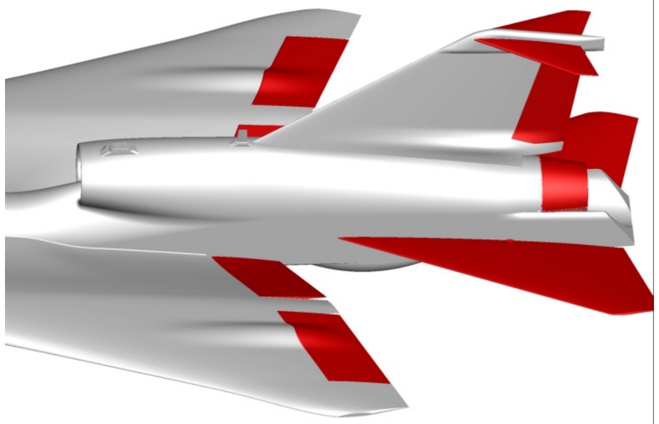


Loudness Metrics	ASEL	BSEL	CSEL	PL
CFD	63.172	76.057	90.467	**76.781**
Space Marching	63.443	76.509	90.901	**77.167**

Database capabilities driven by scripting



Reducing potential for human error + enabling rapid predictions for O(100) cases



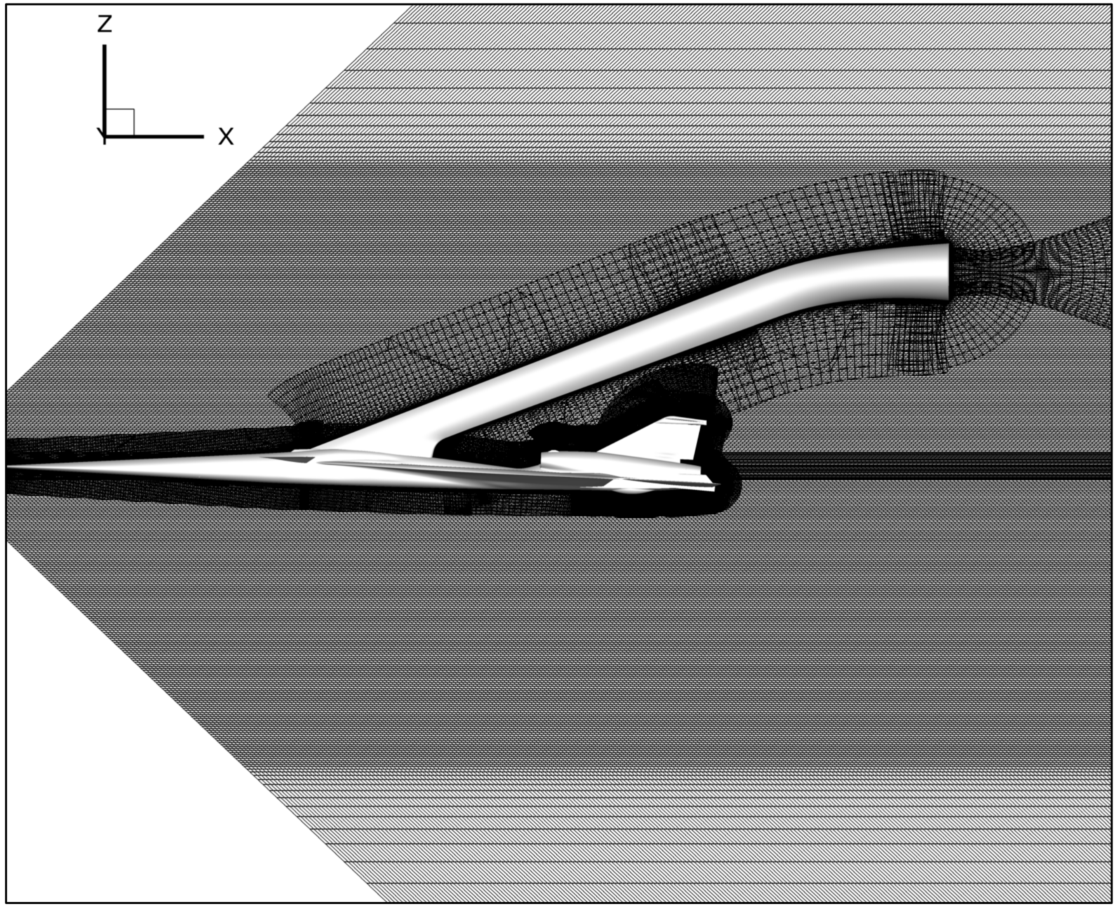
Deflectable control surfaces

Computational Cost

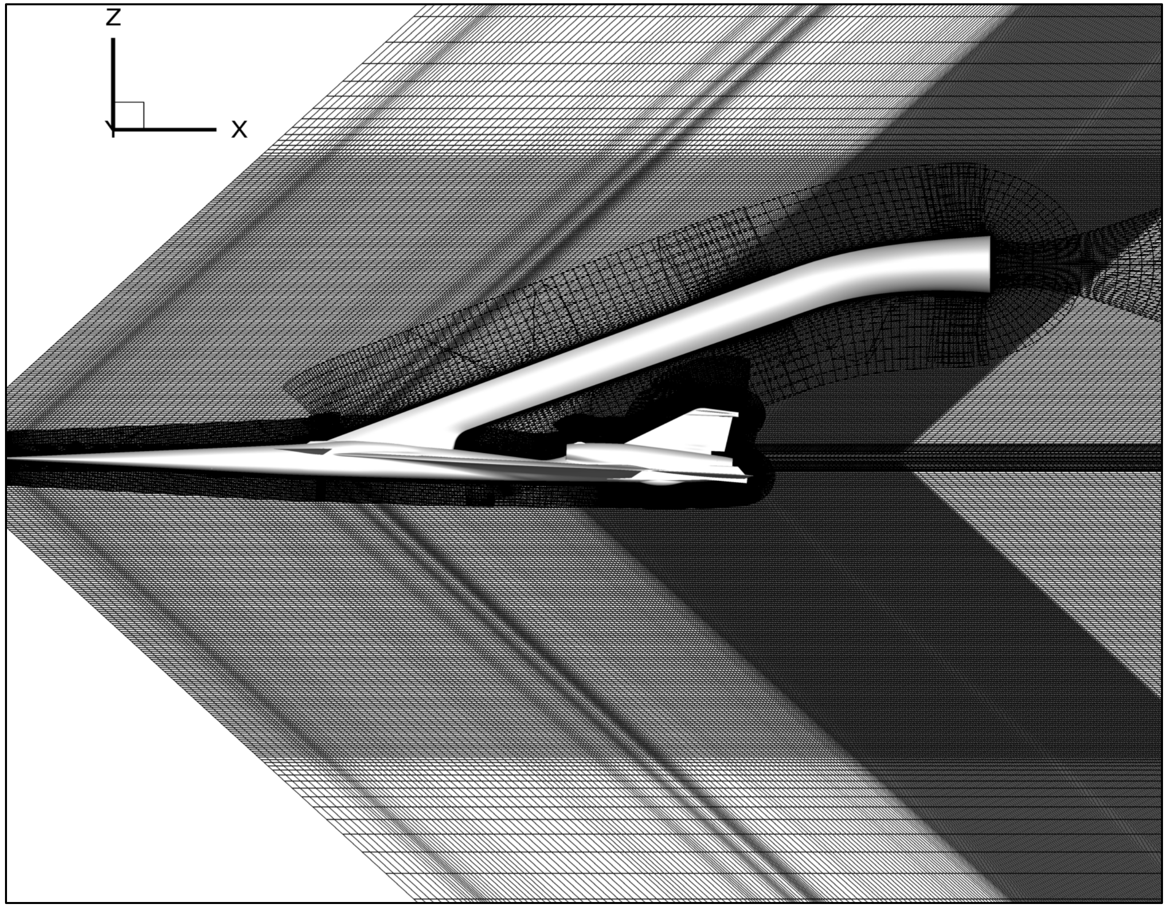
CPU-hours	2 step	3 step
Grid Generation	0.5	0.16
Near-Field Solution	690	400
Space Marching	--	0.28
sBOOM Propagation	0.1	0.1
Total	**690.6**	**400.54**

3 step procedure achieves ≥50% cost reduction with no loss in accuracy

Anisotropic Mach Cone Aligned Mesh Redistribution



Initial Off-body



Adapted Grid

Adaptation Equations

- Governing adaptation equation

$$w_i \underbrace{\Delta s_i}_{\text{cell-size}} = C$$

Discrete equidistribution principle

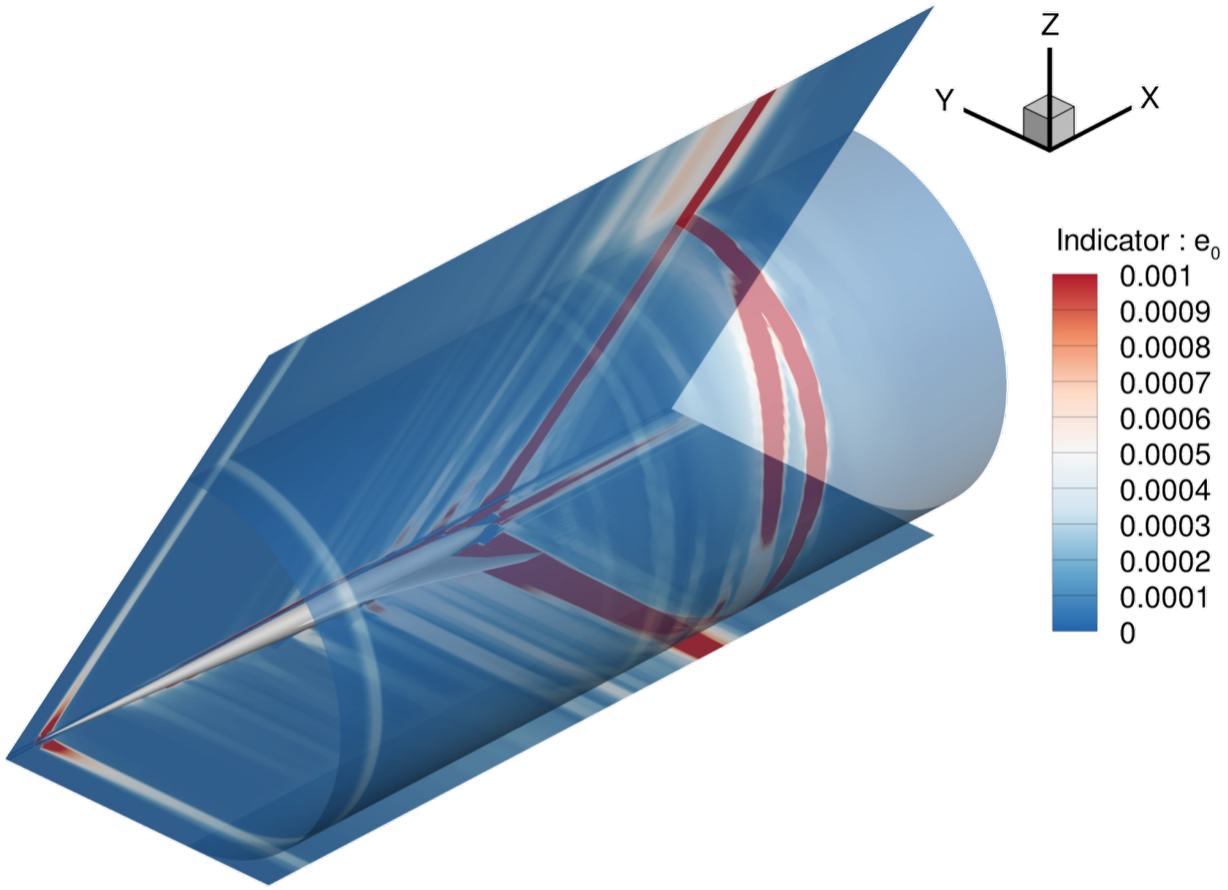
- Adaptation weights control the location of local refinement

$$w_i = 1 + A \underbrace{f_i}_{\text{adaptation indicator}}$$

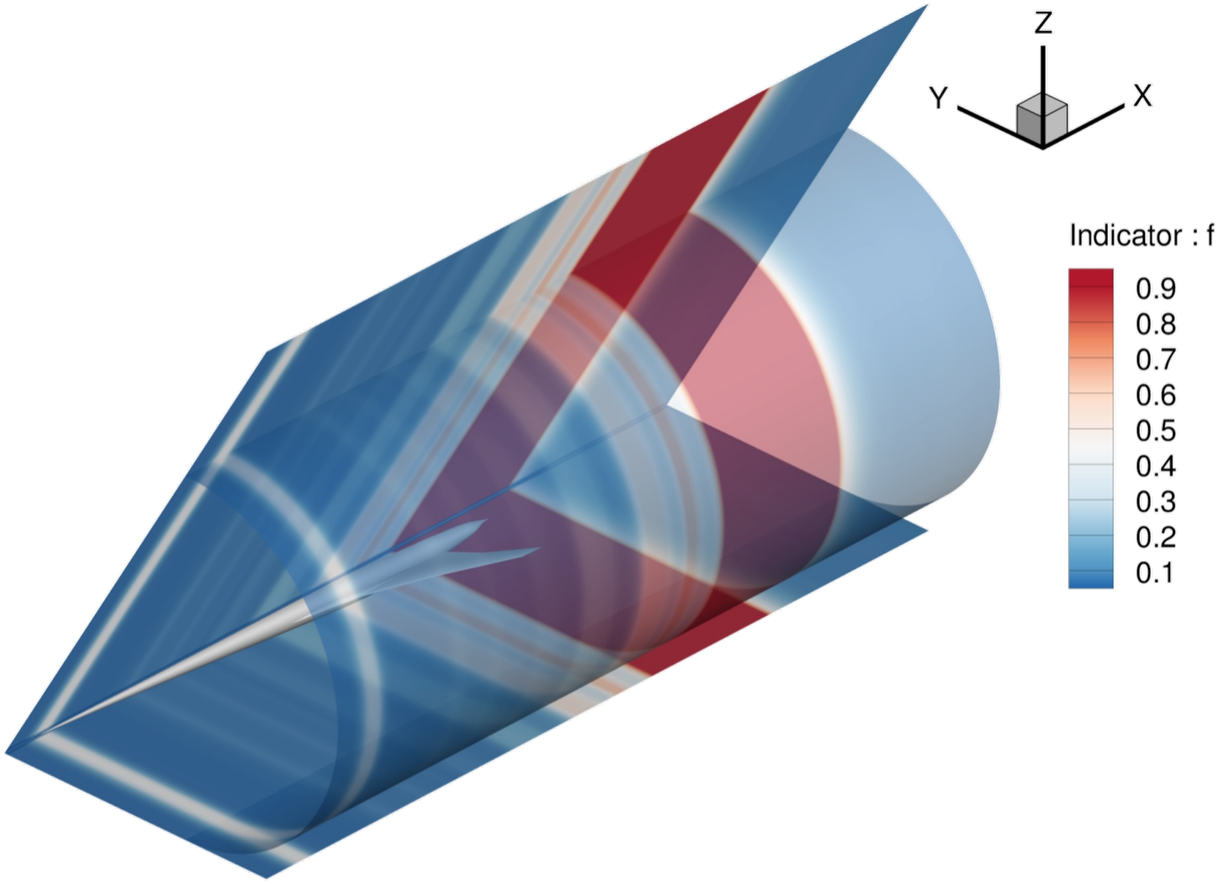
- Clustering constant limits the maximum and minimum cell-size

$$A = \underbrace{c_\mathrm{f} r_\mathrm{f}}_{\text{coarsening and refinement factors}} \frac{\Delta s^0_\mathrm{max}}{\Delta s^0_\mathrm{min}} - 1$$

Direction-Based Indicators



Initial Adaptation Indicator



Direction-based Adaptation Indicator

Representative X-59 Case

Flight Conditions

- Mach: 1.4
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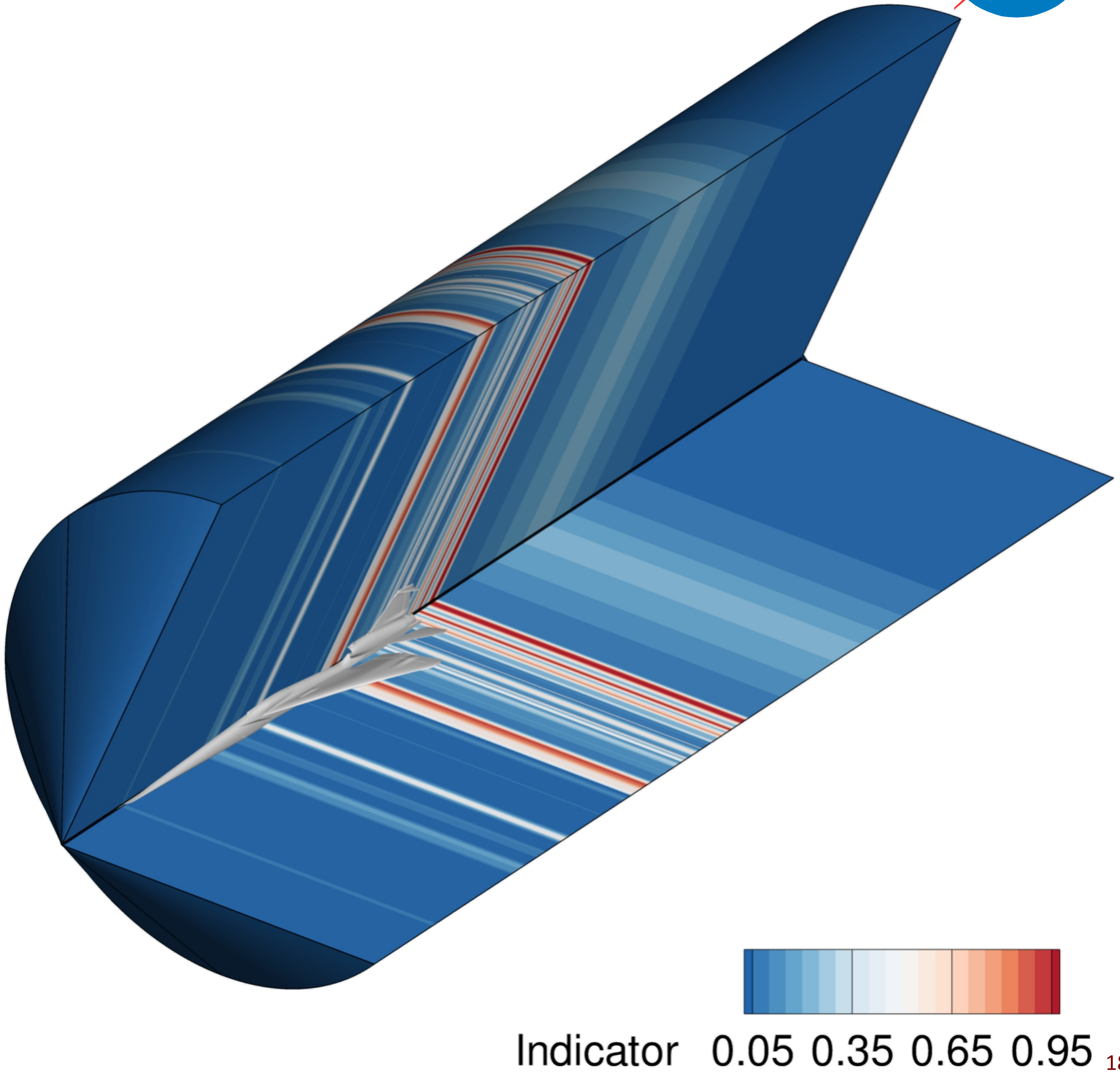
- Pref: 10520 Pa
- Angle of attack: 2.04 degrees
- Length: 27.432 m

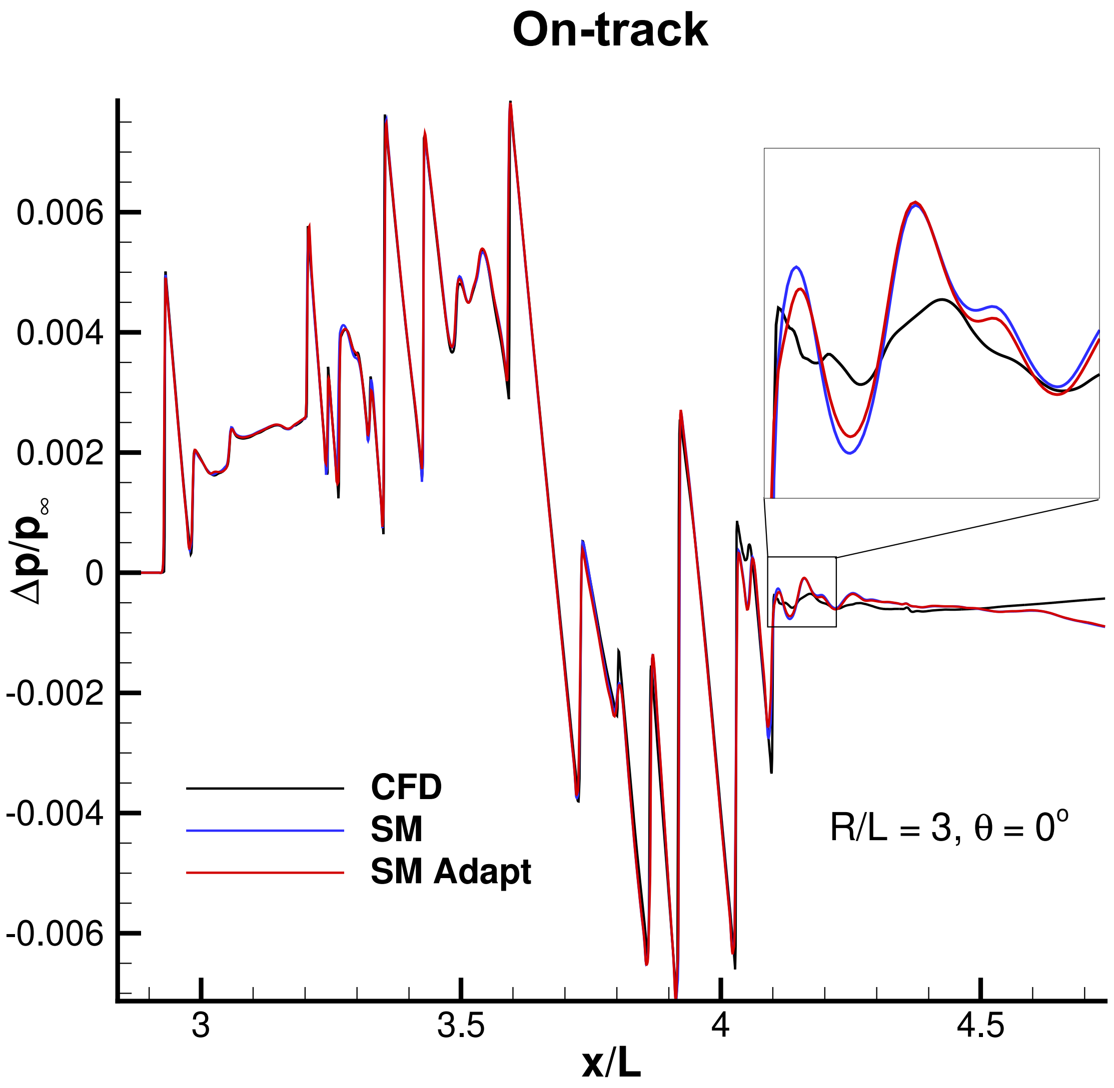
Adaptation Indicator

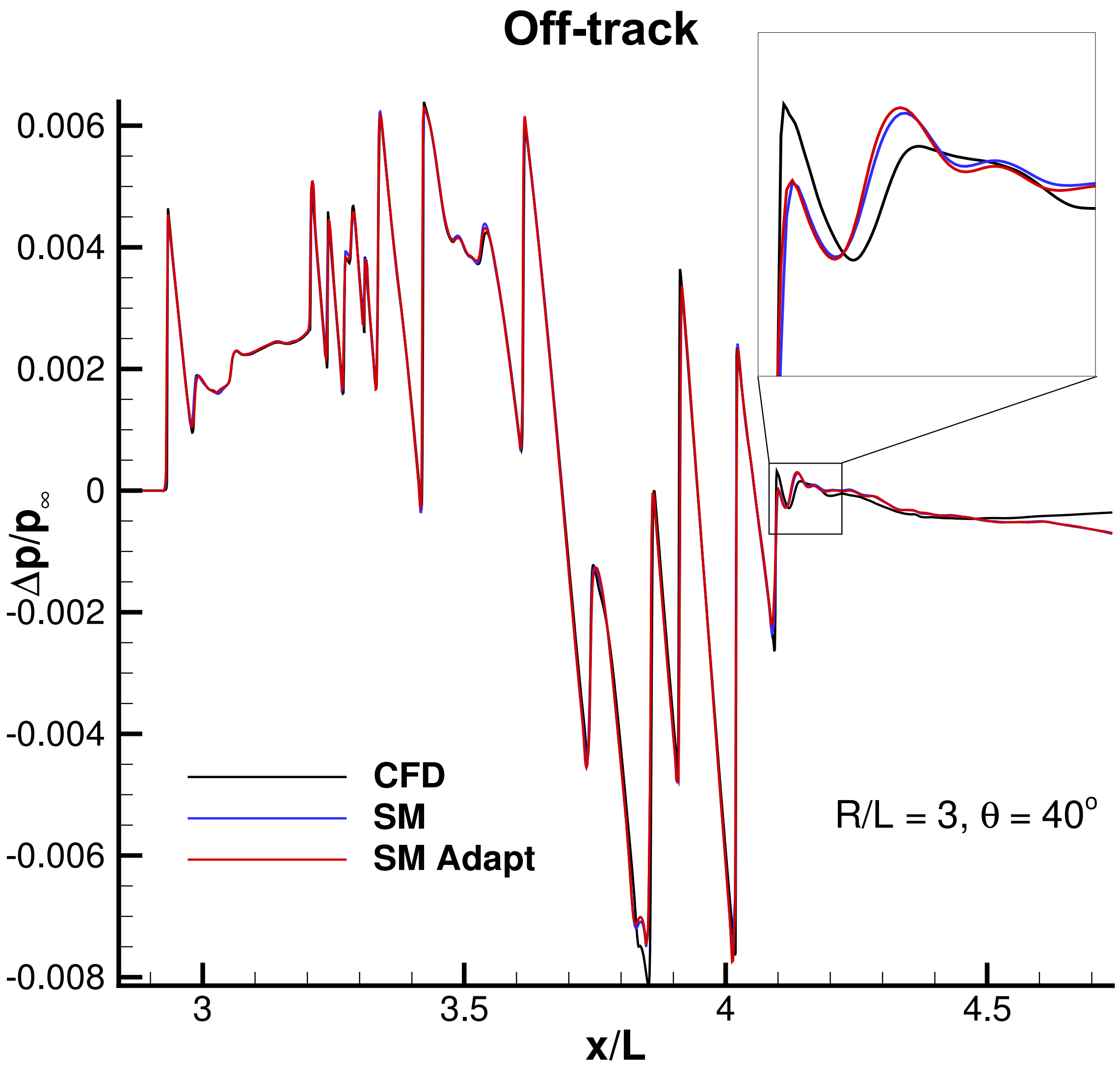
- Quantity: Mach
- Direction: Streamwise

Task	Wall-Clock Time
1st Order Flow Solve	1 hr 51 min 58s
Adaptation	2 min 37s
Restart Flow Solve	8 hr

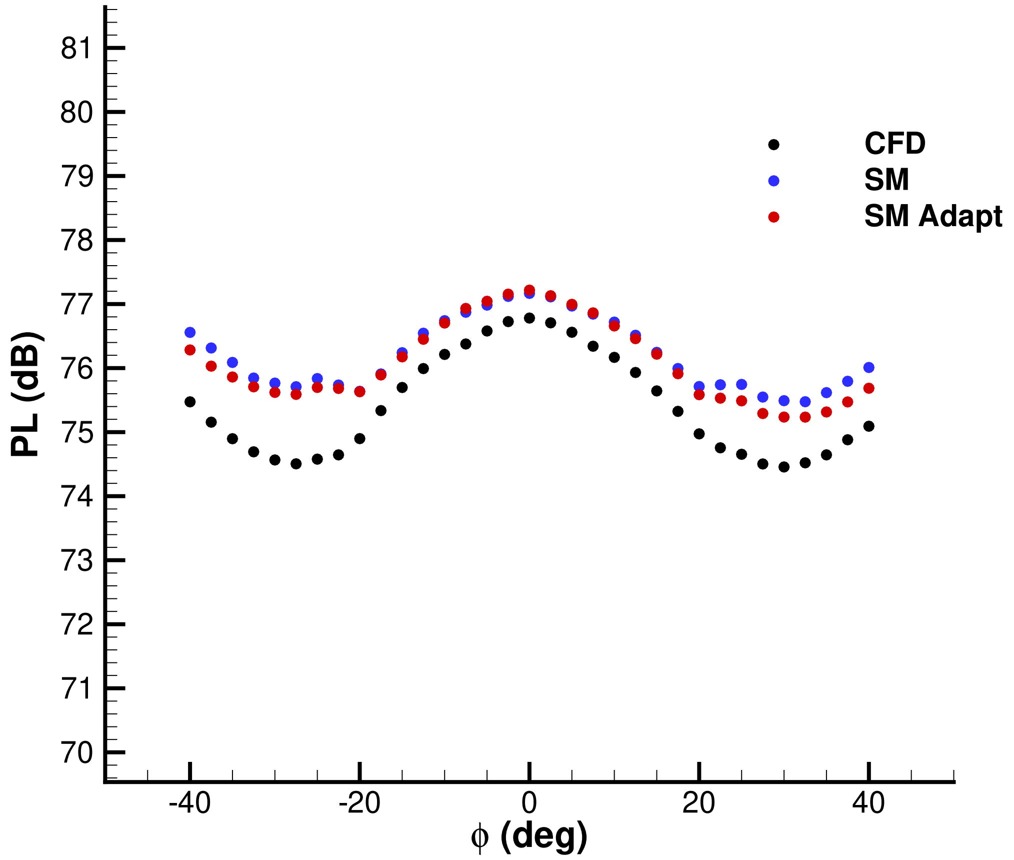


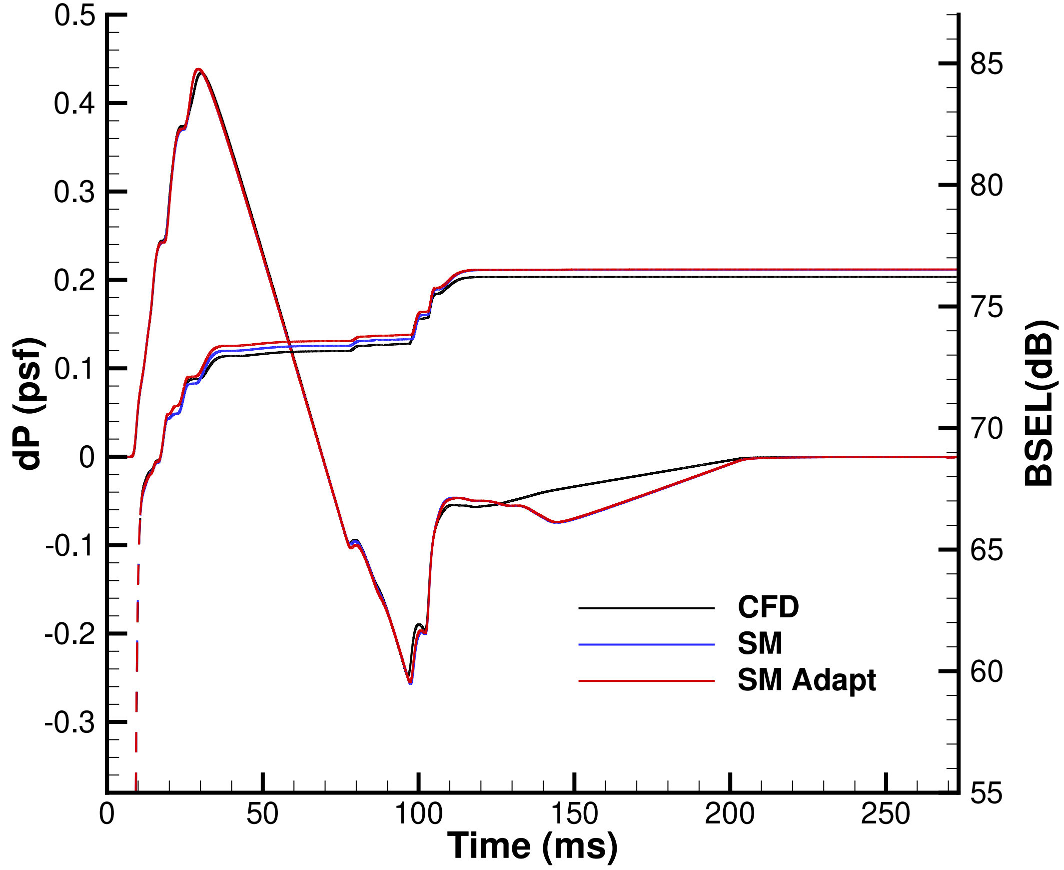
Near-field Pressure Signatures





Loudness Predictions





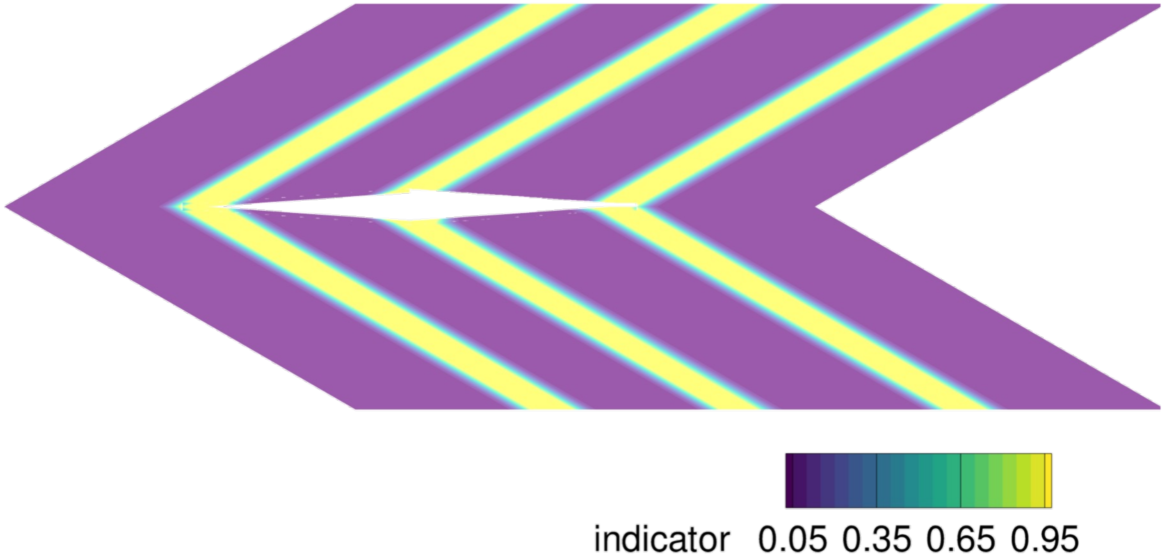
Loudness Metrics	ASEL	BSEL	CSEL	PL
CFD	63.172	76.057	90.467	**76.781**
Space Marching	63.443	76.509	90.901	**77.167**
SM + Adapt	63.582	76.523	90.865	**77.217**

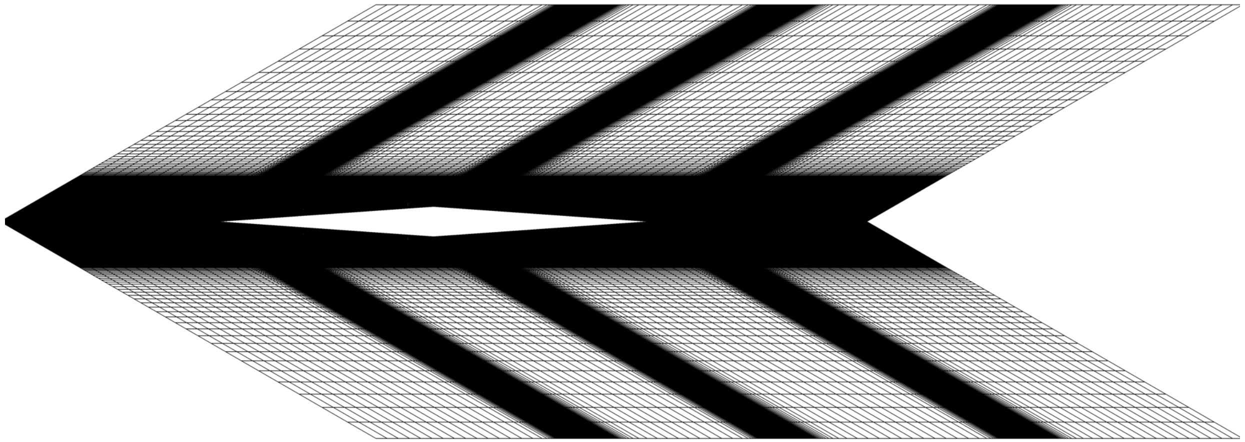
Summary

- Space marching for mid-field computation: >50% cost reduction with no loss in accuracy
- Database scripting and grid generation improvements enable rapid loudness predictions for large sets of cases
- Mesh redistribution increases robustness enabling a wider range of flight conditions

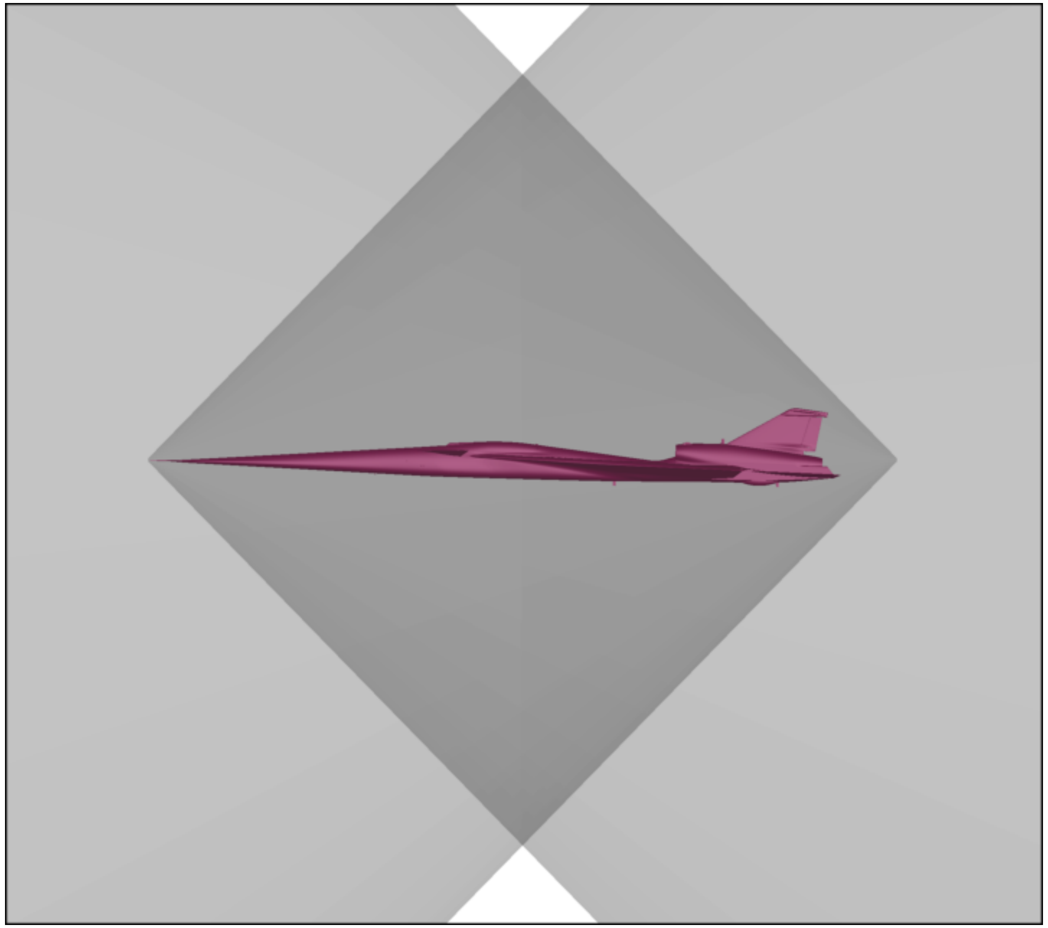
Acknowledgments

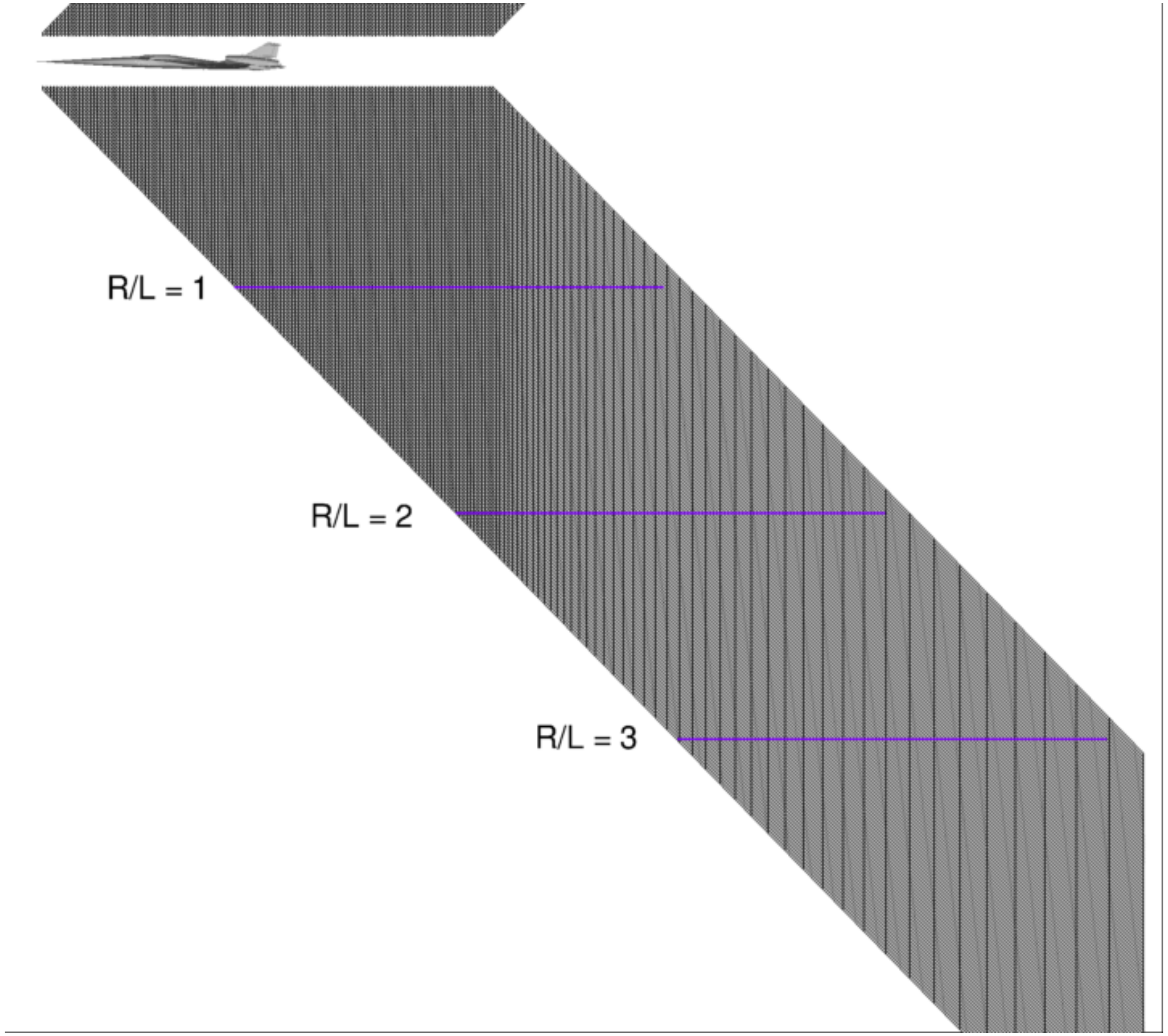
- Work partially supported by NASA's Commercial Supersonic Technology (CST) and Transformational Tools and Technologies (TTT) projects within the Aeronautics Research Mission Directorate (ARMD)
- Support from James Koch, James Jensen, Brandon Lowe, and Emre Sozer of the LAVA team
- Computer time has been provided by NASA's Advanced Supercomputing (NAS) at NASA Ames Research Center



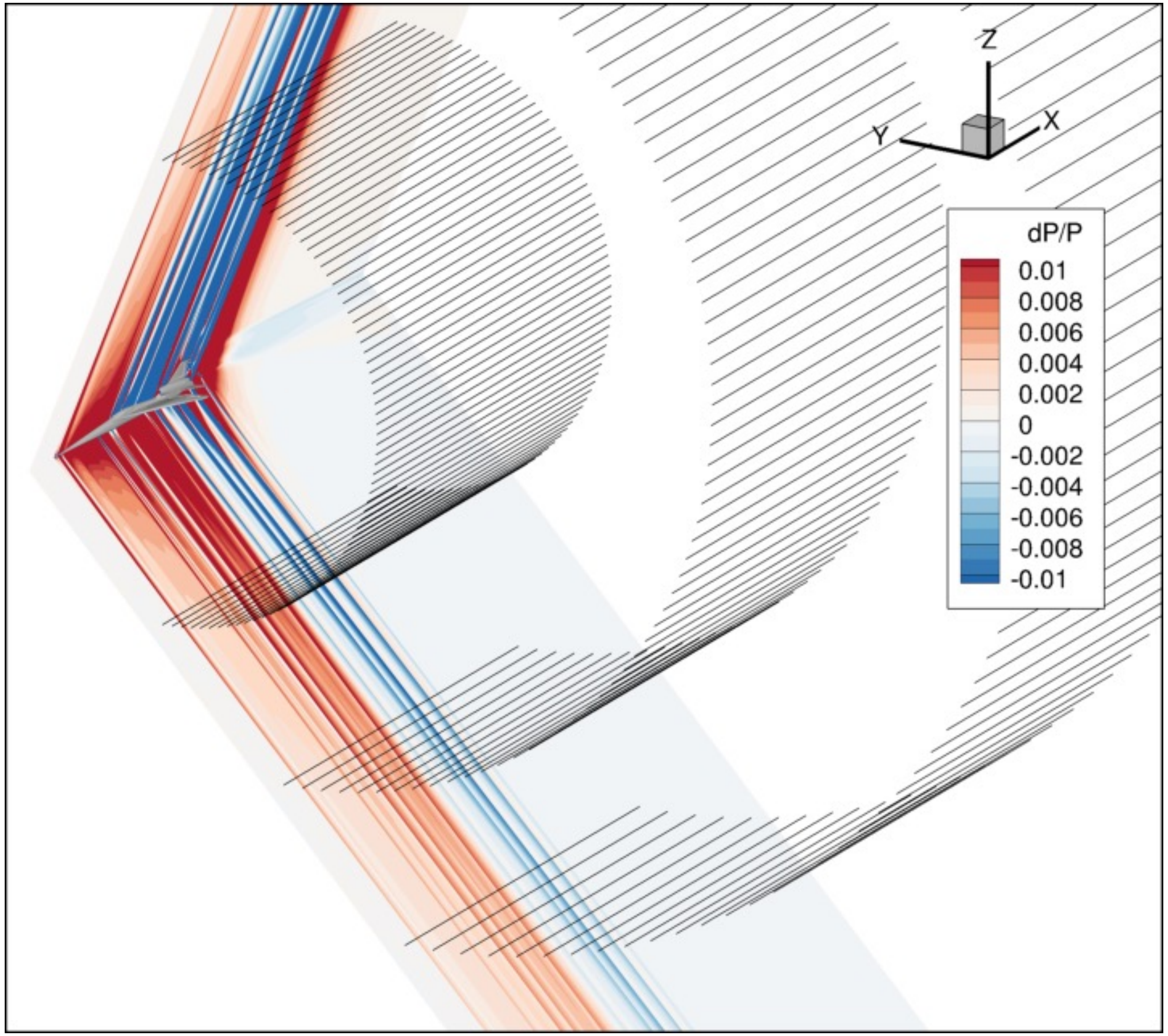


Space marching domain reduction





Two Step Loudness Prediction Procedure



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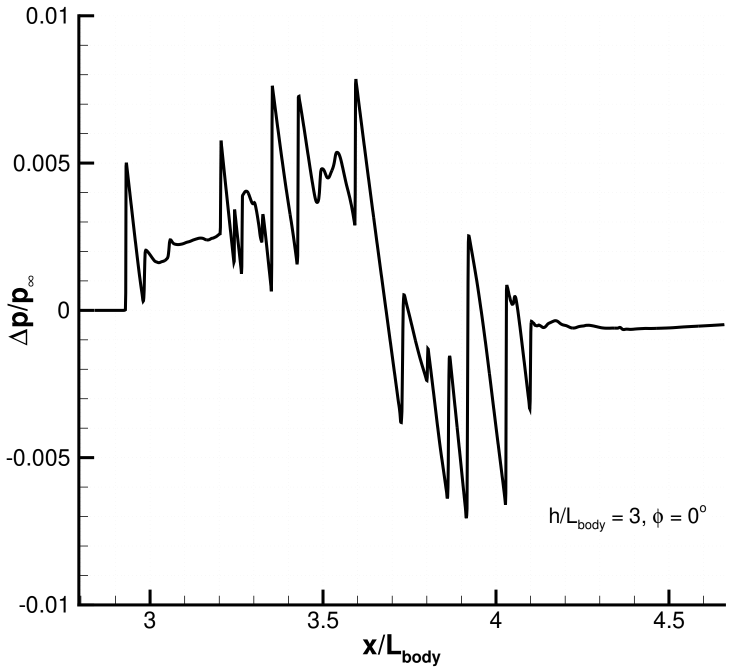
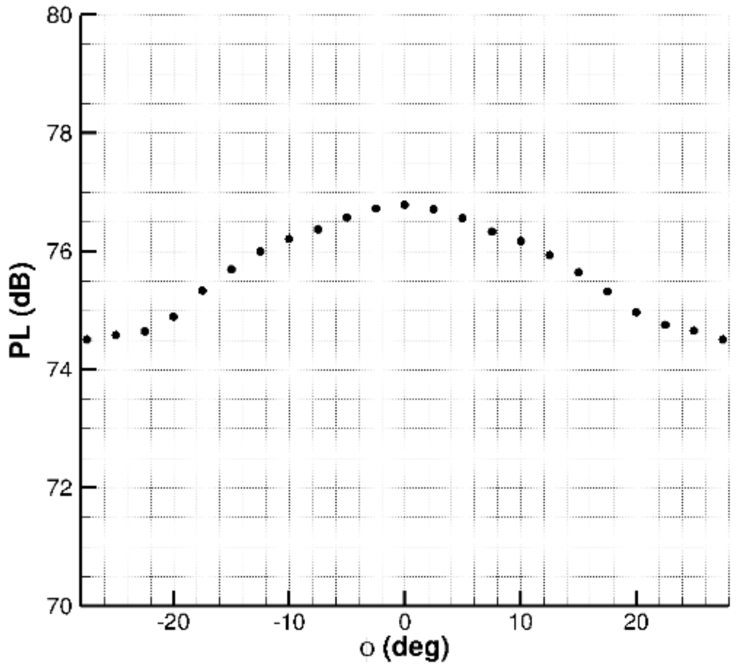
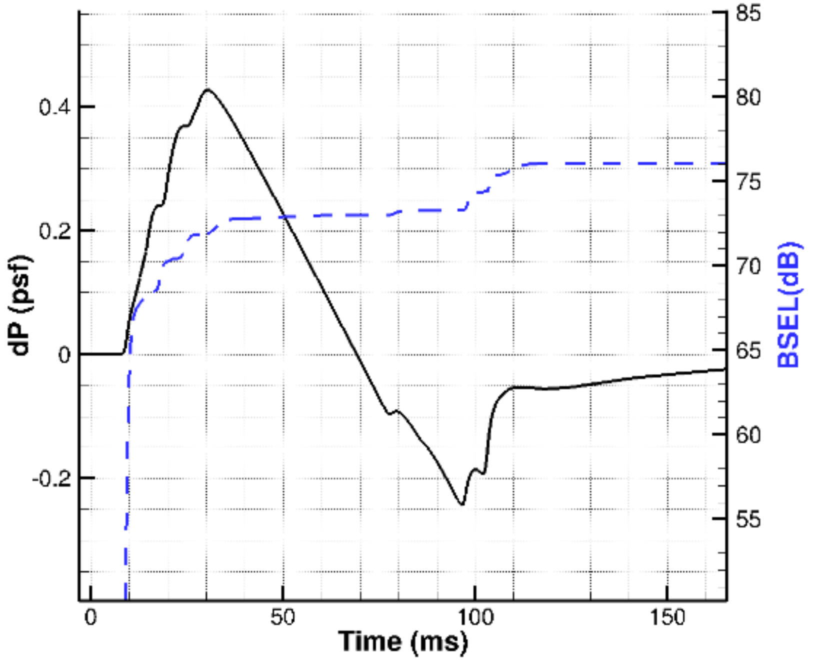


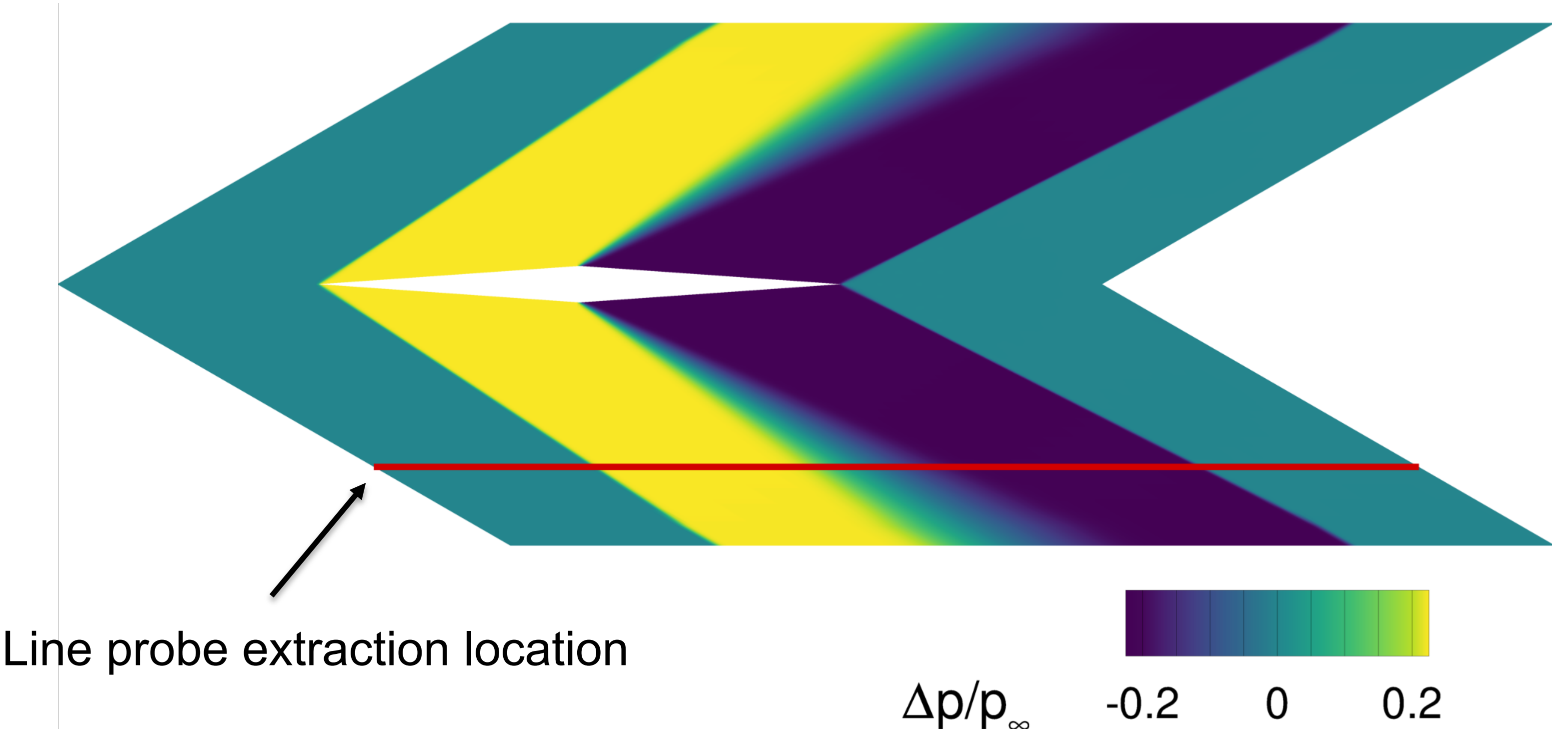




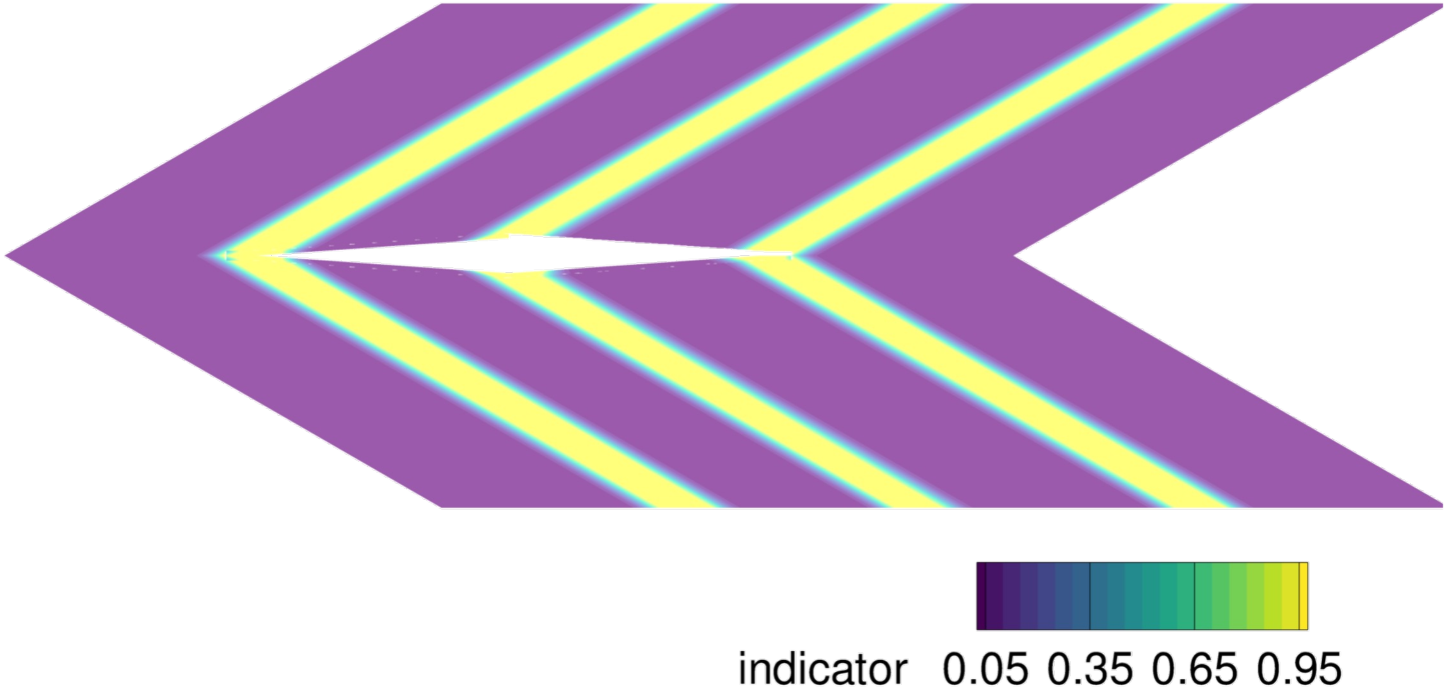
Adaptation Verification

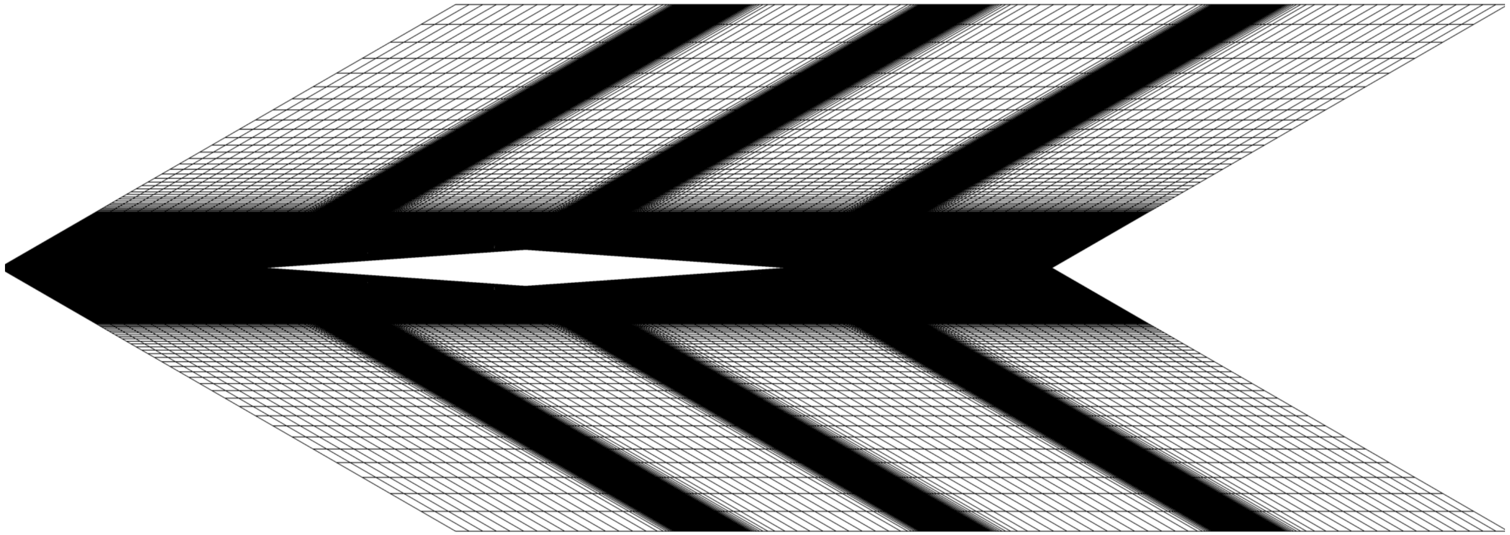
- Diamond airfoil reference conditions
  - Mach number: 2.0
  - Freestream pressure: 101,325 Pa
  - Freestream temperature: 288.2 K

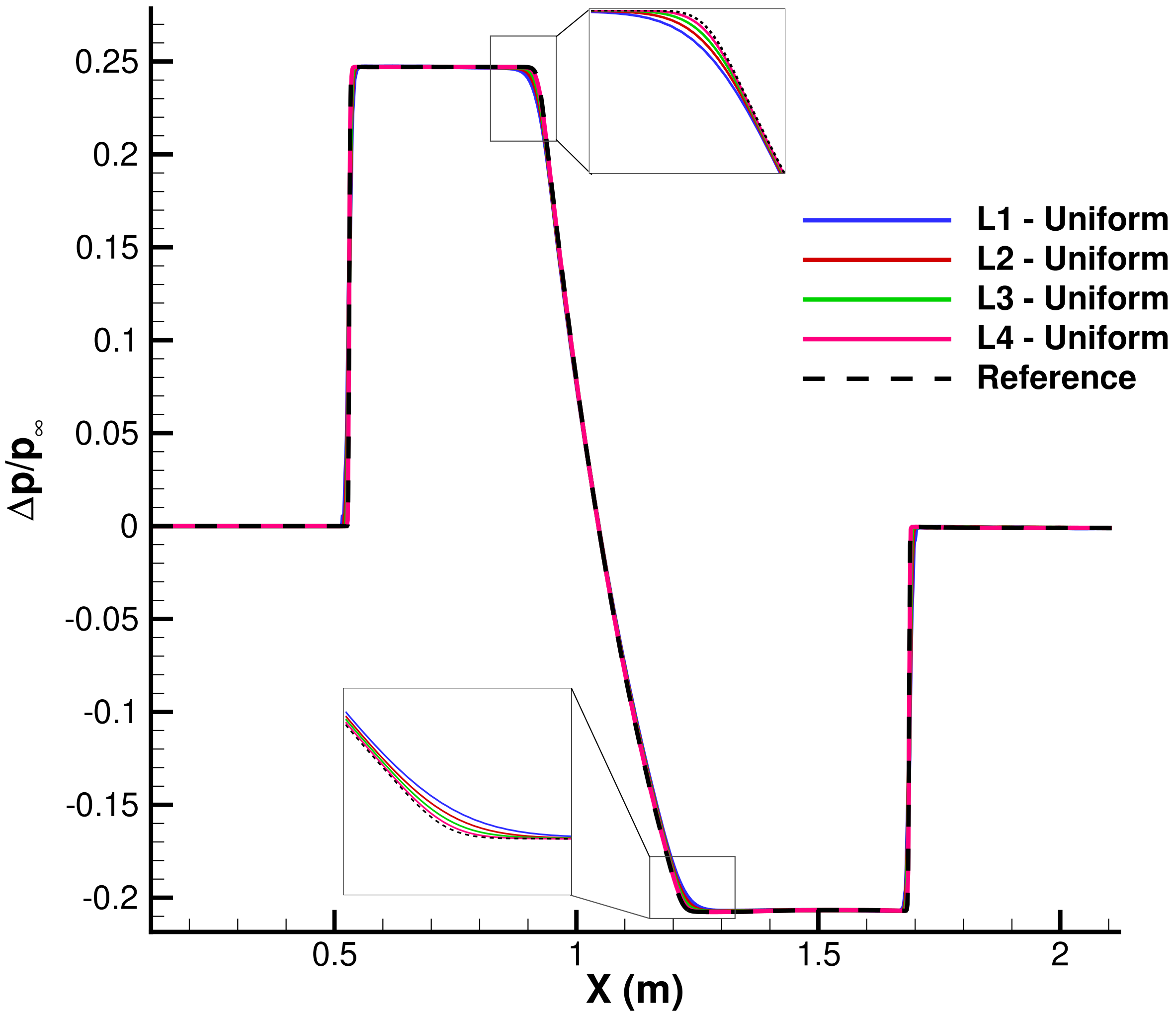
- Mesh details
  - 8 near-body blocks
  - Mach cone aligned off-body grid with uniform streamwise spacing
  - 110,866 solution nodes



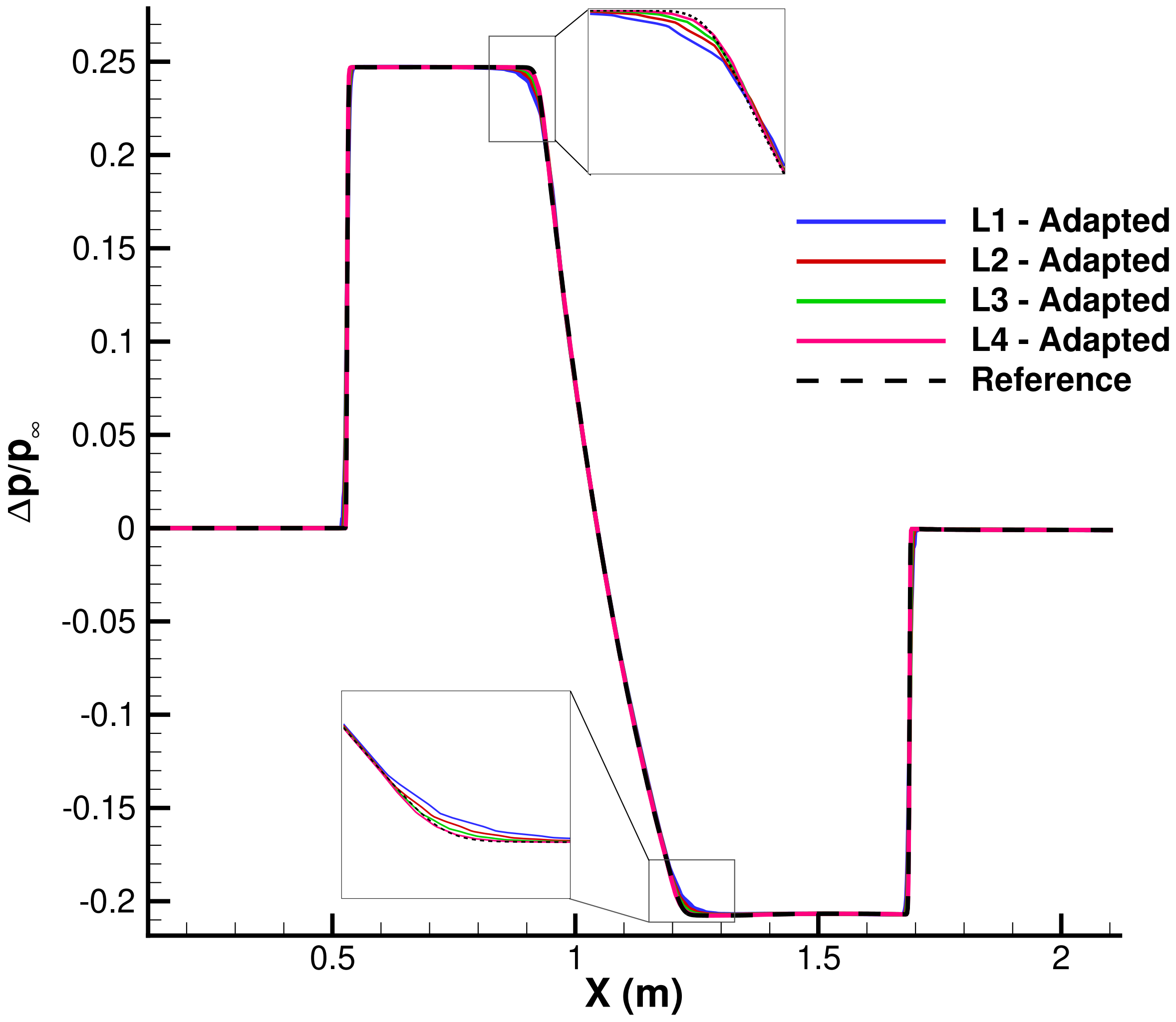
Adaptation Results



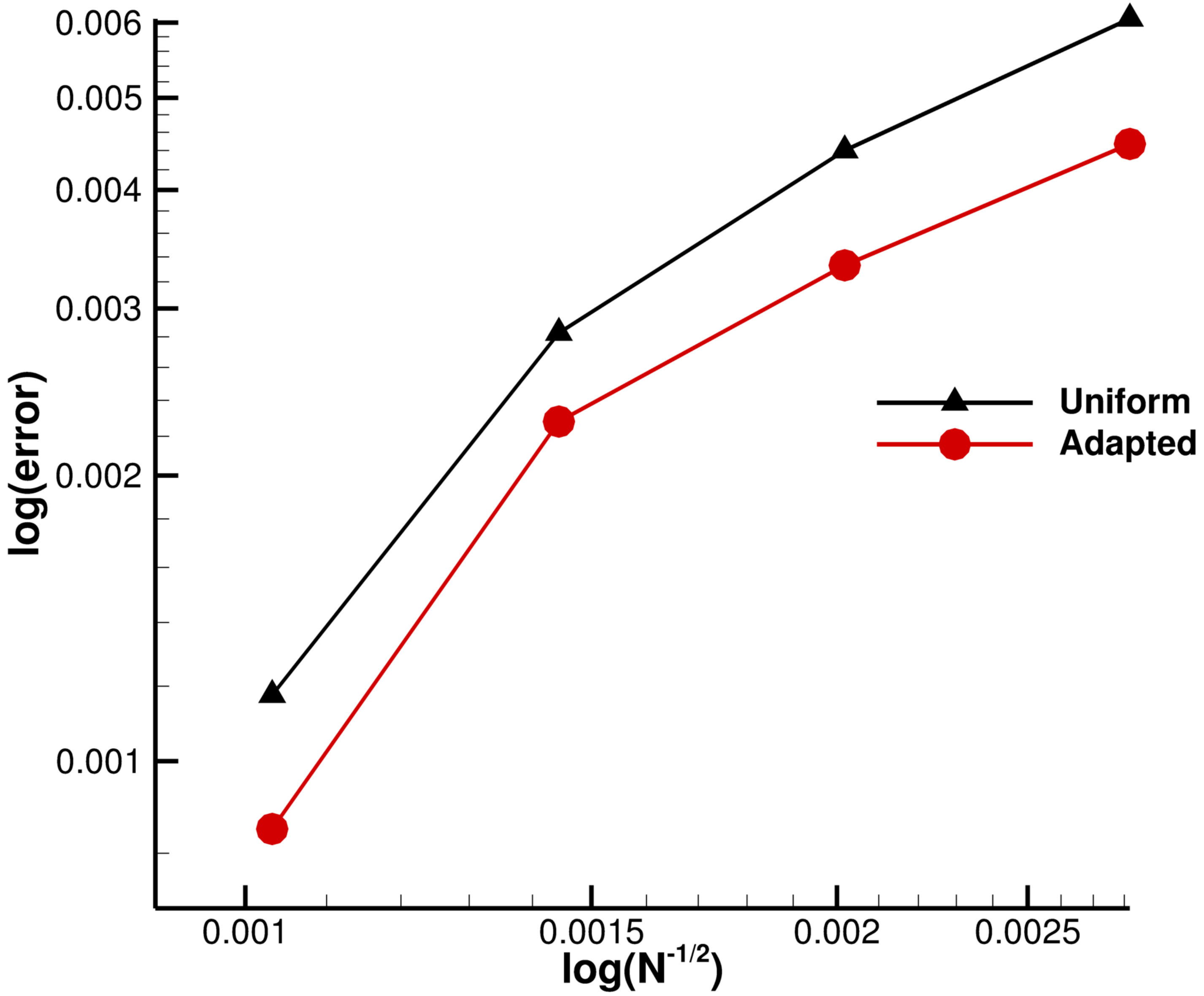


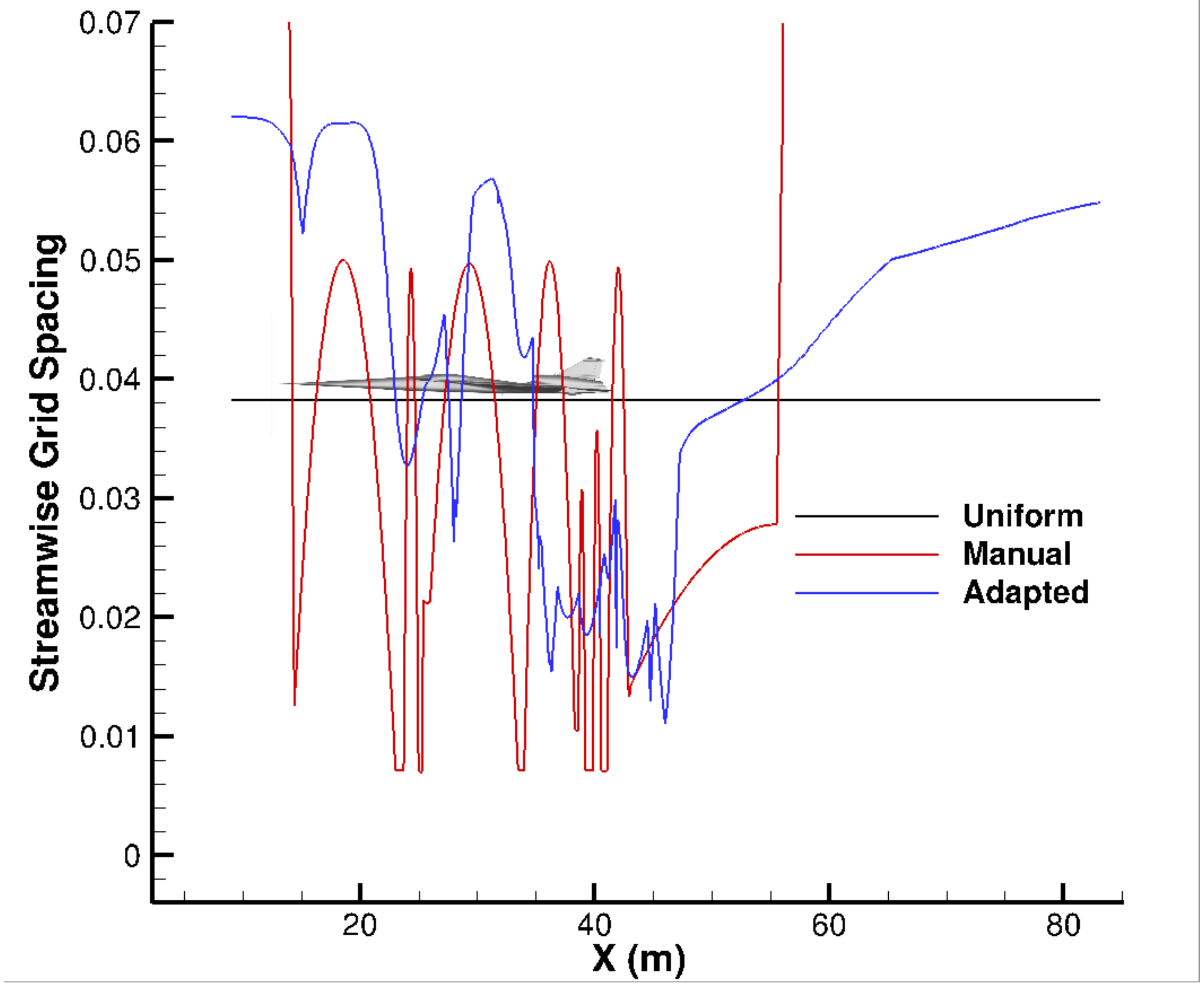


L1 - Uniform
L2 - Uniform
L3 - Uniform
L4 - Uniform
Reference
Δp/p∞
X (m)
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0.5
1
1.5
2



L1 - Adapted
L2 - Adapted
L3 - Adapted
L4 - Adapted
Reference
Δp/p∞
X (m)
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0.5
1
1.5
2


0.006
0.005
0.004
0.003
0.002
0.001
log(error)
0.001
0.0015
0.002
0.0025
log(N^{-1/2})
Uniform
Adapted



Streamwise Grid Spacing
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
20
40
60
80
X (m)
Uniform
Manual
Adapted

Motivation

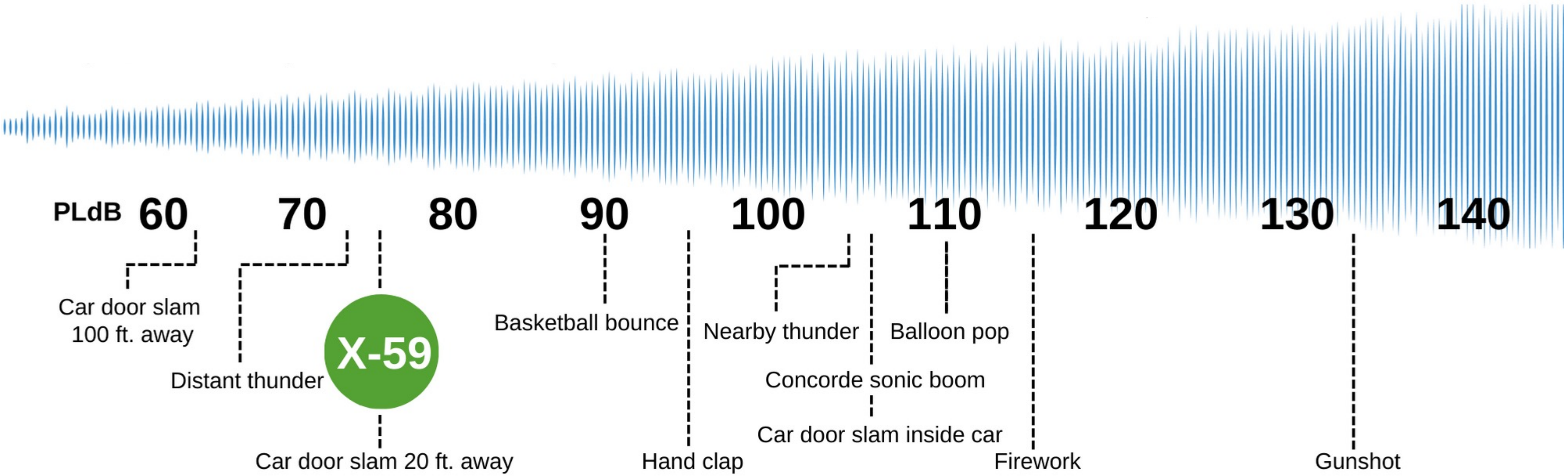


Image credit: NASA/QueSST