Cart3D Simulations

for the 2nd AIAA Sonic Boom Prediction Workshop

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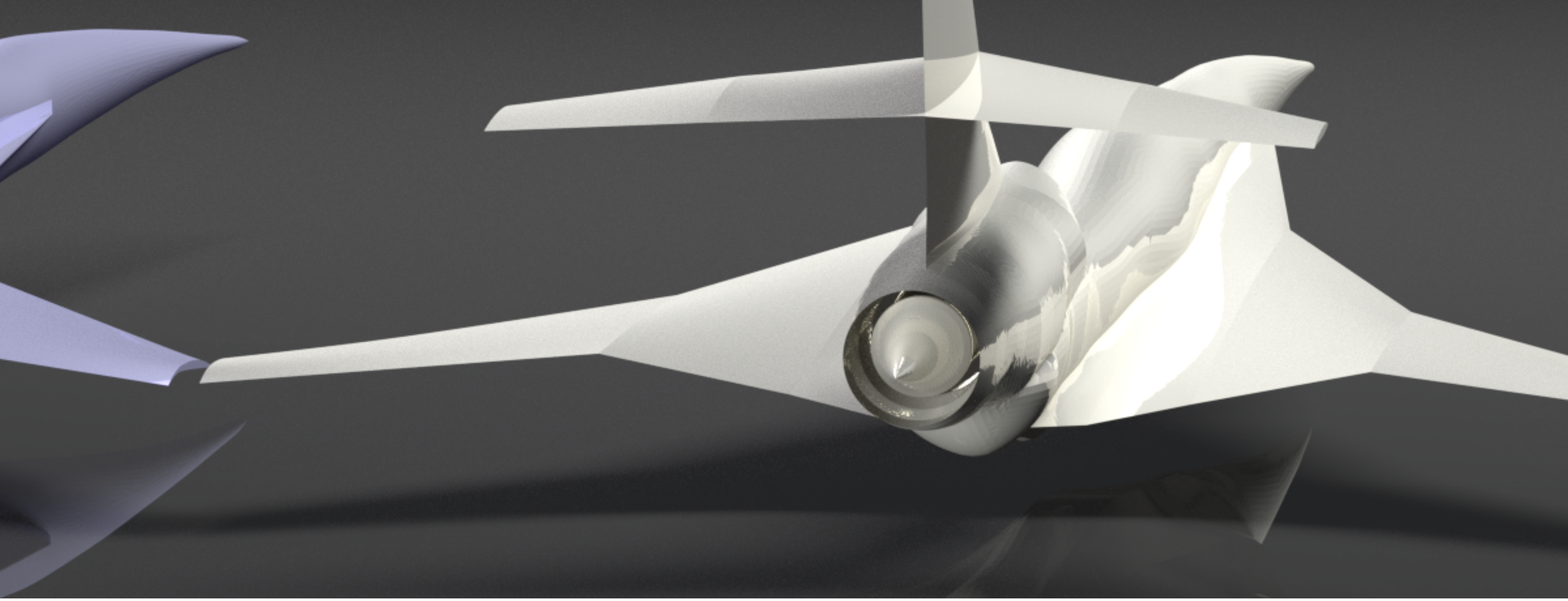
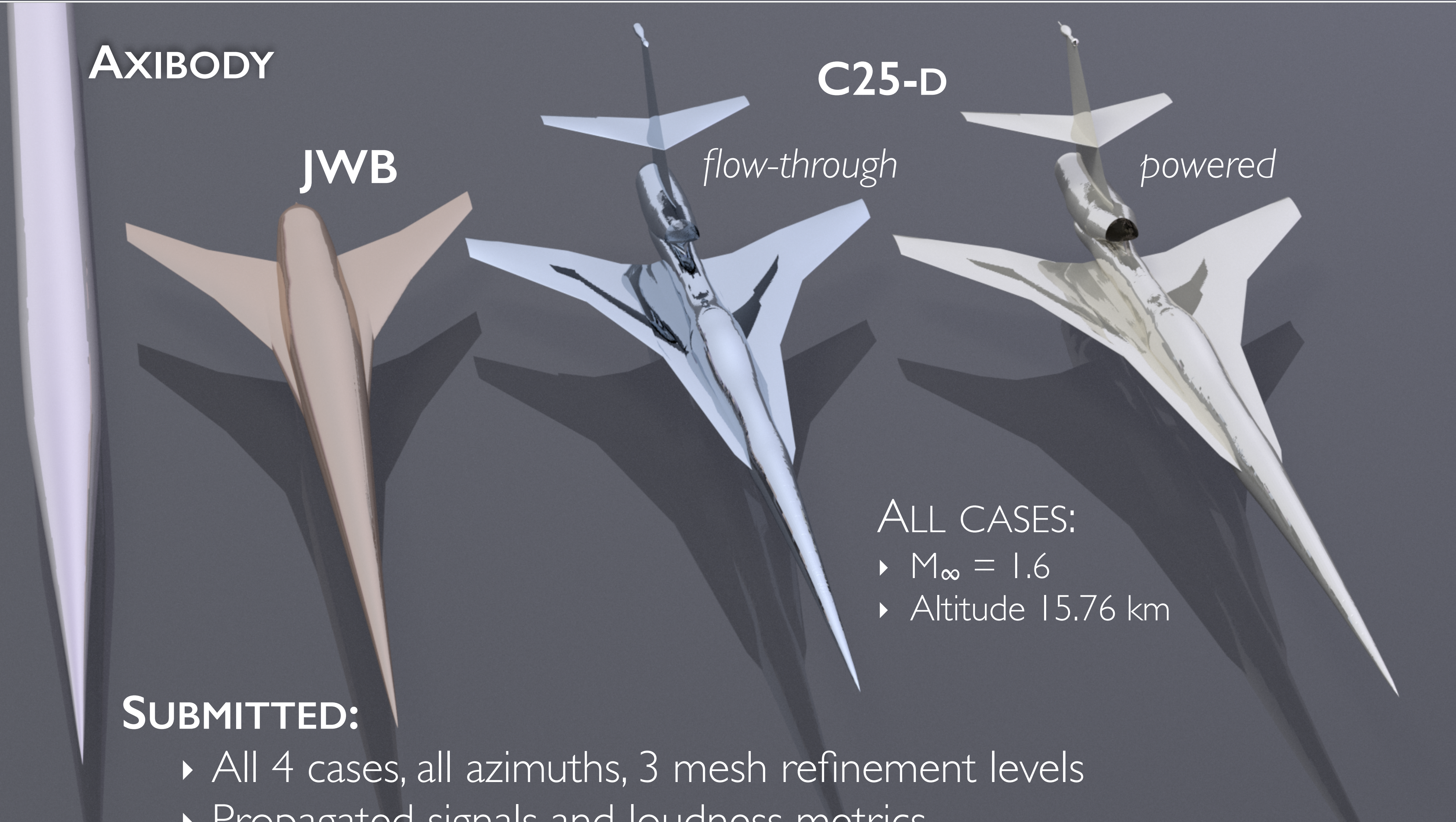


CASES SUBMITTED



ALL CASES:

- $M_\infty = 1.6$
- Altitude 15.76 km

SUBMITTED:

- All 4 cases, all azimuths, 3 mesh refinement levels
- Propagated signals and loudness metrics

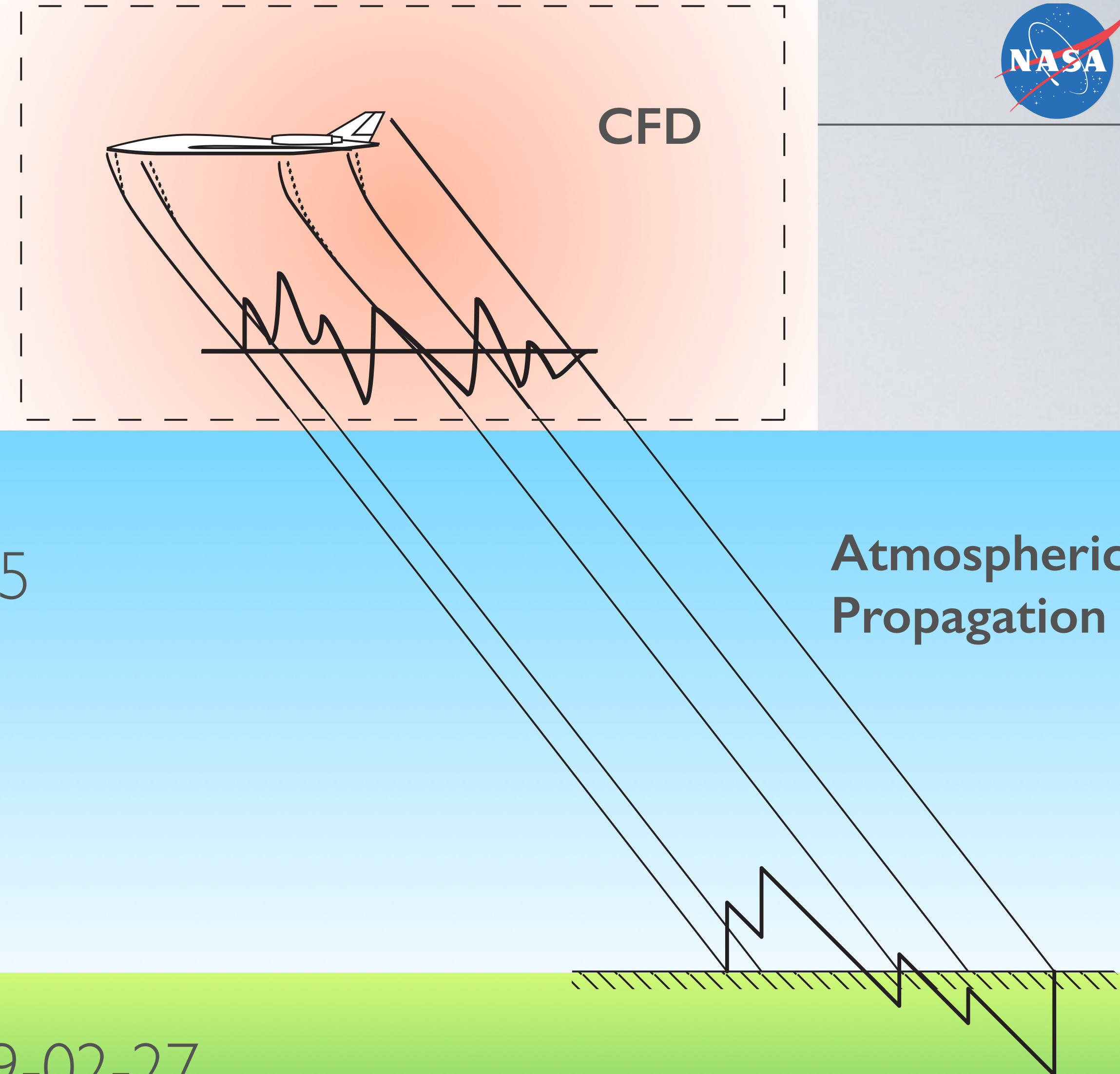
OUTLINE

- **Solvers and Adaptive Meshing**
  Axibody results as demo
- **Multi-azimuth Problems with Cartesian Meshes**
- **Selected Workshop Results**
- **Mesh Size and Cost**
- **Conclusions**

APPROACH

Flow Solver — Cart3D v1.5

- Steady, inviscid flow
- Adjoint-based mesh refinement



Propagation — sBOOM* v2.5

- Augmented Burgers' Equation
- Standard atmosphere model

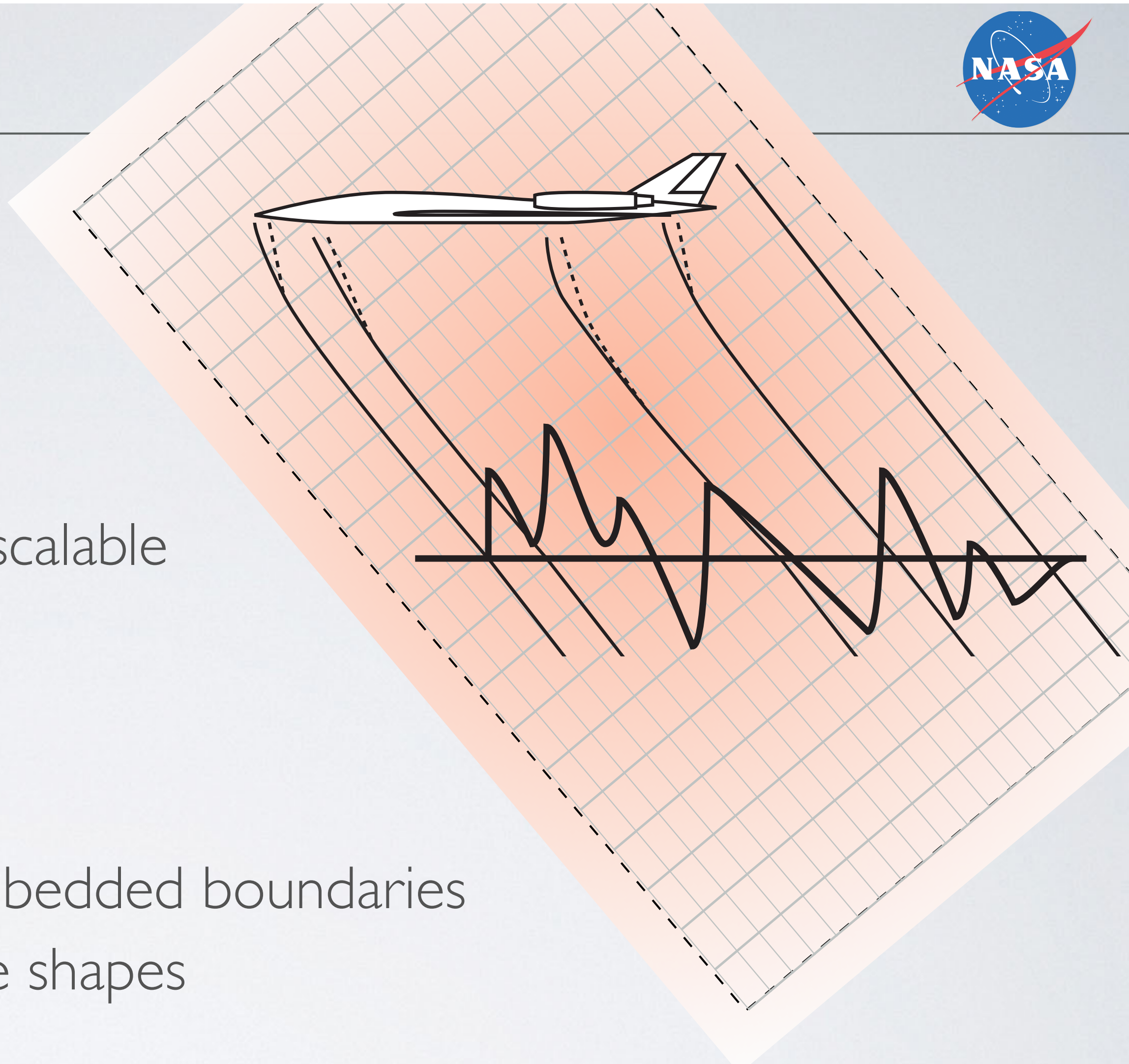
Loudness — LCASB** v. 2009-02-27

- *"Loudness Code for Asymmetric Sonic Booms"*
- Computes Perceived Loudness (PLdB)

* Rallabhandi, ***"Advanced Sonic Boom Prediction Using the Augmented Burgers Equation"*** J. Aircraft, 2011.

** Shepherd and Sullivan, ***"A Loudness Calculation Procedure Applied to Shaped Sonic Booms"***, *NASA TP, 1991.*

CFD AND MESHING



Flow Solver — Cart3D v1.5

- Steady, inviscid flow
- 2nd-order upwind method
- Multigrid acceleration
- Domain decomposition — highly scalable
- *For today: van Leer, Barth-Jespersen*

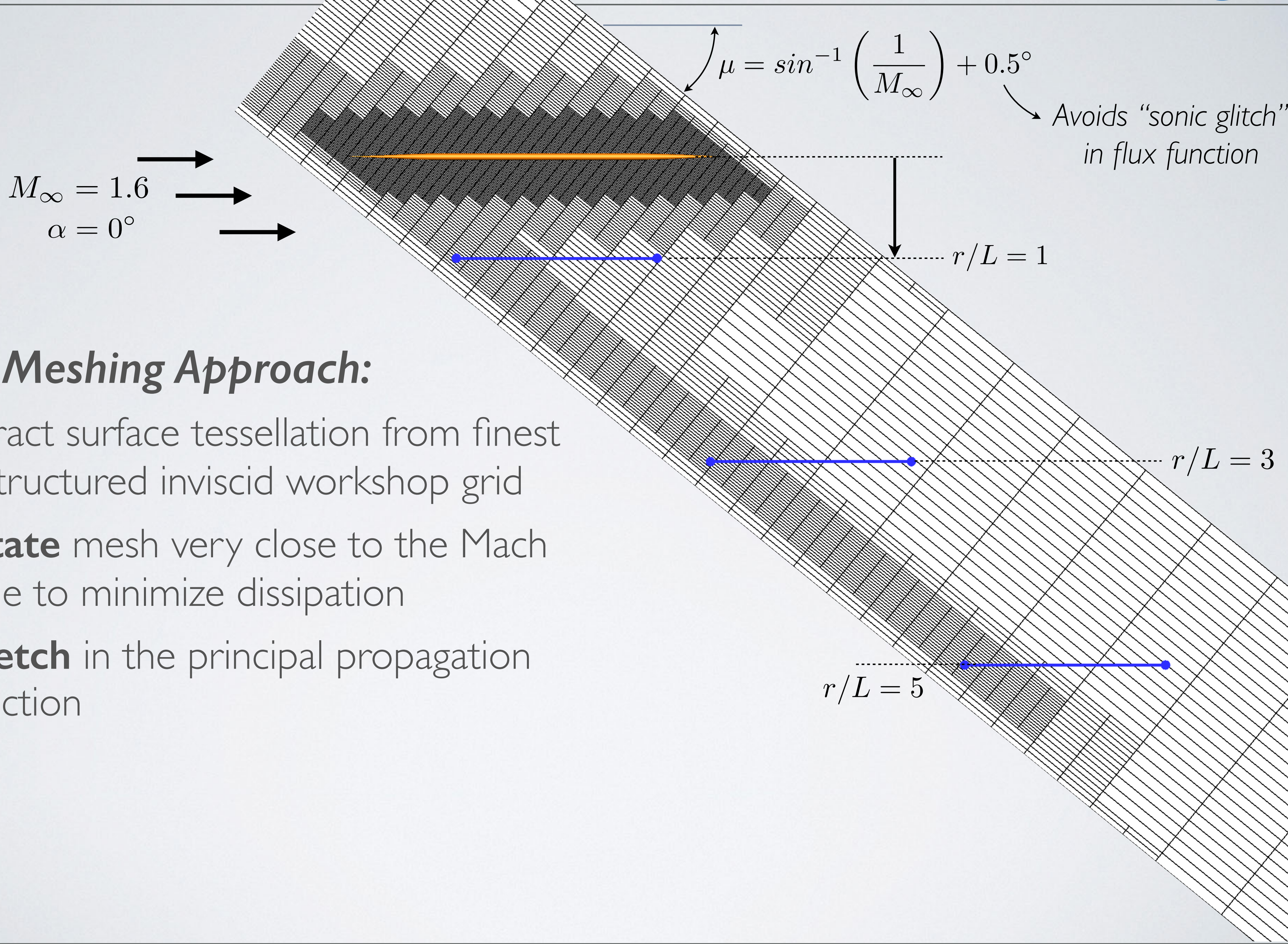
Automatic Meshing

- Multilevel Cartesian mesh with embedded boundaries
- Handles arbitrarily complex vehicle shapes

Output-Driven Mesh Adaptation

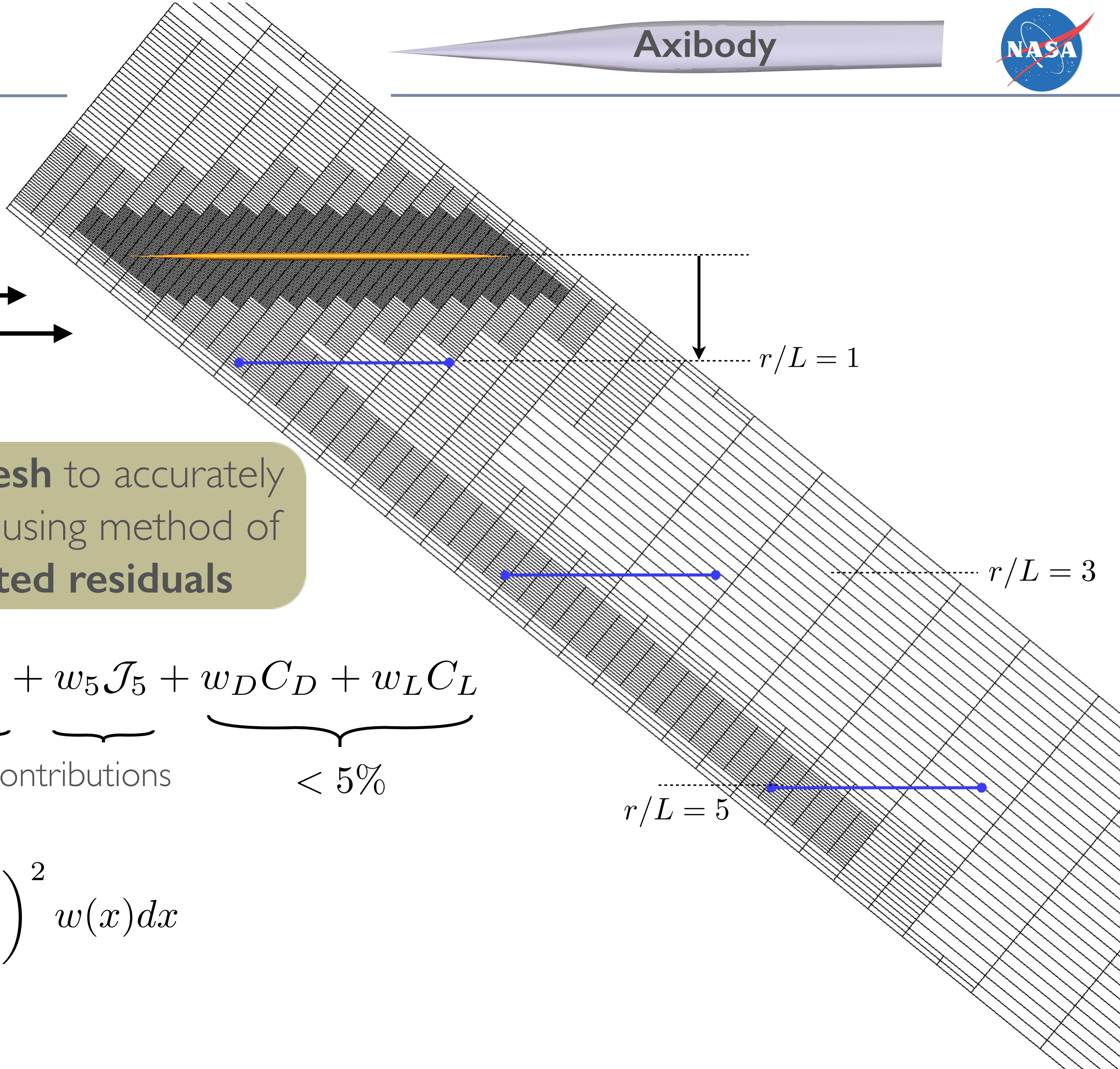
- Local error estimates computed via discrete adjoint
- Mesh is refined in locations with highest impact on pressure signatures

MESHING



Basic Meshing Approach:

- Extract surface tessellation from finest unstructured inviscid workshop grid
- **Rotate** mesh very close to the Mach angle to minimize dissipation
- **Stretch** in the principal propagation direction



$M_\infty = 1.6$
$\alpha = 0^\circ$

Locally refine mesh to accurately compute outputs, using method of **adjoint-weighted residuals**

$$\mathcal{J} = \underbrace{w_1 \mathcal{J}_1}_{} + \underbrace{w_3 \mathcal{J}_3}_{} + \underbrace{w_5 \mathcal{J}_5}_{} + \underbrace{w_D C_D + w_L C_L}_{< 5\%}$$

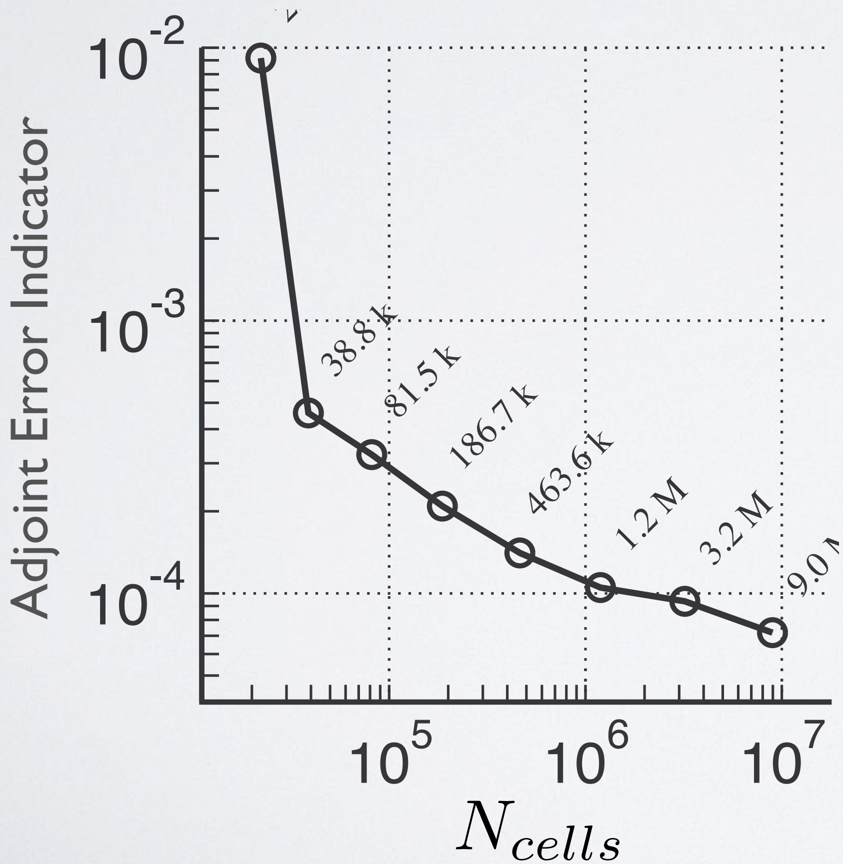
Roughly equal contributions

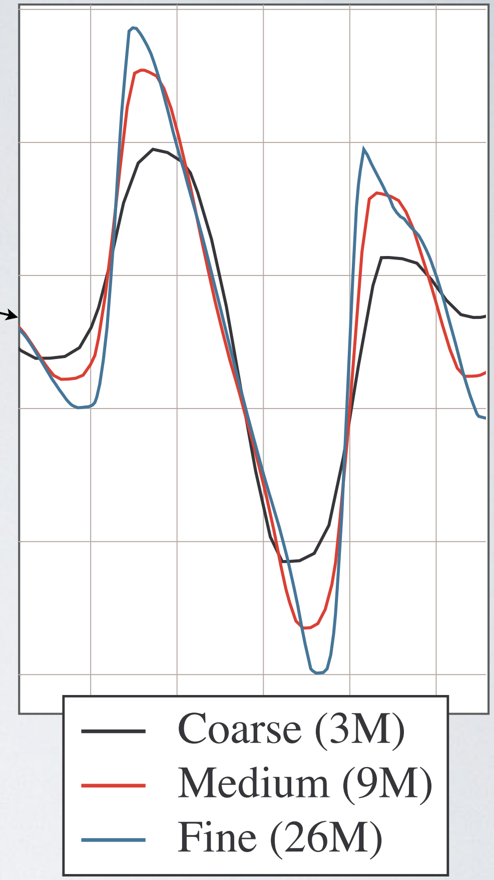
$$\mathcal{J}_i = \int_0^L \left(\frac{p - p_\infty}{p_\infty} \right)^2 w(x) dx$$

MESH CONVERGENCE GUIDELINES

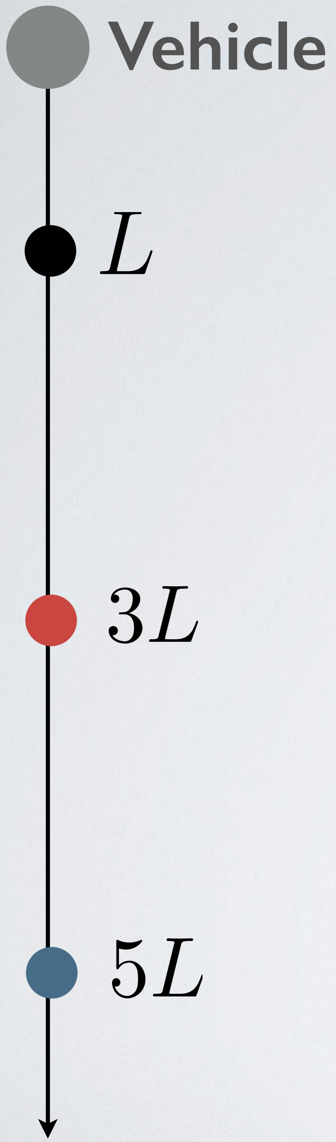
What do we call *"coarse"*, *"medium"* and *"fine"*?

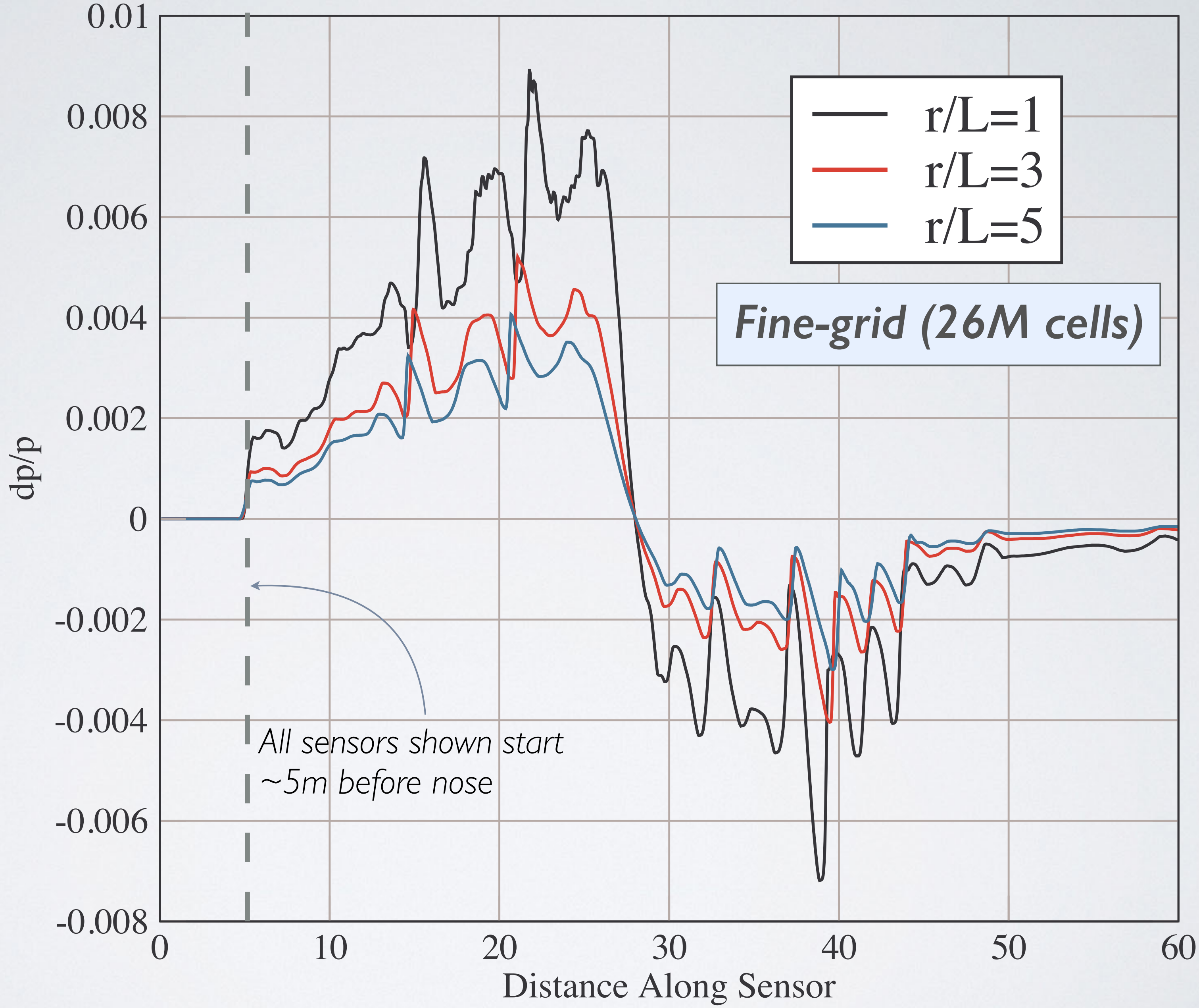
- *Aware* of workshop mesh sizes and guidelines, but allow adaptation to discover unexpected features!
- Guidelines we used:
  - ***Qualitative:*** Consistent signal features over consecutive meshes
  - ***Quantitative:*** Convergence of functional and **error** with refinement



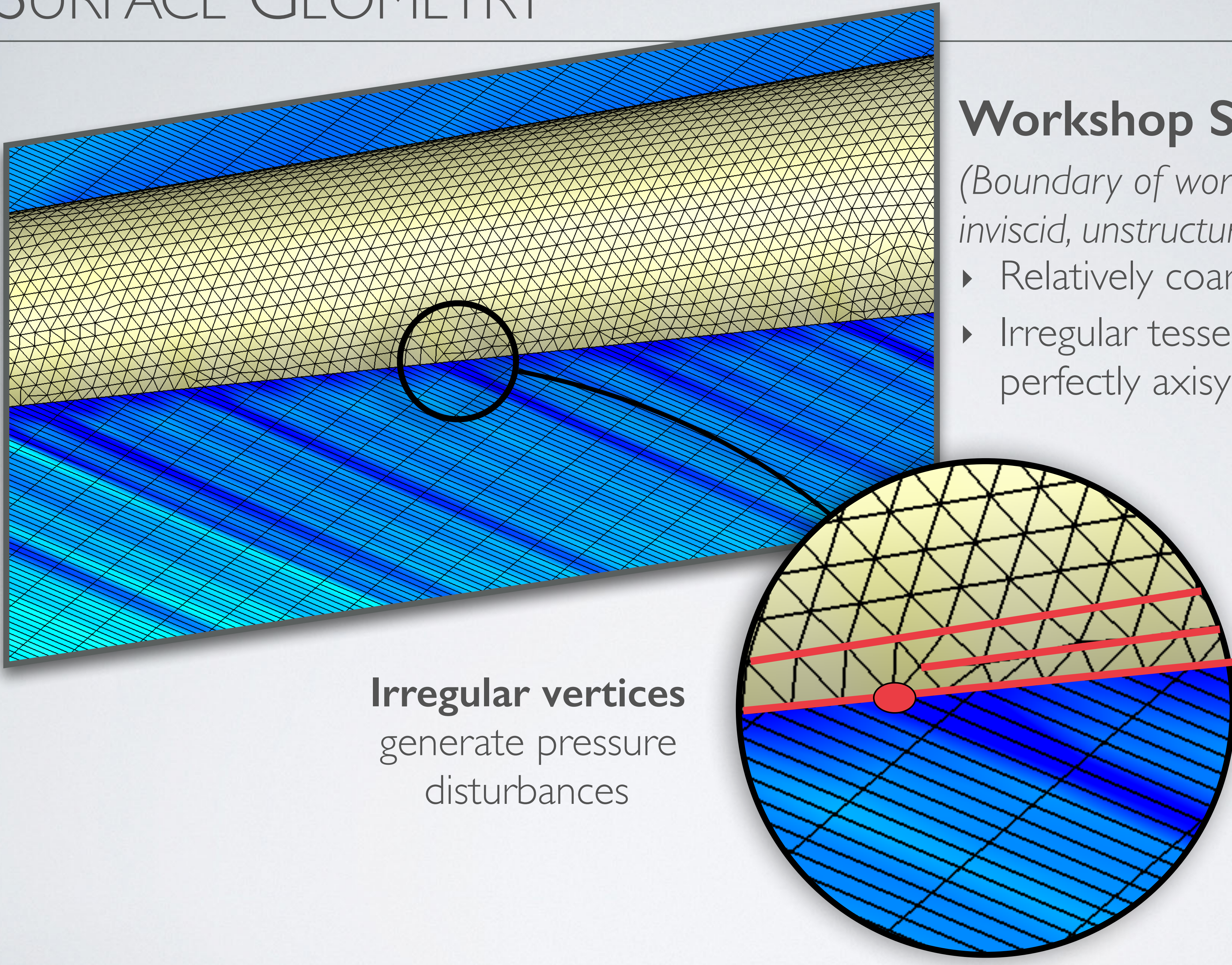



Axibody


Vehicle
L
$3L$
$5L$


0.01
0.008
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
dp/p
0
10
20
30
40
50
60
Distance Along Sensor
r/L=1
r/L=3
r/L=5
Fine-grid (26M cells)
All sensors shown start
~5m before nose

Surface Geometry



Workshop Surface Mesh

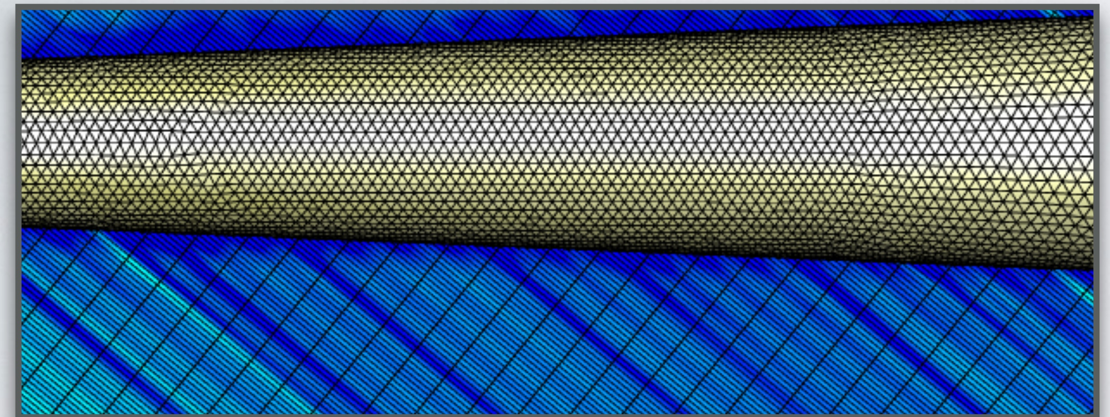
(Boundary of workshop "fine", inviscid, unstructured grid)

- Relatively coarse for Cart3D
- Irregular tessellation, not perfectly axisymmetric

Irregular vertices generate pressure disturbances

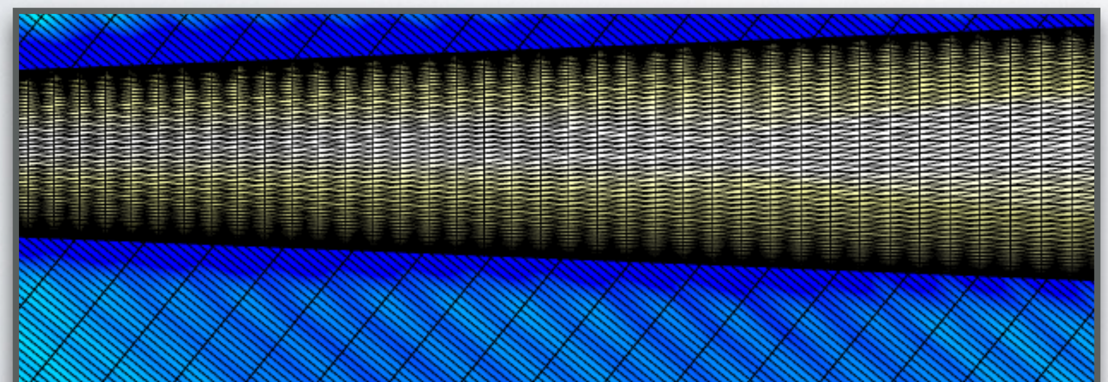
Workshop Grid

- Irregular oscillations, **persist through r/L=1.**

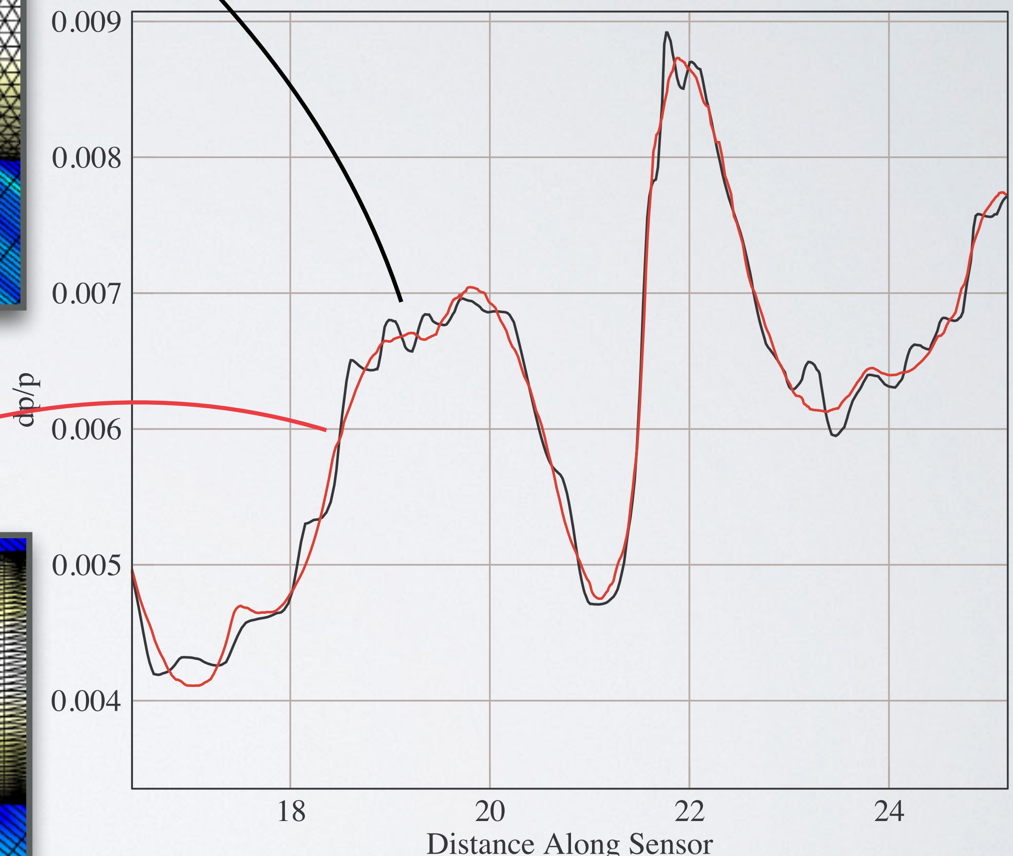


In-house Grid

- Regular oscillations, **cancel quickly.**



Fine-grid Signatures at r/L=1

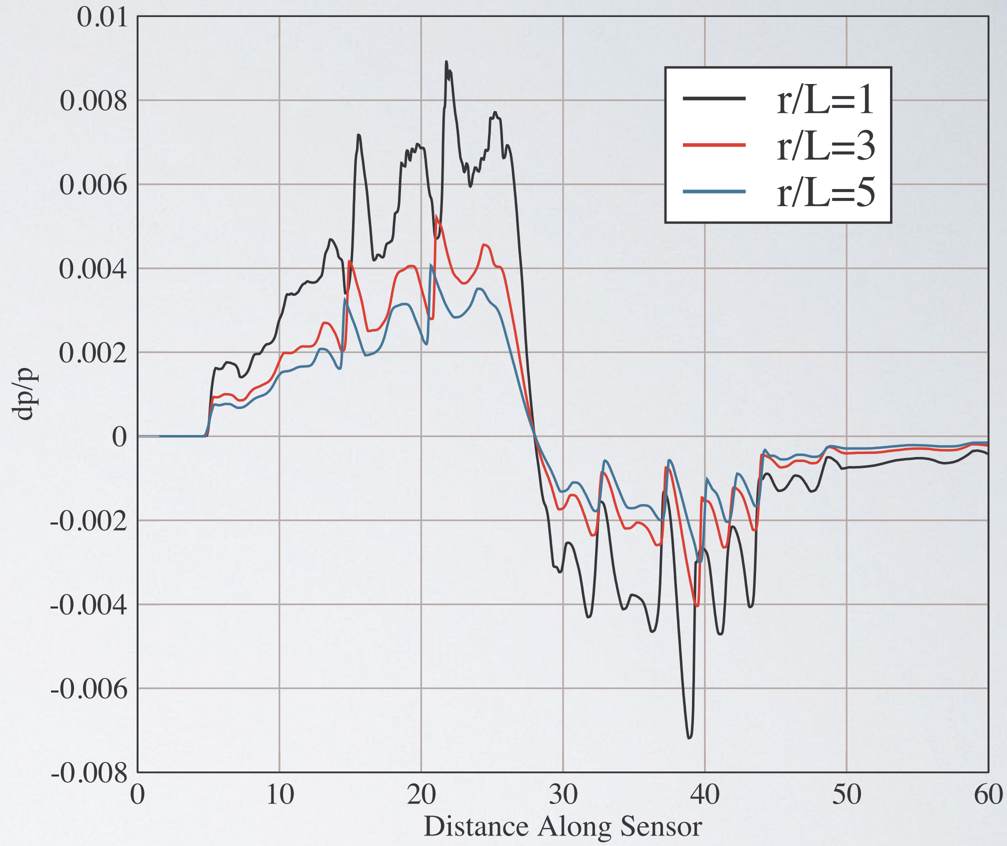


Surface Geometry

- At the farther distances, the oscillations disappear, even using the workshop meshes.

All results submitted use the provided workshop surface grids

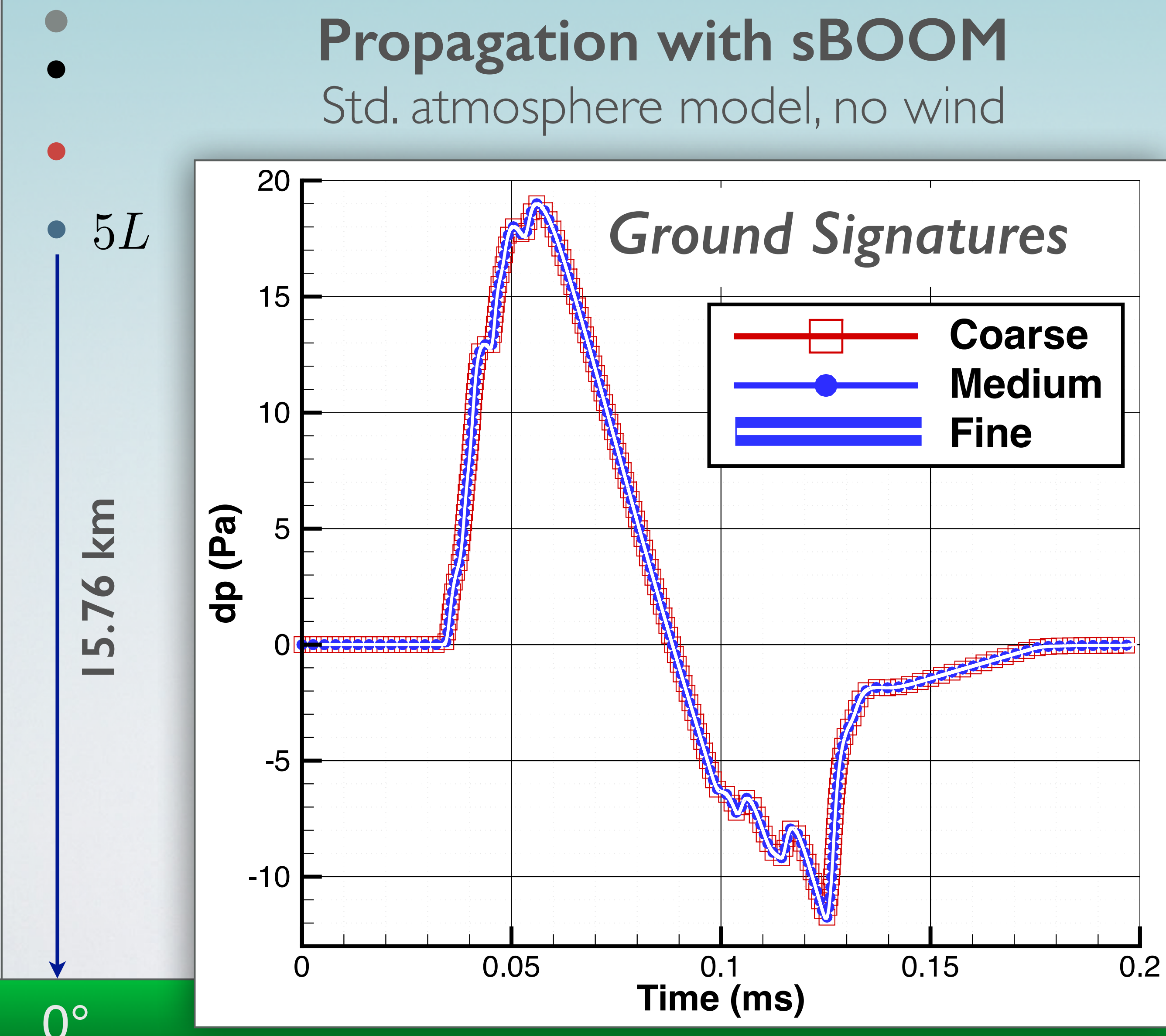
- ***Downside:*** Near-body signals are somewhat oscillatory
- ***Upside:*** Consistency with workshop, faster than generating in-house grids.



Axibody — Propagation and Loudness

Propagation with sBOOM

Std. atmosphere model, no wind



Perceived Loudness (PLdB)

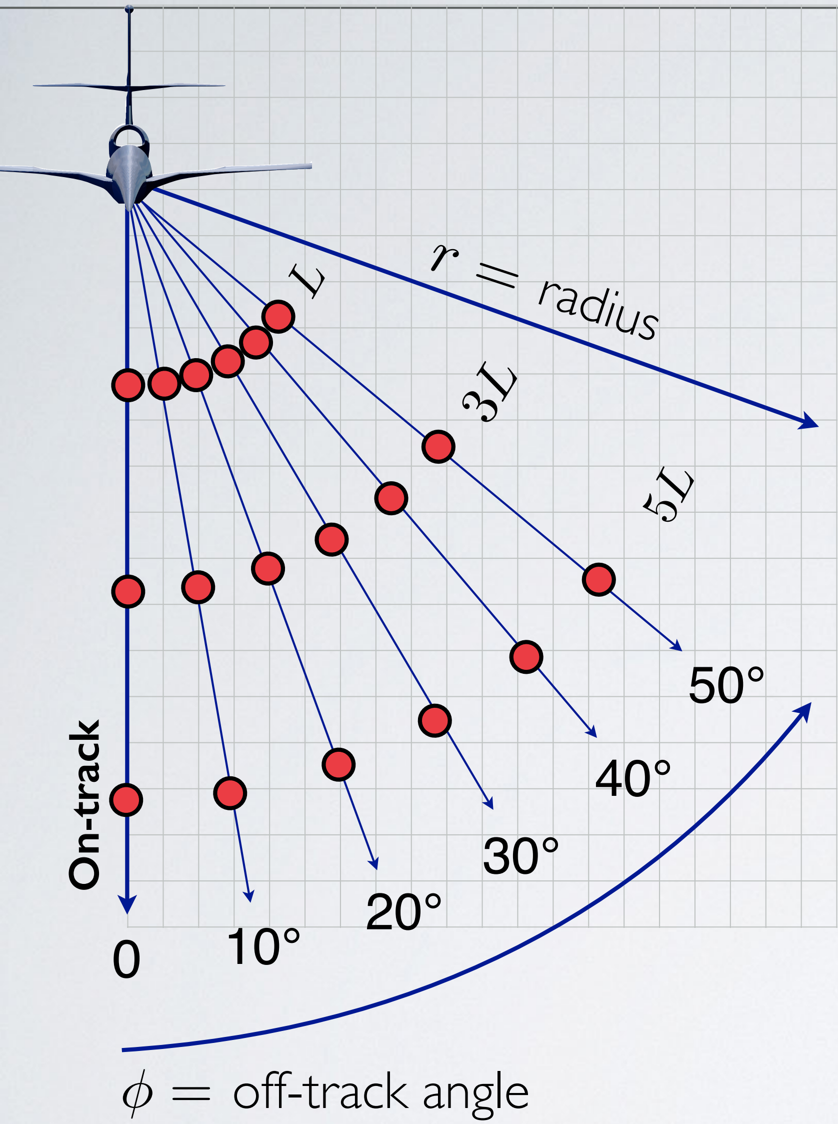
(LCASB)

78.5	78.3	78.1
Coarse	Medium	Fine
10min	30min	1hr15min

CFD time

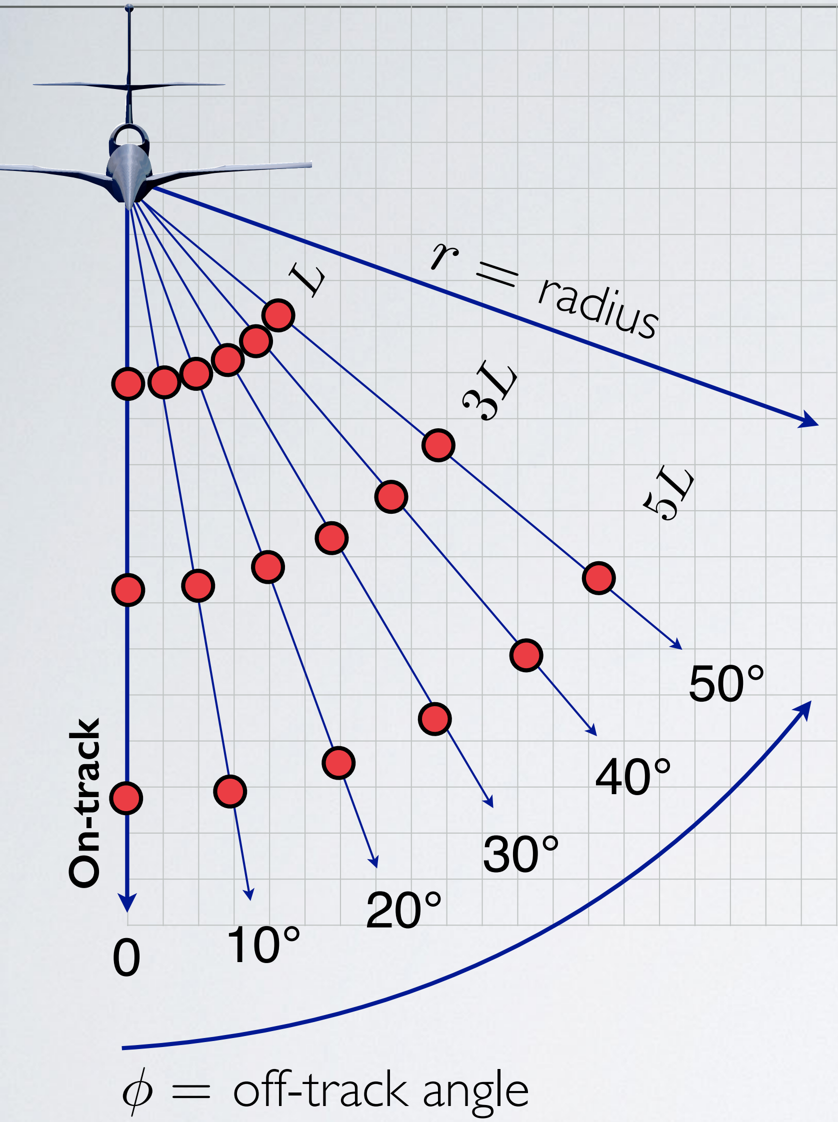
Loudness is fairly insensitive to CFD resolution

OFF-TRACK SOLUTIONS



- Straightforward approach — ***compute all sensors with a single mesh***
- With Cartesian-aligned grids, off-track angles are misaligned, leading to high dissipation and **high cell-counts**.

OFF-TRACK SOLUTIONS



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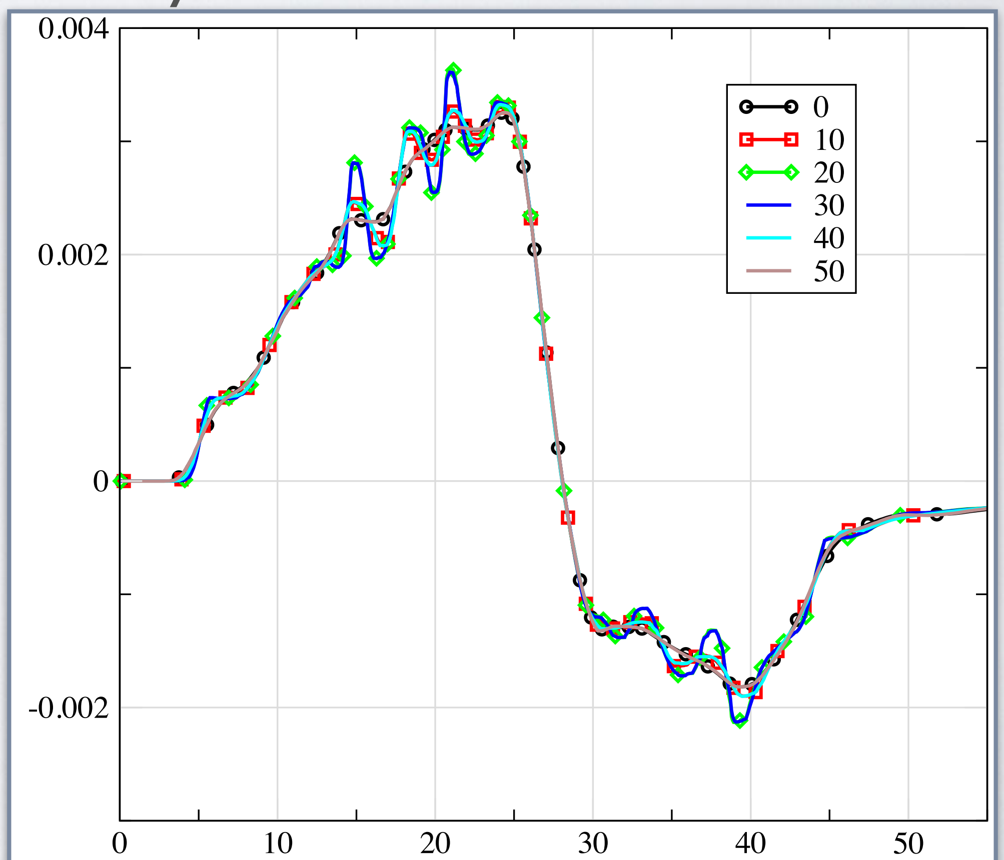
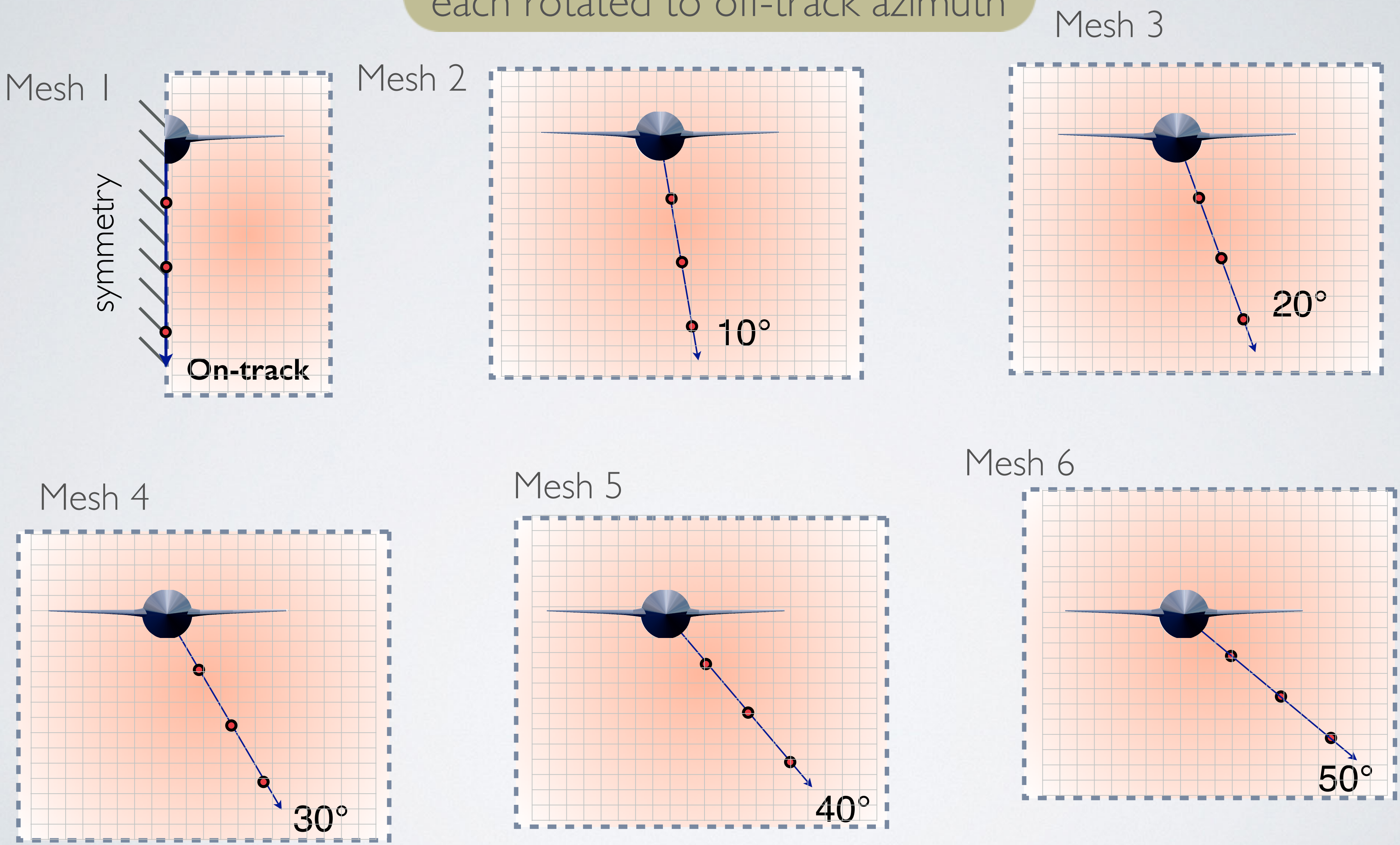
Axibody case at all azimuths in one mesh



Off-Track Solutions

Use independent meshes,
each rotated to off-track azimuth



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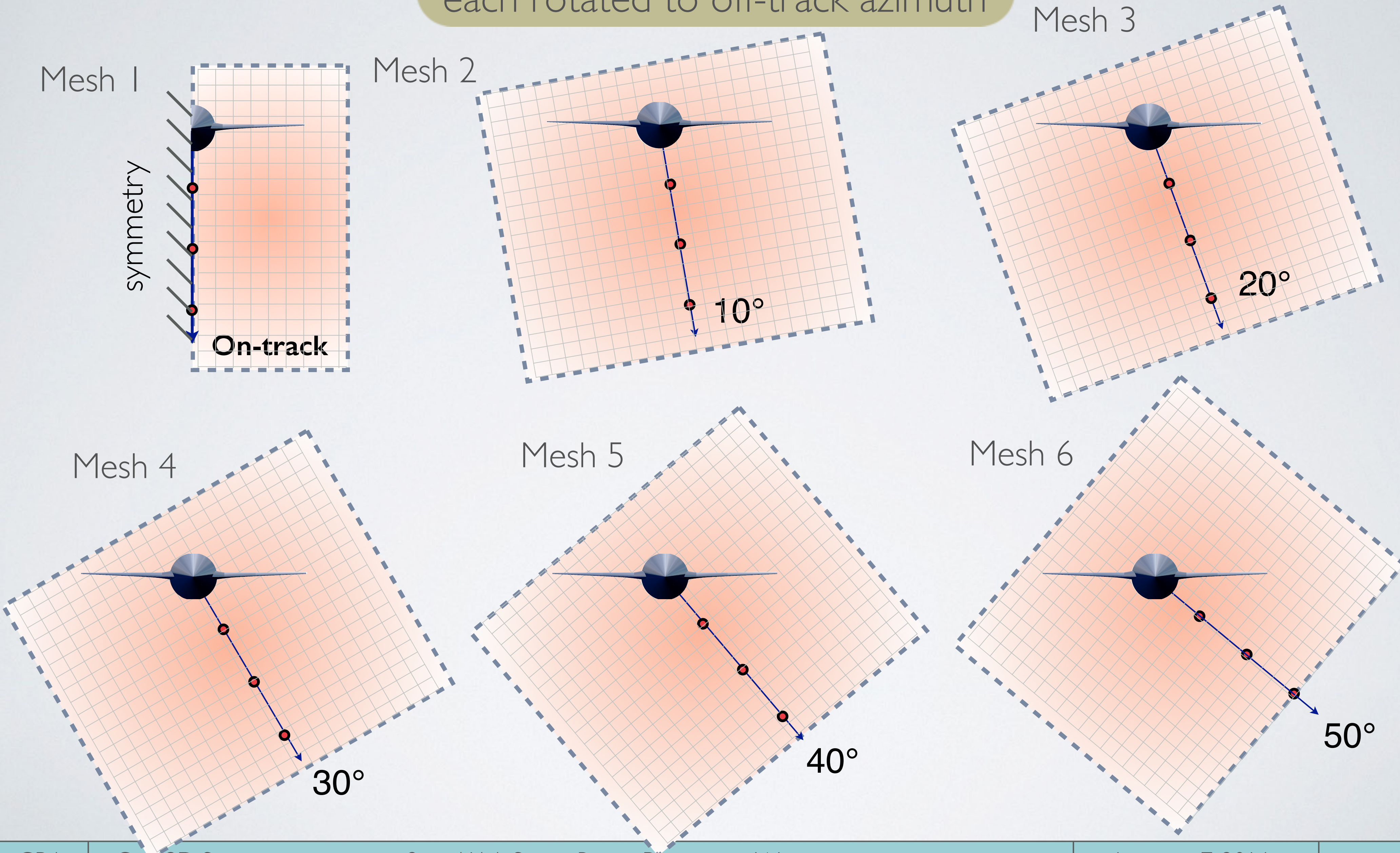
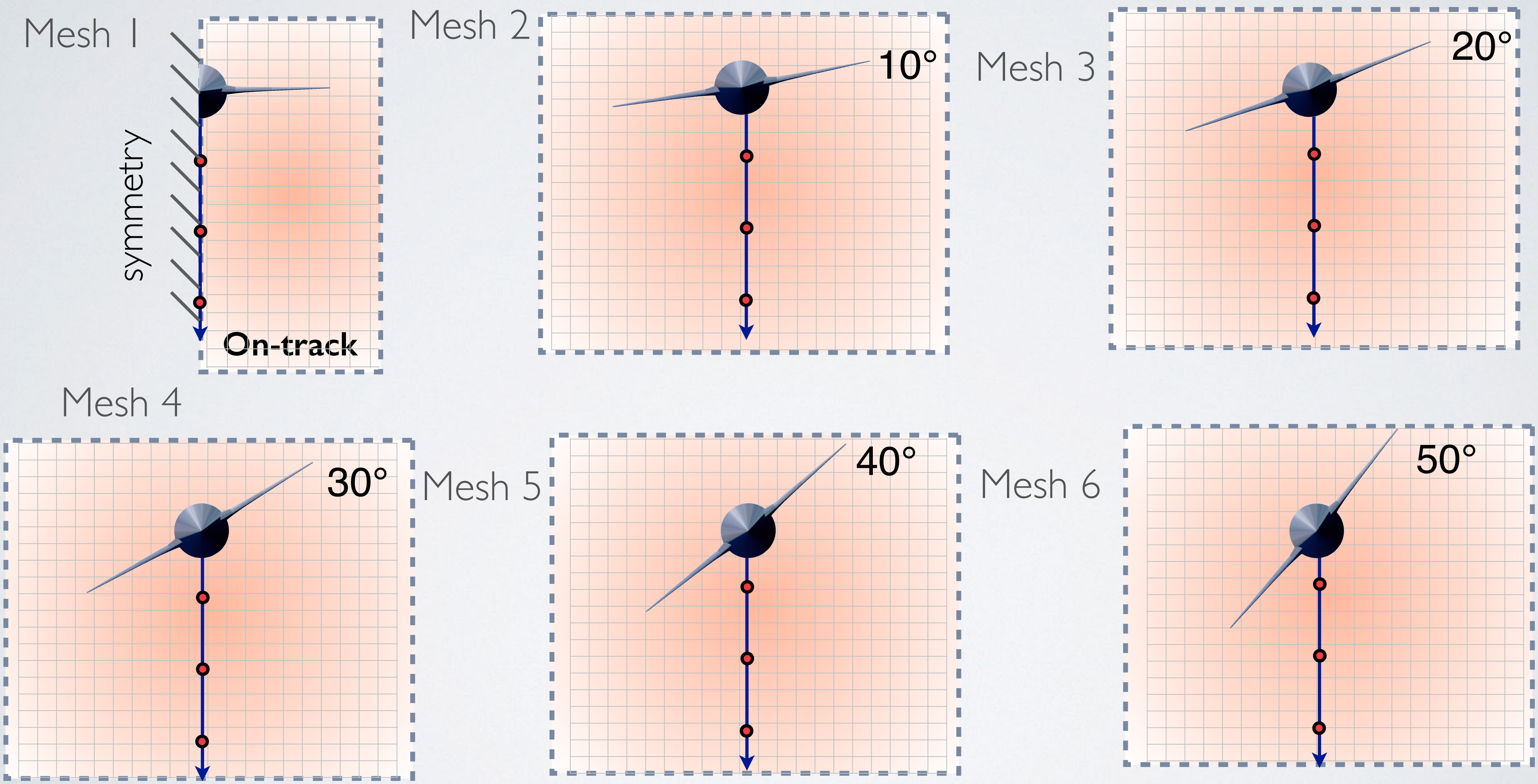


Off-Track Solutions

- **Better quality** solutions — off-track signals are well-aligned with propagation
- **More efficient** — alignment permits much higher aspect ratio stretching
- **More parallel** — run each azimuth on a separate compute node



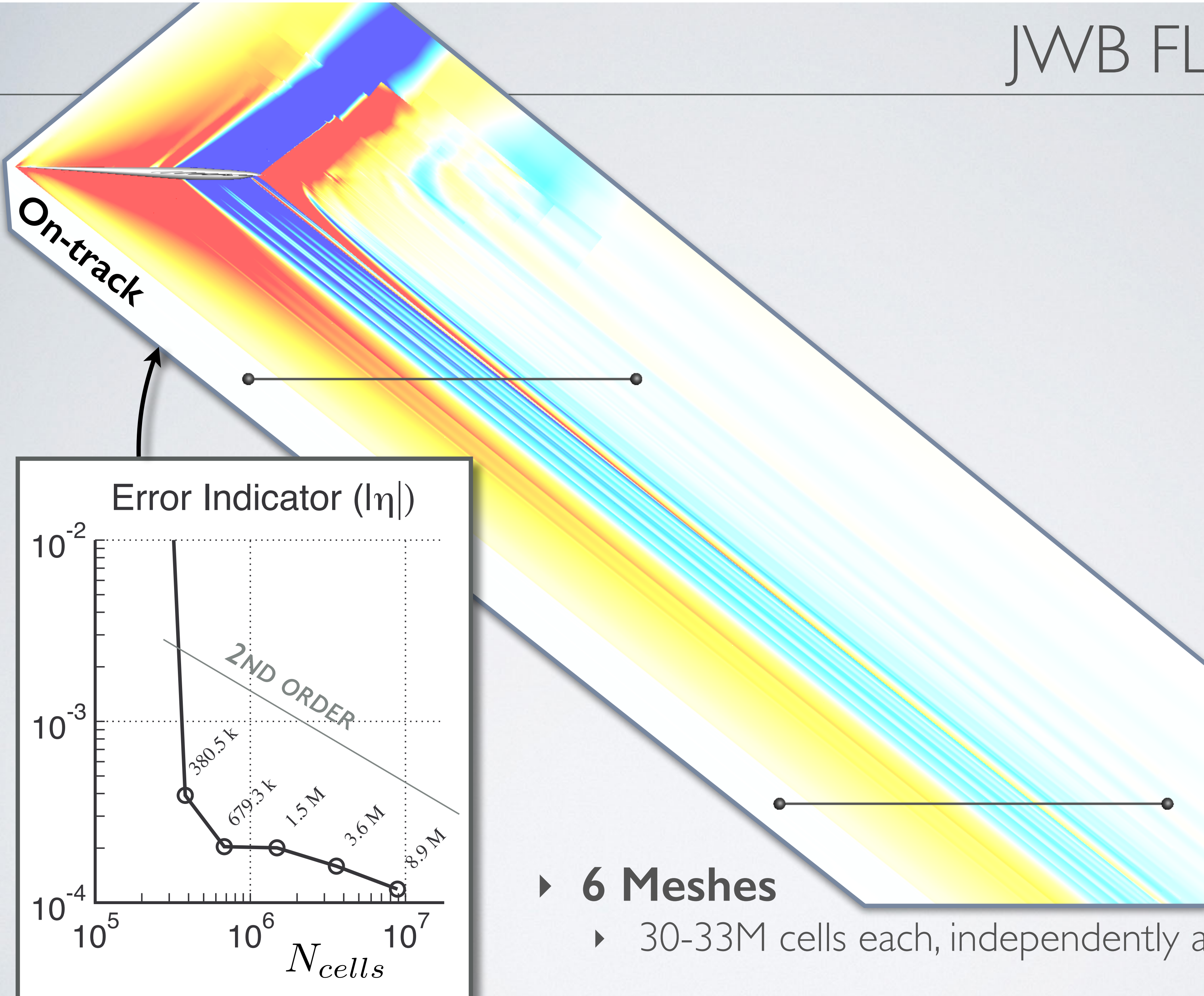
OUTLINE

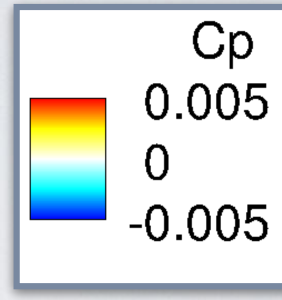
- ✓ **Solvers and Adaptive Meshing**
  Axibody results as demo
- ✓ **Multi-azimuth Problems with Cartesian Meshes**
- ‣ **Selected Workshop Results**
- **Mesh Size and Cost**
- **Conclusions**

JAXA Wing-Body (JWB)

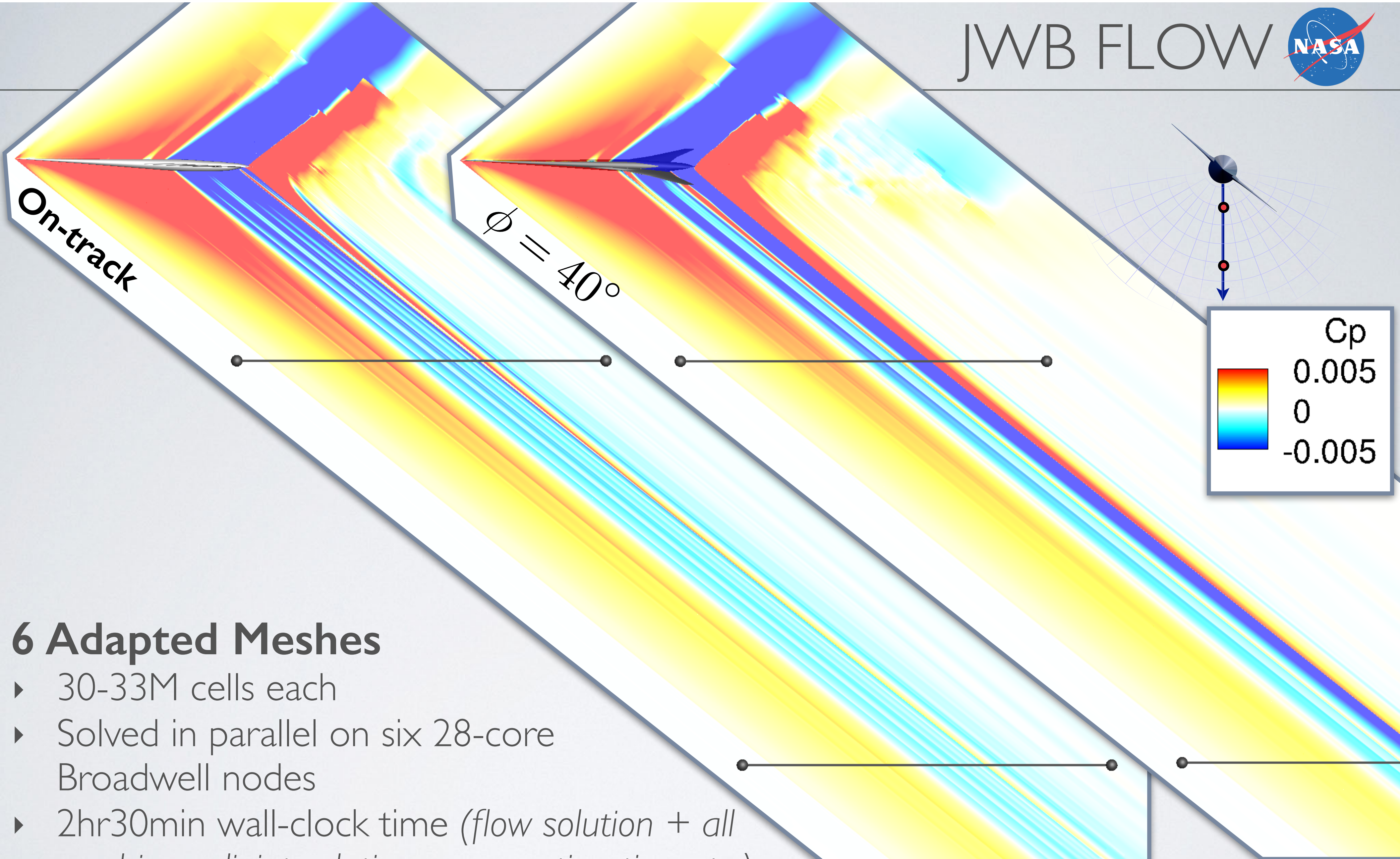
- Mach 1.6
- $\alpha = 2.3067°$
- Computed $\mathbf{C_L} \approx 0.077$

JWB FLOW





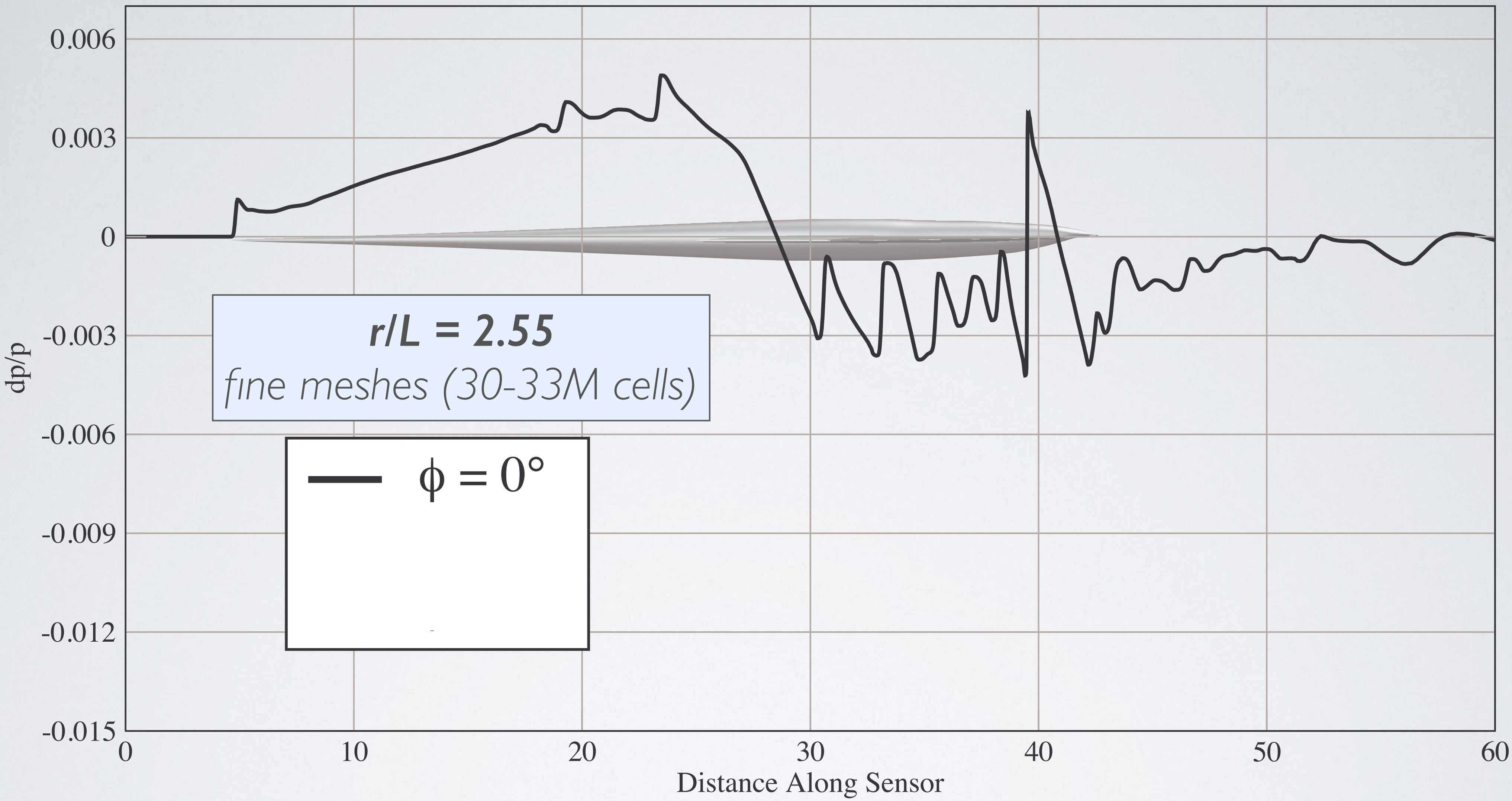
- **6 Meshes**
  - 30-33M cells each, independently adapted



6 Adapted Meshes

- 30-33M cells each
- Solved in parallel on six 28-core Broadwell nodes
- 2hr30min wall-clock time *(flow solution + all meshing, adjoint solutions, error estimation, etc.)*

JWB — SIGNATURES



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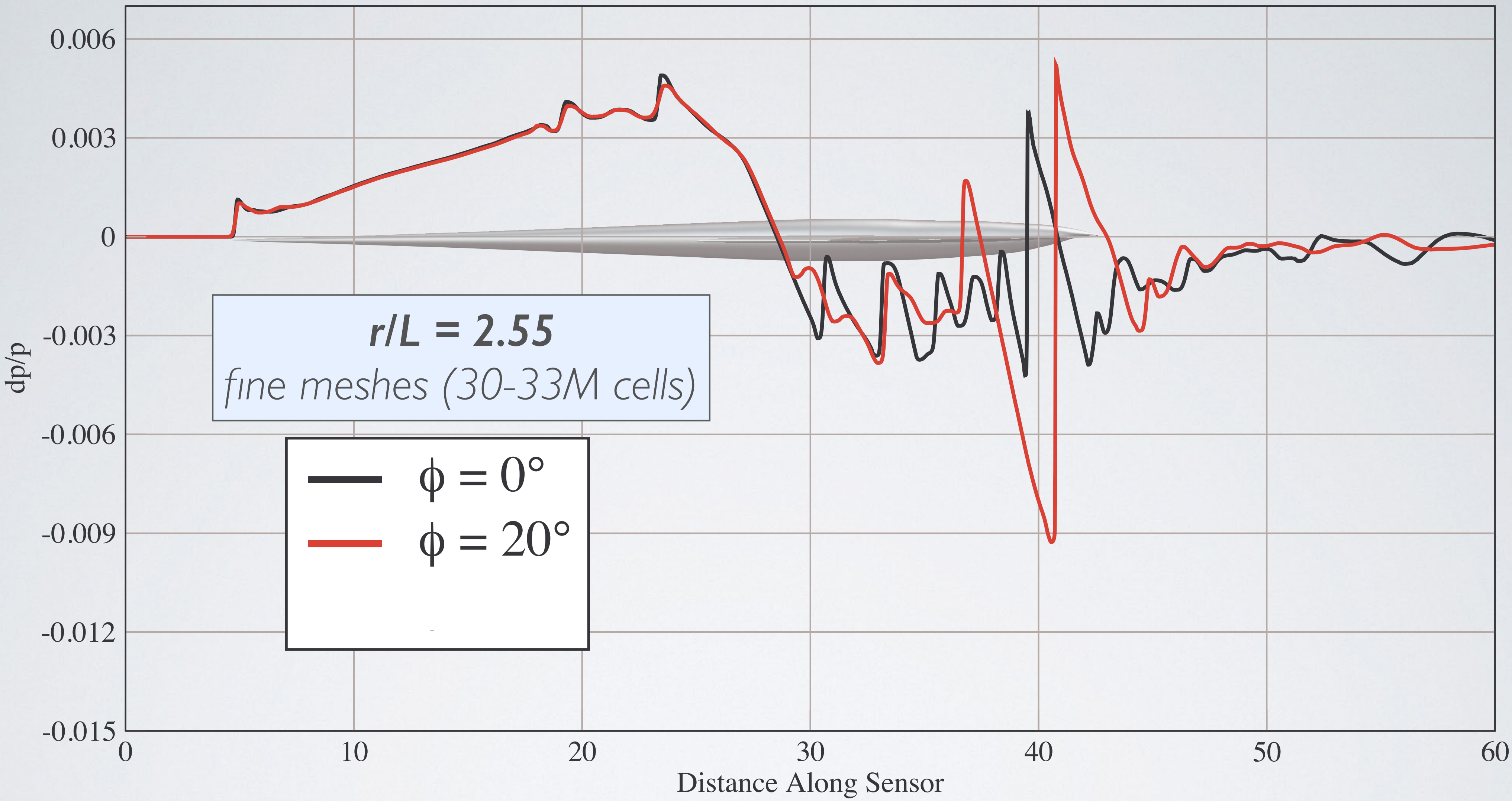

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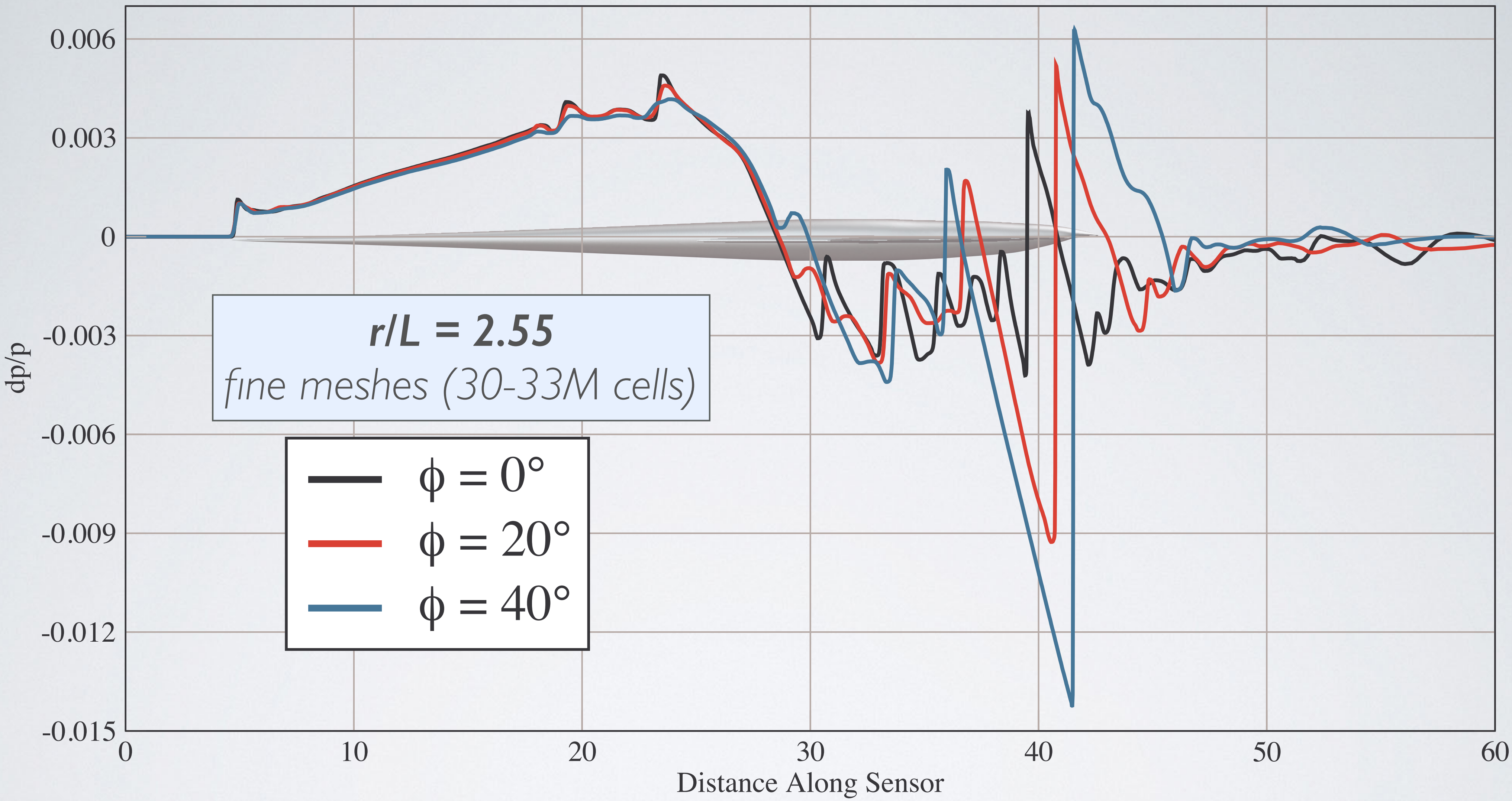
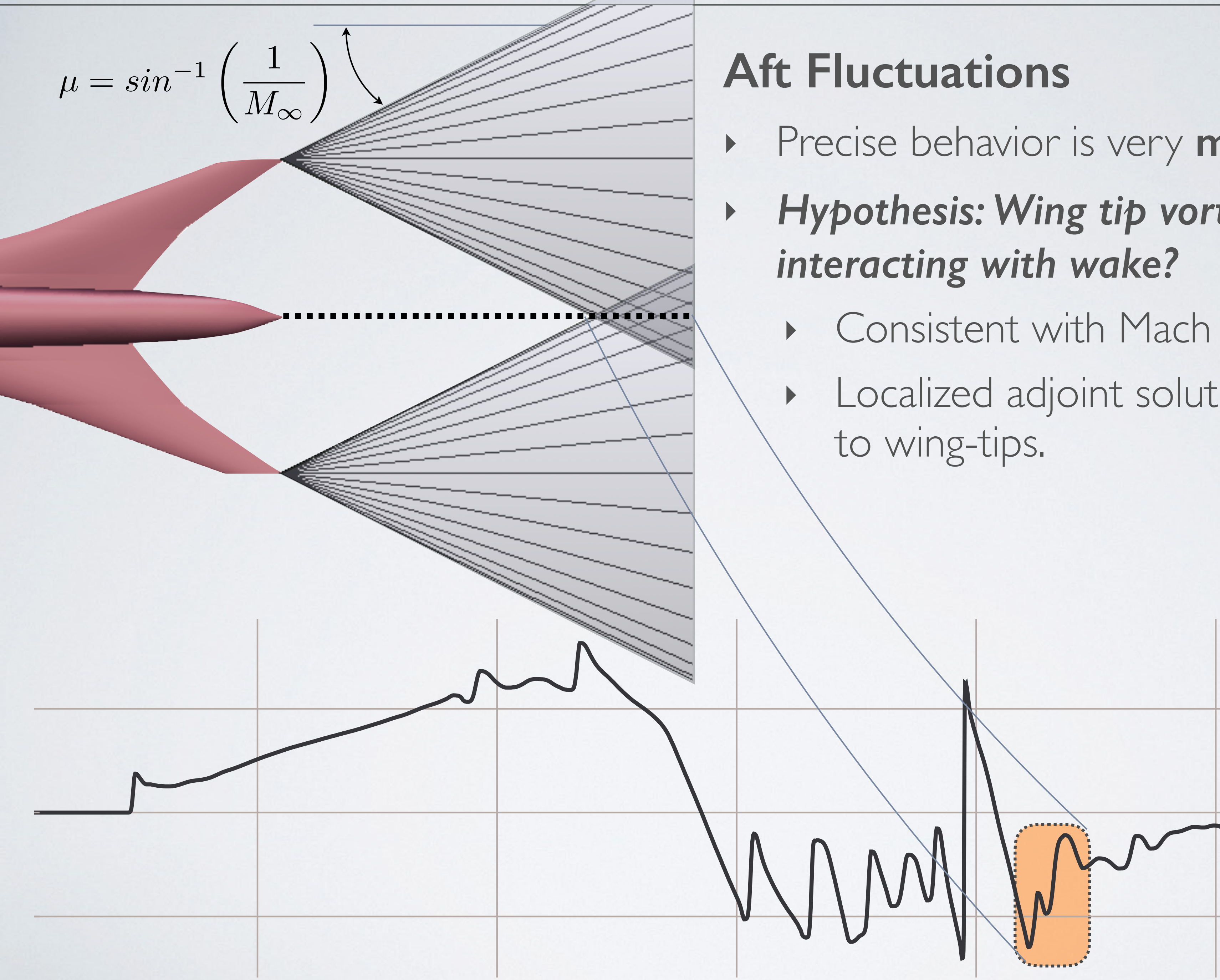




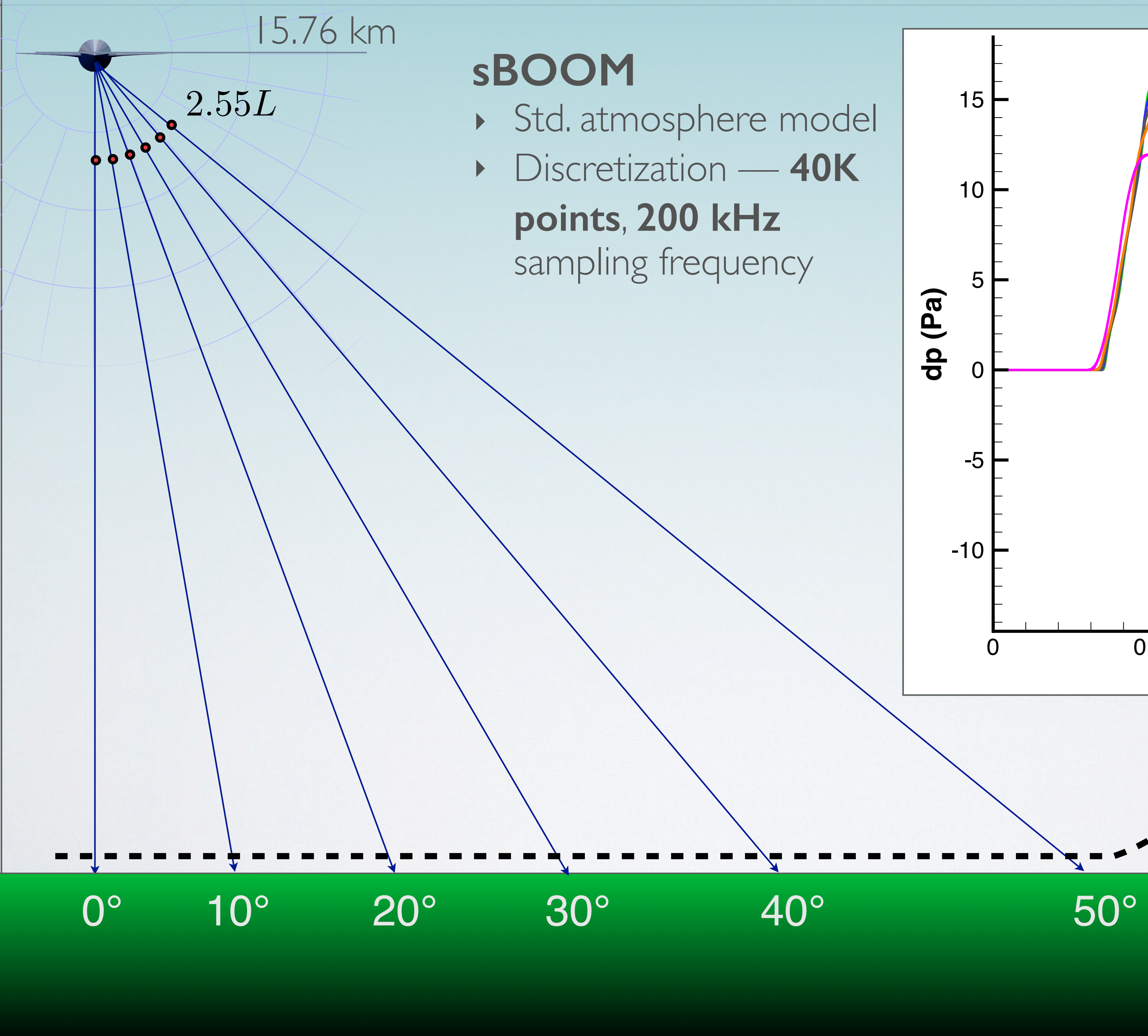
Aft Fluctuations

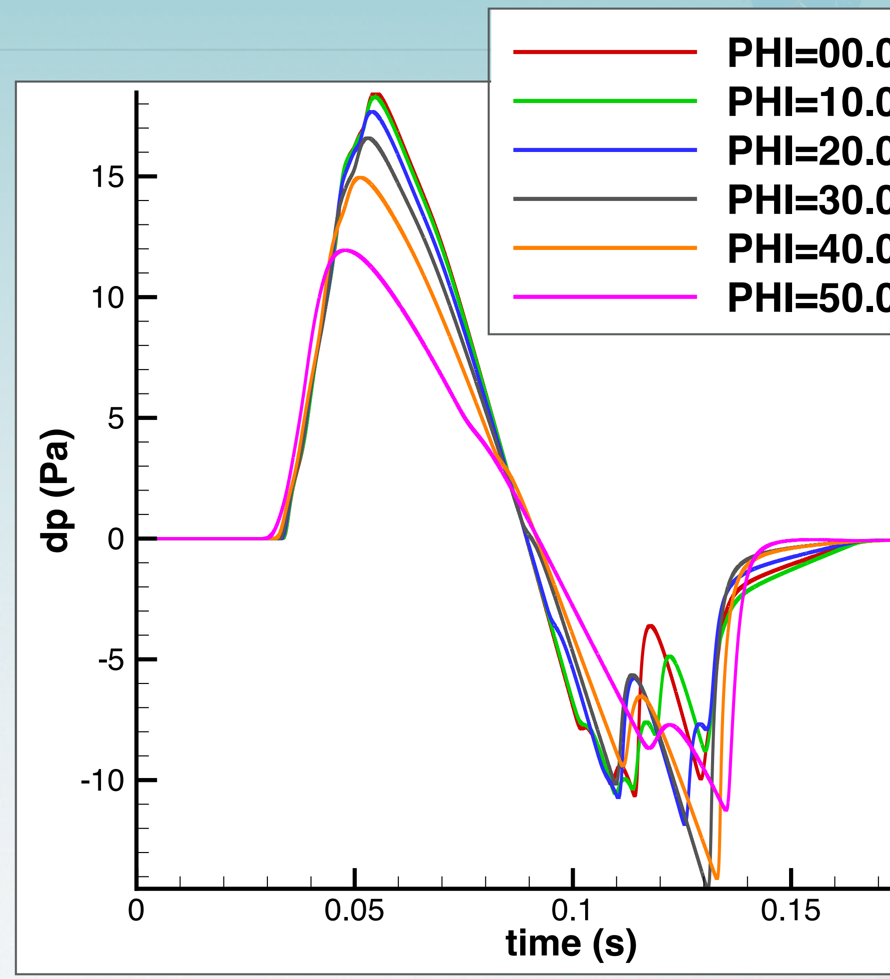
- Precise behavior is very **mesh-sensitive**
- ***Hypothesis: Wing tip vortices interacting with wake?***
  - Consistent with Mach cones
  - Localized adjoint solution traces back to wing-tips.

JWB — Propagation

sBOOM

- Std. atmosphere model
- Discretization — **40K points**, **200 kHz** sampling frequency

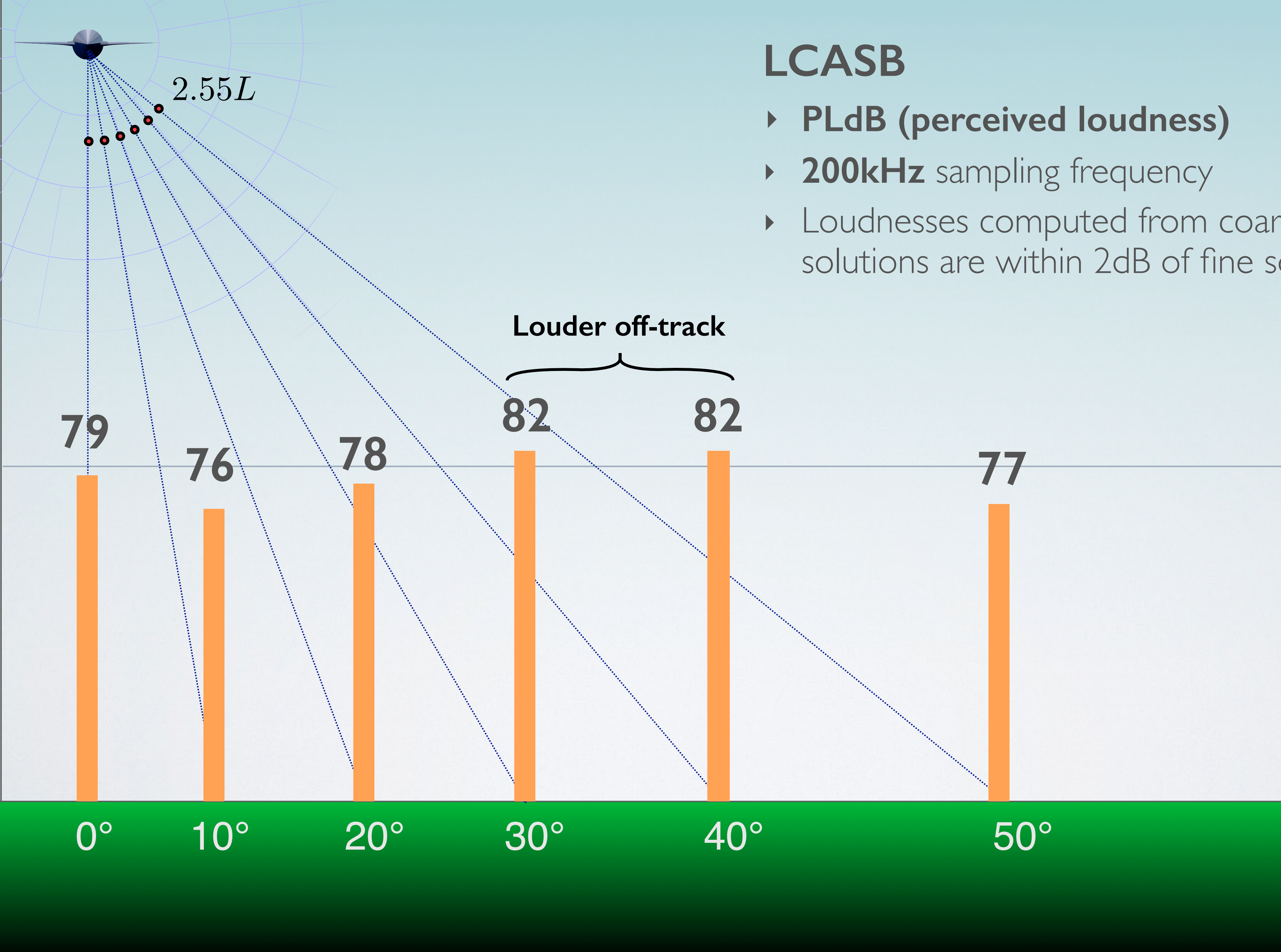




JWB — Ground Loudness

LCASB

- **PLdB (perceived loudness)**
- **200kHz** sampling frequency
- Loudnesses computed from coarse solutions are within 2dB of fine solutions



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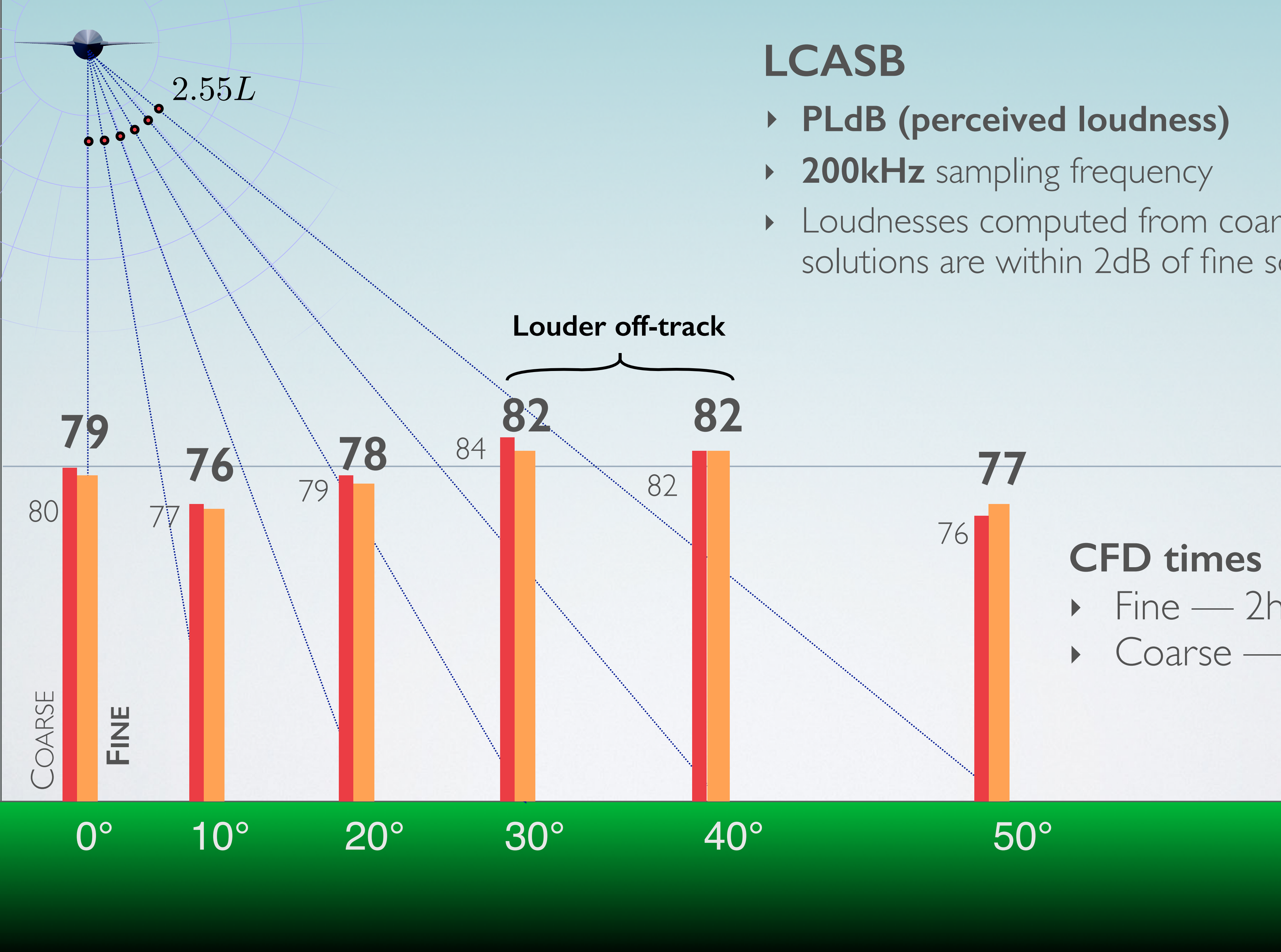
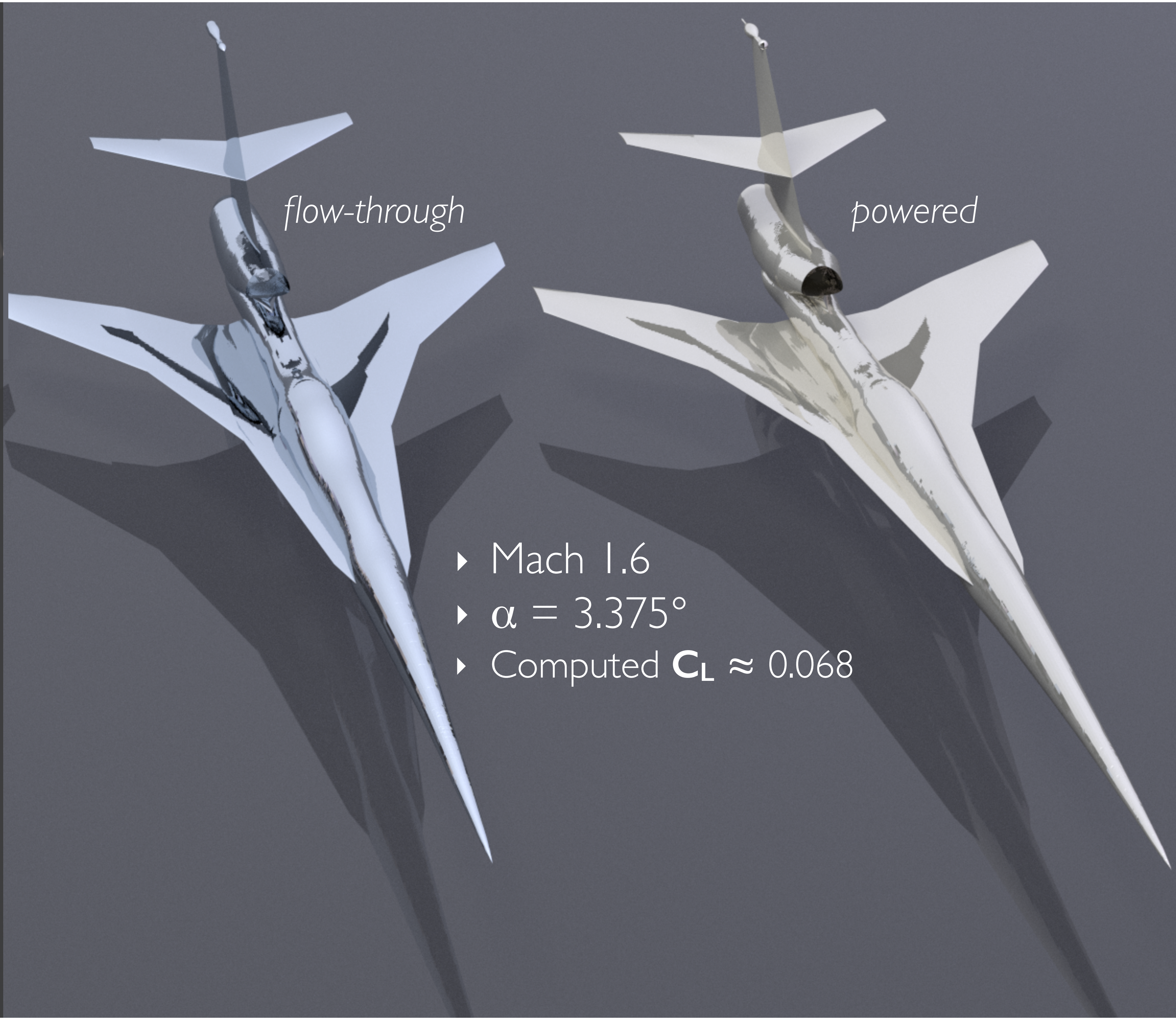


CFD times

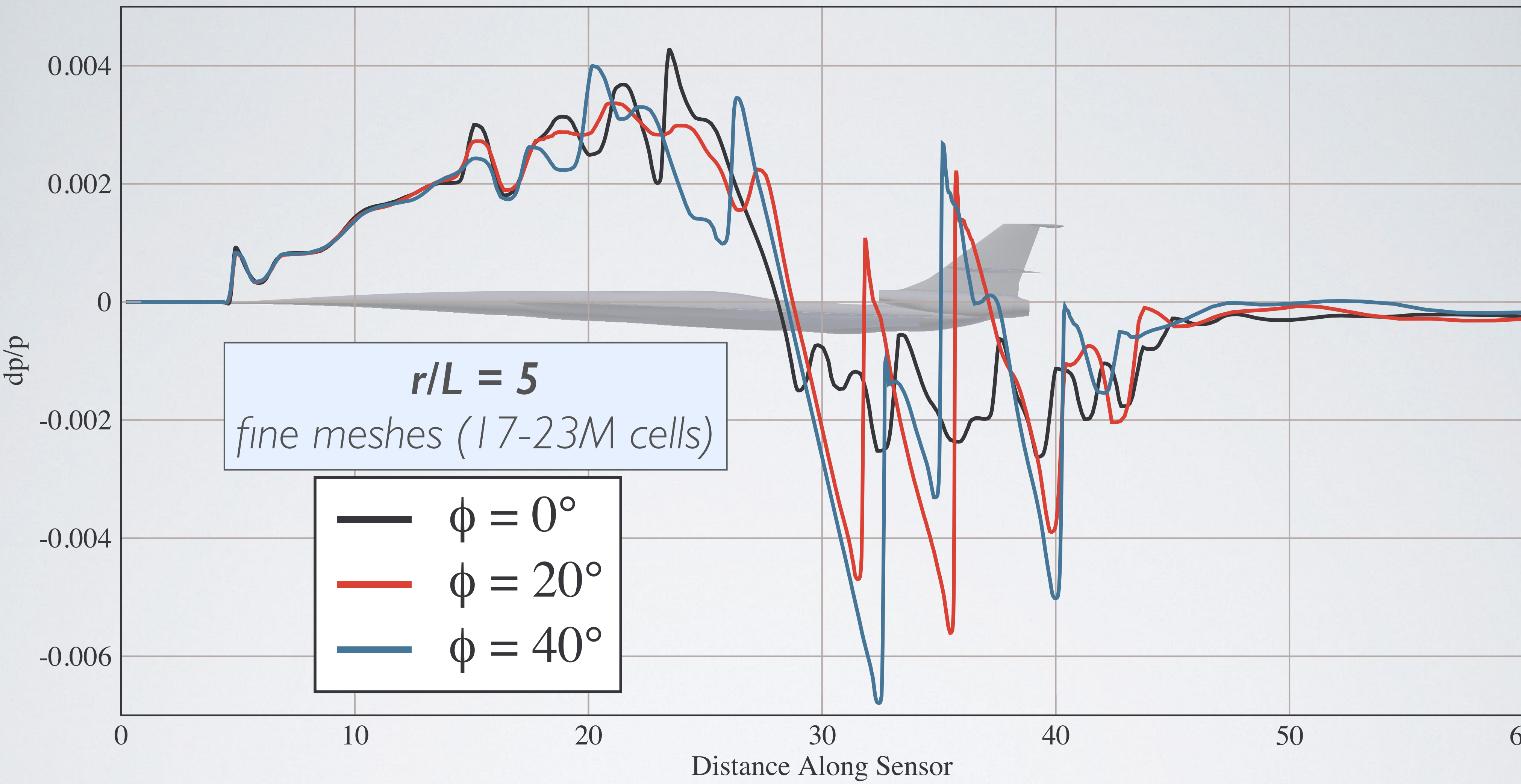
- Fine — 2hr30min
- Coarse — 23min

C25-D

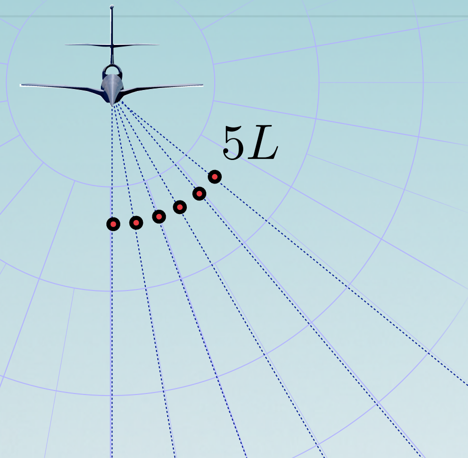


- Mach 1.6
- $\alpha = 3.375°$
- Computed $\mathbf{C_L} \approx 0.068$

C25-D FLOWTHRU — SIGNATURES

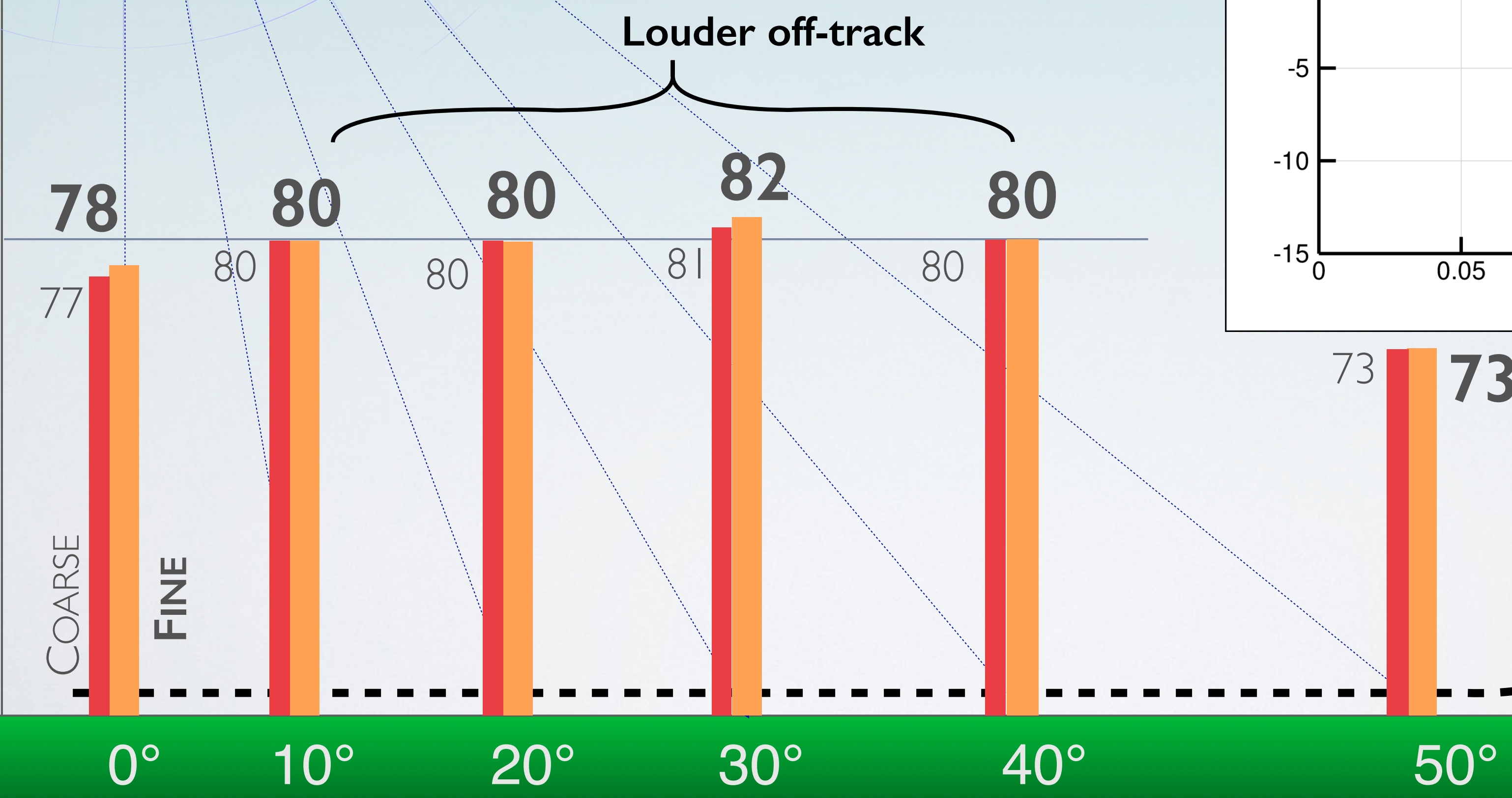


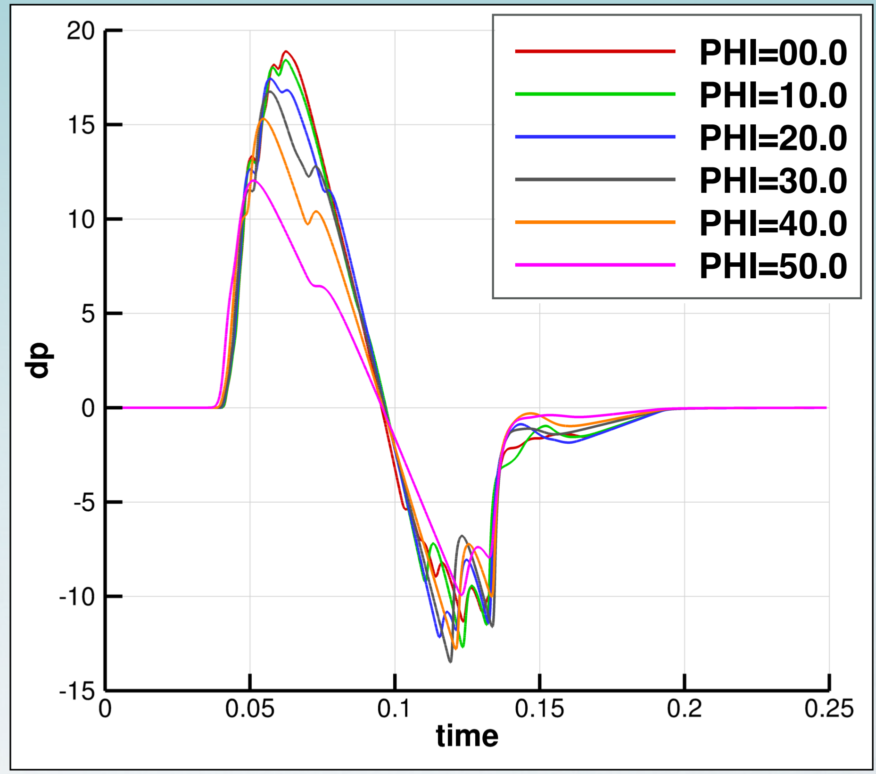
C25-D FLOWTHRU — PROPAGATION



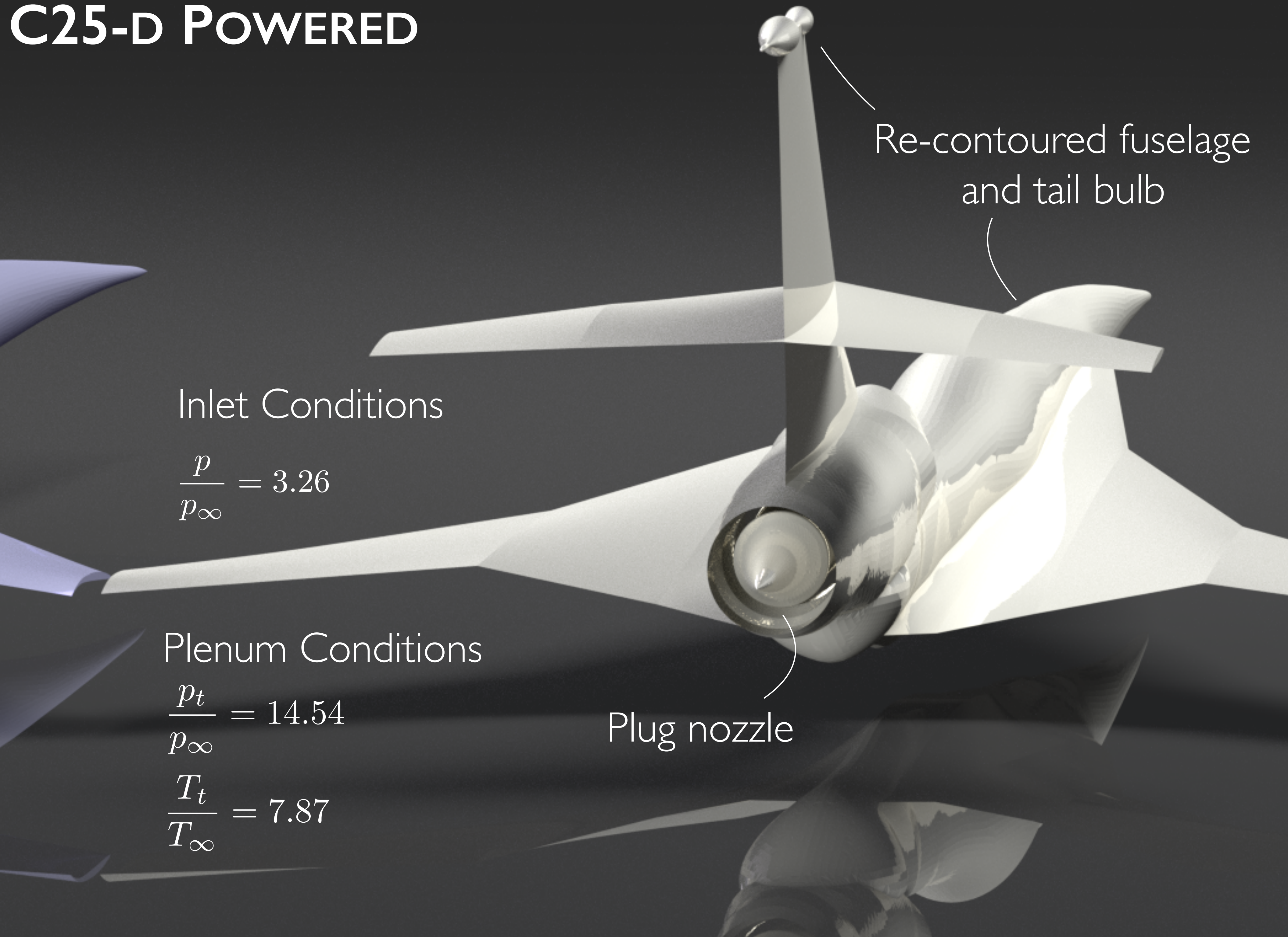
sBOOM + LCASB

- Std. atmosphere model
- Loudnesses computed from coarse solutions are within 1dB of fine solutions





C25-D Powered



Inlet Conditions

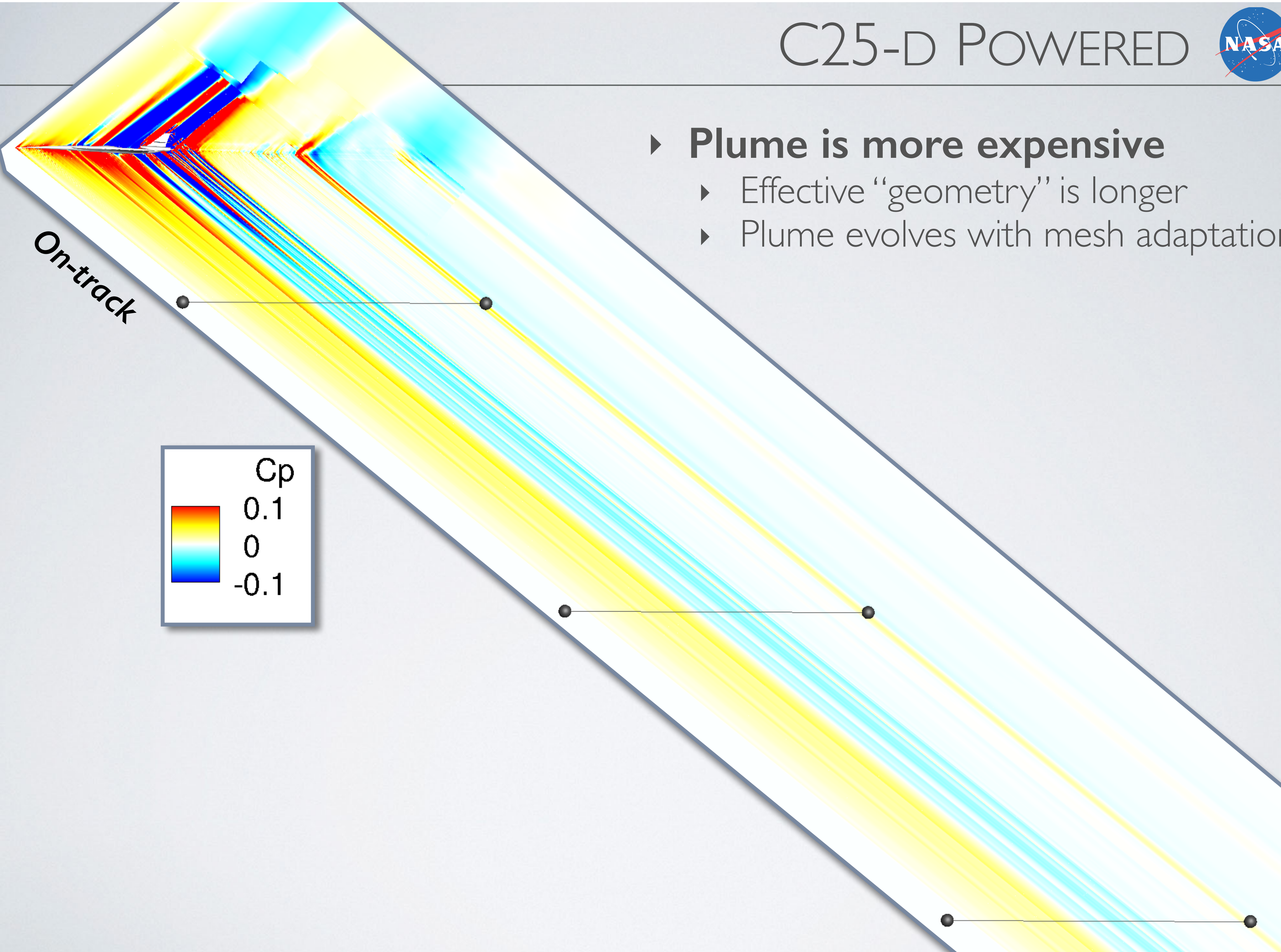
$$\frac{p}{p_\infty} = 3.26$$

Plenum Conditions

$$\frac{p_t}{p_\infty} = 14.54$$

$$\frac{T_t}{T_\infty} = 7.87$$

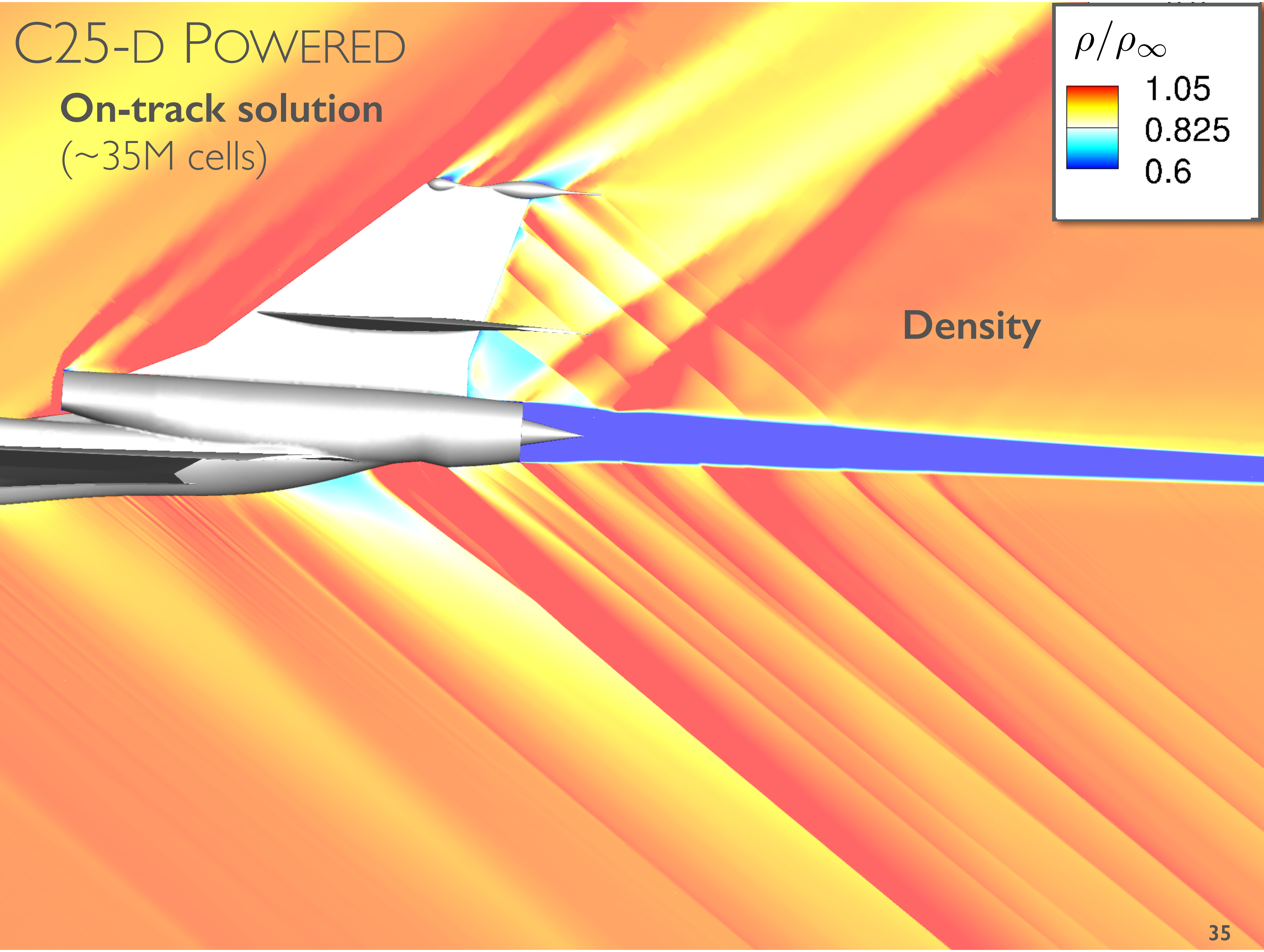
- **Plume is more expensive**
  - Effective "geometry" is longer
  - Plume evolves with mesh adaptation



C25-D Powered

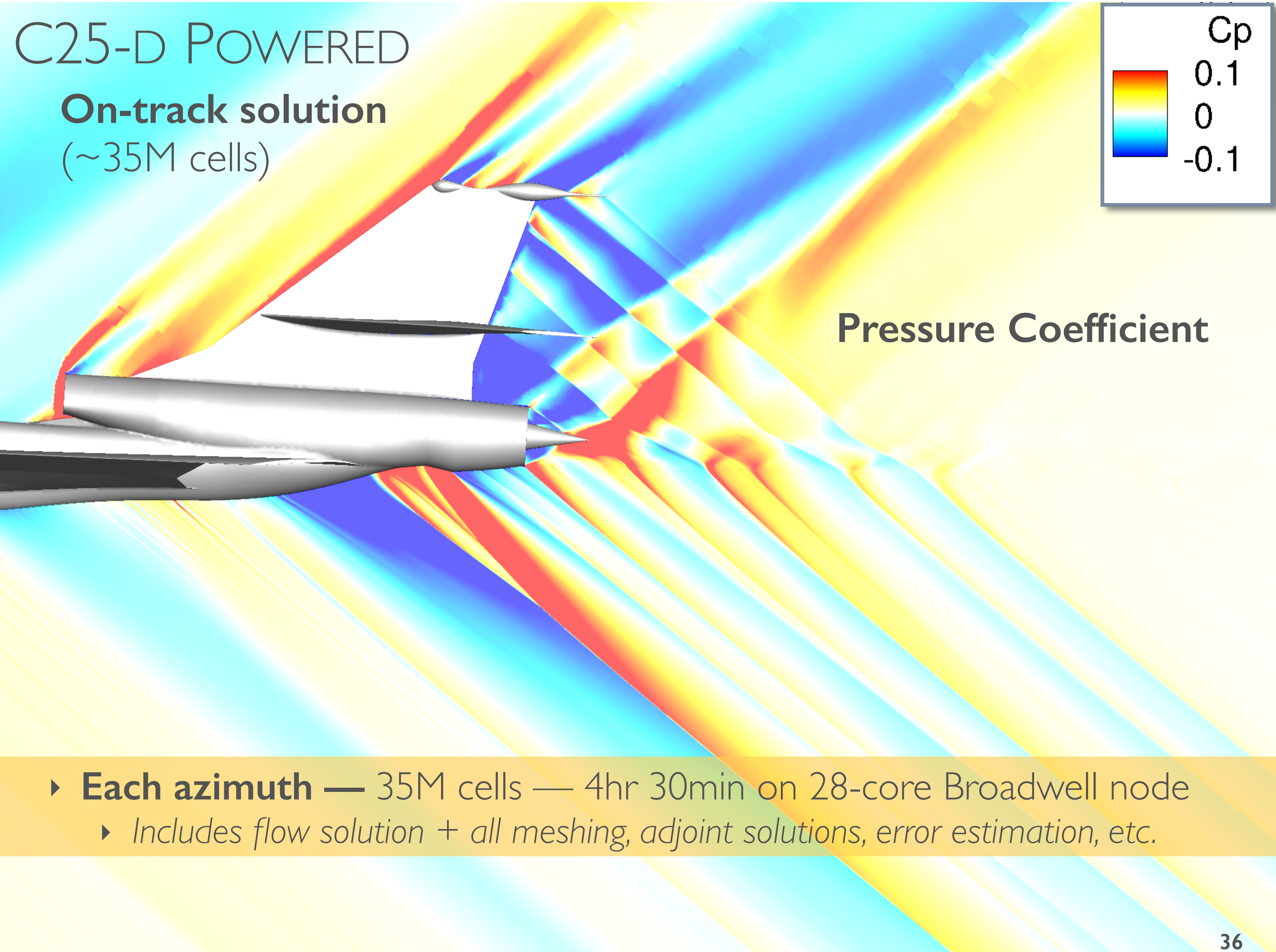
On-track solution

(~35M cells)



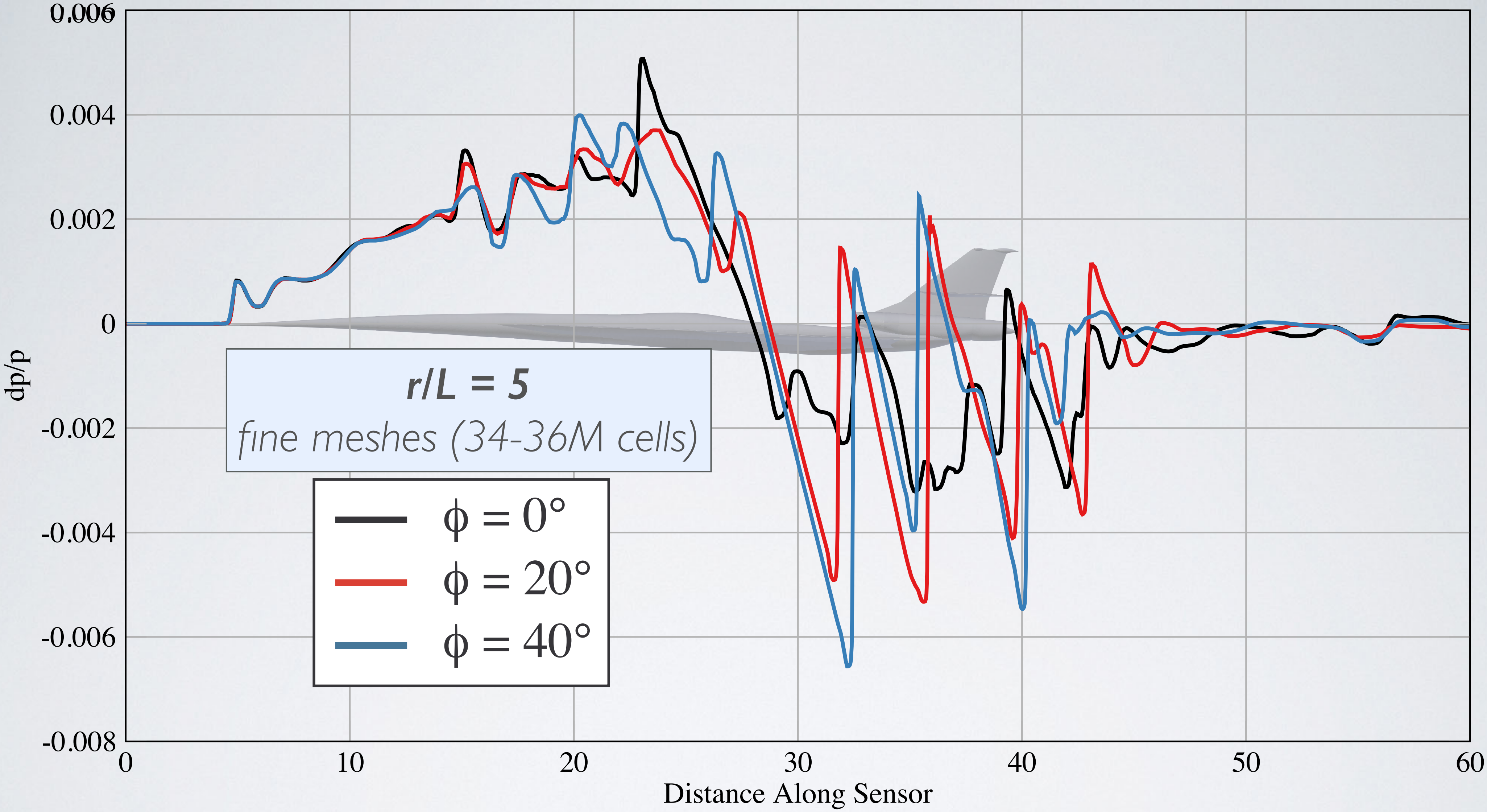
C25-D Powered

On-track solution
(~35M cells)



- **Each azimuth —** 35M cells — 4hr 30min on 28-core Broadwell node
  - *Includes flow solution + all meshing, adjoint solutions, error estimation, etc.*

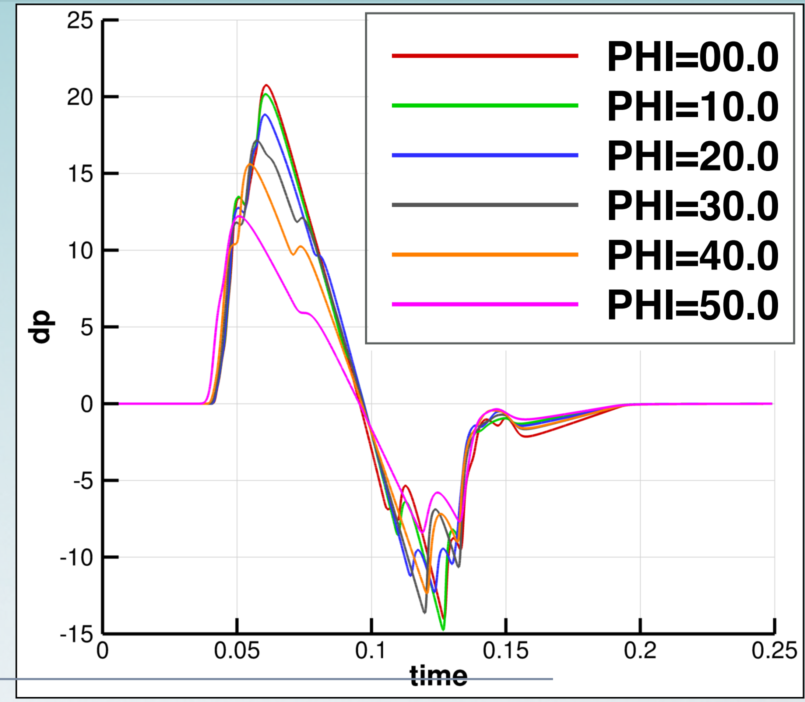
C25-D POWERED — SIGNATURES

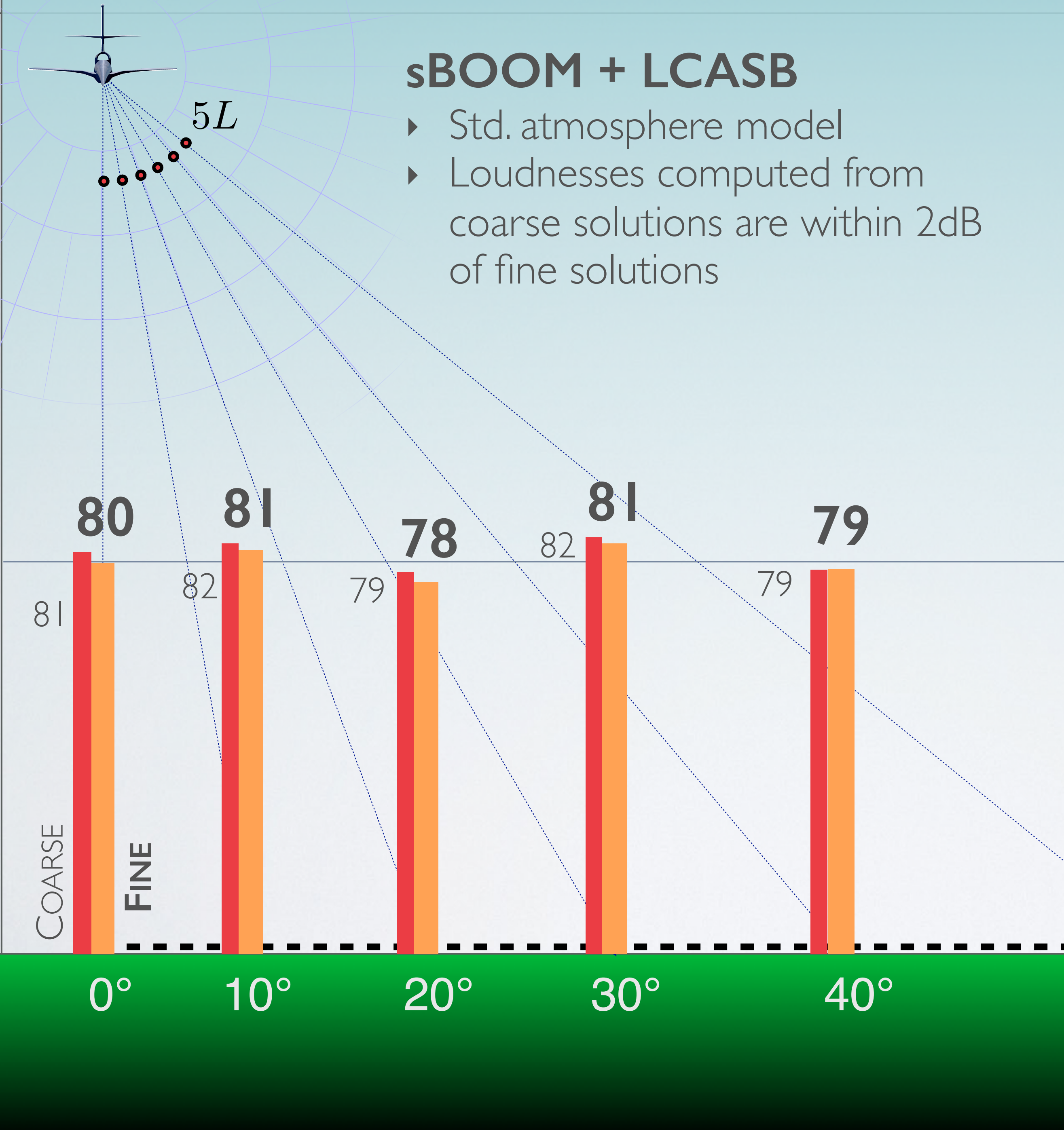


C25-D Powered — Propagation

sBOOM + LCASB

- Std. atmosphere model
- Loudnesses computed from coarse solutions are within 2dB of fine solutions





Outline

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  Axibody results as demo
- ✓ **Multi-azimuth Problems with Cartesian Meshes**
- ✓ **Selected Workshop Results**
- ‣ **Mesh Size and Cost**
- **Conclusions**

Cost

- All results and timings were performed on **single Broadwell nodes:**
  - 28 cores, 120GB memory — roughly equivalent to a powerful Linux workstation
- For multi-azimuth cases, **azimuths computed in parallel on 6 separate nodes** on NASA's Pleiades supercomputer

Total costs for **all problems, all azimuths**	
1450	CPU-hours
52	Node-hours
4hr 30min	Max wall-clock time

Break-down:

- *1x Axibody — (1hr 17min)*
- *6x JWB — (2hr 28min each)*
- *6x Flowthru — (1hr 30min each)*
- *6x Powered — (4hr 27min each)*

- **50-50 split** — Typically, about half the time is spent on adaptive meshing and half on the final flow solution.

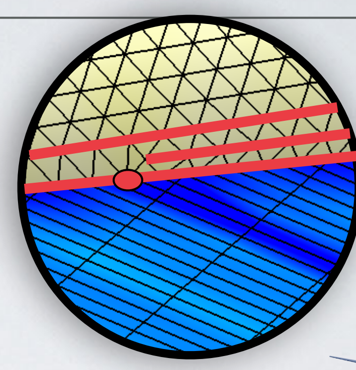
Finest Grid Comparison

Cell Counts	Cart3D Adapted		Workshop Inviscid
	per azimuth (avg)	Total*	
Axibody	26M	**26M**	**56M**
JWB	32M	**190M**	**18M**
C25-d Flowthru	19M	**114M**	**104M**
C25-d Powered	35M	**209M**	**52M**

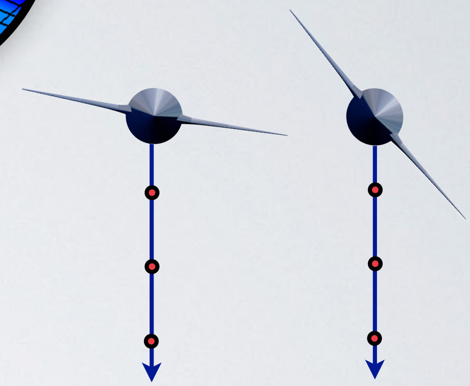
* *Sum of cell counts across azimuths*

Highlights

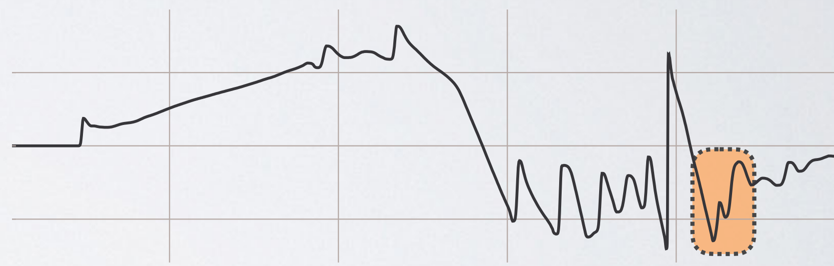
- Spurious high-frequency oscillations from irregular surface geometry discretization.



- **Splitting azimuths greatly accelerates process:**
  - Run in parallel
  - Align mesh to azimuth → stretch to high AR



- JWB exhibits mesh-sensitive wake behavior — requires lots of resolution.



- Perceived loudness from coarse and fine CFD solutions differ by less than 2 PLdB for all cases and azimuths.