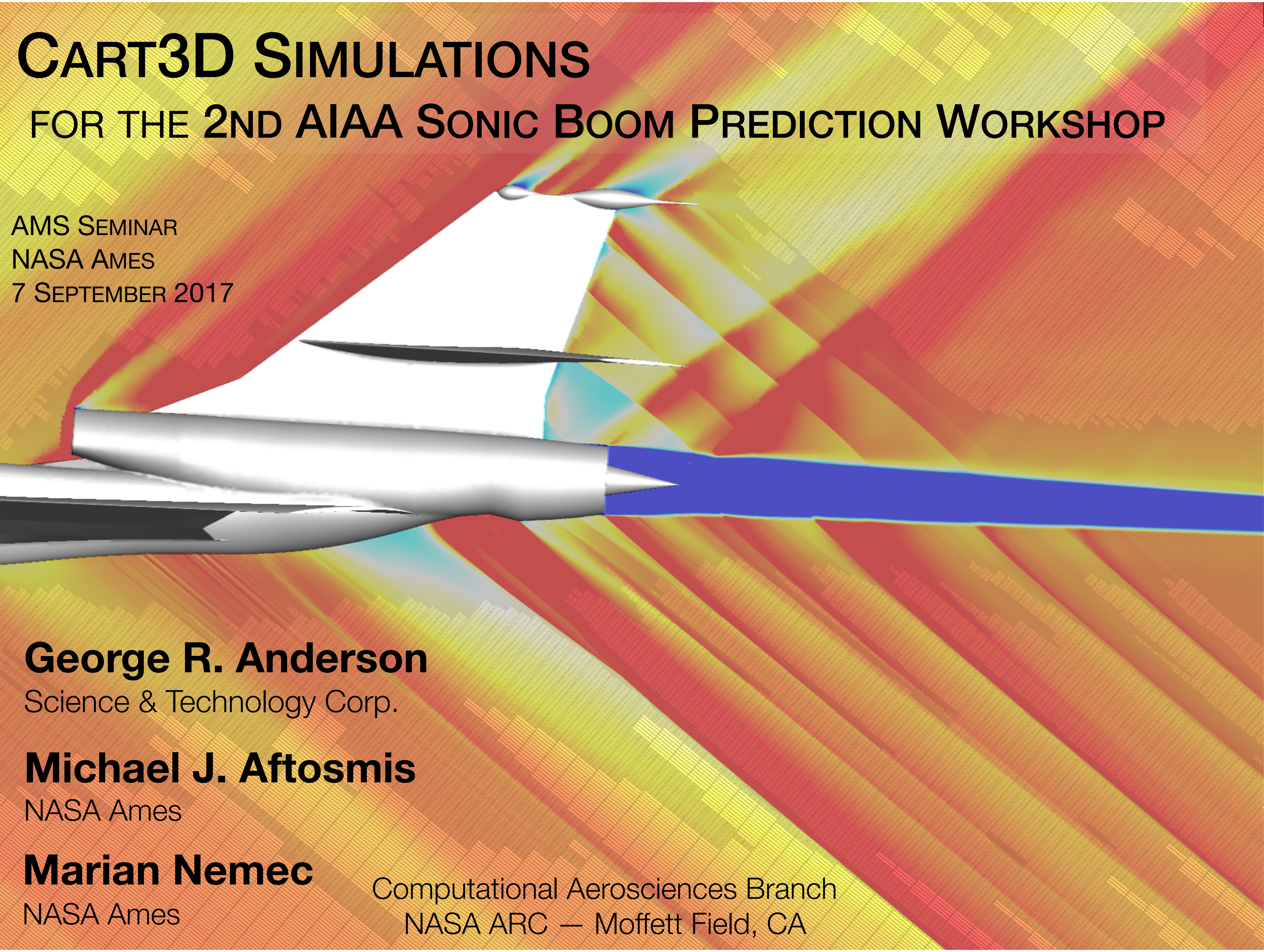
CART3D SIMULATIONS
FOR THE 2ND AIAA SONIC BOOM PREDICTION WORKSHOP



AMS SEMINAR
NASA AMES
7 SEPTEMBER 2017

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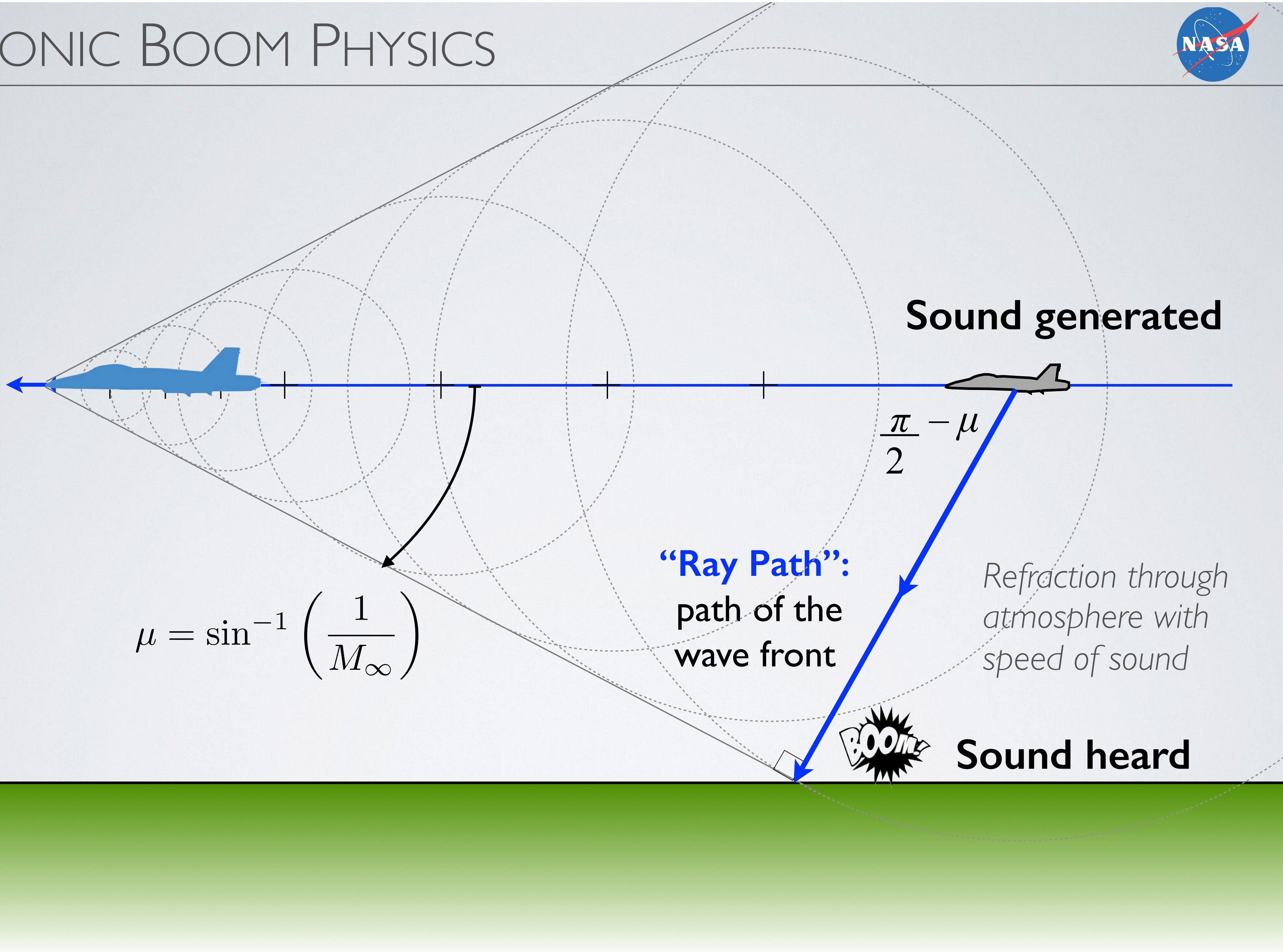
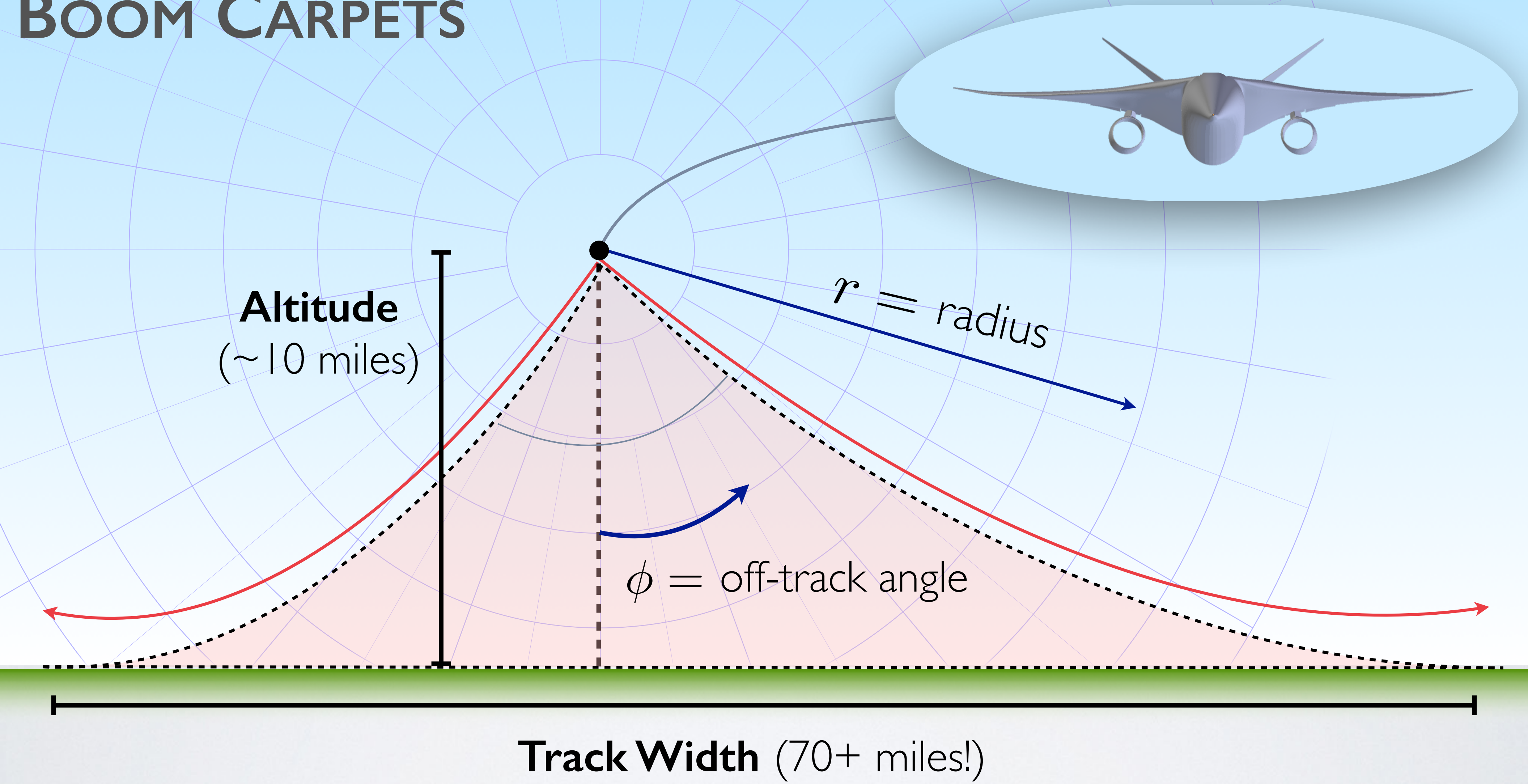
Motivation

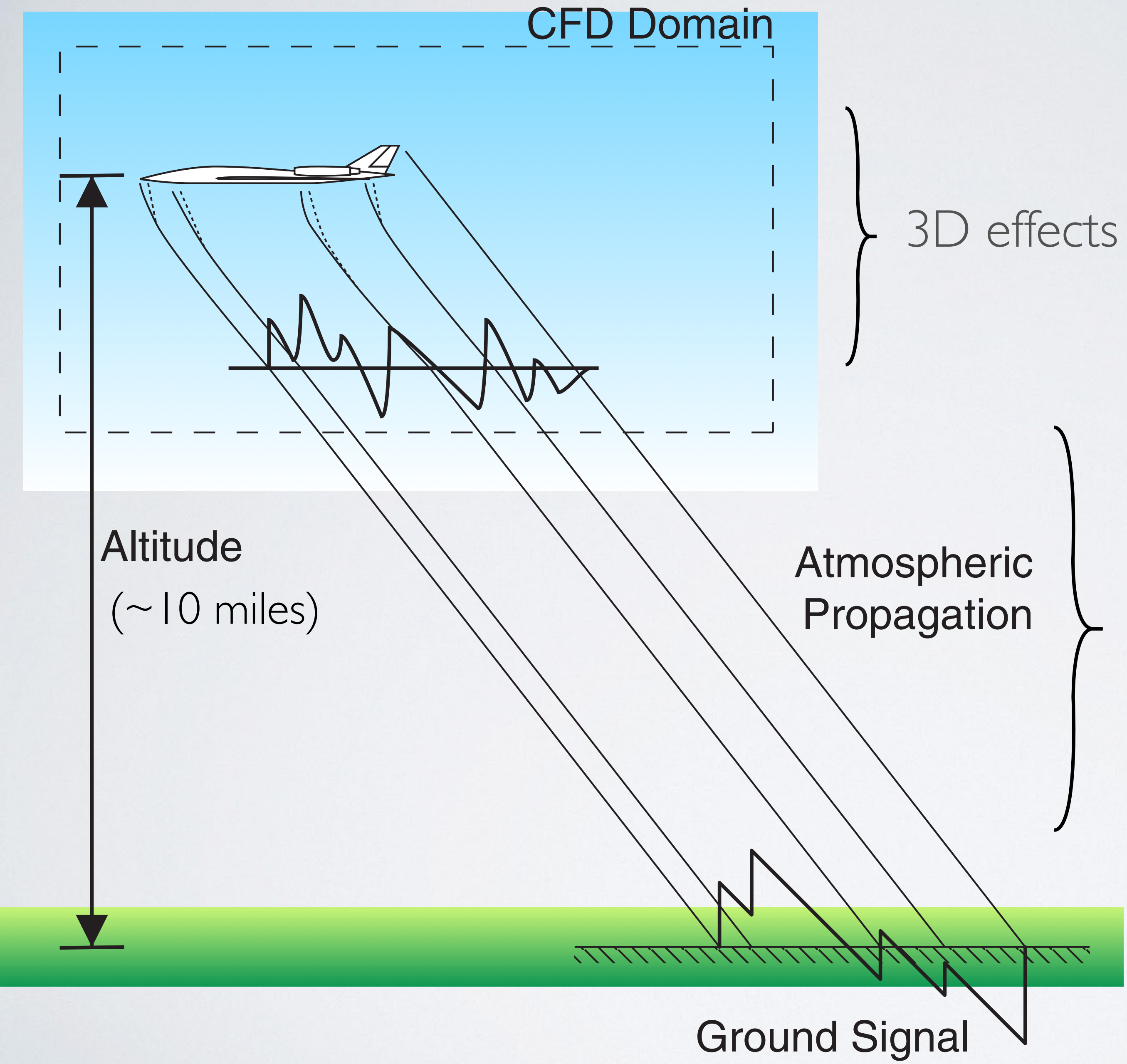
- **Commercial supersonic flight** banned over the US because of objectionable sonic boom
- Hope to overturn this with demonstrably quiet aircraft (e.g. QueSST/LBFD)
- **CFD tools are a major contributor to design efforts**
- Sonic Boom Prediction Workshops
  - (2008) NASA FAP SBPW
  - (2014) AIAA SBPW1
  - ➡ **(2017) AIAA SBPW2**


Sound generated
$\frac{\pi}{2} - \mu$
$\mu = \sin^{-1}\left(\frac{1}{M_\infty}\right)$
"Ray Path": path of the wave front
Refraction through atmosphere with speed of sound
BOOM!
Sound heard

Boom Carpets



Sonic Boom Prediction



Nearfield

3D effects (aircraft shape and plume)

Use CFD

Propagation

Atmospheric variability

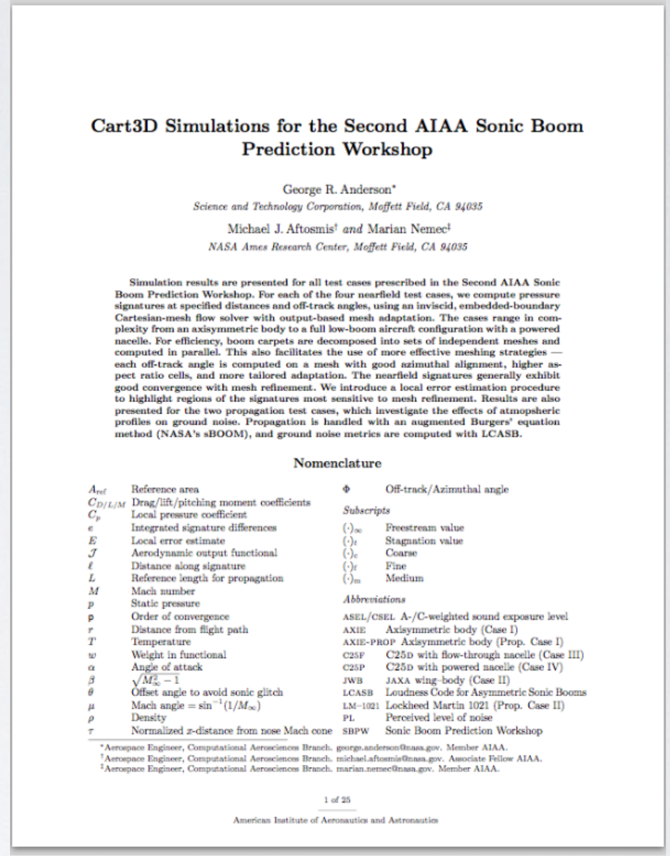
Absorption

Use quasi-1D PDE

OUTLINE

- Workshop Results
  - Nearfield (2/4 cases)
  - Propagation
- Full Vehicle-to-Boom Simulation Path
- Conclusions

AIAA PAPER 2017-3255



Cart3D Simulations for the Second AIAA Sonic Boom Prediction Workshop

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Simulation results are presented for all test cases prescribed in the Second AIAA Sonic Boom Prediction Workshop. For each of the four nearfield test cases, we compute pressure signatures at specified distances and off-track angles, using an inviscid, embedded-boundary Cartesian-mesh flow solver with output-based mesh adaptation. The cases range in complexity from an axisymmetric body to a full low-boom aircraft configuration with a powered nacelle. For efficiency, boom carpets are decomposed into sets of independent meshes and computed in parallel. This also facilitates the use of more effective meshing strategies — each off-track angle is computed on a mesh with good azimuthal alignment, higher aspect ratio cells, and more tailored adaptation. The nearfield signatures generally exhibit good convergence with mesh refinement. We introduce a local error estimation procedure to highlight regions of the signatures most sensitive to mesh refinement. Results are also presented for the two propagation test cases, which investigate the effects of atmospheric profiles on ground noise. Propagation is handled with an augmented Burgers' equation method (NASA's sBOOM), and ground noise metrics are computed with LCASB.

Nomenclature

A_{ref}	Reference area
$C_{D/L/M}$	Drag/lift/pitching moment coefficients
C_p	Local pressure coefficient
ϵ	Integrated signature differences
E	Local error estimate
$\mathcal{J}$	Aerodynamic output functional
ℓ	Distance along signature
L	Reference length for propagation
M	Mach number
p	Static pressure
p	Order of convergence
r	Distance from flight path
T	Temperature
w	Weight in functional
α	Angle of attack
β	$\sqrt{M_\infty^2 - 1}$
θ	Offset angle to avoid sonic glitch
μ	Mach angle $= \sin^{-1}(1/M_\infty)$
ρ	Density
τ	Normalized x-distance from nose Mach cone
Φ	Off-track/Azimuthal angle

Subscripts

$(\cdot)_\infty$	Freestream value
$(\cdot)_t$	Stagnation value
$(\cdot)_c$	Coarse
$(\cdot)_f$	Fine
$(\cdot)_m$	Medium

Abbreviations

ASEL/CSEL	A-/C-weighted sound exposure level
AXIE	Axisymmetric body (Case I)
AXIE-PROP	Axisymmetric body (Prop. Case I)
C25F	C25D with flow-through nacelle (Case III)
C25P	C25D with powered nacelle (Case IV)
JWB	JAXA wing–body (Case II)
LCASB	Loudness Code for Asymmetric Sonic Booms
LM–1021	Lockheed Martin 1021 (Prop. Case II)
PL	Perceived level of noise
SBPW	Sonic Boom Prediction Workshop

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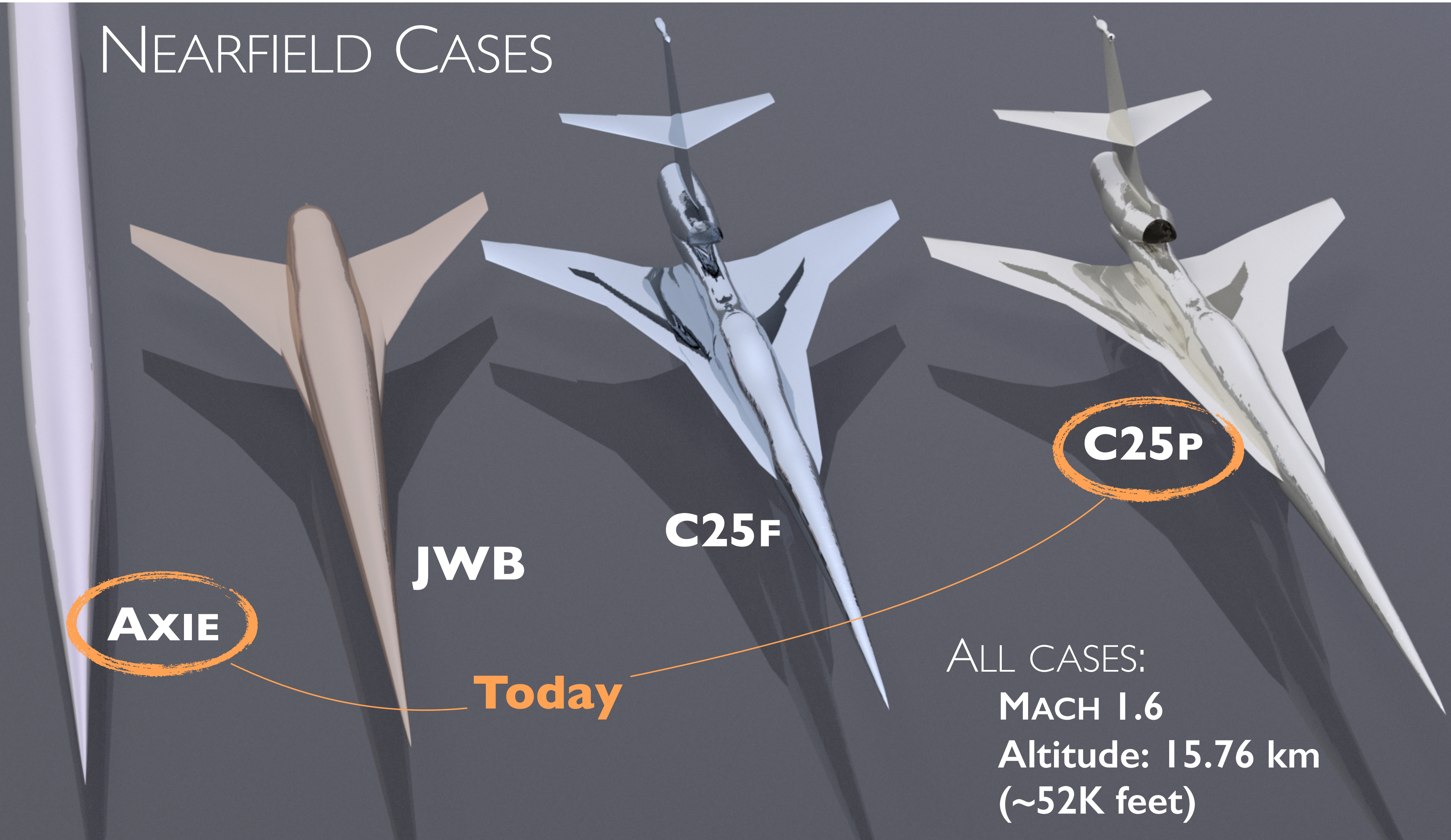
ALL REQUIRED AND OPTIONAL CASES FROM BOTH WORKSHOPS

Nearfield Cases



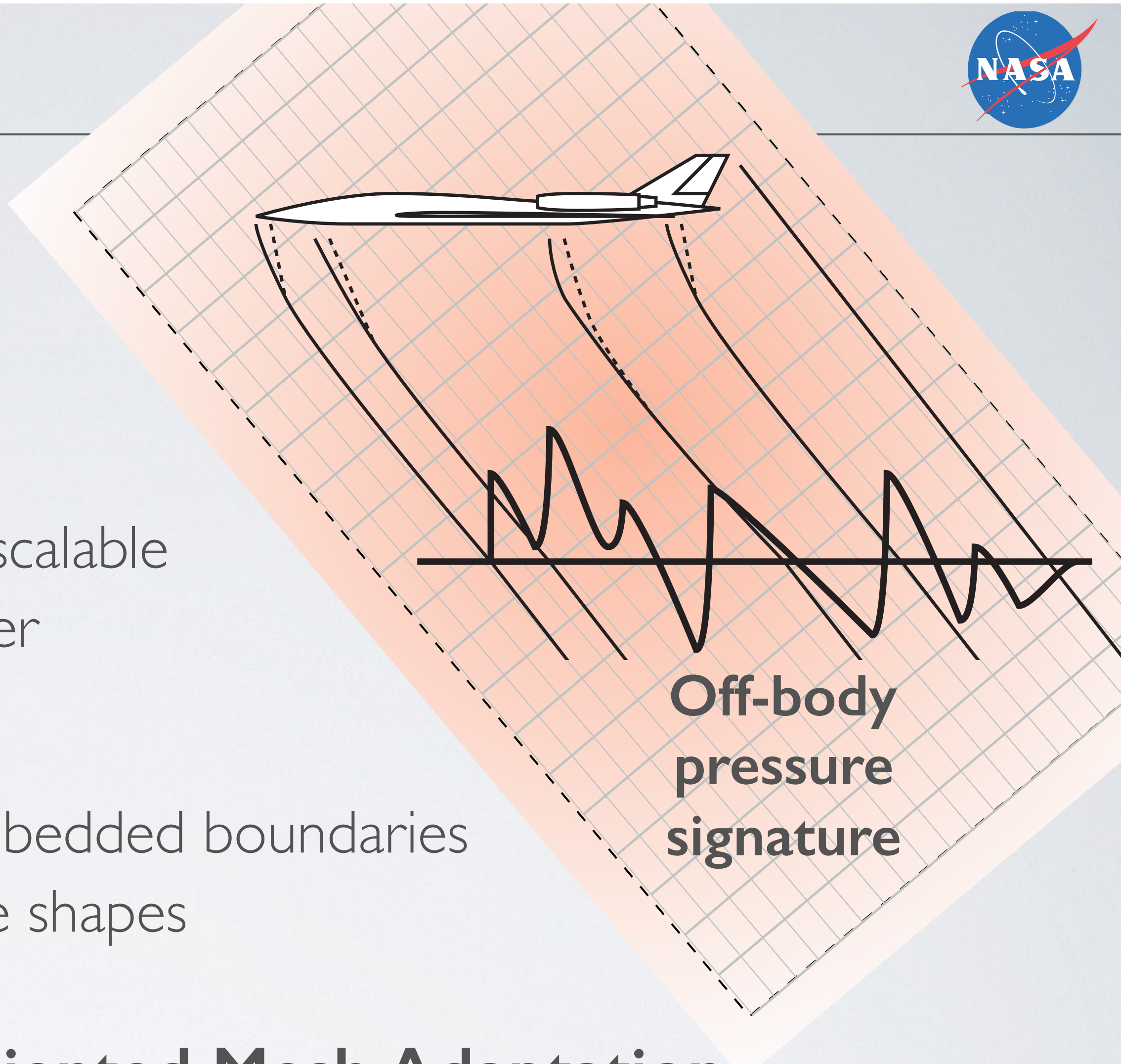
All cases:

- Mach 1.6
- Altitude: 15.76 km (~52K feet)

OUTLINE

- **Nearfield Workshop — Cart3D**
  - **Meshing approach** — Mach Alignment + Adaptation
  - **Boom Carpets** — Azimuthal Alignment
  - **Results** for Cases 1 and 4
  - **Local Error Analysis**
- **Propagation Workshop**
- **Full Vehicle-to-Boom Simulation Path**
- **Conclusions**

CFD and Meshing



Flow Solver — Cart3D v1.5

- Steady, inviscid flow
- 2nd-order upwind method
- Multigrid acceleration
- Domain decomposition — highly scalable
- *For this work:* Barth-Jespersen limiter

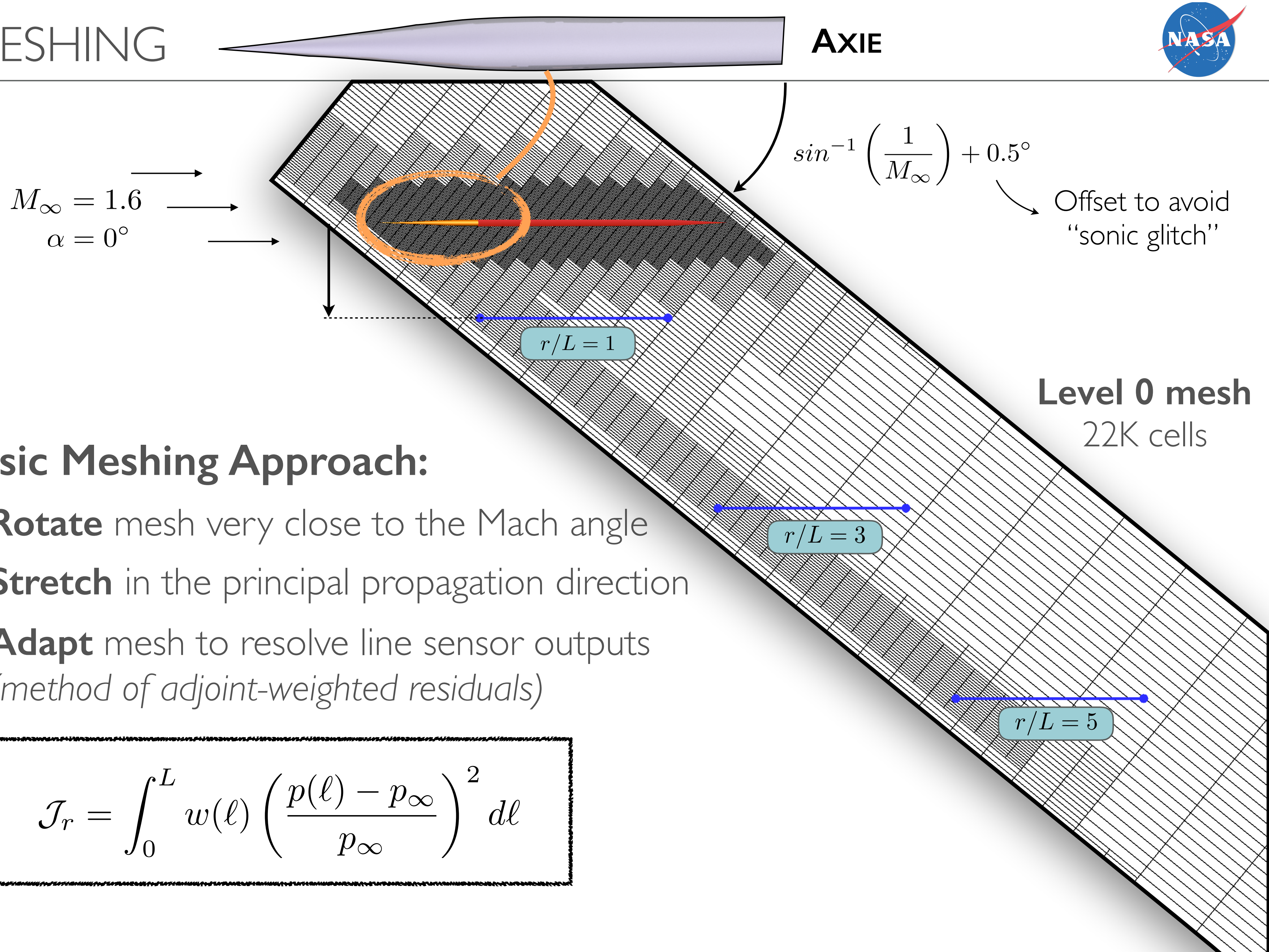
Automatic Meshing

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

Error Estimation and Goal-Oriented Mesh Adaptation

- Discretization error estimates computed via method of adjoint-weighted residuals
- Mesh automatically refined in locations with most impact on signatures

Meshing

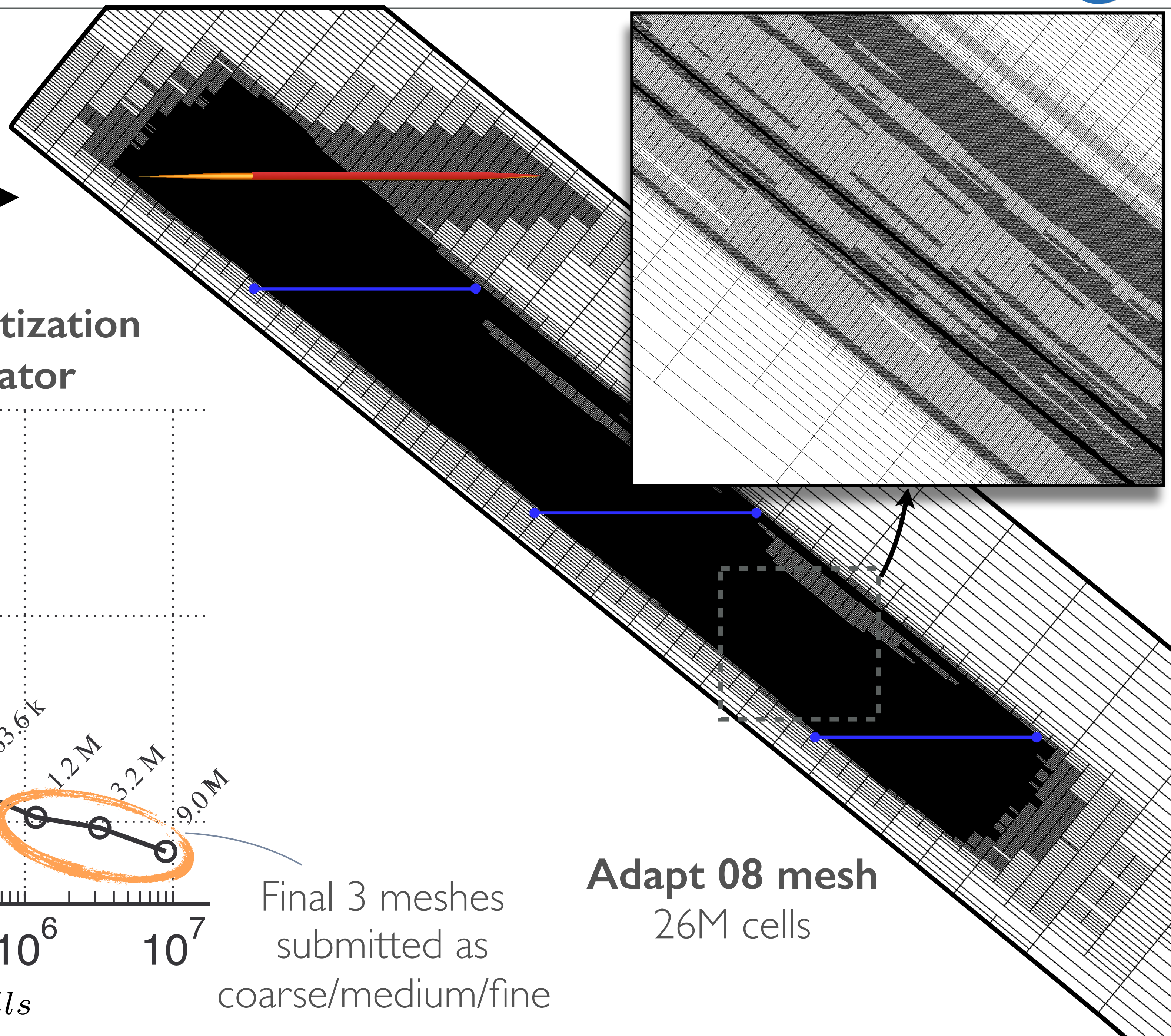


Basic Meshing Approach:

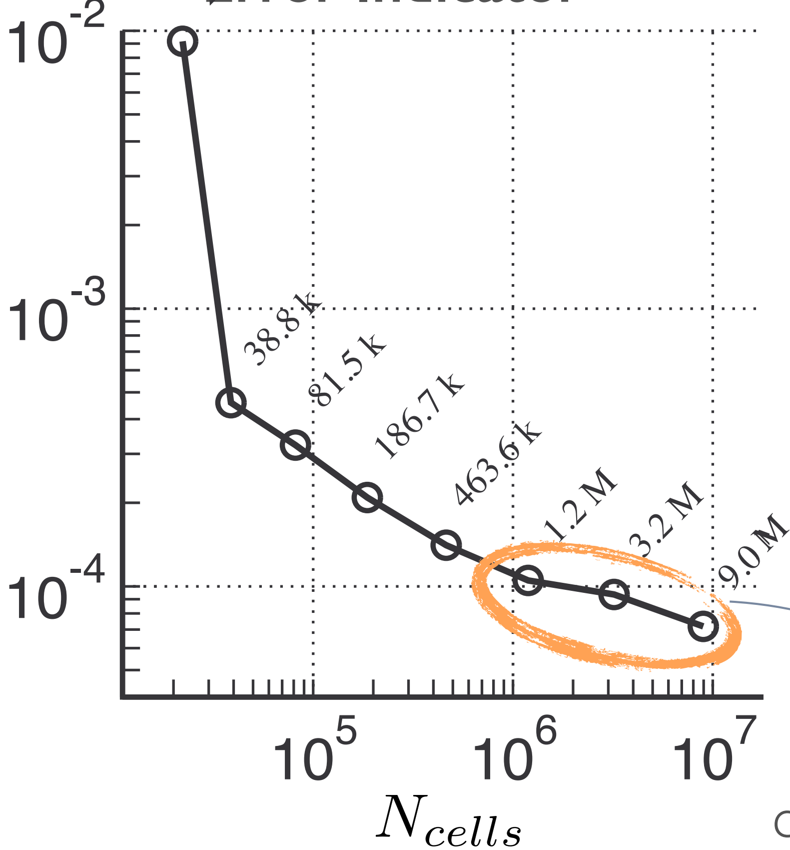
1. **Rotate** mesh very close to the Mach angle
2. **Stretch** in the principal propagation direction
3. **Adapt** mesh to resolve line sensor outputs
(method of adjoint-weighted residuals)

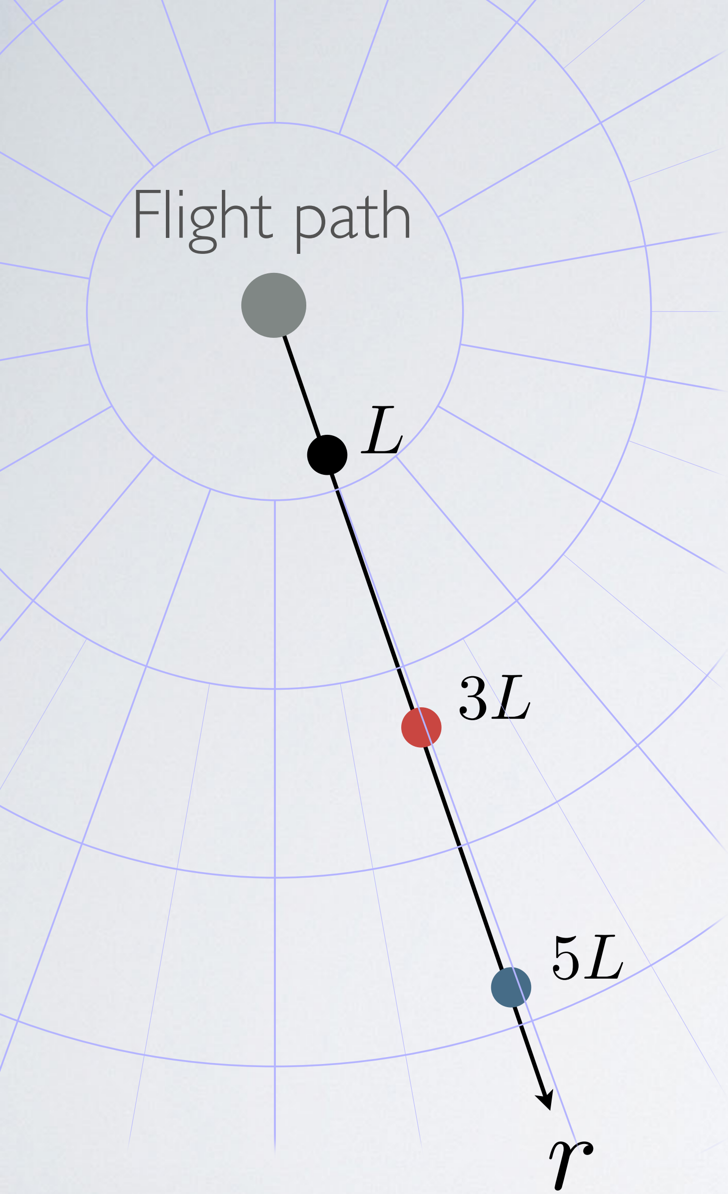
$$\mathcal{J}_r = \int_0^L w(\ell)\left(\frac{p(\ell) - p_\infty}{p_\infty}\right)^2 d\ell$$

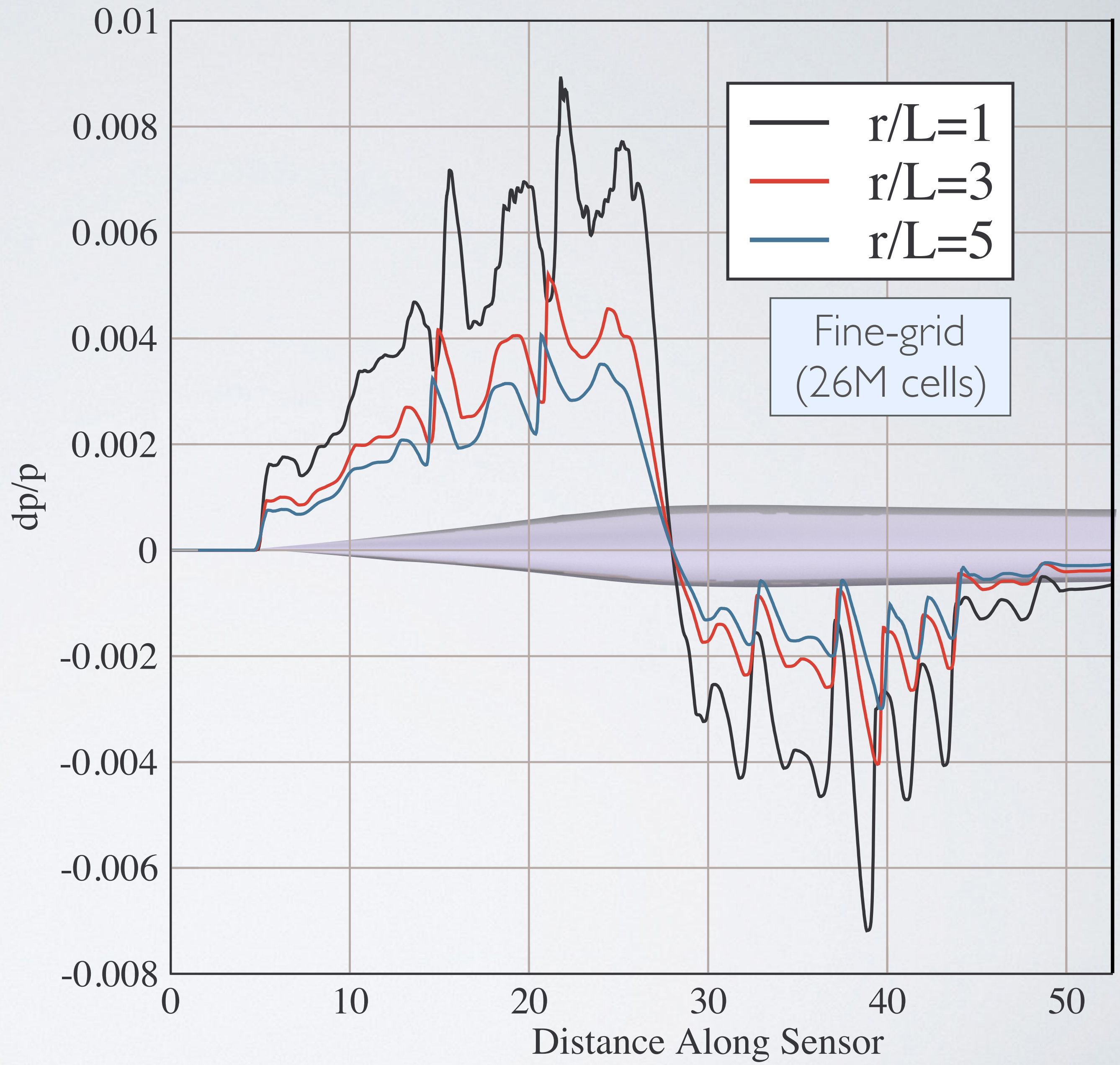
ADAPTATION

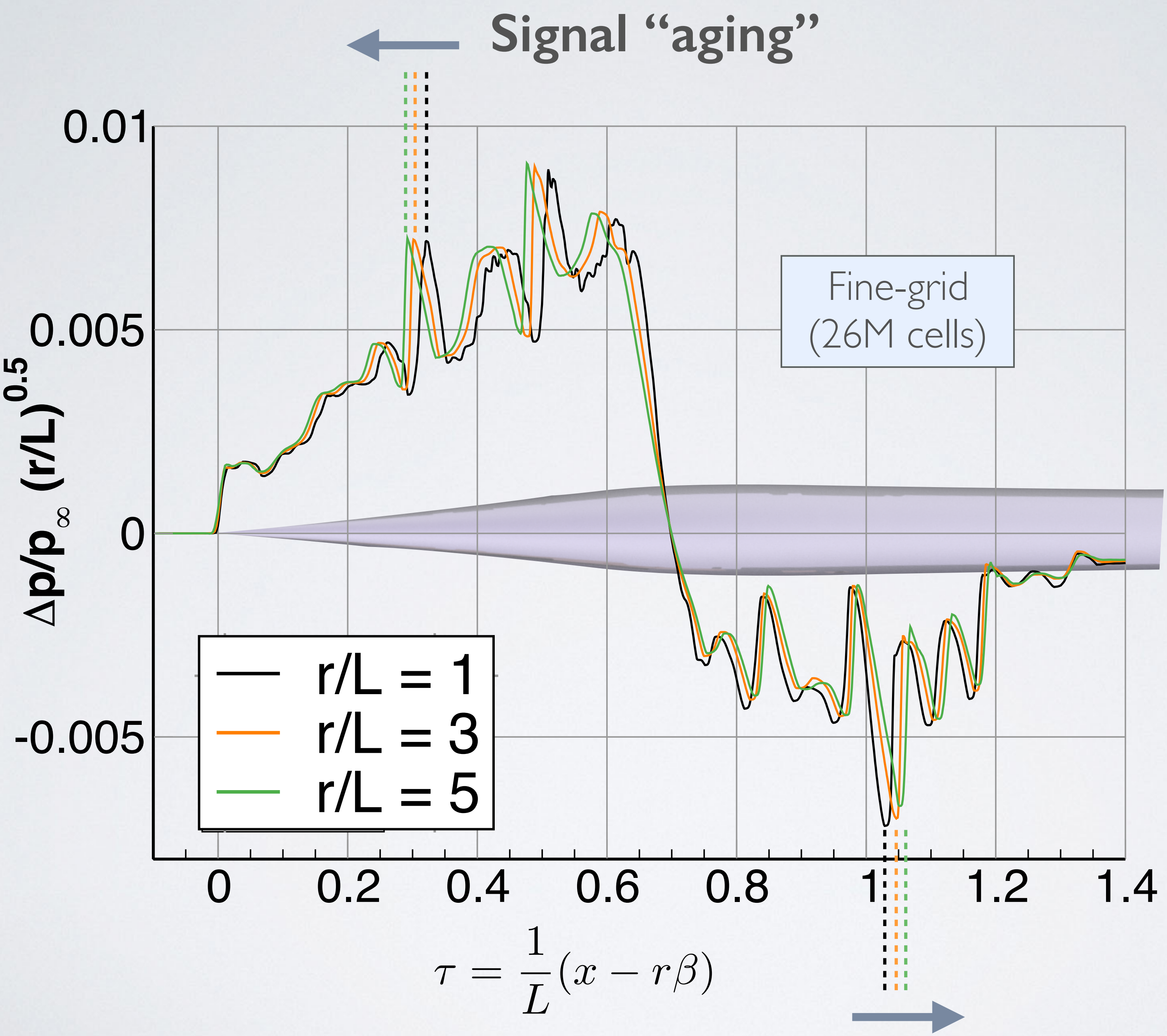


Adjoint Discretization Error Indicator

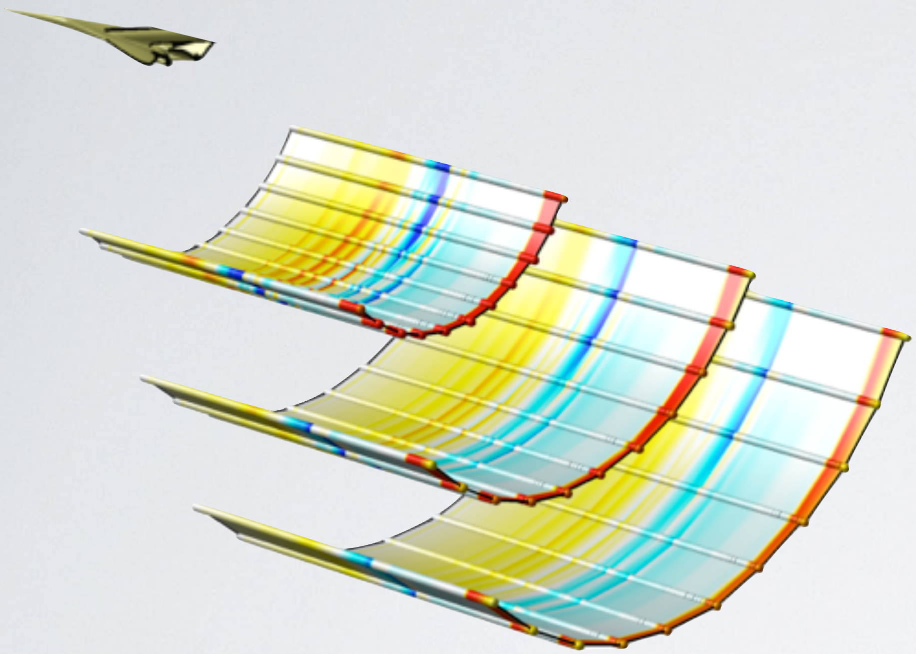



Flight path
L
$3L$
$5L$
r

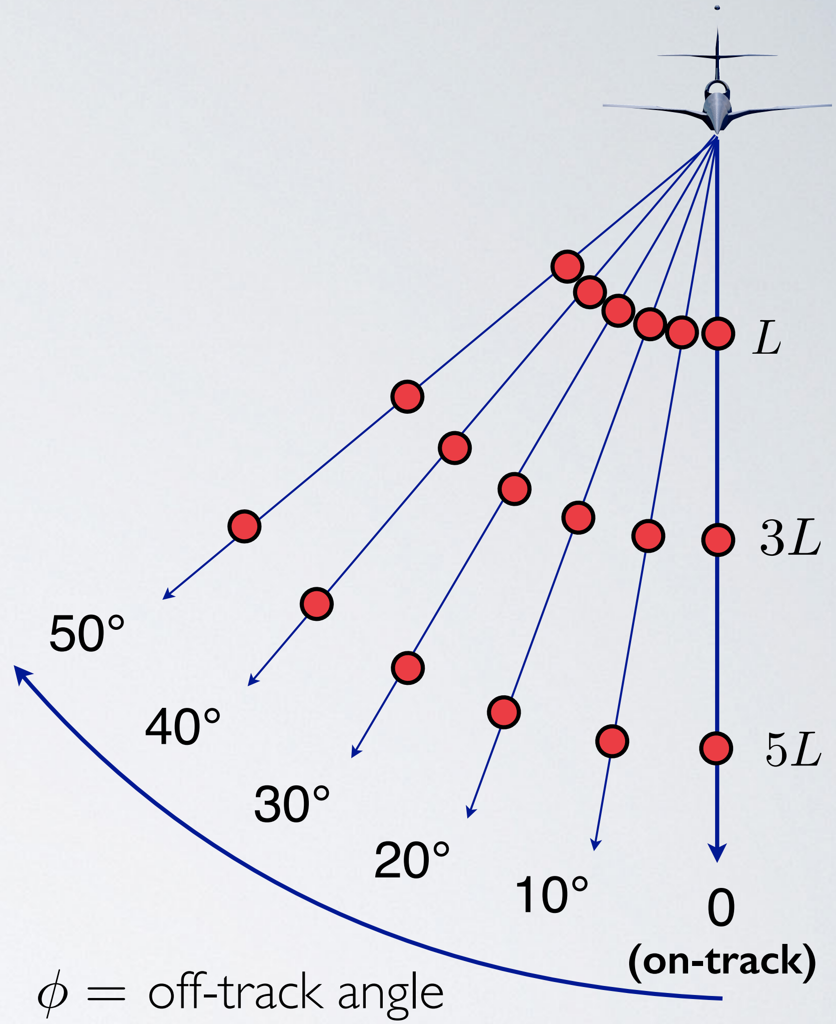

0.01
0.008
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
dp/p
0
10
20
30
40
50
Distance Along Sensor
r/L=1
r/L=3
r/L=5
Fine-grid
(26M cells)


Signal "aging"
0.01
0.005
0
-0.005
$\Delta p/p_\infty\ (r/L)^{0.5}$
0
0.2
0.4
0.6
0.8
1
1.2
1.4
$\tau = \frac{1}{L}(x - r\beta)$
Fine-grid
(26M cells)
r/L = 1
r/L = 3
r/L = 5

Boom Carpets

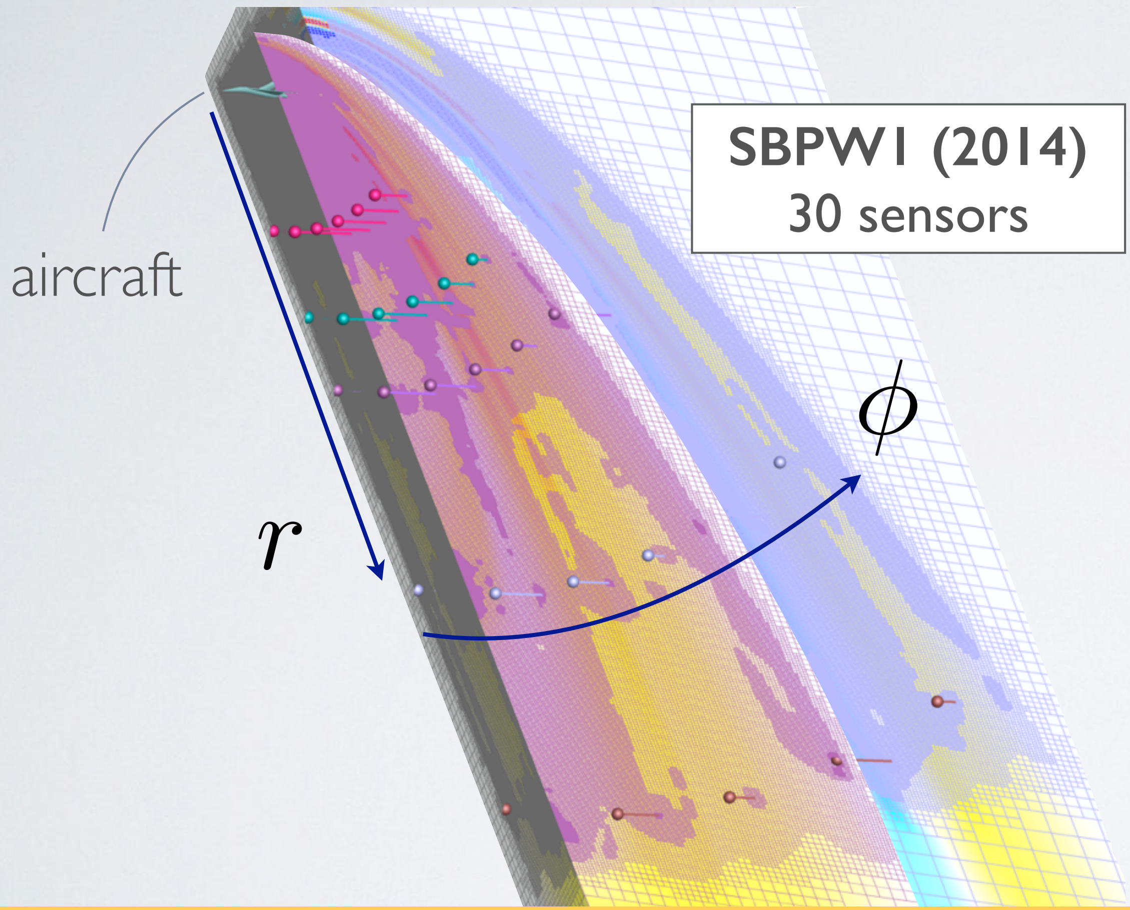


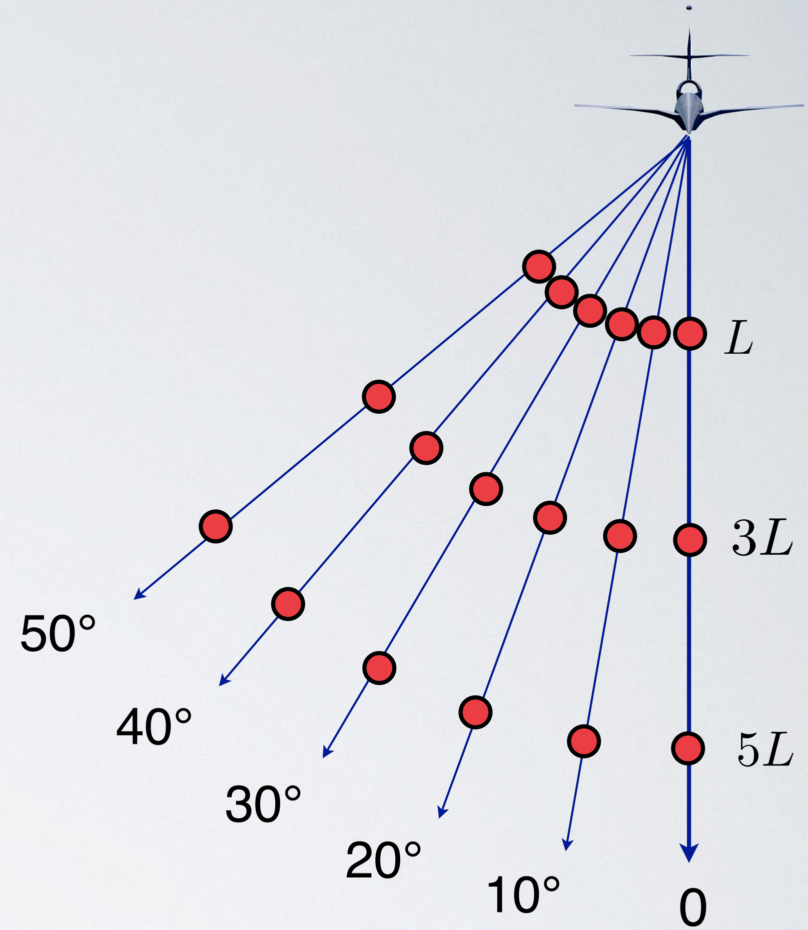
Boom Carpets



Boom Carpets with Monolithic Mesh

Compute entire carpet
in a single Cartesian mesh





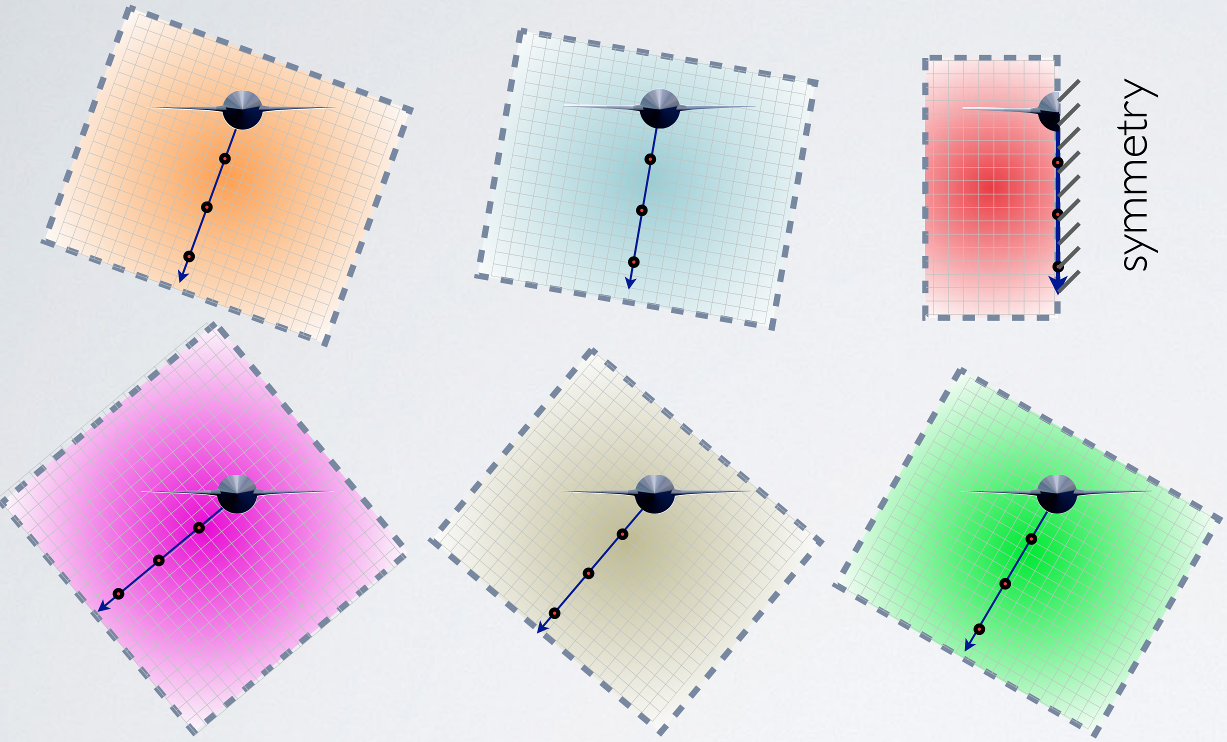
- Off-track angles are misaligned
- Aspect ratio is constrained

} **high cell-counts**

Decomposing Boom Carpets

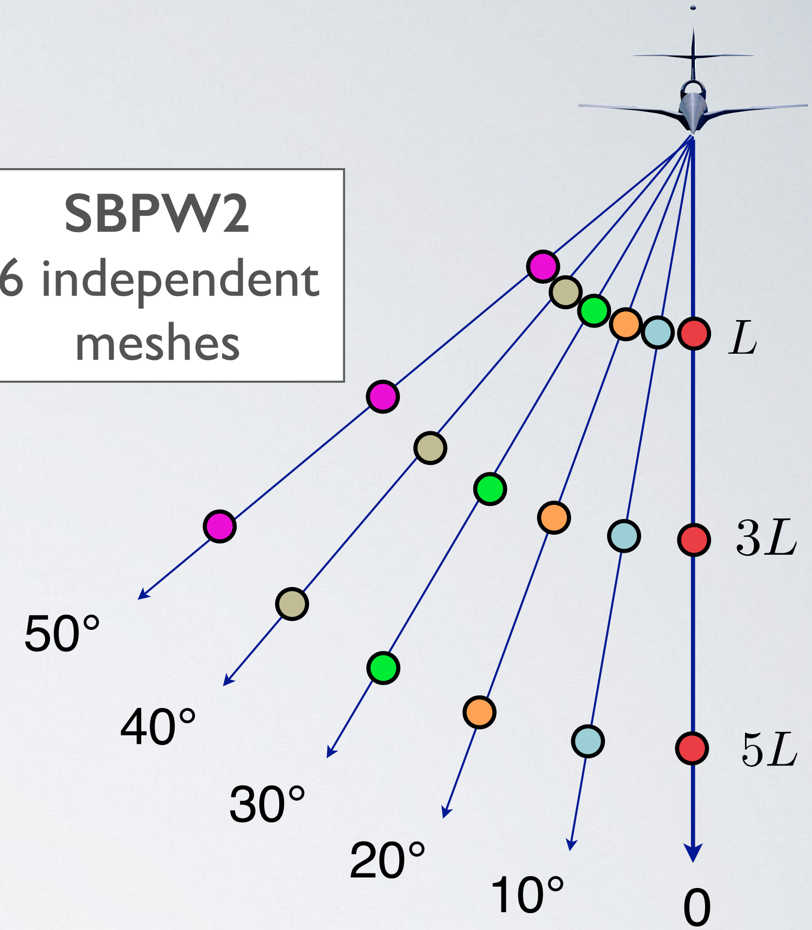
Use independent meshes

each rotated to off-track angle



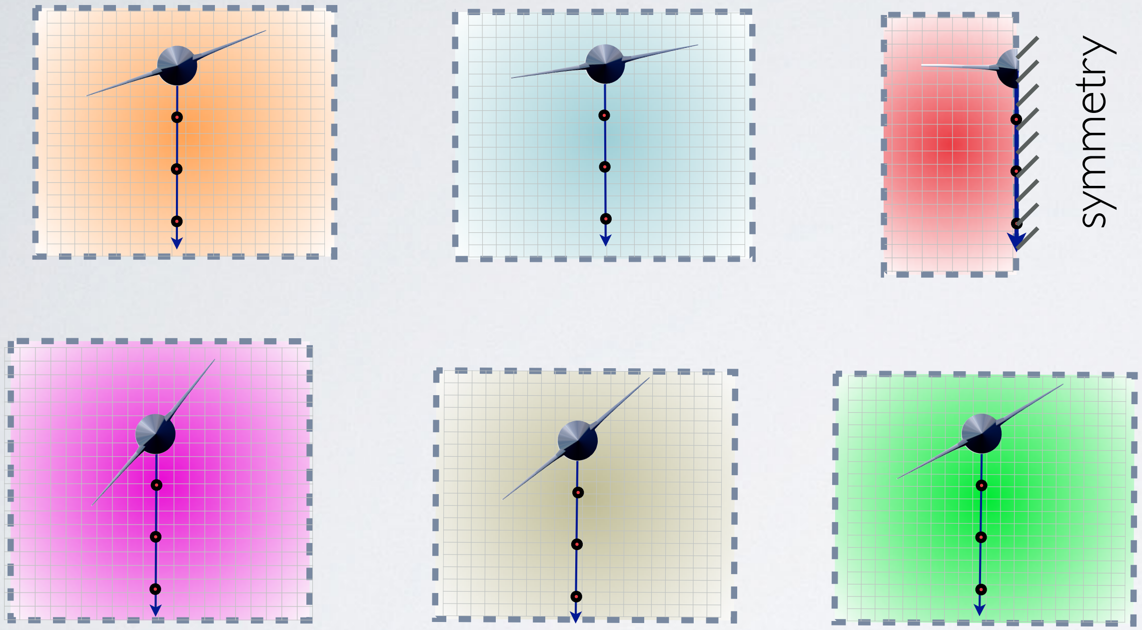
SBPW2

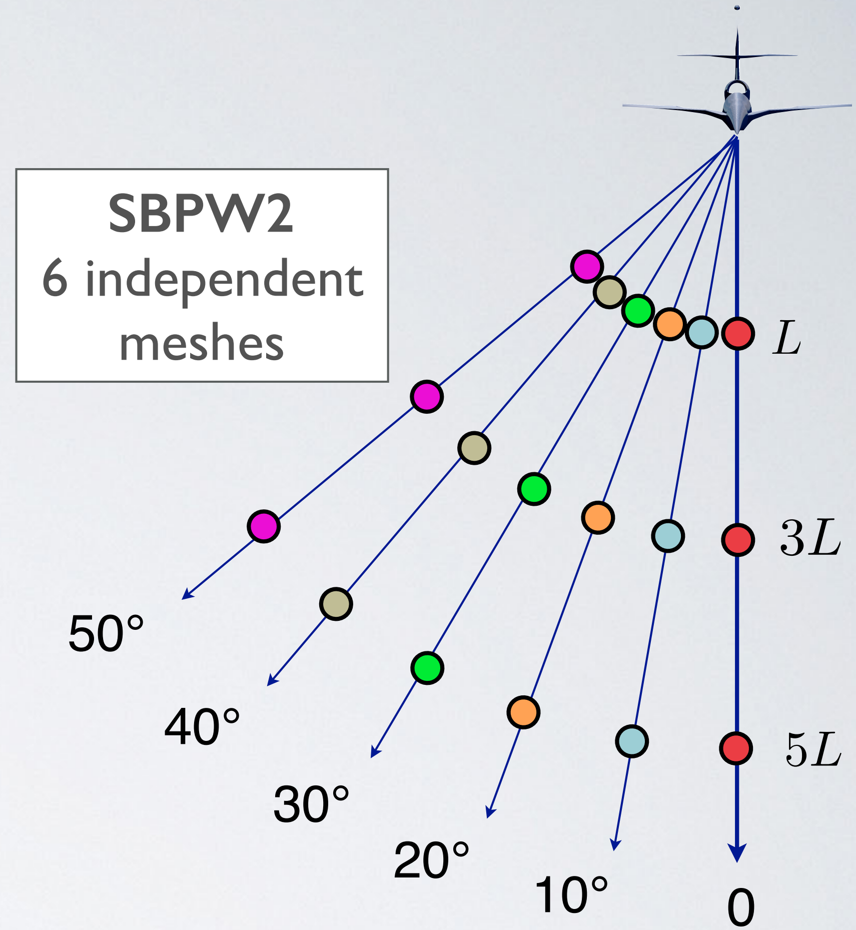
6 independent meshes



Decomposing Boom Carpets

Use independent meshes
each rotated to off-track angle

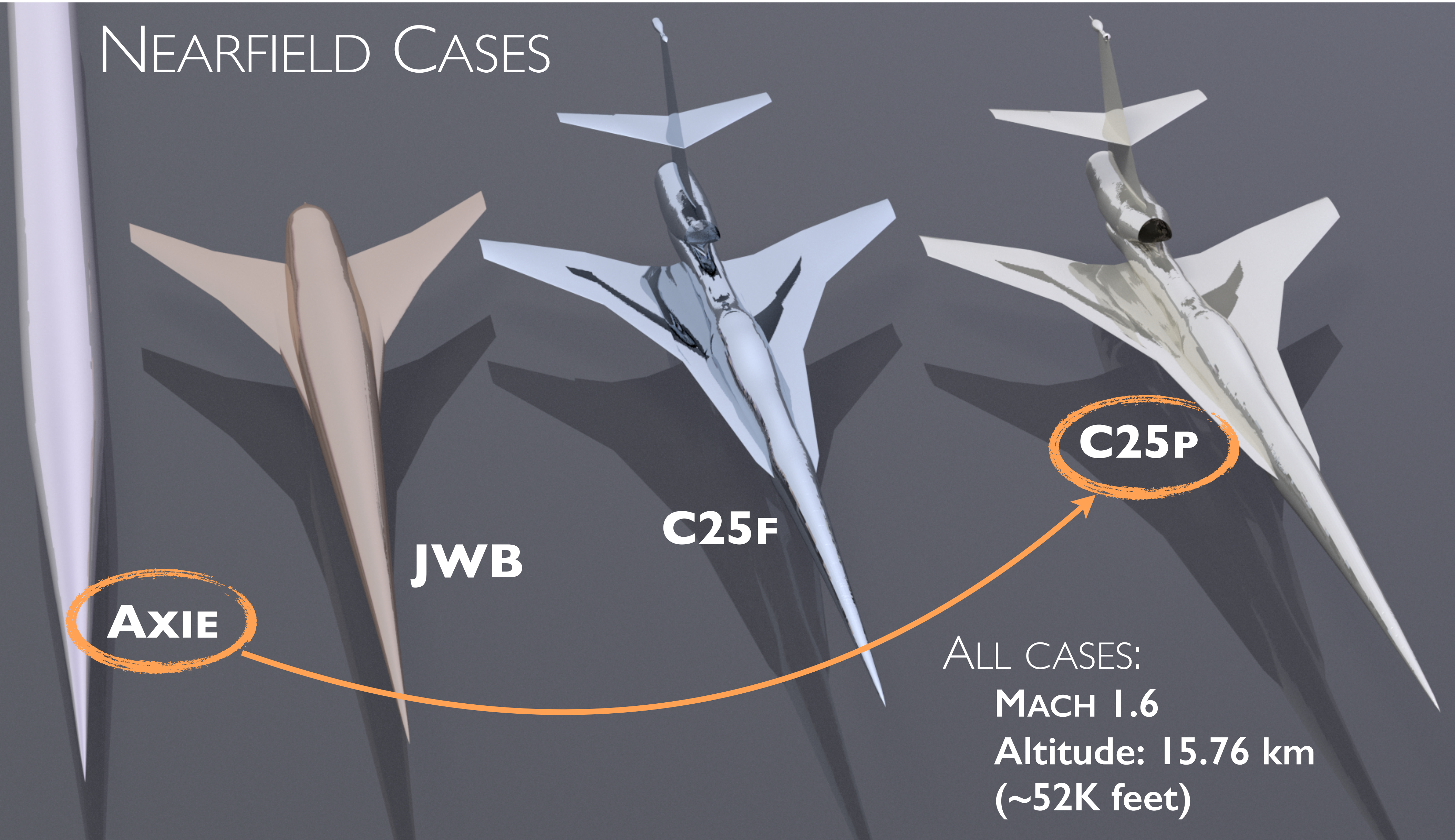




Splitting permits

- **azimuthal alignment**, which permits:
  - higher **stretching**
- Simultaneous computation of off-track angles in carpet

Nearfield Cases



All cases:

Mach 1.6
Altitude: 15.76 km
(~52K feet)

Concept 25D

Powered Variant (**C25P**)

Flight Conditions

Mach 1.6

$\alpha = 3.375°$

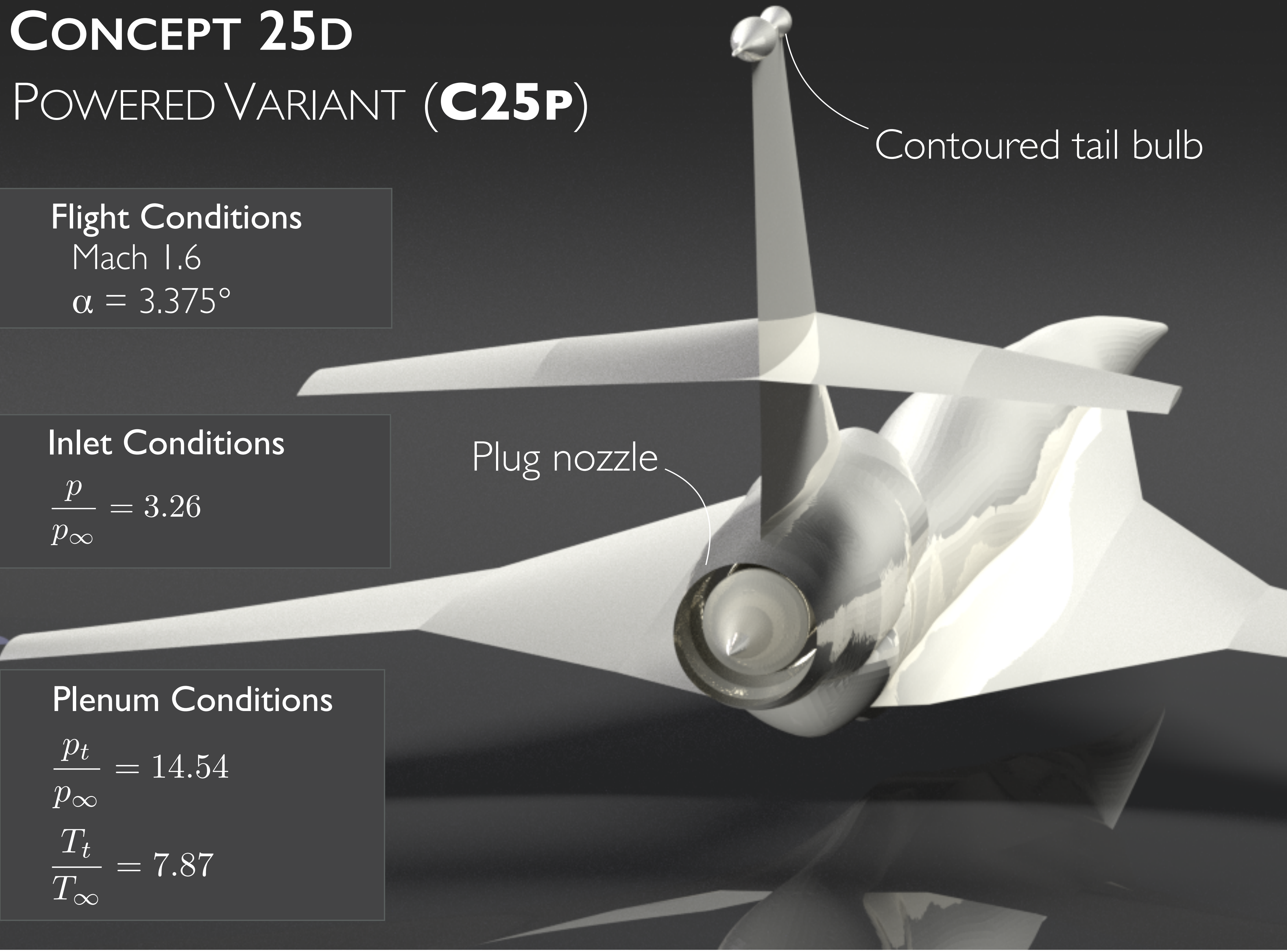
Inlet Conditions

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

Plenum Conditions

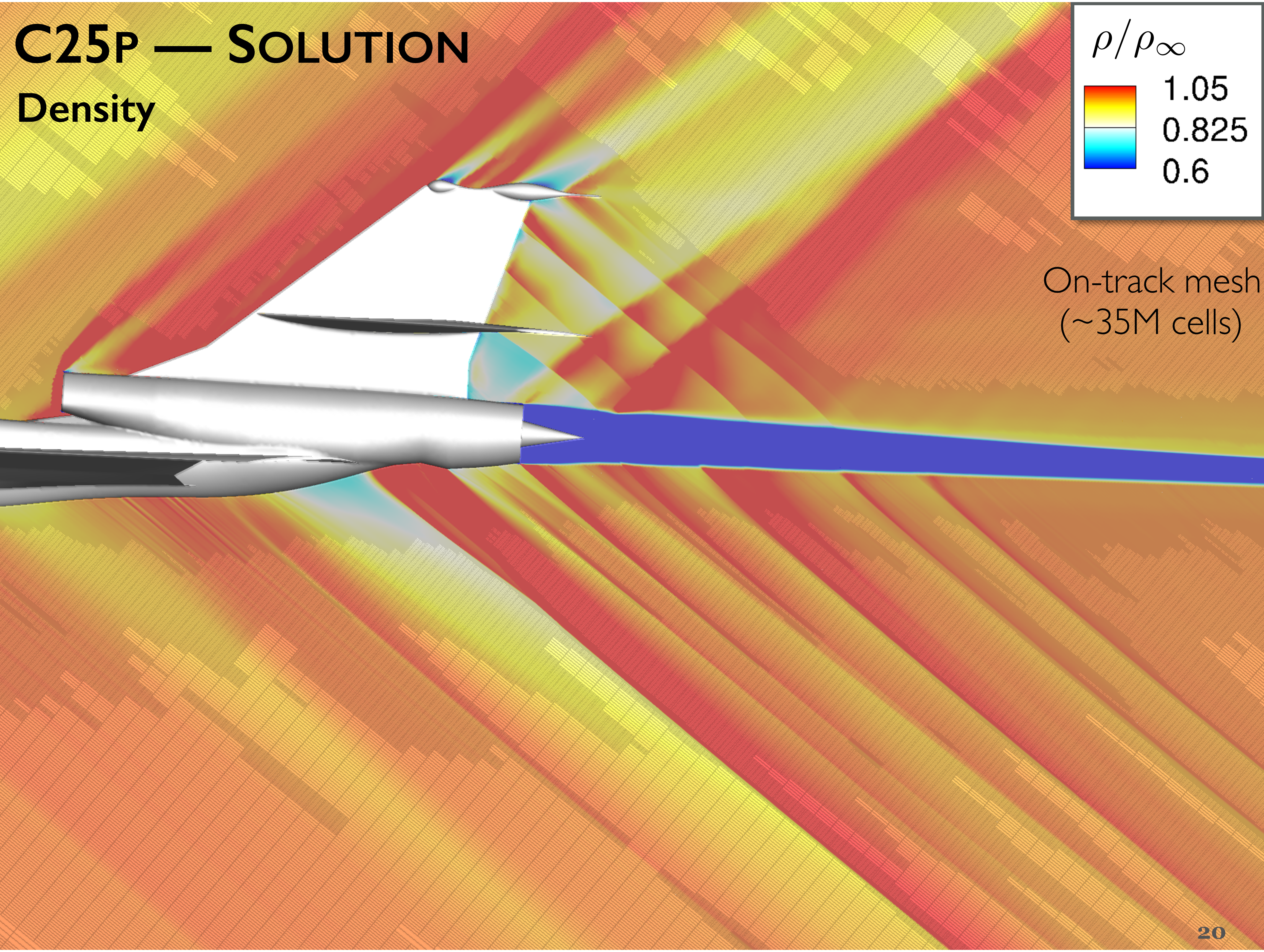
$$\frac{p_t}{p_\infty} = 14.54$$

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



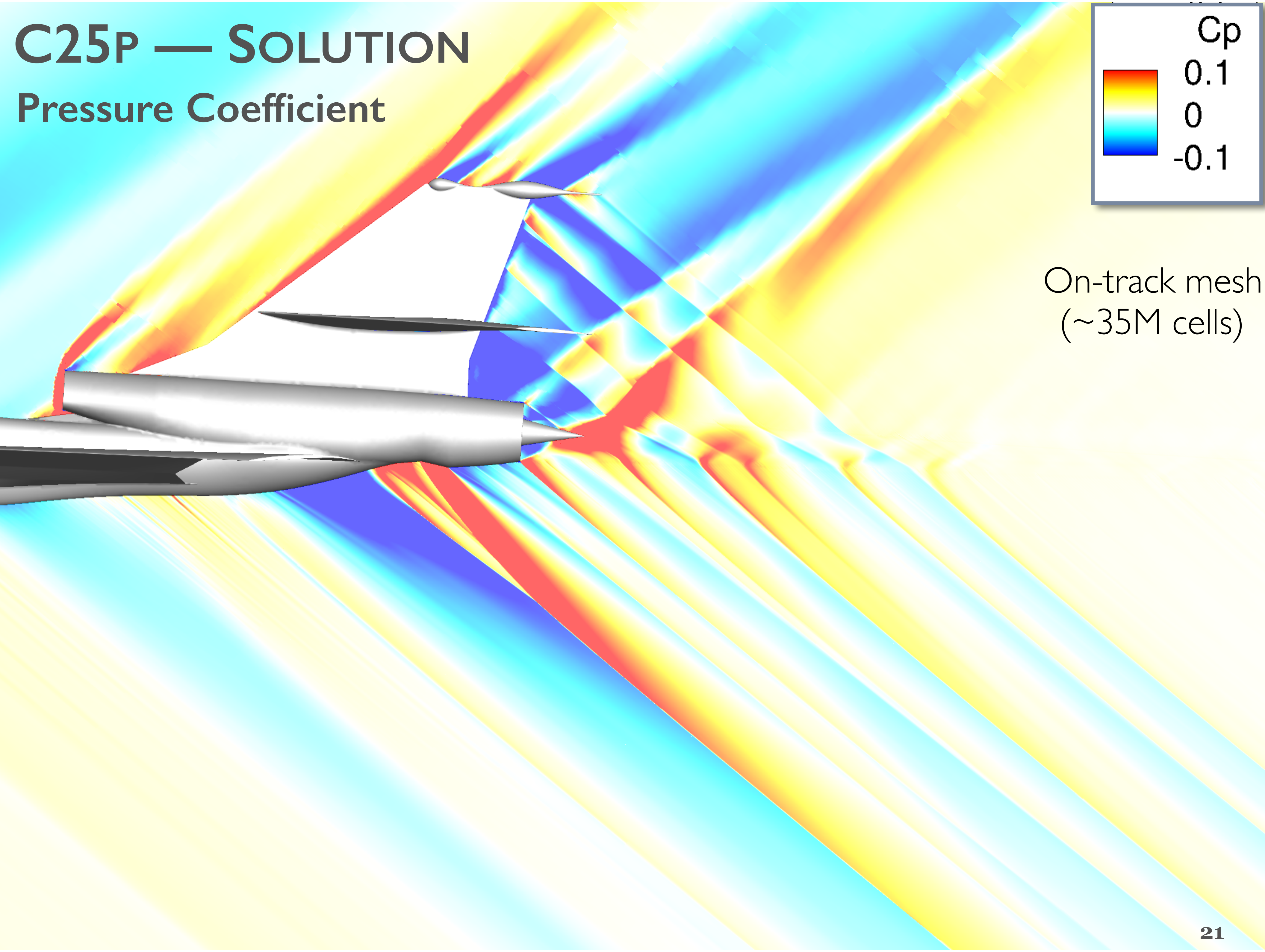
C25P — Solution

Density

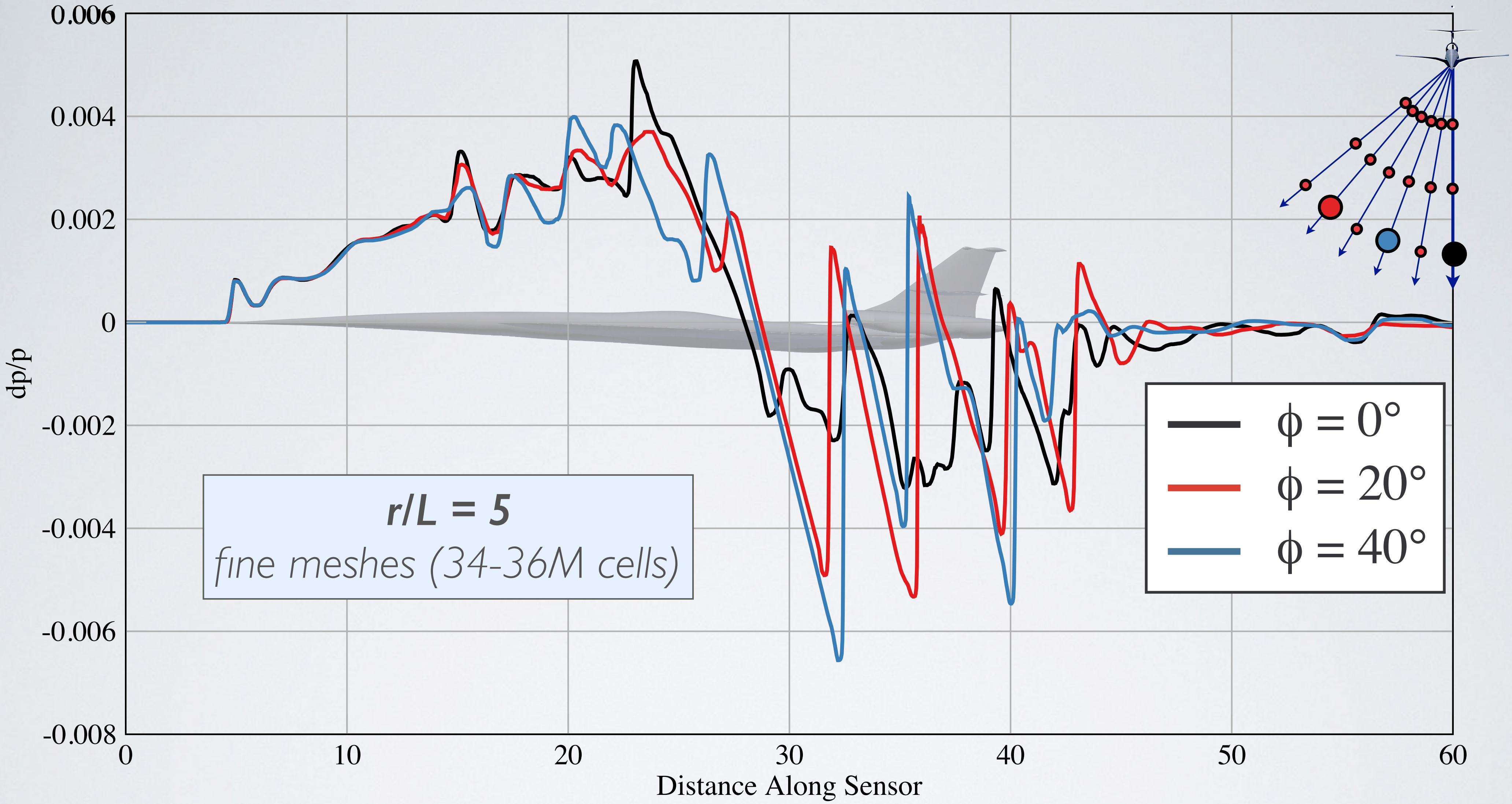


C25P — Solution

Pressure Coefficient



C25P — SIGNATURES



Each off-track angle — 35M cell mesh: 4hr 30min on 28 cores

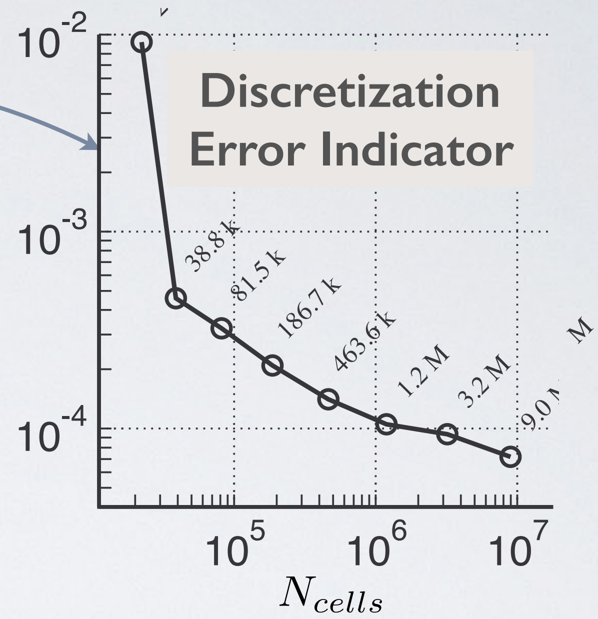
Includes flow solution + all meshing, adjoint solutions, error estimation, etc.

Assessing Mesh Convergence

Adjoint: Is the integrated functional converging asymptotically?

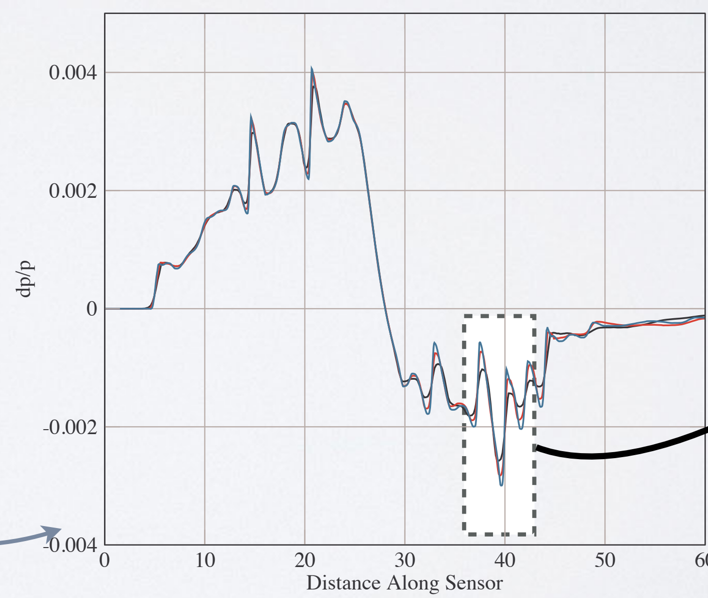
- Non-intuitive units on error

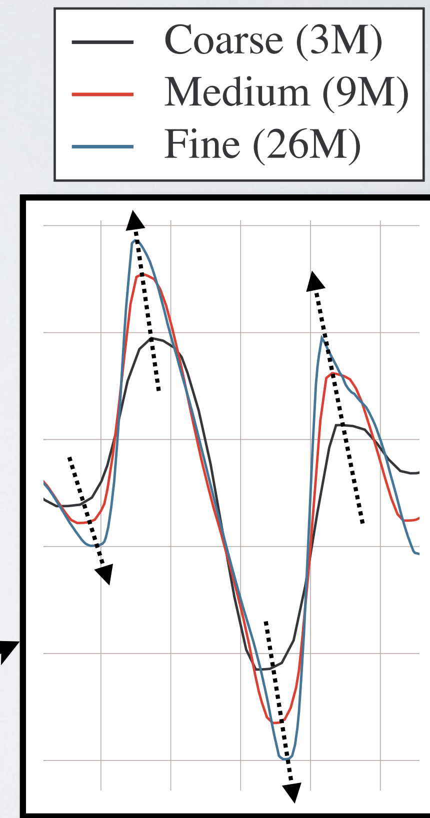
$$\mathcal{J}_r = \int_0^L w(\ell) \left(\frac{p(\ell) - p_\infty}{p_\infty} \right)^2 d\ell$$



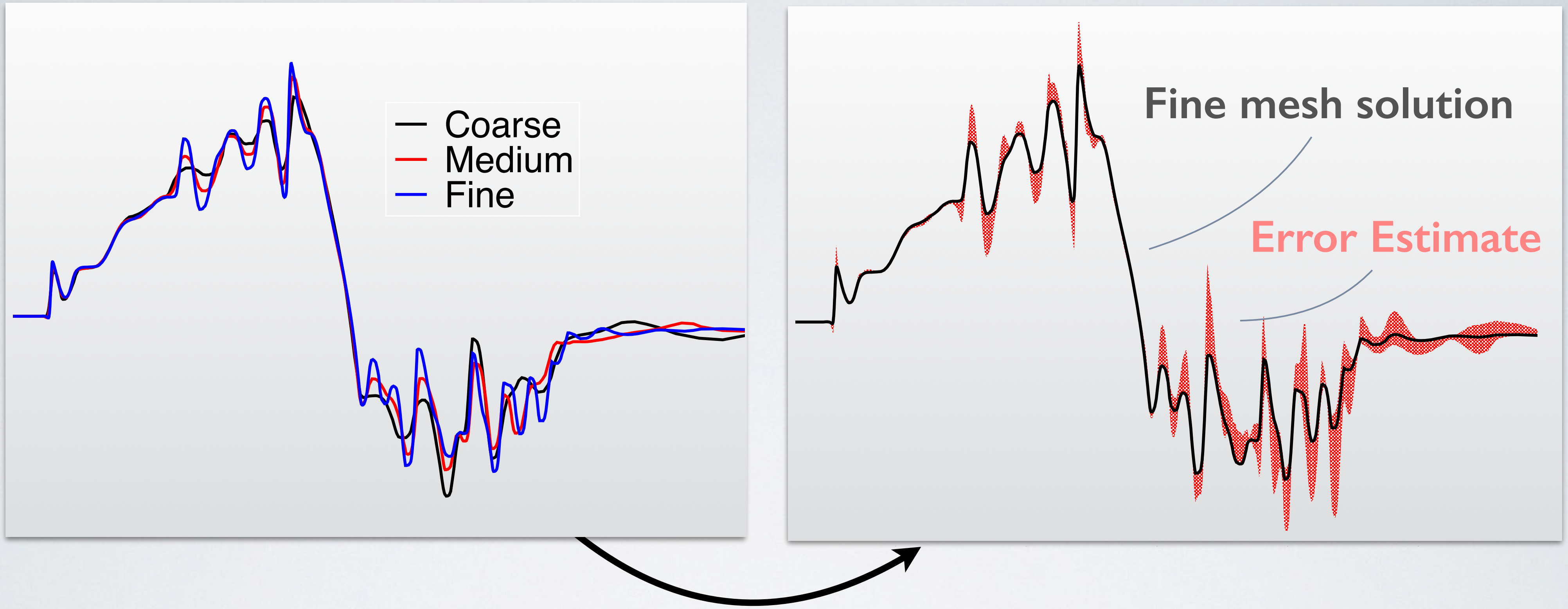
Qualitative: Are signal features converging with mesh refinement?

- Out of context, has no quantitative anchor, however:
- The signatures are the result of a error reducing process.





LOCAL ERROR ANALYSIS



Local Richardson extrapolation

- Incorporates estimate of global rate of convergence
- Reveals significant **local** variation in error and rate of convergence
- Can be used for any mesh refinement technique (not just adjoint-based)

Details: ***AIAA Paper 2017-3255***

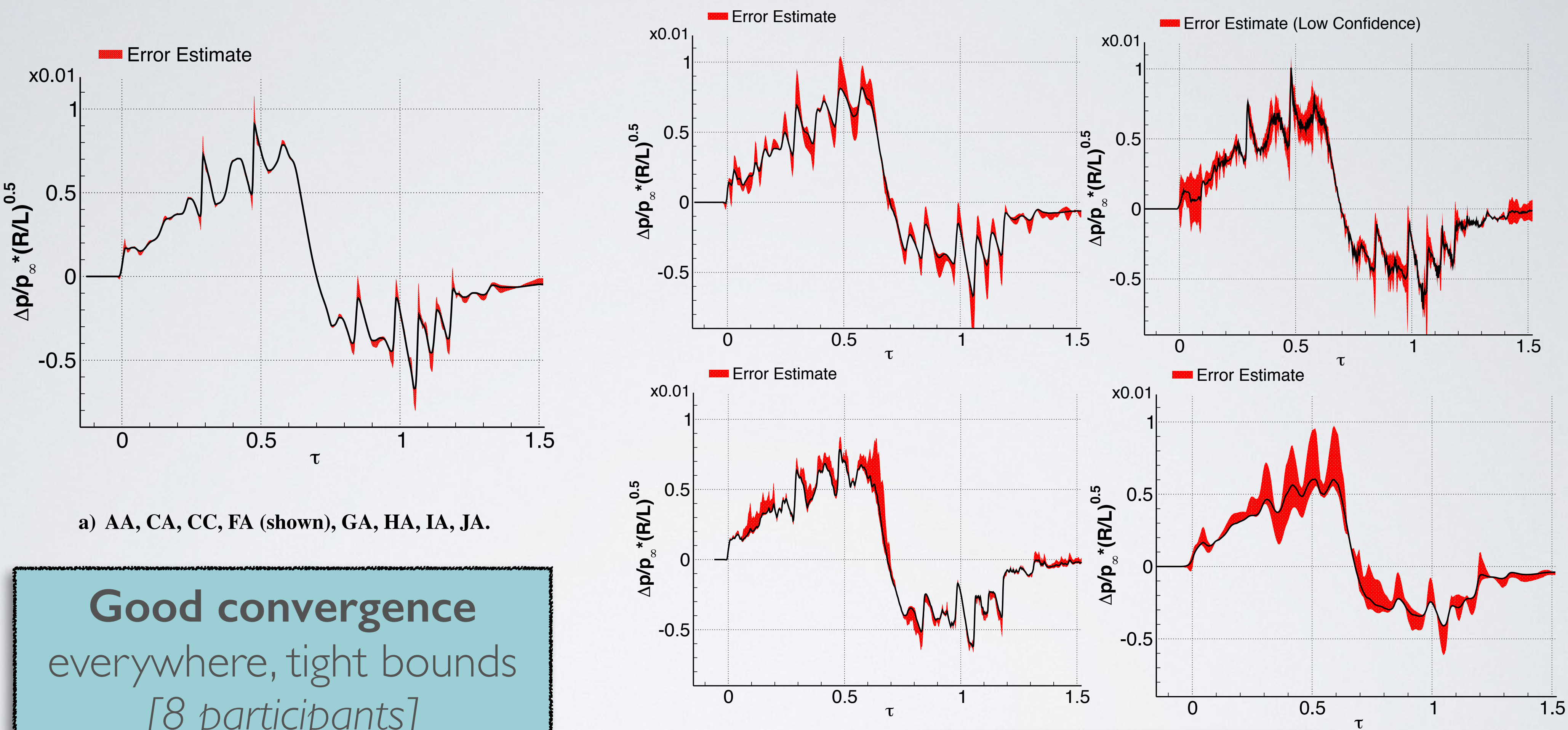
Figure 10. AXIE signature computed on fine grids plotted with discretization error estimates (R = 5).

a) AA, CA, CC, FA (shown), GA, HA, IA, JA.

Good convergence
everywhere, tight bounds
[8 participants]

(2017) Park and Nemec, ***"Nearfield Summary and Statistical Analysis of the Second AIAA Sonic Boom Prediction Workshop"***

Figure 10. AXIE signature computed on fine grids plotted with discretization error estimates (R = 5).



a) AA, CA, CC, FA (shown), GA, HA, IA, JA.

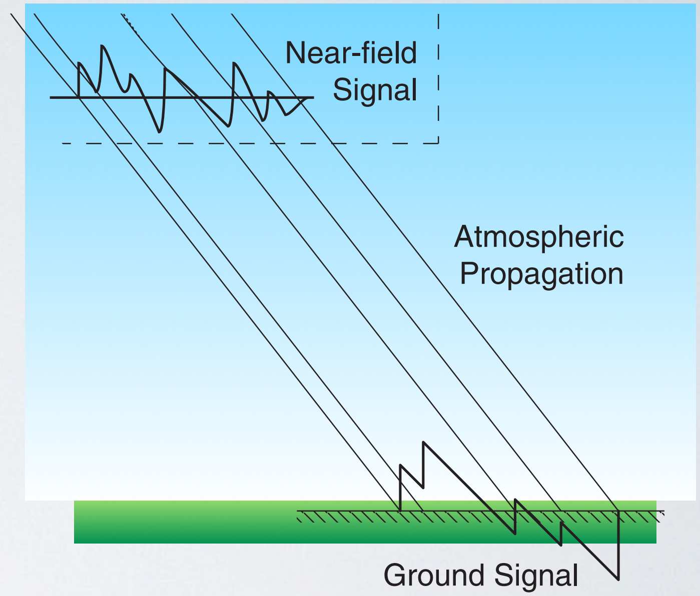
Good convergence
everywhere, tight bounds
[8 participants]

Individual poorly converged results

(2017) Park and Nemec, ***"Nearfield Summary and Statistical Analysis of the Second AIAA Sonic Boom Prediction Workshop"***

OUTLINE

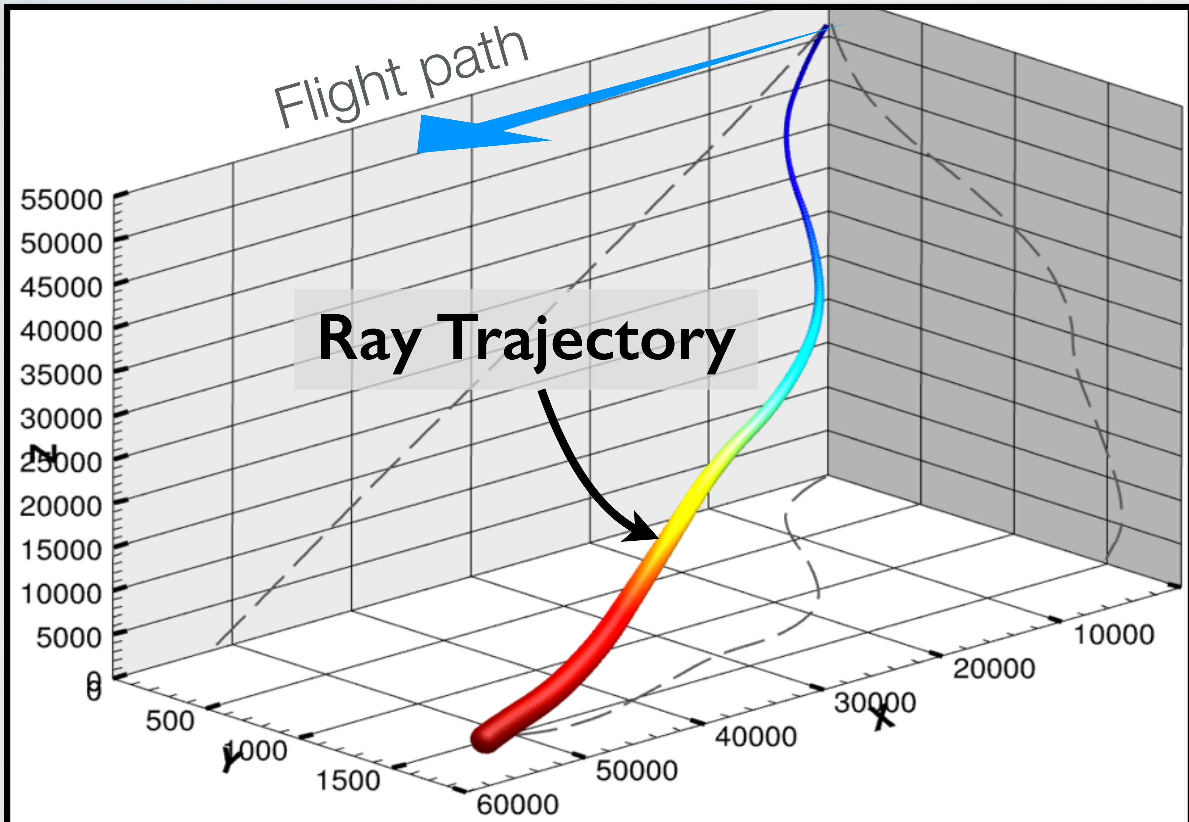
- ✓ Nearfield Workshop
- Propagation Workshop — sBOOM
  - Numerical approach
  - Propagation Results
- Full Vehicle-to-Boom Simulation Path
- Conclusions



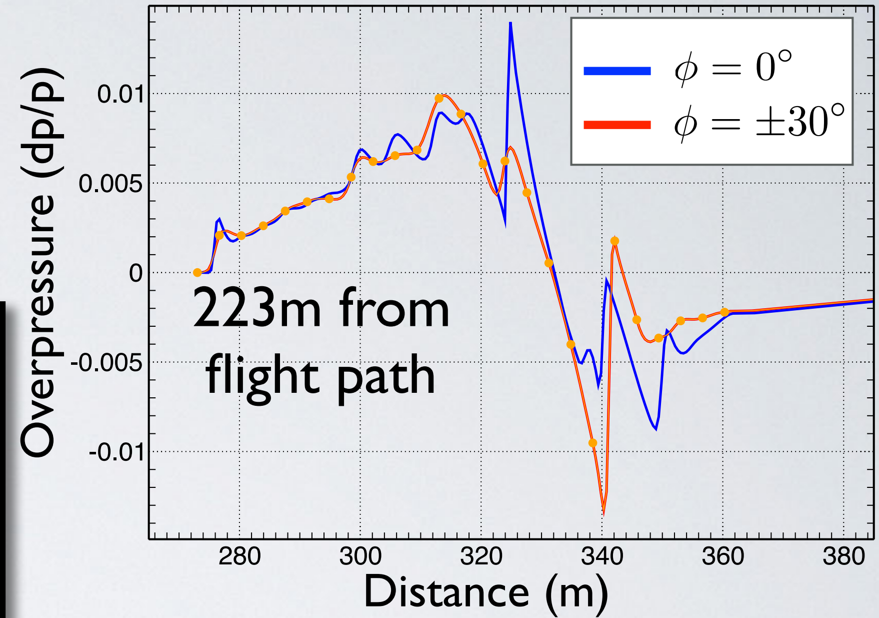
ATMOSPHERIC PROPAGATION WITH sBOOM

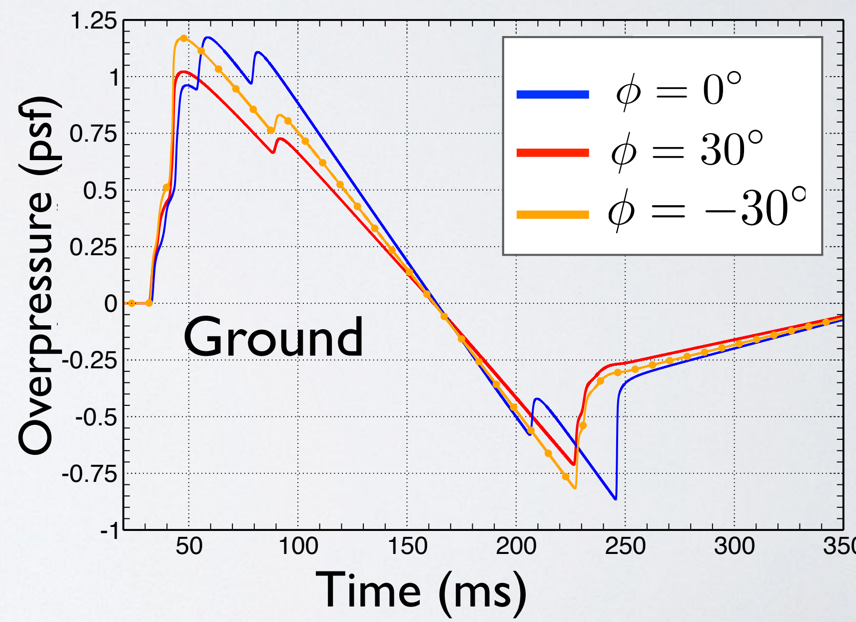
sBOOM

1. Ray-tracing
2. Quasi-1D, augmented Burgers' equation



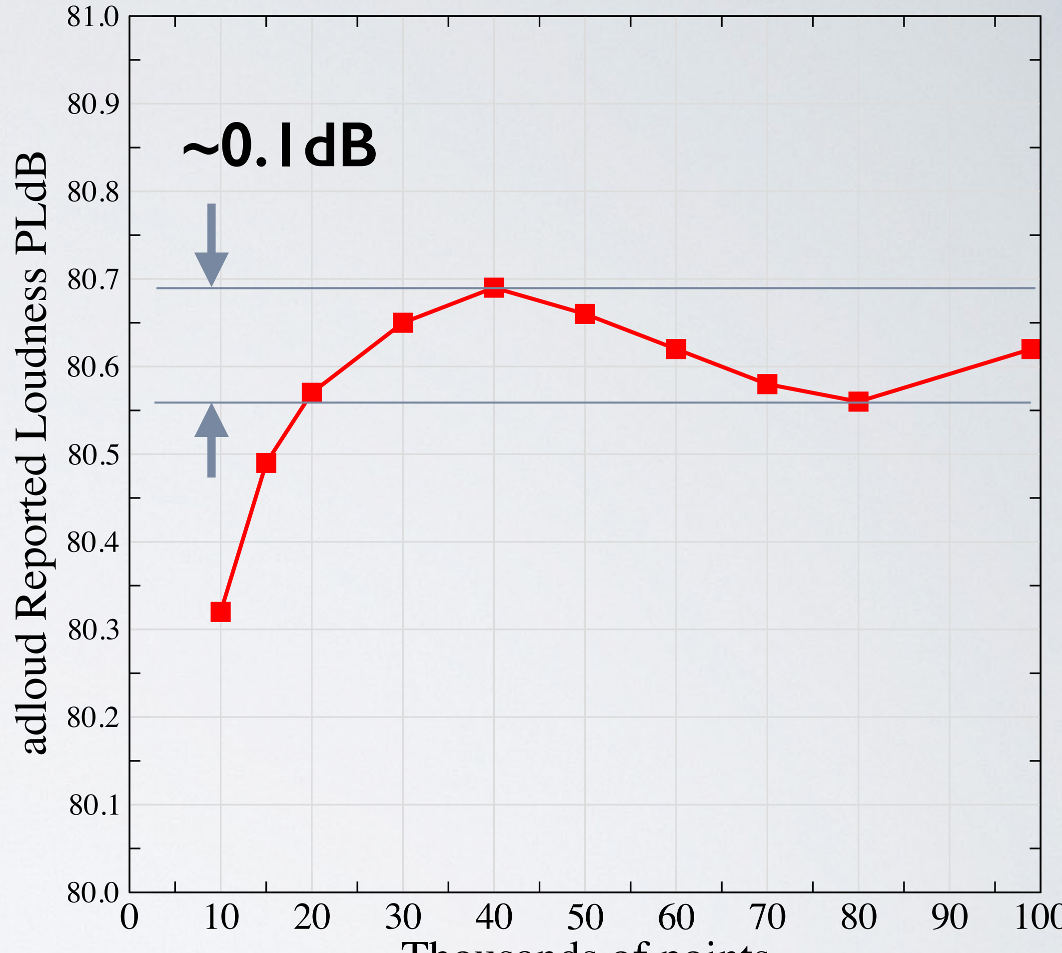
(2011) Rallabhandi, ***"Advanced Sonic Boom Prediction Using the Augmented Burgers Equation"***



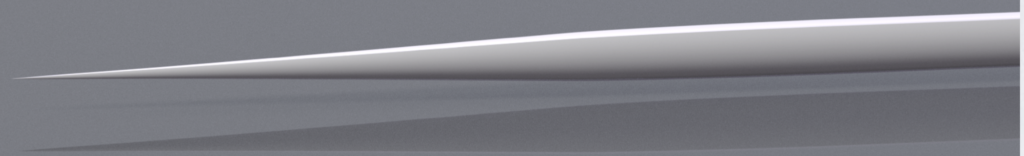


ATMOSPHERIC PROPAGATION WITH sBOOM

- **Discretization error**
  Finite difference solution of PDE on uniform grid
- **Input error**
  Input ~100X coarser than output
  Oversampling introduces high freq.
- **Mesh refinement studies**
  Numerical sources of error **~0.1dB**
  (cf. atmospheric variability of ~5 dB)
  But not clearly asymptotic



AXIE



Lref = 43m (141 ft)

Conditions:

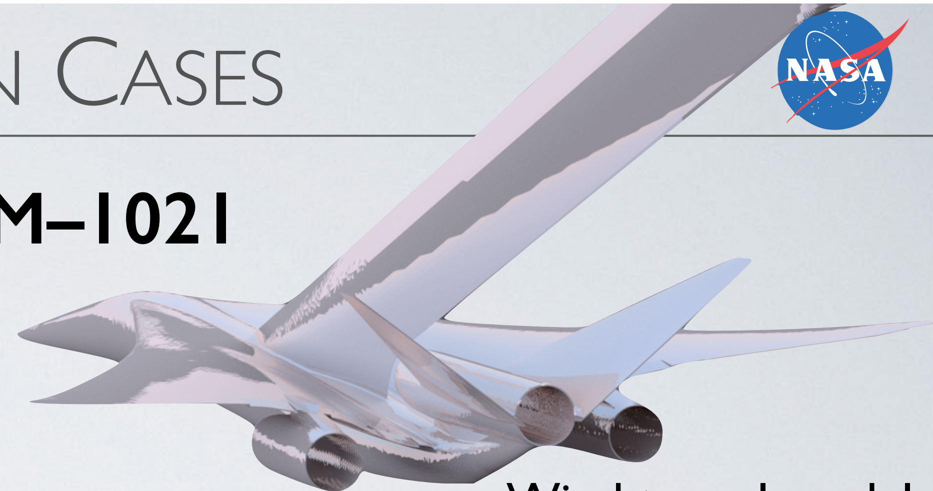
M_∞ = 1.6

Altitude = 15.8 km (~52K ft)

Profiles:

- ISO Standard Atmosphere
- ISO Std. Atm. with 70% humidity
- Hot day, coastal Virginia
- Hot dry day, Edwards AFB

LM–1021



Wind tunnel model from SBPW1 (2014)

Lref = 71m (233 ft)

Conditions:

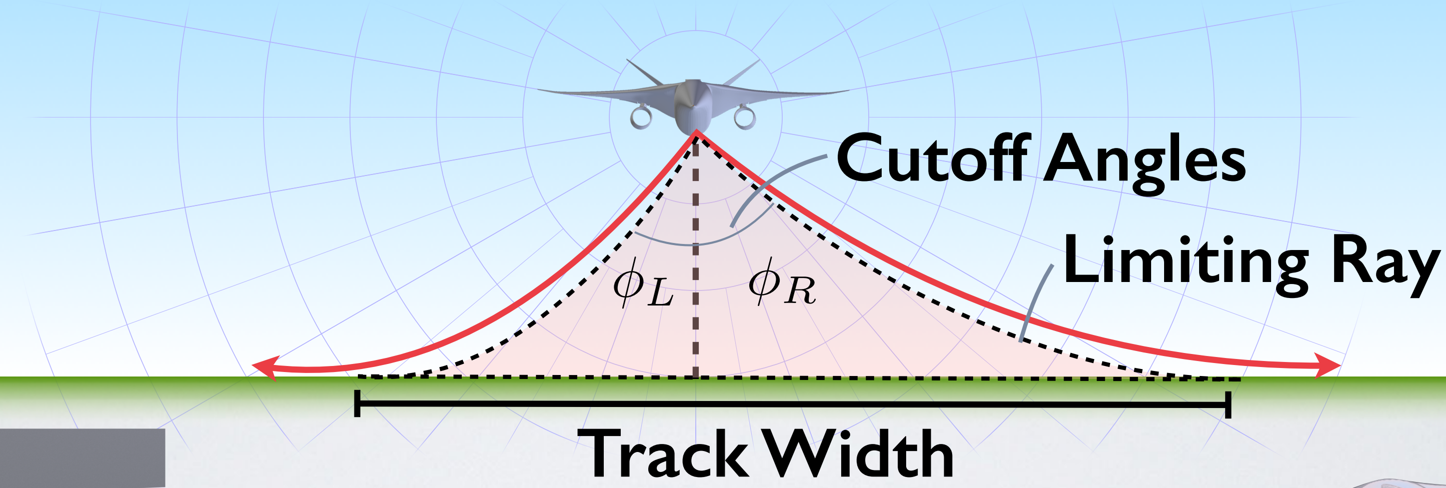
M_∞ = 1.6

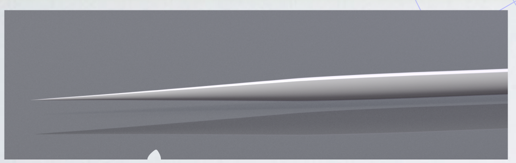
Altitude = 16.7 km (~55K ft)

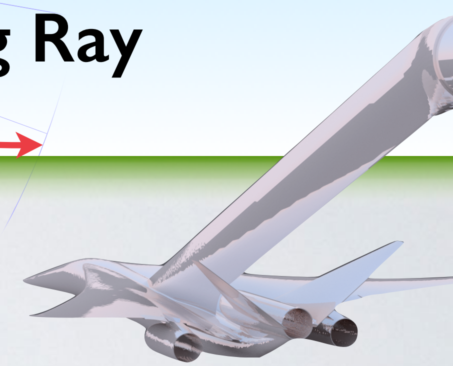
Profiles:

- ISO Standard Atmosphere
- ISO Std. Atm. with 70% humidity
- 2 consecutive winter days in Green Bay, WI

Boom Footprint



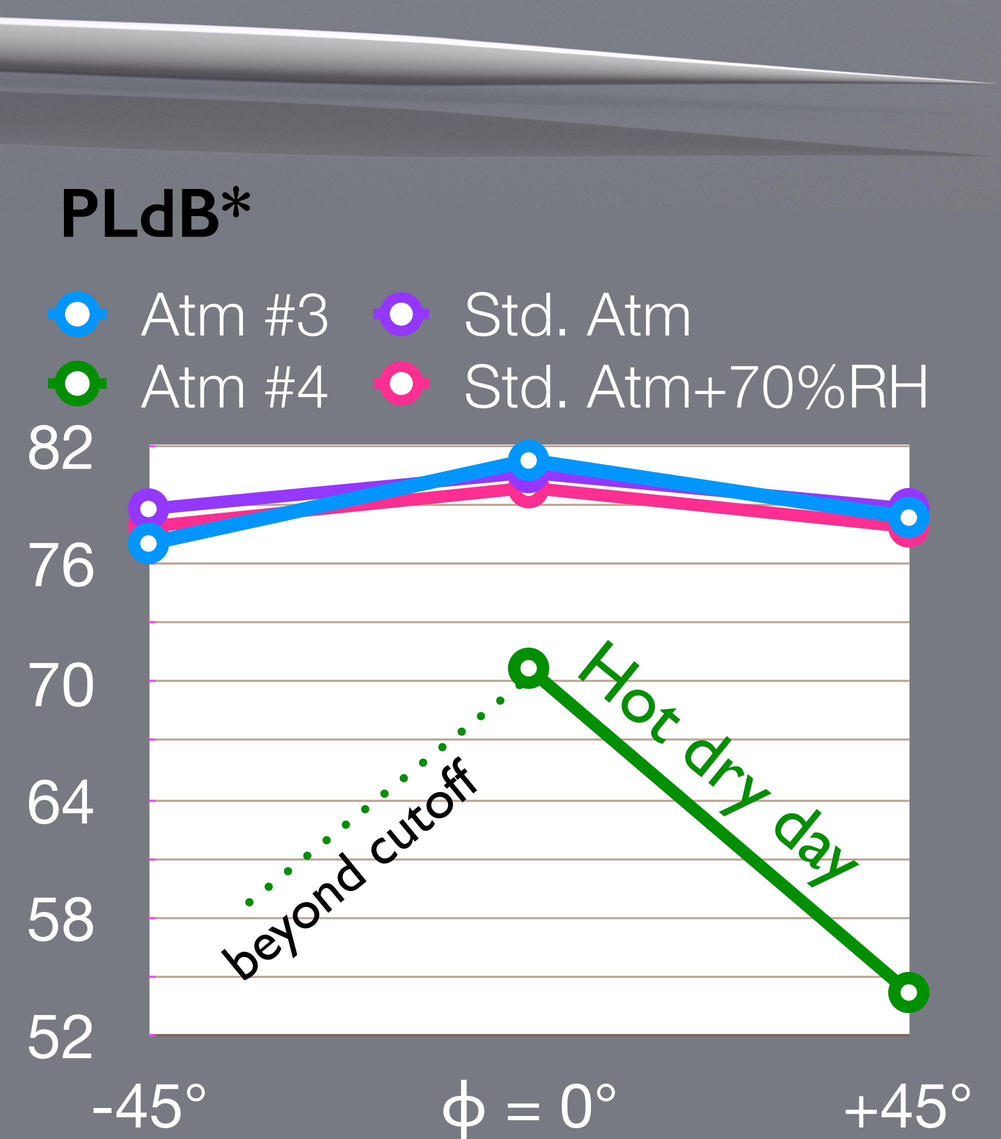




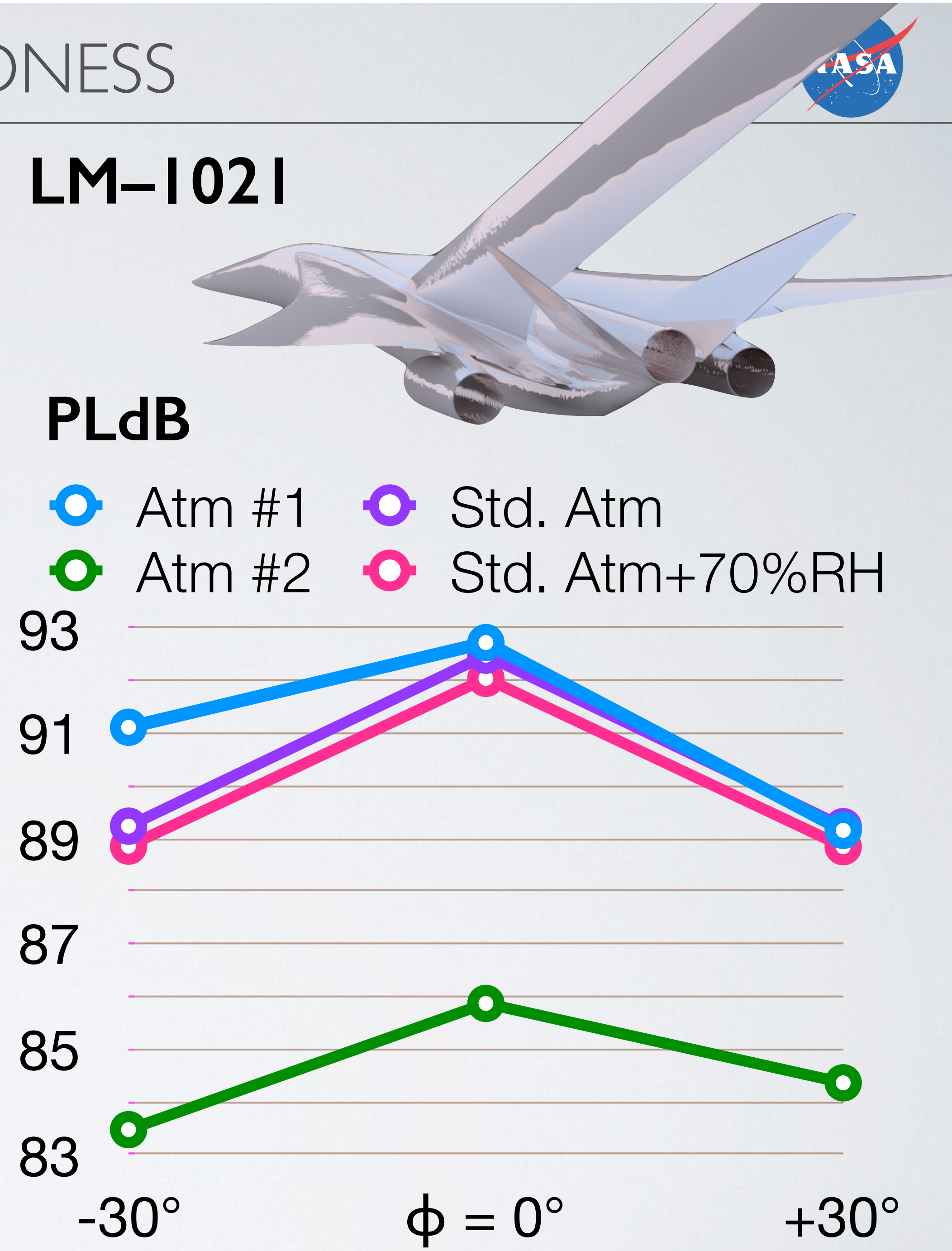
Axie	Cutoff		Track Width
Std. Atm	±50°		69 km
Atm # 3	-53°	50°	85 km
Atm # 4	-44°	47°	72 km

LM–1021	Cutoff		Track Width
Std. Atm	±50°		71 km
Atm # 1	**-74°**	57°	87 km
Atm # 2	-59°	65°	**111 km**

AXIE



LM–1021



*(**1991**) Shepherd & Sullivan, ***"A Loudness Calculation Procedure Applied to Shaped Sonic Booms"***

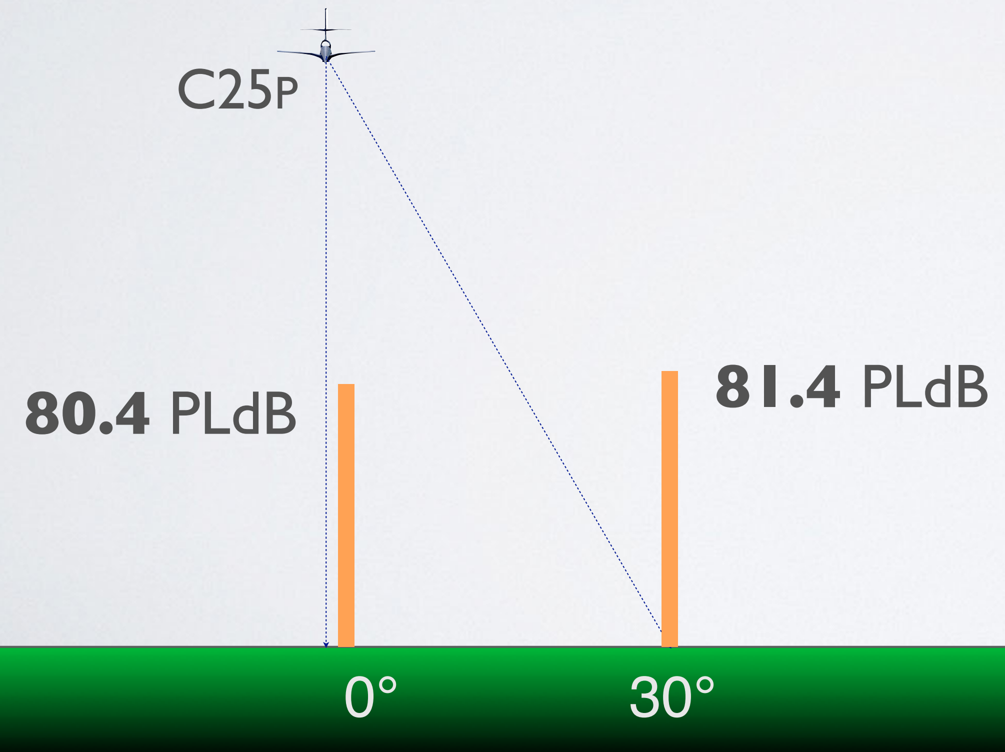
Outline

- ✓ **Nearfield Workshop**
- ✓ **Propagation Workshop — sBOOM**
- ▸ **Full Vehicle-to-Boom Simulation Path**
  - Propagate nearfield CFD signatures through standard atmosphere
  - Overall convergence and accuracy
- **Conclusions**

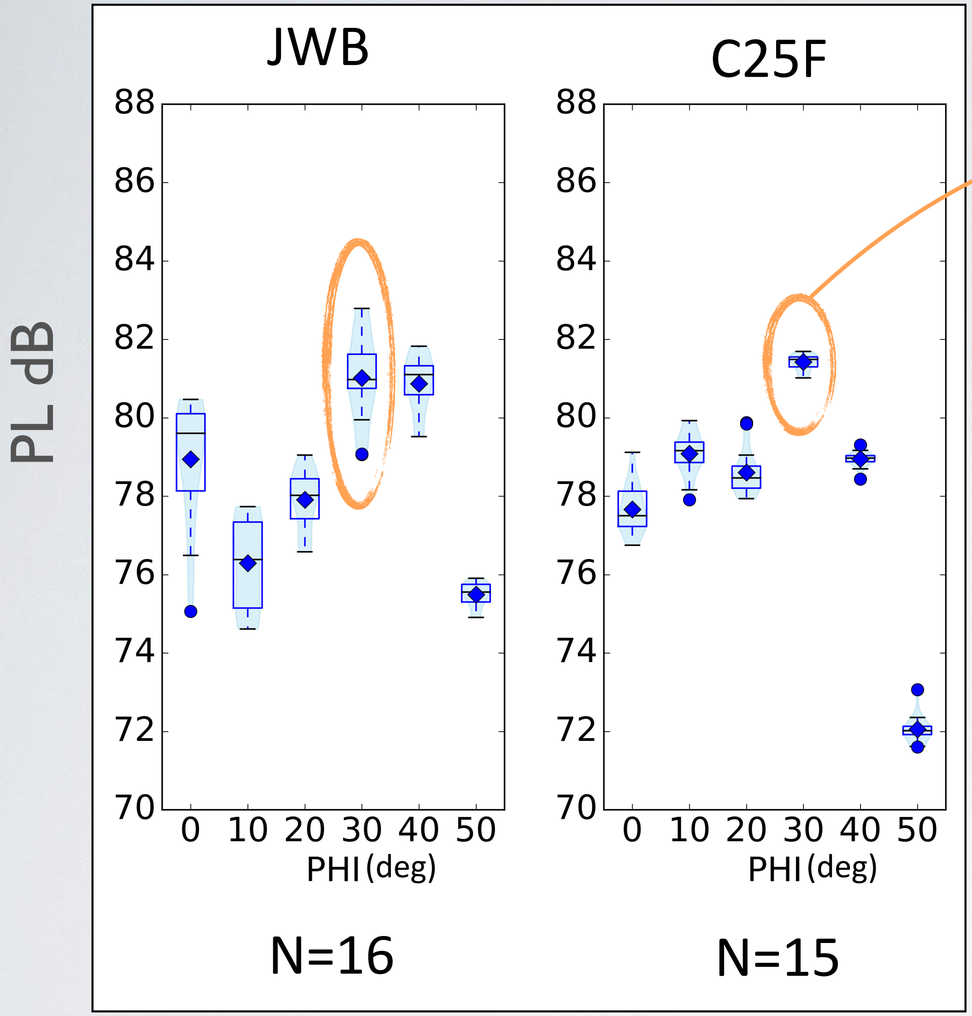
Perceived loudness (PLdB)

from r/L=5 on fine CFD mesh

Case	$\Phi = 0°$	$\Phi = 10°$	$\Phi = 20°$	$\Phi = 30°$	$\Phi = 40°$	$\Phi = 50°$
AXIE	78.1	—	—	—	—	—
JWB	79.5	76.5	78.2	**82.2**	81.6	76.6
C25F	78.1	80.4	80.1	**82.2**	80.1	73.3
C25P	80.4	81.3	78.3	**81.4**	78.7	73.3



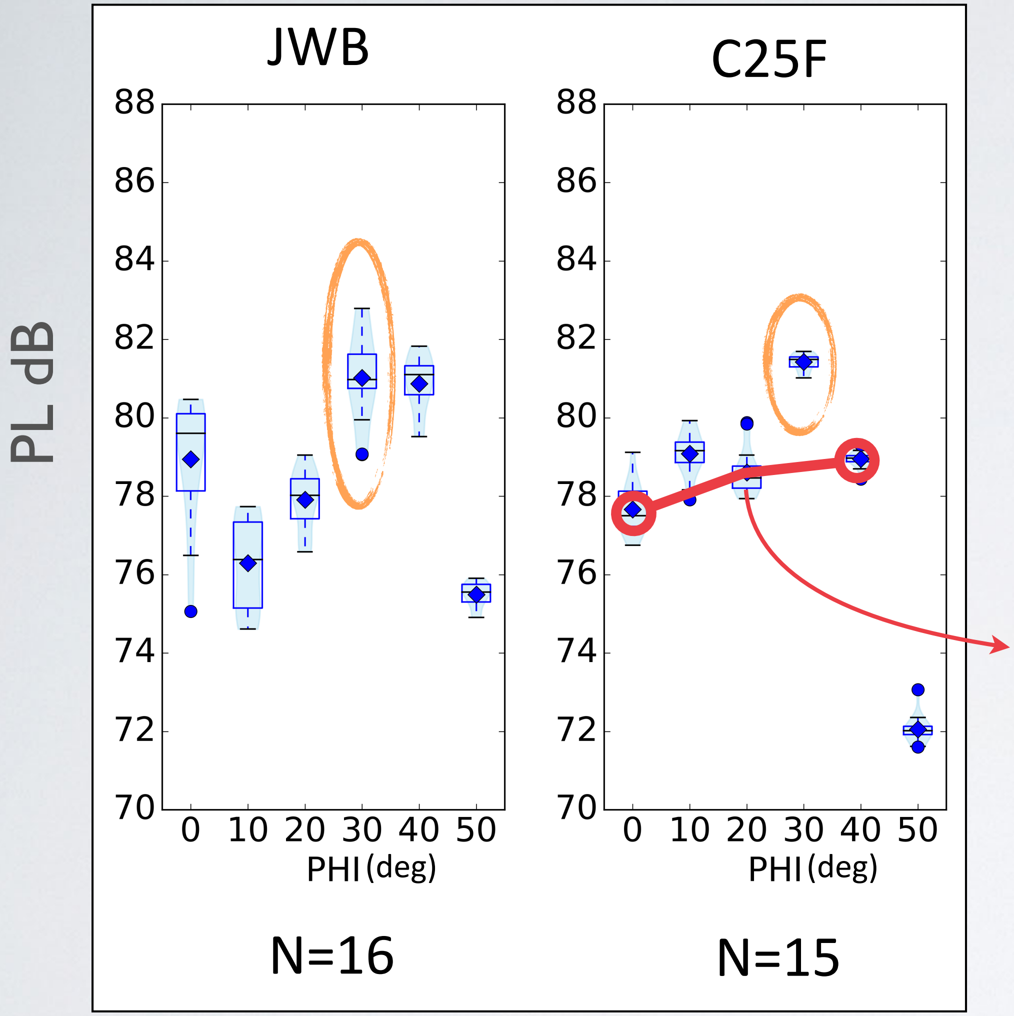
Comparison



Off-track boom is not just relevant, but critical!

(2017) Park and Nemec, ***"Nearfield Summary and Statistical Analysis of the Second AIAA Sonic Boom Prediction Workshop"***

COMPARISON



Off-track boom is not just relevant, but critical!

A coarser carpet discretization **(ΔΦ=20°)** would have under-predicted the worst boom by ~3 dB!

(2017) Park and Nemec, ***"Nearfield Summary and Statistical Analysis of the Second AIAA Sonic Boom Prediction Workshop"***

CFD Mesh Convergence of Loudness

Perceived loudness (PLdB)

from r/L=5 on fine CFD mesh

Case	$\Phi = 0°$	$\Phi = 10°$	$\Phi = 20°$	$\Phi = 30°$	$\Phi = 40°$	$\Phi = 50°$
AXIE	78.1 (*0.4*)	—	—	—	—	—
JWB	79.5 (*0.6*)	76.5 (*0.7*)	78.2 (*0.4*)	**82.2** (*1.5*)	81.6 (*0.1*)	76.6 (*0.5*)
C25F	78.1 (*0.8*)	80.4 (*0.6*)	80.1 (*0.1*)	**82.2** (*0.8*)	80.1 (*0.6*)	73.3 (*0.0*)
C25P	80.4 (*0.5*)	81.3 (*0.5*)	78.3 (*0.3*)	**81.4** (*0.6*)	78.7 (*0.4*)	73.3 (*1.6*)

***ΔPLdB** from coarse to fine CFD mesh*

- Typically <1 dB change from coarse to fine CFD mesh (max 1.6 dB)
- Most do not demonstrate **asymptotic** convergence.
- Summary results indicate similar behavior across many codes

CFD functional

$$\mathcal{J}_r = \int_0^L w(\ell) \left(\frac{p(\ell) - p_\infty}{p_\infty} \right)^2 d\ell$$

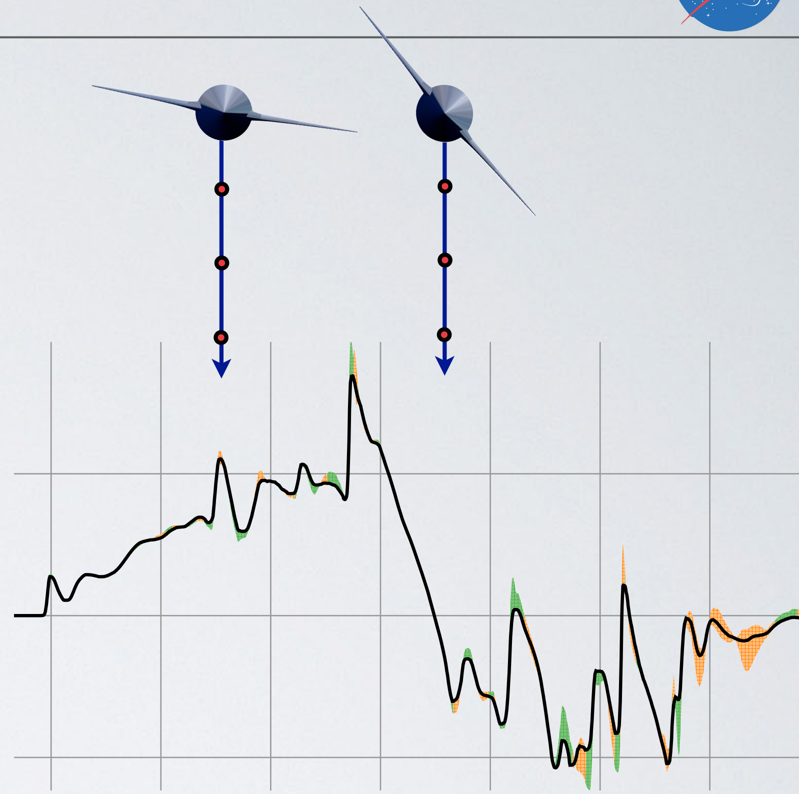
used as a convenient **surrogate** for loudness

Future Work

- **Improving CFD/Propagation Coupling**
  - Better understanding the CFD meshing requirements
  - Using noise sensitivities to guide CFD mesh adaptation (direct adaptation to noise vs. surrogate functionals)
  - Better interpolation/transfer of signatures
- **Physics**
  - Wake unsteadiness
  - Maneuver, elastic effects, control surfaces
  - Propagation — secondary booms, reflections

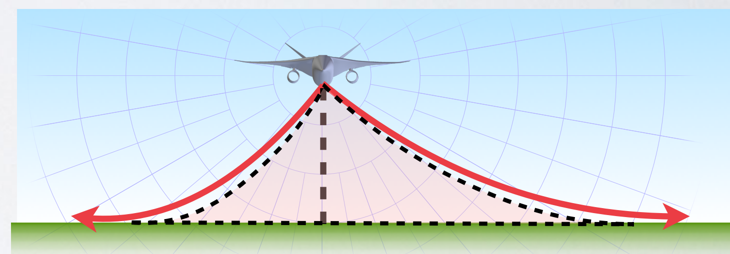
Nearfield with Cart3D

- Improved efficiency by carpet splitting, azimuthal alignment, and stretching
- Method for assessing local signature mesh convergence *[scripts available]*



Propagation with sBOOM

- Major atmospheric variability: 2-5 dB typical, 10-20 dB in extreme cases.
- With cross-wind, **75° off-track** can hit ground, **track widths widen by 50%**



Full Boom Simulation Path

- Need to better understand asymptotic convergence of noise

QueSSTions?

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