# Cartesian Mesh Simulations and Farfield Propagation Results for the 3rd AIAA Sonic Boom Prediction Workshop

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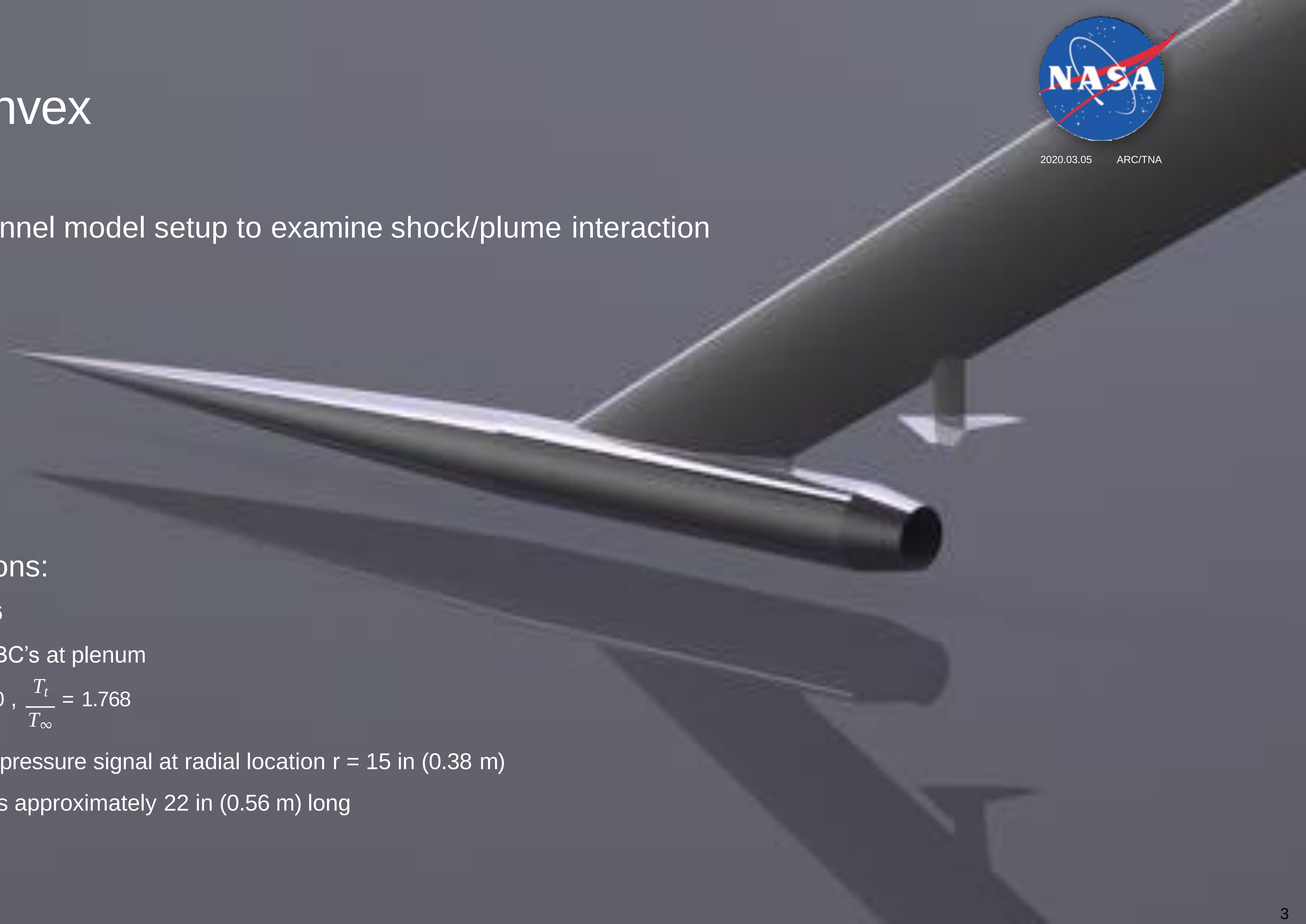
# Nearfield CFD Outline

- Cases
  - Biconvex - shock/plume interaction
  - C608 - full aircraft geometry
- Flow solver & computational resources
- Geometry & grids
- Numerical convergence
- Results
- Challenges
- Conclusions

# Biconvex

Wind tunnel model setup to examine shock/plume interaction



## Conditions:

- $M_\infty = 1.6$
- Power BC's at plenum
- $\frac{p_t}{p_\infty} = 8.0$ , $\frac{T_t}{T_\infty} = 1.768$
- Extract pressure signal at radial location r = 15 in (0.38 m)
- Model is approximately 22 in (0.56 m) long

# C608

- Modified version of X-59 Low Boom Flight Demonstrator design iteration
- Full aircraft, complex geometry, multiple inflow/outflow BC's

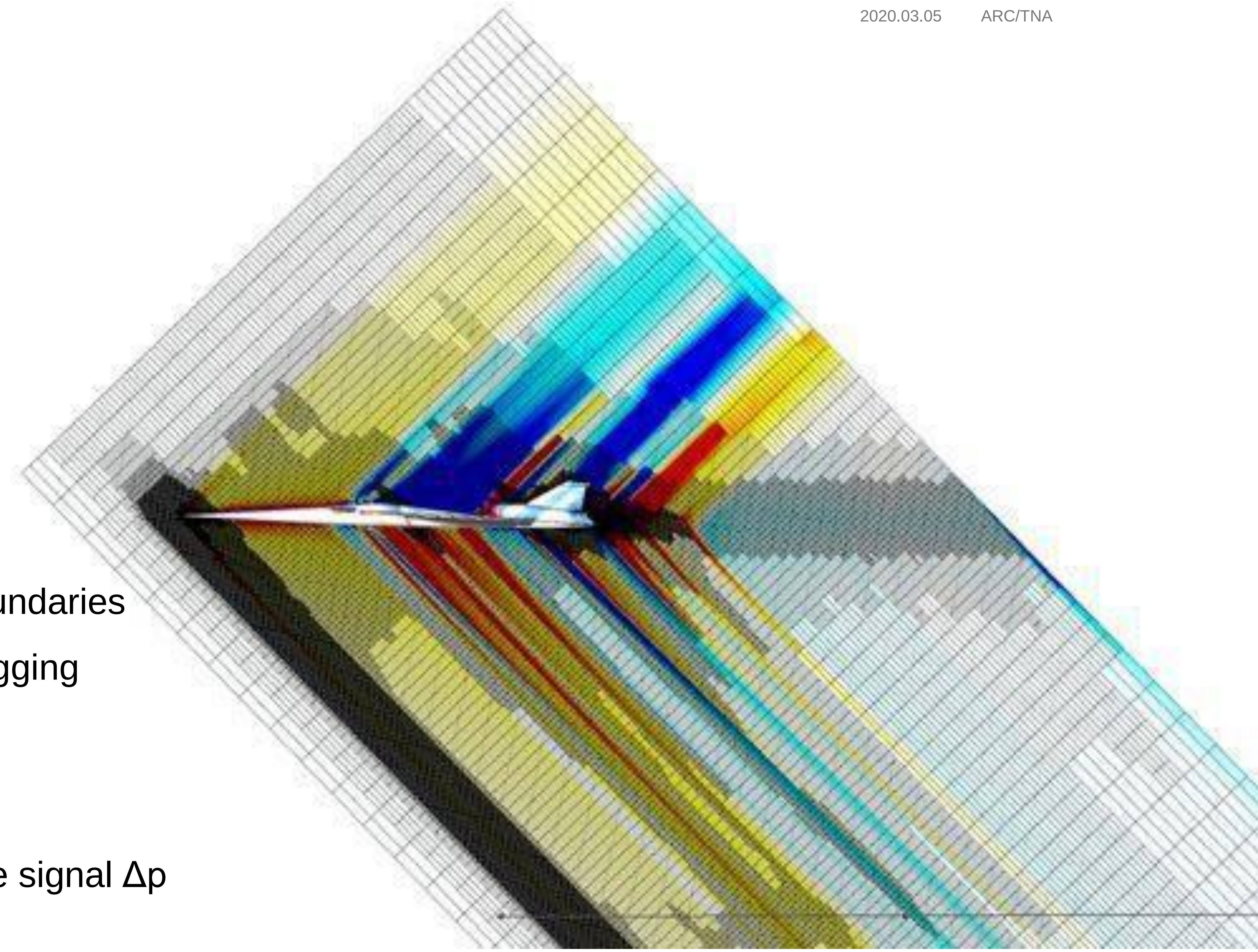
## Conditions:

- $M_\infty =$ 1.4, Altitude $h = 53{,}200 ft$
- Power BC's at engine nozzle $p_t / p_\infty =$ 10.0 , $T_t / T_\infty = 7.0$
- Power BC's at bypass nozzle $p_t / p_\infty =$ 2.4 , $T_t / T_\infty = 2.0$
- Engine fan inlet $p_b / p_\infty =$ 2.6 (desired Mach 0.4 flow at engine fan face)
- Environmental Control System vent inlets $p_b / p_\infty =$ 1.4 (desired Mach 0.35 flow at ECS inlets)
- Extract pressure signal at radial location $L$
- Model is approximately 1080 in (27.43 m) long

# Cart3D Software



- Flow solver: Cart3D v1.5.5.3
  - Inviscid Euler equation solver, multigrid acceleration
  - Domain decomposition, highly scalable
  - Current work: steady-state, 4 MG levels
  - Second-order upwind method
  - 5-stage RK scheme, van Leer limiter
- Automatic meshing
  - Multilevel Cartesian mesh with embedded cut-cell boundaries
  - Unstructured surface triangulation with component tagging
- Output-driven mesh refinement
  - Discrete adjoint solution and local error estimate
  - Several different adjoint functionals, including pressure signal Δp
- Computing platform
  - NASA ARC Electra, 1 Skylake node (40 cores, Intel Xeon Gold 6148)
  - Biconvex: 19.9 M cells, 40 min final flow solve, 32 min adaptive meshing (x3 sim's)
  - C608: 29.6 M cells, 60 min final flow solve, 53 min adaptive meshing (x19 sim's)

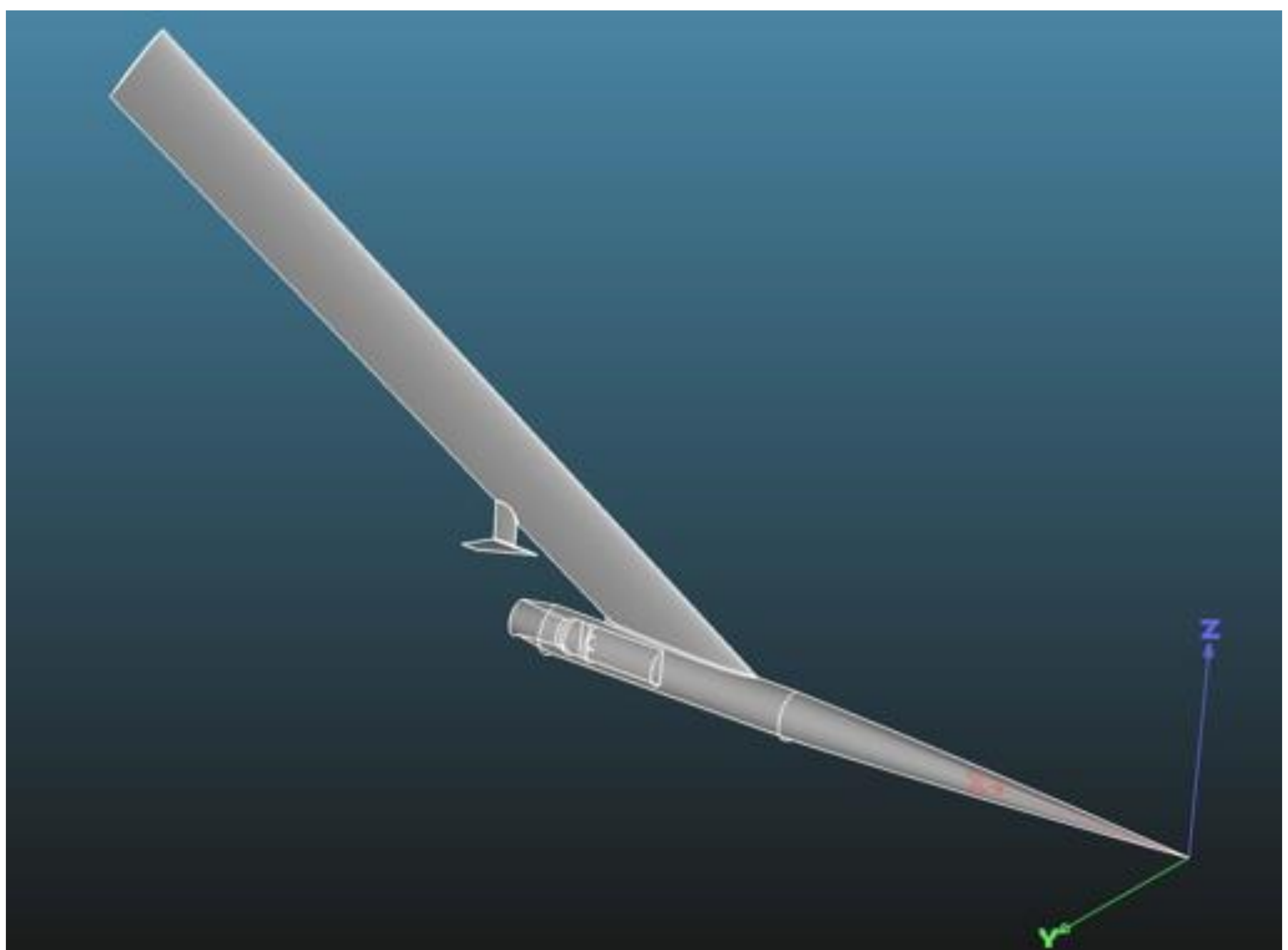


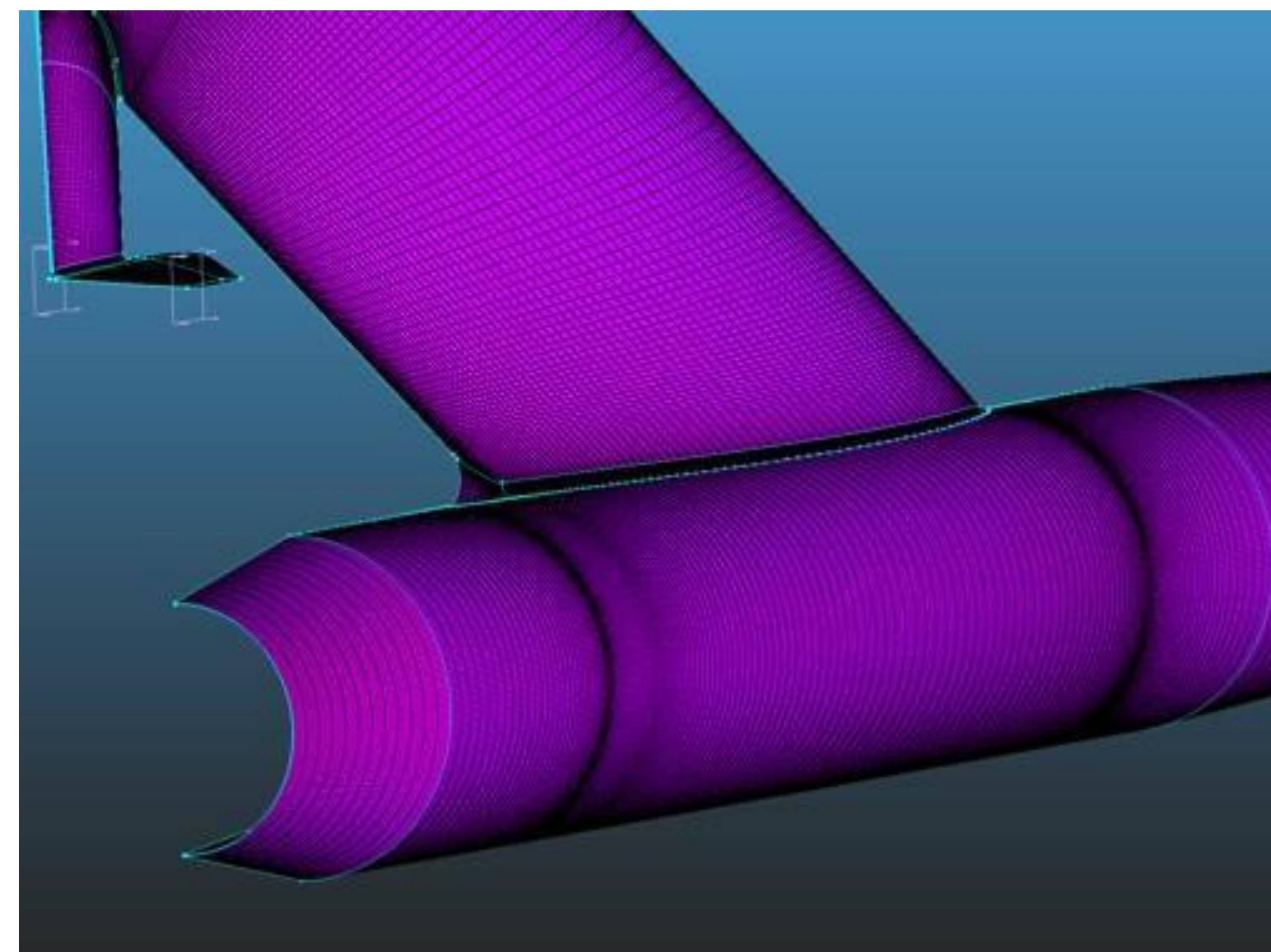
Cart3D

# Geometry



- Biconvex
  - Created surface triangulation from STP and IGS files
  - Diagonalized structured grid where possible
  - Filled in planar and irregularly shaped areas with unstructured cells



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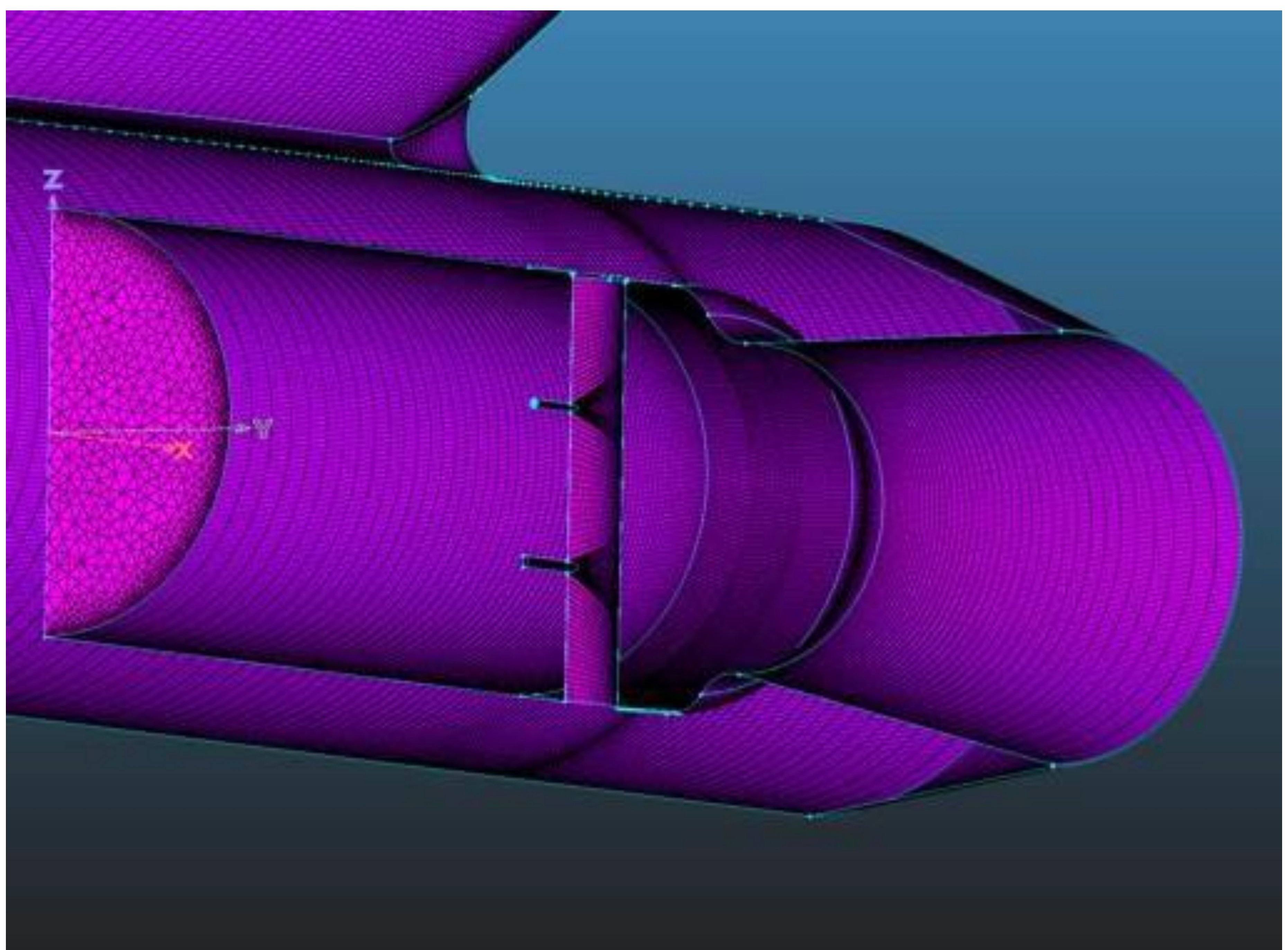
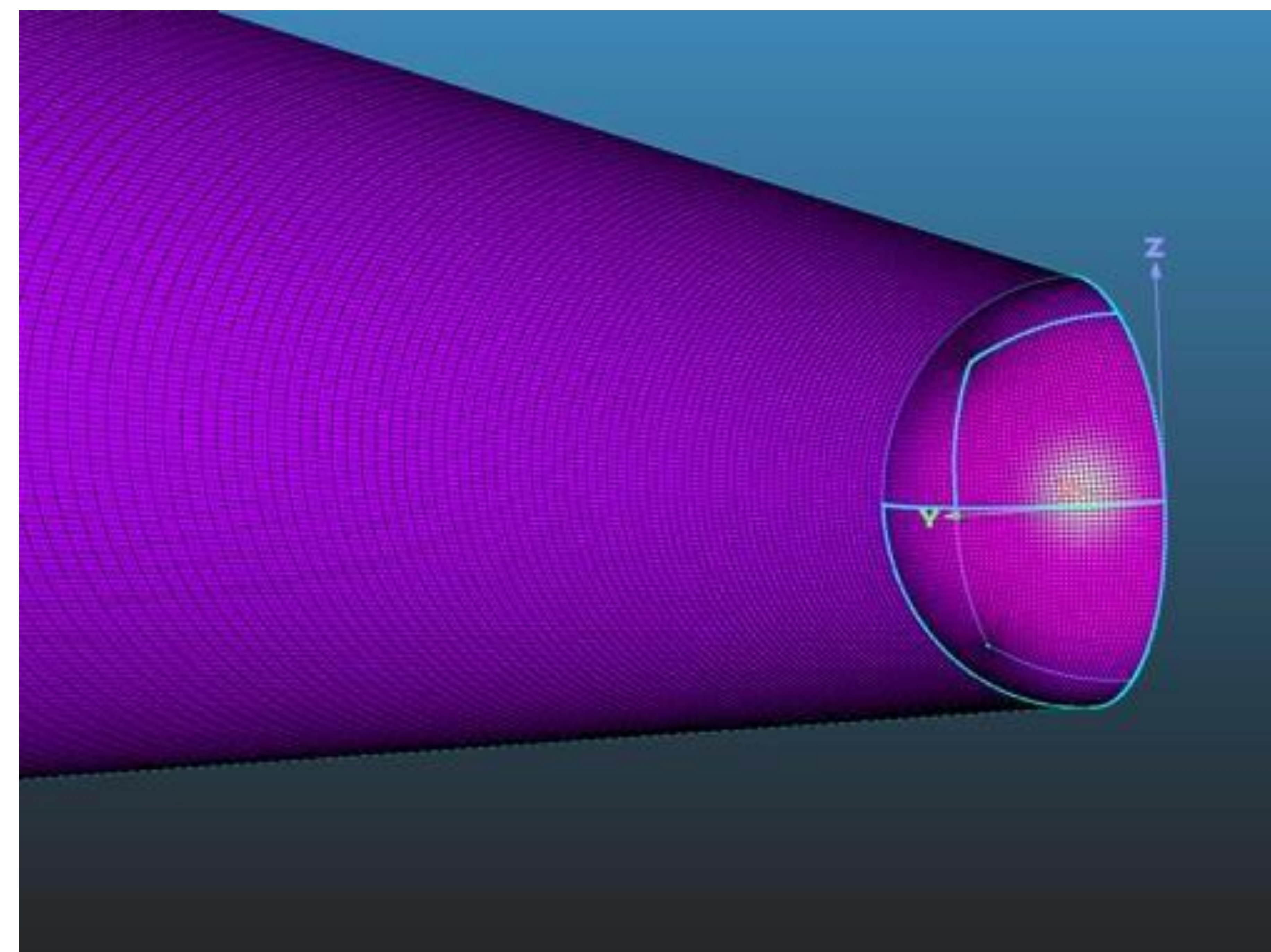
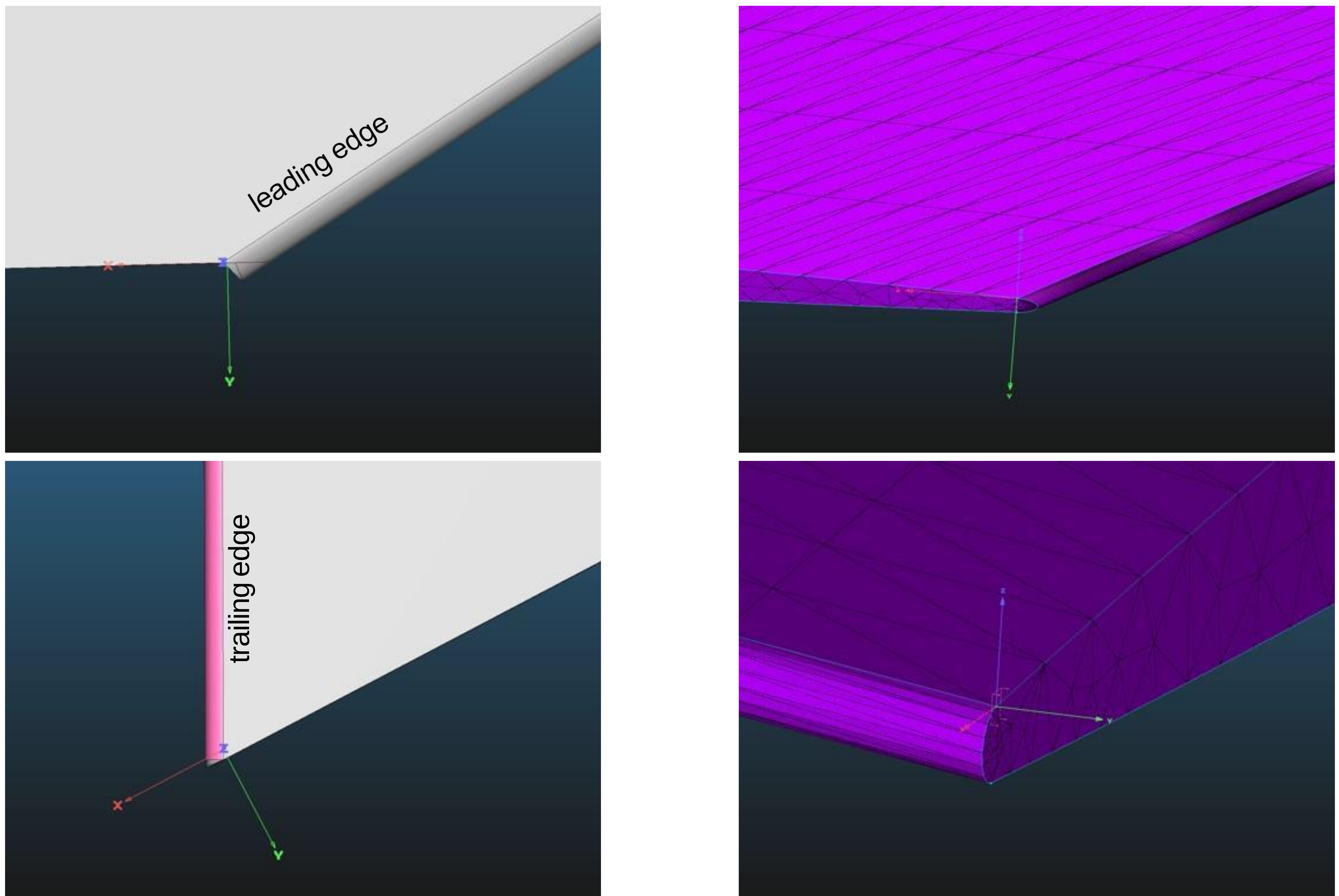




# Geometry



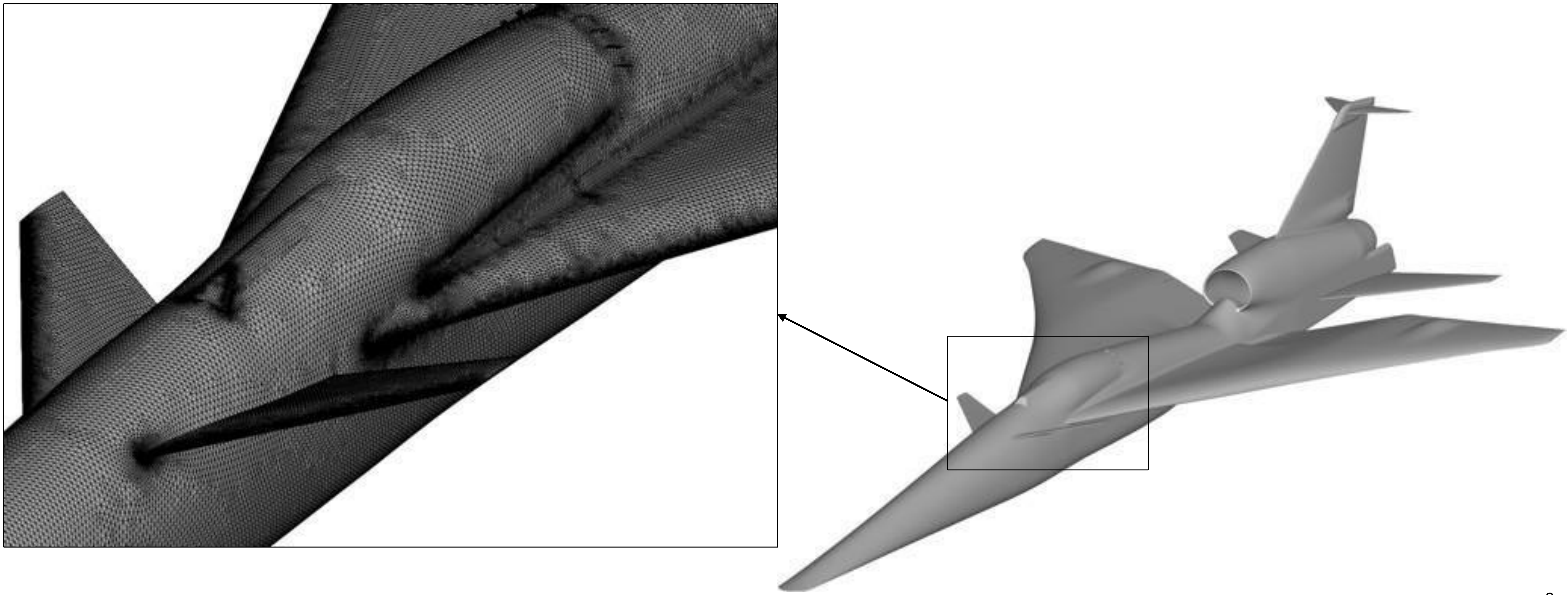
- Issues with leading edge and trailing edge at tip of airfoil
- Cleaned up geometry by projecting LE and TE onto plane of wing tip



# Geometry



- C608
  - Received unstructured surface triangulation from J. Jensen (NASAARC)
  - 494 k vertices, 987 k triangles



# Volume Mesh

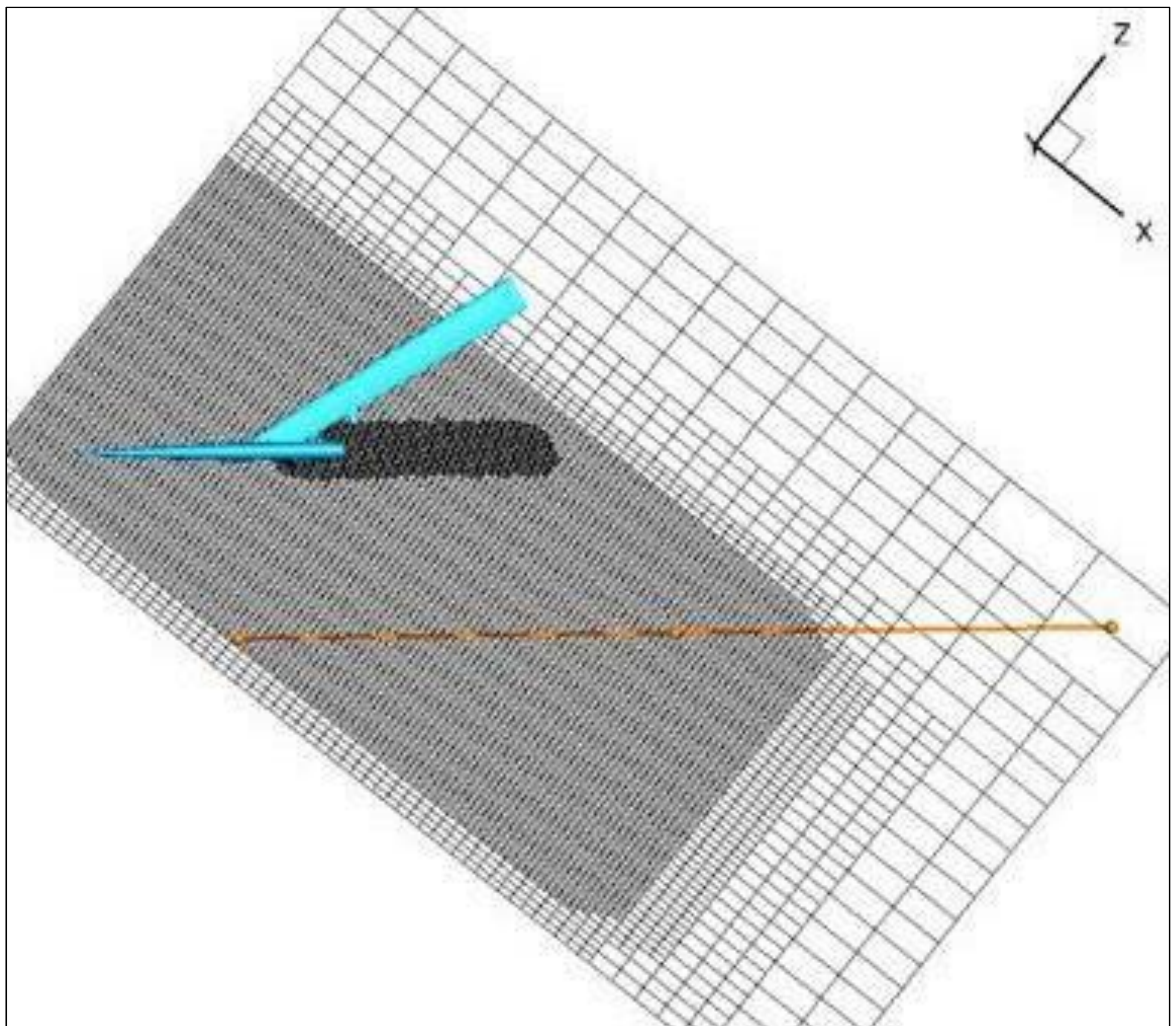


- Cartesian cut-cell volume mesh for inviscid flow solver
- Cart3D autoBoom - previous SBPW2 work
  - Aligned with Mach angle (with tiny offset to avoid sonic glitch)
  - Roll the model geometry for different off-track ϕ angles
  - Separate simulation for each off-track ϕ on 1 node, can be run simultaneously
  - Tested different cell aspect ratios in the propagation and spanwise directions
- Adjoint-driven mesh adaptation
  - Line sensor at multiple body lengths away
  - Objective function is integrated pressure $\Delta p/p_\infty$
- Final grid sizes for data submittal
  - Biconvex: 4.5, 8.9, 19.9 million cells for coarse, medium, fine
  - C608: 7.1, 14.2, 29.6 million cells for coarse, medium, fine

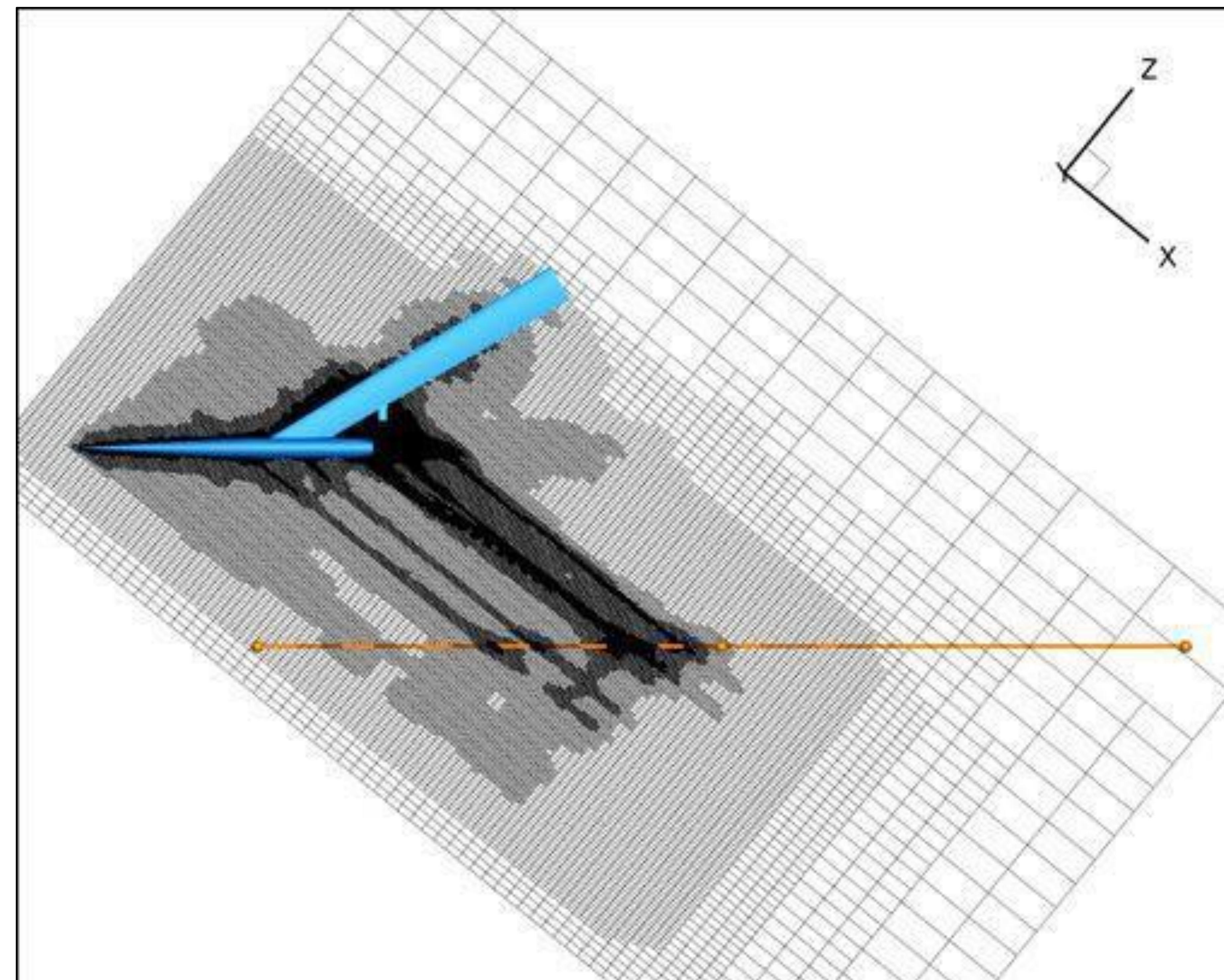
# Volume Mesh



- Adjoint-driven mesh adaptation
  - Line sensor at multiple body lengths away
  - Objective function is weighted integral of $\Delta p / p_\infty$




Initial mesh

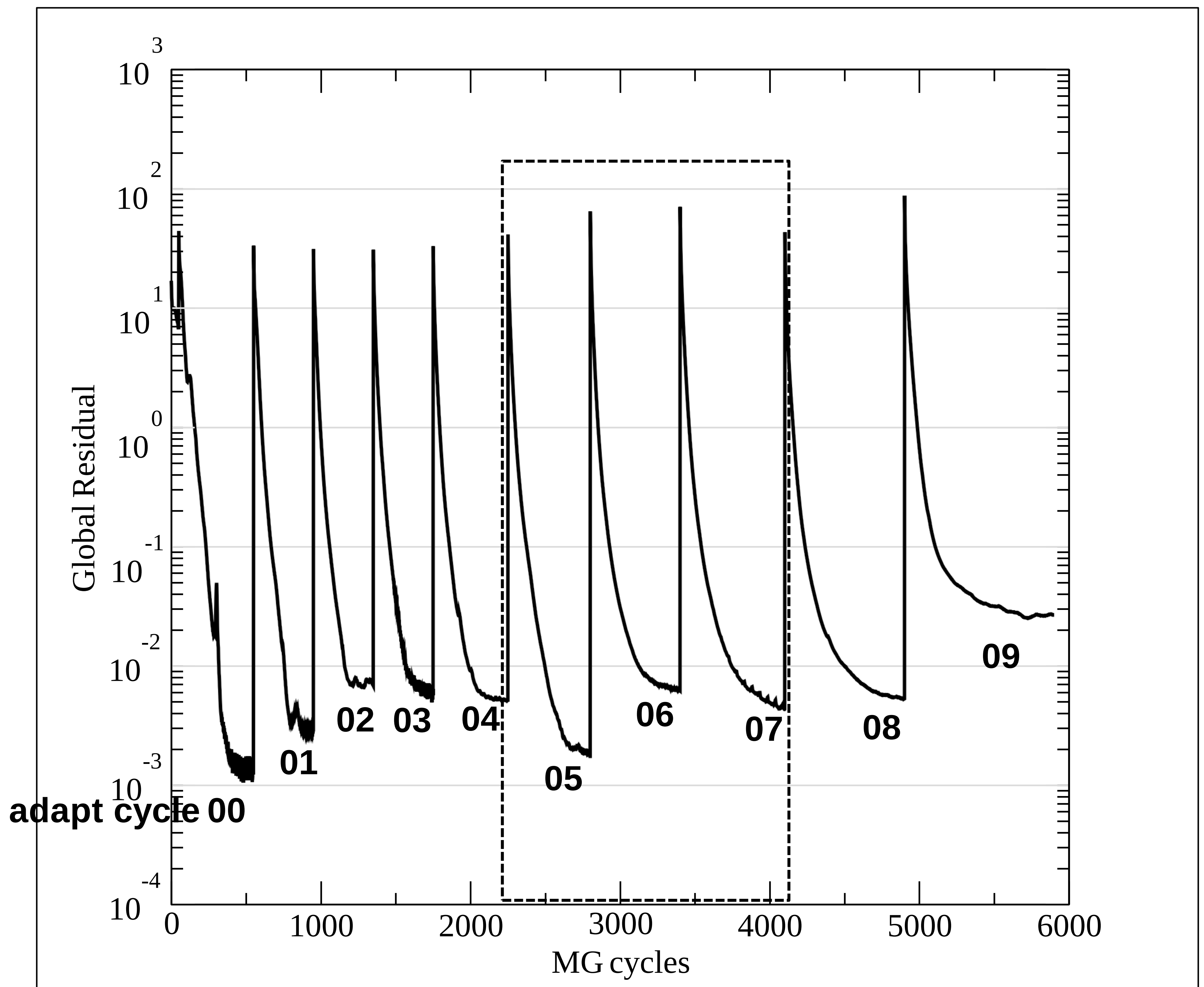



After adaptation
(coarse mesh)

# Numerical Convergence



- Biconvex
  - 550, 600, 700 iterations on coarse, medium, fine grids
  - Submitted adapt cycles 05, 06, 07 (ran 2 more out to 09 to check)



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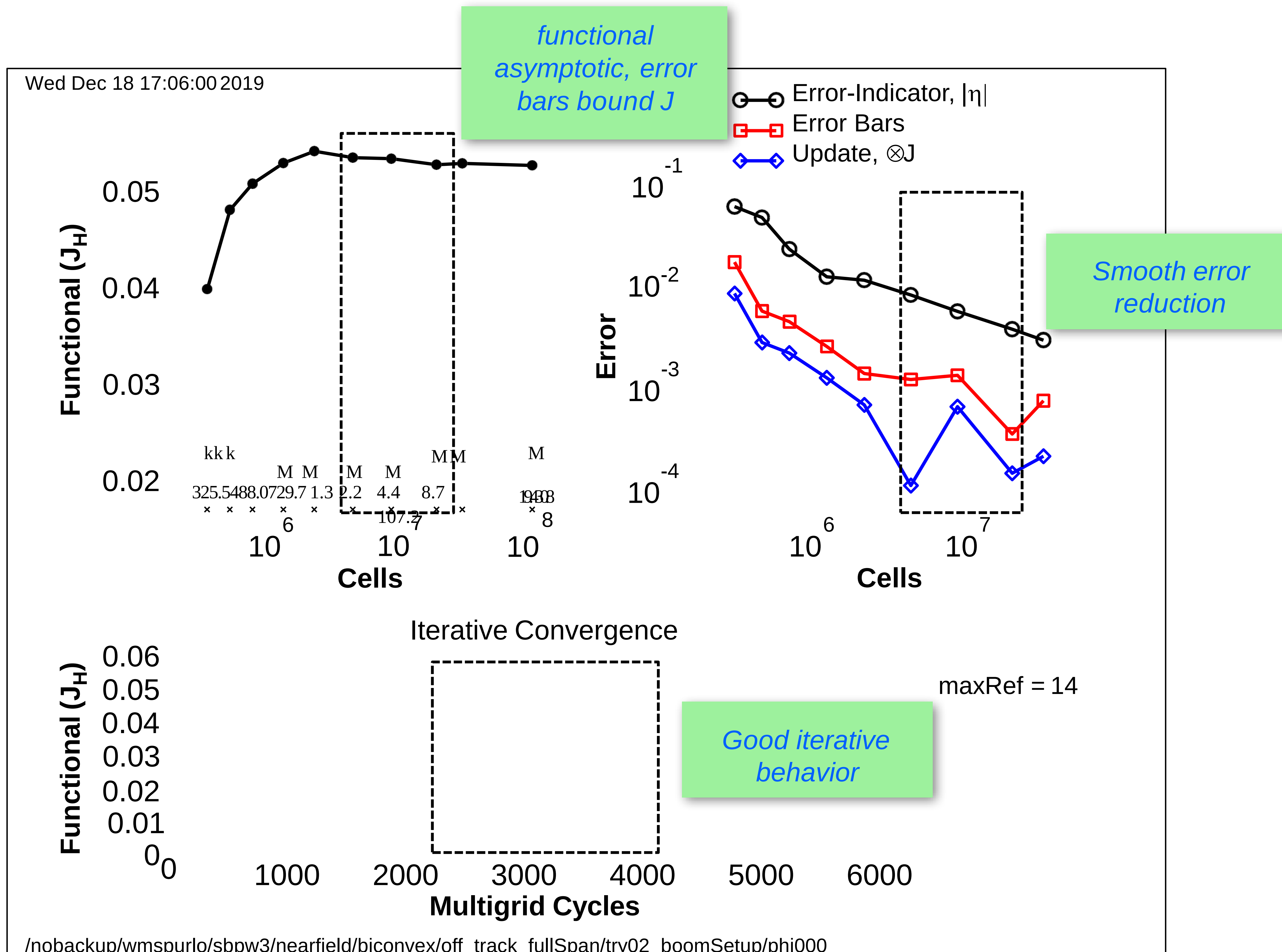
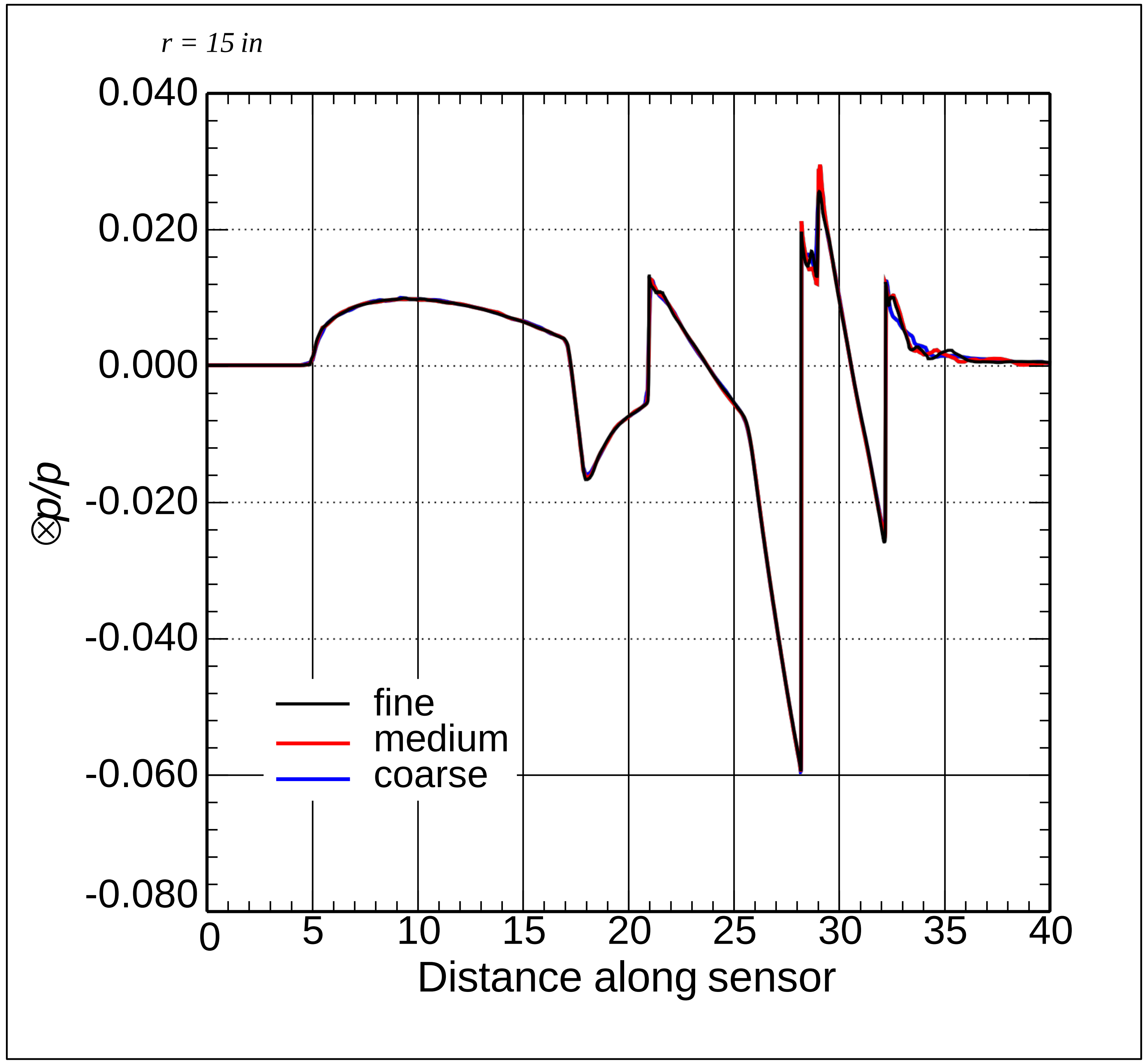
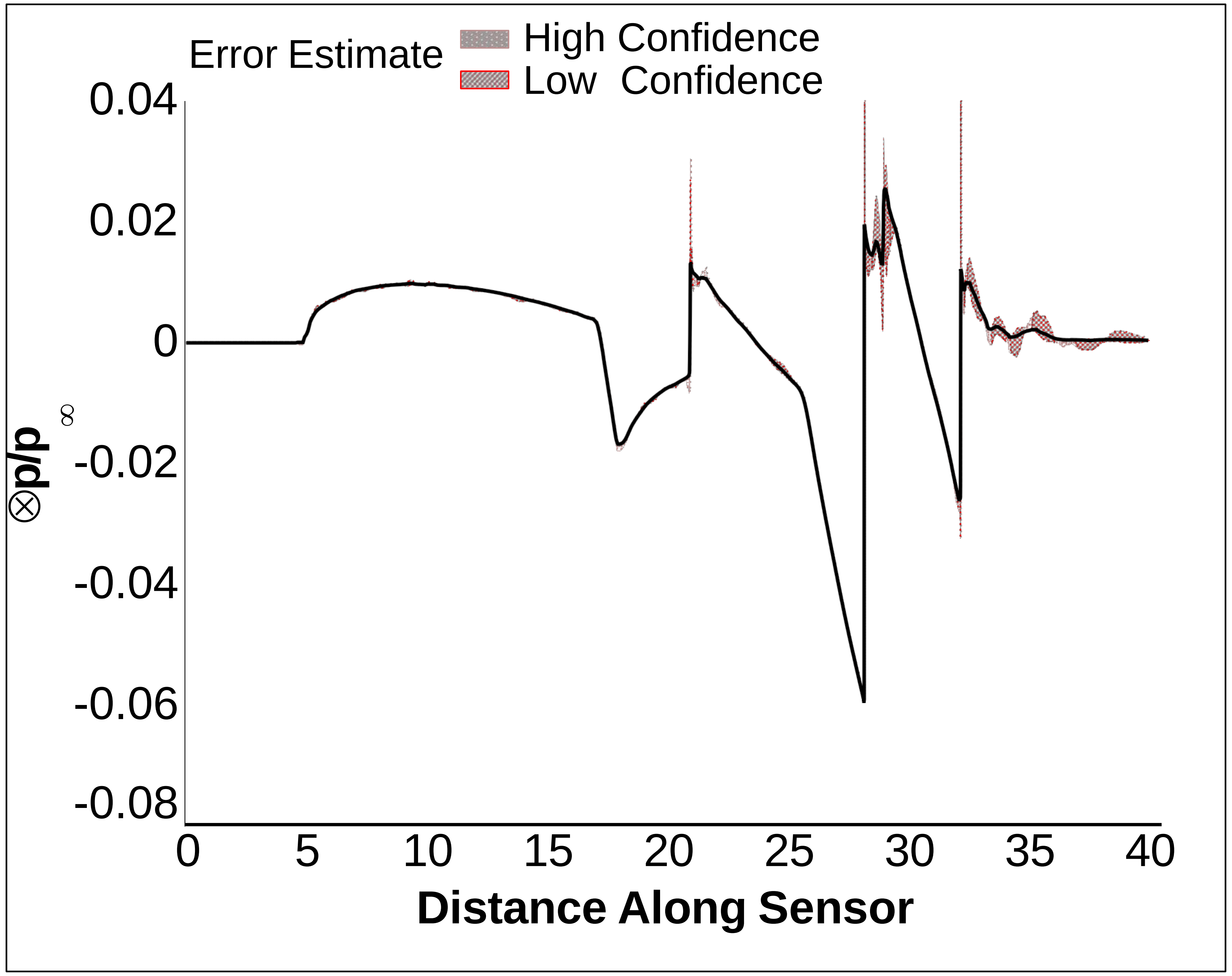


# Numerical Convergence



- Biconvex
  - 550, 600, 700 iterations on coarse, medium, fine grids
  - Solutions are well converged by adapt 05, 06, 07 cycles
  - Richardson extrapolation used for error estimate



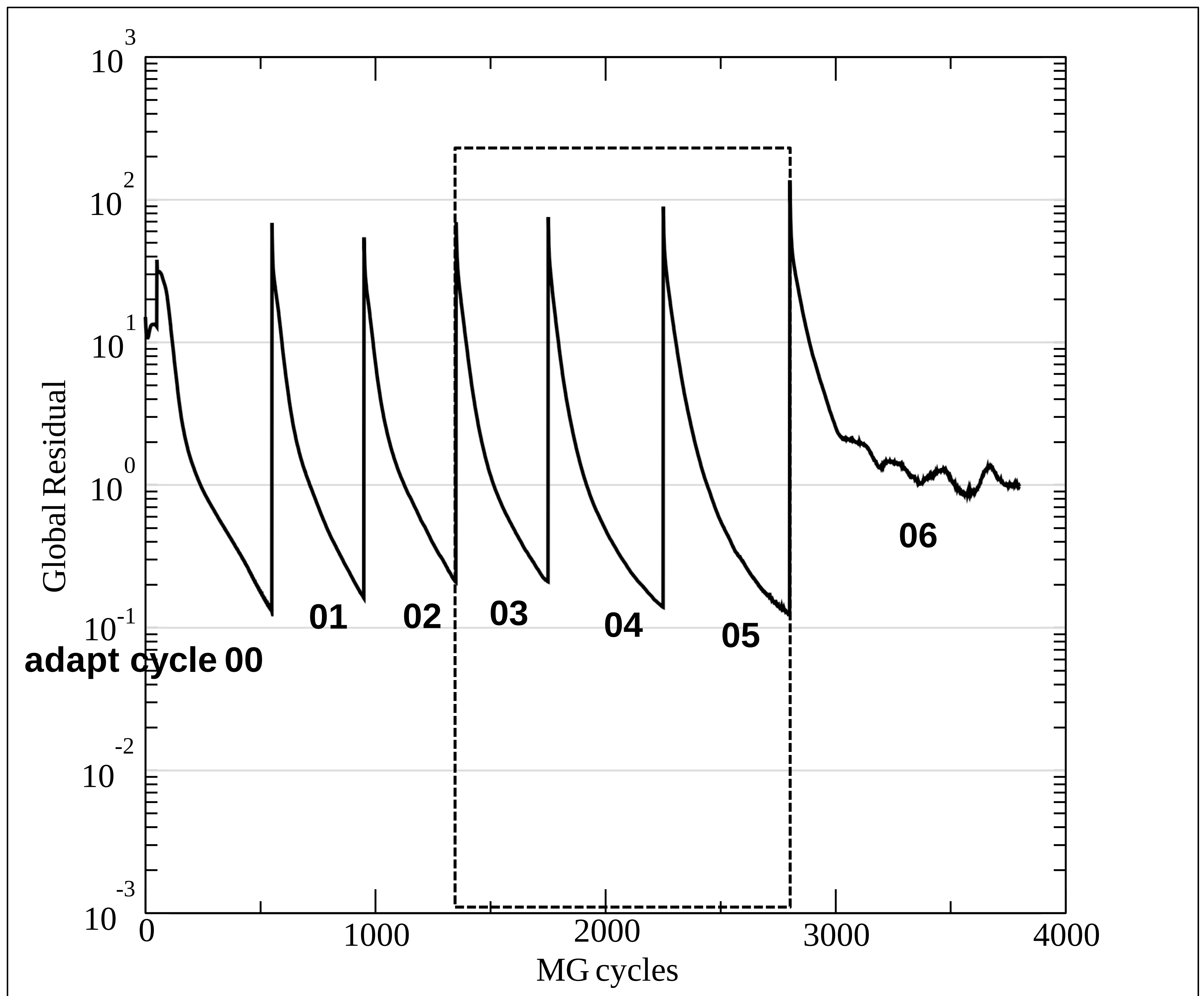



# Numerical Convergence



- C608
  - 400, 500, 550 iterations on coarse, medium, fine grids
  - Submitted adapt cycles 03, 04, 05 (ran 1 more out to 06 to check)

$\phi = 0°$



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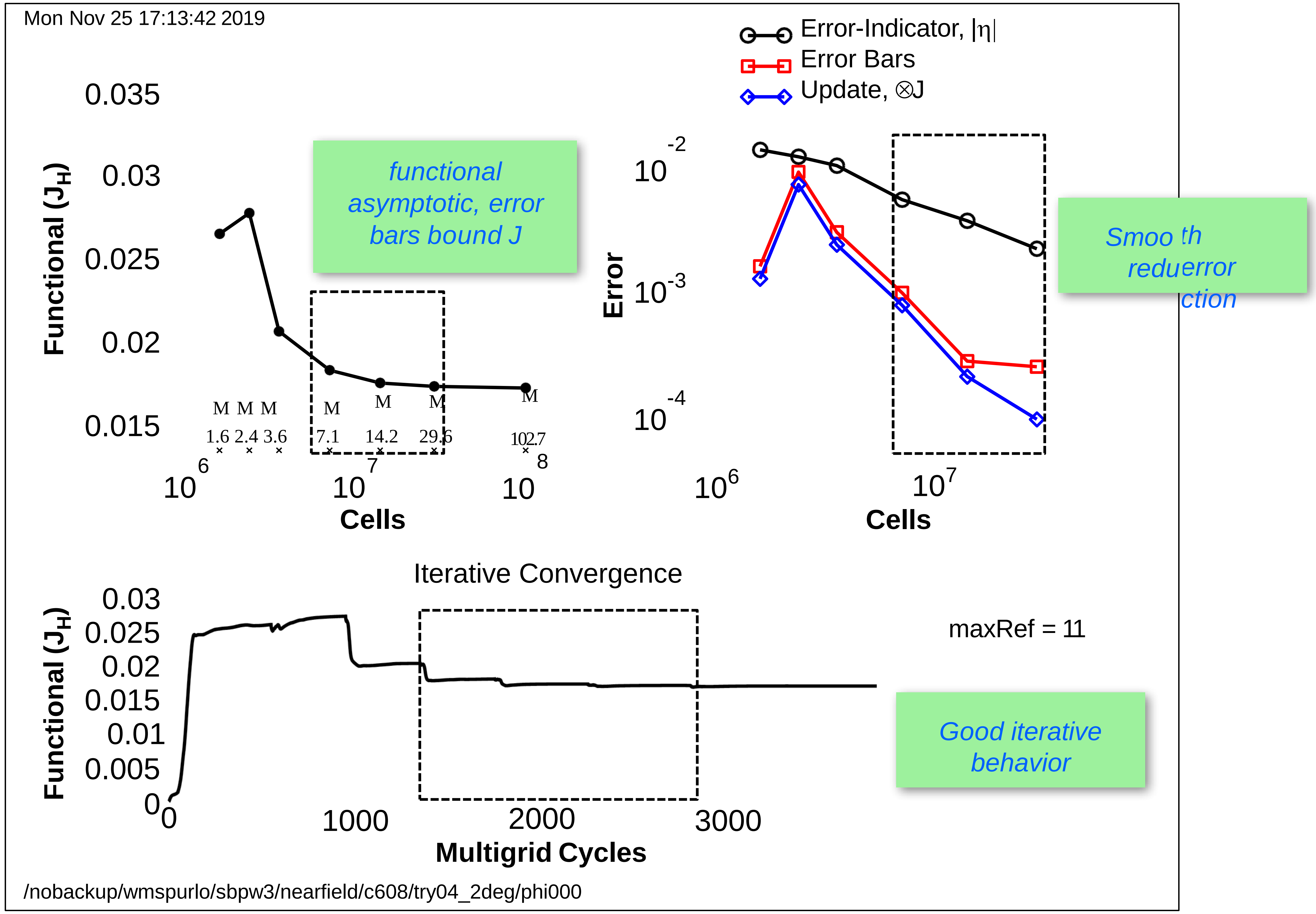

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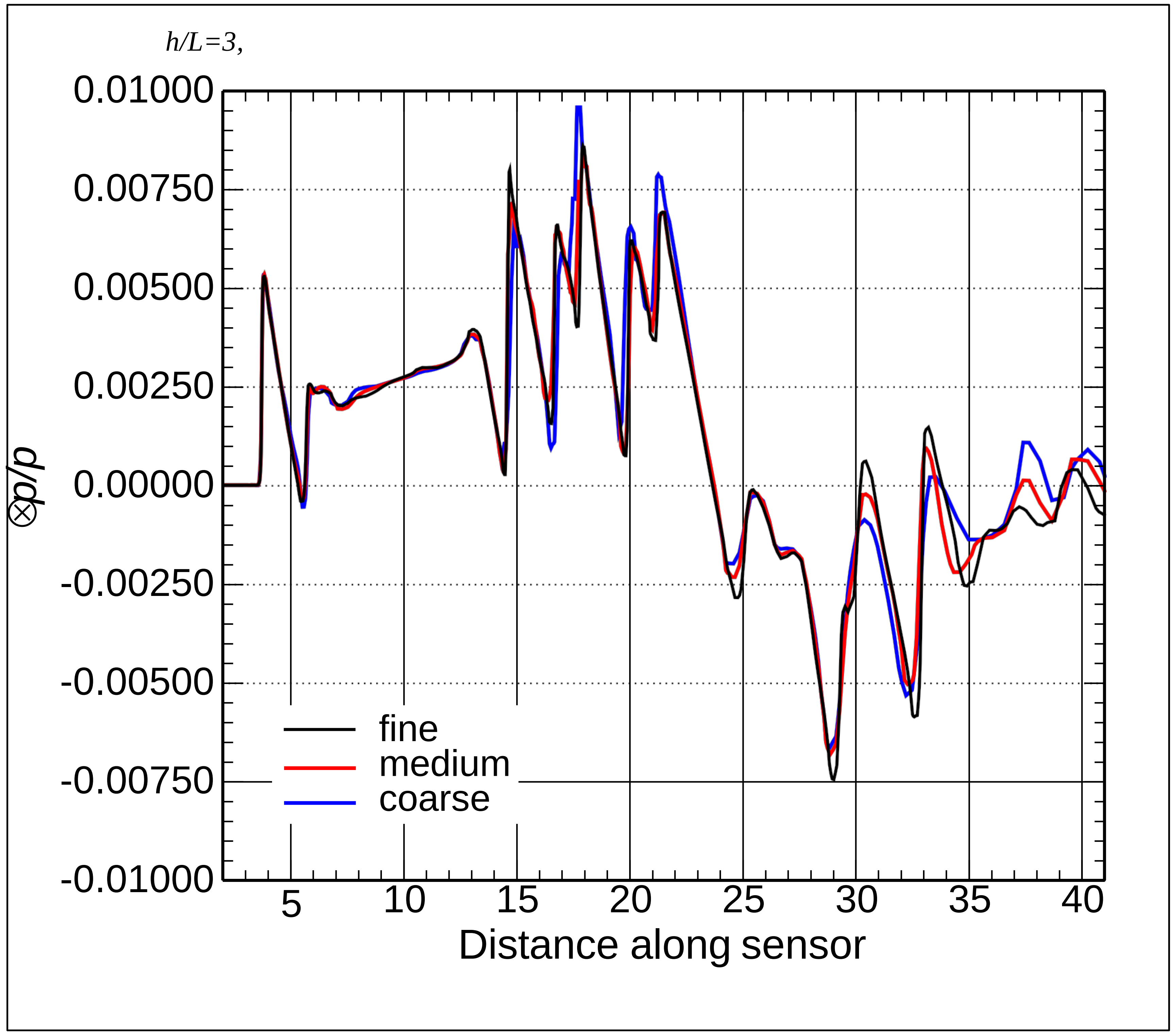
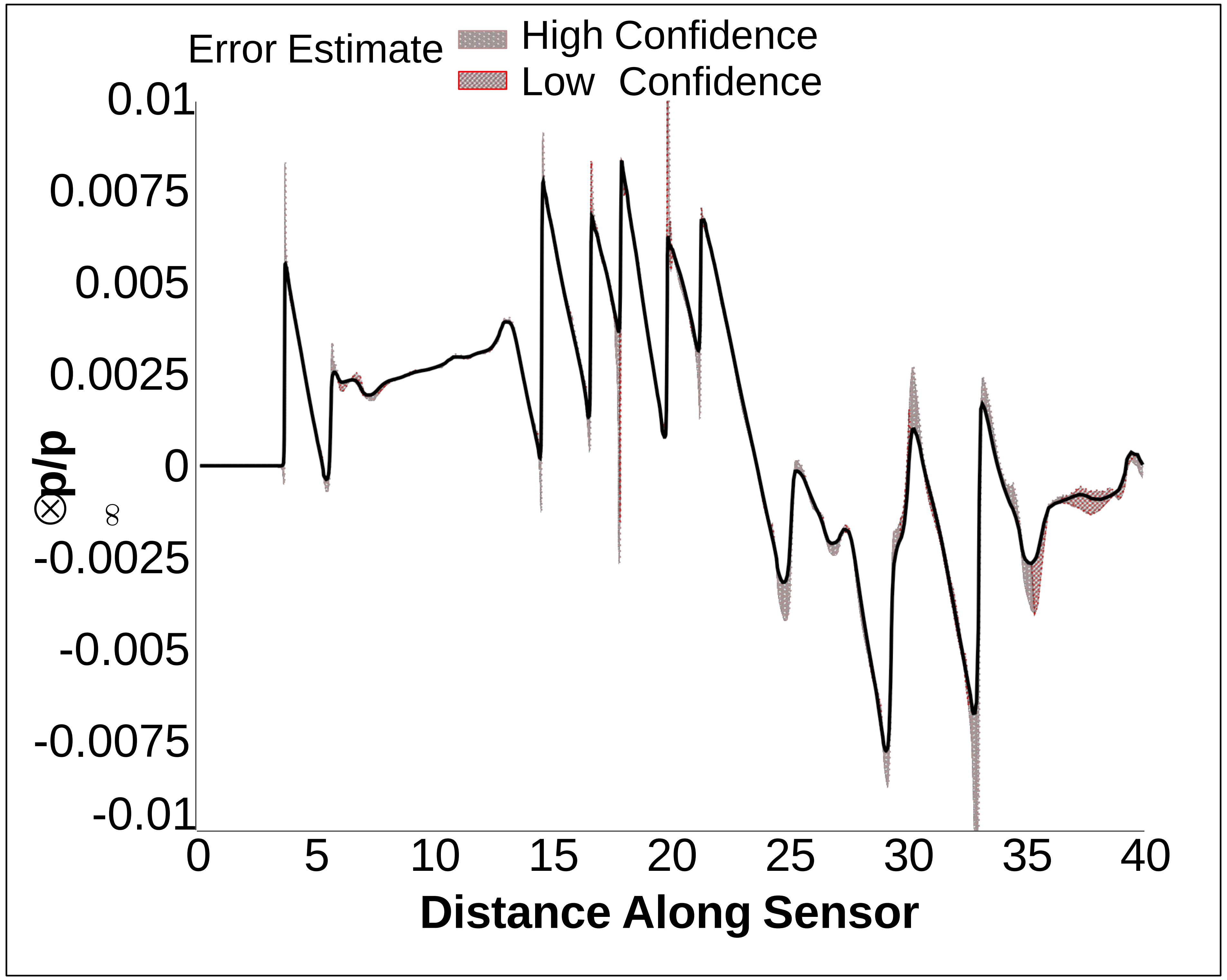
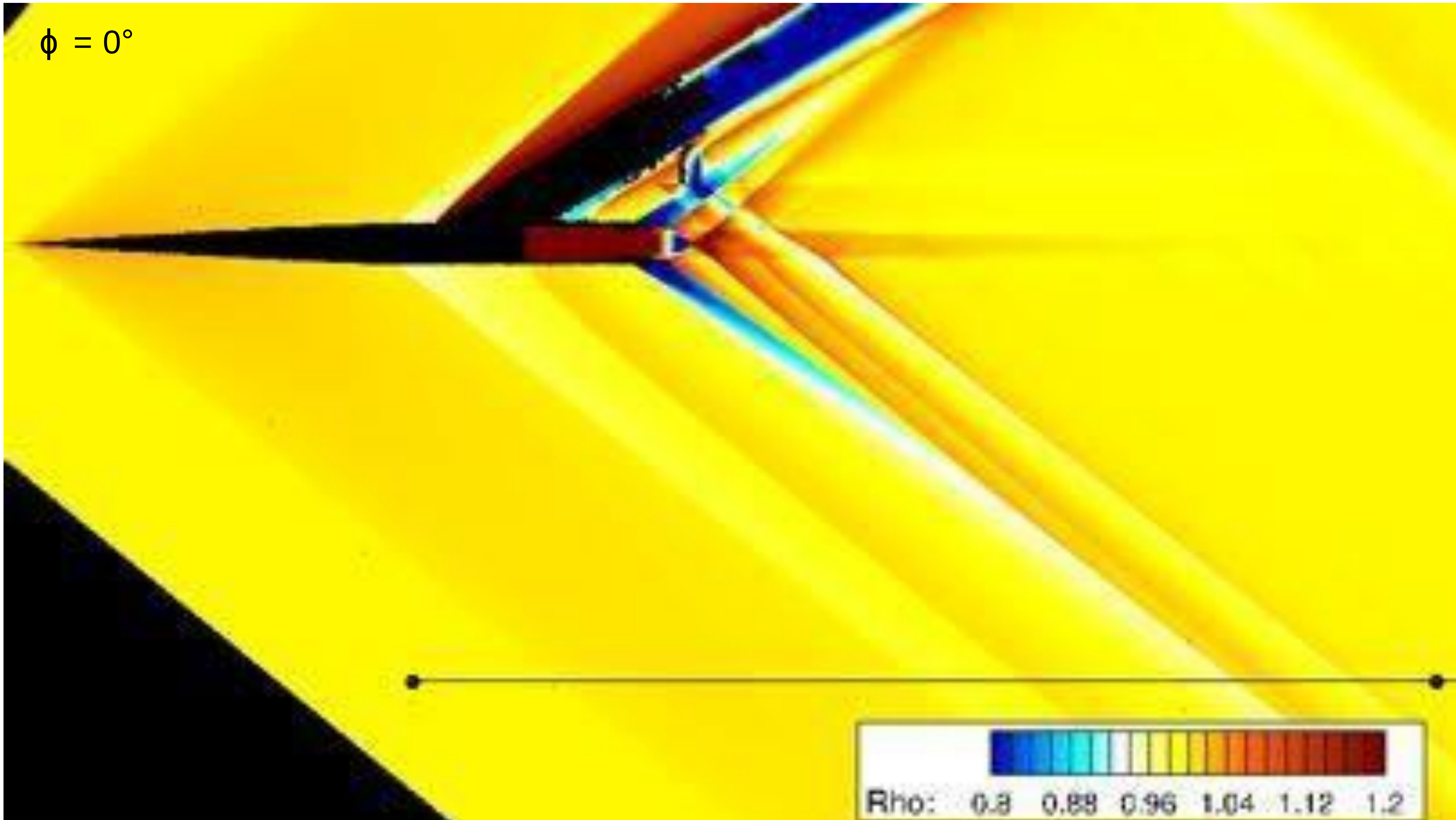


# Results: Biconvex



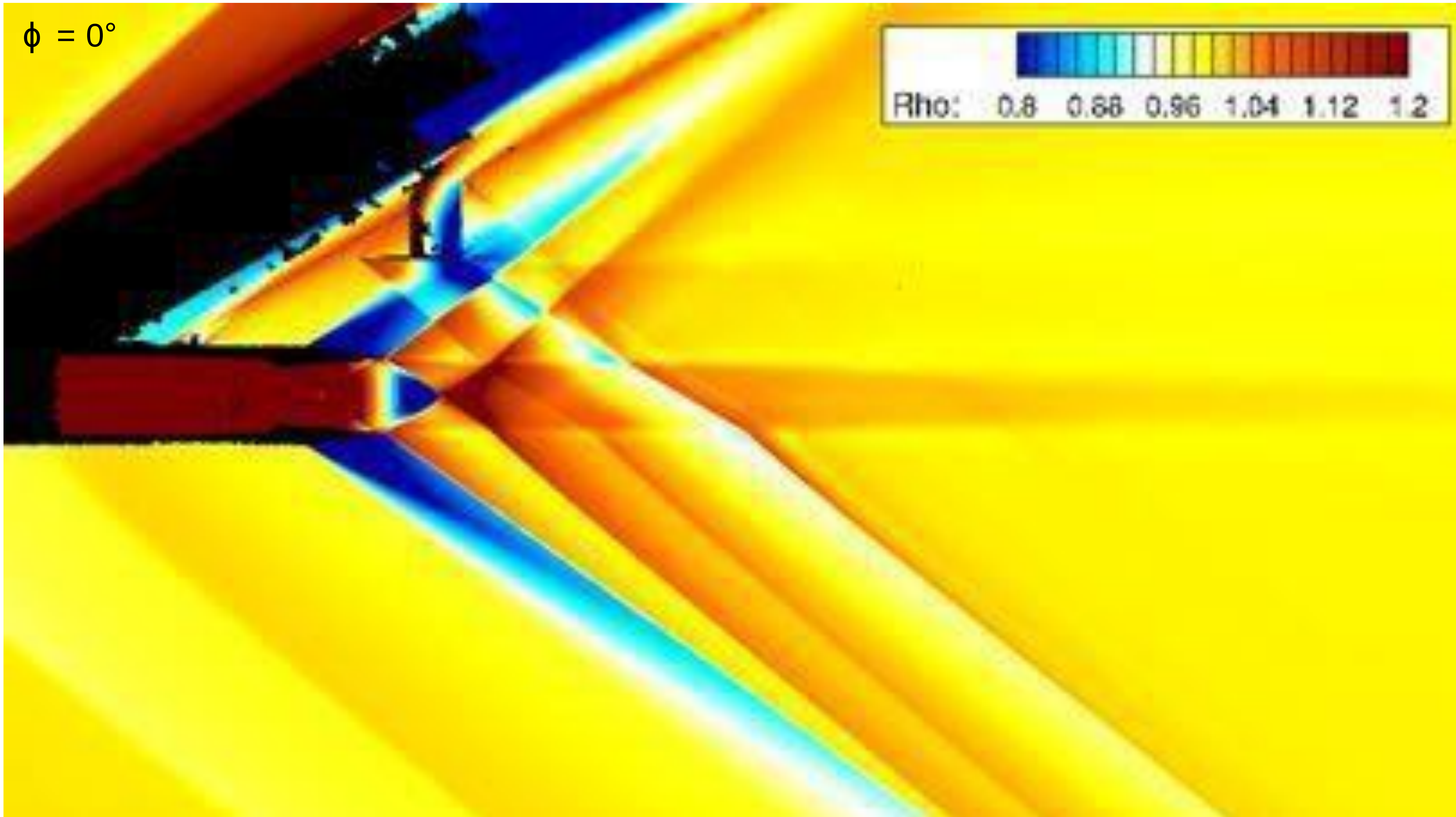
- Density contours



# Results: Biconvex



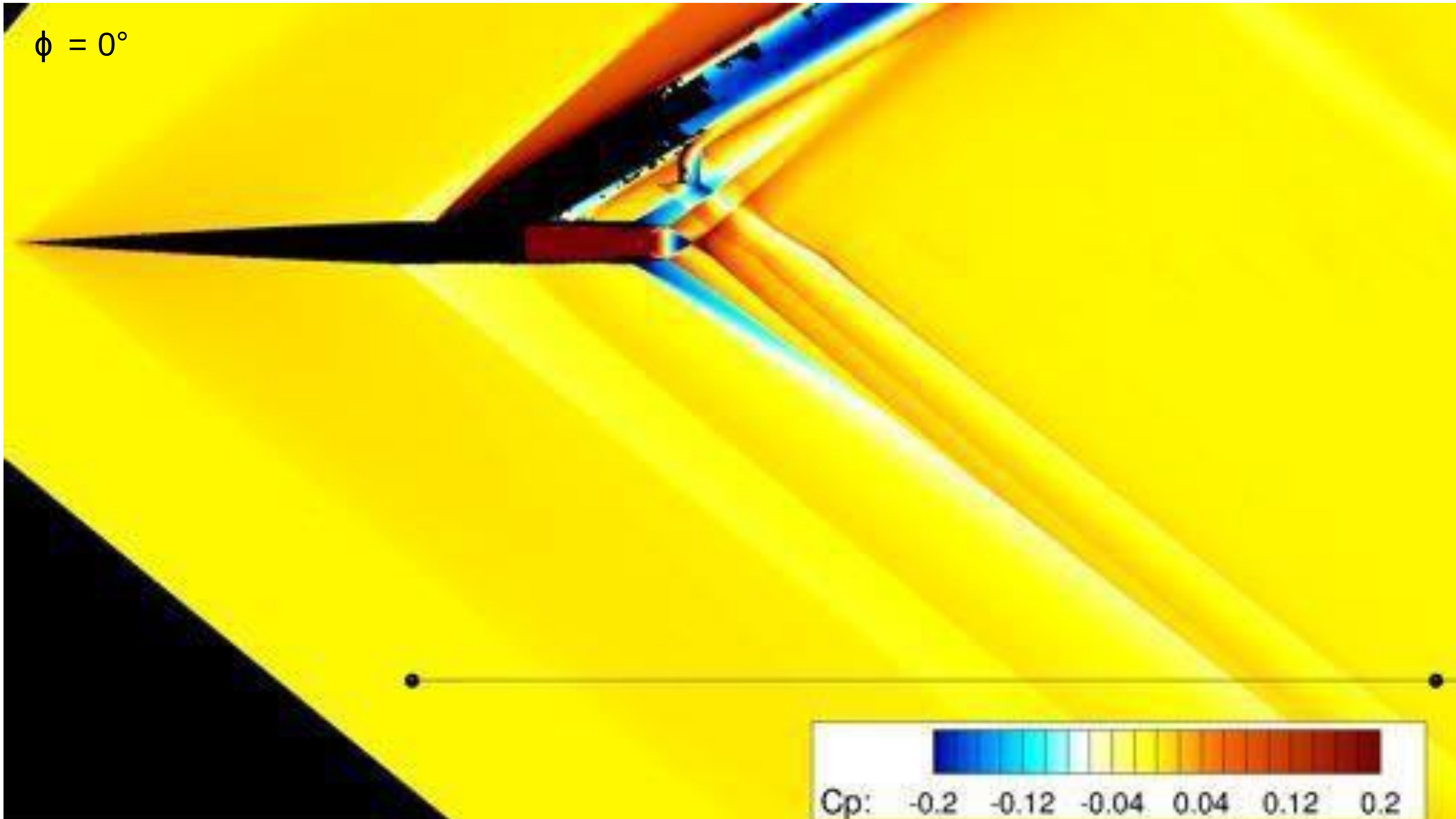
- Density contours (zoomed in on plume-shock interaction region)



# Results: Biconvex

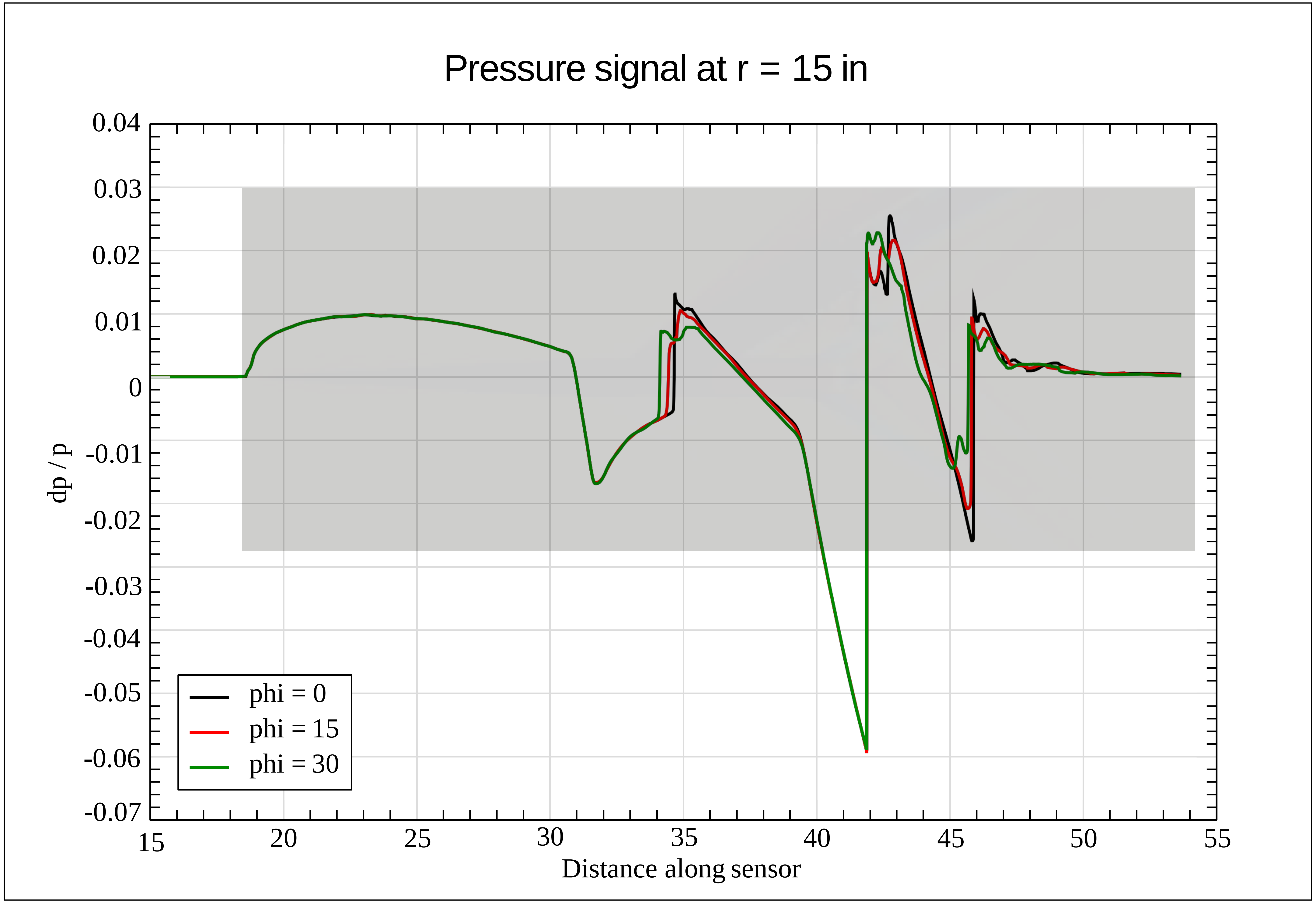


- Pressure coefficient contours



# Results: Biconvex

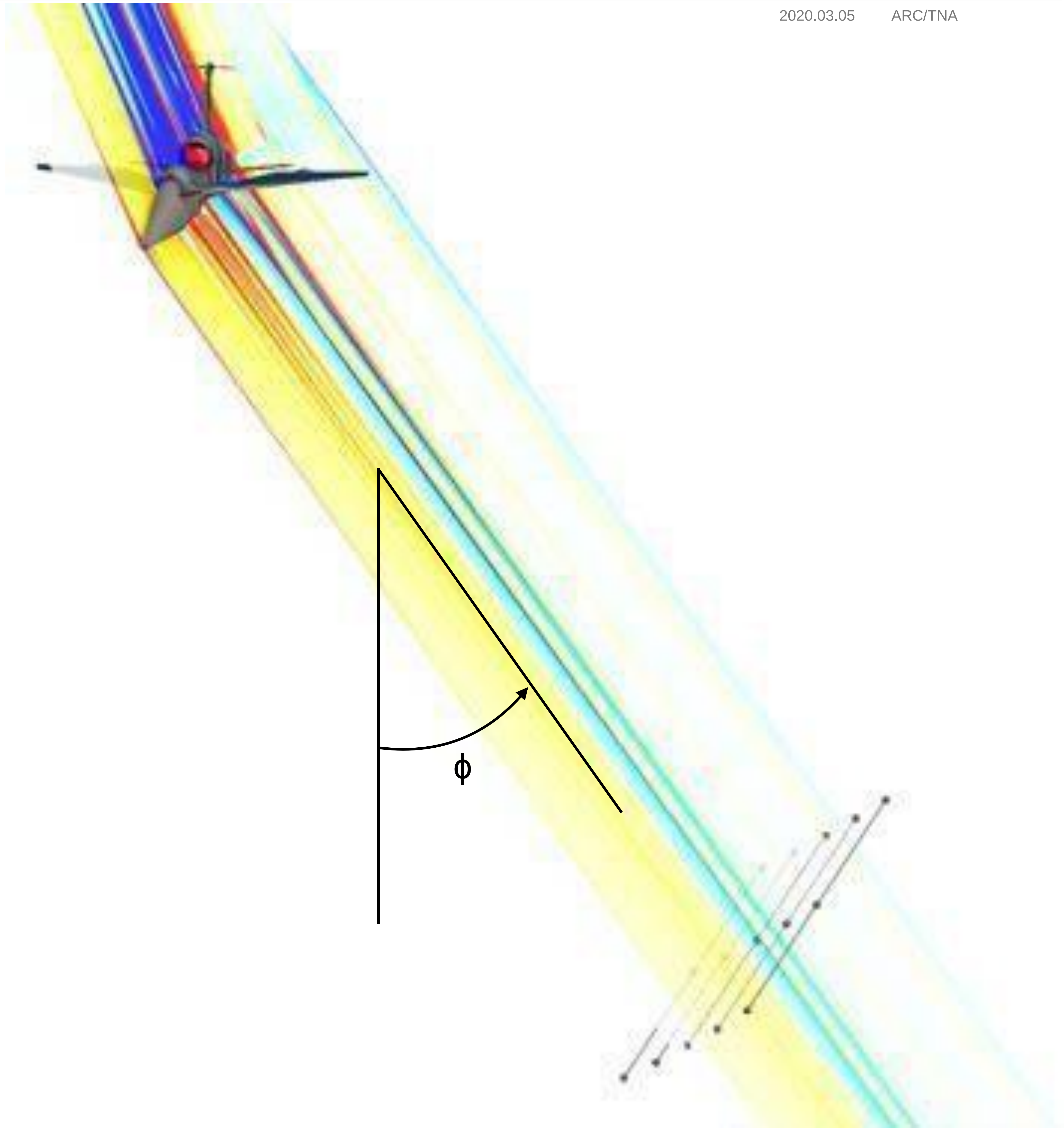




# Results: C608



- Separate simulation run at off-track ϕ every 10° for 19 total simulations
- Five line sensors in each sim at offsets of Δϕ = [-4, -2, 0, +2, +4]
- Covers full half-cylinder 0 ≤ ϕ ≤ 180° in increments of 2°



# Results: C608

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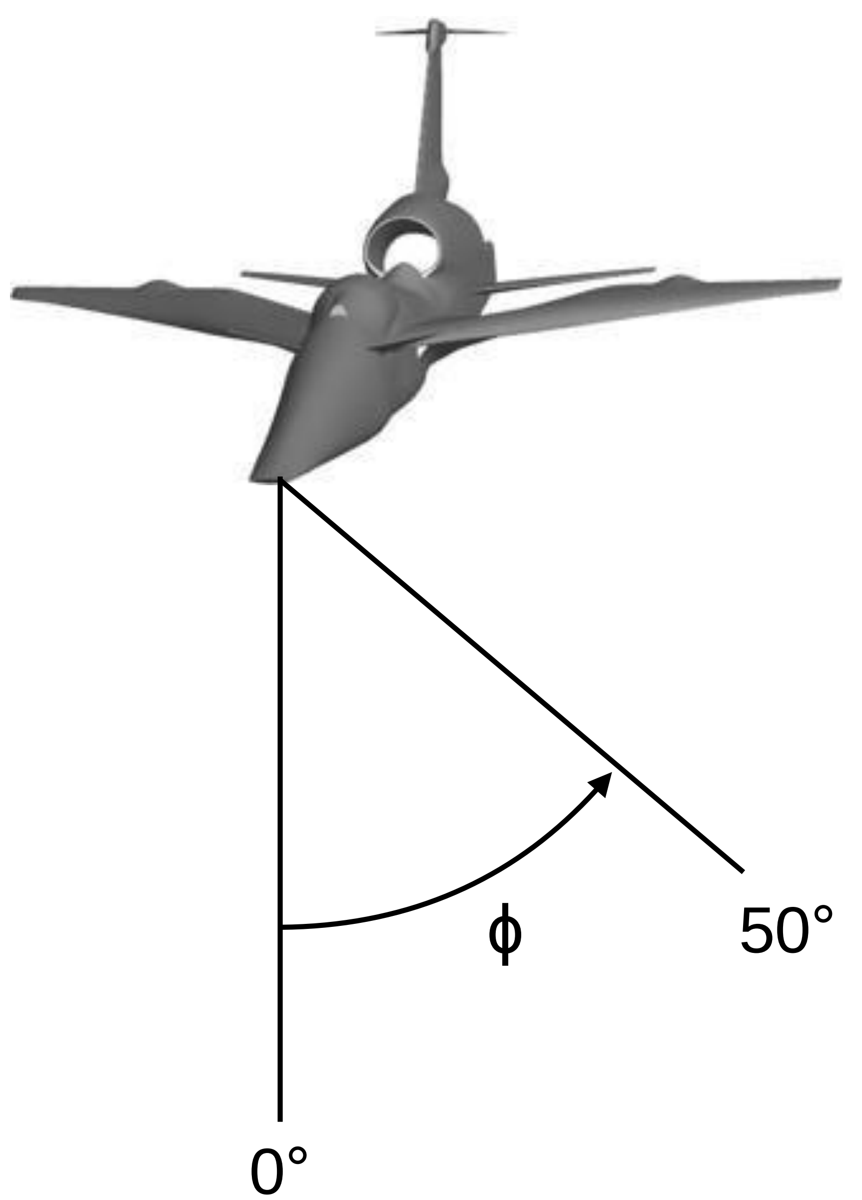


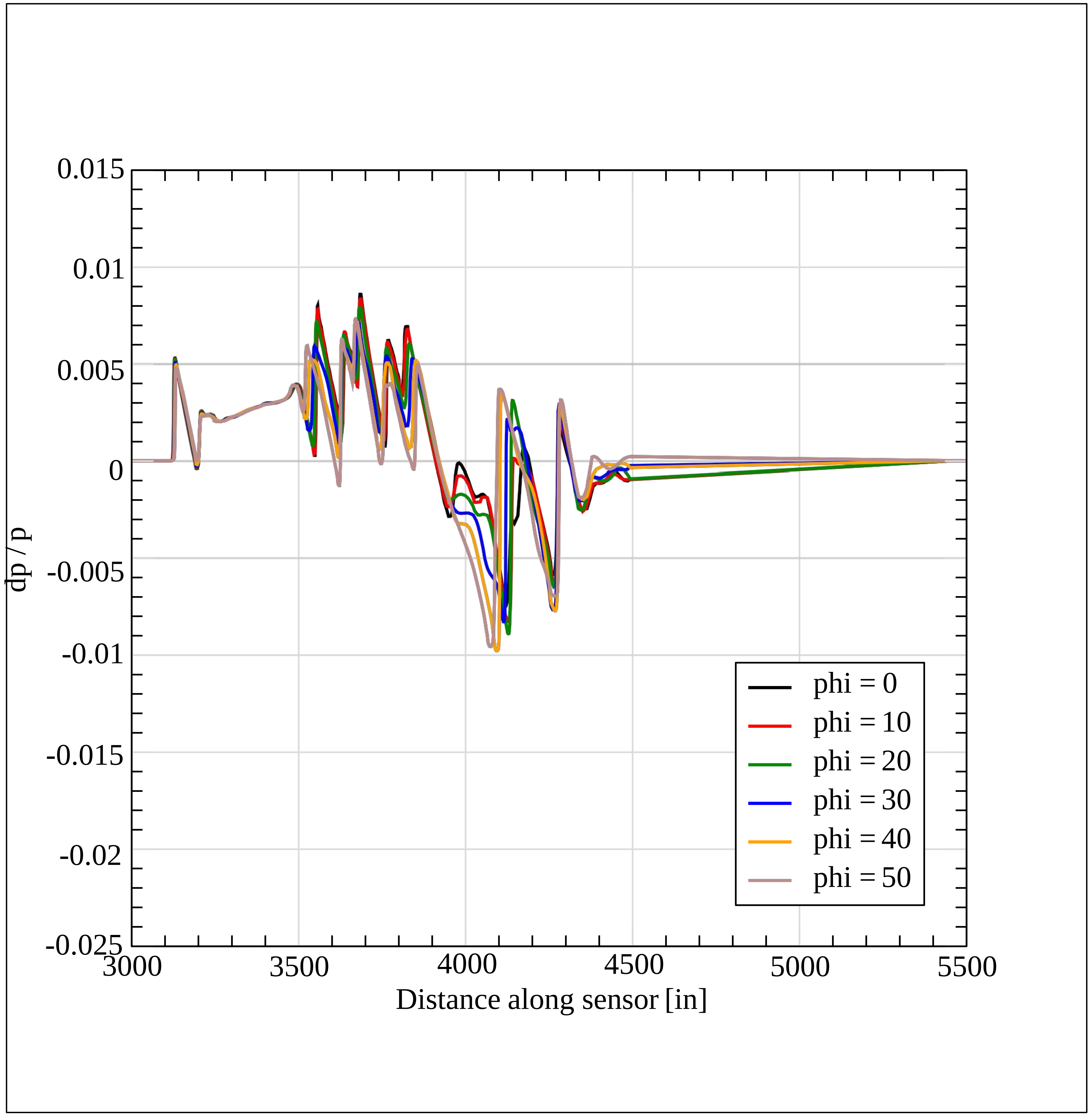

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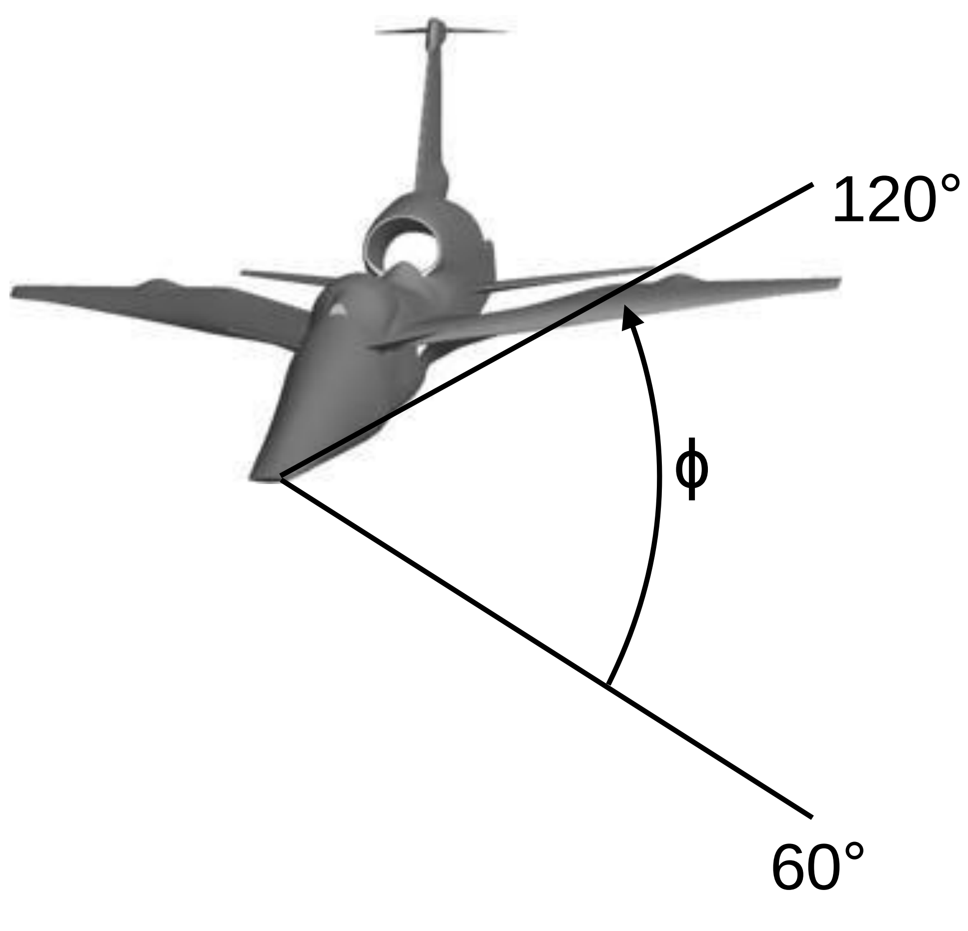


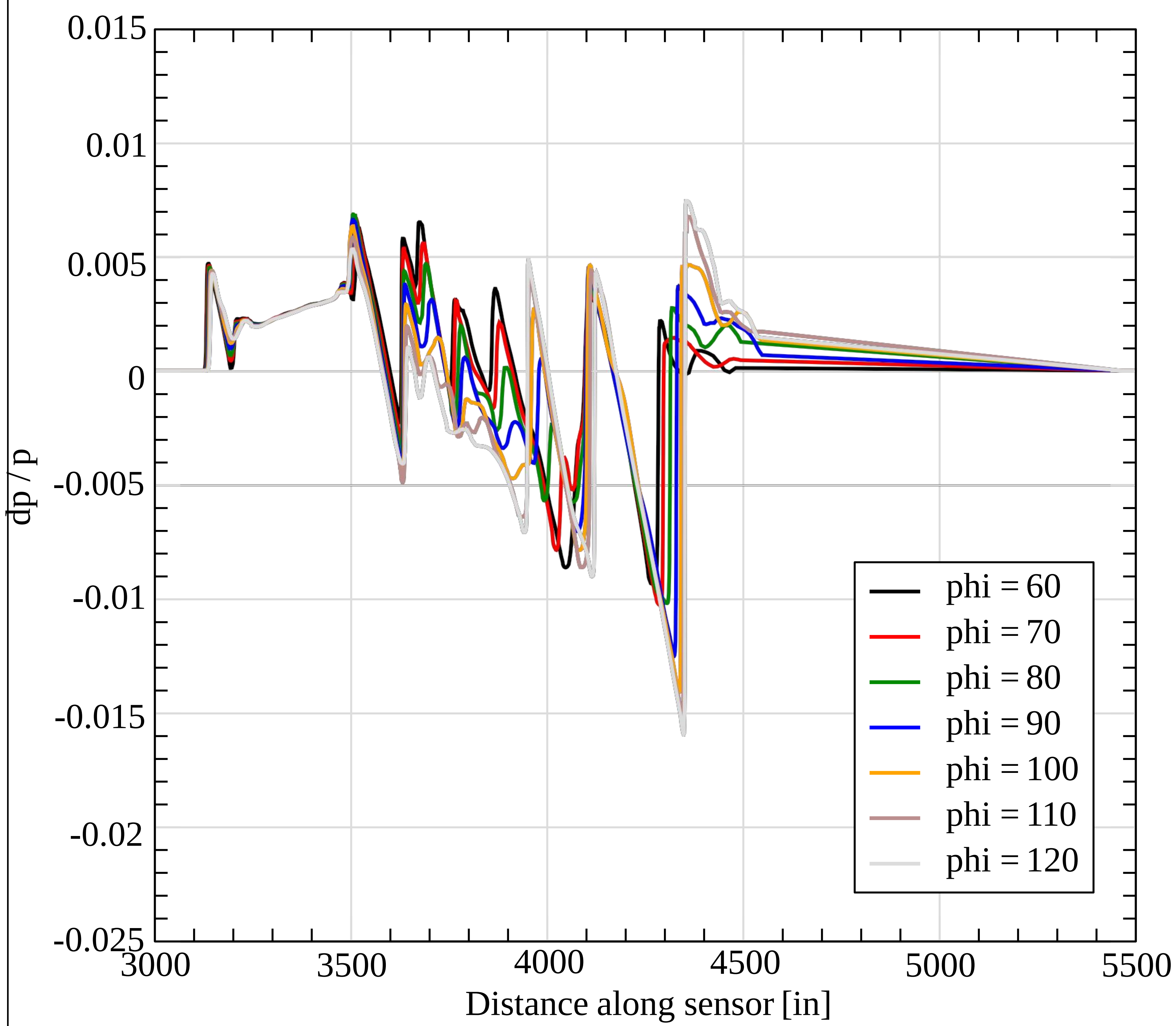

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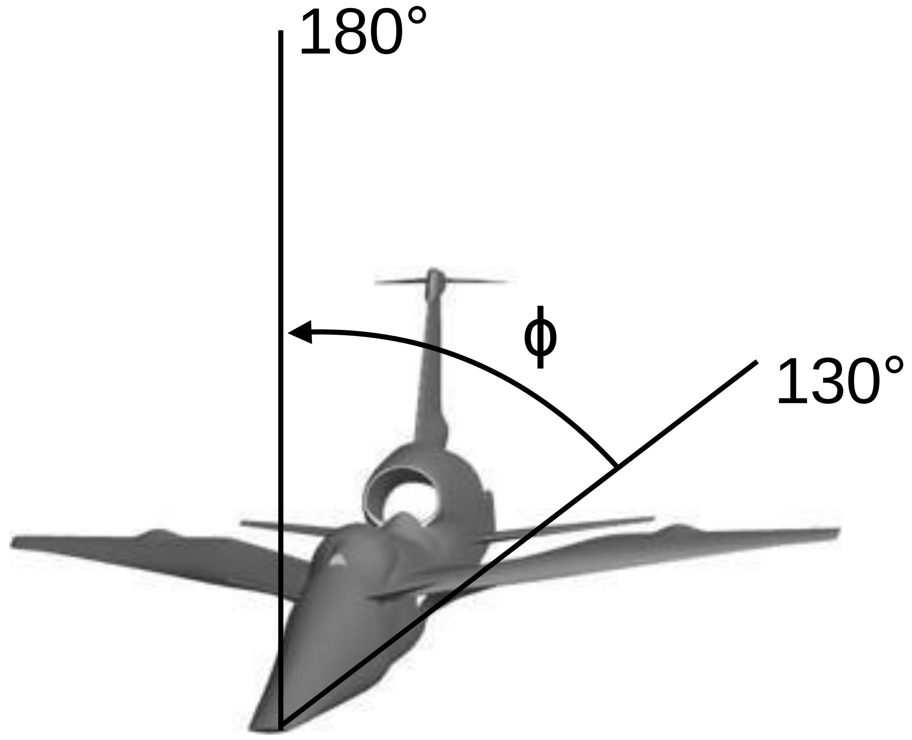


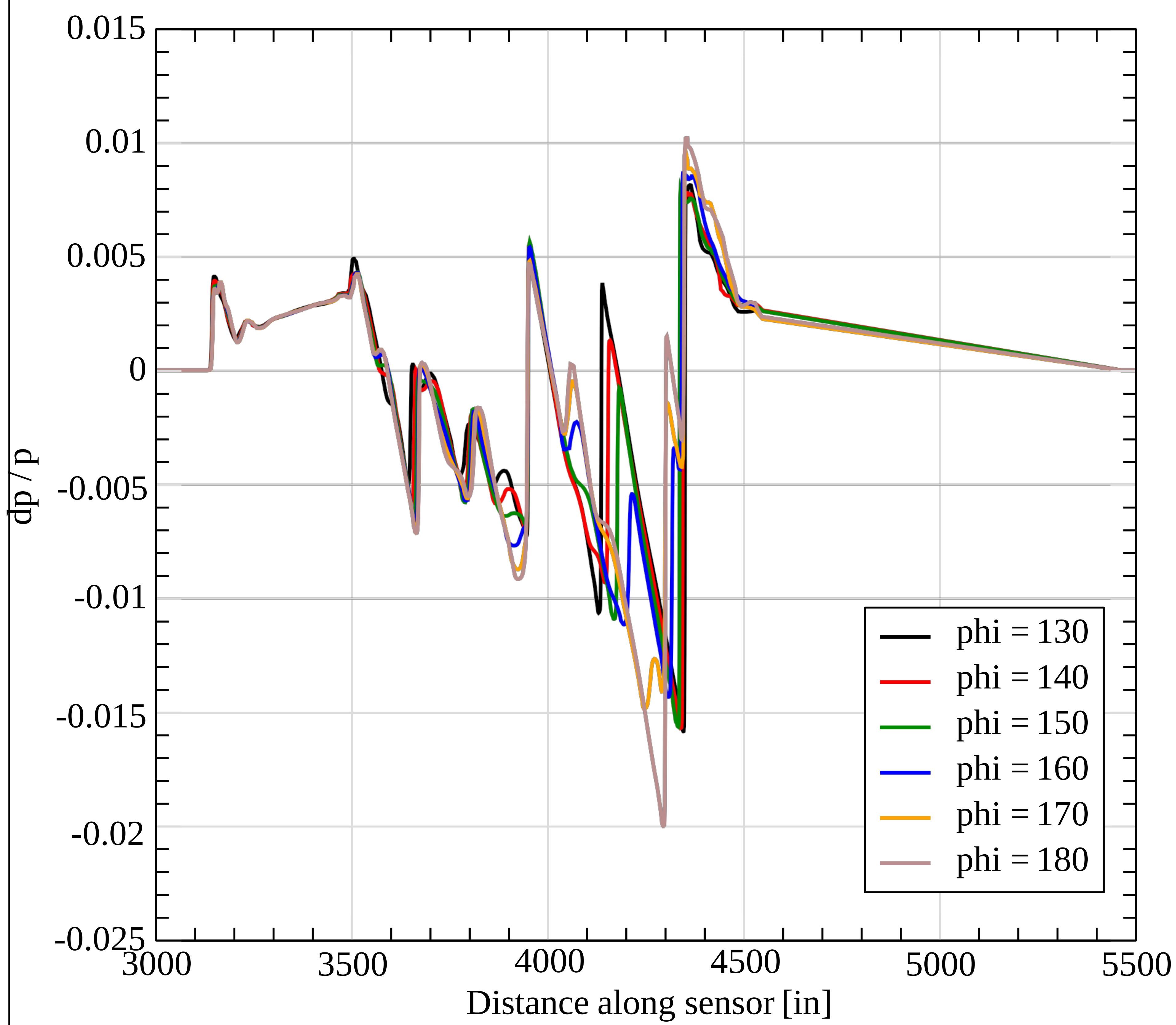

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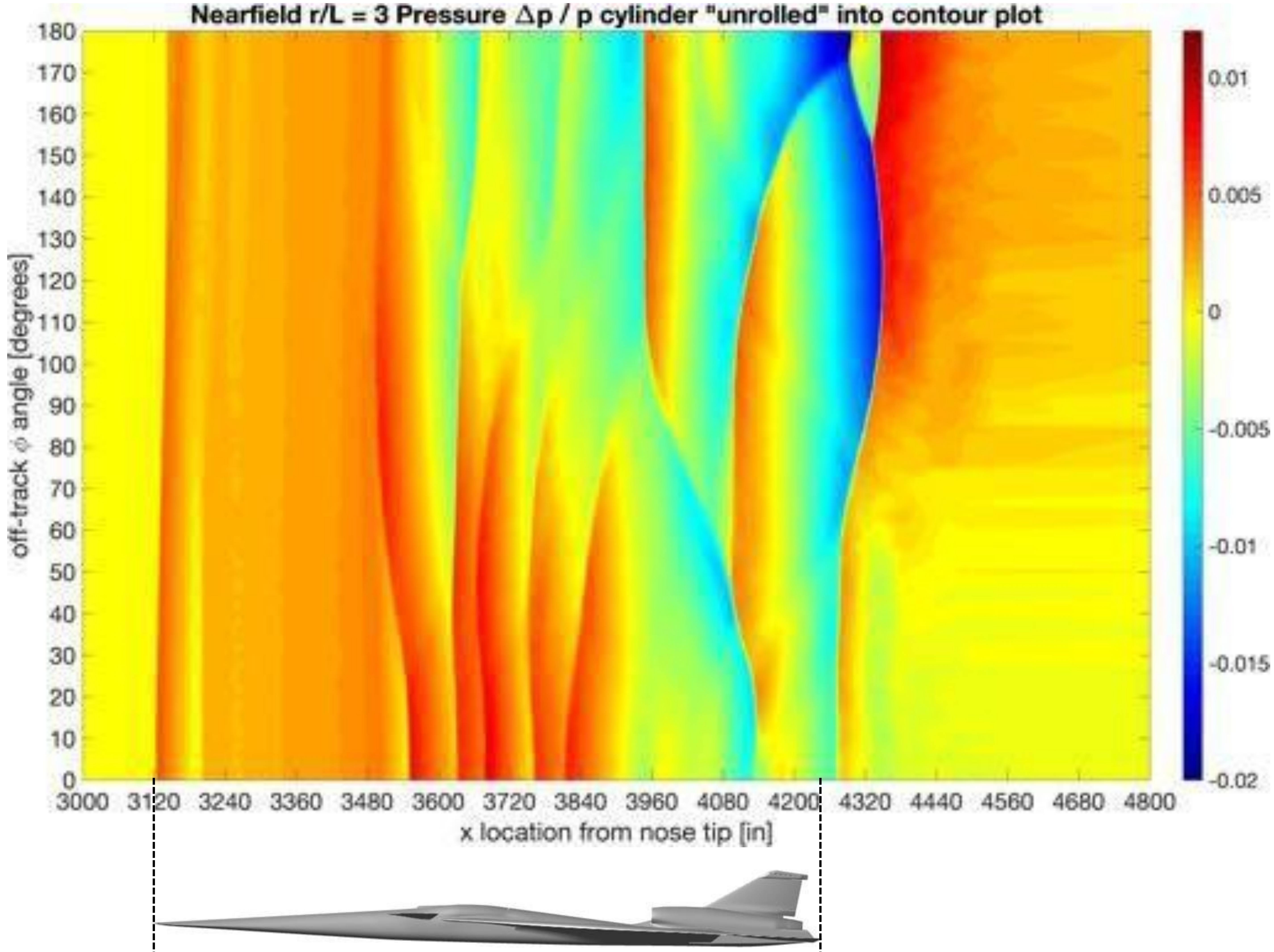


# Challenges



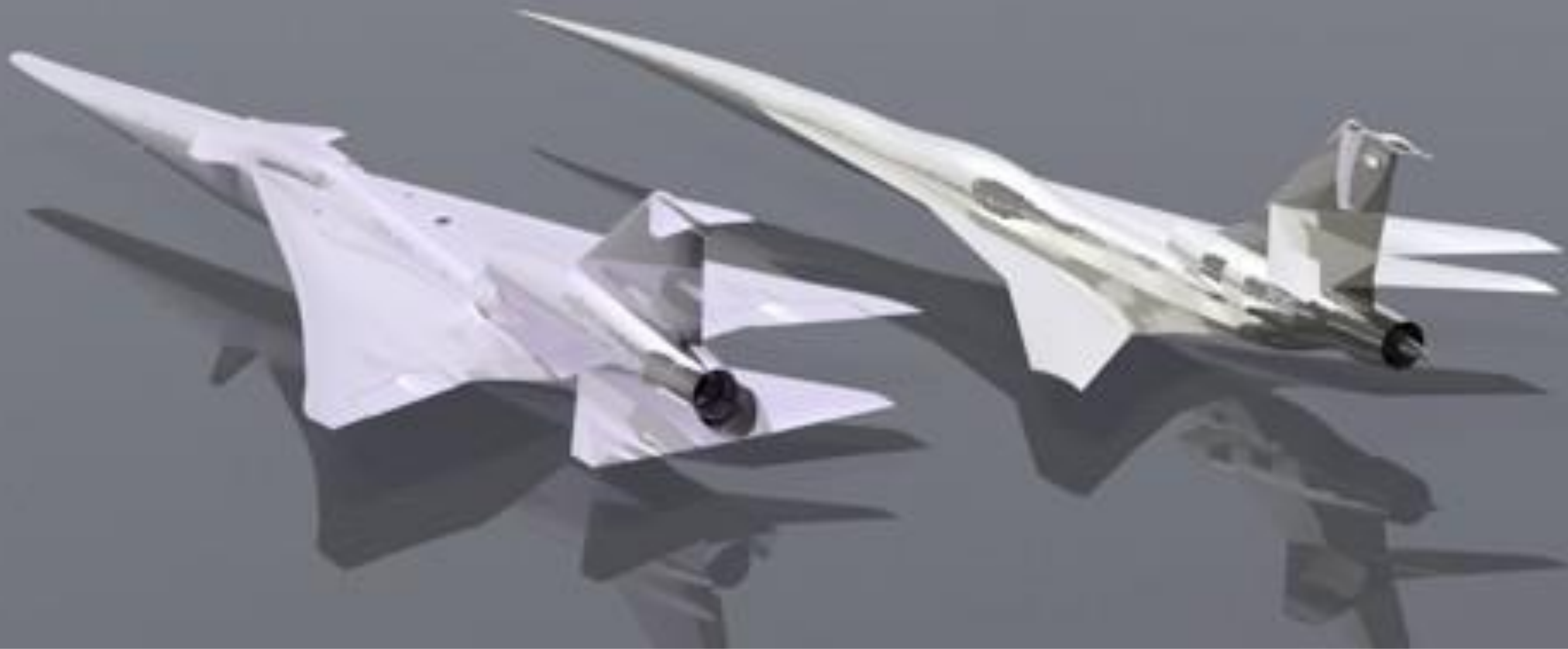
- C608
  - Getting outflow BC's to correct desired Mach number
    - Adjusted the back pressure
      - Engine inlet from suggested 2.6 to 2.75
      - ECS inlets from suggested 1.4 to 2.70
  - Consistent closeouts are challenging
    - Plume/shock is difficult to capture
    - Mesh coarsening farther back in plume can create spurious artifacts in pressure signal

# Conclusions



- Complex geometry increases computational cost
  - More features to resolve
  - Must take pressure signal farther from body
- Adaptive meshing refines based on solution error and objective function
- Must routinely check for solution quality
  - Numerical convergence and adjoint performance
  - Grid sequencing with coarse, medium, fine grid pressure signal
  - Comparison metrics for multiple off-track ϕ sim’s: mass flow through inflow/outflow boundaries, force & moment coefficients
- Richardson extrapolation shows highest uncertainty in aft portion of signal, which is particularly challenging with propulsion and plumes
- Inviscid simulation can effectively capture supersonic flow features of shocks, expansions, and coalescence

# Farfield Propagation Results Using sBOOM



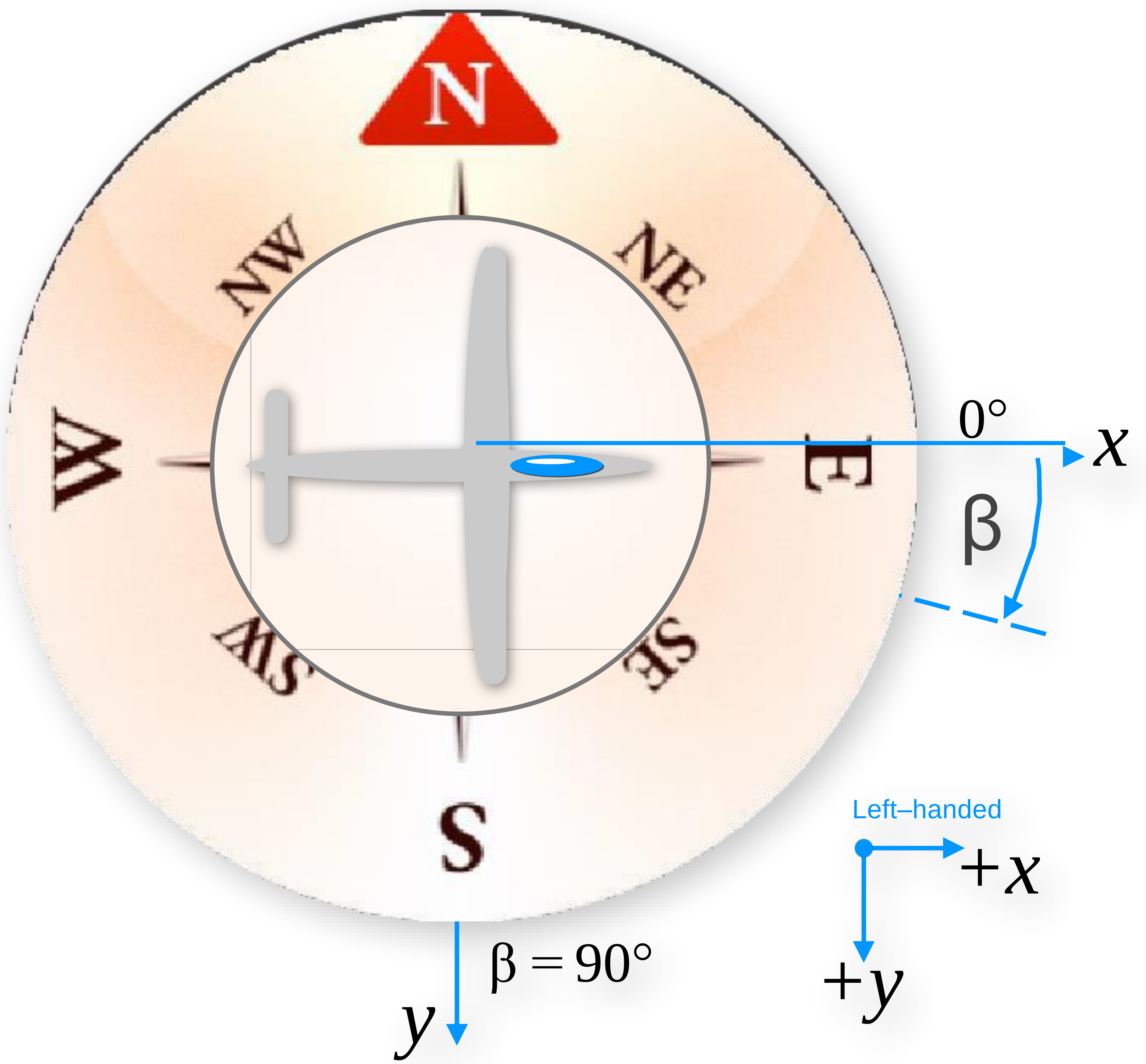
# Farfield Propagation Overview



- Preliminaries
  - Conventions & propagation primer
  - Mesh Convergence & oversampling
- Results for Cases 1 & 2
  - Ground signals for Standard Atm. & Required Atm.
  - Cutoff angles
  - Carpet noise metrics
  - Ground Intercepts, boom carpets & raytubes
- Summary & observations

# Wind Convention in sBOOM

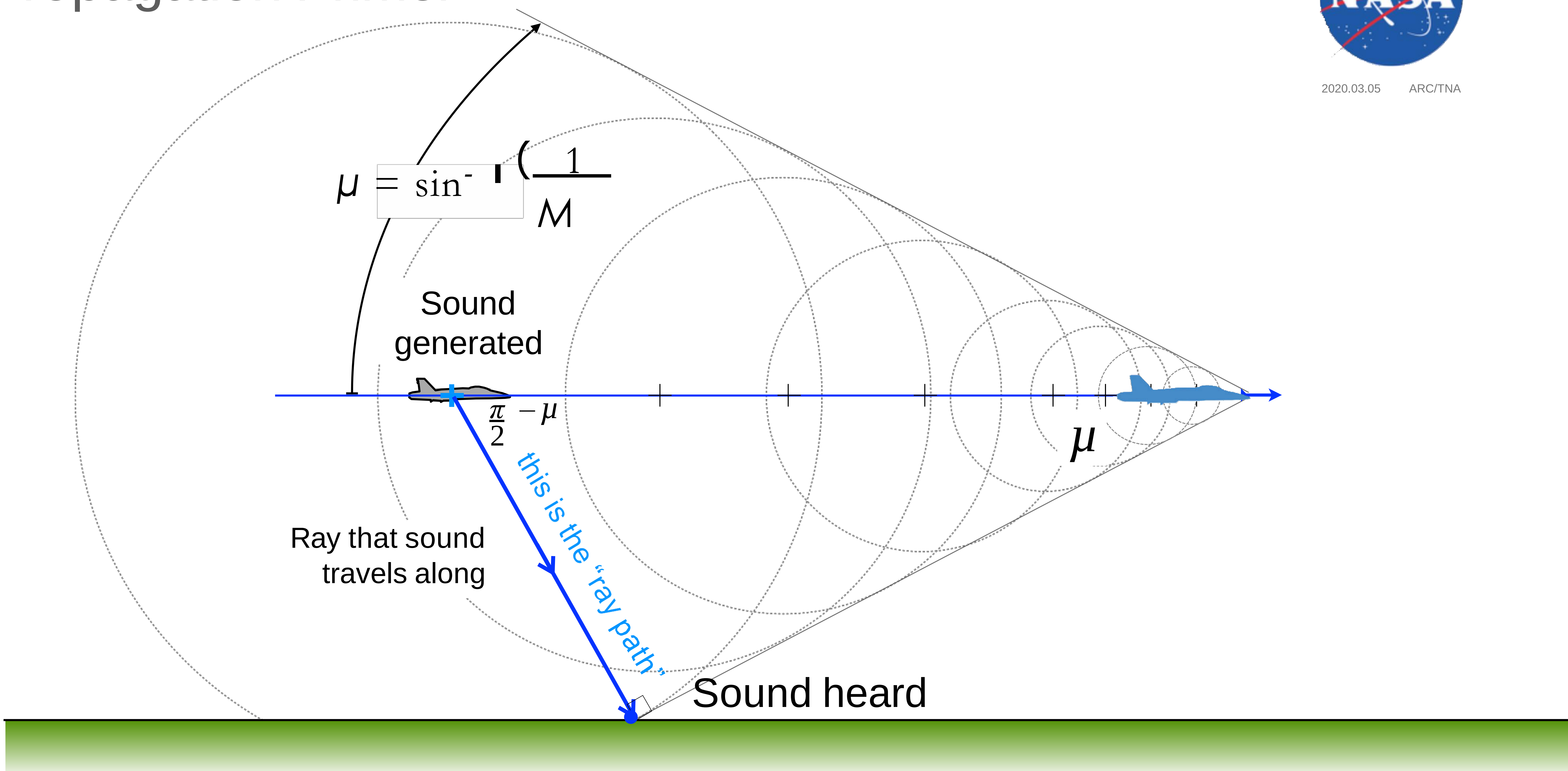





- sBOOM wind uses *left handed* coord. sys.
- β = heading
- β = 0° A/C pointed East, cw+
- sBOOM wind tables are in meters vs m/s
- $x$ and $y$ are wind components (“blows toward”)
  - → (x, y) = (1, 0) is tail wind if heading is East
  - ↓ (x, y) = (0, 1) is tail wind if heading is South
  - ↘ (x, y) = (1, 1) is tail wind if heading is SE

- Workshop has aircraft flying E,
  - This is 0° heading in sBOOM

# Propagation Primer

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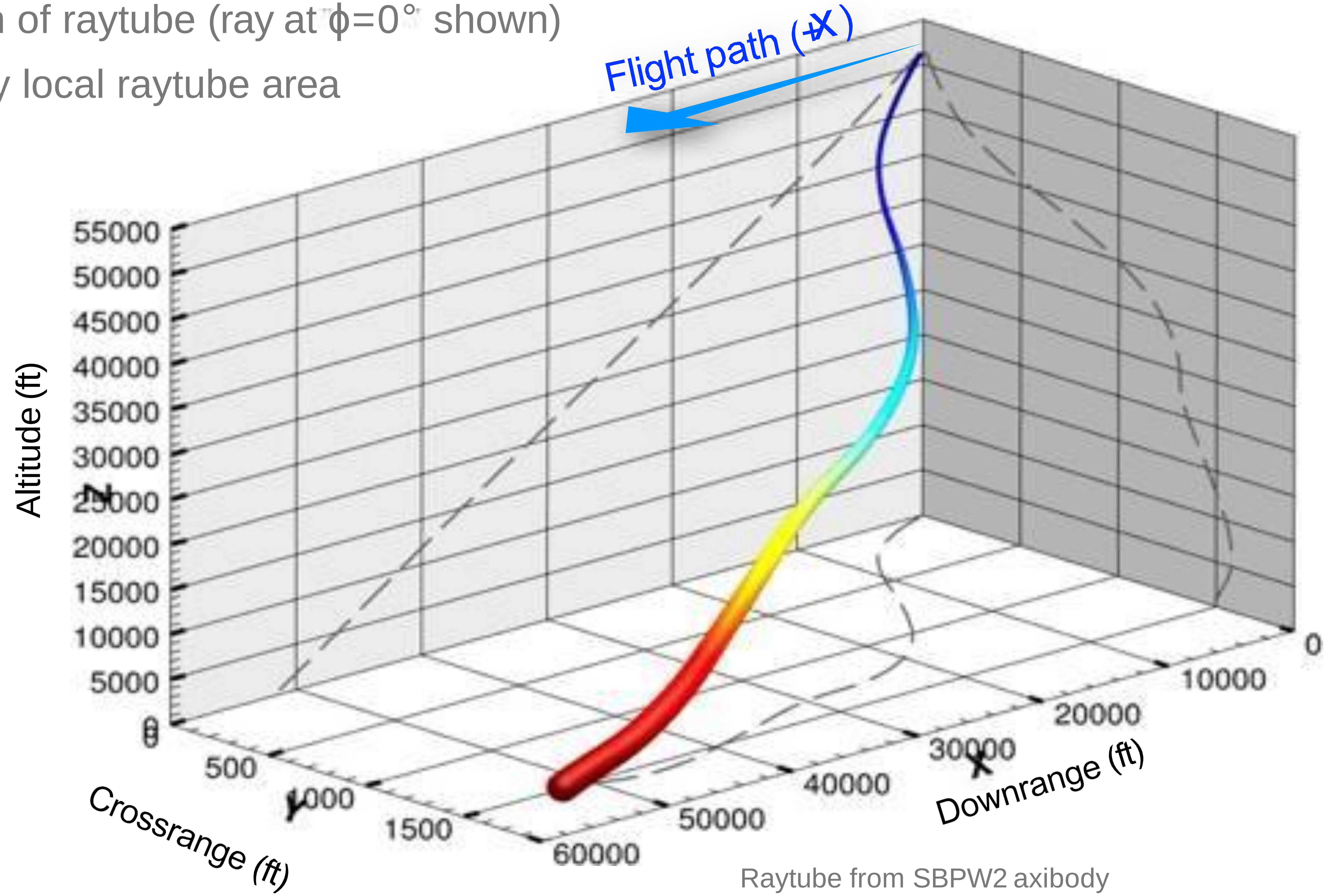
- Quasi-1D integration of Burgers' equations occurs in tube along the ray path
- Determines the ground intercept of sound emanating from given trajectory point & azimuth
- Ray path determines time required for signal propagation

# Wind Effects



- Only consider crossrange and downrange winds (no up/down drafts)
- Wind can alter path of raytube (ray at $\phi=0°$ shown)
- Paths are scaled by local raytube area




Raytube from SBPW2 axibody

# Mesh Convergence



## Sensitivity of noise output to discretization of near field signal

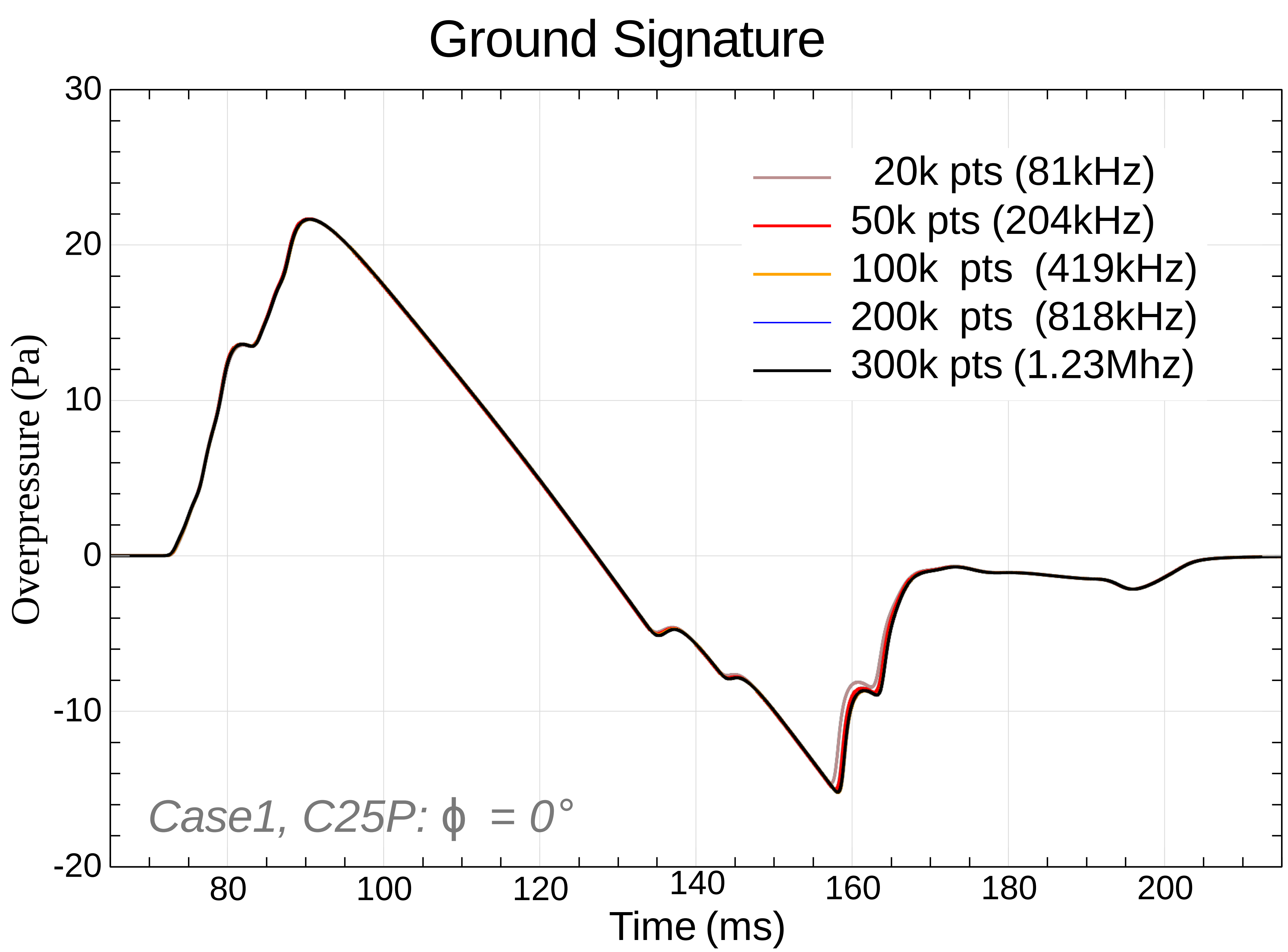
- Propagation code is solving augmented Burgers' via finite difference method
- Need to make sure loudness metrics are sufficiently mesh converged
  - Mesh convergence of propagation is case dependent ( on signal, azimuth &atm.)
  - Mesh refinement study done for each near field signal (using Std. and Reqd. Atm.'s)
- Truncation error directly impacts accuracy, resolution requirements are driven by need to minimize error in propagation
  - Initial signal from nearfield CFD typically has < 2000 points
  - Propagation typically requires 40000-100000 points (oversampled by 20-50x)
  - Discrete ASEL filter can be poorly behaved at high sampling frequencies (> ~250kHz)

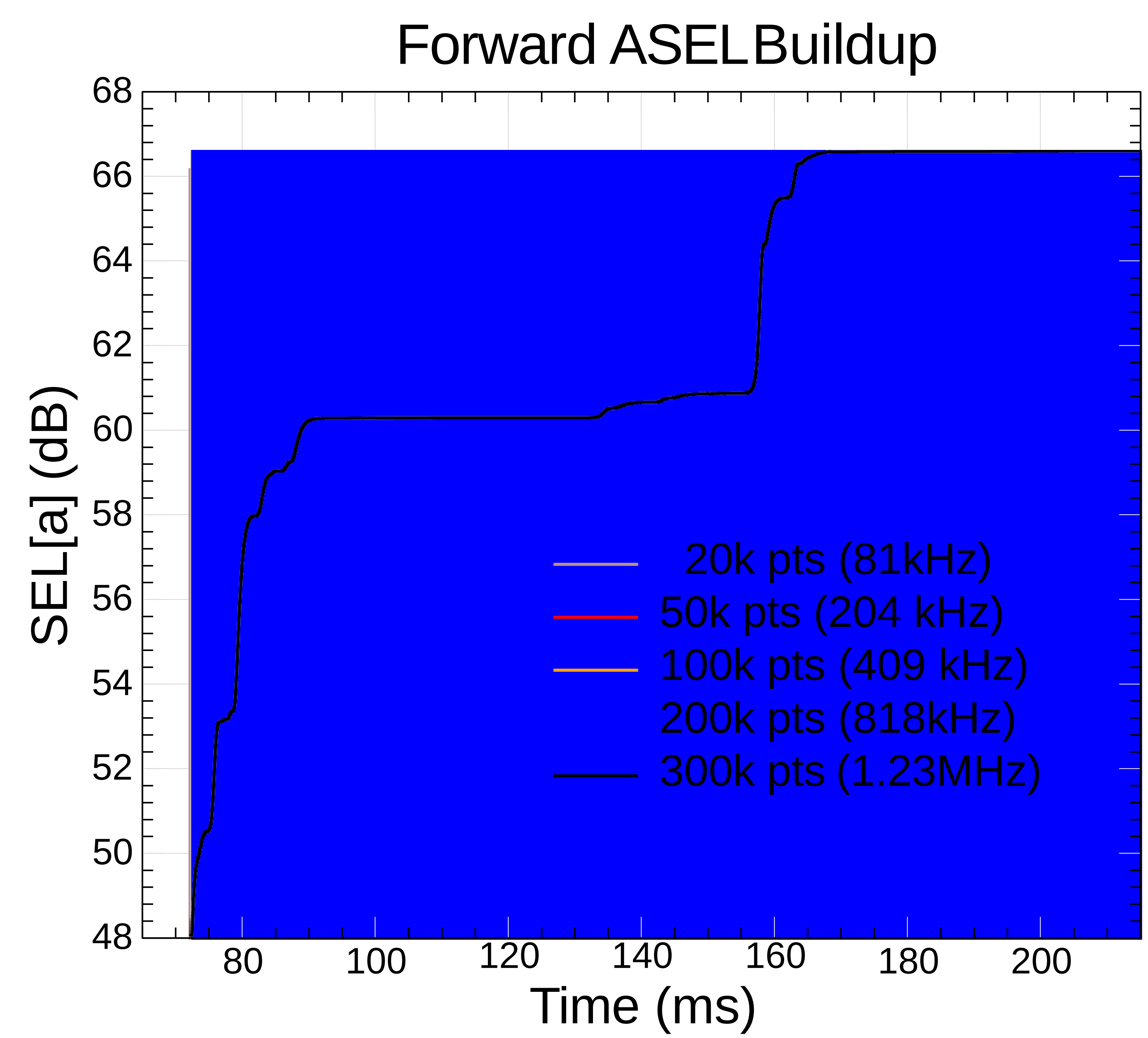
    ➢ *this limits maximum allowable oversampling*
- How much accuracy is needed?
  - Atmospheric variability generally 2-5 dB, but may be ~10 dB in some cases
  - Generally tried to keep propagation error under ±0.2 dB

# Mesh Convergence

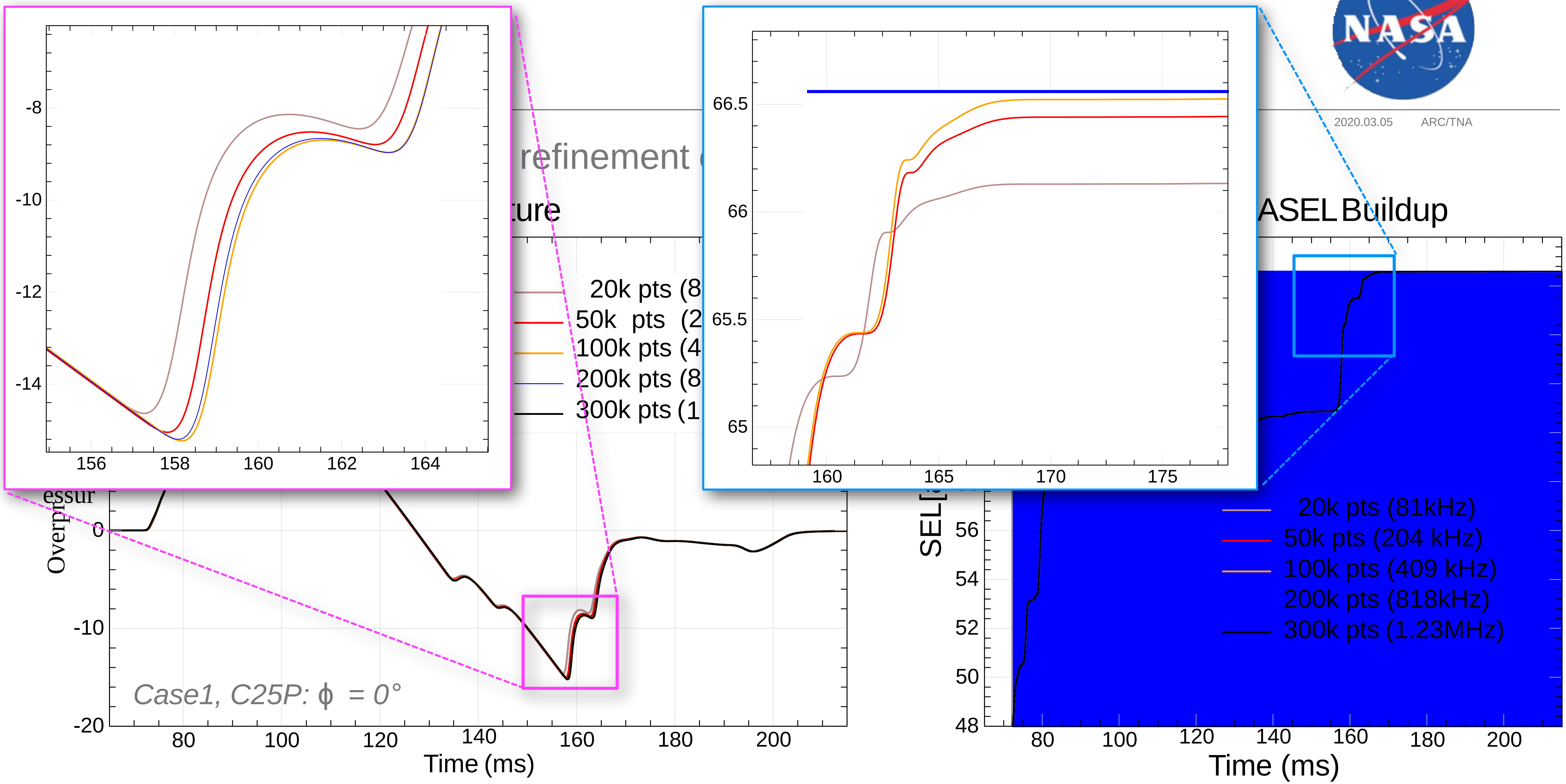


Sensitivity of noise outputs to refinement of the propagation mesh




- C25P signals at ϕ = 0°, using from 20k-300k points (80-1230 kHz) for propagation
- Despite similarities in ground signal, mesh convergence of ASEL is quite slow

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# Mesh Convergence

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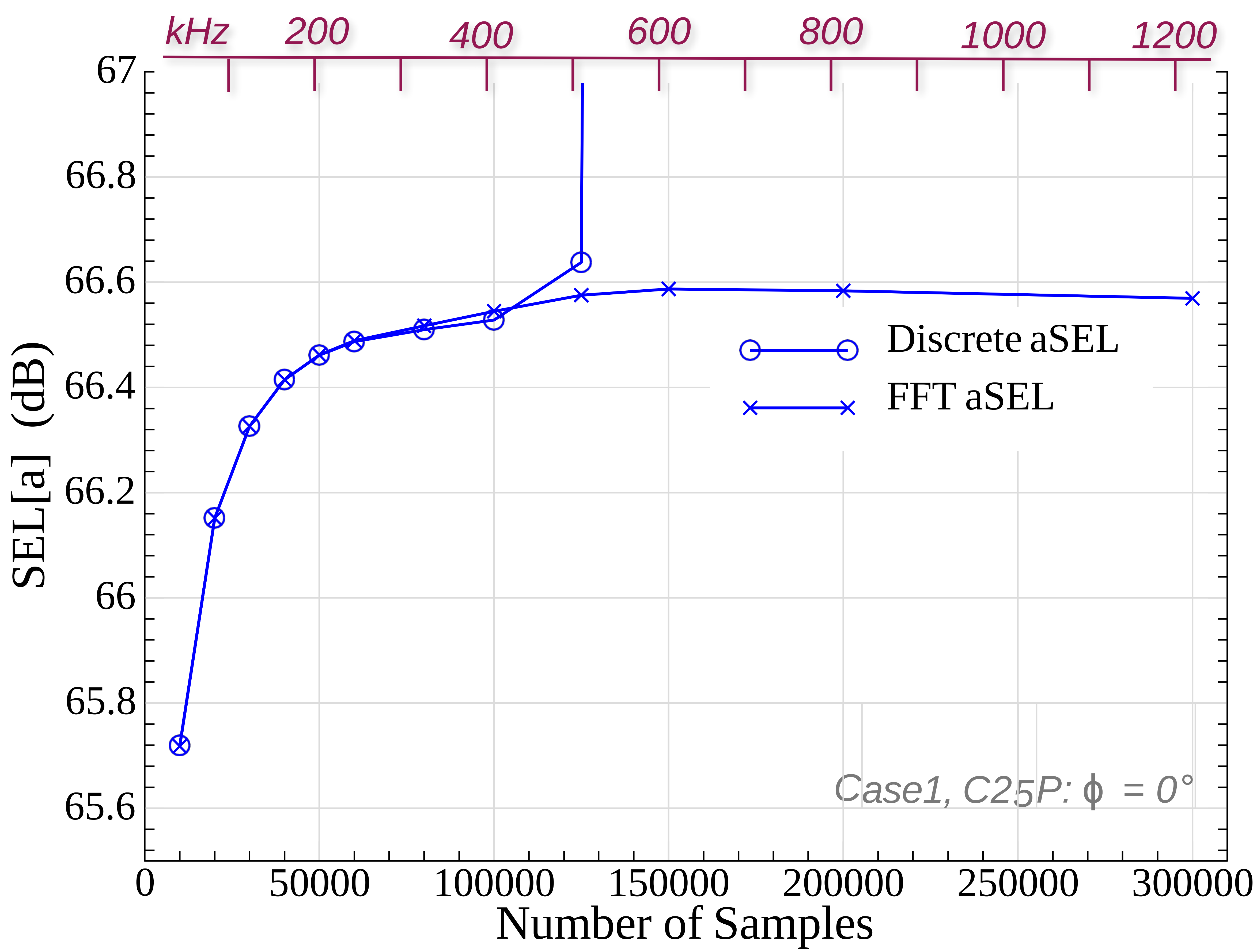
## Convergence ASEL noise metric with sampling frequency




- ASEL converges slowly
  - Need ~600kHz (~150k pts) to converge ASEL to ±0.01dB
- However, discrete ASEL filter starts to have issues at ~250kHz, and blows up ~500kHz
- On this case (C25P) hard to guarantee ASEL error < ± 0.1dB
- Discrete BSEL and CSEL remain well behaved till ~1 & 10 MHz (respectively), so generally easier to mesh converge

# Mesh Convergence

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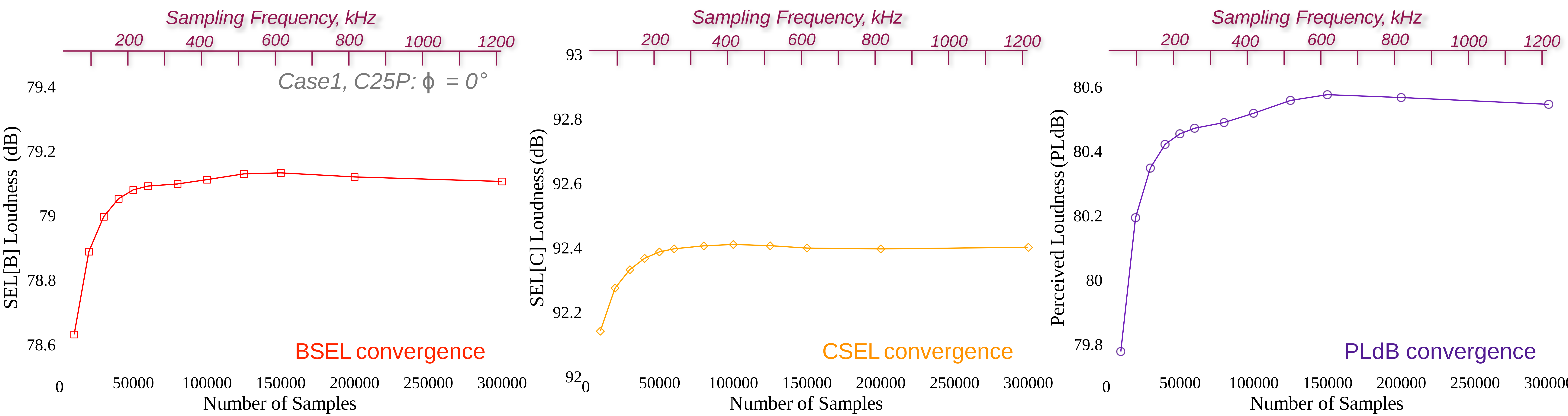
## Convergence of BSEL, CSEL & PLdB noise metrics with sampling frequency

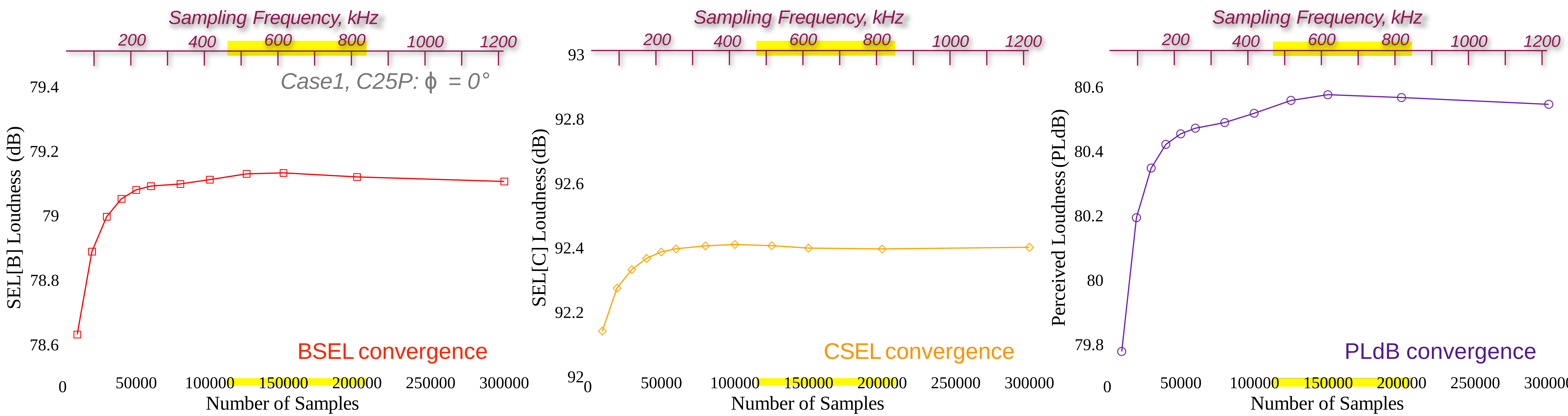



- BSEL, CSEL and PLdB all show good mesh convergence (all on 1dB scale)
- FFT used for all metrics except for BSEL, but appears to be well behaved
- C-weighting converges fastest (±0.02 dB @200kHz)
- PLdB converges slowest (approx. ±0.1 dB @200kHz)

# Mesh Convergence



## Convergence of BSEL, CSEL & PLdB noise metrics with sampling frequency




- To avoid excessive discretization error in propagation used 500-800kHz sampling frequencies for all workshop cases
- Computed noise metrics with FFT in LCASB (*adloud*) for ASEL, CSEL and PLdB noise metrics
- Used digital BSEL filter in sBOOM (well behaved at 500-800kHz)

# Case 1: C25P

## Powered version of the NASA Concept 25D

### Conditions:

- $M_\infty$ = 1.6
- Altitude = 15.760 km (52k ft)
- Ground height = 264.069m (866ft)
- *Lprop* = 33.53m (110 ft)
- *r*/*L* = 3.0 at signal extraction
- Ground reflection factor = 1.9
- Heading East (β = 0°)

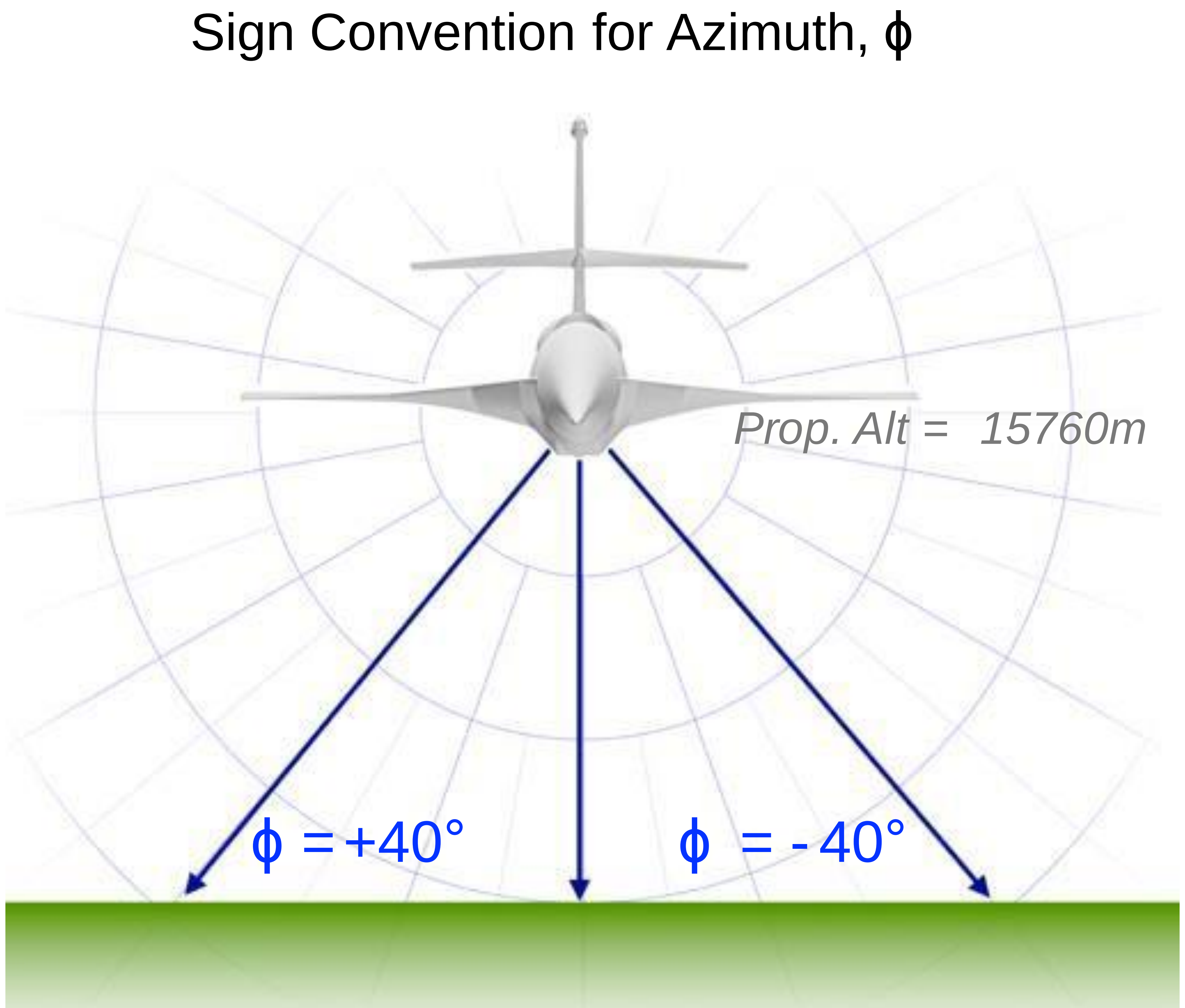
### Atmospheric Profiles:

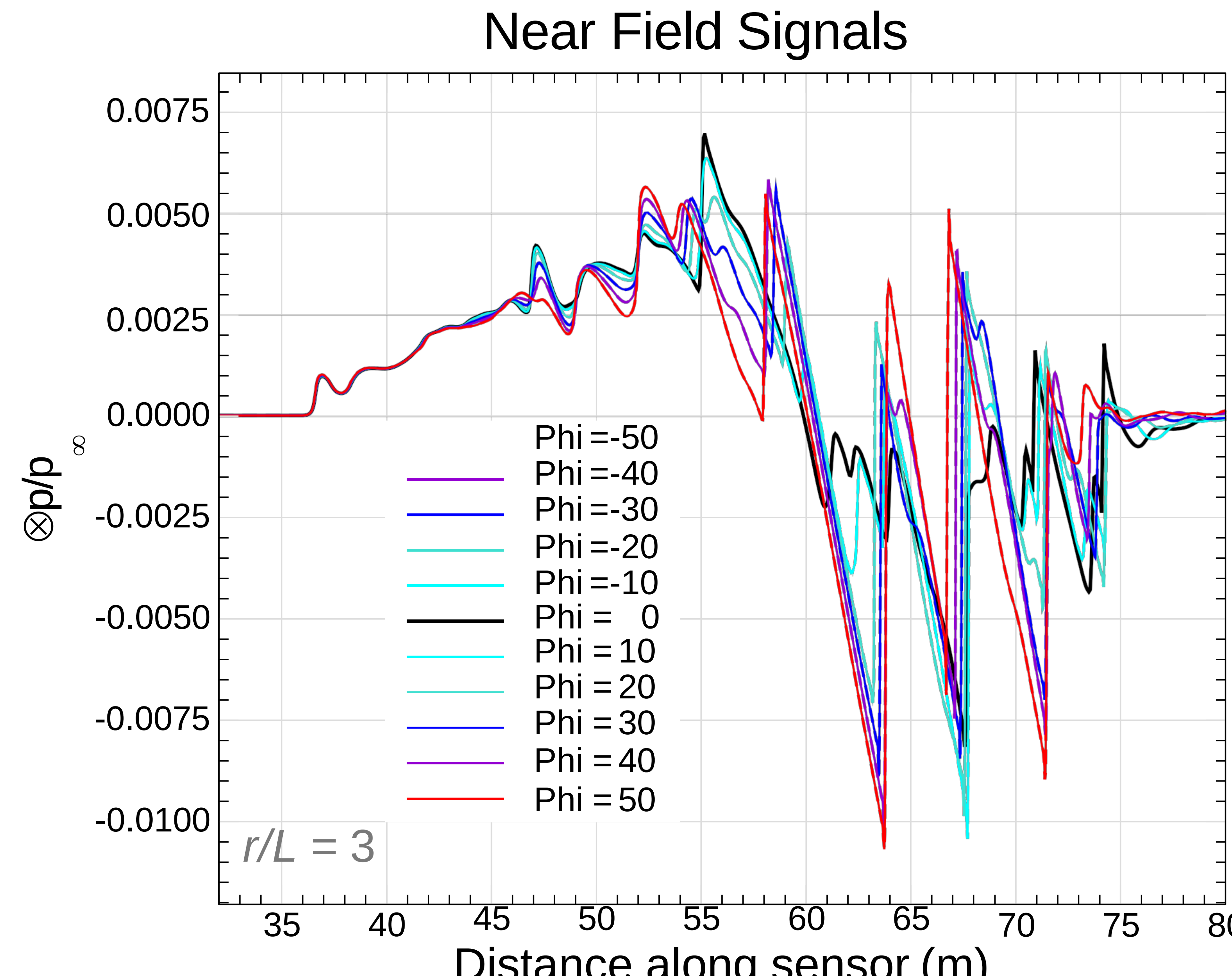
1. Required Atm: with profiles for wind, temp, pressure & humidity
2. Standard Atmosphere

# Case 1: C25P Standard Atmosphere



## Near field and ground pressure signals



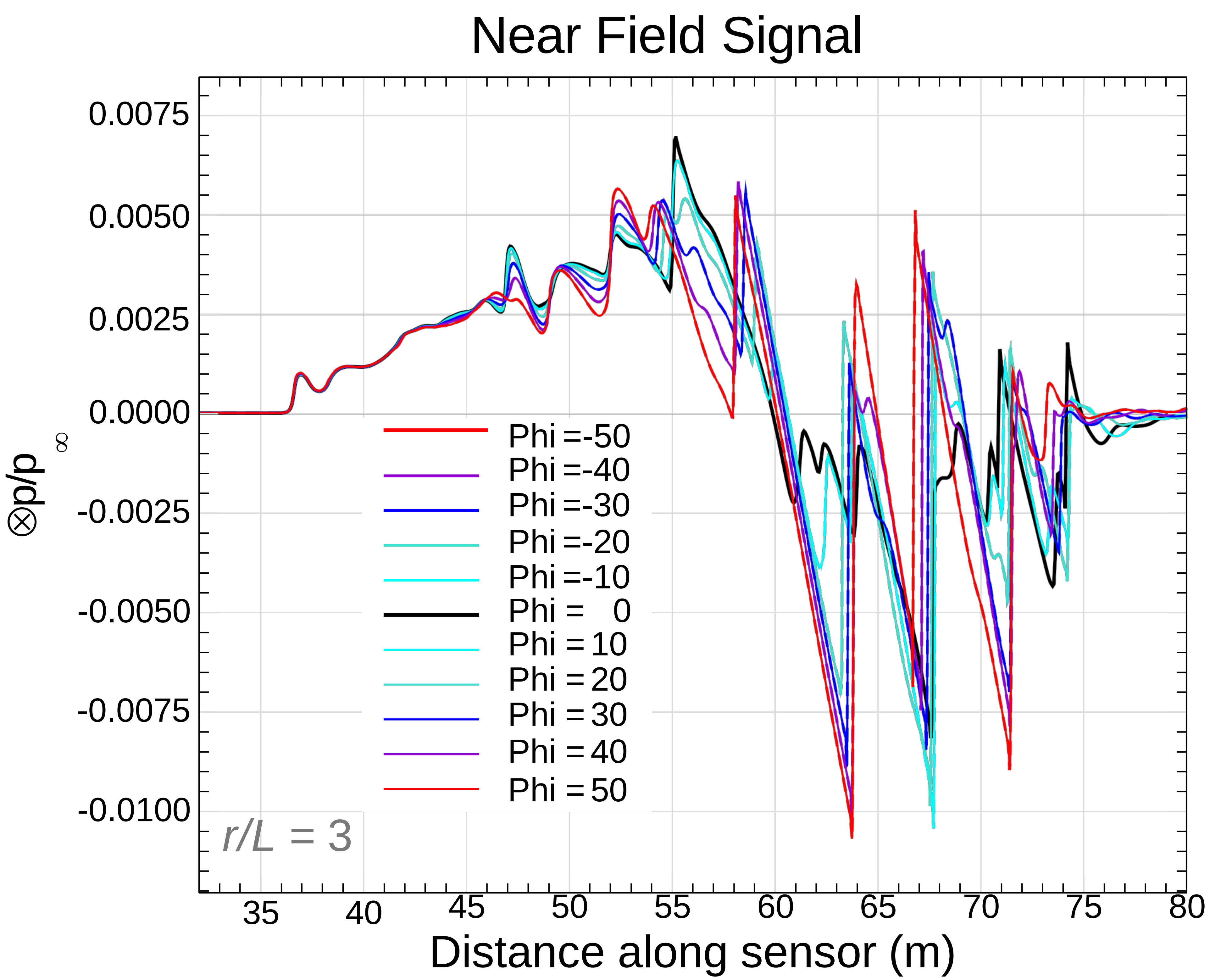



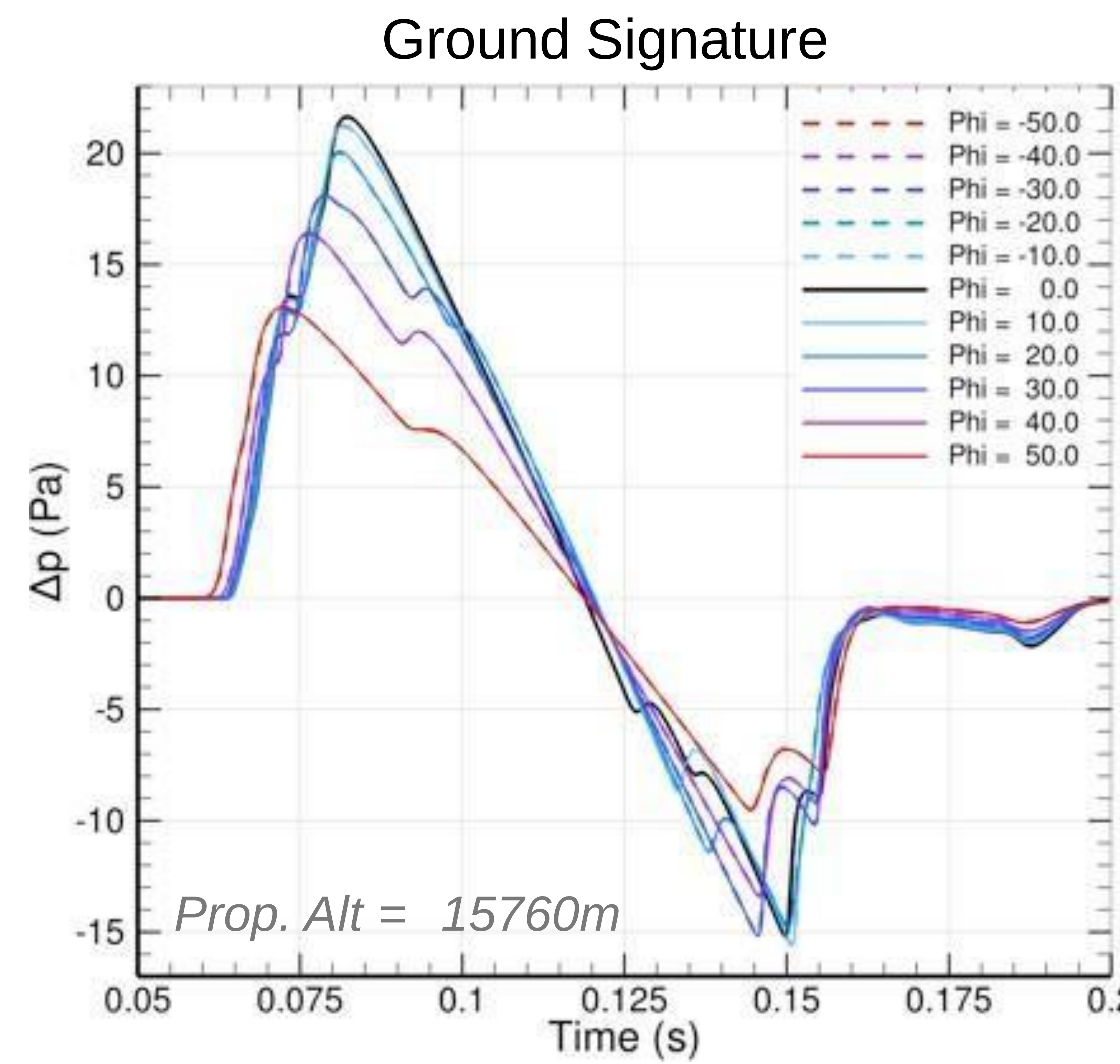

- Near field data provided for half-cylinder {-90°, 90°}, ({-50°, 50°} shown)

# Case 1: C25P Standard Atmosphere



Propagation altitude = 15760m, ground height = 264m




- Near field data provided for half-cylinder {-90°, 90°}, ({-50°, 50°} shown)
- Propagation shown used 500kHz sampling frequency (142k pts)

# Case 1: C25P Ground Signatures

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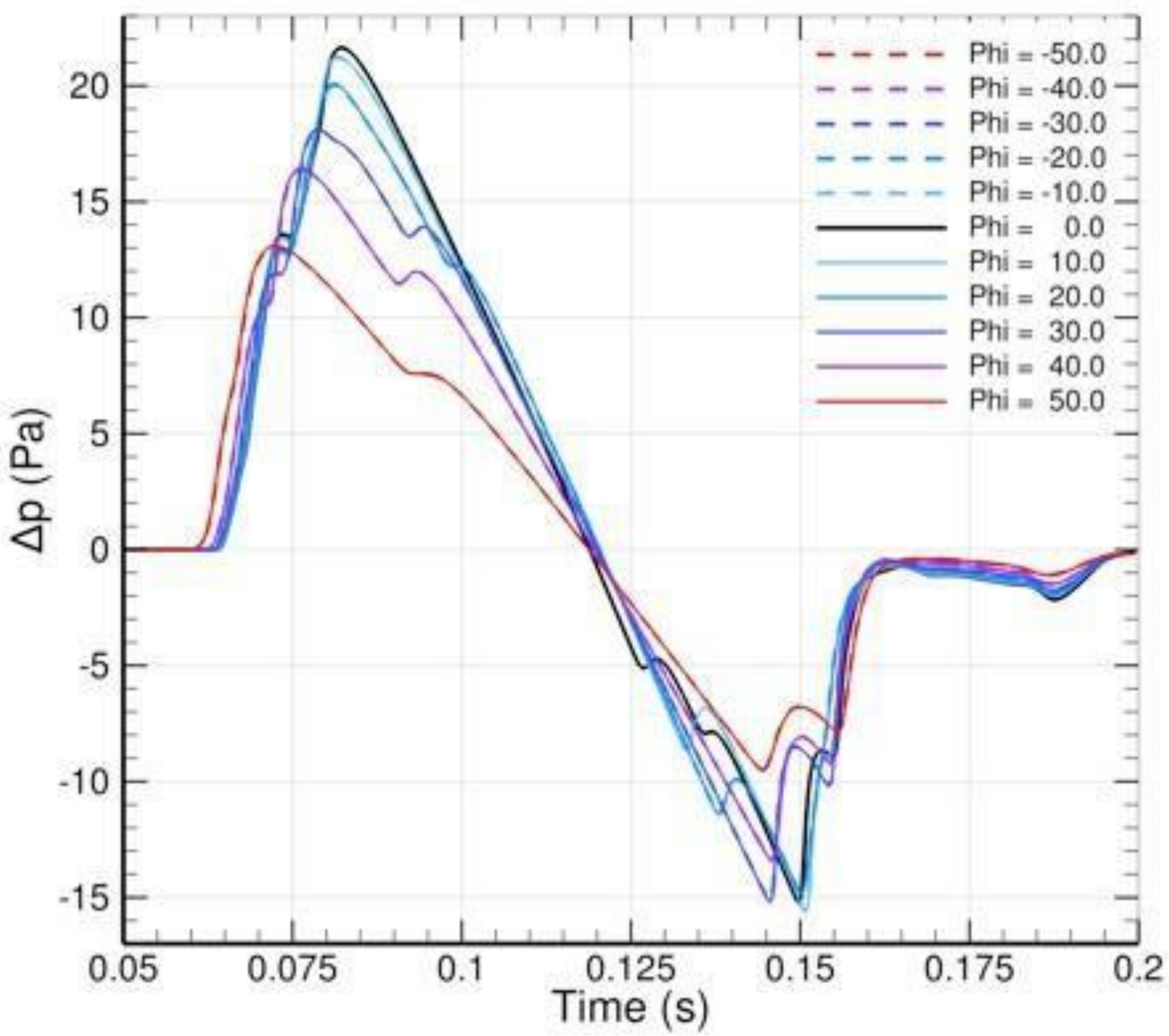
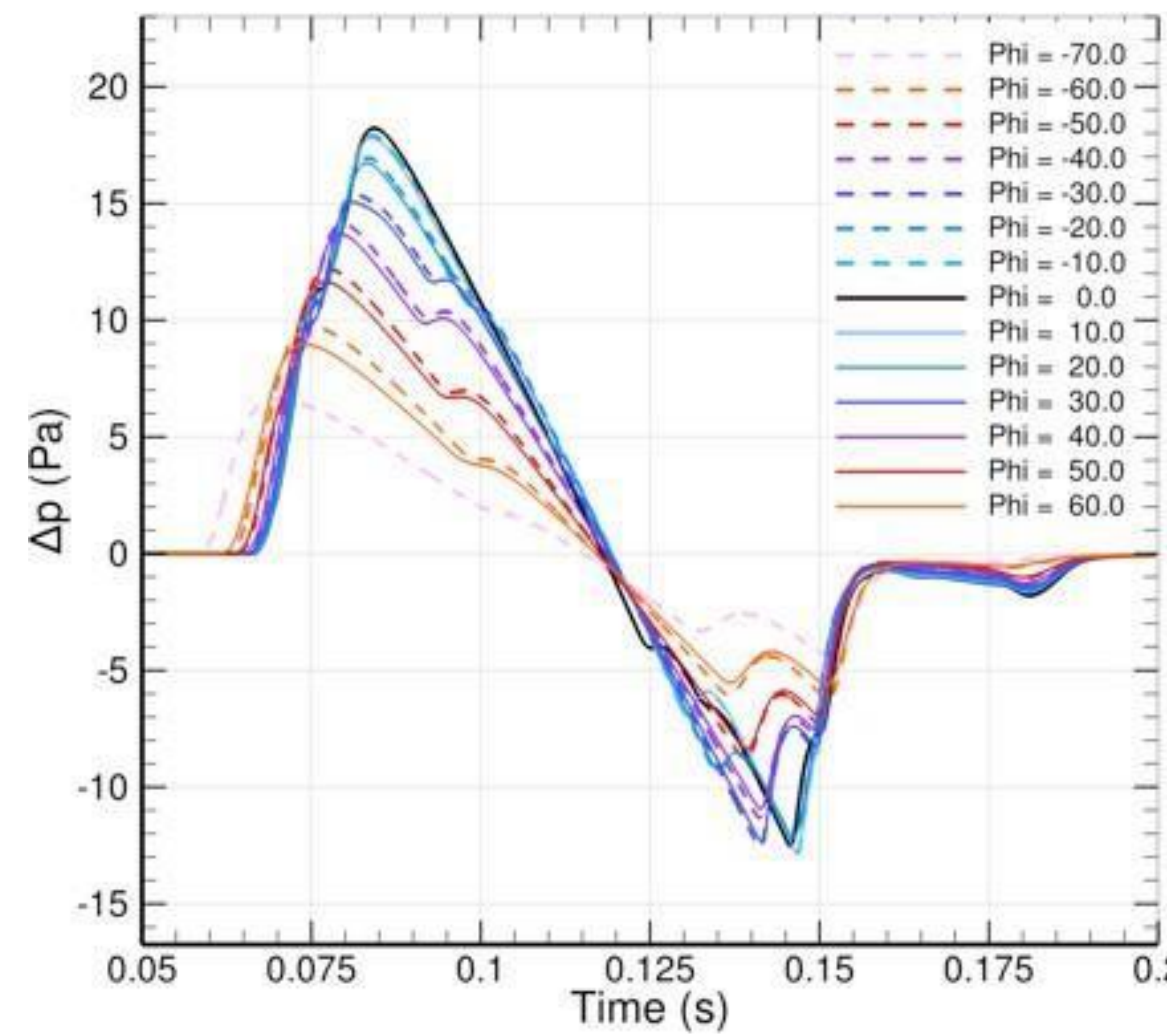
Propagation altitude = 15760m, ground height = 264m

Standard Atmosphere




Required Atmosphere

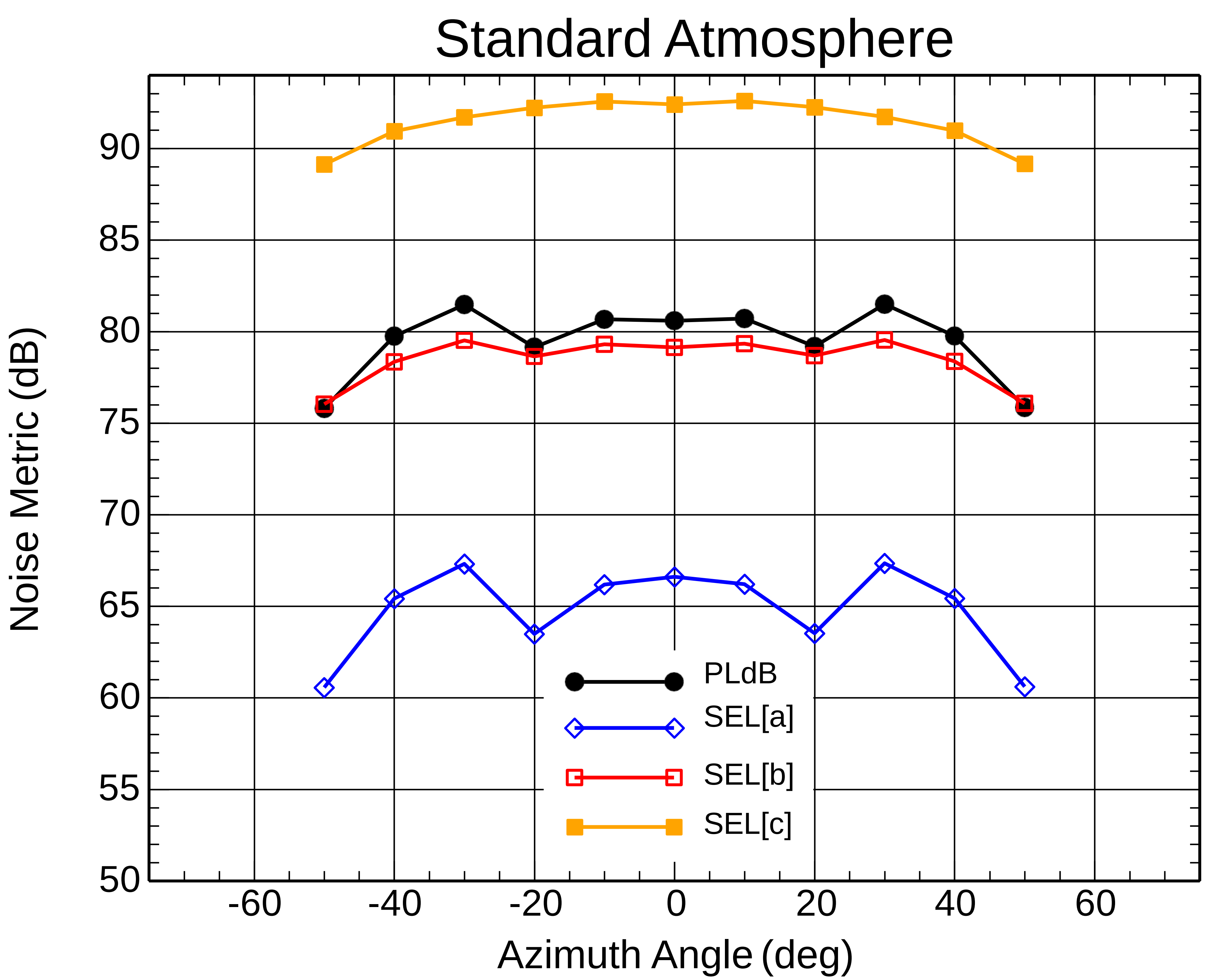


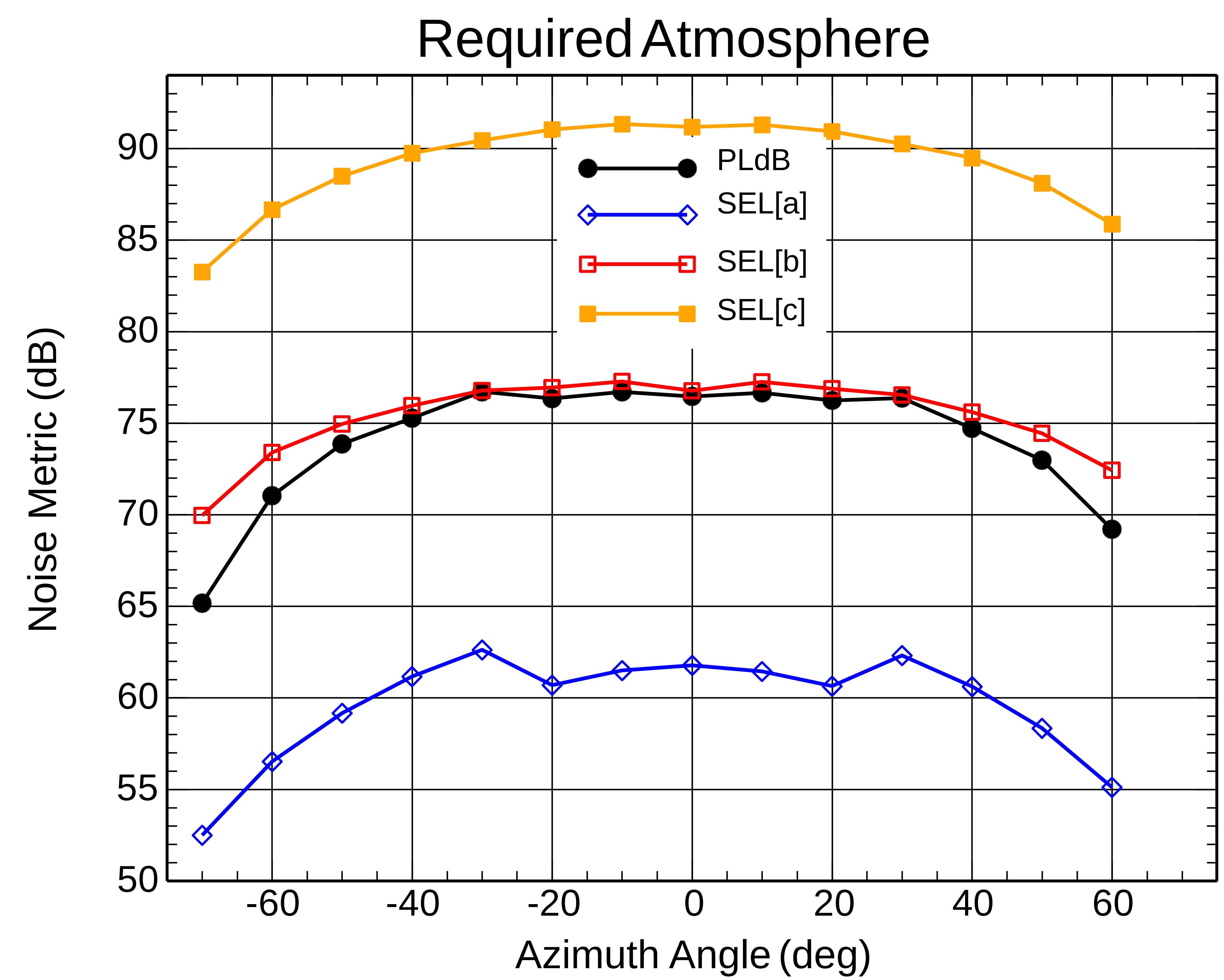

- Reqired Atm. has profiles of crosswind, temperature, humidity and pressure
  - Shows lots of asymmetry, and cutoffs are farther out on both sides

# Case 1: C25P Ground Noise

2020.03.05 ARC/TNA

Compare ground noise metrics across the carpet as a function of azimuth



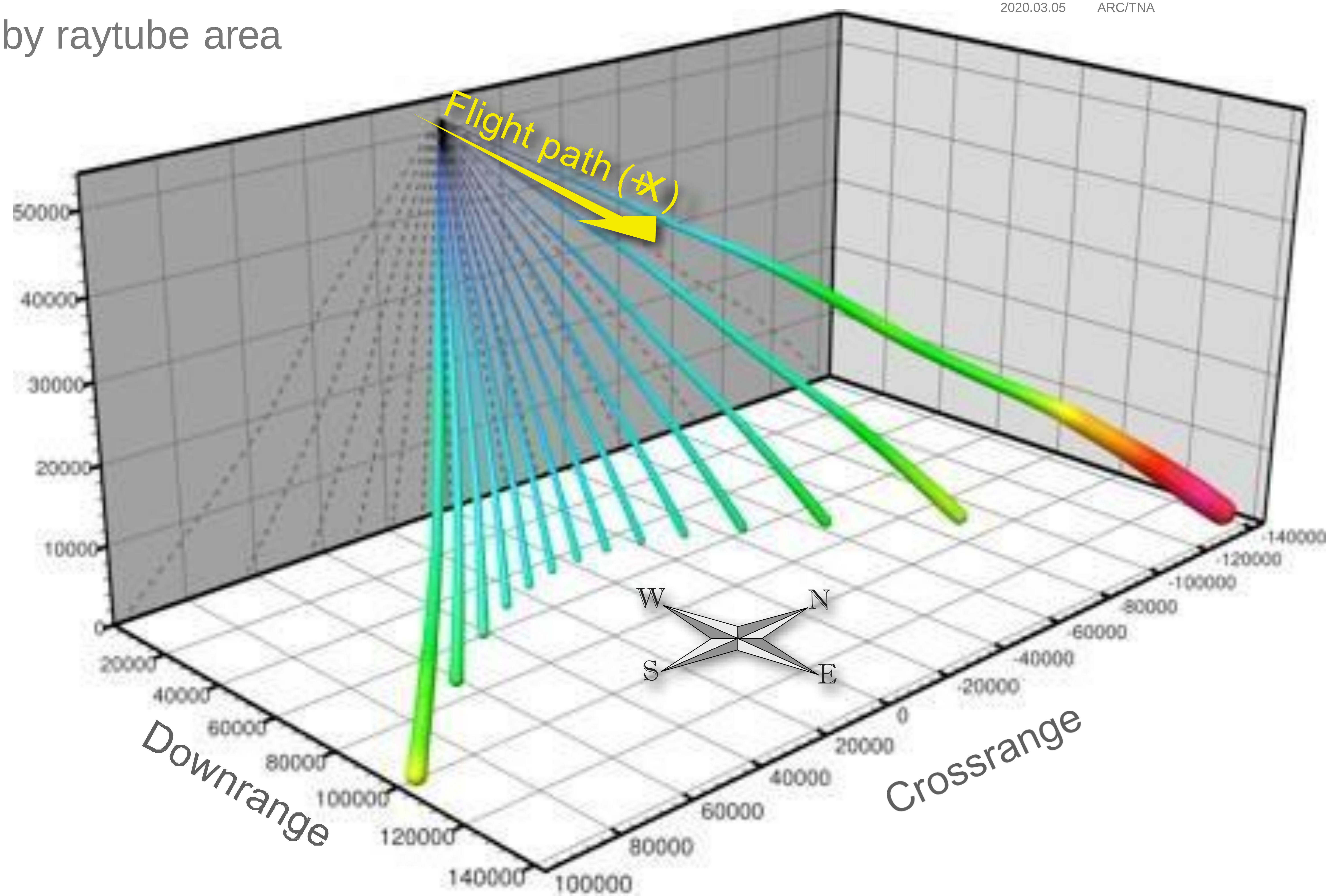

- Azimuthal range of carpet with real atm. is much wider than Standard Atm.
- Real atm. (with wind) reduces peak loudness by ~4 dBA, ~2.5 dBB, ~2 dBC & ~4 PLdB
- Noise at carpet edge drops, but can still be significant

# Case 1: C25P Raytubes for Required Atmosphere



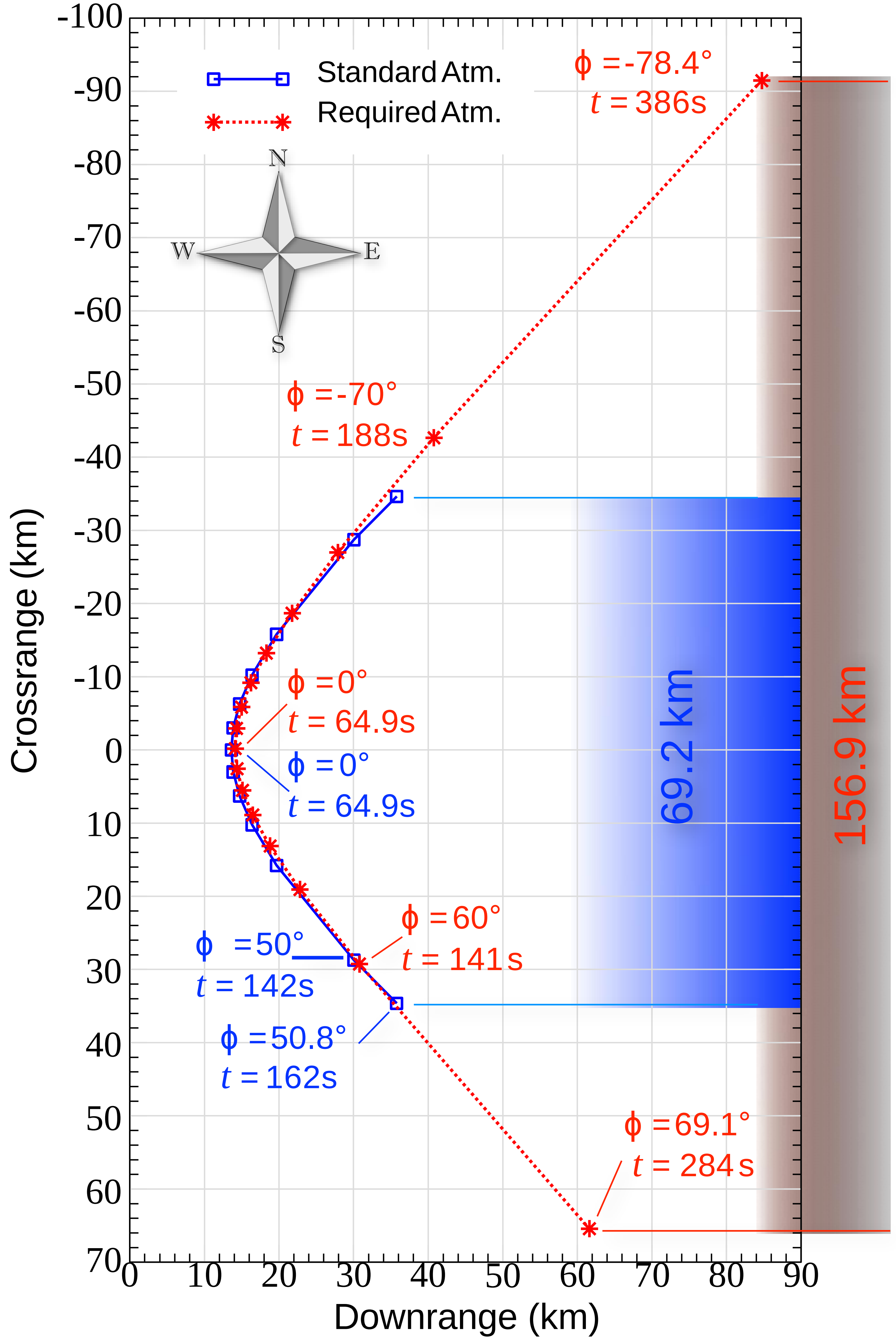
Plot 3D raytubes colored by raytube area

- 3D plot of raytubes for real atmosphere
- Shows extremely long propagation times & large raytube areas near edges of the carpet
- Near cutoff, sensitivity to atmosphere increases uncertainty in ground signal



# Case 1: C25P Ground Carpet

2020.03.05 ARC/TNA



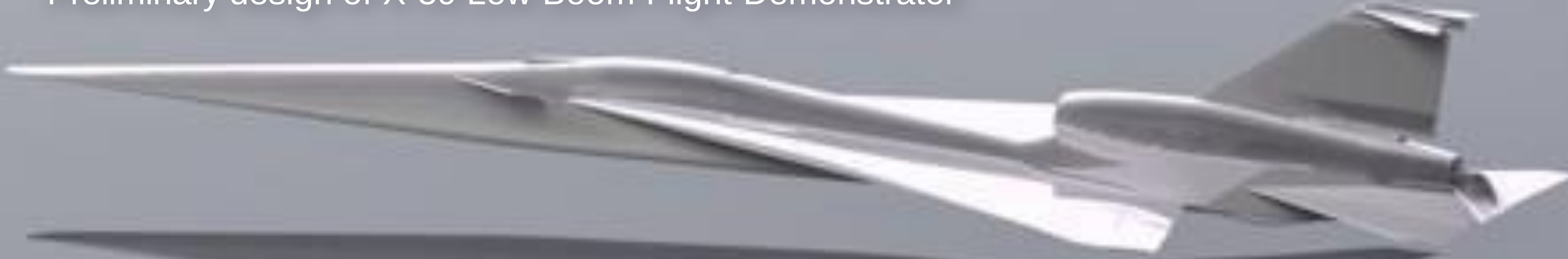

Project raytube ground intercepts on aircraft ground track

- Cutoff angles: Std. Atm = [±50.8°], Req. Atm = [-78.4°,+69.1°]
- Long propagation distances near signal cutoff imply that these raytubes take a long time to reach the ground
  – Raytube for ϕ = -78.4° takes over 6 mins in Required atm.
  – Mesh convergence near signal cutoff is not nearly as good as at low azimuth angles
  – Higher discretization error due to much longer propagation
  – Propagation for signal cutoff used higher sampling frequency (800 kHz)

# Case 2: C609

## Preliminary design of X-59 Low Boom Flight Demonstrator

2020.03.05 ARC/TNA



### Conditions:

- $M_\infty$ = 1.4
- Altitude = 16.4592 km (54k ft)
- Ground height = 110.011 m (361 ft)
- *Lref* = 27.43 m (90 ft)
- *r*/*L* = 3 at signal extraction
- Ground reflection factor = 1.9
- Heading East (β = 0°)

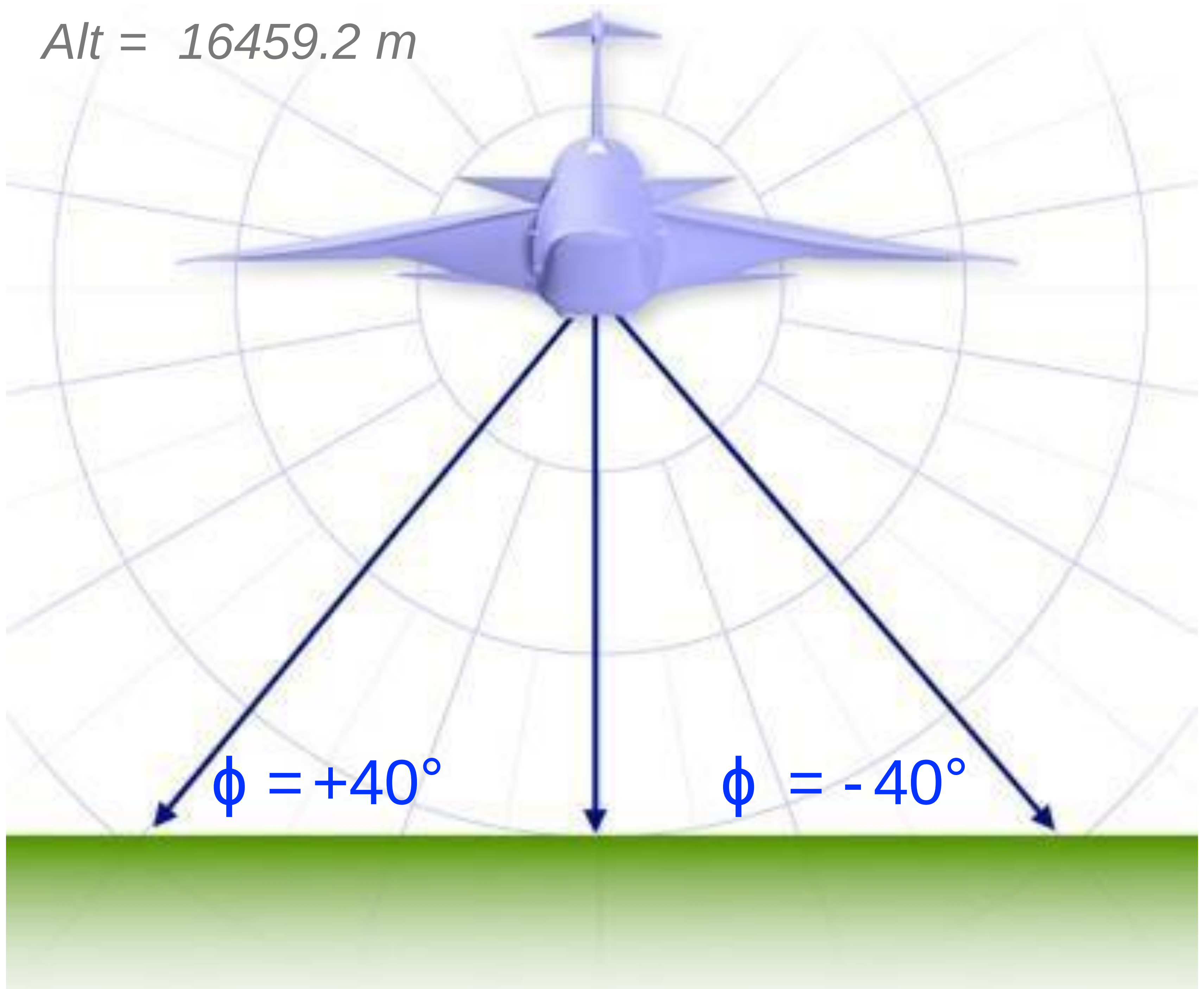
### Atmospheric Profiles:

1. Required Atm: with profiles for wind, temp, pressure & humidity
2. Standard Atmosphere

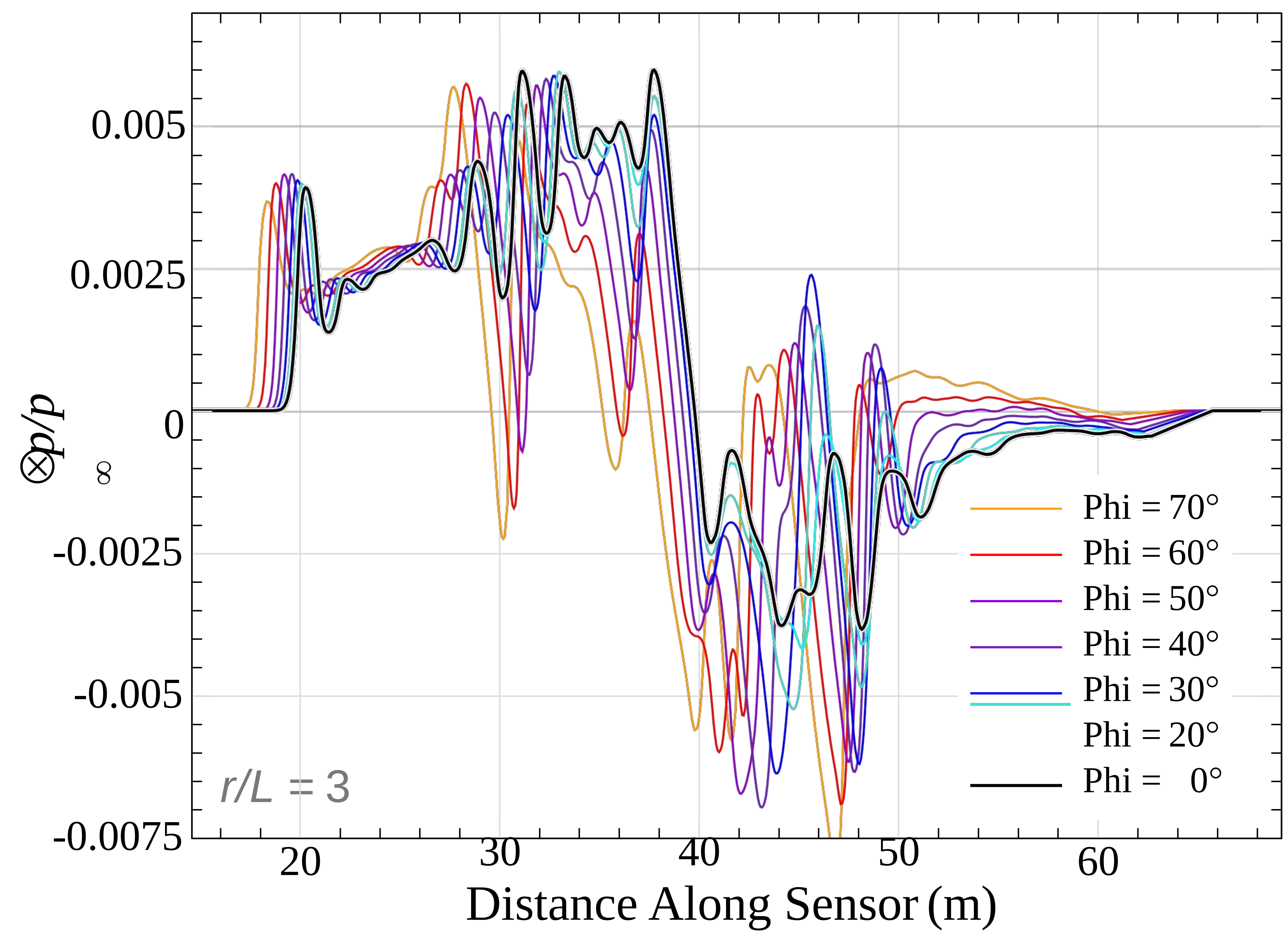
# Case 2: C609 Near Field Signals



Sign Convention for Azimuth, ϕ




Subset of Near Field Signals

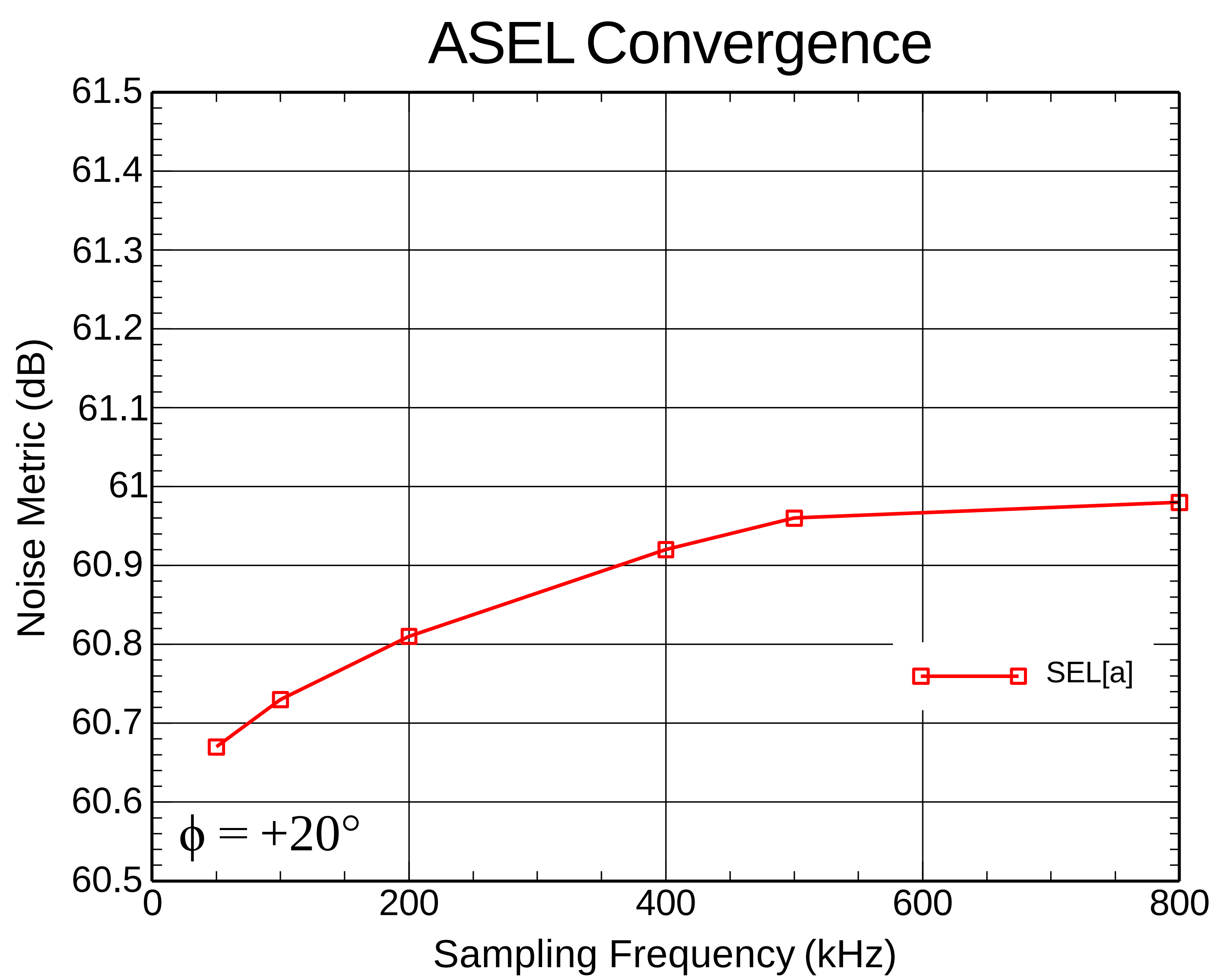


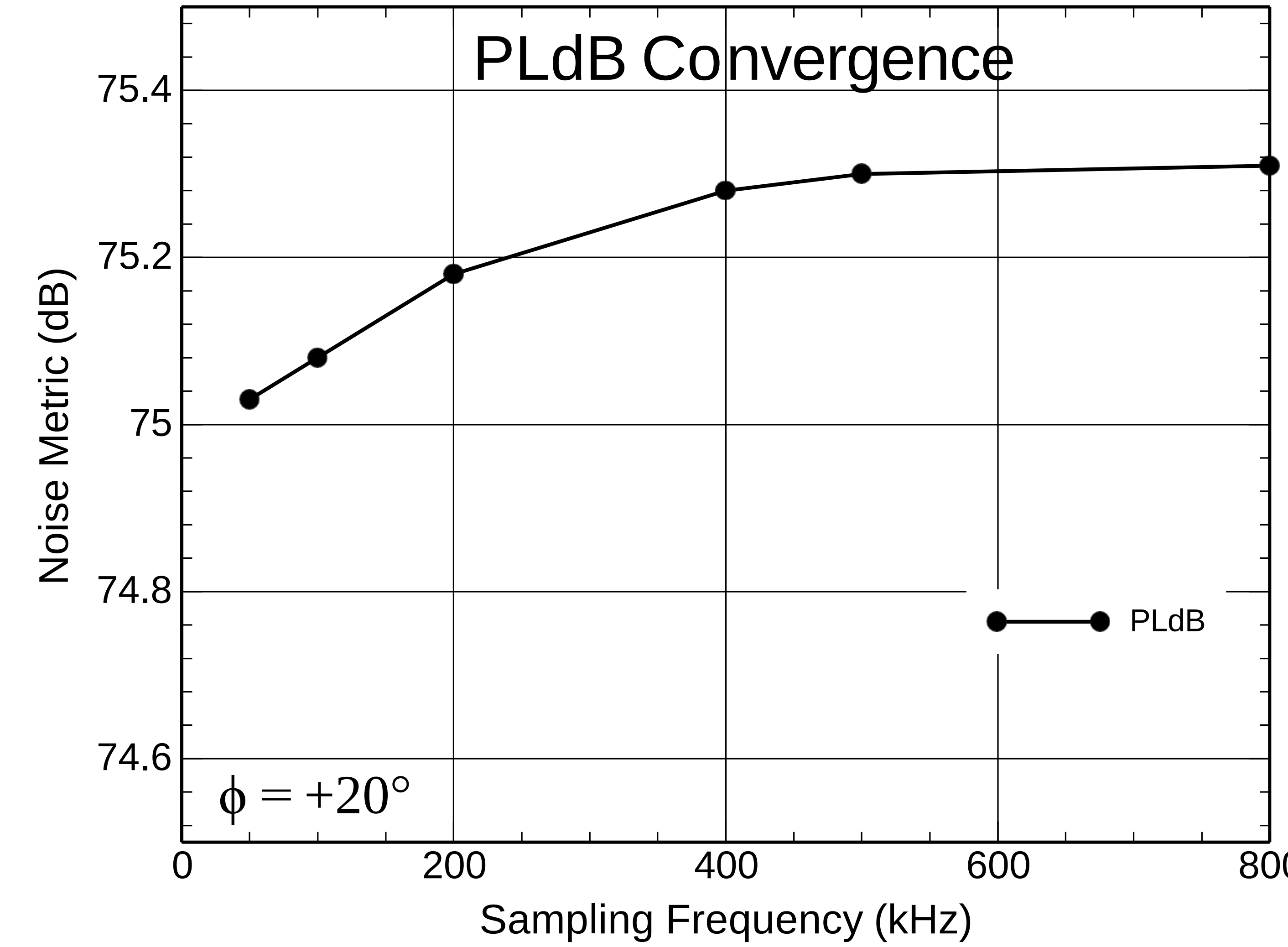

- Near field signals provided for 23 azimuths from -70° to +70°
  ϕ = [0, ±10, ±20, ±30, ±40, ±50, ±60, ±62, ±64, ±66, ±68, ±70]
- Signals symmetric ±ϕ

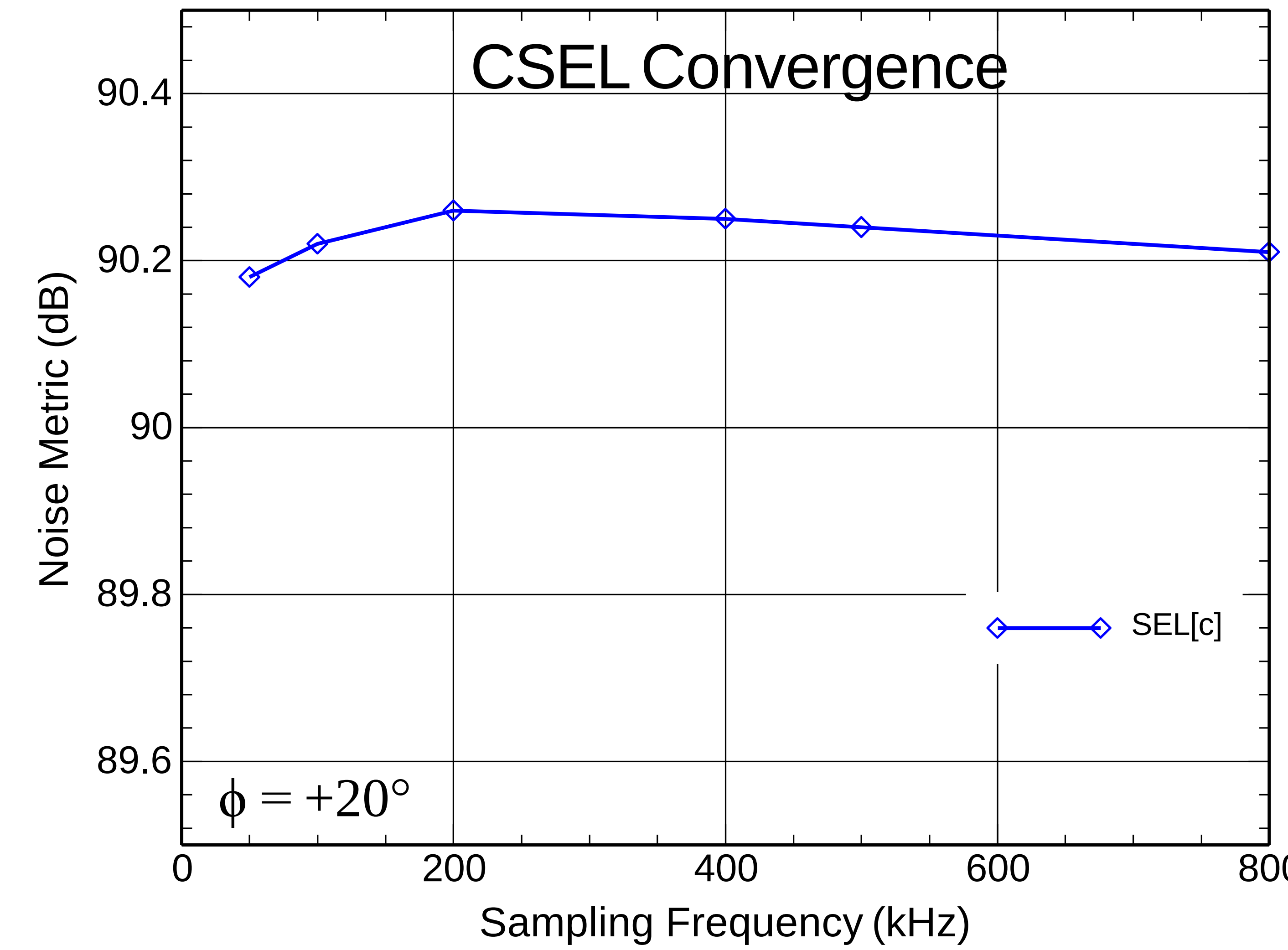
# Case 2: C609 Sampling Frequency



## Metric convergence with sampling frequency (Std. Atm.)



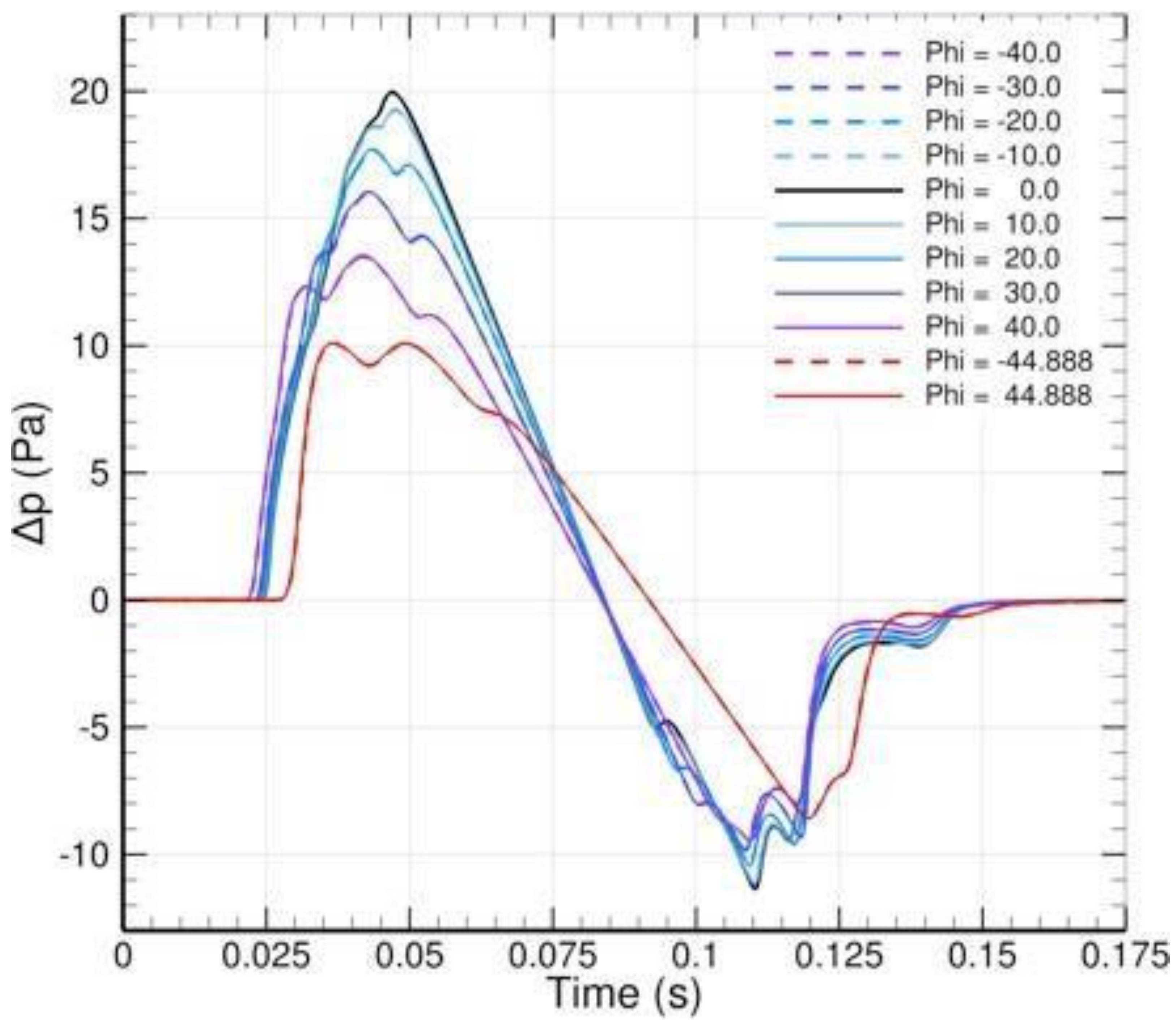

- Using FFT for metric computation get reasonable mesh convergence of ASEL, CSEL and PLdB by 500kHz.
- Discrete BSEL filter appears well behaved as well
- Similar mesh convergence behavior for other azimuths. Used 500kHz sampling frequency away from cutoff.

# Case 2: C609 Ground Signals

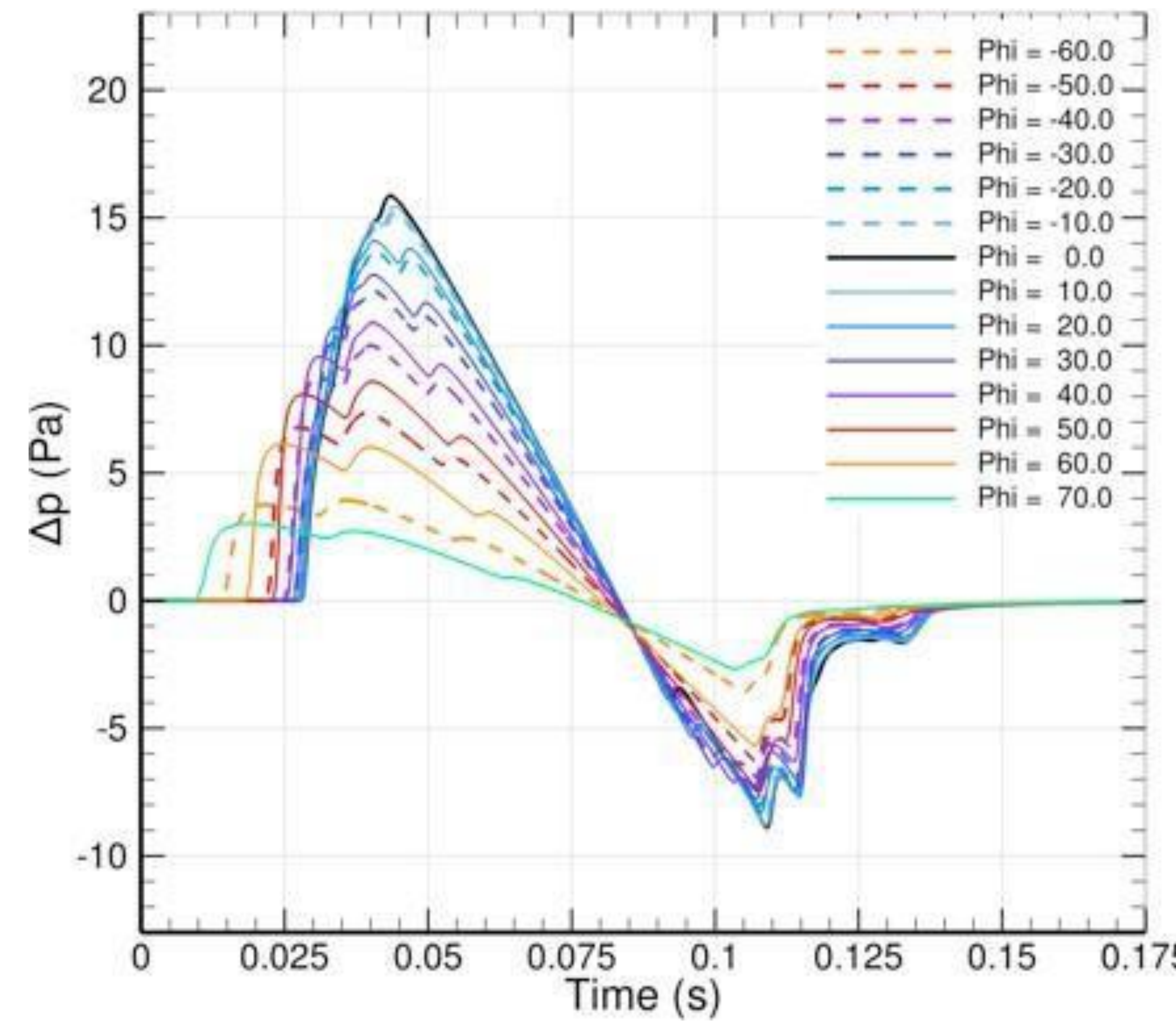


Propagation altitude = 16460m, ground elevation = 110m

Standard Atmosphere




Required Atmosphere

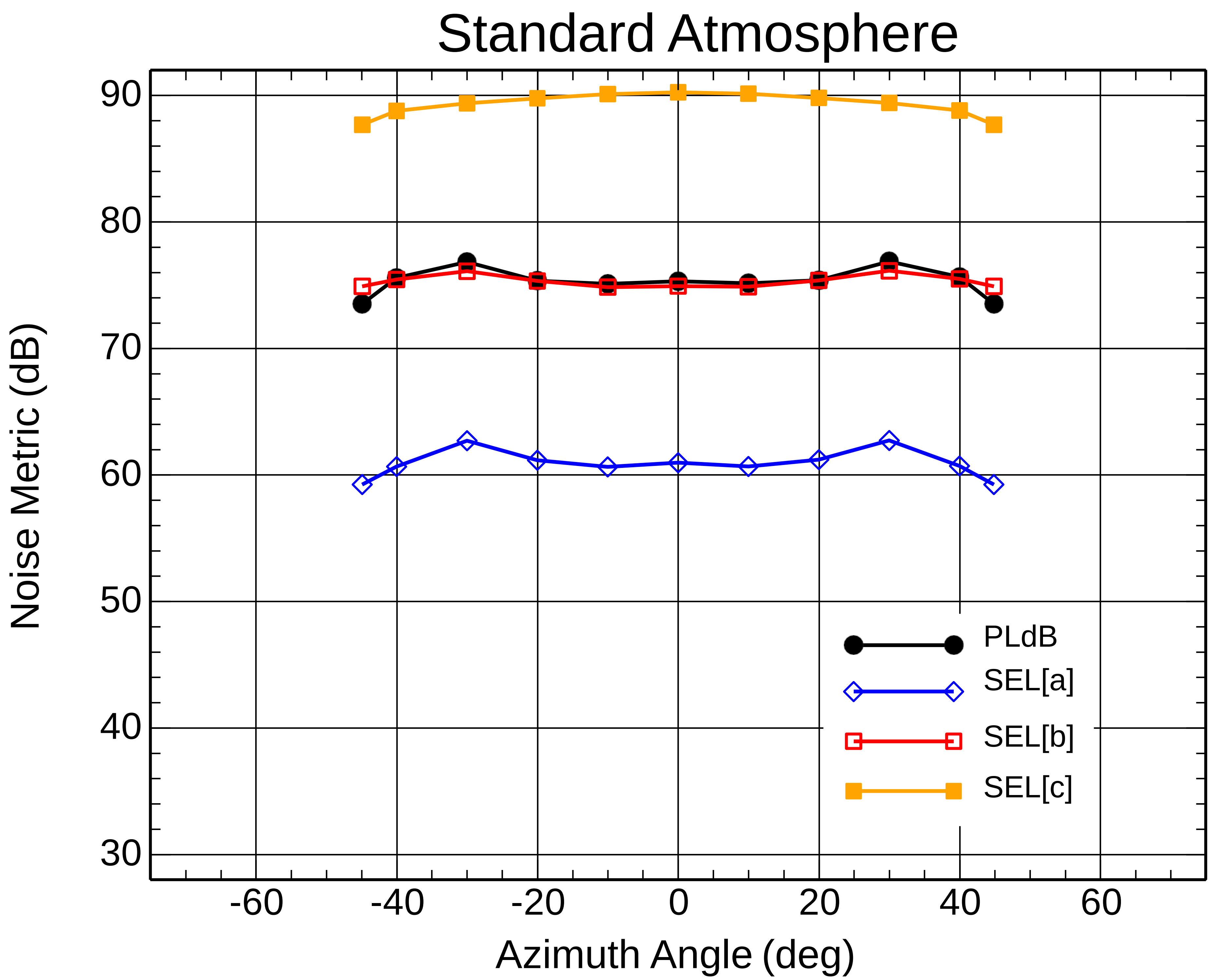


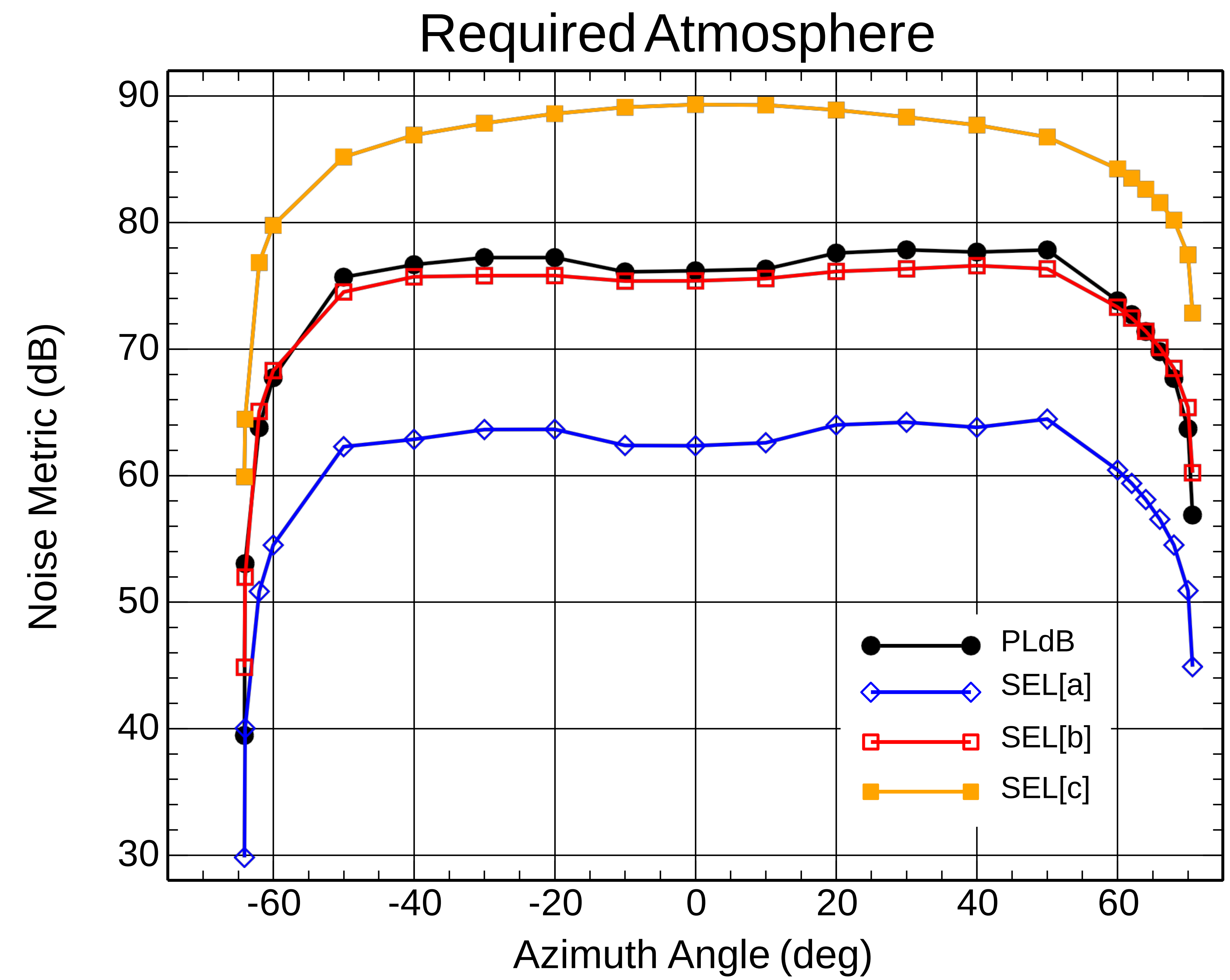

- Required Atm. includes profiles of crosswind, temperature, humidity and pressure
  - Very asymmetric, with much wider cutoffs on both sides
- Amplitude of ground signal in real atmosphere significantly reduced from Std. Atm.

# Case 2: C609 Ground Noise



Compare ground noise metrics across the carpet as a function of azimuth



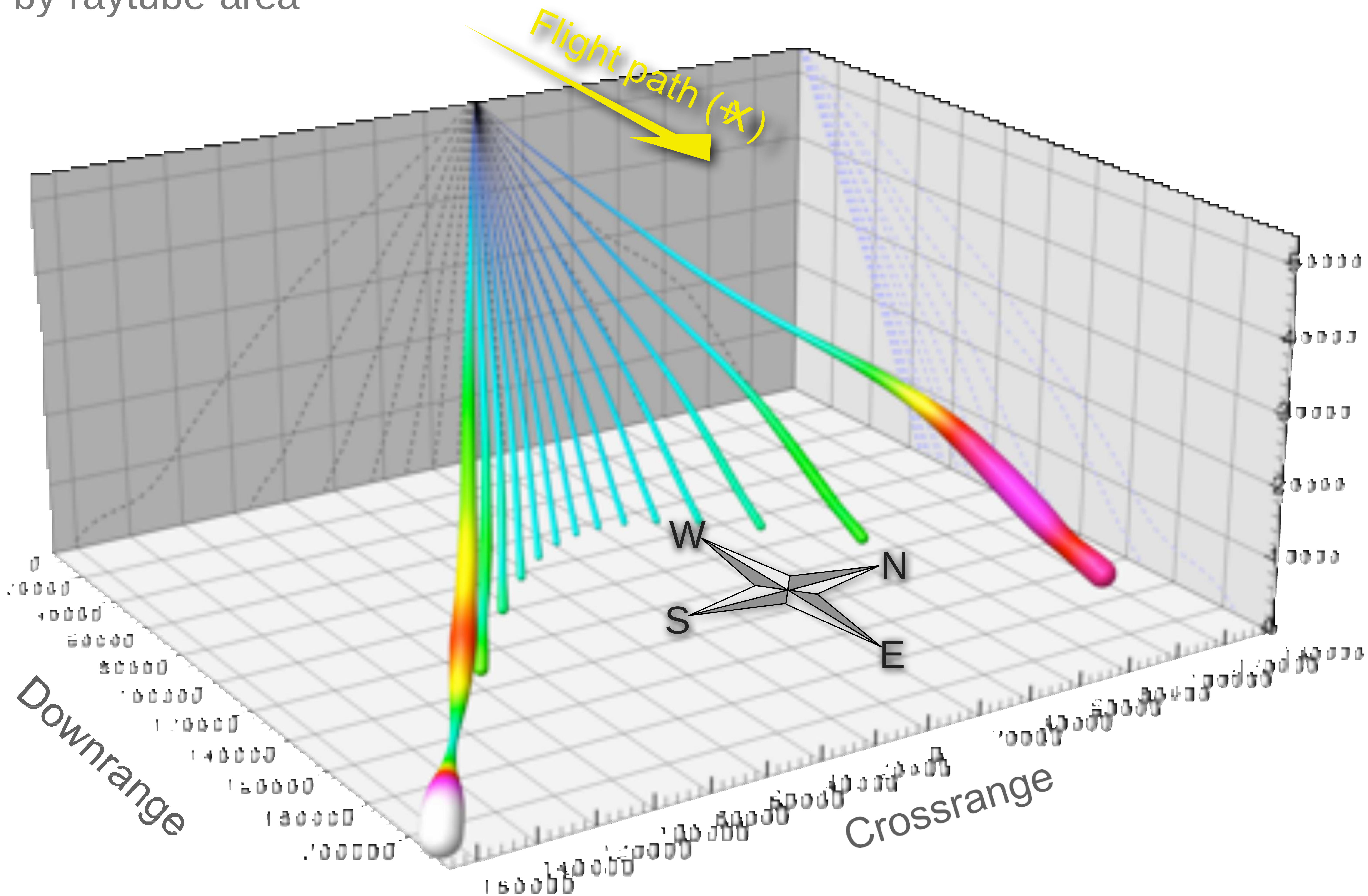

- Azimuthal range of carpet with Required Atm. is much wider than Standard Atm.
- Despite wind & reduced ground amplitude, Real Atm. and Std. Atm. have similar loudness
- Noise at carpet edge drops significantly in Required Atm.

# Case 2: C609 Raytubes for Required Atmosphere



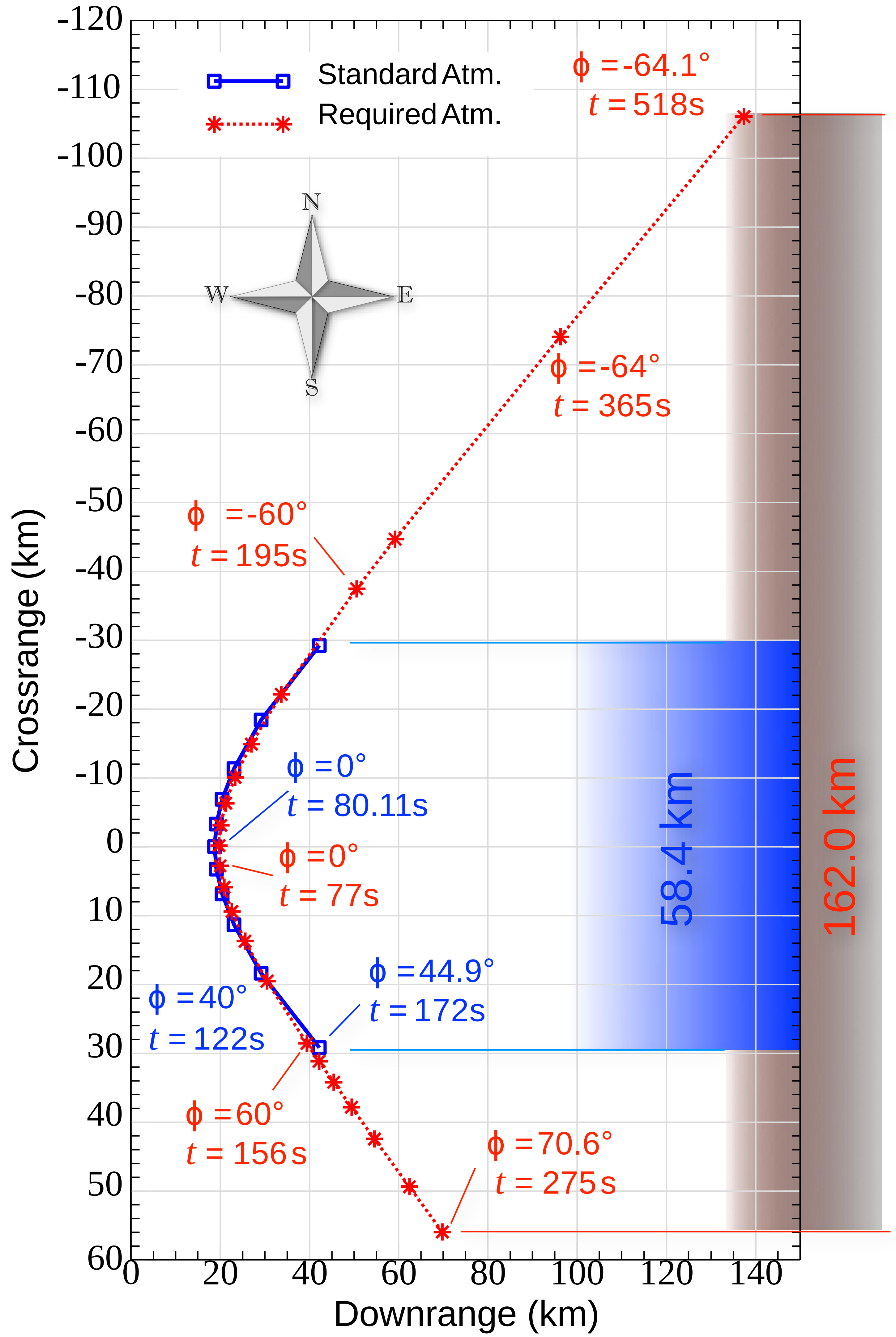
Plot 3D raytubes colored by raytube area

- 3D plot of raytubes for real atmosphere
- Shows extremely long propagation times & large raytube areas near edges of the carpet
- Near cutoff, sensitivity to atmosphere increases uncertainty in ground signal



# Case 2: C609 Ground Carpet






Project raytube ground intercepts on aircraft ground track

- Cutoff angles Req. Atm = [-64.1°, 70.6°], Std. Atm = [±44.9°]
- Long propagation distances near signal cutoff imply that these raytubes take a long time to reach the ground
  - Raytube for ϕ = -64.1° cutoff takes over 8.5 mins in Reqd. atm.
  - Mesh convergence near signal cutoff is not nearly as good as at low azimuth angles
  - Higher discretization error due to much longer propagation
  - Propagation for signal cutoff rays used higher sampling frequency (800 kHz)

# Summary

2020.03.05 ARC/TNA

- Applied sBOOM v2.82 & LCASB to all required and optional steady propagation cases
- Mesh convergence studies across the carpet to ensure accuracy of the ground signal and loudness metrics. Error in noise metrics can be 2-4x higher near signal cutoff.
- Mesh convergence is relatively slow on intricate non-smooth input signals
- Real atmosphere is *usually* quieter than Standard Atmosphere, (but not always - *e.g.* case 2)
- Ground track of real atmosphere can be nearly 3x wider than Standard day. Crosswinds generally increase track width and can result in large cutoff azimuths
- On windy days, boom may not arrive off-track for over 5 mins after a/c passes (case 2 took 8 mins!)
- Raytube visualization shows potential for loud off-track azimuths to be blown back under-track

# SBPW3 Highlights

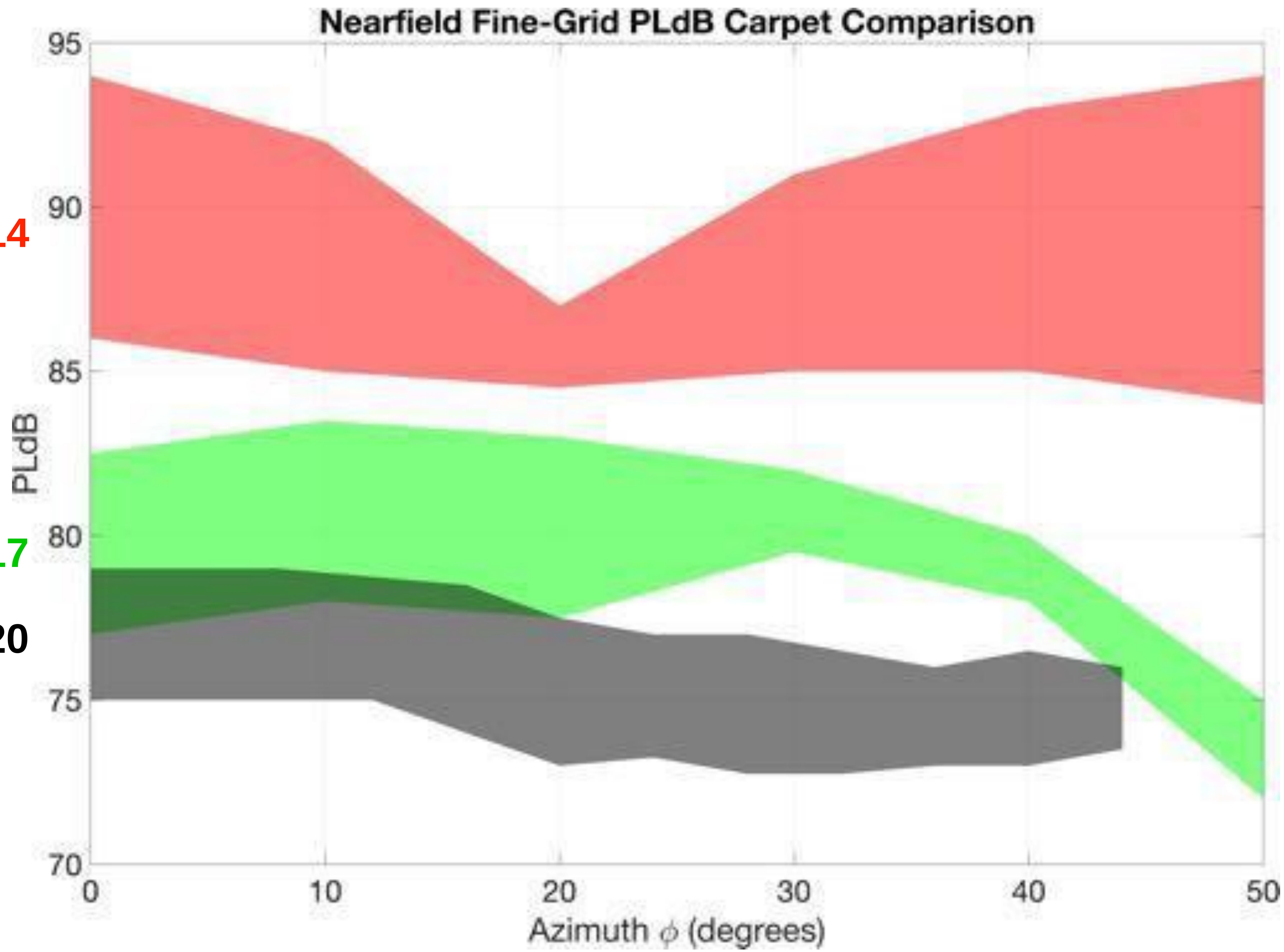
- Nearfield CFD
  - Overall, very good agreement among participants
  - Interesting to see clusters of results for adapted grids and workshop-provided grids
  - Progression from first workshop to now
- Propagation
  - More exposure (pun intended!) to propagation methods and noise metric calculations
  - Ray paths, cutoff angles, and underneath carpets agreed well
  - More variation past ±20°, more challenging out toward edges of boom carpet

# SBPW3 Highlights

SBPW1 2014

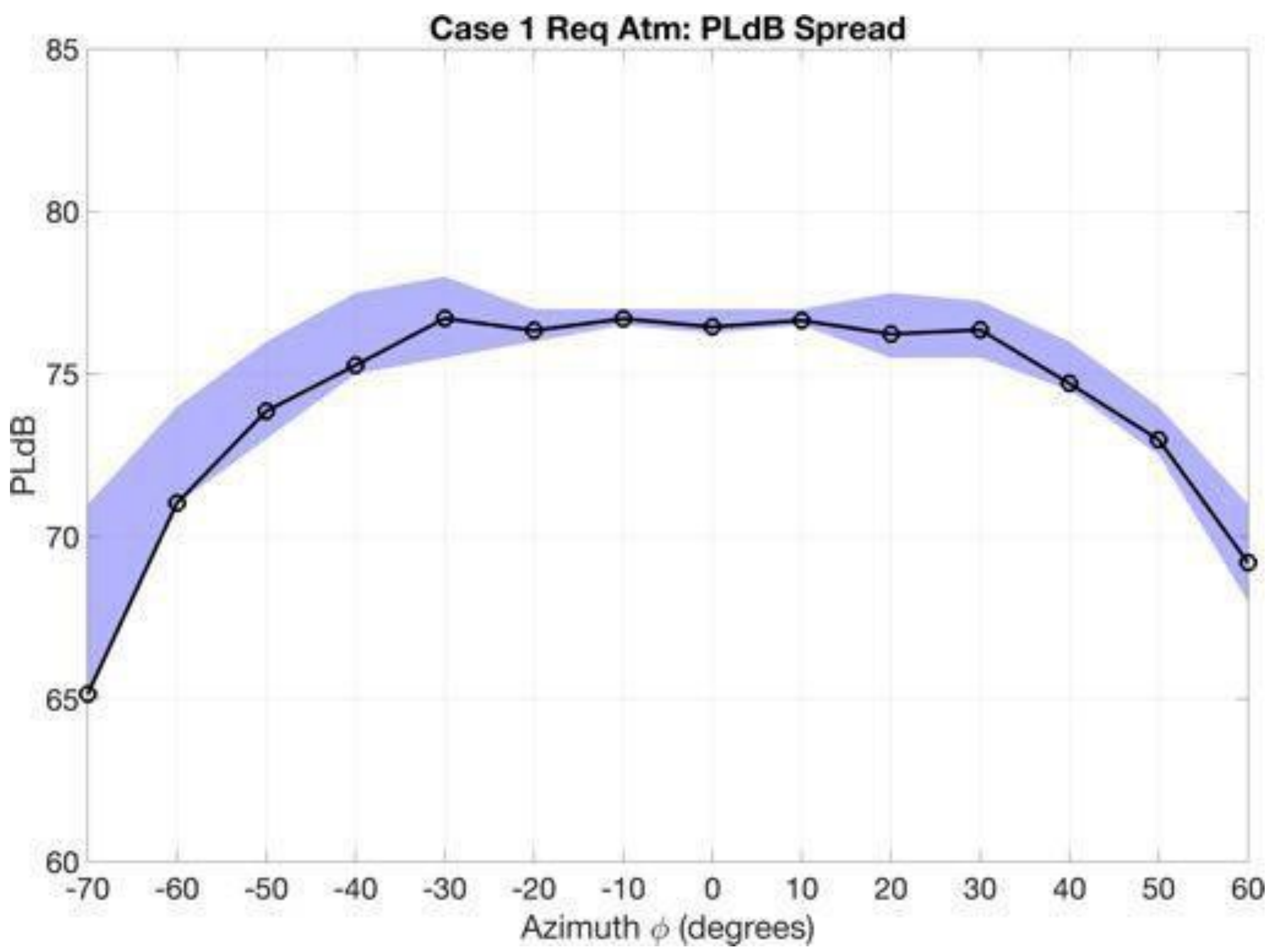
SBPW2 2017

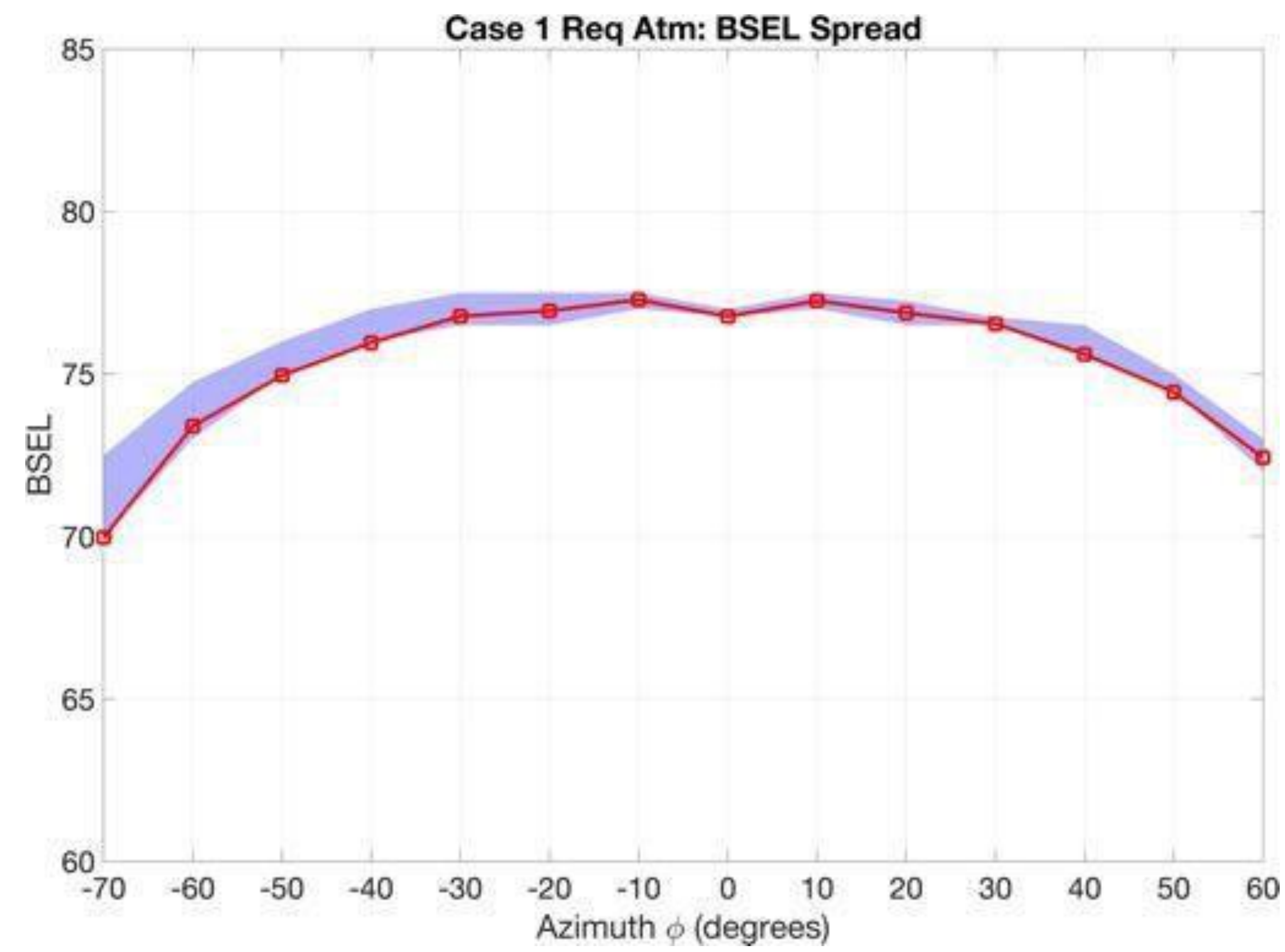
SBPW3 2020



# SBPW3 Highlights

- Our results (lines/symbols) and spread over workshop submissions (shaded)



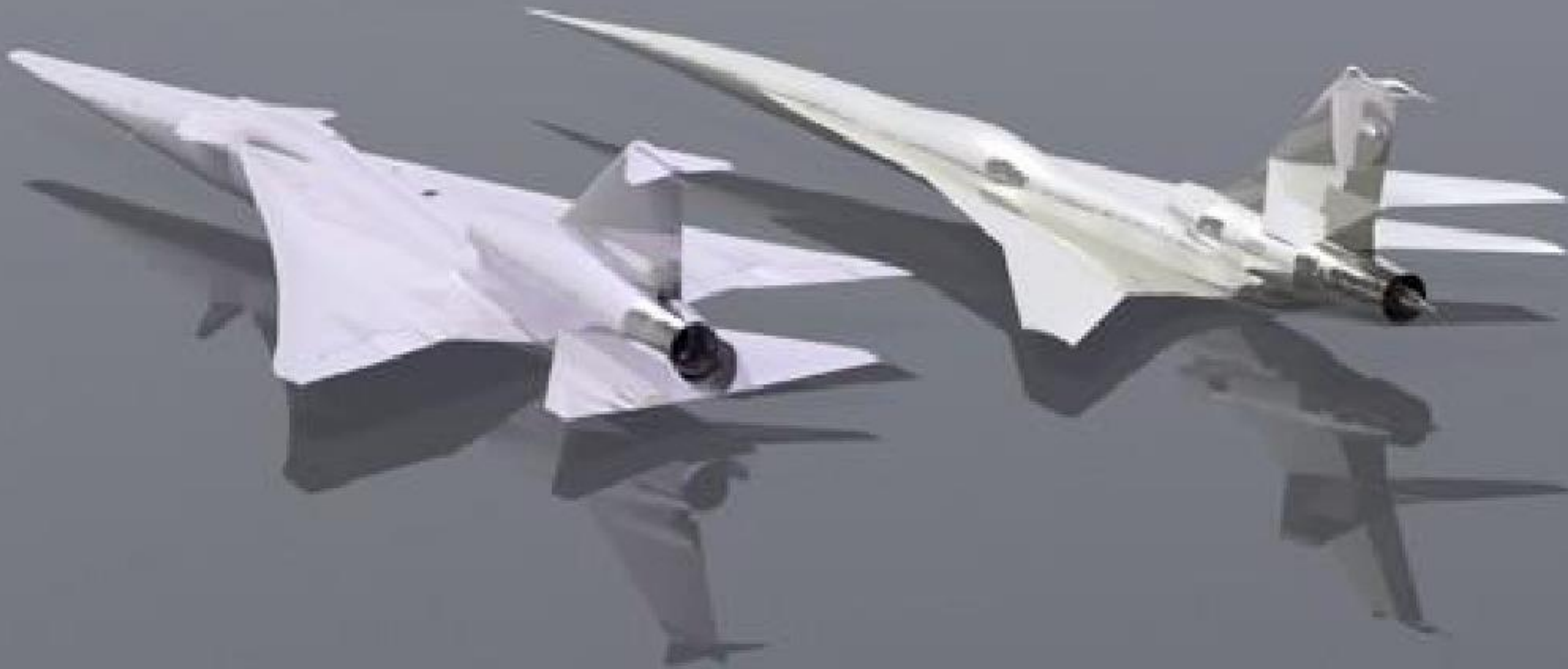



# Acknowledgements




- Thanks to James Jensen for surface triangulation of workshop C608 geometry
- Thanks to Sriram Rallabhandi for developing and supporting sBOOM, and to Marian Nemec and David Rodriguez for technical discussions on the various cases
- SBPW3 organizers for their effort in organizing and coordinating the workshop, particularly Melissa Carter, Sriram Rallabhandi, and Mike Park
- ARMD Commercial Supersonic Technology Project for support of this work and advancing the state of the art in boom prediction over the last decade
- NASA Advanced Supercomputing Division for providing computing resources
- NASA Ames Research Center contract NNA16BD60 and Science & Technology Corp. for supporting Wade Spurlock’s involvement

# Questions?

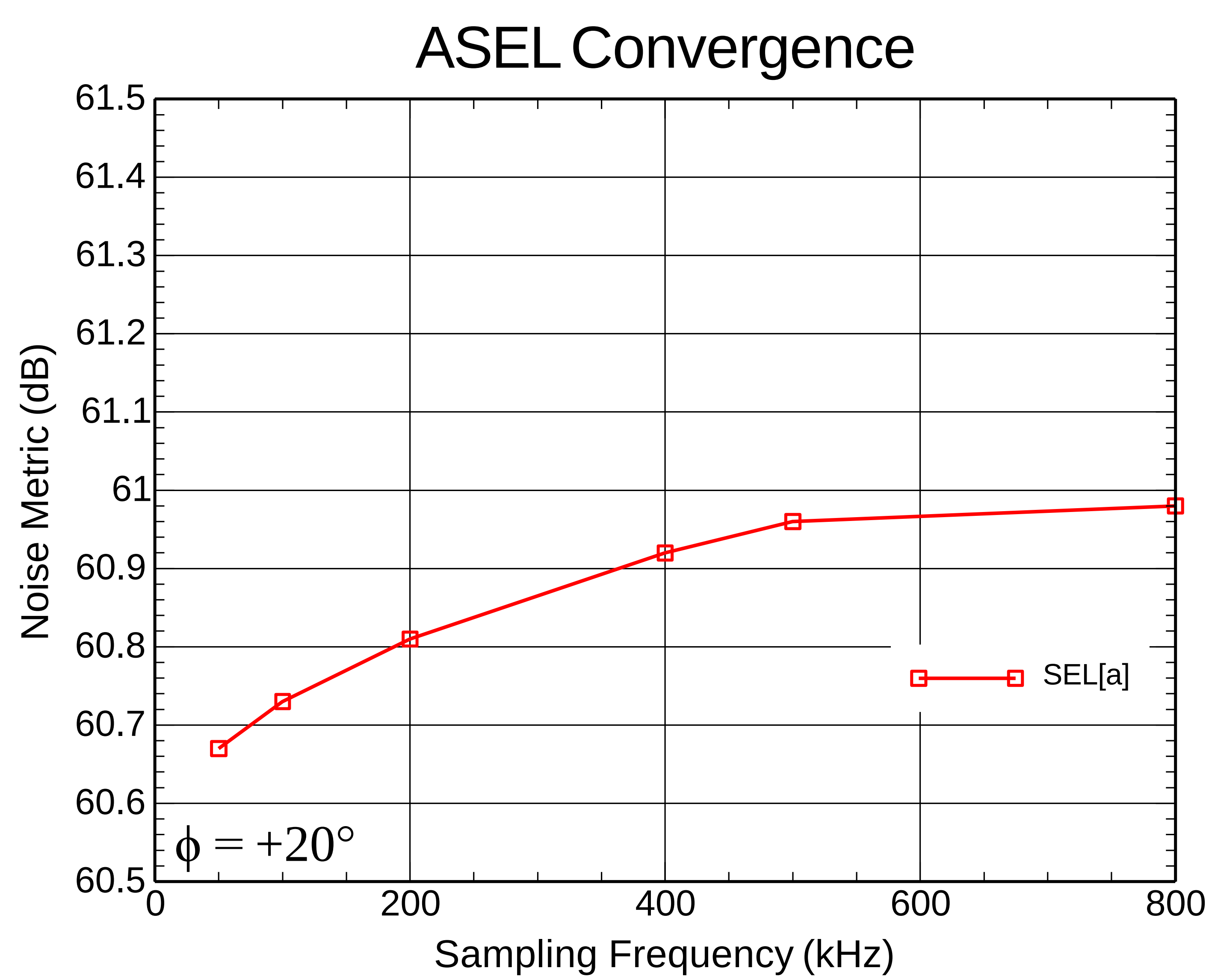


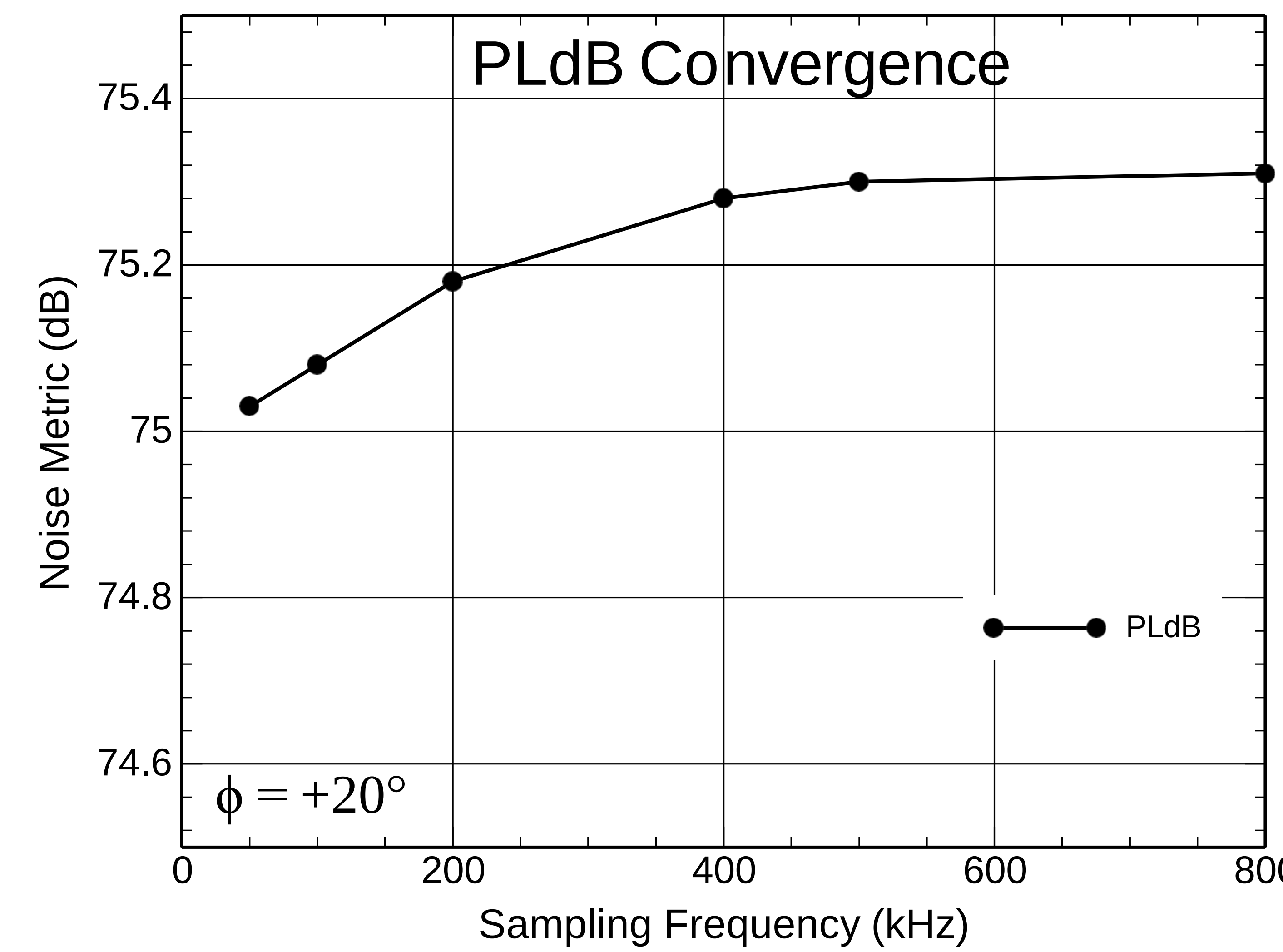
# Backup

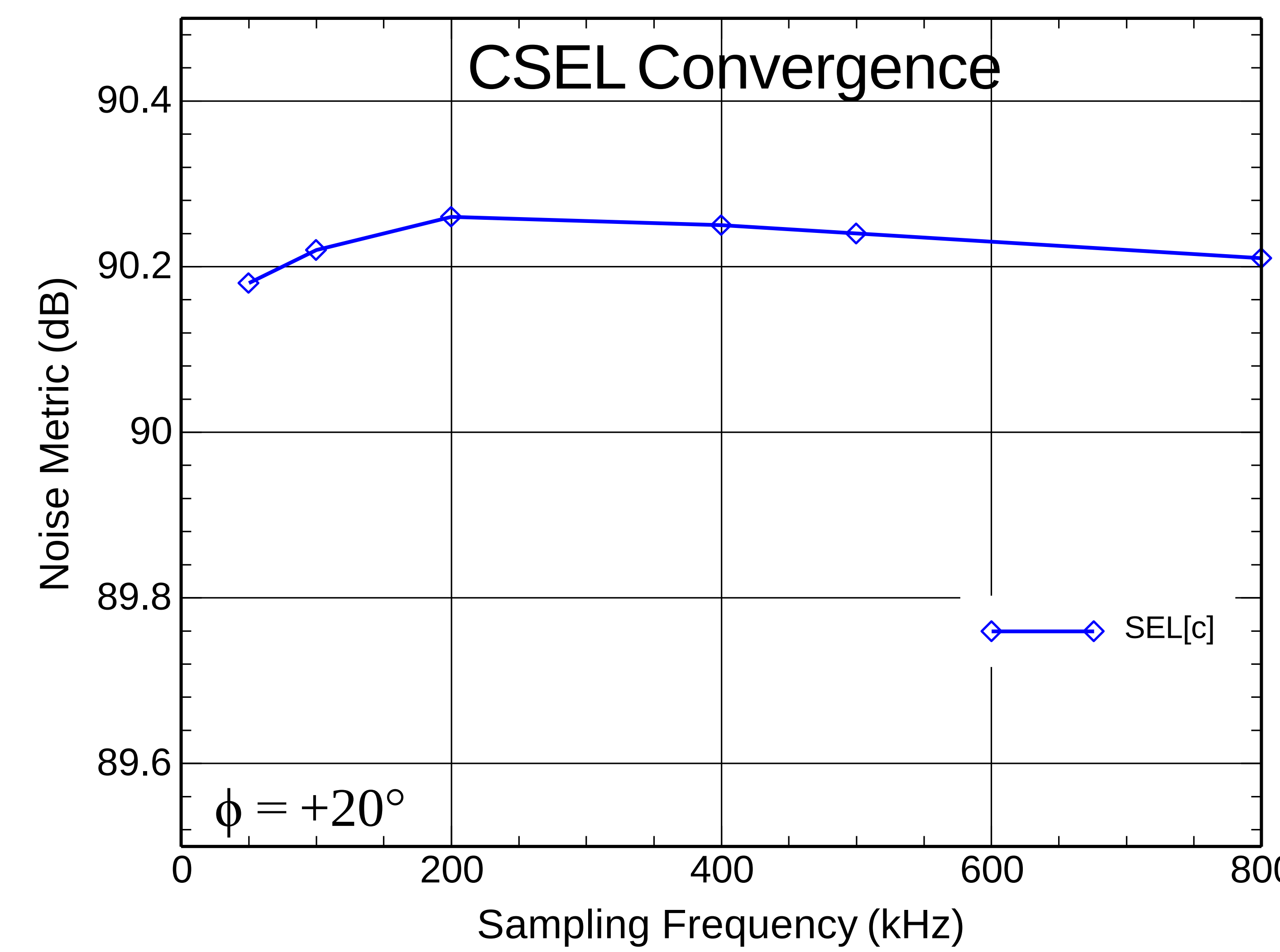
# Case 2: C609 Sampling Frequency



## Metric convergence with sampling frequency (Std. Atm.)



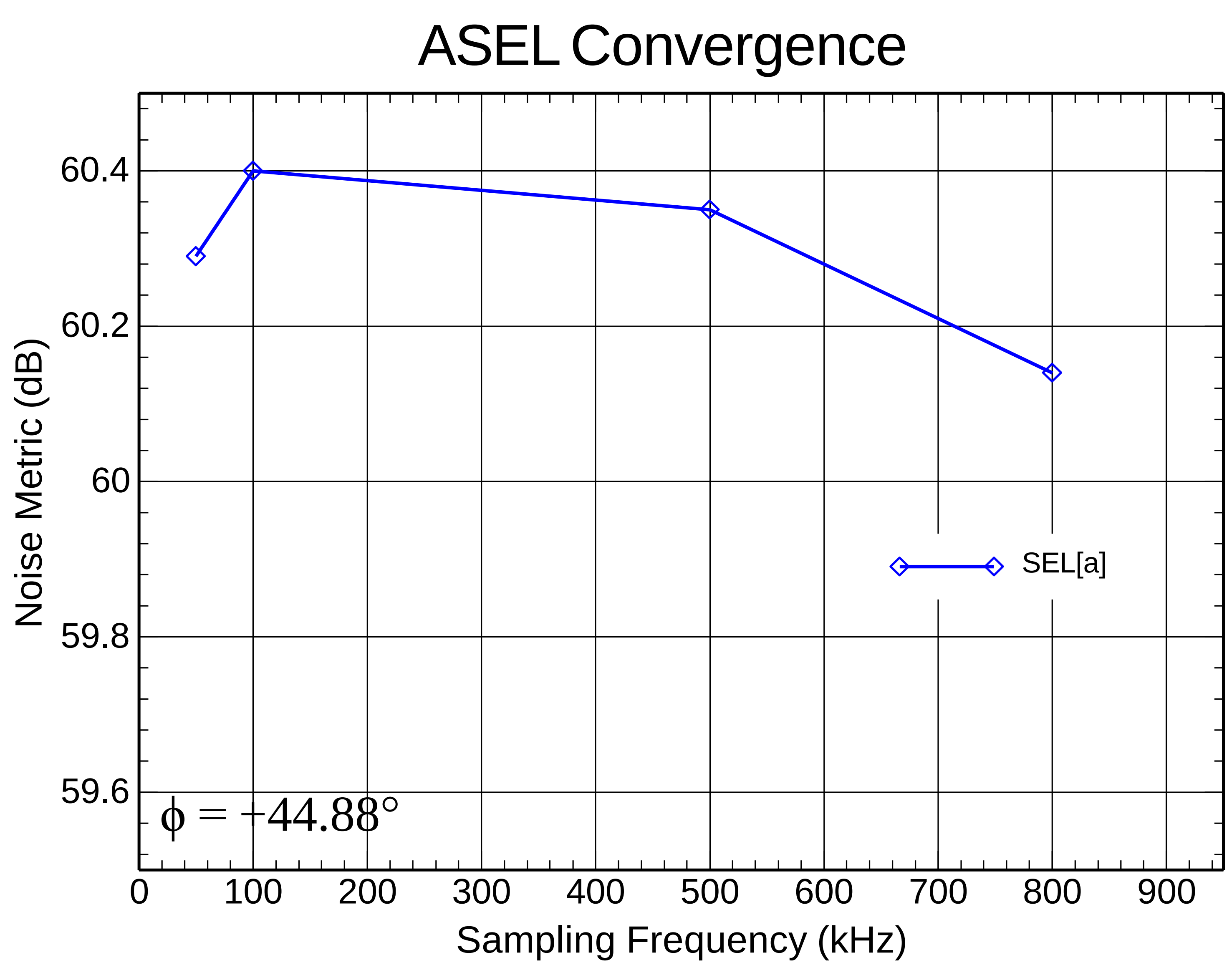



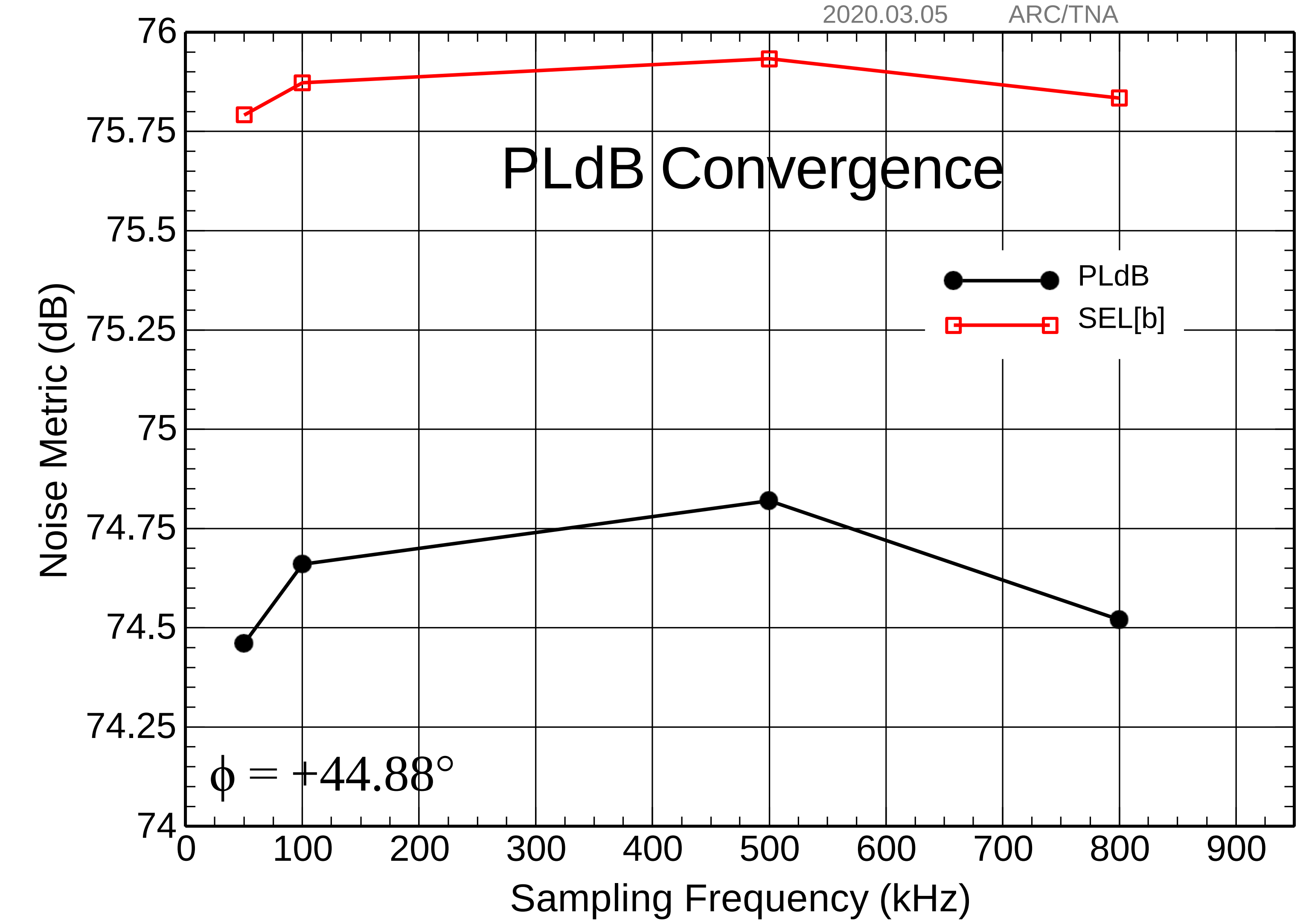

- Using FFT for metric computation get reasonable mesh convergence of ASEL, CSEL and PLdB by 500kHz.
- Discrete BSEL filter appears well behaved as well
- Similar mesh convergence behavior for other azimuths. Used 500kHz sampling frequency away from cutoff.

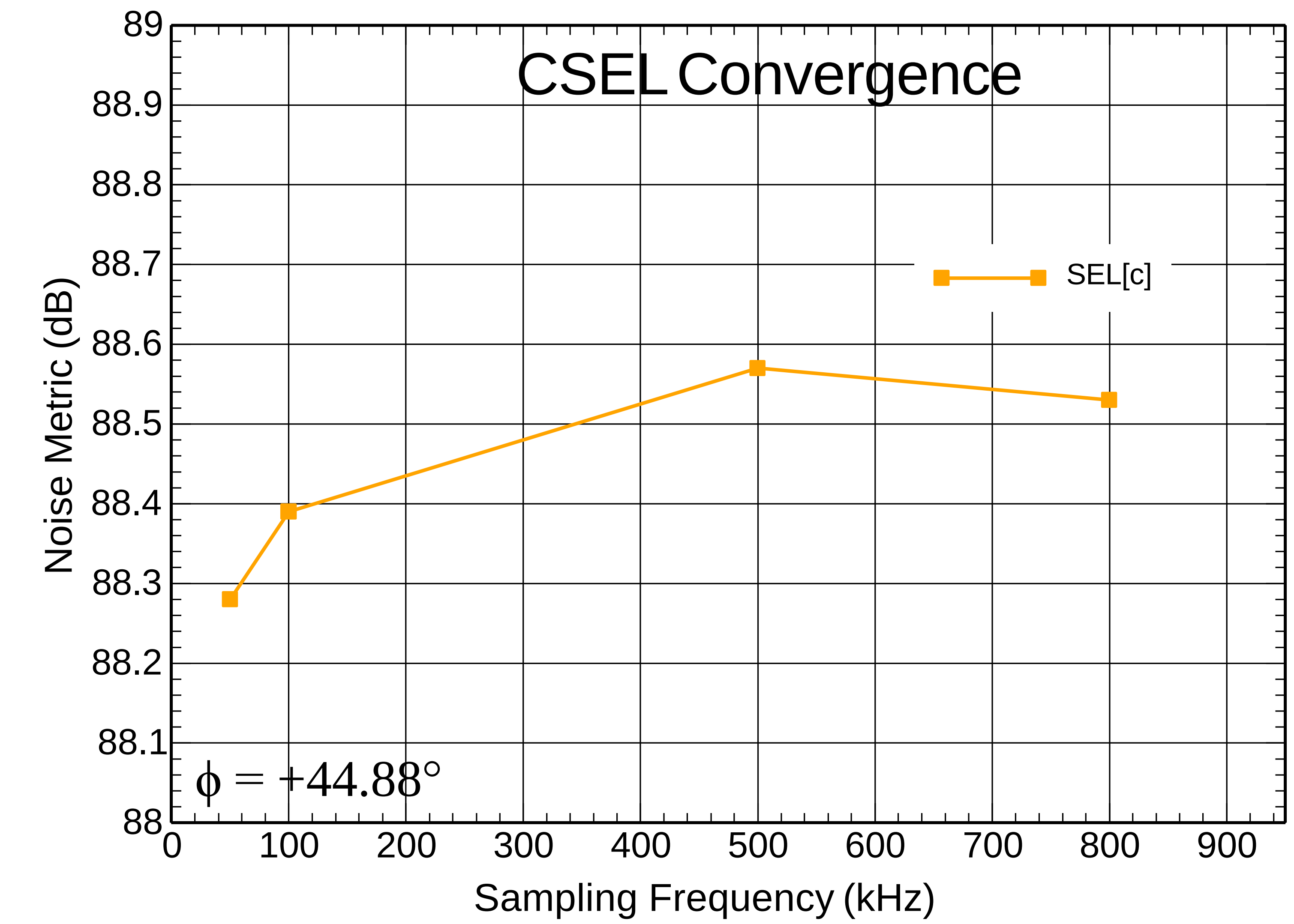
# Case 2: C609 Sampling Frequency



## Metric convergence with sampling frequency



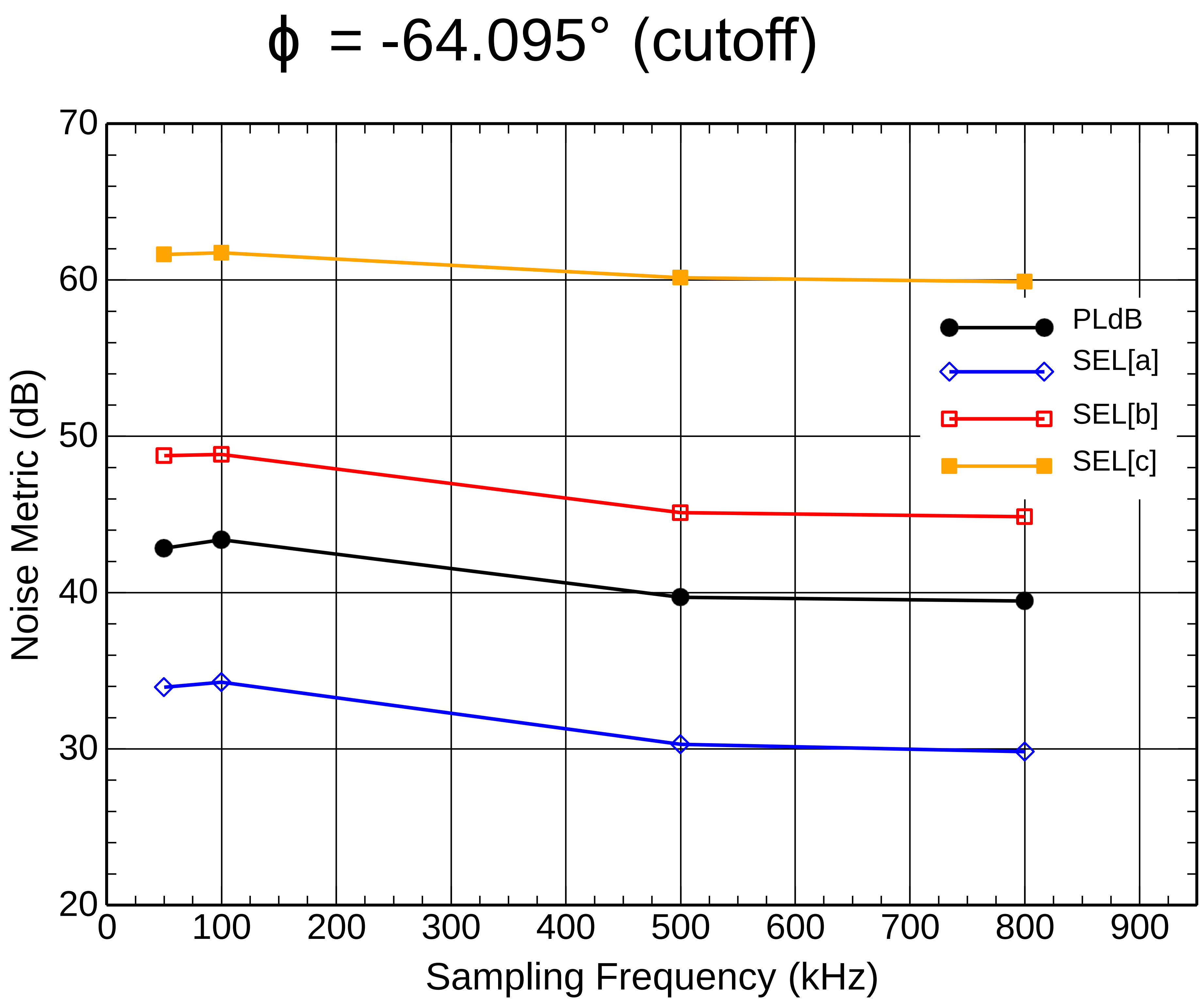



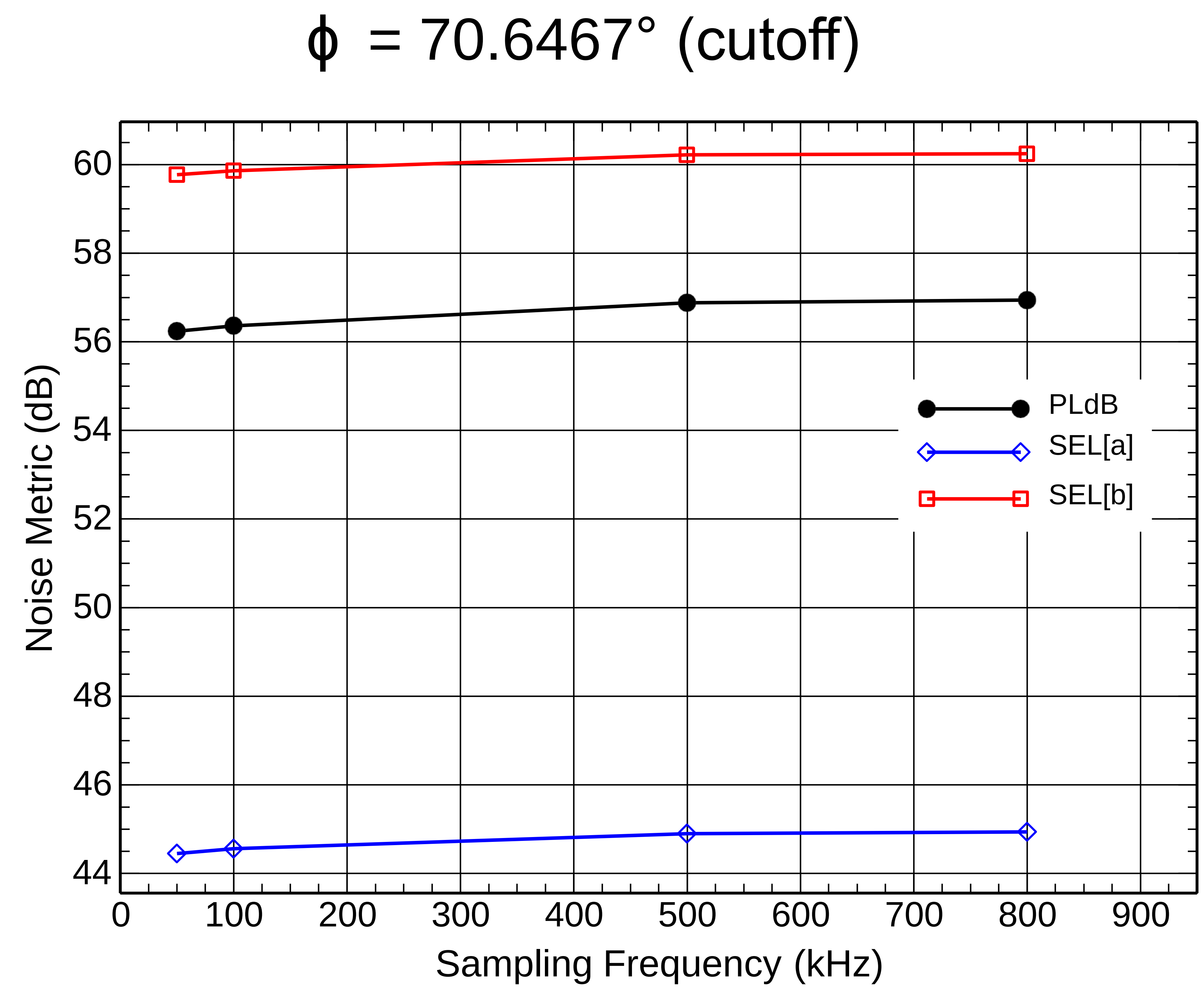

- Near signal cutoff, mesh convergence degrades
- Used 800kHz sampling frequency at cutoff
- Discrete BSEL filter appears to remain well behaved
- Std. Atm. worse behaved than Required Atm.

# Case 2: C609 Sampling Frequency

2020.03.05 ARC/TNA

## PLdB metric convergence with sampling frequency (Required Atm)




- Used 800kHz sampling frequency for propagation at outside ±60°