

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

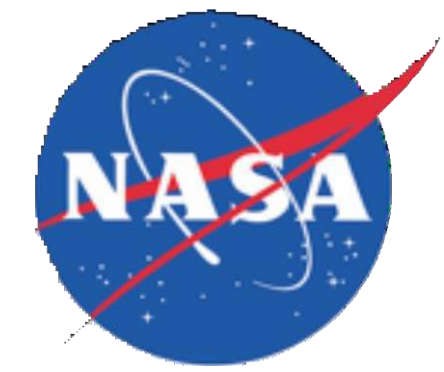
AMS Seminar
NASA Ames Research Center
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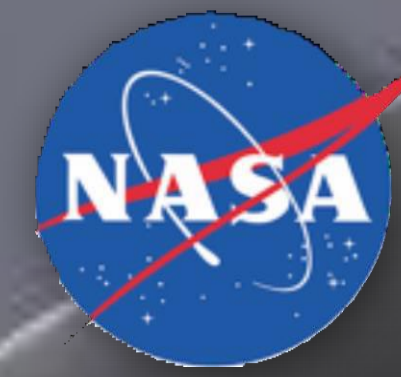
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Nearfield CFD Outline

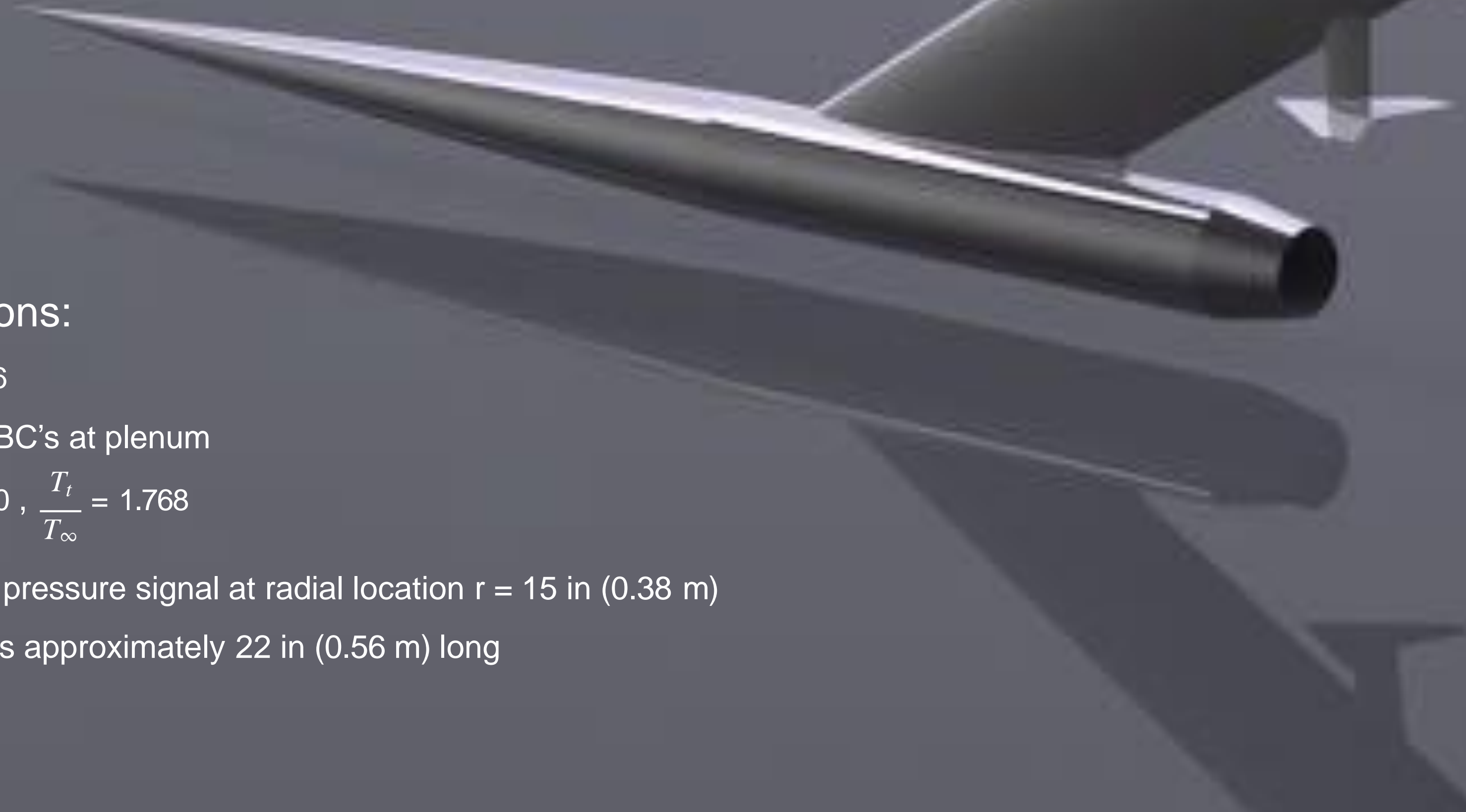
- Cases
 - Biconvex - shock/plume interaction
 - C608 - full aircraft geometry
- Flow solver & computational resources
- Geometry & grids
- Numerical convergence
- Results
- Challenges
- Conclusions



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Biconvex

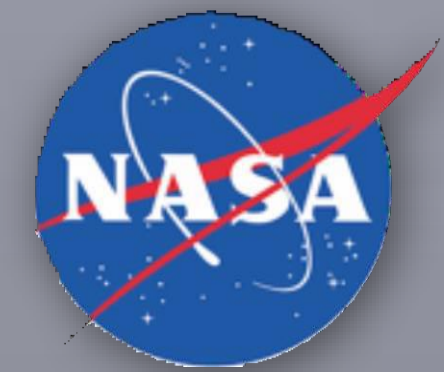
Wind tunnel model setup to examine shock/plume interaction



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



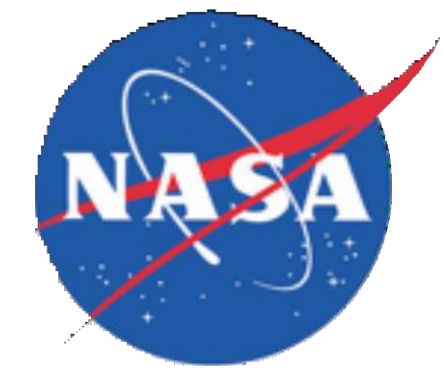
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- Modified version of X-59 Low Boom Flight Demonstrator design iteration
- Full aircraft, complex geometry, multiple inflow/outflow BC's

Conditions:

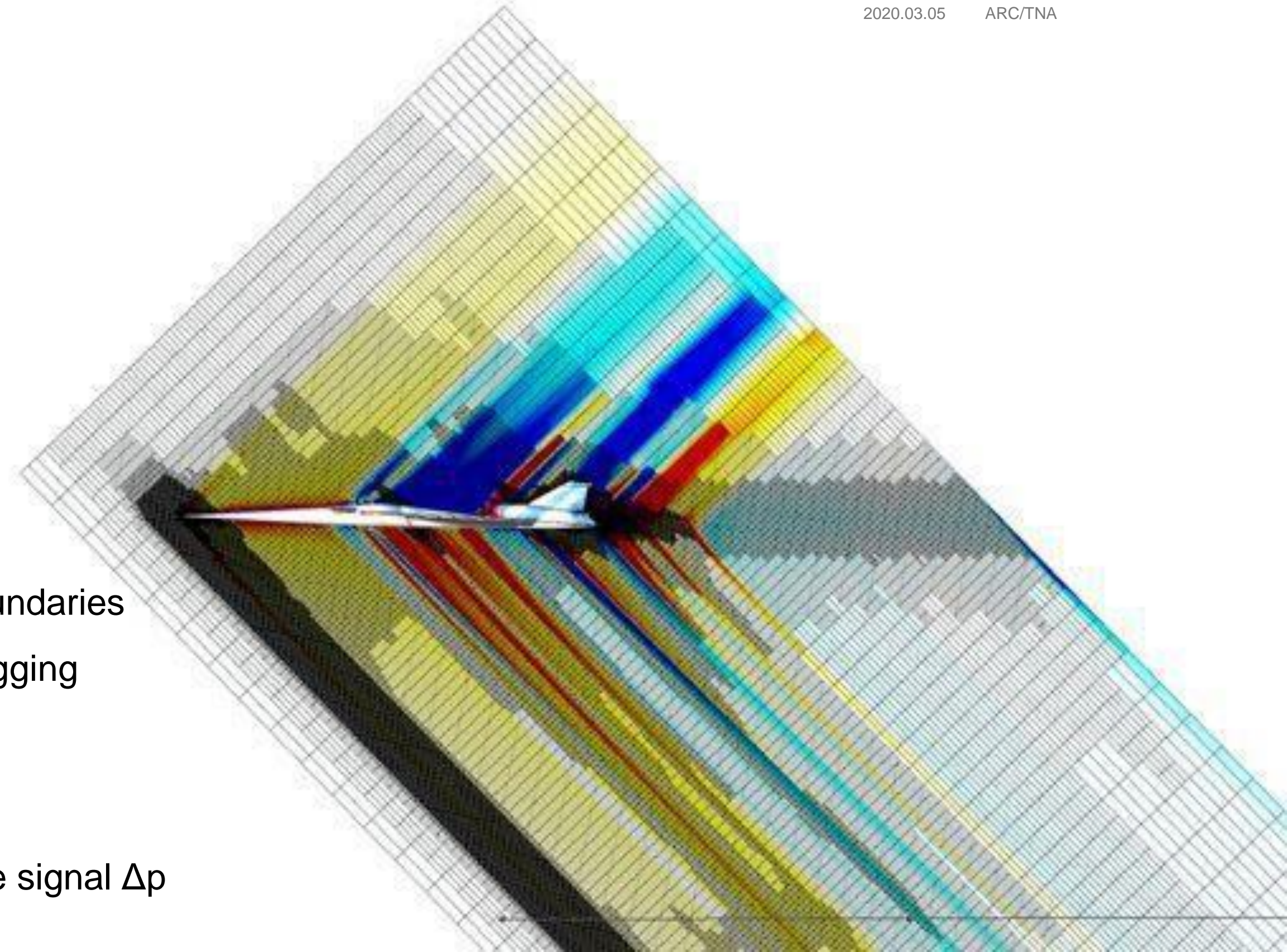
- $M_\infty = 1.4$, Altitude $h = 53,200ft$
- Power BC's at engine nozzle $p_t/p_\infty = 10.0$, $T_t/T_\infty = 7.0$
- Power BC's at bypass nozzle $p_t/p_\infty = 2.4$, $T_t/T_\infty = 2.0$
- Engine fan inlet $p_b/p_\infty = 2.6$ (desired Mach 0.4 flow at engine fan face)
- Environmental Control System 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



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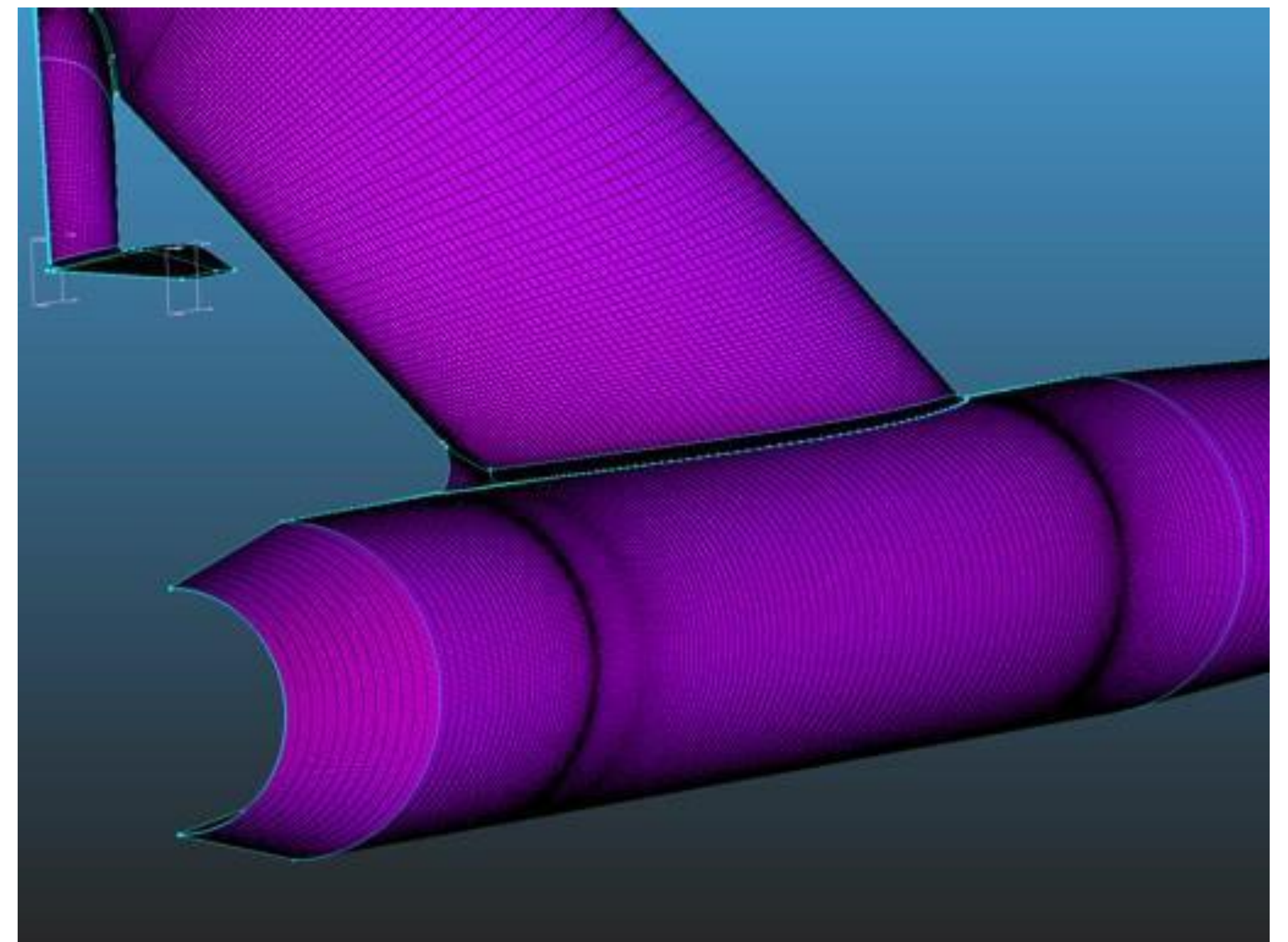
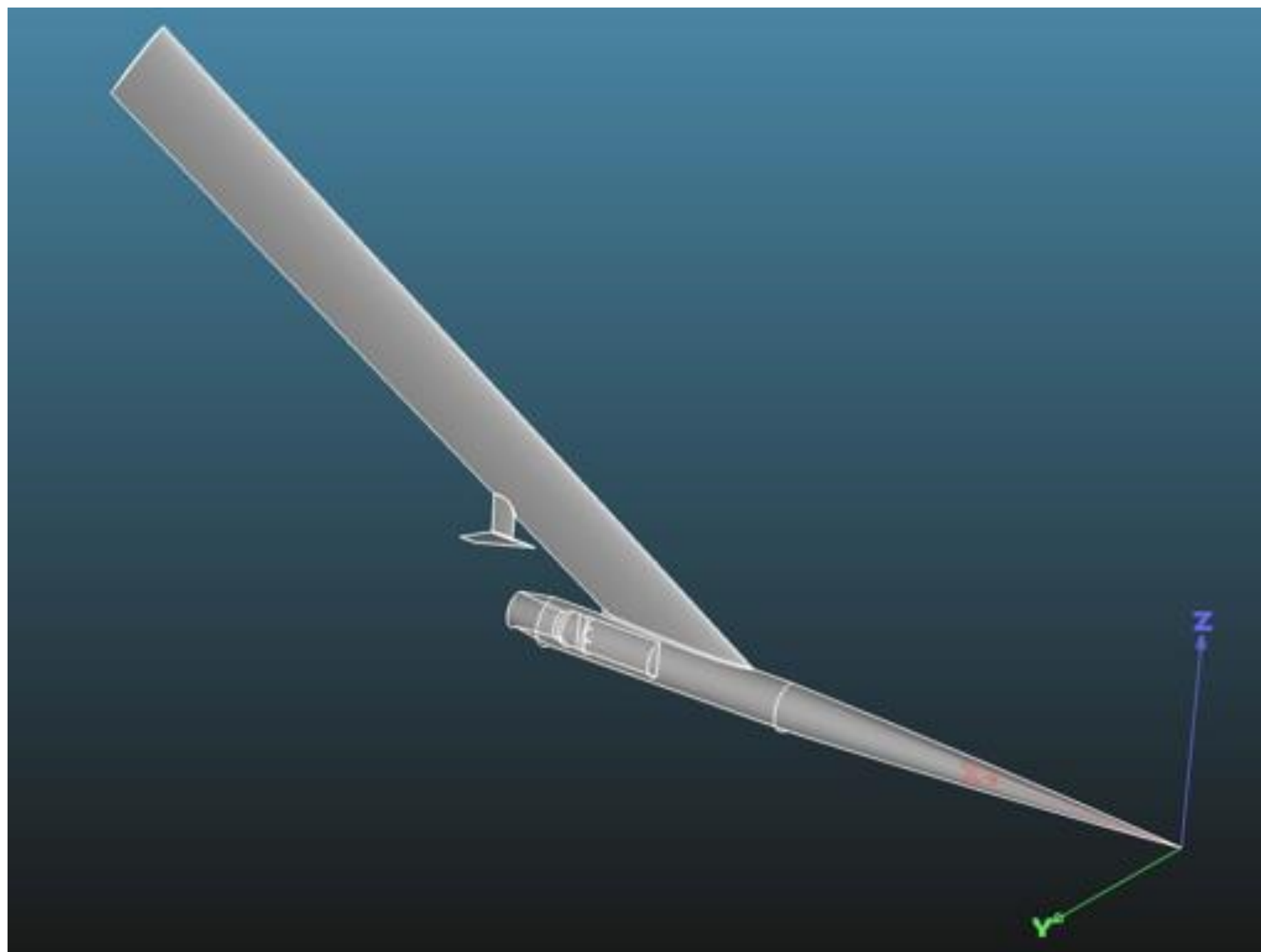
Cart3D Software

- 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)

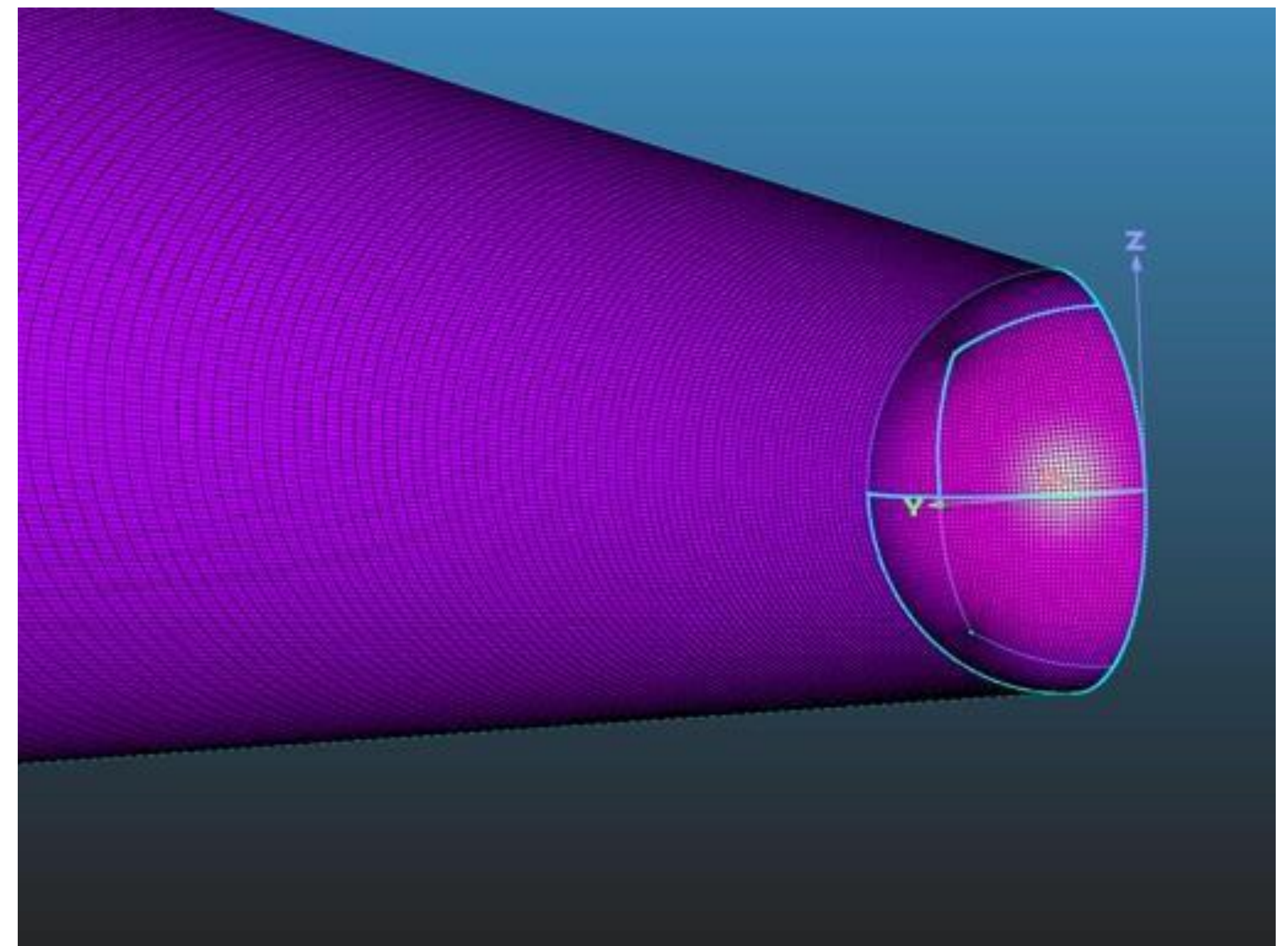
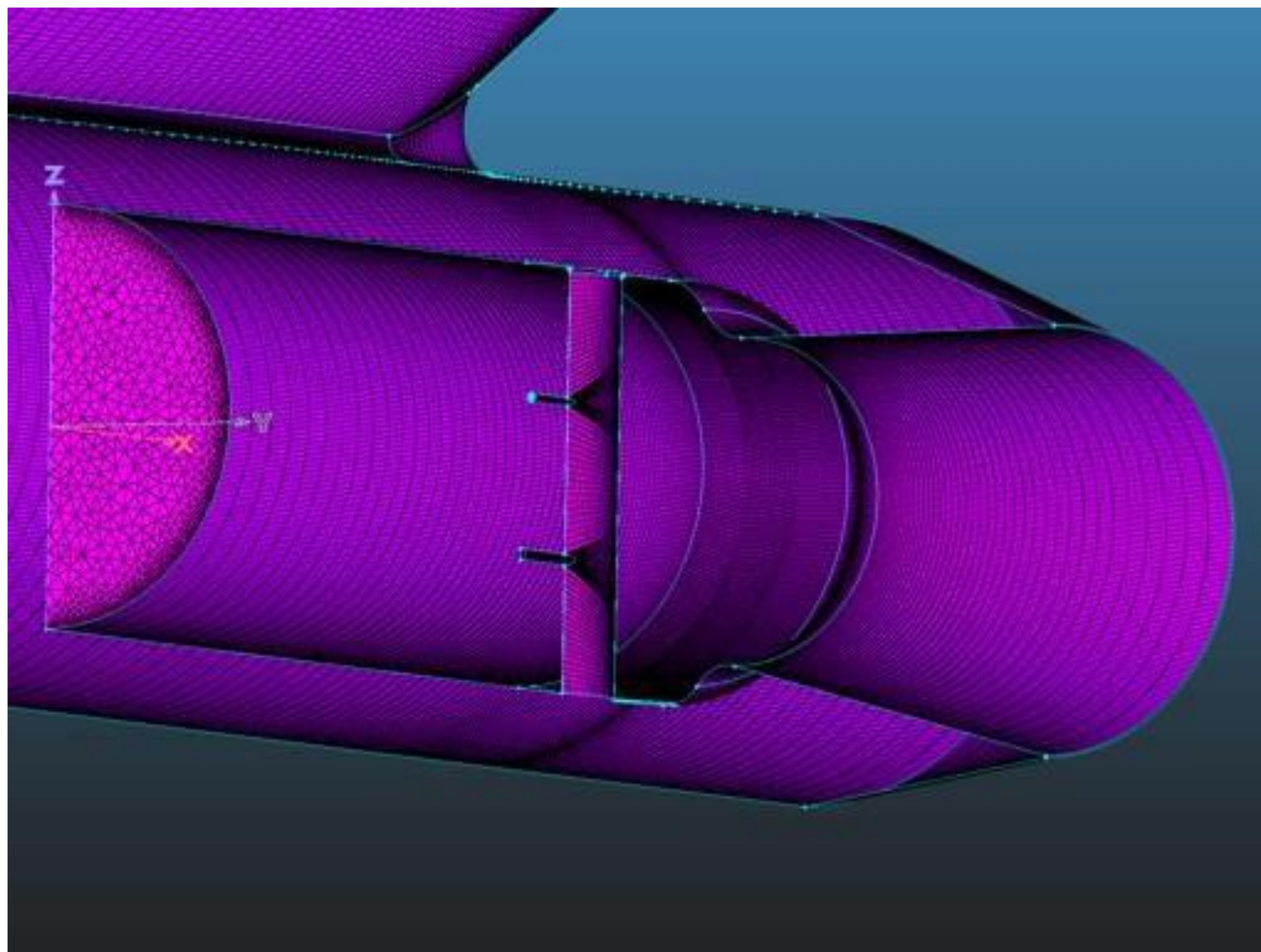


Cart3D

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

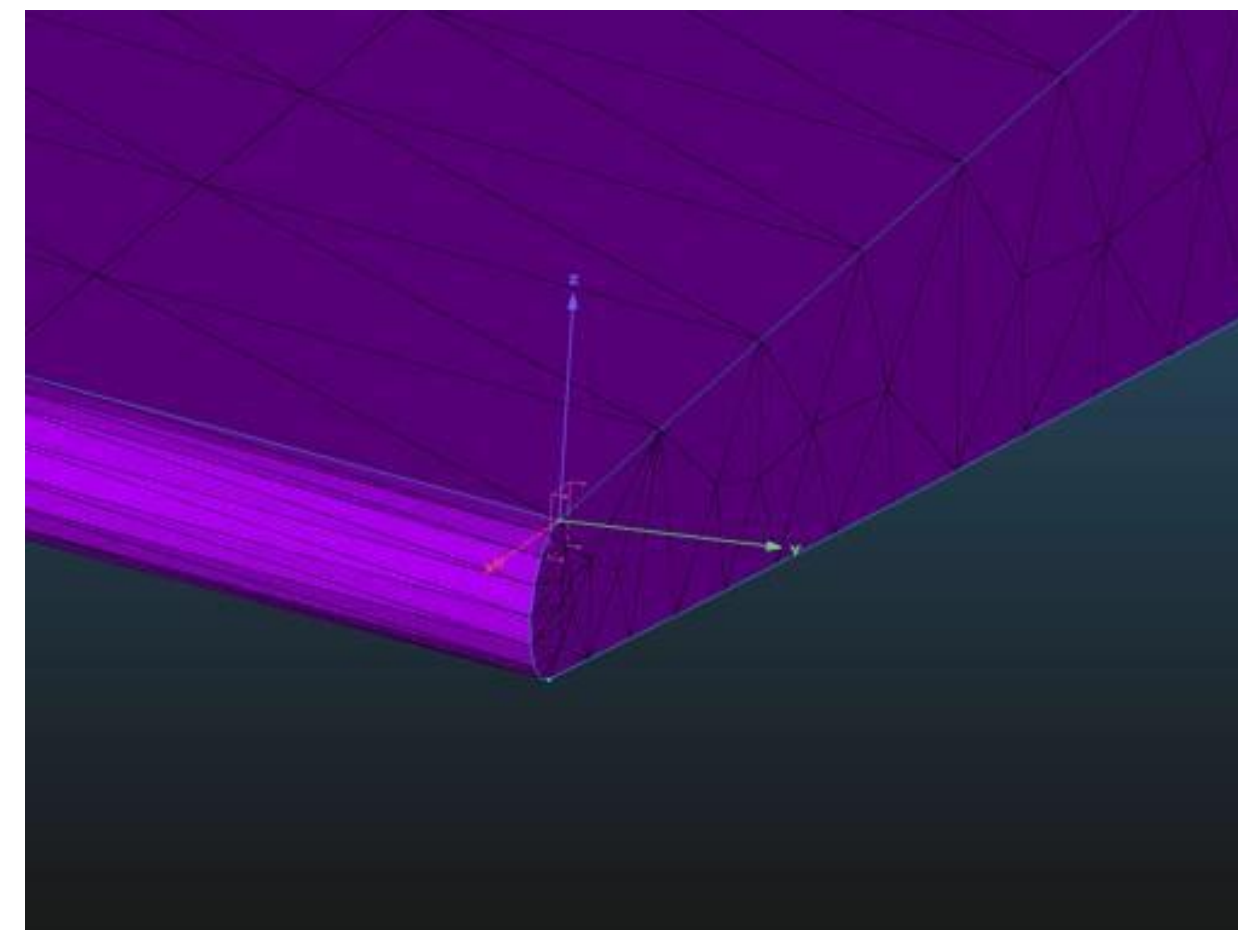
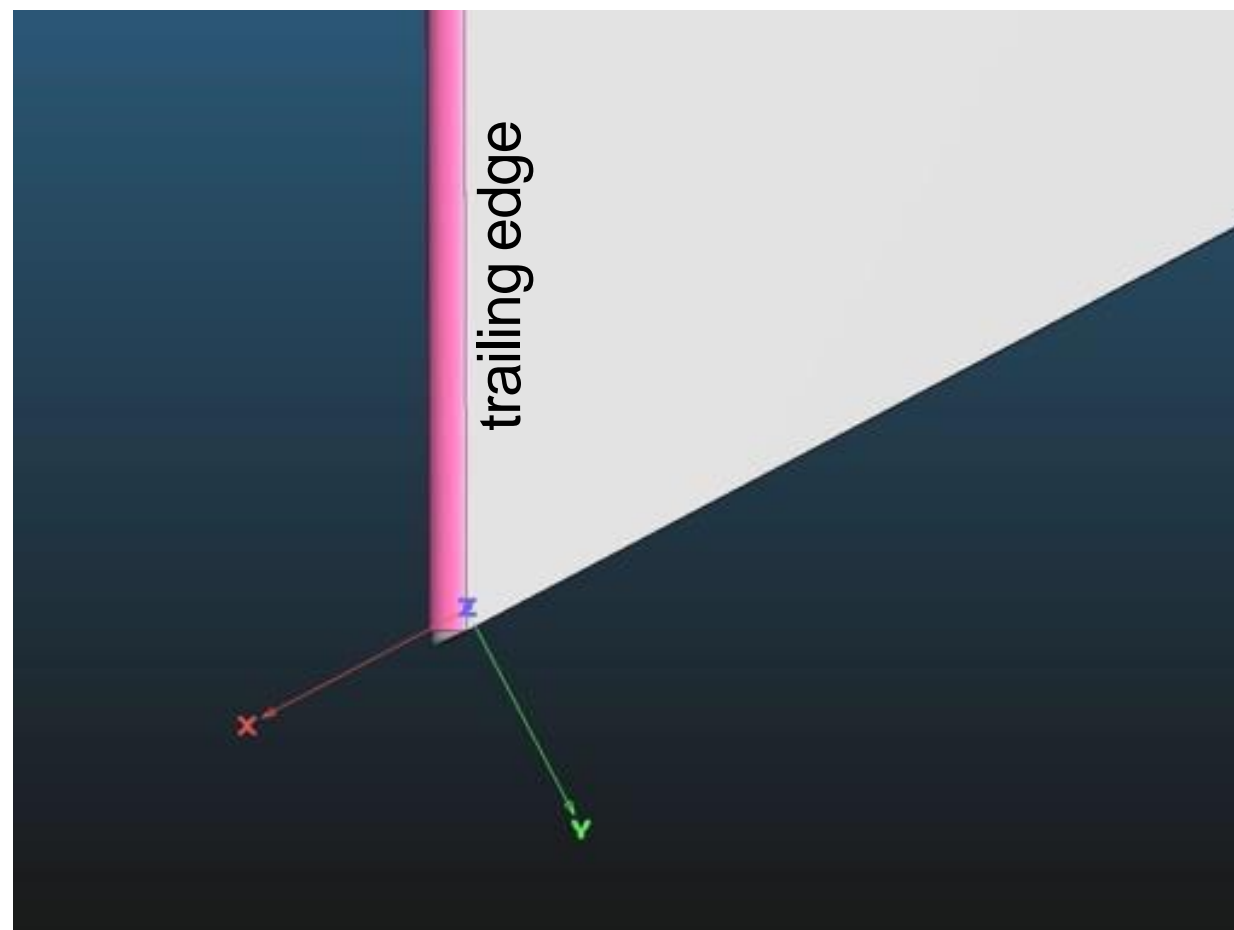
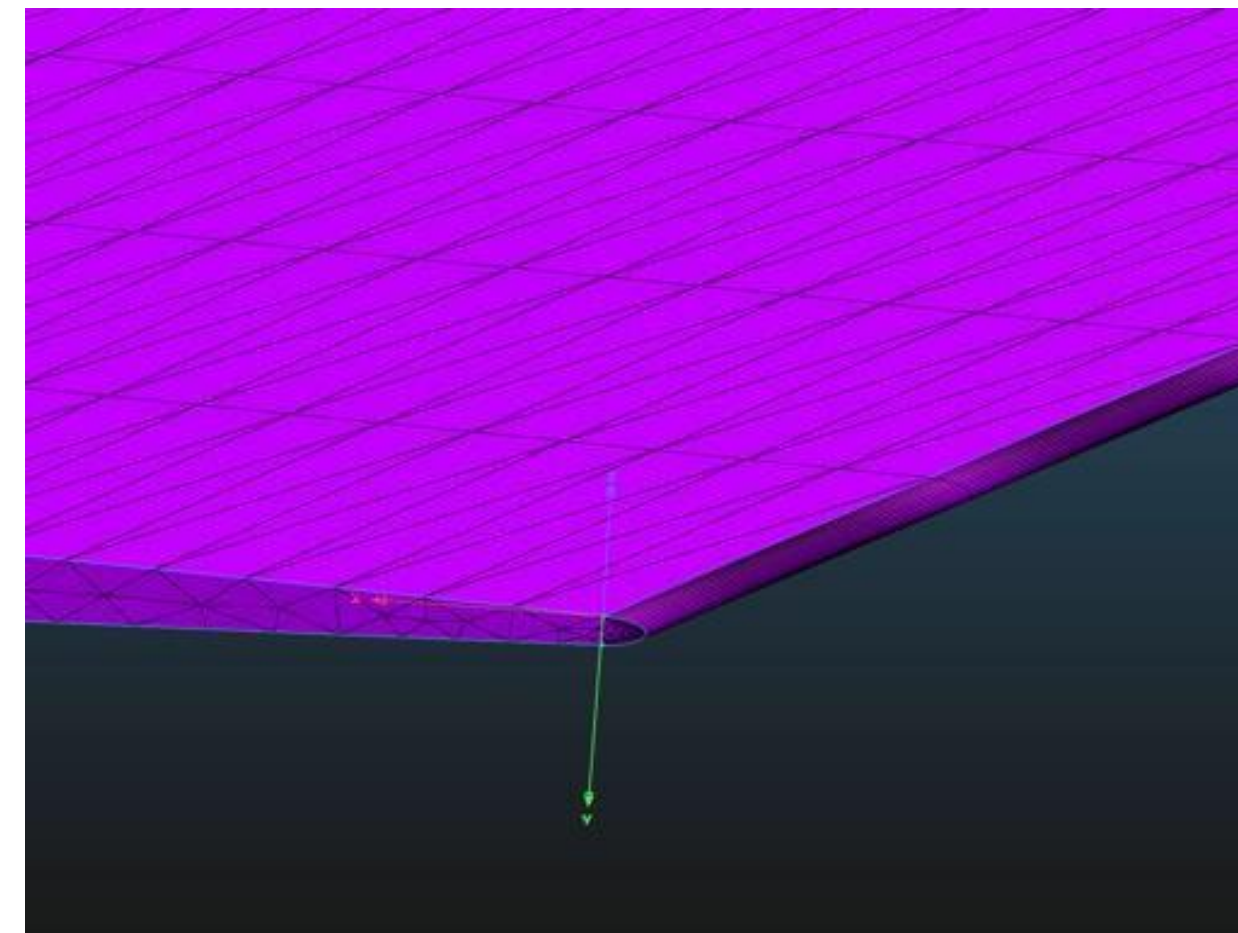
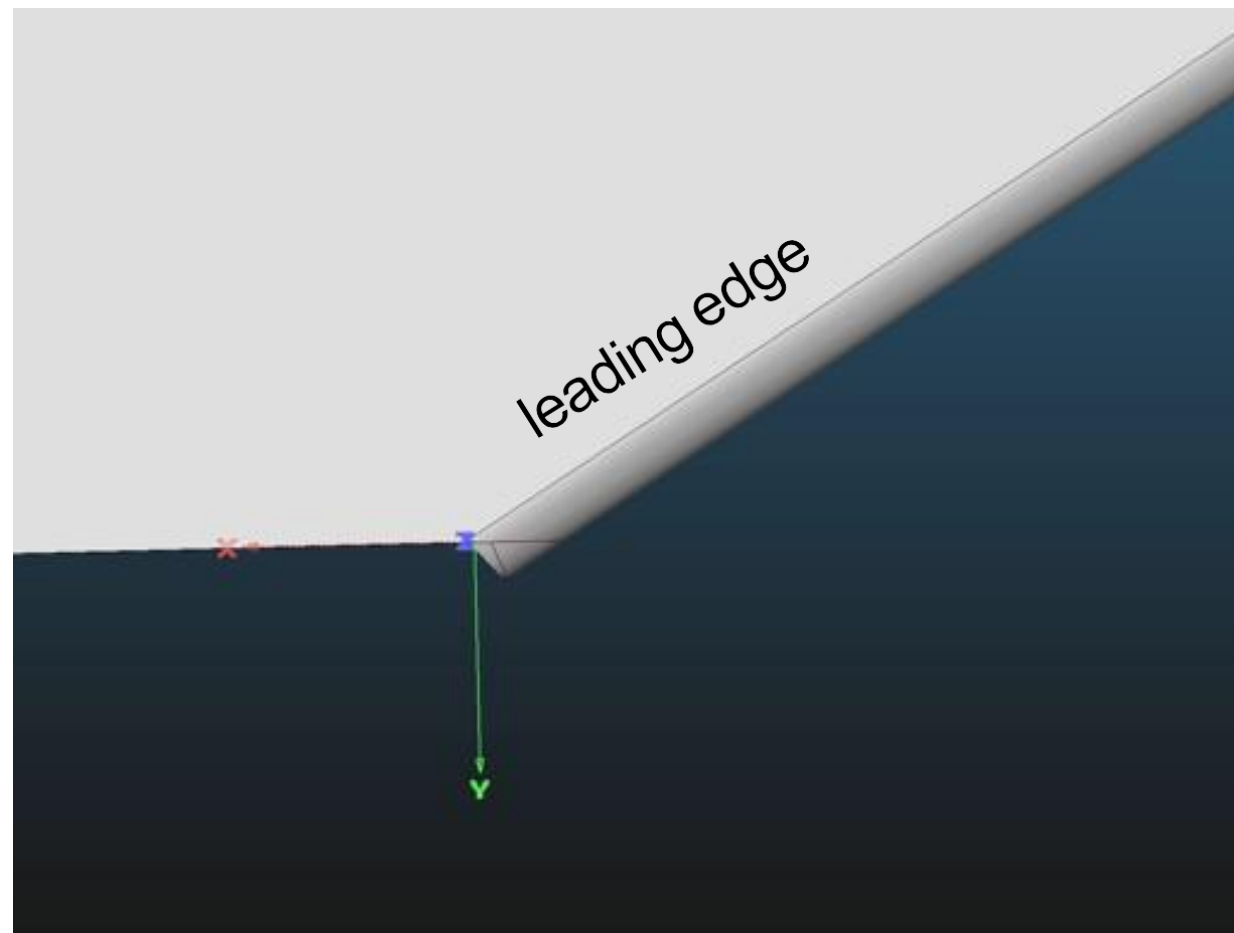


- Biconvex
 - Created surface triangulation from STP and IGS files
 - Diagonalized structured grid where possible
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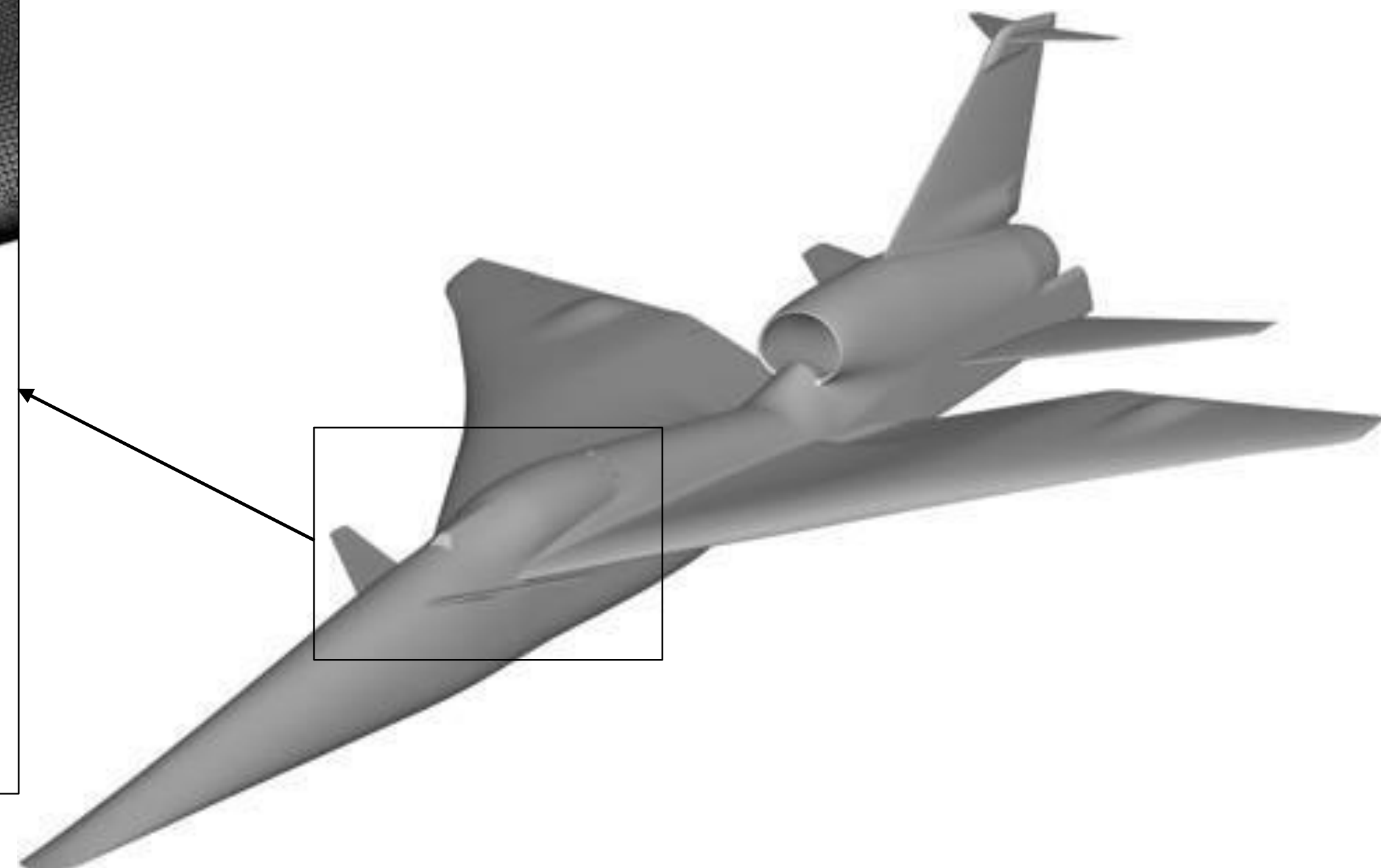
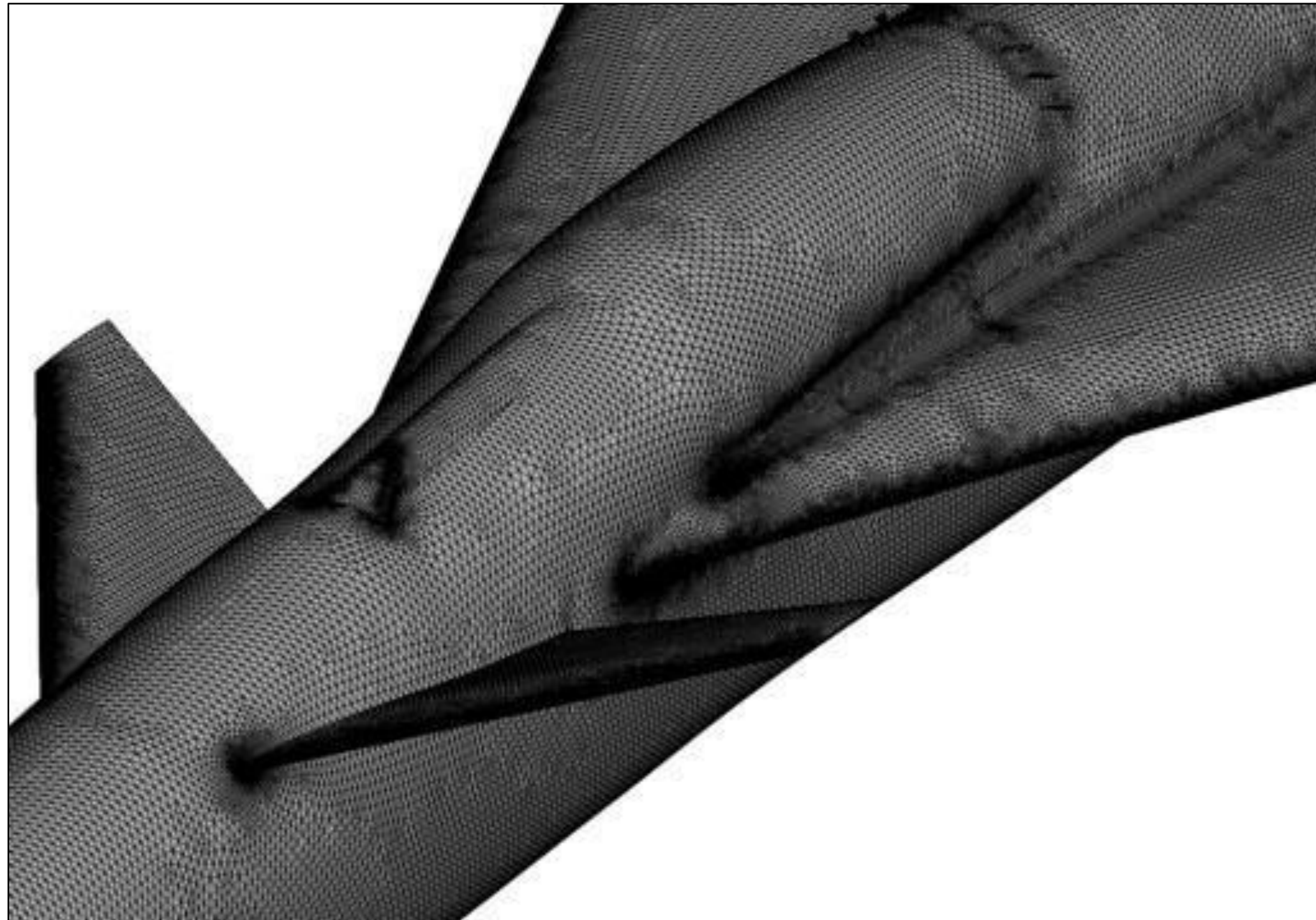


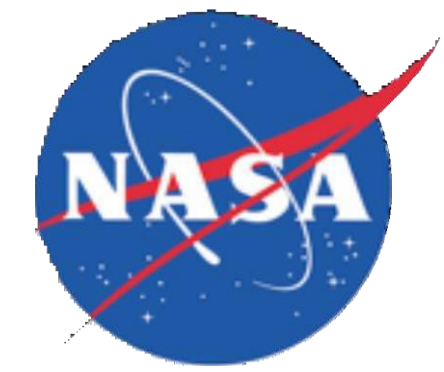
Geometry

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



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





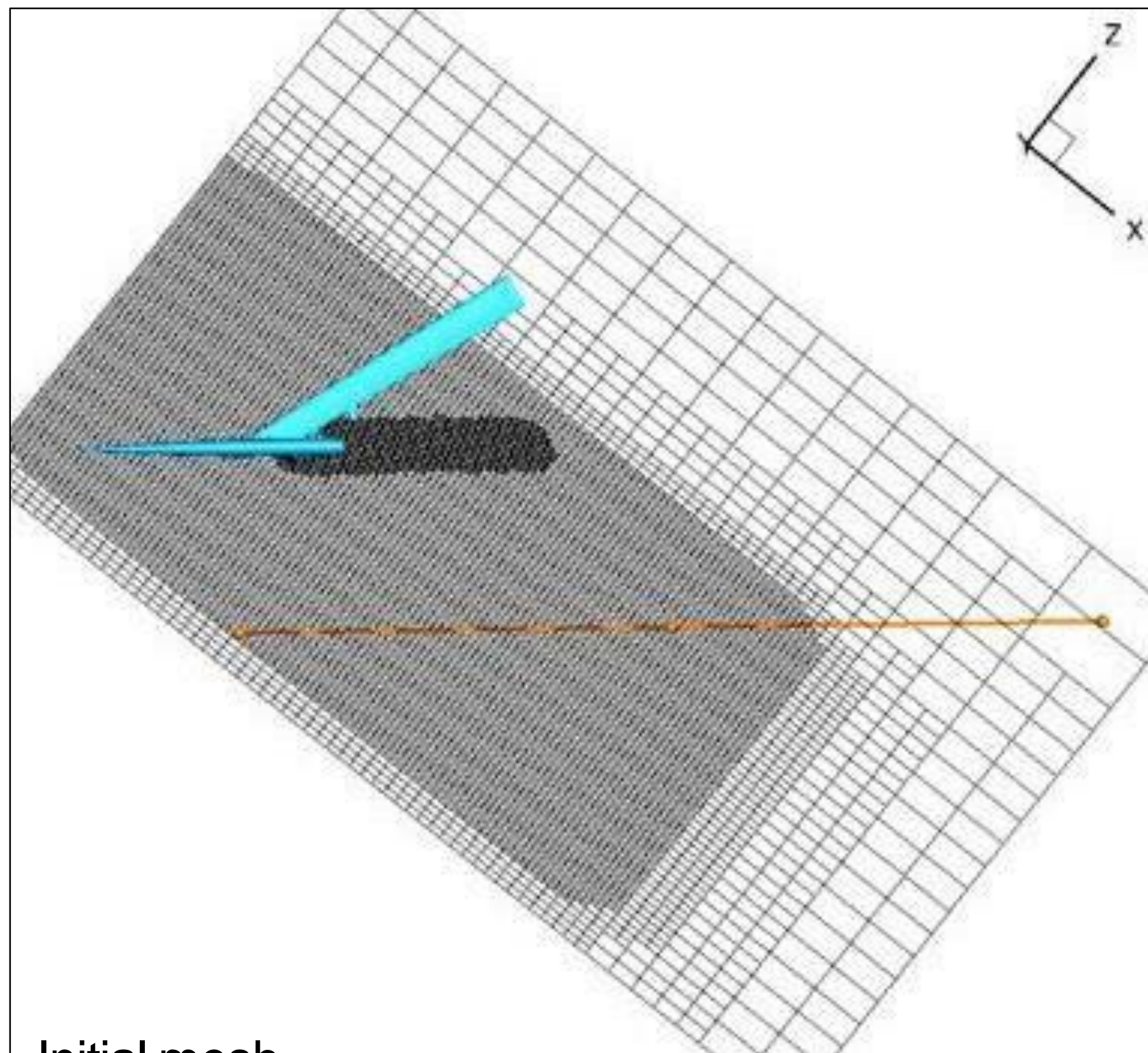
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Volume Mesh

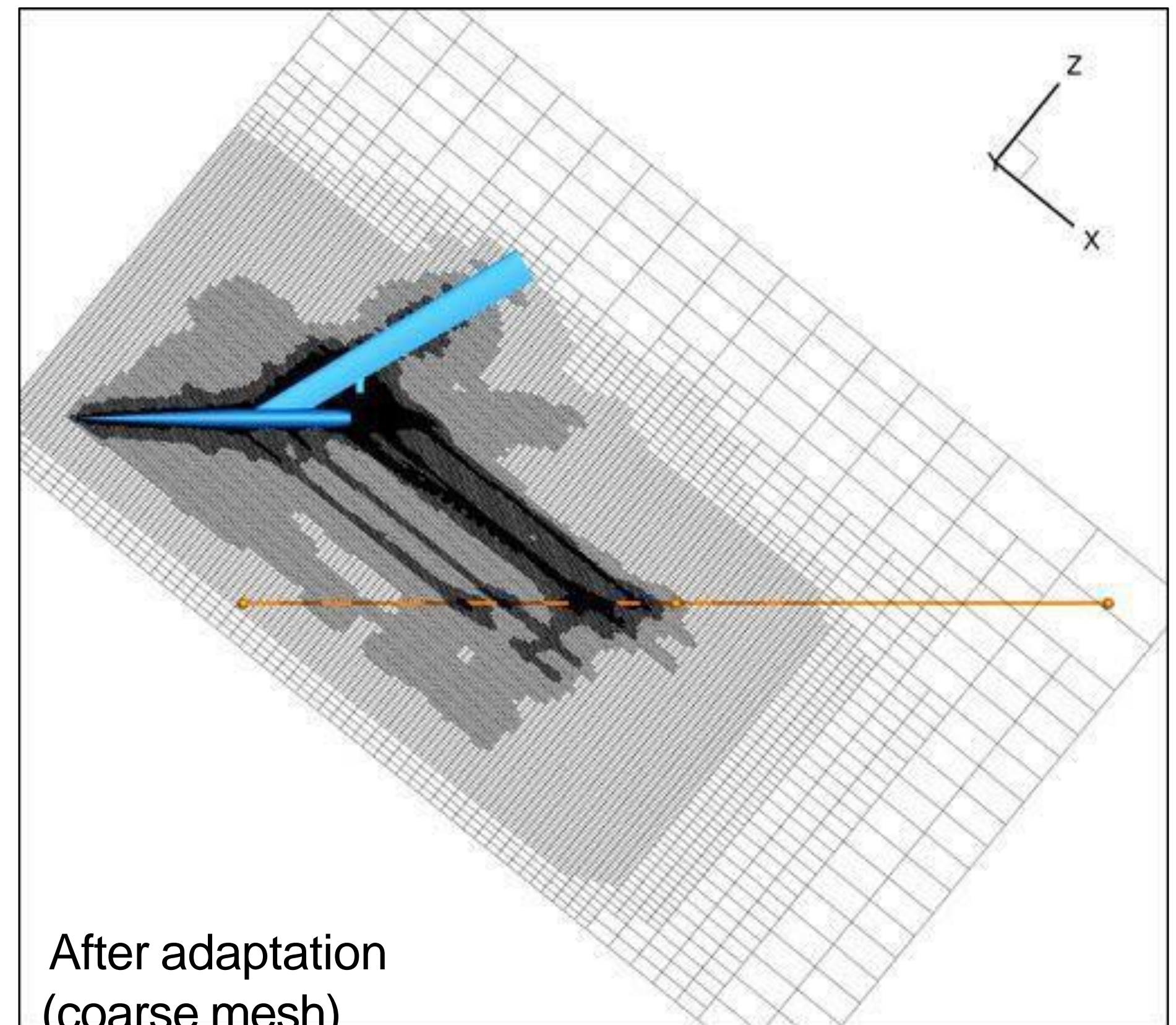
- Cartesian cut-cell volume mesh for inviscid flow solver
- Cart3D autoBoom - previous SBPW2 work
 - Aligned with Mach angle (with tiny offset to avoid sonic glitch)
 - Roll the model geometry for different off-track ϕ angles
 - Separate simulation for each off-track ϕ on 1 node, can be run simultaneously
 - 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

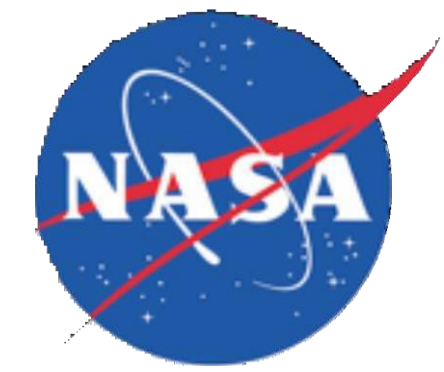
- Adjoint-driven mesh adaptation
 - Line sensor at multiple body lengths away
 - Objective function is weighted integral of $\Delta p/p_\infty$



Initial mesh

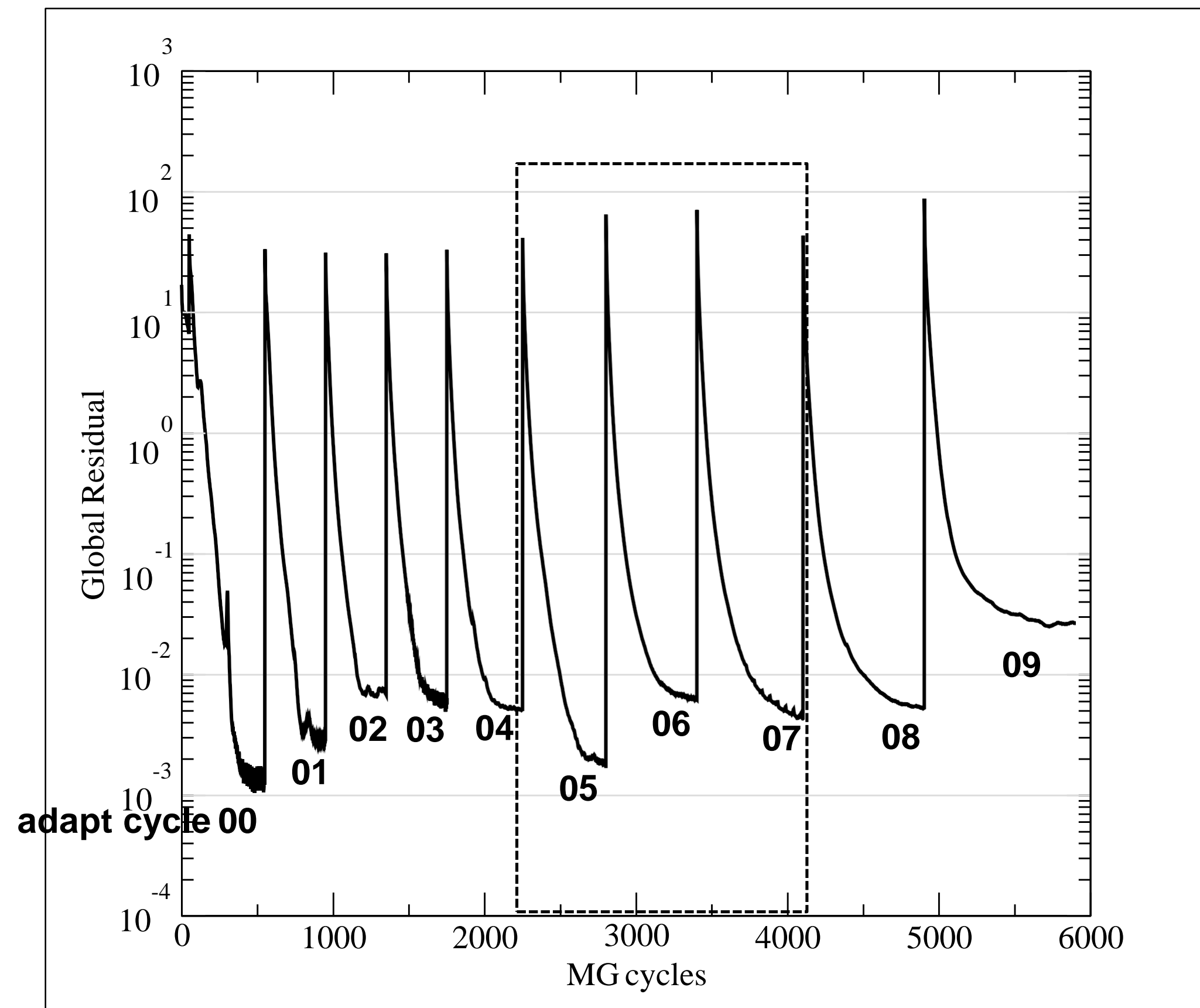


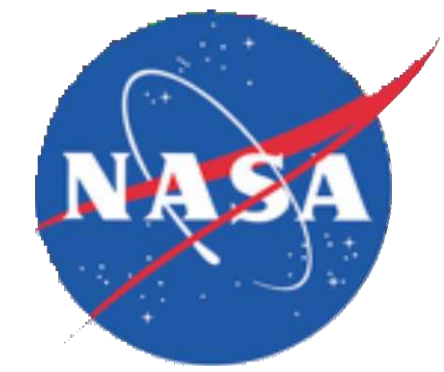
After adaptation
(coarse mesh)



Numerical Convergence

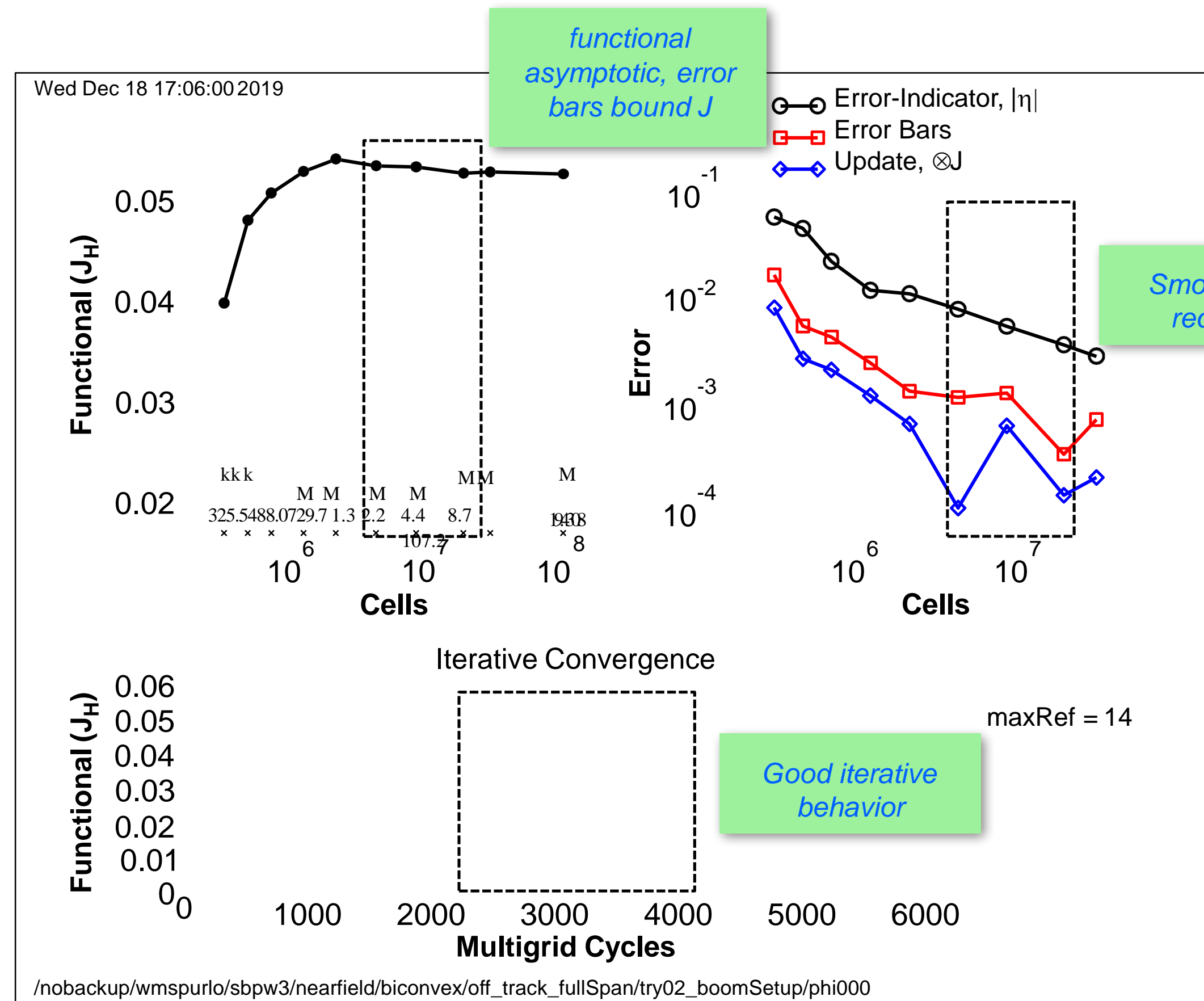
- Biconvex
 - 550, 600, 700 iterations on coarse, medium, fine grids
 - Submitted adapt cycles 05, 06, 07 (ran 2 more out to 09 to check)

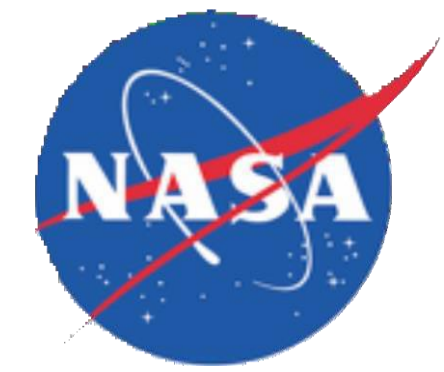




Numerical Convergence

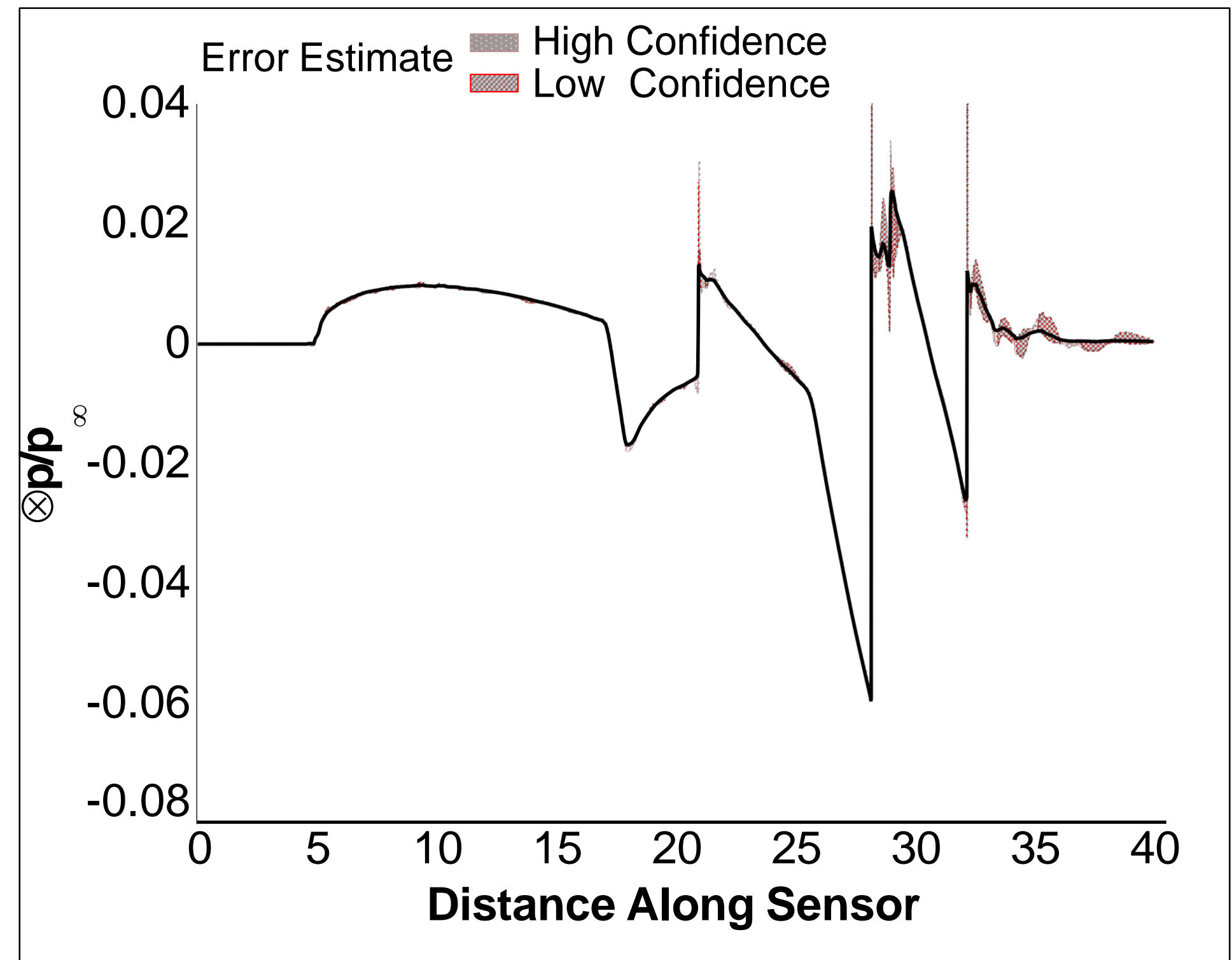
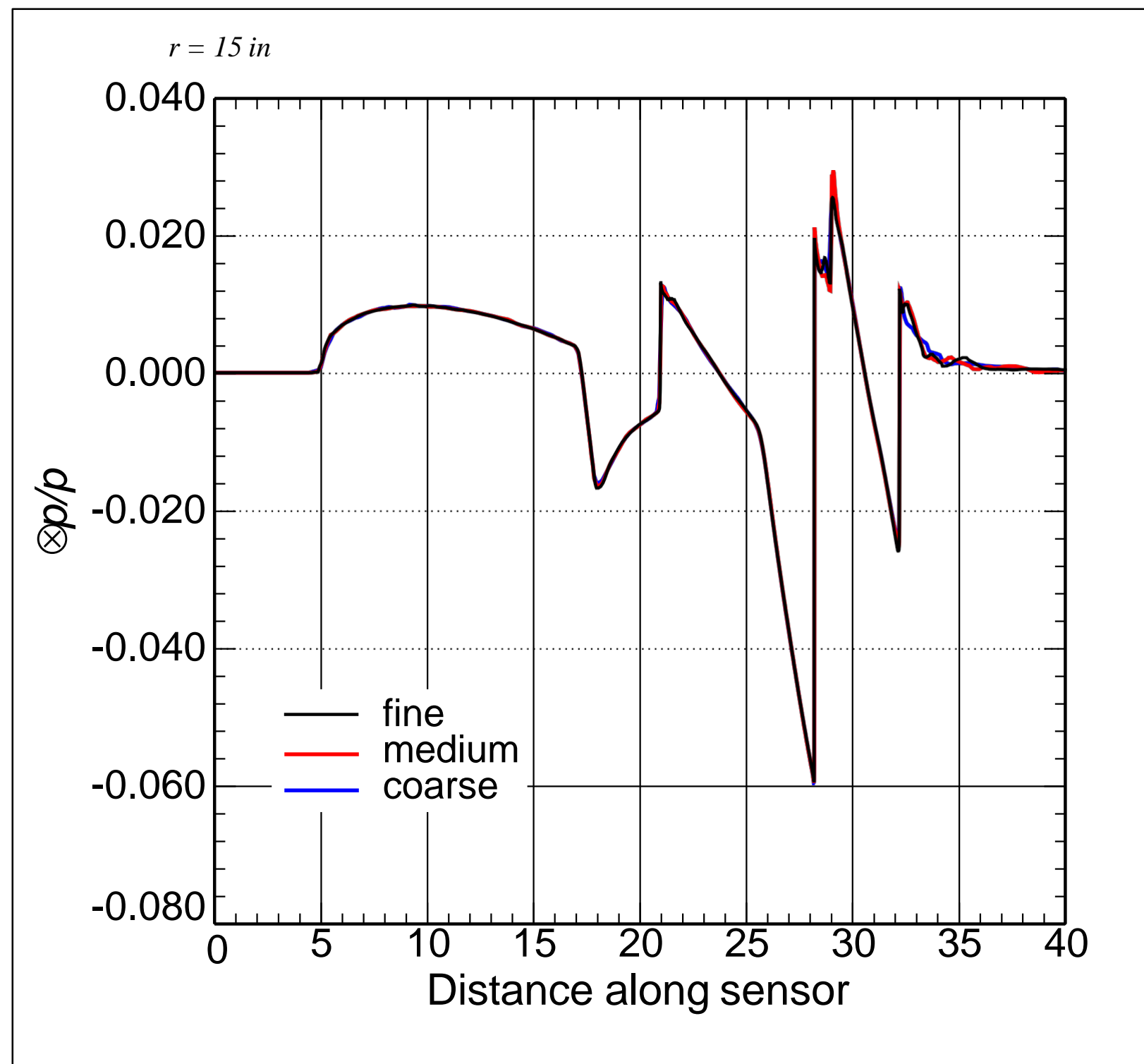
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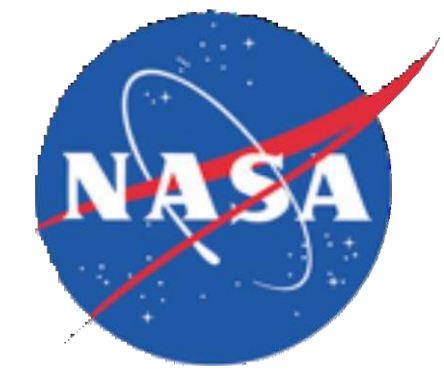




Numerical Convergence

- 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

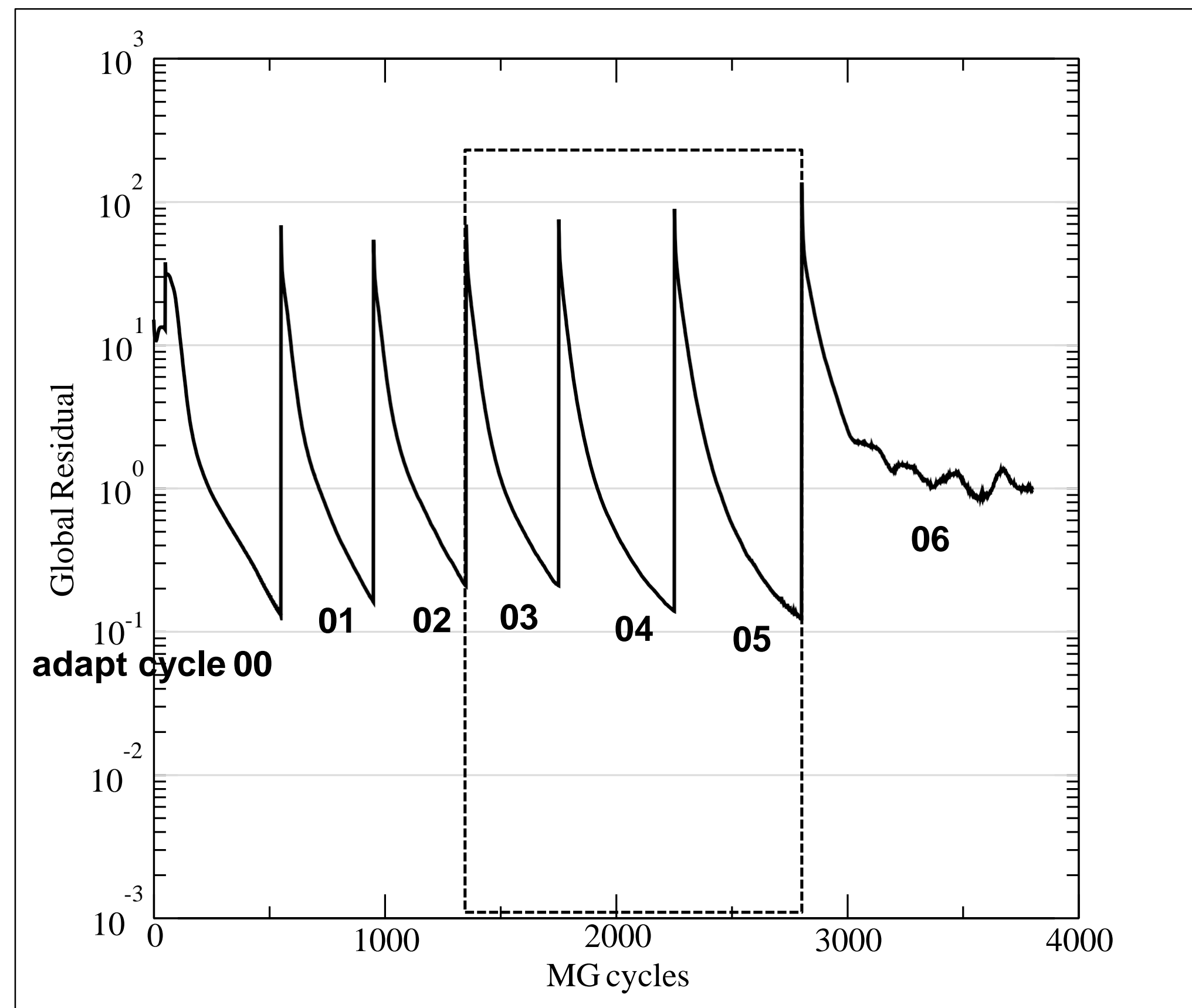


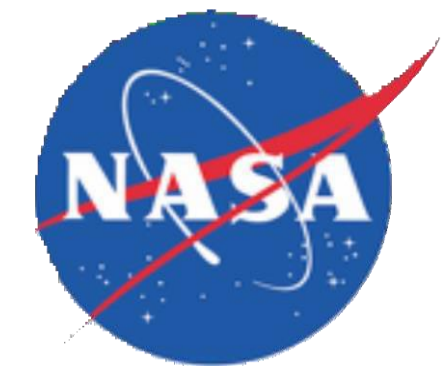


Numerical Convergence

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

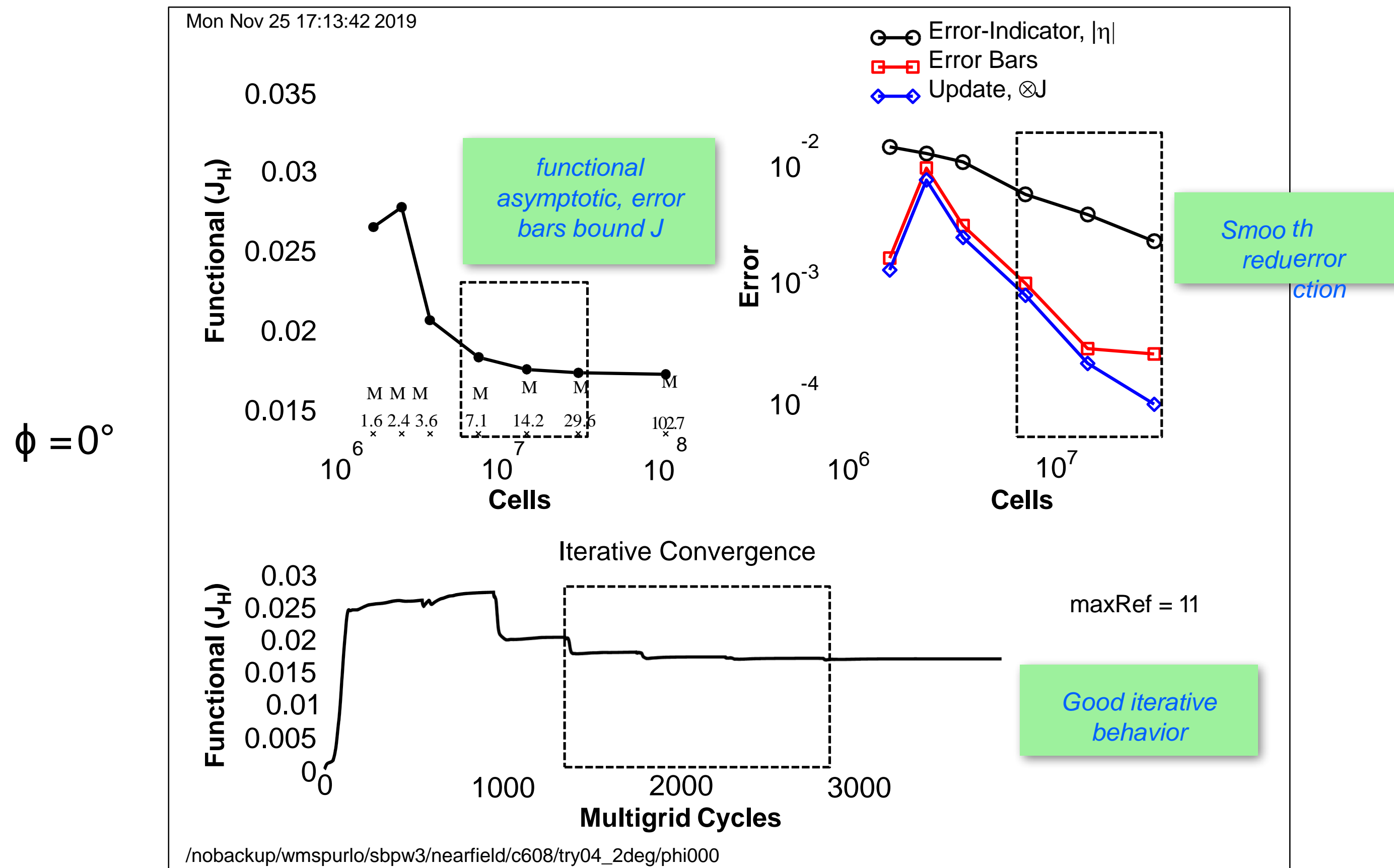
$\phi = 0^\circ$

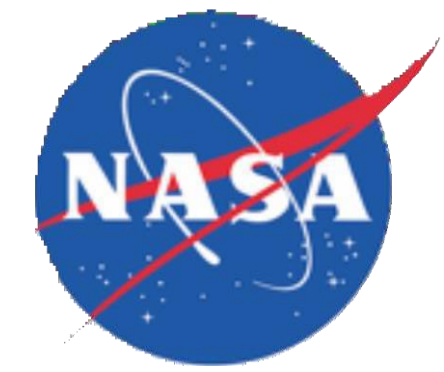




Numerical Convergence

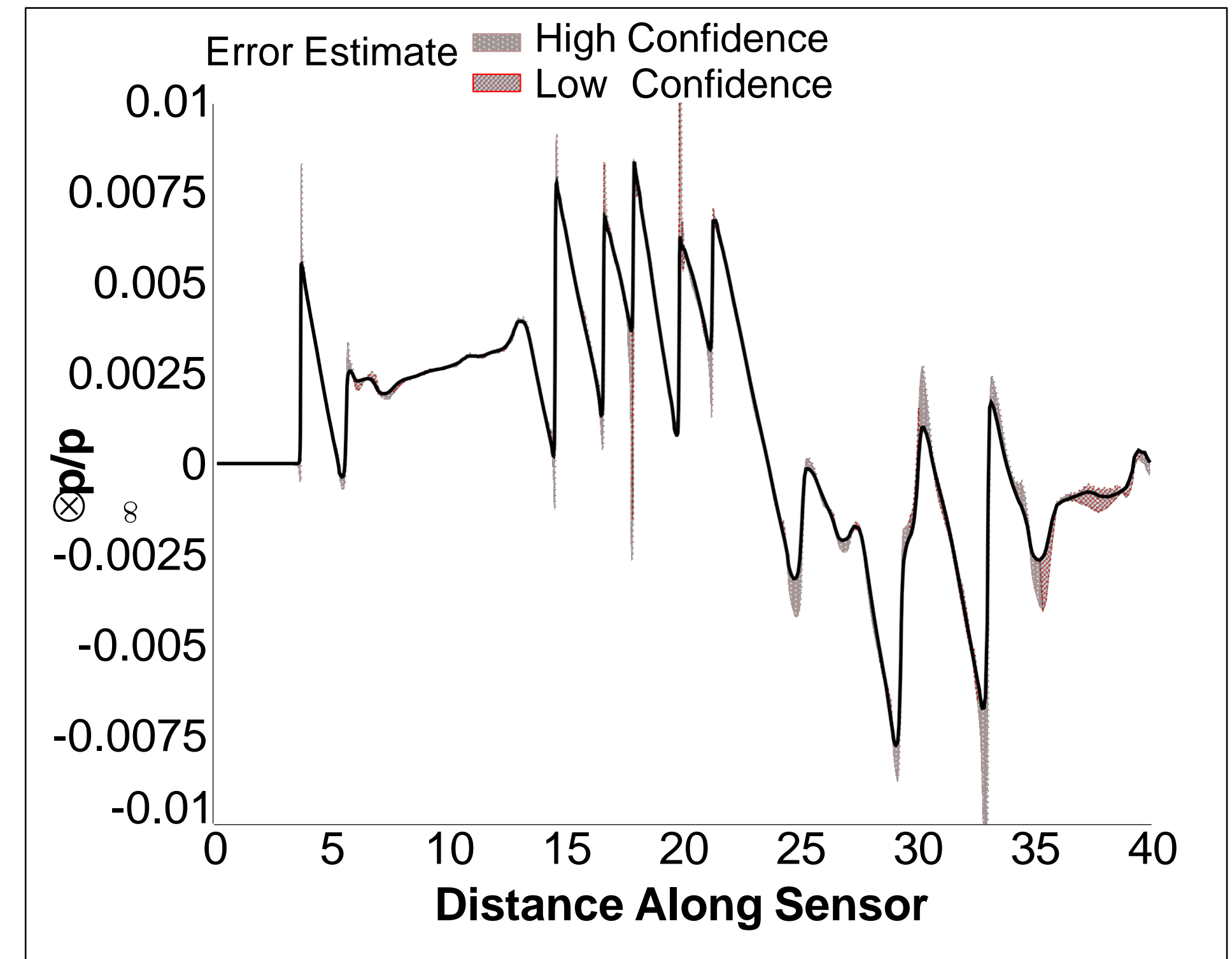
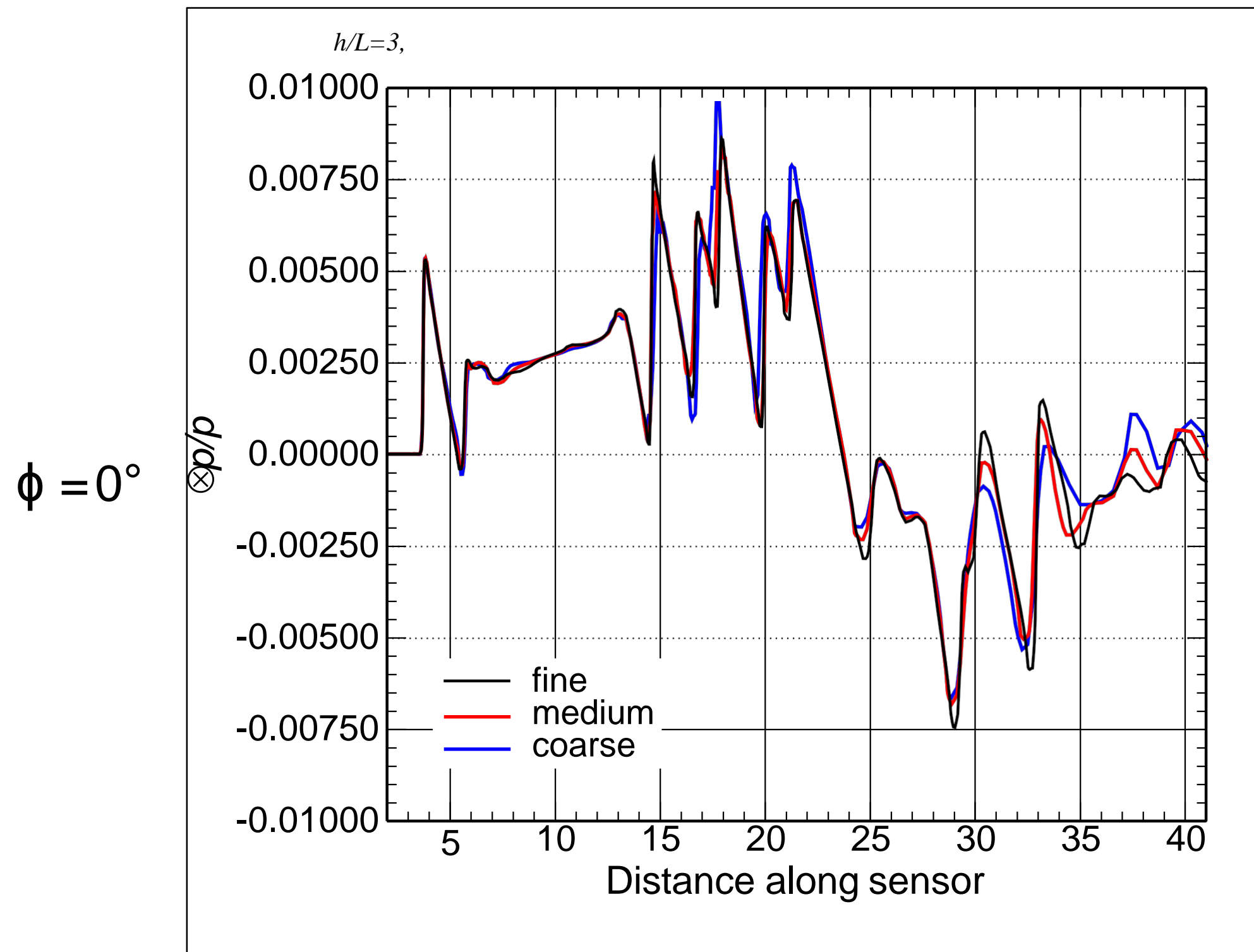
- C608
 - 400, 500, 550 iterations on coarse, medium, fine grids
 - Adapt cycles 03, 04, 05 (ran 1 more out to 06 to check)





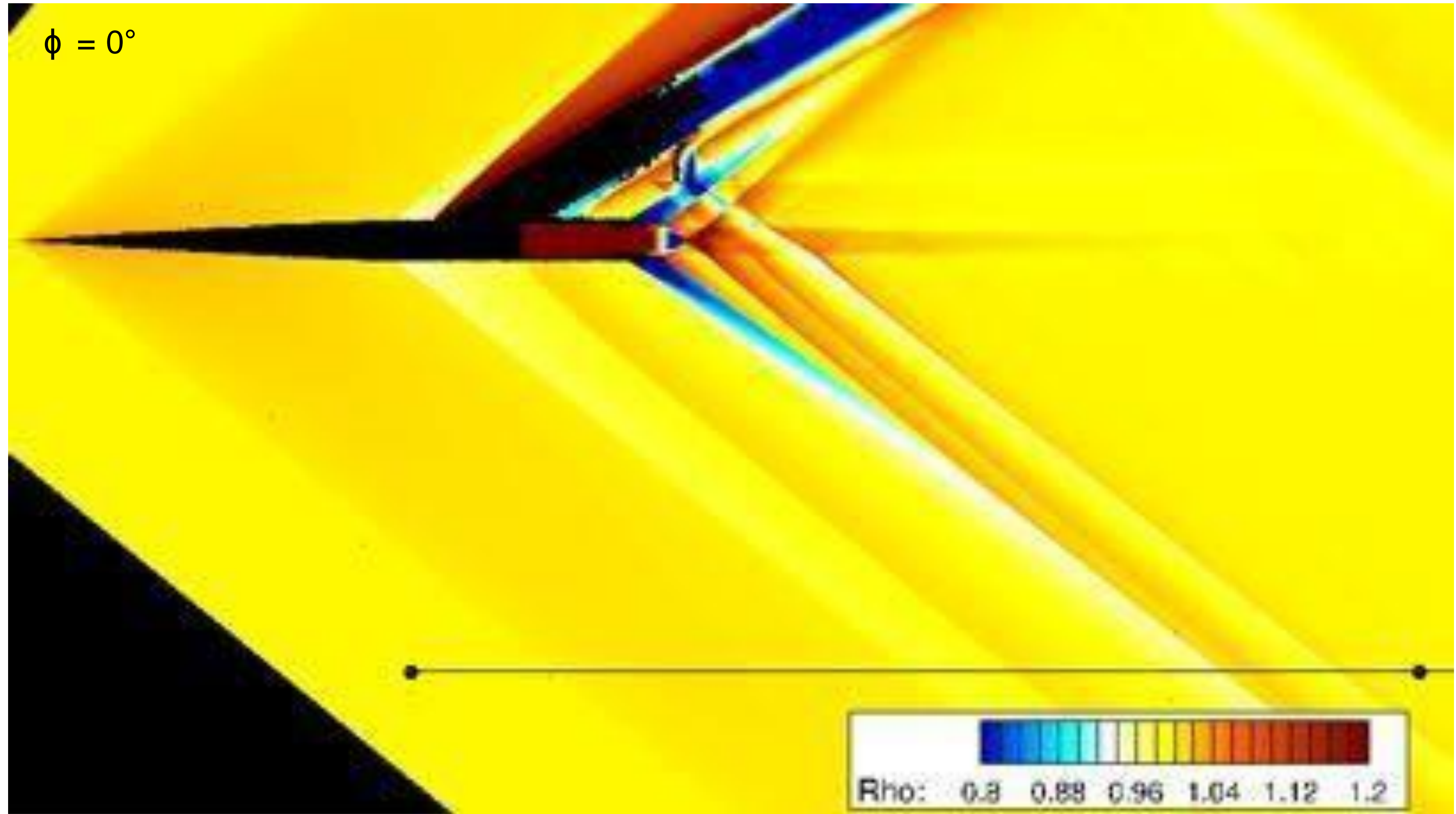
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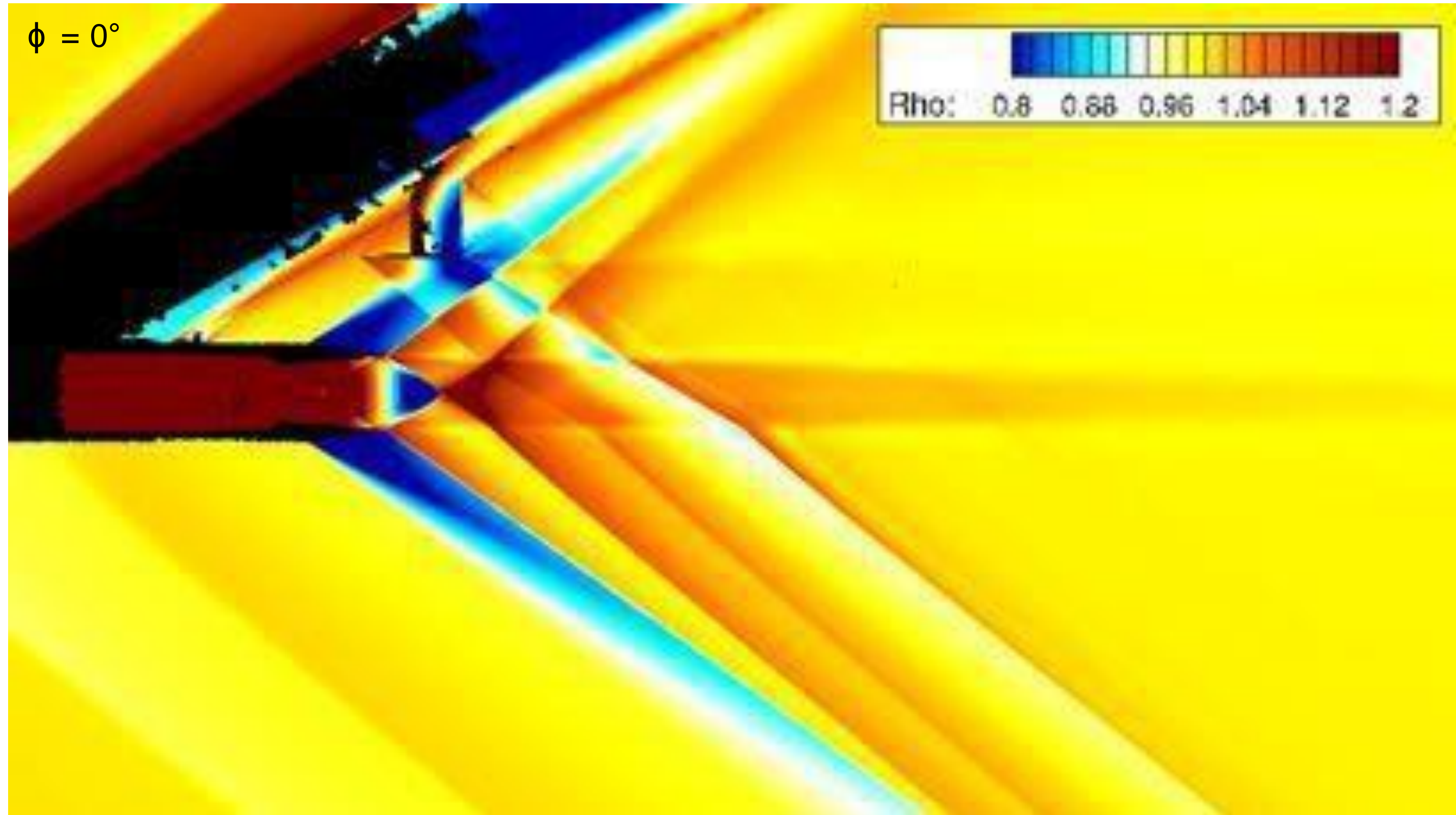
Results: Biconvex

- Density contours



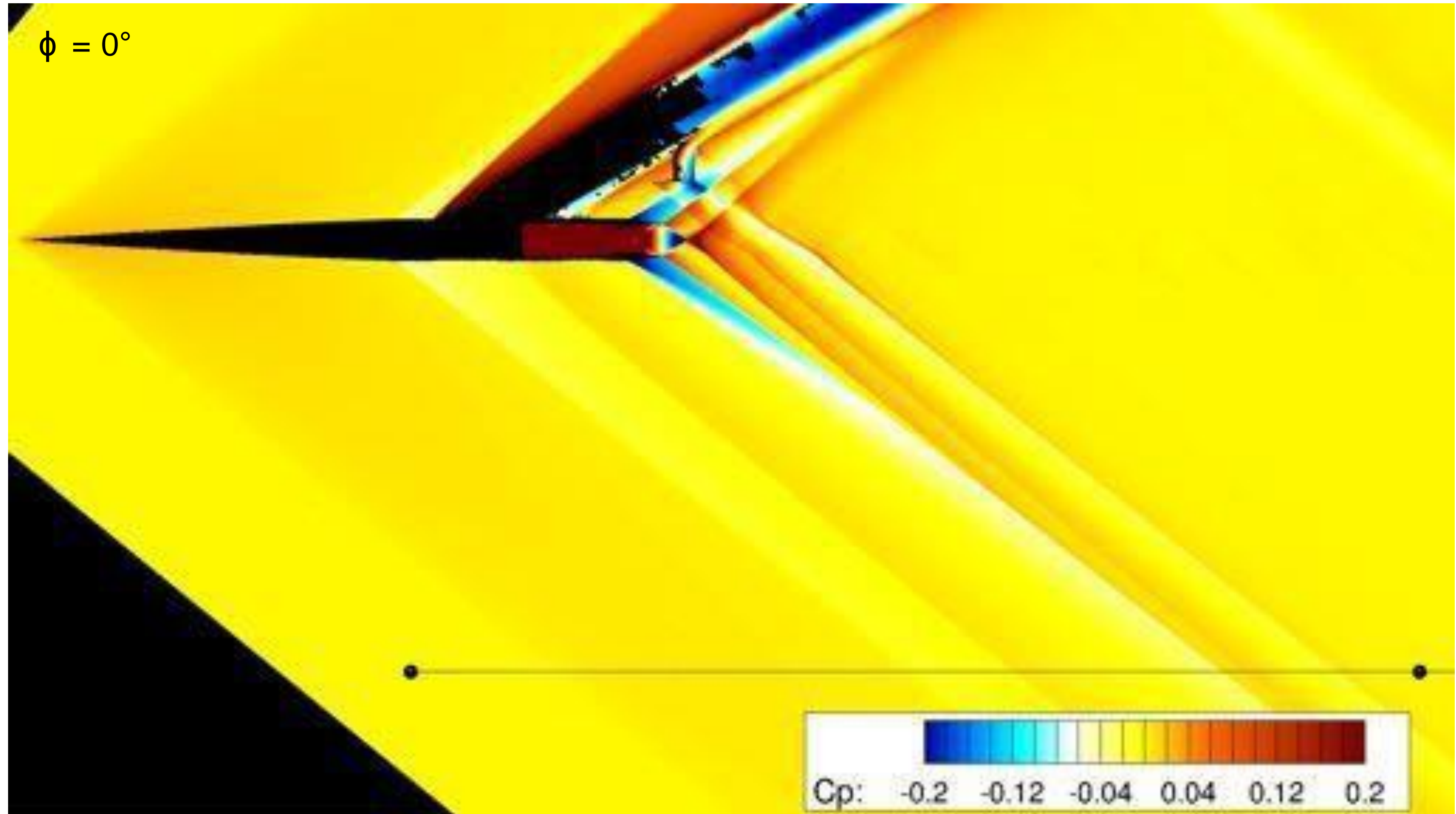
Results: Biconvex

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

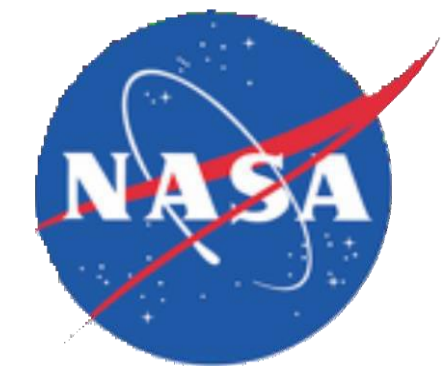


Results: Biconvex

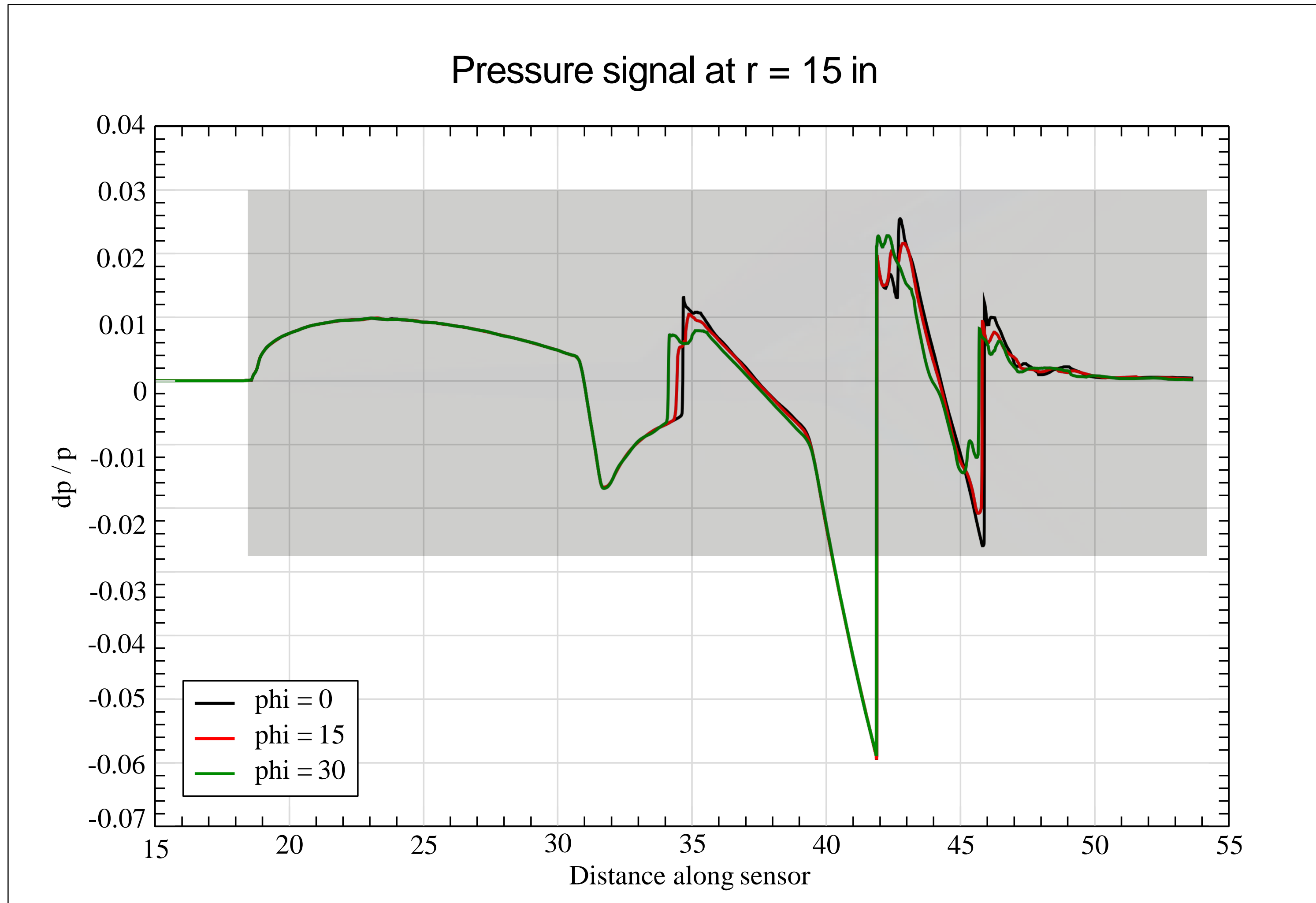
- Pressure coefficient contours



Results: Biconvex

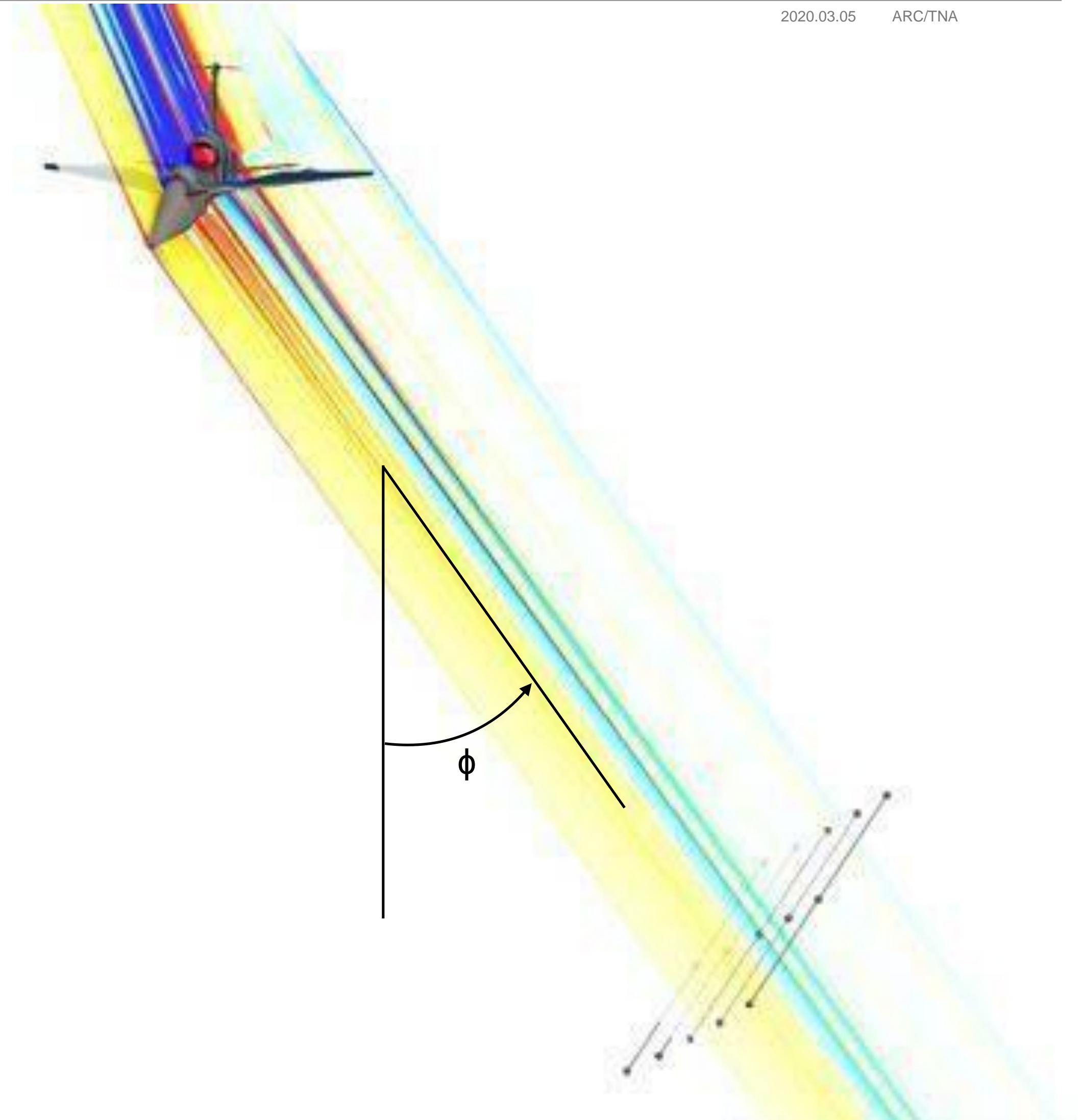


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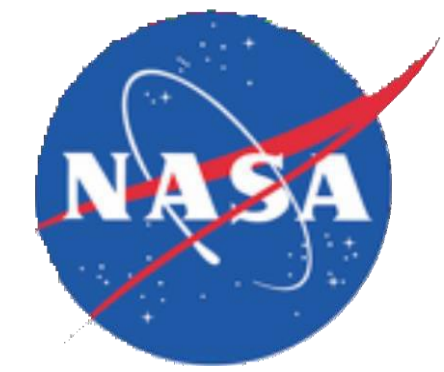


Results: C608

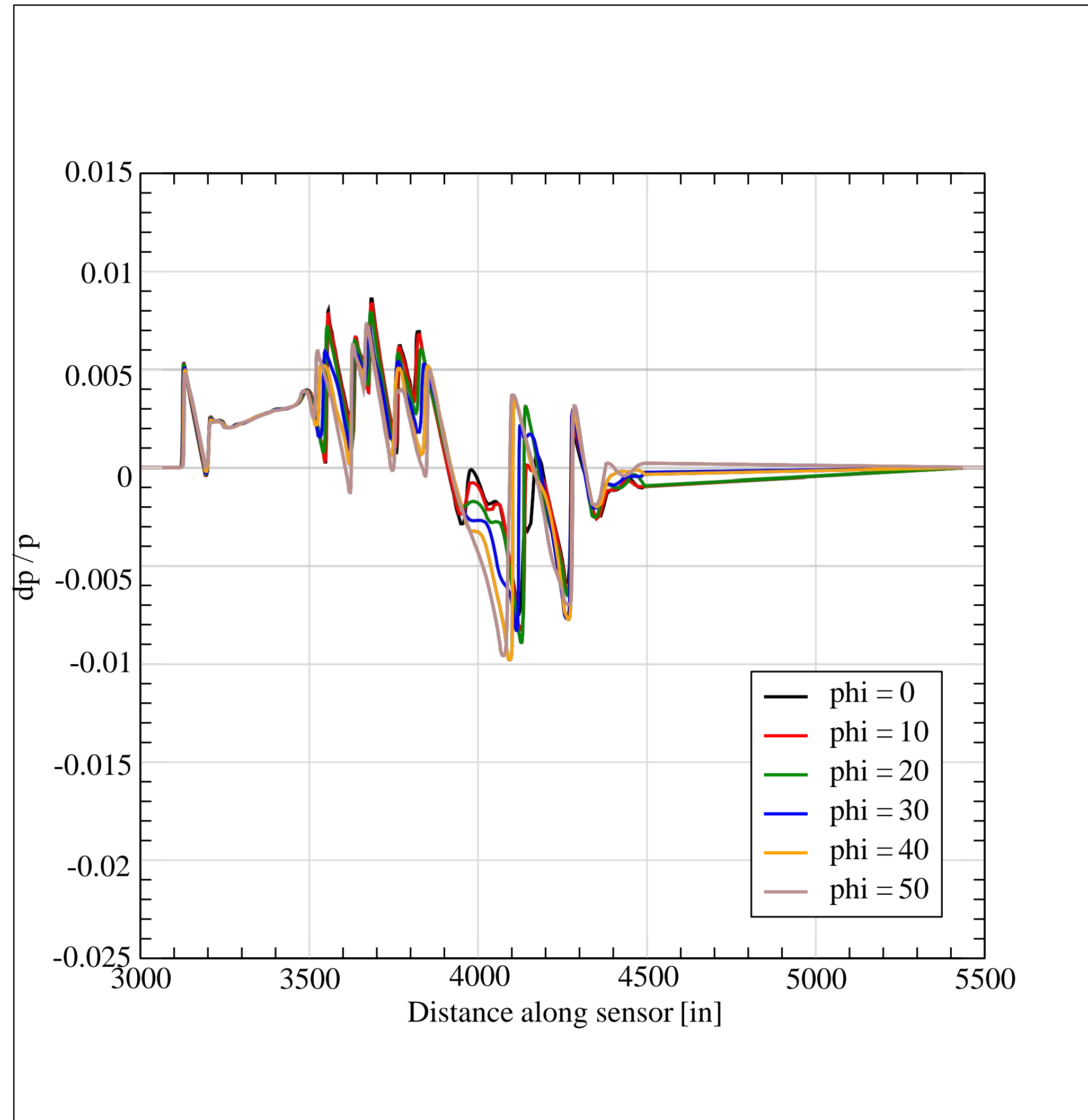
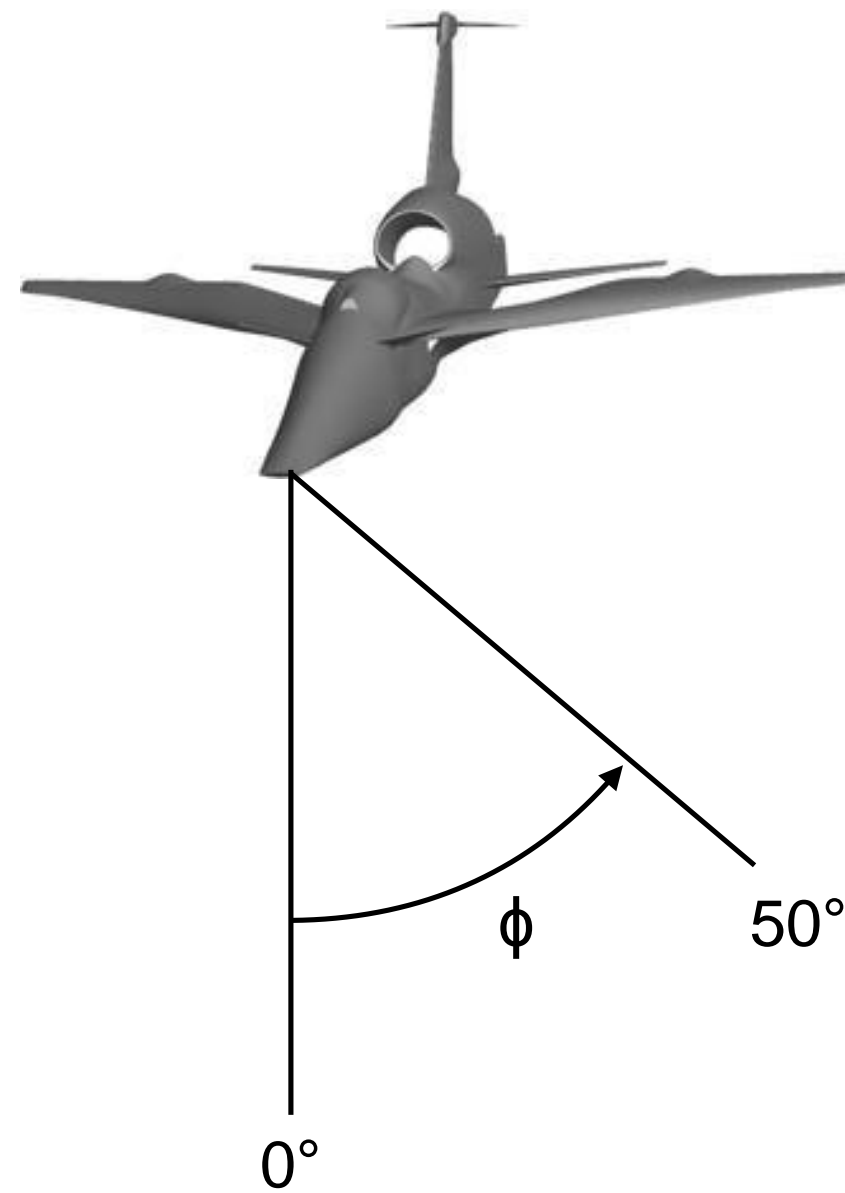
- Separate simulation run at off-track ϕ every 10° for 19 total simulations
- Five line sensors in each sim at offsets of $\Delta\phi = [-4, -2, 0, +2, +4]$
- Covers full half-cylinder $0 \leq \phi \leq 180^\circ$ in increments of 2°



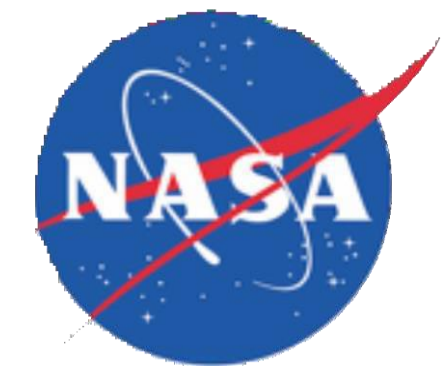
Results: C608



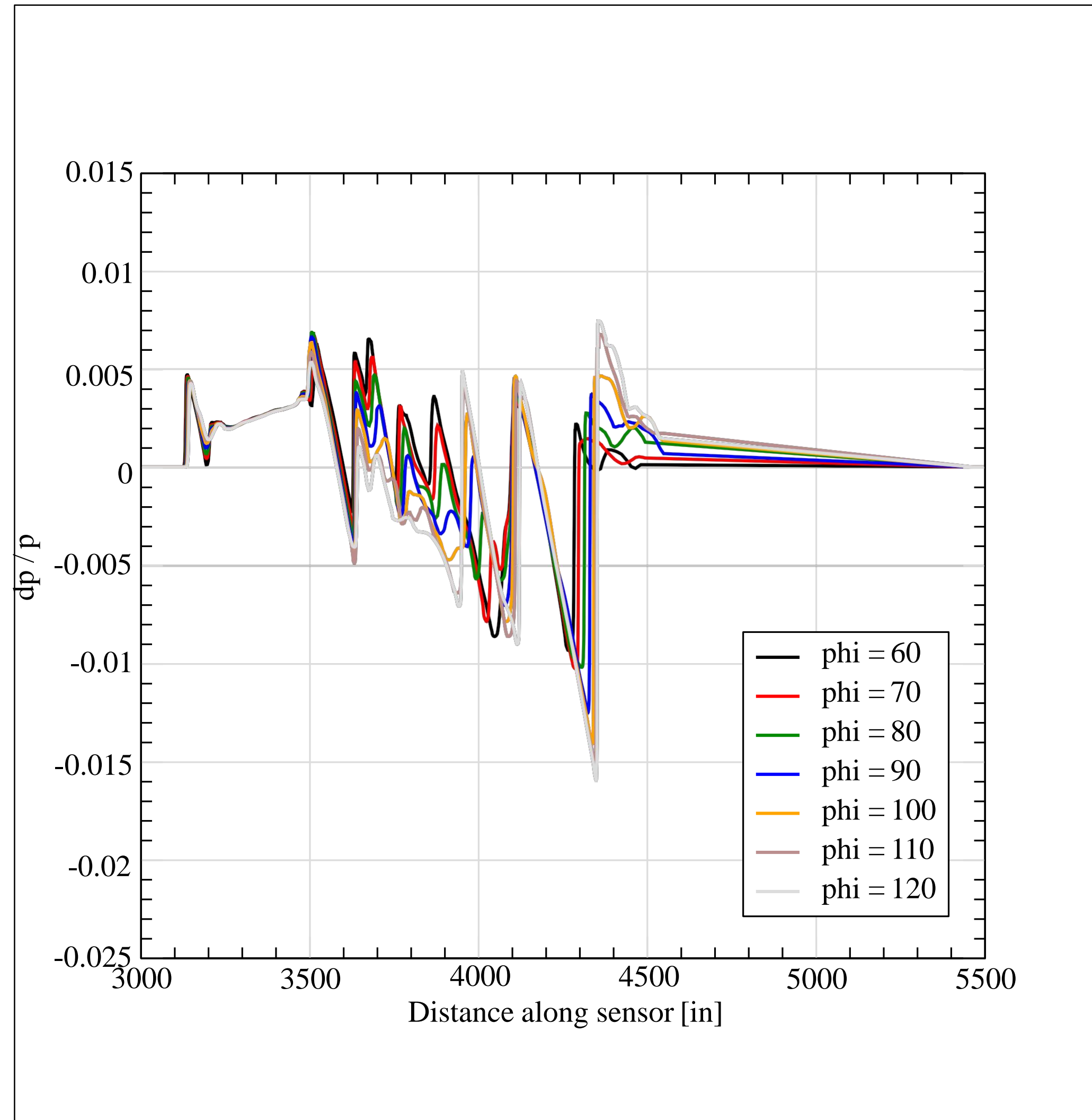
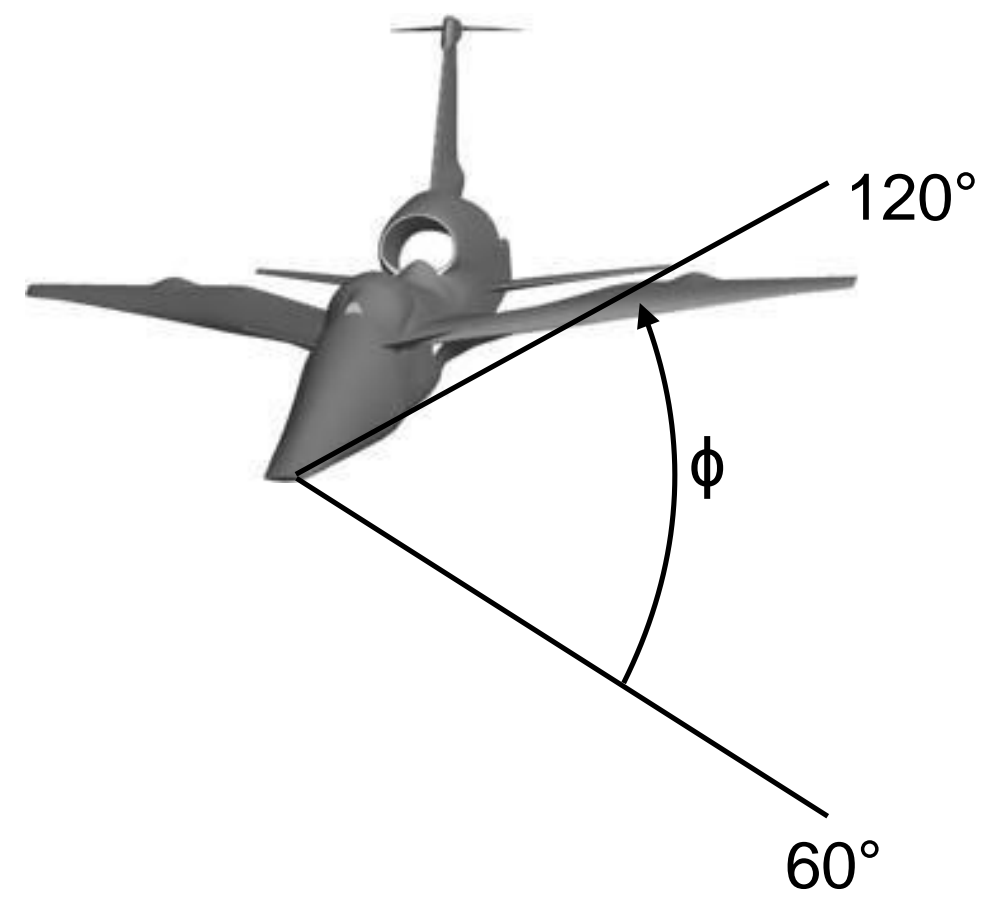
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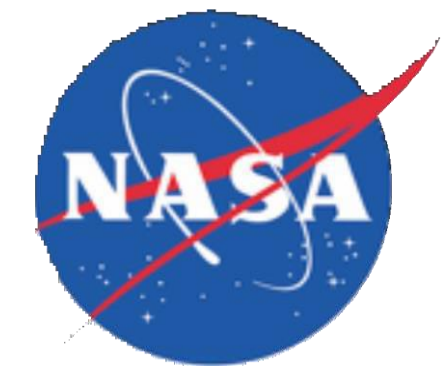
Results: C608



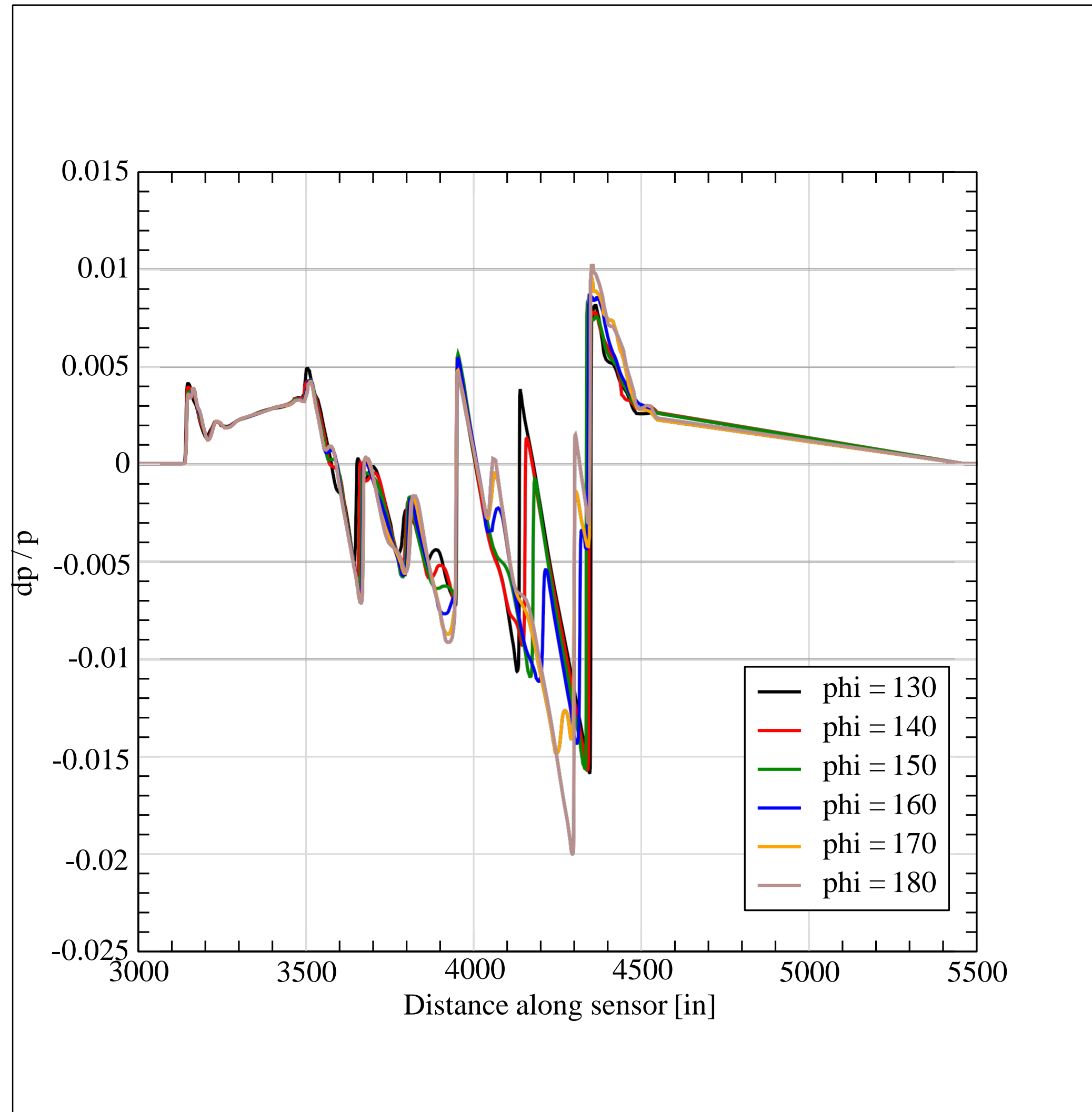
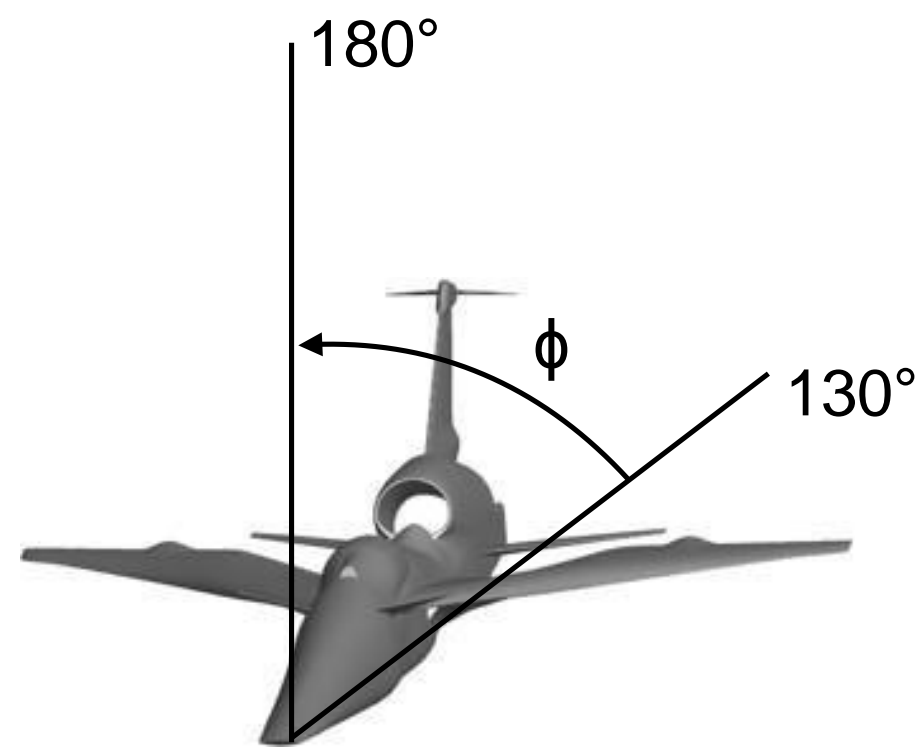
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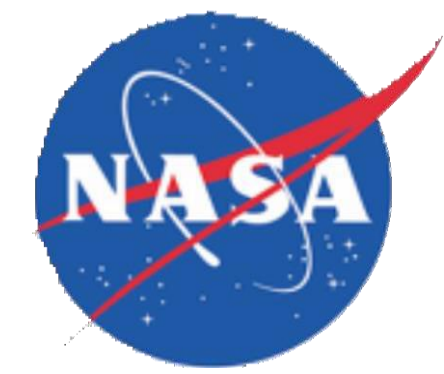
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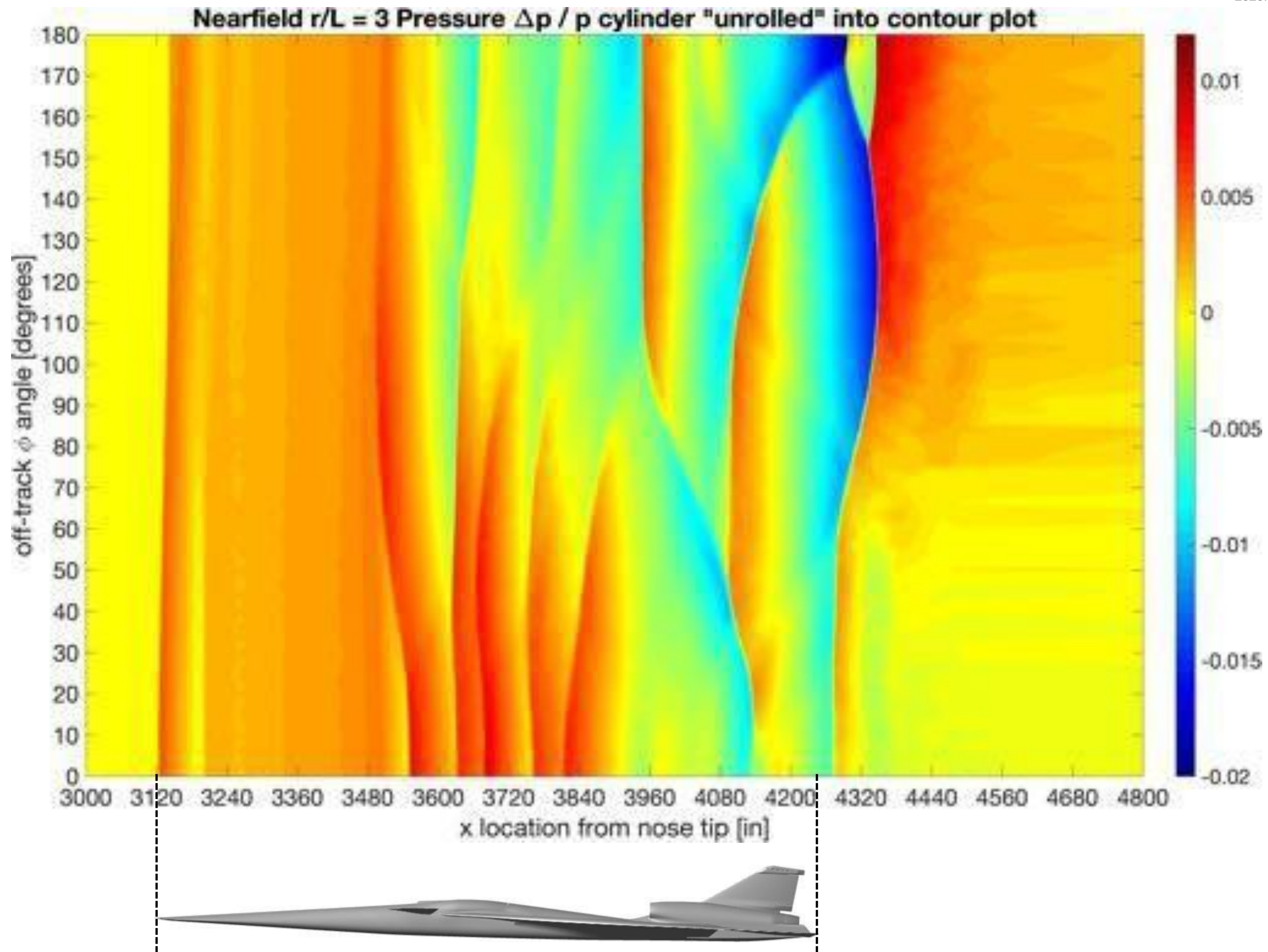
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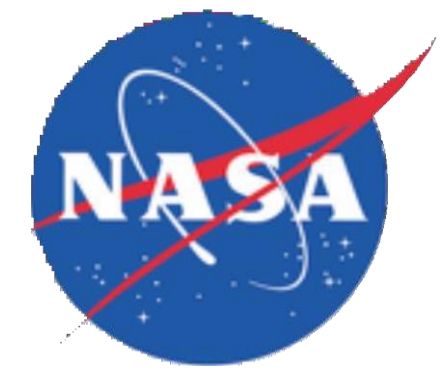
Results: C608



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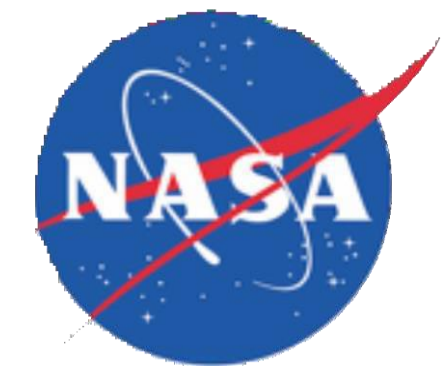
Challenges



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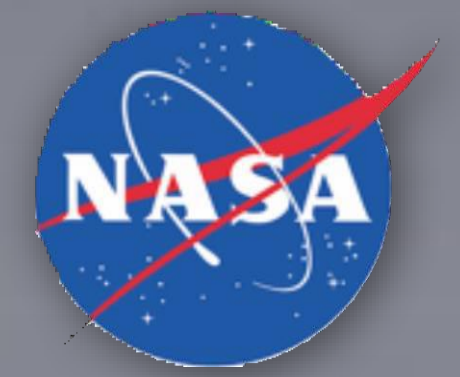
- C608
 - Getting outflow BC's to correct desired Mach number
 - Adjusted the back pressure
 - Engine inlet from suggested 2.6 to 2.75
 - ECS inlets from suggested 1.4 to 2.70
 - Consistent closeouts are challenging
 - Plume/shock is difficult to capture
 - Mesh coarsening farther back in plume can create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

Conclusions

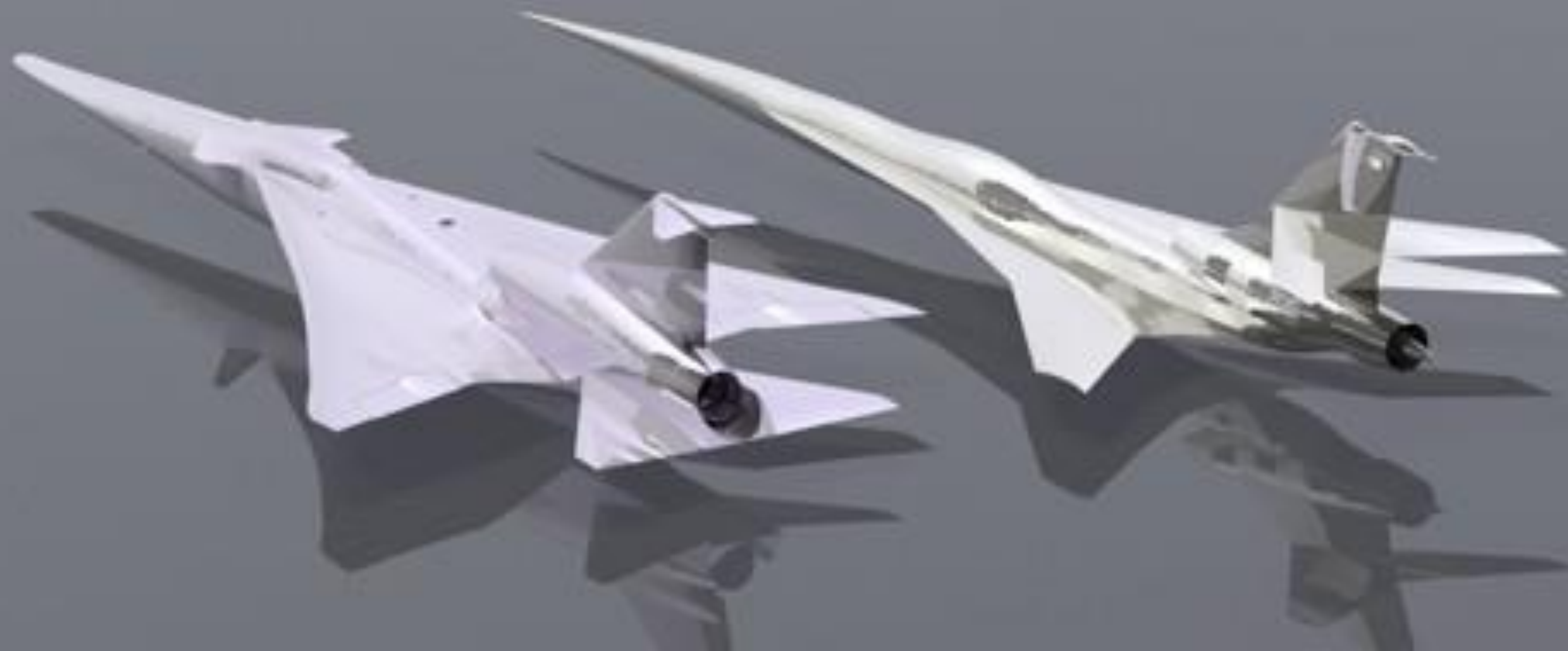


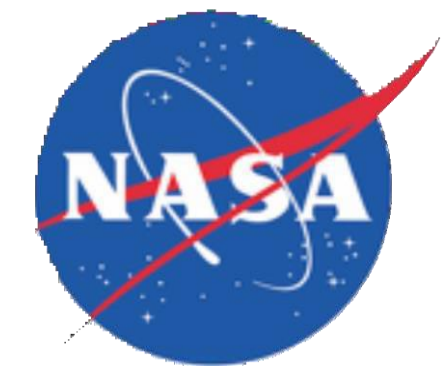
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- Complex geometry increases computational cost
 - More features to resolve
 - Must take pressure signal farther from body
- Adaptive meshing refines based on solution error and objective function
- Must routinely check for solution quality
 - Numerical 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



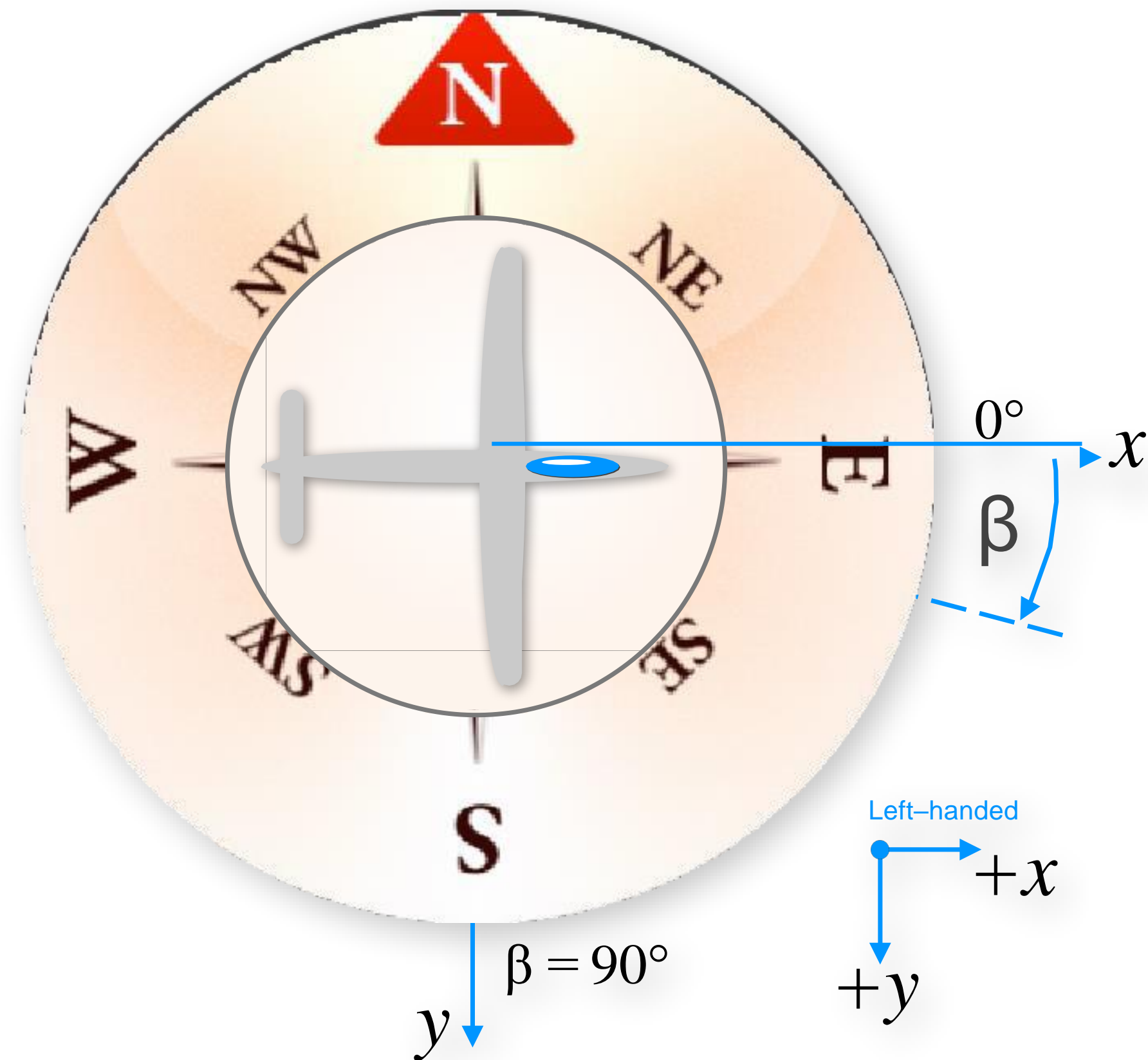


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Farfield Propagation Overview

- 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

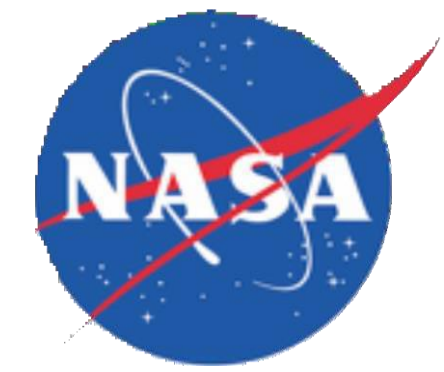
Wind Convention in sBOOM



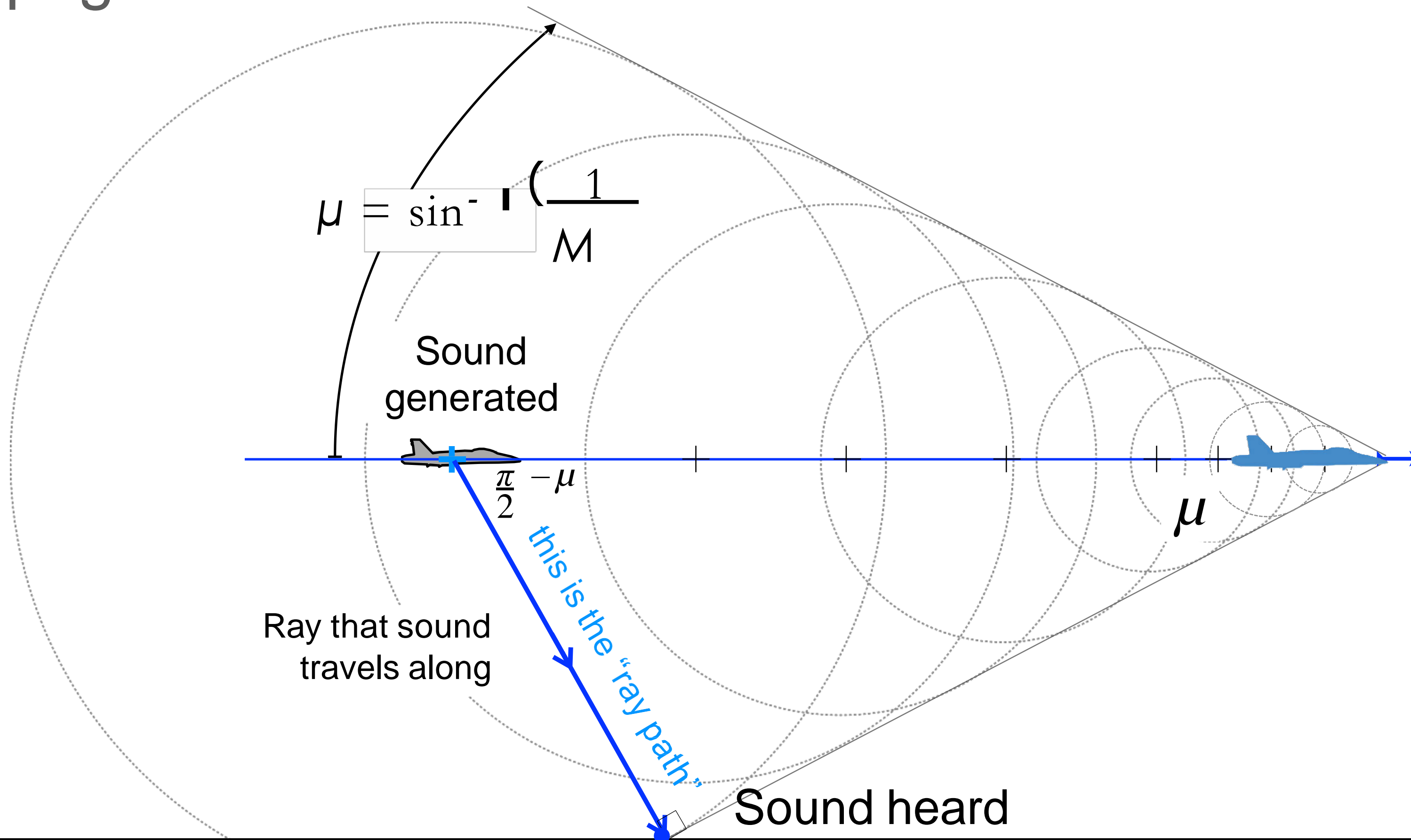
- sBOOM wind uses *left handed* coord. sys.
- β = heading
- $\beta = 0^\circ$ A/C pointed East, cw+
- sBOOM wind tables are in meters vs m/s
- x and y are wind components (“blows toward”)
 - $(x, y) = (1, 0)$ is tail wind if heading is East
 - ↓ $(x, y) = (0, 1)$ is tail wind if heading is South
 - ↘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

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

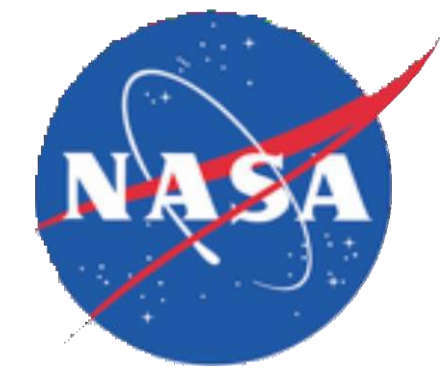
Propagation Primer



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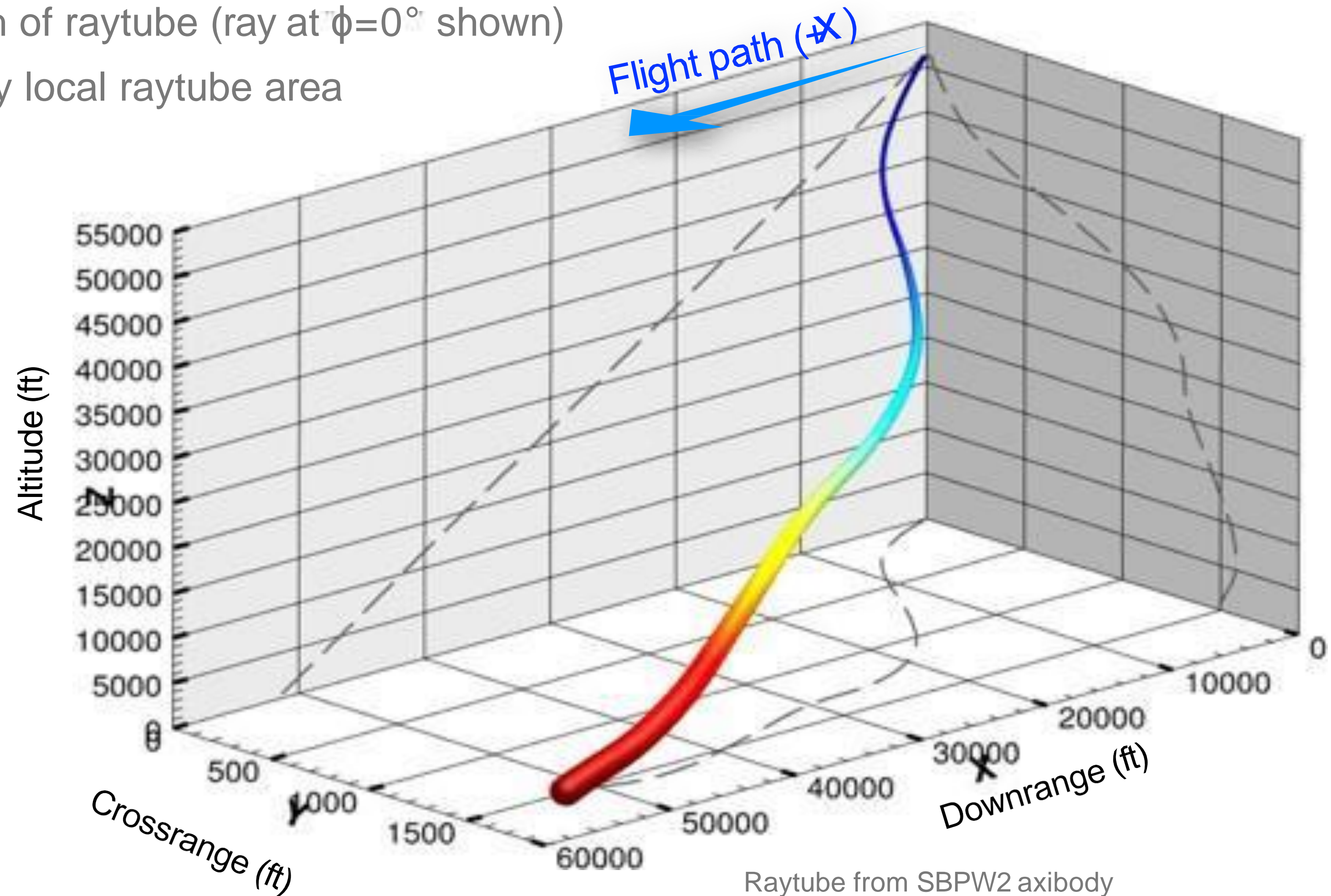
- Quasi-1D integration of Burgers' equations occurs in tube along the ray path
- Determines the ground intercept of sound emanating from given trajectory point & azimuth
- Ray path determines time required for signal propagation

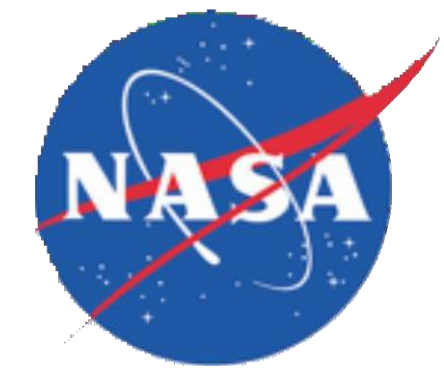


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Wind Effects

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

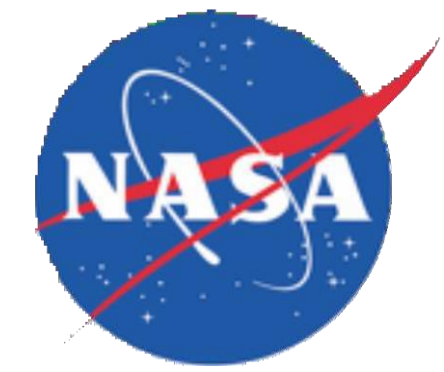




Mesh Convergence

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 Req'd. 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

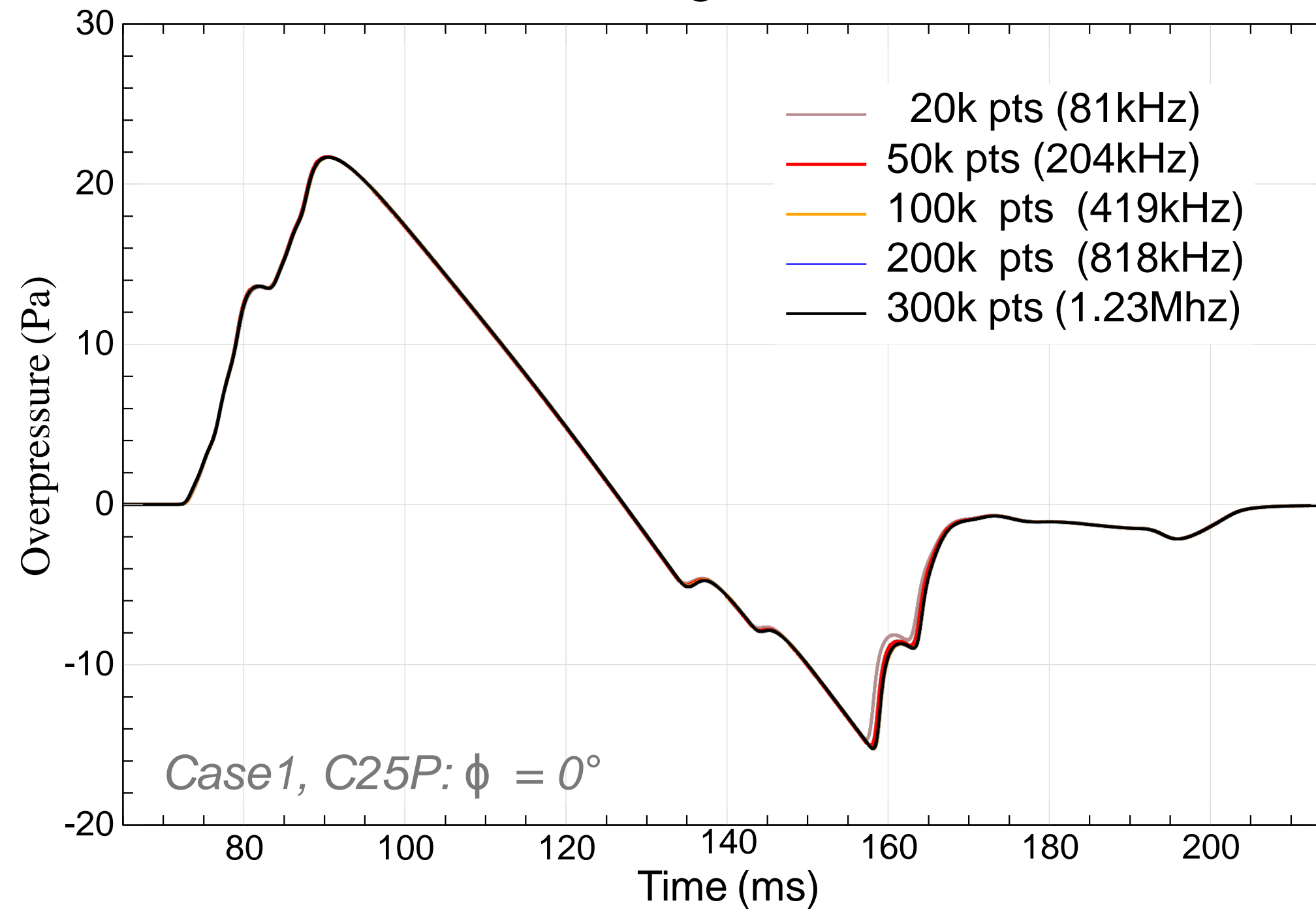


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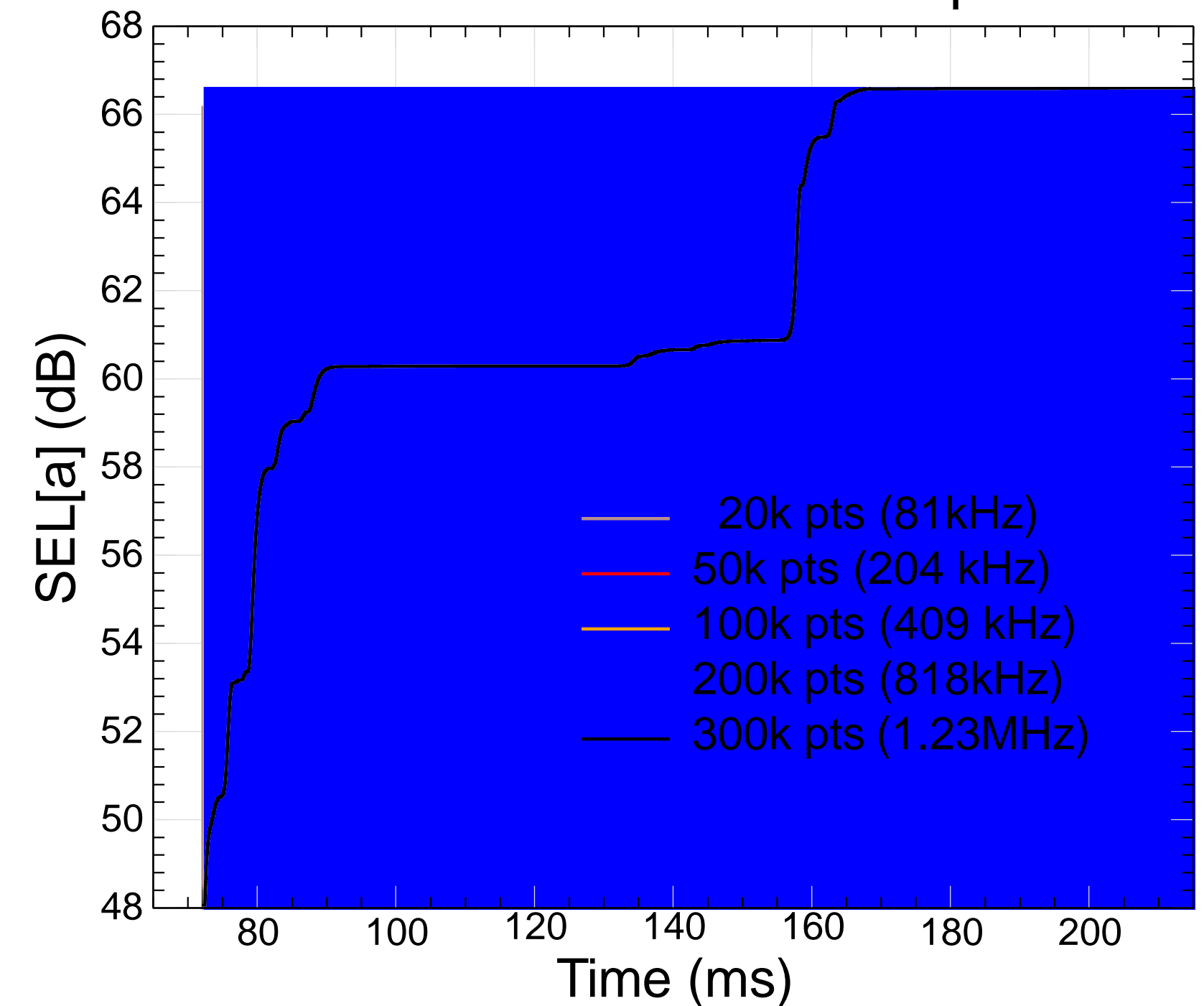
Mesh Convergence

Sensitivity of noise outputs to refinement of the propagation mesh

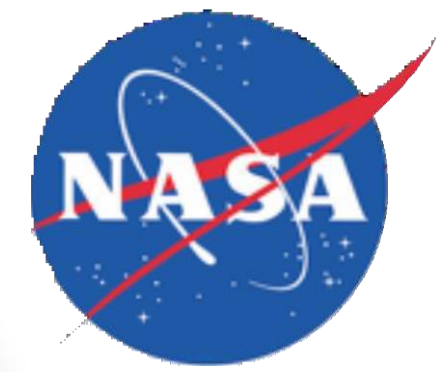
Ground Signature



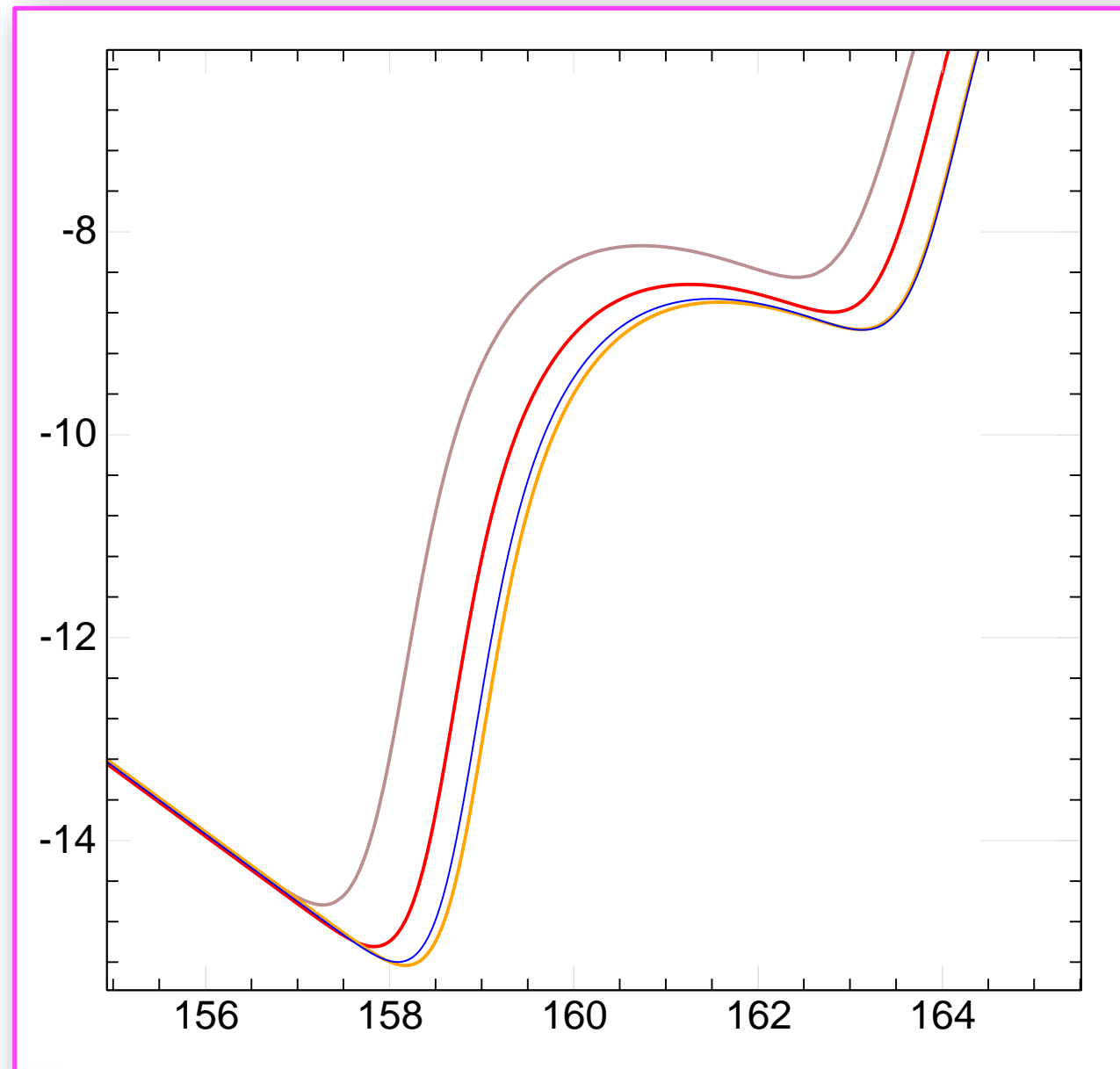
Forward ASEL Buildup



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

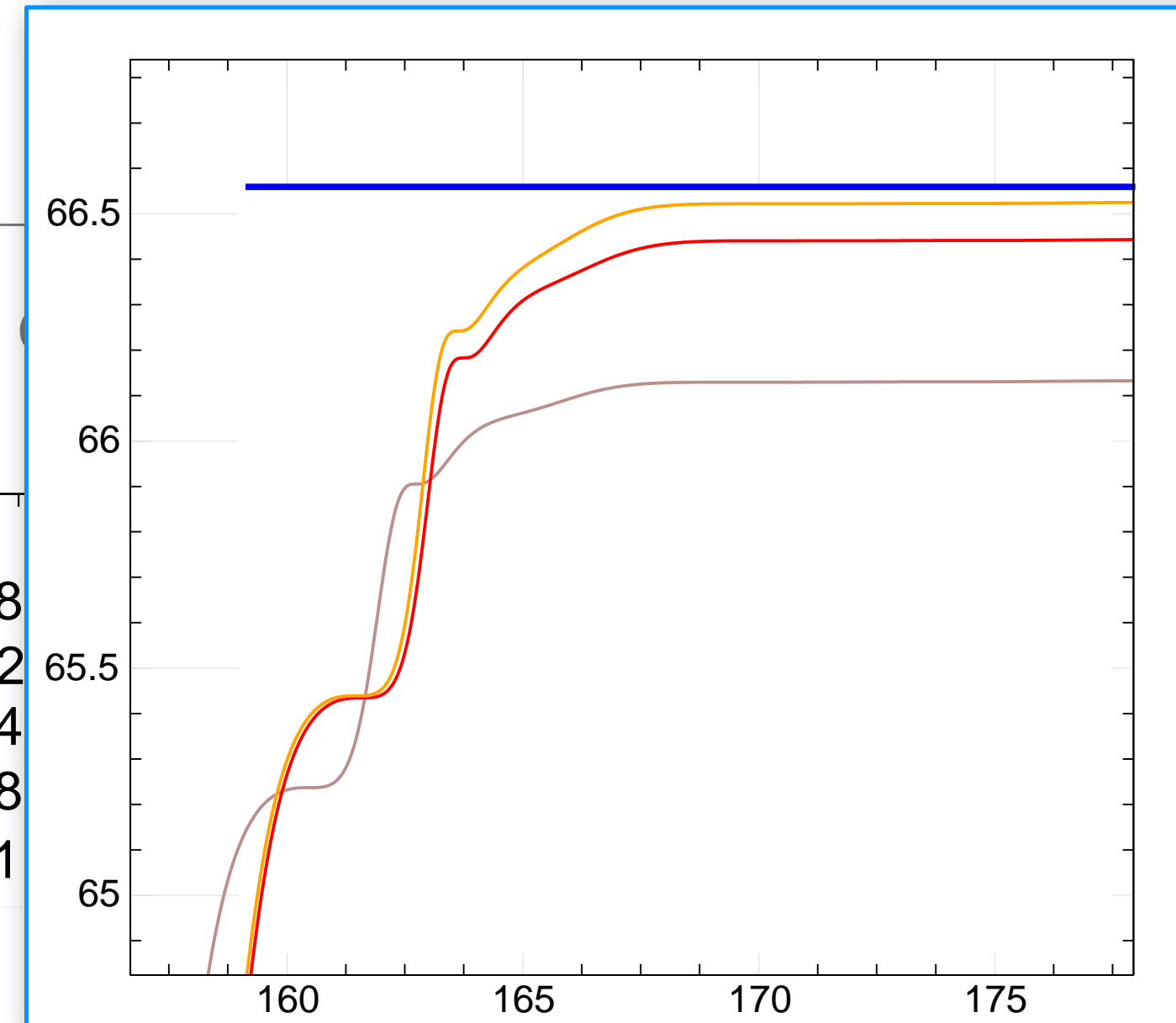


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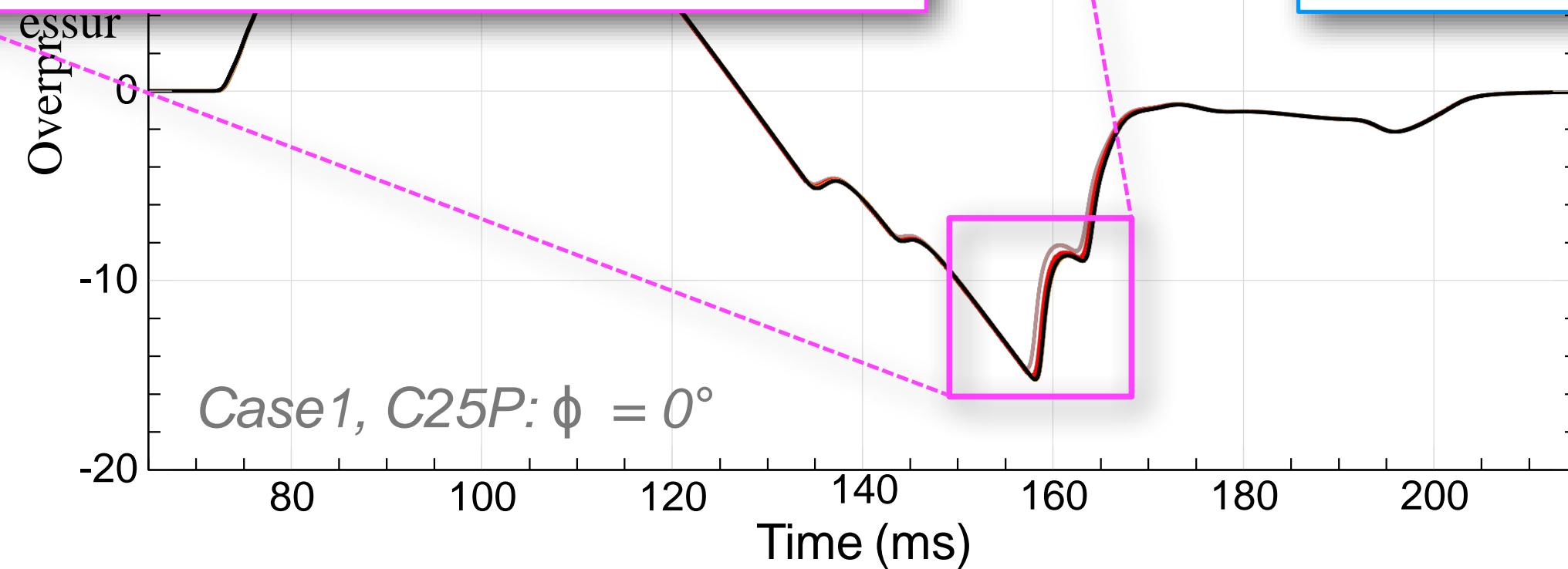
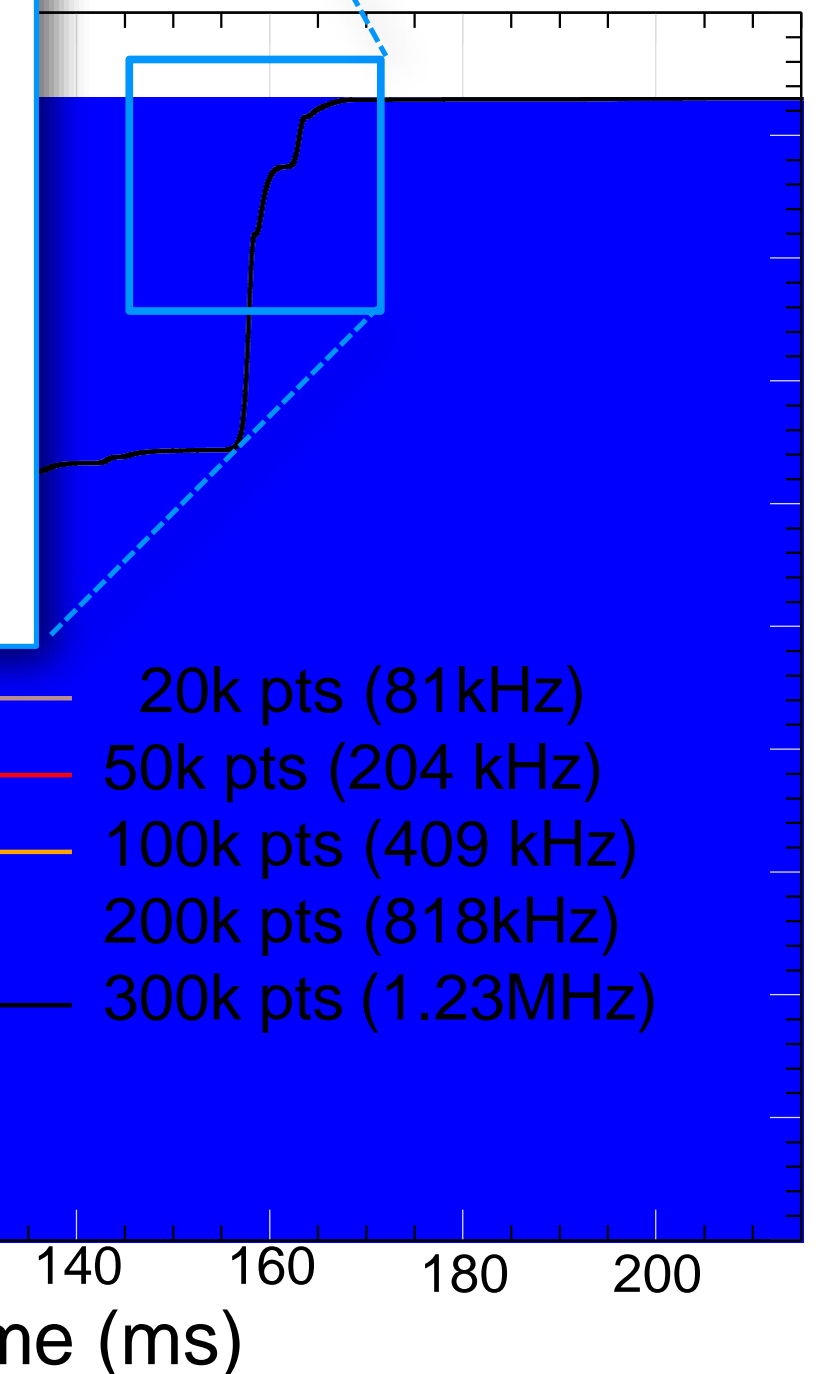


refinement
ure

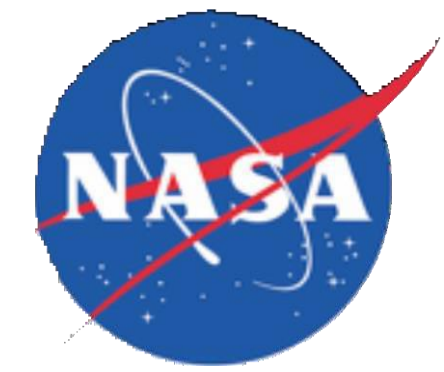
- 20k pts (81 kHz)
- 50k pts (204 kHz)
- 100k pts (409 kHz)
- 200k pts (818 kHz)
- 300k pts (1.23 MHz)



ASEL Buildup

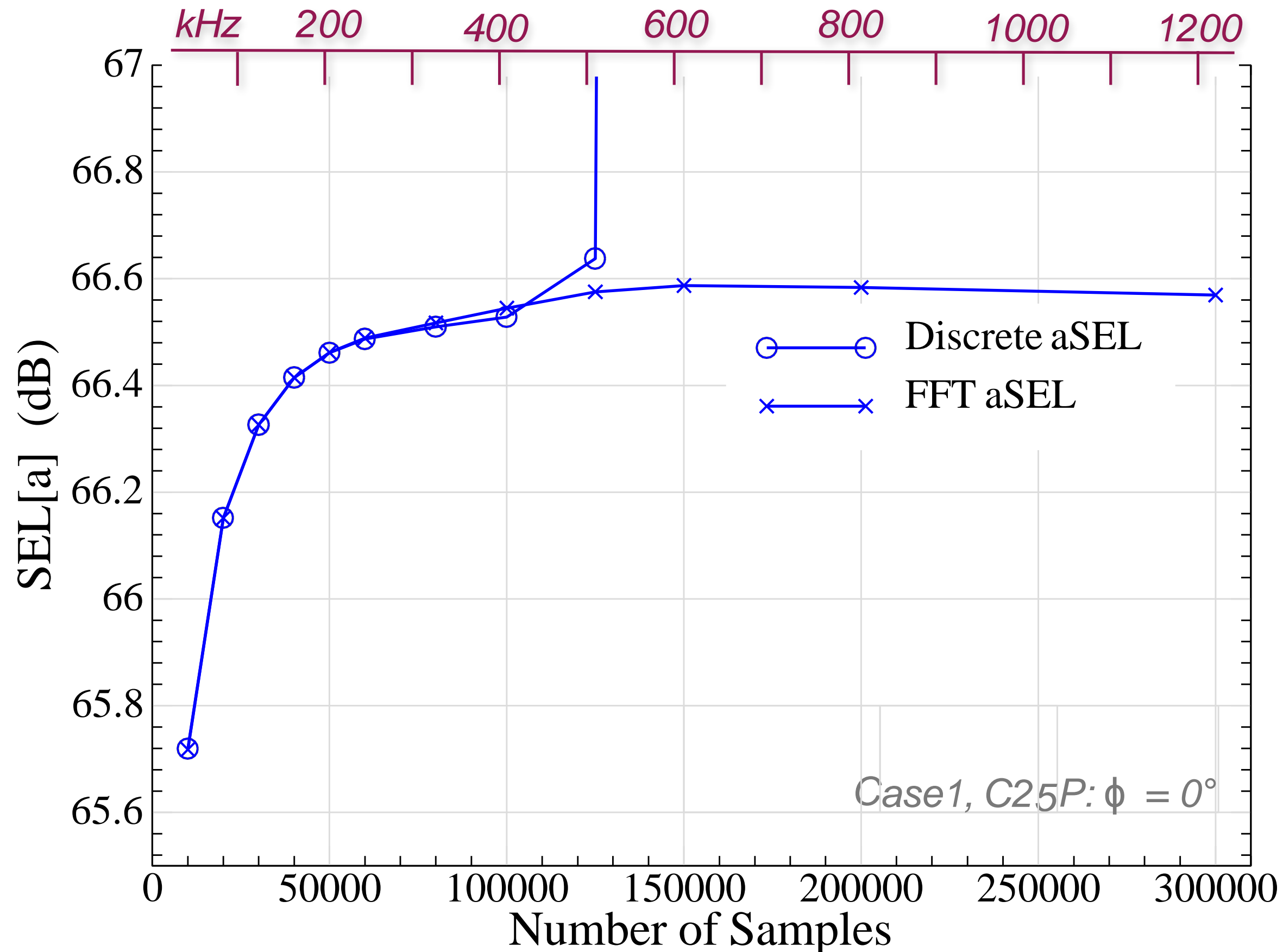


- C25P signals at $\phi = 0^\circ$, using from 20k 300k points (80-1230 kHz) for propagation
- Despite similarities in ground signal, mesh convergence of ASEL is quite slow

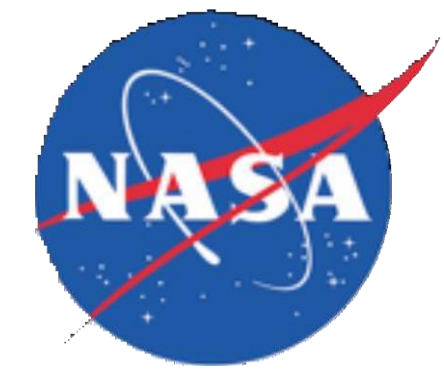


Mesh Convergence

Convergence ASEL noise metric with sampling frequency

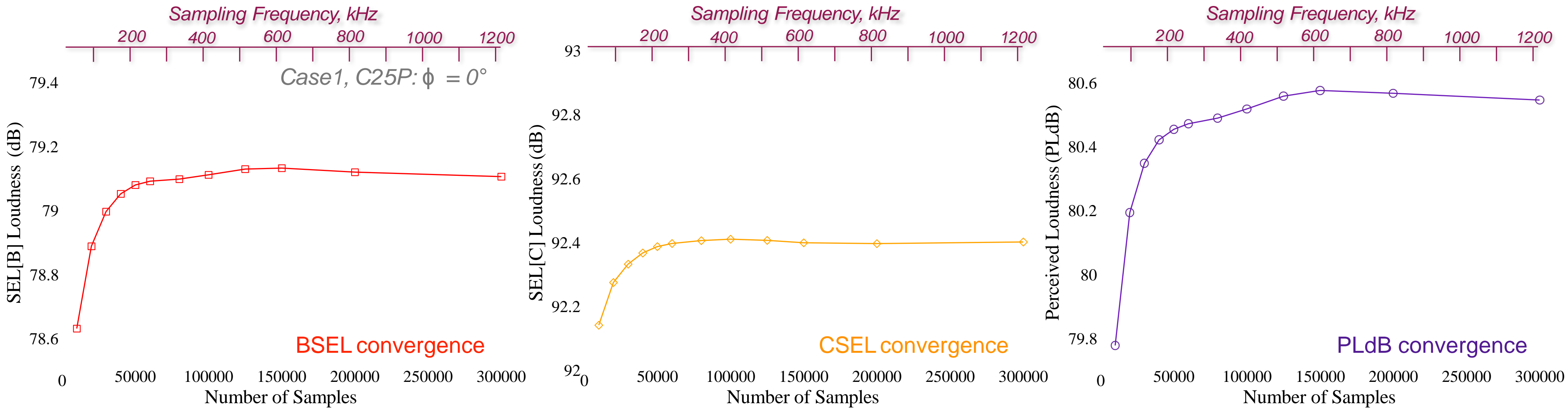


- ASEL converges slowly
 - Need ~600kHz (~150k pts) to converge ASEL to ± 0.01 dB
- However, discrete ASEL filter starts to have issues at ~250kHz, and blows up ~500kHz
- On this case (C25P) hard to guarantee ASEL error $< \pm 0.1$ dB
- Discrete BSEL and CSEL remain well behaved till ~1 & 10 MHz (respectively),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

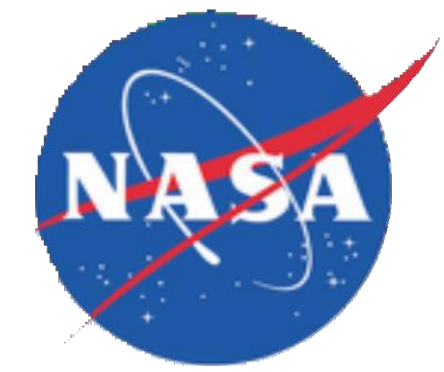


Mesh Convergence

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

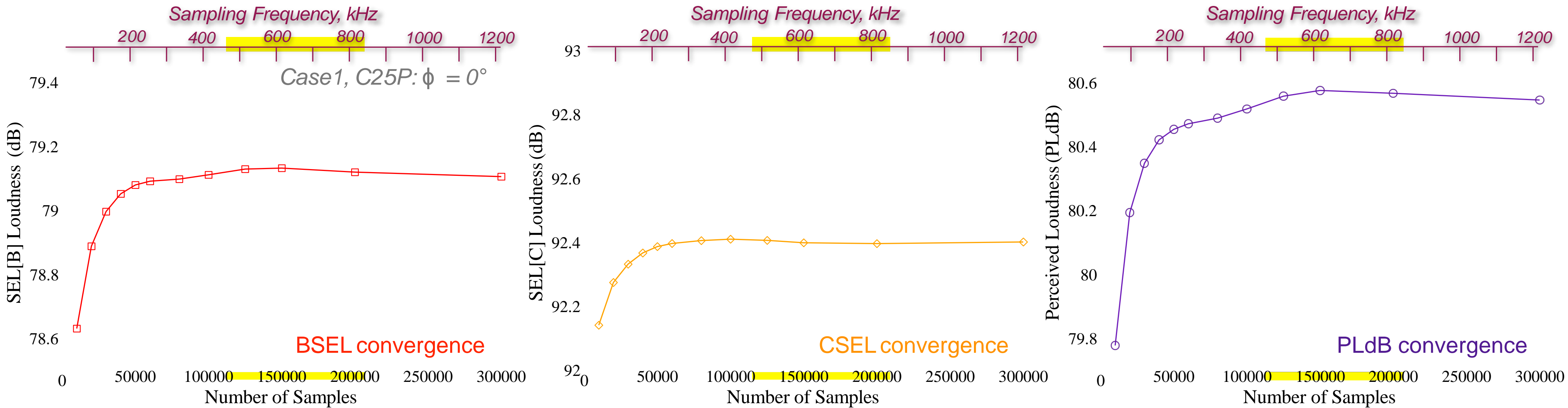


- BSEL, CSEL and PLdB all show good mesh convergence (all on 1 dB scale)
- FFT used for all metrics except for BSEL, but appears to be well behaved
- C-weighting converges fastest (± 0.02 dB @200kHz)
- PLdB converges slowest (approx. ± 0.1 dB @200kHz)

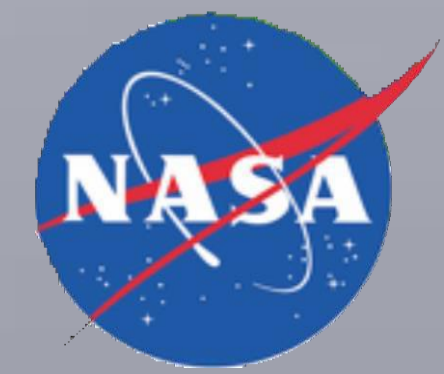


Mesh Convergence

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



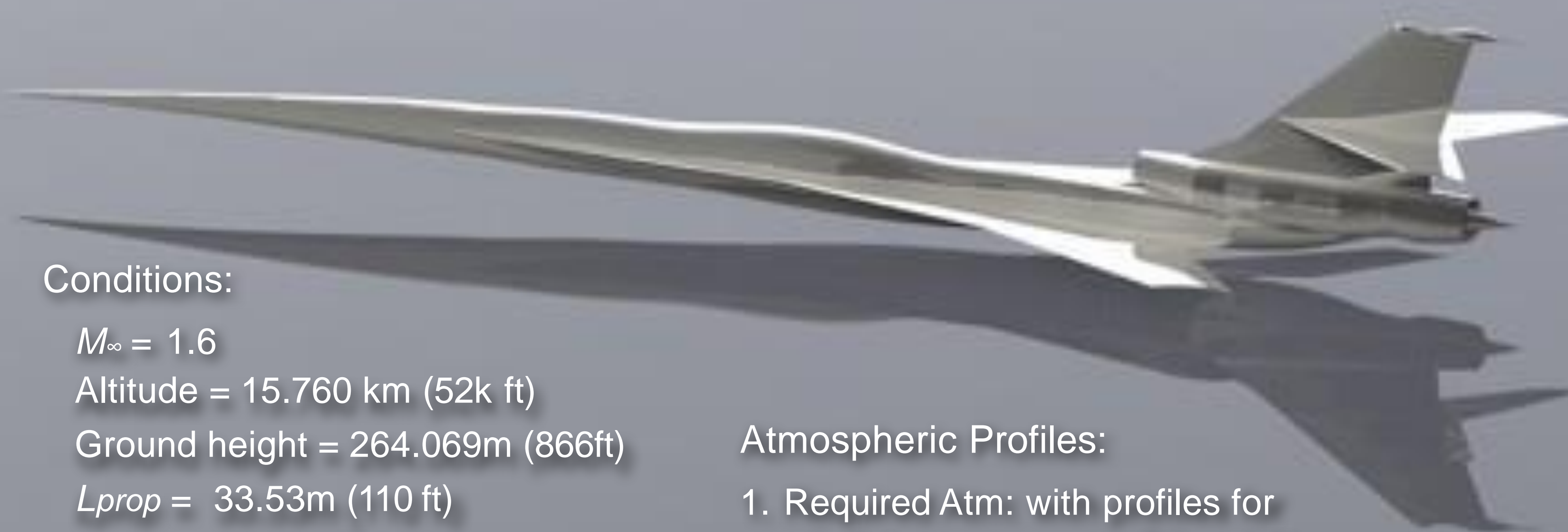
- To avoid excessive discretization error in propagation used 500-800kHz sampling frequencies for all workshop cases
- Computed noise metrics with FFT in LCASB (*adlound*) for ASEL, CSEL and PLdB noise metrics
- Used digital BSEL filter in sBOOM (well behaved at 500-800kHz)



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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)

$$L_{prop} = 33.53\text{m (110 ft)}$$

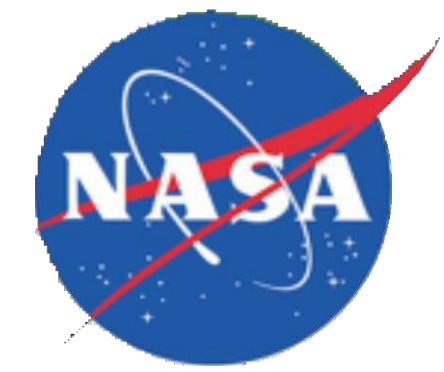
$r/L = 3.0$ at signal extraction

Ground reflection factor = 1.9

Heading East ($\beta = 0^{\circ}$)

Atmospheric Profiles:

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

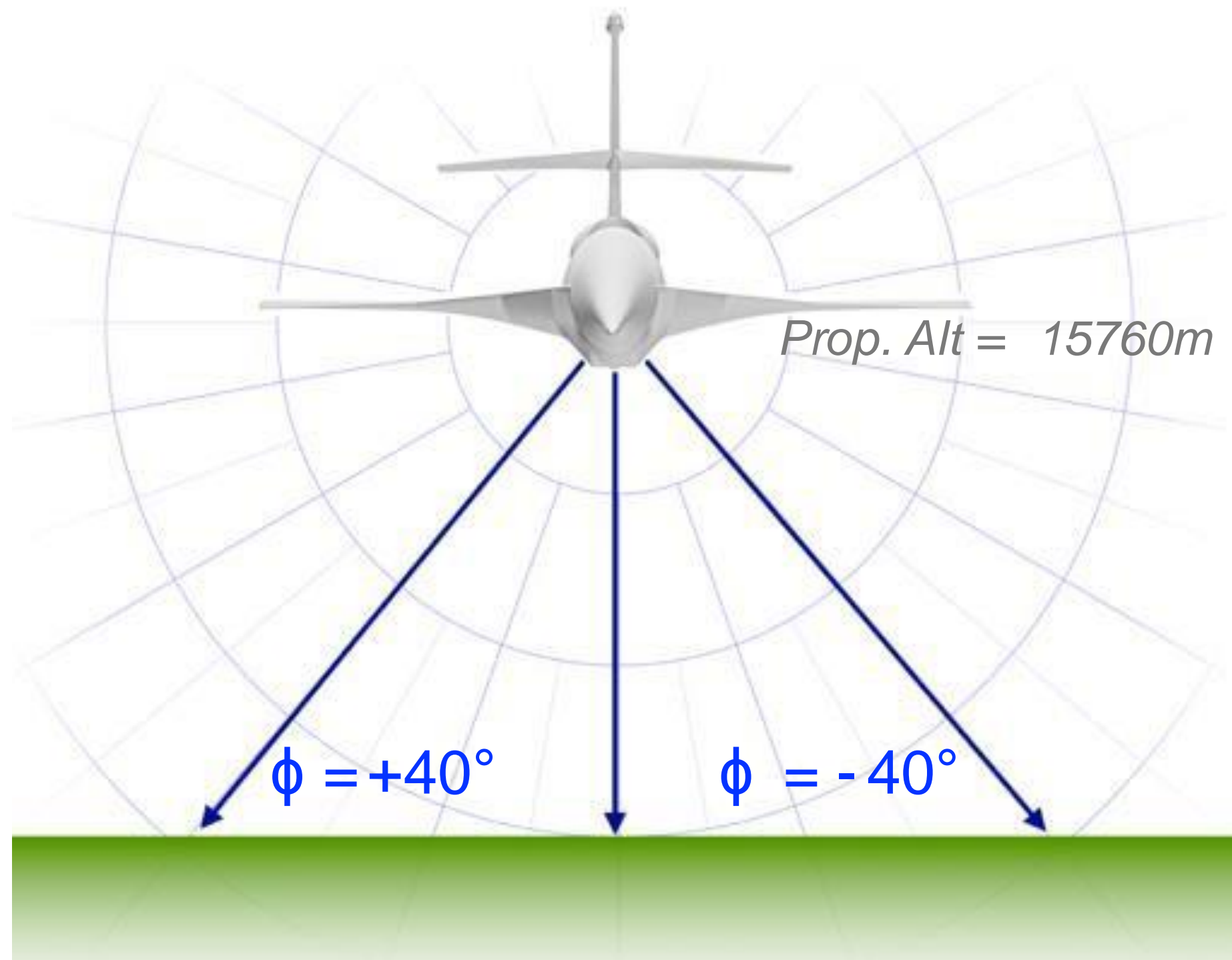


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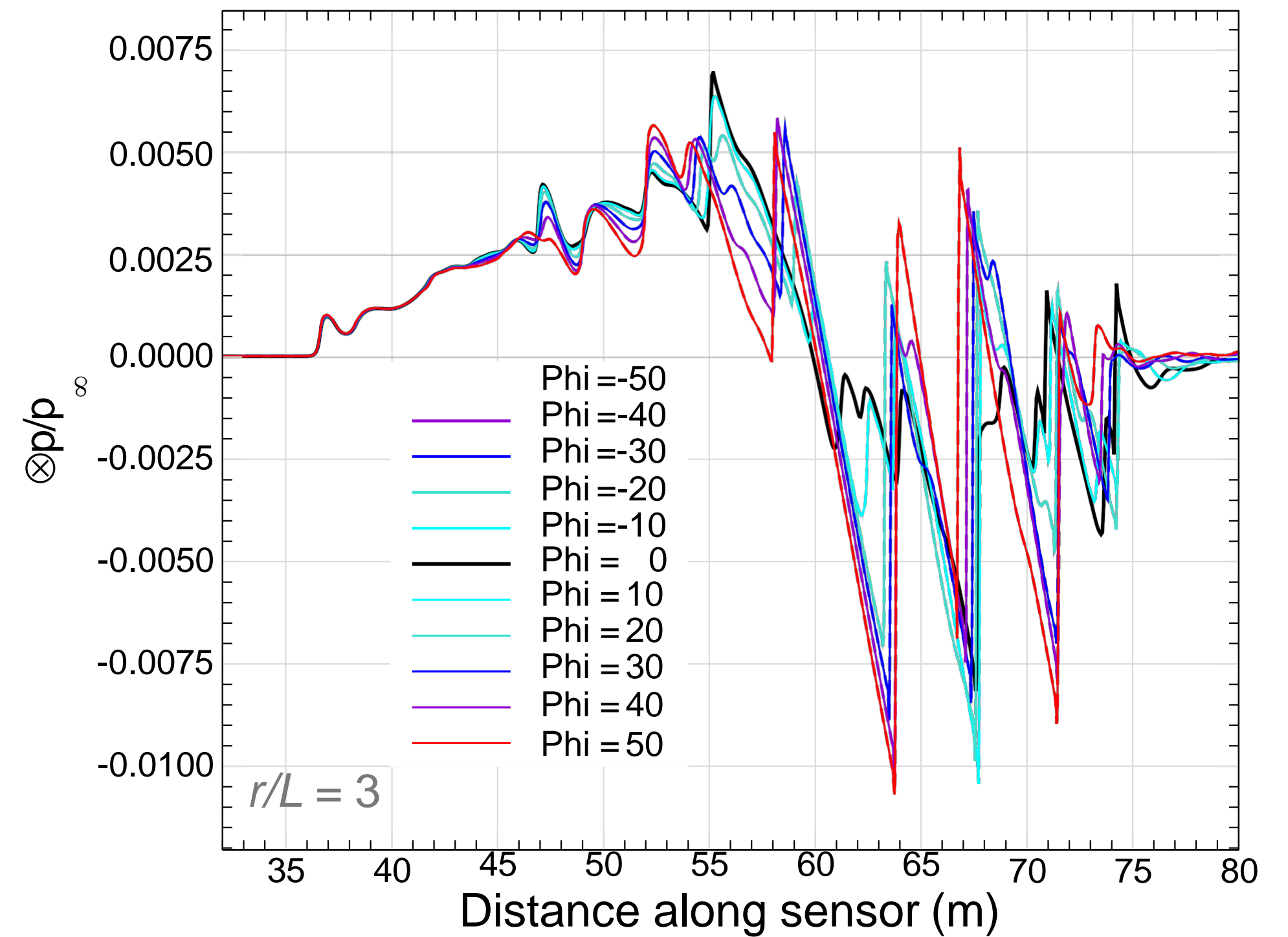
Case 1: C25P Standard Atmosphere

Near field and ground pressure signals

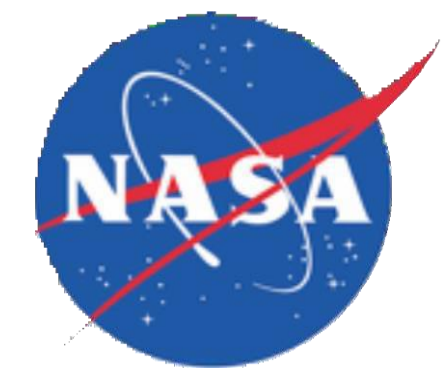
Sign Convention for Azimuth, ϕ



Near Field Signals



- Near field data provided for half-cylinder $\{-90^\circ, 90^\circ\}$, ($\{-50^\circ, 50^\circ\}$ shown)

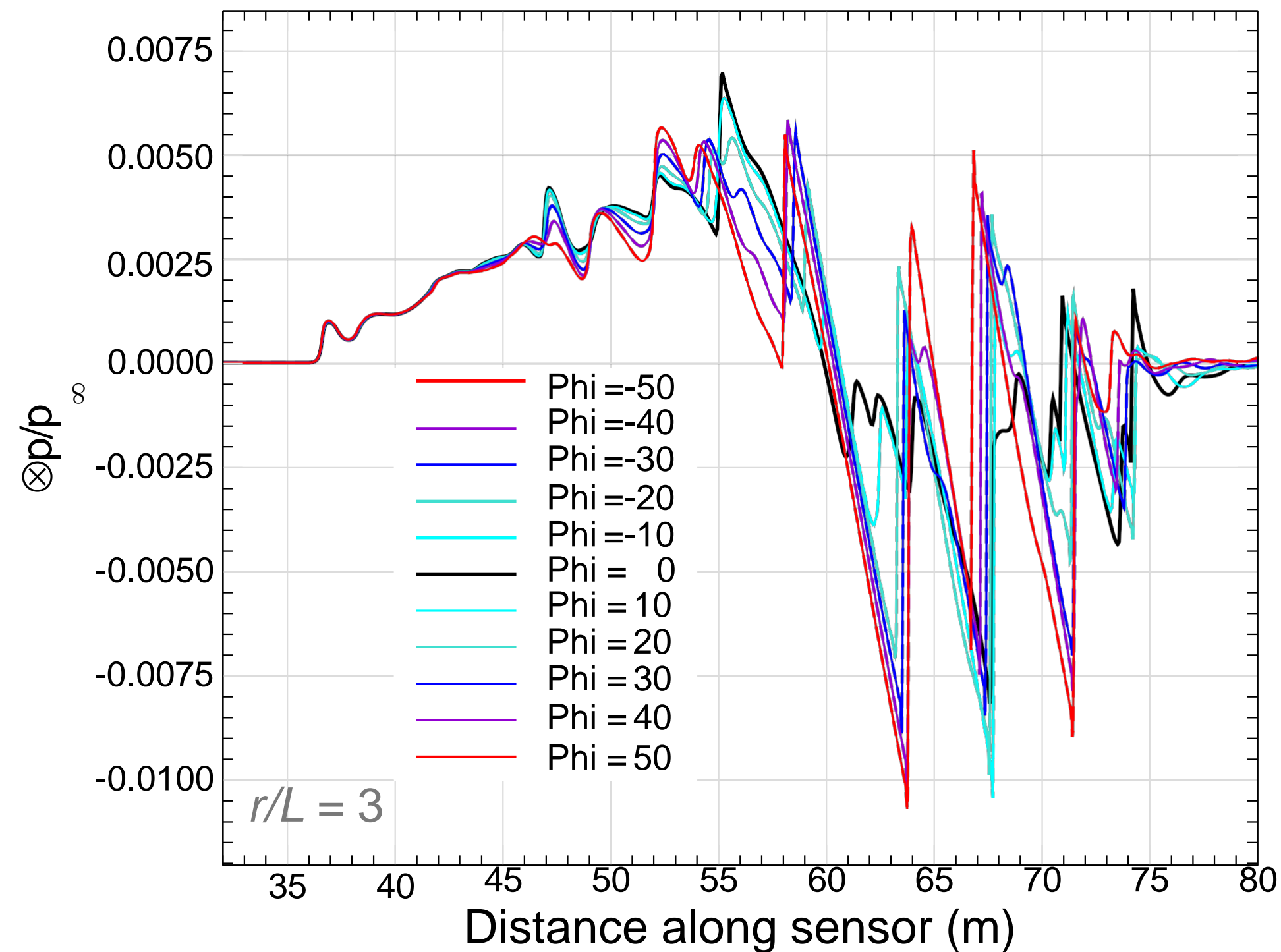


2020.03.05 ARC/TNA

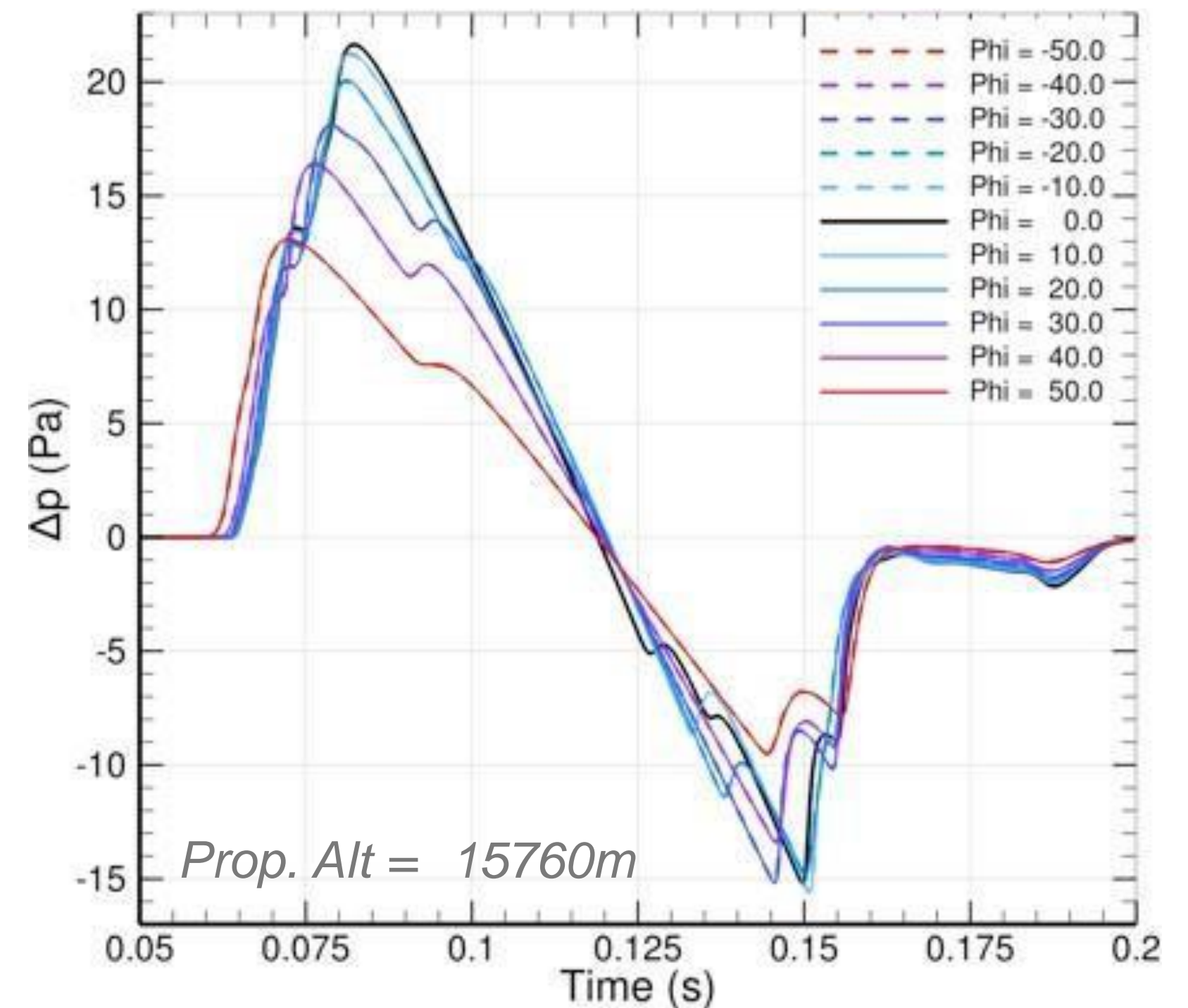
Case 1: C25P Standard Atmosphere

Propagation altitude = 15760m, ground height = 264m

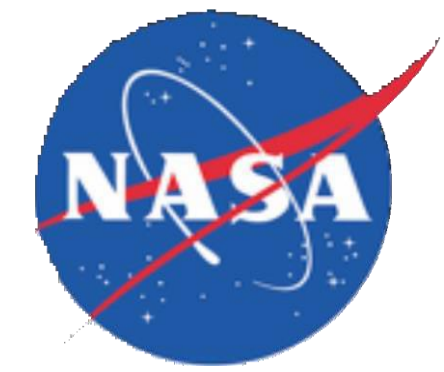
Near Field Signal



Ground Signature



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

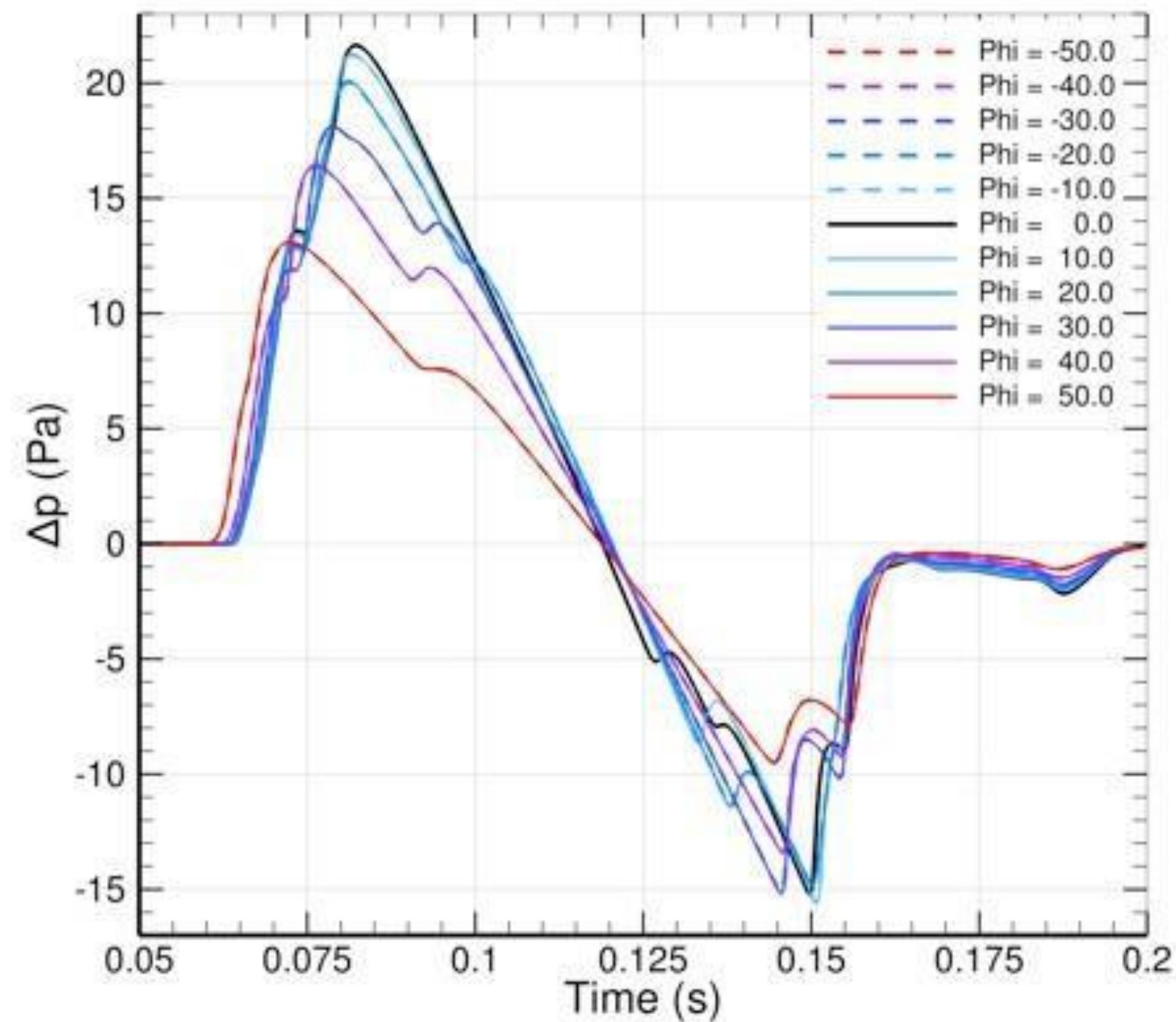


2020.03.05 ARC/TNA

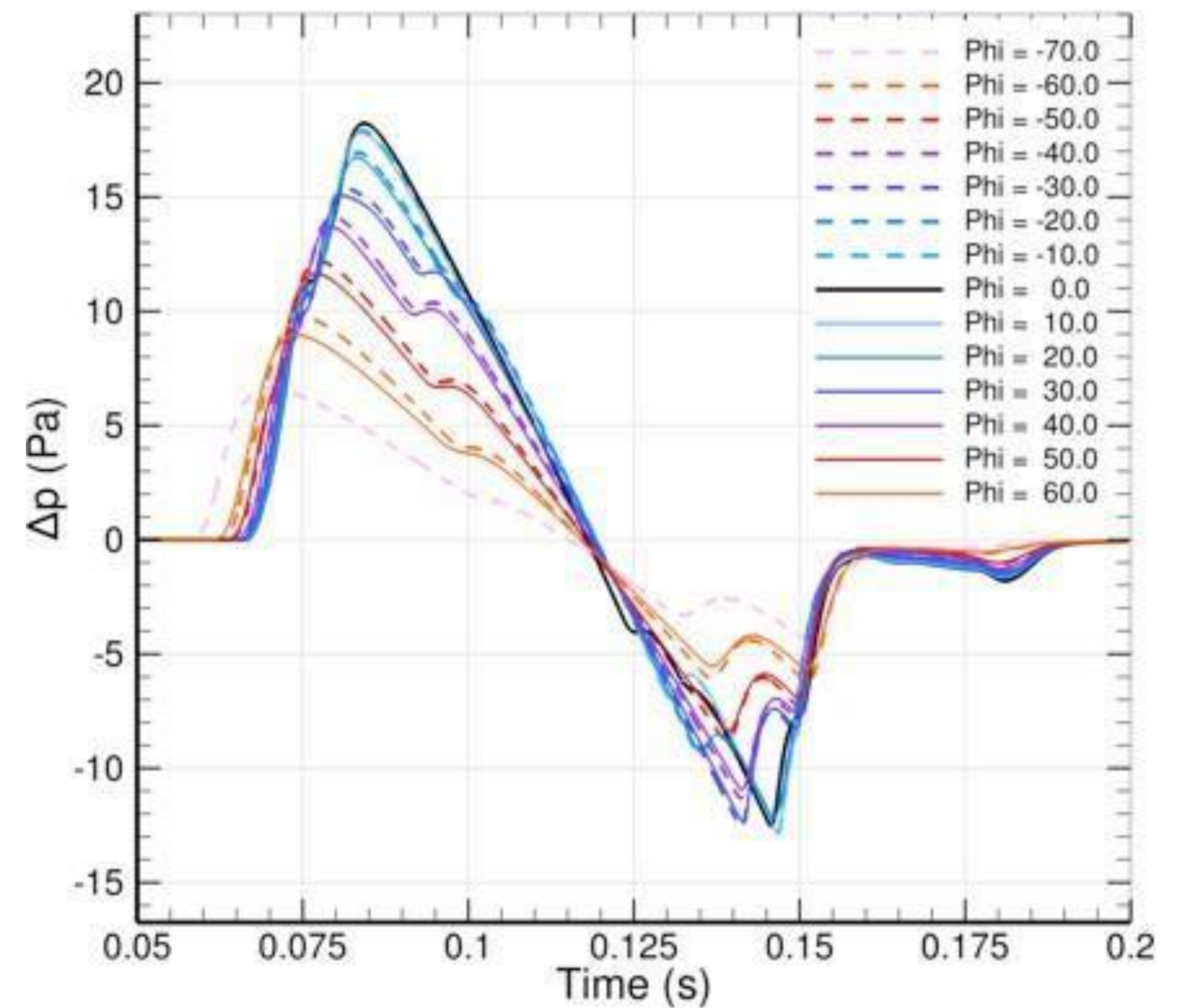
Case 1: C25P Ground Signatures

Propagation altitude = 15760m, ground height = 264m

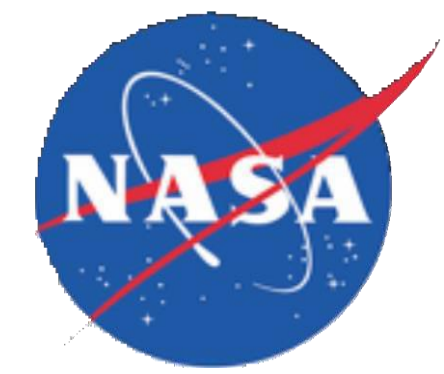
Standard Atmosphere



Required Atmosphere



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

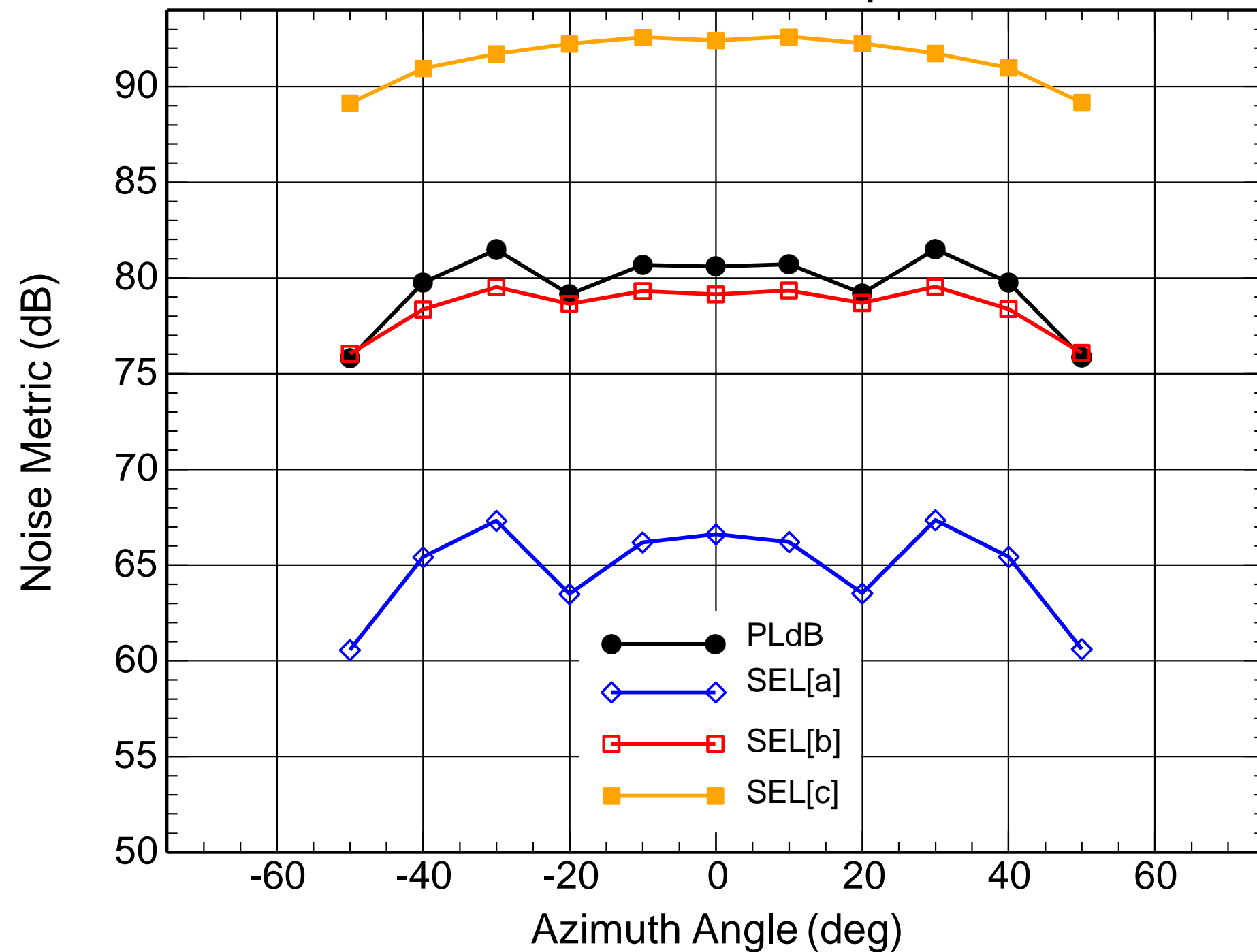


2020.03.05 ARC/TNA

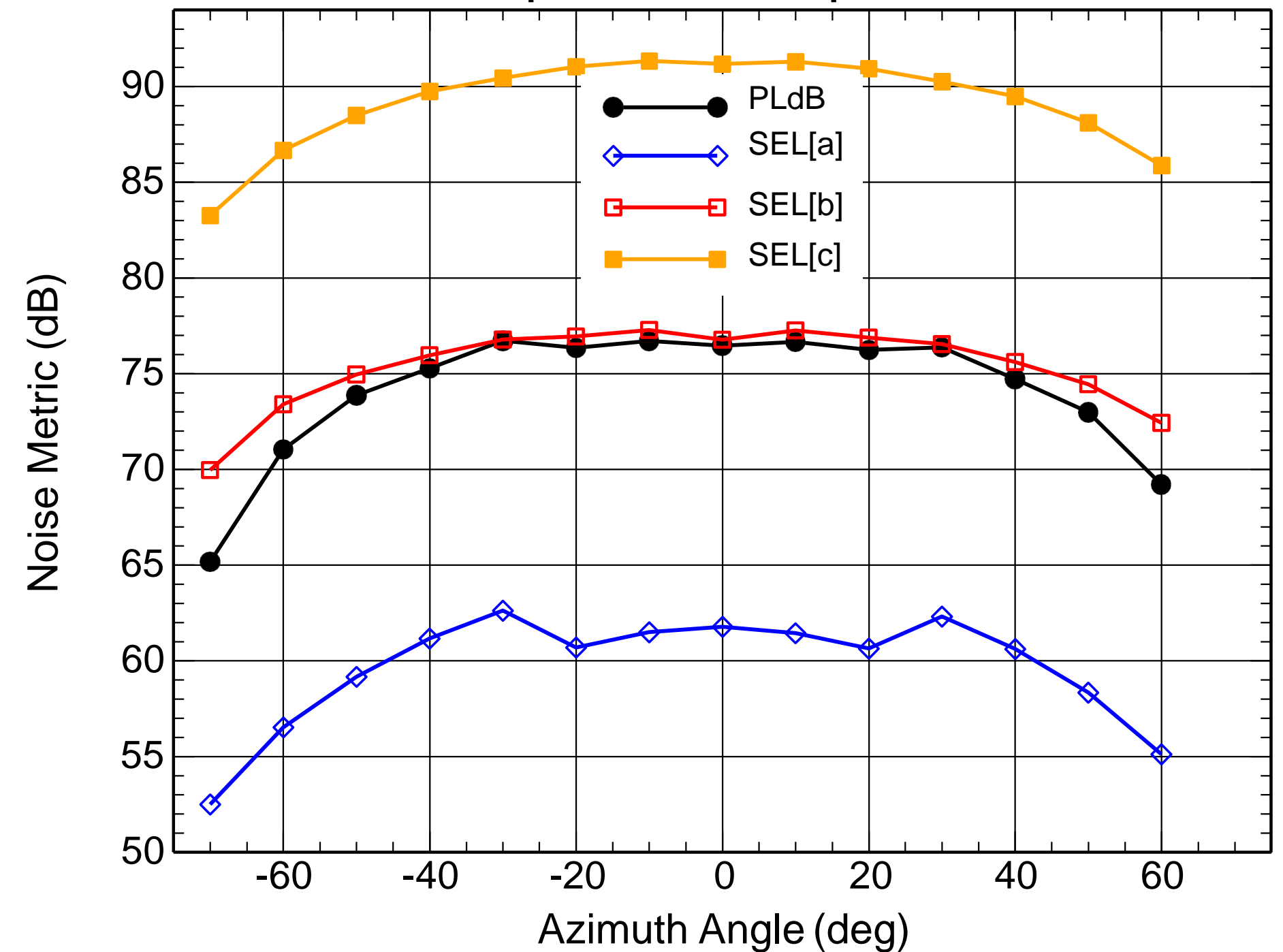
Case 1: C25P Ground Noise

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

Standard Atmosphere



Required Atmosphere

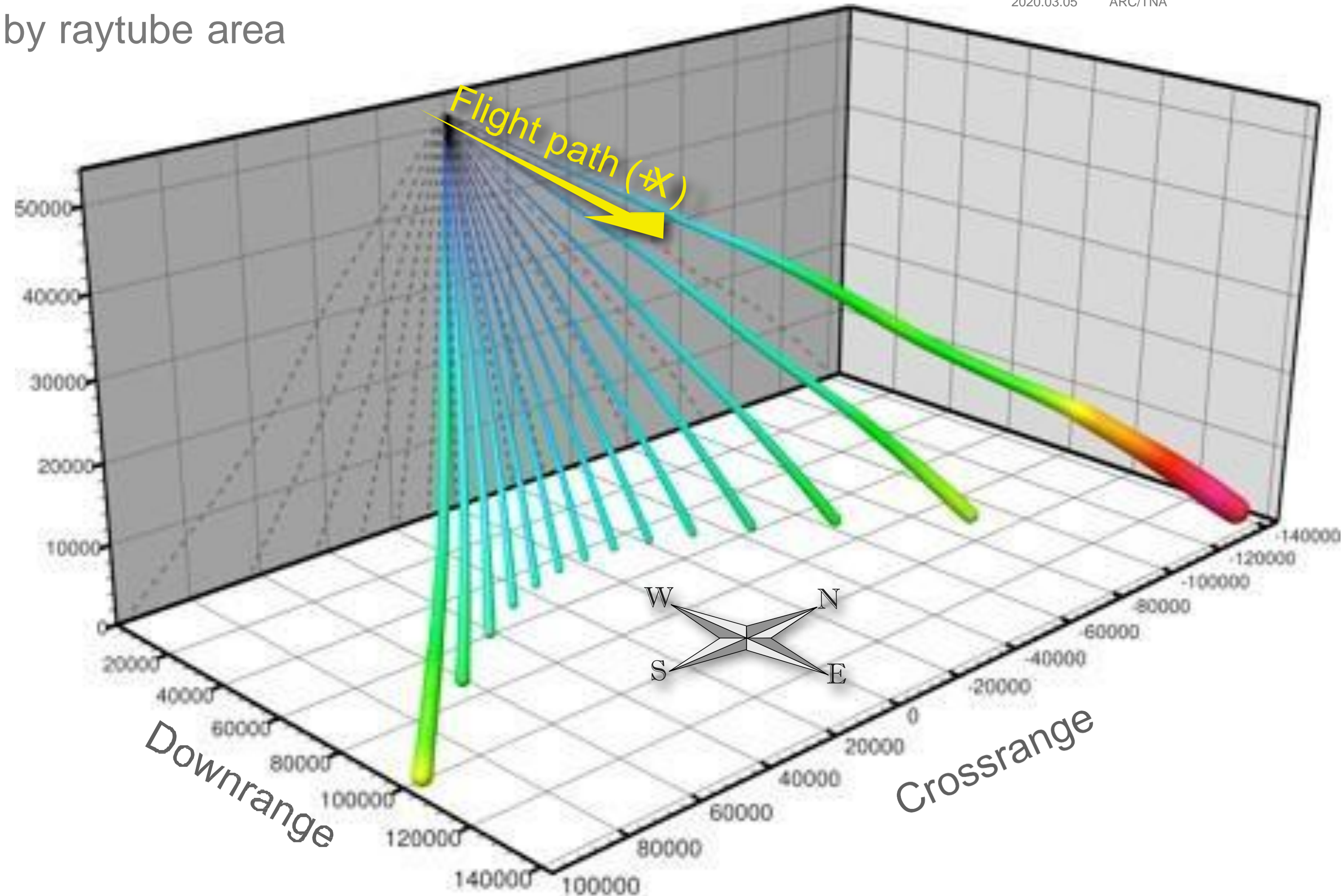


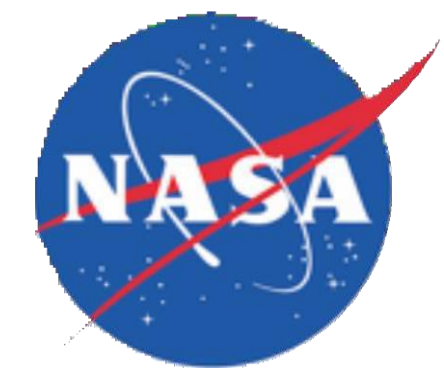
- Azimuthal range of carpet with real atm. is much wider than Standard Atm.
- Real atm. (with wind) reduces peak loudness by ~4 dBA, ~2.5 dBB, ~2 dBC & ~4 PLdB
- Noise at carpet edge drops, but can still be significant

Case 1: C25P Raytubes for Required Atmosphere

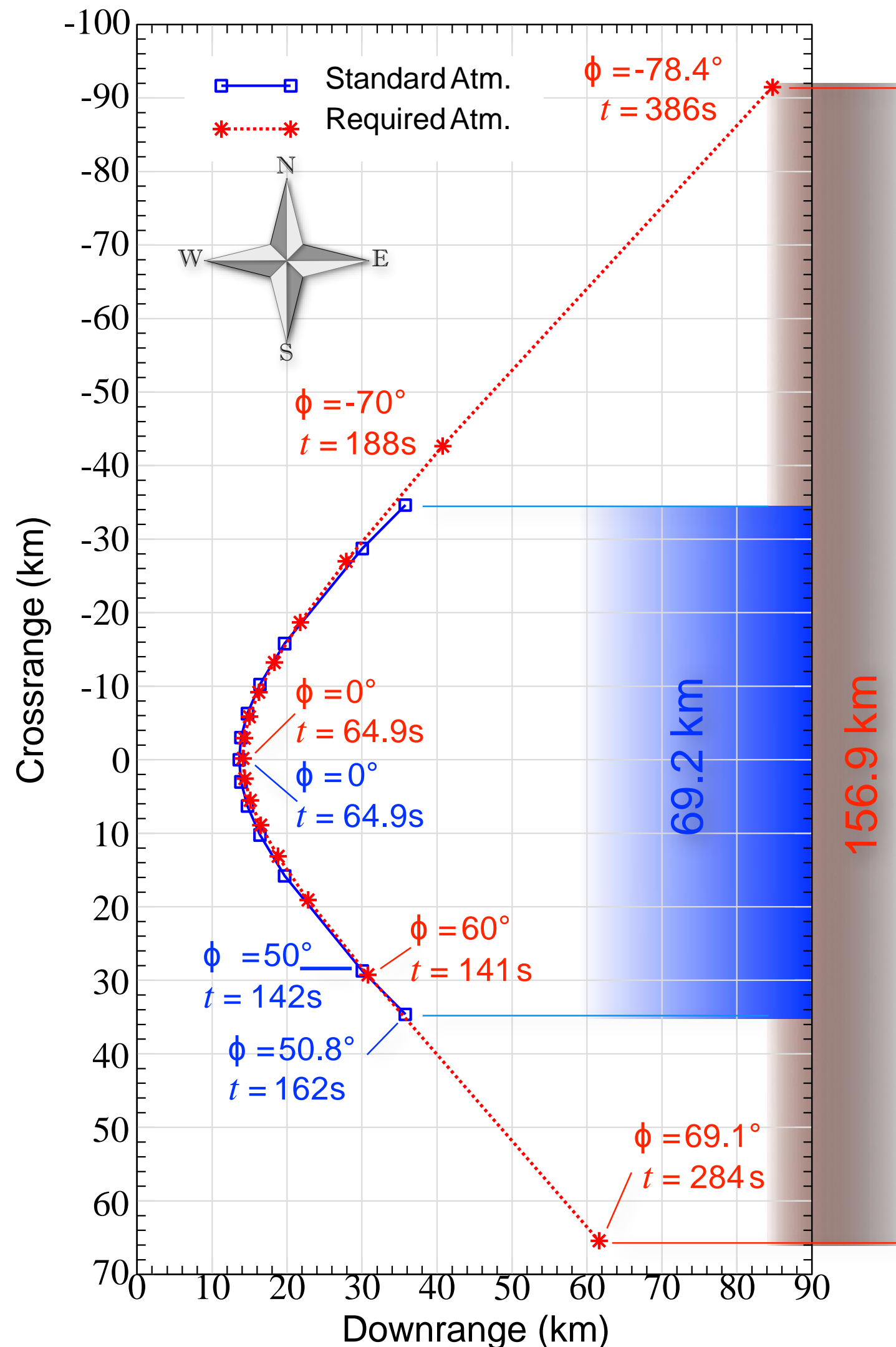
Plot 3D raytubes colored by raytube area

- 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



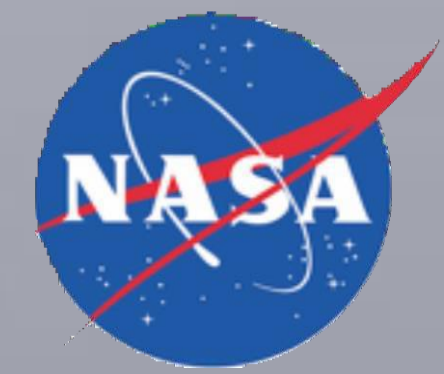


Case 1: C25P Ground Carpet



Project raytube ground intercepts on aircraft ground track

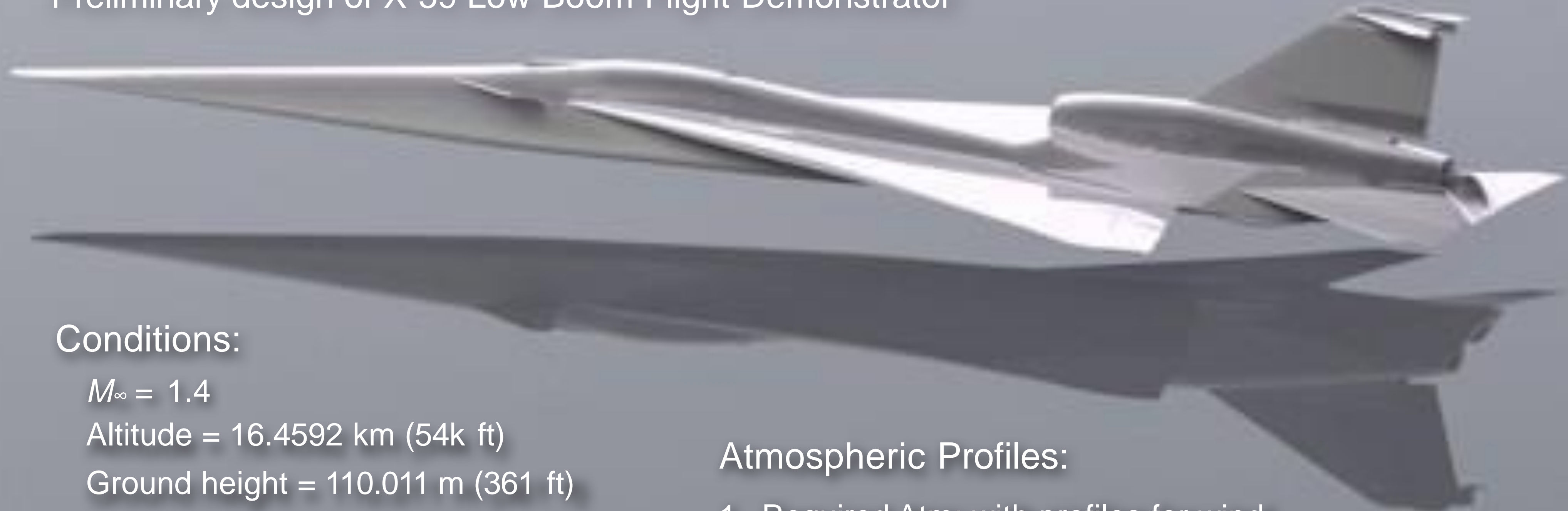
- Cutoff angles: Std. Atm = $[\pm 50.8^\circ]$, Req. Atm = $[-78.4^\circ, +69.1^\circ]$
- Long propagation distances near signal cutoff imply that these raytubes take a long time to reach the ground
 - Raytube for $\phi = -78.4^\circ$ takes over 6 mins in Required atm.
 - Mesh convergence near signal 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)



2020.03.05 ARC/TNA

Case 2: C609

Preliminary design of X-59 Low Boom Flight Demonstrator



Conditions:

$$M_{\infty} = 1.4$$

Altitude = 16.4592 km (54k ft)

Ground height = 110.011 m (361 ft)

$L_{ref} = 27.43$ m (90 ft)

$r/L = 3$ at signal extraction

Ground reflection factor = 1.9

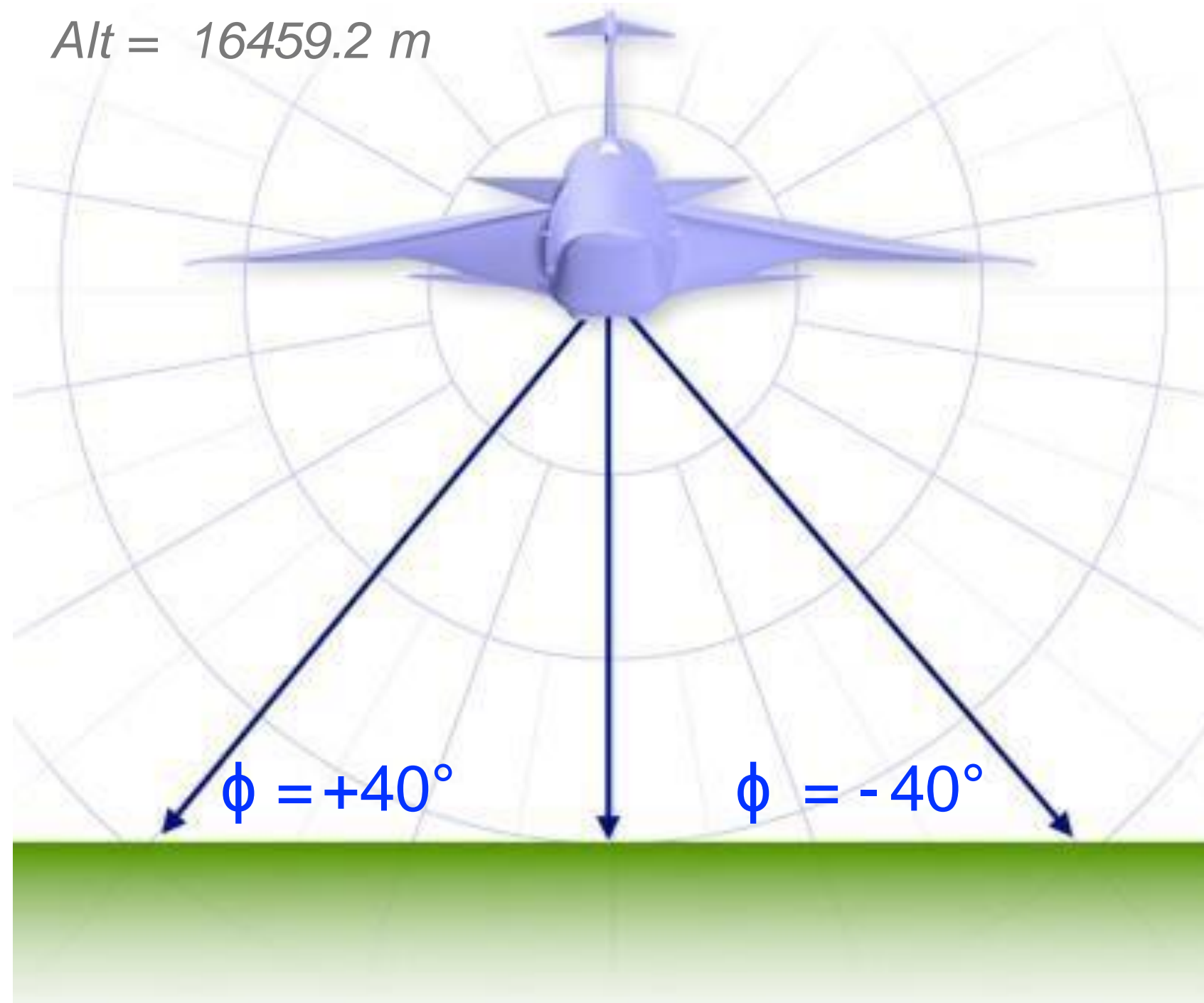
Heading East ($\beta = 0^{\circ}$)

Atmospheric Profiles:

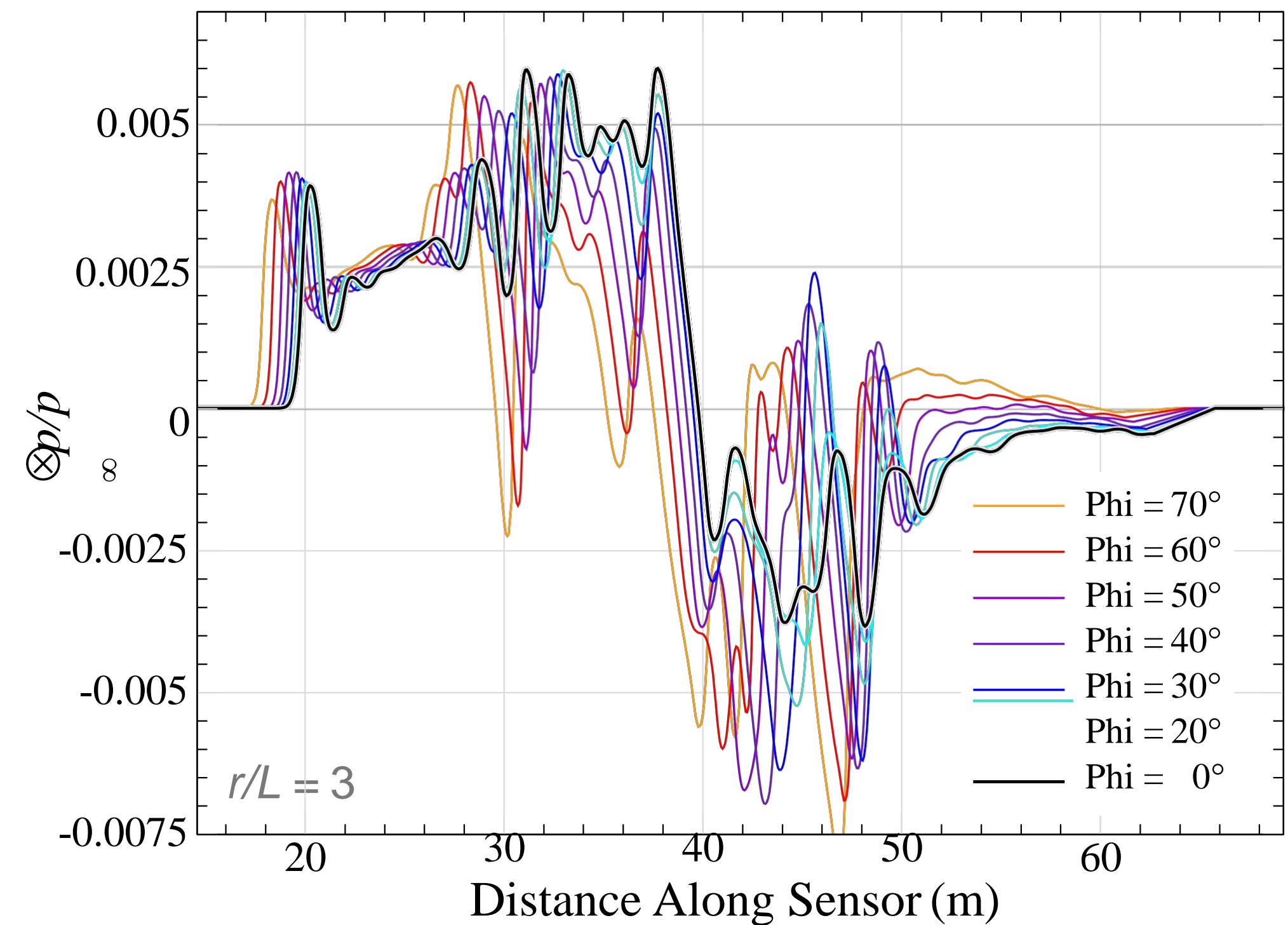
1. Required Atm: with profiles for wind, temp, pressure & humidity
2. Standard Atmosphere

Case 2: C609 Near Field Signals

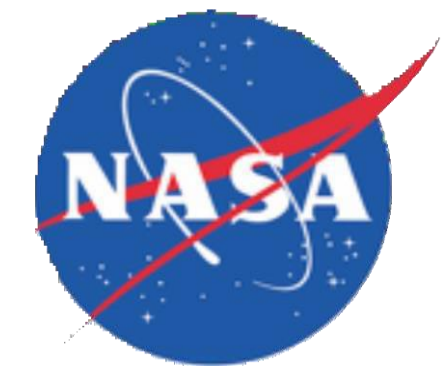
Sign Convention for Azimuth, ϕ



Subset of Near Field Signals



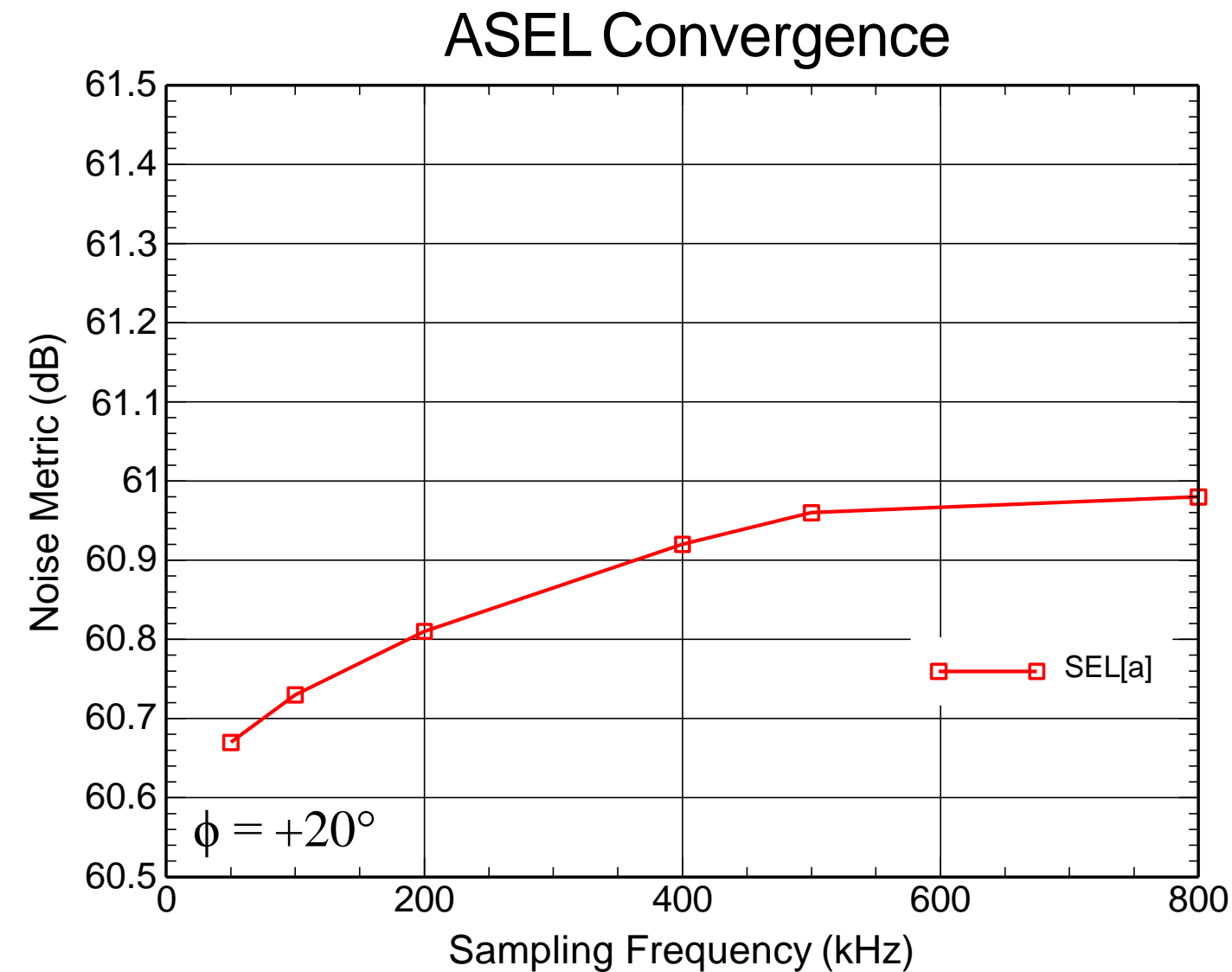
- Near field signals provided for 23 azimuths from -70° to $+70^\circ$
 $\phi = [0, \pm 10, \pm 20, \pm 30, \pm 40, \pm 50, \pm 60, \pm 62, \pm 64, \pm 66, \pm 68, \pm 70]$
- Signals symmetric $\pm \phi$



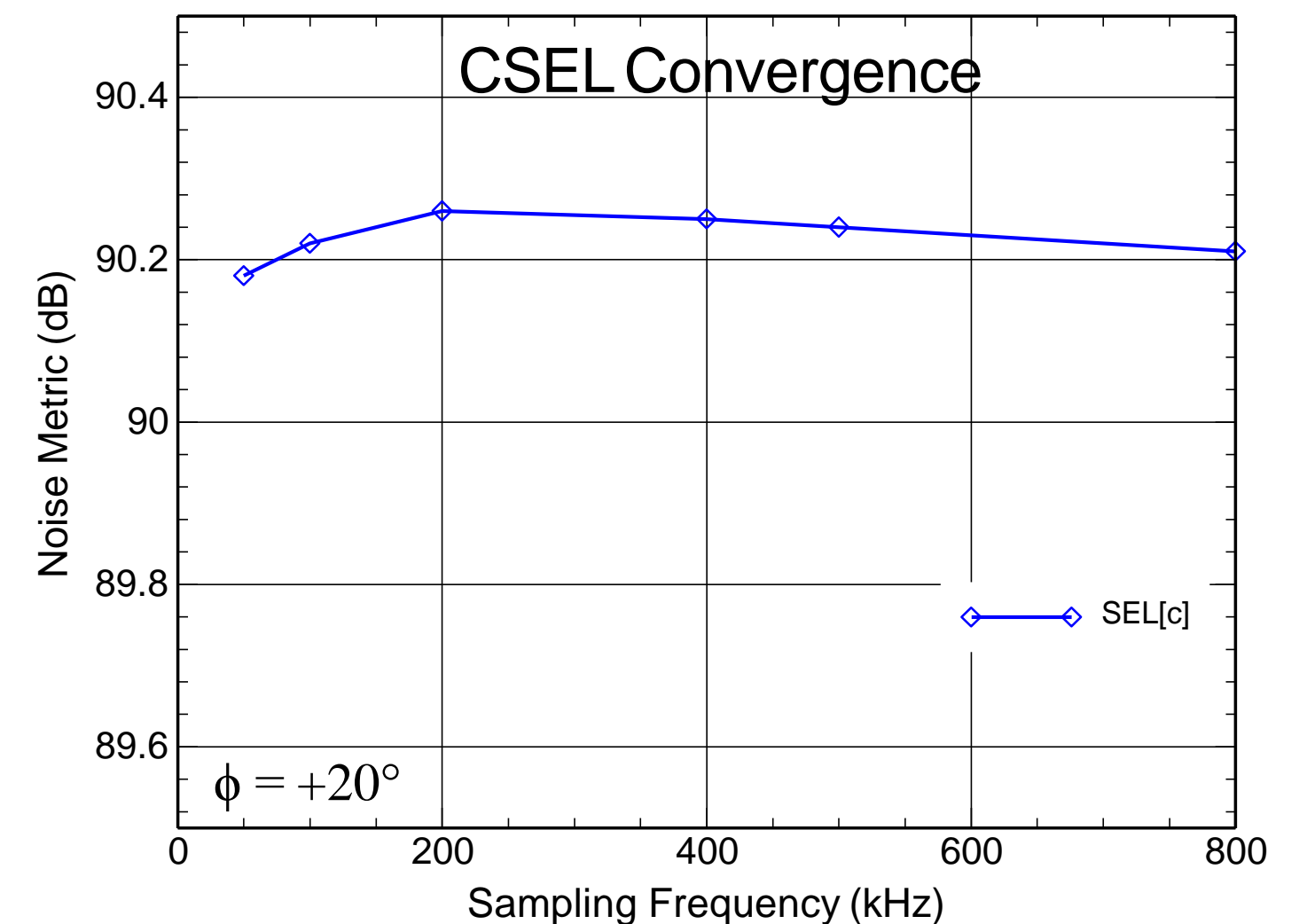
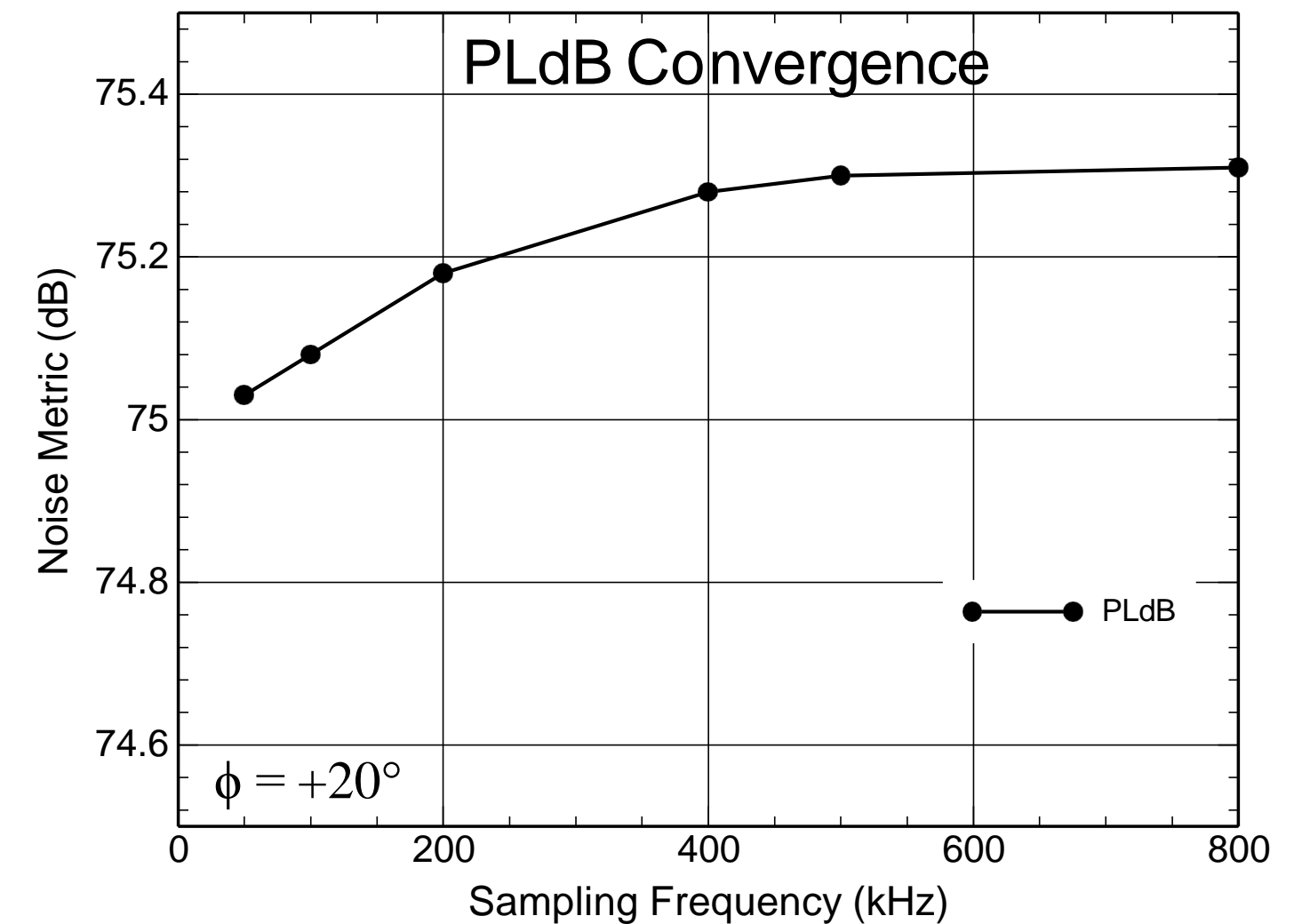
2020.03.05 ARC/TNA

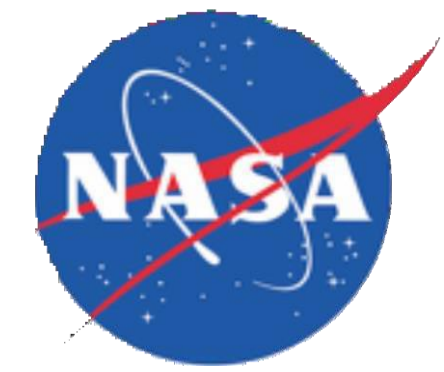
Case 2: C609 Sampling Frequency

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.



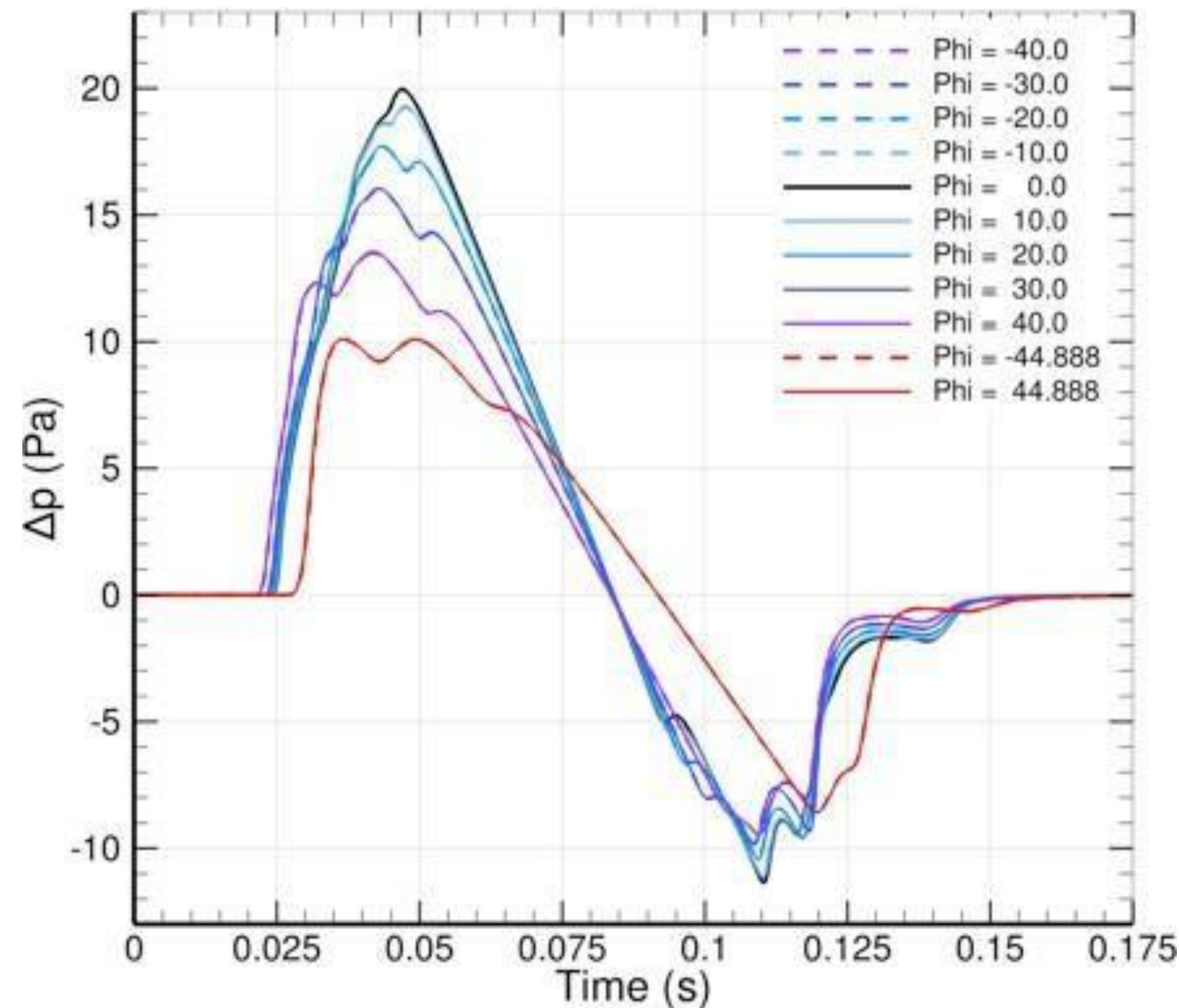


2020.03.05 ARC/TNA

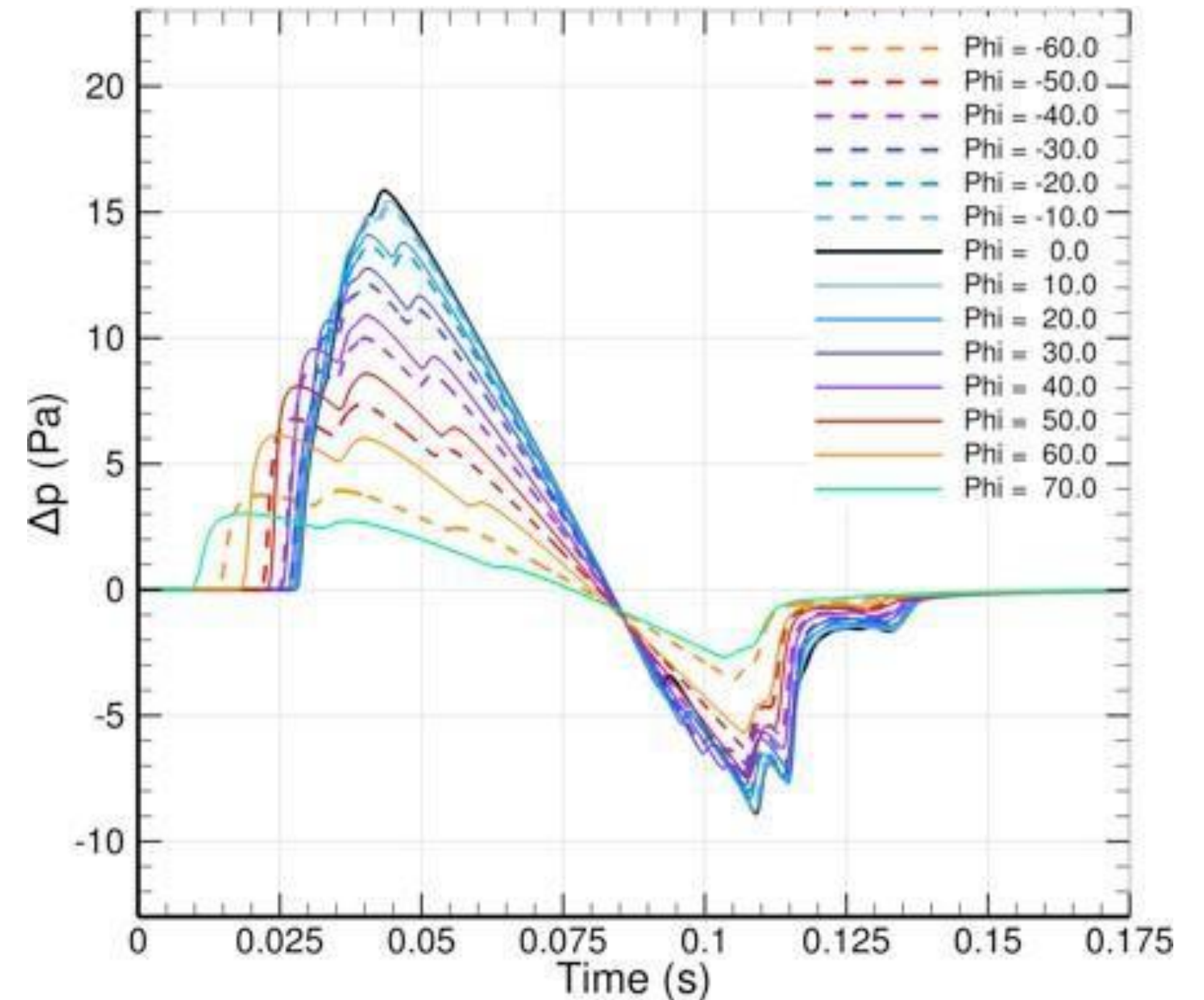
Case 2: C609 Ground Signals

Propagation altitude = 16460m, ground elevation = 110m

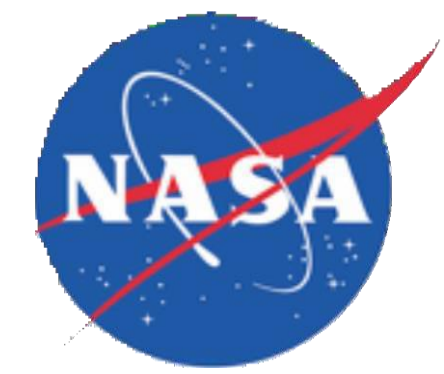
Standard Atmosphere



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.

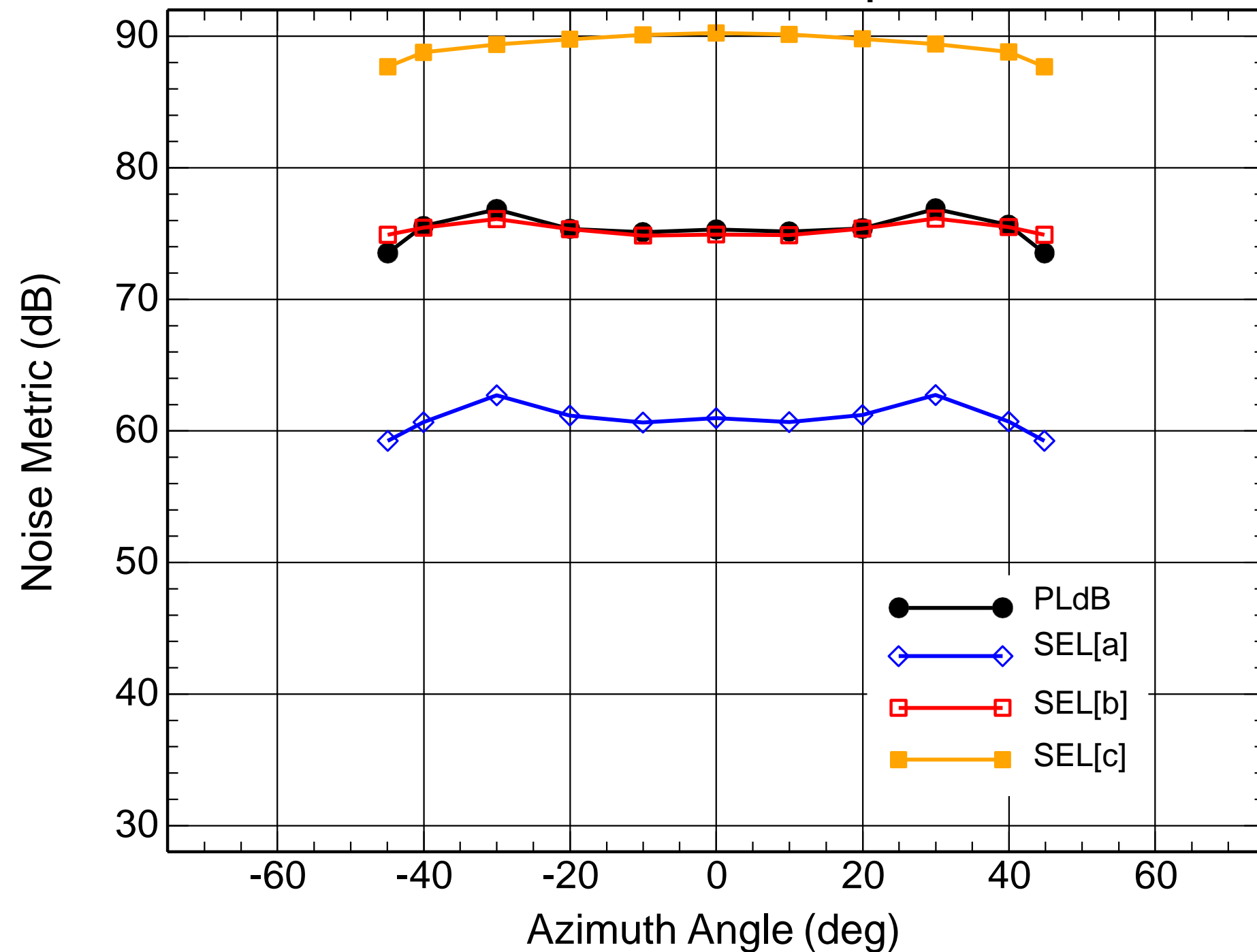


2020.03.05 ARC/TNA

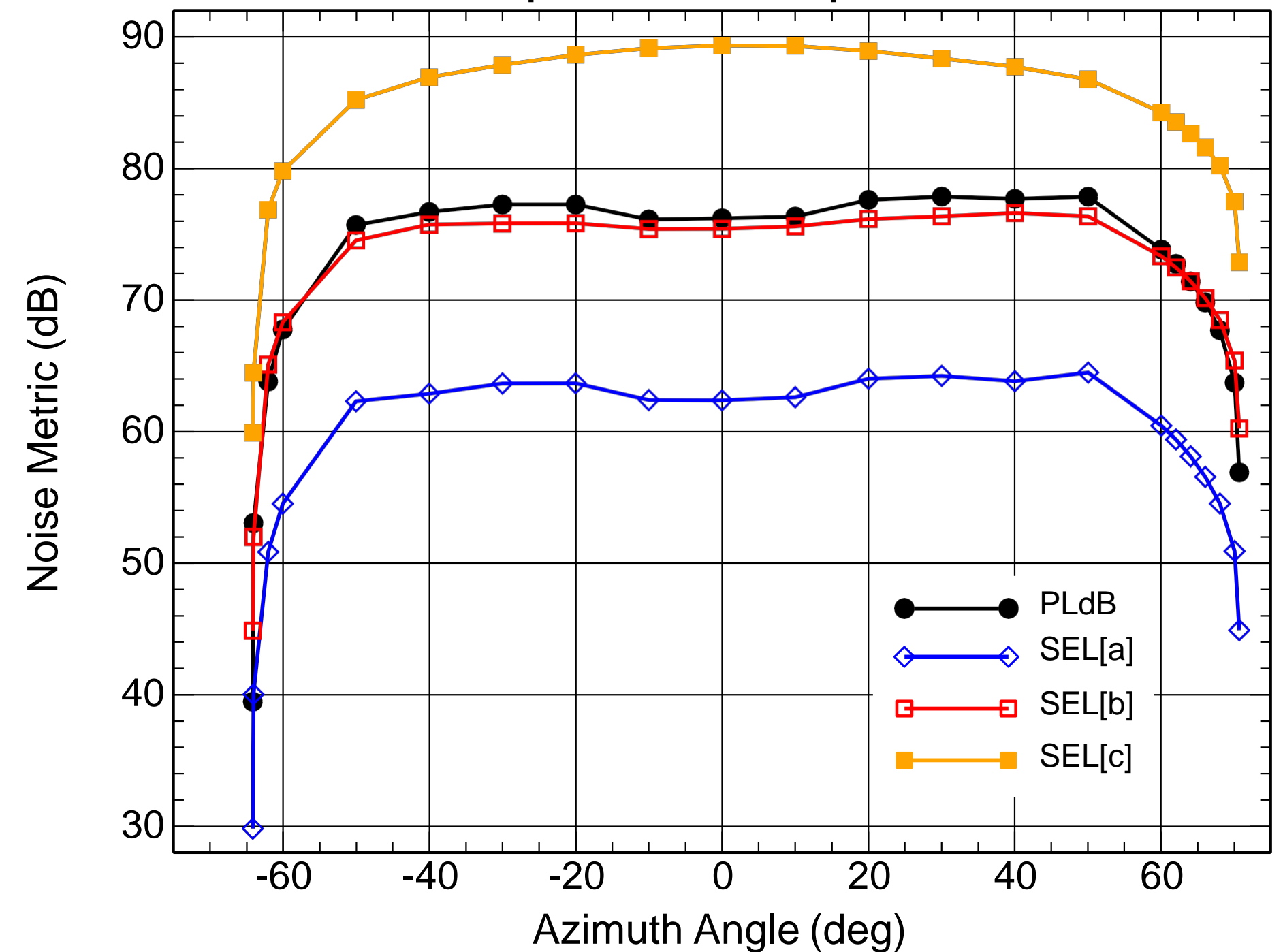
Case 2: C609 Ground Noise

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

Standard Atmosphere



Required Atmosphere

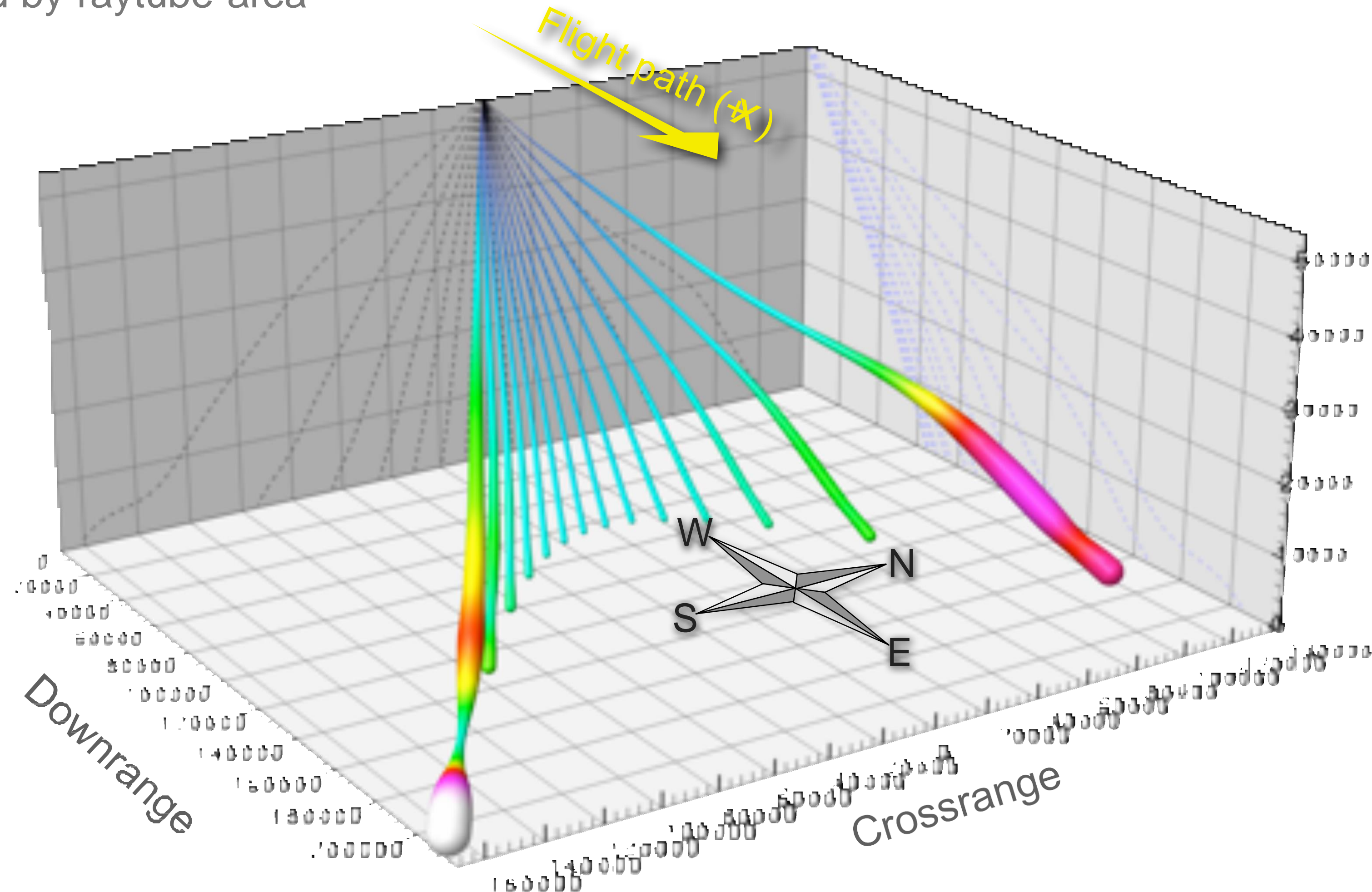


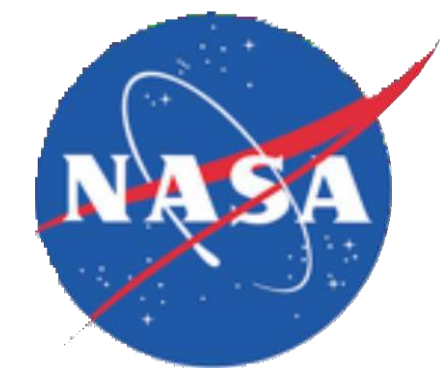
- Azimuthal range of carpet with Required Atm. is much wider than Standard Atm.
- Despite wind & reduced ground amplitude, Real Atm. and Std. Atm. have similar loudness
- Noise at carpet edge drops significantly in Required Atm.

Case 2: C609 Raytubes for Required Atmosphere

Plot 3D raytubes colored by raytube area

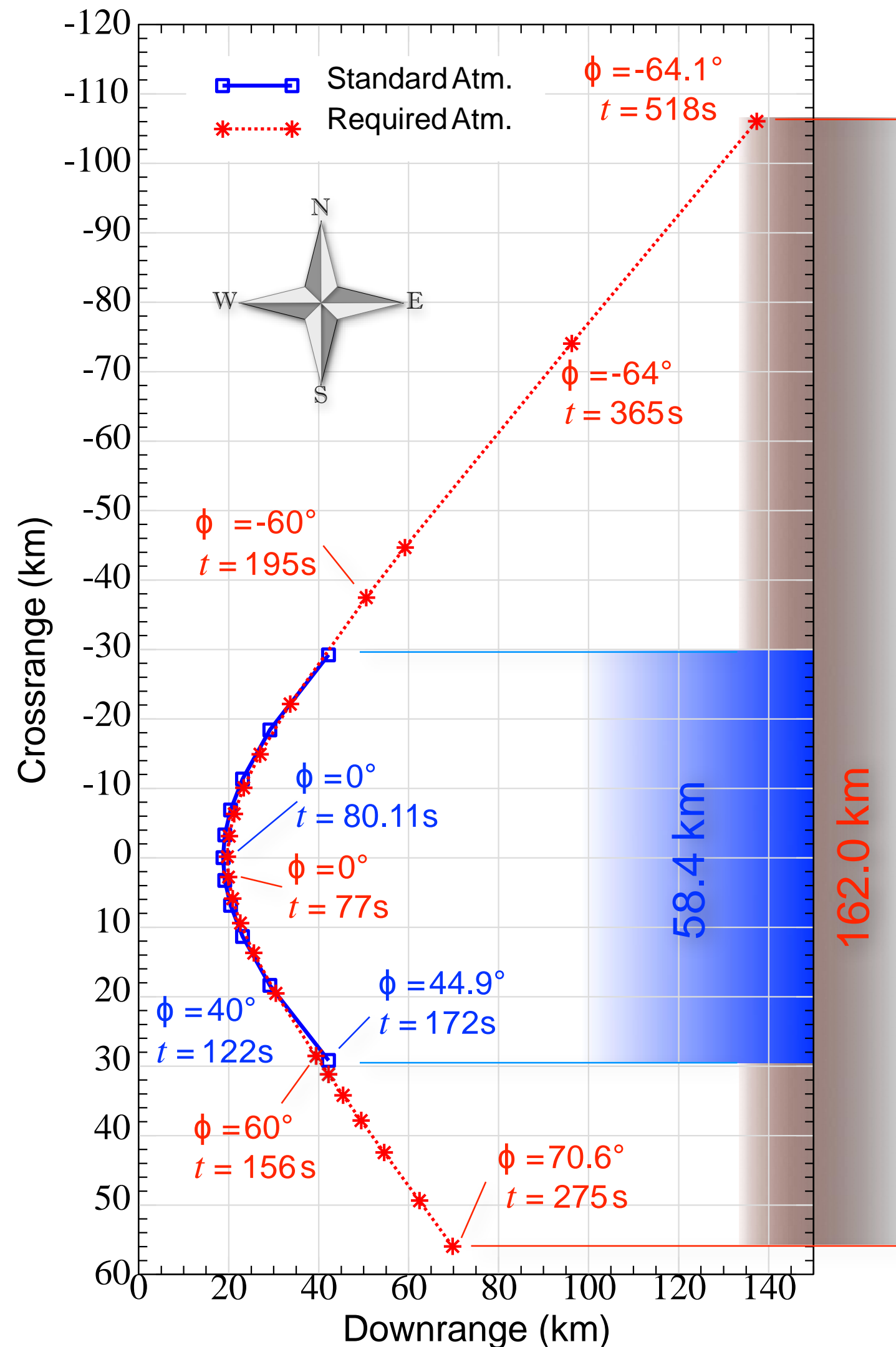
- 3D plot of raytubes for real atmosphere
- Shows extremely long propagation times & large raytube areas near edges of the carpet
- Near cutoff, sensitivity to atmosphere increases uncertainty in ground signal





Case 2: C609 Ground Carpet

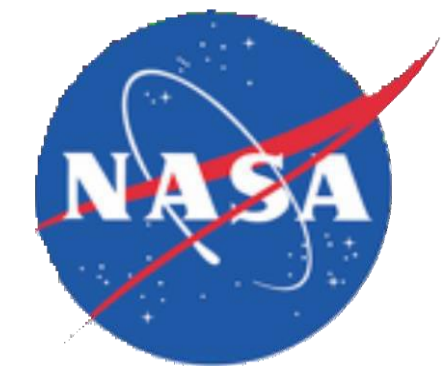
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Project raytube ground intercepts on aircraft ground track

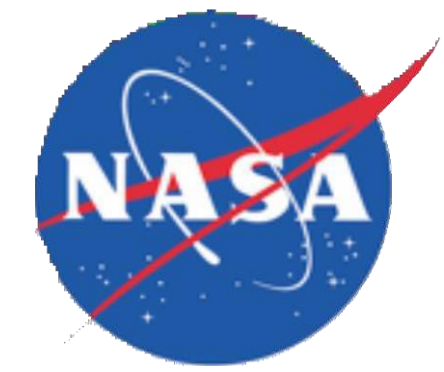
- Cutoff angles Req. Atm = $[-64.1^\circ, 70.6^\circ]$, Std. Atm = $[\pm 44.9^\circ]$
- Long propagation distances near signal cutoff imply that these raytubes take a long time to reach the ground
 - Raytube for $\phi = -64.1^\circ$ cutoff takes over 8.5 mins in Reqd. atm.
 - Mesh convergence near signal 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



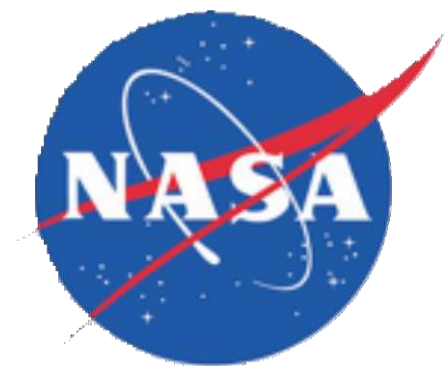
2020.03.05 ARC/TNA

- 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

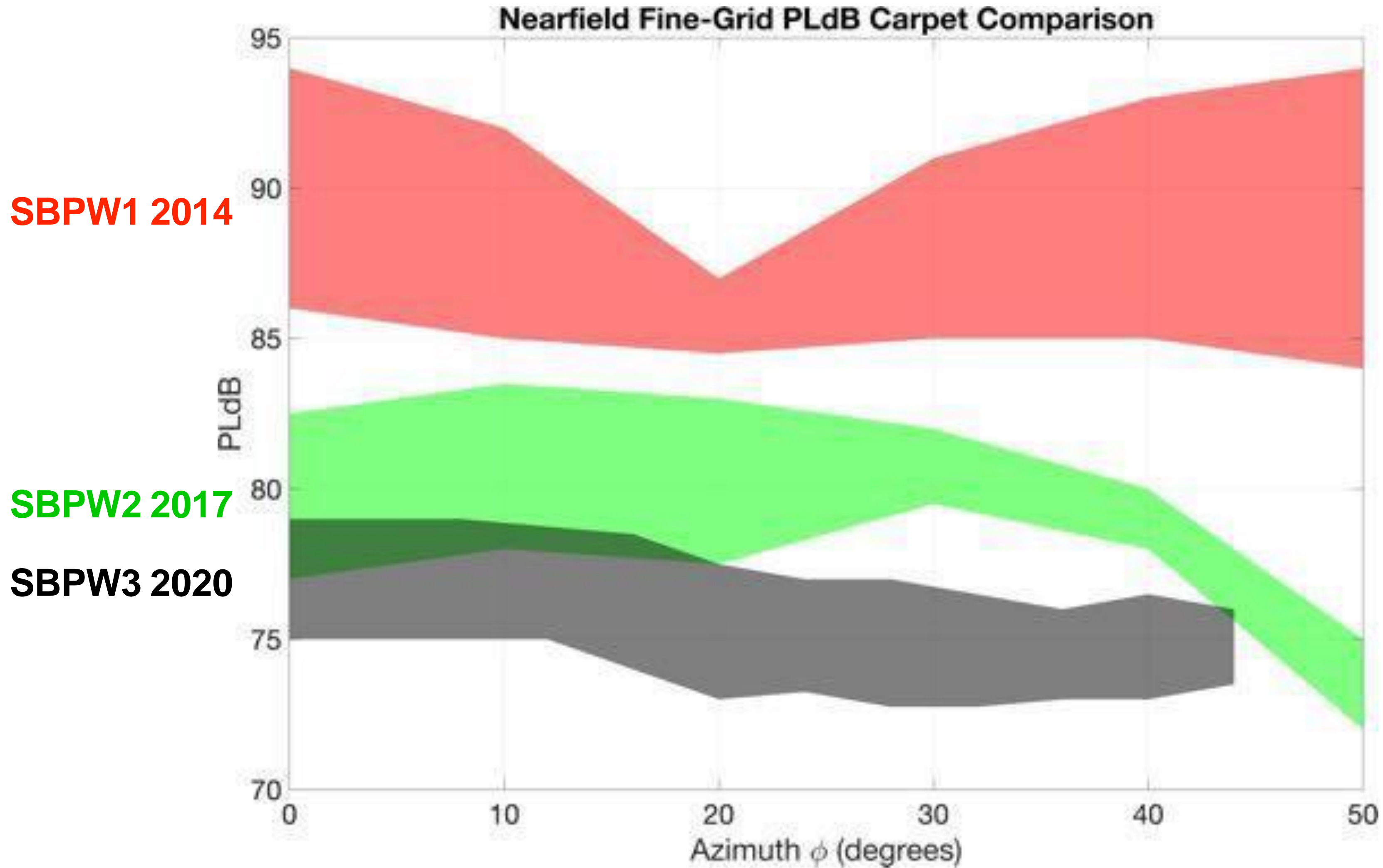


SBPW3 Highlights

- 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 $\pm 20^\circ$, more challenging out toward edges of boom carpet



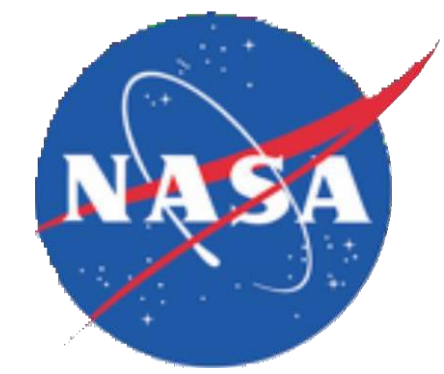
SBPW3 Highlights



SBPW1 2014

SBPW2 2017

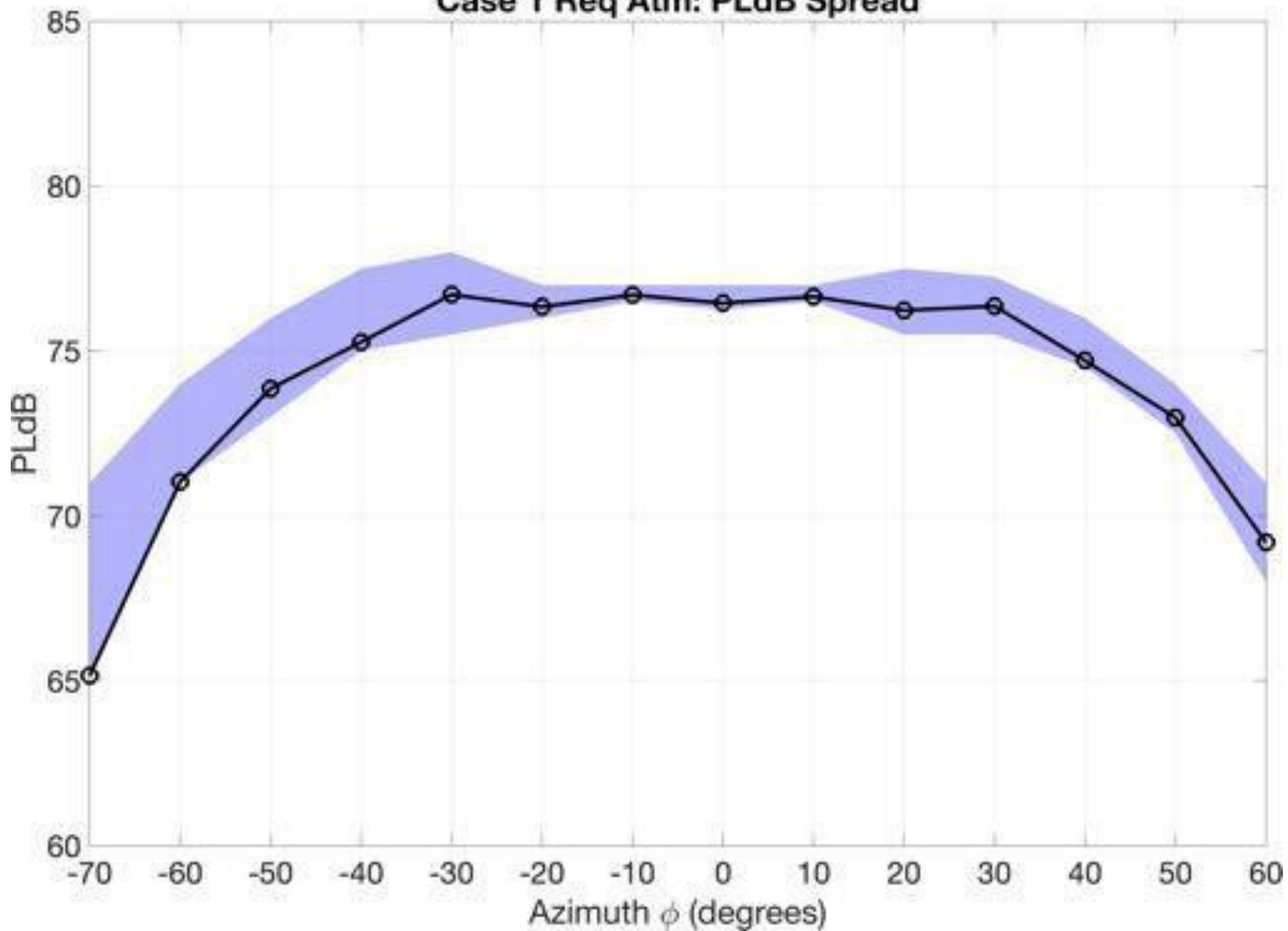
SBPW3 2020



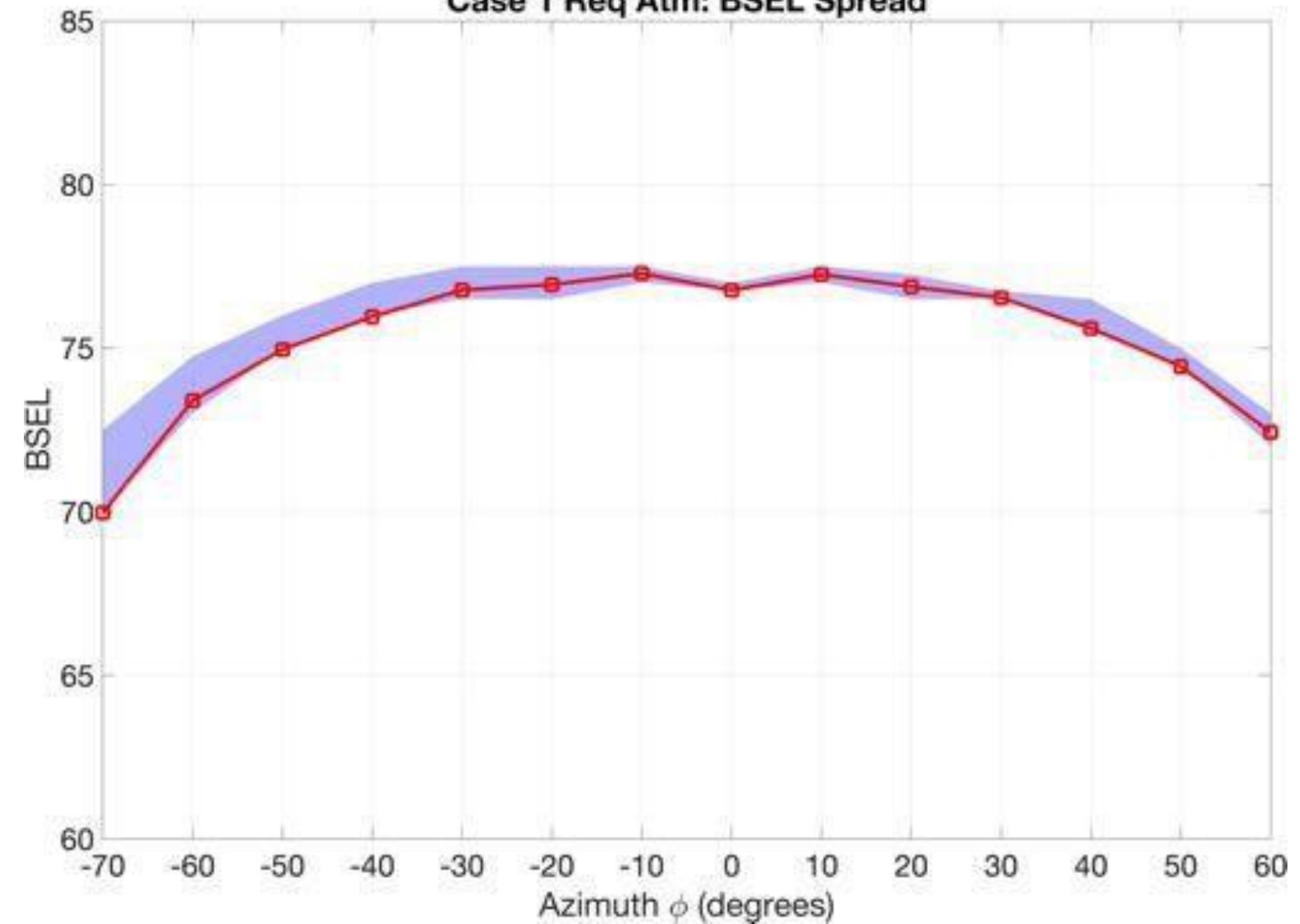
SBPW3 Highlights

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

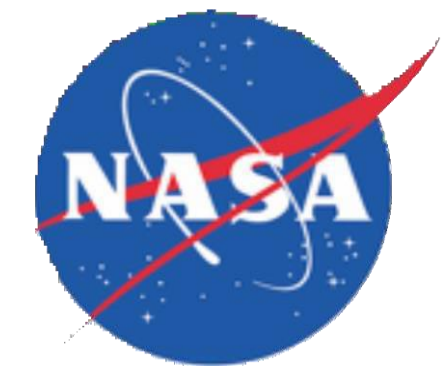
Case 1 Req Atm: PLdB Spread



Case 1 Req Atm: BSEL Spread



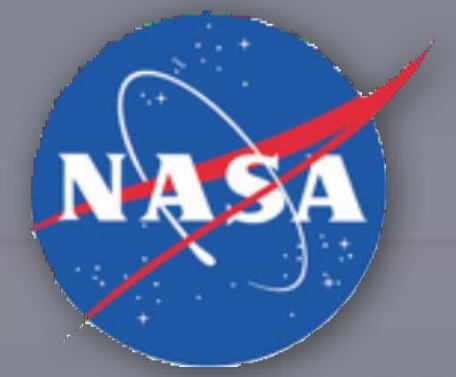
Acknowledgements



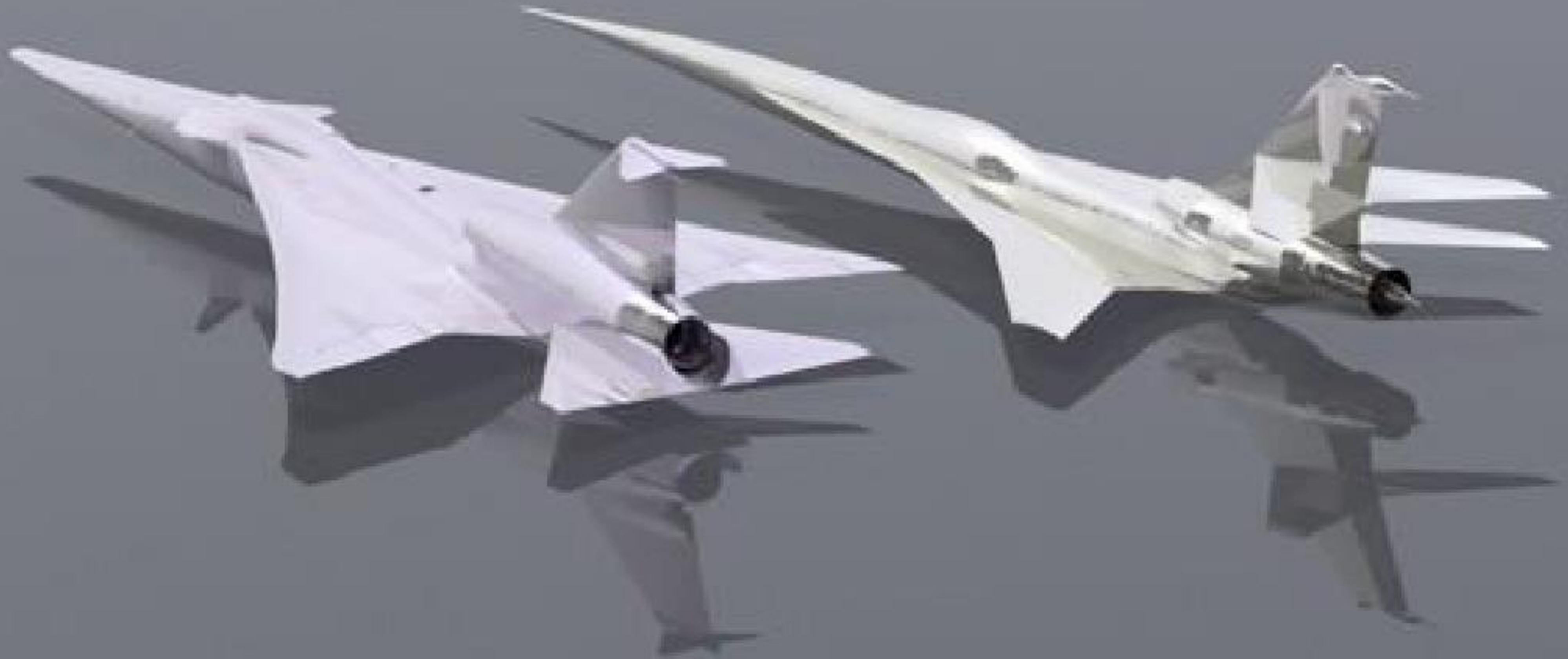
2020.03.05 ARC/TNA

- 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

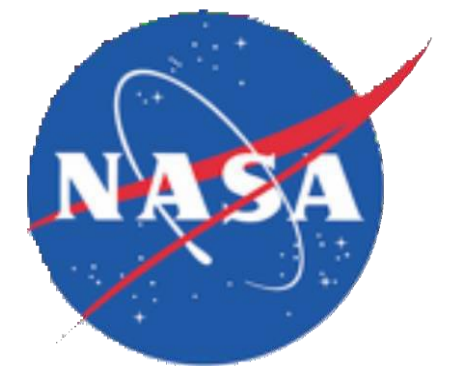
Questions?



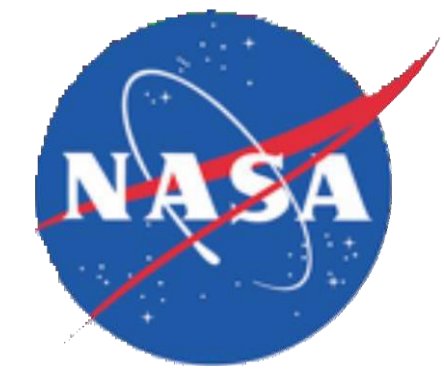
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Backup



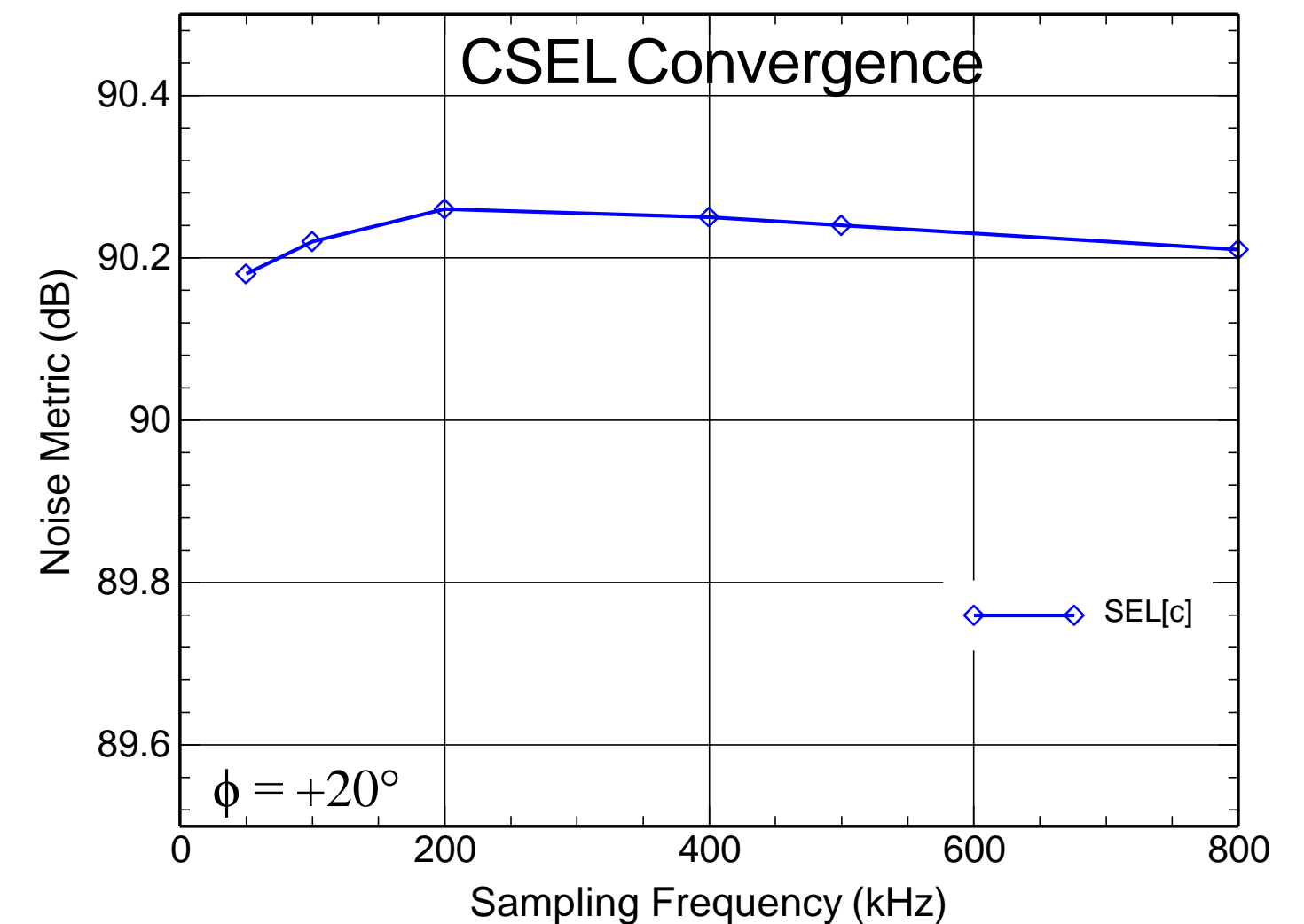
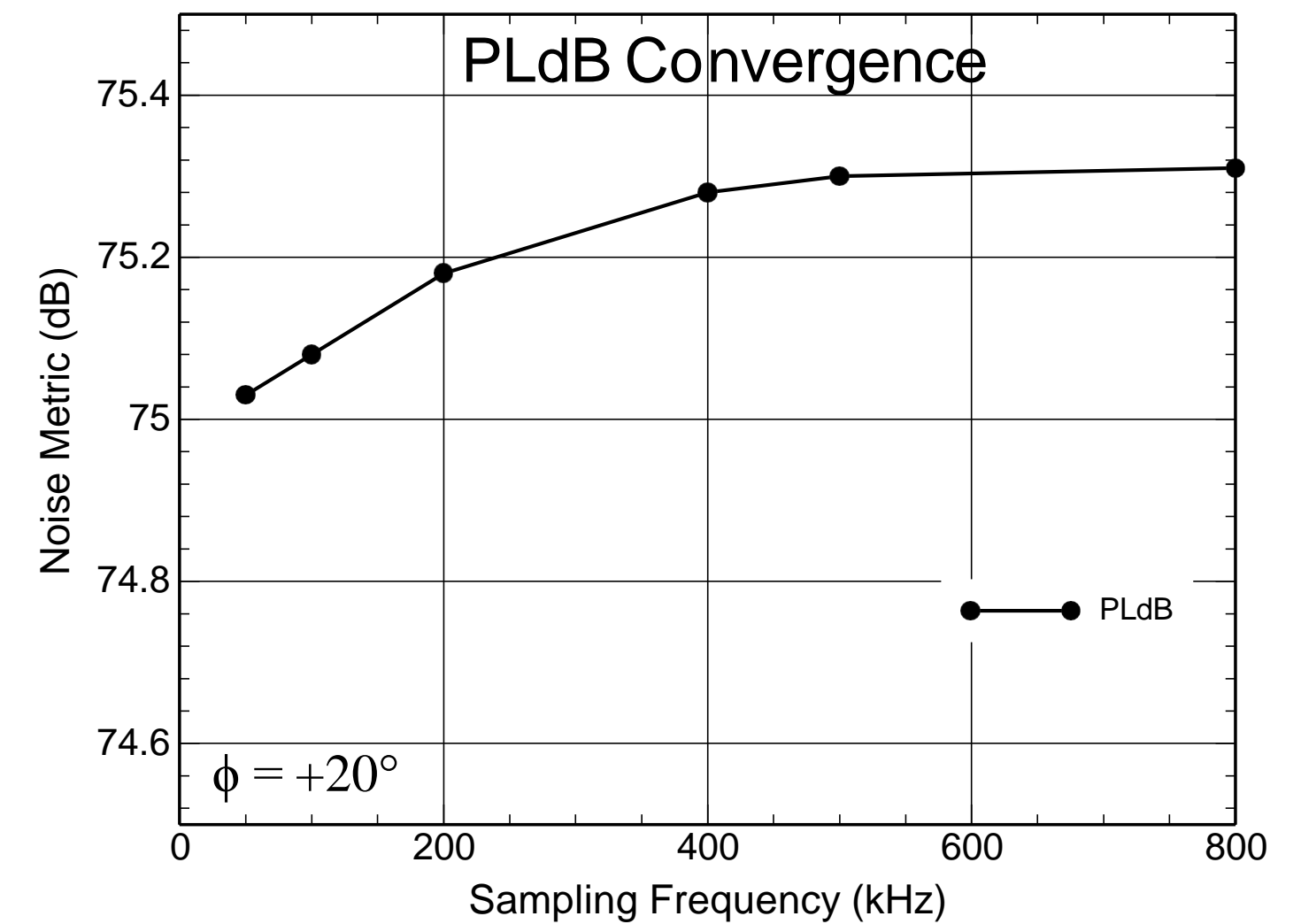
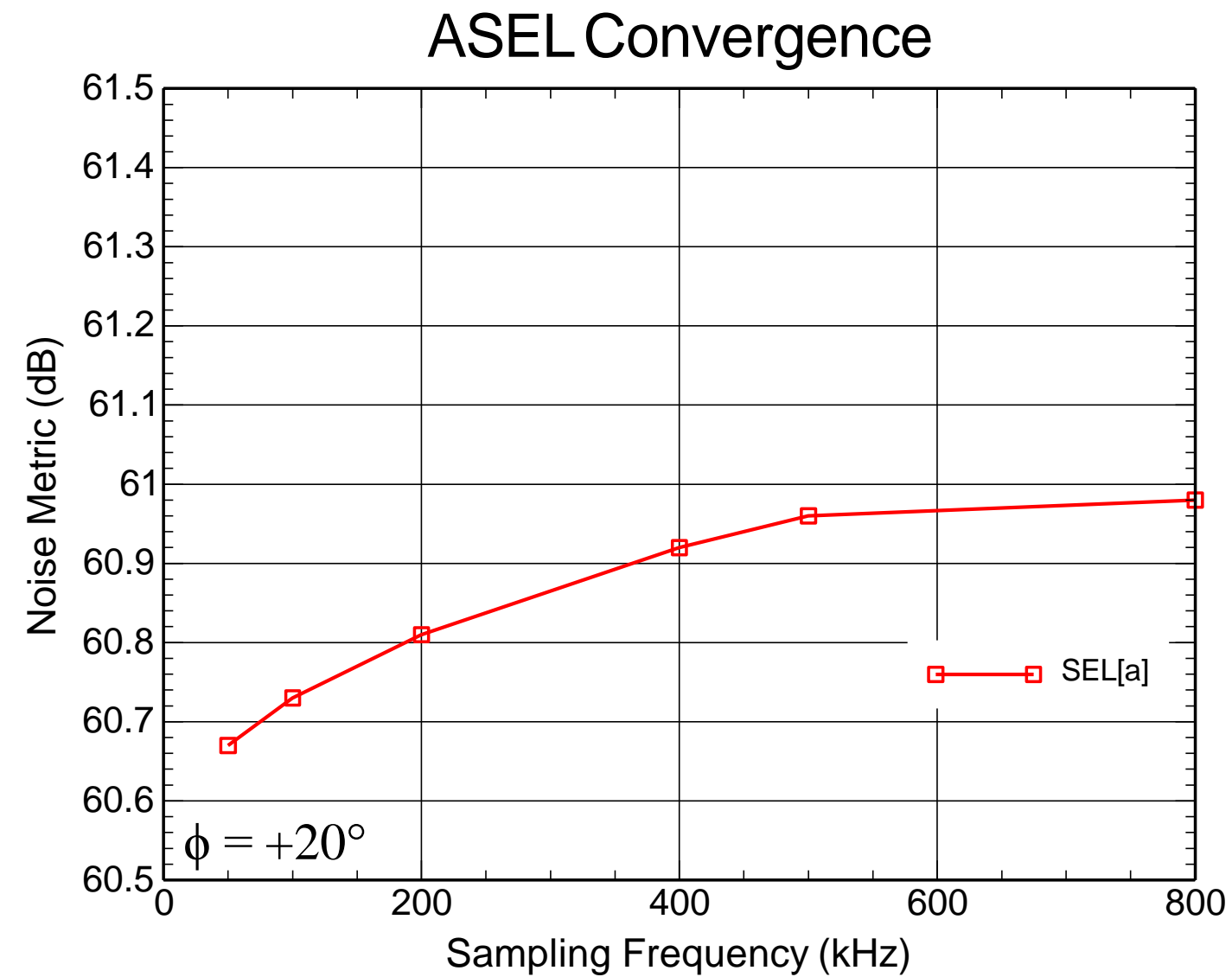
2020.03.05 ARC/TNA



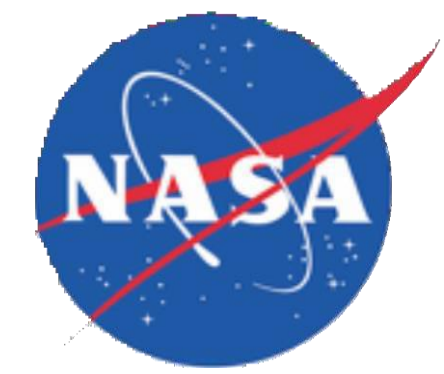
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Case 2: C609 Sampling Frequency

Metric convergence with sampling frequency (Std. Atm.)

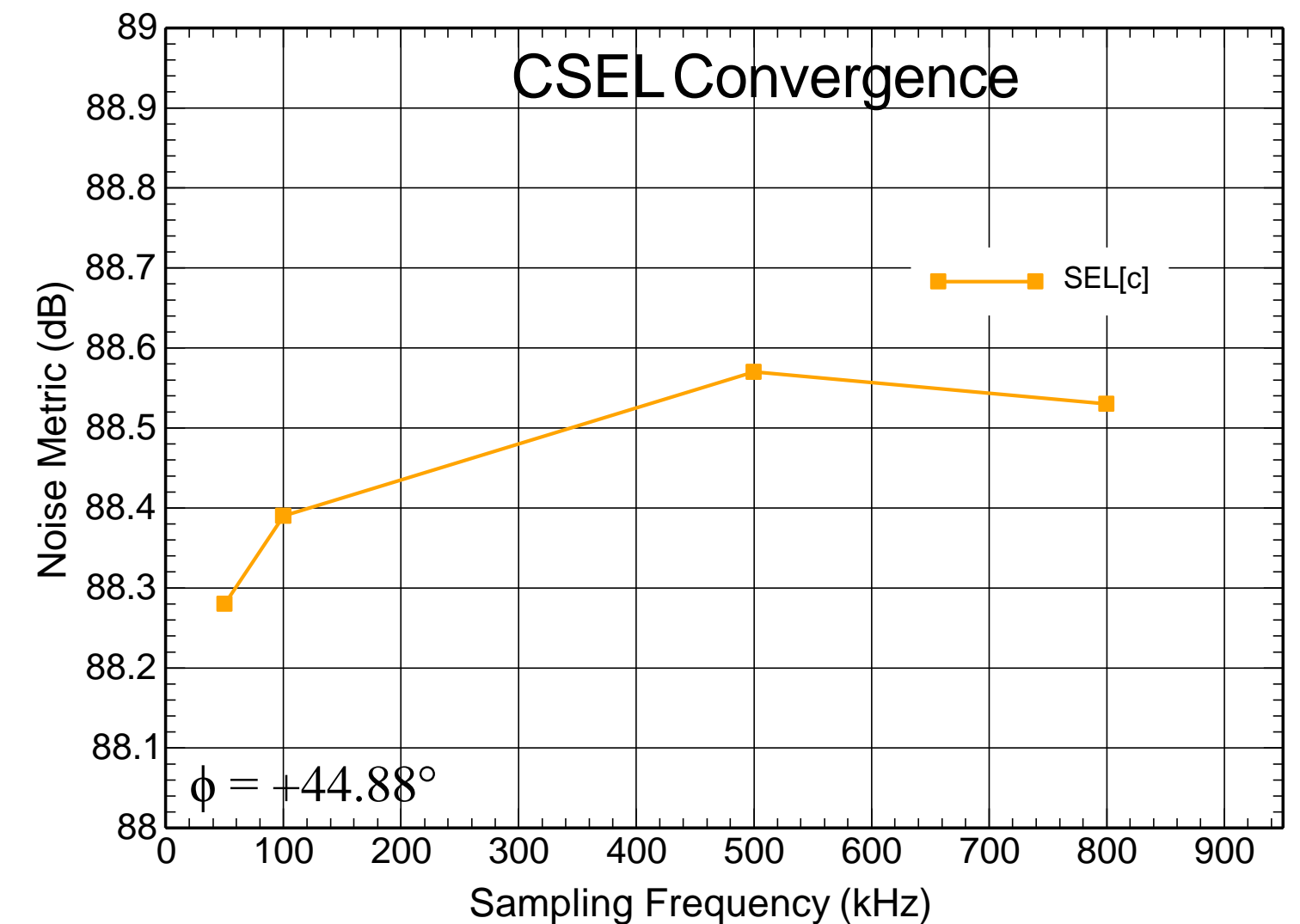
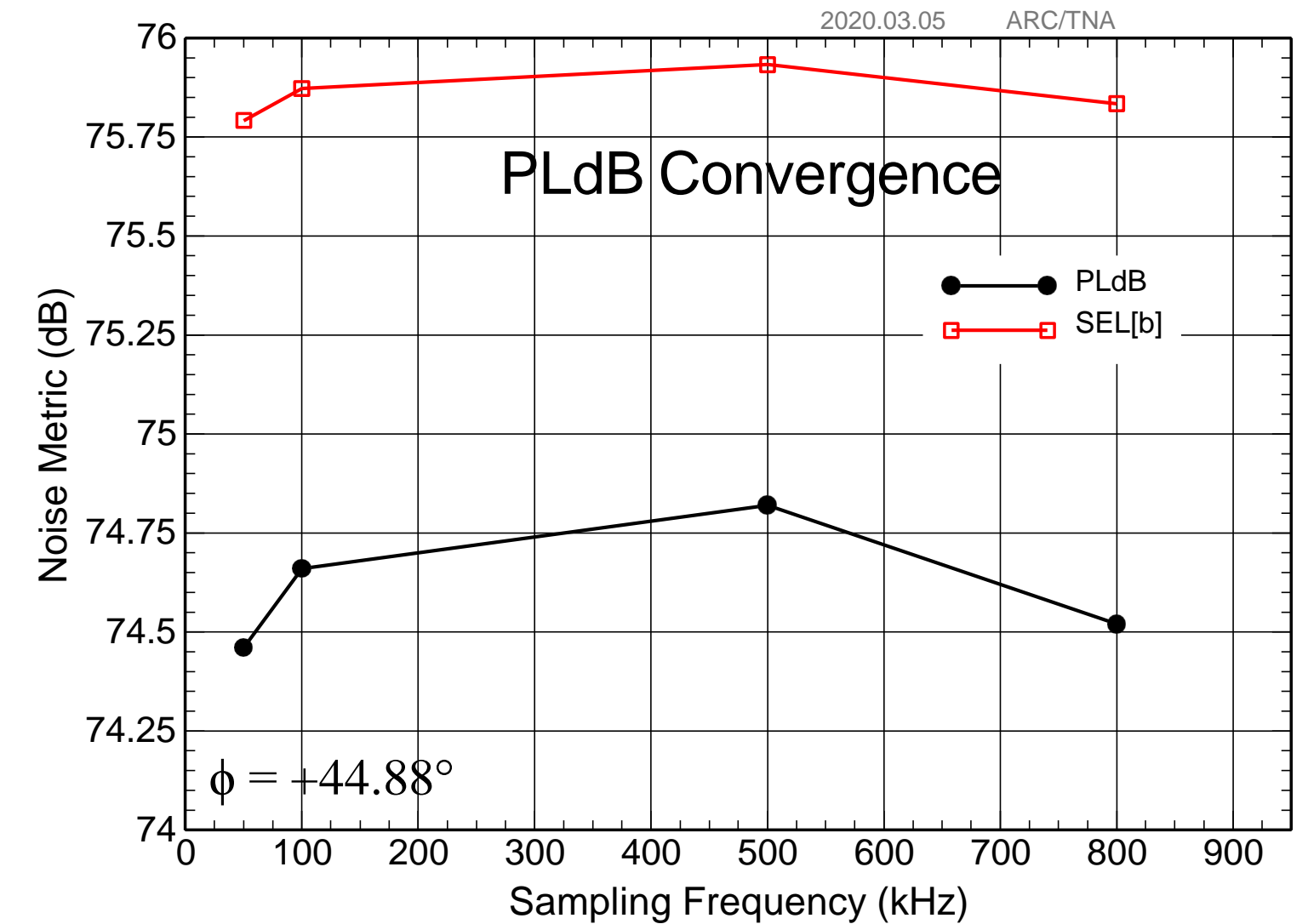
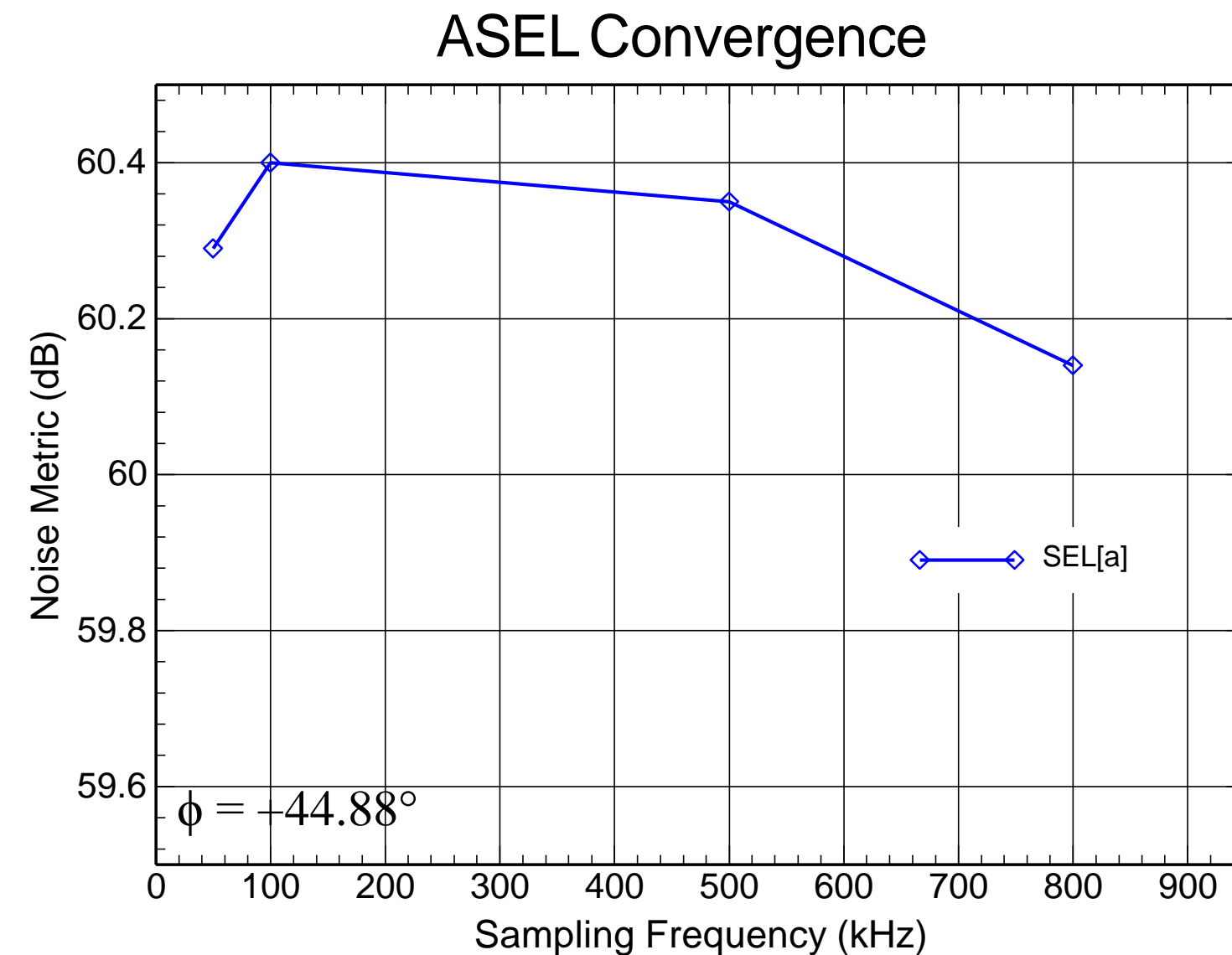


- Using FFT for metric computation get reasonable mesh convergence of ASEL, CSEL and PLdB by 500kHz.
- Discrete BSEL filter appears well behaved as well
- Similar mesh convergence behavior for other azimuths. Used 500kHz sampling frequency away from cutoff.

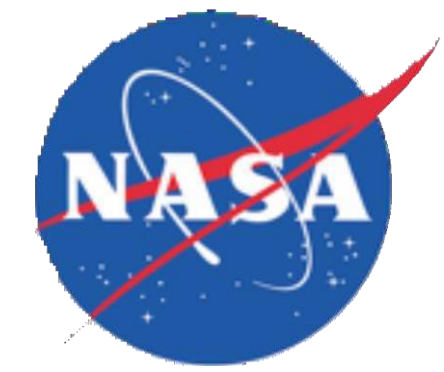


Case 2: C609 Sampling Frequency

Metric convergence with sampling frequency



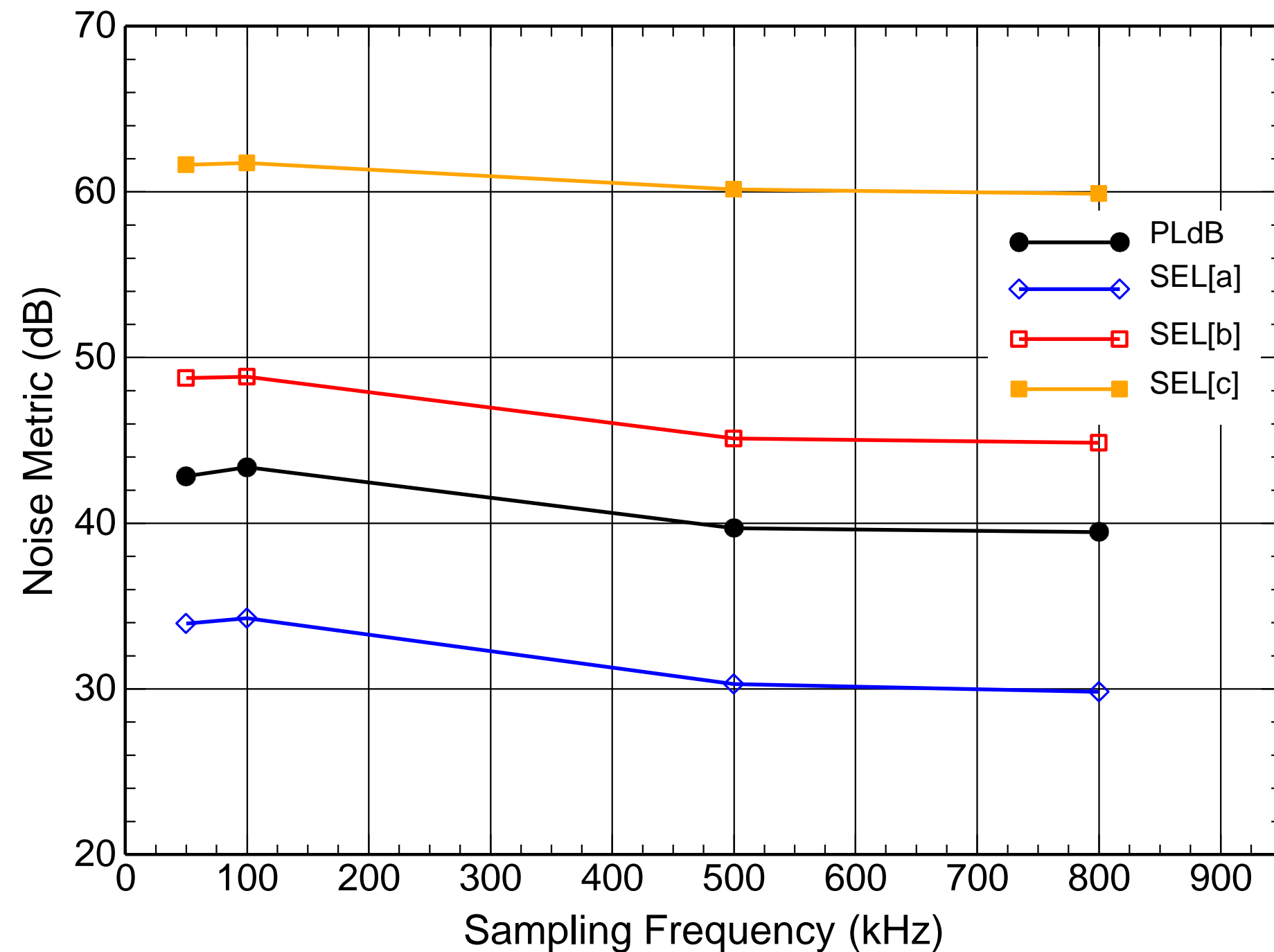
- Near signal cutoff, mesh convergence degrades
- Used 800kHz sampling frequency at cutoff
- Discrete BSEL filter appears to remain well behaved
- Std. Atm. worse behaved than Required Atm.



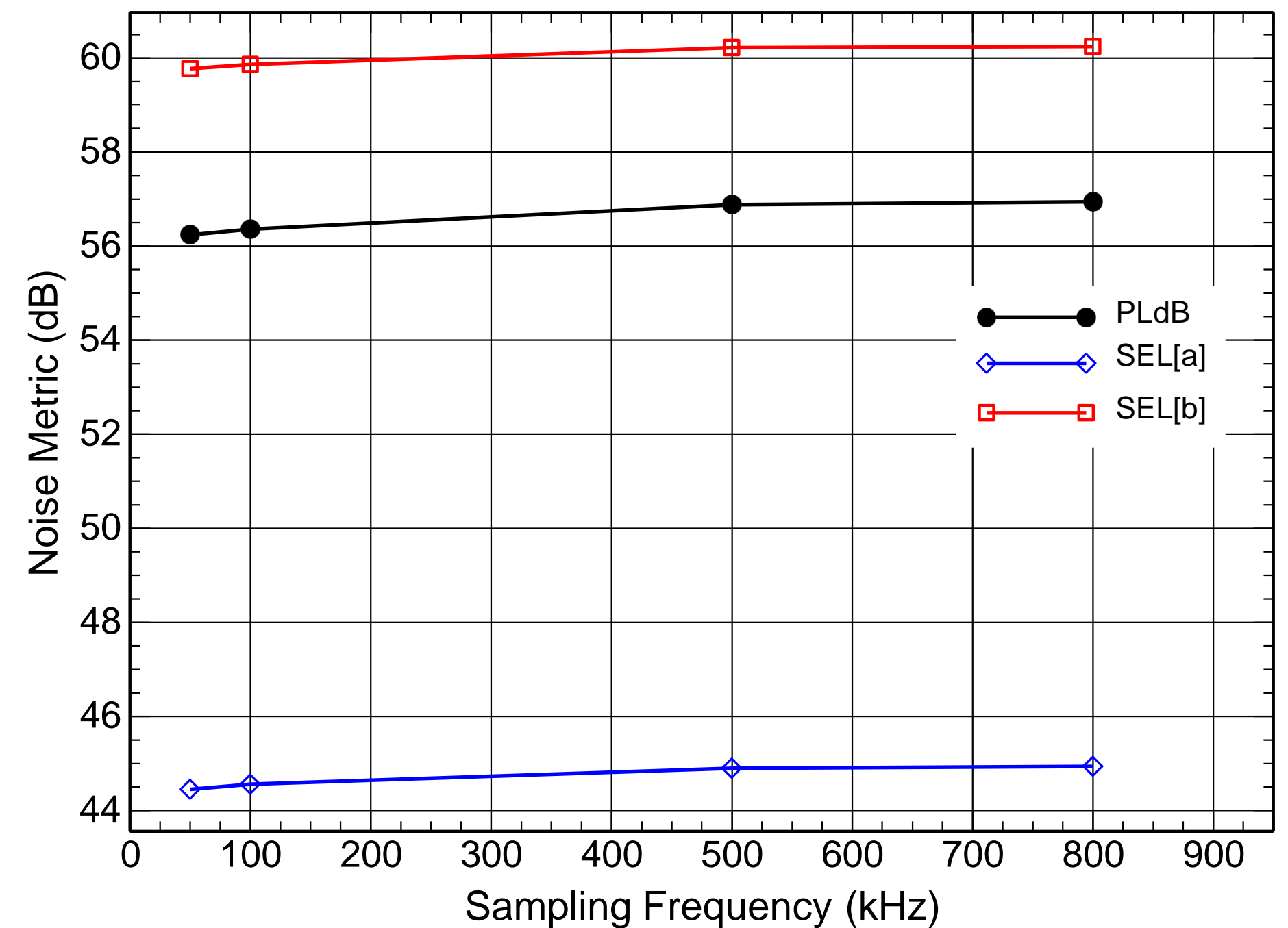
Case 2: C609 Sampling Frequency

PLdB metric convergence with sampling frequency (Required Atm)

$\phi = -64.095^\circ$ (cutoff)



$\phi = 70.6467^\circ$ (cutoff)



- Used 800kHz sampling frequency for propagation at outside $\pm 60^\circ$