Second AIAA Sonic Boom Prediction Workshop Nearfield CFD Summary

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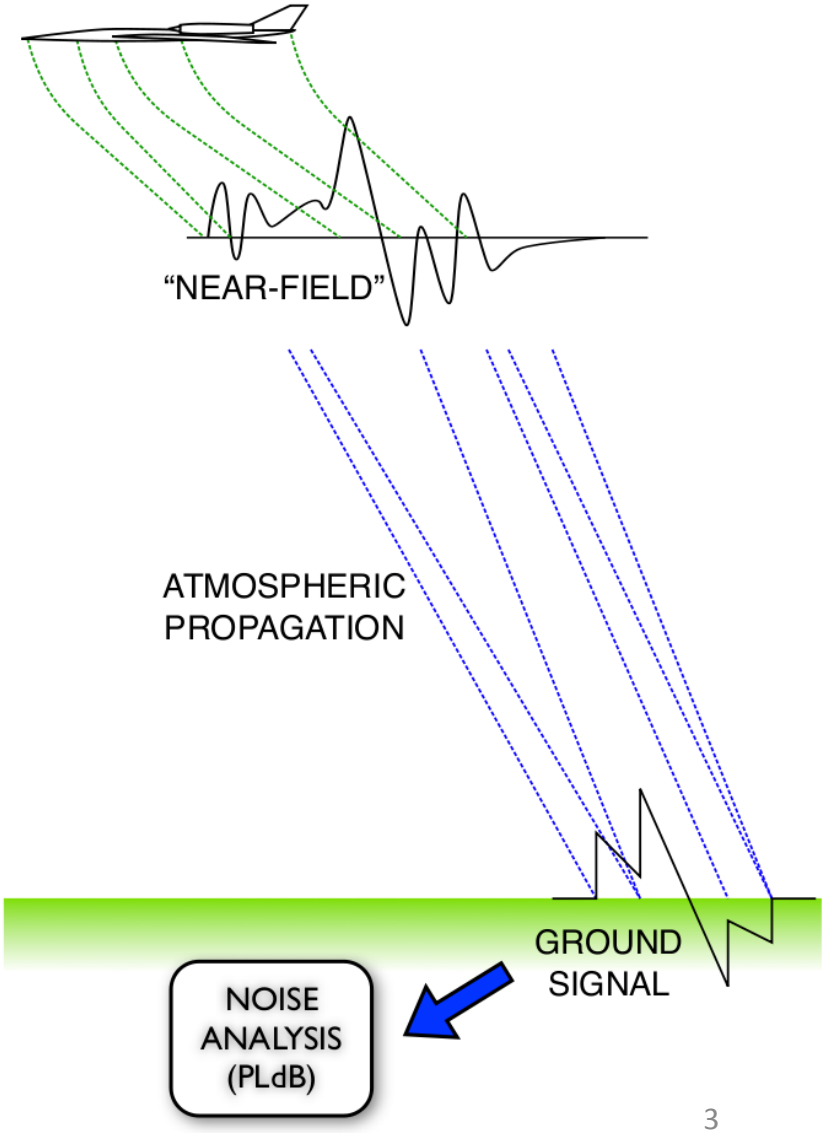
Motivation

- Commercial supersonic overland flight is currently prohibited
  - Supersonic overland flight is an enabler for entry into new vehicle market
- Replacing the prohibition with a certification standard requires an international effort to quantify the accuracy and reliability of prediction methods
- Deficiencies in existing methods should be noted to focus research on addressing weaknesses

Motivation

- Nearfield CFD is part of sonic boom prediction
- Explore the issues
- Impartially compare signatures by uniform application of
  - Nearfield statistics
  - Propagation
  - Loudness measures



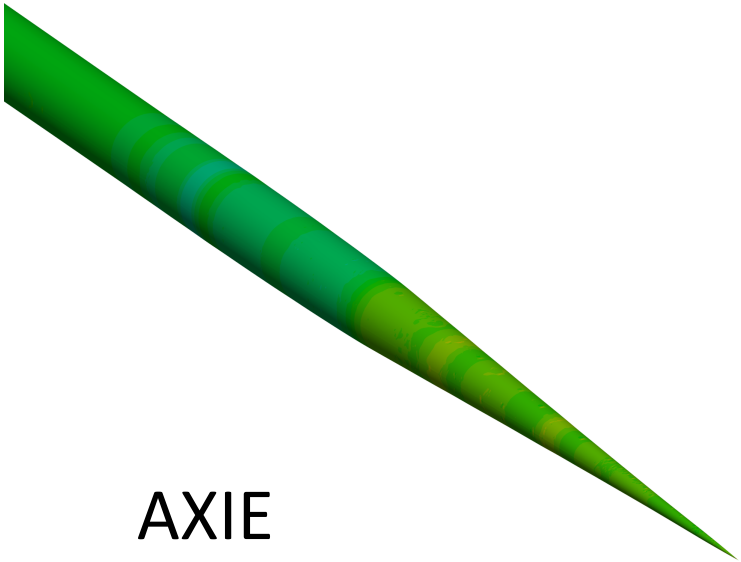
Workshop Culture

- Adjectives such as good, bad, right, and wrong oversimplify issues and should be avoided
- Focus on describing observed differences and communicate why things are different

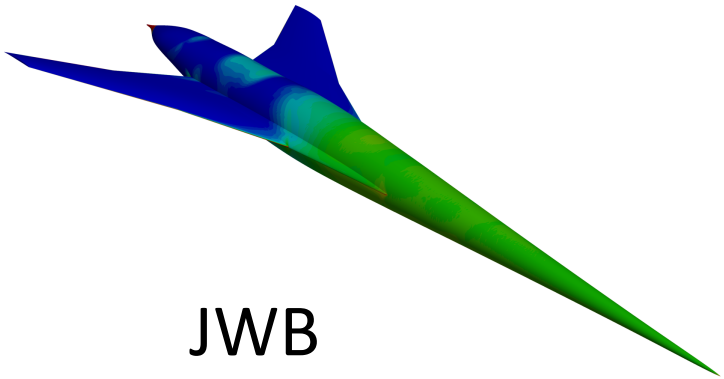
Models and Cases

- Designed to produce similar signatures with a range of simulation complexity
- AXIE C25D Equivalent Area Distribution
- JWB JAXA Delta Wing Body
- C25F C25D Wing Body Flow Through Nacelle
- C25P C25D Wing Body Powered Nacelle (optional)

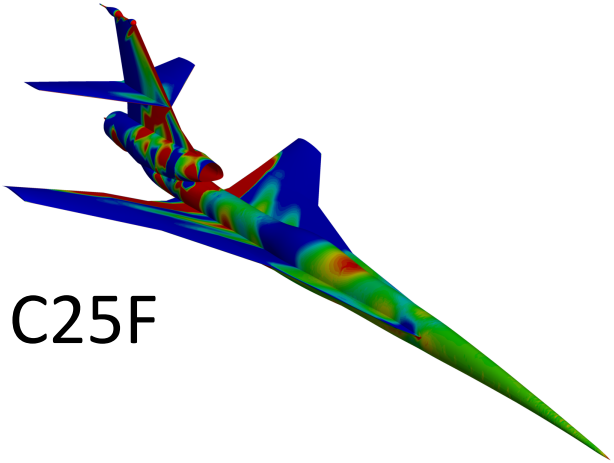
Models and Cases



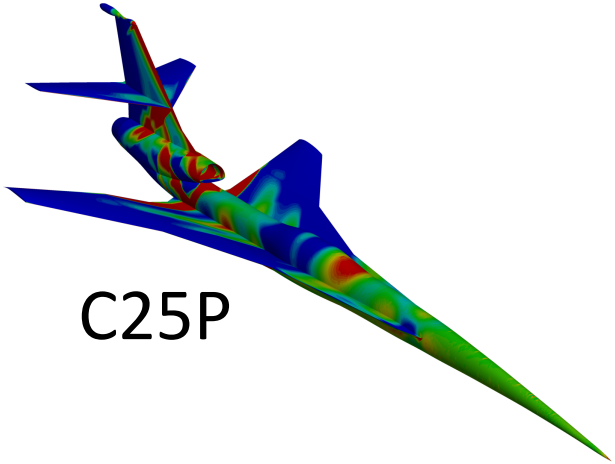
AXIE



JWB



C25F

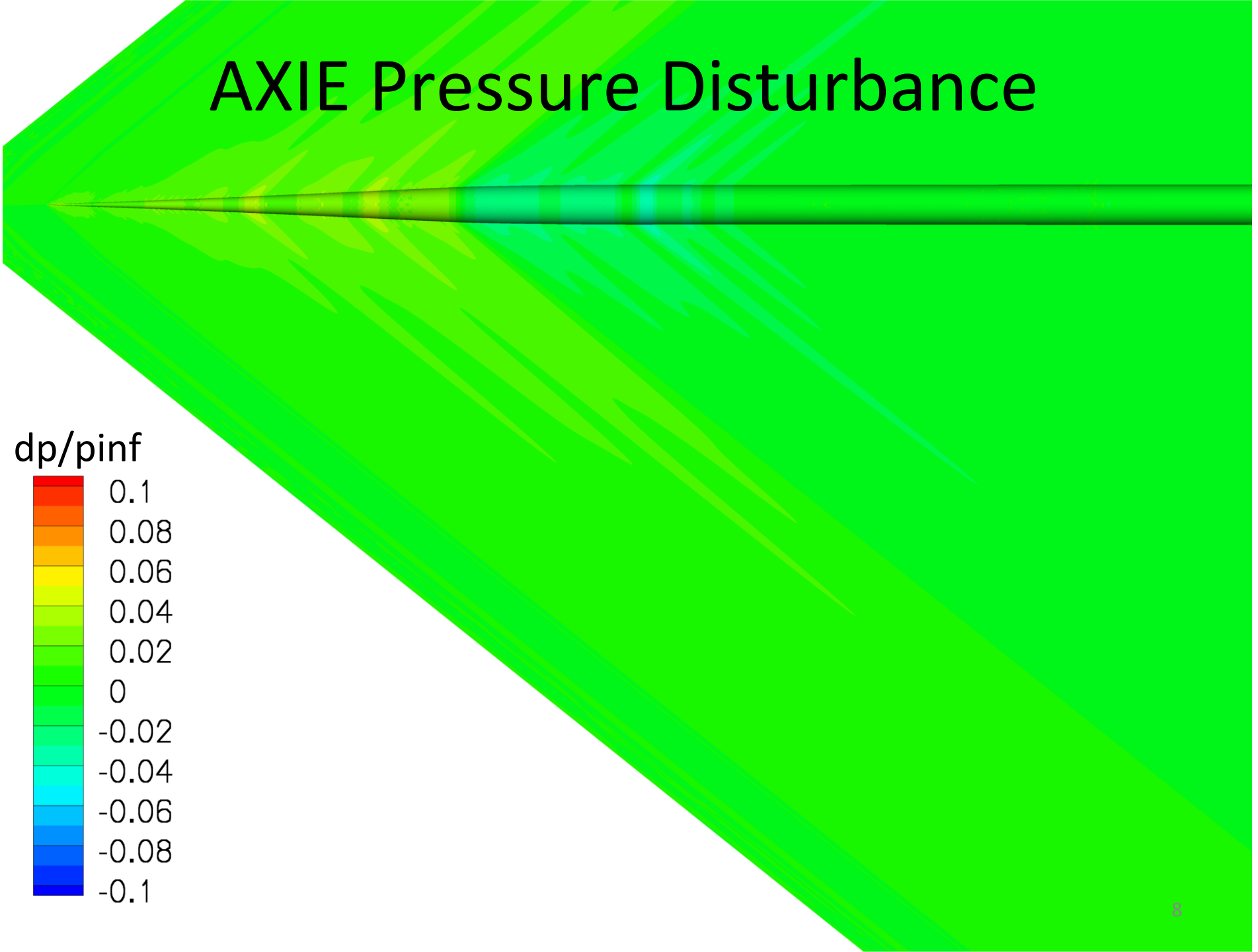


C25P

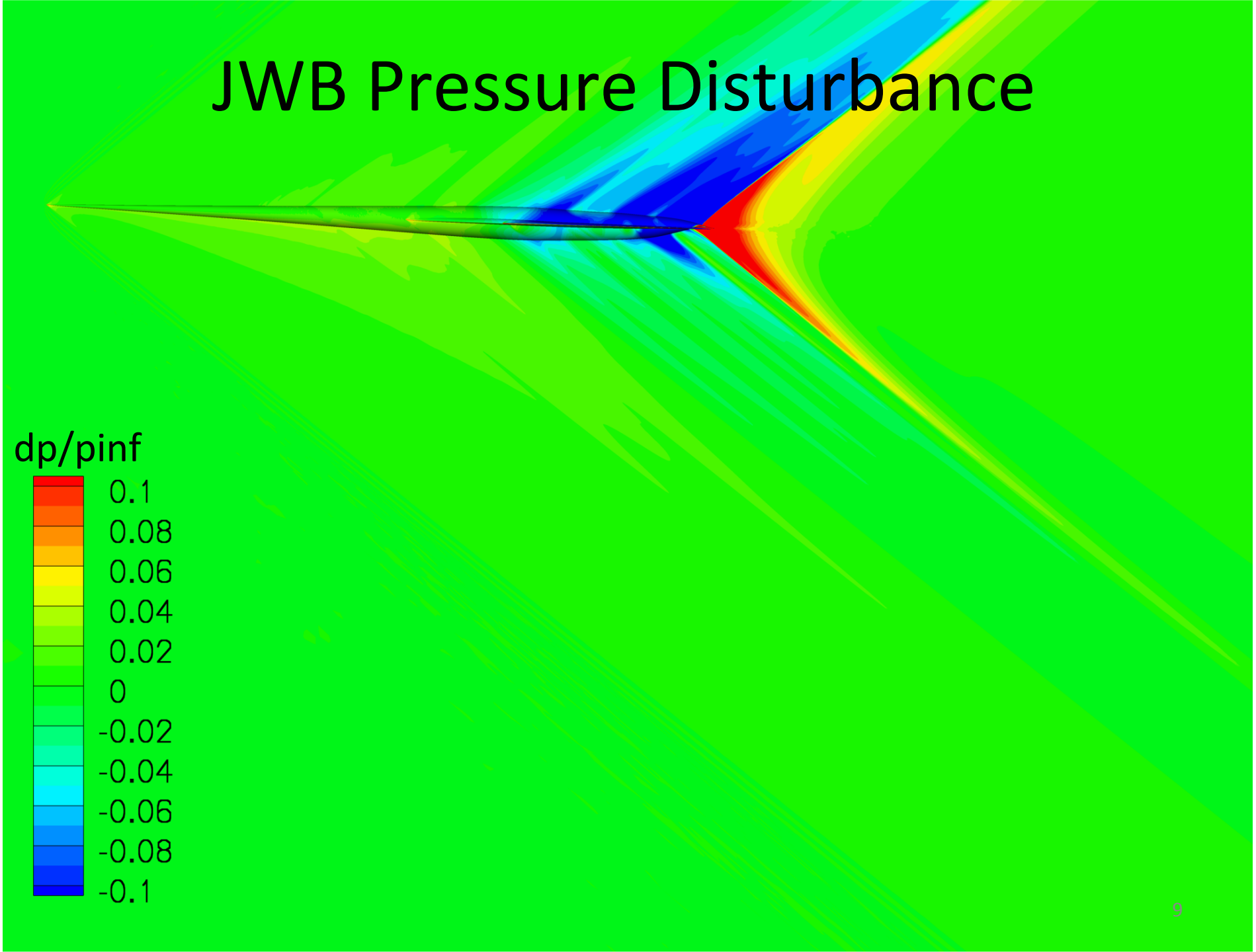
Models and Cases

- All geometry and grids included required angle of attack
- Mach 1.6
- Euler and flight Reynolds number of 5.7 million per meter
- US Standard atmosphere at 15,760 meter altitude
- Propulsion boundary conditions

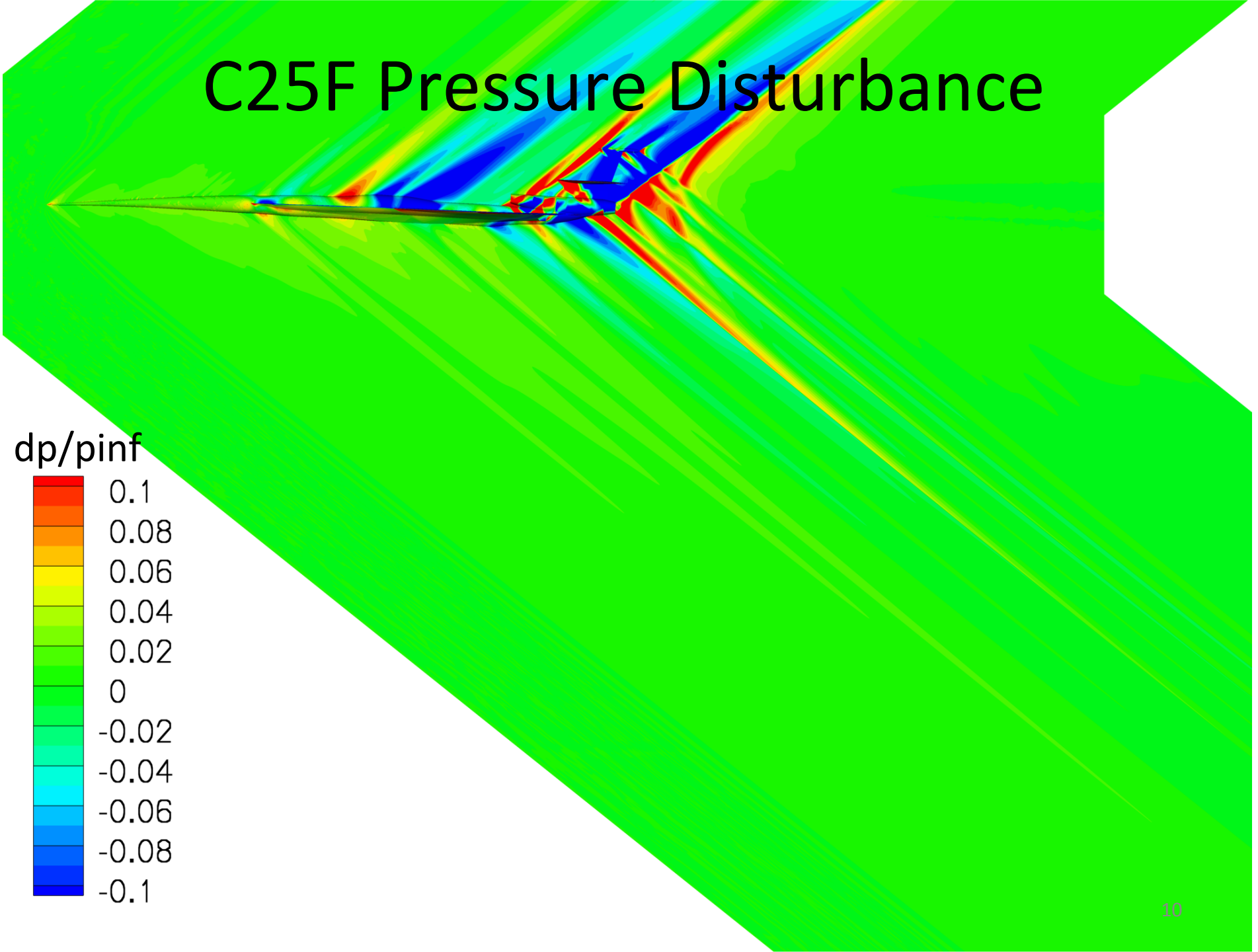
AXIE Pressure Disturbance



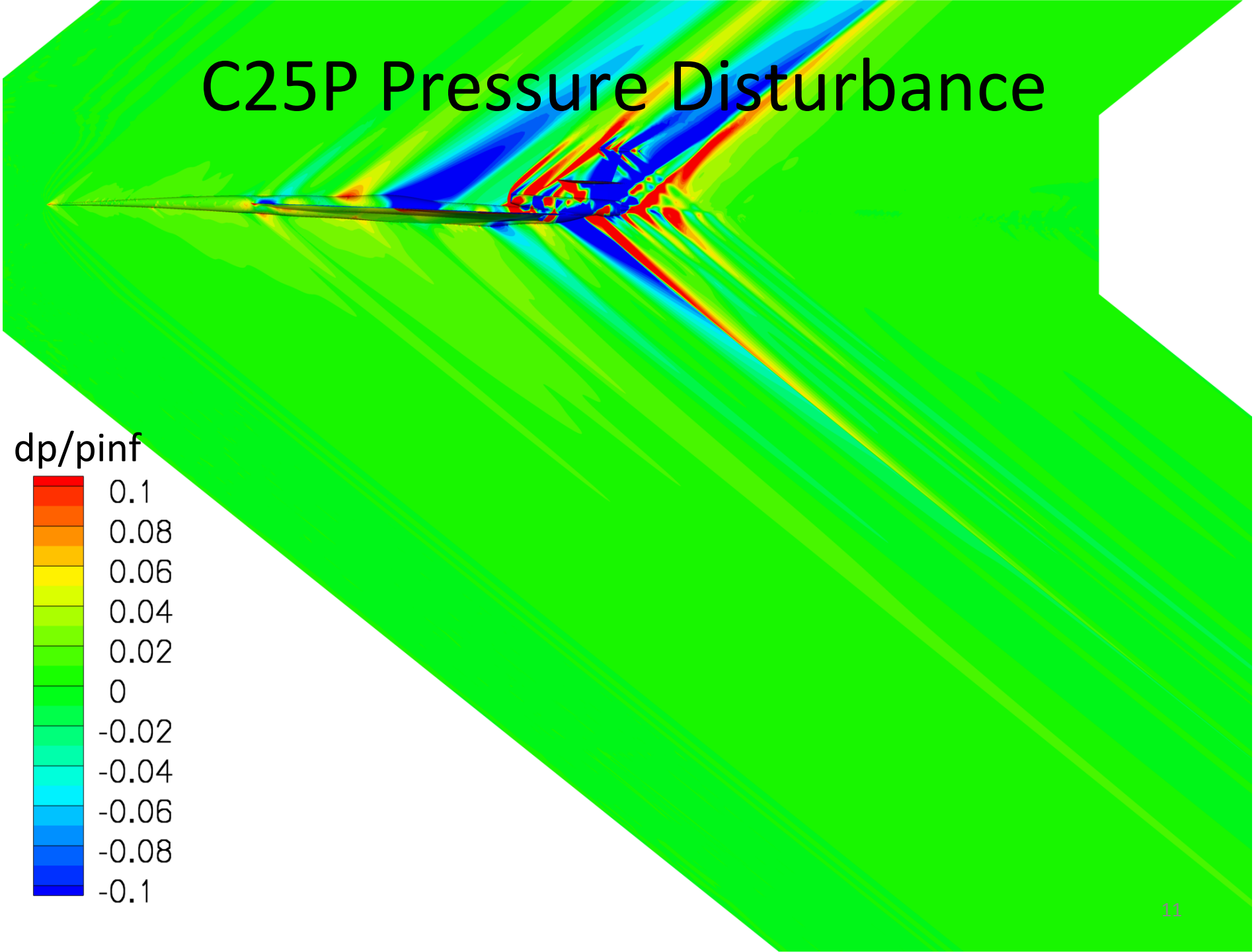
JWB Pressure Disturbance



C25F Pressure Disturbance



C25P Pressure Disturbance



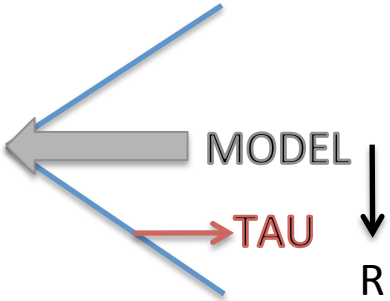
Grid Sizes

- Mixed-element and tetrahedra-only families with a factor of 0.8 in characteristic length and doubling of nodes and elements between grids
  - 0.6-56 million node Euler AXIE (5)
  - 6, 11, and 18 million node Euler JWB (3, tetra-only)
  - 3-104 million node Euler C25F (6)
  - 5-138 million node viscous C25F (6)
  - 3-52 million node Euler C25P (5)
  - 5-70 million node viscous C25P (5)

Data Processing

- Thank You! Consistency improved from first workshop
- Received signatures via FTP or email
- Some were reformatted, zero padded, or sorted
- Plotted
- Contacted participants for clarification/update when
  - Incorrect location or incomplete signature
  - Significant differences between submissions of same participant (iterative convergence)
  - Reference or boundary conditions suspect

Nearfield Plotting

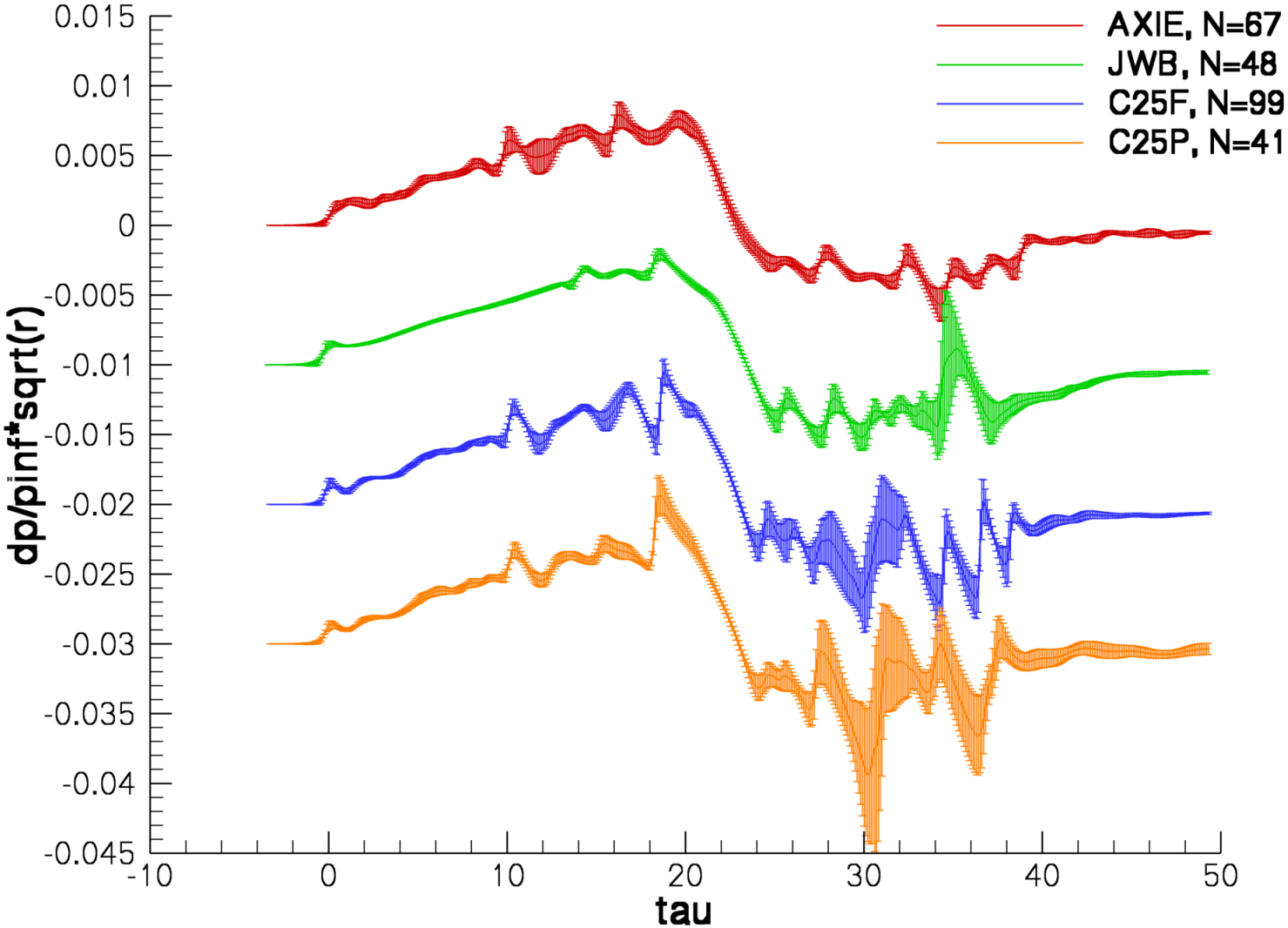


- Tau is distance from freestream Mach cone originating at tip of nose
- Delta pressure divided by freestream pressure is scaled by the square root of radius in body lengths
- Signatures at different radii readily comparable and “aging” effect observed

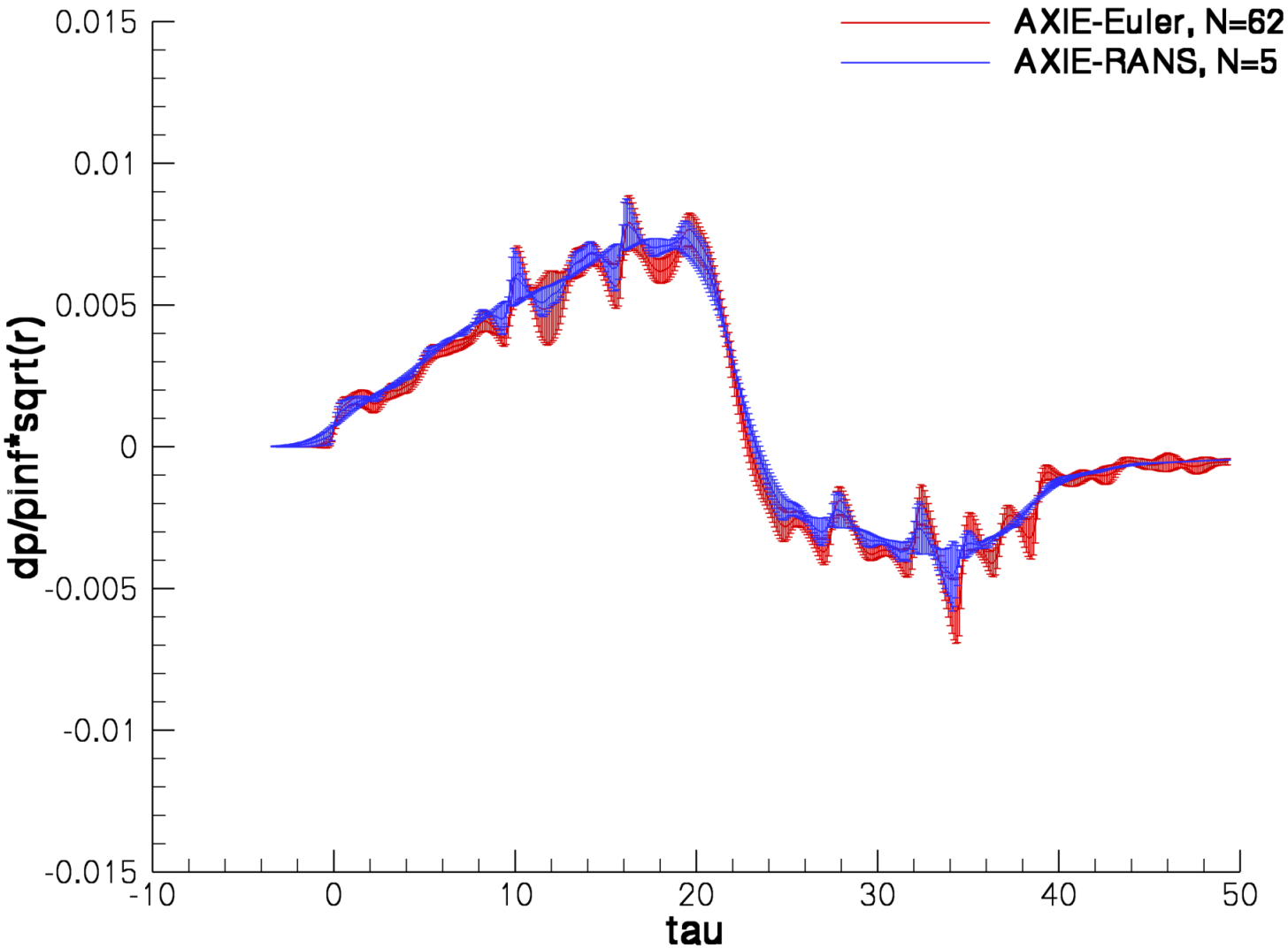
Nearfield Signature Statistics

- Population mean and standard deviation of interpolated signature every centimeter
- Analogous to wind tunnel spatial averaging
- Outliers impact these statistics and will be identified and examined later in the talk

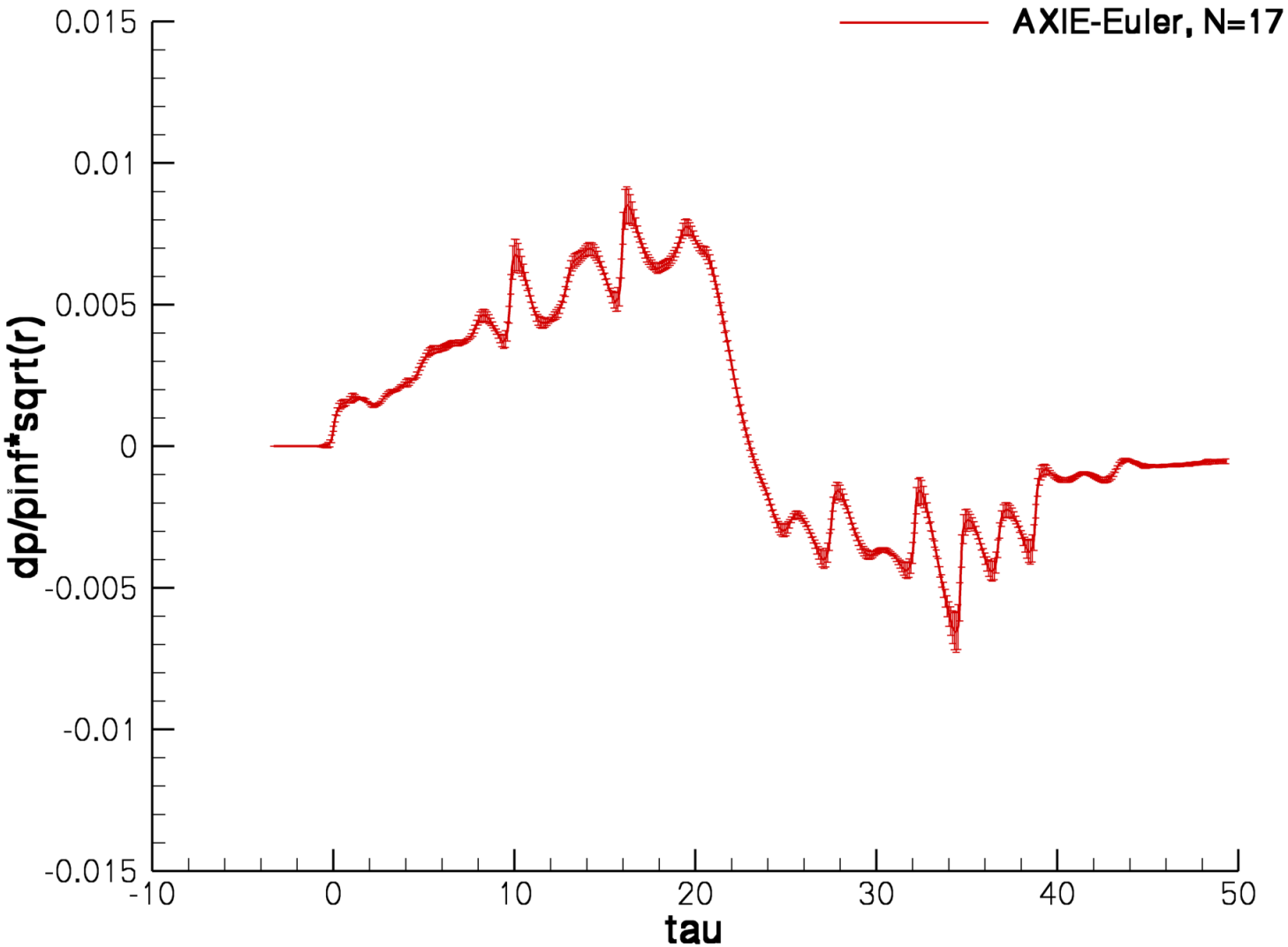
Nearfield Variation R=3, PHI=0°



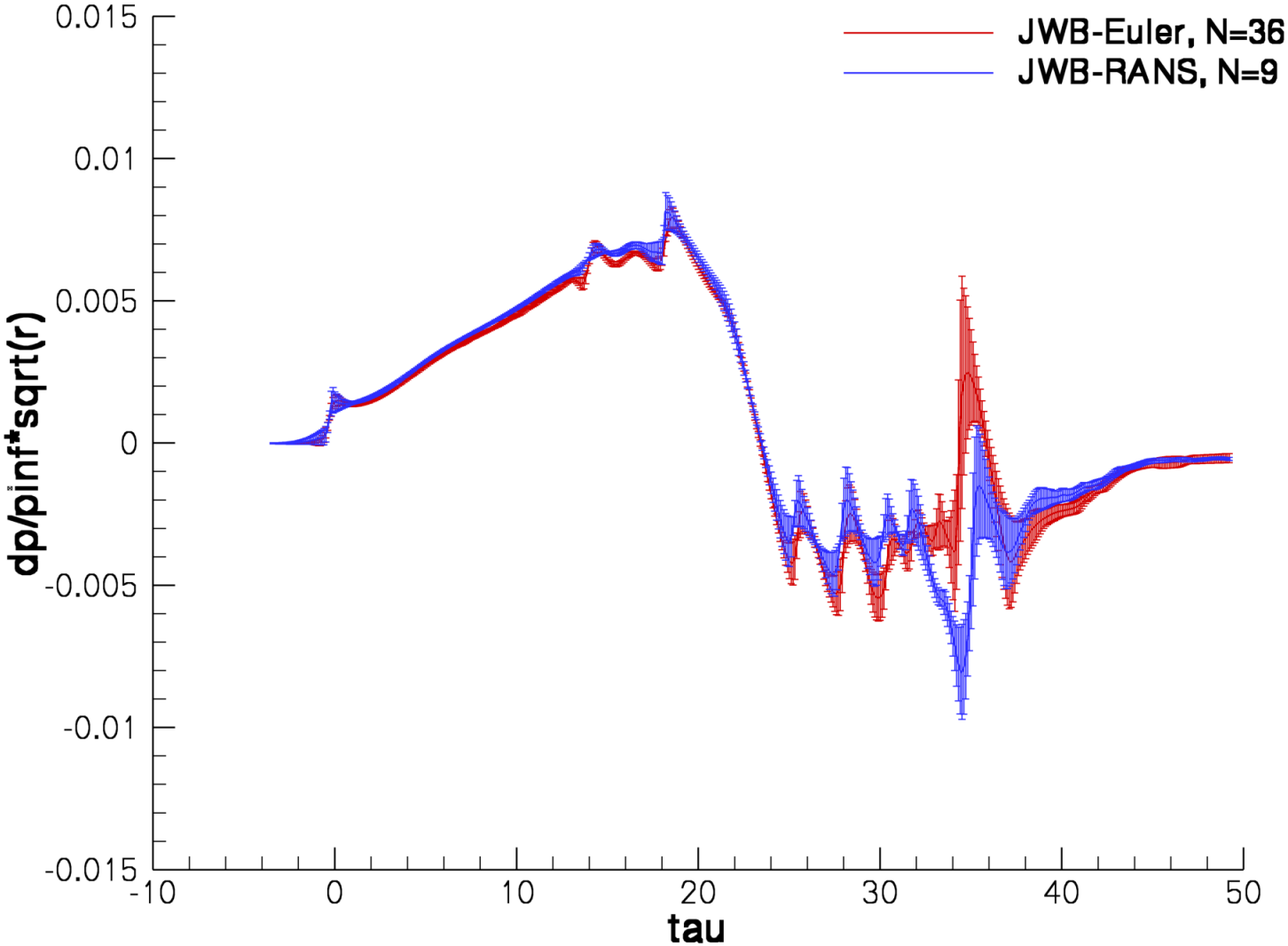
AXIE Nearfield Physics R=3, PHI=0°



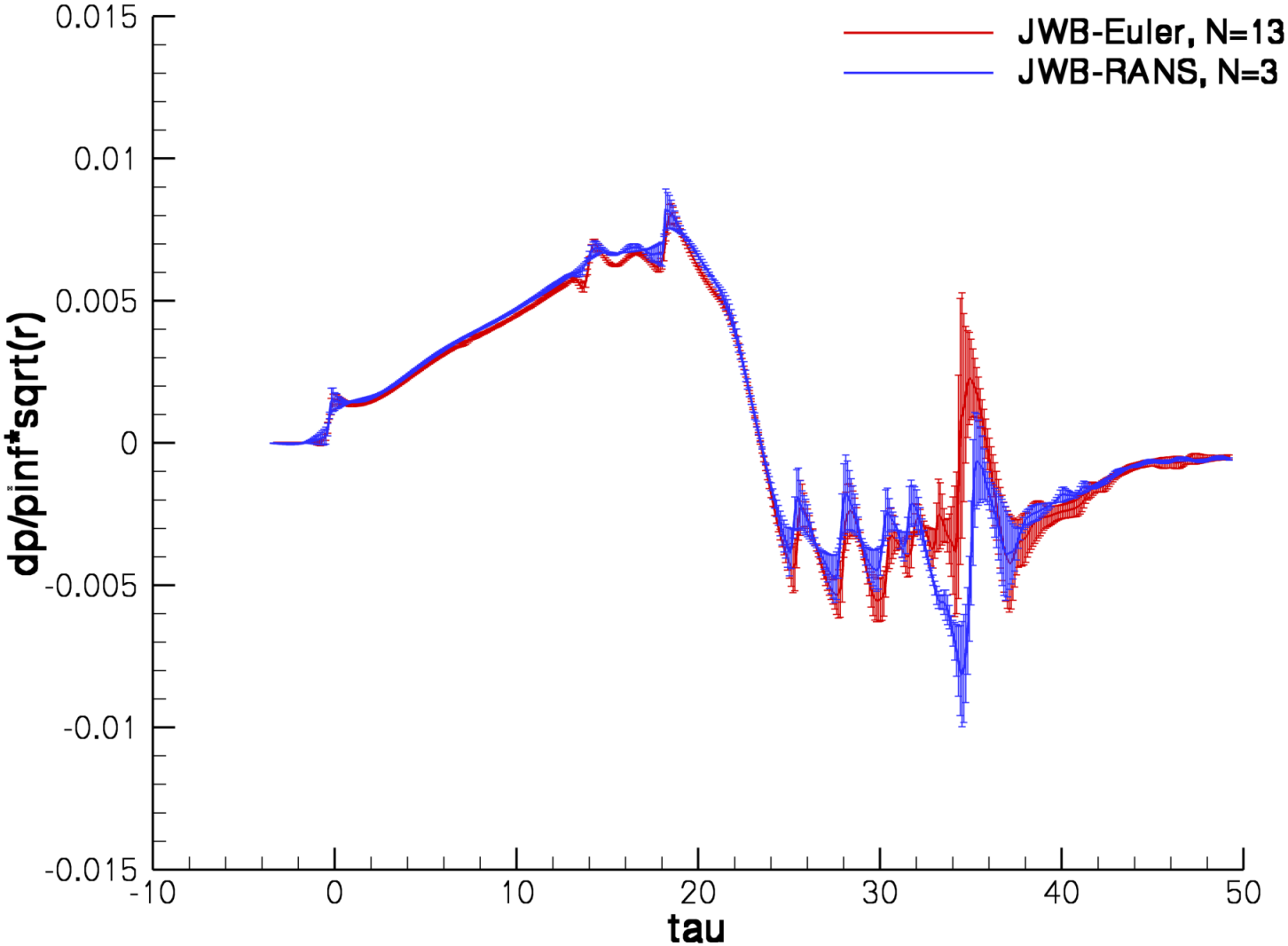
AXIE Nearfield Fine Grid R=3, PHI=0°



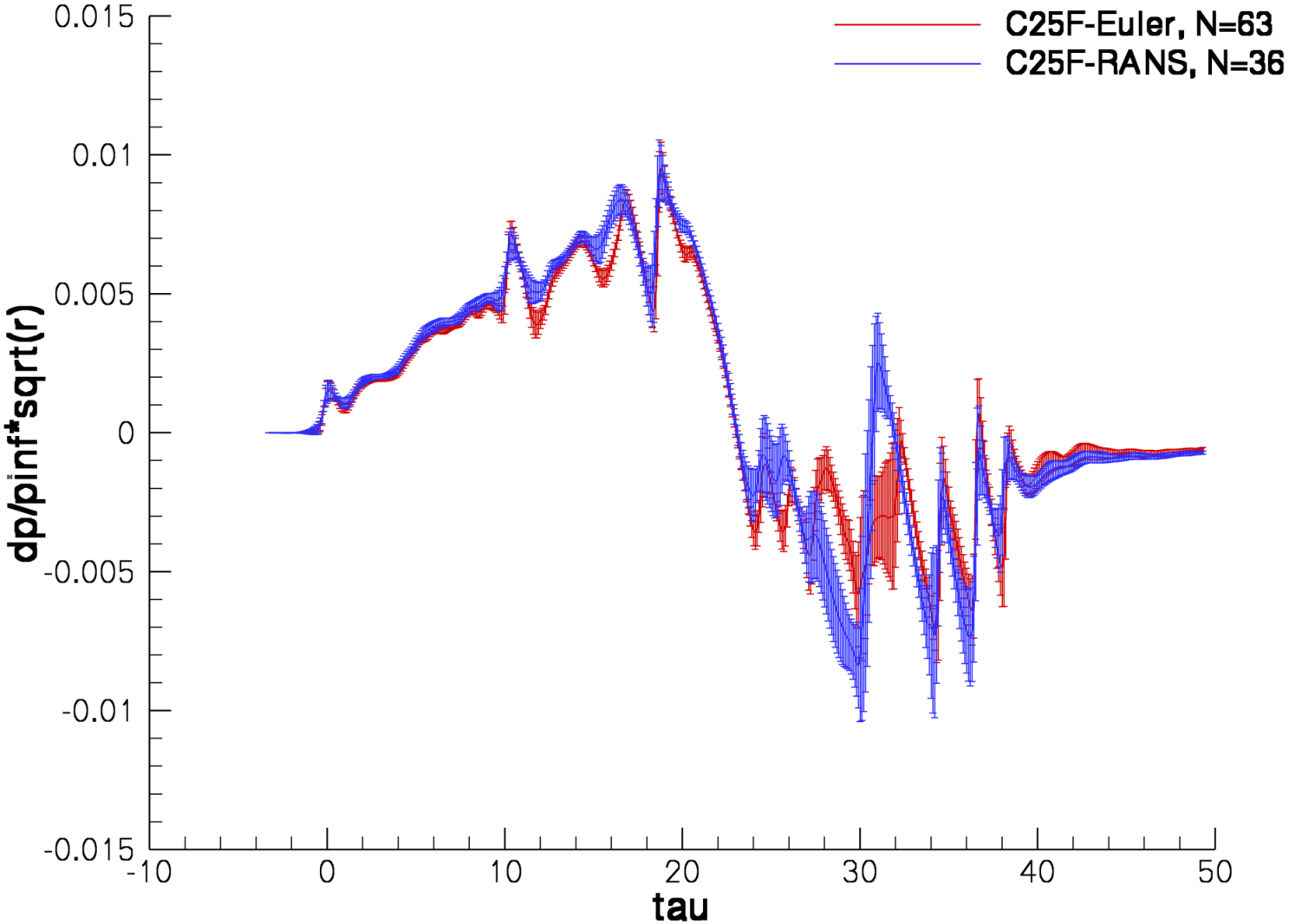
JWB Nearfield Physics R=3, PHI=0°



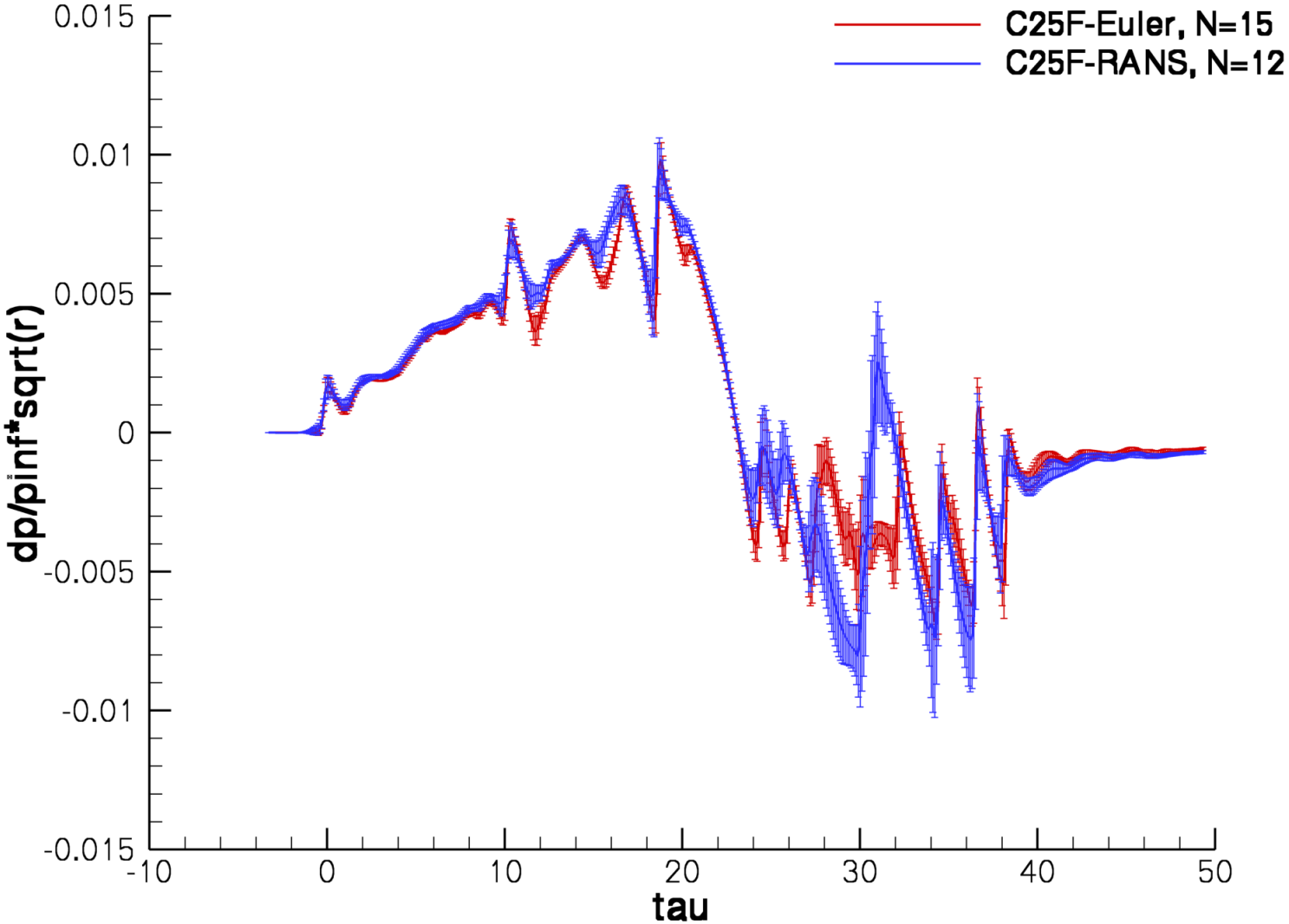
JWB Nearfield Fine Grid R=3, PHI=0°



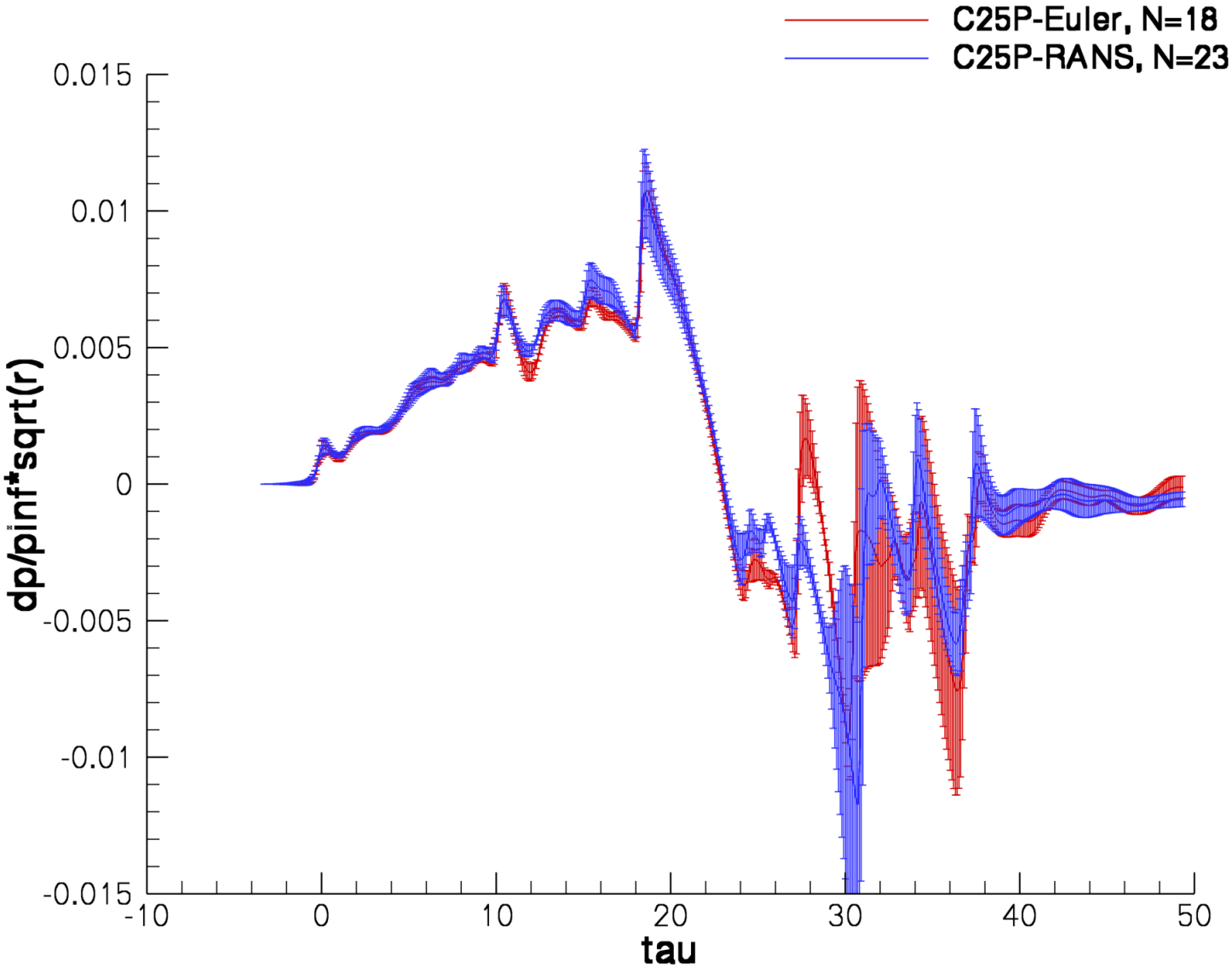
C25F Nearfield Physics R=3, PHI=0°



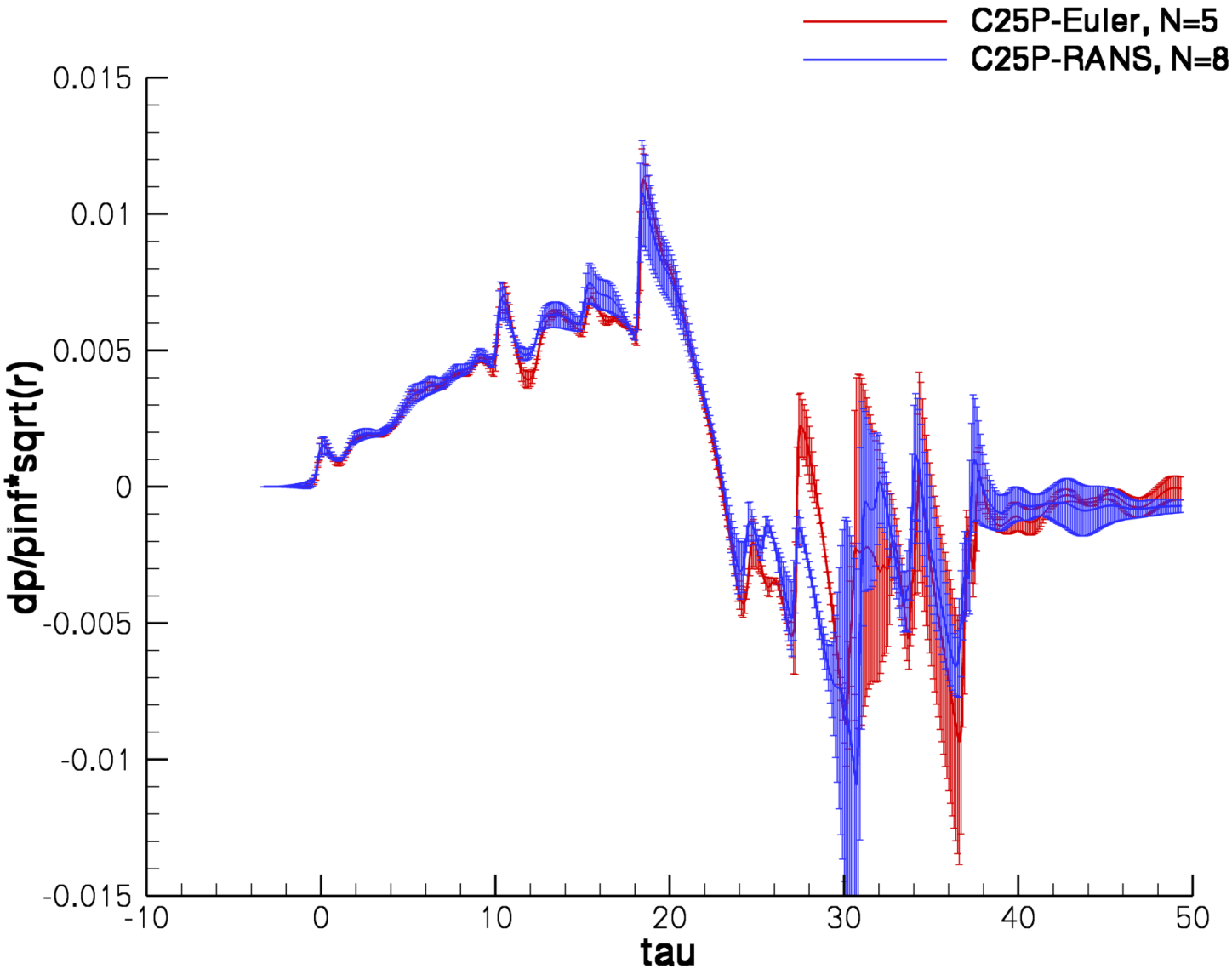
C25F Nearfield Fine Grid R=3, PHI=0°



C25P Nearfield Physics R=3, PHI=0°



C25P Nearfield Fine Grid R=3, PHI=0°

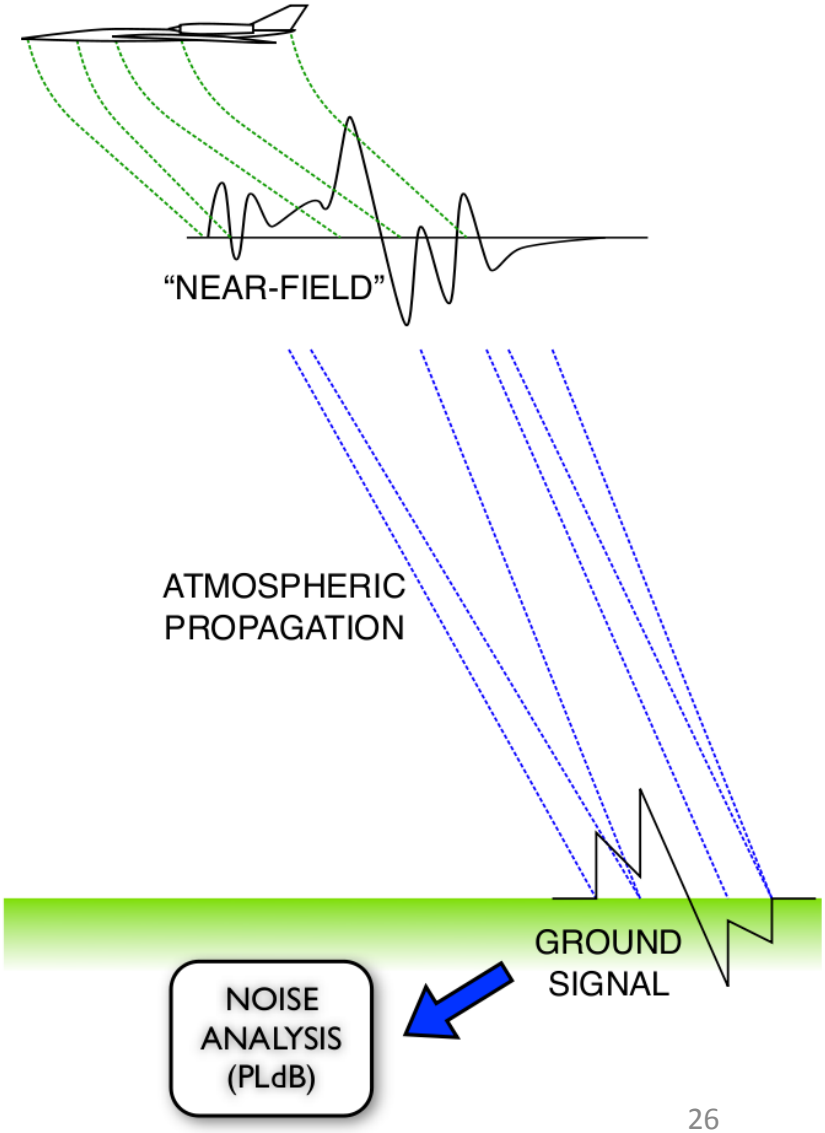


Summary: Nearfield Statistics

- Variation increased with complexity
- Euler and RANS have non-overlapping one standard deviation ranges
  - Low number of submissions (N) is a caveat
- Examining finest grid submissions reduced variation (except C25P)
- Examining all submissions includes grid sensitivity
- Variation is larger in aft portion of signature

Return to Motivation

- Nearfield CFD is part of sonic boom prediction
- Explore the issues
- Impartially compare signatures by uniform application of
  - Nearfield statistics
  - Propagation
  - Loudness measures

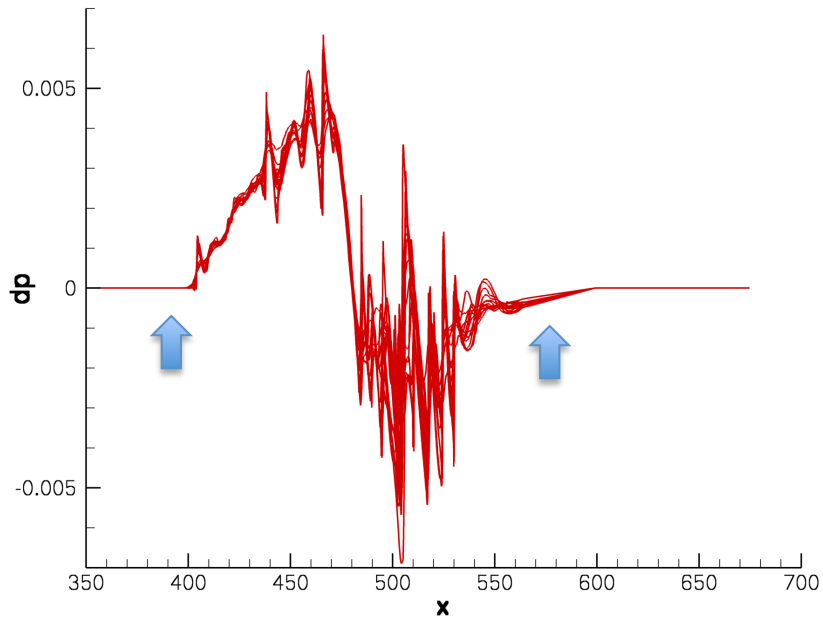


Ground Propagation

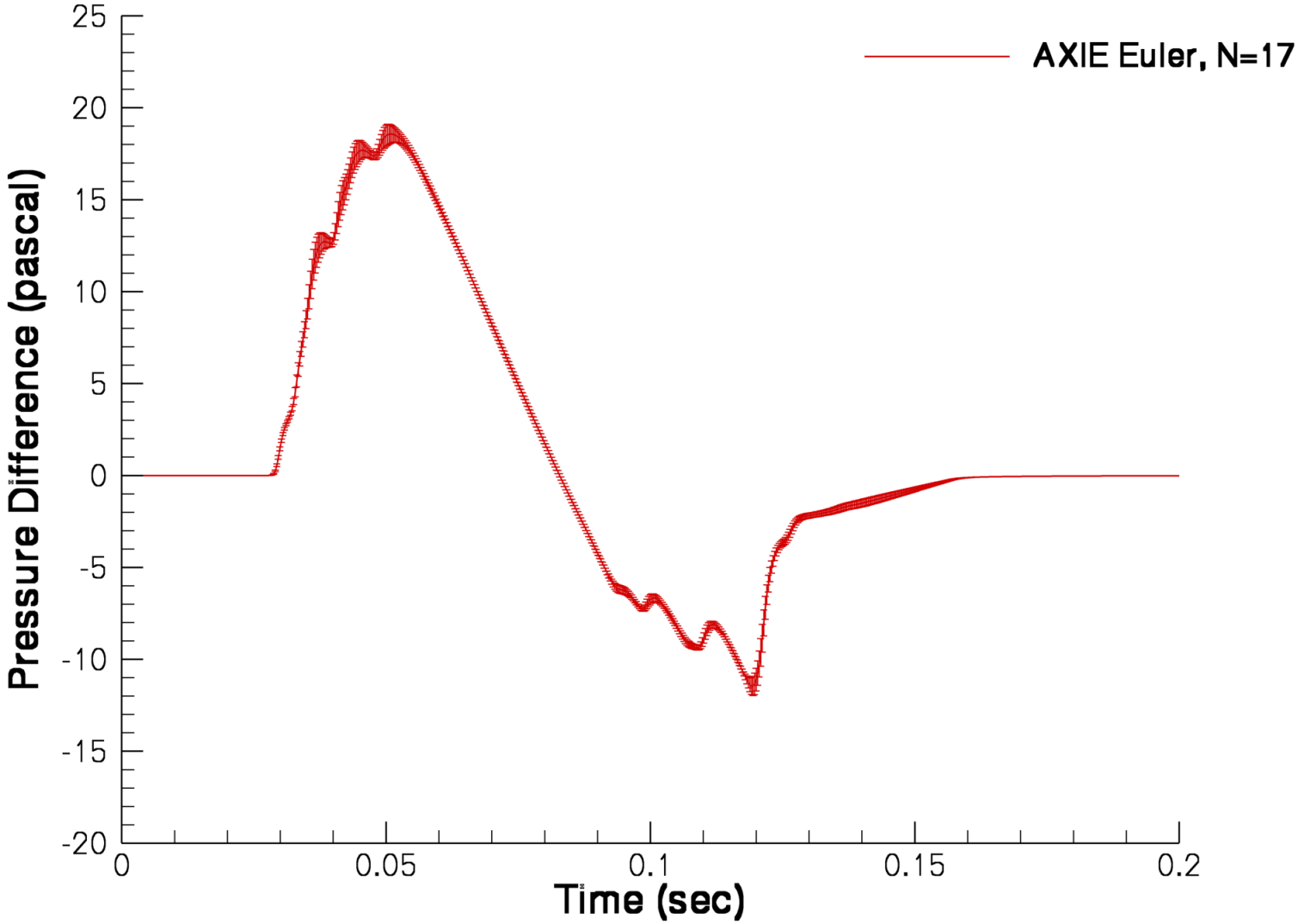
- Geometry and grids provided in “full-scale”
- US Standard atmosphere and ANSI S1.26 Annex C relative humidity from 15760 meter altitude
- sBOOM (Rallabhandi)
  - Burgers equation with molecular relaxation
- Submission are windowed with fore and aft ramps using a consistent tau (distance from freestream Mach cone)

Nearfield Window for Propagation

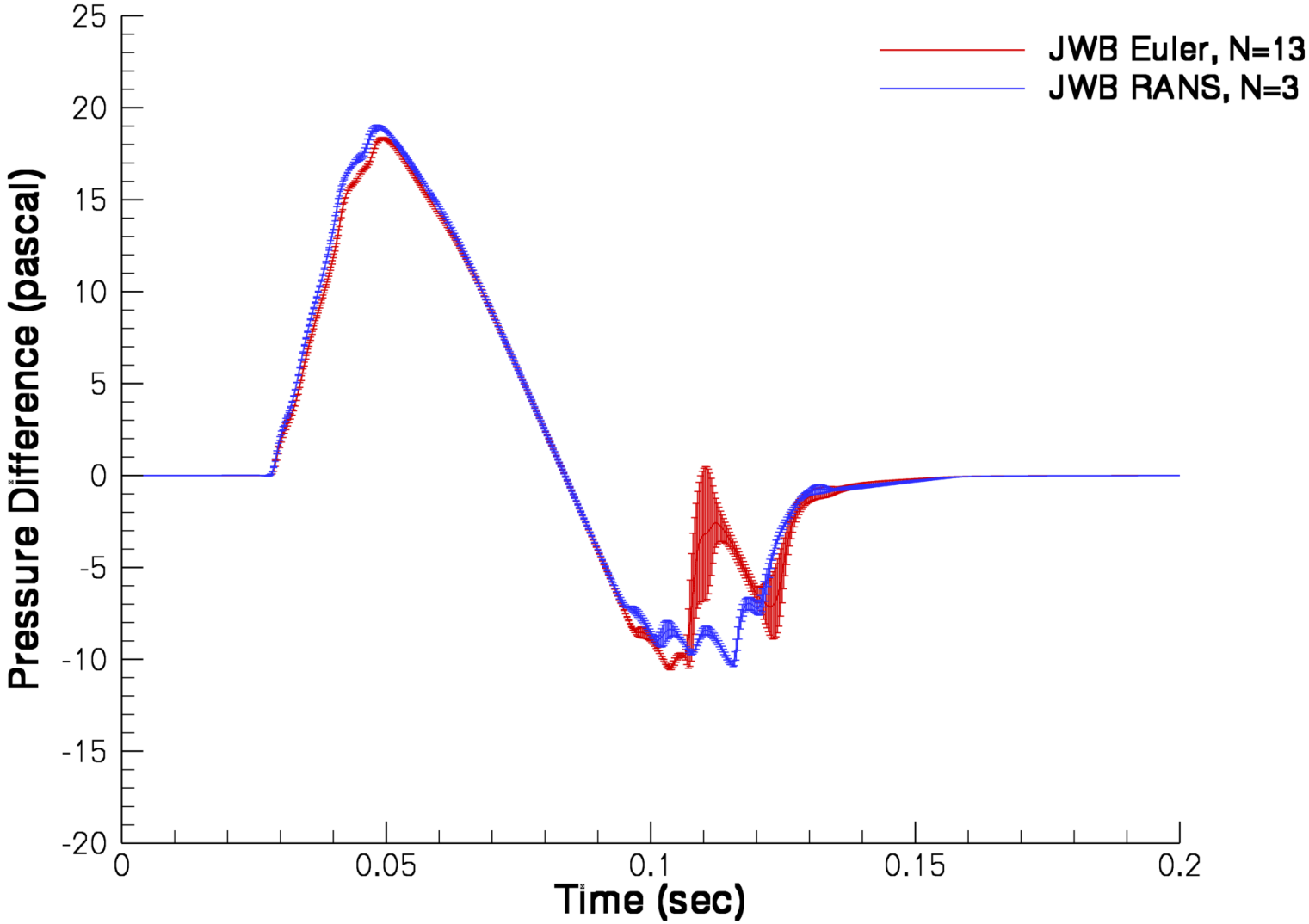
- Nearfield submission is ramped to zero
  - TAU = [-0.2,-0.1] ahead of signature
  - TAU = [1.5,1.8] aft of signature
- Signature is zero-padded [-0.5,2.5]



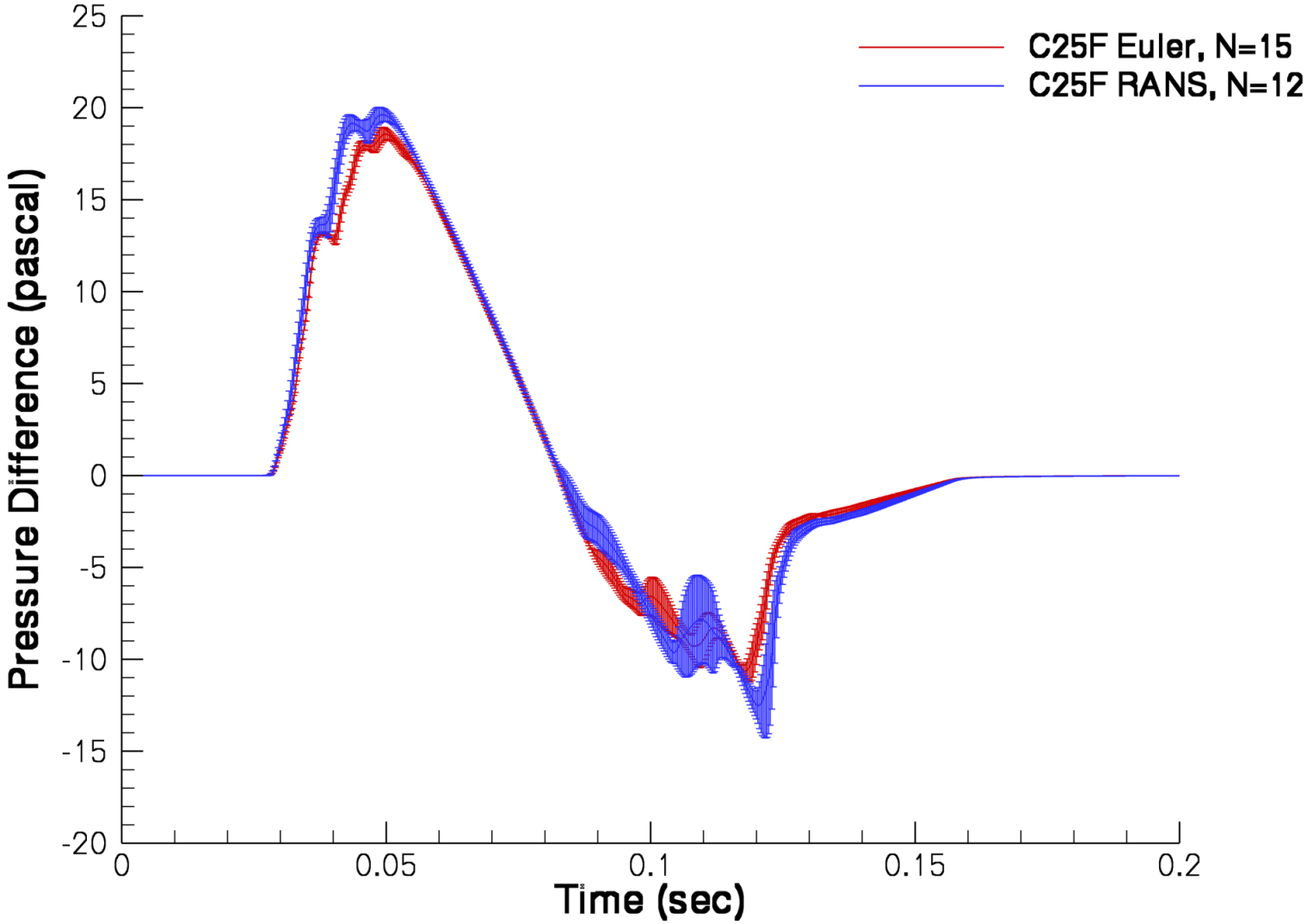
AXIE Ground Fine Grid R=3, PHI=0°



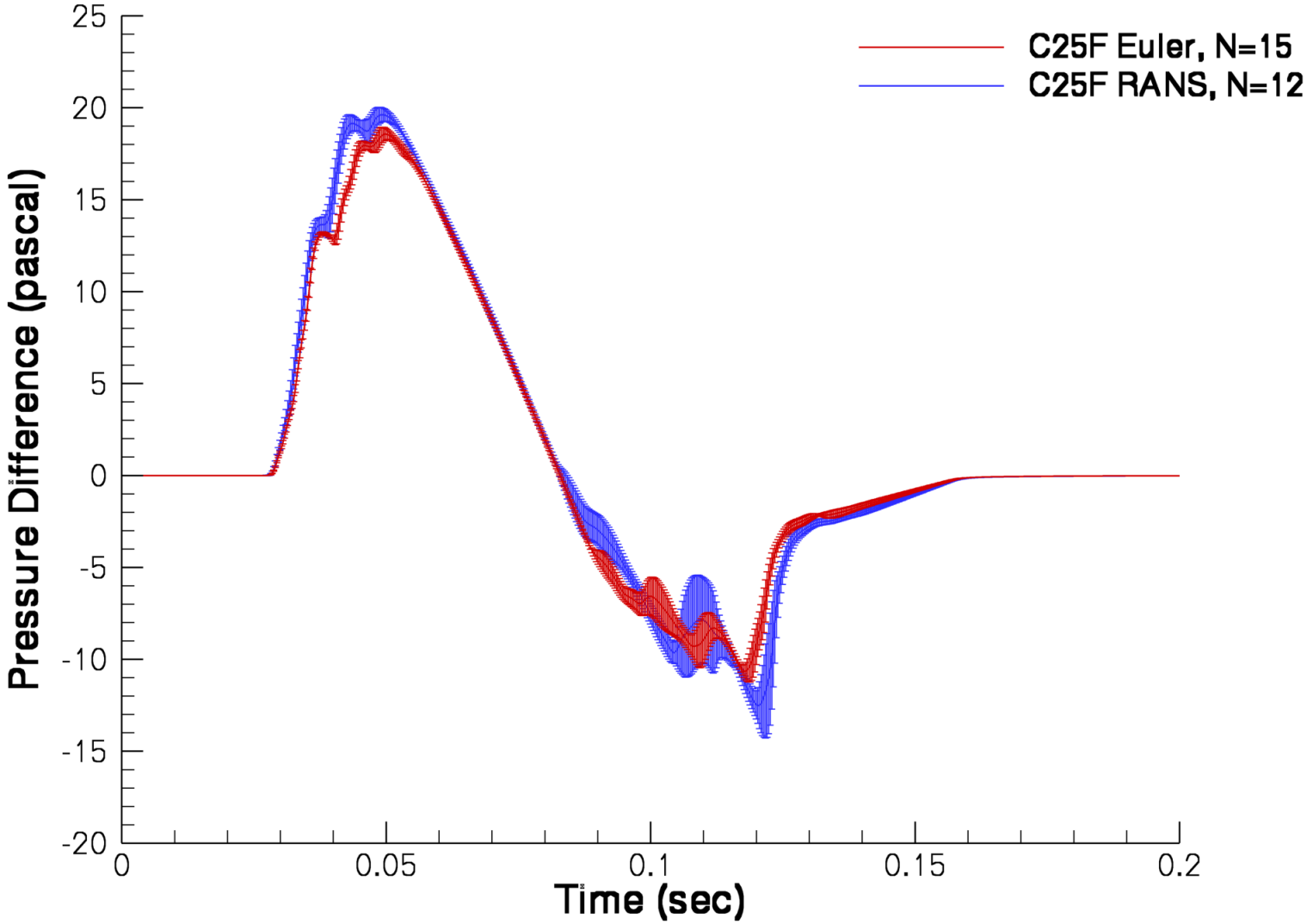
JWB Ground Fine Grid R=3, PHI=0°



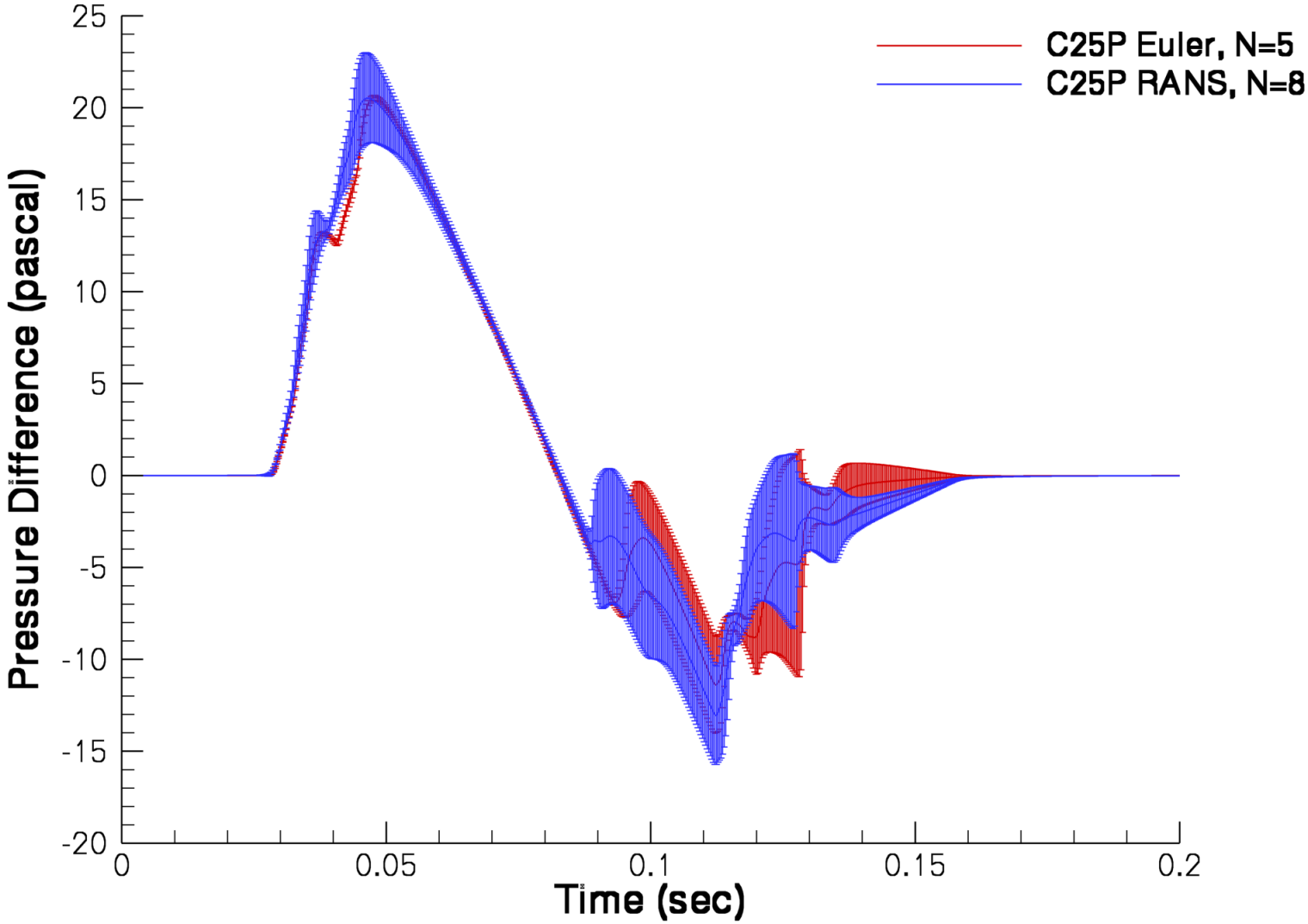
C25F Ground Fine Grid R=3, PHI=0°



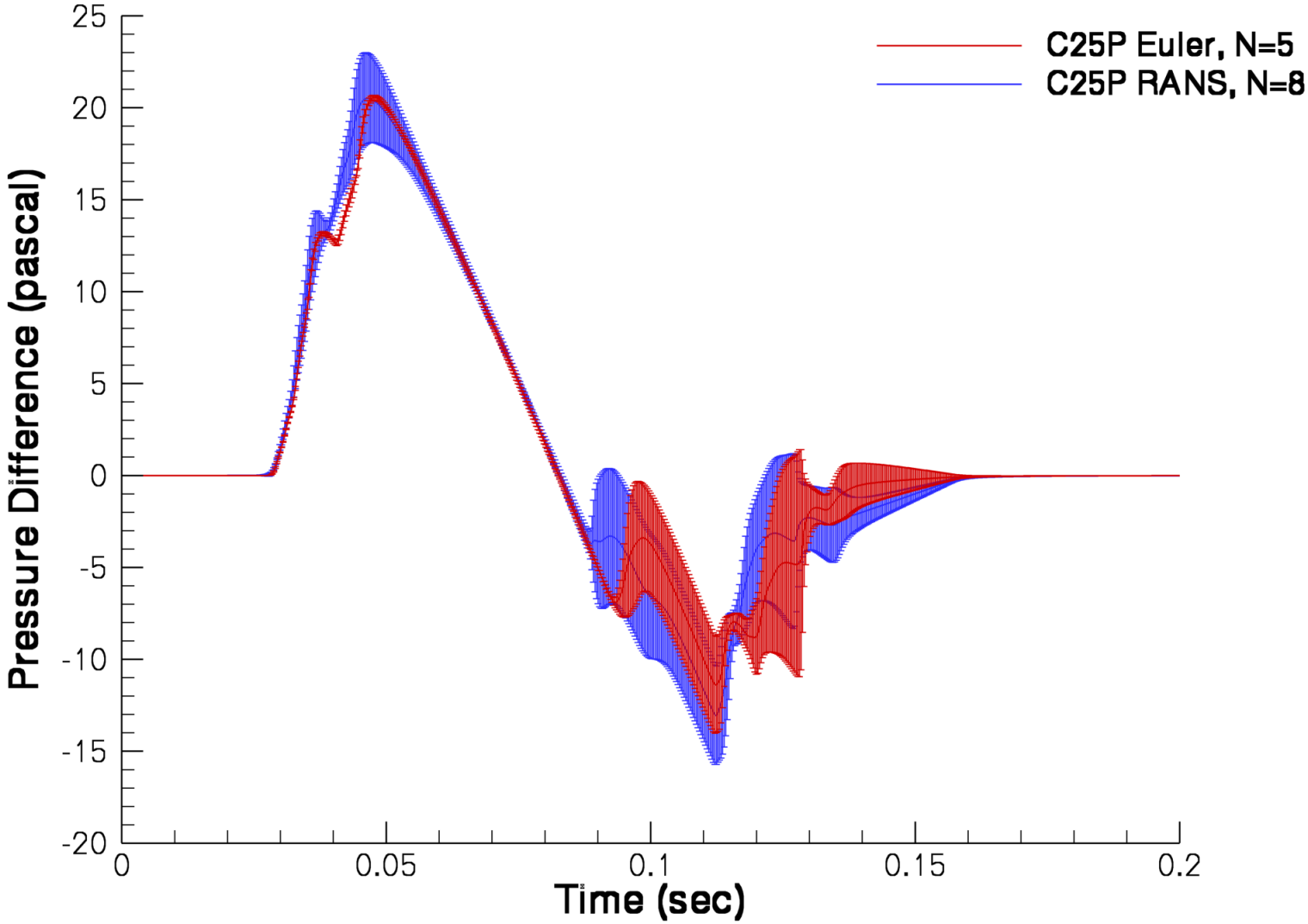
C25F Ground Fine Grid R=3, PHI=0°



C25P Ground Fine Grid R=3, PHI=0°



C25P Ground Fine Grid R=3, PHI=0°



Summary: Ground Signature Statistics

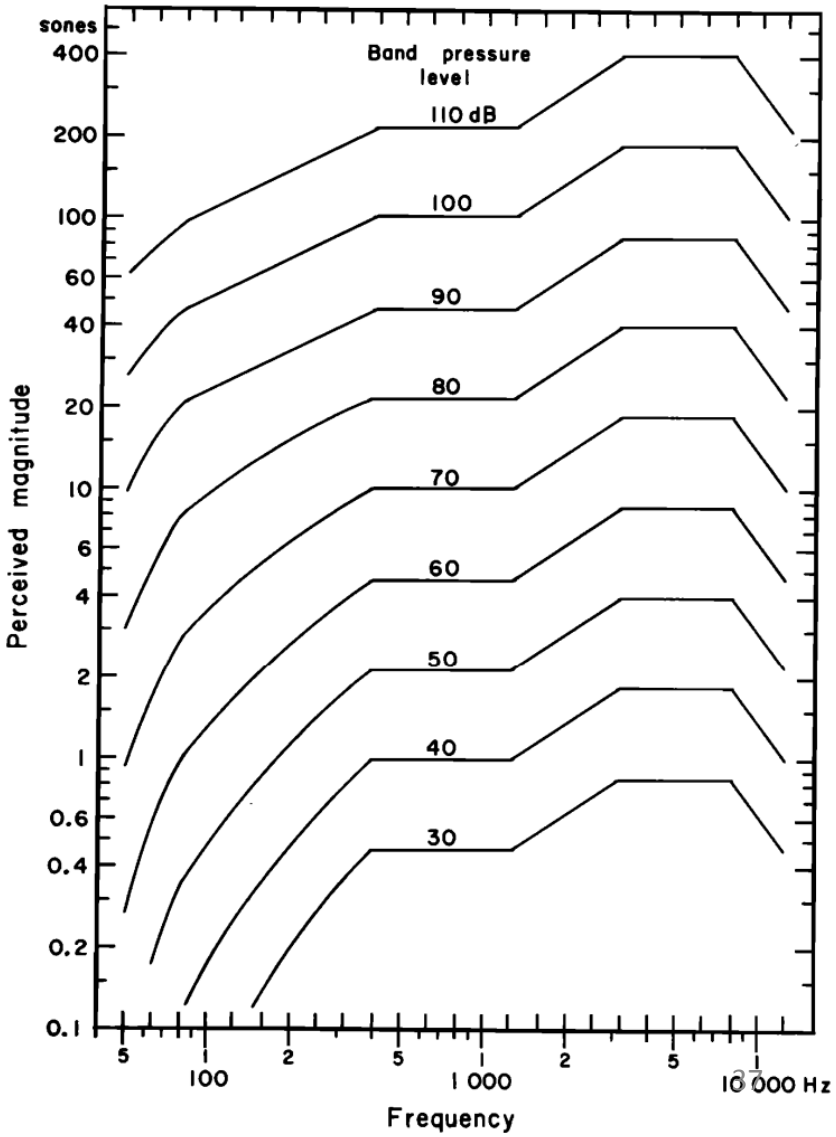
- Similar trends to nearfield (only presented fine grid submission)
- Variation increased with complexity
- Euler and RANS have non-overlapping one standard deviation ranges for JWB
  - Low number of submissions (N) is a caveat
- C25F Euler variation is lower than RANS for similar N
- Variation is larger in aft portion of signature
  - Particular for C25P

Loudness and Annoyance

- Subjective metrics
- These human experiences are correlated to noise descriptors through experiments
  - Leatherwood et al. JASA 2002
  - Stevens Mark VII Perceived Level (PL)
  - Loubeau et al. 2nd International Sonic Boom Forum 2015 meta-study
  - A-weighted Sound Exposure Level (ASEL)

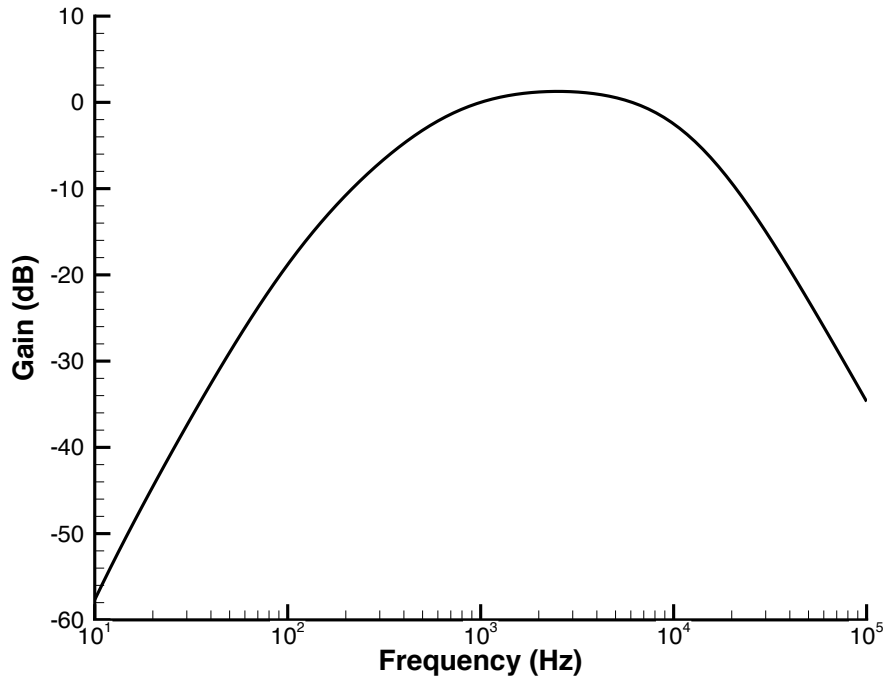
Perceived Level (PL)

- Signature sound pressure level is gathered into 1/3 octave bands
- Band levels are converted into sones (loudness)
- Sones from each band are combined
- Sones are converted into PL via logarithm

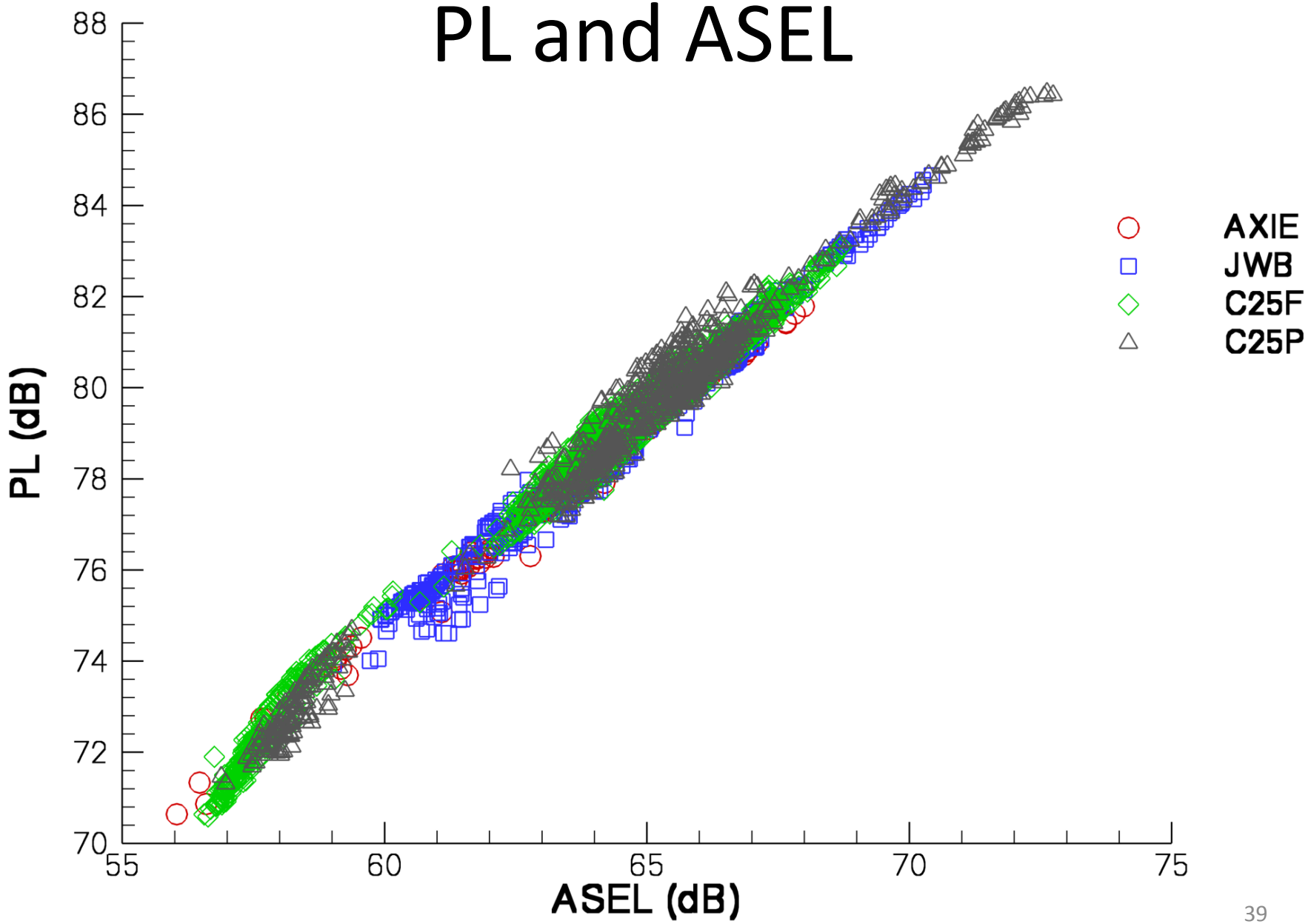


A-weighted Sound Exposure Level (ASEL)

- Continuous weighting that can be applied in frequency and time domain
- Good properties for sensitivity analysis



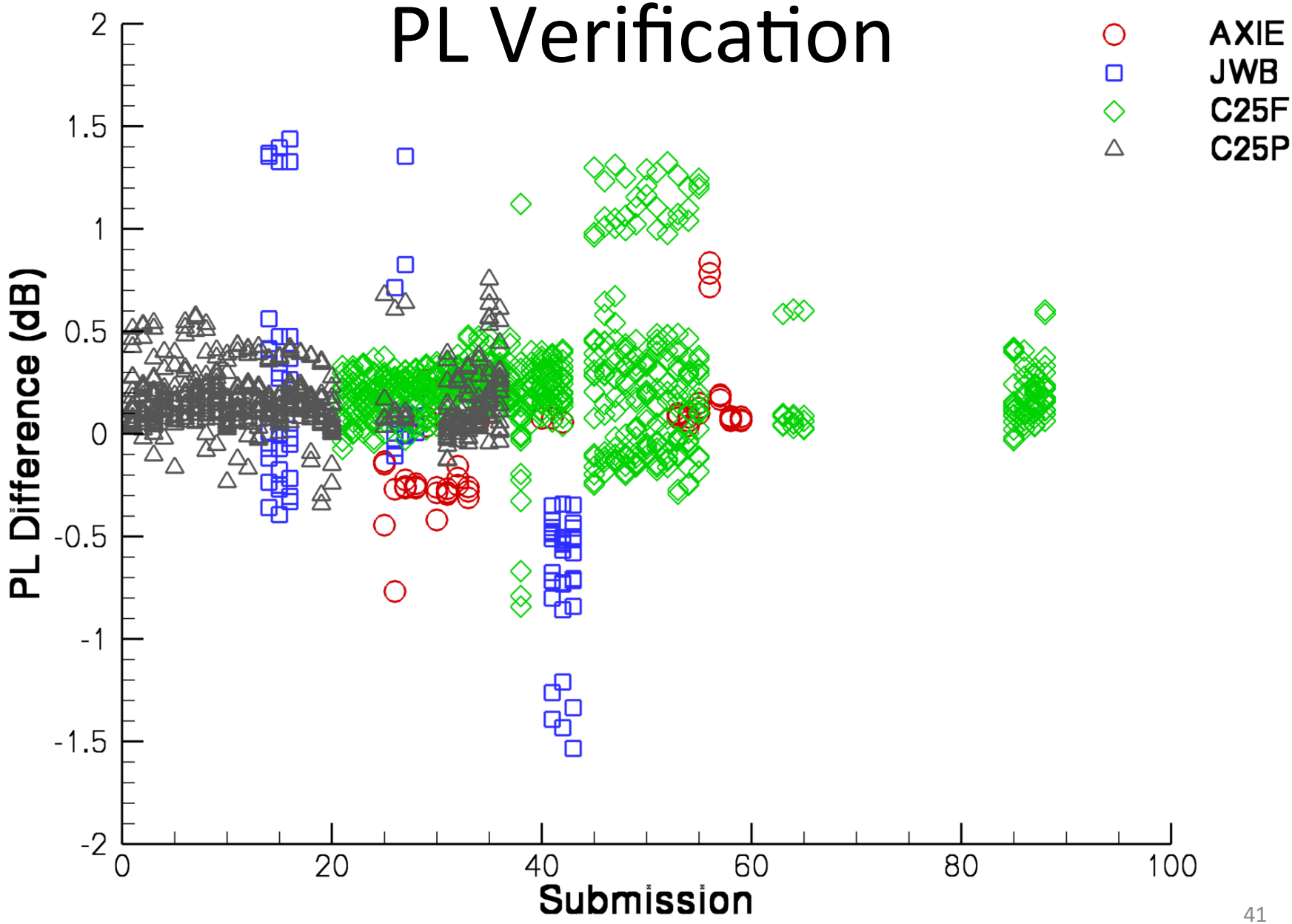
PL and ASEL


88
86
84
82
80
78
76
74
72
70
PL (dB)
55
60
65
70
75
ASEL (dB)
AXIE
JWB
C25F
C25P

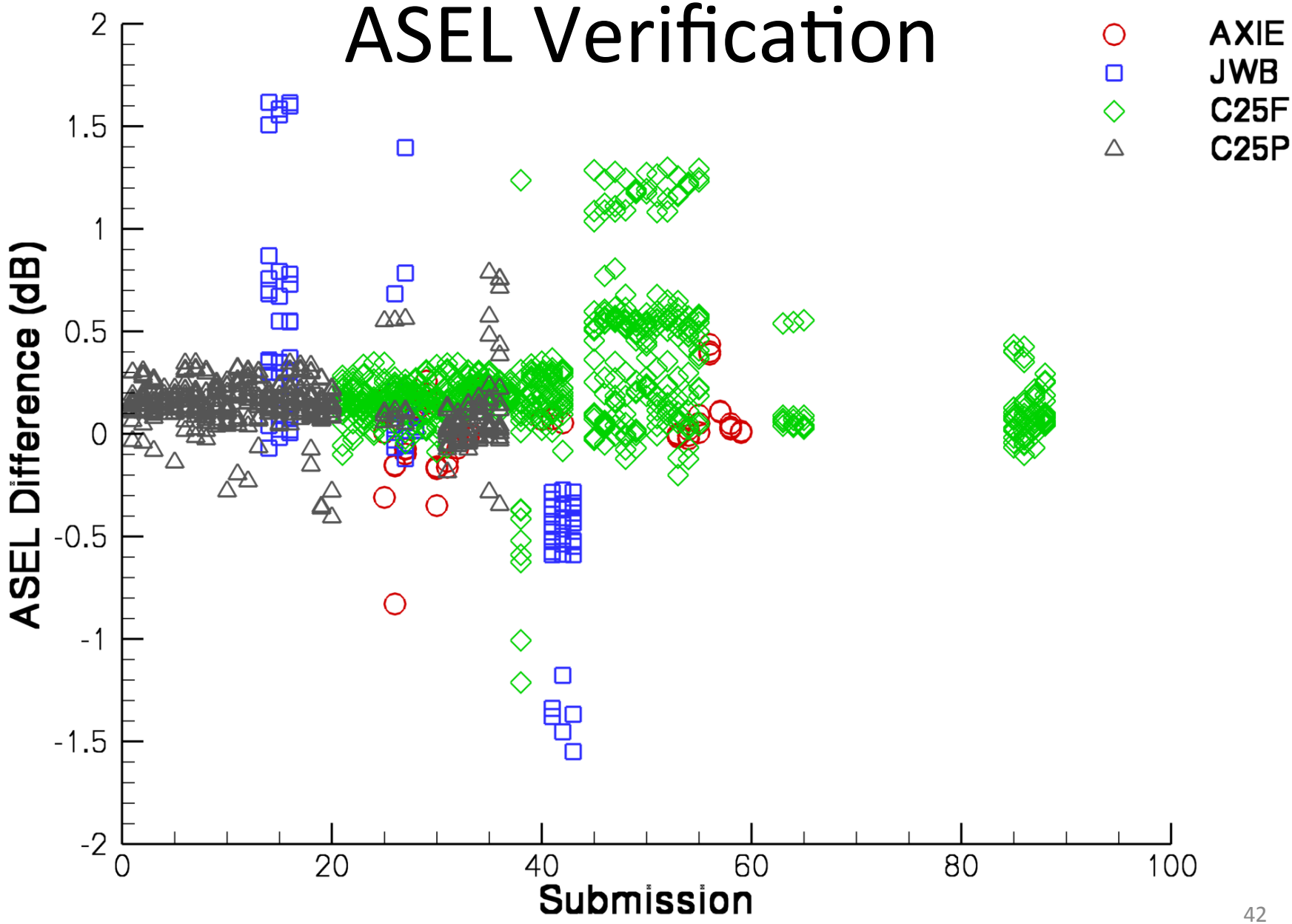
PL and ASEL Verification

- Participants optionally propagated signatures to ground and computed PL and ASEL
  - Different propagation method and nearfield windowing
- Provides a verification of the workshop organizing committee processes
- The difference of the submitted signatures from the workshop computed value is presented

PL Verification



ASEL Verification

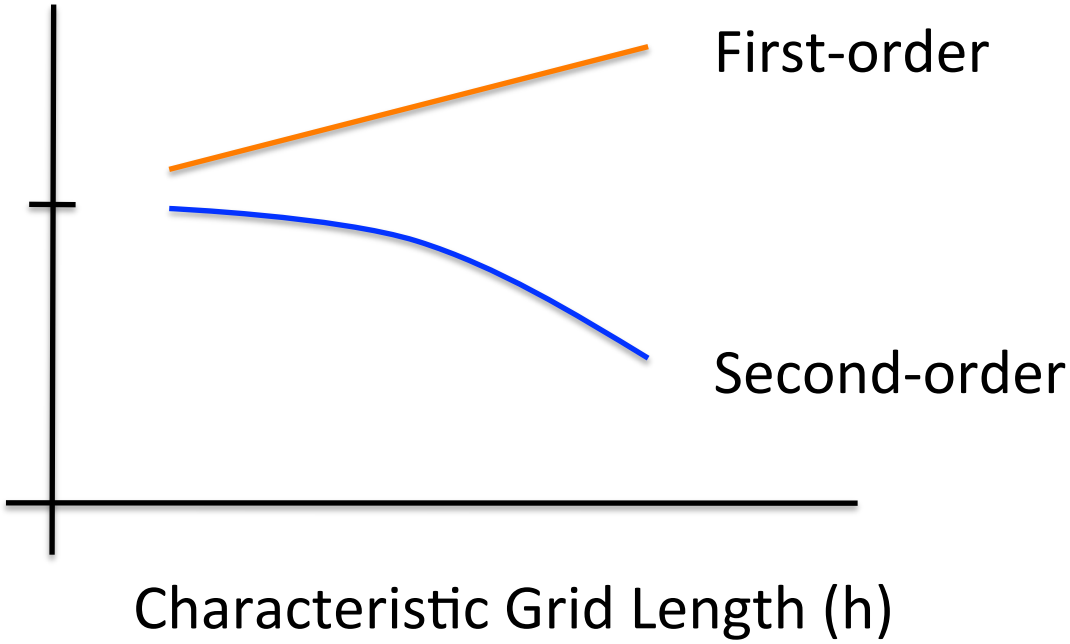


Summary: Loudness Verification

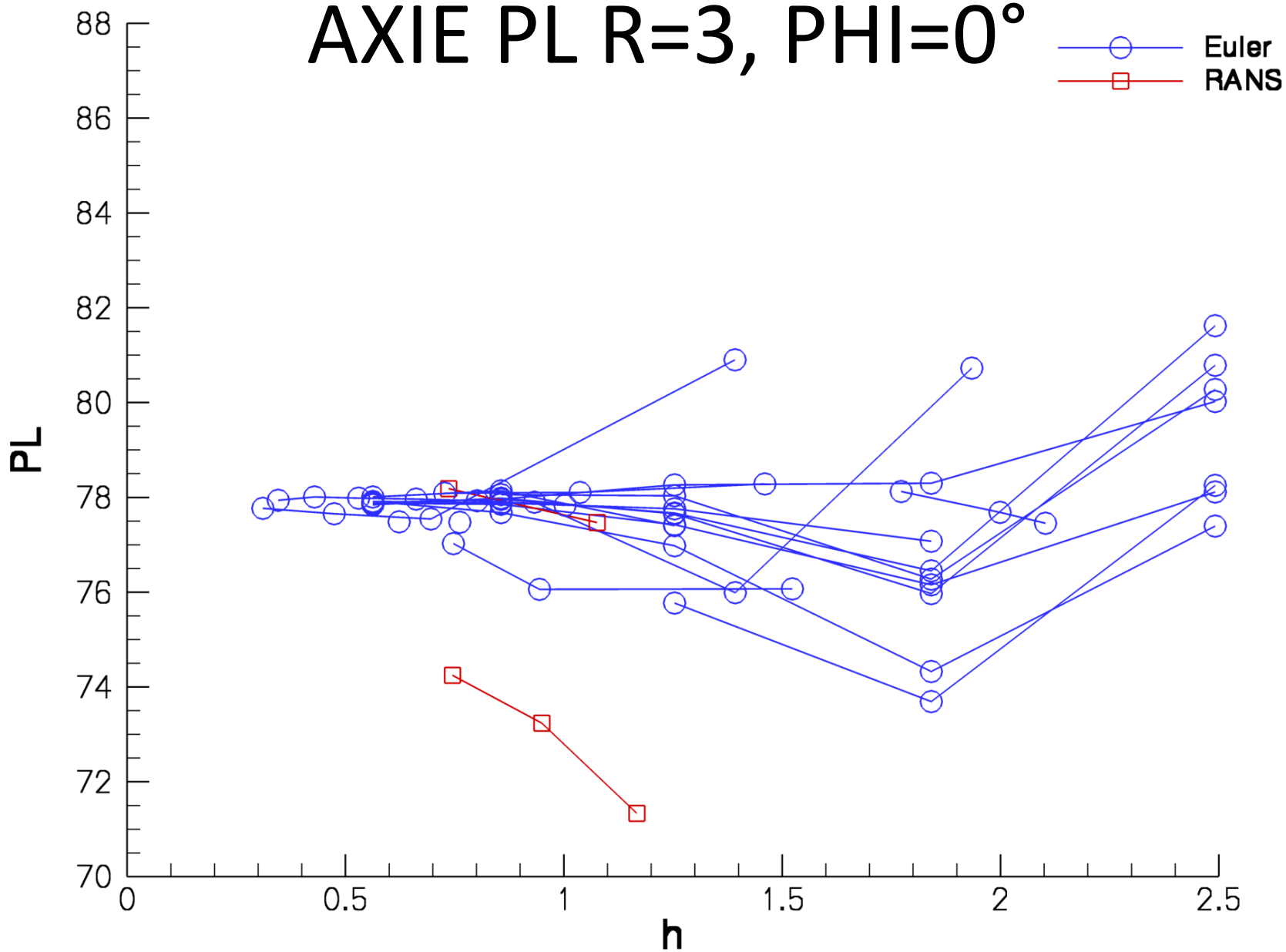
- PL and ASEL very well correlated within a +/- 1 dB spread for all models and extraction locations
- The largest differences between submitted and workshop derived loudness are +/- 1.5 dB for the JWB
- ASEL had a smaller difference between submitted and workshop derived loudness for C25P and C25F
- Standard nearfield windowing process should be defined to reduce differences
  - Some participants also used sBOOM (standardize settings)
- Propagation methods will be examined tomorrow

Expected Grid Convergence

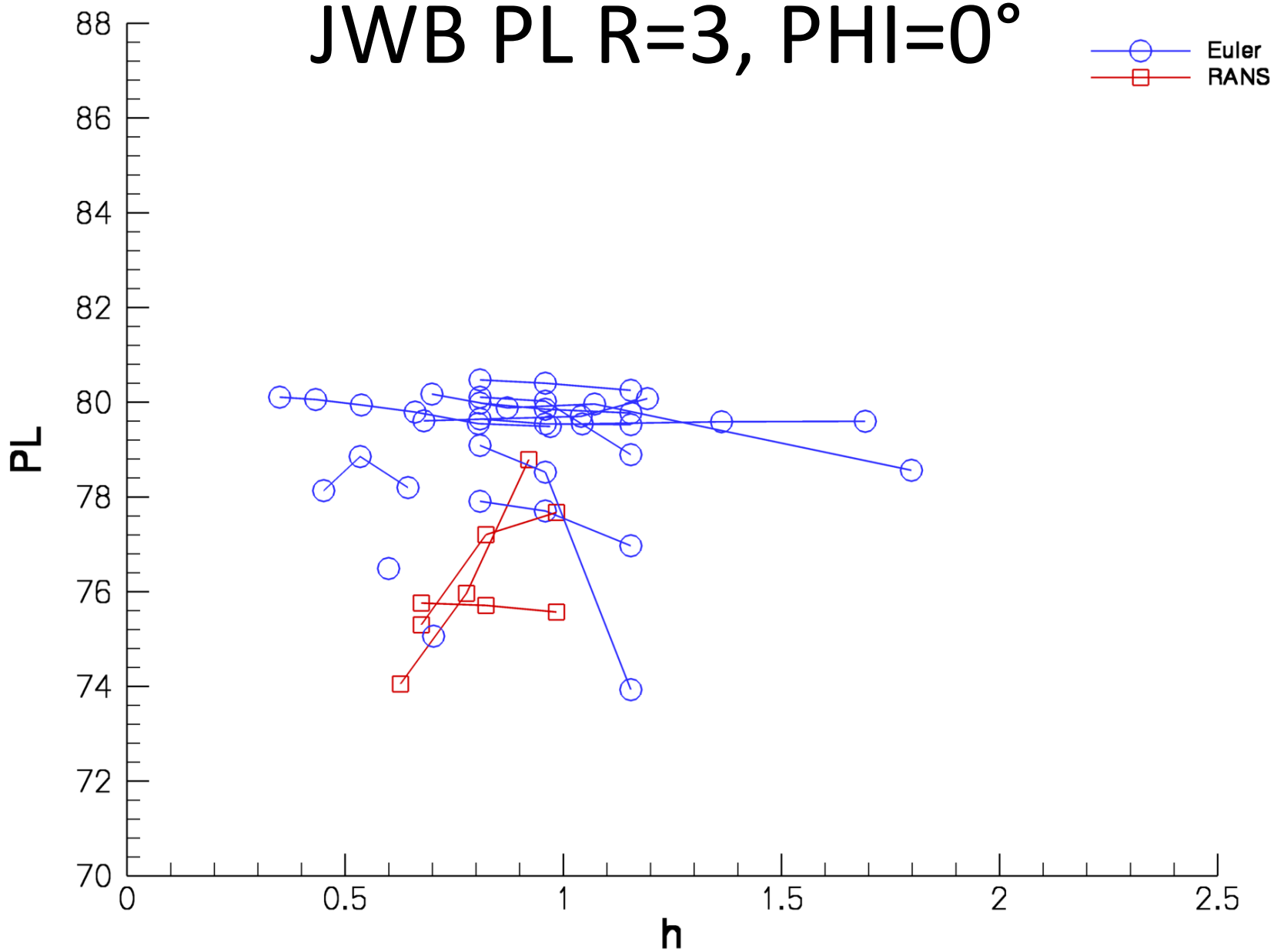
- Consistent methods should approach a value as the grid is refined to "zero" h
- Ten million control volumes is h=1



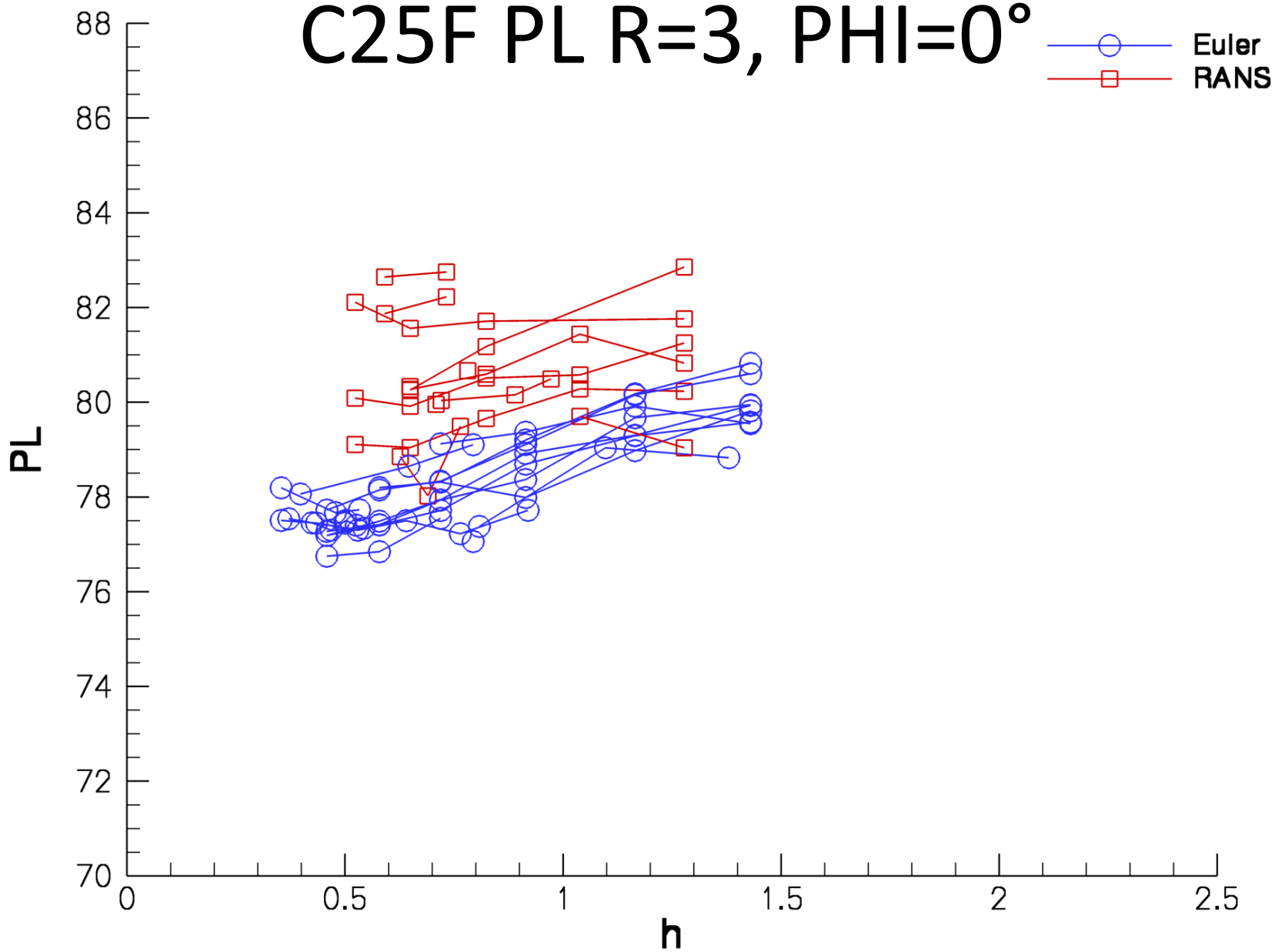
AXIE PL R=3, PHI=0°



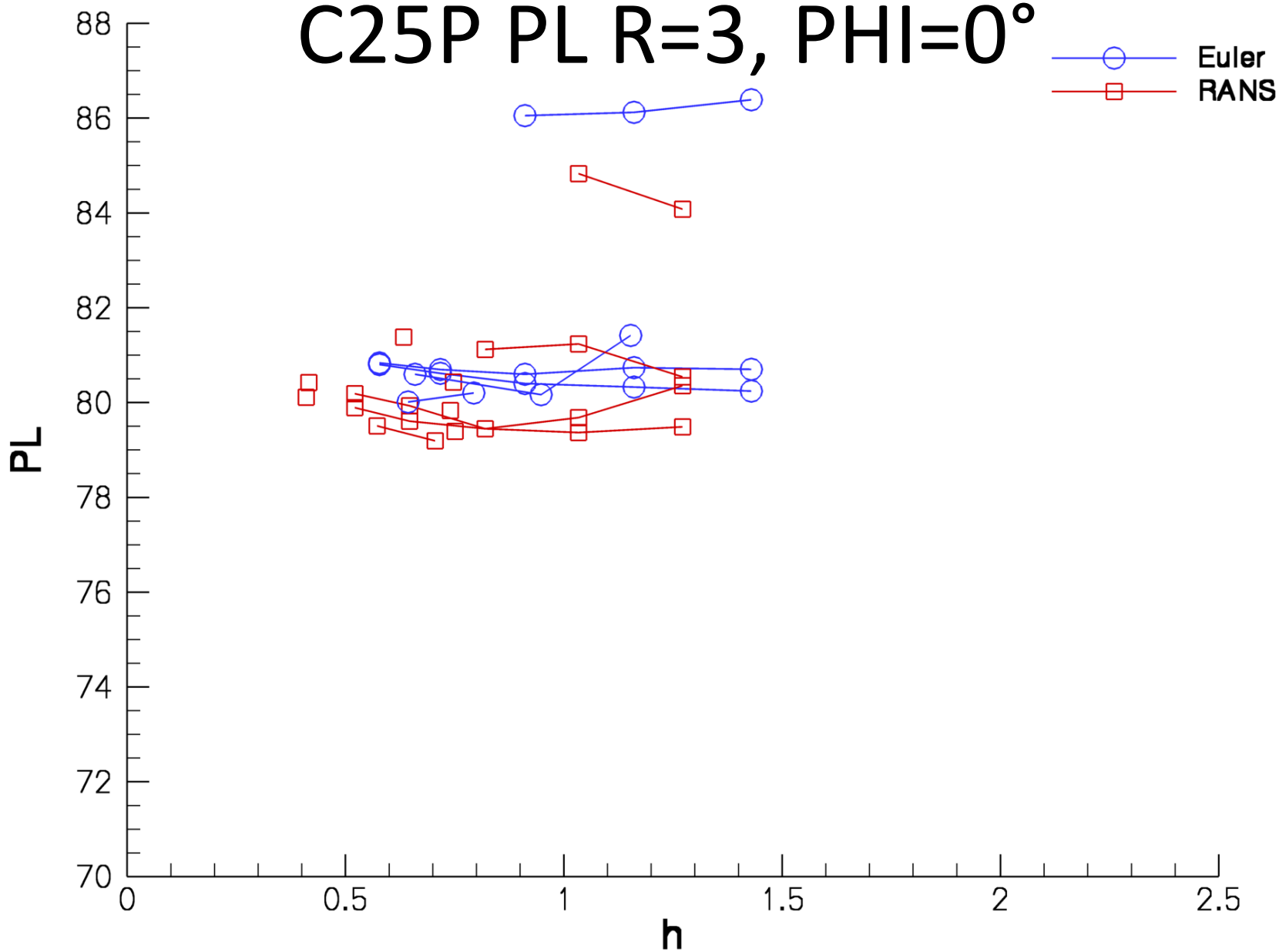
JWB PL R=3, PHI=0°



C25F PL R=3, PHI=0°



C25P PL R=3, PHI=0°



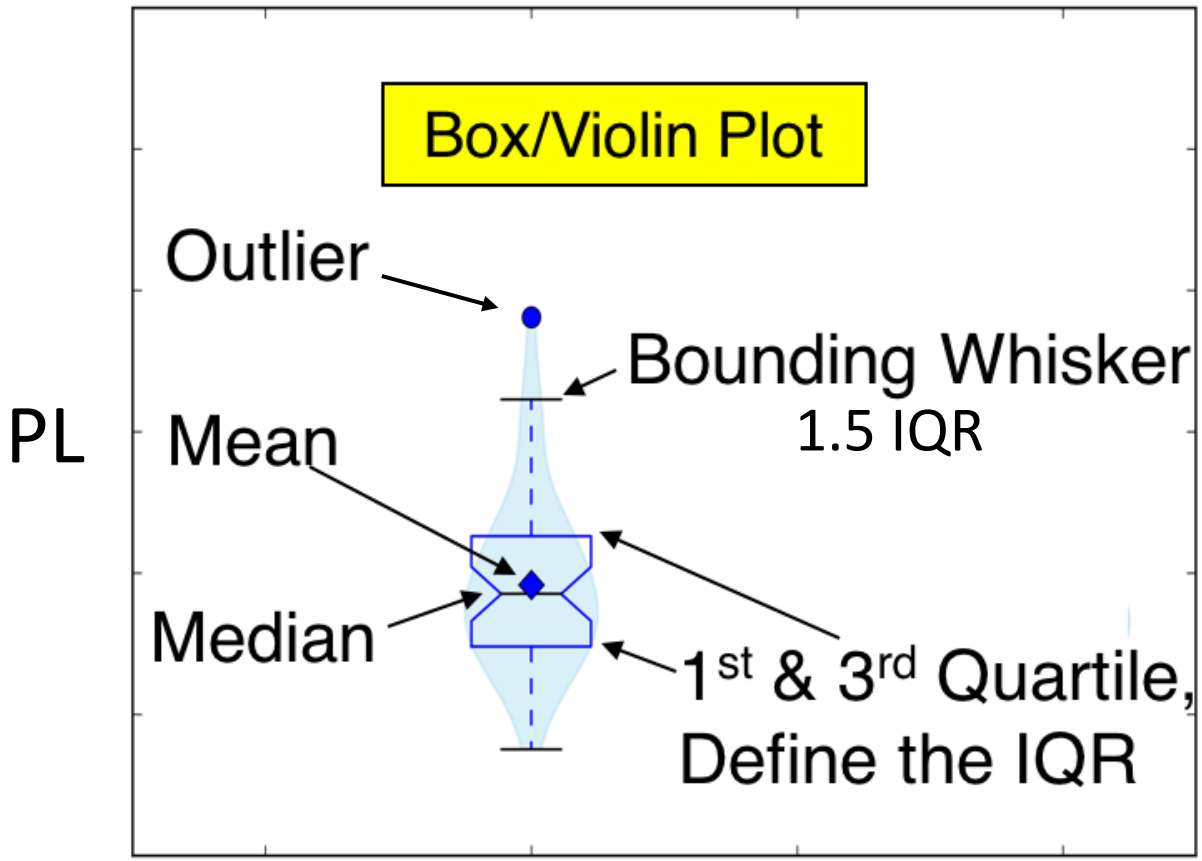
Summary: Loudness Grid Convergence

- AXIE had the largest range in grid sizes and Euler converged to 78 PL (dB)
- JWB Euler had smallest range in workshop grid sizes and a tight grouping at 80 PL (dB) with quieter outliers
- Few JWB RANS solutions are quieter than most Euler submissions
- C25F Euler PL showed a downward trend with grid refinement toward 78.5-76.5 PL (dB)
- C25F RANS PL showed a 79-83 PL dB spread at h=0.5
- C25P approached 80-82 PL dB excluding two louder submissions

Statistical Method

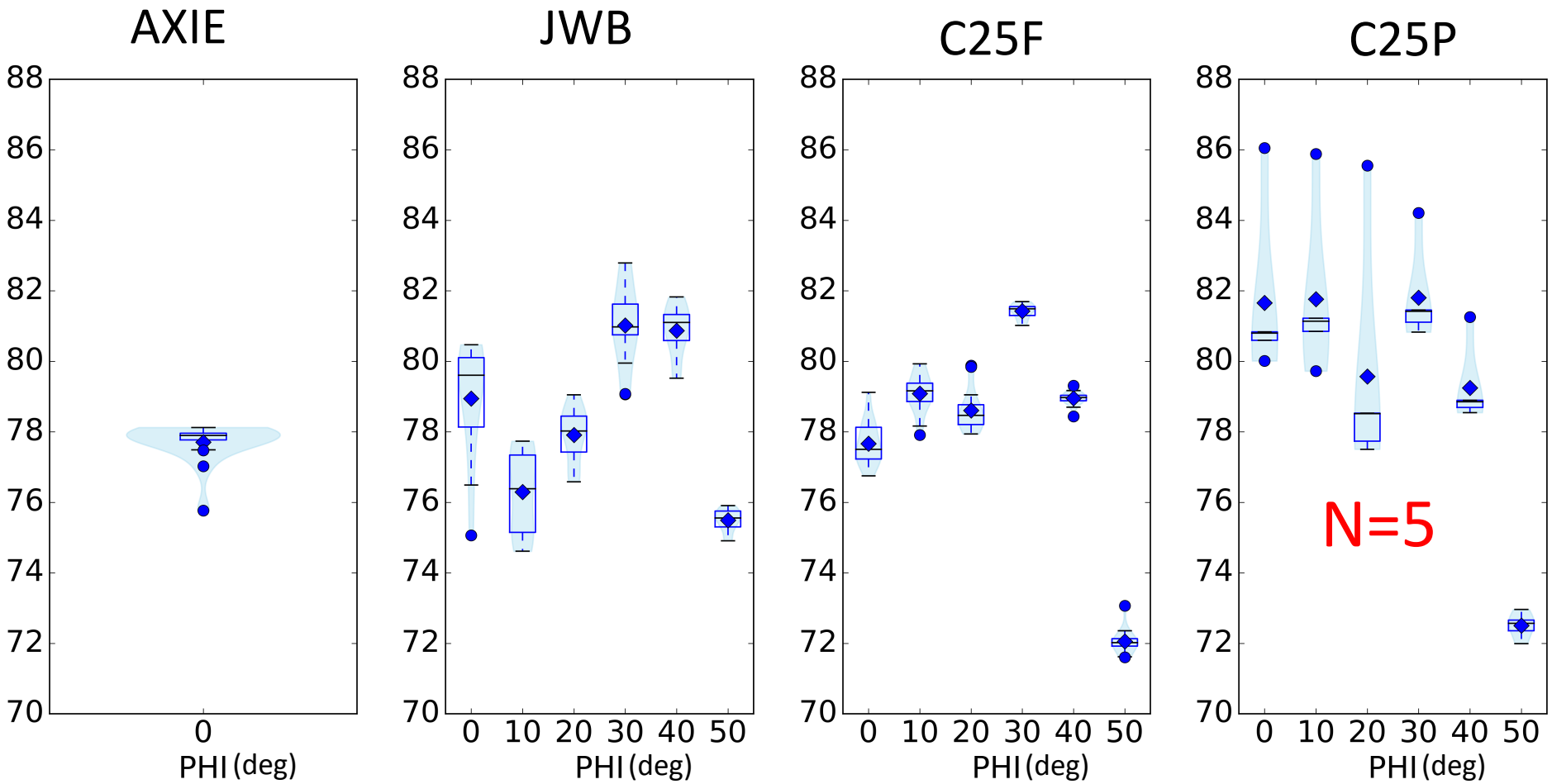
- Goal is to identify “different” results, not “correct” or “wrong”
- Box and whisker plots
- Kernel or “smoothed histogram”
- Small sample size (finest grid submissions)
- Used by other workshops

Violin Plots



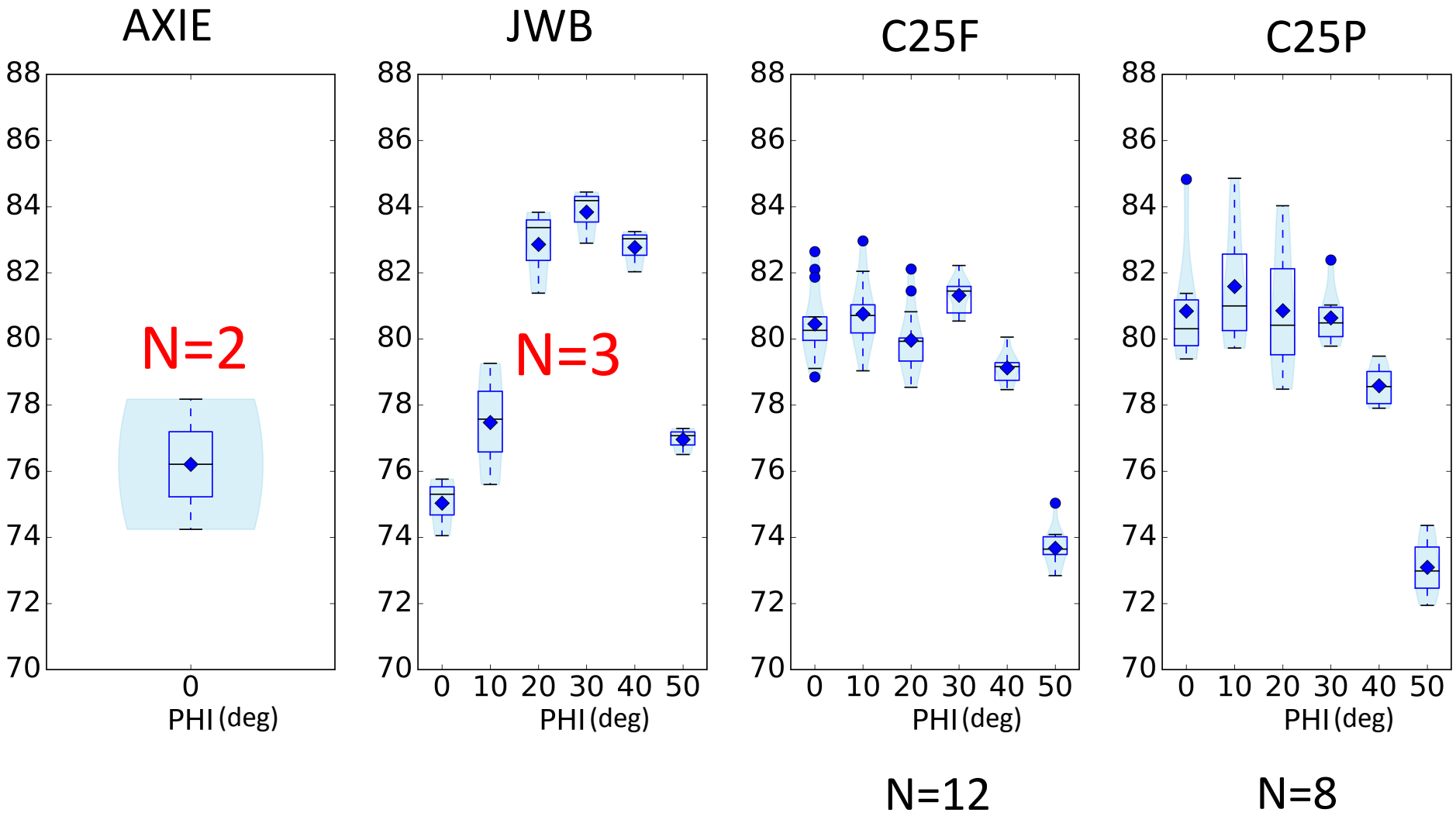
Blue shading is probability density function (PDF)

PL Euler from R=3



N=17 N=16 N=15

PL RANS from R=3



PL Statistics

Model	N	Median (dB)	IQR (dB)	Mean (dB)	SD (dB)
AXIE Euler	17	77.9	0.2	77.7	0.6
JWB Euler	13	79.6	2.0	78.9	1.6
C25F Euler	15	77.5	0.9	77.7	0.6
C25F RANS	13	80.3	0.7	80.5	1.2
C25P RANS	8	80.3	1.4	80.8	1.8

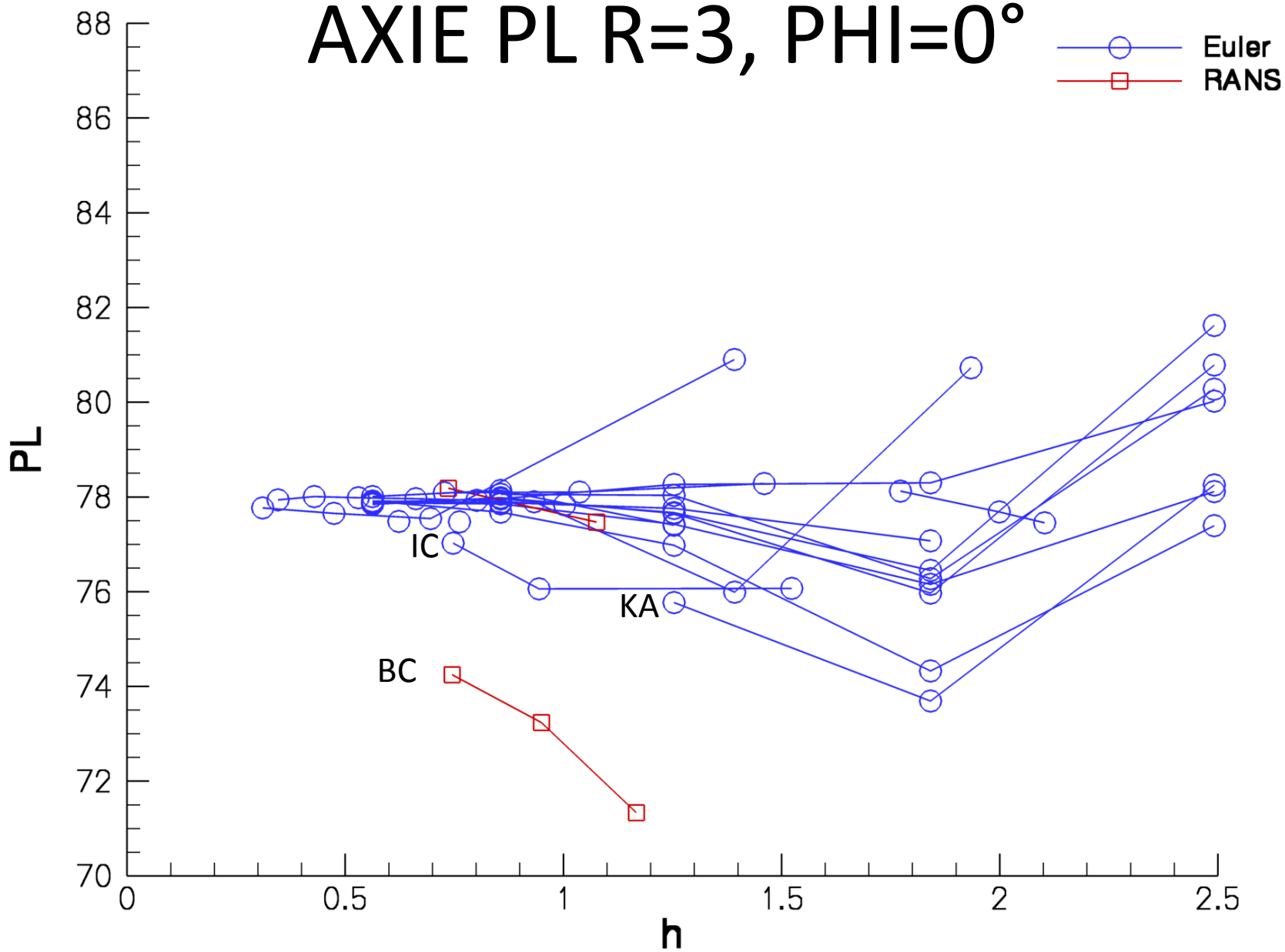
Summary: Loudness Statistics

- Mean and median 78 to 81 PL dB
- Interquartile range (IQR) 0.2-2.0 dB
- Standard deviation (SD) 0.6-1.8 dB
- Number of fine grid submissions was low for Euler C25P and RANS AXIE and JWB
- AXIE Euler has the smallest IQR
- JWB Euler and C25P RANS had the largest IQR and SD

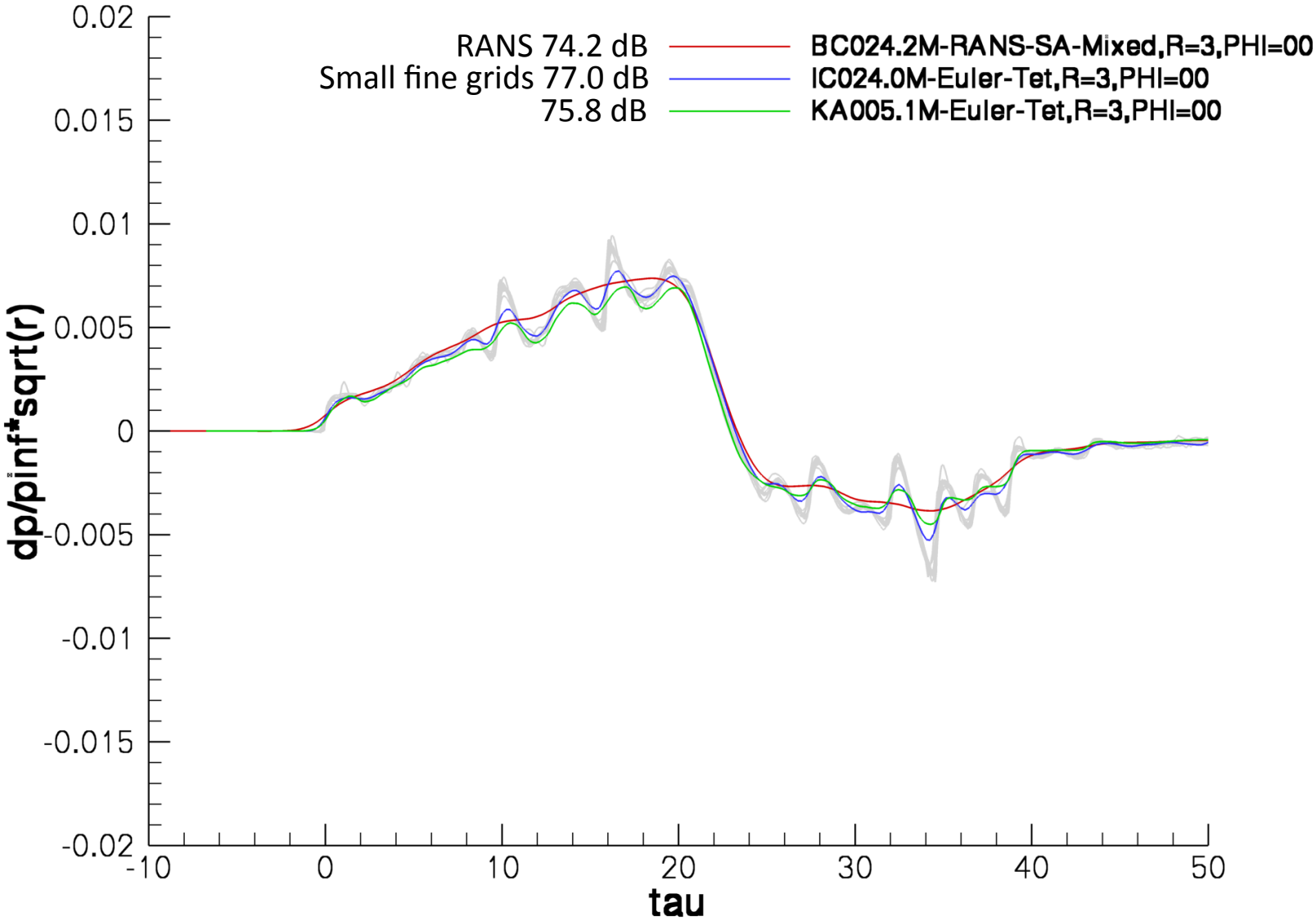
Examination of Outliers

- Goal is to examine “different” results
- Identified with statistical methods
- Identified by grid refinement trends

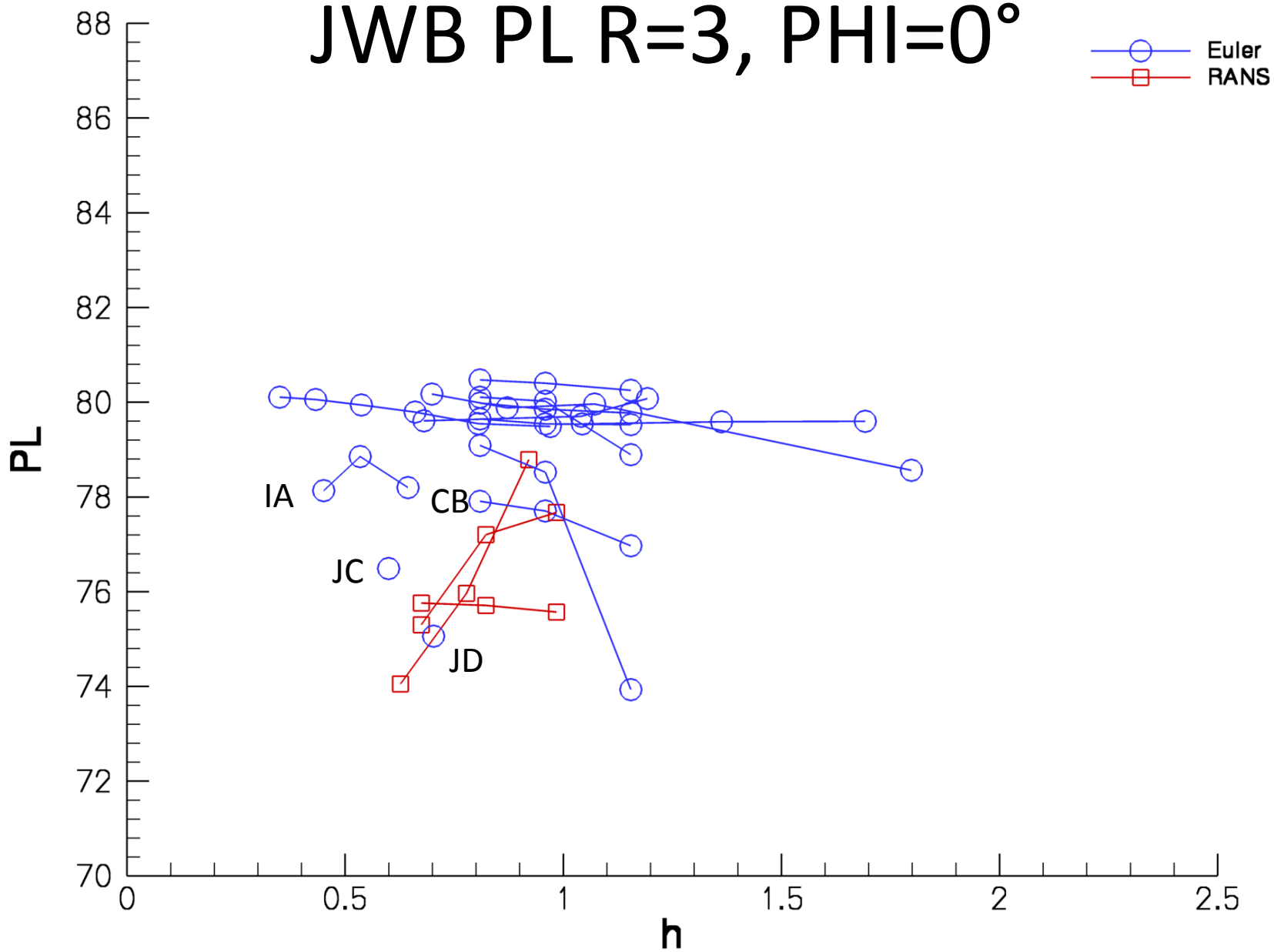
AXIE PL R=3, PHI=0°



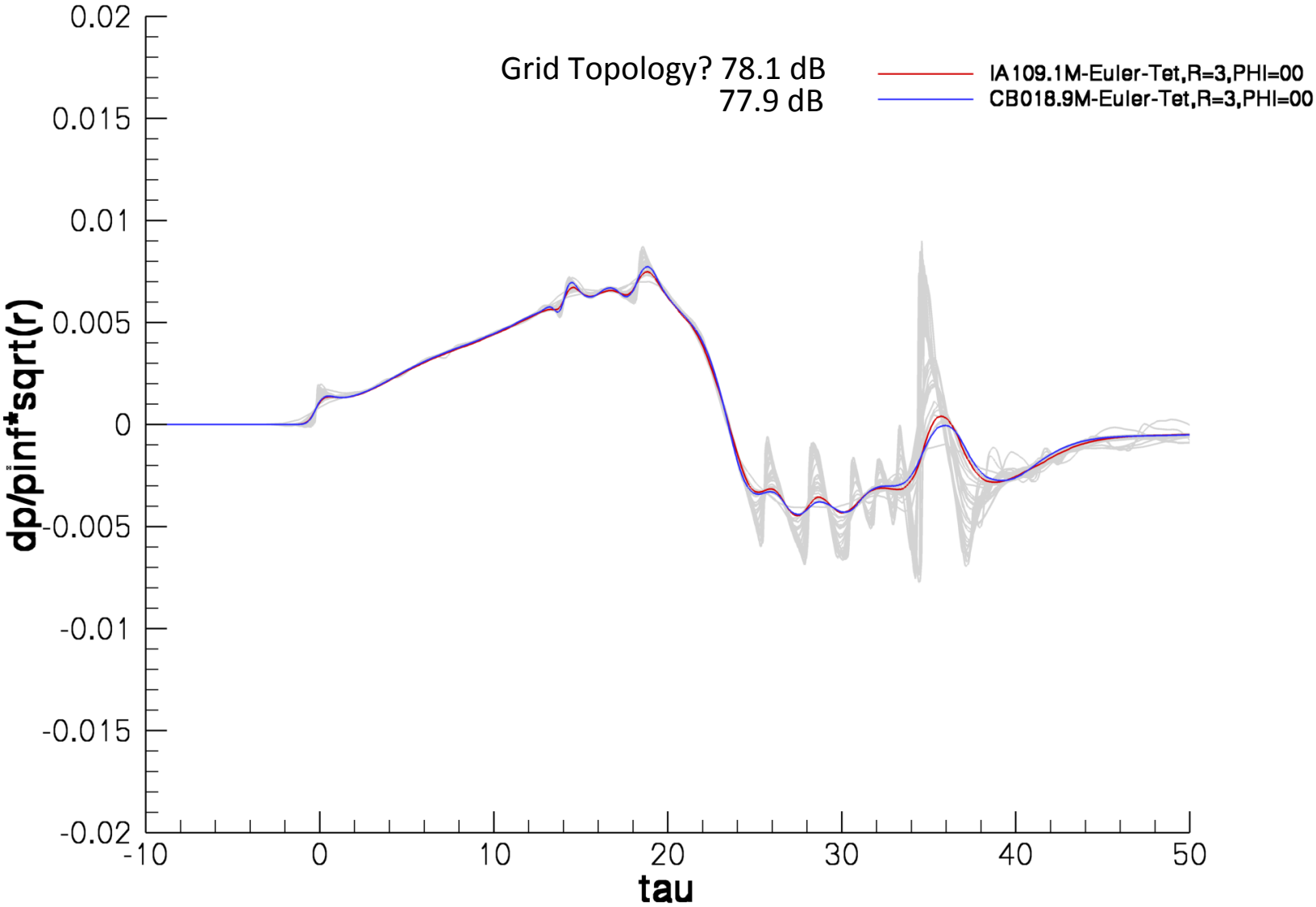
AXIE Nearfield BC IC KA R=3, PHI=0°



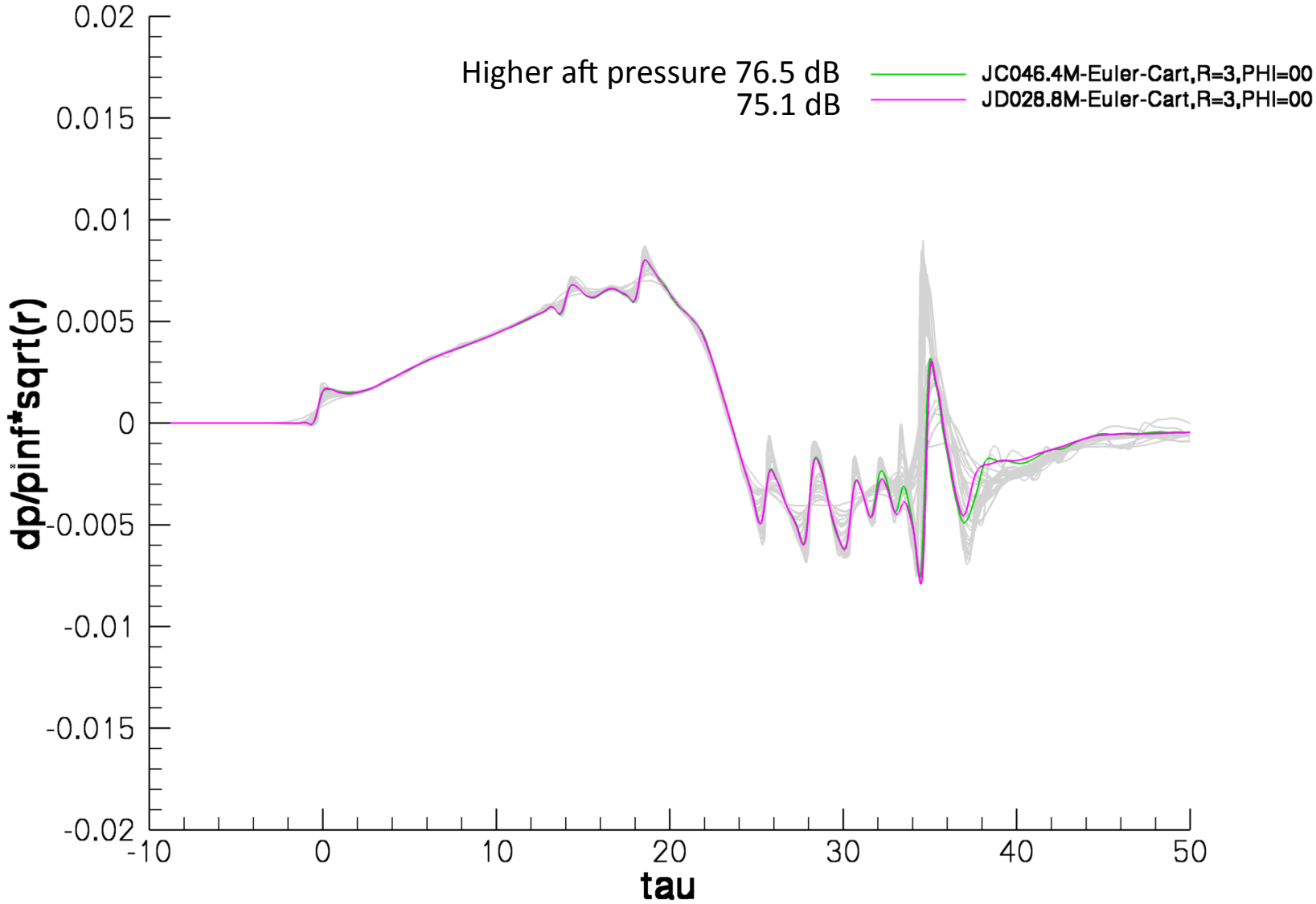
JWB PL R=3, PHI=0°



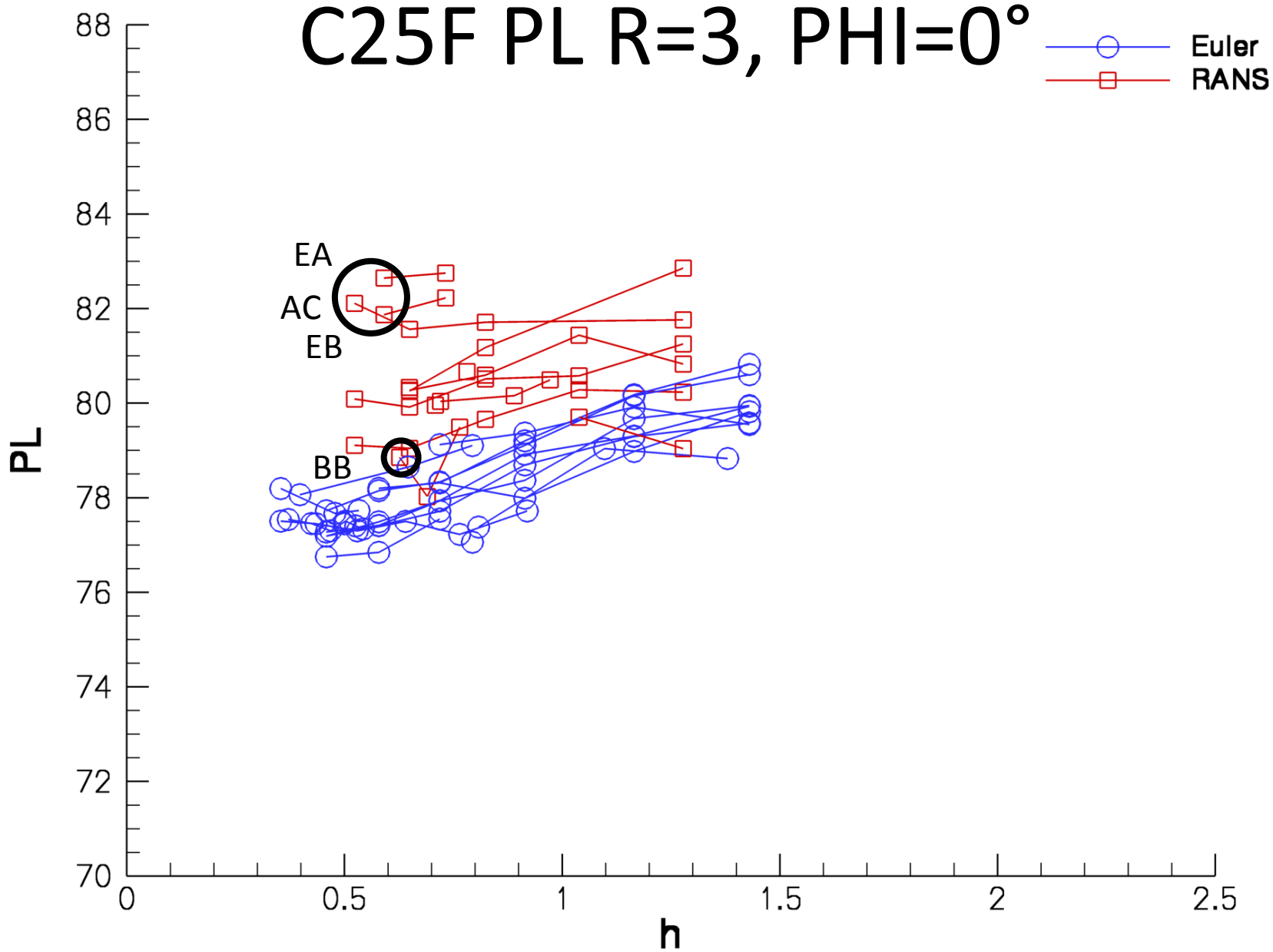
JWB Nearfield IA CB R=3, PHI=0°



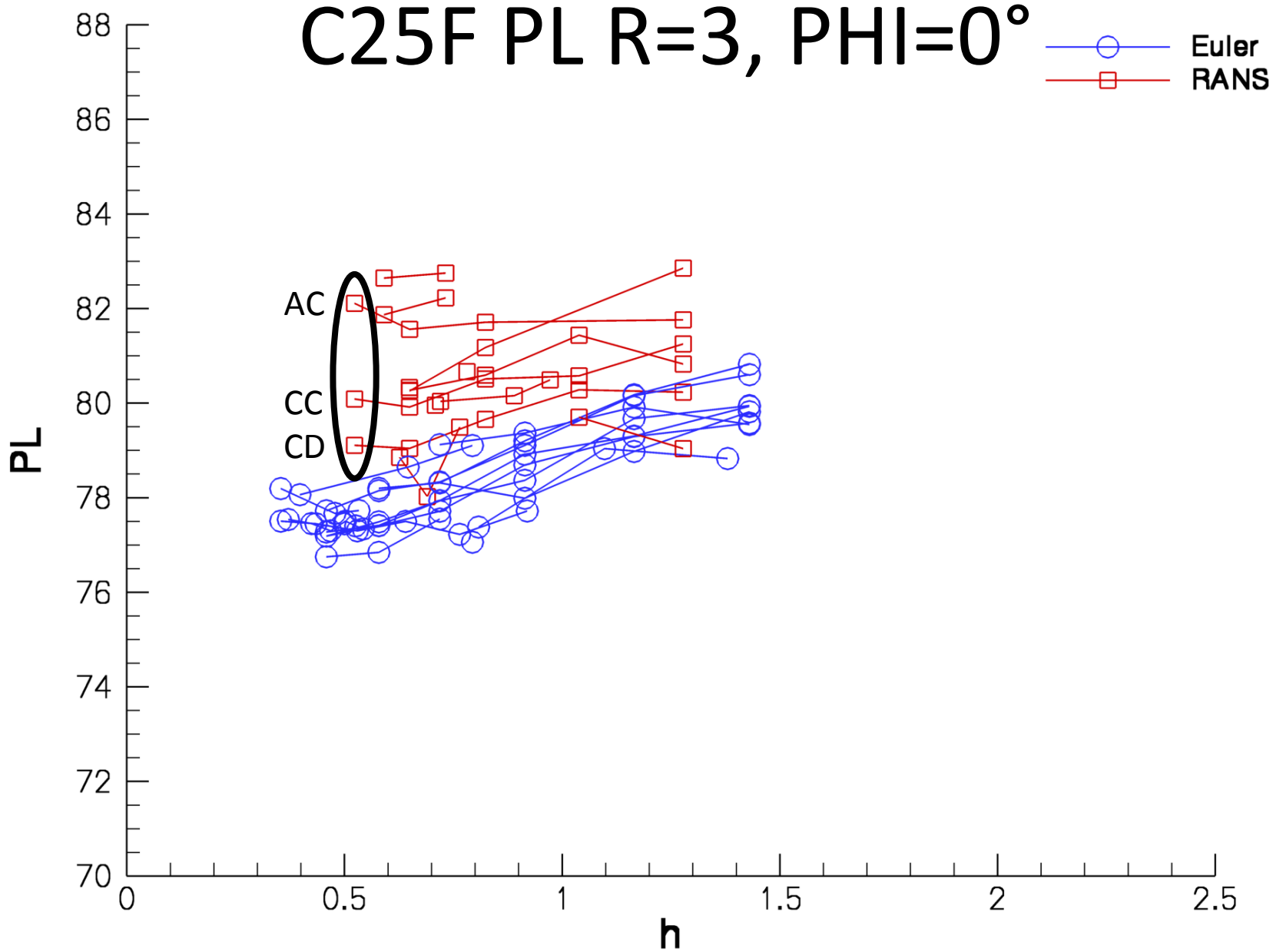
JWB Nearfield JC JD R=3, PHI=0°



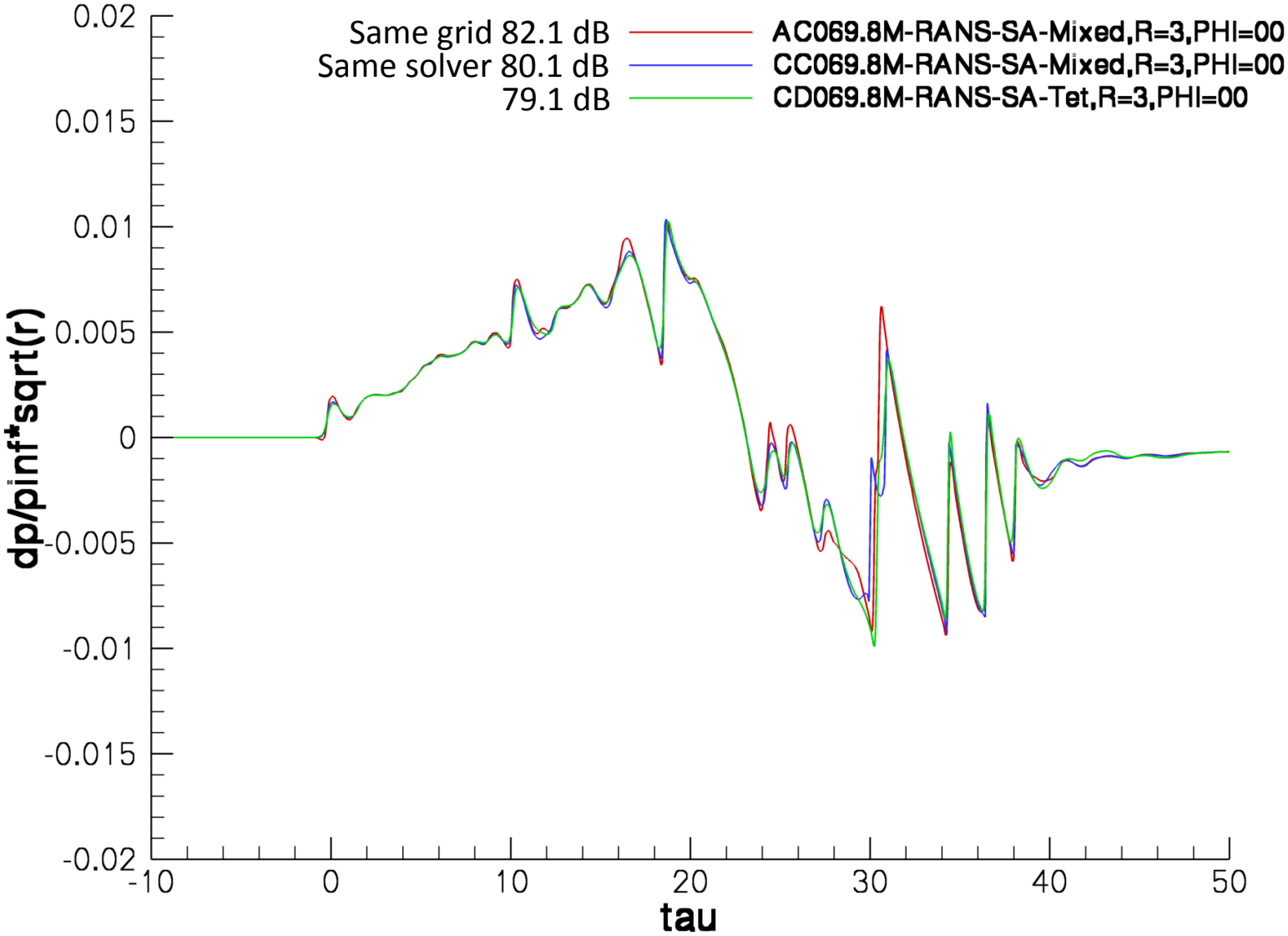
C25F PL R=3, PHI=0°



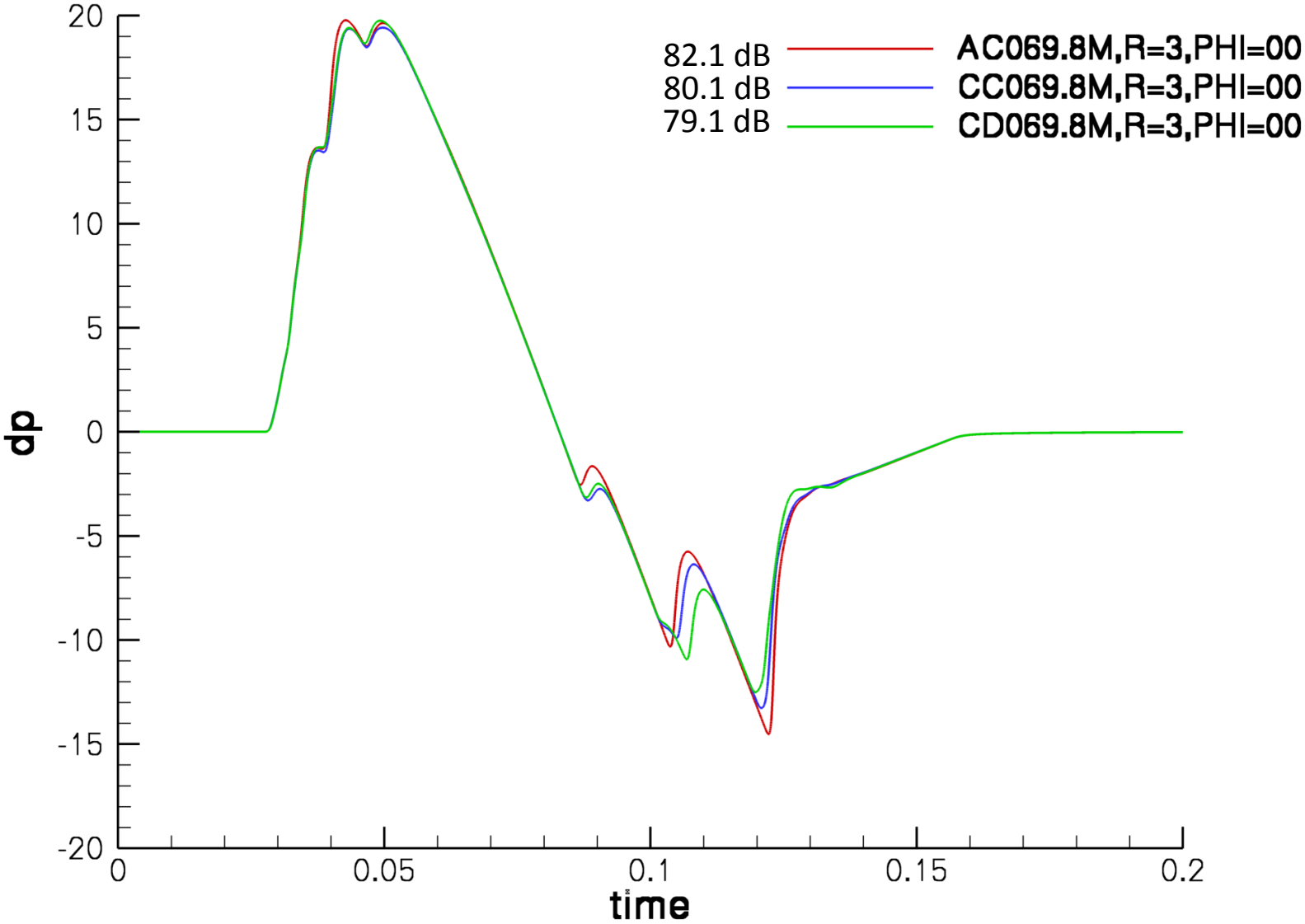
C25F PL R=3, PHI=0°



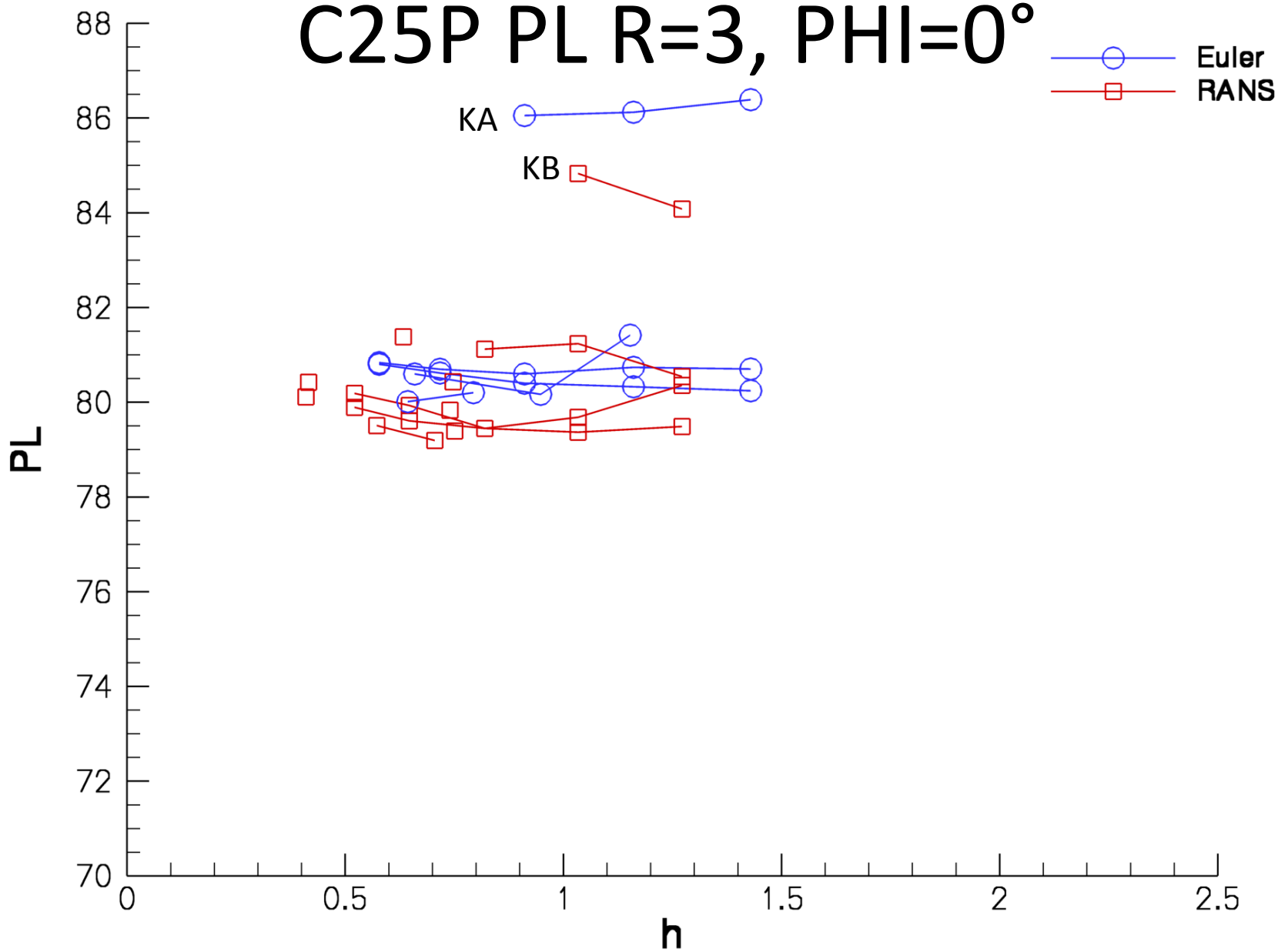
C25F Nearbody R=3, PHI=0°



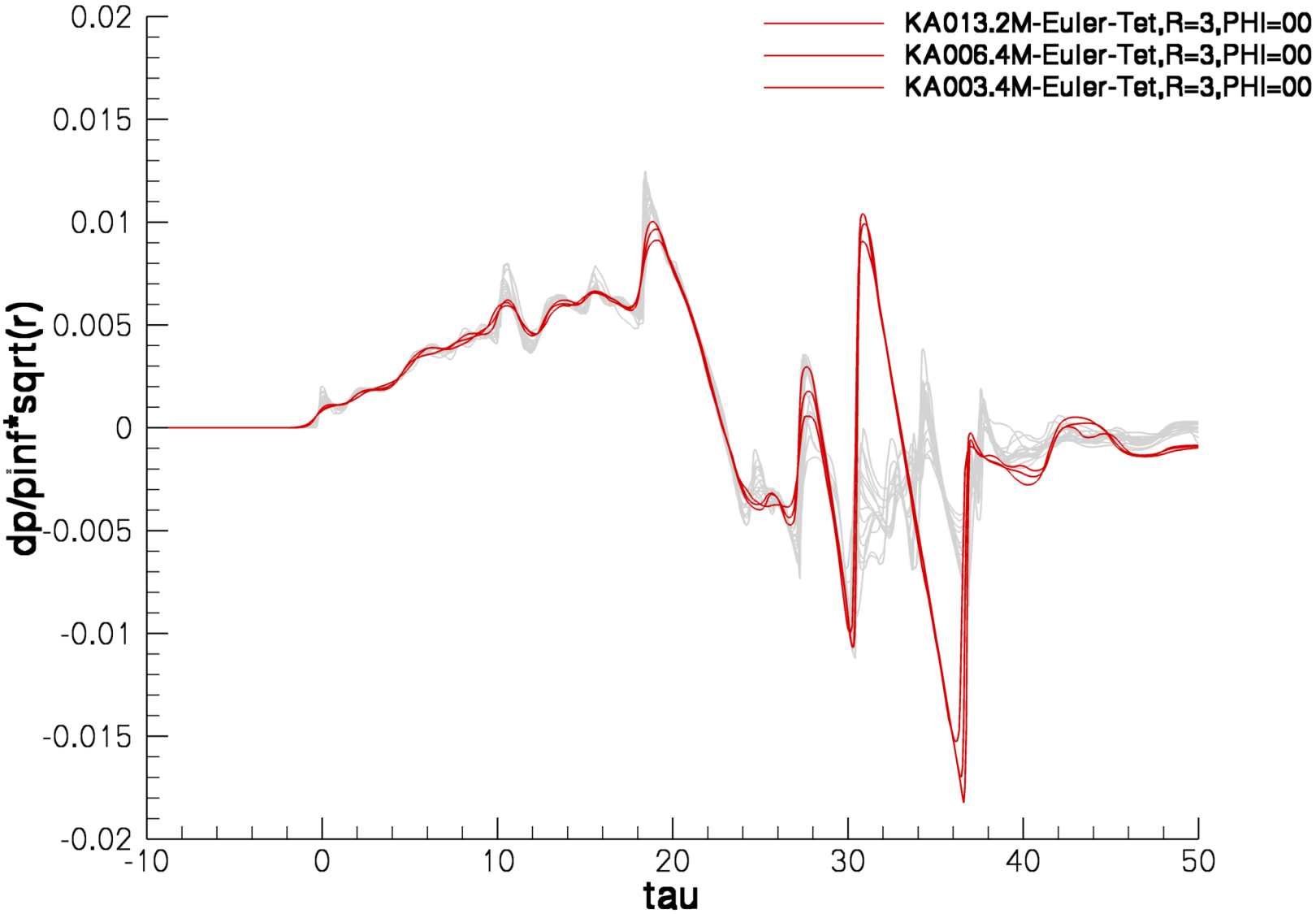
C25F Ground from R=3, PHI=0°



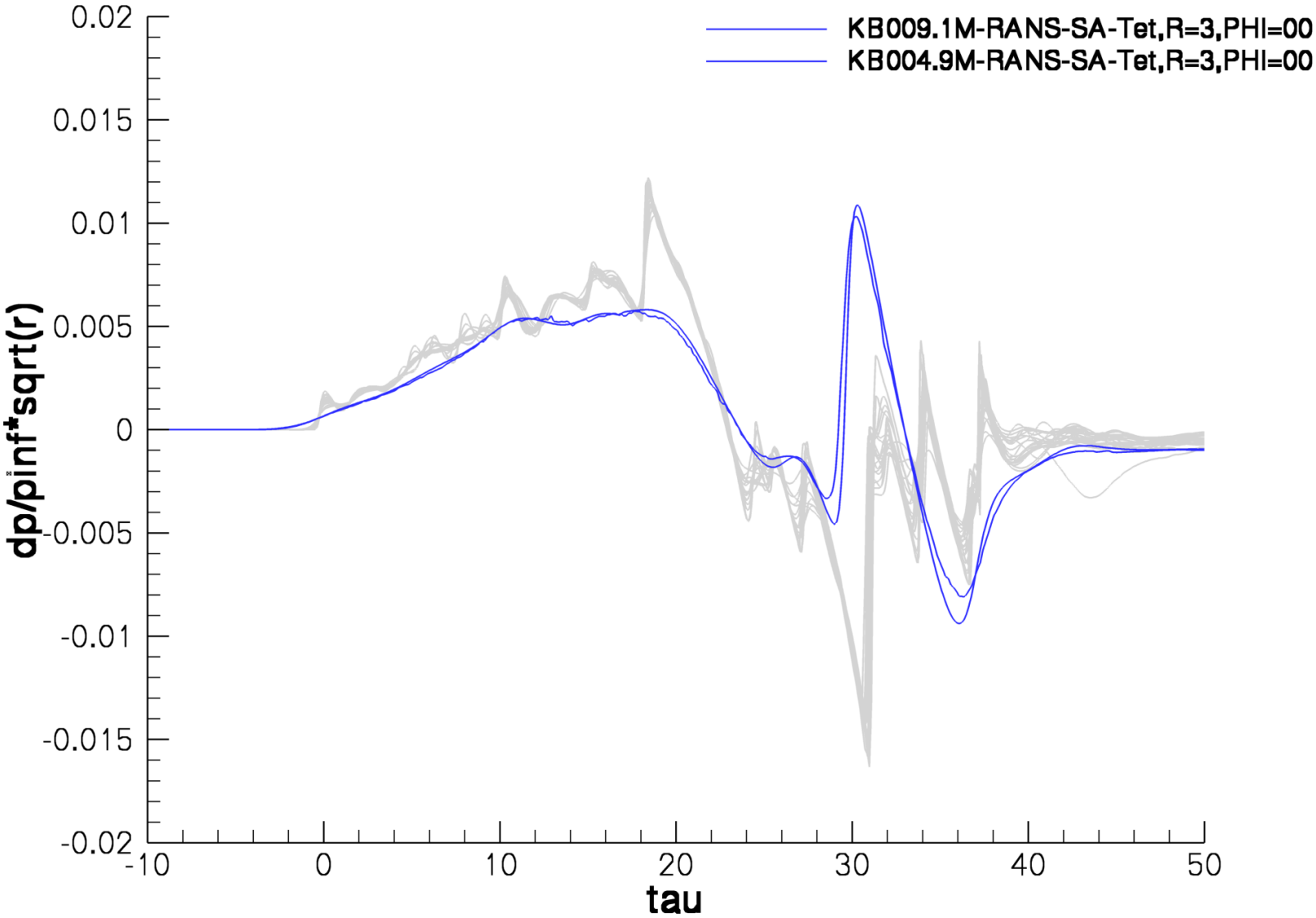
C25P PL R=3, PHI=0°



C25P Nearfield KA R=3, PHI=0°



C25P Nearfield KB R=3, PHI=0°



Summary: Outlier Details

- AXIE outliers are quieter by up to 2-4 PL (dB) with under resolved details
- Underresolved JWB nearfield signatures are 2 PL (dB) quieter
- Higher JWB aft nearfield pressure is 4 PL (dB) quieter
- Small differences in C25F RANS nearfield and ground signatures can produce 3 PL (dB) loudness differences
- C25P outliers have the largest nearfield difference, possibly propulsion boundary conditions

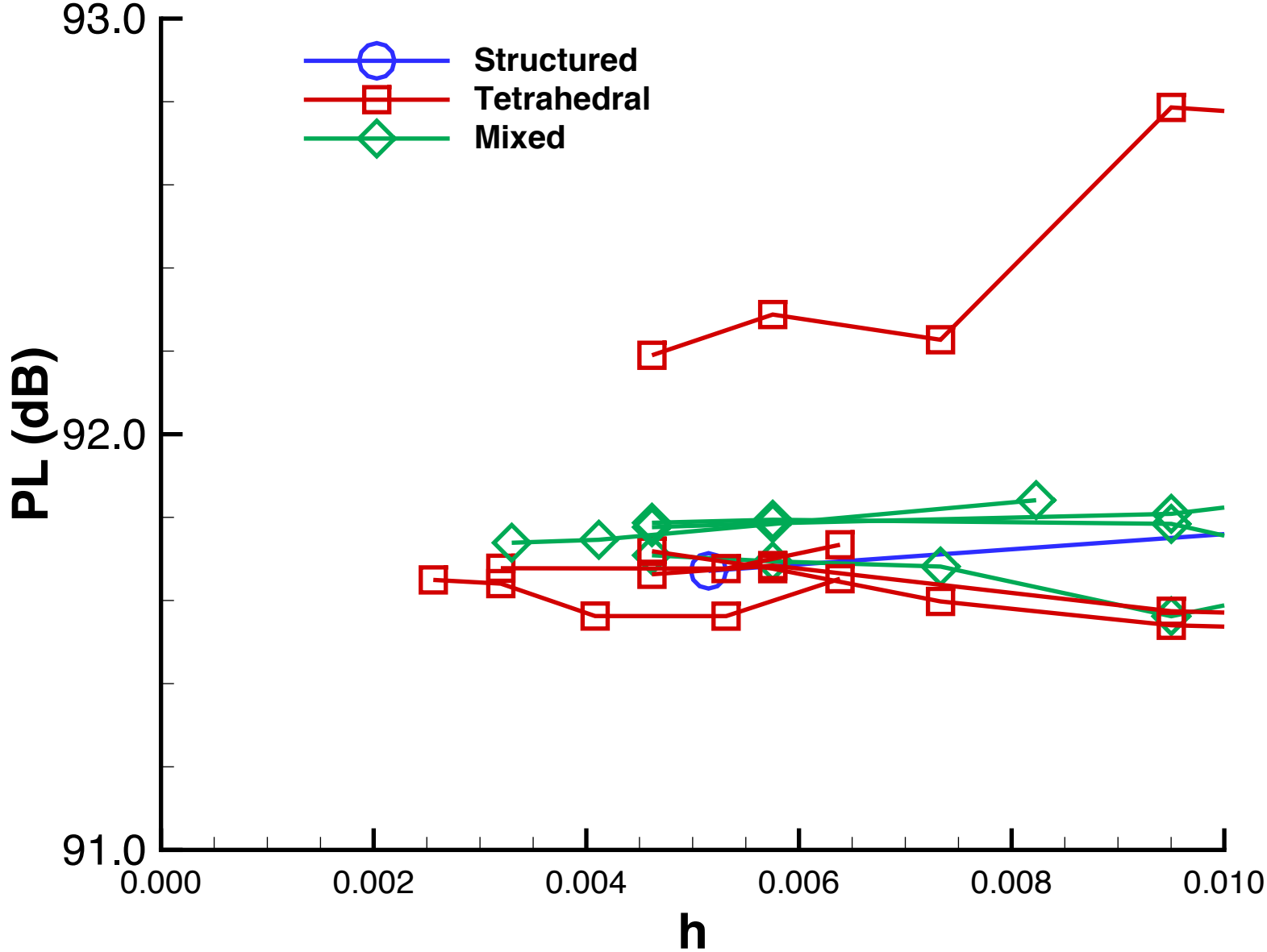
SBPW1

[image: Aftosmis, Nemec AIAA-2014-558]

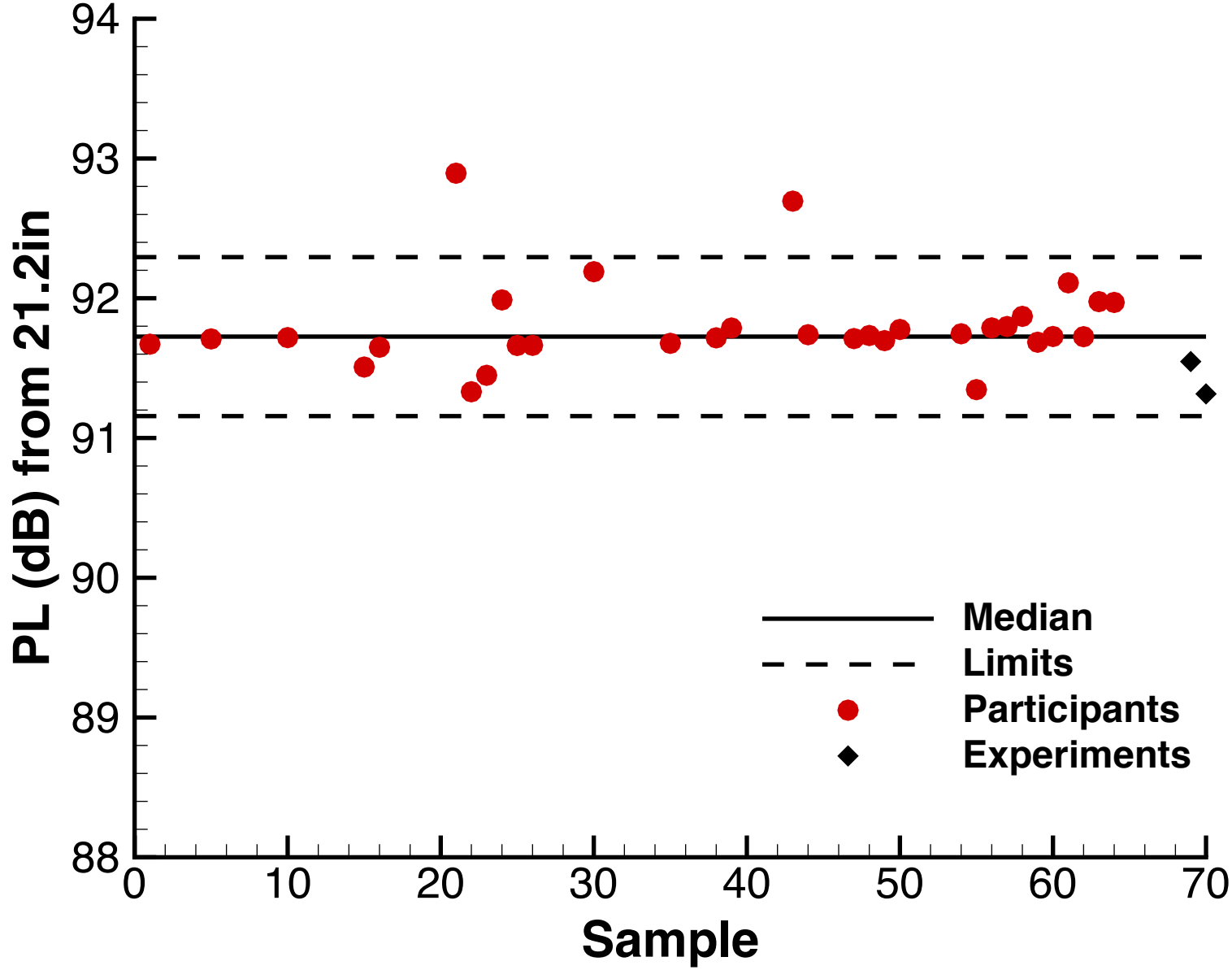
SBPW1

- SEEB-ALR: 91.8 PL (dB) median, 0.3 dB standard deviation
- Delta Wing Body on centerline: 95.5 PL (dB) median, 0.2 dB standard deviation
- Resubmission of data lowered the workshop standard deviations (from 0.5 and 0.3 dB)
- LM1021 wind tunnel configuration: large 85 PL (dB) to 95 PL (dB) variation and small sample size (no statistics)

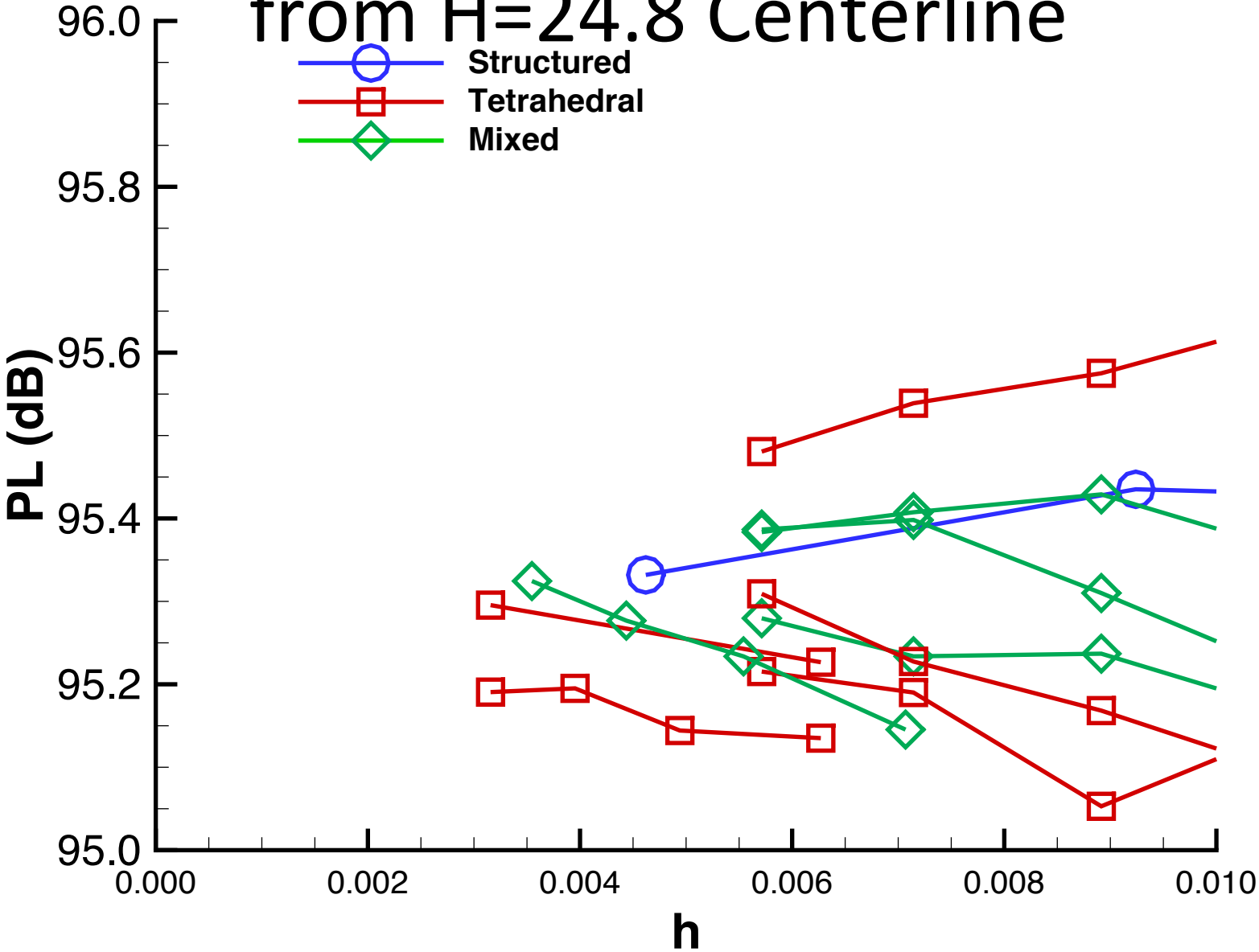
SEEB-ALR Perceived Level



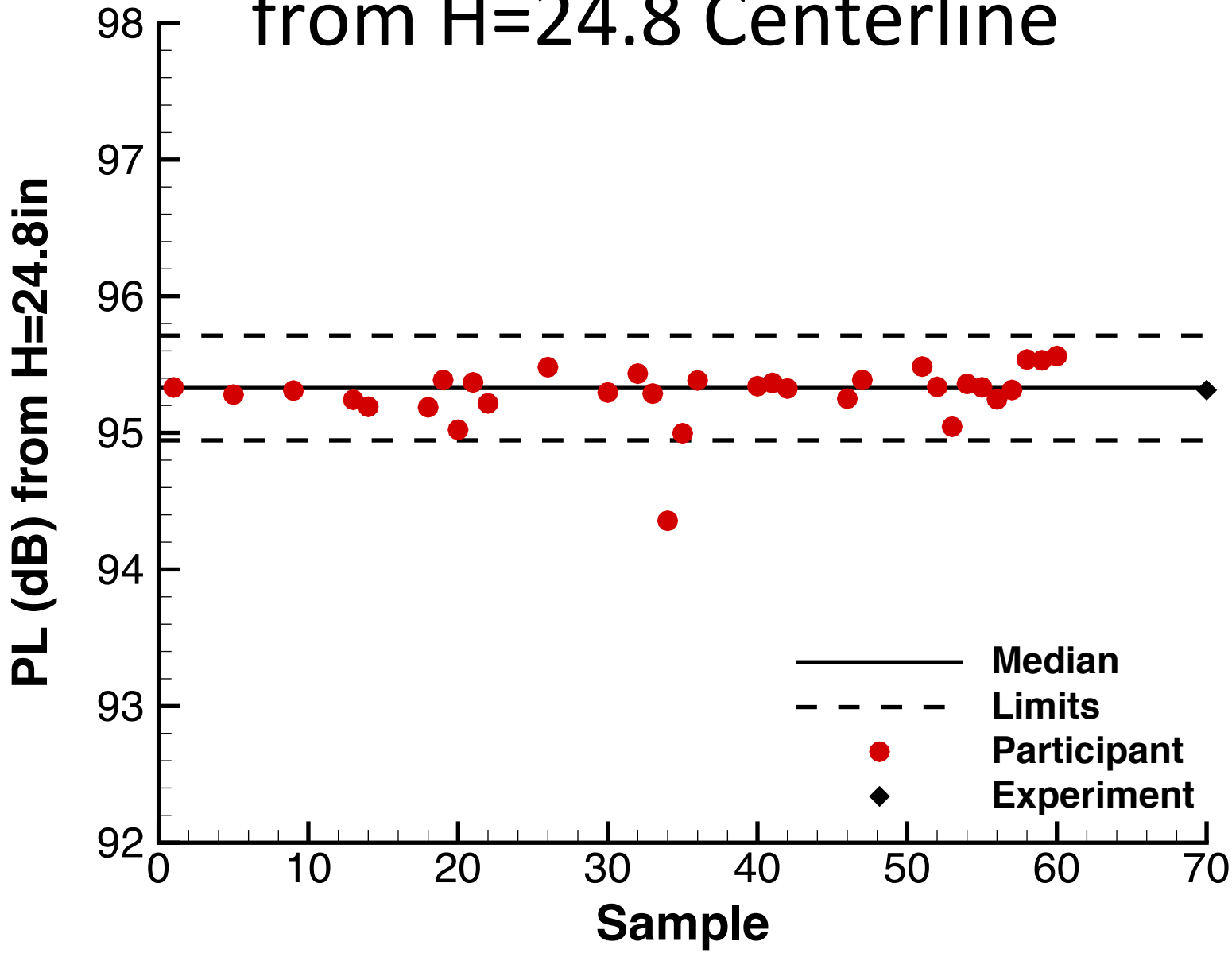
Finest-Grid SEEB-ALR Perceived Level



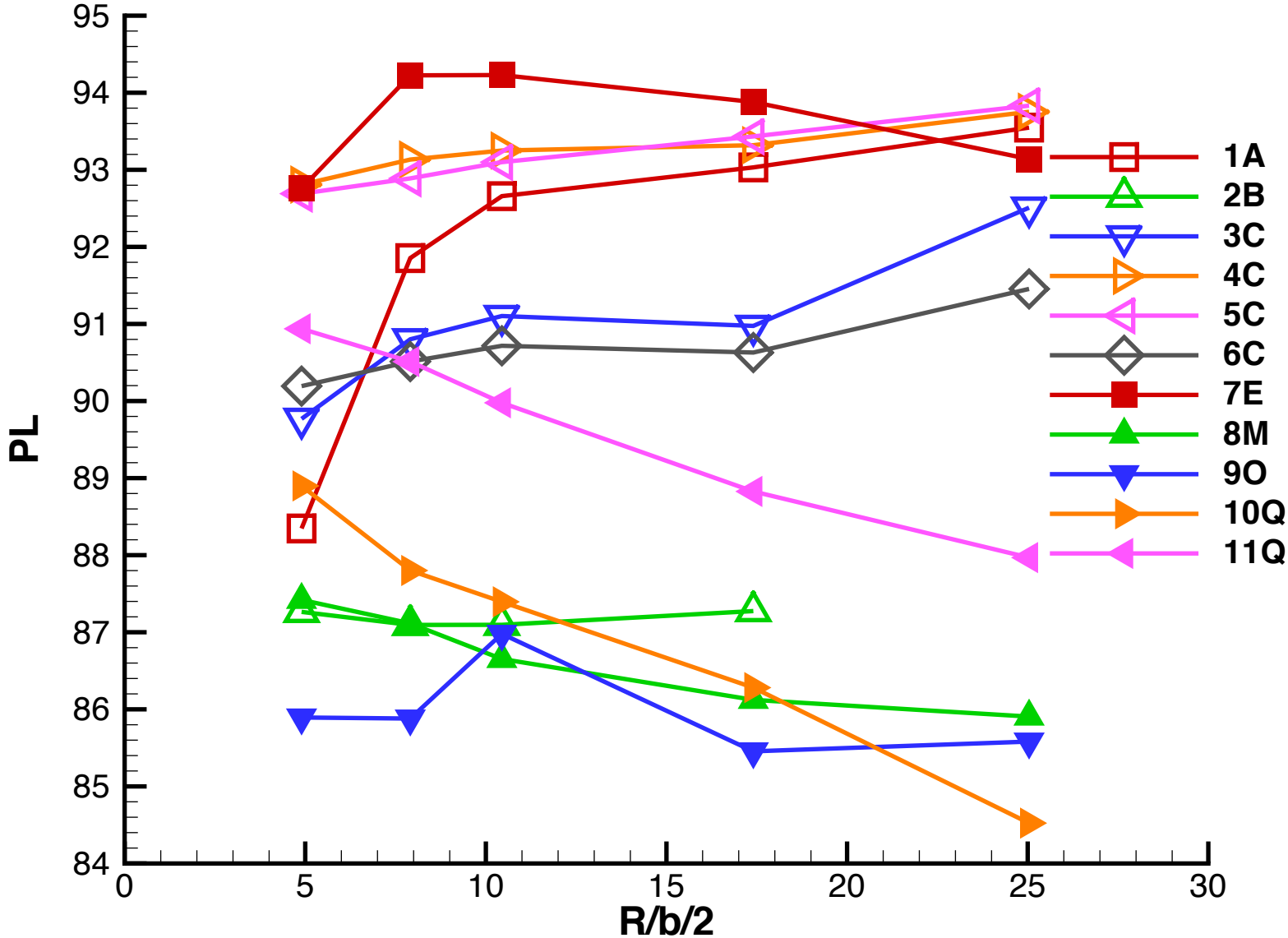
Delta Wing Body Perceived Level from H=24.8 Centerline



Fine-Grid Delta Wing Body Perceived Level from H=24.8 Centerline



LM1021 Centerline Perceived Level



Progress

- Much quieter mean PL (dB)
  - SBPW1: 91.8 axisymmetric, 95.5 wing body
  - SBPW2: 77.7 axisymmetric, 78.9 wing body
- Standard deviation is difficult to compare, PL (dB) is logarithmic
  - SBPW1: 0.3 axisymmetric, 0.2 wing body
  - SBPW2: 0.6 axisymmetric, 1.6 wing body
- More complex and more submissions
  - Statistics for required full configuration
  - Optional propulsion boundary condition case

Conclusions

- Mean and standard deviation of nearfield submissions
  - Variation larger in aft portion of signature
  - Euler and RANS nearfield differ by more than one standard deviation in many locations
  - Fine grid only statistics reduced standard deviation except for C25P
- Uniform process applied to window nearfield signature, propagate to ground, and compute loudness measure
  - Verified with participant submissions
  - Most within a few tenths of a dB
  - Largest difference was 1.5 dB for JWB

Conclusions

- PL and ASEL strongly correlated
  - Spread of less than 1 dB
- Convergence of PL shown with grid refinement
  - Euler and RANS clusters for C25F
- PL statistics visualized with box, whisker, and violin plots
  - Euler and RANS analyzed separately
  - Some cases had insufficient samples

Conclusions

- Mean, median, interquartile range, and standard deviation compiled
- Differences in nearfield and ground examined for fine grid RANS submissions with largest variation
- Progress made since the first workshop identified

Recommendations

- Formalize nearfield signature windowing process
- Track nearfield signature differences to CFD scheme properties and grid construction
  - Request symmetry plane solution or other volume data

Discussion

- Was SBPW2 the right suite of cases and data submittal requirements?
- Further analyze SBPW2 data set
  - Best dissemination method?
- AVIATION 2017 paper and talk
  - Additional analysis or investigation?

SBPW3?

- Goals
- Models and cases
- Workshop provided grids
- Data requests

Notes

- Gather AXIE off-centerline
- Gathering surface of volume data from participants (multipole compatible)
- Limiter discussions (higher aspect ratio collar grids? Too aggressive?)
- Triangular surface discretization issues (alignment, higher order?)
- Wing and horizontal tail vortex
- Off-track has less spanwise distortion