Computational and Experimental Assessment of Models for the First AIAA Sonic Boom Prediction Workshop

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Applied Modeling & Simulation Seminar Series
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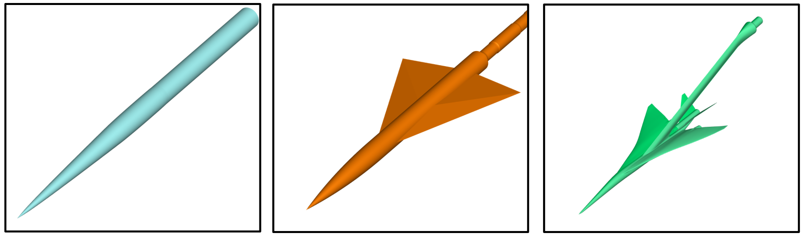
AIAA 2014-0560 by Cliff S., Durston D., Elmiligui A., Jensen J., and Chan W.

Outline

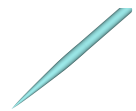
- Sonic Boom Workshop
  - Purpose and Objectives
  - Study Configurations



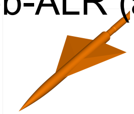
- Wind Tunnel Tests
  - Overview of facility and Instrumentation
  - Test Techniques
- Computational Tools
- CFD/Experiment Comparisons
  - Ground-level signatures and PLdB for transport model
- Summary

Sonic Boom Workshop

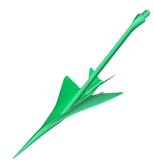
- 1st AIAA Sonic Boom Prediction Workshop held on January 11, 2014
- Purposes
  - Forum for industry & international participation
  - Evaluate and compare computational grids and solutions
  - Obtain better understanding of best practices in CFD
- Common geometries and meshes were distributed
  - Lockheed Martin Seeb-ALR (aft-lift relaxation)



  - 69° Delta Wing-Body

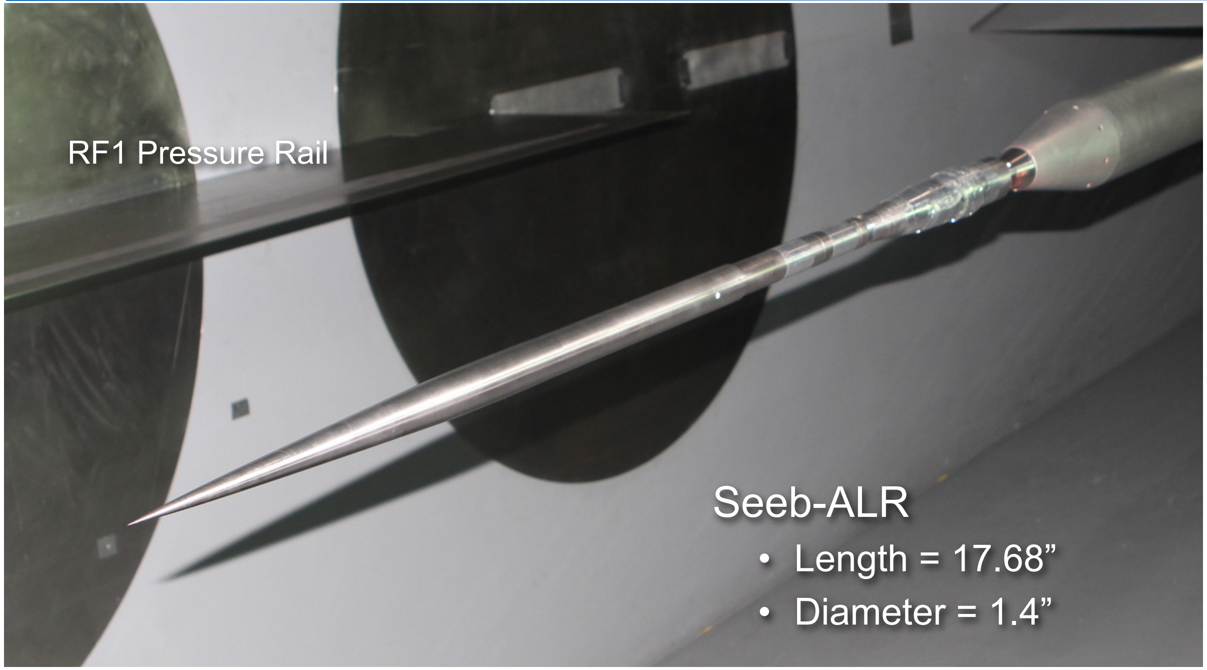


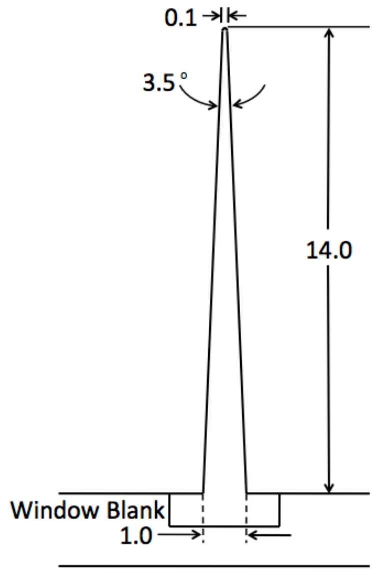
  - Lockheed Martin 1021 low-boom supersonic transport



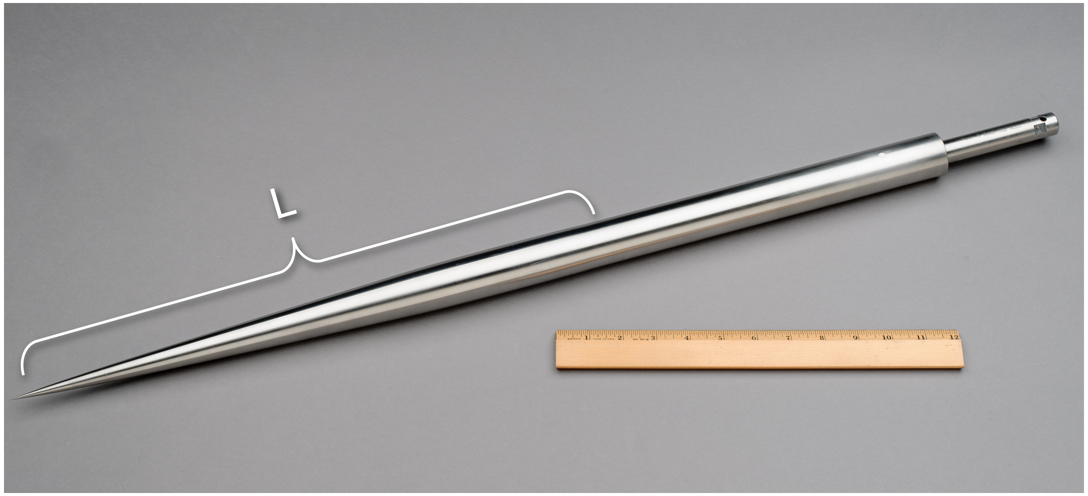
- Tests were conducted in NASA Ames 9x7 Supersonic Wind Tunnel
- USM3D (submitted) and OVERFLOW results
- *AIAA 2014-0560 provides several other conditions (α, h) with computational and experimental comparisons*

Lockheed Martin Seeb-ALR

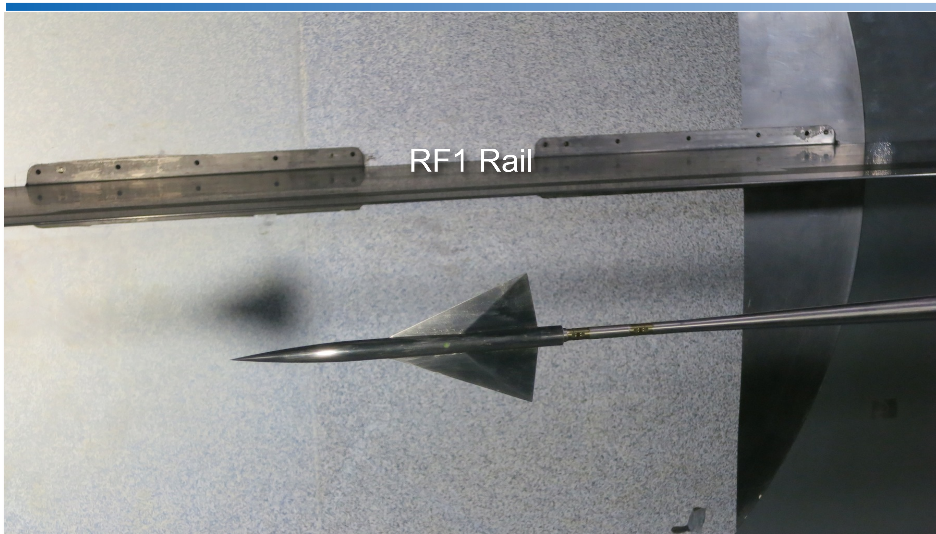




- Calibration Model for RF1 Rail
  - 8" flat forward signature
  - 2" flat aft signature
  - A_e body for low boom and drag
  - Modified aft signature of "Seeb"



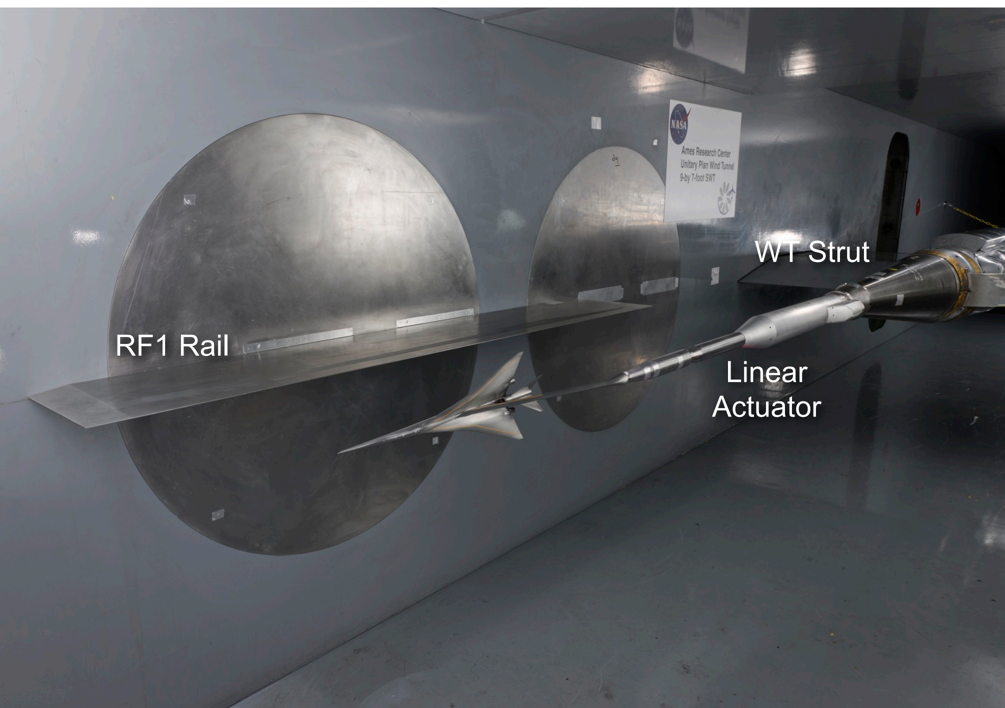
Ames 69° Delta Wing-Body

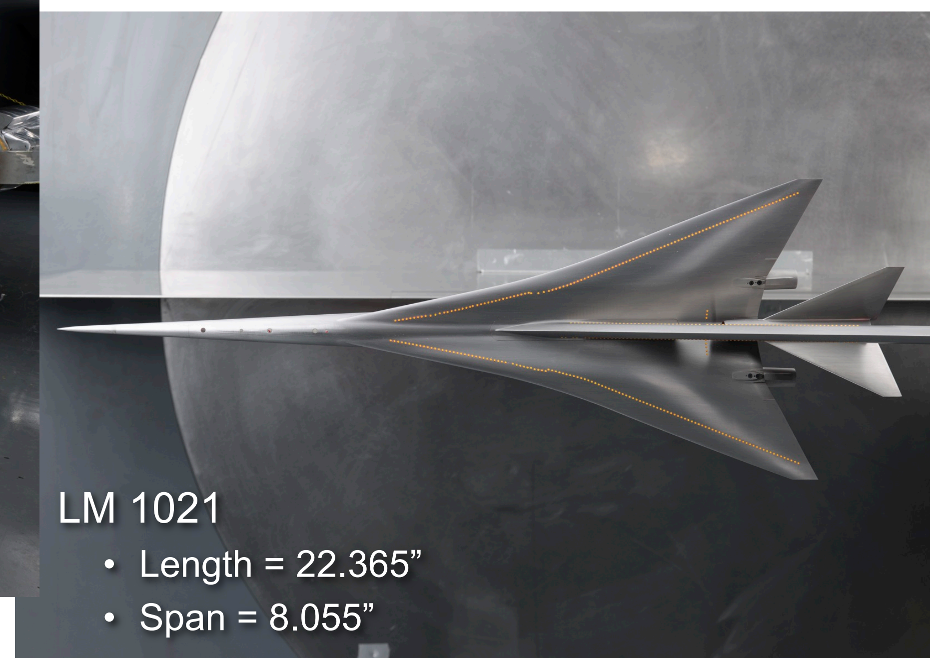


- Legacy configuration for sonic boom measurement / analyses
  - FAP Sonic Boom Workshop 2008
  - CFD comparisons in 1991
  - Tested in 1973

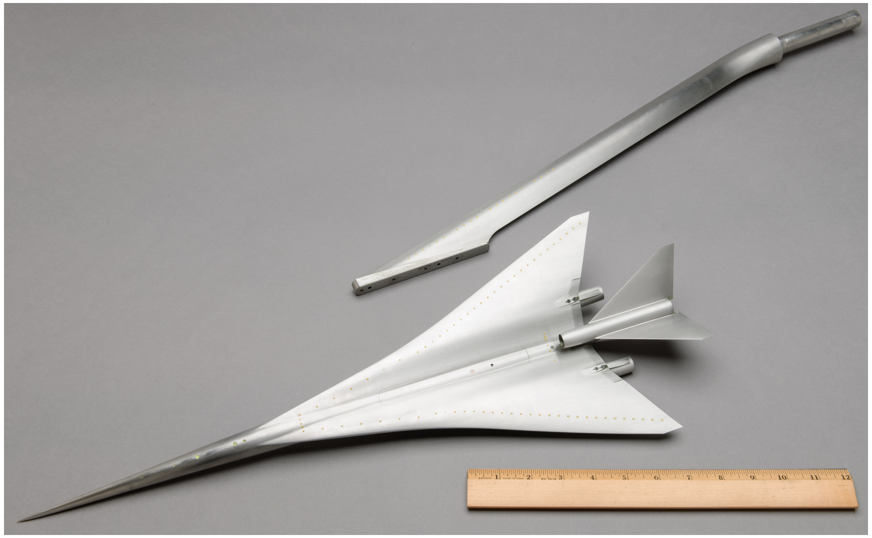
Lockheed Martin 1021 Low-Boom Model

- 1021 is N+2 supersonic transport configuration from Phase I of LM NRA with High Speed Project
  - Mach 1.6 cruise at 50,000 ft
  - 230 feet length
  - 82-100 passengers
- 0.8% scale model installed in 9x7 wind tunnel



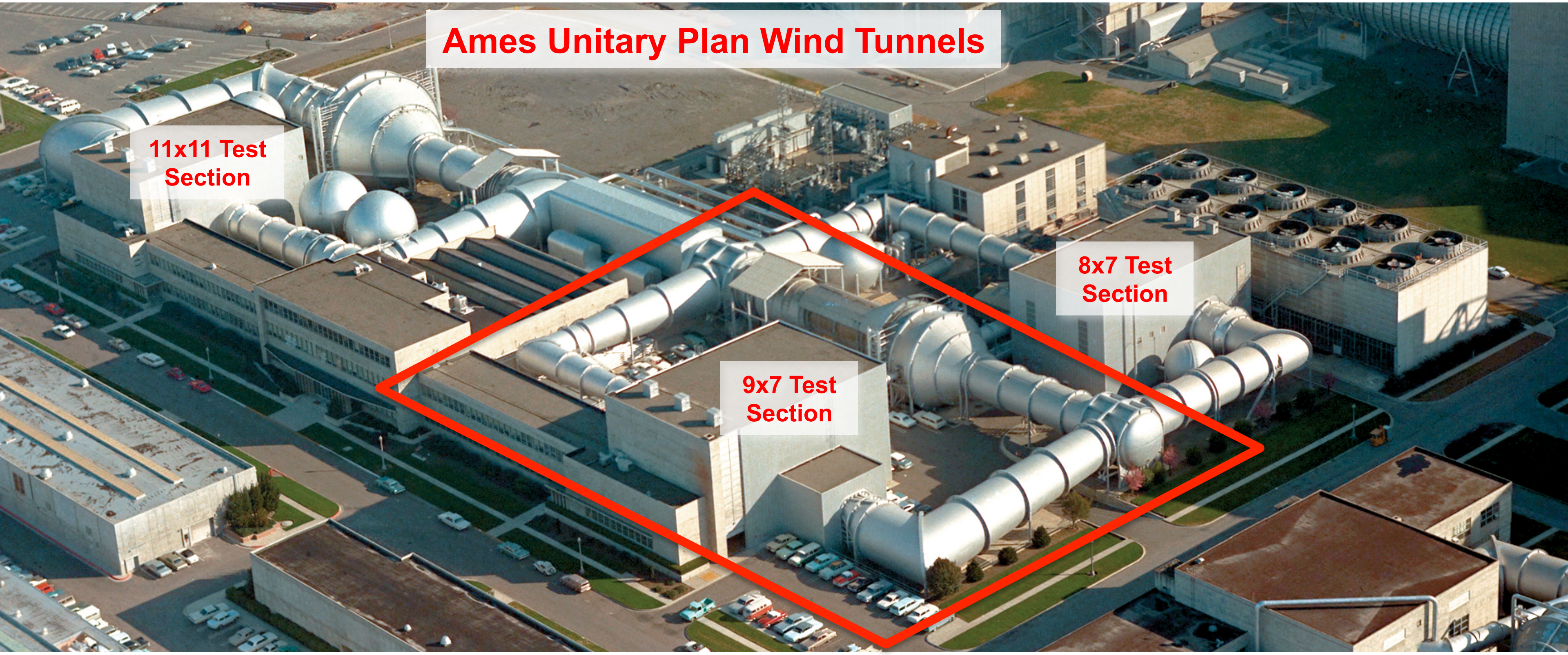


1021 Model Details



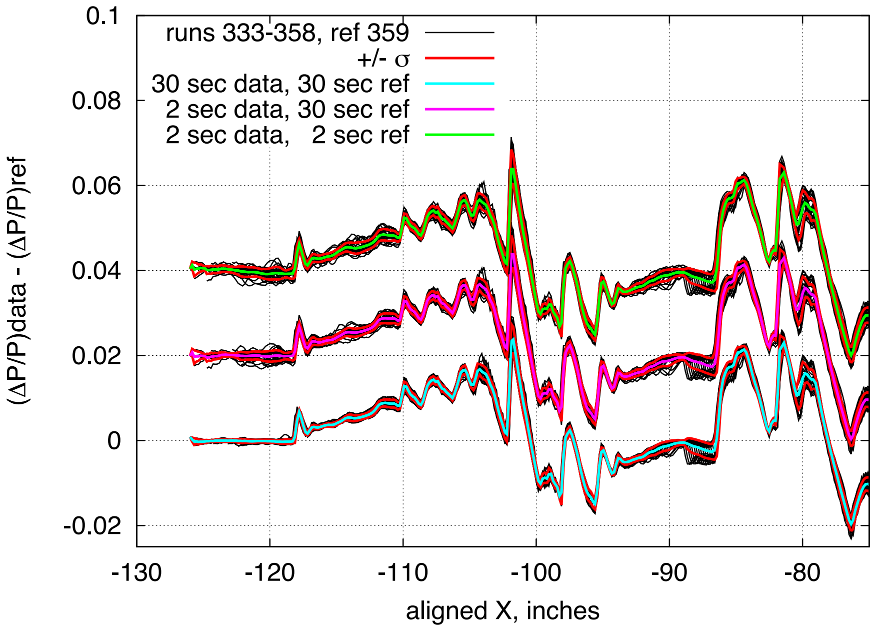
Ames 9- by 7-Foot Supersonic Wind Tunnel

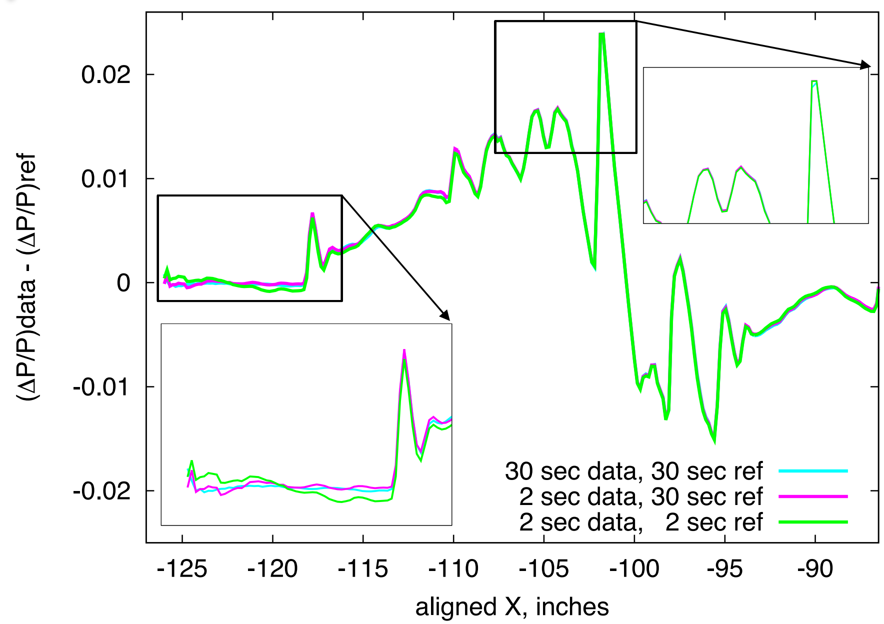
- Lockheed Phase I and II Tests conducted in Oct 2011 and Oct 2012
- Mach 1.6 and 1.7 (Mach set by sliding nozzle block/floor)
- Reynolds number 4.3×10^6 per foot
- Reflection Factor 1 (RF1) pressure rail used for sonic boom data



Primary Test Technique Differences

Phase I	Phase II
• 30 second duration data runs	• 6 second duration data runs
• Full length pressure tubing 4.5 second lag time	• Reduced length pressure tubing 2.0 second lag time
• Humidity 230 ppm, < 4 ppm, avg 2	• Humidity 250 ppm, < 10 ppm, avg 4
• PT < 0.5 psf	• PT < 2.0 psf
• RF1 on forward window blank	• RF1 on forward & aft window blanks





Simplified Run Matrix AIAA 2014-0560 Paper

- Experimental data plots (avg. and individual)
- Repeat data plots
- Experiment overlaid with CFD

Configuration	*M*	*α*	*h*	*ϕ*	*Sweep*	*Runs*	*Exp. Fig.*	*CFD Fig.*
1021 with all nacelles, blade strut (Phase I)	1.6	2.09	20.7	-2.37	*X*	333_358-359	14	33a
	1.6	1.95	20.6	-4.21	*X*	390_415-387		
	1.6	2.10	20.8	-0.75	*X*	939_964-938		
	1.6	2.29	20.7	-0.5	*X*	774_799-828	15	33b
	1.6	2.46	20.8	-0.6	*X*	800_825-828		
	1.6	2.32	31.3	-0.6	*X*	829_854-876	16	33c
	1.6	2.51	31.4	-0.7	*X*	855_874-876		
	1.6	2.31	20.8	24.6	*X*	748_773-828	17	34a
	1.6	2.47	20.8	20.3	*X*	877_902-903		
	1.6	2.30	20.8	47.8	*X*	696_721-828	18	34b
	1.6	2.45	20.9	47.6	*X*	722_747-828		
1021 with all nacelles, blade strut (Phase II)	1.6	2.18	24.6	0.12	*Z*	3728_3776-3777	19	N/A
	1.6	1.97	31.8	0.25	*X*	3698_3715-3727		
	1.6	2.14	42.1	0.0	*X*	3801_3839-3840		
	1.6	1.84	48.6	1.08	*Z*	272_304-271		
	1.6	2.03	62.8	0.53	*Z*	247_270-271		
	1.6	2.12	69.6	0.4	*X*	160_200-204		
Seeb-ALR (Phase I)	1.6	-0.29	20.6	0.5	*X*	195_219-221	21	35a
	1.6	-0.27	20.6	0.5	*X*	553_578-580		
	1.6	-0.27	31.2	0.3	*X*	581_606-608	22	35b
Seeb-ALR (Phase II)	1.6	-0.06	56.01	0.41	*Z*	845_900-901	23	35c
	1.6	-0.05	56.02	0.27	*Z*	948_1003-1004		
	1.6	-0.02	70.02	0.22	*X*	794_832-834	24	35d
69° Delta Wing-Body (Phase II)	1.7	0.24	24.86	0.16	*X*	5598_5637-5638	25	36
	1.7	-0.20	24.75	29.97	*X*	5530_5549-5550		
	1.7	-0.18	24.75	60.06	*X*	5551_5570-5571		
	1.7	-0.18	24.69	89.87	*X*	5572_5591-5592		
	1.7	-0.06	31.64	0.60	*X*	5240_5274-5275	27	37
	1.7	-0.17	31.74	29.94	*X*	5284_5301-5275		
	1.7	-0.22	31.56	59.74	*X*	5310_5327-5328		
	1.7	-0.20	31.61	89.96	*X*	5336_5353-5354		
	1.7	0.71	21.33	0.253	*X*	5641_5680-5638	28	38
	1.7	2.37	25.21	0.334	*X*	5469_5488-5489		
	1.7	3.90	25.49	0.687	*X*	5448_5467-5468		
	1.7	1.75	32.10	0.378	*X*	5405_5424-5425	29	39
	1.7	3.10	32.33	0.236	*X*	5426_5445-5446		

repeatability

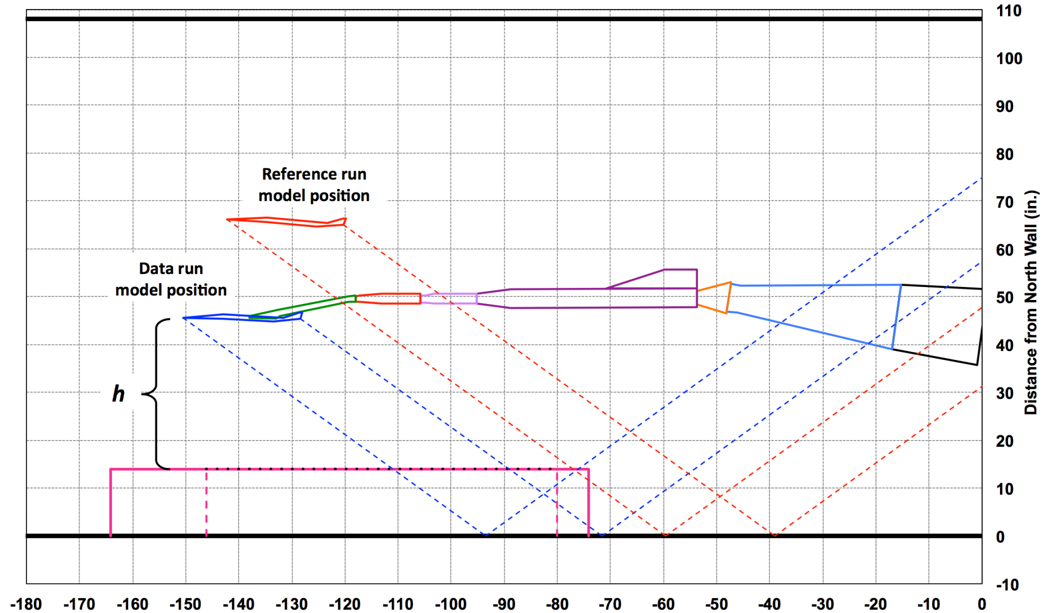
Additional data

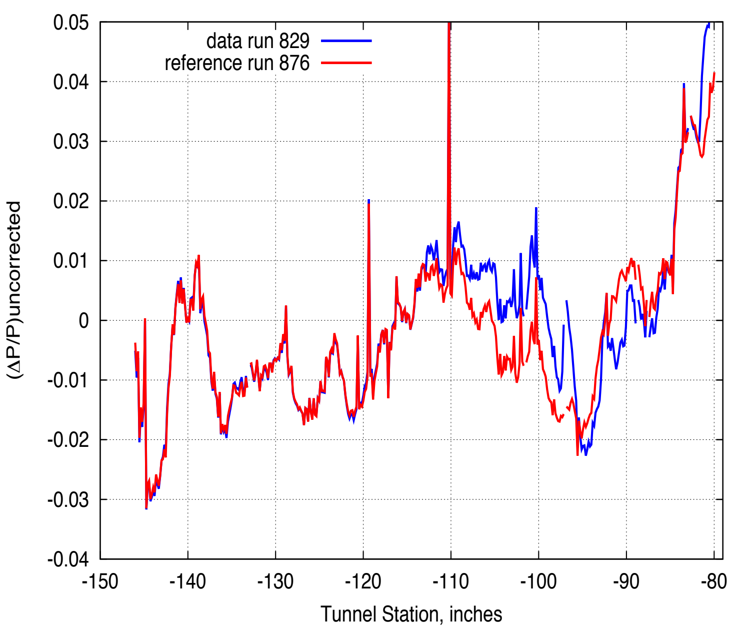
Additional data

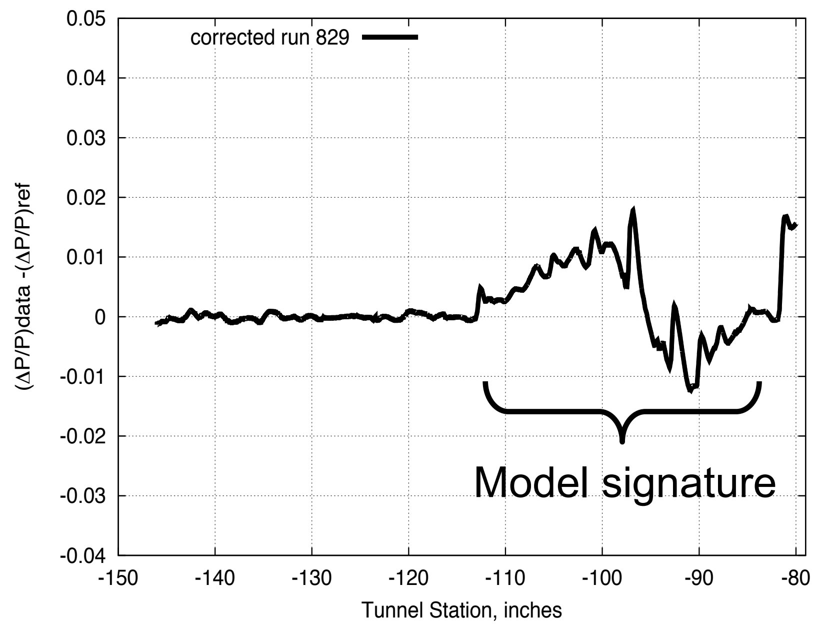
Additional data

Data Acquisition Using Pressure Rail

- Data run: shocks *on* rail
- Reference run taken with model shocks *off* rail (or at least downstream of where model shocks will be)
- Model signature is *difference* of reference run from the data run

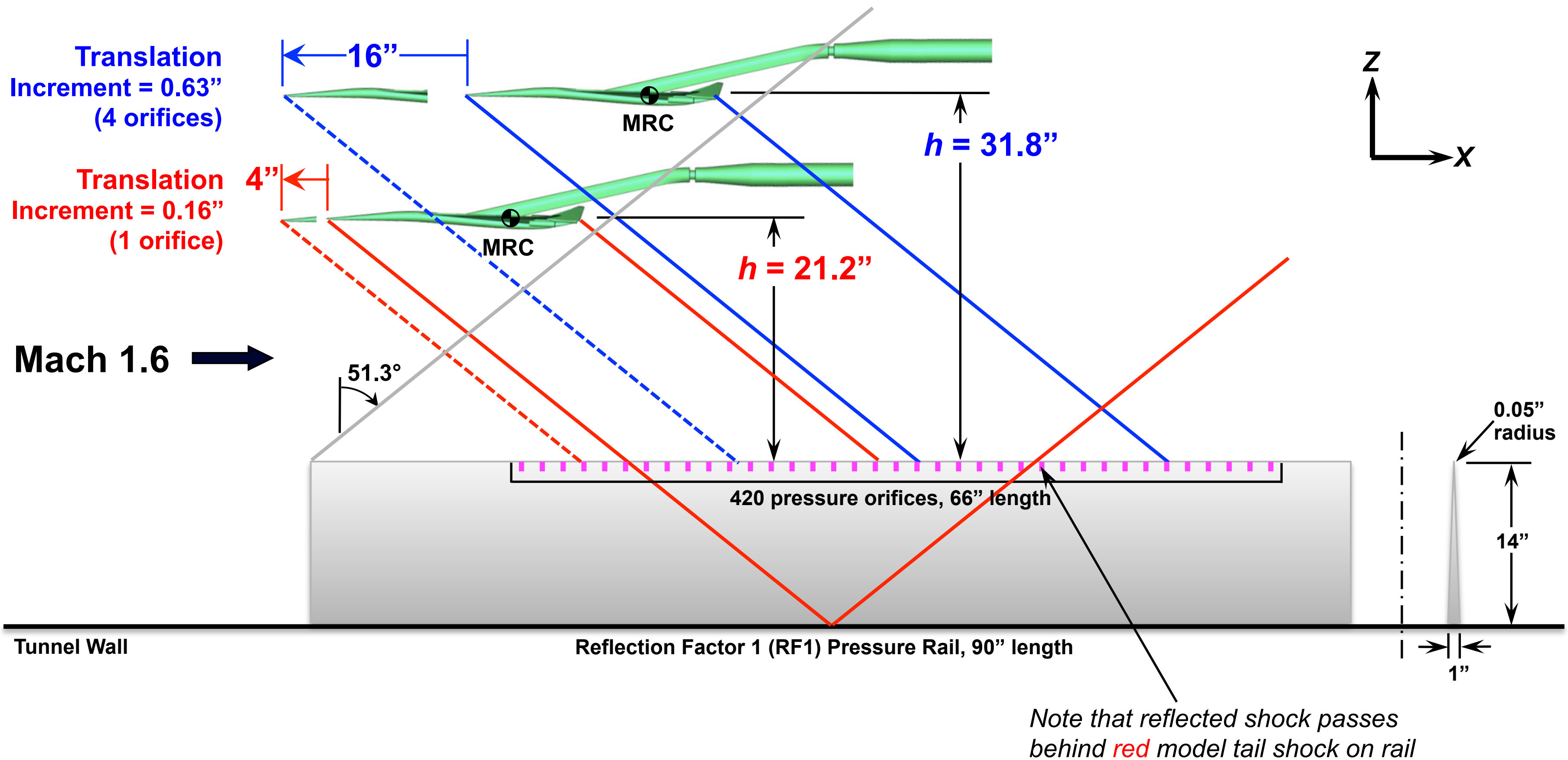






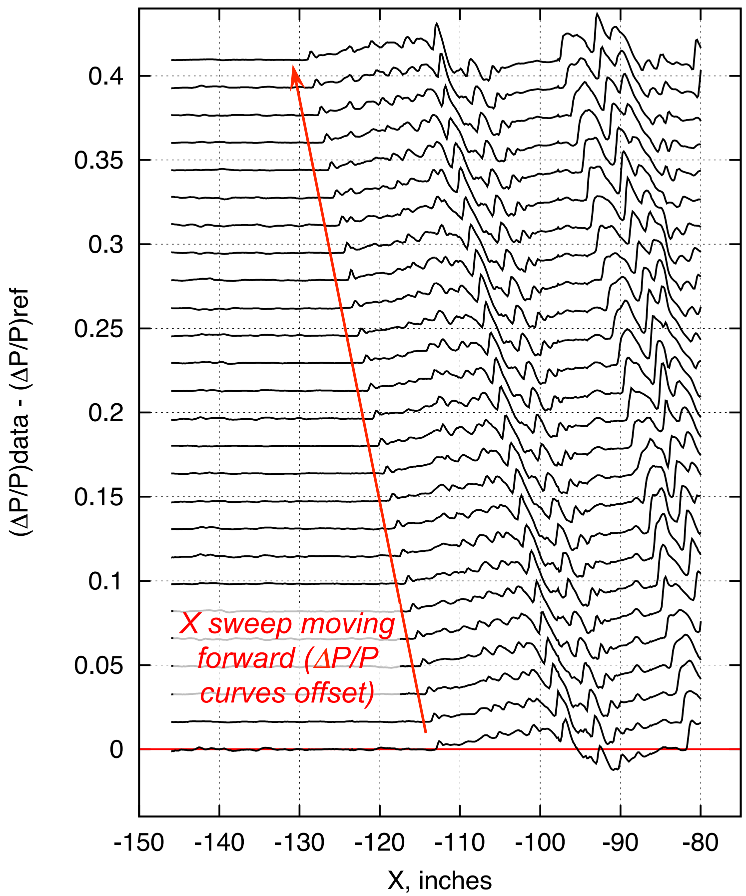
Layout for LM 1021 Model

- X sweeps used to acquire multiple (26) signatures for spatial averaging
- Sweeps used for 1021 model:
  - 16” translation at height of 31.8” above rail
  - 4” translation at height of 21.2” above rail

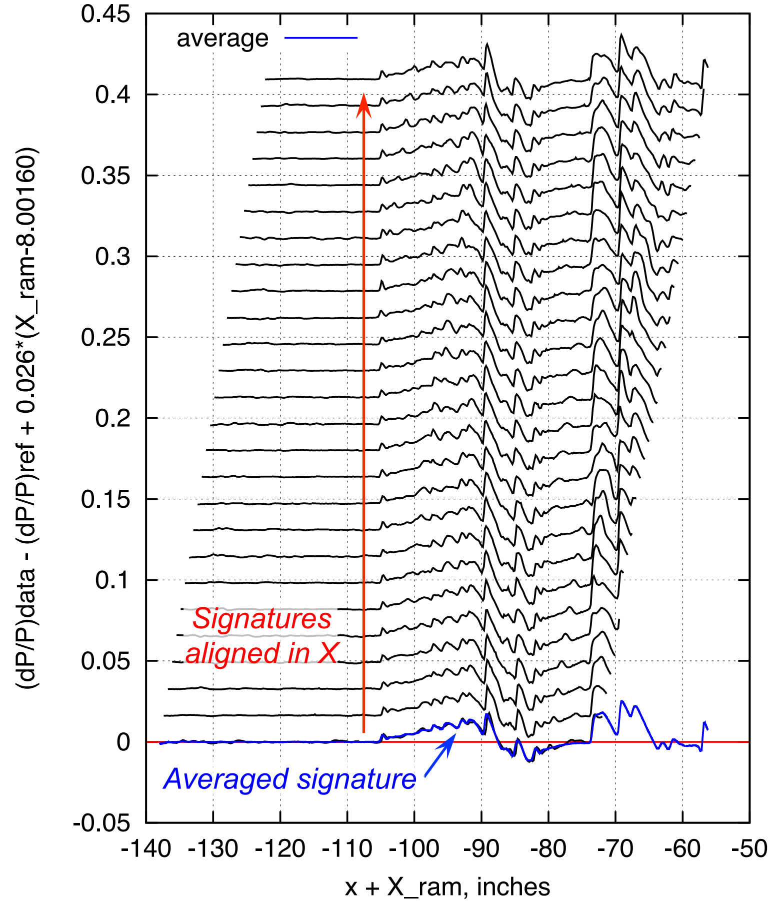


Signature Averaging from X-Sweeps

- Multiple signatures acquired
- Tunnel ambient distortions evident in individual signatures
- Averaging reduces tunnel distortions

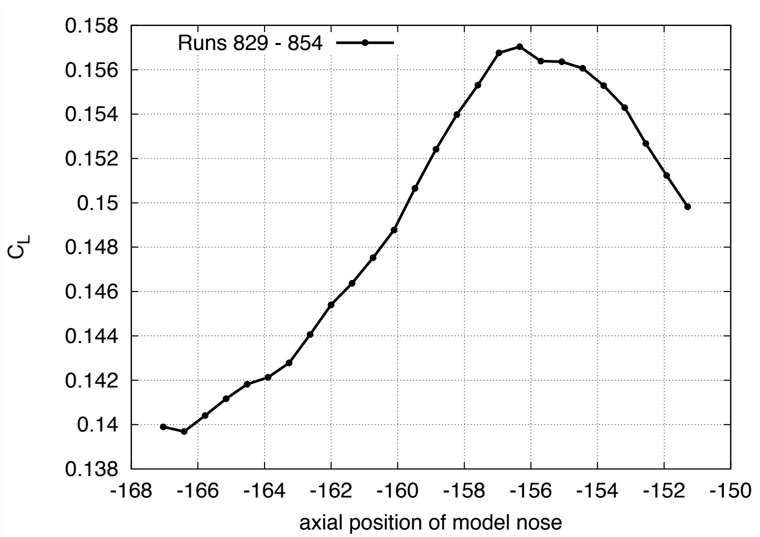


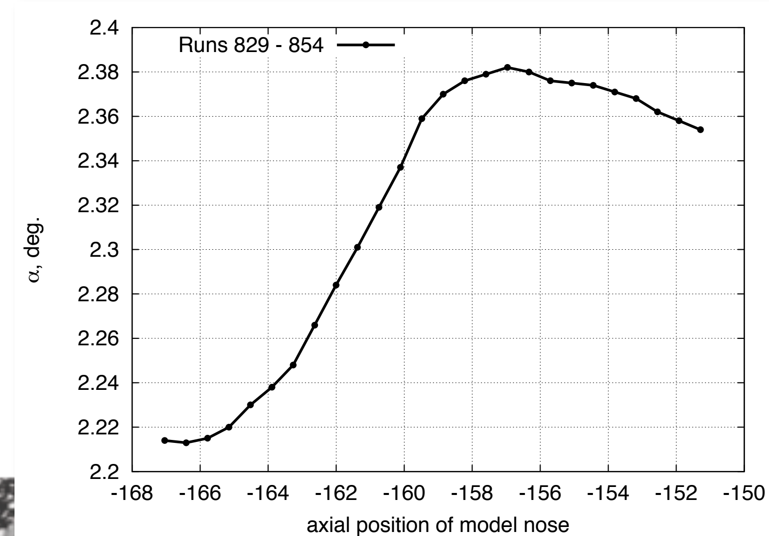
Unaligned model signatures

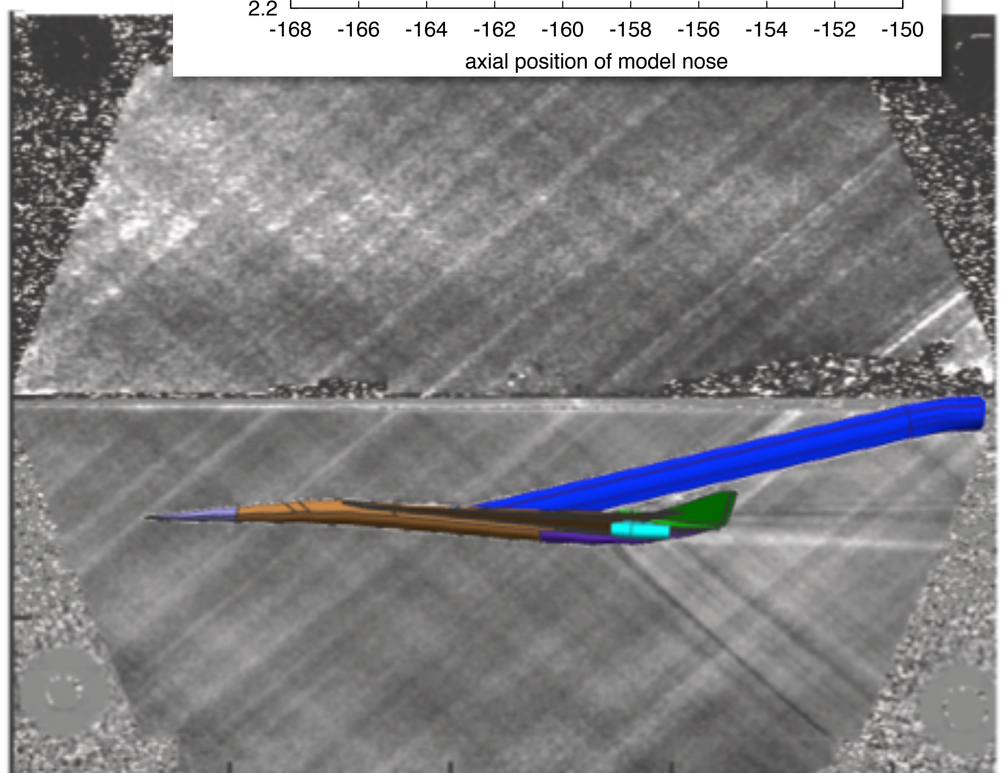


Aligned and averaged signatures

Tunnel Test Section Flow







<u>Shock Rounding Sources</u>

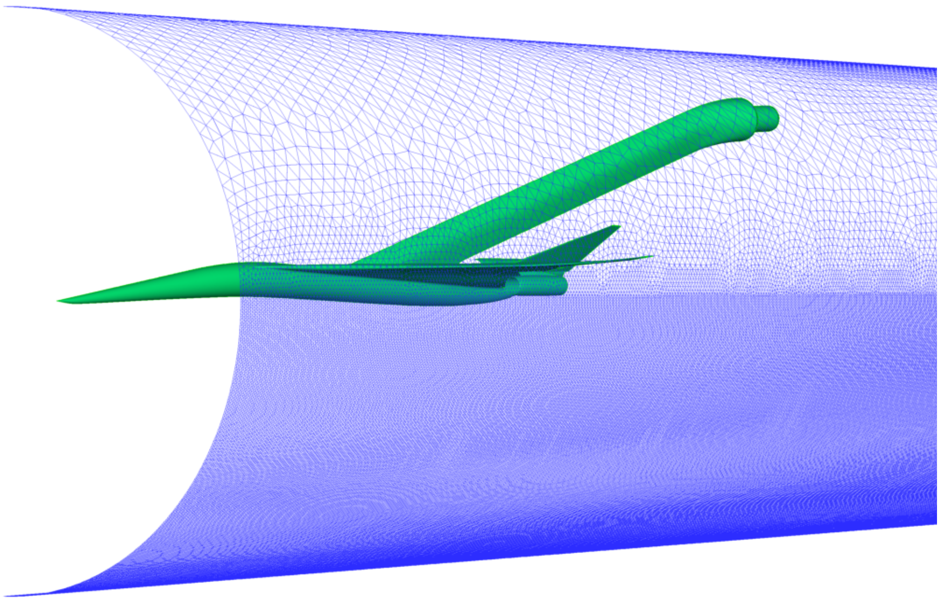
- model vibration
- tunnel shocks (moving)
- tunnel Stream angle
- discrete rail orifice spacing
- humidity

Computational Tools: NASA Codes

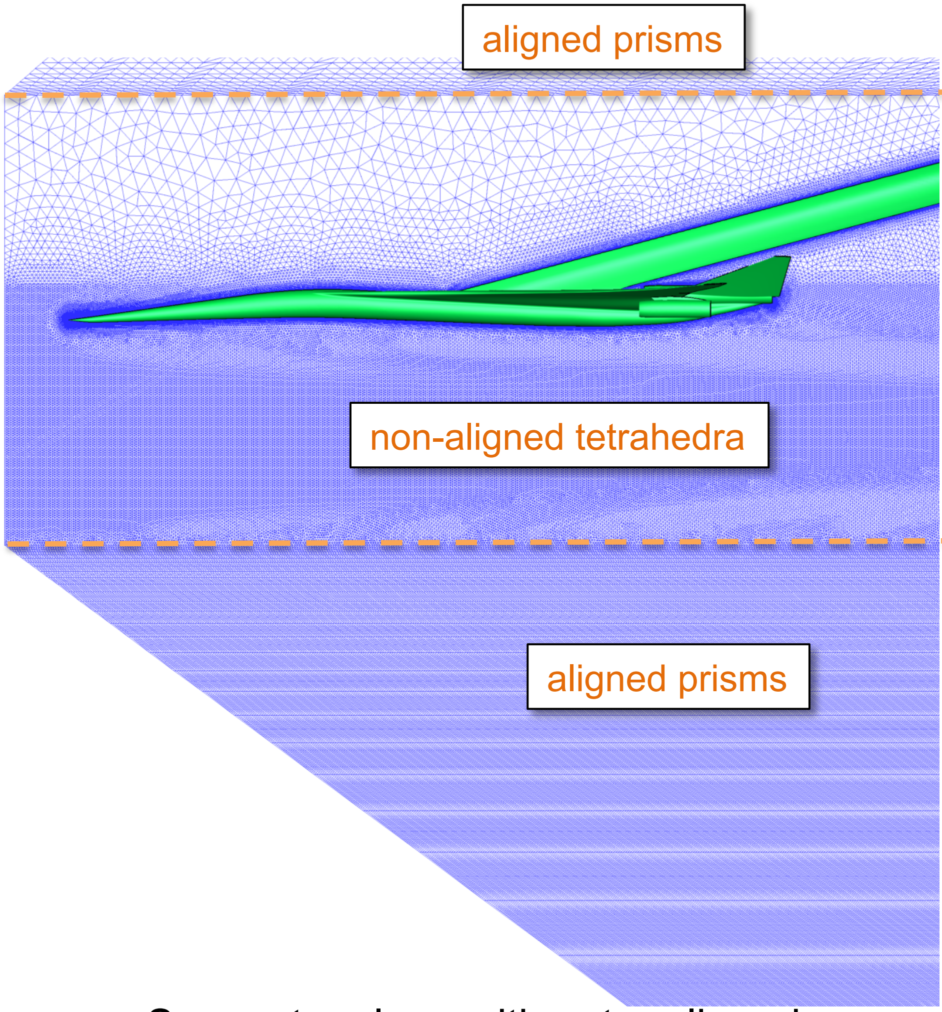
USM3D	OVERFLOW 2.2
• Unstructured tetrahedra, cell-centered, finite volume	• Structured overset, vertex based, finite difference
• Euler & Navier-Stokes	• Navier-Stokes
• Steady state simulations	• Steady state simulations
• Upwind spatial discretization	• Central & upwind spatial discretization
• Standard & characteristic based BC's	• Standard & characteristic based BC's
• Spalart-Allmaras turbulence model	• Spalart-Allmaras turbulence model

Computational Tools: USM3D Meshes

Mach Cone Aligned Prism (MCAP) meshes for 1021 model



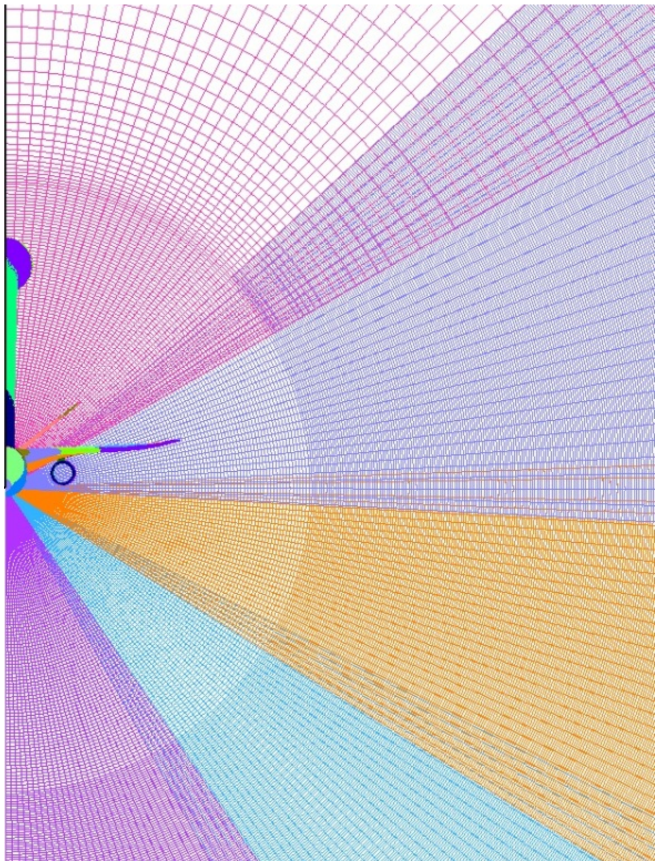
Cylindrical near-body mesh



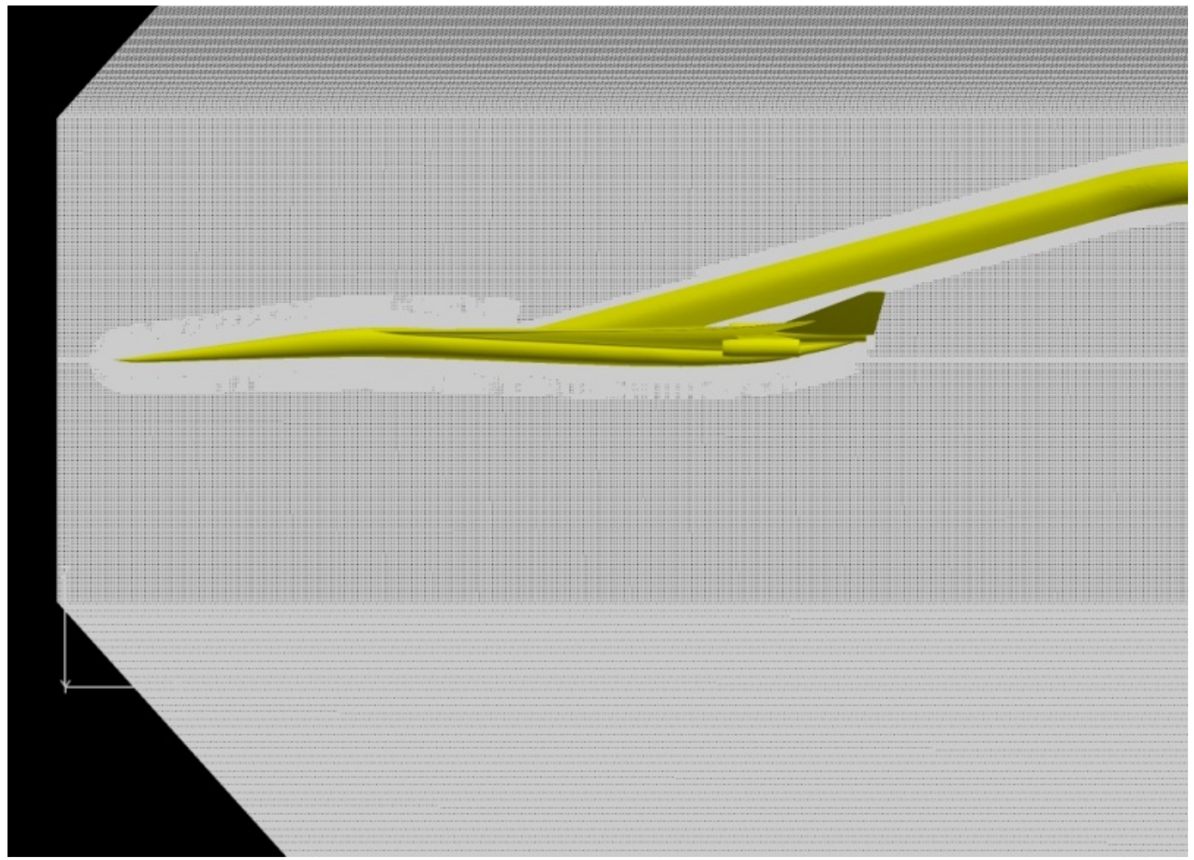
Symmetry plane with outer aligned prism grid

Computational Tools: Overset Meshes

OVERFLOW Overset Meshes for 1021 Model



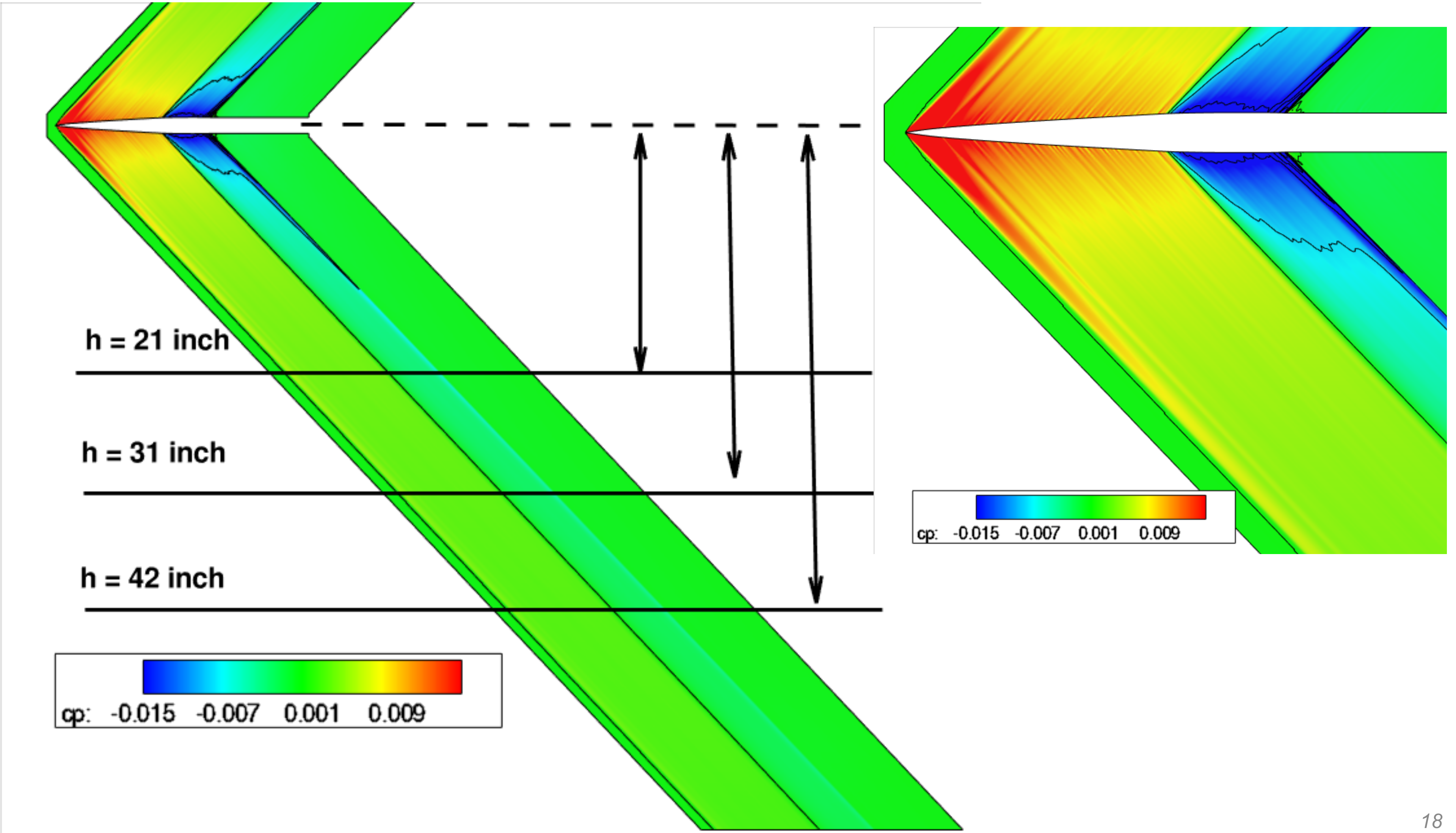
Front View



Symmetry Plane View

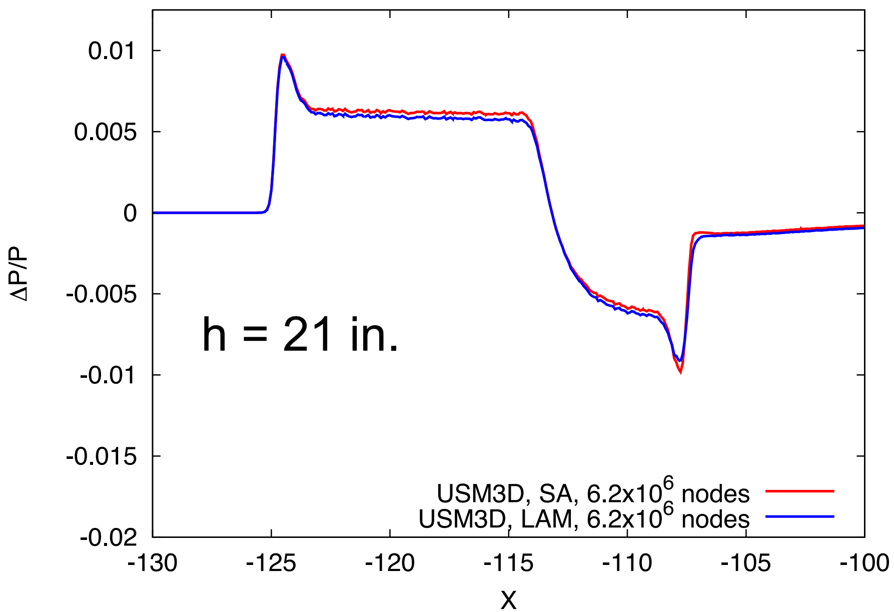
Seeb-ALR Mach Line Contours on C_P

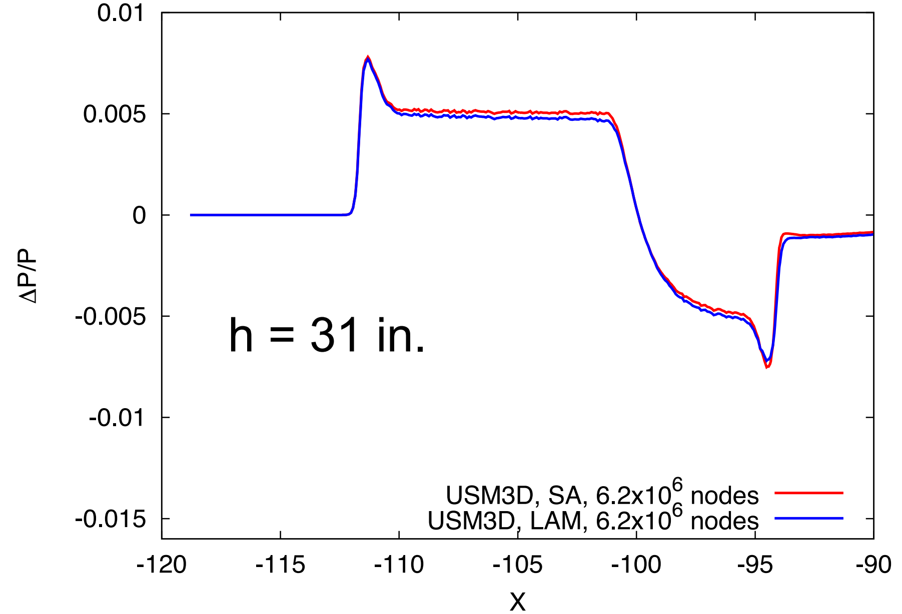
- Mach = 1.6, α = 0°, Re = 6.42x10^6
- USM3D turbulent solution

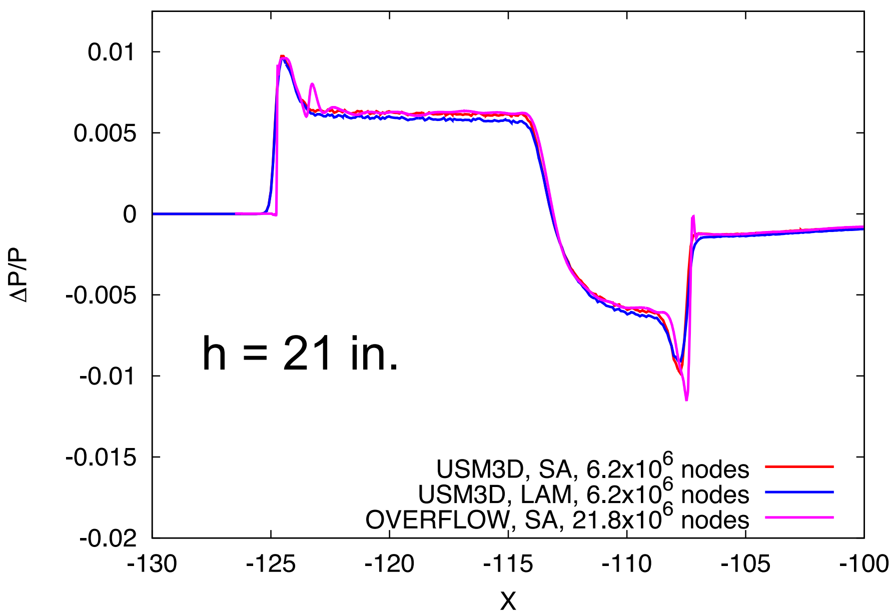


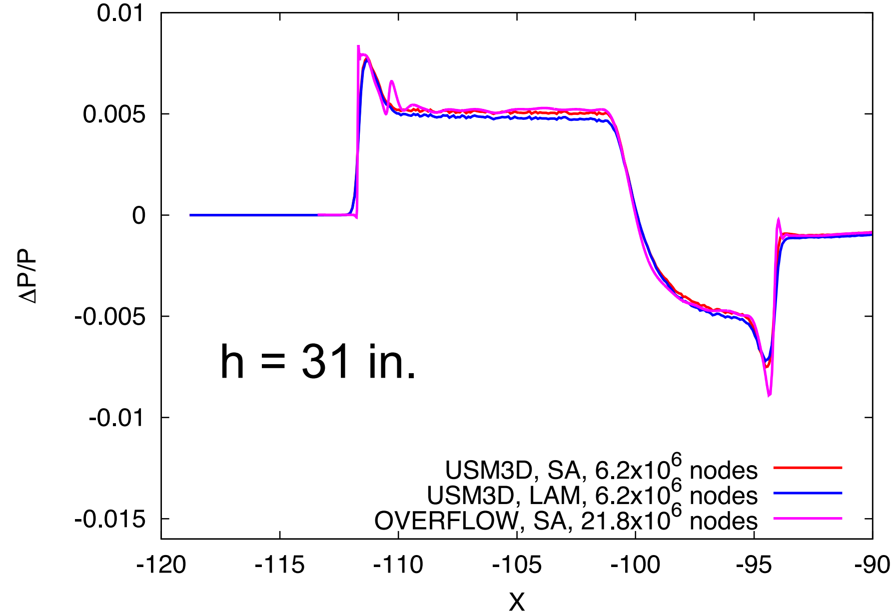
Seeb-ALR CFD Comparisons

Mach = 1.6, α = 0°, Re = 6.42×10^6









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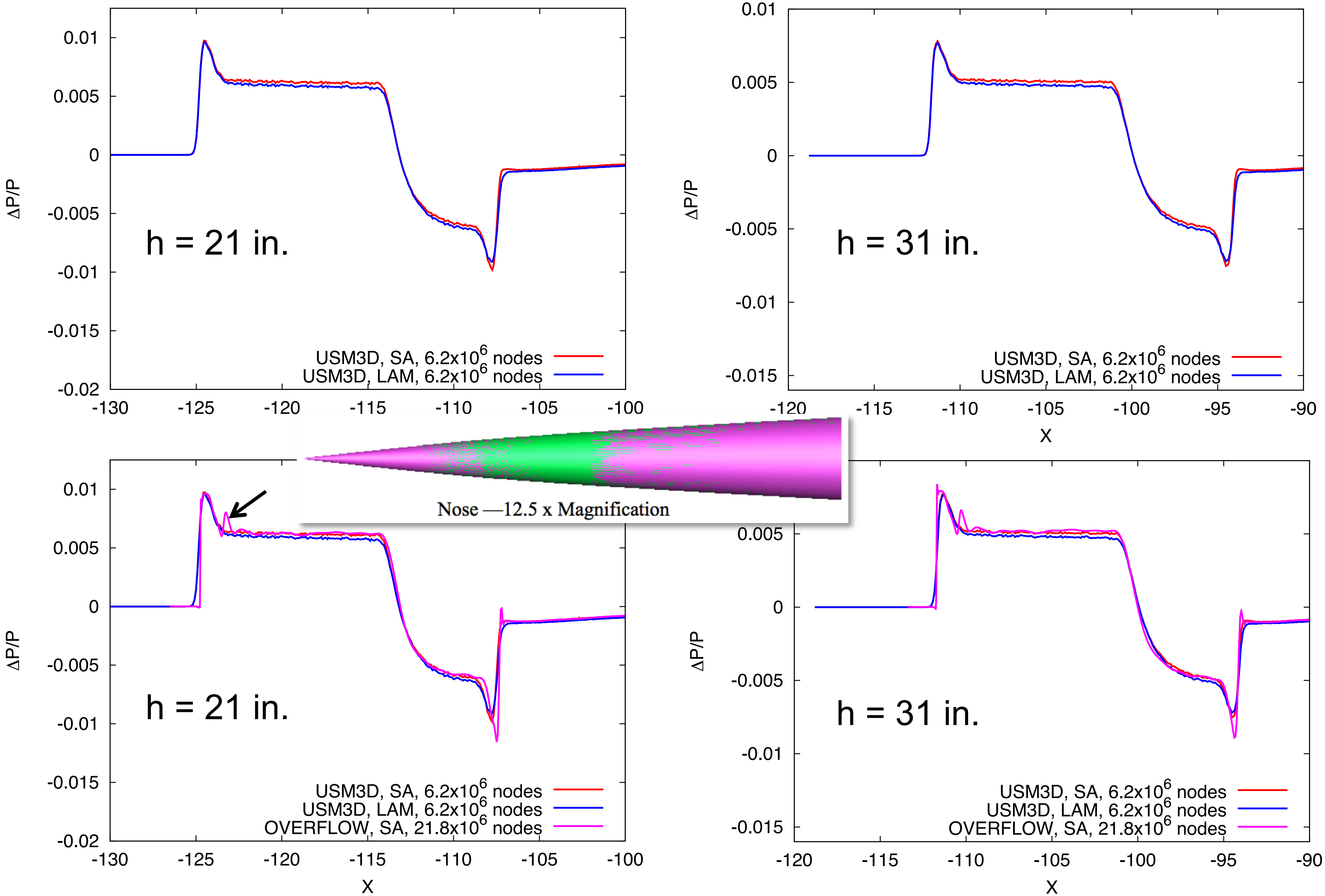
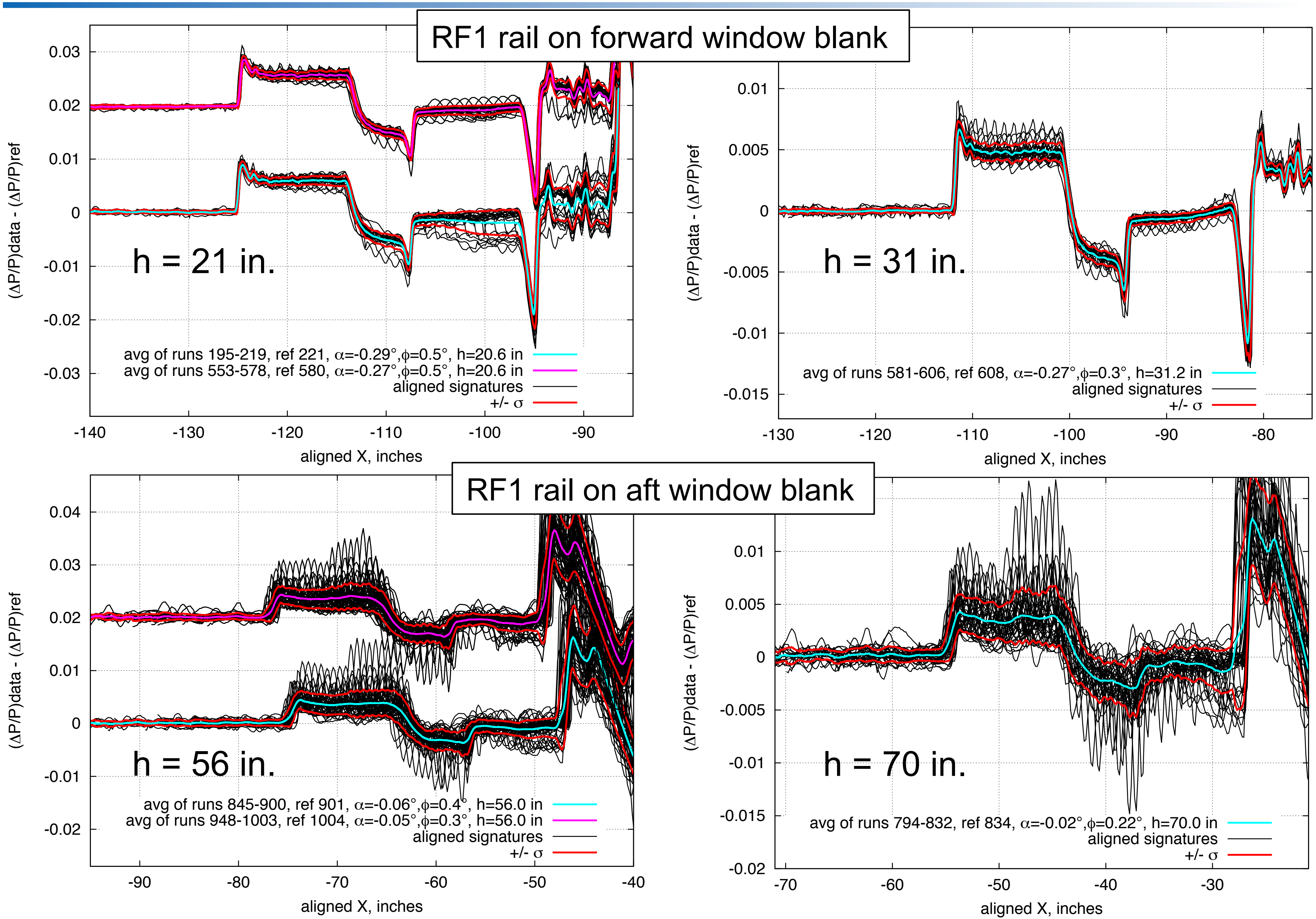
Mach = 1.6, α = 0°, Re = 6.42x10^6

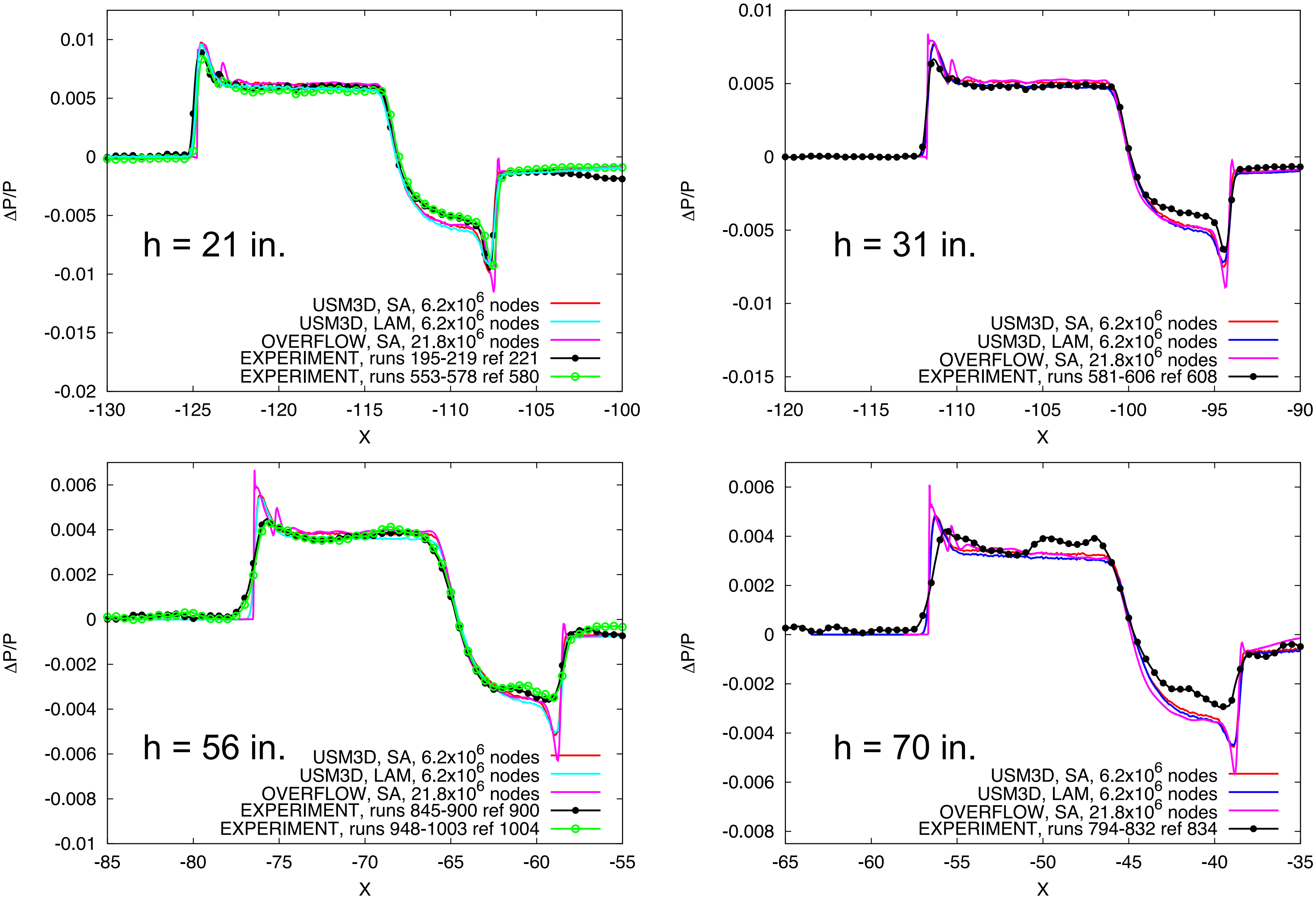


Seeb-ALR Experimental Data

Mach = 1.6, α = 0°, Re = 6.42x10^6

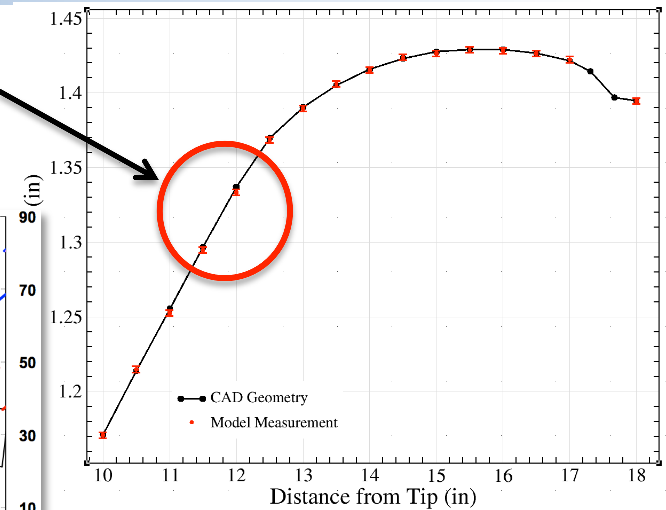


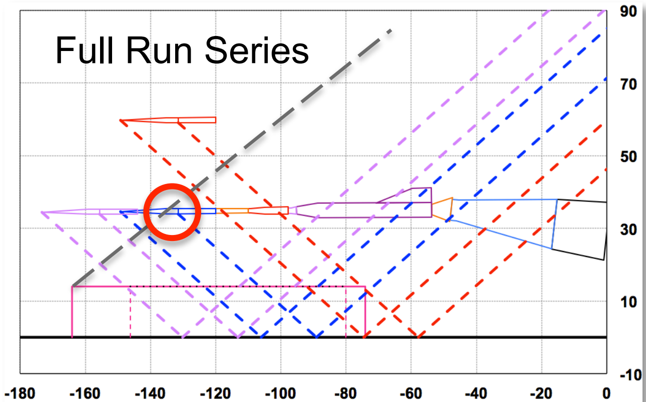
Seeb-ALR CFD vs. Experiment: M=1.6, α=0°

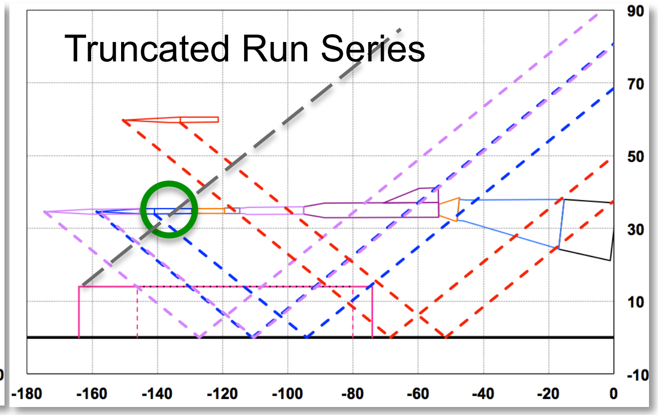


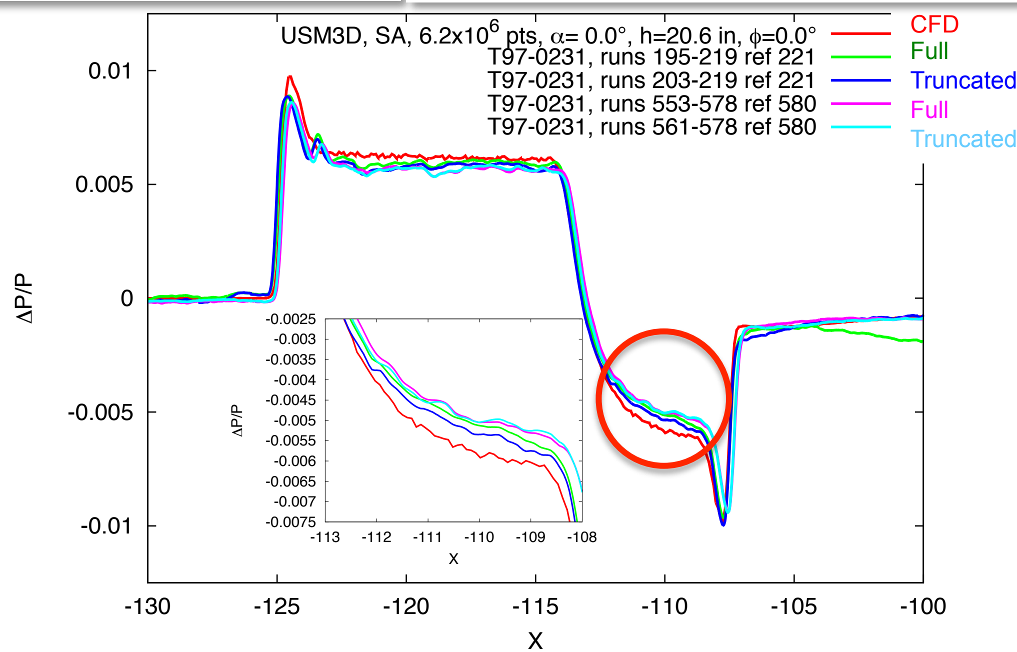
Seeb-ALR Aft Signature Discrepancies

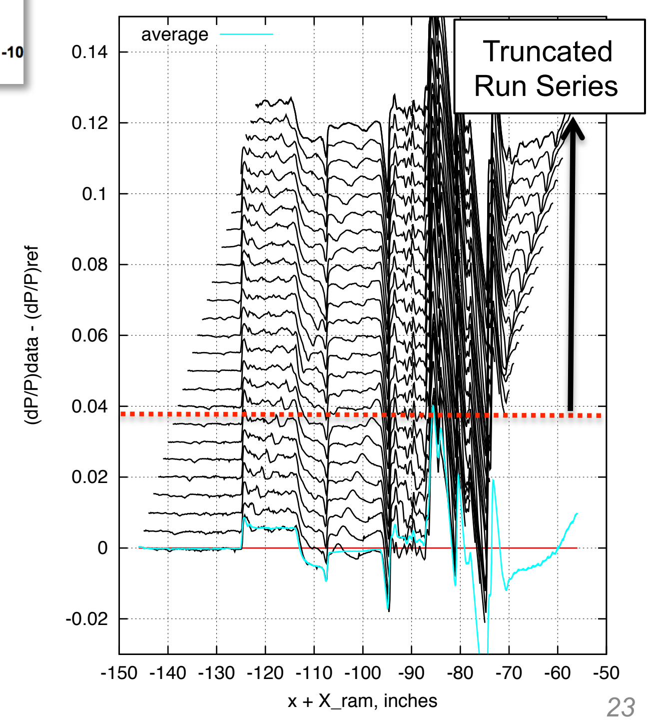
- Model fabrication error?
  - measurements show model with decreased diameter
- RF1 rail leading shock influence at *h*=21”?





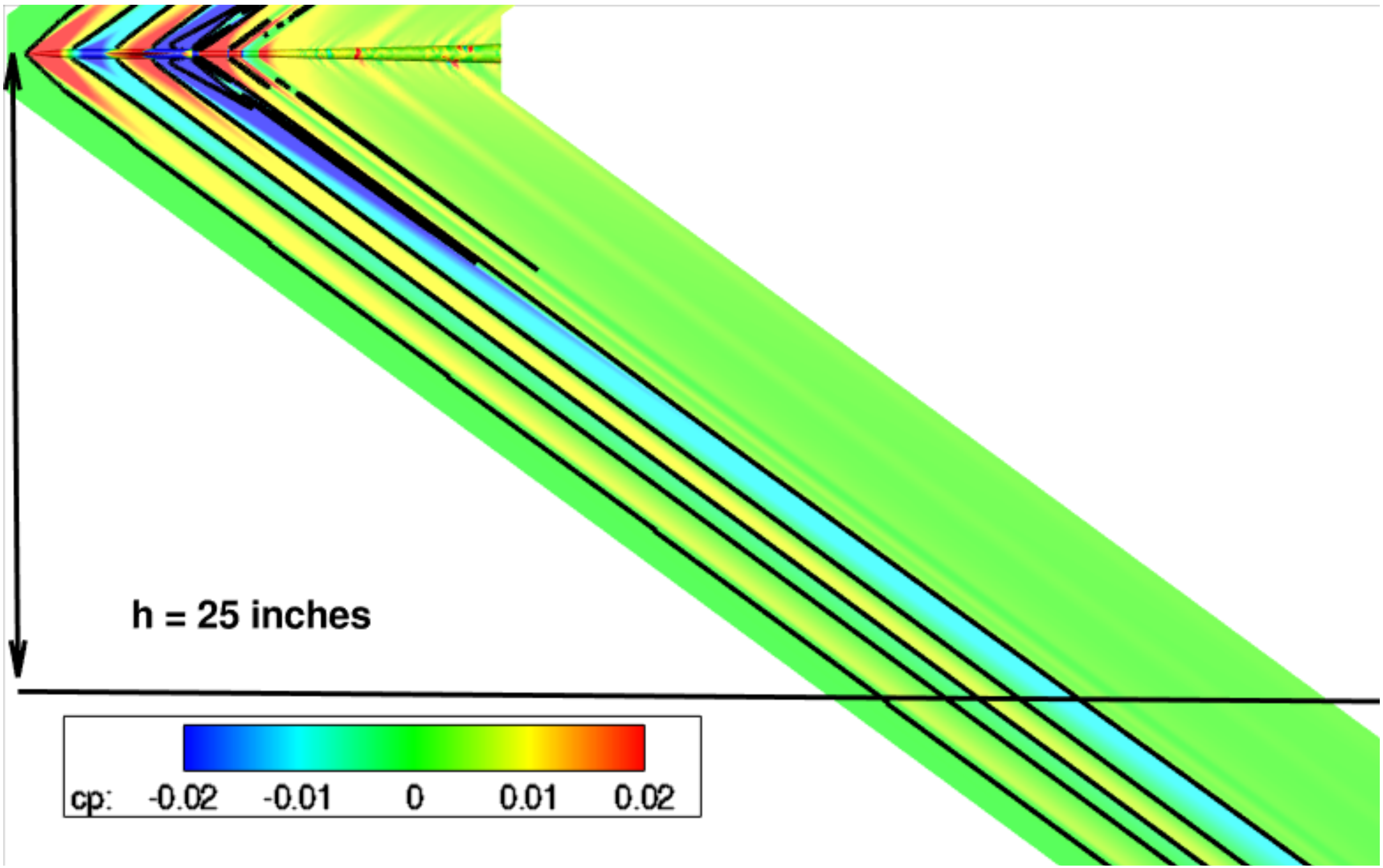




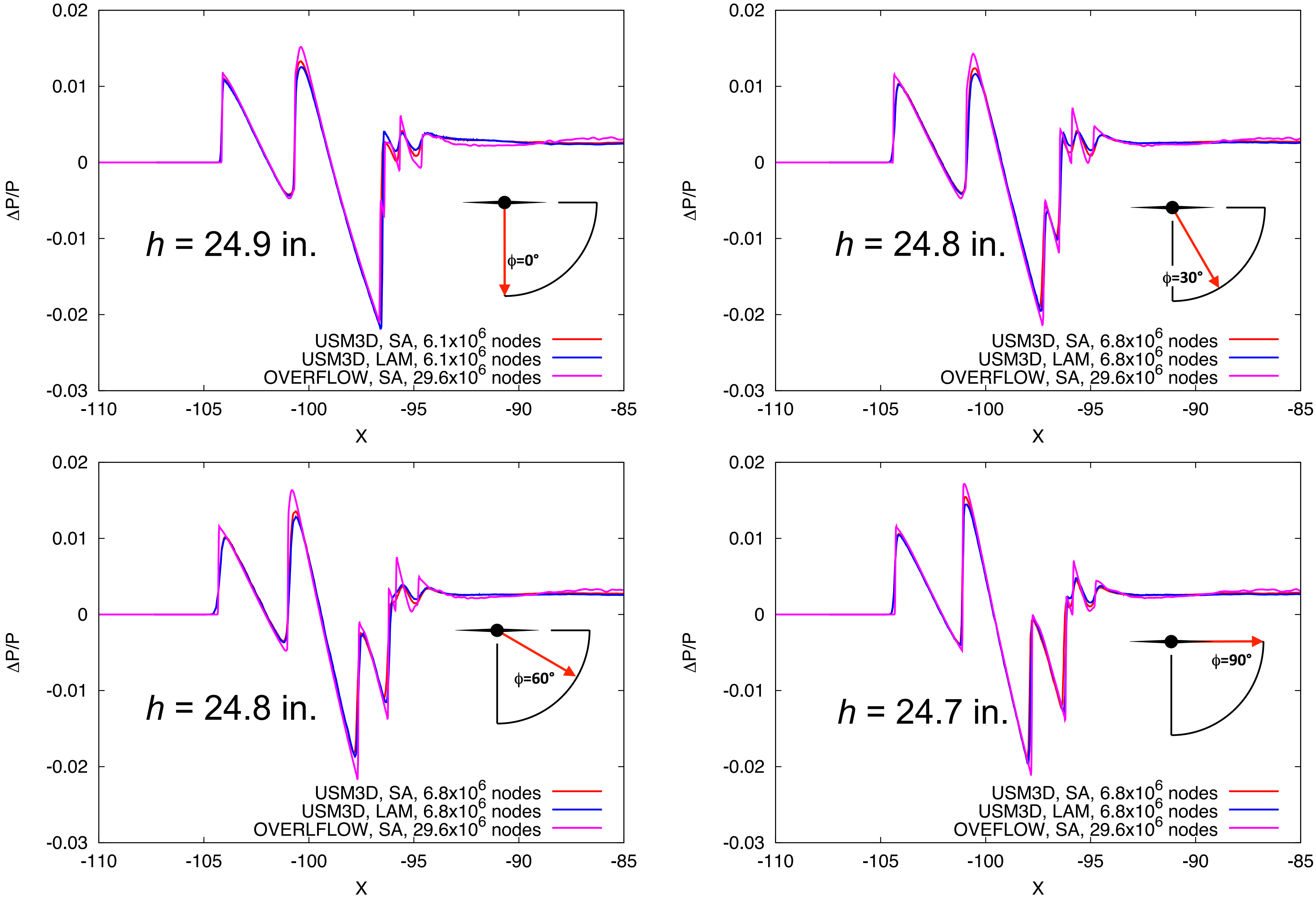


69° Delta Wing-Body Mach Line Contours on C_P

- Mach = 1.7, α = 0°, Re = 2.43×10^6
- USM3D turbulent solution



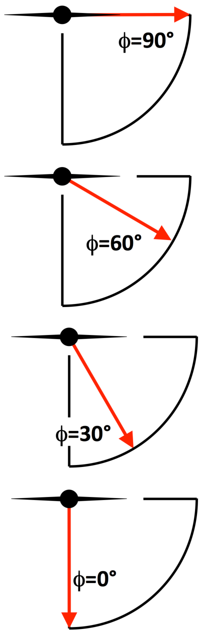
69° Delta Wing-Body CFD Results: M=1.7, α=0°

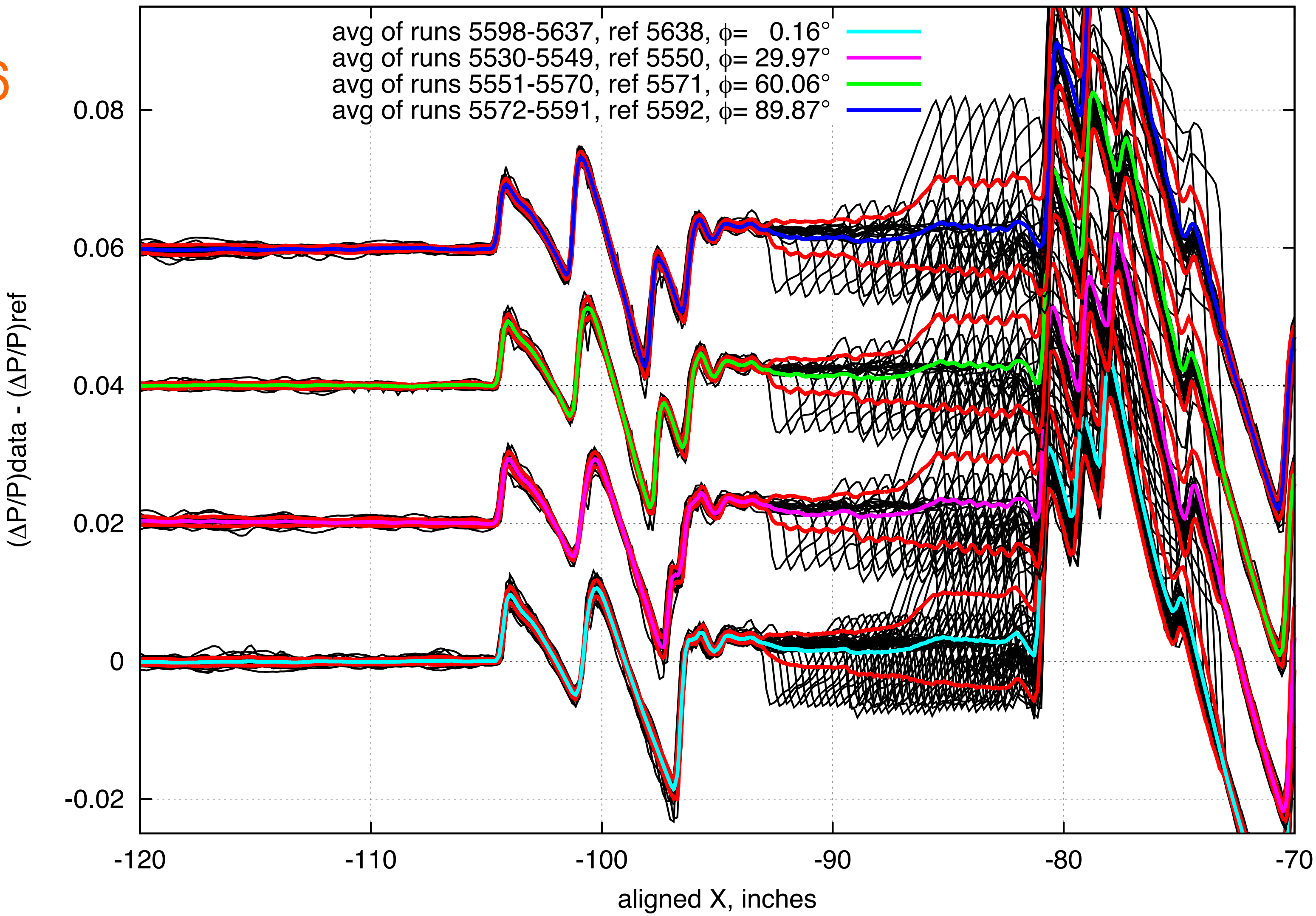


69° Delta Wing-Body Experimental Data

- On and Off-track
- Mach = 1.7, α = 0°, *h* [24.7 – 24.9] in, *Re* = 2.43x10^6

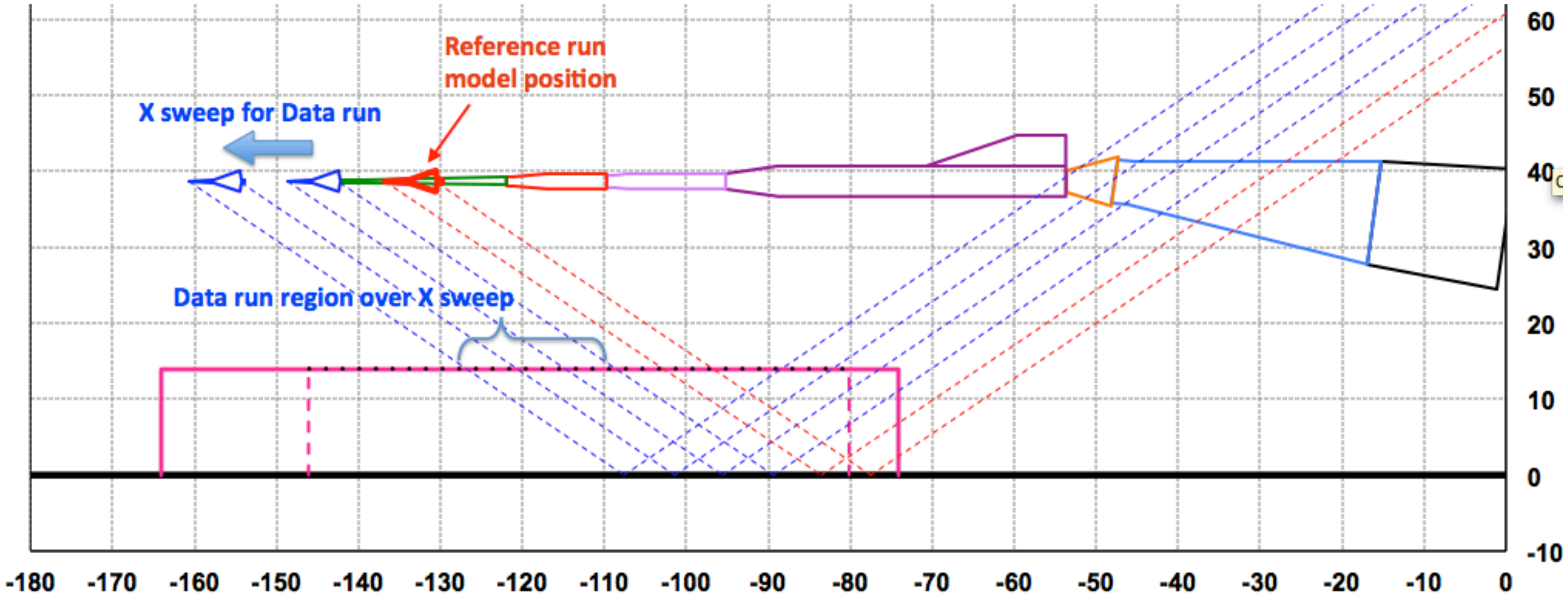
h/L = 3.6



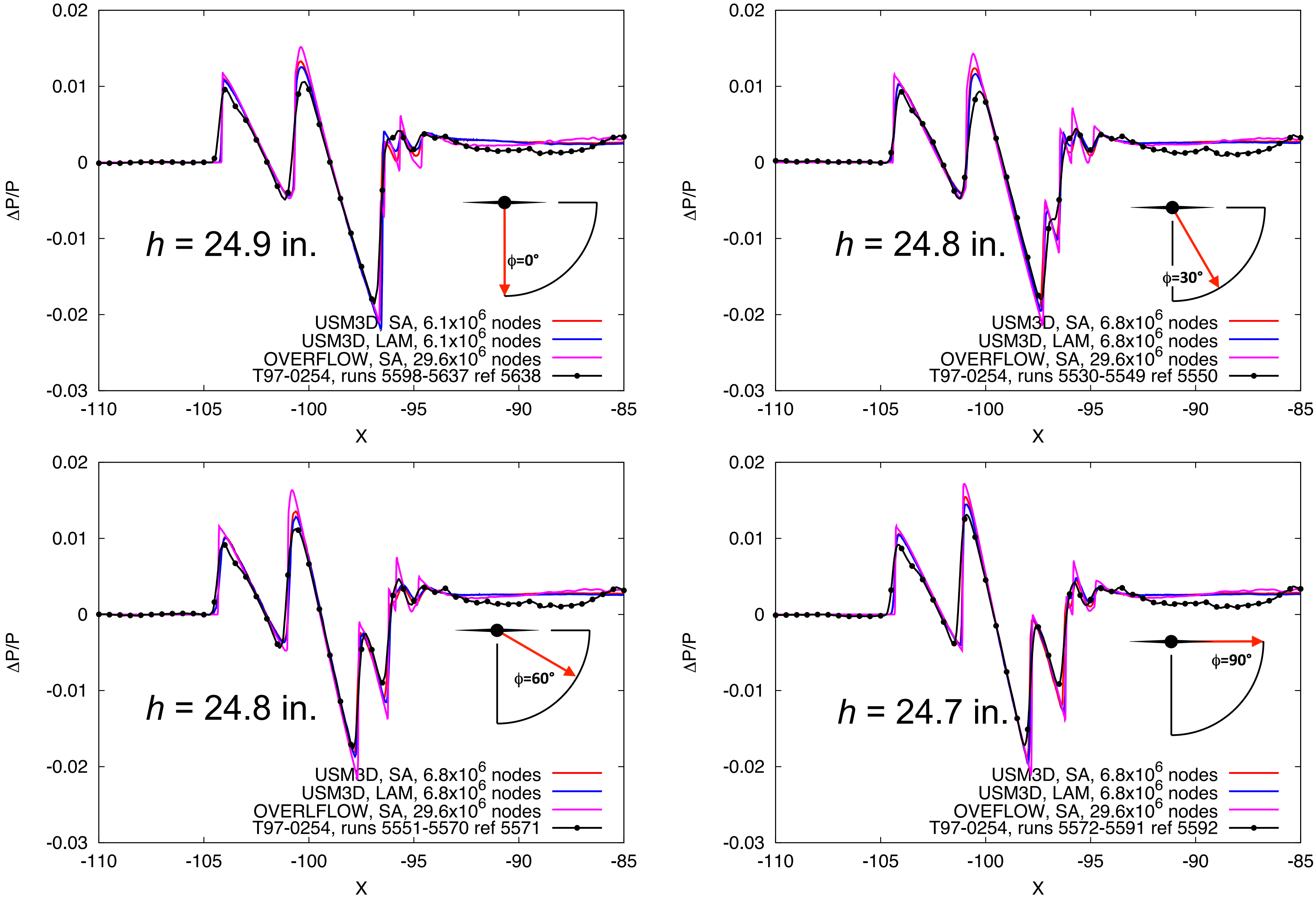


69° Delta Wing-Body Layout

- Inline reference runs
- Reference runs on RF1 rail
- Signature ranges were truncated to eliminate reference run contamination



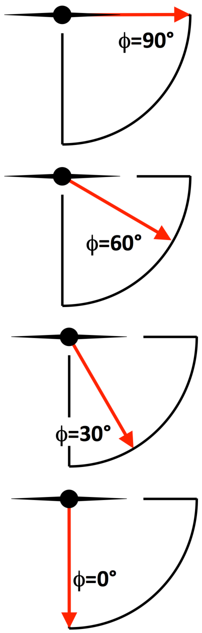
69° Delta Wing, CFD vs. Experiment: M=1.7 α=0°

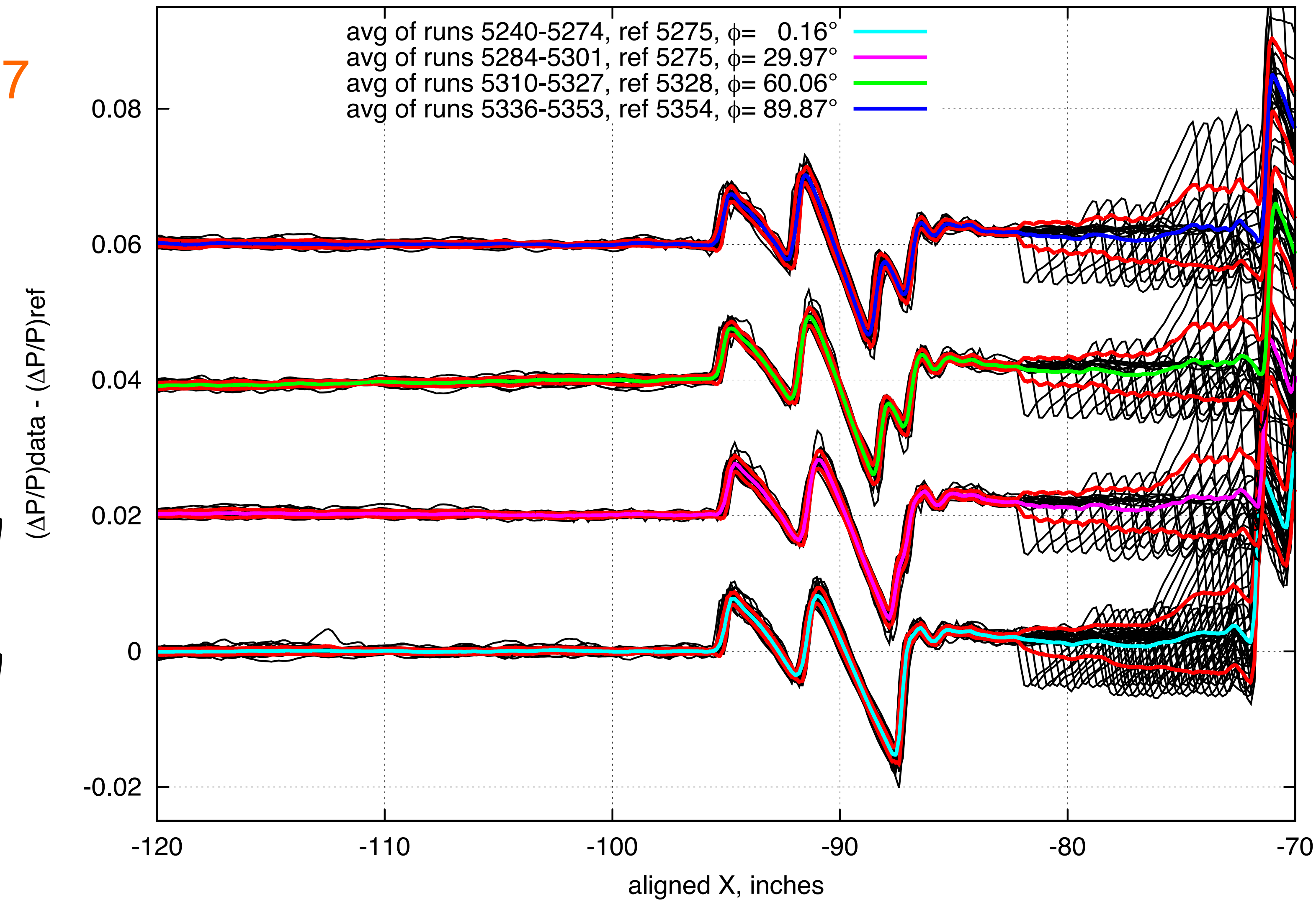


69° Delta Wing-Body Experimental Data

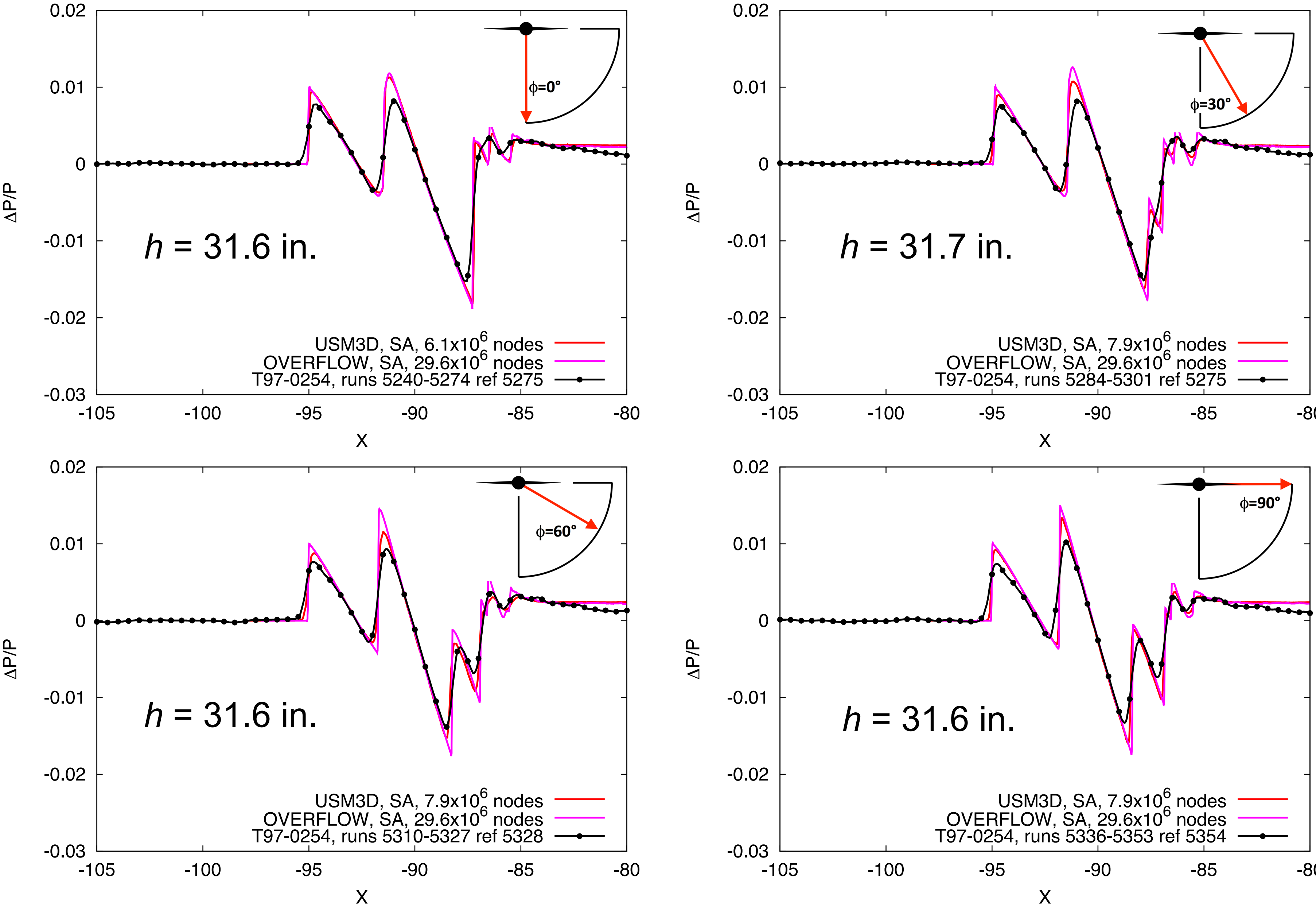
- On and Off-track
- Mach = 1.7, α = 0°, *h* [31.6 – 31.7] in, *Re* = 2.43x10[6]

h/L = 4.7

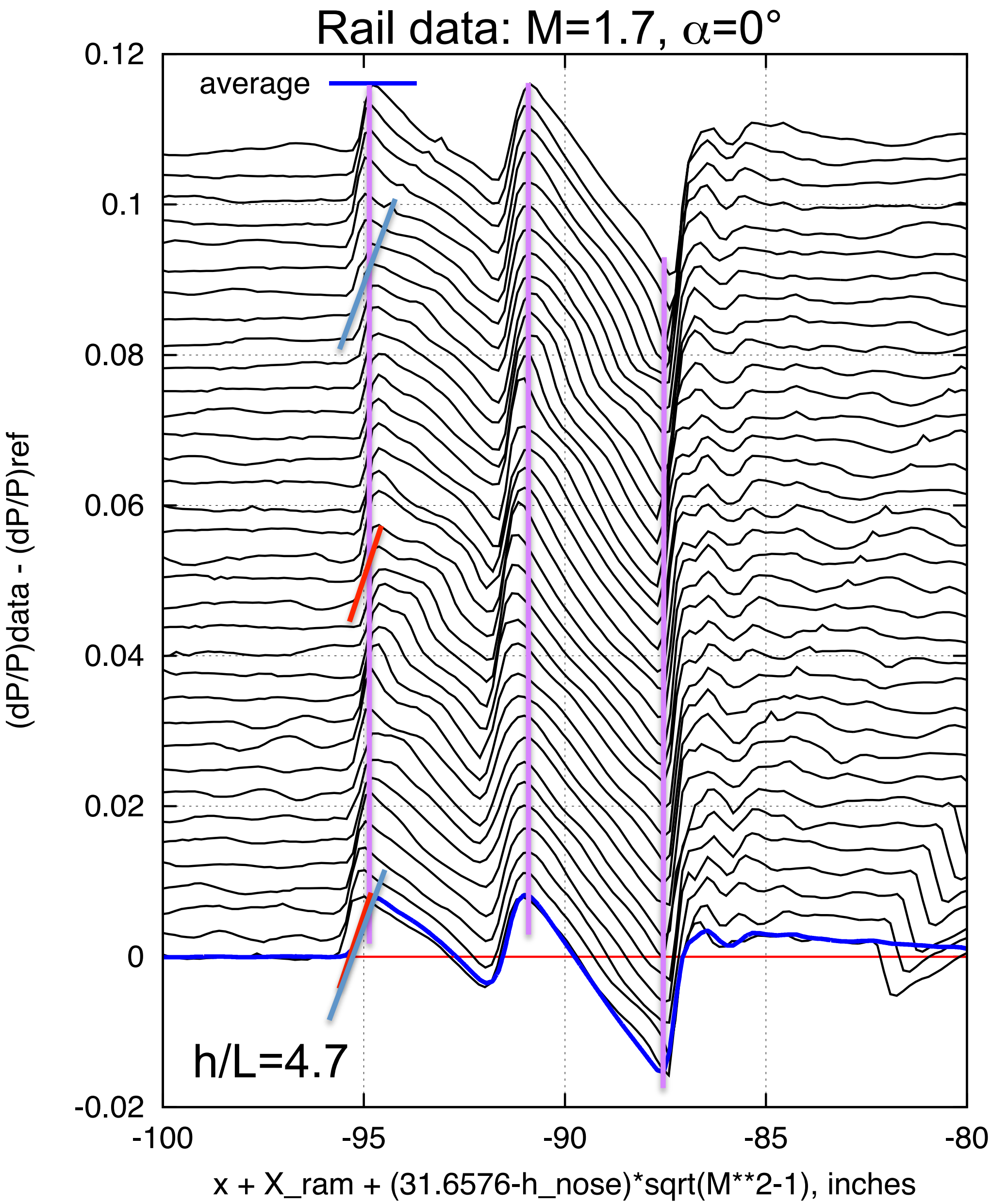




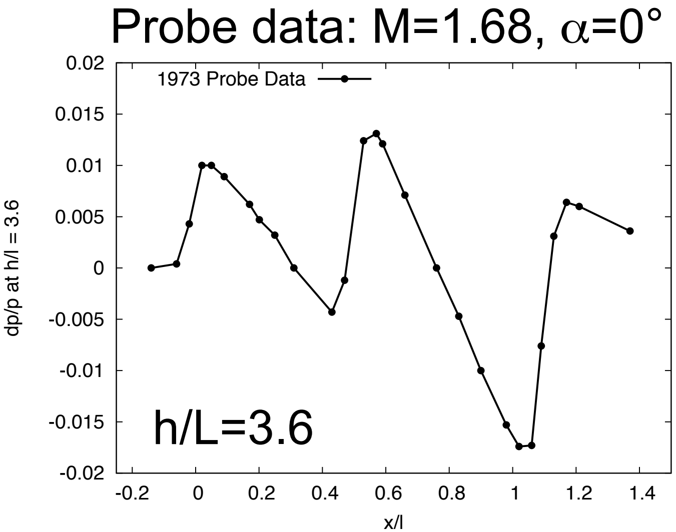
69° Delta Wing, CFD vs. Experiment: M=1.7 α=0°



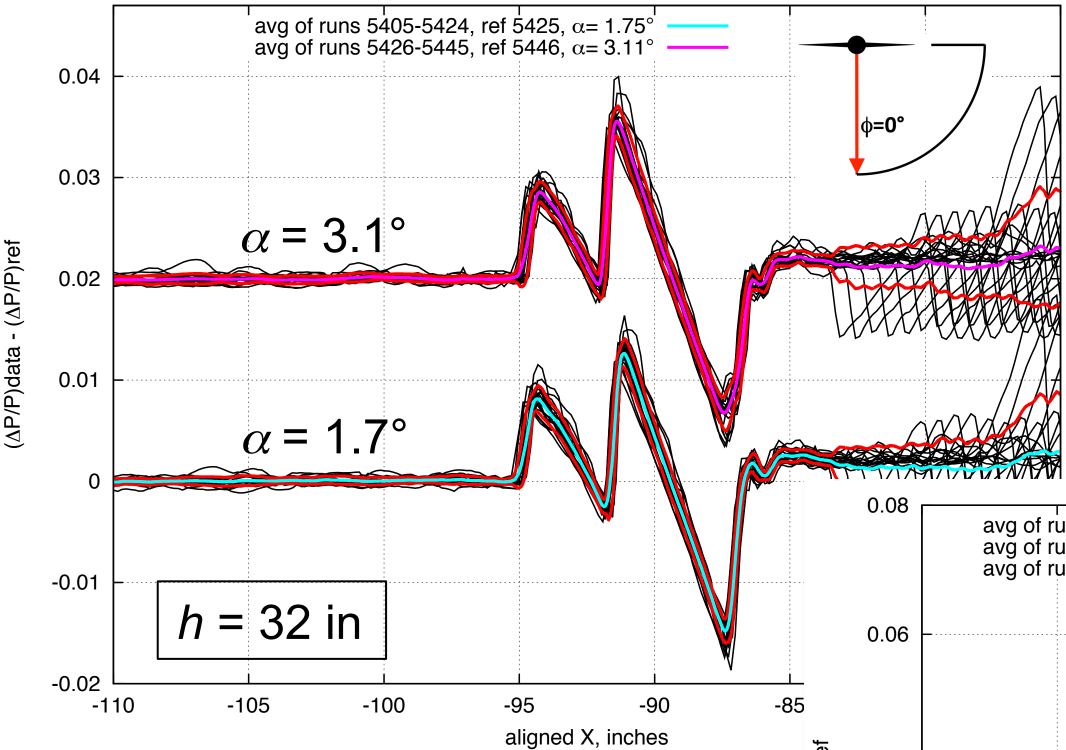
Waterfall of Rail Data & 1973 Probe Data

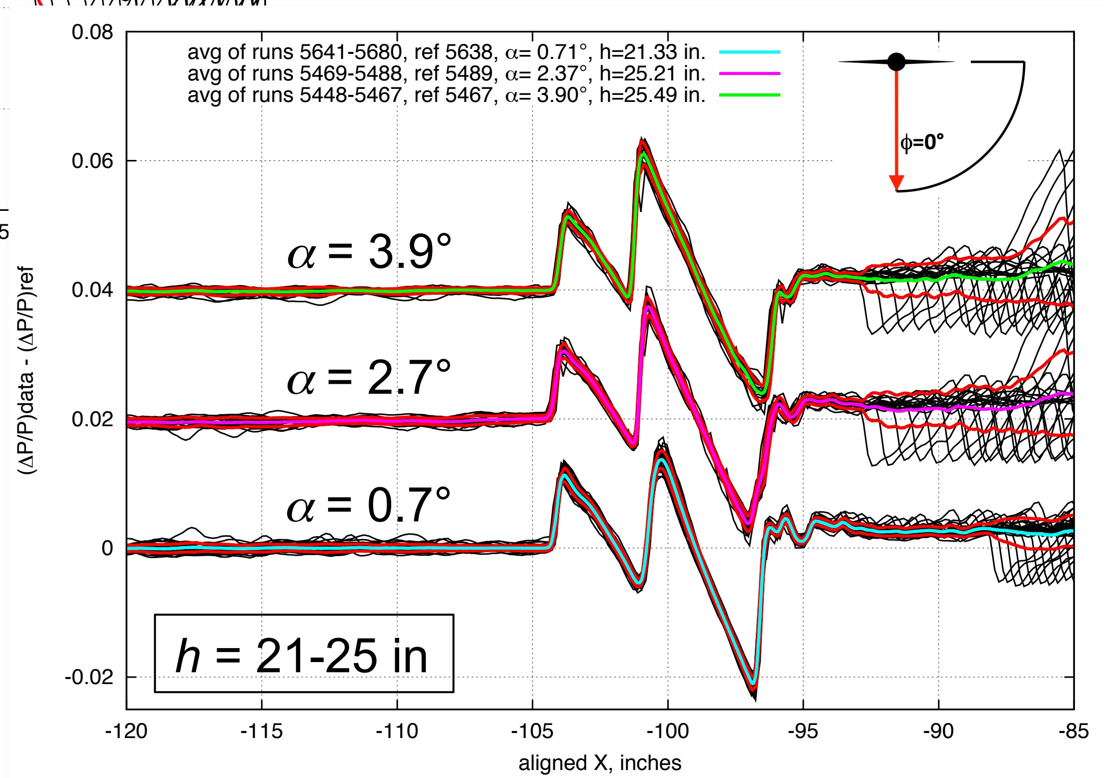


- Averaging not responsible for CFD/Exp rise time differences
- Rise time similar to probe data

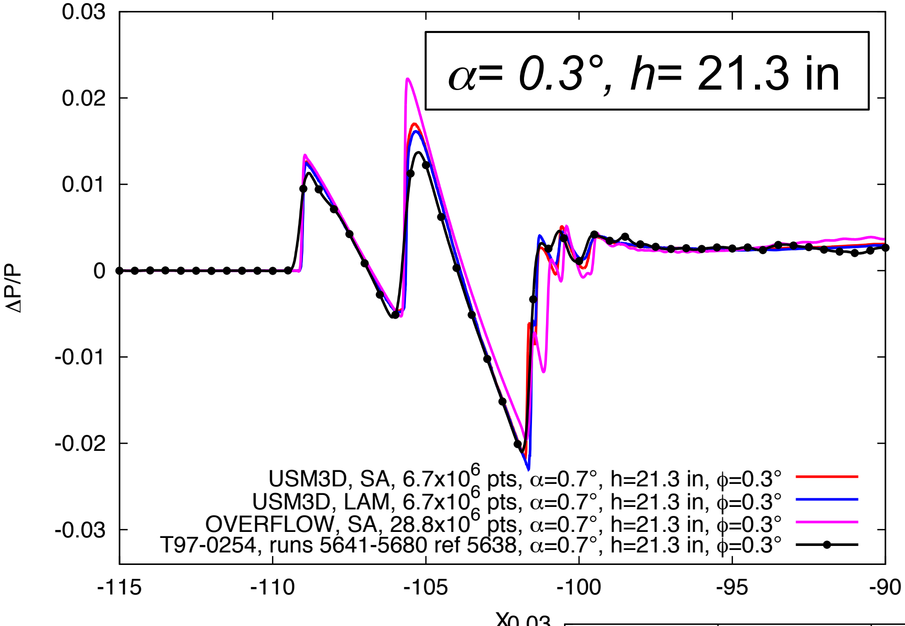


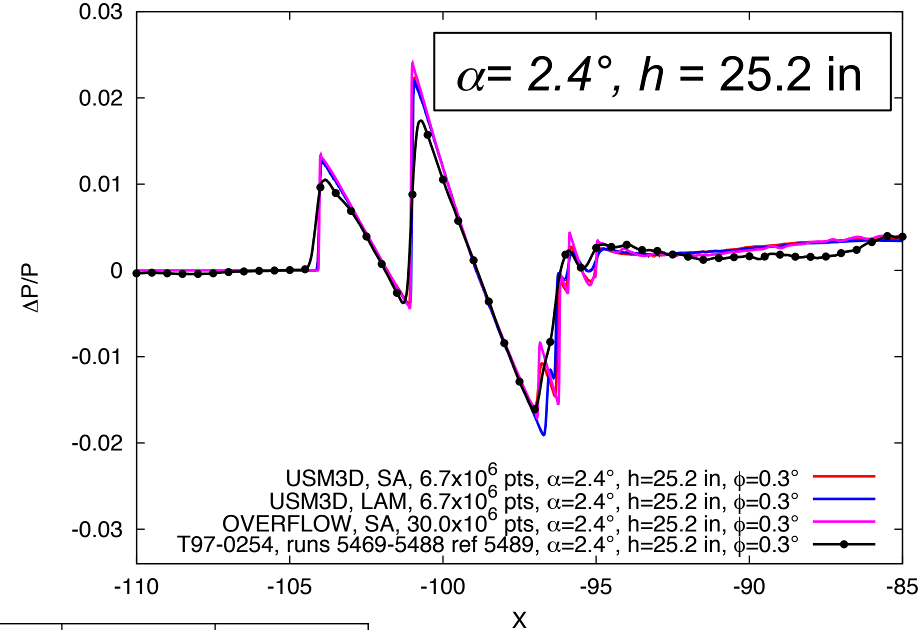
69° Delta Wing-Body Data at Lifting Conditions

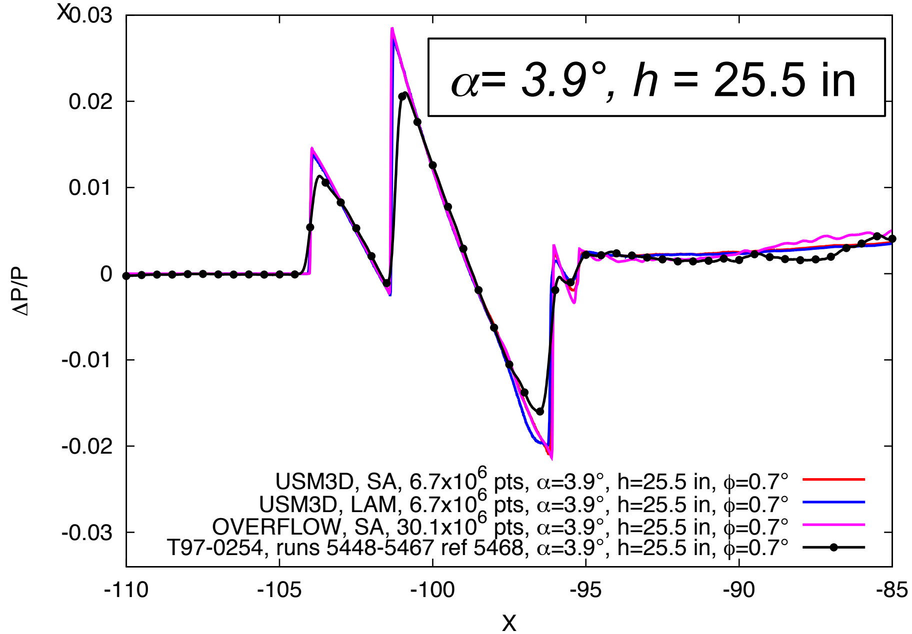




69° Delta Wing-Body Data at Lifting Conditions



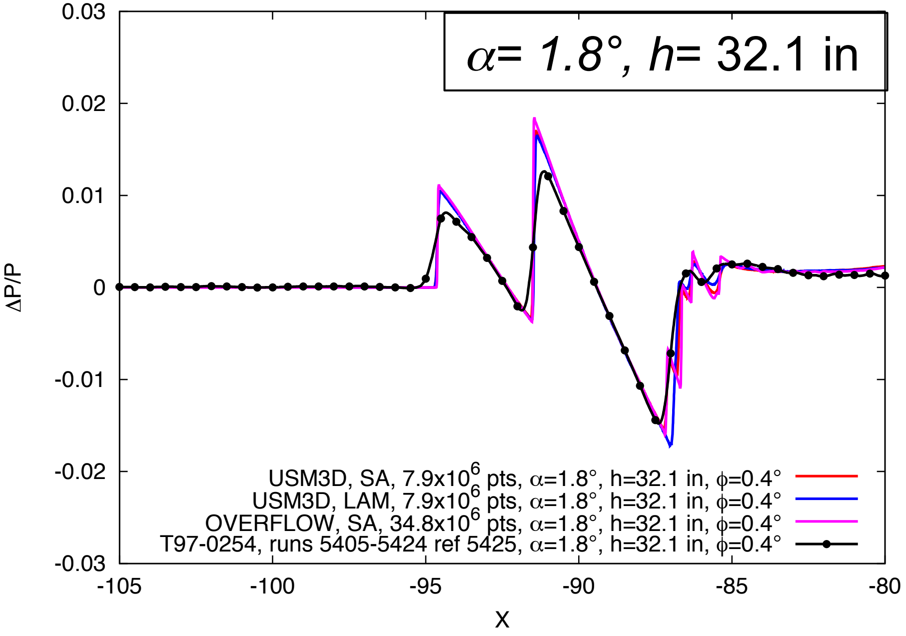


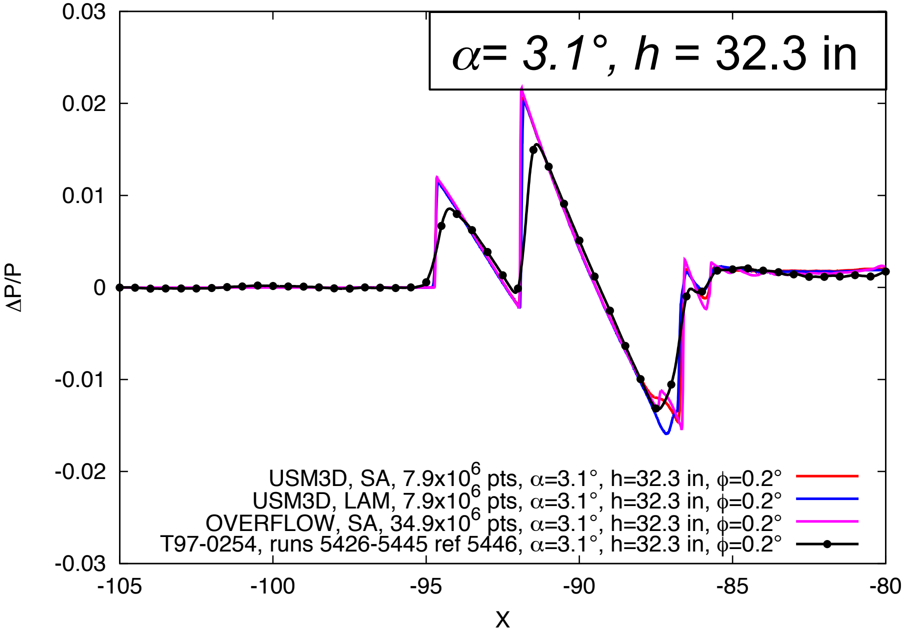


Greater differences in experimental shock strength at larger α

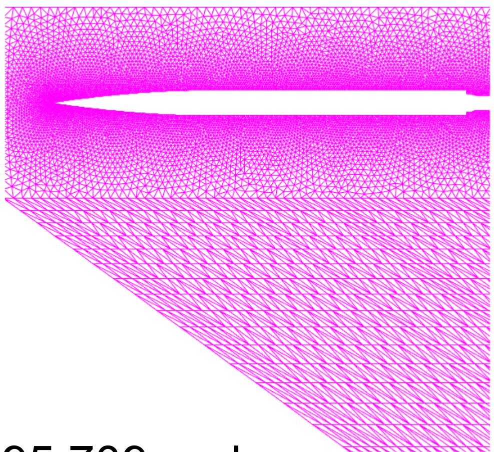
CFD shock strengths are nearly equivalent

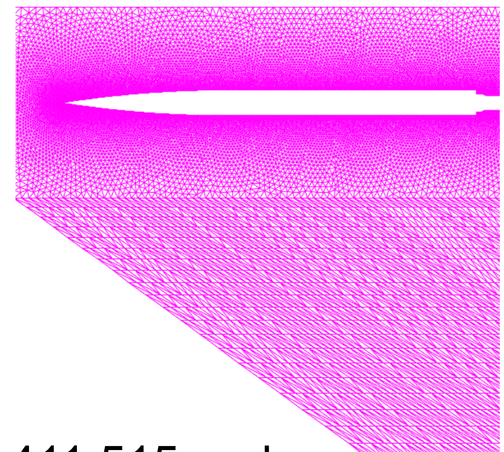
69° Delta Wing-Body Data at Lifting Conditions

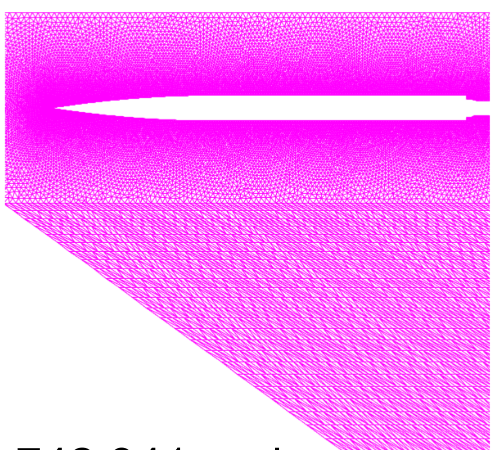


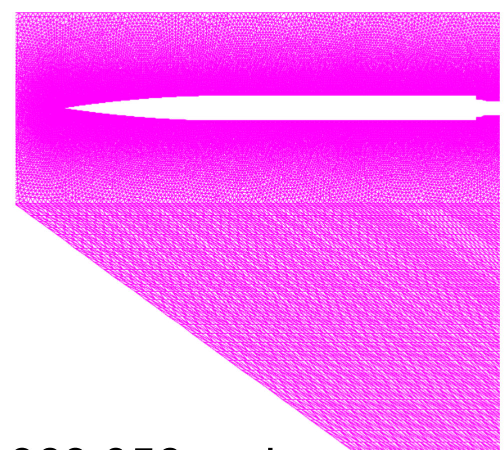


Euler Grid Refinement on Delta Wing-Body

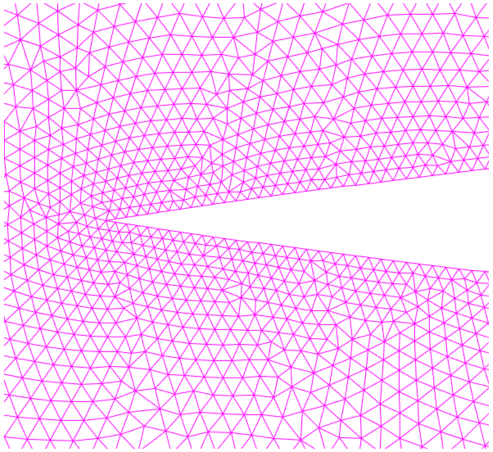

695,709 nodes


1,411,515 nodes

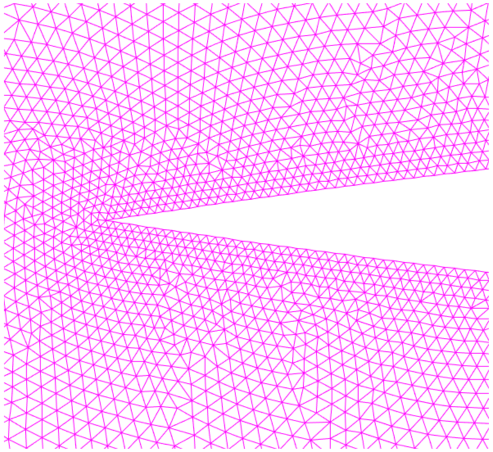

2,742,341 nodes


5,363,056 nodes

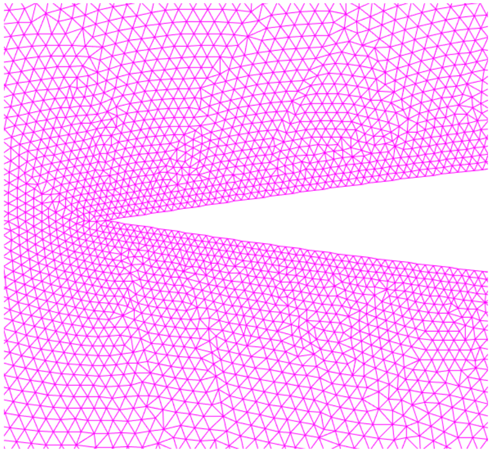
Euler Grid Refinement on Delta Wing-Body Nose



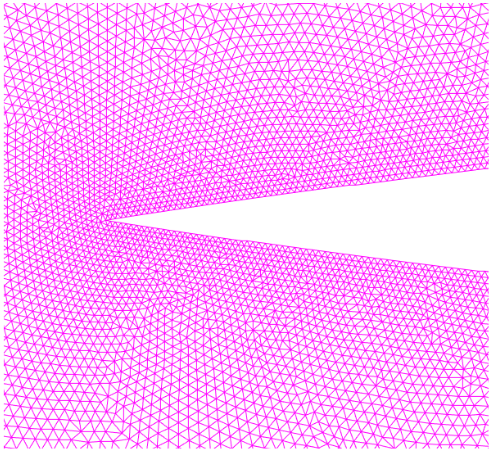
695,709 nodes



1,411,515 nodes

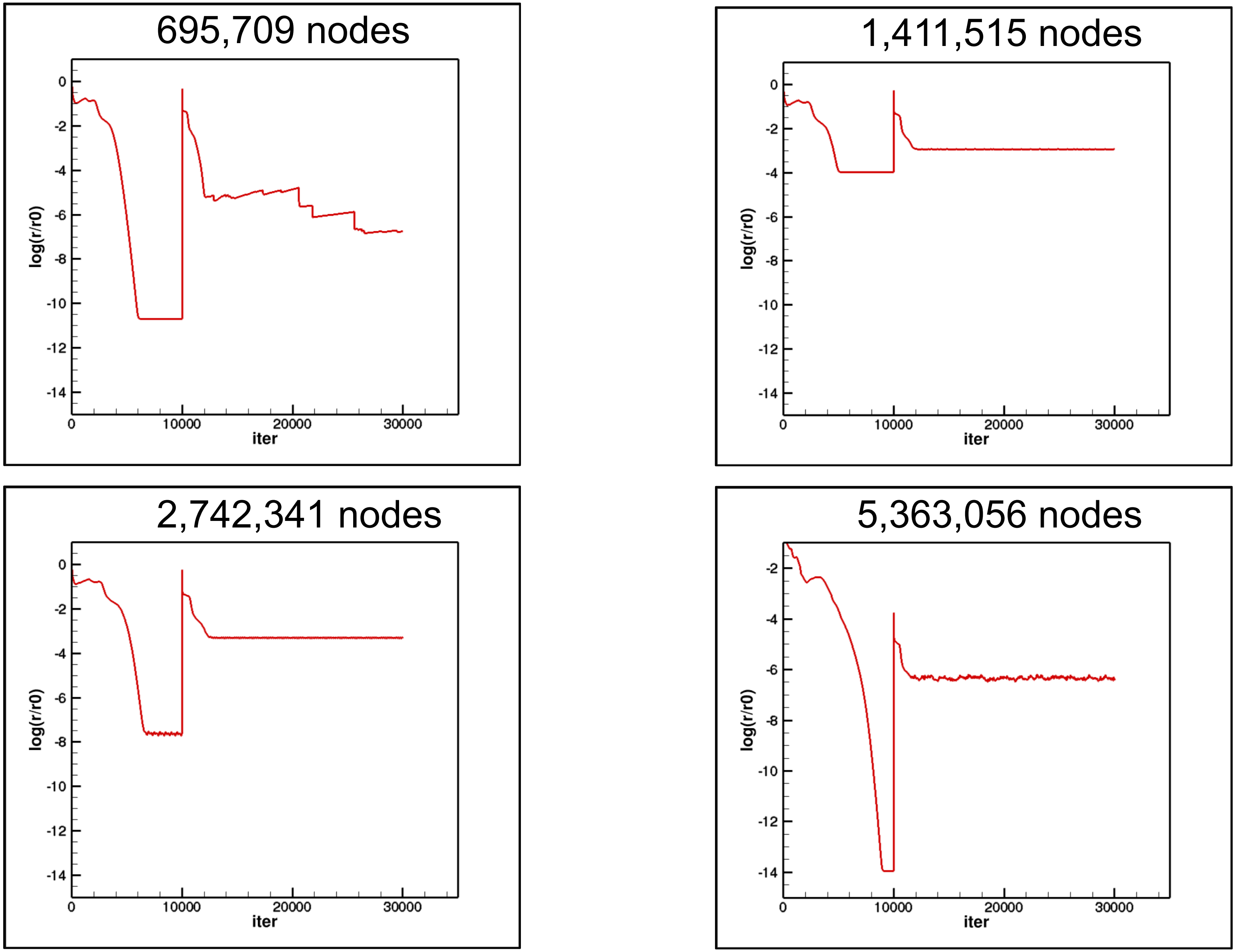


2,742,341 nodes

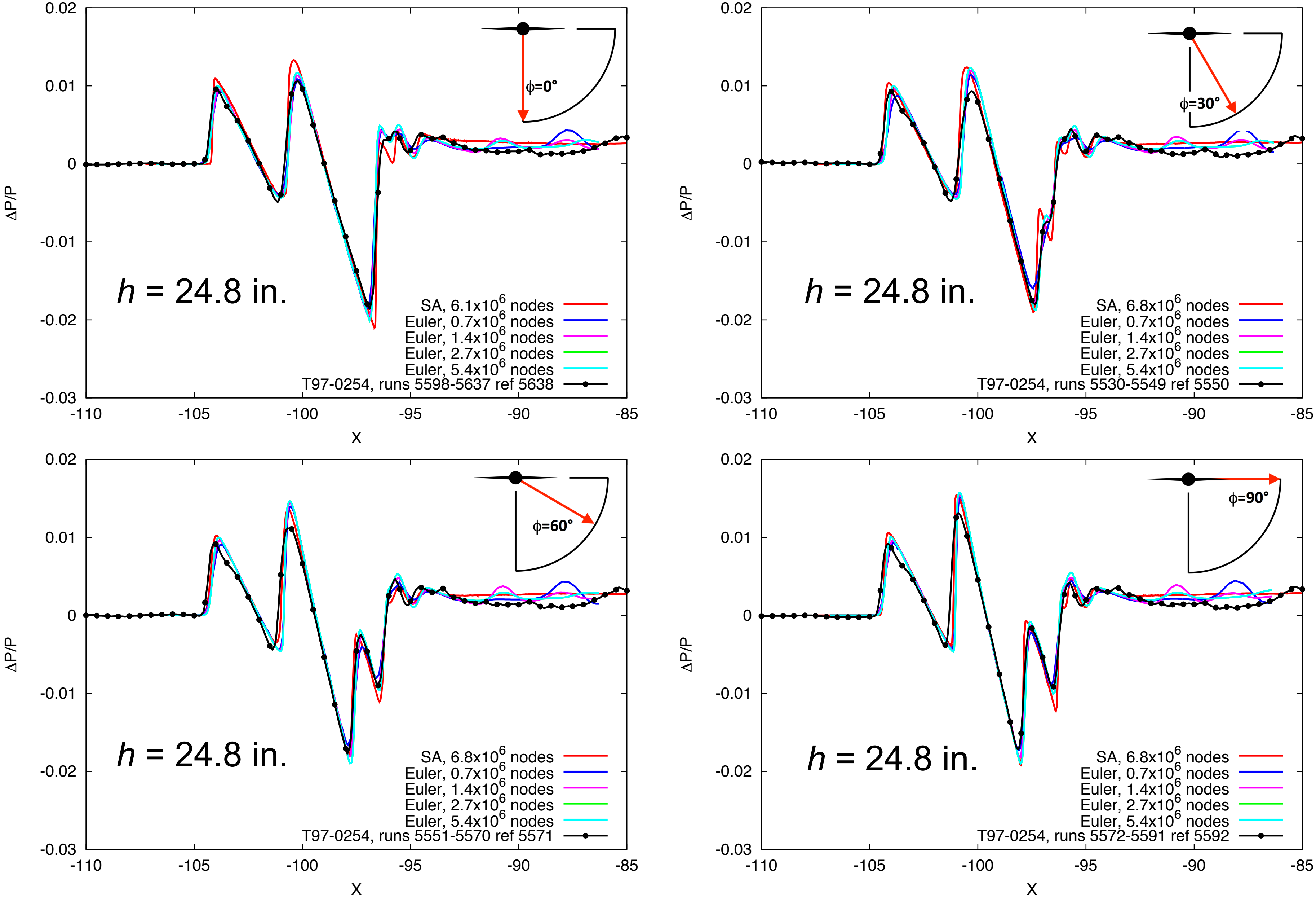


5,363,056 nodes

Euler Grid Convergence on Delta Wing-Body

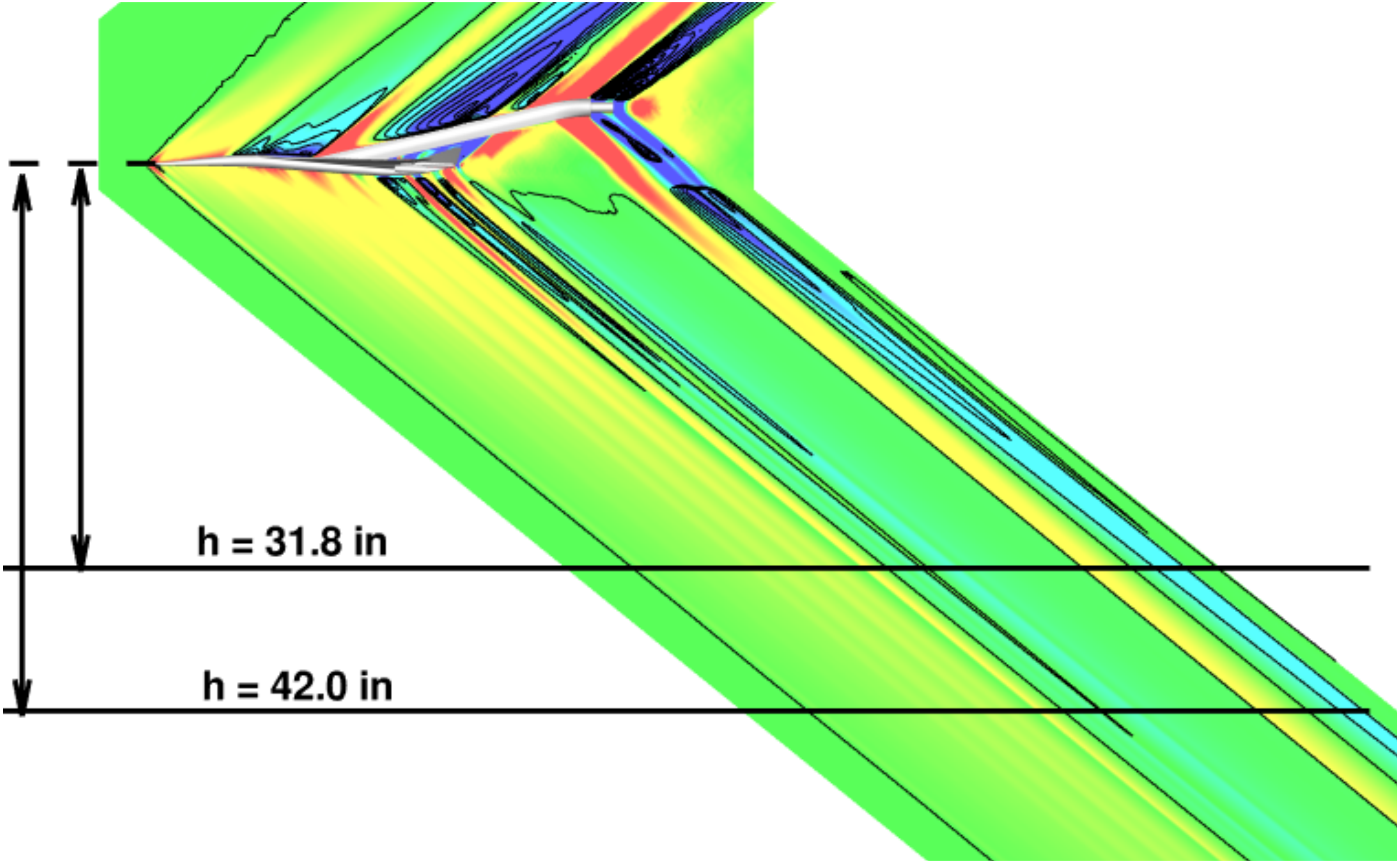


Euler /NS /Exp. USM3D Comparisons: M=1.7 α=0°



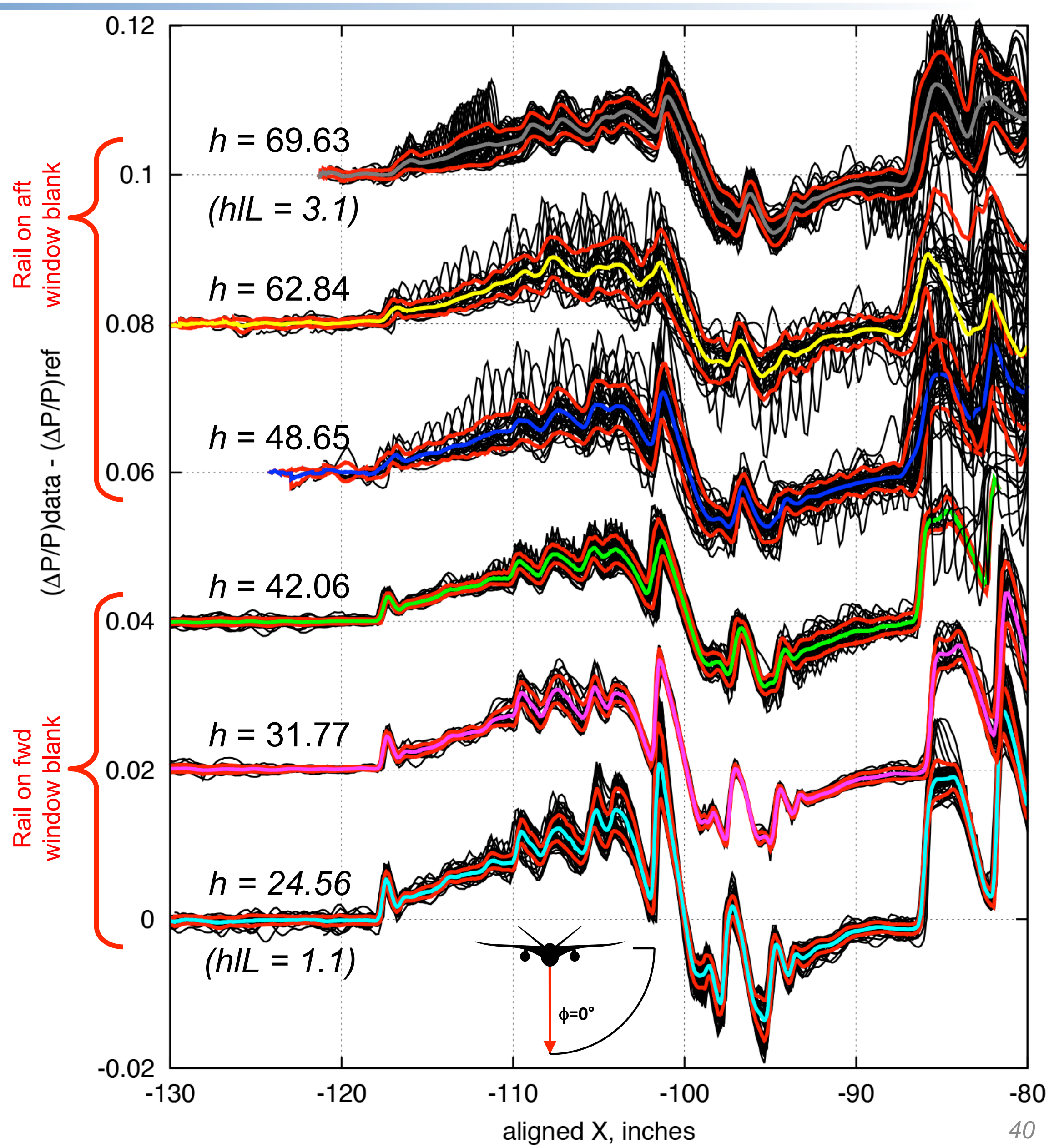
LM 1021 Mach Line Contours on C_P

- Mach = 1.6, α = 2.1°, Re = 8.10x10^6
- USM3D turbulent solution

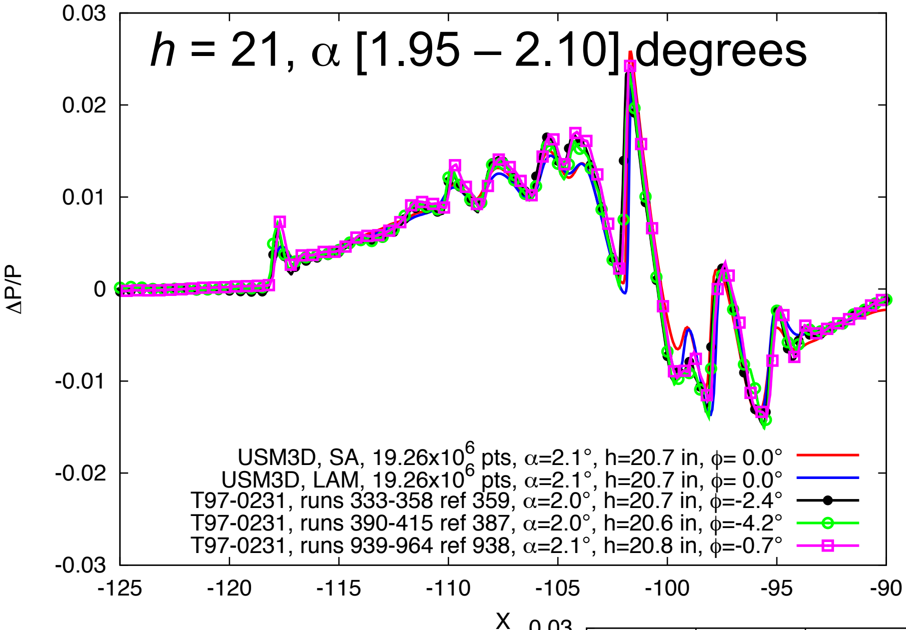


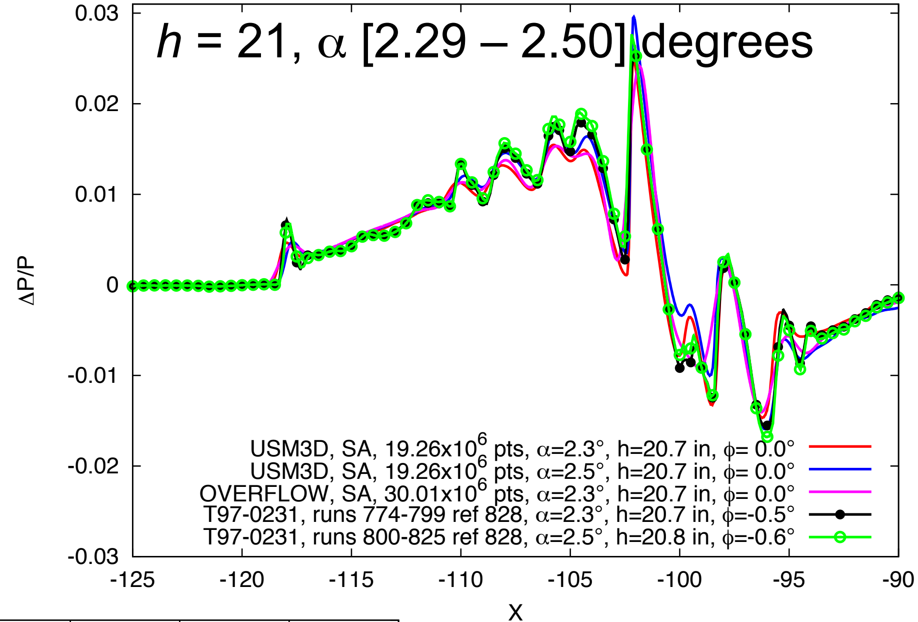
1021 Experimental Data, Height Variation Effect

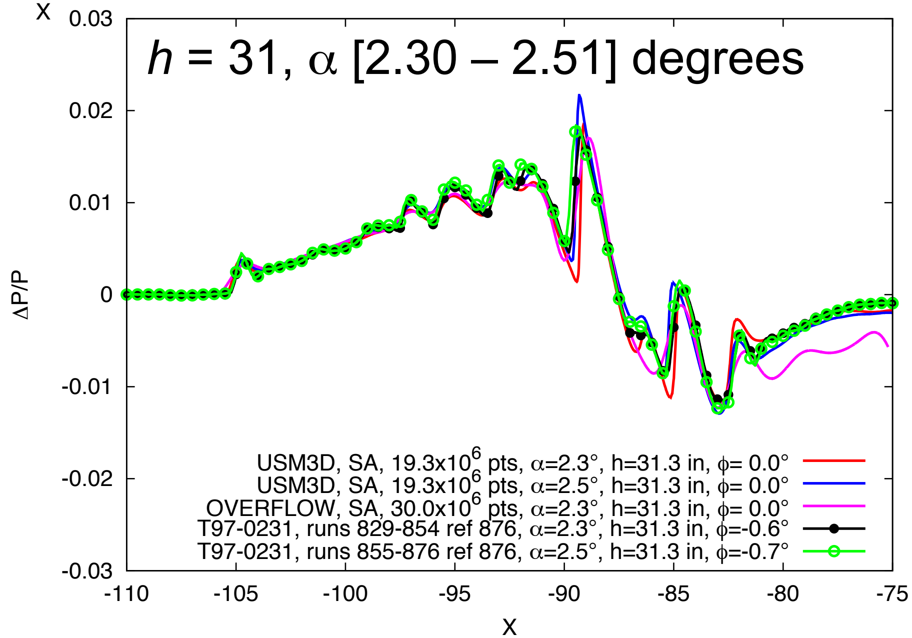
- Mach=1.6, α [1.84°: 2.18°]
- Shock peaks and overall pressure levels reduce with height above rail
- General increase in individual signature variation with height
- Significantly more variation in individual signatures with rail on aft window blank
  - Greater height, more distance for shock to travel
  - Flow field in aft part of test section may result in more distortions



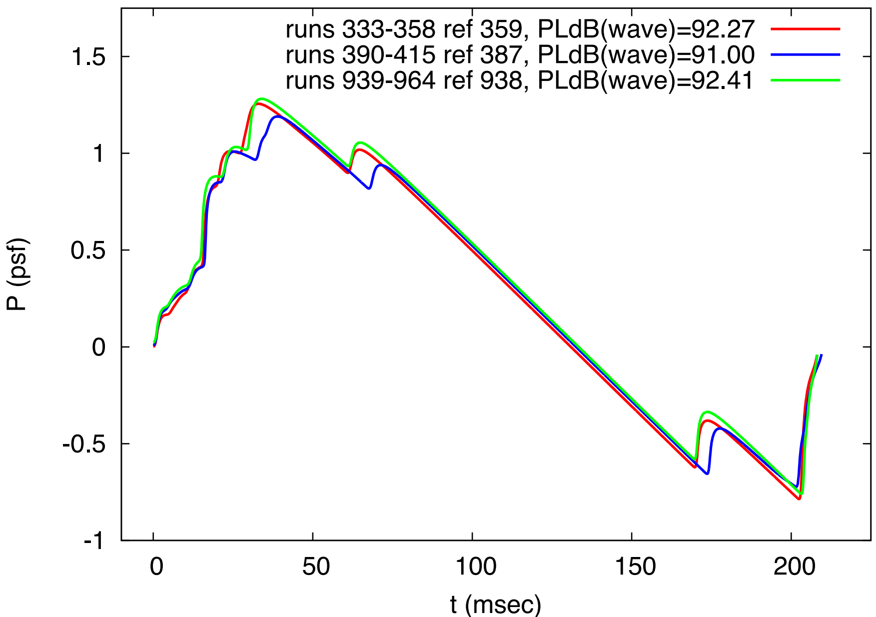
On-Track Signatures for 1021 Model, M=1.6

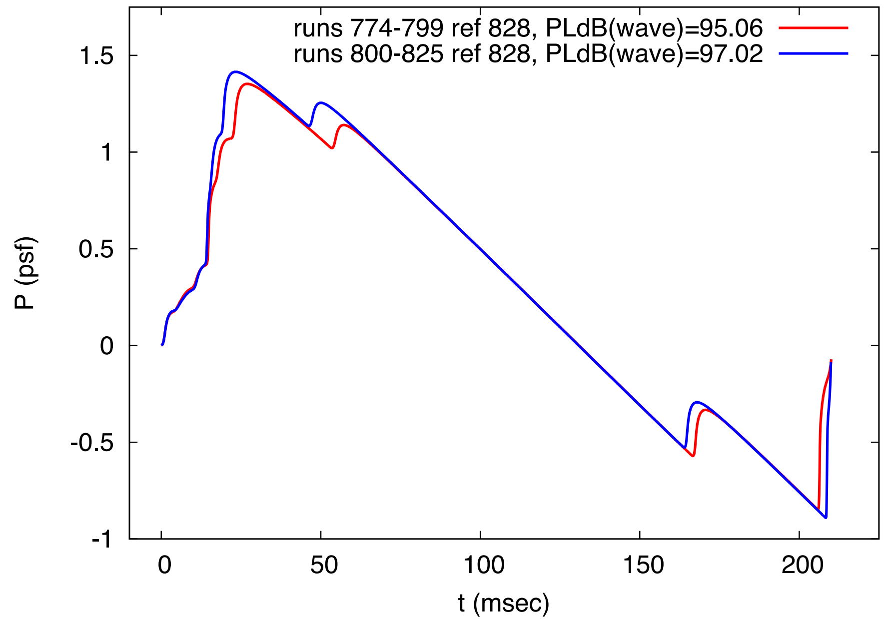






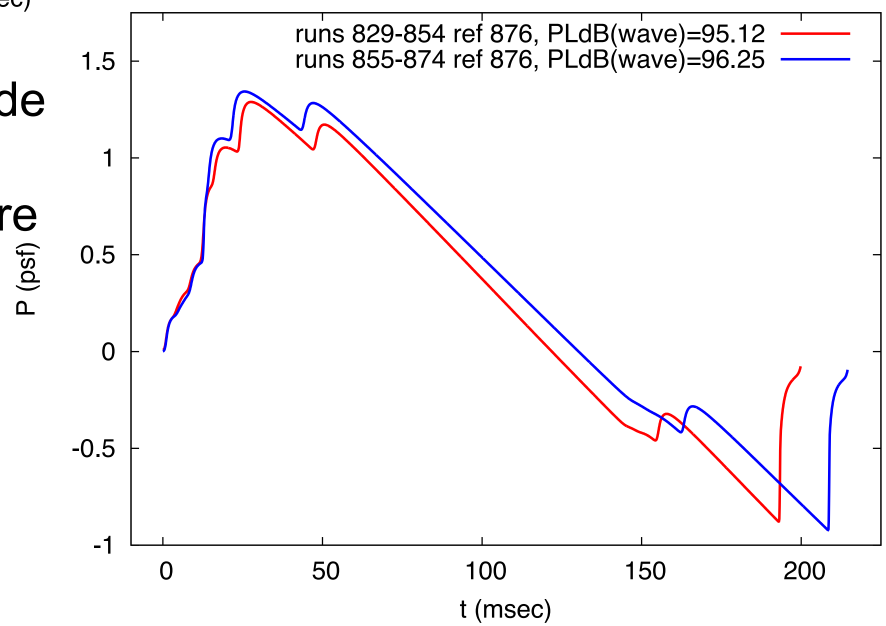
Extrapolated Experimental Data via SBOOM





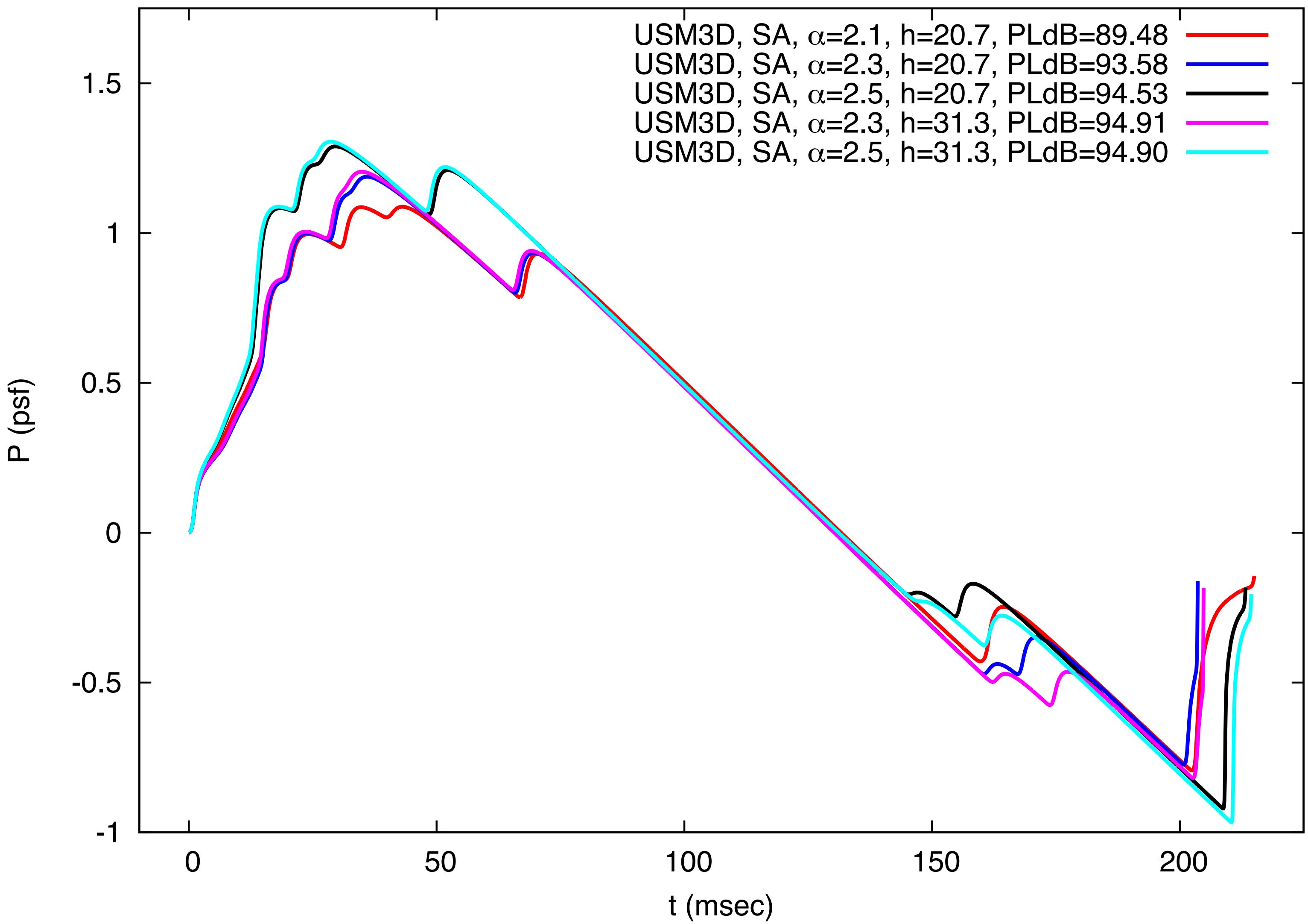
<u>SBOOM Inputs</u>

- 50,000 ft flight altitude
- 230 ft aircraft length
- Standard atmosphere
- No Winds
- 1.9 Ground RF



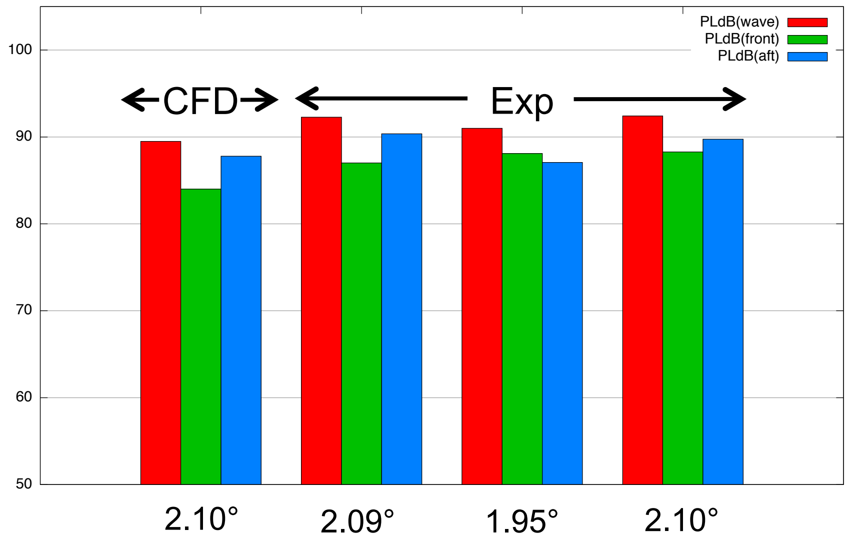
Extrapolated USM3D to Ground via SBOOM

- Near field USM3D taken from 20.7 and 31.3 inches
- Mach 1.6, α =2.1°,2.3°, 2.5°

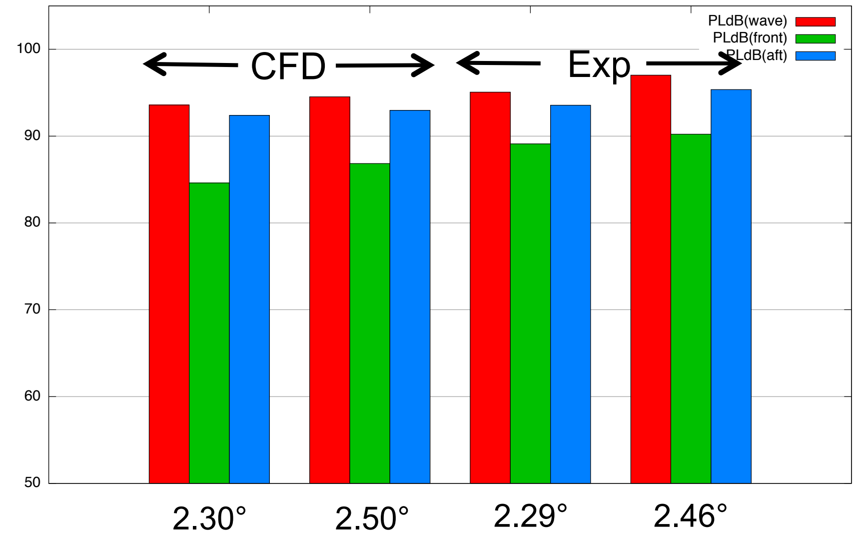


Loudness Level Predictions: USM3D & Experiment

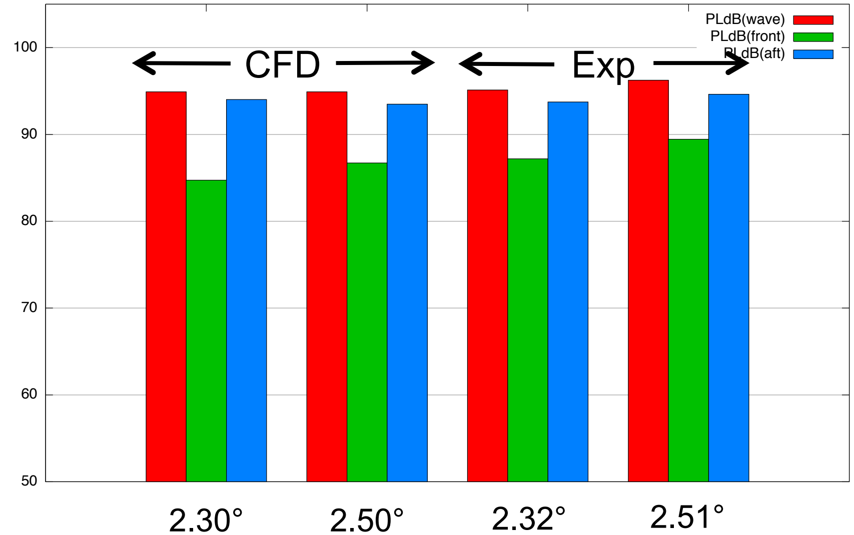
h = 21, α [1.95 – 2.10] degrees



h = 21, α [2.29 – 2.50] degrees

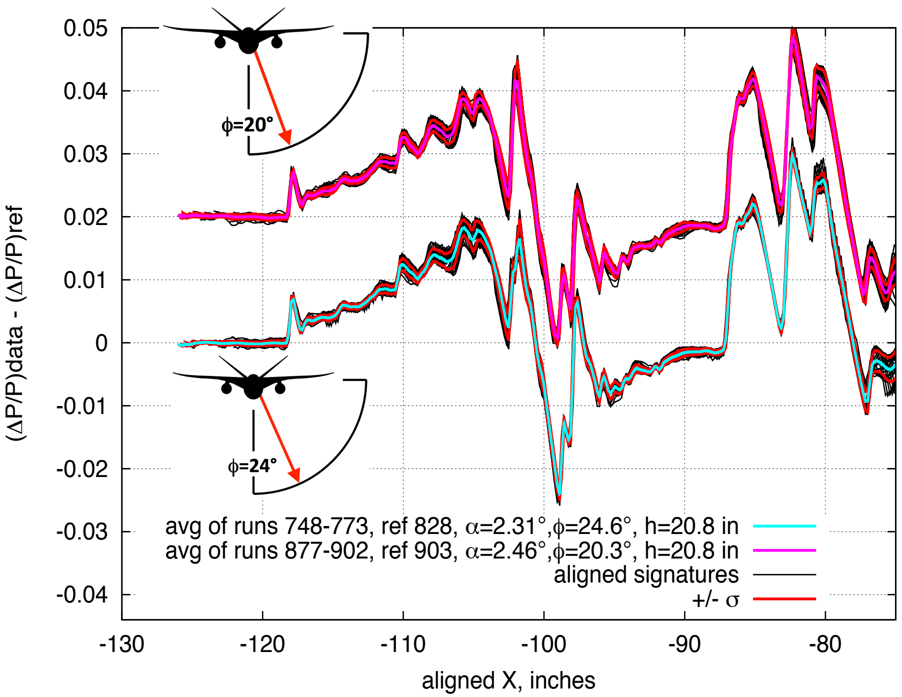


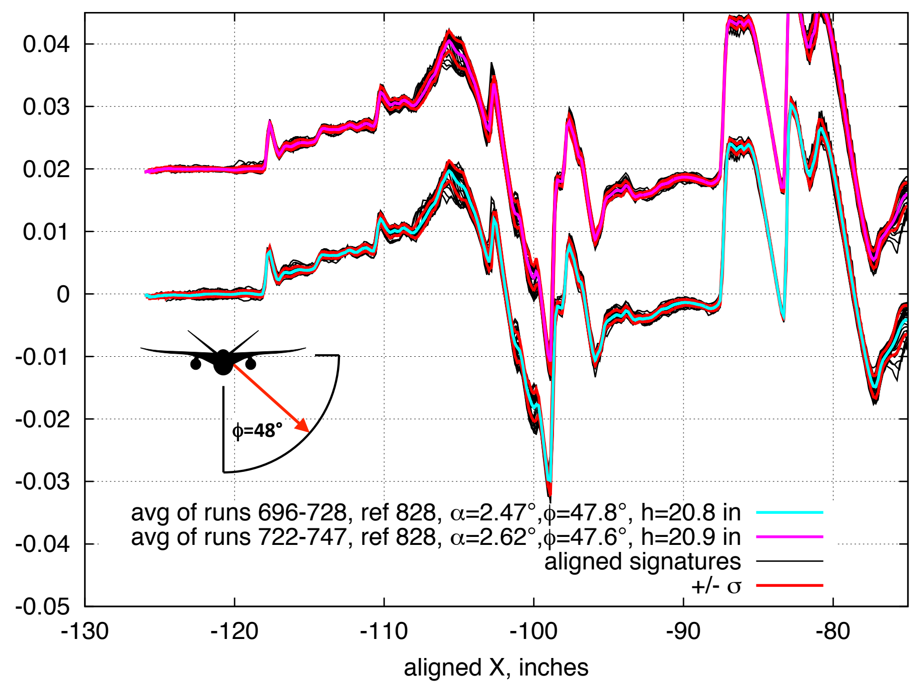
h = 31, α [2.30 – 2.51] degrees



Off-Track Signatures for 1021 Model

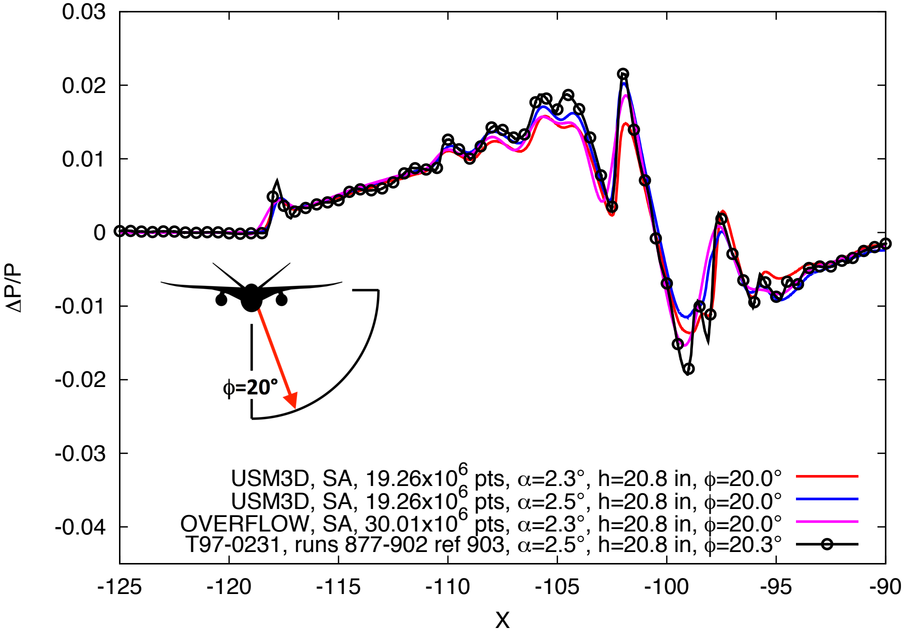
- Individual signatures show little variation, so averages are of good quality
- Very little differences due to small α changes
- off-track signatures show different characteristic shapes because of the different angle from the model

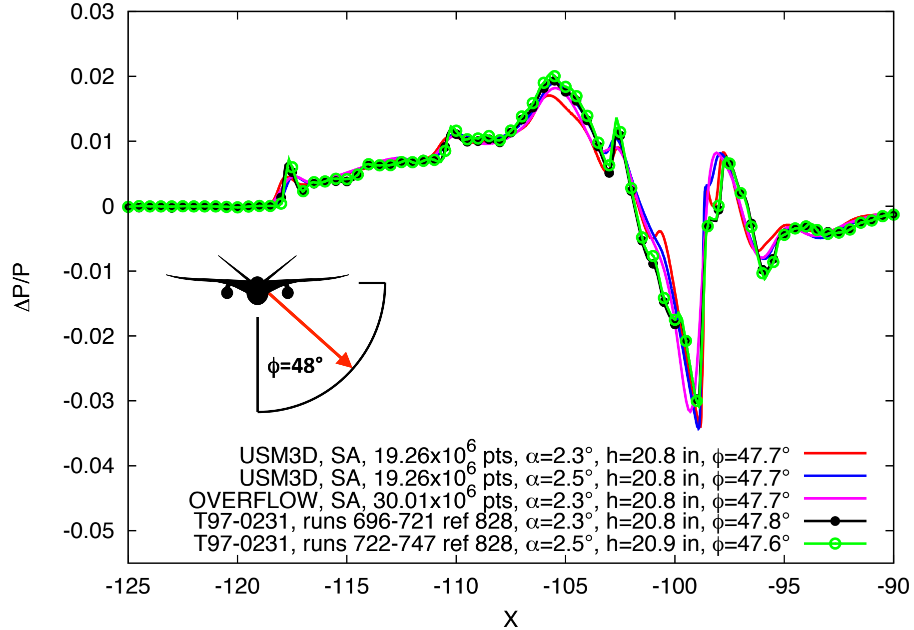




Off-Track, 1021, CFD vs. Exp: M=1.6 α=2.3°, 2.5°

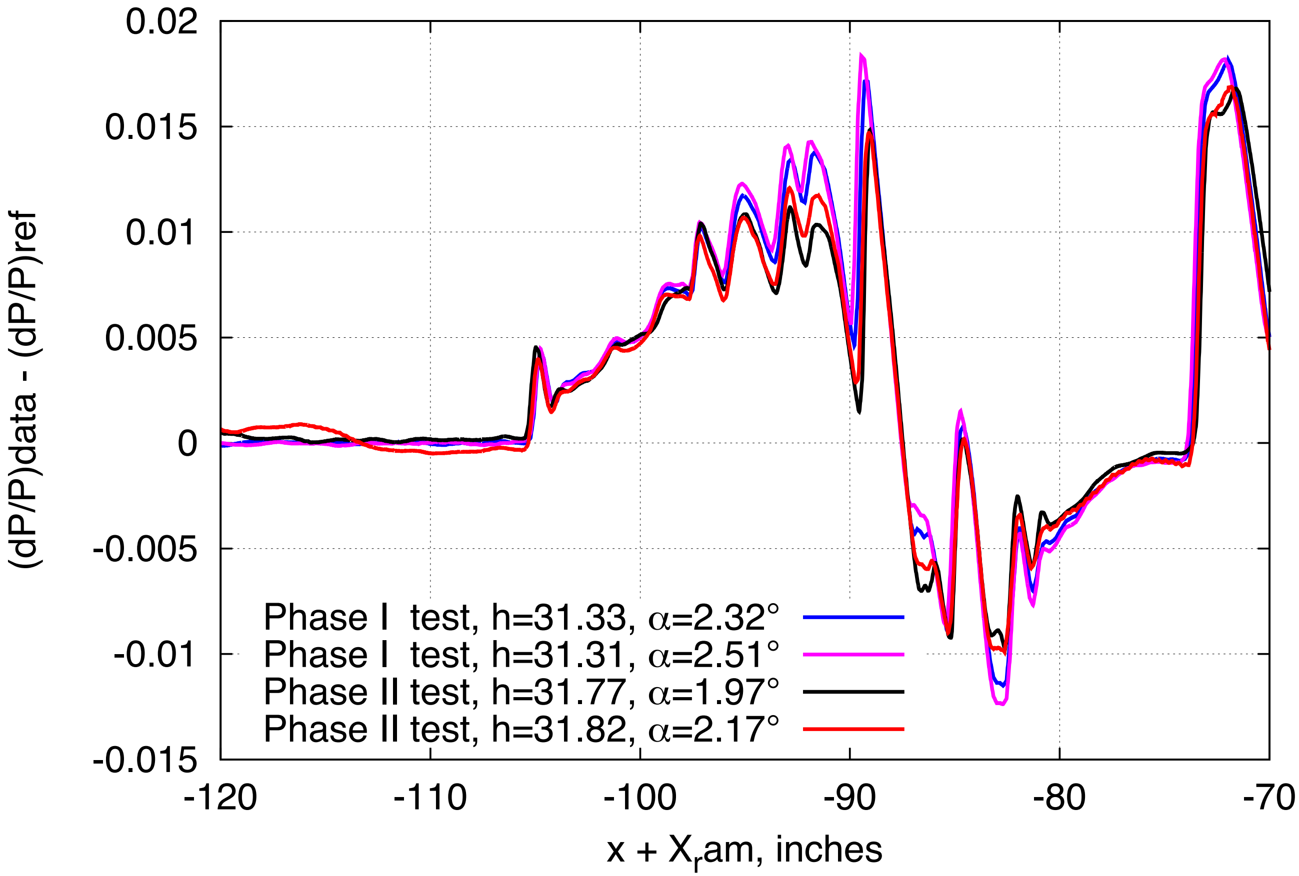
- Experiment average α =2.5°, *Re* = 8.10x10^6
- USM3D shown at α=2.3° and 2.5°
- Excellent comparisons, but CFD has more rounded shocks than experiment



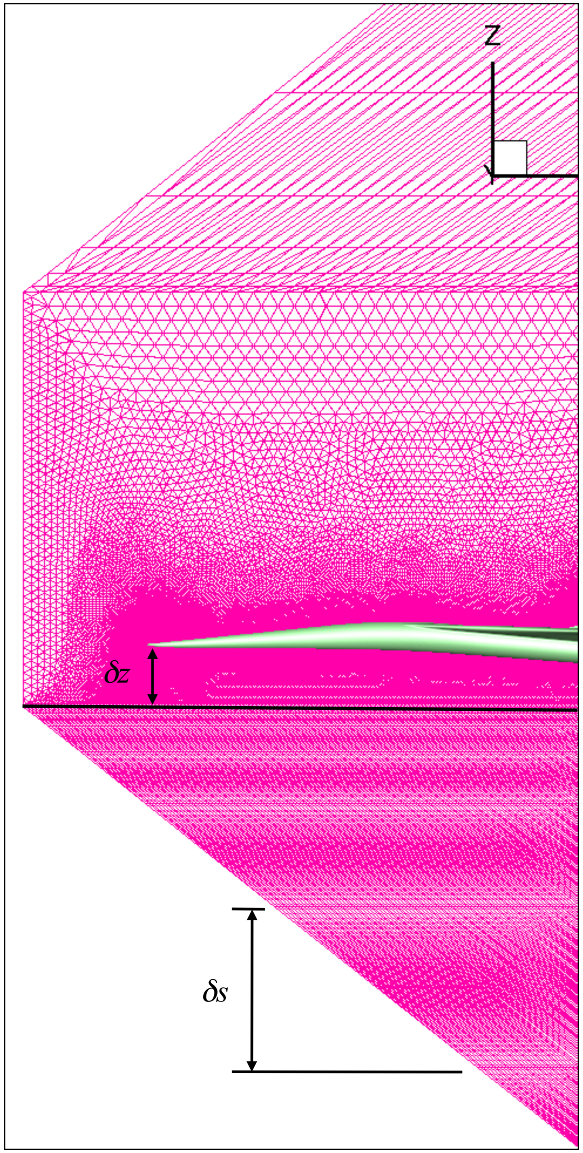


Long-term repeatability 1021 model, M=1.6

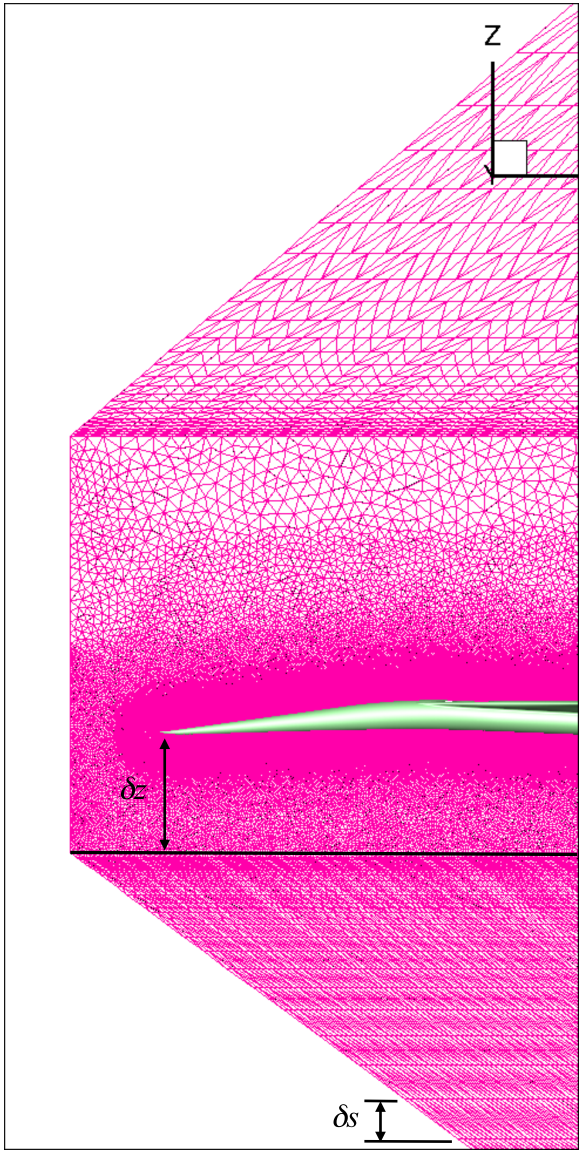
- Experimental data at difference angles of attack
- Differences are attributed to the angle-of-attack differences
  - Wing overpressures consistent with alpha changes



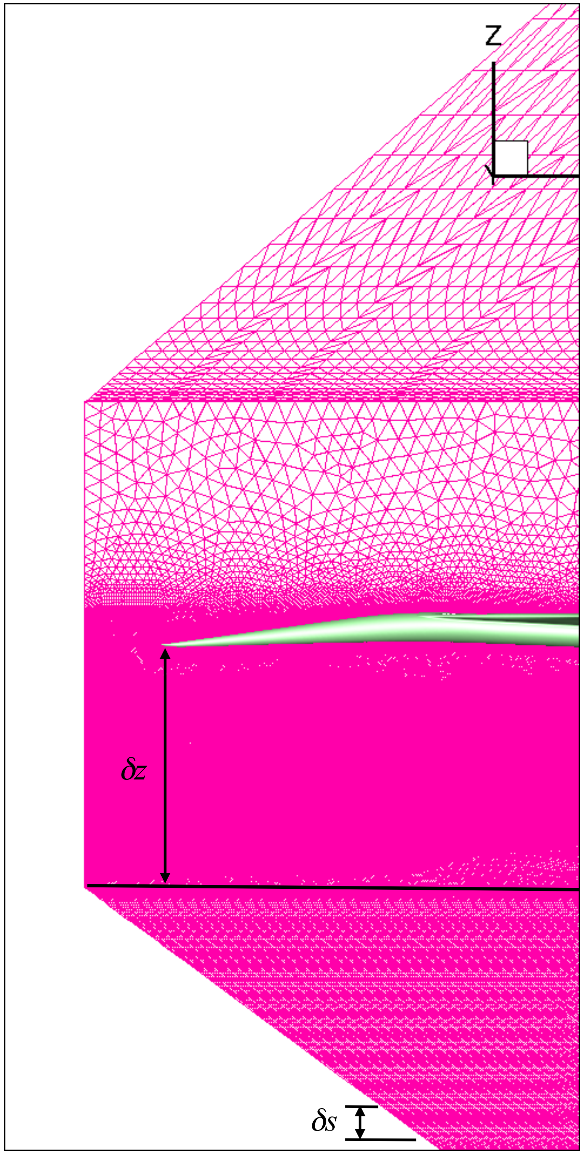
LM 1021 Model Meshes



AFLR3 and BG

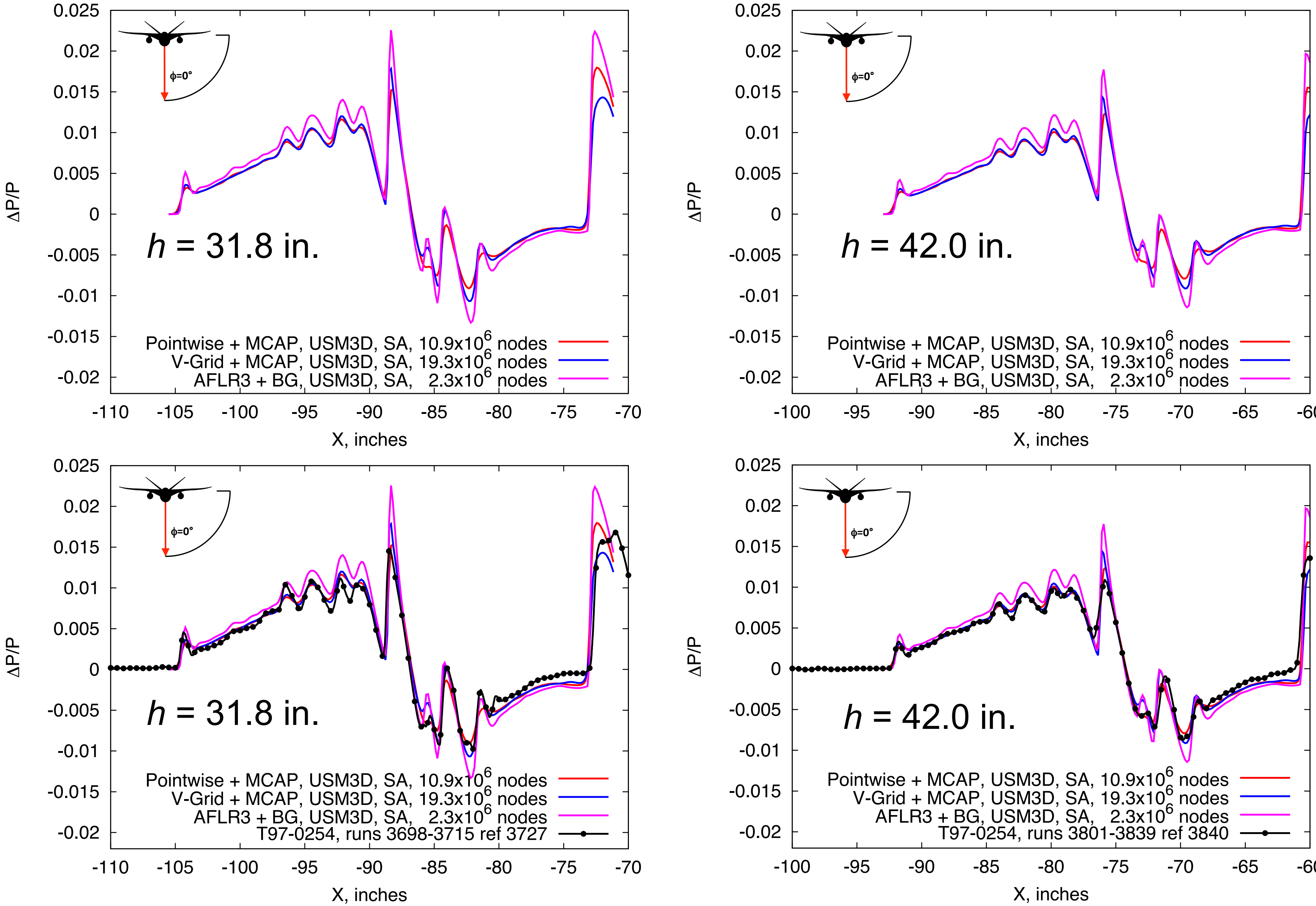


Pointwise and MCAP



V-Grid and MCAP

Mesh Effects for 1021 Model M=1.6, α=2.1°, *Re*=8.10x10⁶



Summary

- Experimental pressure signatures for three Workshop geometries were provided
- USM3D and OVERFLOW comparisons with experiment were provided for all data (on and off-track)
- Numerical simulations are in good agreement with wind tunnel data
- Limitations of experimental testing discussed
- ***Mach cone alignment and stretching along Mach rays are important for accurate sonic boom computations for unstructured or structured overset methods***
- Meshing best practices are emerging from the 1st AIAA Sonic Boom Prediction Workshop

Acknowledgments

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Questions?