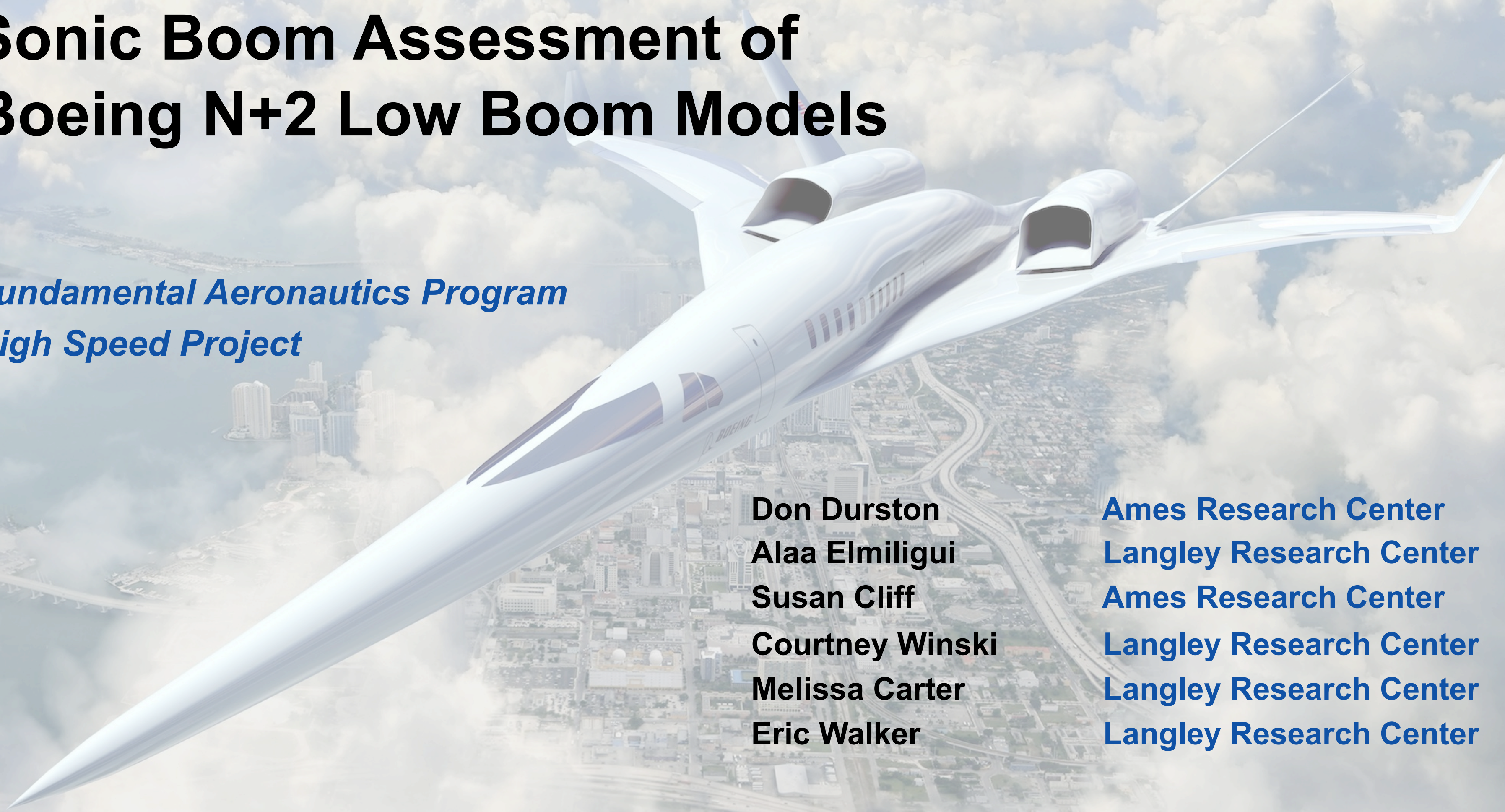
# Experimental and Computational Sonic Boom Assessment of Boeing N+2 Low Boom Models



*Fundamental Aeronautics Program*

*High Speed Project*


| | |
|---|---|
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*Image courtesy of The Boeing Company*

# Outline

- N+2 NRA Studies
  - Study Goals and Objectives
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  - Test Techniques
  - Selected Results
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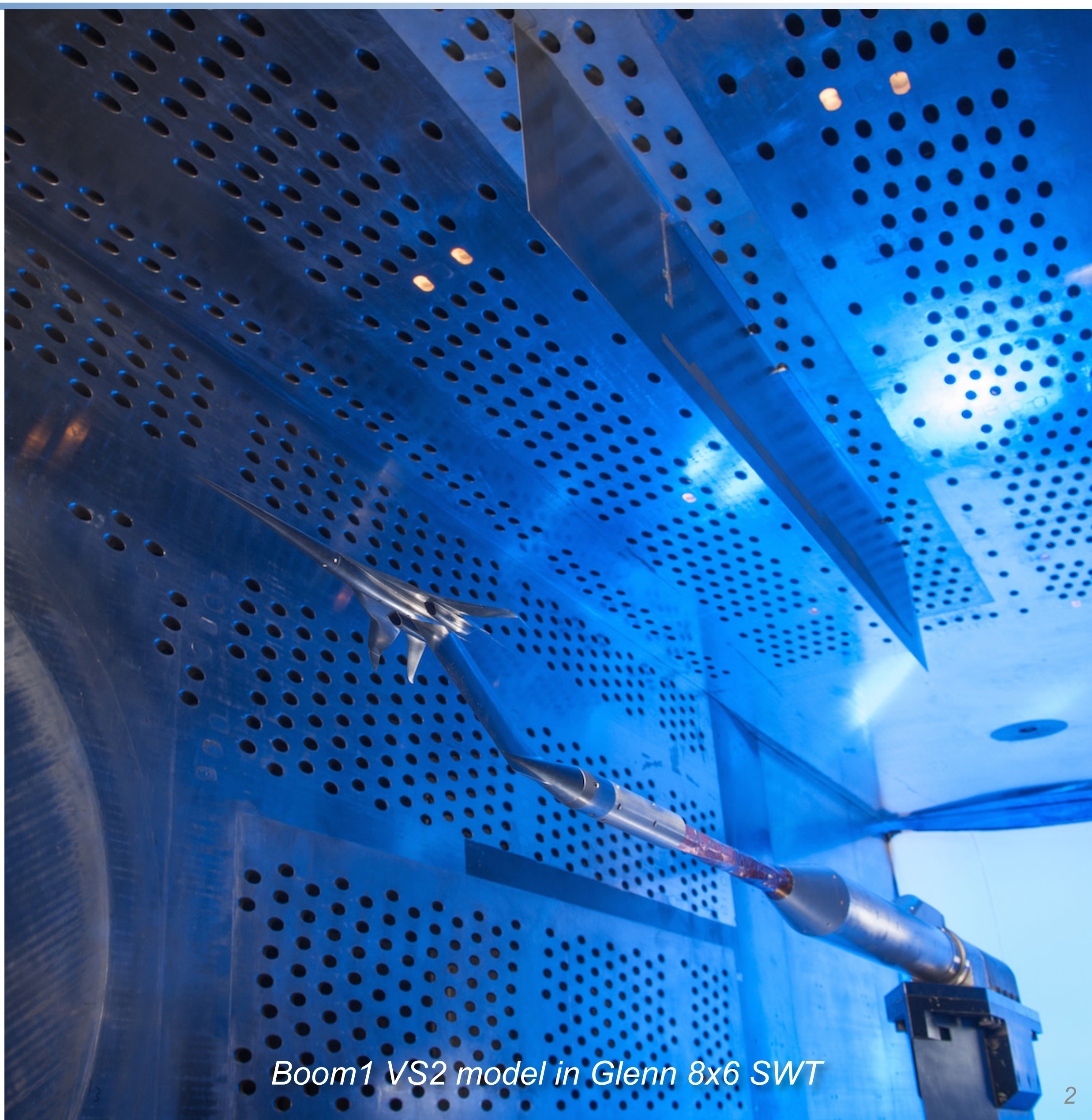
- Conclusions



*Boom1 VS2 model in Glenn 8x6 SWT*

# N+2 NRA Studies

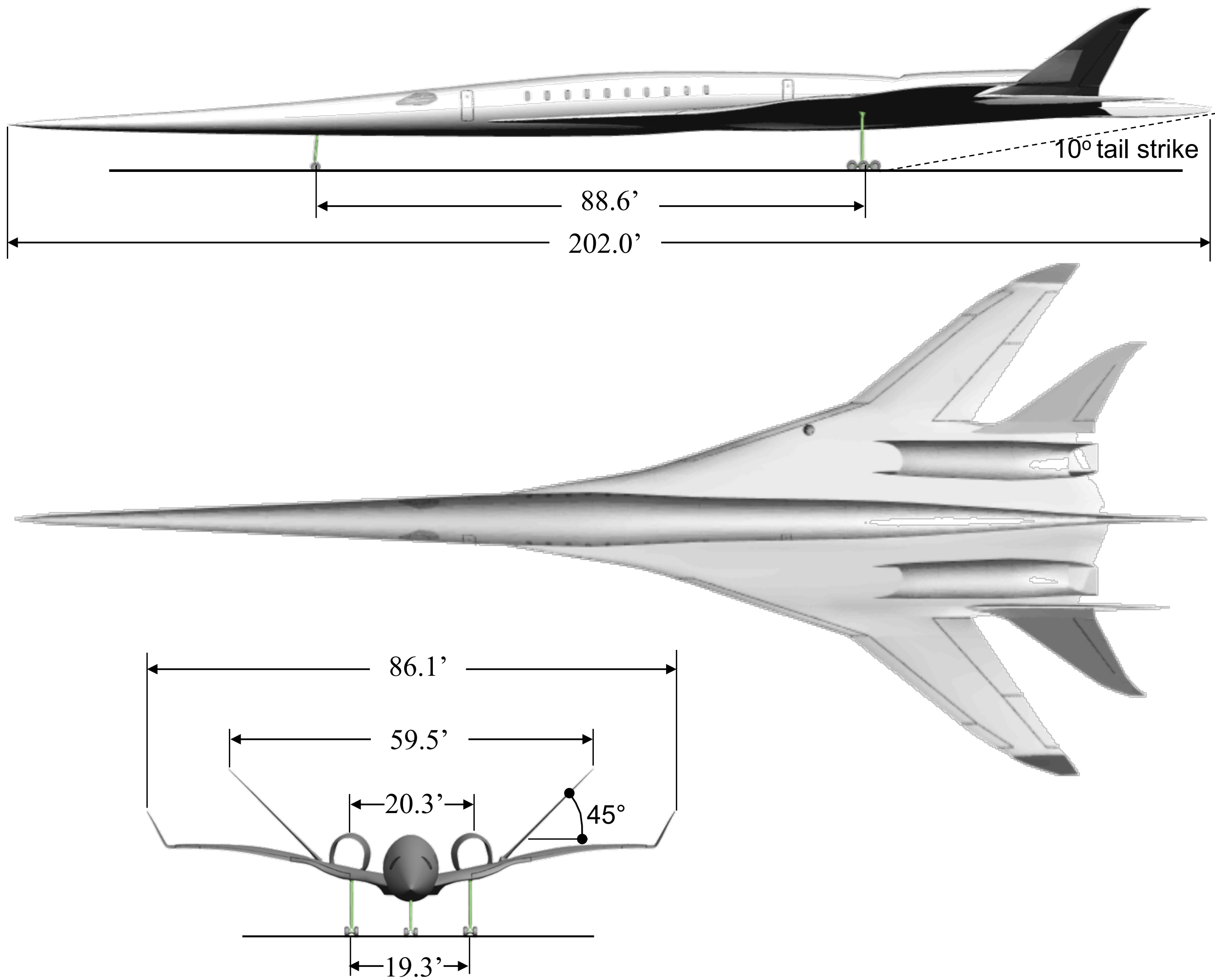
- 3-year, 2-phase study contracts with Boeing and Lockheed-Martin
- Design for N+2 (2nd-generation) supersonic transport to meet goals:

| Environmental Goals | |
|---|---|
| Sonic Boom | 85 PLdB |
| Airport Noise (cumulative below stage 3) | 10–20 EPNdB |
| Cruise Emissions | < 10 EIN Ox |
| **Performance Goals** | |
| Cruise Speed | Mach 1.6–1.8 low boom flight |
| Range | 4000 nm |
| Passengers | 35–70 |
| Fuel Efficiency (px-nm per lb of fuel) | 3.0 |

- Phase I: Design for low boom and aerodynamic efficiency
- Phase II: Nacelle/airframe integration, inlet performance and effects on boom

# Boeing QEVC

- Quiet Experimental Validation Concept designed in 2009
- Design flight conditions:
  - Mach 1.8
  - $C_L = 0.104$
  - $\alpha = 3.28°$
- 35 to 70 passengers
- Range 4000 nm

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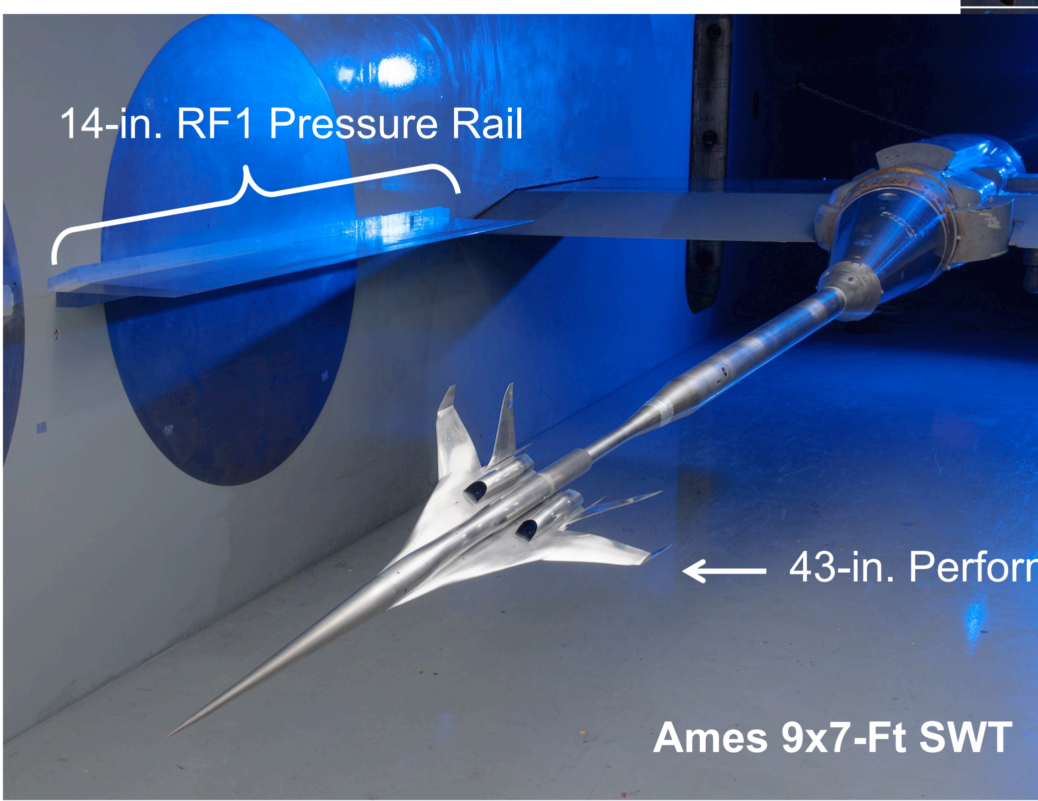
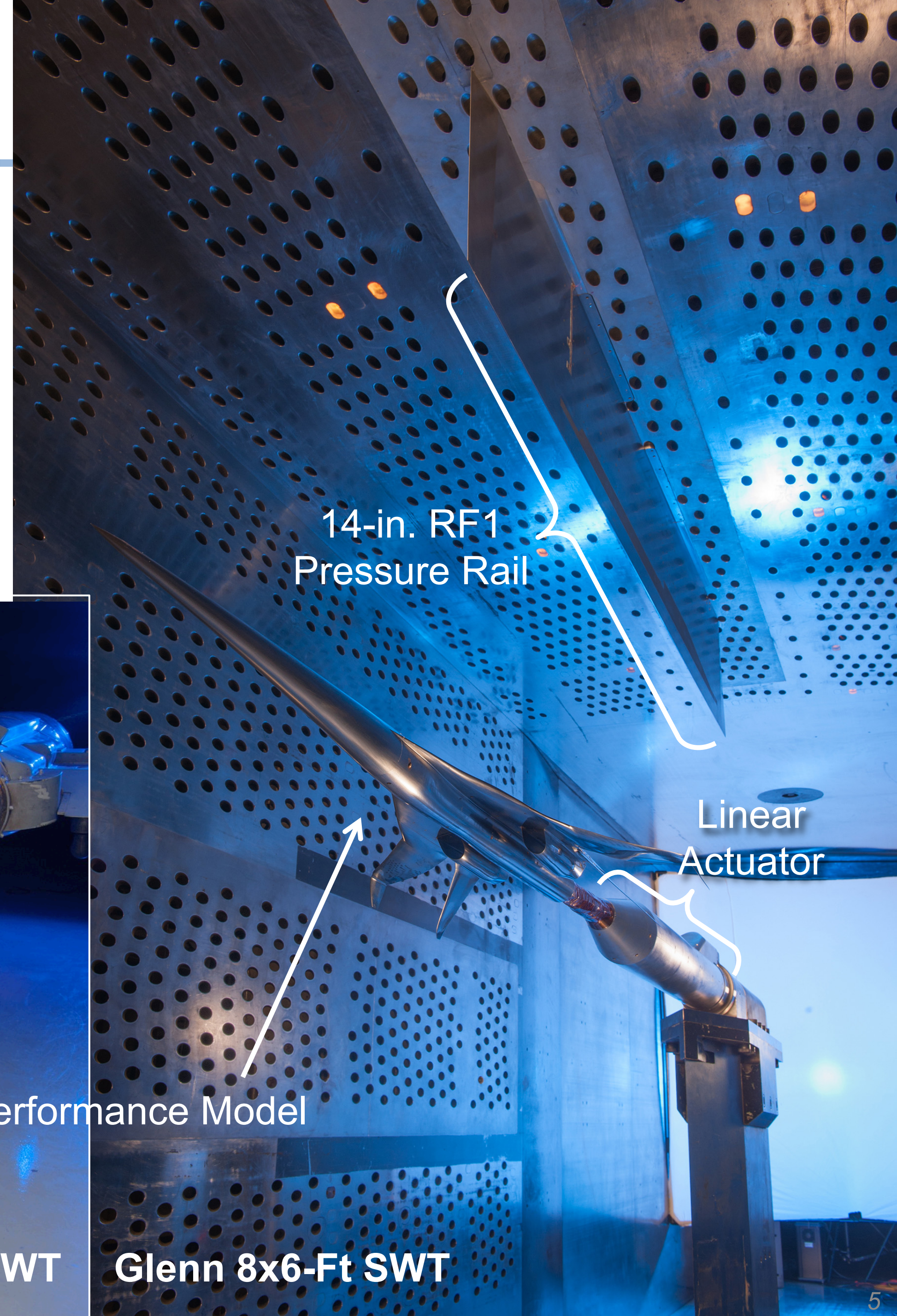
# Wind Tunnel Tests

- Ames 9x7 and Glenn 8x6 Supersonic Wind Tunnels
- 14” RF1 pressure rail and
  2” flat-top pressure rail
- Mostly Mach 1.6 and 1.8
- Performance model shown here, plus AS2 and Boom models (next page)

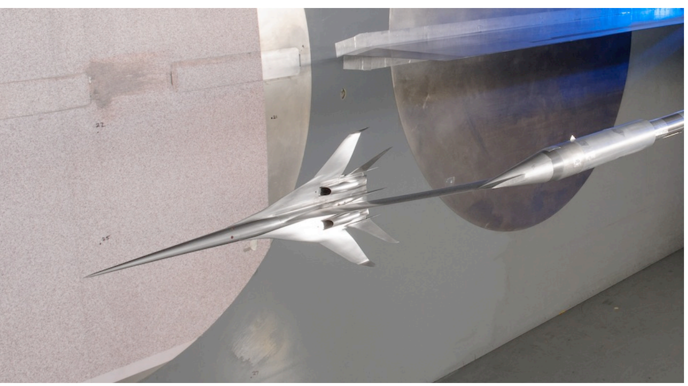


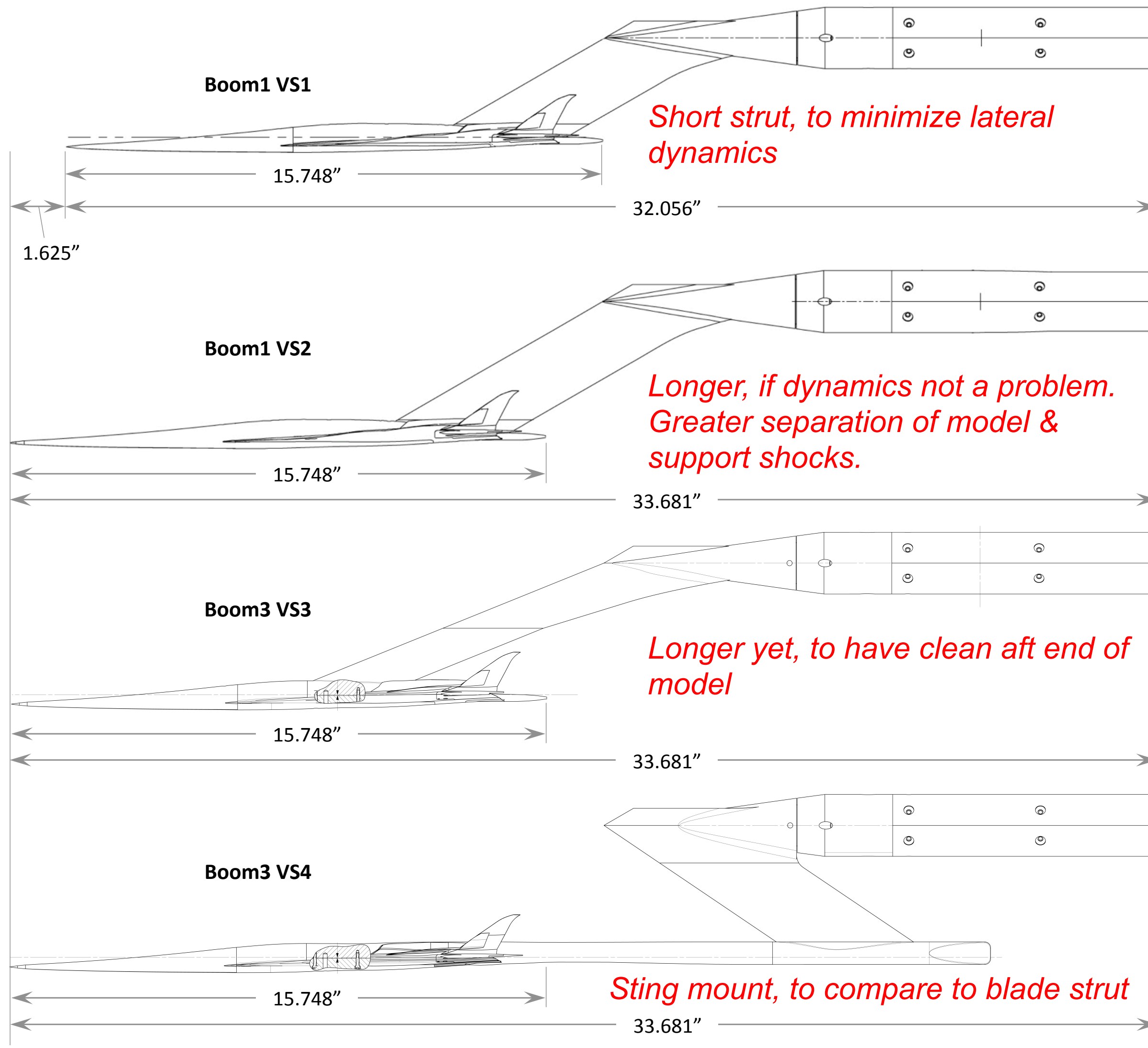
# AS2 and Boom Models and Struts

AS2 body of revolution

Boom1 model, VS2 strut

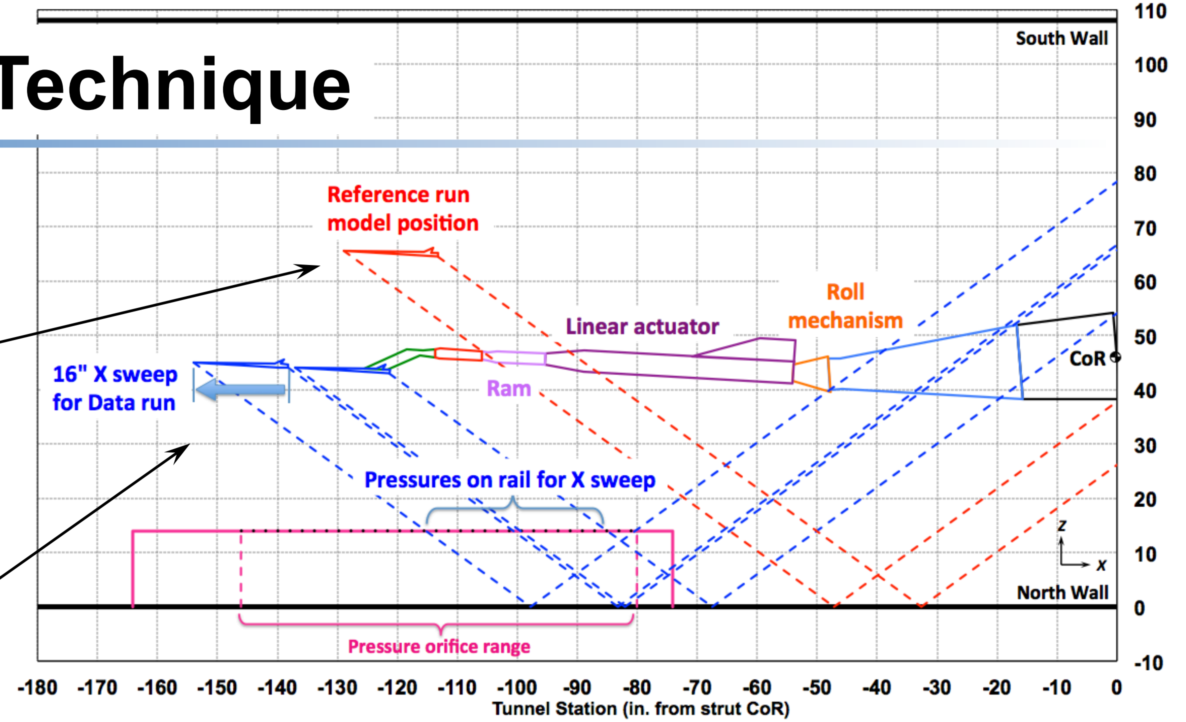


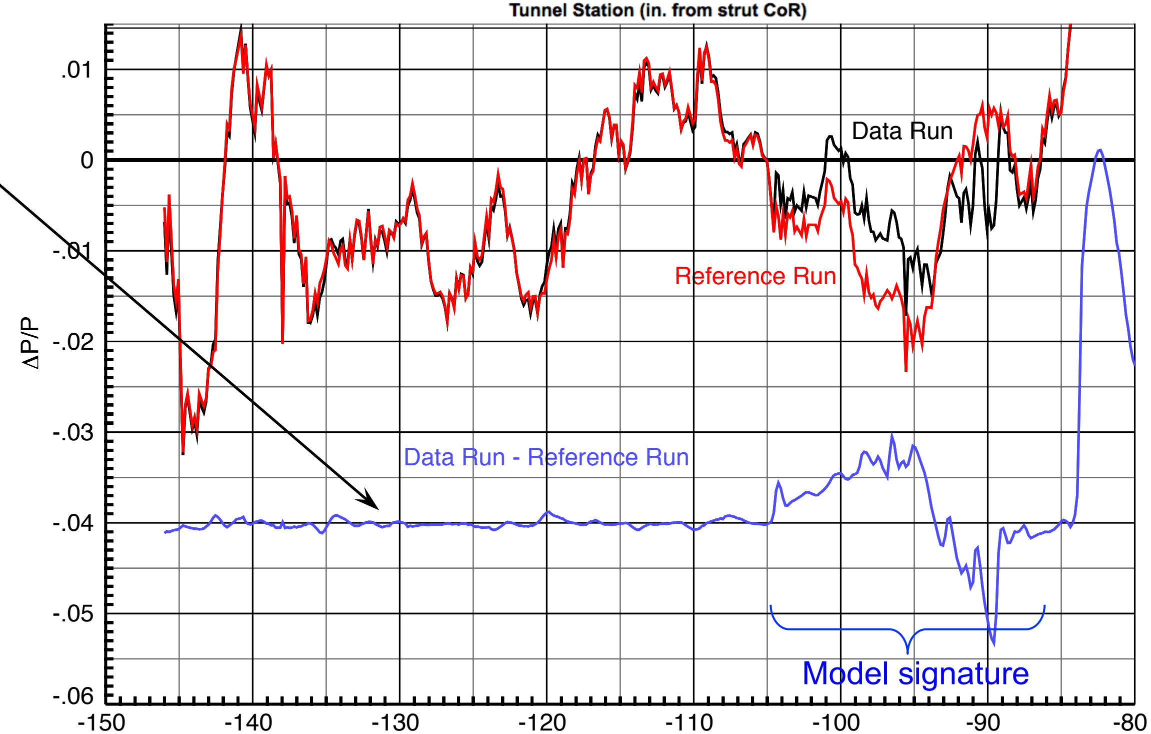
4 blade strut options for Boom models



# Pressure Rail Test Technique

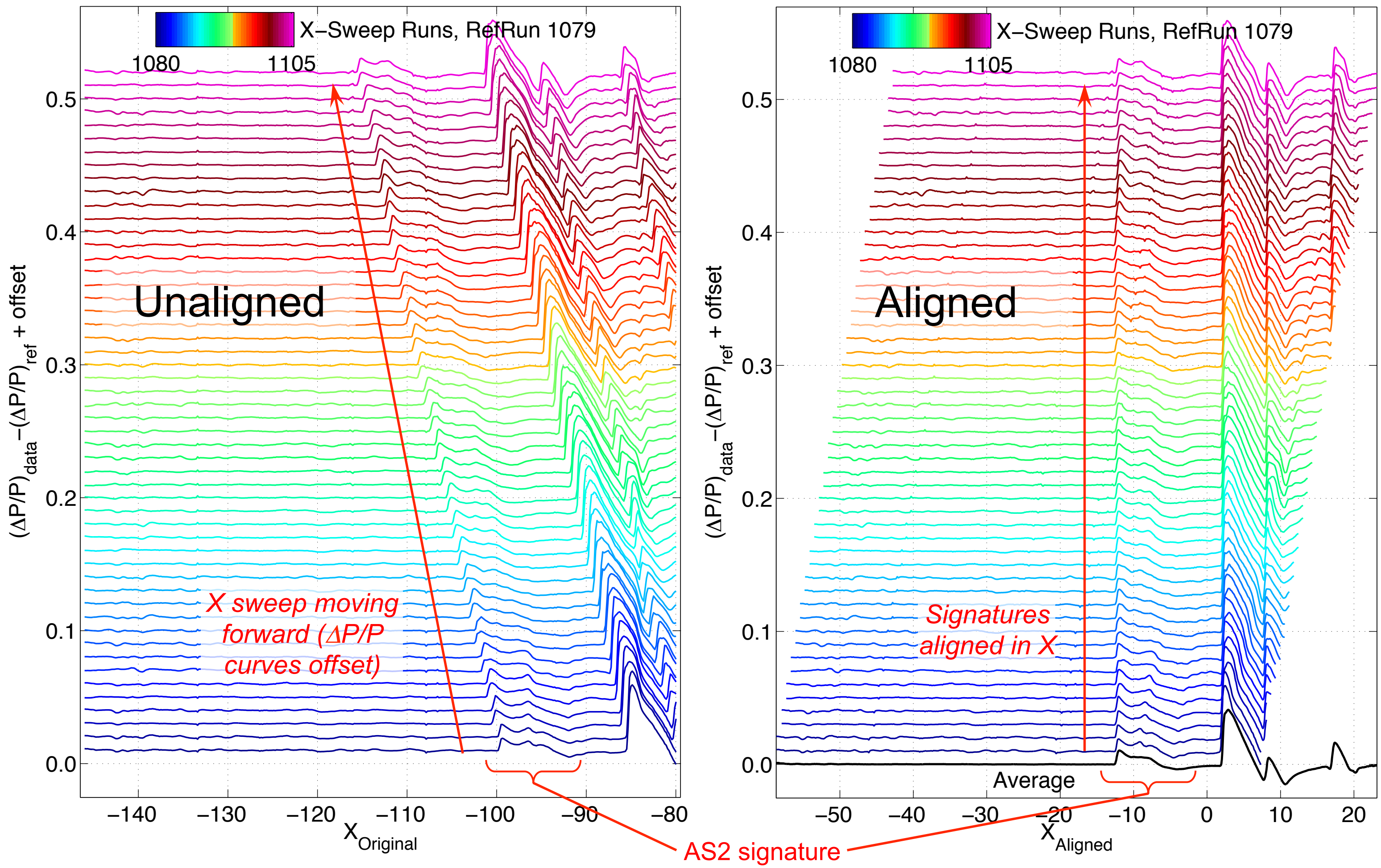
- Pressure rail on wall has 420 orifices to capture entire model signature at once
- Reference run taken with model shocks *off* rail (or at least downstream of where model shocks will be)
- Data run taken with model shocks *on* rail
- Model signature is *difference* between reference and data runs
- *X* or *Z* sweeps conducted to acquire signatures in different regions of tunnel flow
- Sweeps allow for averaging out tunnel spatial flow variations
- Temporal averaging also done with appropriate sampling durations



# Spatial Averaging of Model Signatures

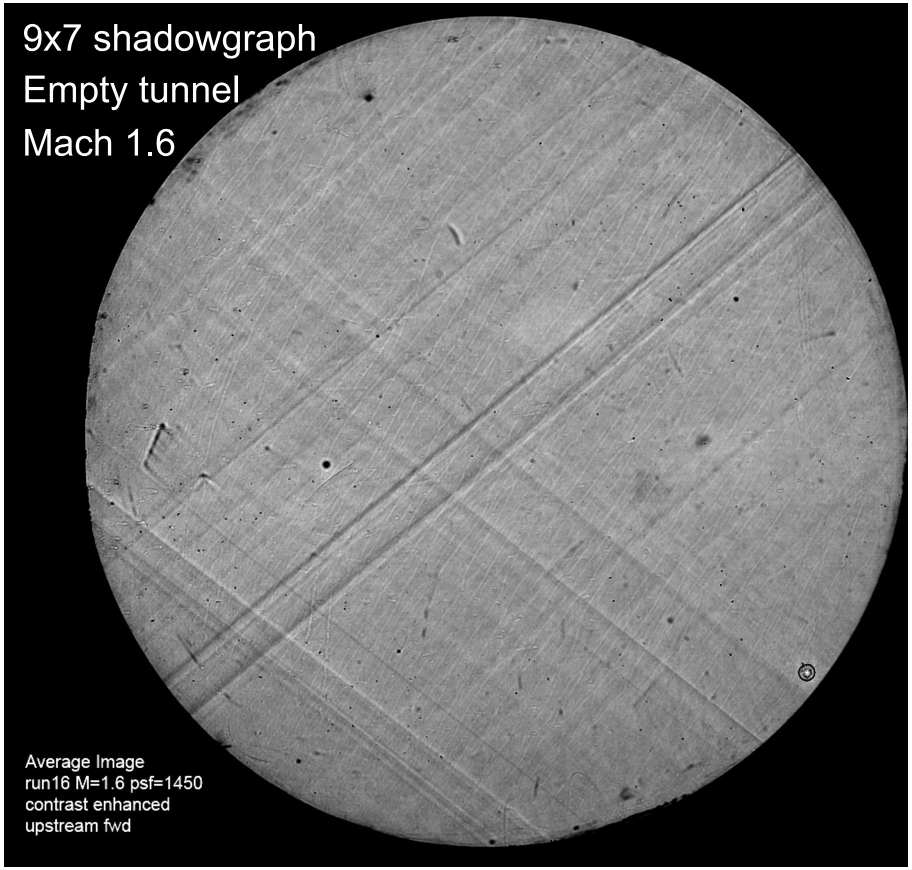
- Example: 26 signatures acquired with ram extension from 8” to 24” (0.63” spacing)
- Distortions due to tunnel flow spatial variations and model vibrations are evident in individual signatures, but averaging reduces these effects

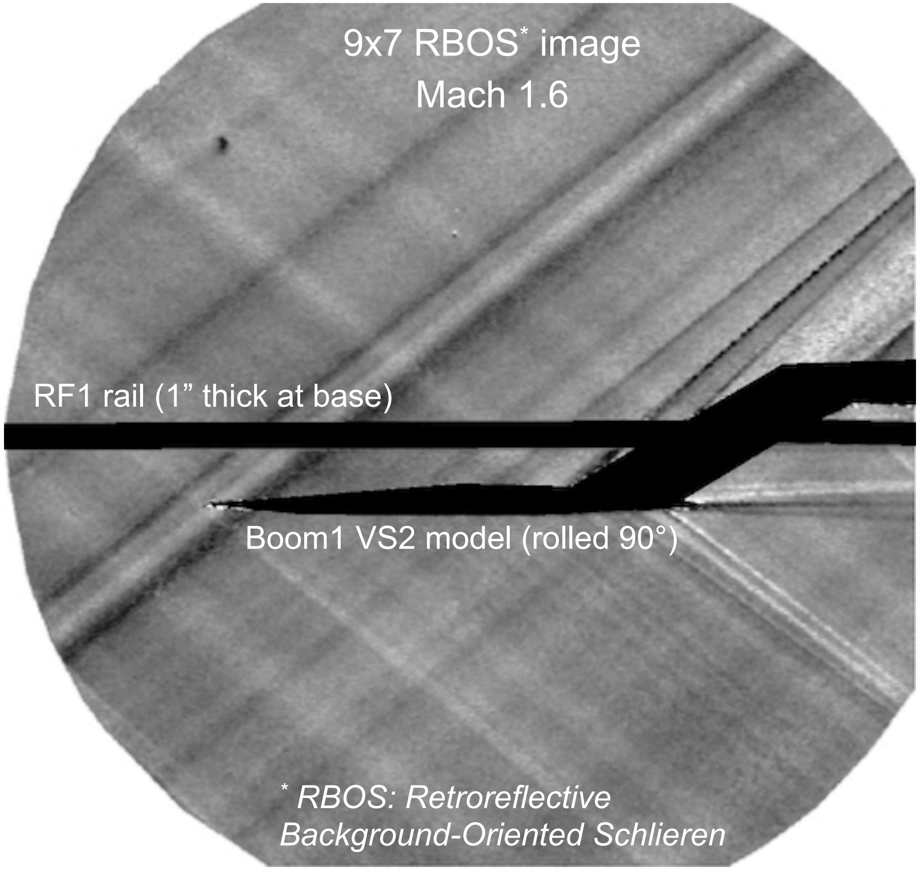



AS2 model X sweep in 9x7 WT, Mach 1.6

# Shock Wave Imaging

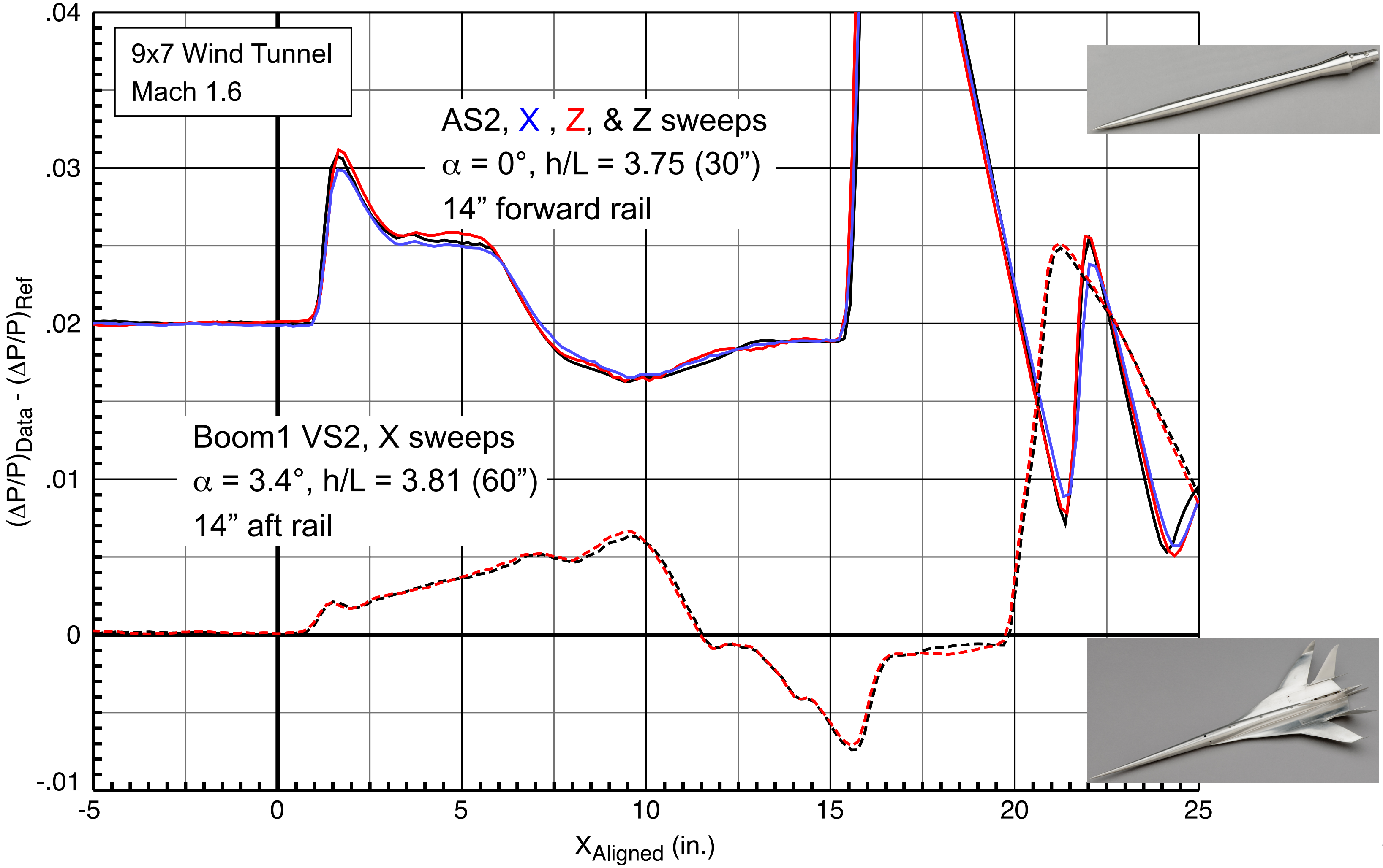
- Facility-generated shock waves often as strong or stronger than model shocks being measured
- Reference runs and spatial averaging minimize effects of facility shocks but cannot eliminate these effects



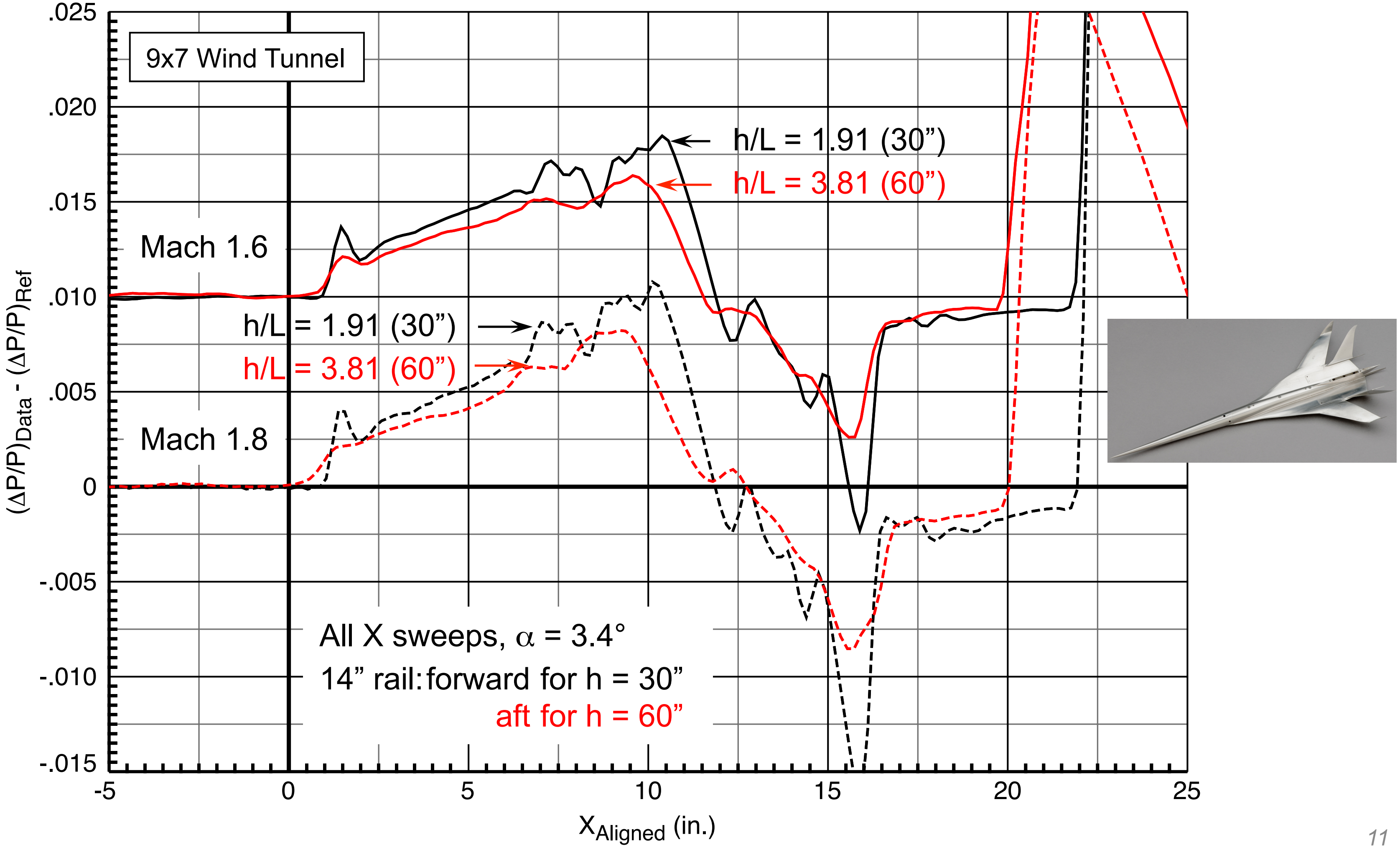
# Repeatability of Experimental Data

- AS2 and Boom1 VS2 repeat runs show excellent repeatability
- X and Z sweeps give similar results



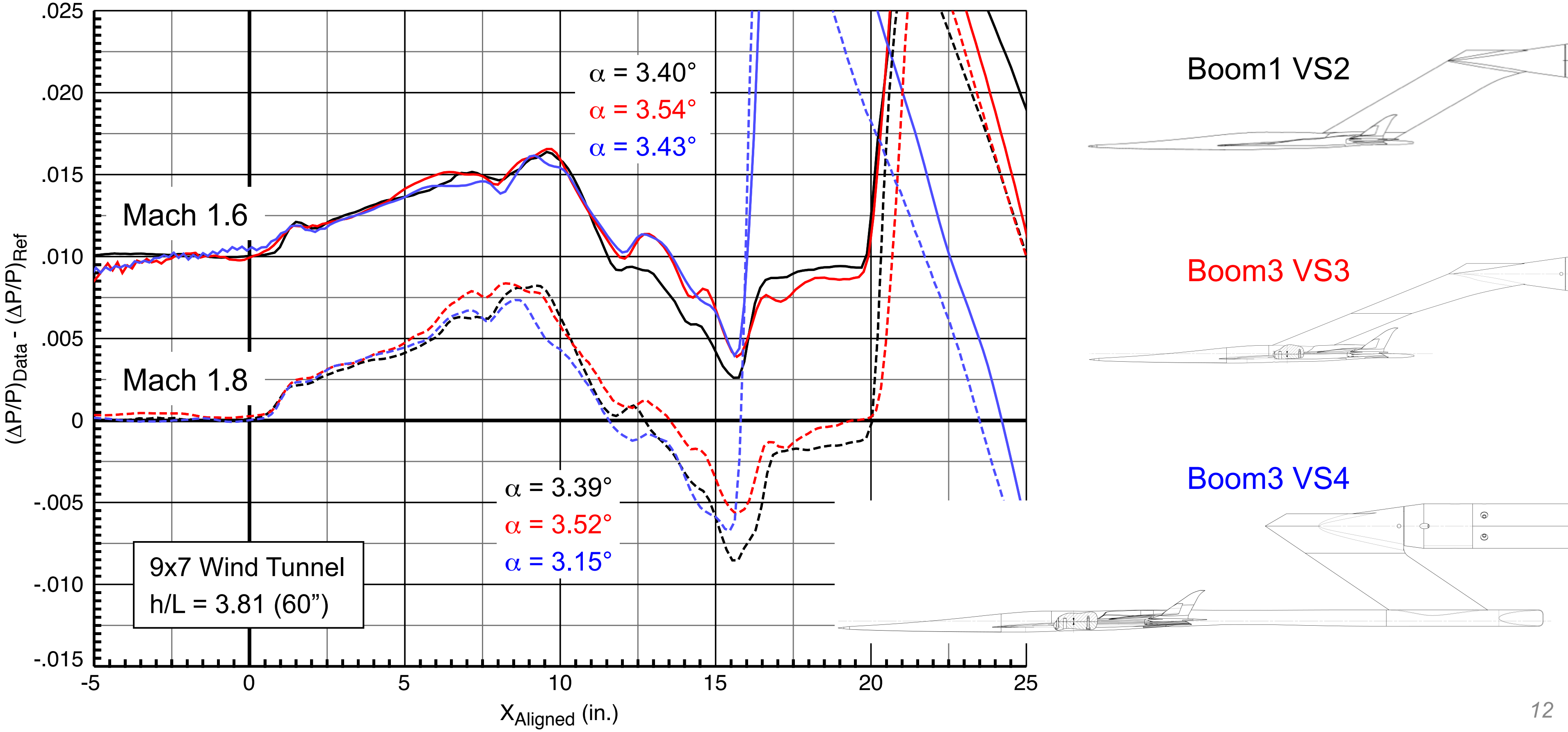
# Effect of Model Height, Boom1 VS2

- Increased height causes rounding of signatures due to aging
- Overall pressure levels decrease with height



# Mounting Strut Effects, Boom Models

- VS2,3,4 struts, Mach 1.6 & 1.8, 14” aft rail, height = 60”
- VS2 & VS3 more similar to each other than to VS4, but VS3 & 4 pressures more similar at Mach 1.6
- Greater differences between VS3 & 4 exist at Mach 1.8, though angle-of-attack differences could account for part of this
- VS4 blade shock overtakes aft end of model signature at both Mach numbers



# Computational Methods

Results from 3 codes presented here:

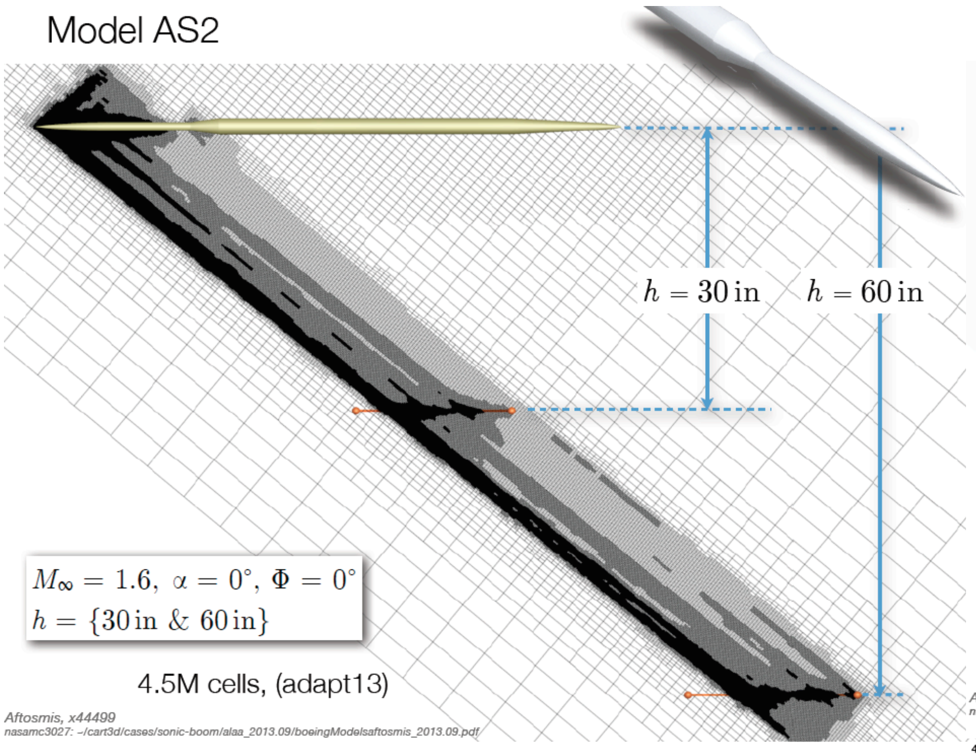
- Cart3D
  - Fast, inviscid, unstructured-mesh analysis package for conceptual and preliminary aerodynamic design
  - Used with Adjoint Error Optimization (AERO) module

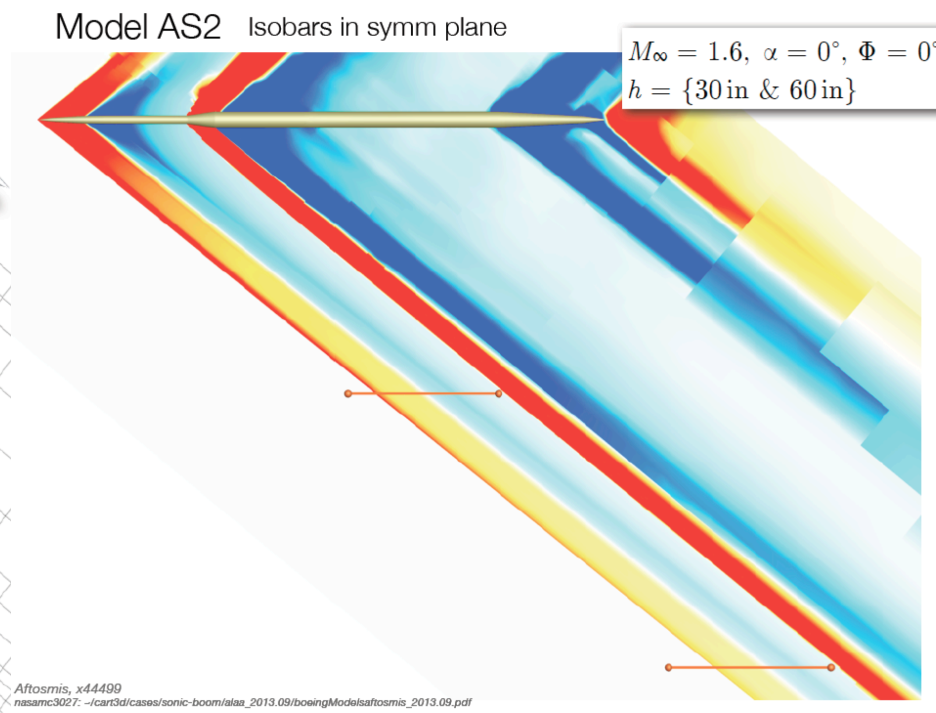
- USM3D
  - Tetrahedral cell-centered, finite volume Euler and Navier-Stokes (N-S) method
  - Run both inviscid and viscous (laminar, and turbulent with Spalart-Allmaras turbulence model) for this study

- OVERFLOW
  - OVERset structured grid FLOW solver used by Boeing for present results
  - Inviscid and turbulent with Spalart-Allmaras turbulence model

# AS2 Grid and Pressure Contours

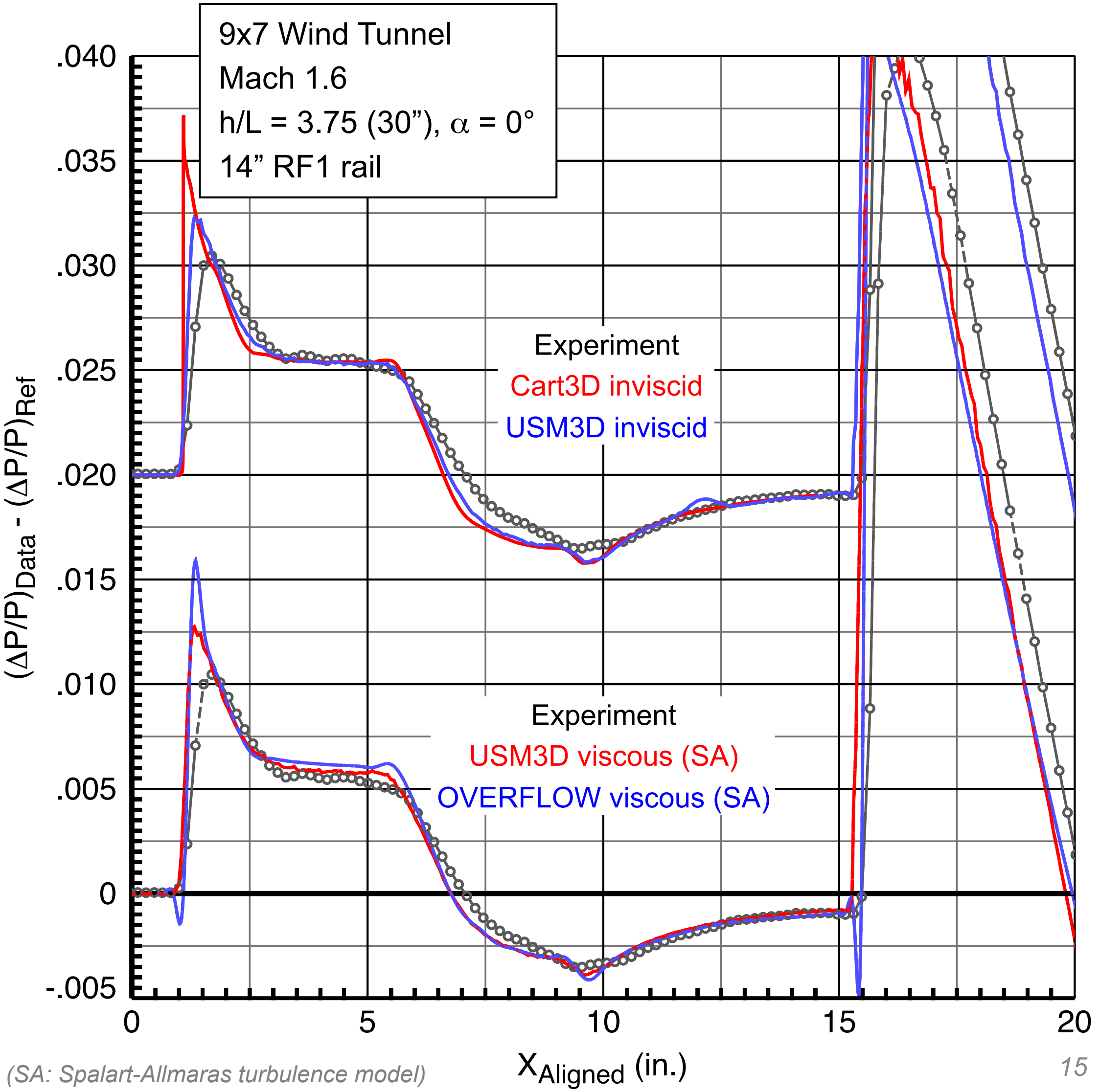
- Cart3D adjoint-adapted grid and isobars in symmetry plane
- Sensor lines shown at heights of 30” and 60” for extracting pressure signatures
- Mach 1.6, $\alpha$ = 0°



# AS2 Experiment / CFD Comparisons

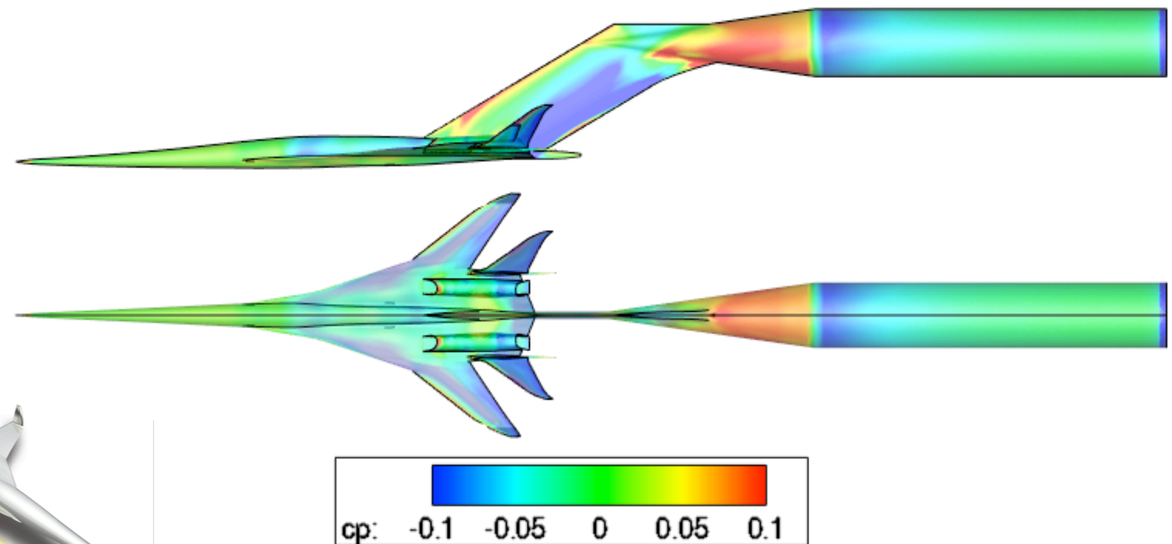
- Flat region aft of nose shock predicted well
- All CFD codes overpredict nose shock relative to experiment
  - Shock in WT data may be rounded due to flow irregularities
  - Viscous solutions not necessarily better than inviscid
- All CFD codes predict lower pressures in main expansion than experiment
  - Similar differences found for other bodies of revolution tested (not shown here)
  - Error was thought to be related to impingement of rail LE shock on aft part of model, but that was found to not be a factor

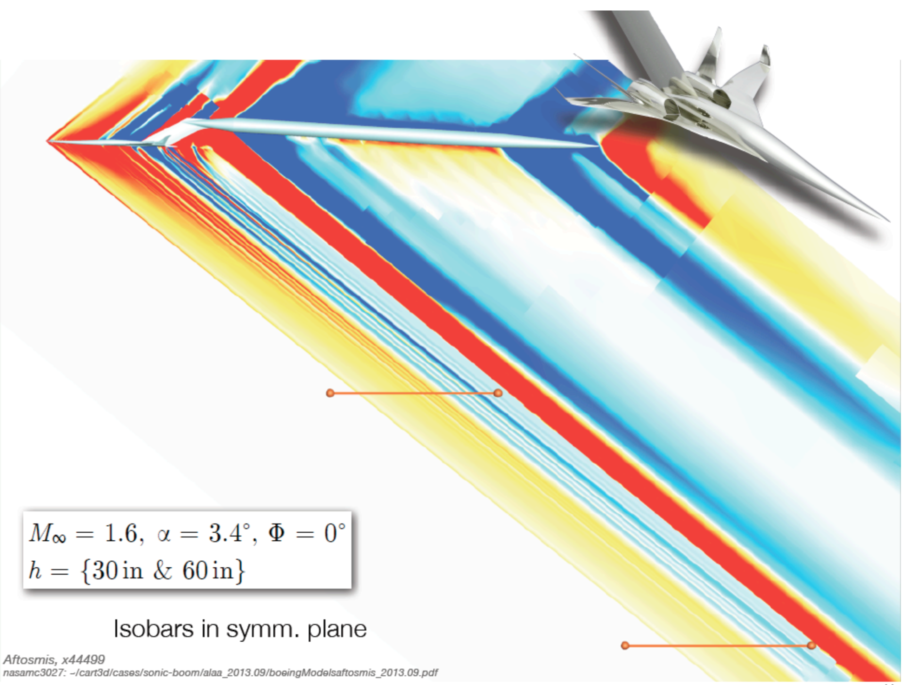



(SA: Spalart-Allmaras turbulence model)

# Boom1 VS2 Pressure Contours

- Surface pressure contours computed by USM3D with laminar boundary layers
- Mach 1.6, $\alpha$ = 3.4°

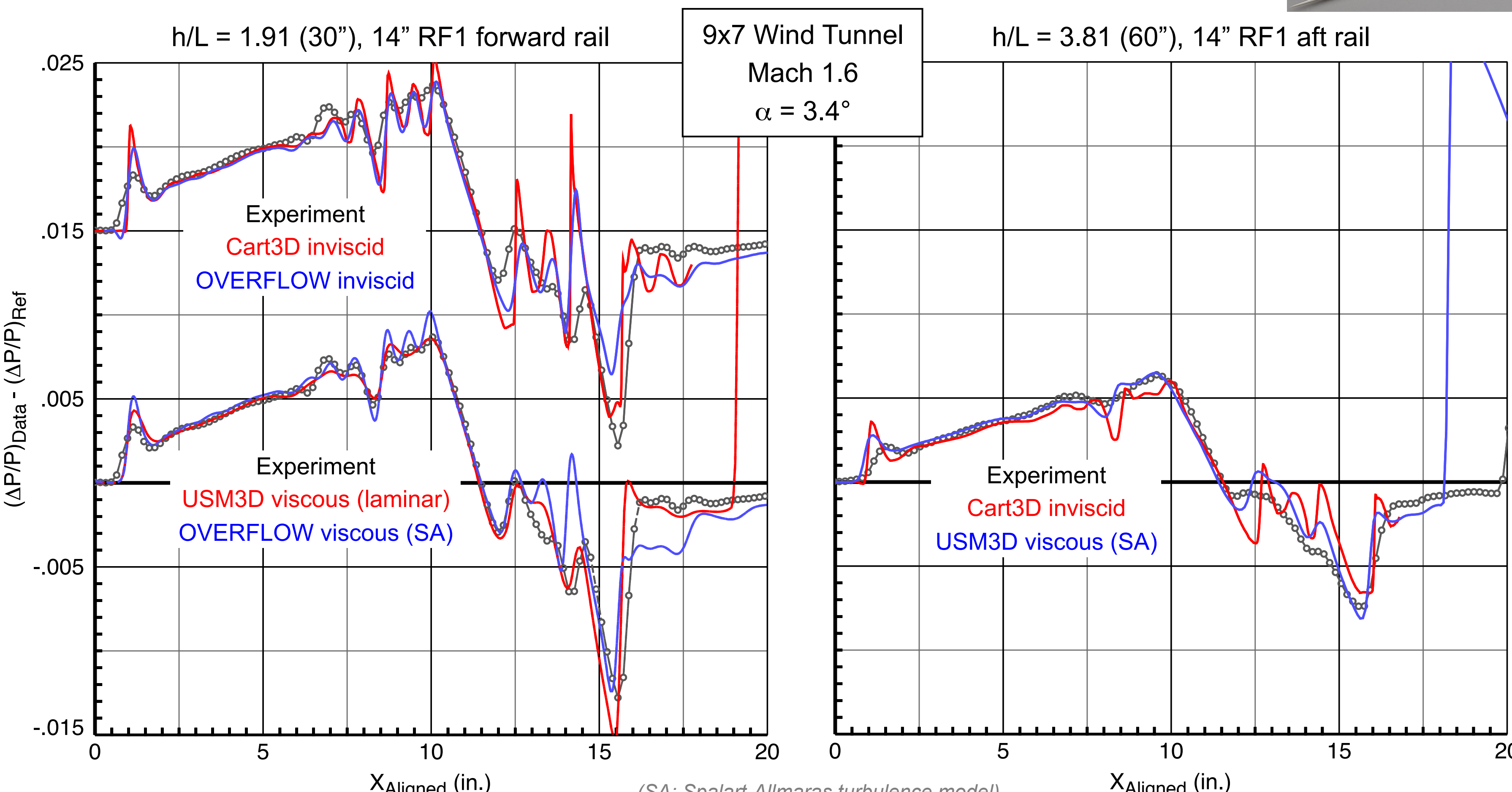



- Symmetry plane pressure contours computed by Cart3D
- Mach 1.6, $\alpha$ = 3.4°

# Boom1 VS2 Experiment / CFD Comparisons

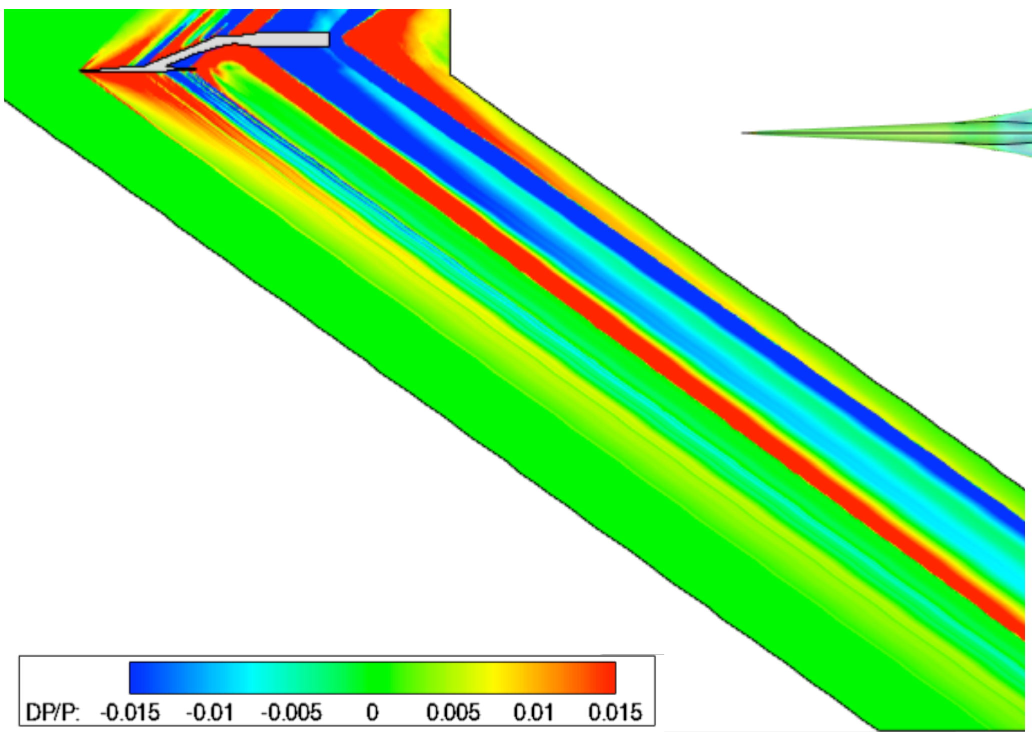
- Inviscid shock peaks are overpredicted relative to viscous
- USM3D laminar prediction matches exp. data better than turbulent prediction from OVERFLOW
- Effects of model height well-captured by predictions

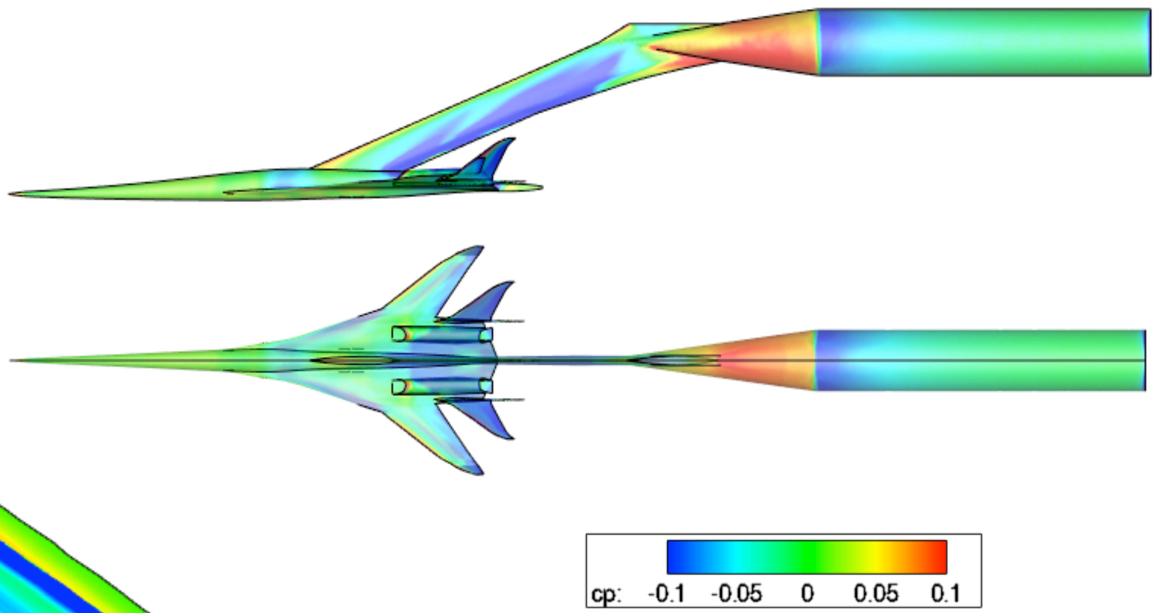



*(SA: Spalart-Allmaras turbulence model)*

# Boom3 VS3 Pressure Contours

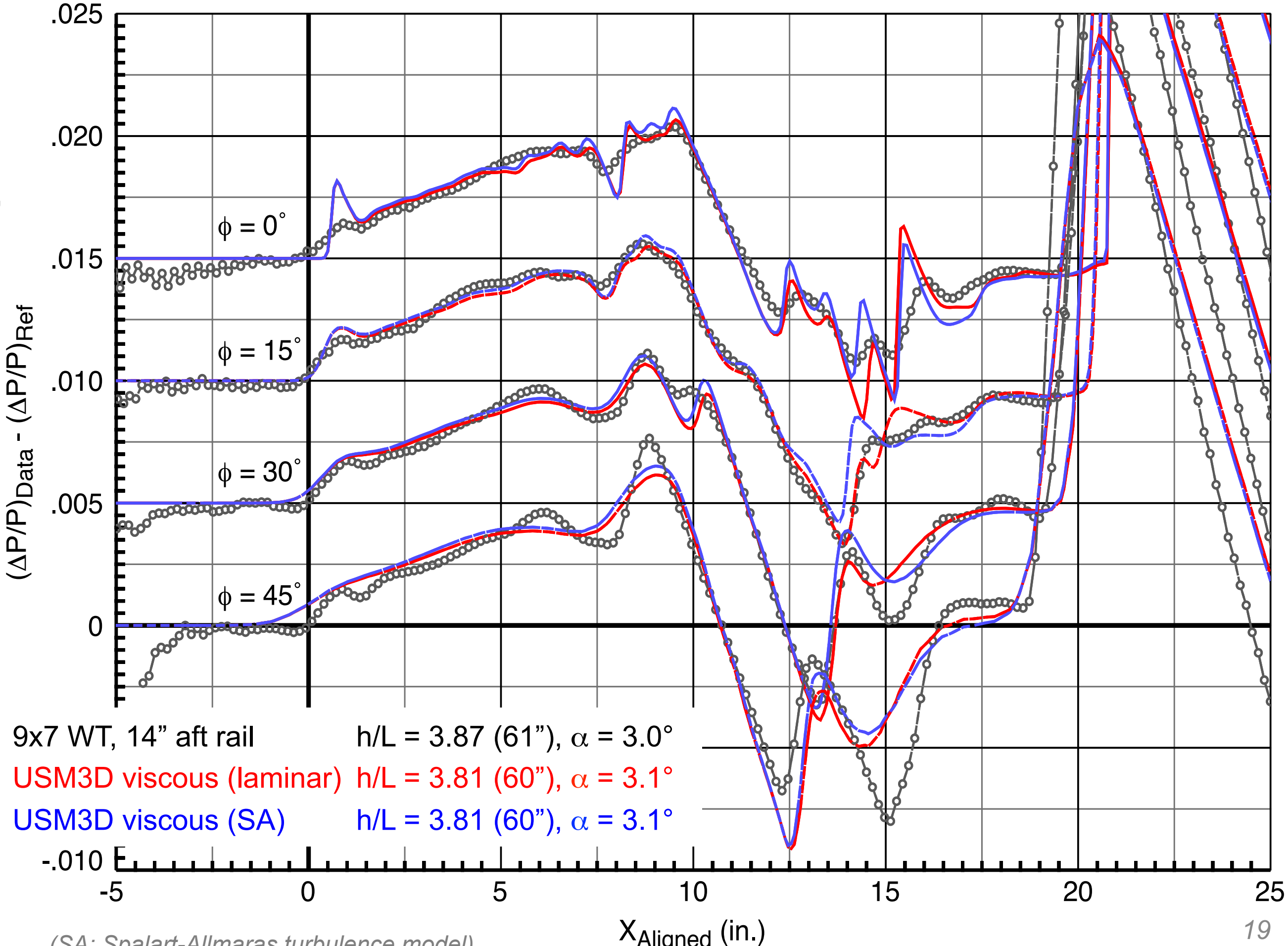
- Surface pressures and symmetry plane flow field pressures computed by USM3D with laminar boundary layers
- Mach 1.6, $\alpha = 3.1°$



# Boom3 VS3 Experiment / CFD Comparisons at Various Off-Track Angles

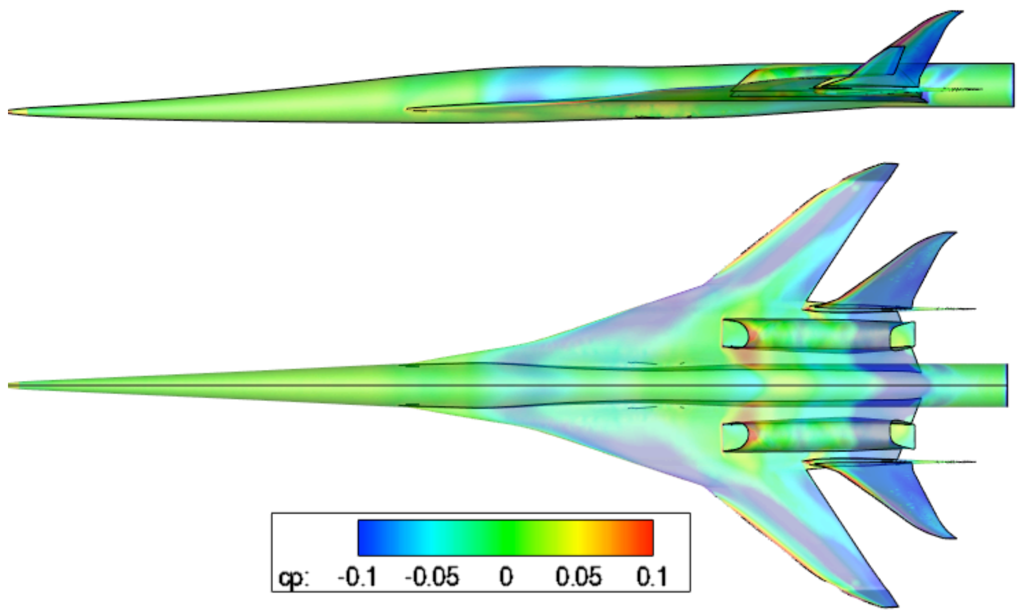
- Best exp./CFD agreement at 15° off-track angle, though all predictions capture front ramp and main expansion fairly well
- Nose shock strength overpredicted by USM3D at $\phi$ = 0°, but this diminishes to no shock by $\phi$ = 45°, even though experimental data still show it
- Experimental shocks somewhat washed out by spatial averaging, CFD tends to show more detail, especially at $\phi$ = 0°
- *Issues with experimental & CFD data are still being investigated…*

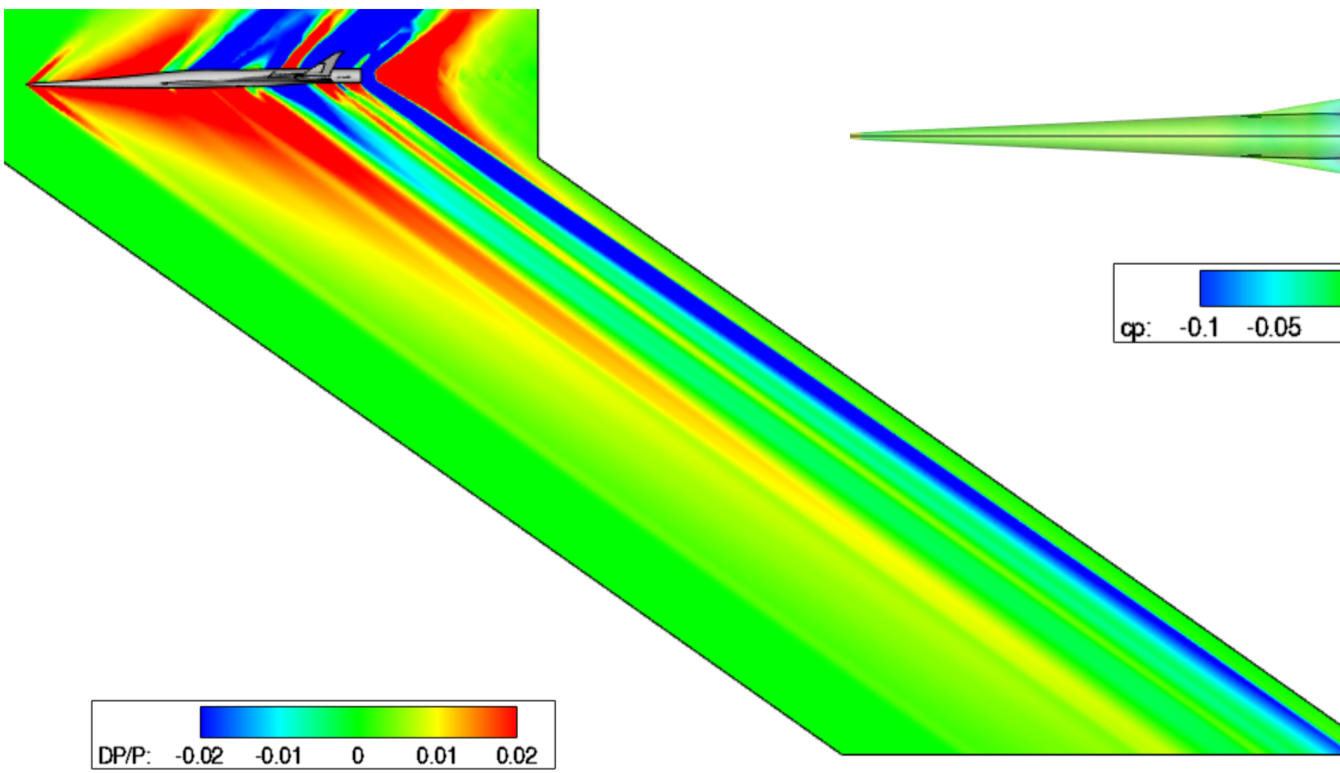



(SA: Spalart-Allmaras turbulence model)

# Performance Model Surface Pressure Contours

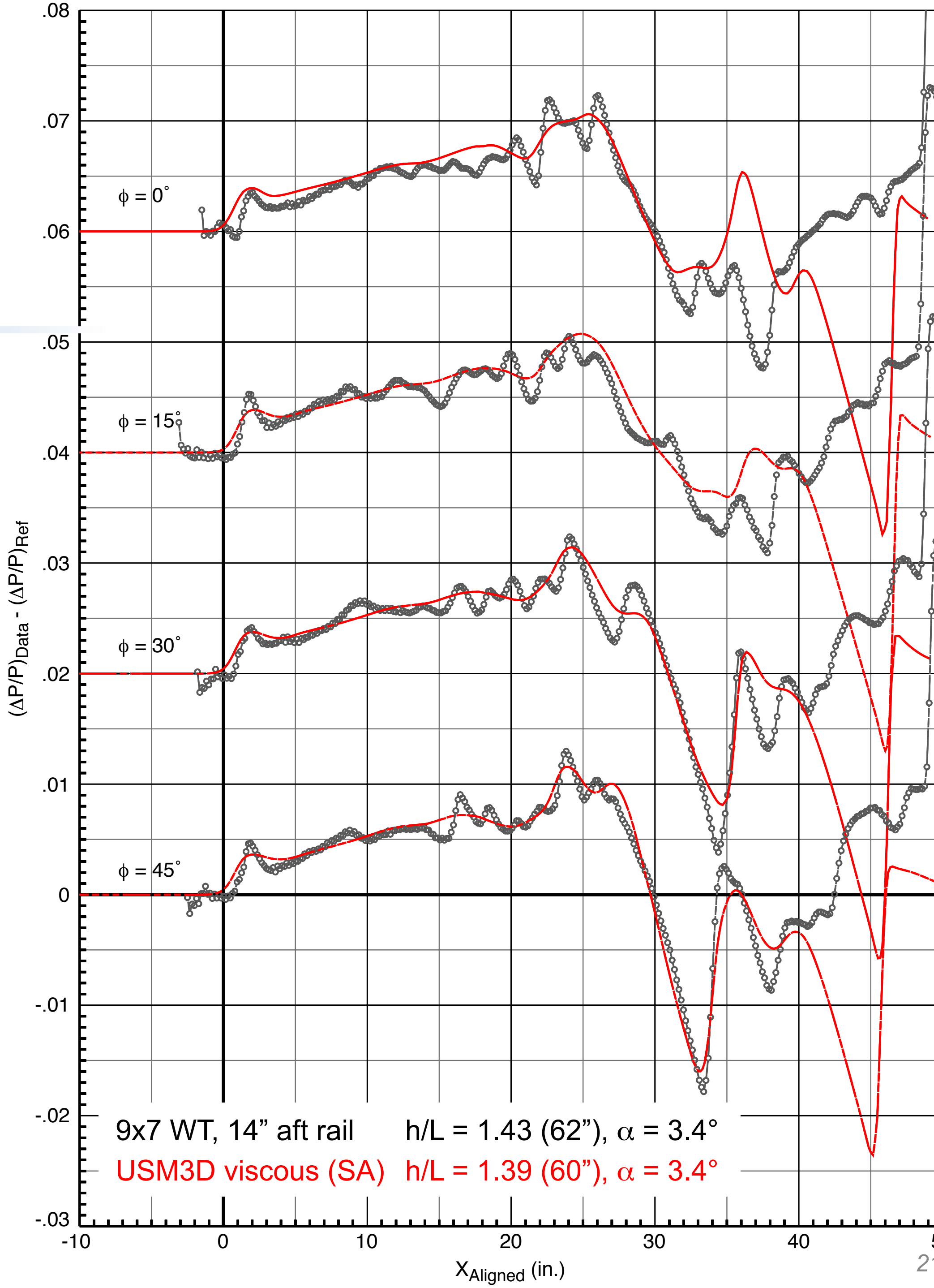
- Surface pressures and symmetry plane flow field pressures computed by USM3D with SA turbulent model
- Mach 1.6, $\alpha$ = 3.4°



# Performance Model Experiment / CFD Comparisons at Various Off-Track Angles

- Exp.: Performance model with <u>tailored dummy sting</u>
  CFD: Performance model with <u>sting can</u>
  - Shocks after main expansion not expected to match
- CFD captures general trends of front ramp and main expansion, but exp. data have many more small shocks
  - These small shocks not seen in Boom model data
  - Forebody contours on Performance model are smooth, not sure what is causing the shocks
- *Issues with experimental & CFD data are still being investigated…*



# Performance Model Sting Options

- Model originally run with sting can
  - Extends circular shape of aft body about 6”
  - Has cavity and aft-facing step down to sting diameter
- Tailored dummy sting (covers) made during Phase II
  - Used in place of sting can
  - Continues aft-body shape about 17” behind model
  - Intended to move effect of cross-section change further aft for cleaner aft signature
  - Only for boom signatures, not force data since balance is “fouled”

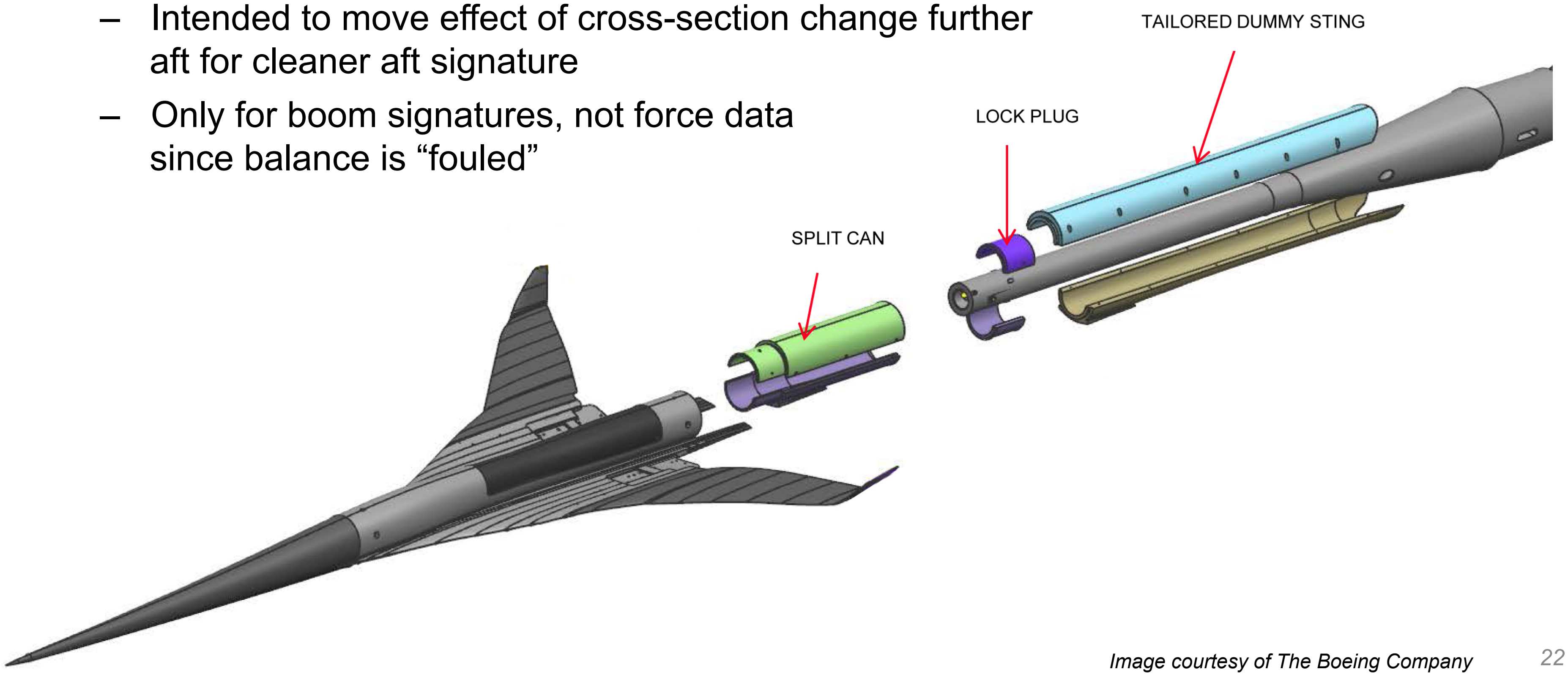



*Image courtesy of The Boeing Company*

# Conclusions

- Wind tunnel tests were conducted and CFD predictions were made in support of N+2 NRA studies
- Spatial-averaging test technique yielded good repeatability of model signatures—removed distortions due to different locations of models relative to rail
- 14-in. “RF1” rail data matched CFD fairly well, 2-in. rail data required correction for reflection factor
- Inviscid CFD flow solvers generally overpredicted shock strengths, inclusion of boundary layer effects in viscous solvers gave better results
- **Validation of CFD predictions with test data in these N+2 studies has significantly advanced the state of the art in low-boom aircraft design and test, and gives confidence in being able to design for low boom**

# Questions?