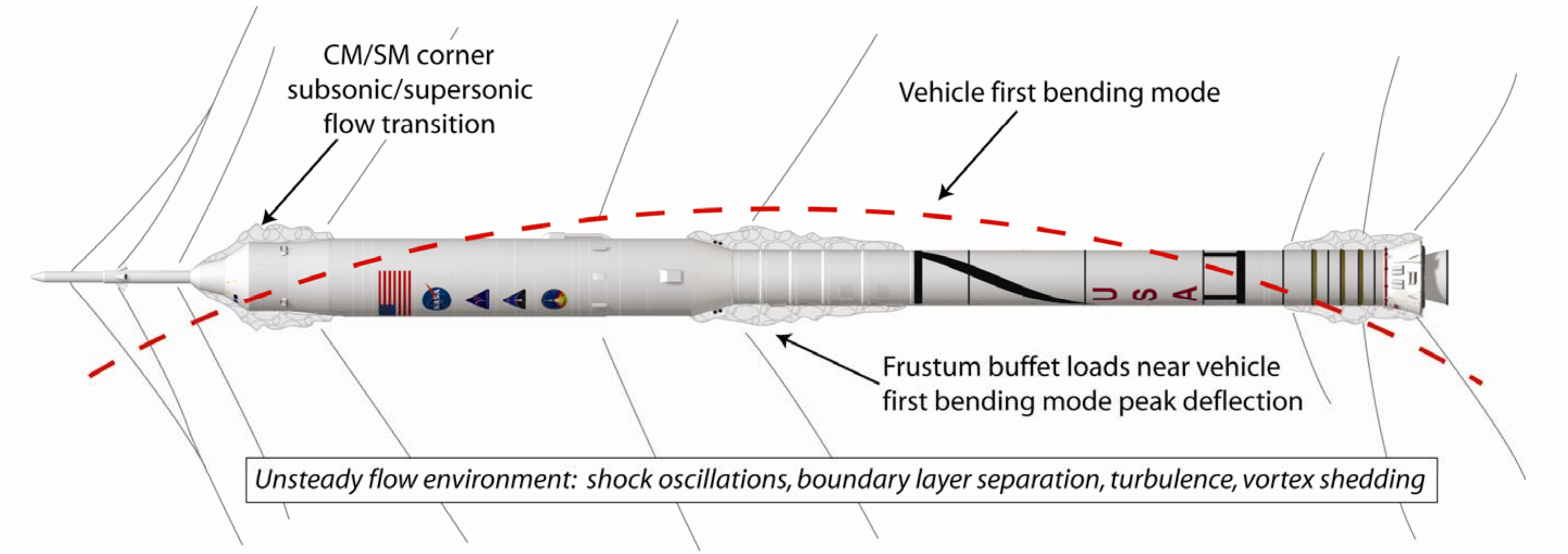
Ares Launch Vehicle Transonic Buffet

David J. Piatak Martin K. Sekula Russ D. Rausch
Aeroelasticity Branch
NASA Langley Research Center
Hampton, VA

NASA Commercial Crew Development Program
Aeroscience Technical Interchange Meeting
November 15, 2011

Launch Vehicle Buffet

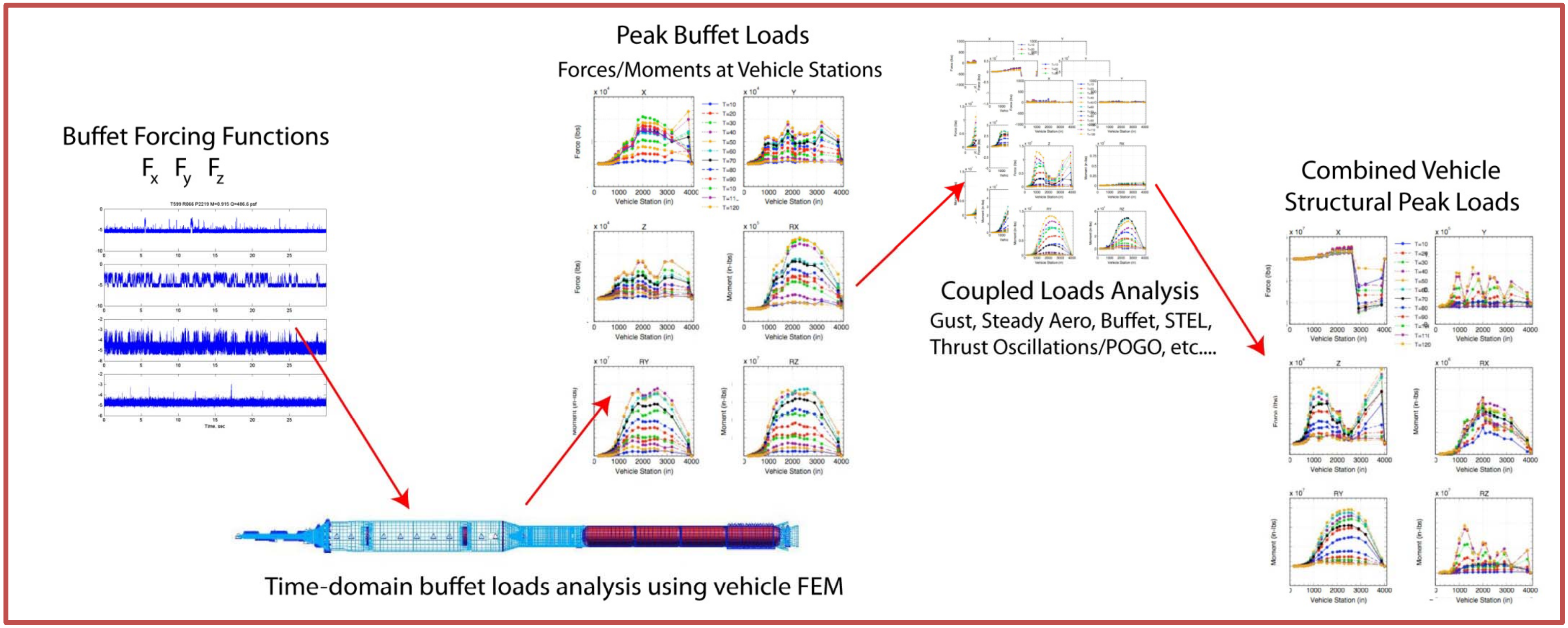
- Buffet due to unsteady aerodynamic phenomena can excite vehicle bending modes and local shell/panel modes
- Transonic regime is typically most critical for buffet (*max-Q next runner-up*)



"Buffeting During Atmospheric Ascent" NASA SP-8001 provides guidelines, but not definitive.

Buffet and Launch Vehicle Design Loads

- Buffet forcing functions (BFFs) are required for coupled loads analysis (CLA)
- Buffet is just one of many design loads to be considered in launch vehicle design cycles



- Analytical solution is not feasible
  - Experimental buffet forcing functions obtained via rigid buffet model tested in transonic wind-tunnel
- Rigid buffet model testing does not address vehicle aeroelastic stability
  - Computational, time-accurate coupled CFD-CSD aeroelastic analysis: FUN3D
  - Aeroelastic response wind-tunnel model test program: akin to Saturn I or Atlas partial mode tests at TDT

Ares Rigid Buffet Model Summary

Test Objectives:

- Acquire time-correlated unsteady pressures on rigid model at transonic conditions

Key Deliverable:

- Key deliverables are buffet forcing function (BFF) time histories at each longitudinal sensor station for use in buffet loads analysis (MSFC Ares Loads and Dynamics Panel)

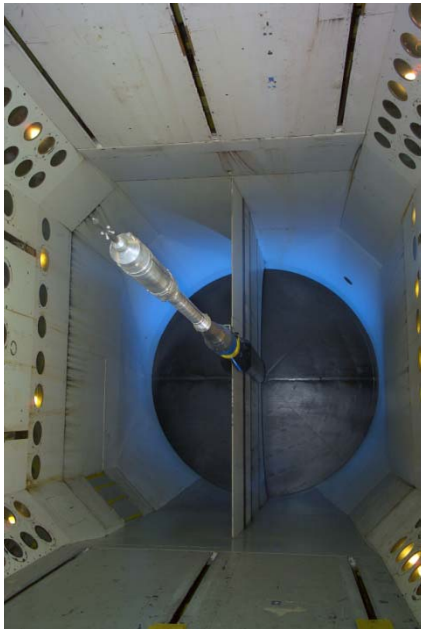
Technical Challenges:

- High Channel Count + High Data Acquisition Rates = Significant Instrumentation Complexity
- Measured buffet environment can be affected by wind-tunnel environment, sensor performance, sensor distribution, and model vibration
- Development of advanced signal analysis techniques to yield buffet forcing functions

Cost of Failure:

- Accurate BFFs not available for vehicle loads analyses which may result in:
  - Over-prediction of buffet environment (heavier vehicle; less payload)
  - Under-prediction of buffet environment (compromised safety margins; vehicle failure)

Ares I-X and Ares I Rigid Buffet Models



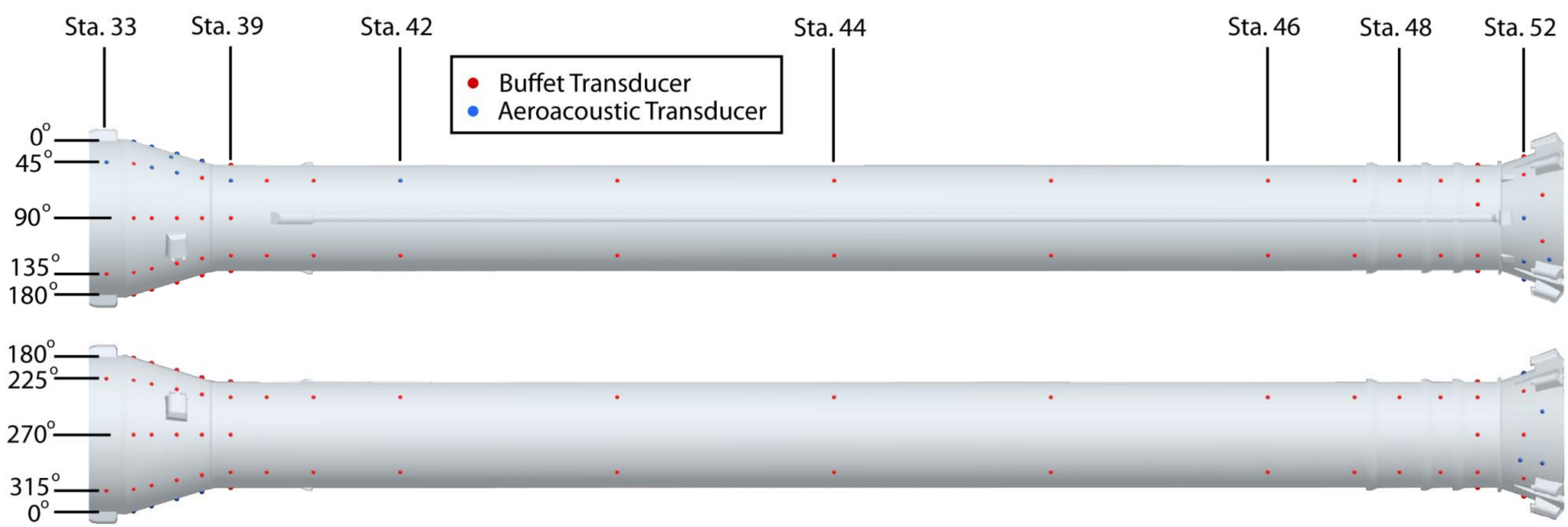
Oct – Dec 2007 **Oct – Dec 2008**

- 3.5% scale; ~11 ft long
- All significant protuberances
- 256 model unsteady pressures

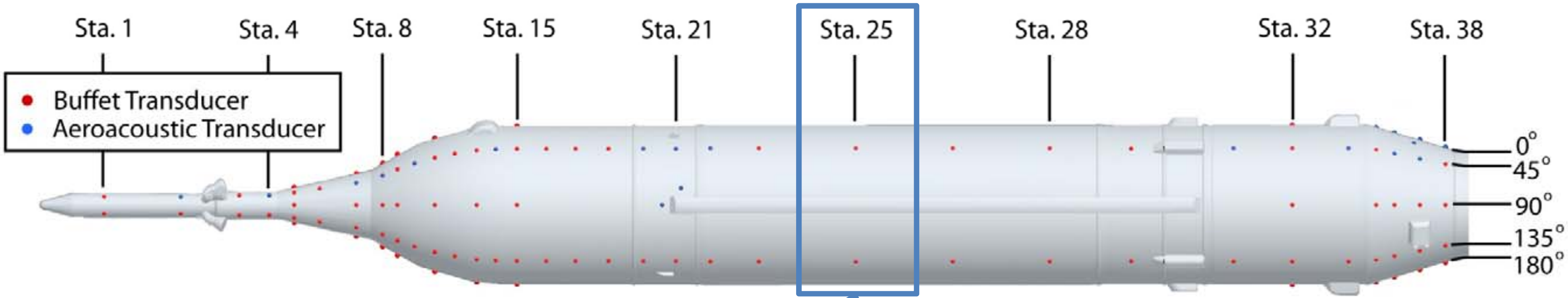
- Langley Transonic Dynamics Tunnel
- Mach 0.5 to 1.2
- R-134a test medium
- Dynamic pressure up to 480 psf
- Reynolds numbers up to 3.6 million
- Model Pitch: ±8° Model Roll: ±180°
- 30-sec records of time history data
- Many terabytes of data!!

Instrumentation

- Model pressure instrumentation
  - 224 buffet bandwidth Kulite pressure transducers
  - 32 aeroacoustic bandwidth Kulite pressure transducers
- Accelerometers and Q-flex inclinometers
  - Six accelerometers for model vibration response
  - 3-axis Q-flex for model orientation (pitch and roll)



Development of Buffet Forcing Functions



Raw Pressure Time Histories (256)

Longitudinal Coherence

Pressure Integration

Scale to Full Scale

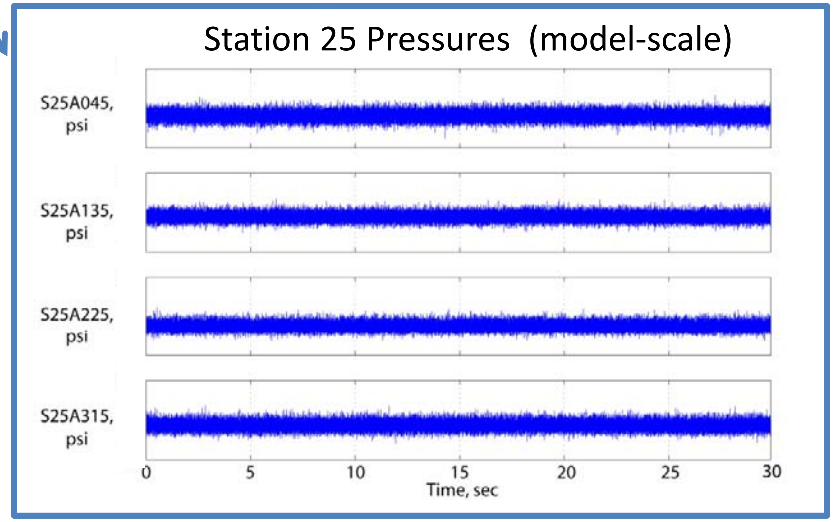
Trajectory Interpolation

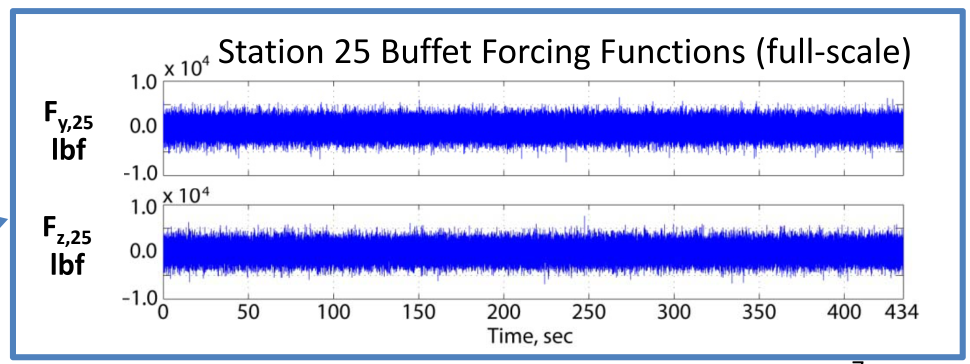
$$F_{fs} = F_{ms} \frac{Q_{fs}}{Q_{ms}} \left(\frac{D_{fs}}{D_{ms}} \right)^2$$

$$T_{fs} = T_{ms} \frac{D_{fs}}{D_{ms}} \frac{V_{ms}}{V_{fs}}$$

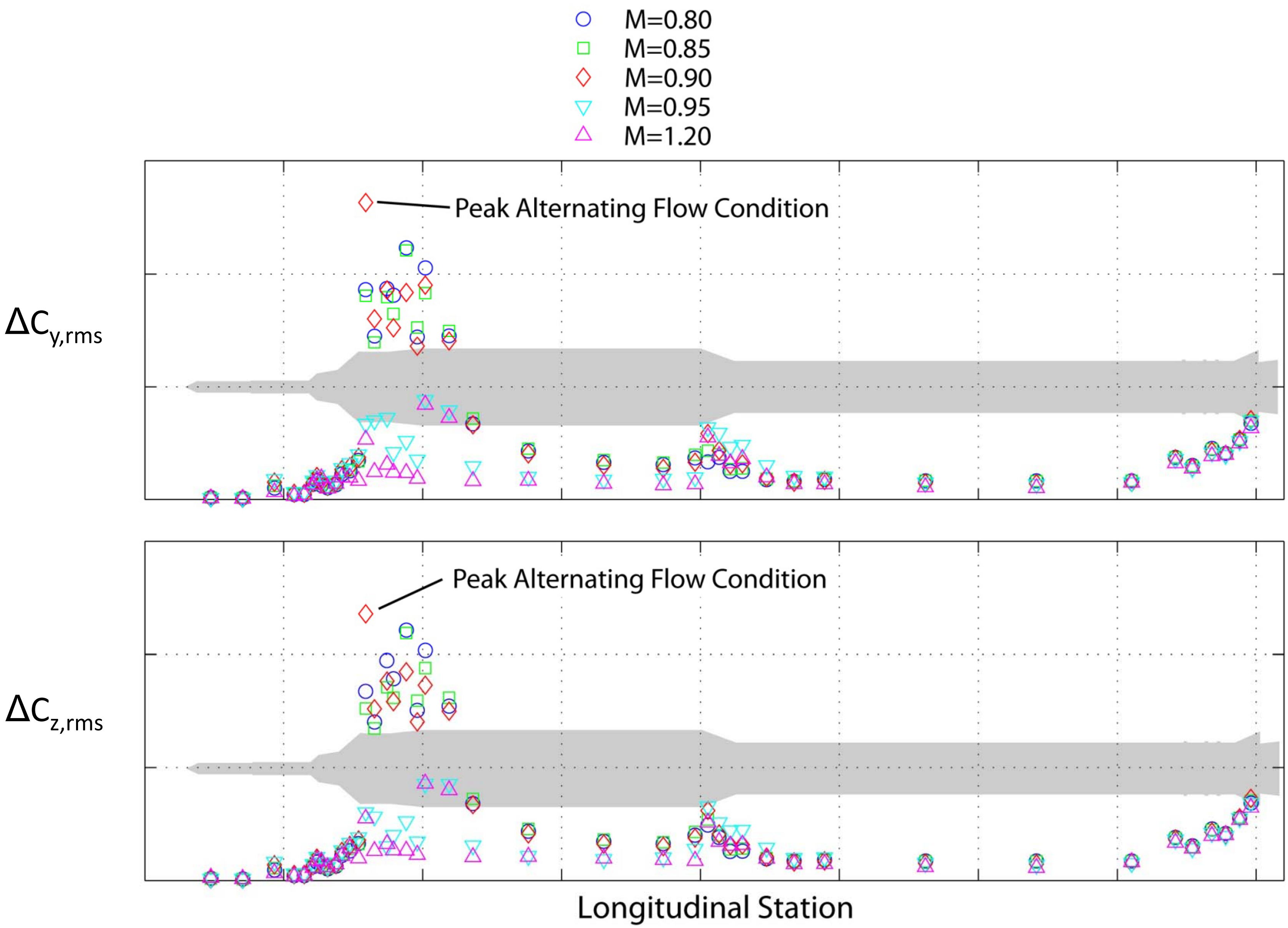
Filter Facility "Noise"

Final BFFs (108)

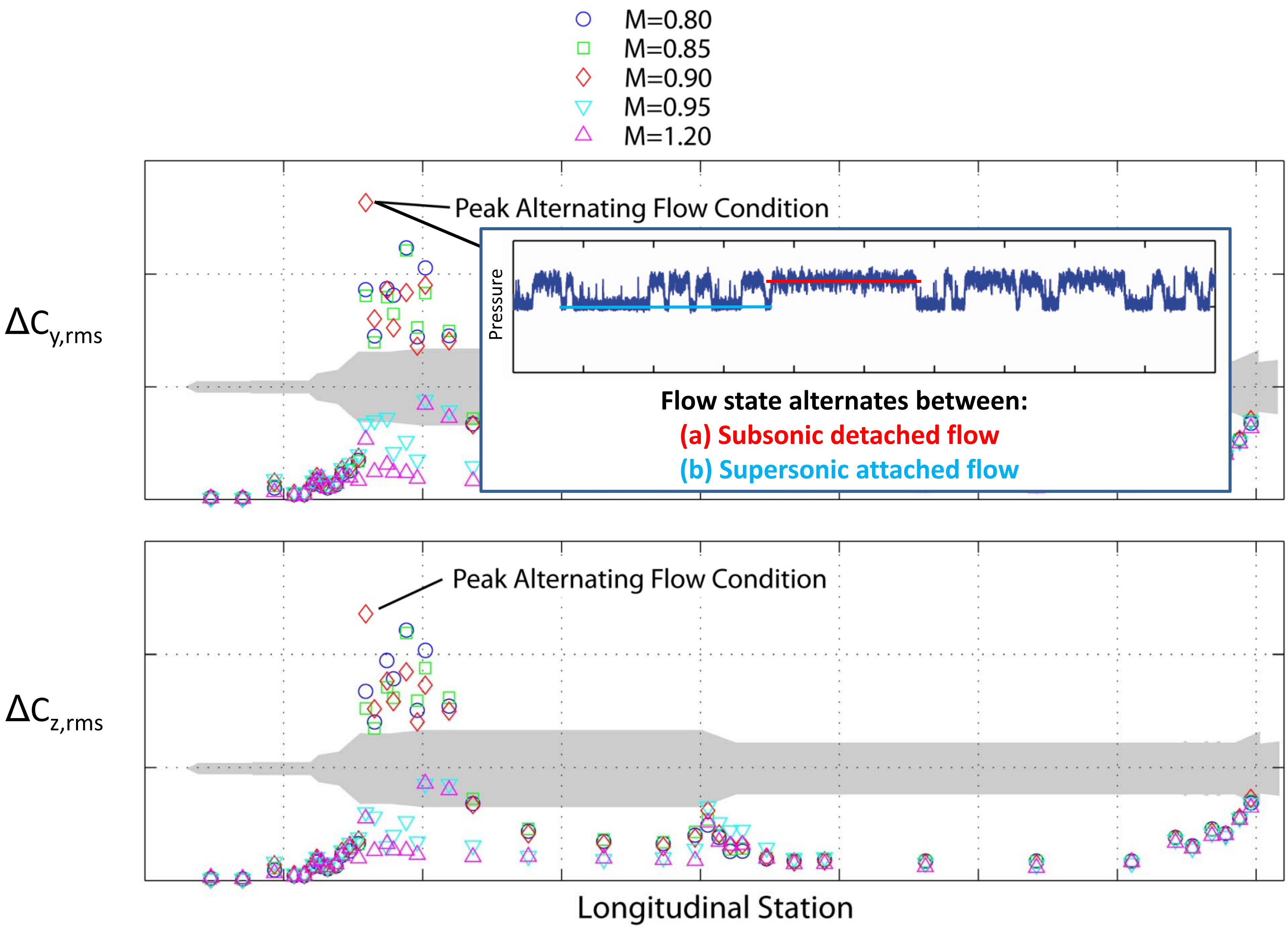




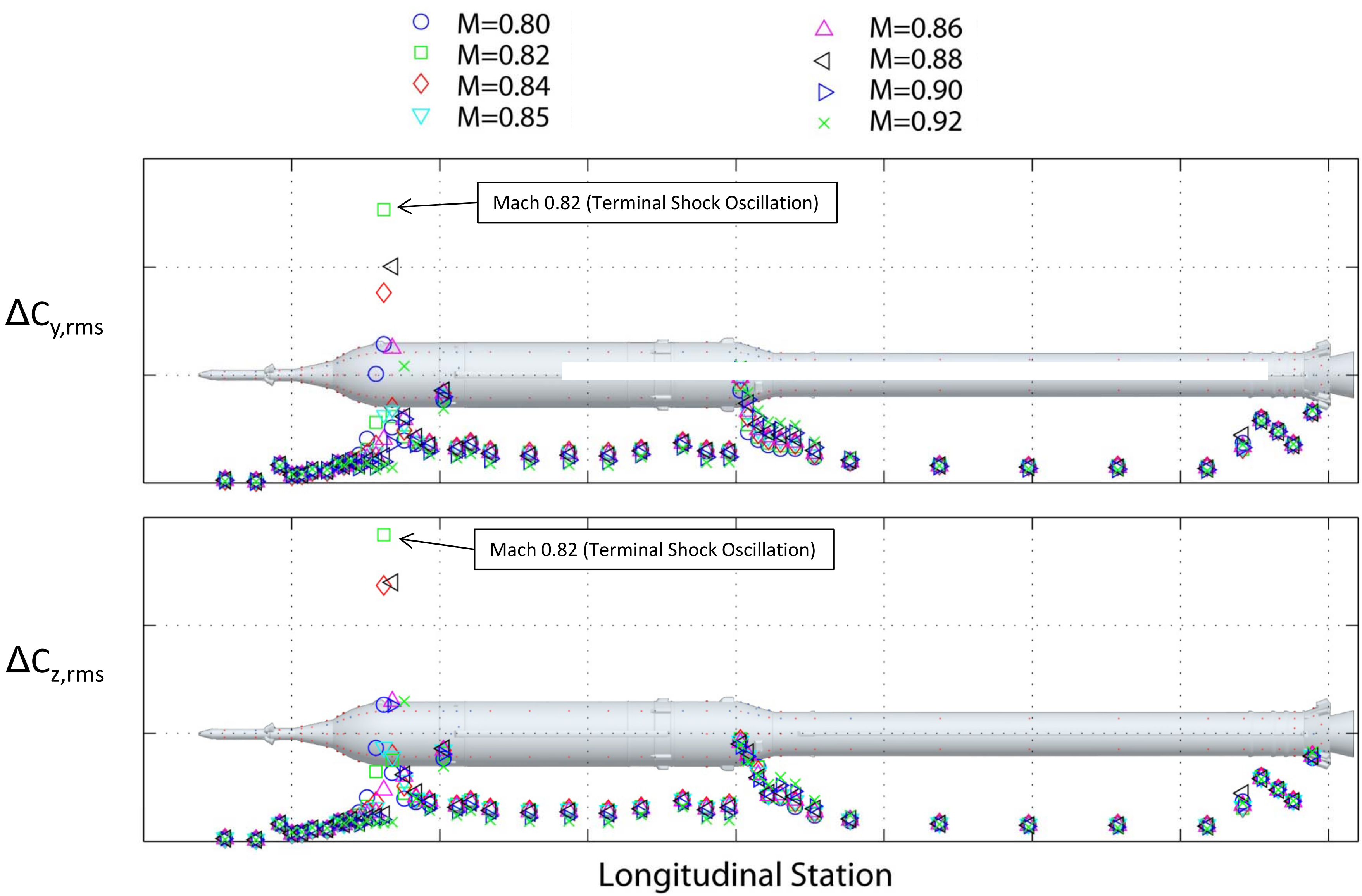
Ares I-X BFF RMS Levels for Mach 0.80 to 1.20



Ares I-X BFF RMS Levels for Mach 0.80 to 1.20



Ares I BFF RMS Levels for Mach 0.80 to 0.92



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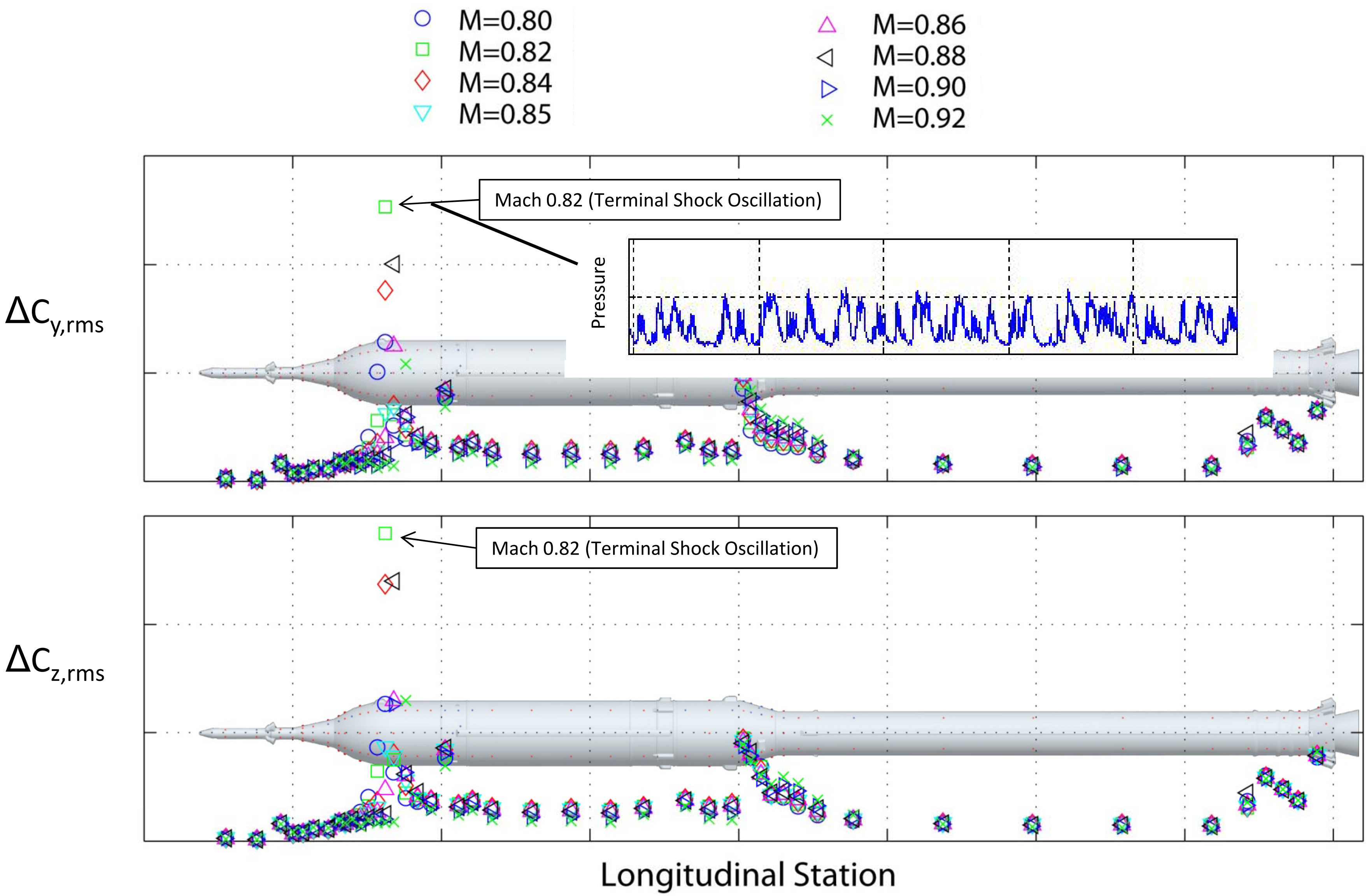
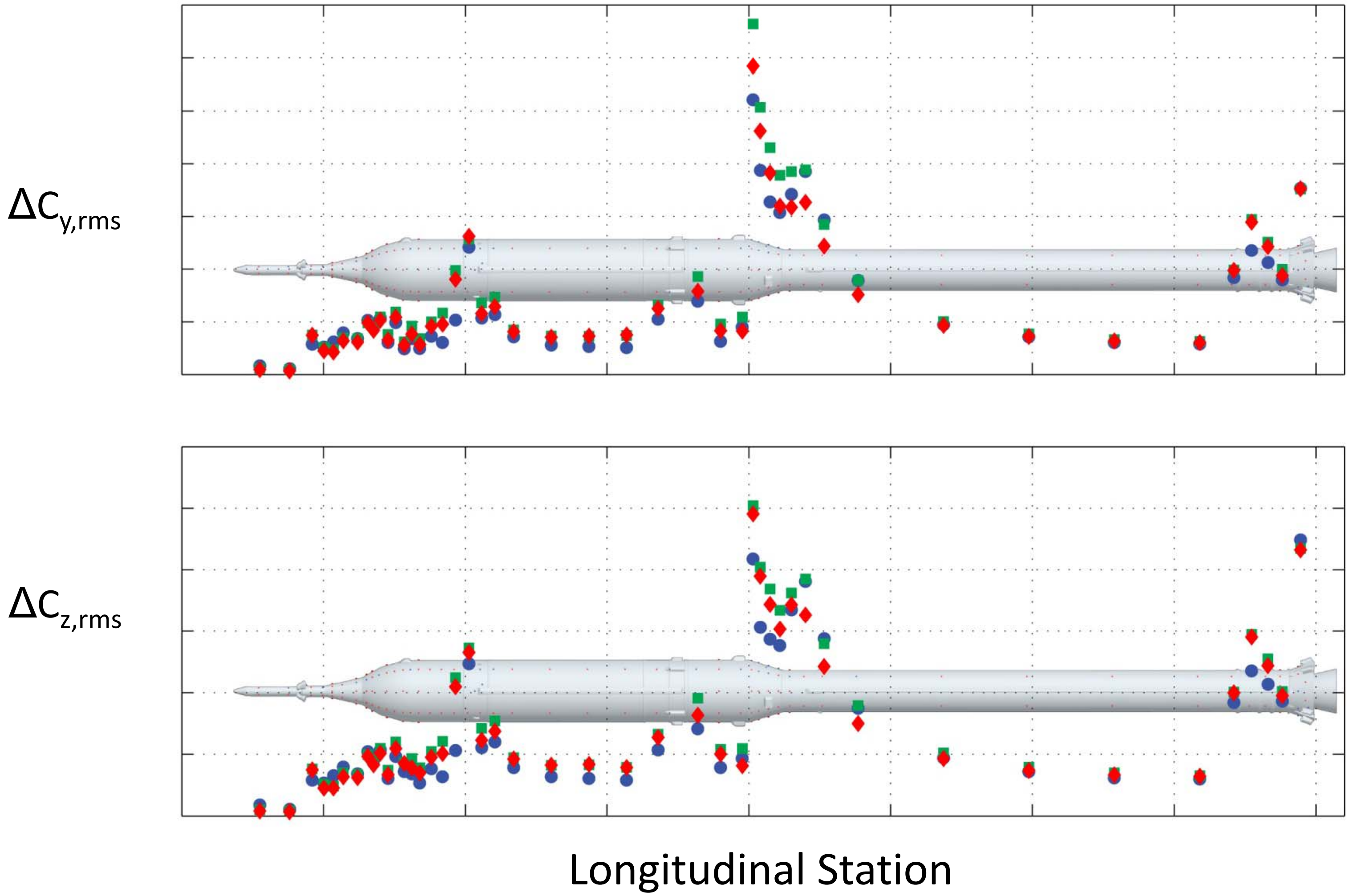
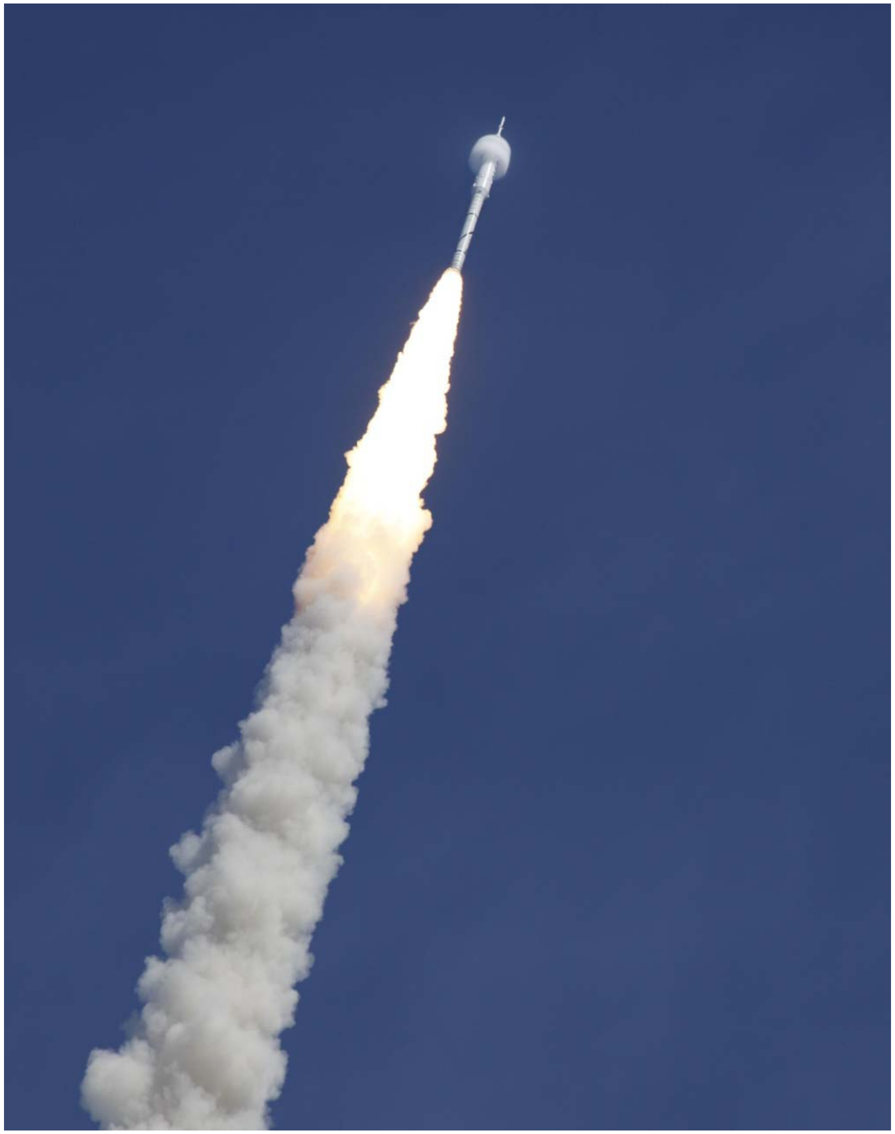


Ares I BFF RMS Levels; High/Low Reynolds Number

- M=0.95 Re=1.07e+006 Air Test Medium; Low Reynolds Number
- M=0.95 Re=3.19e+006 R134a Test Medium; Mid Reynolds Number
- M=0.95 Re=7.17e+006 R134a Test Medium; High Reynolds Number

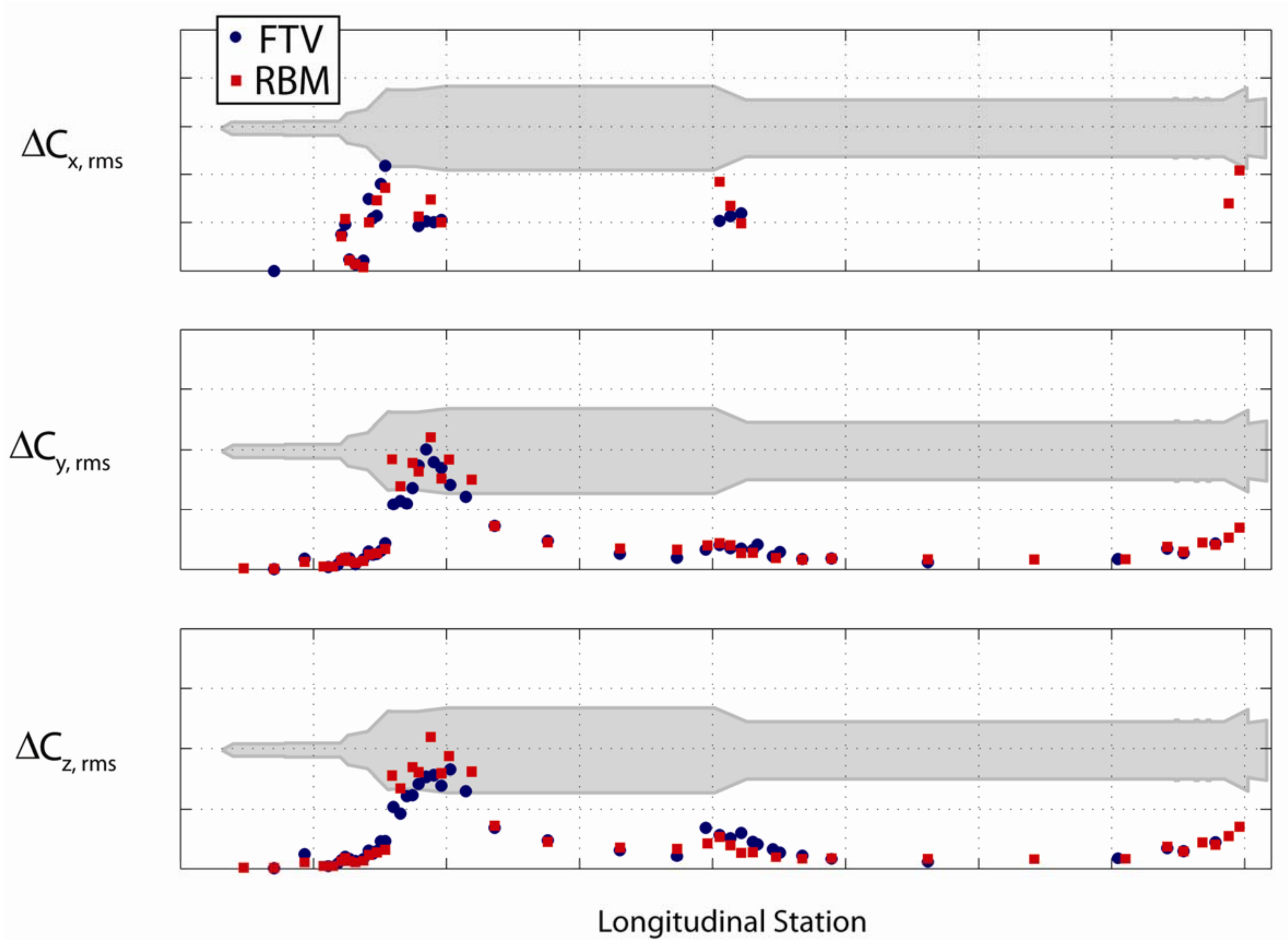


Comparison of Ares I-X FTV and RBM Buffet Environments



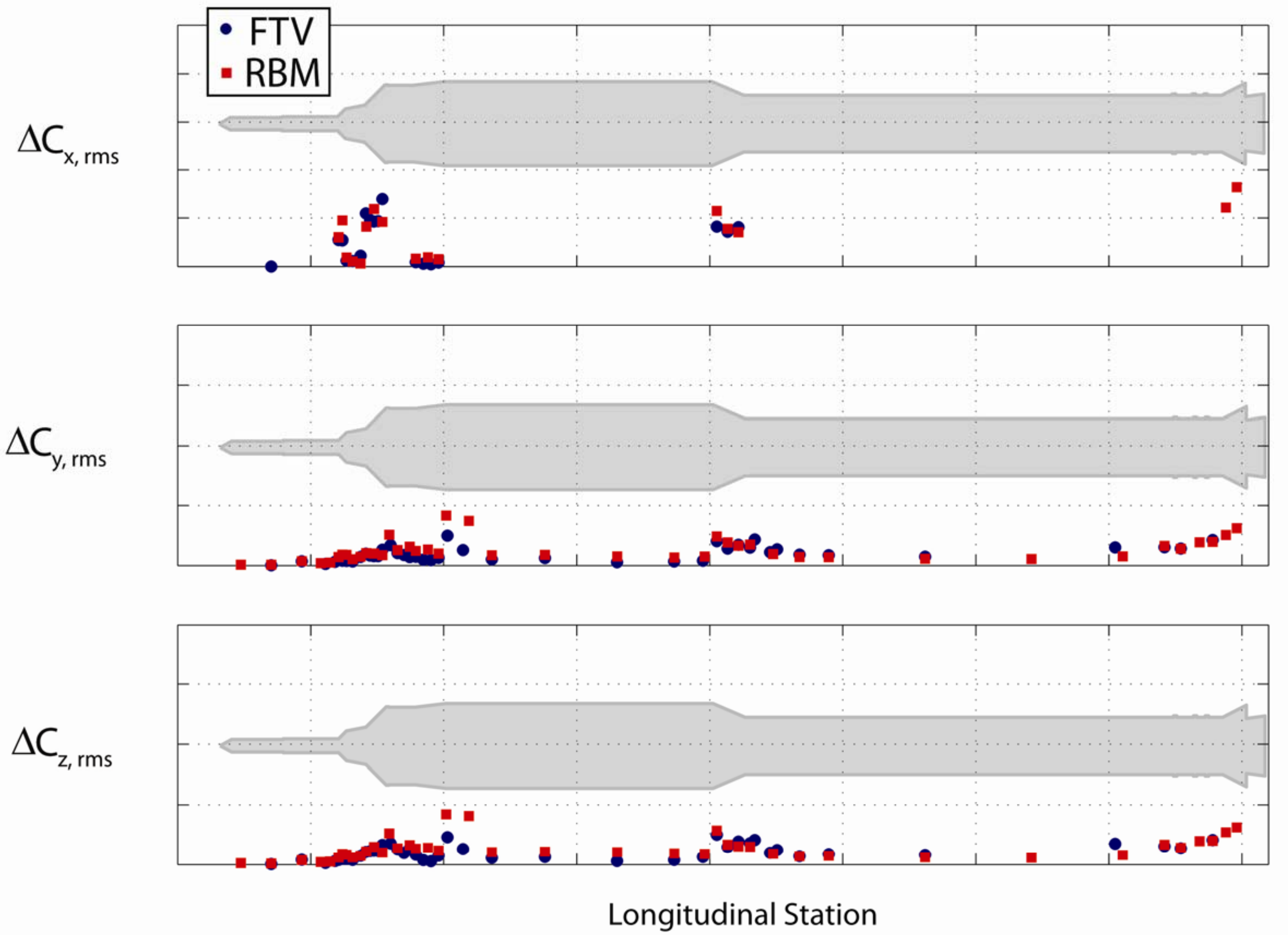
Non-Dimensionalized Sectional BFF RMS; Mach 0.85

- Mach 0.85
- Bandpass 0.5-60 Hz
- Flight Test
  - q=647 psf
  - α=-0.1°; β=-0.8°
  - 1-sec window; detrended
- Wind Tunnel Test
  - q=483 psf
  - scaled to full-scale BET conditions
  - α=0.0°; β=0.0°
  - 433 sec time history

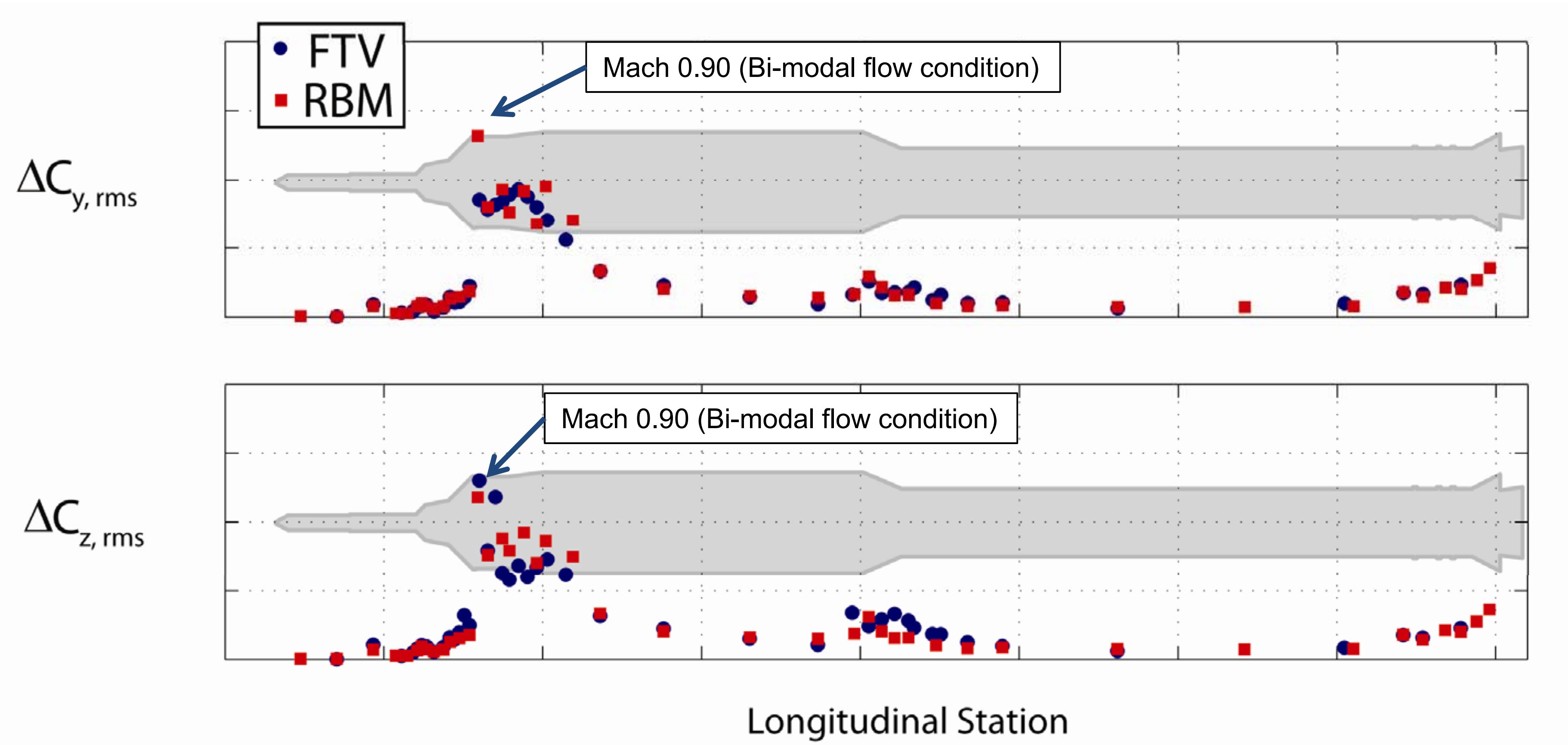


Sectional Buffet Forcing Function RMS; Mach 1.20

- Mach 1.20
- Bandpass 0.5-60 Hz
- Flight Test
  - q=832 psf
  - α=-0.6°; β=-0.5°
  - 1-sec window; detrended
- Wind Tunnel Test
  - q=285 psf
  - scaled to full-scale BET conditions
  - α=0.0°; β=0.0°
  - 433 sec time history



Alternating Flow Separation/Attachment at Mach 0.90



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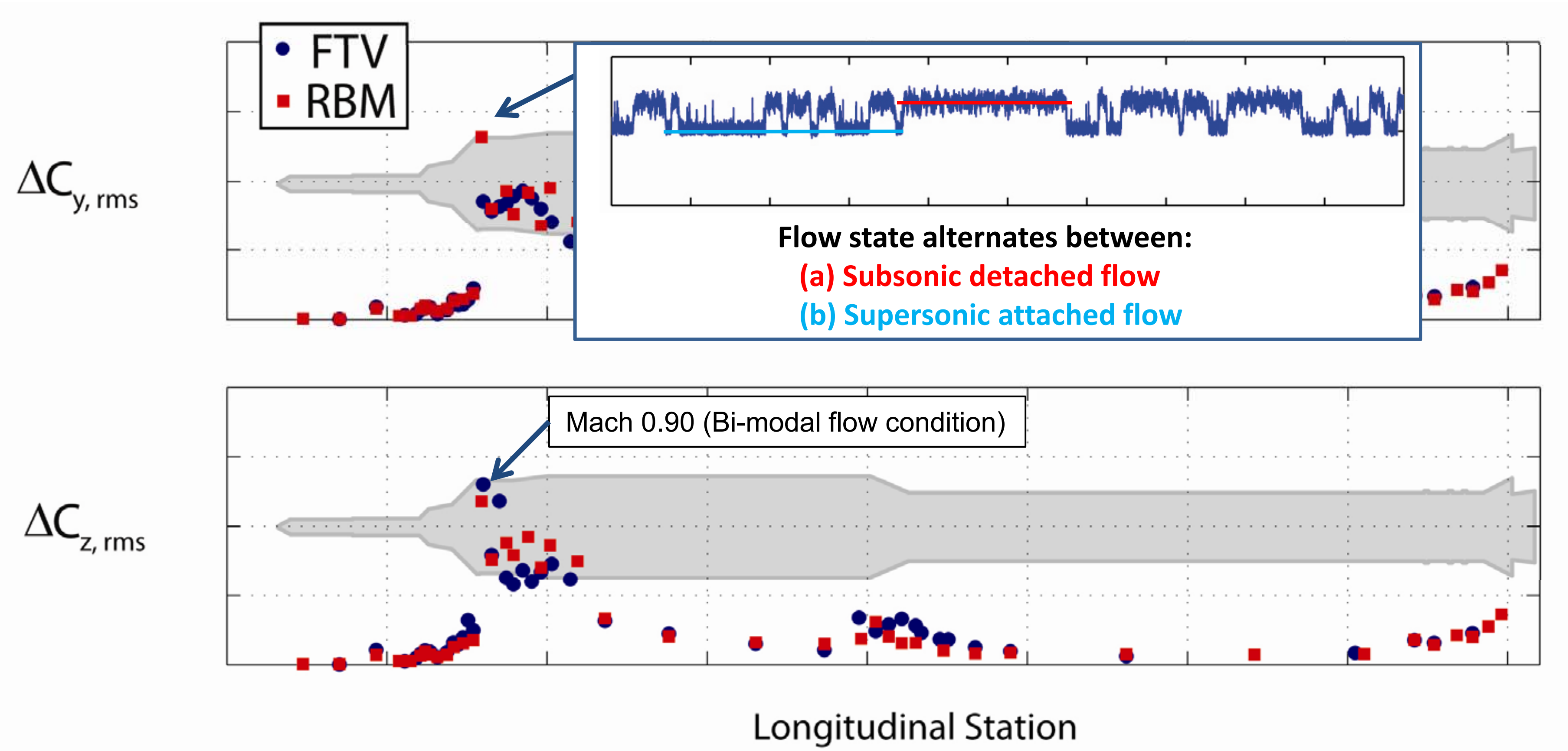
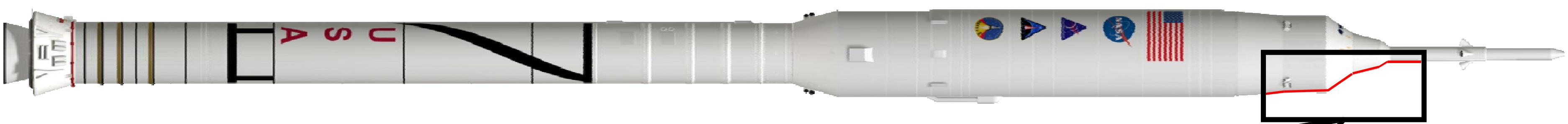
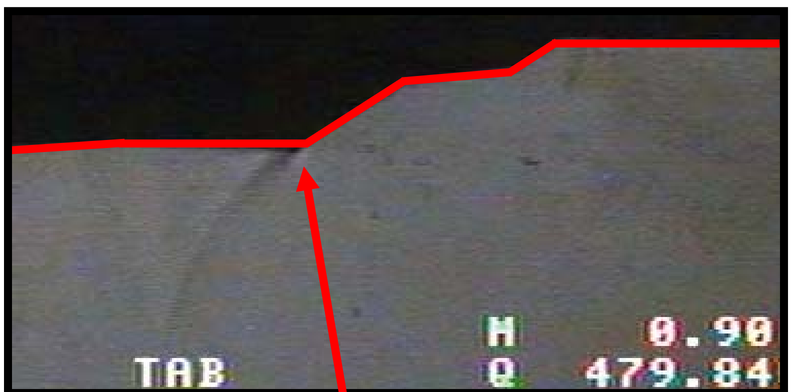


Alternating Flow Separation/Attachment at Mach 0.90

Shadowgraph images used to identify source of large pressure fluctuations

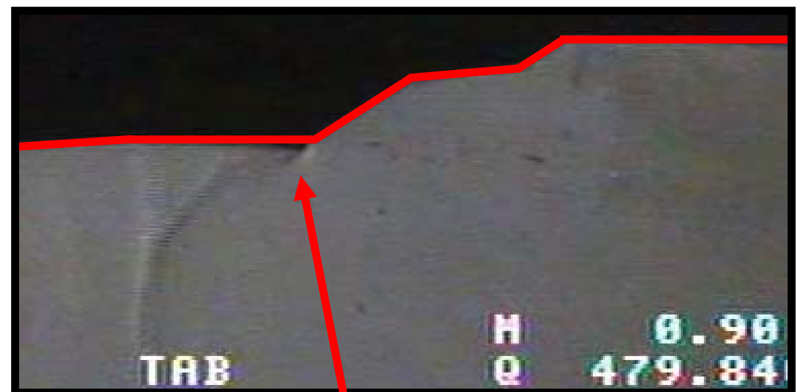


Expansion corner bi-modal state (a)



Subsonic flow at expansion corner

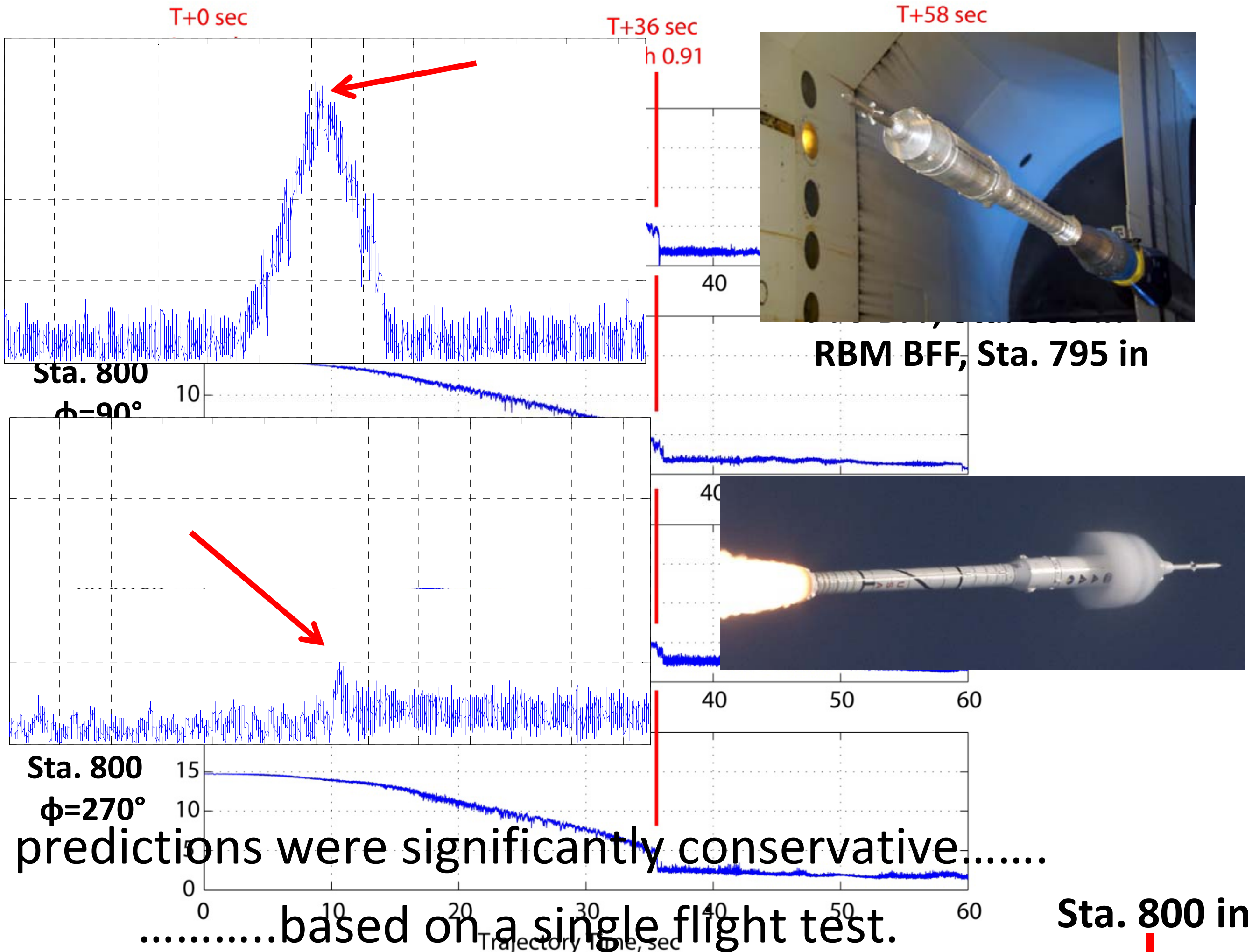
Expansion corner bi-modal state (b)



Supersonic flow at expansion corner w/ normal shock

RBM BFF Magnitude

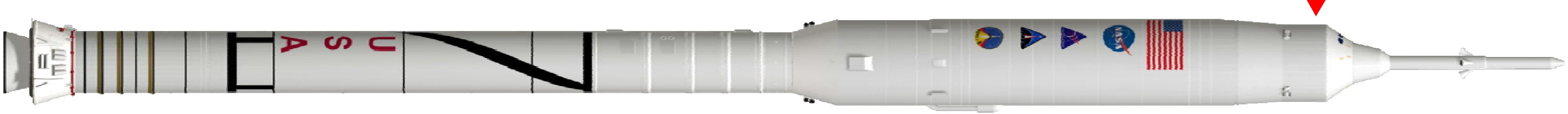
FTV BFF



Wind tunnel predictions were significantly conservative……

……….based on a single flight test.

Sta. 800 in



Lessons Learned

- Wind-tunnel tests of rigid buffet models are complex and expensive, but are the accepted method of obtaining accurate buffet forcing functions
  - Cost of failure is high, though….. Heavy vehicle/less payload or structural failure
- Ares I-X RBM BFFs shown to agree well with flight test buffet environment
- Ares I-X alternating flow pulse load event at Mach 0.9 was over-predicted
  - Was based on worst possible conditions from worst observed wind-tunnel pulse
  - Results from single flight test cannot ensure that significant pulse would not occur
  - Such alternating flow pulse impacts vehicle buffet loads, GNC, and aeroelasticity
- Wind-tunnel phenomenon can impact BFFs, but can be dealt with
  - High conservatism due to discrete measurement locations: coherence analyses to derive "knock down factors" for BFFs
  - Fan blade passage frequencies: Adaptive notch filter technique
- Reynolds number effects observed: recommend testing at highest Rn possible
- Rigid buffet testing does not address when the vehicle structural response interacts with and modifies the unsteady separated flow of the buffet environment
  - For the aeroelastic buffeting loads, you need a buffet response test (partial mode testing)
- Guidelines from literature (NASA SP-8001) can be used to dictate early OML design choices, but BFFs cannot be derived using publicly available reports.

Ares Buffet Documentation

Documents & Databases

- Ares I-X RBM
  - Test Summary Document (ARES-AE-TA-0002)
  - Database of Full-scale Buffet Forcing Functions (ARES-AE-TA-0005 Release 8/21/2008)
- Ares I RBM
  - Database of Full-scale Buffet Forcing Functions (ARES-AE-DBR-0001)
  - Test Summary Document (ARES-AE-TA-0012)
  - Analysis and Results Document (ARES-AE-TA-0013)
  - Database of Buffet Pressure Forcing Functions (ARES-AE-DBR-0003)
  - Orion Ascent Abort Buffet Forcing Functions Database (FTO-AFT-FTA-051)

Orion Program

- Ares I-X FTV
  - Buffet Assessment Technical Analysis report (AIX-TAR-ARO005)
- Publications
  - Piatak, D. J., Sekula, M.K., Rausch, R.D., "Ares Launch Vehicle Transonic Buffet Testing and Analysis Techniques". AIAA-2010-4369. Presented at the 28th AIAA Applied Aerodynamics Conference, Chicago, IL, June 28- July 1, 2010.
  - Sekula, M.K., Piatak, D.J., Rausch, R.D., "Analysis of a Transonic Alternating Flow Phenomenon Observed During Ares Wind Tunnel Tests". AIAA-2010-4370. Presented at the 28th AIAA Applied Aerodynamics Conference, Chicago, IL, June 28- July 1, 2010.
  - Sekula, M.K., Piatak, D.J., Rausch, R.D., "Comparison of Ares I-X Wind-Tunnel Derived Buffet Environment with Flight Data". AIAA-2011-3013. Presented at the 29th AIAA Applied Aerodynamics Conference, Honolulu, Hawaii, June 27-30, 2011.

Backup Slides

Acknowledgements

The authors wish to acknowledge their collaboration:

- Jamie Canino
- Shin-Hsing Chen
- Sam Lee
- Brian Sako

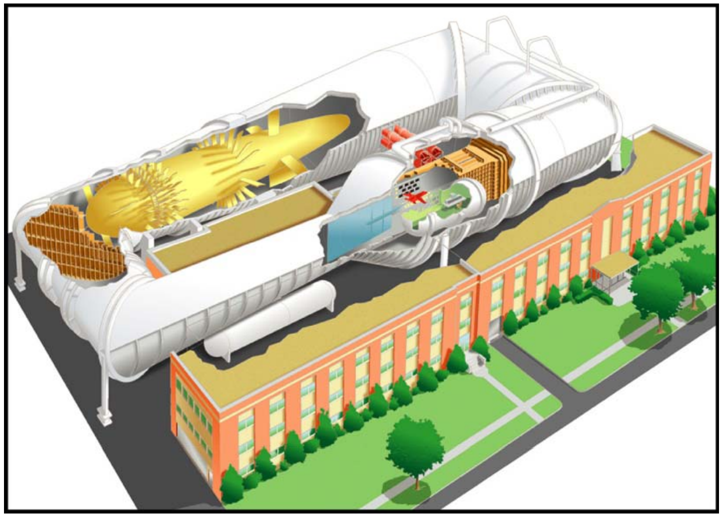
(Aerospace Corporation)

- Craig Streett (NASA Langley)

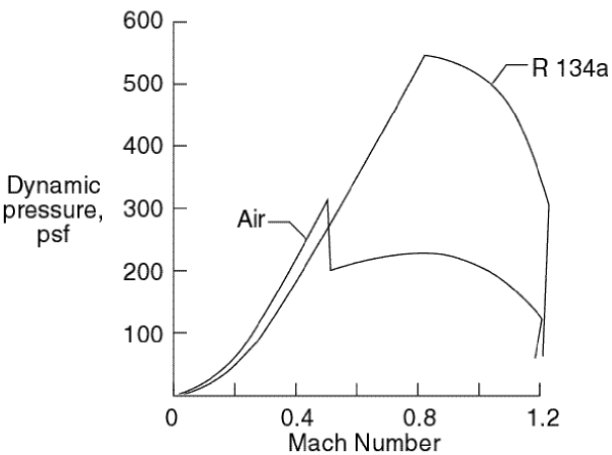
Outline

- Buffet Environments and Buffet Loads
- Overview of Buffet Test Program
- Buffet Test Results
- Ares I-X FTV and RBM Buffet Environment Comparisons
- Conclusions
- Lessons Learned
- Ares Buffet Program Documentation

Test Facility: LaRC Transonic Dynamics Tunnel (TDT)



Wind tunnel	**Closed-circuit, continuous-flow**
Test section	**16 feet x 16 feet**
Test medium	**R-134a or Air**
Mach number	**0 to 1.2, continuous**
Re number (max)	**9.6×10^6 per foot (R-134a)** **3.0×10^6 per foot (Air)**
Dynamic pressure (max)	**550 psf (R-134a)** **320 psf (Air)**



Frequency Scaling

$$f_{fs} = f_{ms} \frac{D_{ms}}{D_{fs}} \frac{V_{fs}}{V_{ms}}$$

Typical Rigid Buffet Model Test Conditions

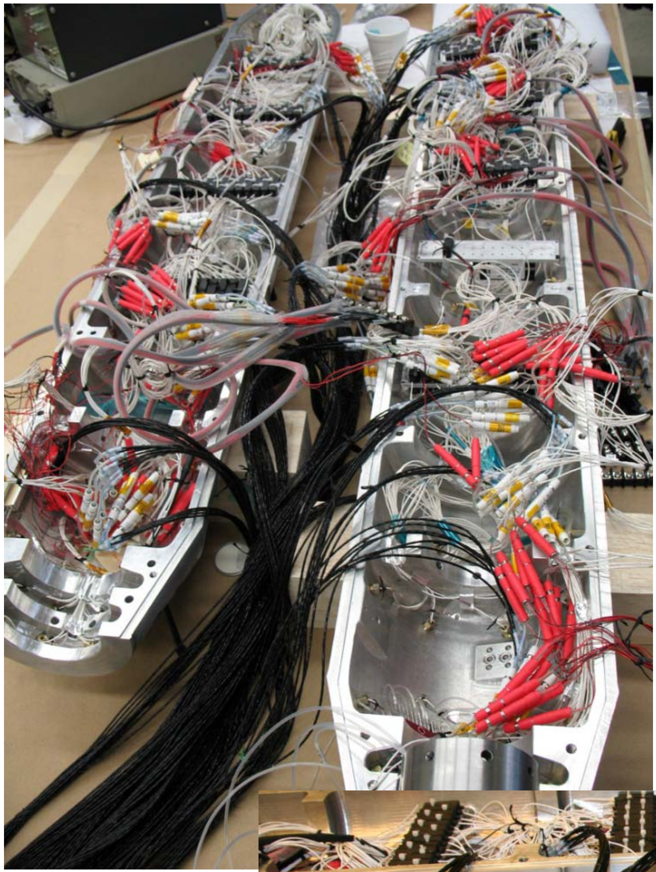
Test Medium	Mach Number	Q, psf	V, ft/s	Speed of Sound, ft/s	Rn (based on 1st stage diameter)	Model Scale Bandwidth, Hz (60Hz Full Scale)	Model Scale Bandwidth, Hz (2KHz Full Scale)
Air	0.80	220	919	1149	522,364	1,817	60,570
Air	1.15	150	1204	1047	316,480	1,673	55,754
R134a	0.80	480	440	550	3,633,500	870	29,000
R134a	1.20	300	653	544	1,573,800	907	30,238

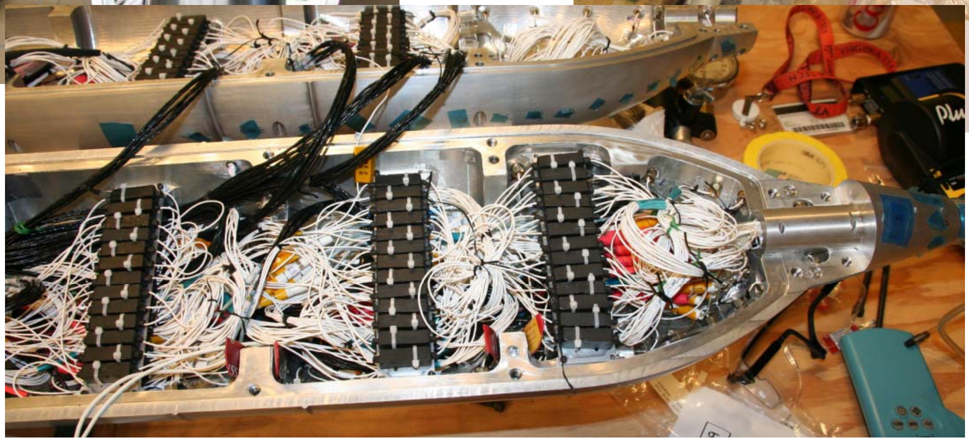
Rigid Buffet Model Scaling Laws

Scaling of PSDs and loads based on dimensional analysis as discussed and verified by Jones and Foughner (1963)

Pressure	Force	Time	Frequency
$P_{fs} = P_{ms} \frac{Q_{fs}}{Q_{ms}}$	$F_{fs} = F_{ms} \frac{Q_{fs}}{Q_{ms}} \left(\frac{D_{fs}}{D_{ms}} \right)^2$	$T_{fs} = T_{ms} \frac{D_{fs}}{D_{ms}} \frac{V_{ms}}{V_{fs}}$	$f_{fs} = f_{ms} \frac{D_{ms}}{D_{fs}} \frac{V_{fs}}{V_{ms}}$

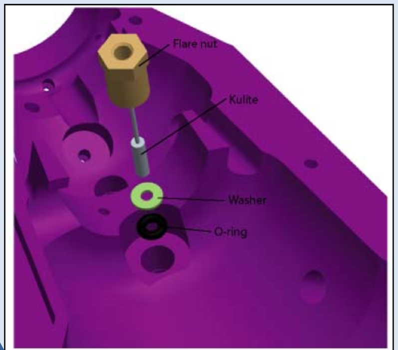
Instrumentation, cont.

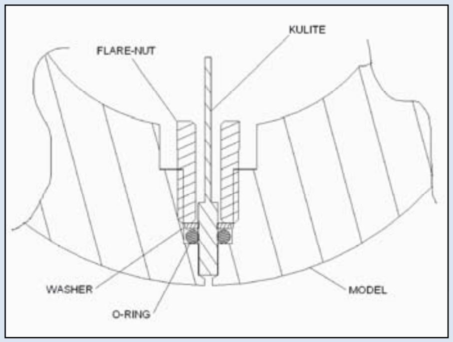




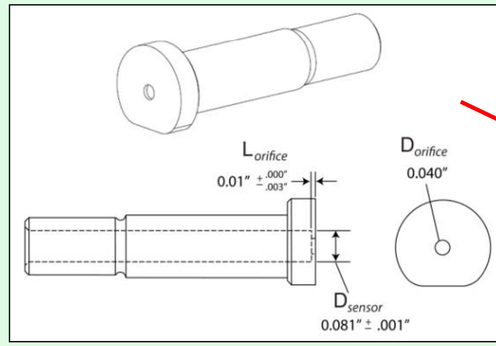
Instrumentation, cont.

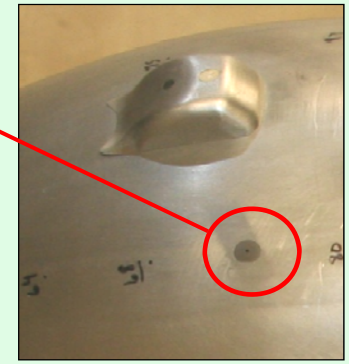
***Buffet Kulite Installation*: Rubber O-ring, washer, and flare tube nut**



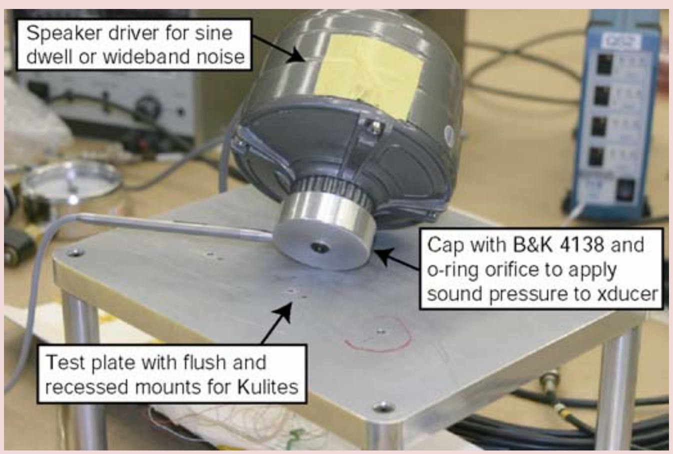


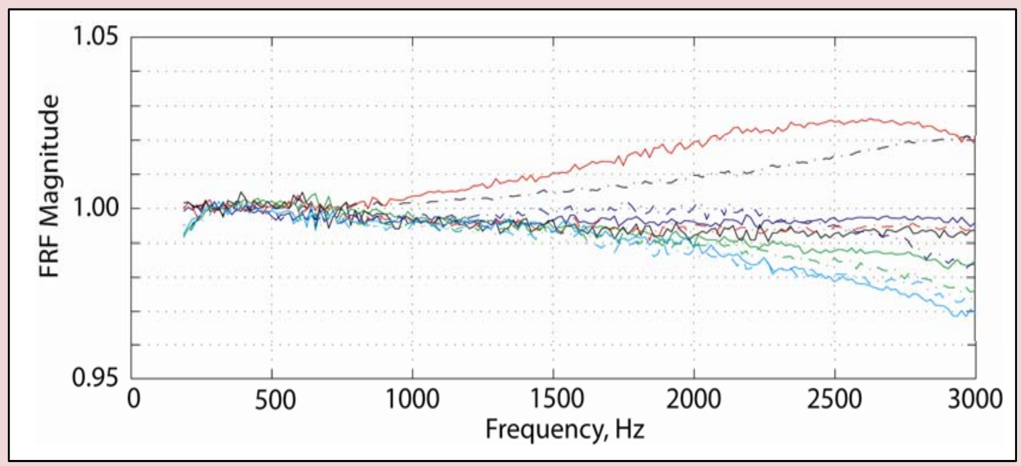
***Aeroacoustic Kulite Installation*: Precision insert and hand-worked to OML**





Transducer Frequency Response In-Situ Testing





Data Acquisition Systems

TDT OADAS NEFF 620

- 1,000 Hz sample rate (200 Hz anti-alias filter)
- Tunnel parameters
- 64 model Kulites
- 6 accels
- 4 q-flexes
- 24 pressure rail Kulites
- ESP steady pressures

Trigger

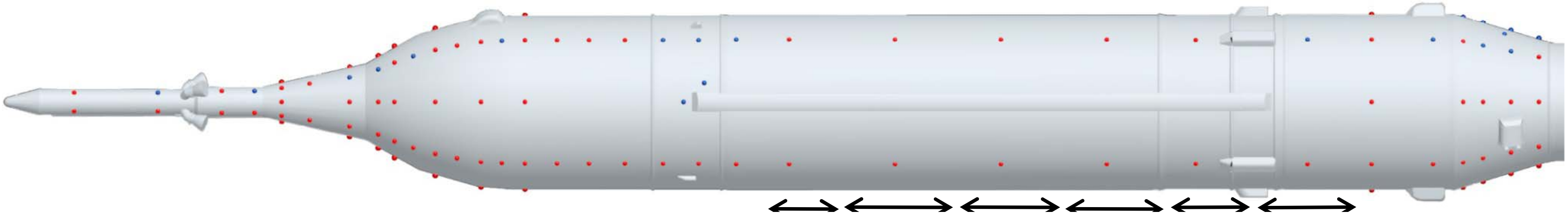
MIIDAS NEFF 730

- **12,000 Hz sample rate (4,500 Hz anti-alias filter)**
- **256 Buffet Kulites**
- **6 accels**
- **Steady and Dynamic Reference signals**

DSPCon Piranha III

- **100,000 Hz sample rate**
- **32 Aeroacoustic Kulites**

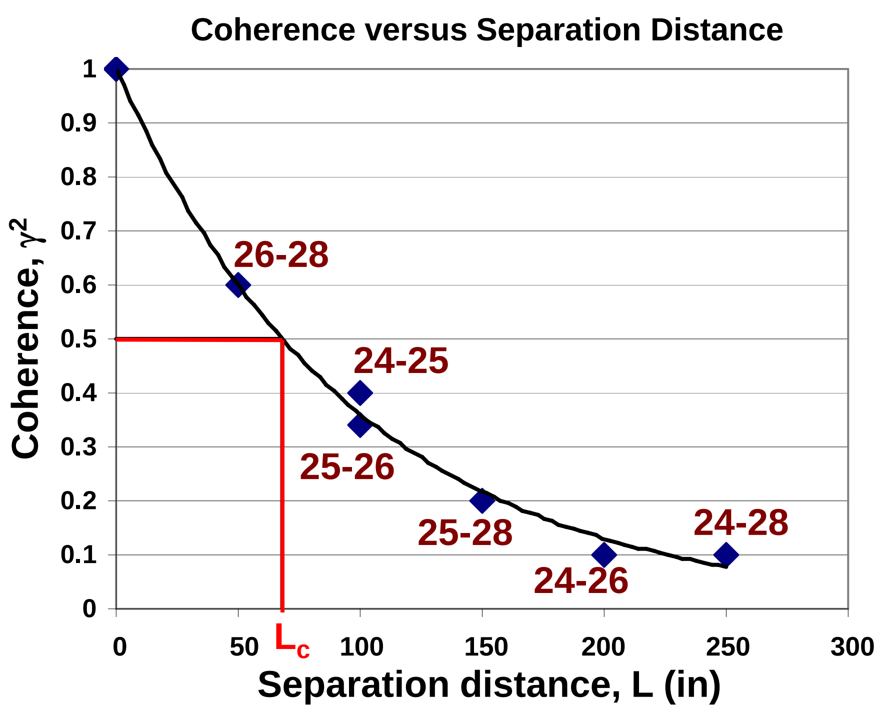
Longitudinal Coherence Analysis



Spatial coherence relates to the degree of correlation between two signals

- **Magnitude, phase, and frequency of pressure signals are not constant on vehicle surface**
- **Integration of pressures assumes that pressure is fully correlated over integration area**
- **Assuming fully correlated pressures would result in over-prediction of buffet loads**

1. **Identify regions dominated by a similar aerodynamic environment**
2. **Calculate longitudinal coherence between in-line sensors over the regions. Full coherence azimuthally is assumed.**
3. **Determine effective length of sensor zonal area based on region coherence.**



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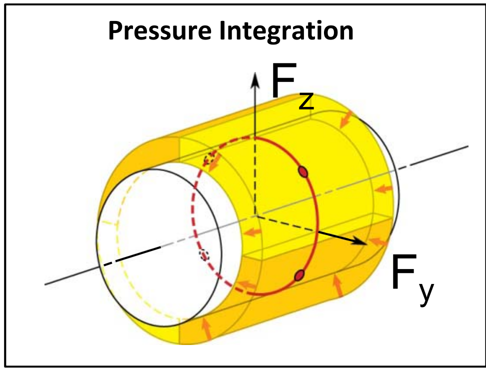

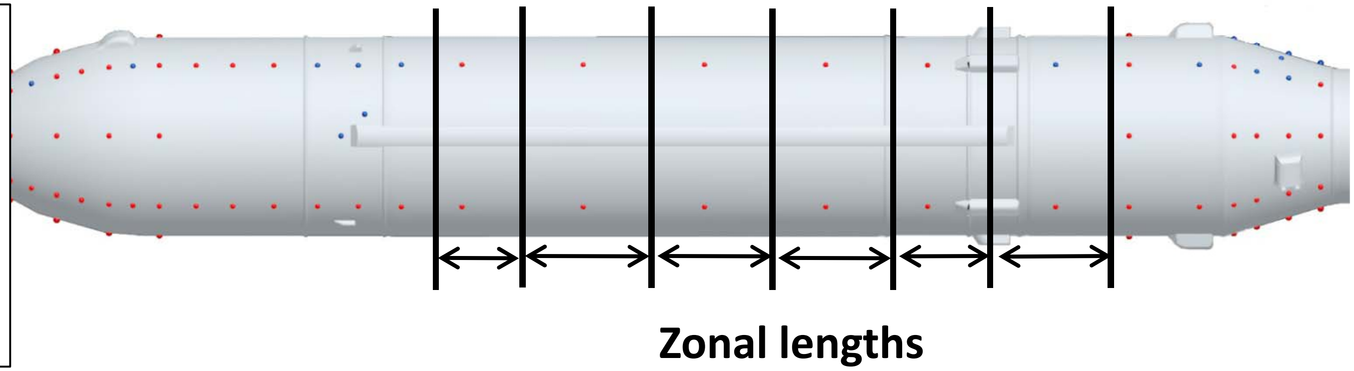

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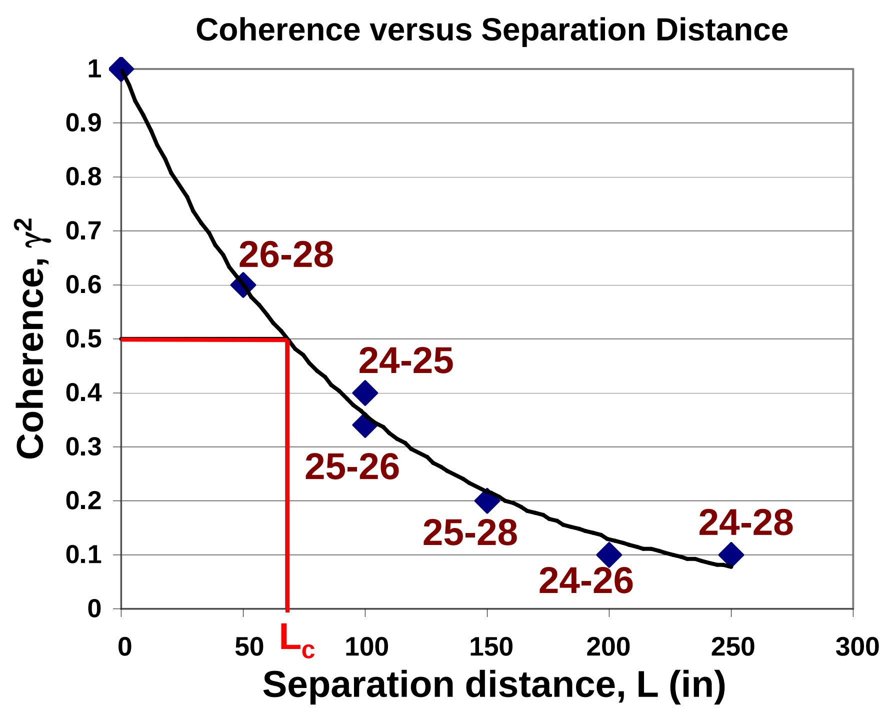

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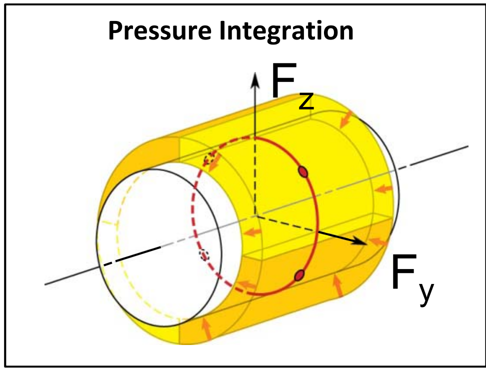

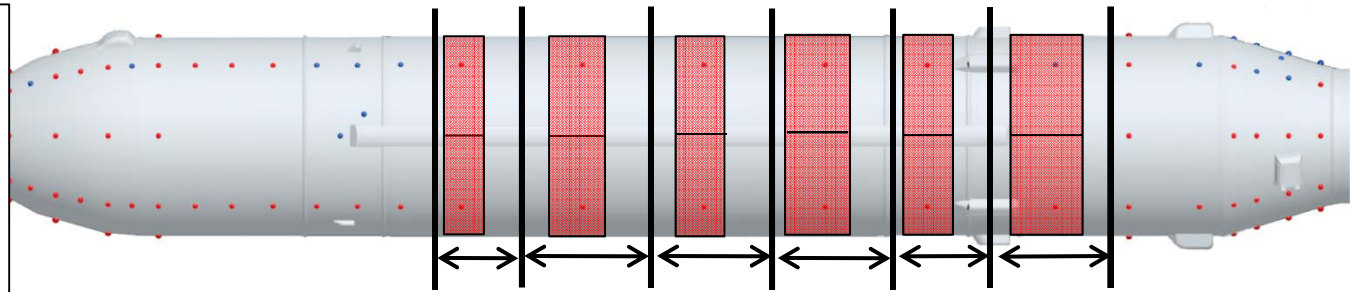

Coherence Lengths

Coherence lengths are determined to reduce the pressure integration area and reduce conservatism of BFFs

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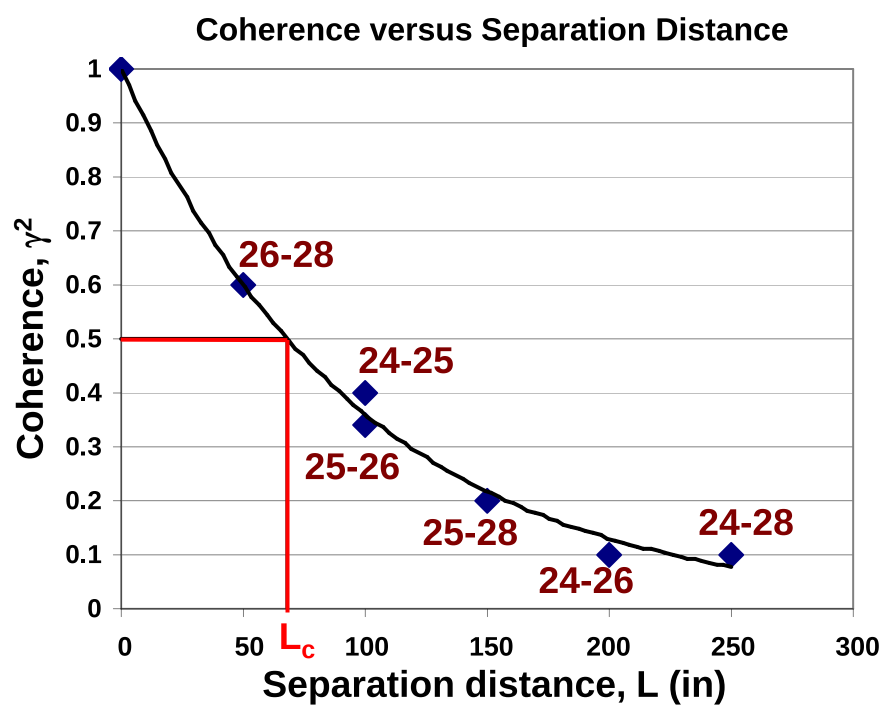
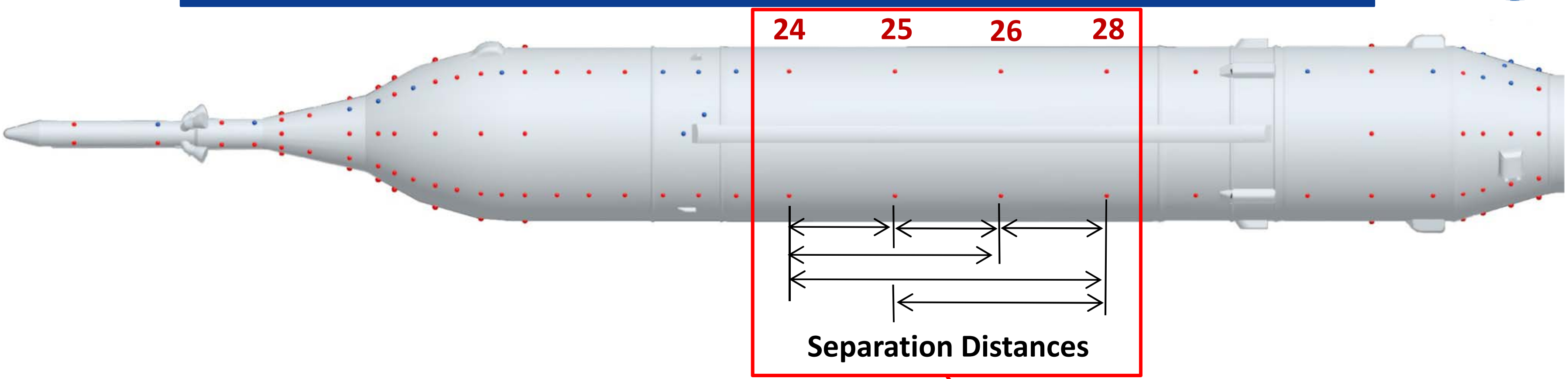
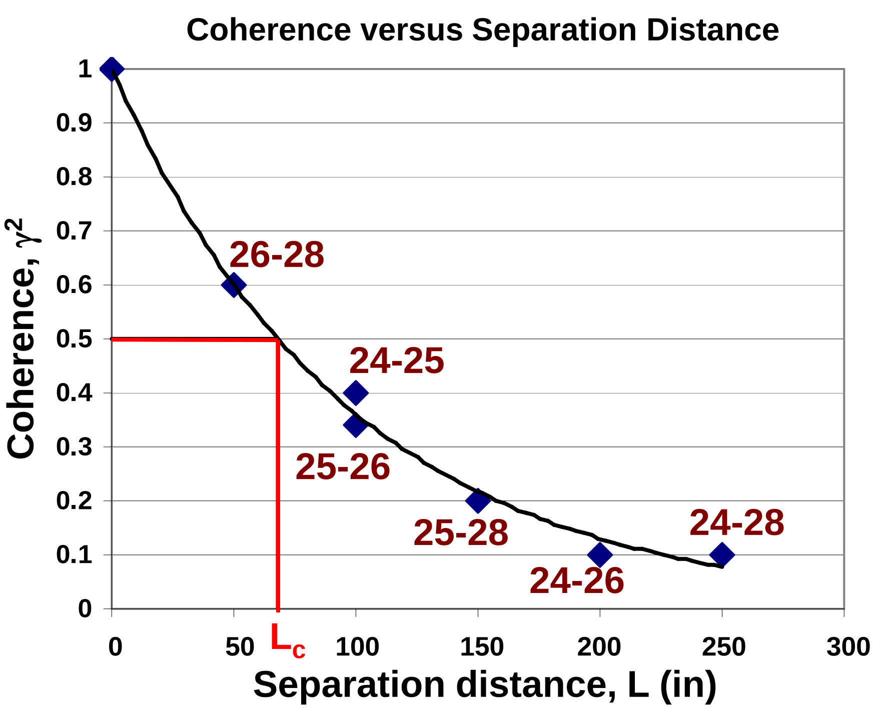


Longitudinal Coherence Analysis





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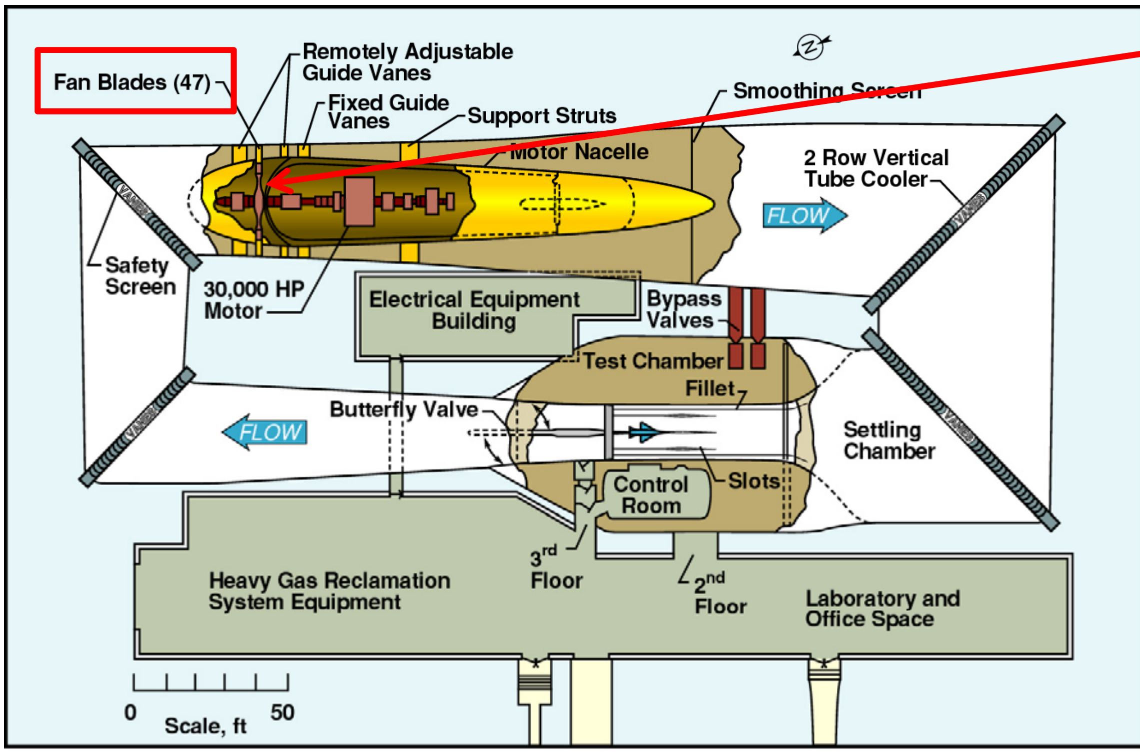
3. **Determine effective length of sensor zonal area based on region coherence.**

Filtering of Facility Noise

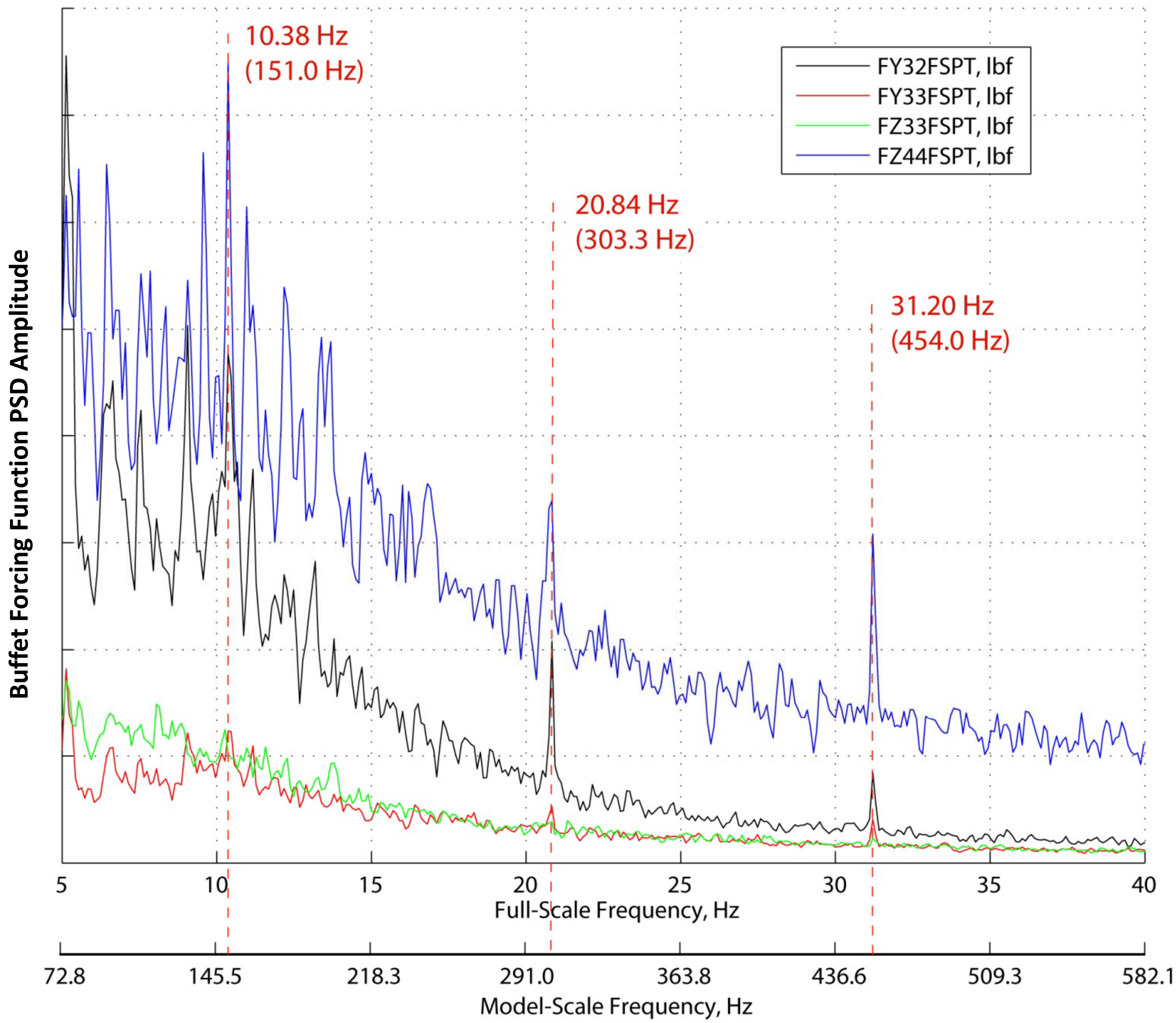
- Harmonics of TDT blade passage frequency (BPF) are present in measured pressure time histories and resulting buffet forcing functions
- This frequency content is an artifact of the wind-tunnel environment and not present in the buffet environment of the Ares I launch vehicle



$$\omega_{BPF} = \frac{47 * RPM}{60}$$

Mach Number	ω_{BPF}
0.80	149.5 Hz
0.85	154.0 Hz
0.90	157.8 Hz
0.95	165.6 Hz
1.1	183.6 Hz
1.2	182.0 Hz

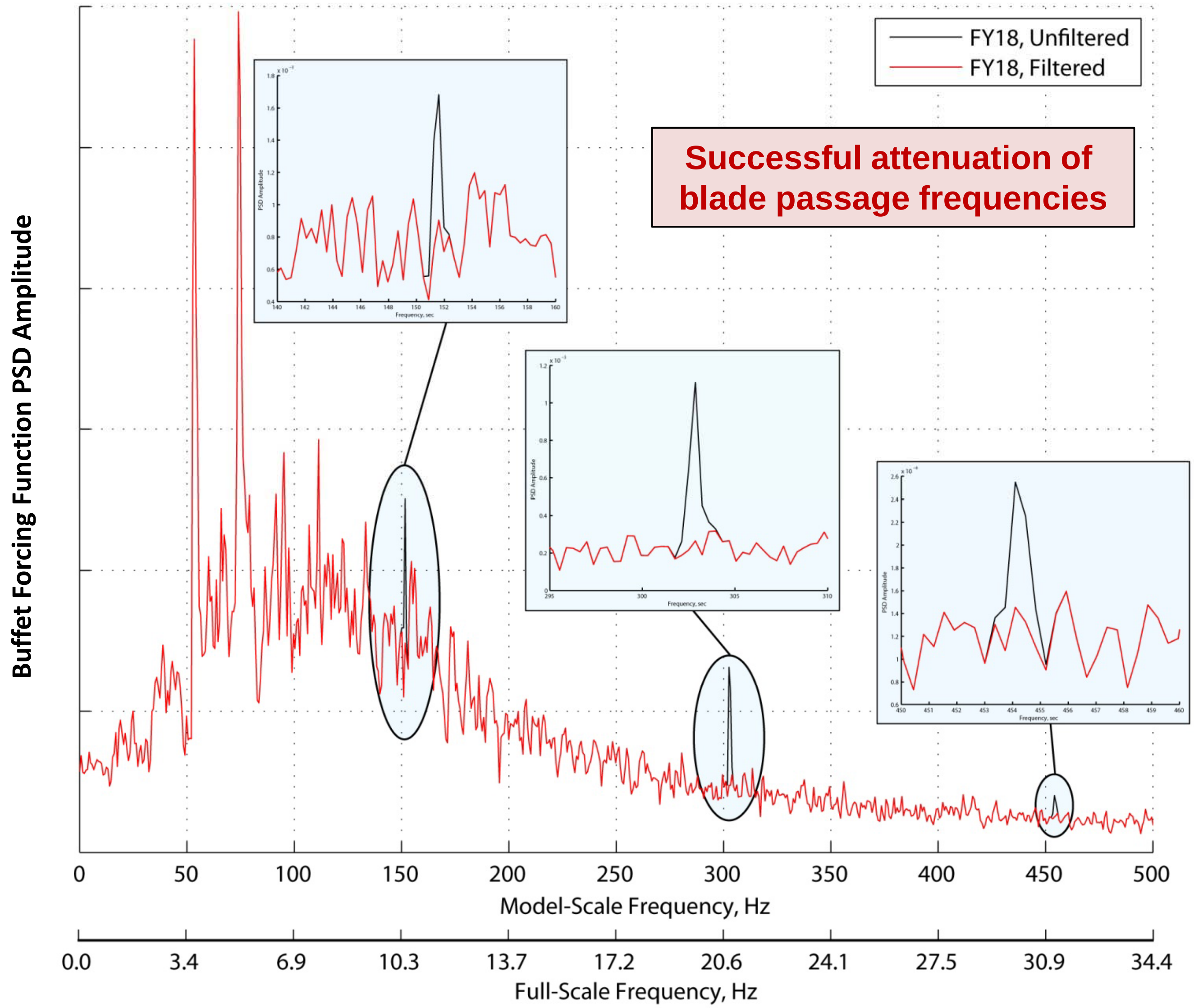
Example of Ares I BFF PSDs; Mach 0.82



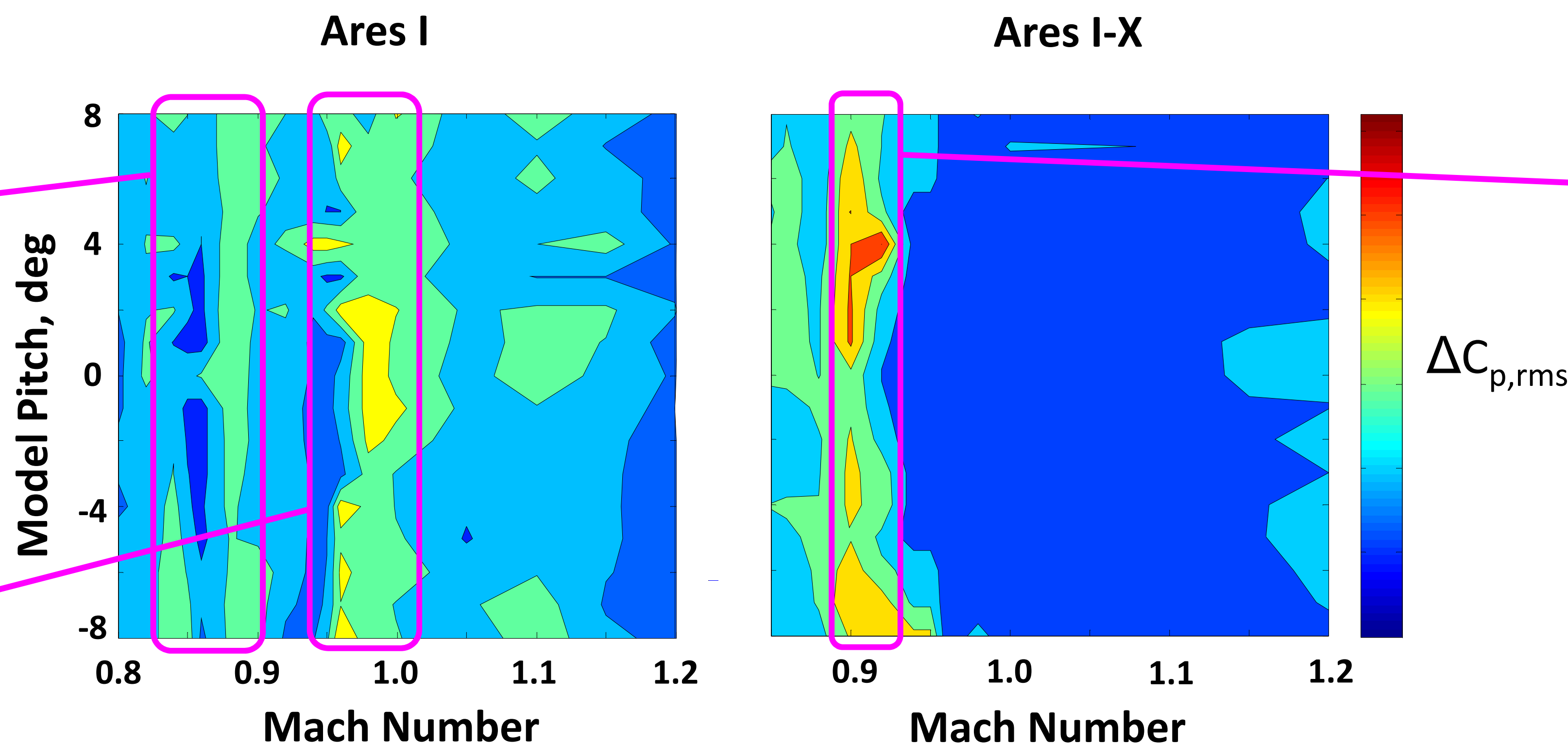
- Filter attenuation must adapt to the BPF harmonic content of each forcing function
- BPF harmonics change with Mach number

- Solution: Develop automated method to determine notch filter frequency response for each BFF and apply filter to time-domain BFFs.

Filter Results; Ares I BFF PSD; Mach 0.82



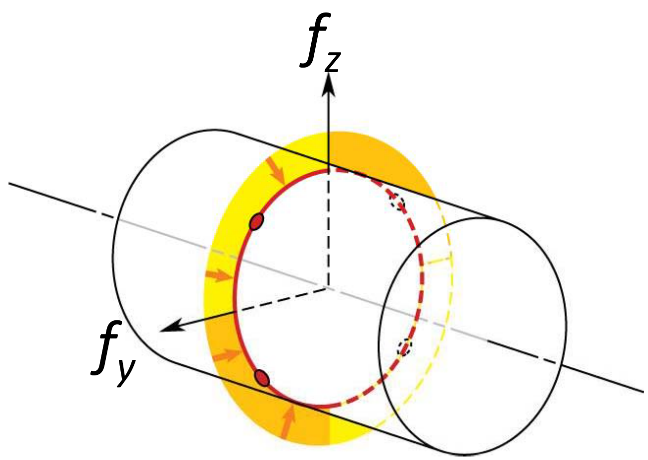
Ares I and I-X Maximum $\Delta C_{p,rms}$



Maximum $\Delta C_{p,rms}$ values for entire vehicle useful for identifying conditions corresponding to peak buffet environments

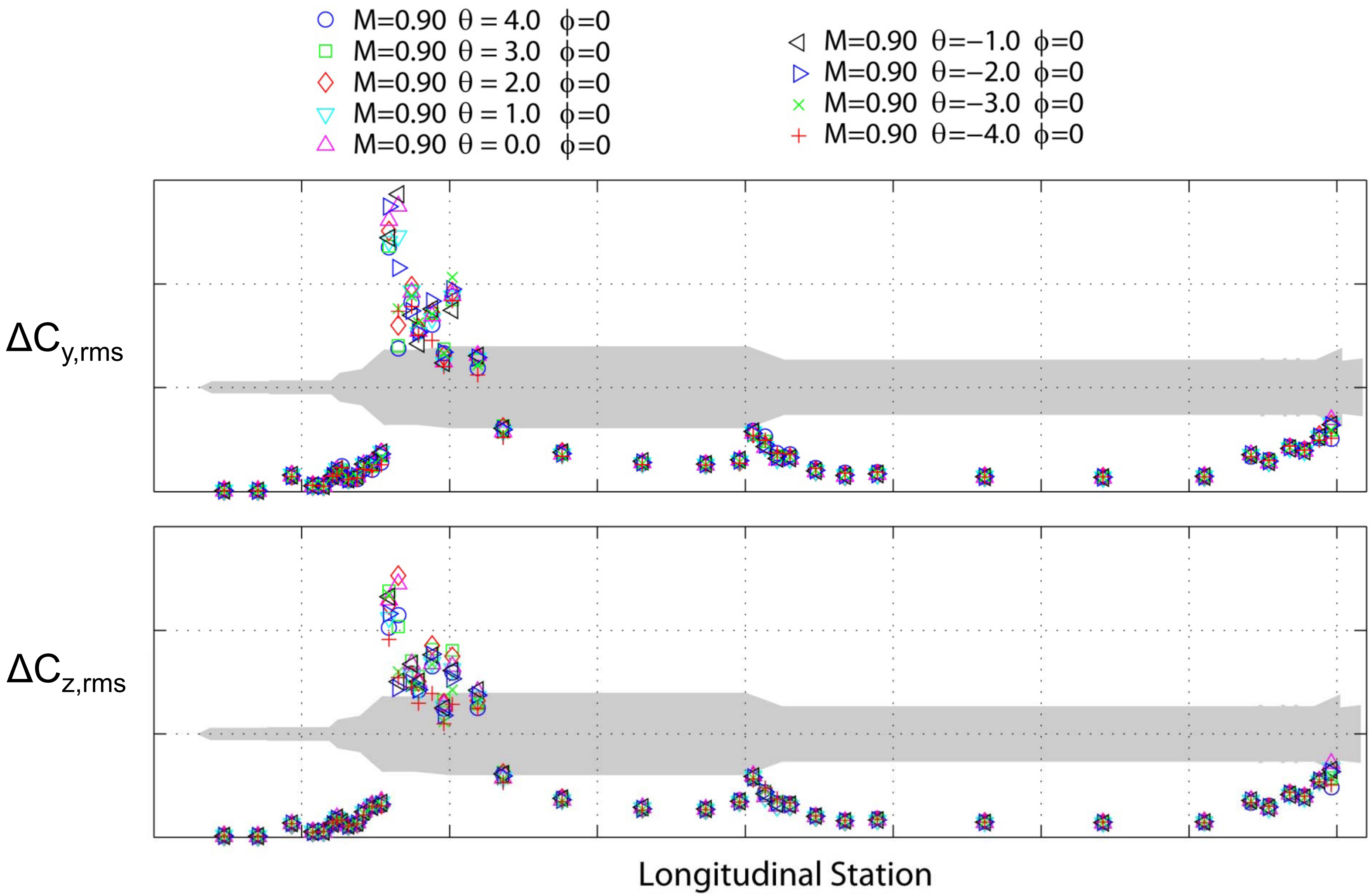
Rigid Buffet Model Test Results

Normalized Sectional Buffet Forcing Function RMS: $\Delta C_{y,rms}$ $\Delta C_{z,rms}$

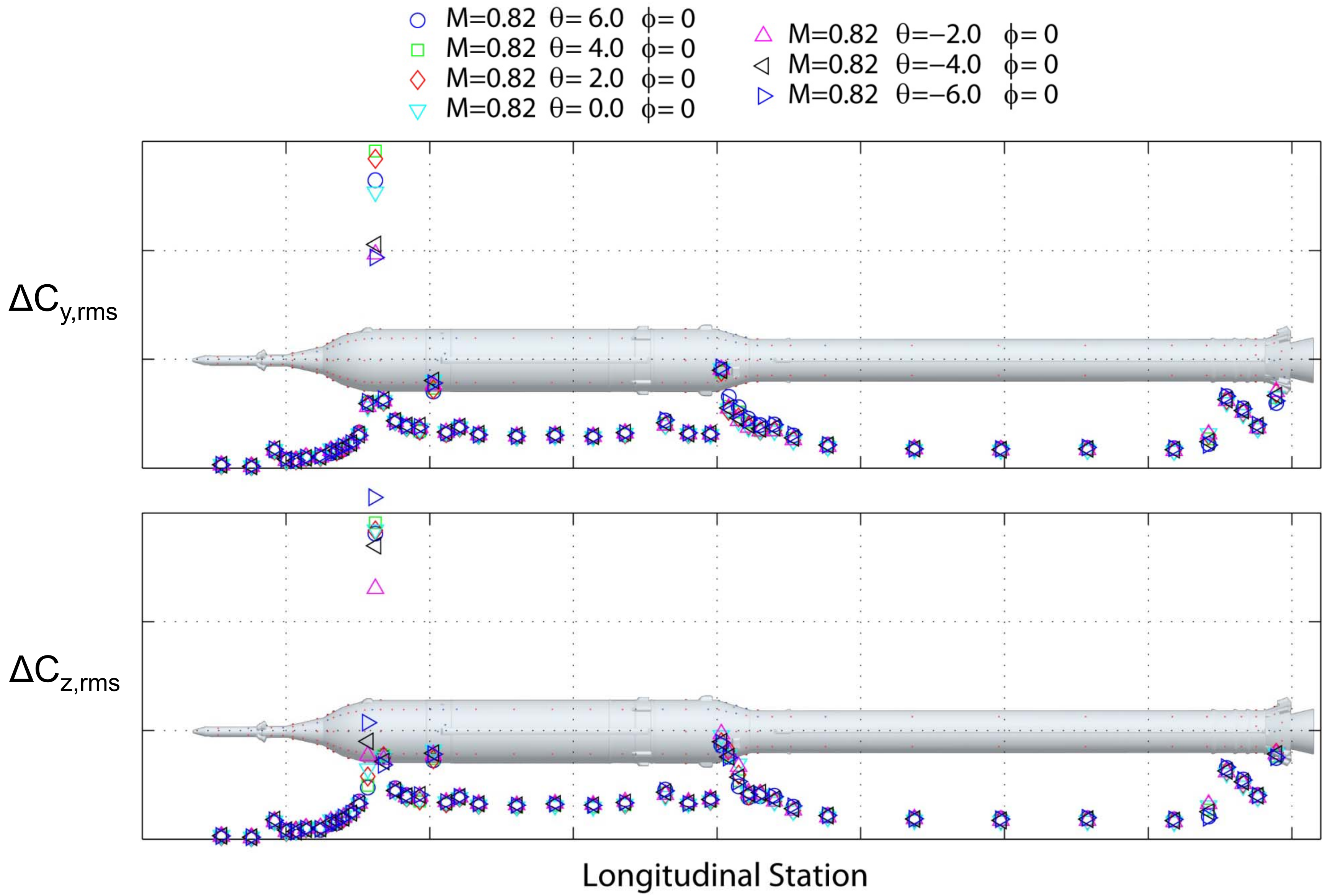


f_y, f_z : *lbf/in*

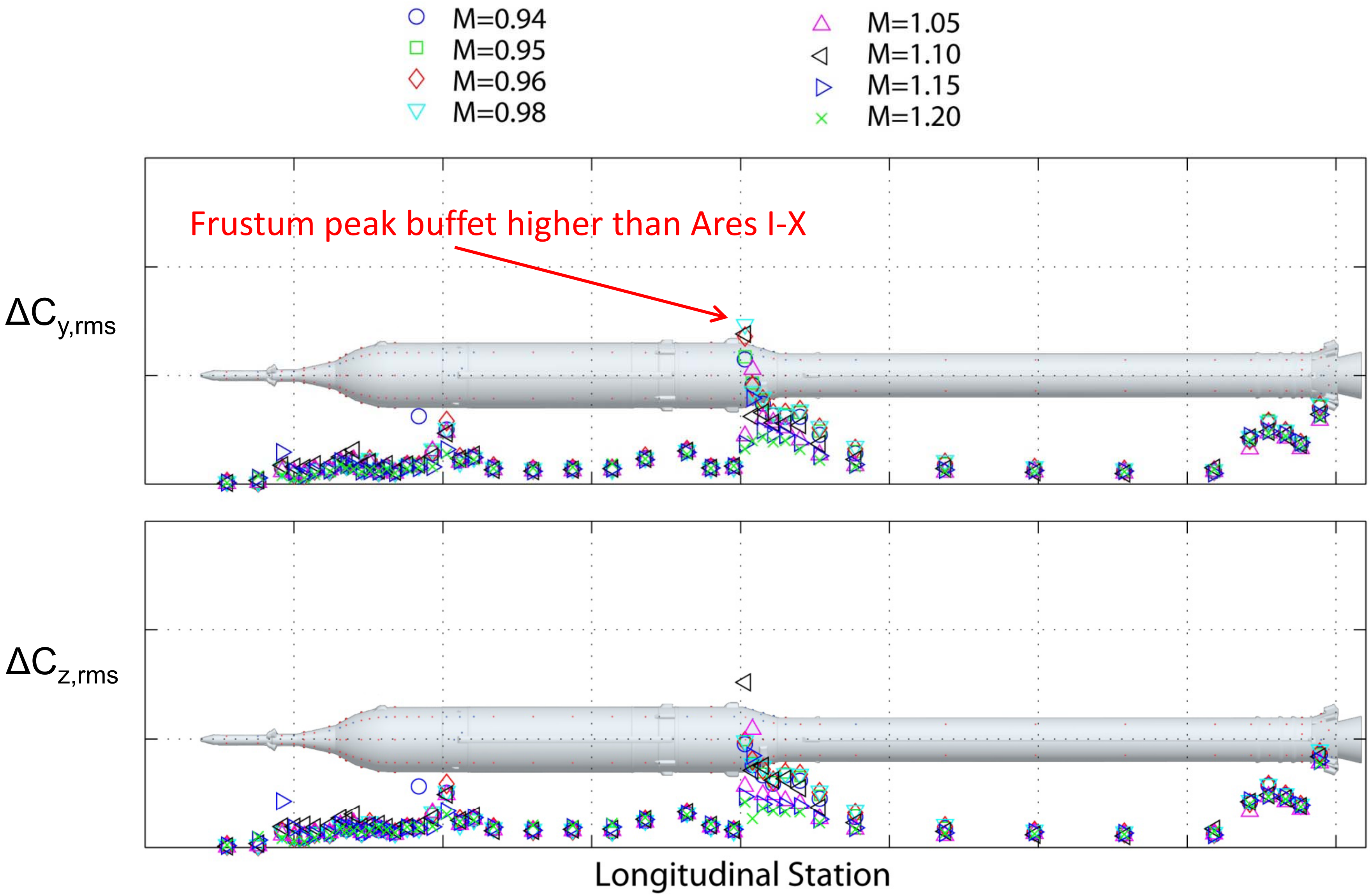
Ares I-X BFF RMS for Pitch Sweep at Mach 0.9



Ares I BFF RMS for Pitch Sweep at Mach 0.82



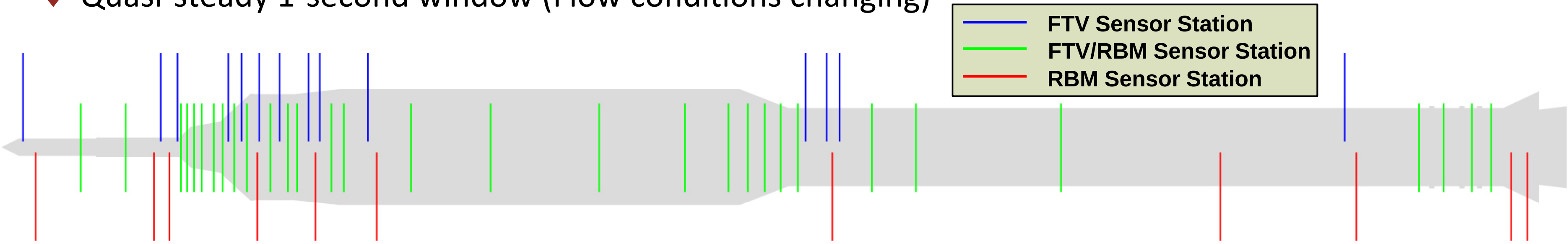
Ares I BFF RMS Levels for Mach 0.94 to 1.20



Ares I-X FTV and RBM Sensor Stations

FTV Buffet Verification Pressure Sensors

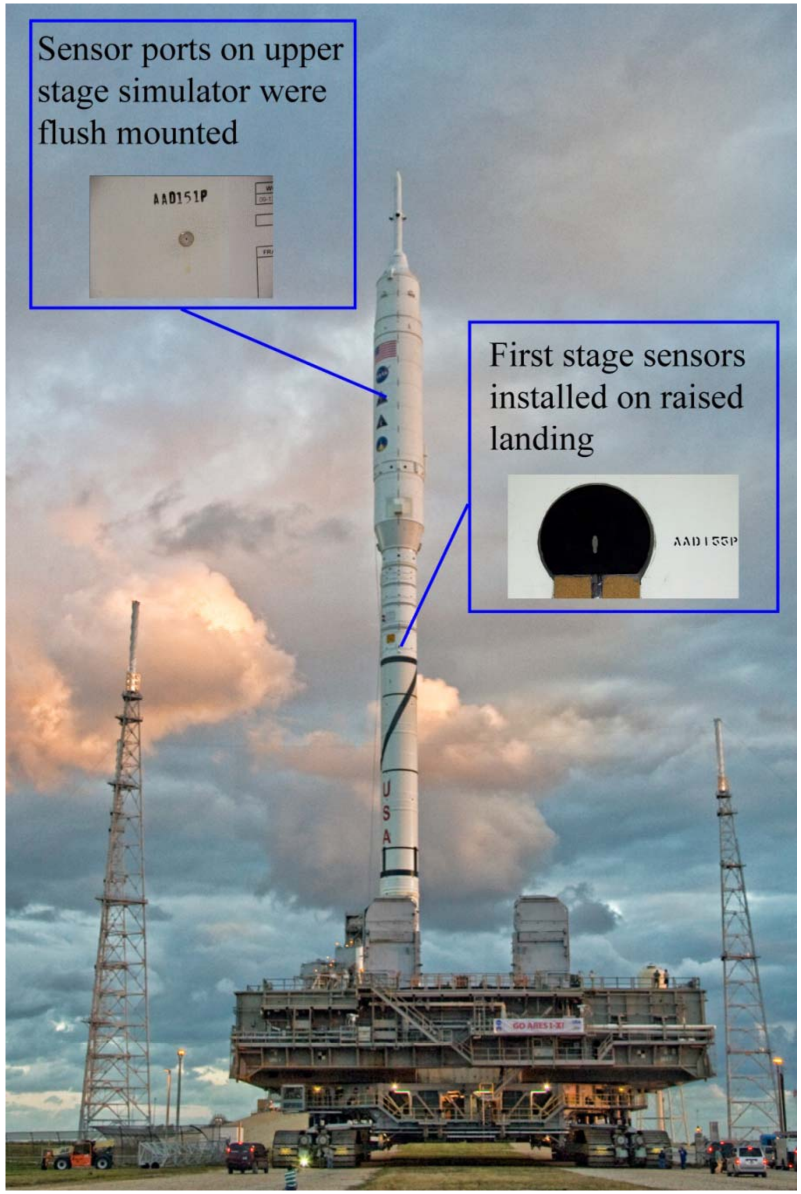
- 243 unsteady pressure measurements
- 45 stations with 4 or 8 sensors for pressure integration
- 0-130 Hz bandwidth (full-scale)
- Mach numbers 0 to 4.6; dynamic pressures up to 875 psf
- Quasi-steady 1-second window (Flow conditions changing)



RBM Unsteady Pressure Sensors

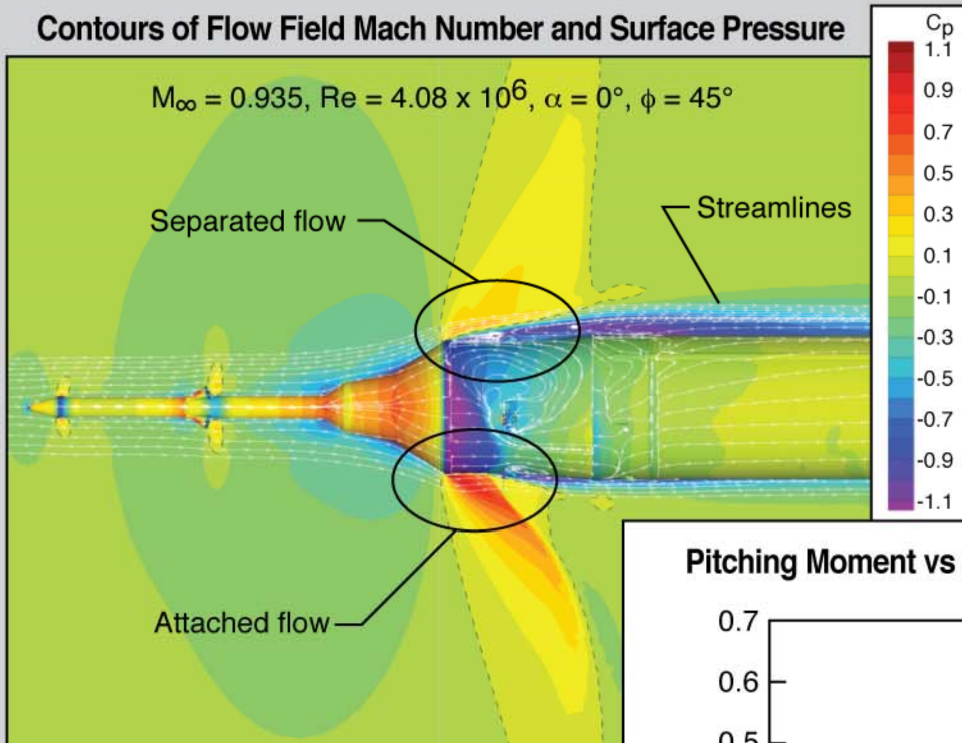
- 256 unsteady pressure measurements
- 43 stations with 4 or 8 sensors for pressure integration
- 0-340 Hz bandwidth (full-scale)
- Mach numbers 0.5 to 1.2 ; dynamic pressure up to 480 psf
- R-134a heavy gas test medium
- 433 second data records at steady flow conditions (full-scale)

FTV Pressure Sensor Mounting

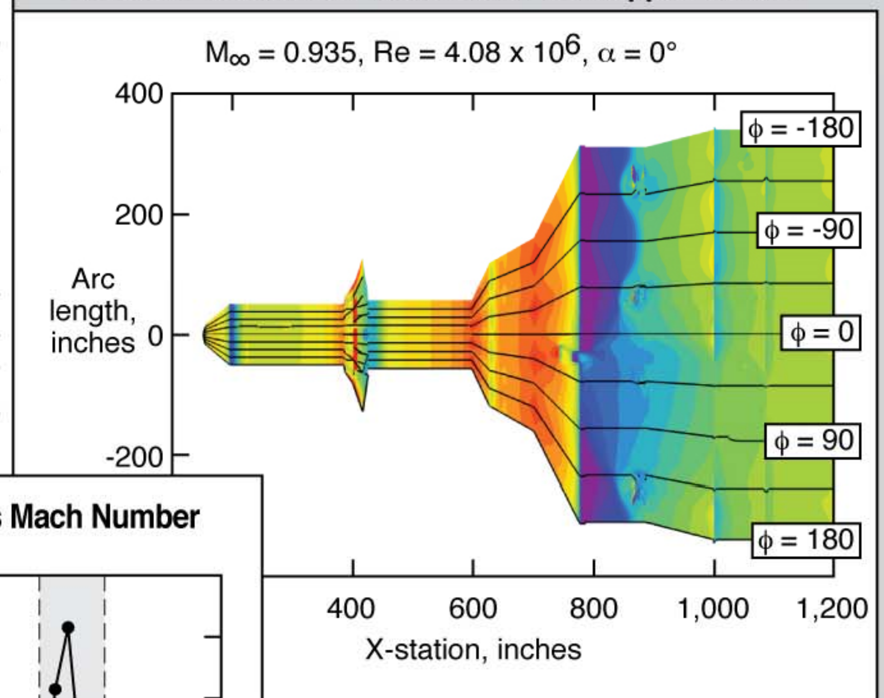


Computational Aeroelastic Analysis of Ares I-X Bi-Modal Flow Field

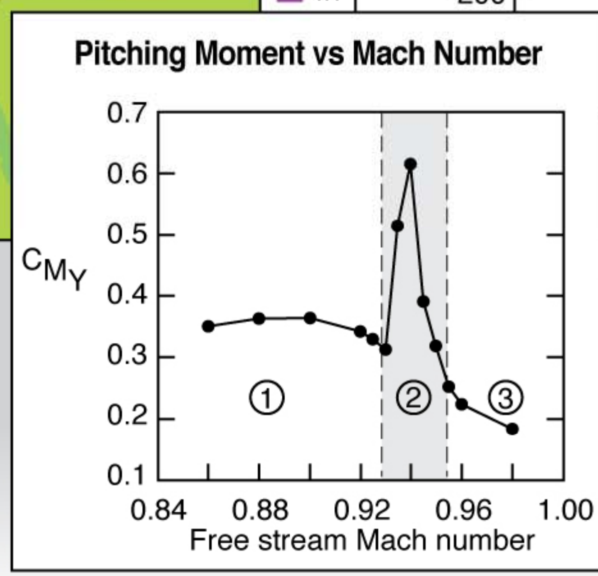
Contours of Flow Field Mach Number and Surface Pressure



Contours of Surface Pressures for Unwrapped Surface



Pitching Moment vs Mach Number



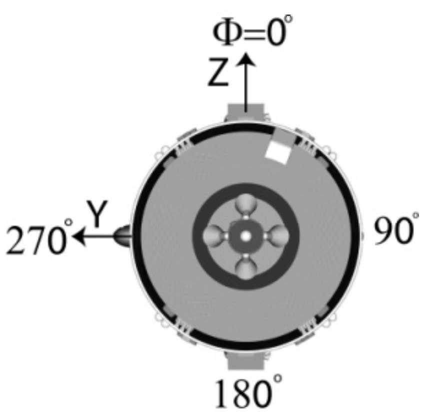
Asymmetry of CM/SM umbilical and apparent vehicle $\alpha - \beta$ drives direction of bi-modal load

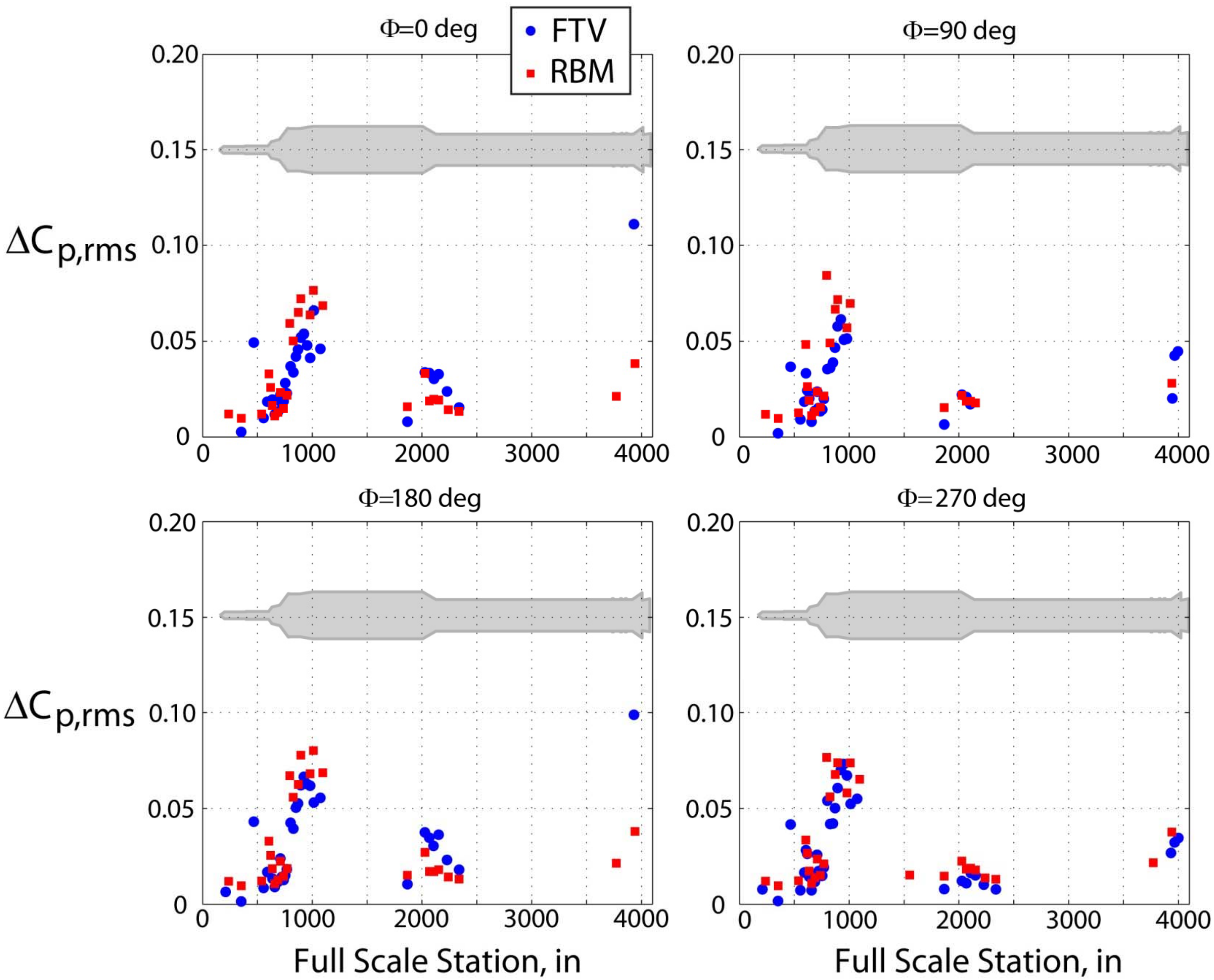
Local flow states at cone / cylinder junction
(~ X-station 800)

① Subsonic separated flow
② Bi-modal flow
③ Supersonic attached flow

Fluctuating Pressure Coefficient (RMS)

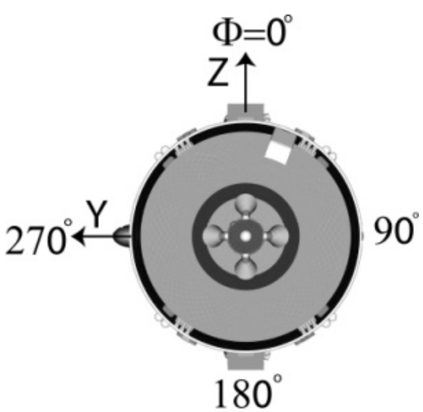
- Mach 0.85
- Φ = 0°, 90°, 180°, 270°
- Bandpass 0.5-60 Hz
- Flight Test
  - q=647 psf
  - α=-0.1°; β=-0.8°
  - 1-sec window; detrended
- Wind Tunnel Test
  - q=483 psf
  - scaled to full-scale BET conditions
  - α=0.0°; β=0.0°
  - 433 sec time history

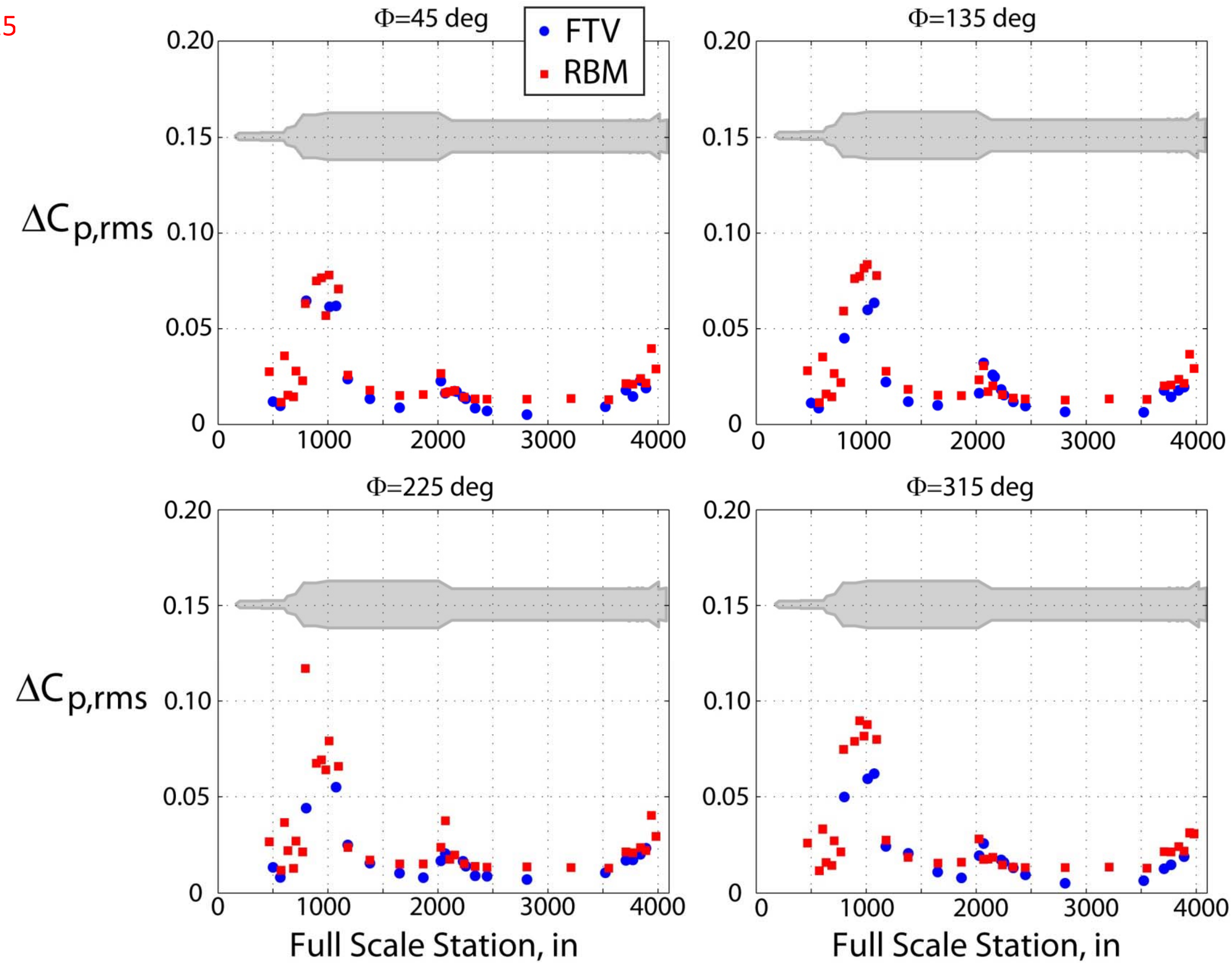




Fluctuating Pressure Coefficient (RMS)

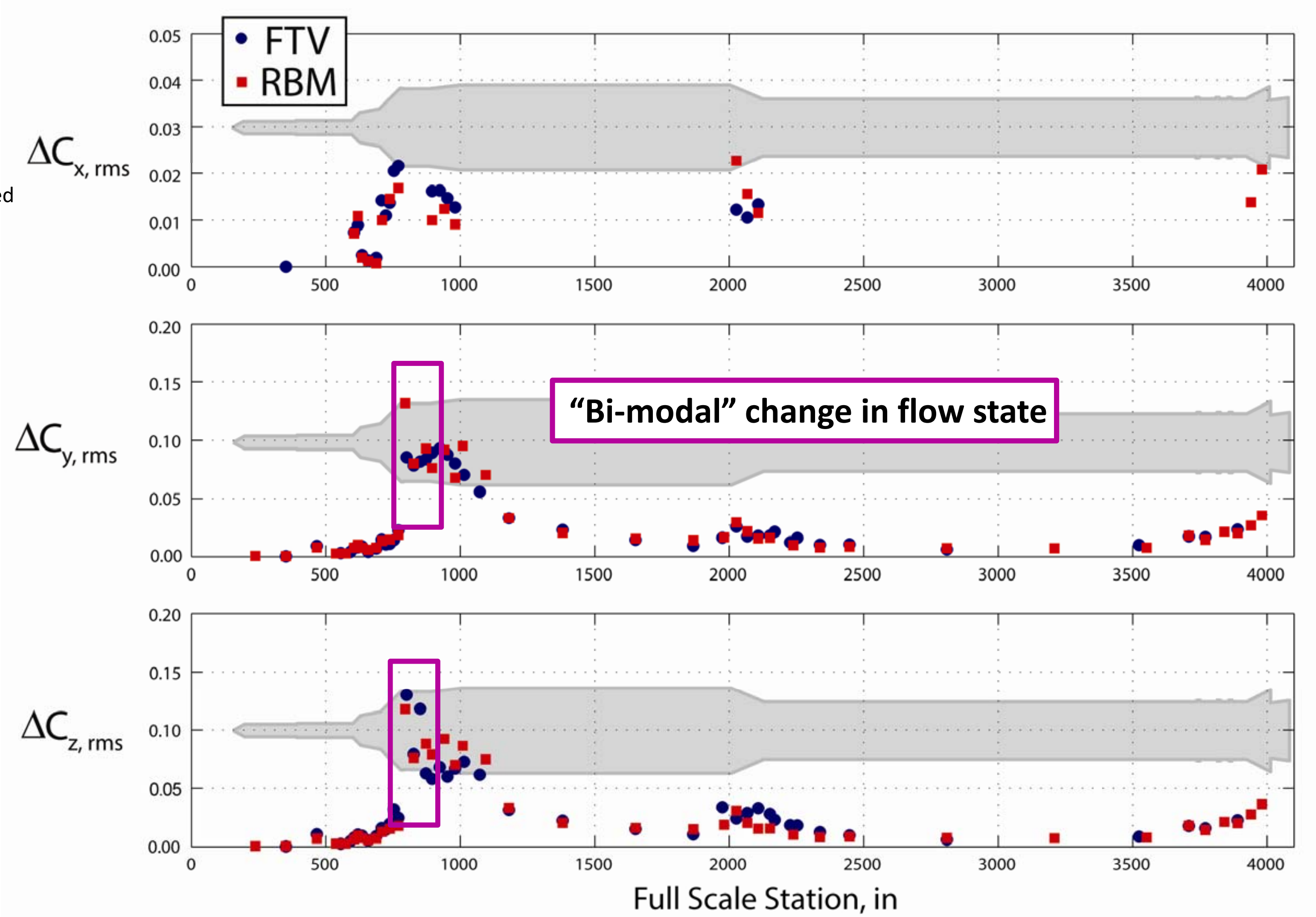
- Mach 0.85
- Φ = 45°, 135°, 225°, 315
- Bandpass 0.5-60 Hz
- Flight Test
  - q=647 psf
  - α=-0.1°; β=-0.8°
  - 1-sec window; detrended
- Wind Tunnel Test
  - q=483 psf
  - scaled to full-scale BET conditions
  - α=0.0°; β=0.0°
  - 433 sec time history



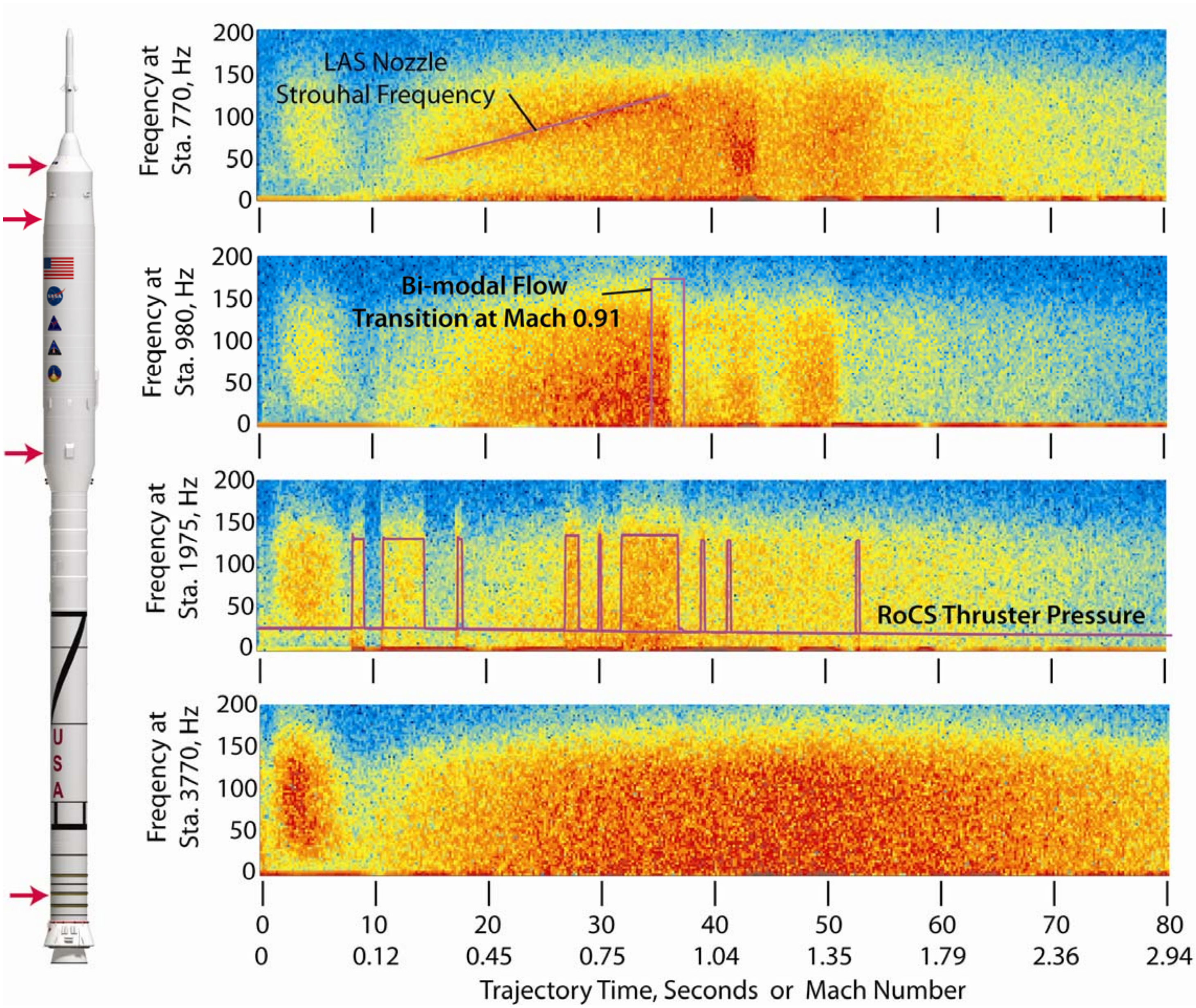


Sectional Buffet Forcing Function RMS; Mach 0.90

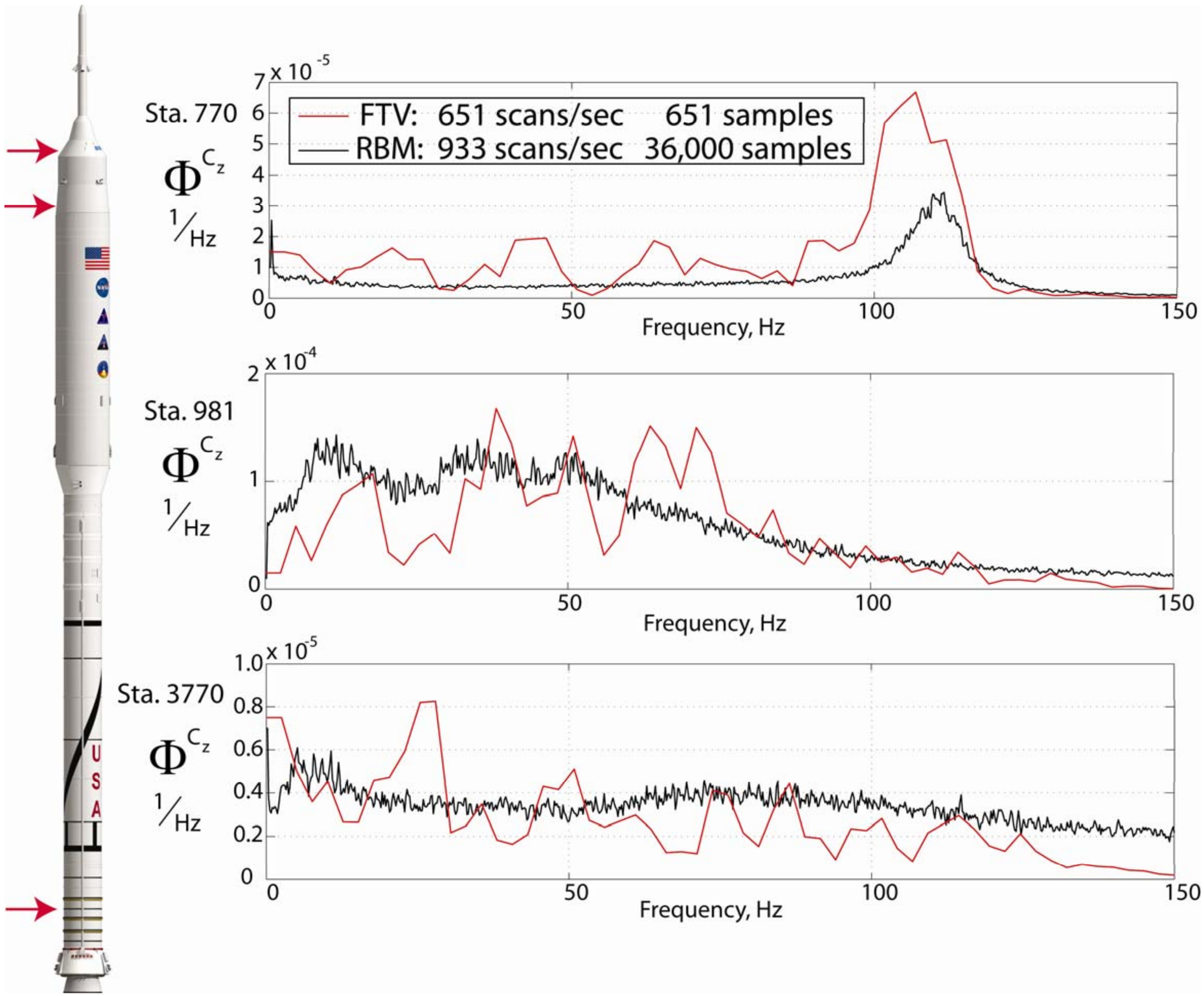
- Mach 0.90
- Bandpass 0.5-60 Hz
- Flight Test
  - q=687 psf
  - α=-0.1°; β=-0.8°
  - 1-sec window; detrended
- Wind Tunnel Test
  - q=475 psf
  - scaled to full-scale BET conditions
  - α=0.0°; β=0.0°
  - 433 sec time history



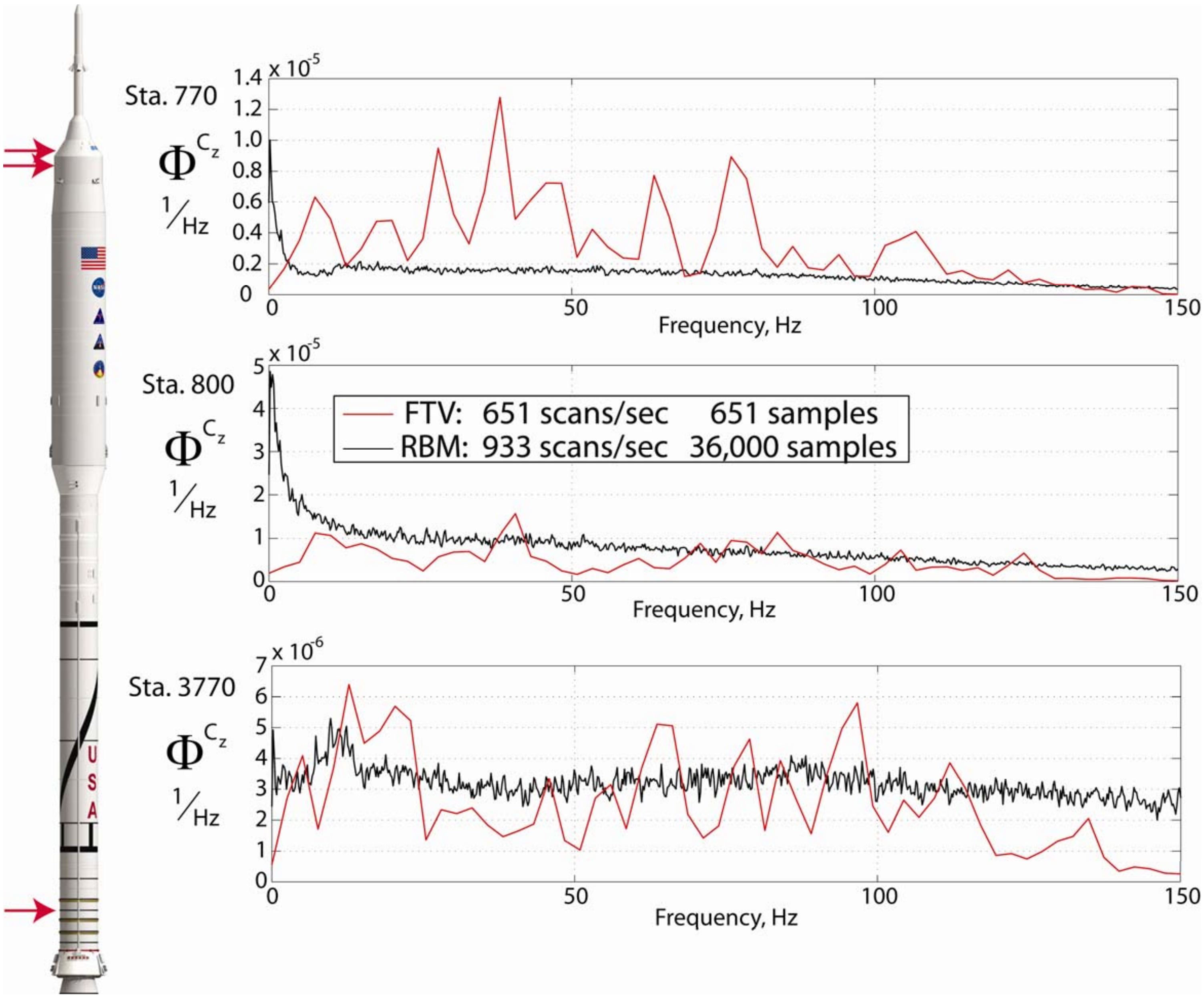
FTV Buffet Forcing Function Spectrograms



Buffet Forcing Function PSDs at Mach 0.85



Buffet Forcing Function PSDs at Mach 1.20



Conclusions

- Two heavily instrumented 3.5% scale rigid buffet models of the Ares I and I-X launch vehicles were tested at the NASA Langley Transonic Dynamics Tunnel
- The maximum buffet environment for the Ares I-X flight test vehicle was determined to be near the CM/SM cone-cylinder interface due to an alternating flow condition at Mach 0.90
- The maximum buffet environment for the Ares I crew launch vehicle was determined to be on the SM due to the random fluctuations of a terminal shock near Mach 0.82
- Good comparison of DFI and Rigid Buffet Model (RBM) Test
  - RBM and FTV buffet environments compared very well: $\Delta C_{p,rms}$, BFFs
  - In general, RBM buffet pressures/loads were conservative
- Alternating flow load event at transonic conditions bounded by pre-flight approach using wind-tunnel data
  - Wind-tunnel derived BFFs were based on WORST-CASE alternating flow loads