Wind-tunnel, static burn and flight tests conducted to establish the aeroacoustics environment of Orion Multi-Purpose Crew Vehicle

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Others….	Others…	Bruce Storms	Boeing Polysonic wind tunnel
		Rob Fong	GRC 8X6 wind tunnel
		Others…	Others…

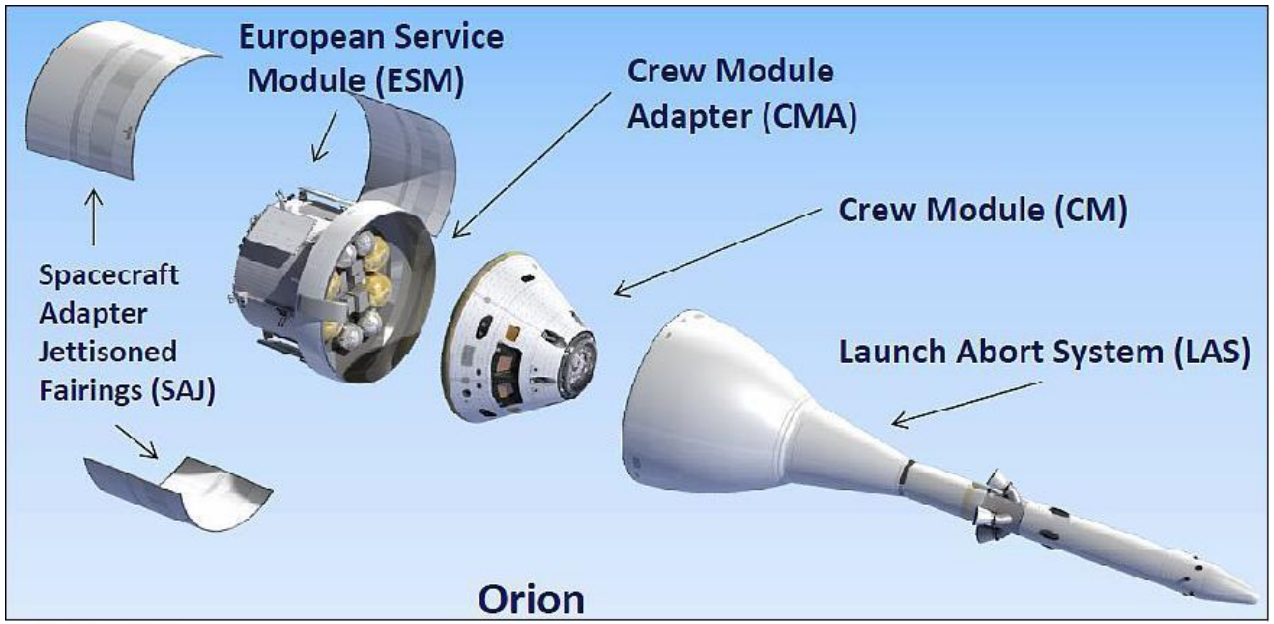
Roadmap

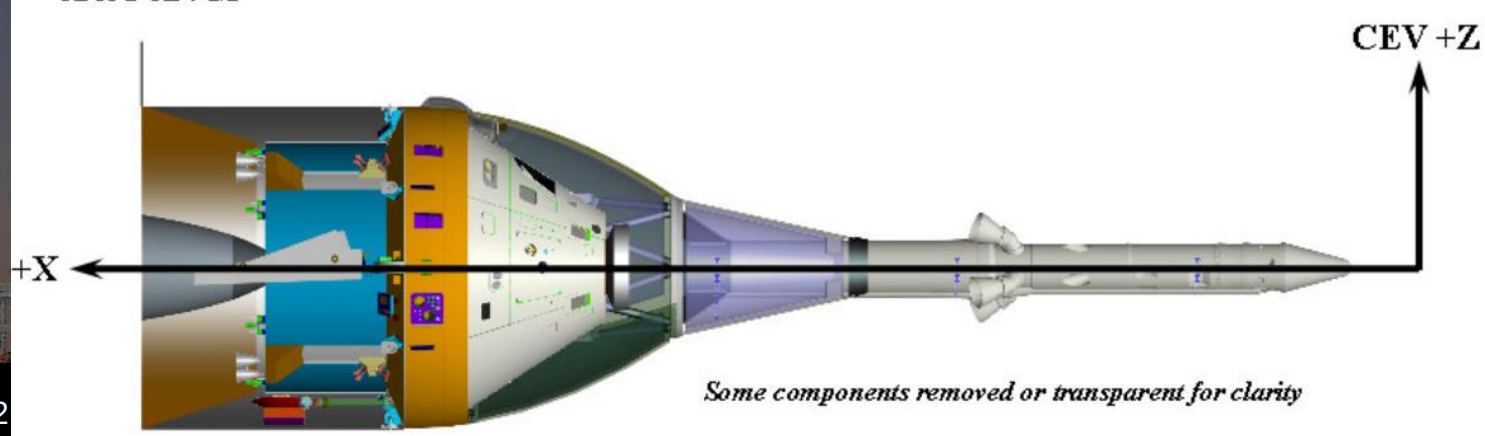
I. Problem at hand and solution approach
II. Launch Acoustics
III. Pressure fluctuations during nominal ascent
IV. Pressure fluctuations during abort
    A. Pad Abort
    B. Ascent Abort
V. Summary

I. Problem at hand and solution approach

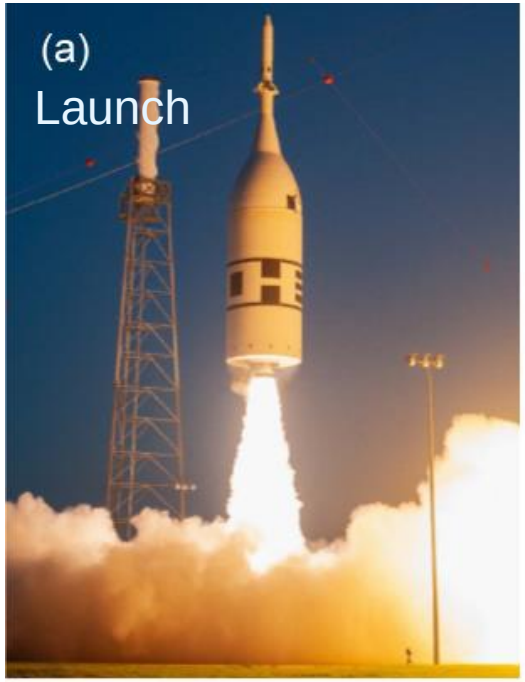
Orion Multi-Purpose Crew Vehicle
(formerly Crew Exploration Vehicle)

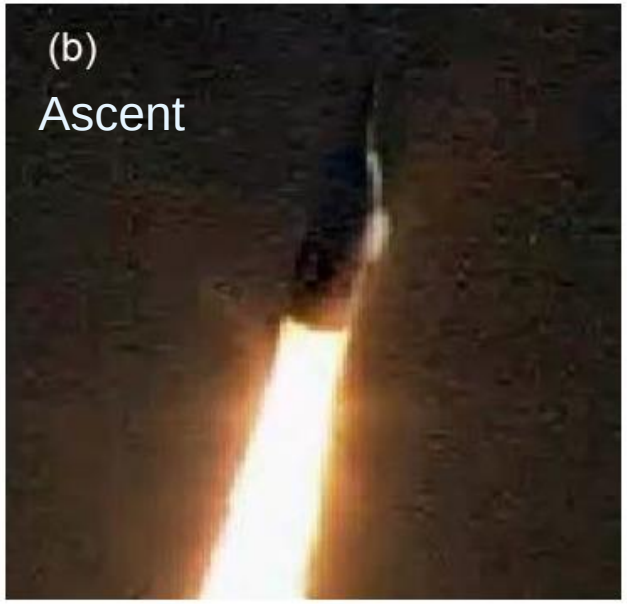






Pressure fluctuations from launch, ascent and ascent-abort
Example from AA2 flight test

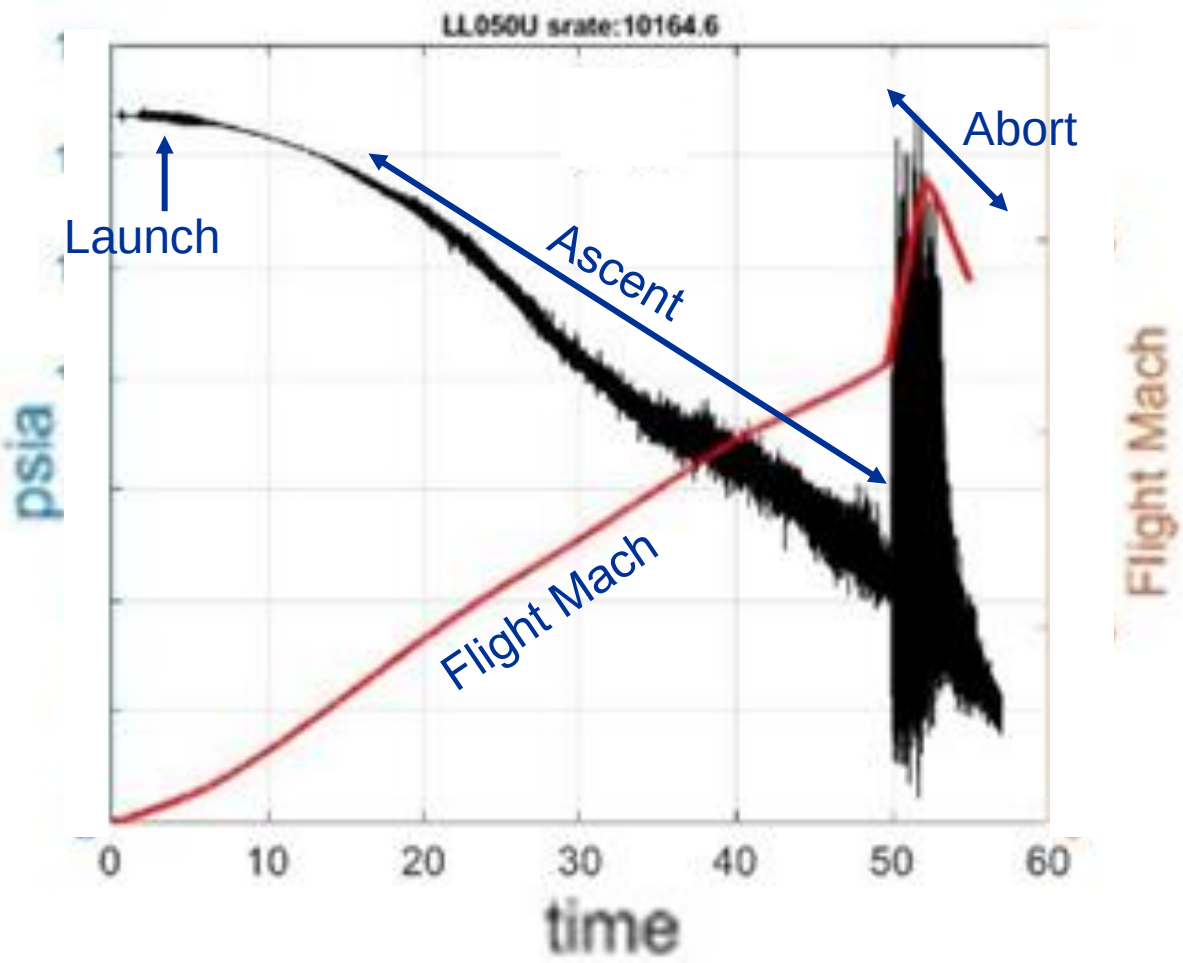








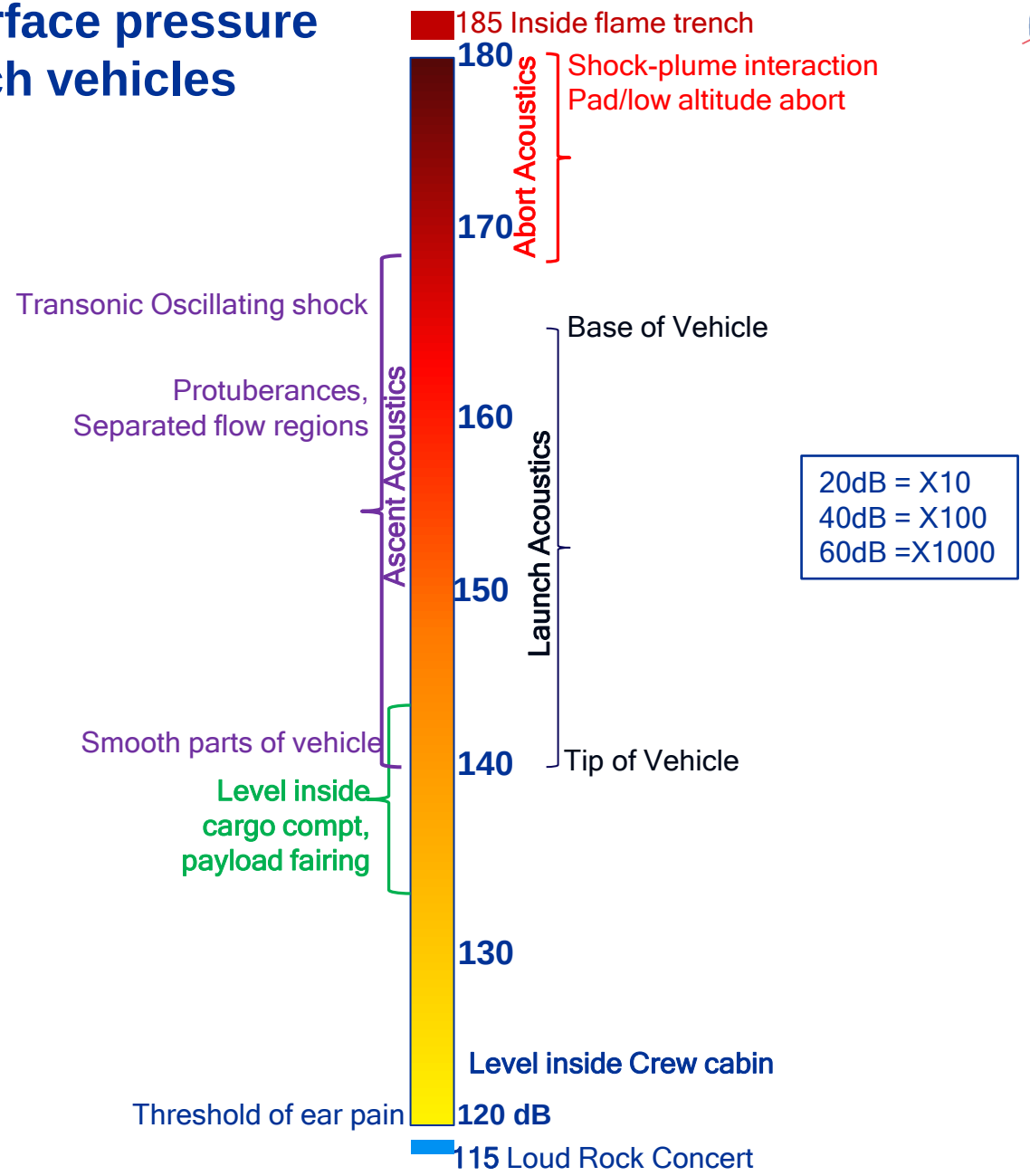
Ascent Abort Flight Test AA2 -2019 – Full-scale Ascent Abort Test of Launch Abort Vehicle



Time evolution of surface pressure measured by a microphone on LAS surface

Typical levels (dB) of surface pressure fluctuations on launch vehicles





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Fluid-structure interaction

Wind tunnel test



+

Vibro-acoustic test
in Acoustic chamber



"aero-vibro-acoustics" AKA "Flow induced sound and vibration"

- exterior surface is subjected to turbulent pressure fluctuations
- panel structure then vibrates and transmit the pressure fluctuations
- Coupling between the two: - modal pressure response

$$\Phi_{pmn}(\omega) = \iint_{k_x,k_y} \Phi_p(k_x, k_y, \omega) \left|S_{mn}(k_x, k_y)\right|^2 dk_x\, dk_y$$

Modal response

Wavenumber-freq spectrum of press fluctuation
- Aeroacoustics
- Forcing function

Mode shape Function
- Vibro-acoustics

Path taken by the space vehicle program

- A Tango sequence of generating forcing function through tests followed by vibro-acoustics analysis.
- A revised cycle was introduced after new results and modifications of the structural components
- Continuing improvements throughout the program
  - Structural dynamics codes to solve the above equation
  - test of full-vehicle in acoustic chambers & Shaker tables

Goal of MPCV aero-acoustic tests

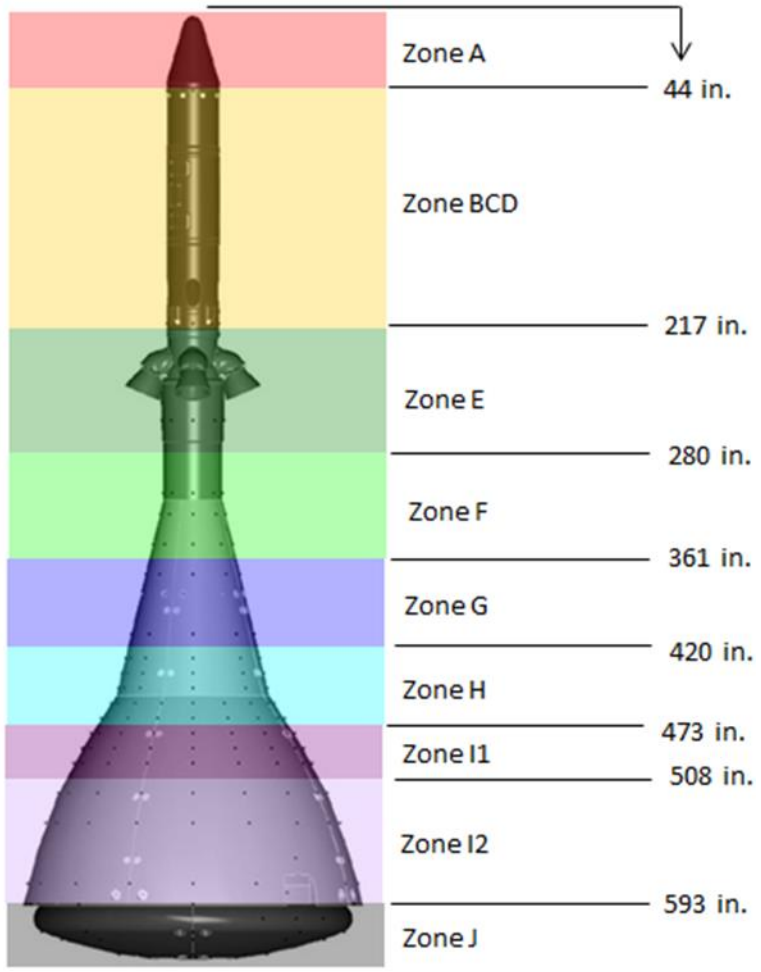
- Determine the wavenumber-frequency spectrum of pressure fluctuations: $\Phi_p(k_x, k_y, \omega)$

  - Very difficult to directly measure $\Phi_p(k_x, k_y, \omega)$
  - Resort to Corcco's model:

$$\Phi_p(k_x, k_y, \omega) = \Phi_{pp}(\omega) e^{-C_x k_x |\Delta x|} \; e^{-C_y k_y |\Delta y|} e^{-i k_x |\Delta x|}$$

  - Divide the vehicle into acoustic zones
  - Determine Corcco's model constants for each zone
    - A. Area weighted auto-spectrum of pressure fluctuations
    - B. Convection/trace velocity
    - C. Axial and circumferential decay coefficients

  - for launch, nominal ascent and ascent abort



Abort Zonal Definition

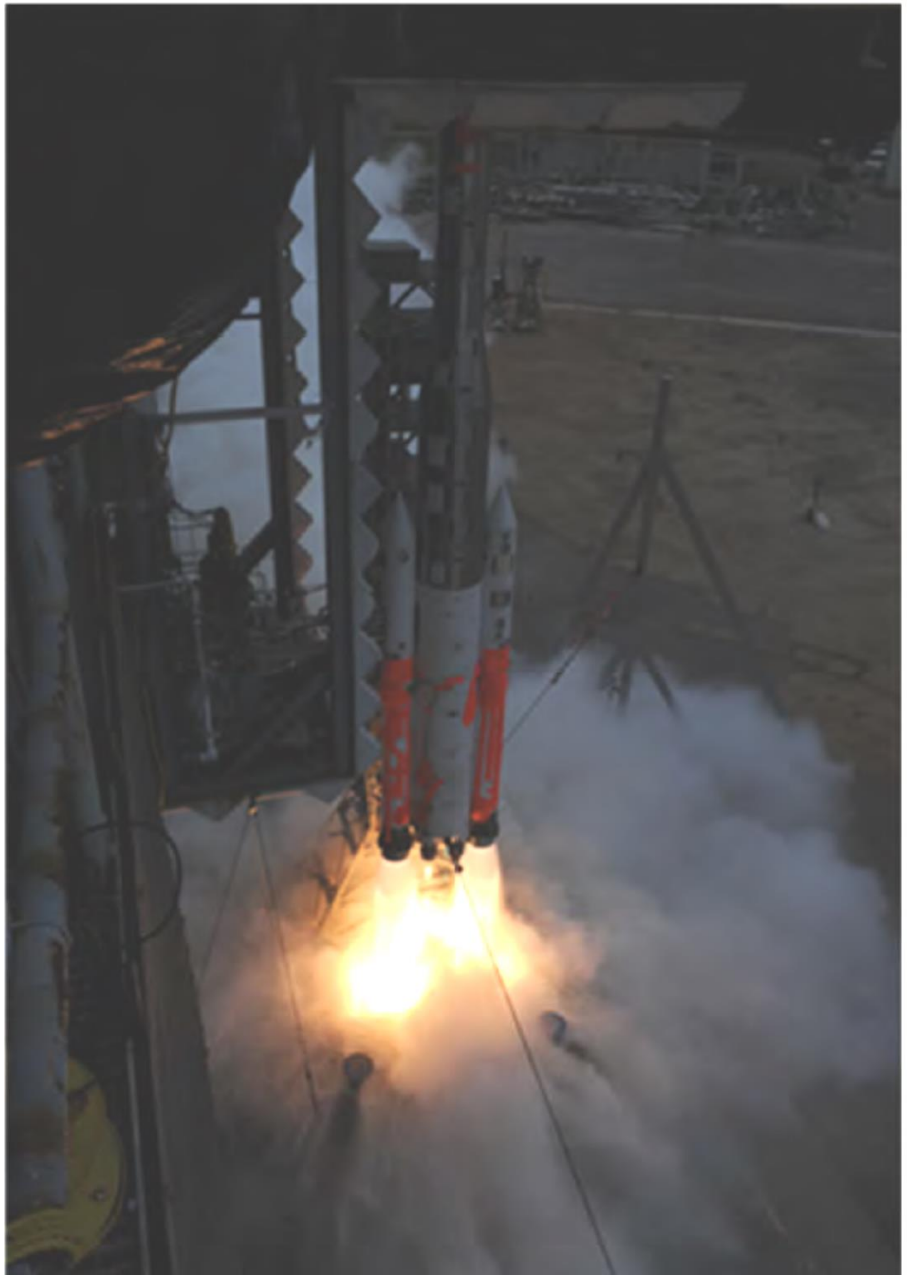
Primary tests to define MPCV aero-acoustics

- **Aeroacoustic WTT 50AS – 2007** at Boeing Polysonic– Launch Abort Vehicle trade study - led to change of the Orion Outer Mold line
- **Aeroacoustic WTT 57AS – 2007** at GRC 8'X6' - same as above
- **Acoustic and Performance WTT of LAV 58AA – 2008** – AEDC 4T tunnel – same as above
- **60AA WTT– 2007** ARC 11-ft– Abort acoustics using unheated air
- **Orion Acoustic WTT 51AS – 2008** - ARC 11ft and 9X7 – Acoustic environment during nominal ascent and ascent abort
- **Static Burn of Improved Orion Motors - 2007** Acoustic environment during Pad abort - NASA Wallops
- **Static Fire Test ST1 – 2008** - Utah, ATK test ground – Acoustic environment during Pad abort
- **Hot Helium WTT 80AS – 2010** – ARC 11ft – Acoustic environment during Ascent abort of the Launch Abort Vehicle
- **Pad Abort Flight Test PA1 - 2010** - Full-scale Pad abort test of Launch Abort Vehicle (Lockheed, NASA)

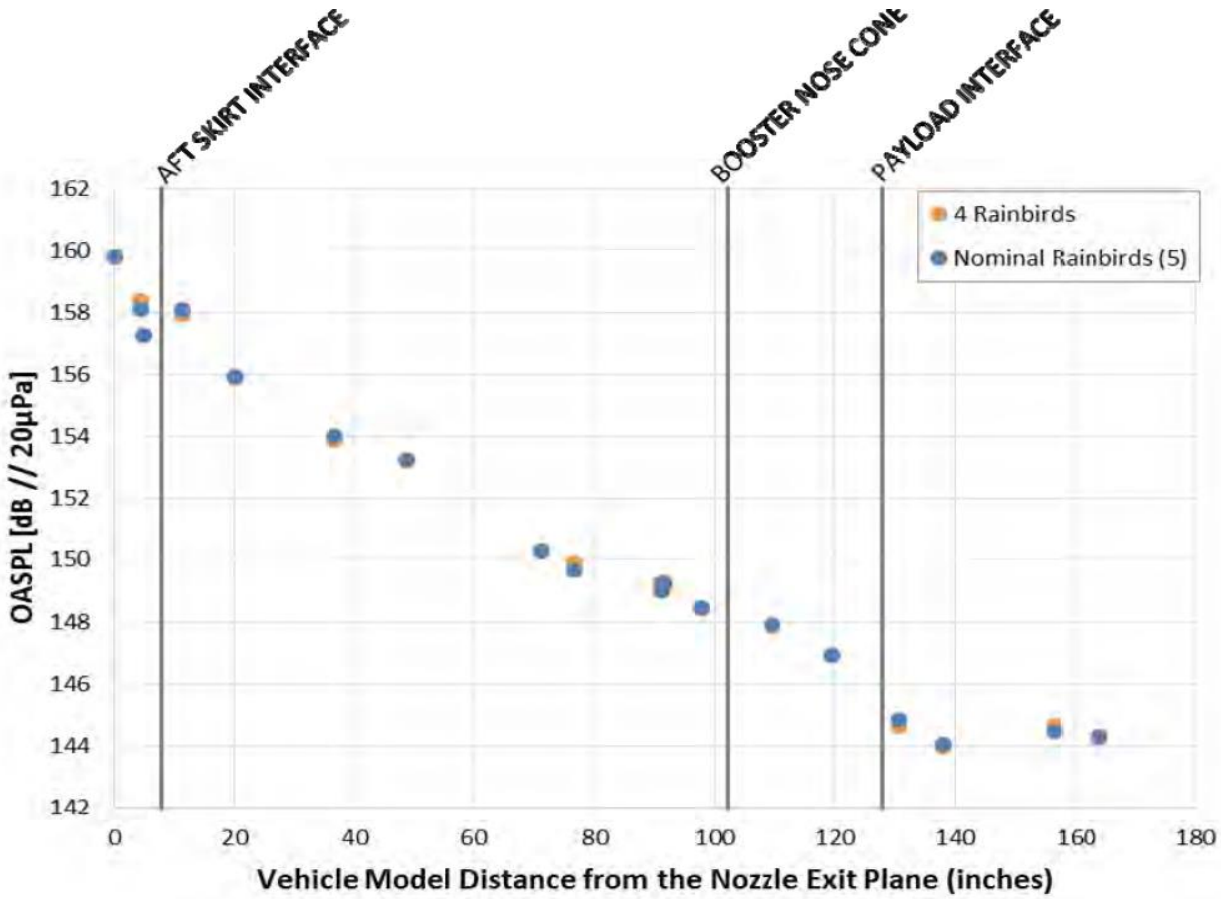
- **Scaled Model Acoustic Test – MSFC, 2014** – Launch acoustics environment on 6.5% scaled model
- **ULA EFT1 buffet test– 2013?** – ULA – Acoustics in nominal ascent
- **Exploration Flight Test EFT1 – 2014** – Full-scale 1st flight Test of Orion – Acoustic environment in Nominal ascent (Lockheed, USA)
- **Static Fire Test QM1 – 2017** – Utah, Orbital/ATK test ground –Acoustic environment during Pad Abort
- **SLS Aeroacoustic Test – 2017** – ARC 11-ft & 9X7 – Nominal ascent of SLS B1B configuration
- **Aeroacoustic of Umbilical cover WTT 134AS – 2019** – ARC 11-ft
- **Ascent Abort Flight Test AA2 -2019** – Full-scale Ascent Abort Test of Launch Abort Vehicle (Lockheed, NASA)

II. Launch Acoustics

Launch Acoustics: Scaled Model Acoustics Test (SMAT)

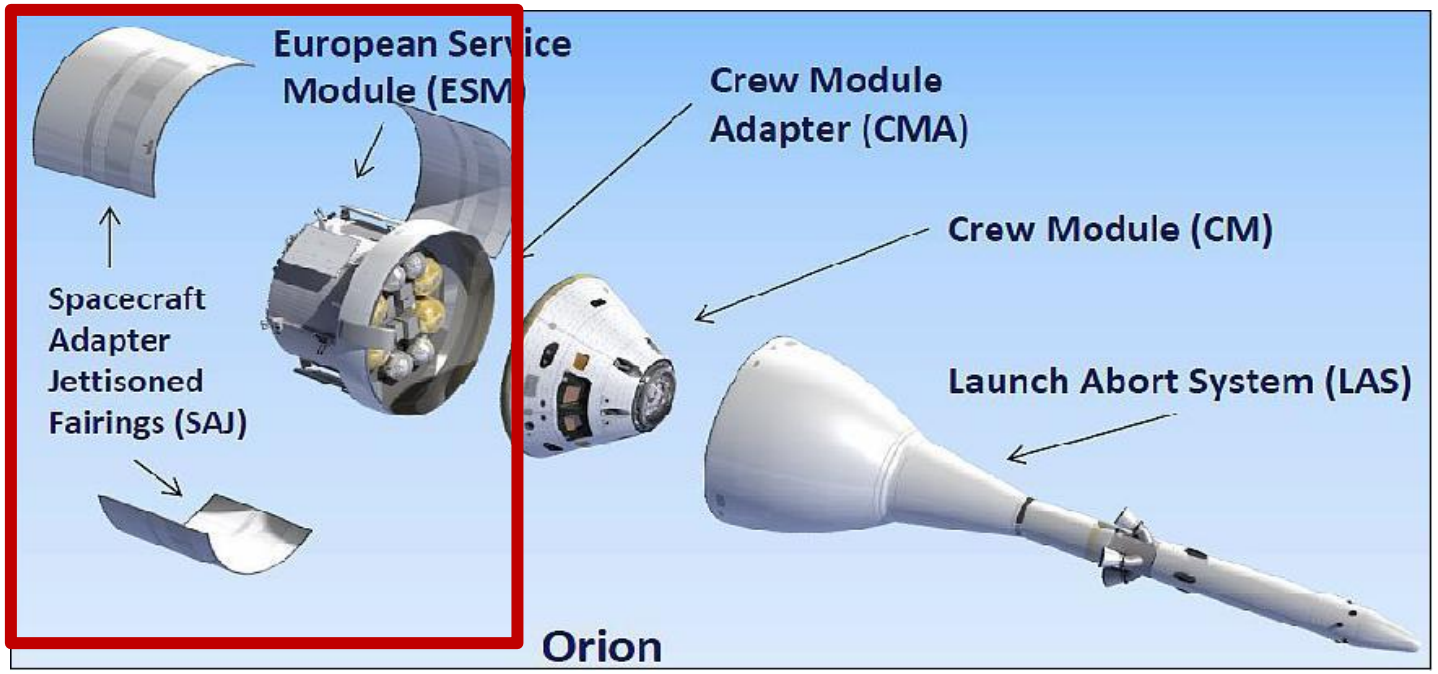


- Conducted at MSFC, 2014
- 6.5% scale model of SLS
- Main engine +boosters
- Confirmation will come from Artemis I flight



III. Surface pressure fluctuations during nominal ascent

- Drives the environment on ESM and components do not participate in abort
- Block 1B version of SLS versus present Block 1
- Cause for the change of OML at the beginning of the program
- Verification from flight test



- Flow of turbulent air over vehicle surface cause pressure fluctuations

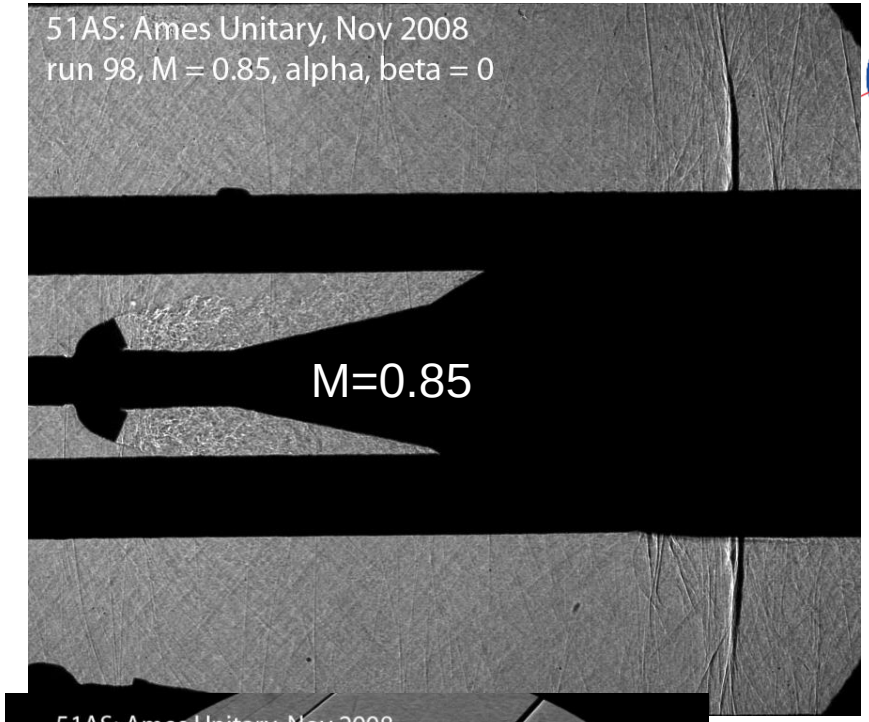
$$P'_{rms} \sim q$$

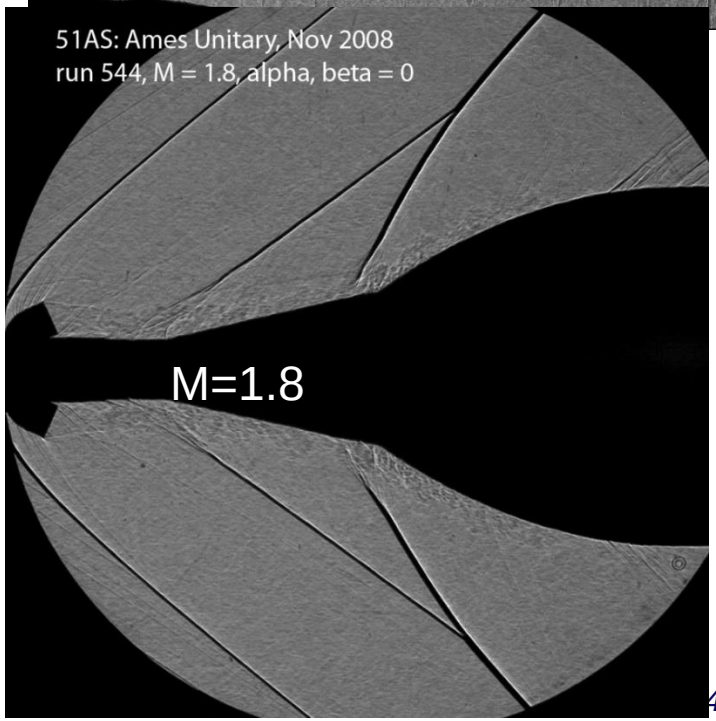
- For M<1 wake shed from AM nozzles is a significant cause of pressure fluctuations

- **Requires two forcing function:**

A. Transonic 0.7 ≤M≤1.2 : Transient local shocks waves and flow separation – transonic environment

B. Supersonic M>1.2 : Formation of stable shock system – max q environment





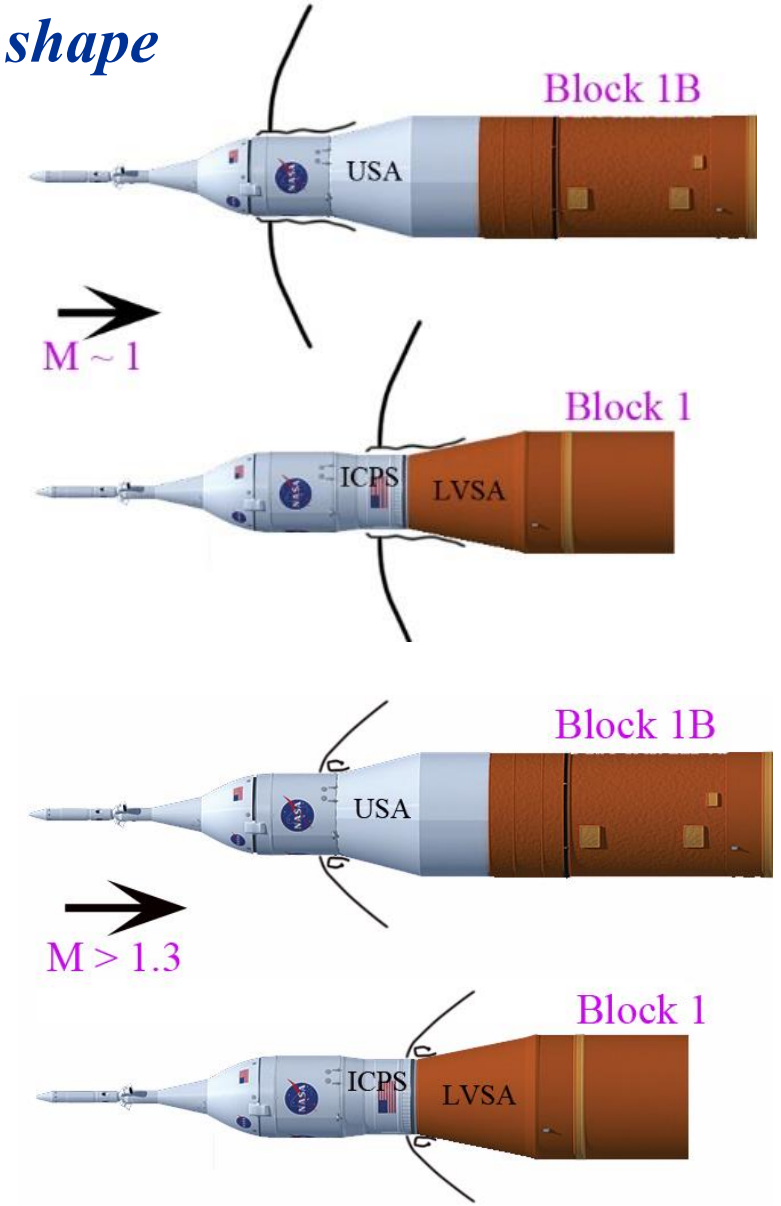
SLS B1 (Artemis-I, II, III) **vs. B1B** (Artemis IV and beyond)

Shock formation on ESM is dependent on downstream shape

- B1B levels on ESM substantially higher than B1. Two reasons:

1. Around M=1 a normal shock is formed on the ESM, which causes it to be encapsulated in separated flows, and the associated high level of pressure fluctuations. For the Block 1 (10k) configuration such shock-boundary layer interaction happened downstream of ESM.

2. For supersonic range M >1.3 a shock-separation zone resides at the corner of ESM-USA on B1B vehicle - causing an increased pressure fluctuations. Such separation regions exist far downstream for the B1 (10k) configuration.



Nominal Ascent wind tunnel tests 51AS &134AS



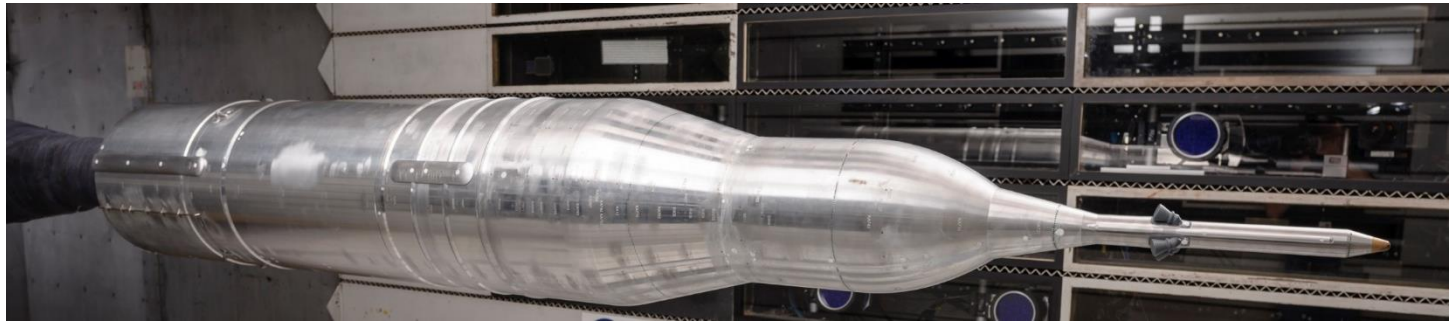
WTT: 51AS, Oct 2008 in ARC 11ft tunnel

- 6% scale model of MPCV on a flow through sting
- Simulated both nominal ascent and ascent abort -mildly heated air simulated motor plumes.



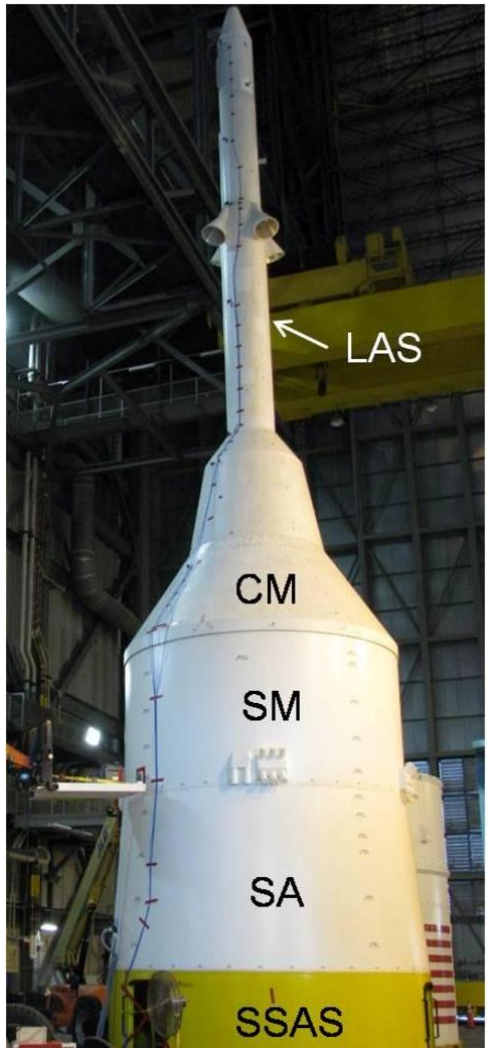
WTT: 134AS: Sept. 2019

- 7.5% model of MPCV in ARC 11ft tunnel
- Goal: Determine protuberance environment around the ESM-CMA Umbilical – nominal ascent only.



- Block 1B 28005 model in Ames 11’ & 9X7 Tunnels, 2017
- 4% scaled model

NESC led Shape Optimization study of Launch Abort Vehicle



Initial 605 - baseline
Shape “Double Party Hat”



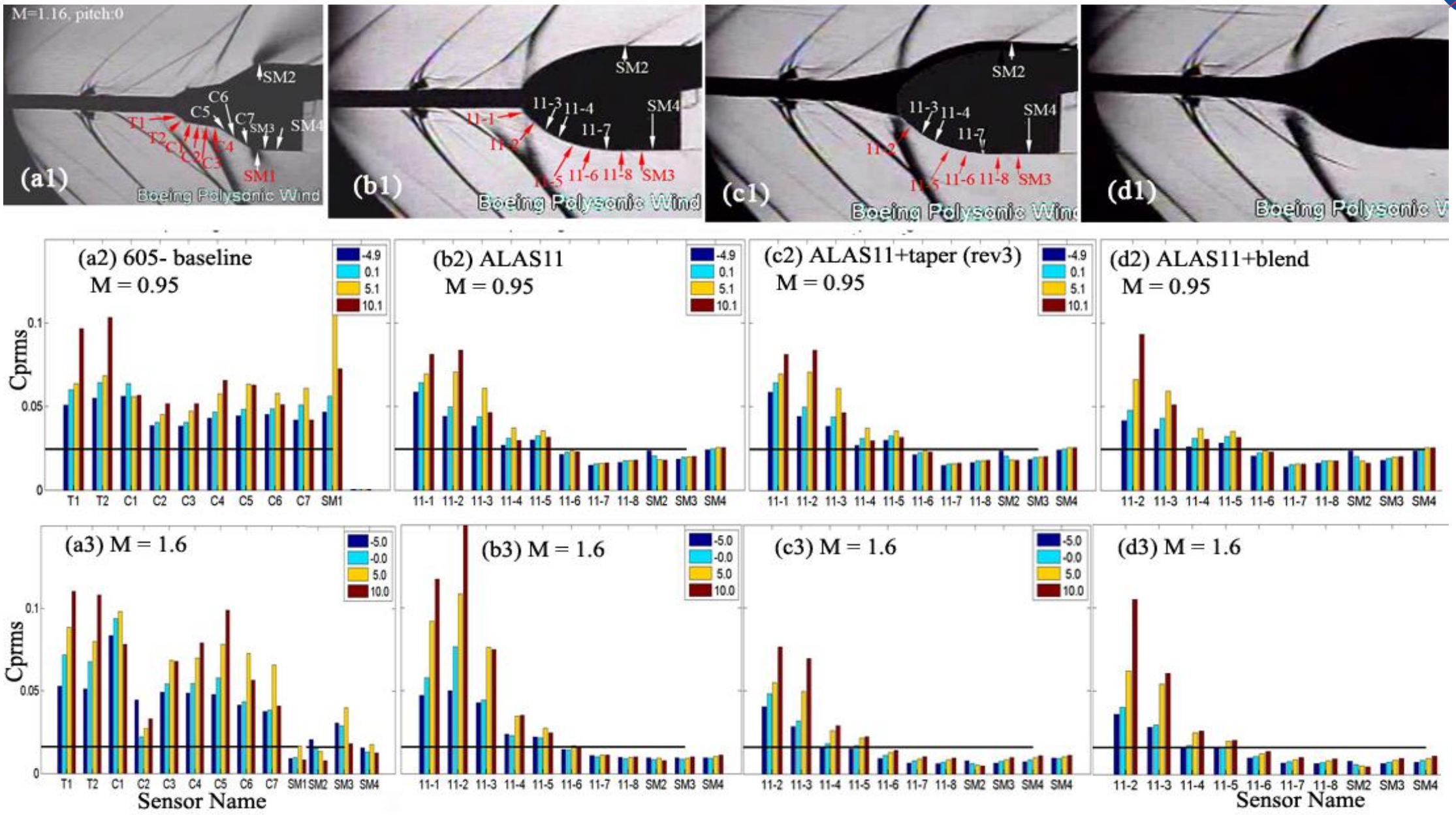
Current “ALAS” shape

- **Aeroacoustic WTT 50AS – 2007** at Boeing Polysonic– Launch Abort Vehicle trade study - led to change of the Orion Outer Mold line

- **Aeroacoustic WTT 57AS – 2007** at GRC 8’X6’ - same as above

- **Acoustic and Performance WTT of LAV 58AA – 2008** – AEDC 4T tunnel – same as above

NESC led Shape Optimization to Reduce Acoustic environment



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Flight test to confirm nominal ascent environment

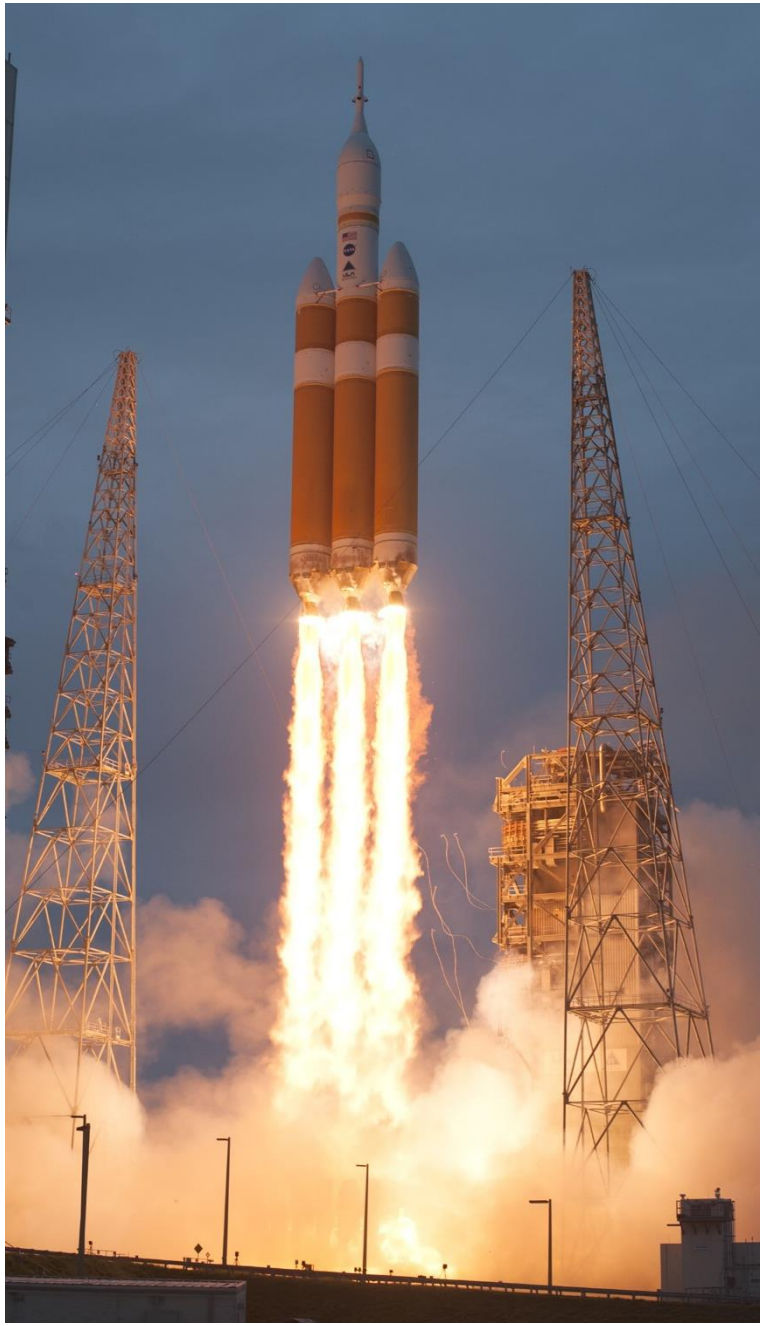
Relationship to scale wind tunnel data to flight condition:

- St = fD/U identity
- Cprms (= p'/q) identity

Nothing else!!

Wind tunnels

- Do not simulate the transient flight Mach
- Lower Reynolds number
- Higher free-stream turbulence



Flight Test to confirm wind tunnel data
Exploration Flight Test -1

- Conducted: Dec. 2014
- Orion atop a Delta-IV heavy

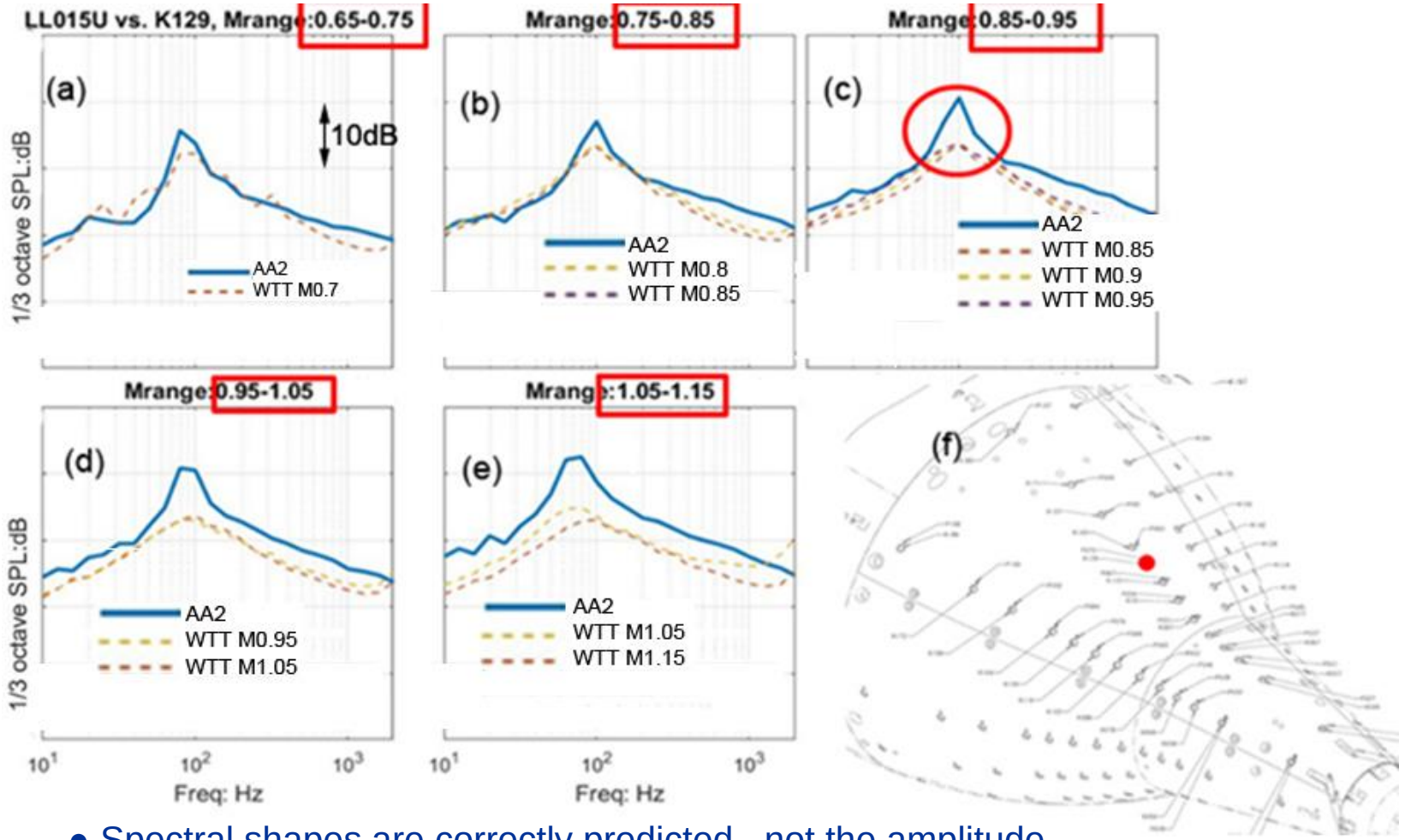
- Ascent acoustics data questionable!
  -Endevco 8510B dynamic pressure sensors
  - Incorrect ranging and sealing of the venting hole
  - Launch acoustic data useful



Flight Test to confirm wind tunnel data
Ascent Abort 2 provided first opportunity to Orion WTT data

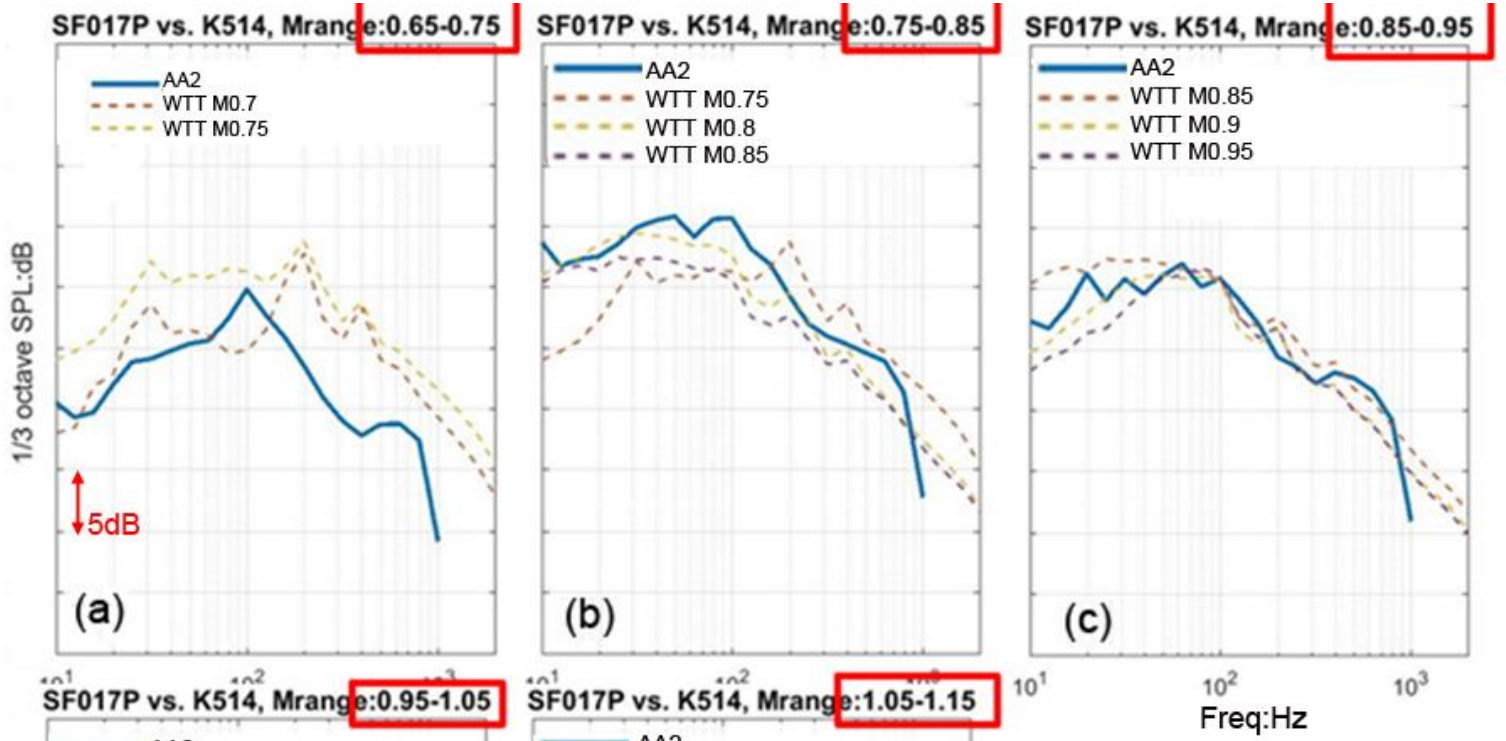


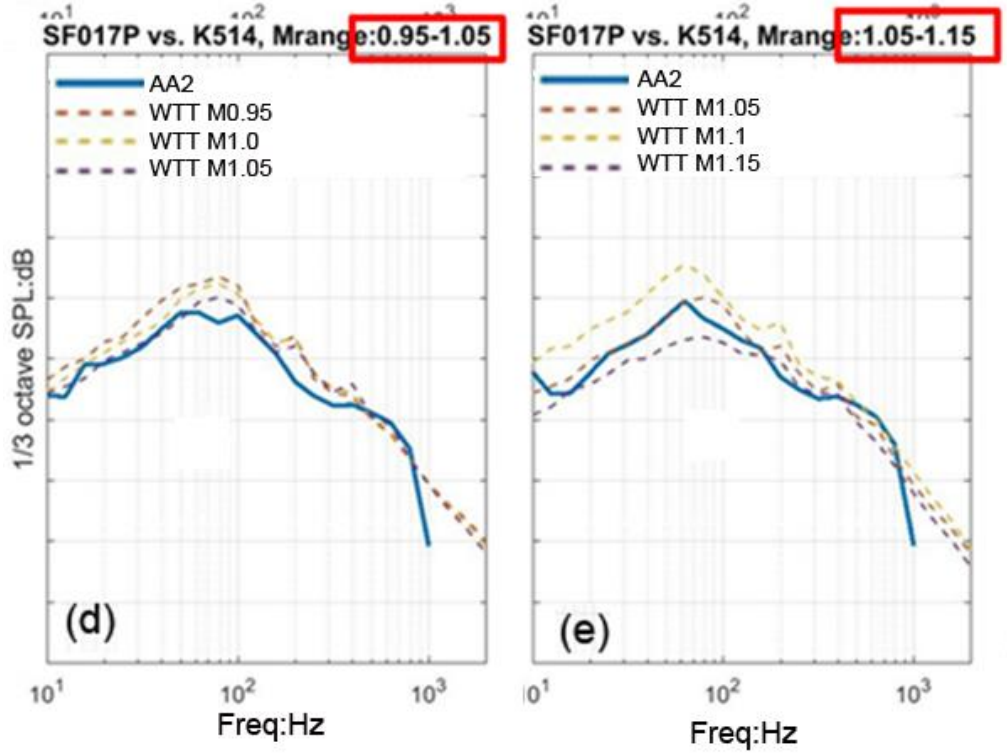
- Flight test AA2
- Nominal flight up to M1.16

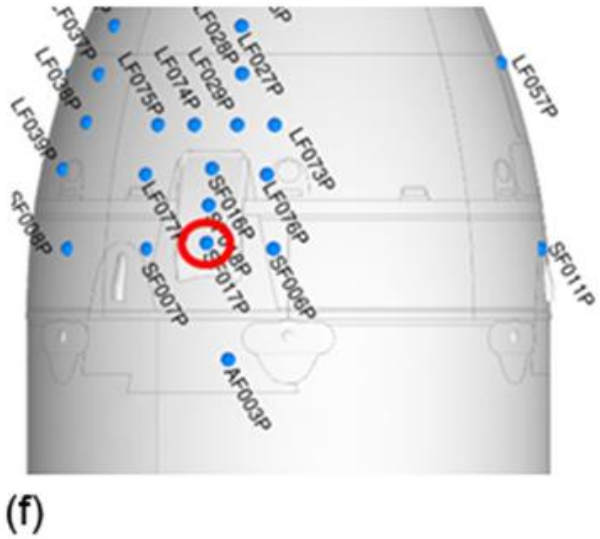


- Spectral shapes are correctly predicted –not the amplitude
- Wind-tunnel underpredicts flight data
  - worsens with Mach number
  - amplitude of vortex shedding underpredicted by 2-10dB!
- Simplified nozzle contour of 51AS wind tunnel model caused increased difference

AA2 vs 134AS







- Reasonable prediction of flight data
- Accurate replication of vehicle geometry pays-off!

Pad and ascent-abort acoustics

Determine the pressure fluctuations for Abort happening from pad to flight Mach ~ 4, and 400,000ft altitude using the Abort Motors

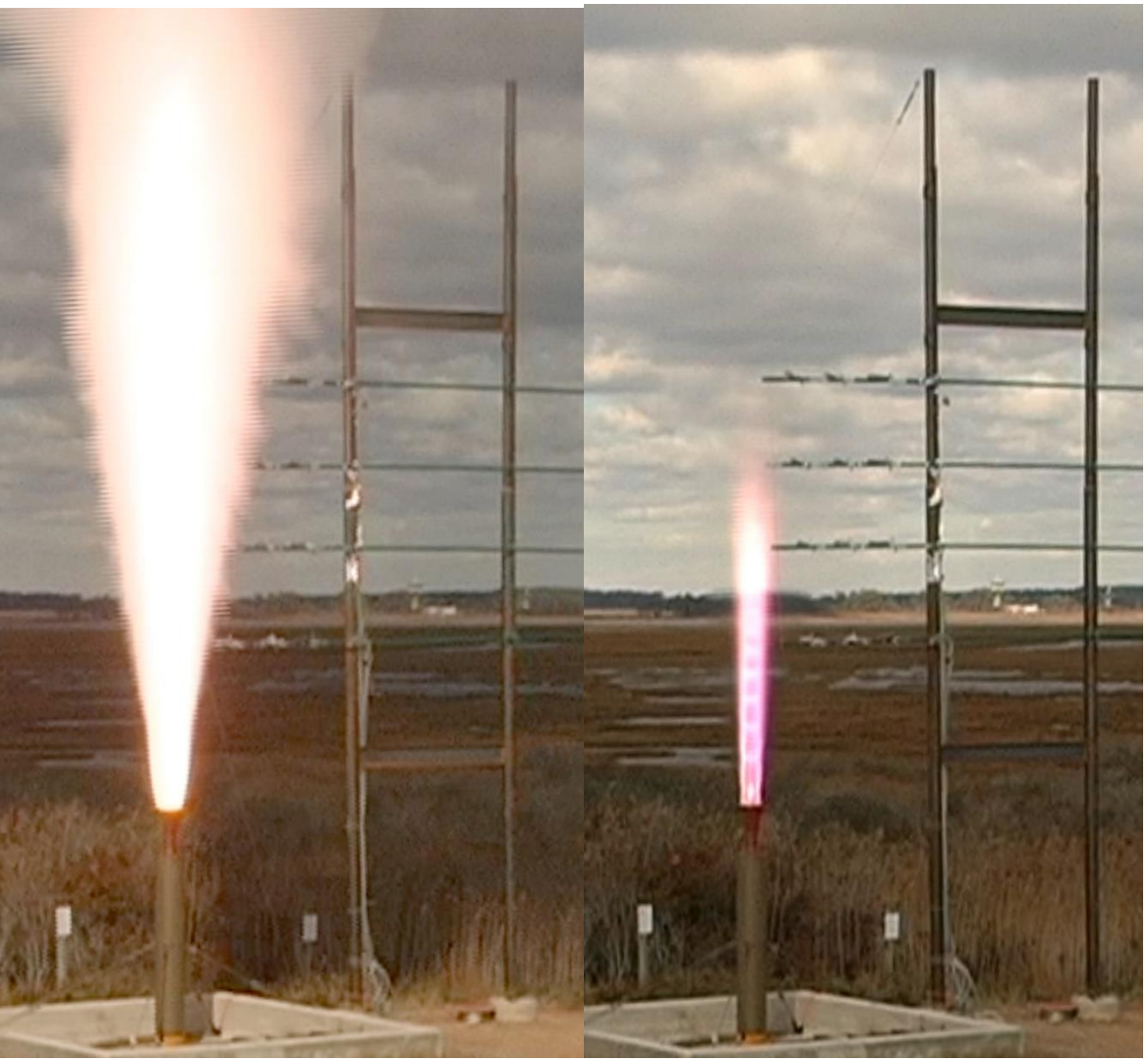
- Most intense and the most challenging
- **No heritage info from the earlier Apollo or Gemini tests**

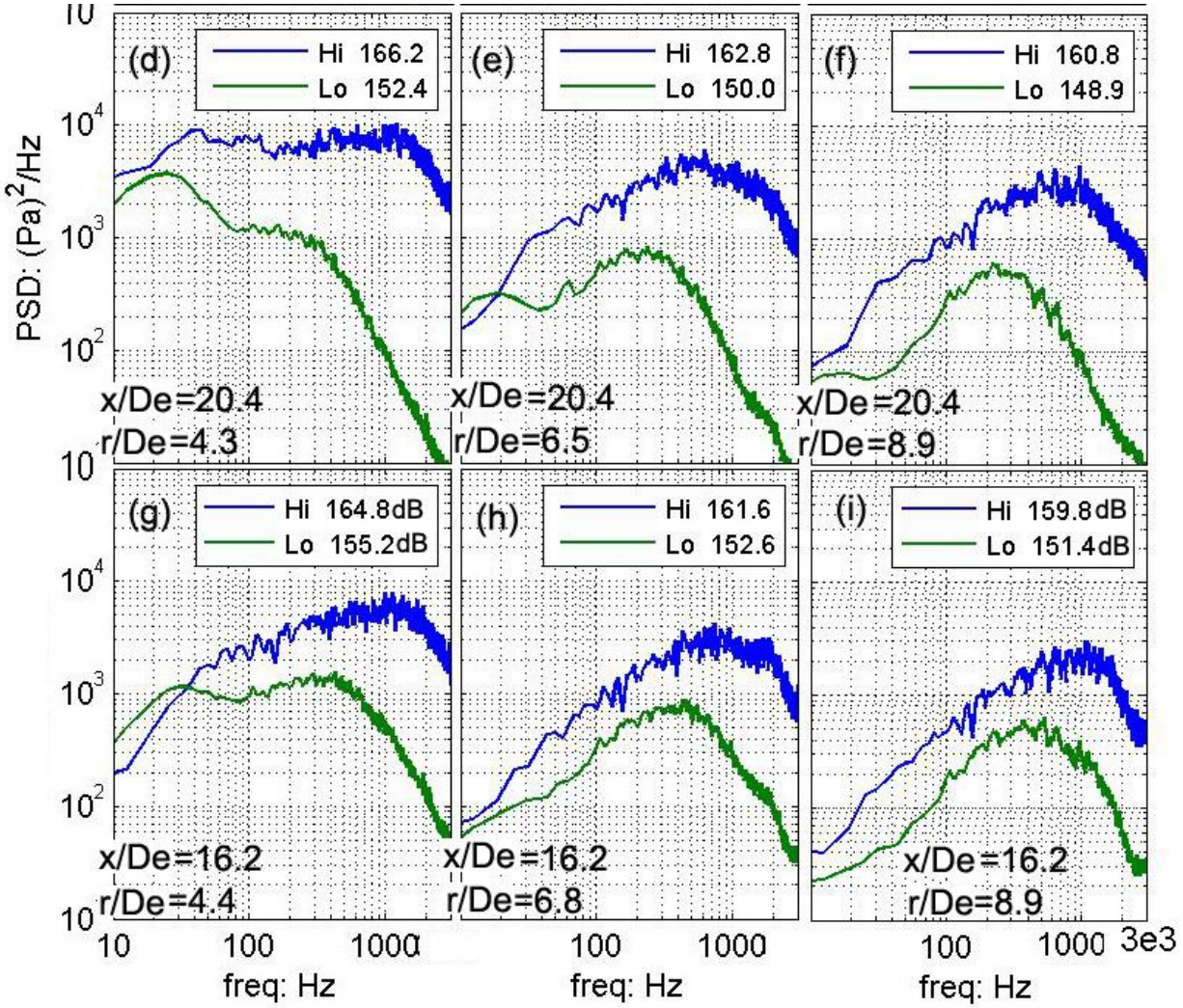
IVA. **Pad Abort**

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Static Burn of Improved Orion Motors

- NASA Wallops, June 2008
- Motors of sounding rockets – two stages of burn
- Microphones at nearfield locations

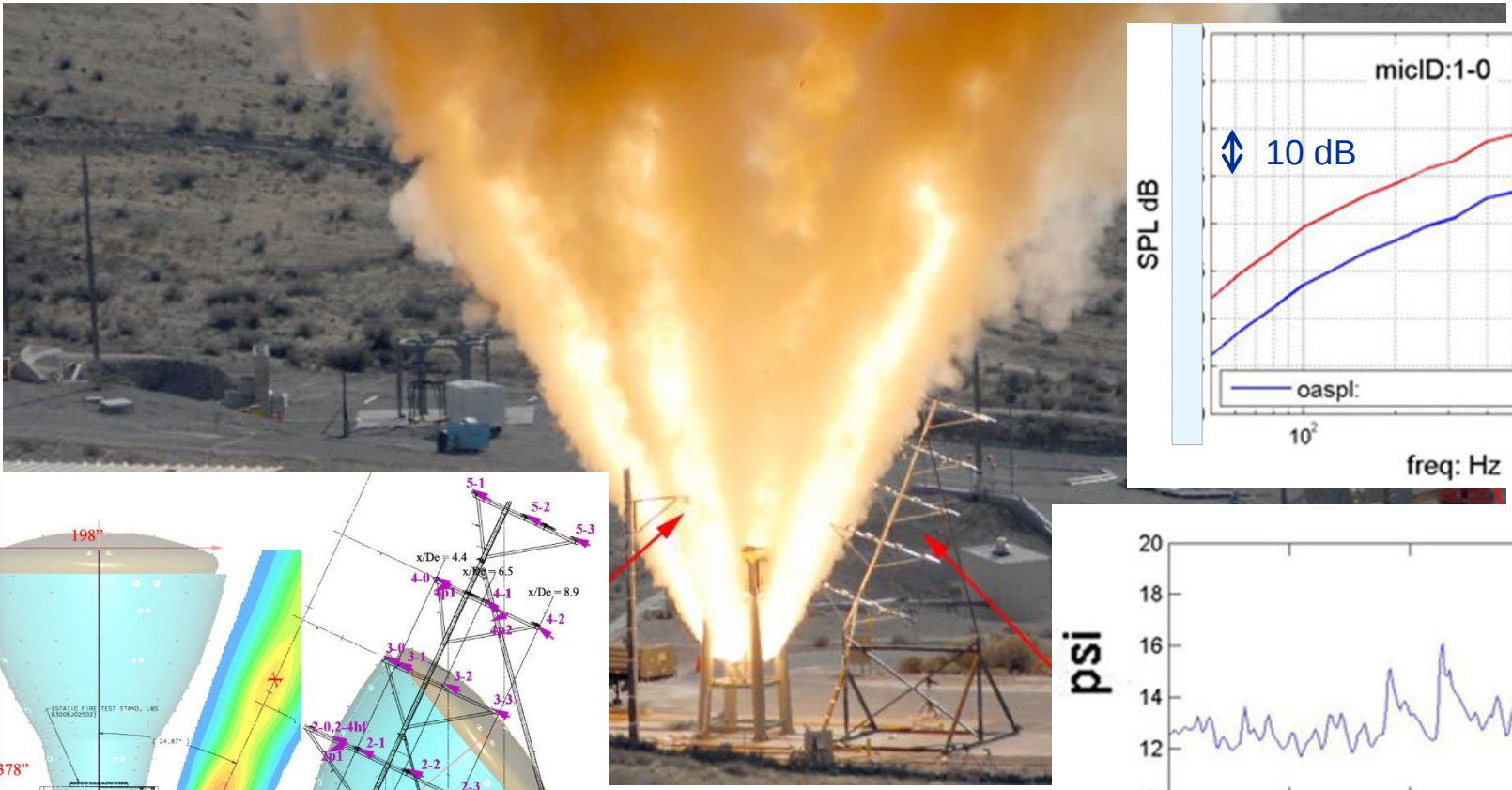


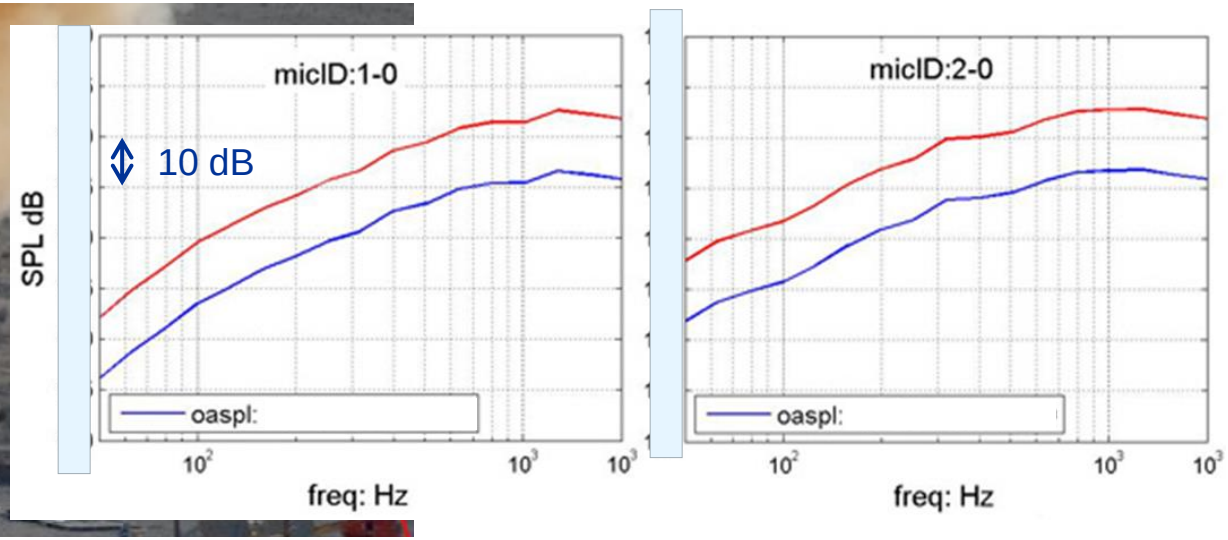


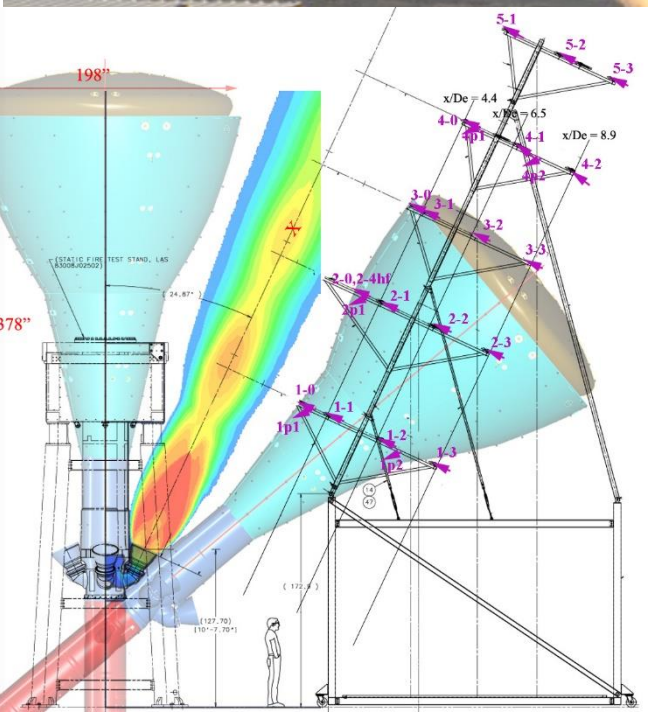
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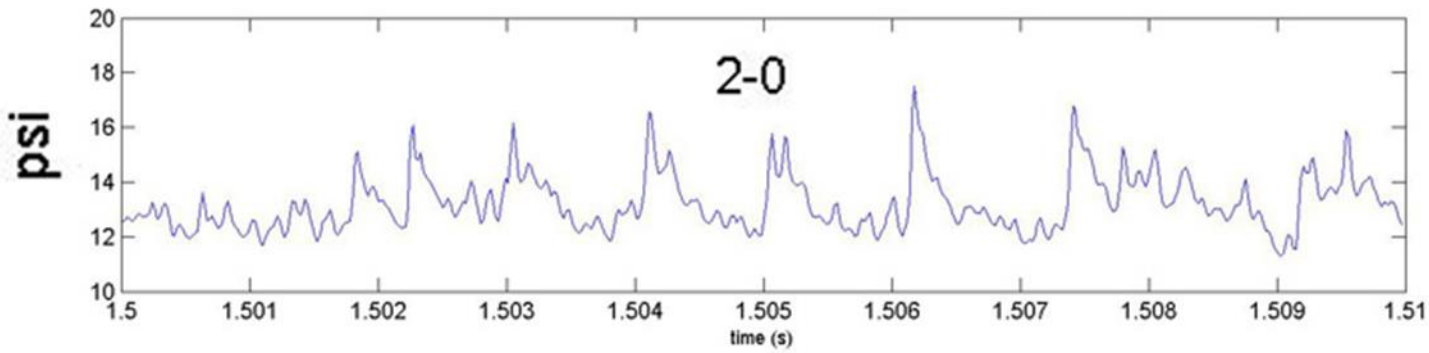
Static Fire Test ST1

- Nov 2008– Promontory, Utah, Orbital/ATK test ground
- Acoustic environment during Pad Abort







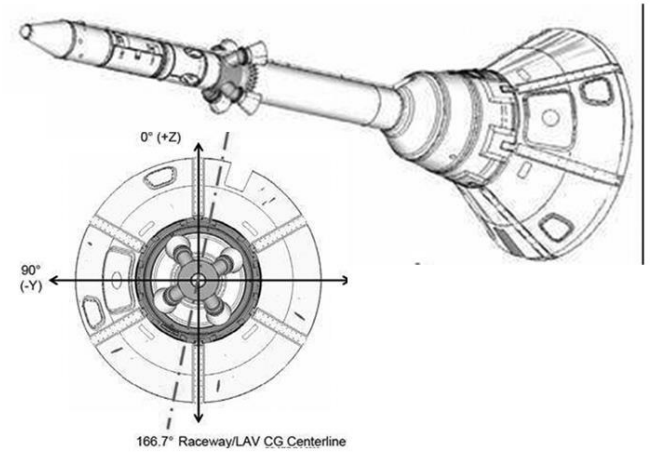


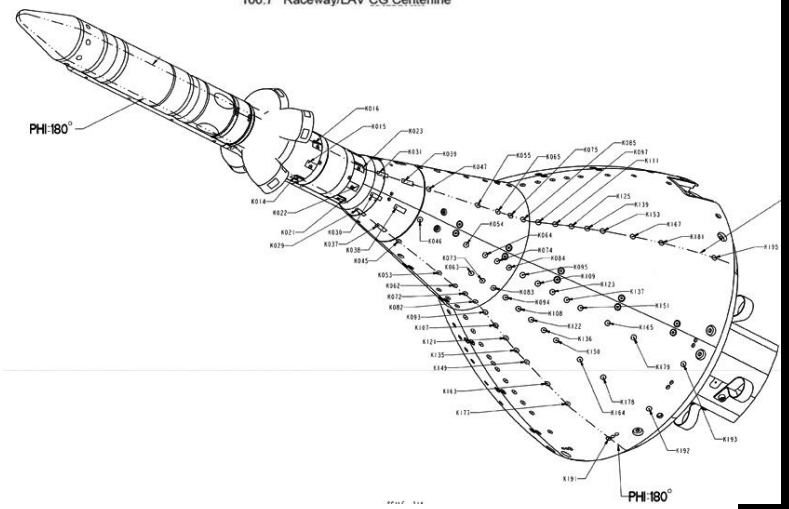
- High freq dominated
- Non-linear, shock dominated

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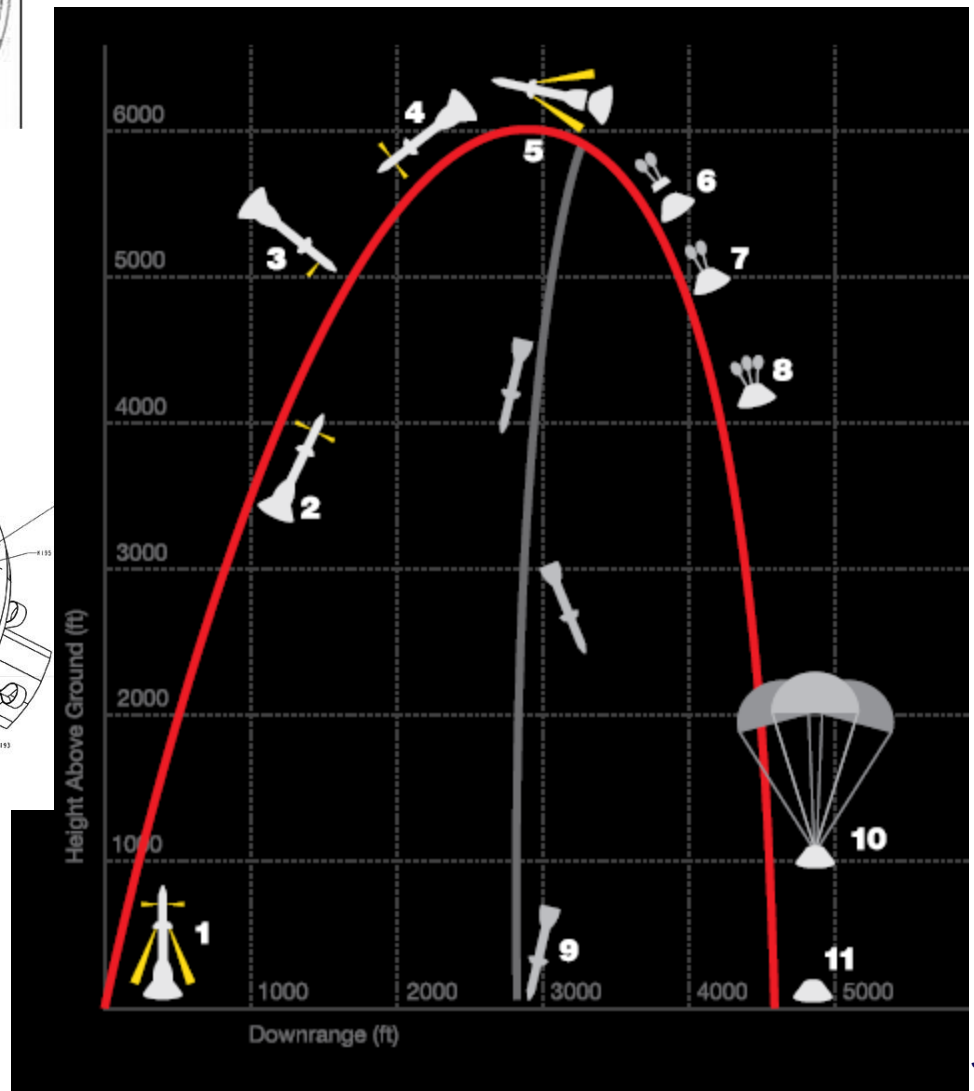
First Abort flight test Pad Abort 1 (PA1)

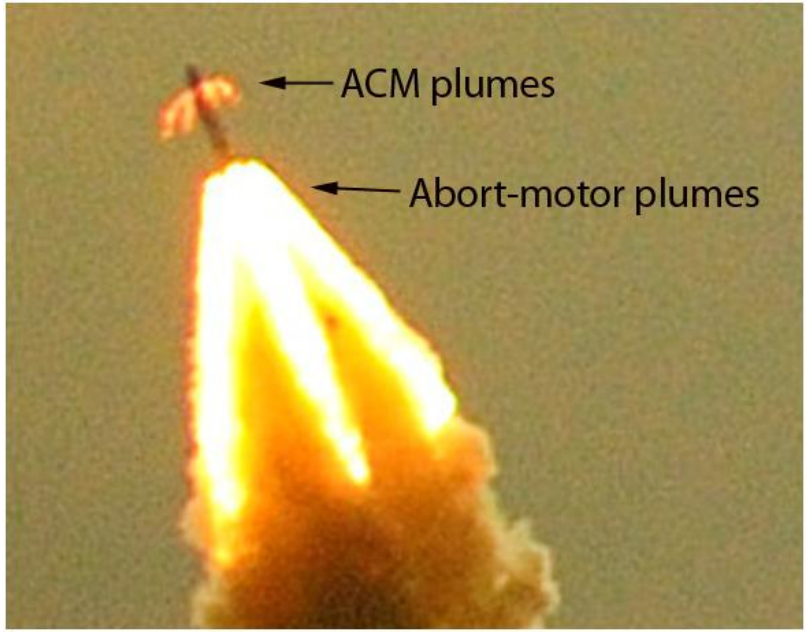
- July 2010 from White Sands
- Full scale unmanned flight vehicle, old Mold Line,
- accelerated from M 0 to ~ 0.7 over the burn duration.
- 57 sensors distributed over lower tower and Party-hat





- Older, slimmer “Party-Hat” profile





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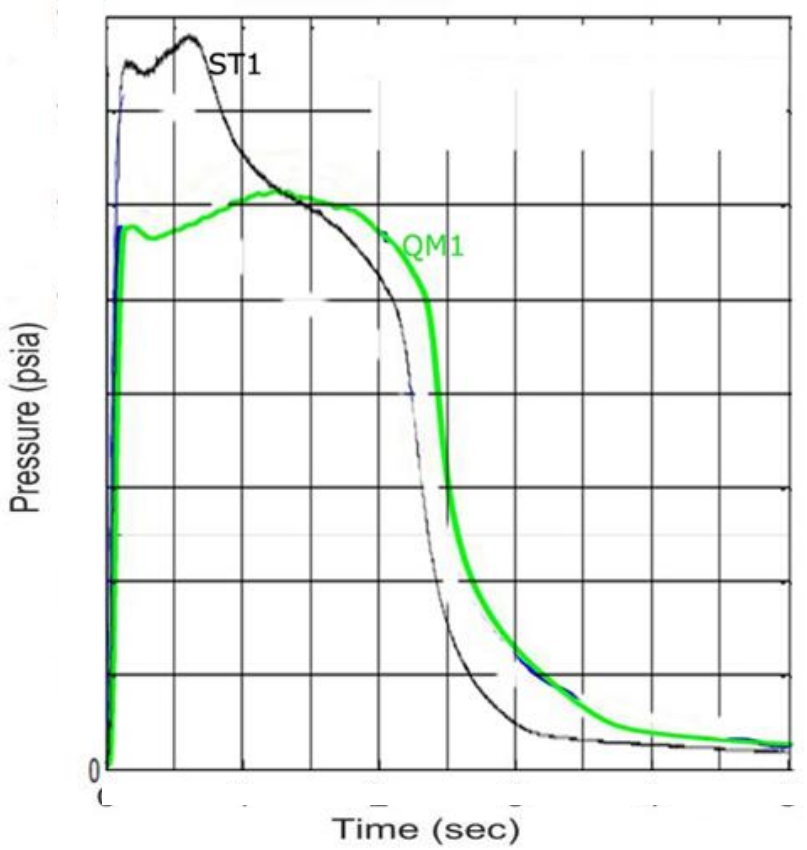


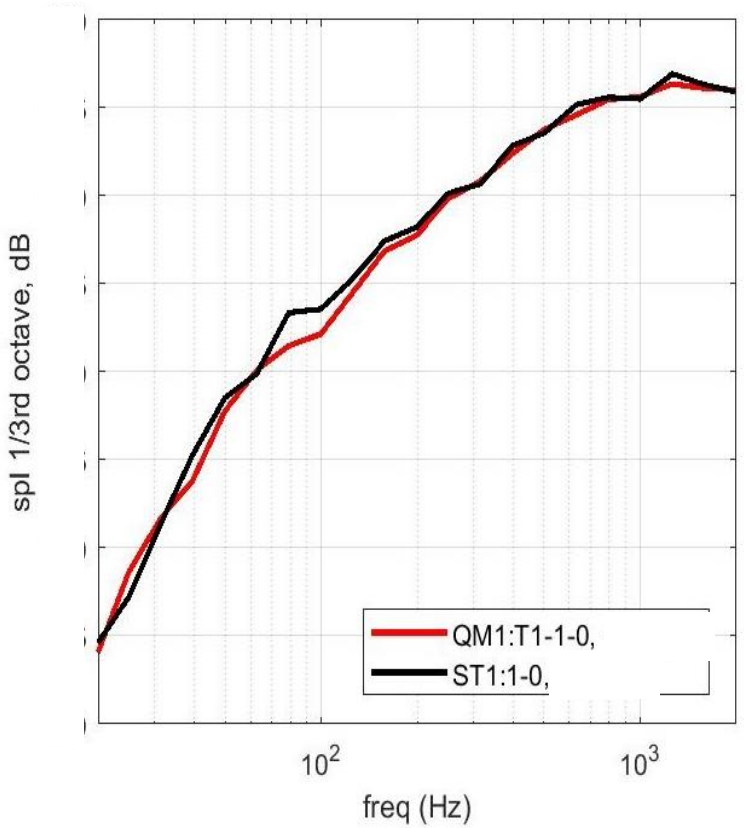
Static Fire Test QM1

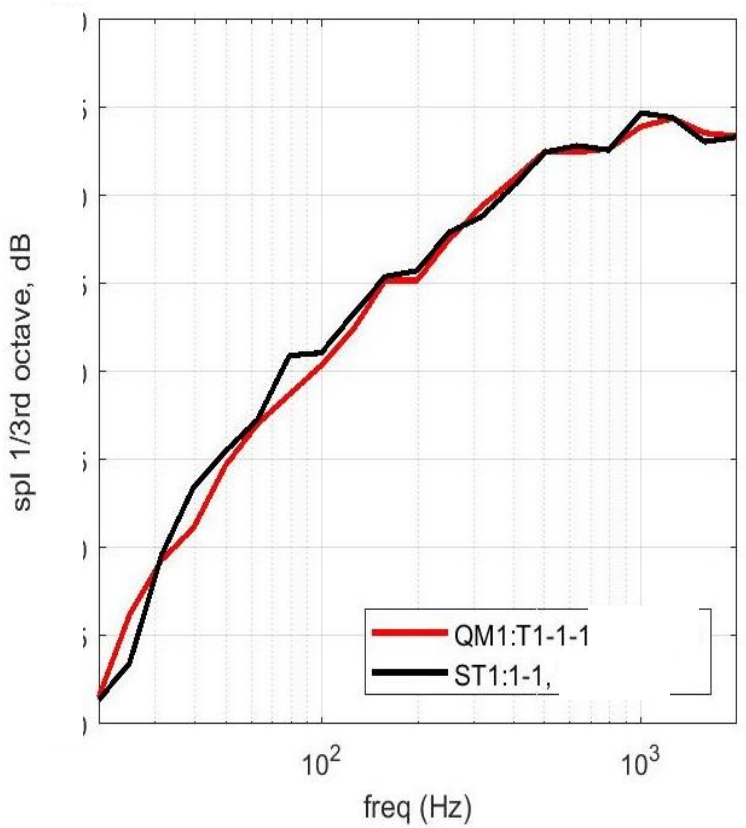
- June 2017 – Promontory, Utah, Orbital/ATK test ground
- Acoustic environment during Pad Abort
- Lower thrust Motor



Little impact of changing thrust, different motor

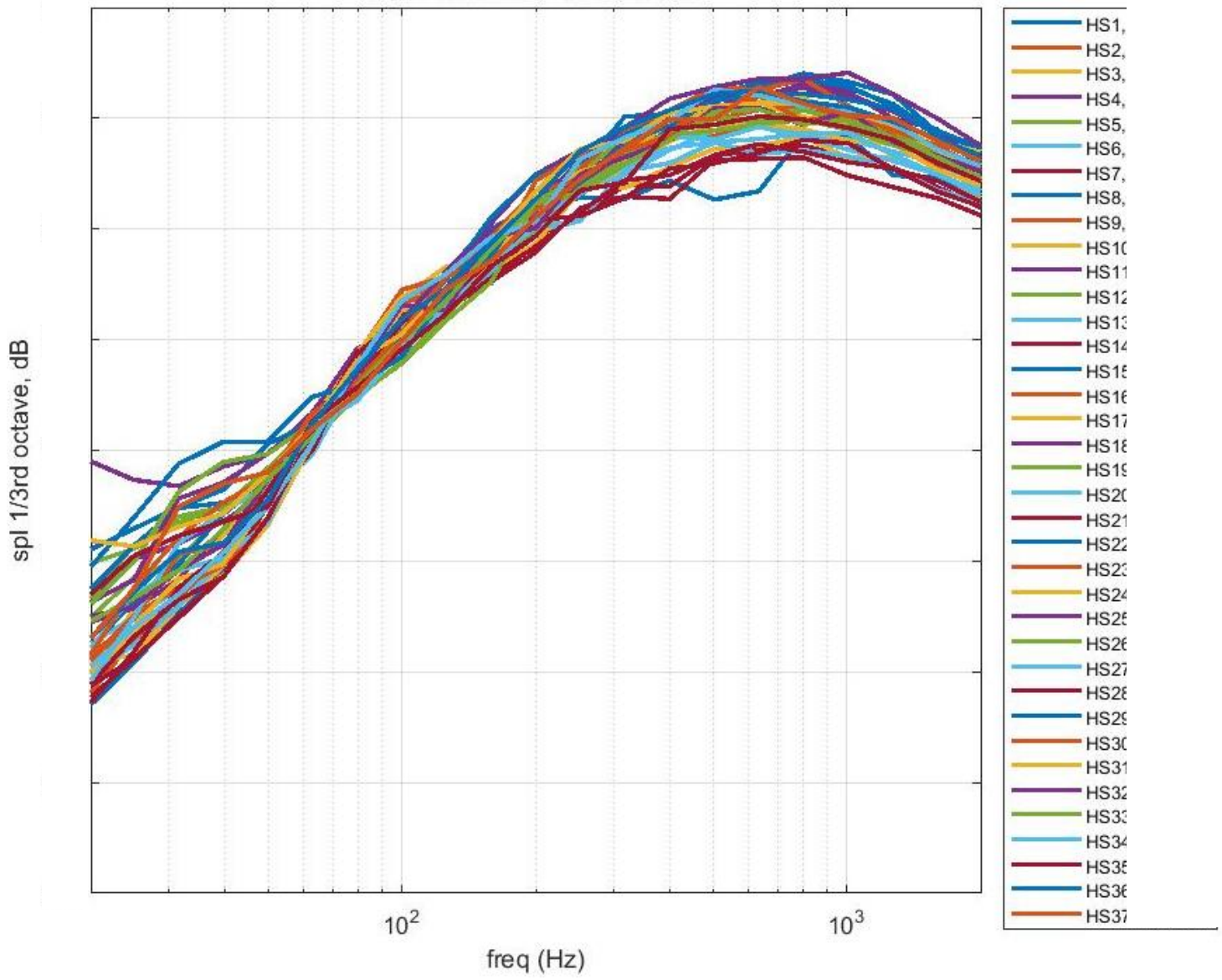






- 20% reduction of peak thrust
  - But similar acoustic level

Heat shield environment

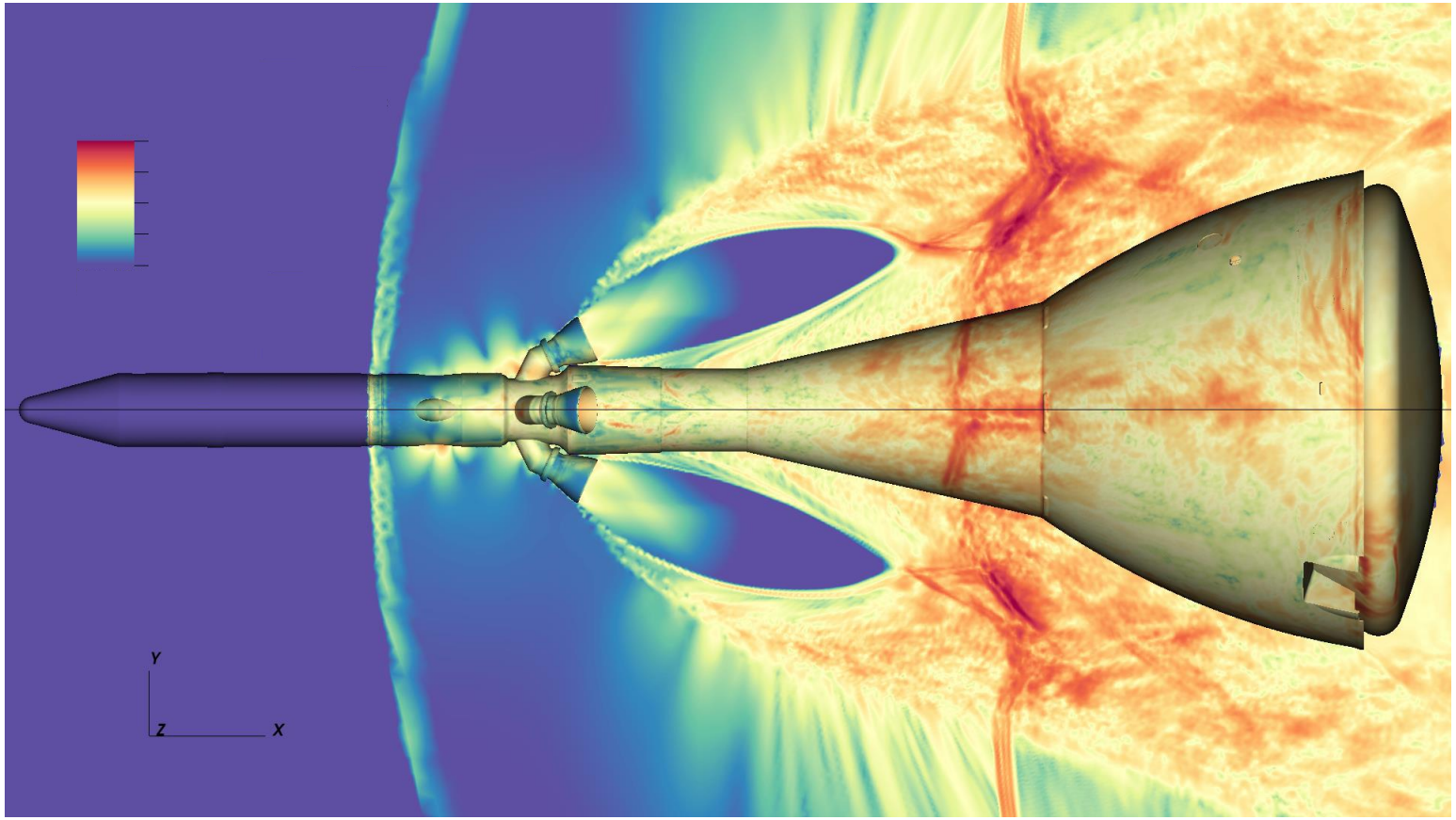


- All in family
  - Small dispersion in levels, in spite of different proximity to a plume

- **Markedly lower low-frequency energy than Ogive sensors**

IVB. Ascent Abort

- Single flight tests are unsuitable to create a design environment
- we needed to know levels over $0 \le M \le 4$ and $10° \le \alpha, \beta \le -10°$
- Requires transonic supersonic wind tunnel to simulate forward flight
- Hot Helium to simulate plumes from rocket motors



Unsteady CFD simulation of ascent abort at M=1.17, Aug 2020

by Francois Cadieux, Michael Barad, James Jensen, Jordan, B. Angel, Cetin Kiris

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Why hot-Helium?

- Hot He reproduces acoustically relevant parameters:
  speed of sound, velocity, density.

  Pressure fluctuations at a point **X** on LAV (Ffowcs-Williams,1965):

$$p(\mathbf{X},\tau) = \frac{1}{2\pi}\int_V \frac{\partial^2 T_{ik}}{\partial Z_i \partial Z_k}\left(\mathbf{Z}, \tau - \frac{r}{c}\right)\frac{d\mathbf{Z}}{r} \quad (1)$$

$$T_{ik} = \rho u_i u_k + \delta_{ik}(p - c^2\rho) \quad (2)$$

- Validation from prior small-scale tests:
  SRM vs. He: Morgan & Young (1963)
  Jet engine noise: Doty & McLaughlin (2001), Kinzie & McLaughlin (1999)
  Papamoschou (2007), Greska & Krothapalli (2009)

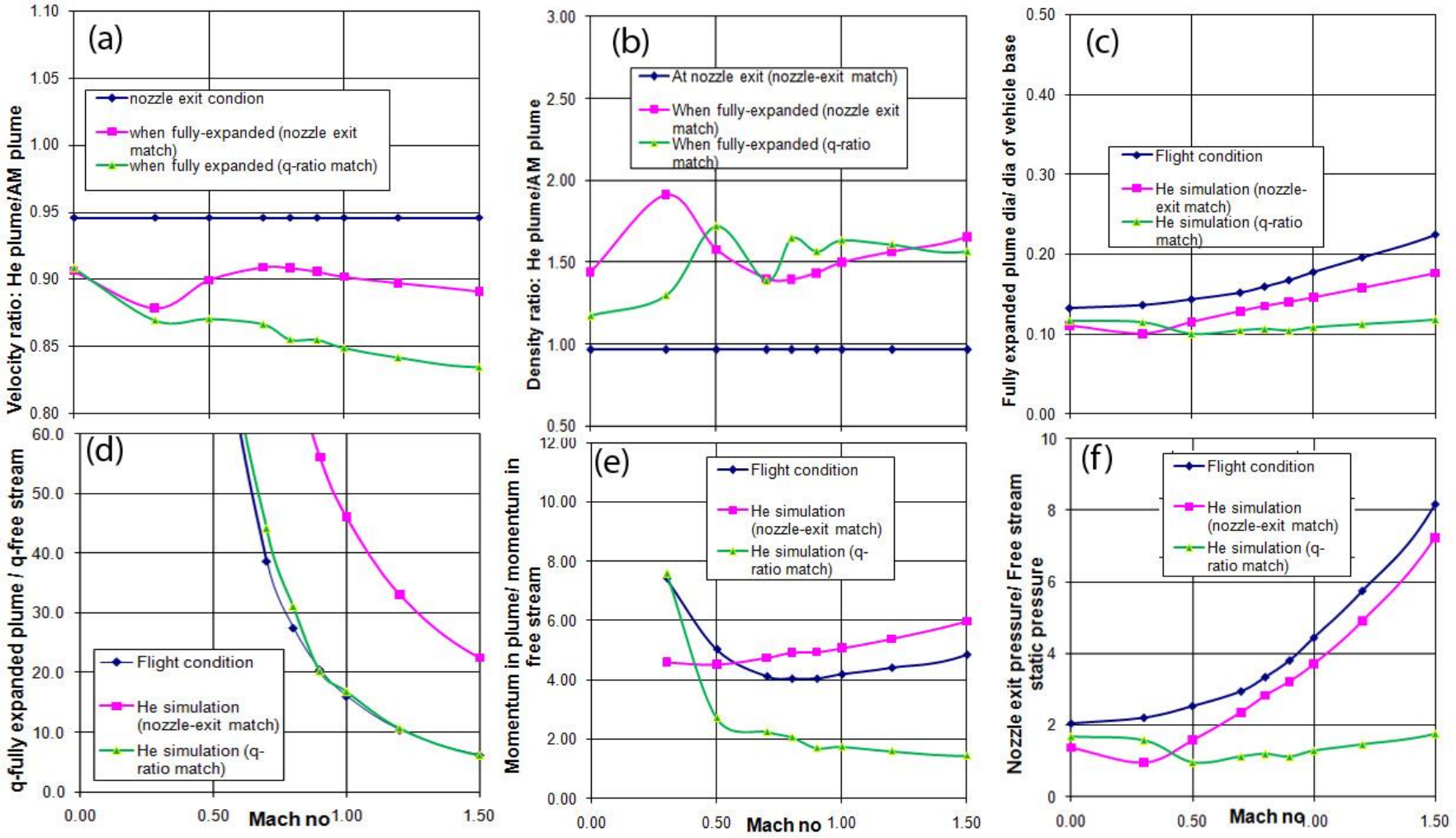
- Practicality of operation:
  - Suitable in a wind tunnel .
  - Use of high fidelity model with all 4 nozzles.
  - Survivability of the kulite sensors
- Cost effective means of creating 80 abort conditions.

- Primary differences between He and rocket plume:
  - Lack of afterburning;
  - Absence of Al_2O_3 particles;
  - Different γ

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Matching between wind tunnel and flight conditions

$$\frac{p_f'}{p_t'} = f\left(\frac{D_{er}}{D_{eh}}, \frac{D_{jr}}{D_{jh}}, \frac{\alpha_r}{\alpha_h}, \frac{\beta_r}{\beta_h}, \frac{M_{jr}}{M_{jh}}, \frac{M_{er}}{M_{eh}}, \frac{(p_e/p_a)_r}{(p_e/p_a)_h}, \frac{c_{jr}}{c_{jh}}, \frac{\rho_{jr}}{\rho_{jh}}, \frac{\rho_{er}}{\rho_{eh}}, \frac{U_{jr}}{U_{jh}}, \frac{U_{er}}{U_{eh}}, \frac{(J_e/J_a)_r}{(J_e/J_a)_h}, \frac{W_{er}}{W_{eh}}, \frac{q_f}{q_t}, \frac{q_{jr}}{q_{jh}}\right) \quad (7)$$



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How to scale hot Helium data to flight condition?

- Problem of two different ratios of dynamic pressures q: $\frac{q_{flight-stream}}{q_{wind-tunnel}}, \frac{q_{abort\ motor}}{q_{Helium}}$

- Heavily under-expanded plume, what plume condition to use?
- Don not use any plume scaling, only scale for the model size?

- Each abort condition was simulated by two Helium + Wind tunnel setup:
  - Nozzle exit match
  - q-ratio match

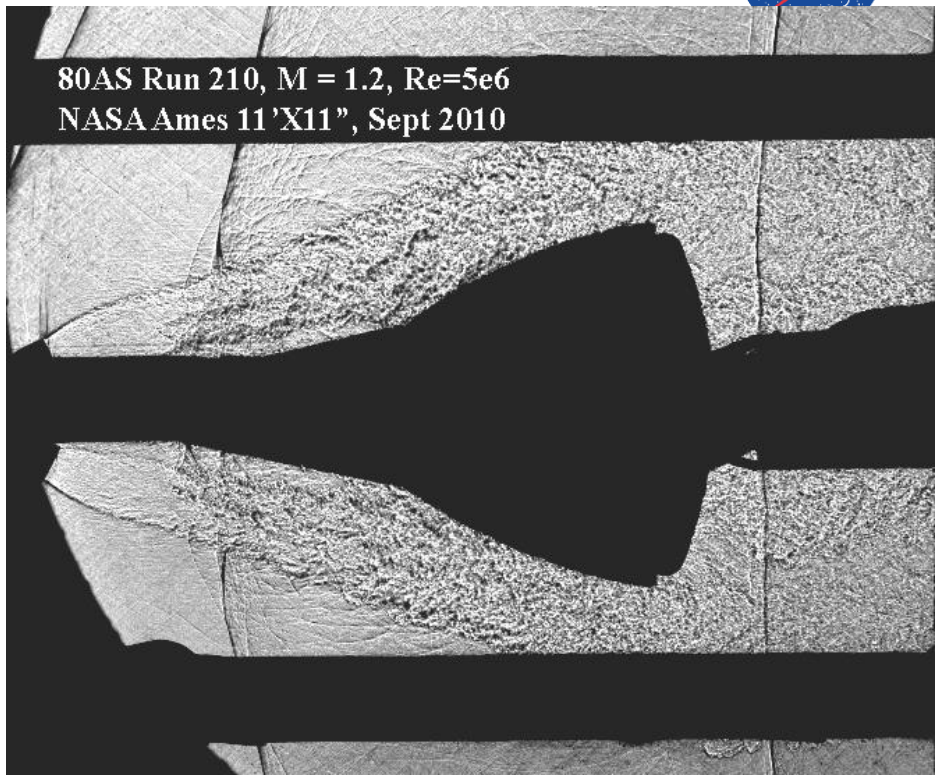
$$\frac{q_{Helium}}{q_{wind-tunnel}} = \frac{q_{abort\ motor}}{q_{flight-stream}}$$

  - Different static pressure to simulate abort at different altitudes but same Mach

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Hot Helium Test

- Test conducted in the NASA Ames 11-Ft Unitary Plan wind tunnel
- Mach Range 0.3 – 1.2
- Reynolds Number: $2x10^6$ - $5.0x10^6$/foot,
- He pressure at Model Plenum: 300psi to 600psi
- He temperature at Model Plenum: 660F to 700F
- Internal piping for 11 different model attitudes:



Hot Helium simulation of ascent abort at M1.2

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Hot Helium Test to simulate ascent abort





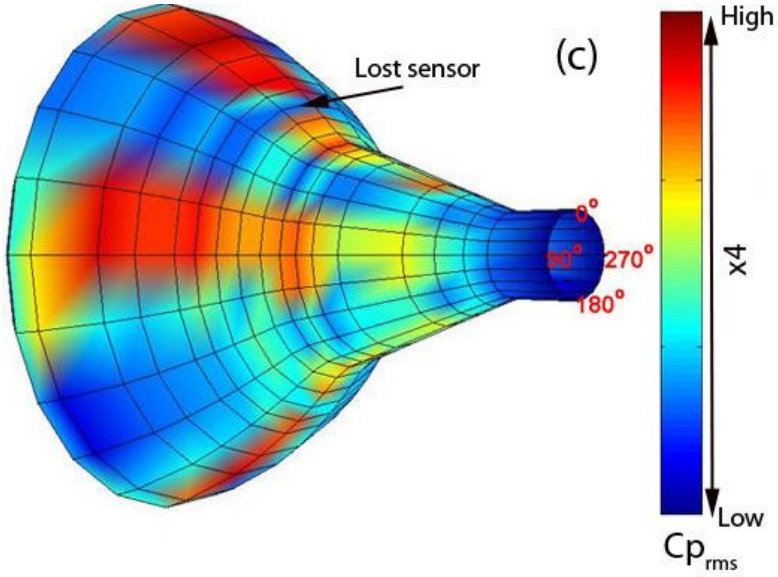


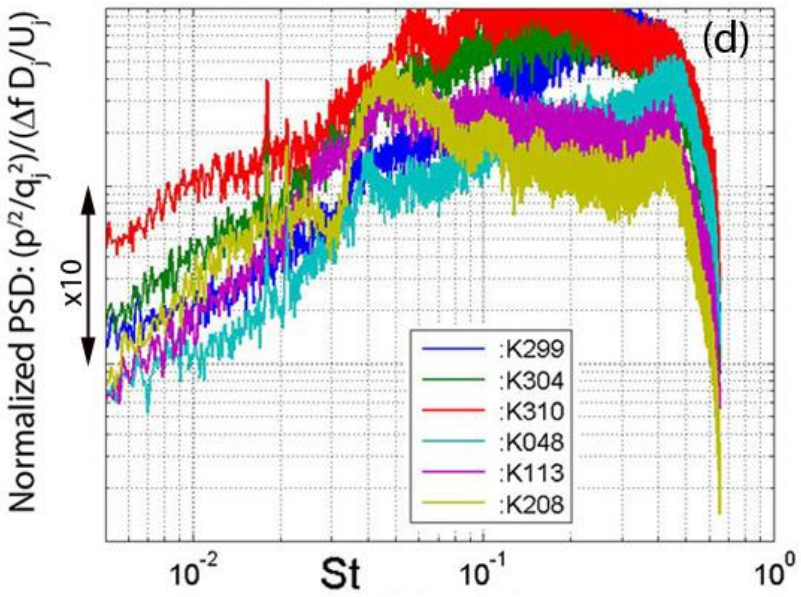


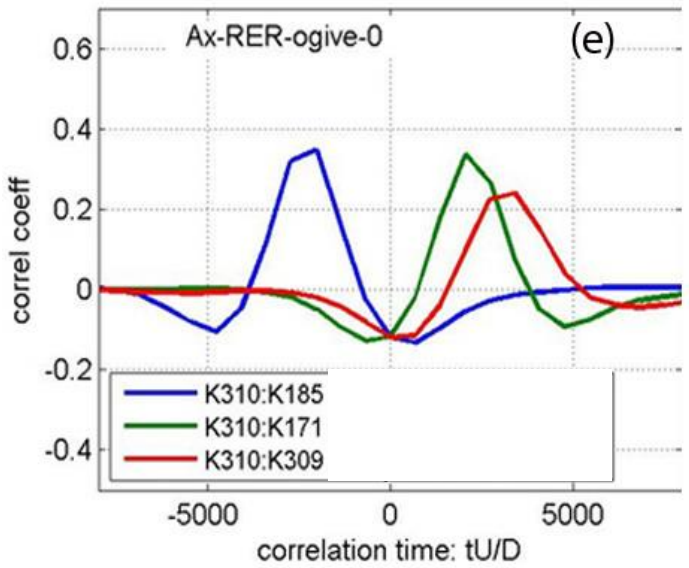
- 6% scaled of LAV 606 F.1
- Continuous active cooling of the model core
- Subjected to very large temperature cycle – periodic heating and cooling.
- 237 Kulite sensors

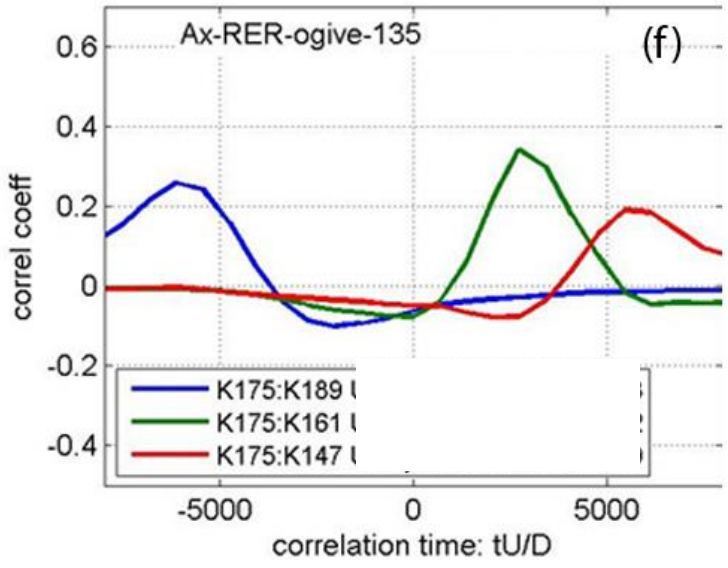
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Sample Result: Run 184: M = 0.3, Re = 3e6, a=0, b=0





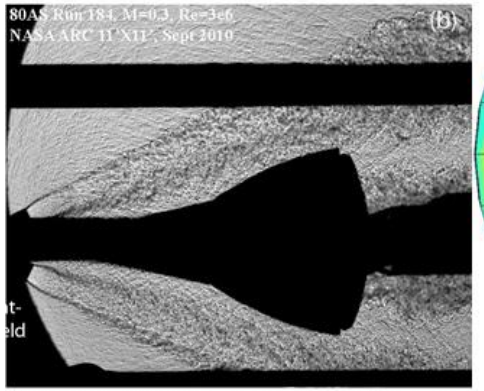


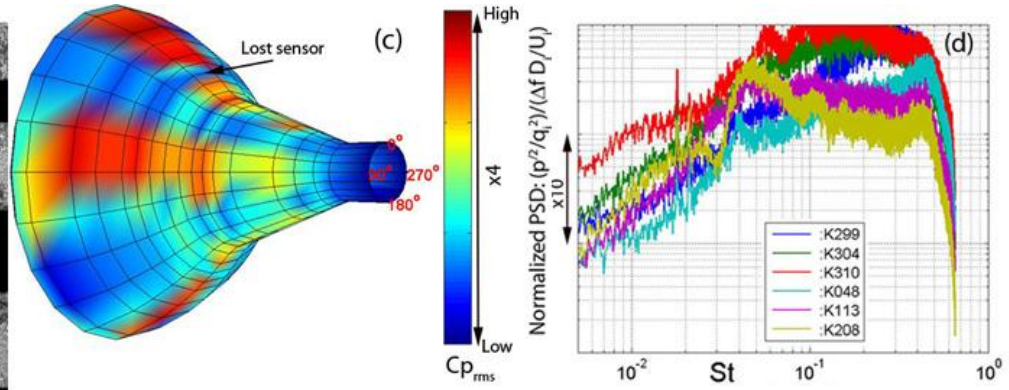


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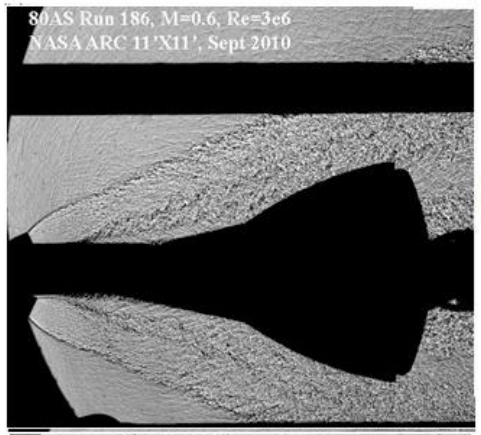
Effect of Forward Flight

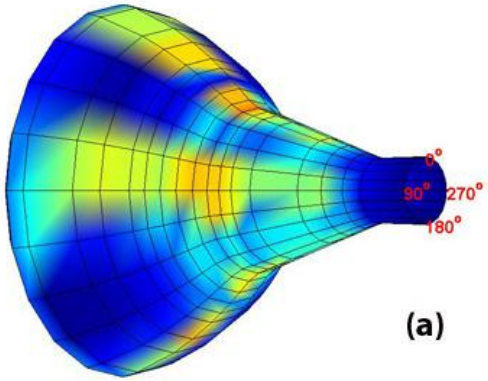
M = 0.3

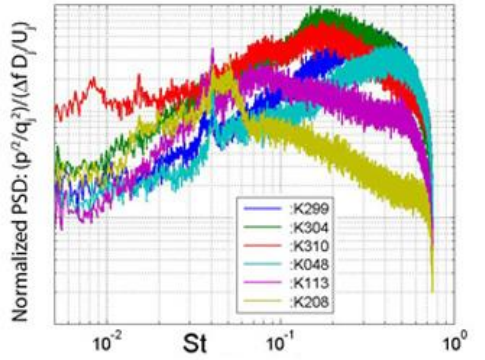




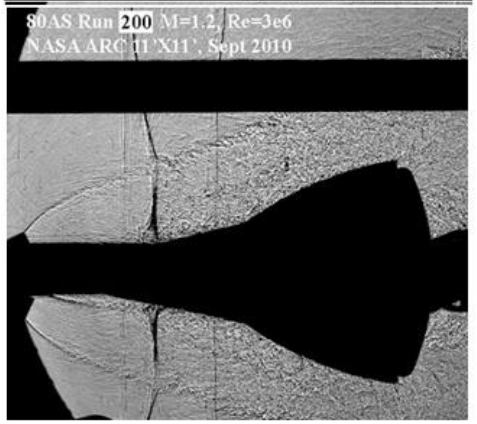
M = 0.6

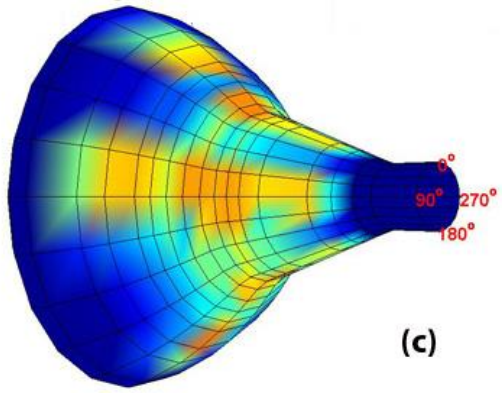


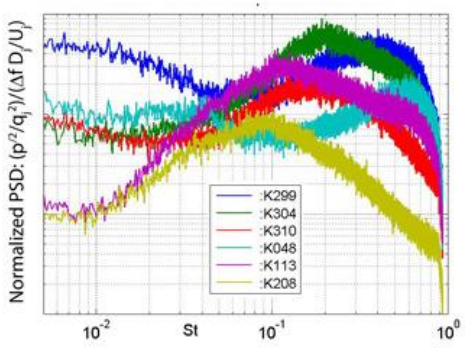




M = 1.2

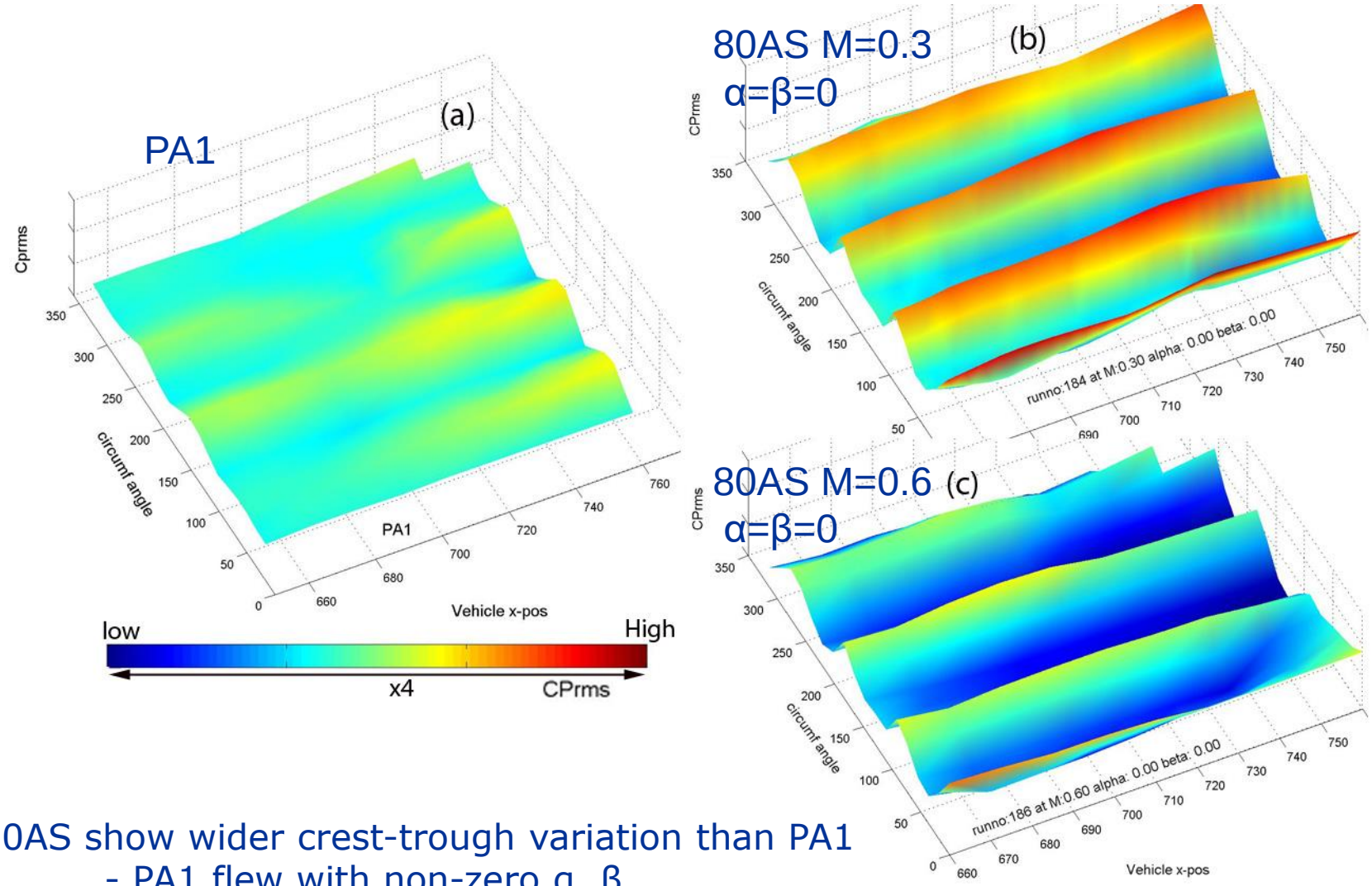






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Comparison with PA1 flight data

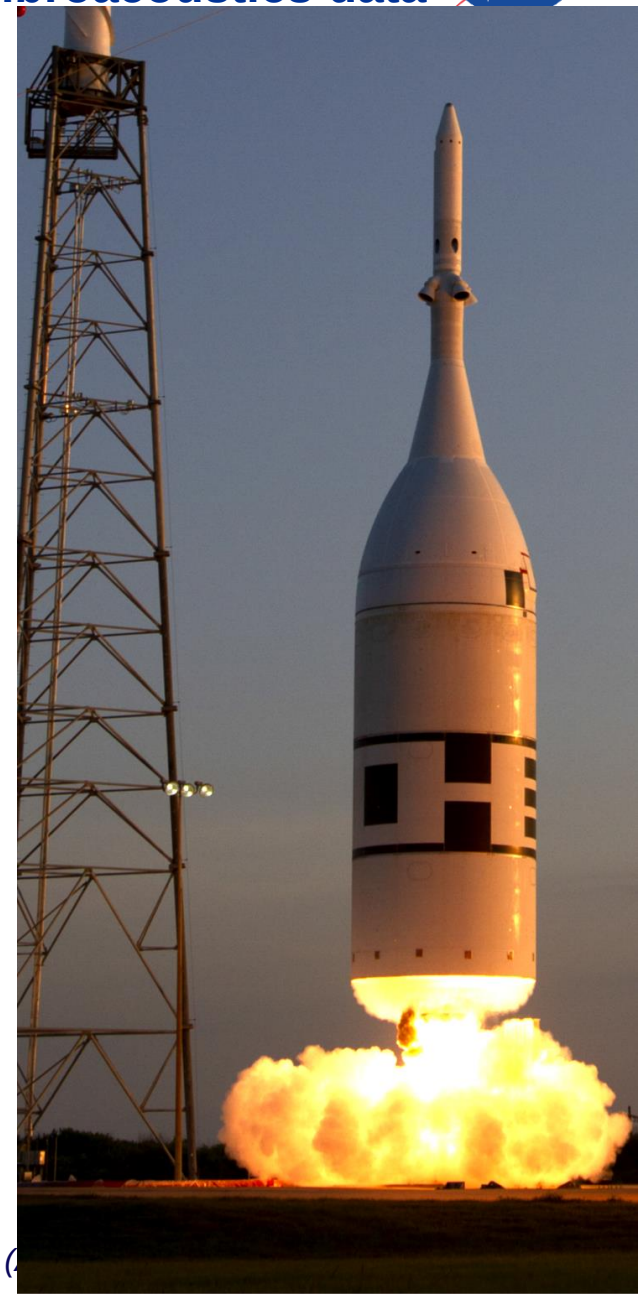


- 80AS show wider crest-trough variation than PA1
  - PA1 flew with non-zero α, β
  - PA1 had ACM induced turbulence

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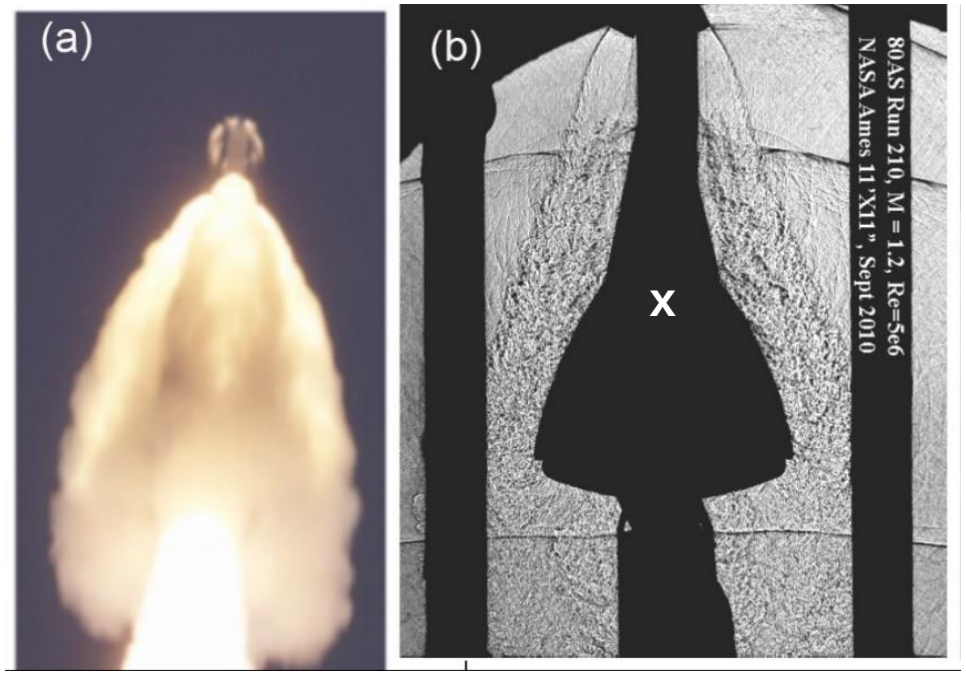
AA2 flight test – the gold standard of aeroacoustics and vibroacoustics data

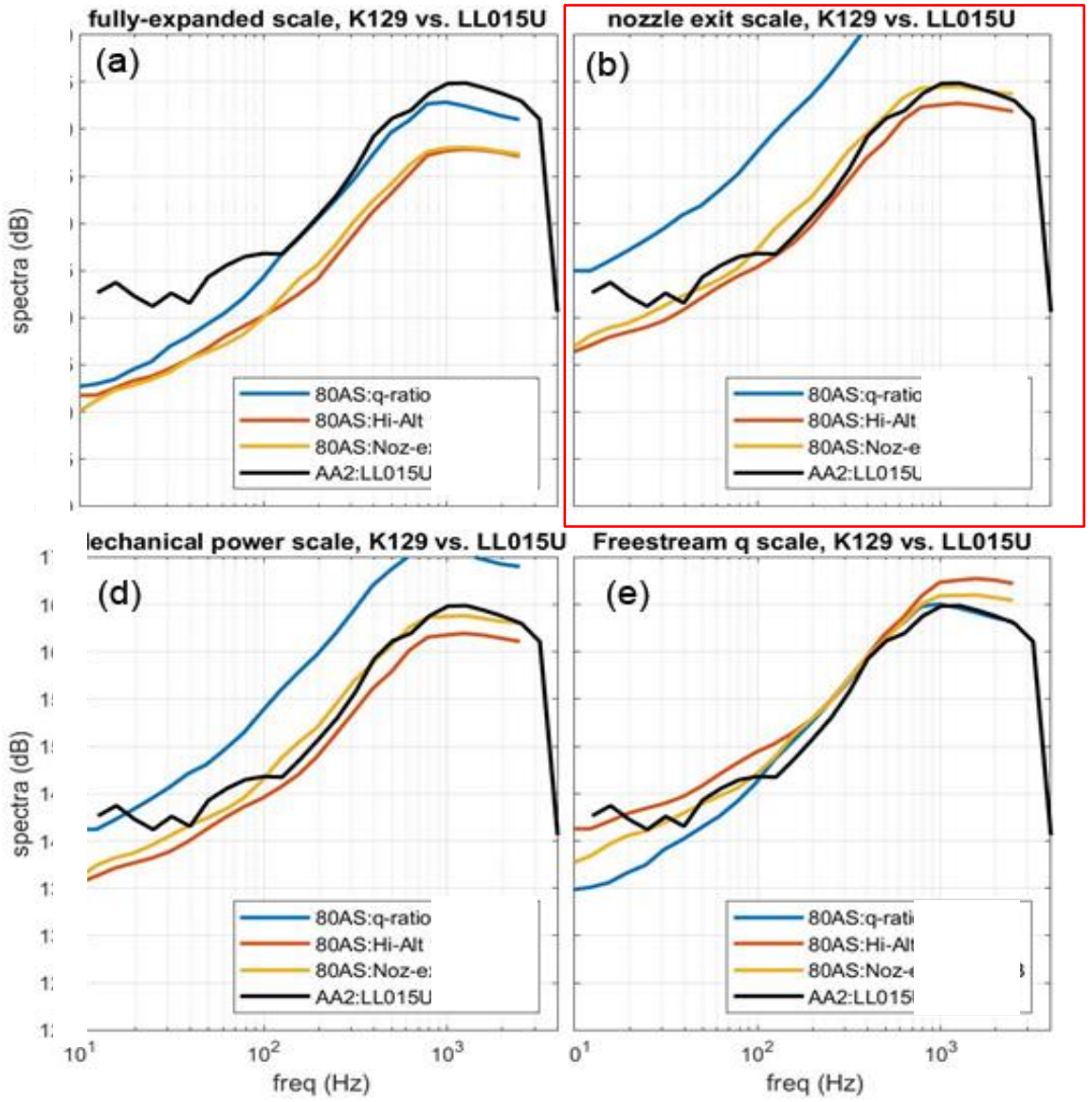
- July 2, 2019 at Space Launch Complex 46 (SLC-46), Cape Canaveral, Florida
- Boiler plate Crew module in a fully operative LAS mounted on Abort Test Booster
- 75 external microphones for aeroacoustic data
- CM & LAS acceleration environment via accelerometers and strain gauges
- Fully successful



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Comparison with AA2 flight data –
Answer to What scaling law to use for the hot Helium simulation?



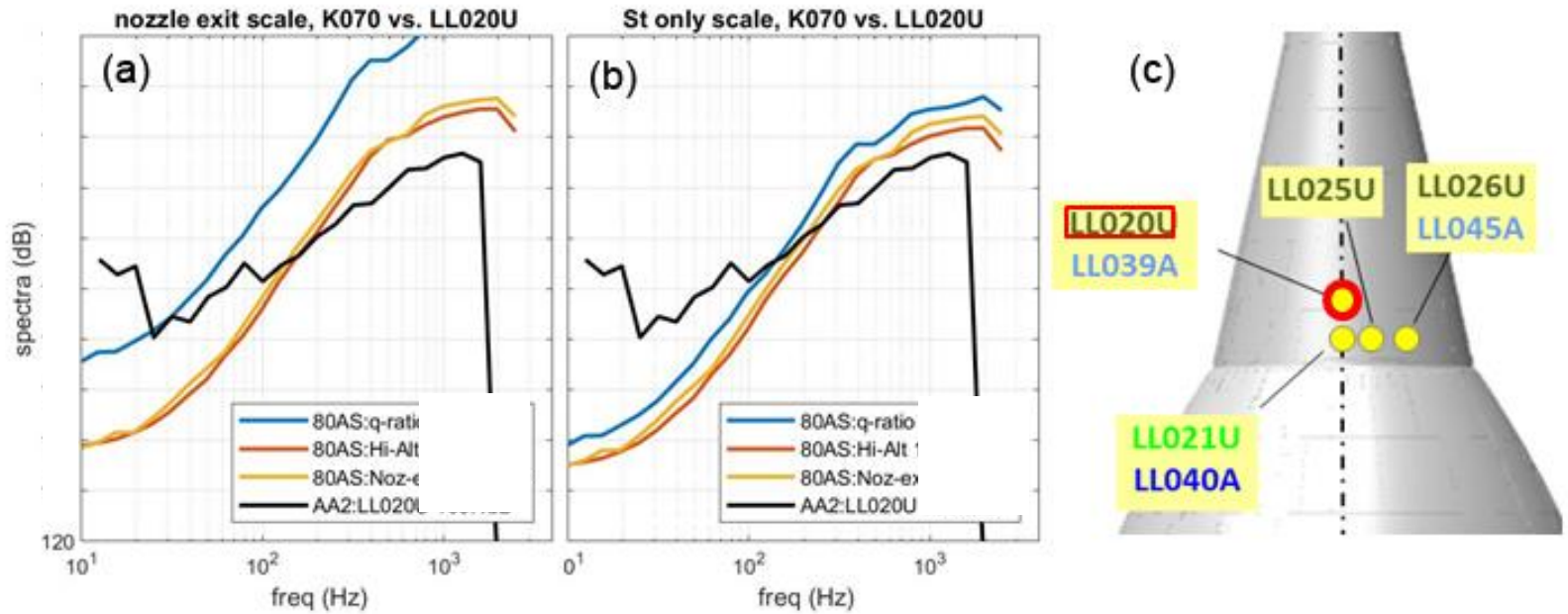


- Helium simulation: Use data from nozzle exit match cases

- Use scaling based on the plume state at the nozzle exit

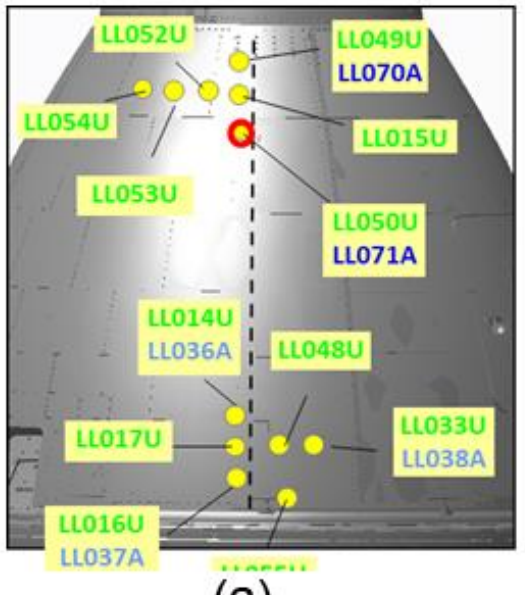
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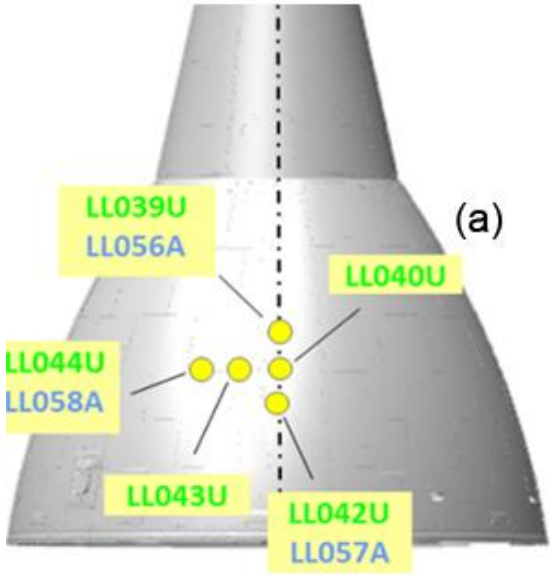
What scaling to use for Helium simulation?

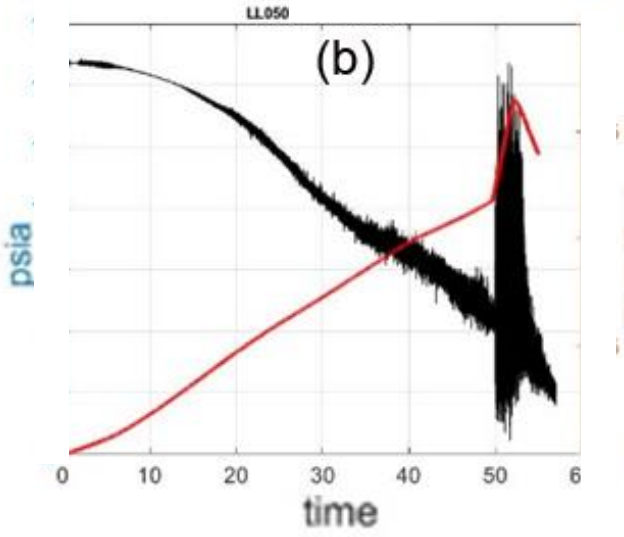


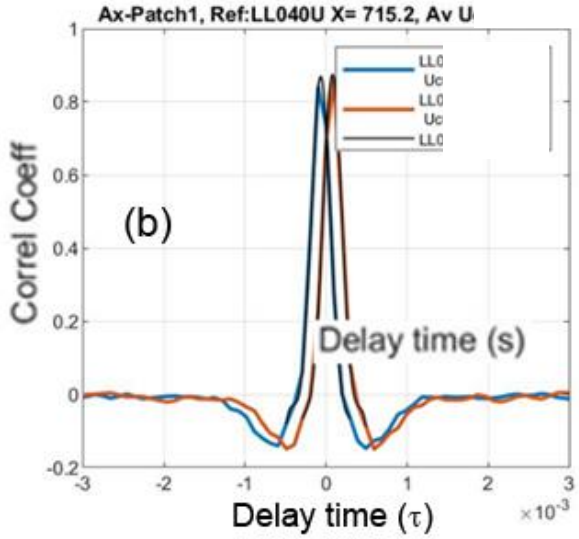
- For certain regions (e.g. Fillet-Ogive junction) Helium simulation produce different spectral shape
  - He data is limited to M1.2 only
  - Shock position changes for M>1.2 change the local pressure fluctuations

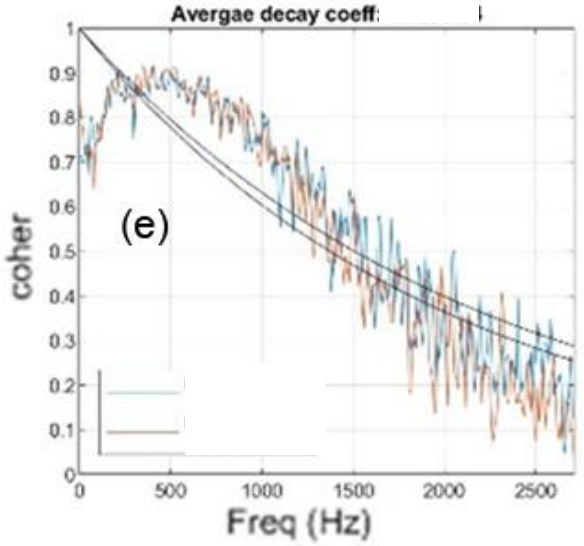
AA2 provided clear measurements of spectra, convection velocity and correlation coeff for one abort condition

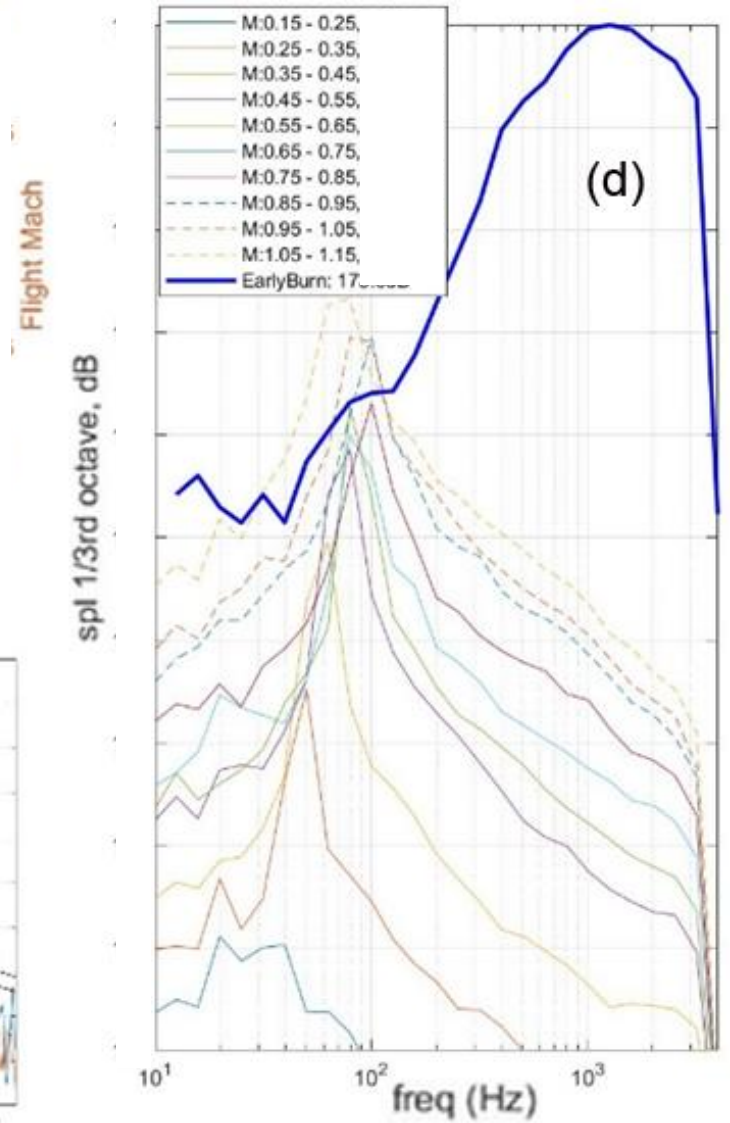




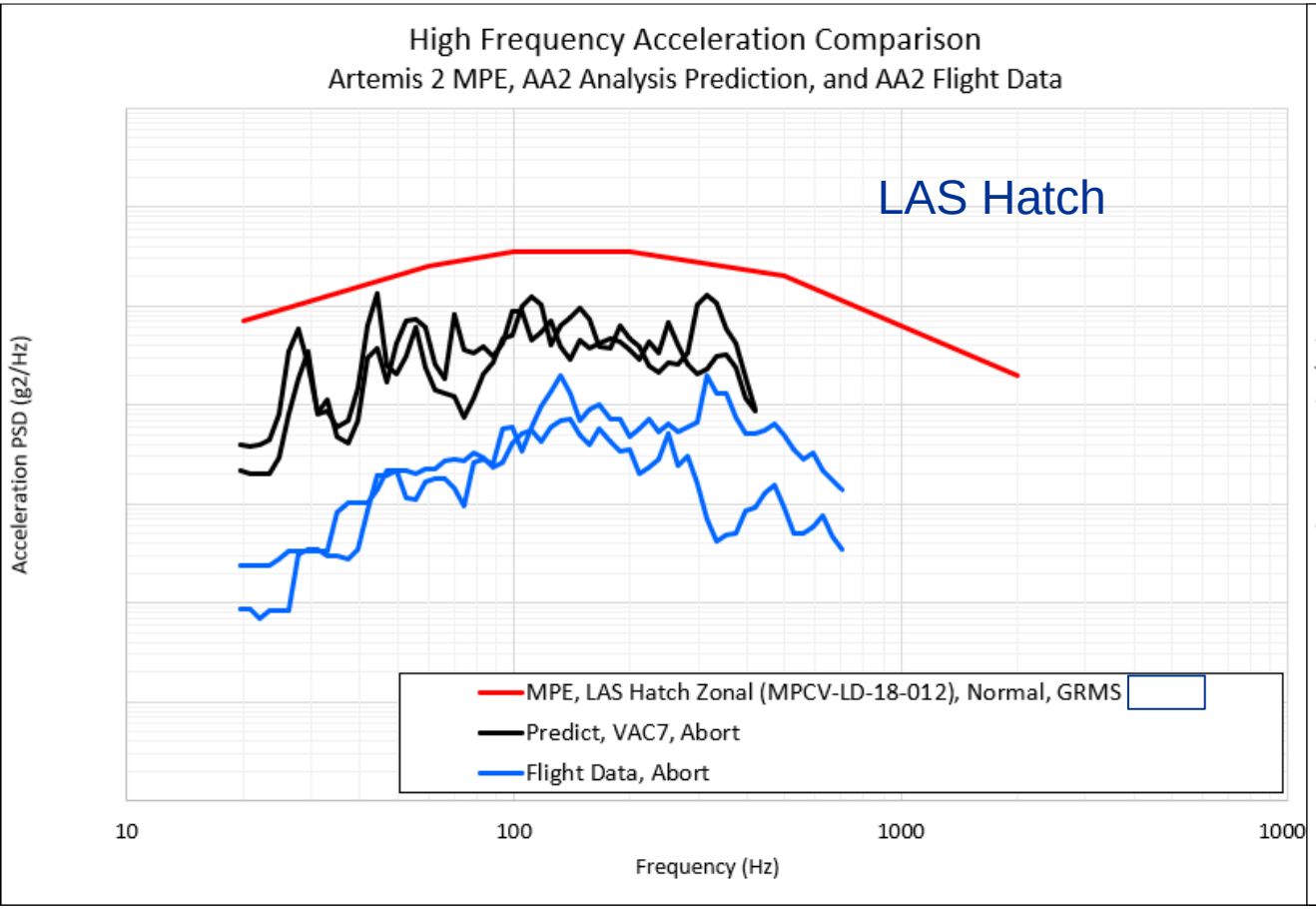


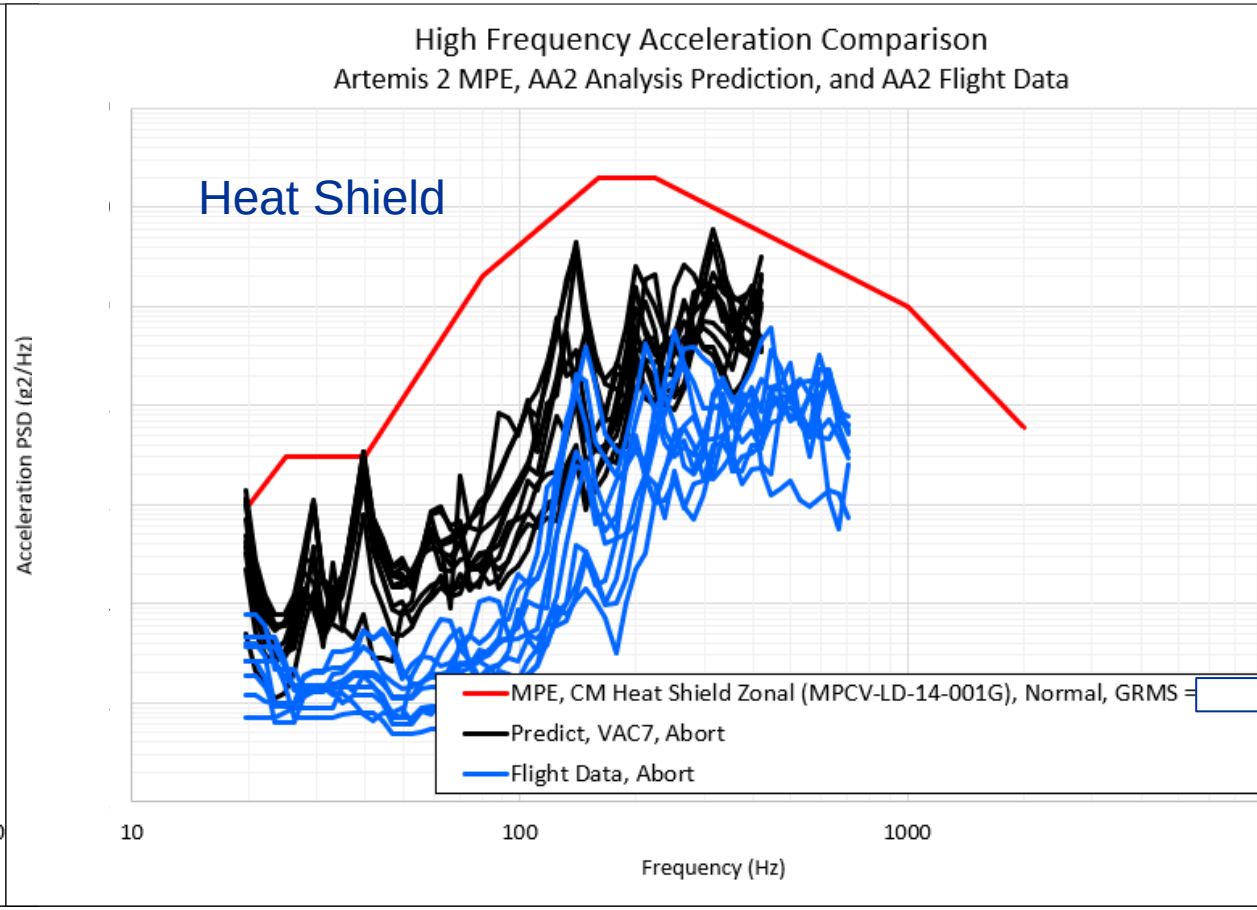






Significant over-prediction of AA2 vibroacoustic environment





Post-flight reconciliation

- Lowering of early-burn abort acoustic environment
  - Low and mid frequency range
- Extensive use of Hot-Helium to determine variation at other M, α, β conditions

Summary:

Basics

- Three components of aeroacoustics environment on MPCV – Launch, nominal ascent and Abort
- Aeroacoustics is a part of fluid-structure interaction problem
  - separation into Aeroacoustics (forcing function) and Vibro-acoustics (structural response)
- Requirements: auto-spectra, spatial correlation, convection velocity of pressure fluctuations on defined acoustic zones.

Launch Acoustics – not a driving factor for MPCV

- Model scale static burn test - SMAT

Ascent Acoustics – drives environment on CMA, ESM etc. – components not participating in abort

- Transonic and supersonic environments determined from 7 different wind tunnel test
- NESC led shape optimization study
  - change of MPCV shape from “party-hat” to the present “cone-Ogive” (ALAS)
- Difference of shock formation on Block 1 and Block 1B versions of SLS
- Verification from flight test AA2

Abort Acoustics – most intense - drives environment on LAS, CM etc. that participate in abort

- Lack of prior experience and database
- Progressive buildup of knowledge base from static fire test of single motor to Abort motor (ST1, QM1)
  – spectral trends, shock amplitude, heat-shield level
- Pad abort test PA1 and ensuing controversy on the extent of conservativeness in forcing functions
- Challenge of Ascent abort – simulation of rocket plumes in transonic wind tunnel
  - Hot helium to simulate rocket plume - similarity parameters, scaling problems, effects of increasing Mach, vehicle attitude
- Comparison with flight data from Ascent Abort 2: gold standard of acoustic data
  - resolution of scaling problem of Helium simulation
  - various insights on spectral shapes
  - significantly lower vibration response than predicted – reevaluation and changes of the abort environment

►Reasonable completion of the environment development effort – looking forward to Artemis I flight data



Backup

Announcement

The surface pressure fluctuations created during launch, ascent through the lower part of the atmosphere, and most importantly, in the event of an abort initiated to safe keep the astronauts, produce intense vibro-acoustics environment on the MPCV vehicle. The pressure fluctuations were defined primarily through a series of tests since the initiation of the program in 2006. The information was used to modify the initial shape of MPCV, followed by the design and certification of a vast number of systems and subsystems for vibro-acoustics and buffet responses. The presentation will summarize such tests and discuss the progression of the knowledge and data bases. Among the three sources of pressure fluctuations, it was the abort scenarios - both at the launch pad and during flight through the lower Mach number ranges – that were found to create the most intense levels. The MPCV performs abort by lighting up the abort motor (AM) at the top. The hot plumes from the motor pass over the vehicle outer mold line. While the abort acoustics dominated all other sources for the entire Launch Abort Vehicle portion of MPCV, little information could be collected from prior space vehicle programs. The building up of the knowledge base started with the measurement of pressure fluctuations in single rocket burns, and then progressed to the full-scale static burn of the abort motors, to wind tunnel simulations of ascent abort using mildly heated air, followed by simulations using highly heated Helium, and finally via a pad-abort and an ascent abort flight test. CFD simulations were performed to bridge the gaps in the database. For the European Service Module (ESM) and the nearby parts of MPCV, not involved in abort, pressure fluctuations created during nominal ascent through the transonic Mach number range were found to produce the limiting environment. This environment was also established through a couple of wind tunnel tests. In the earlier days of the program three different wind tunnel tests were conducted to arrive at the present ALAS shape, which replaced the earlier party-hat shape. In the end MPCV is designed to sustain the most intense acoustics environment in the history of the spaceflight.