



Aeroacoustics of Space Vehicles

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- Definition **Aeroacoustics**

- **Aeroacoustics for Airplanes**

- Mostly for community noise reduction
- very few vibro-acoustics concerns (such as failures of nozzle cowlings)

- **Aeroacoustics for space vehicles**

- Mostly for vibro-acoustic concern

- Intense vibrational environment for payload, electronics and navigational equipment and a large number of subsystems

- Community noise - little concern until recent time

- Environment inside ISS— separate issue

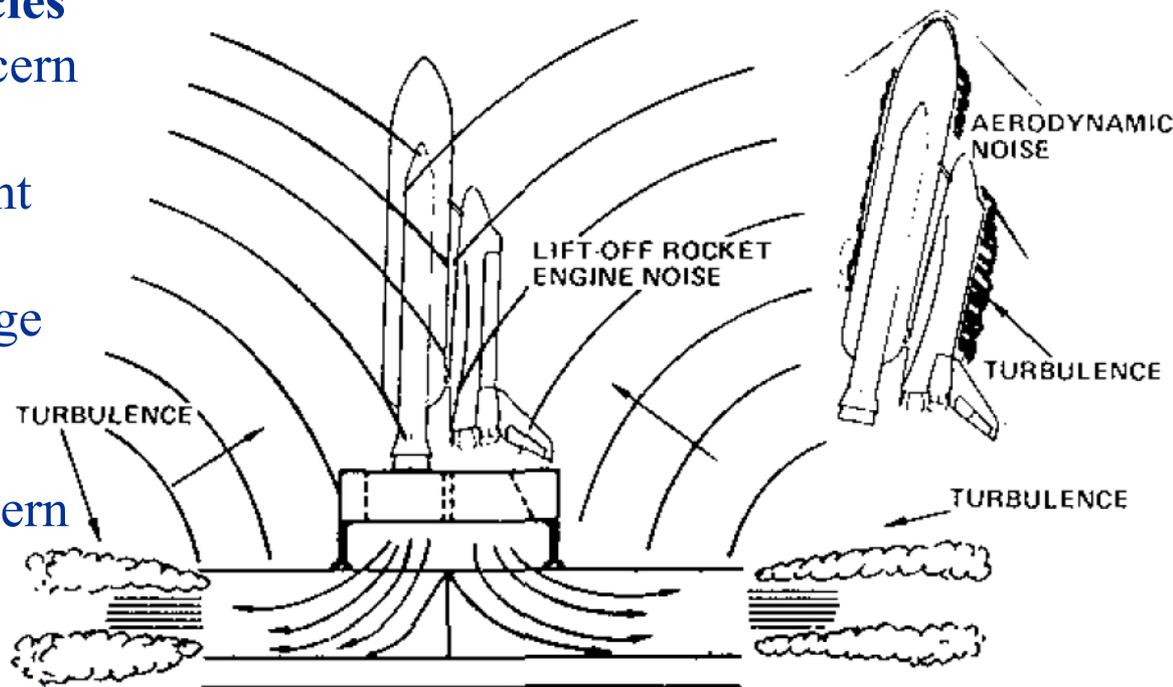
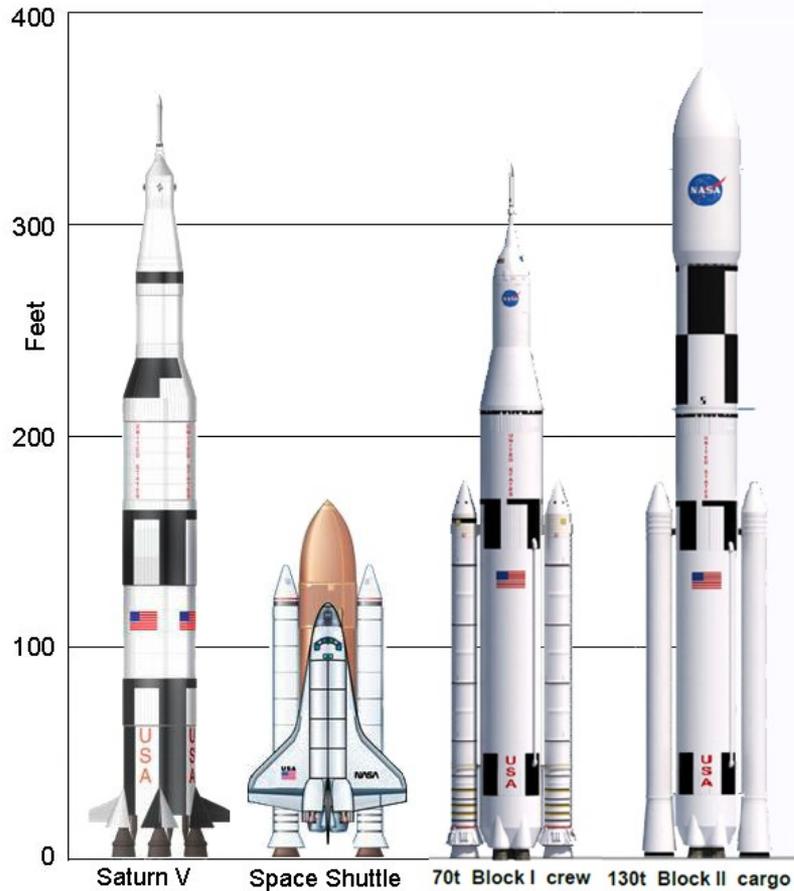


Fig. 1 Shuttle payload bay vibration and acoustic environment sources.

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

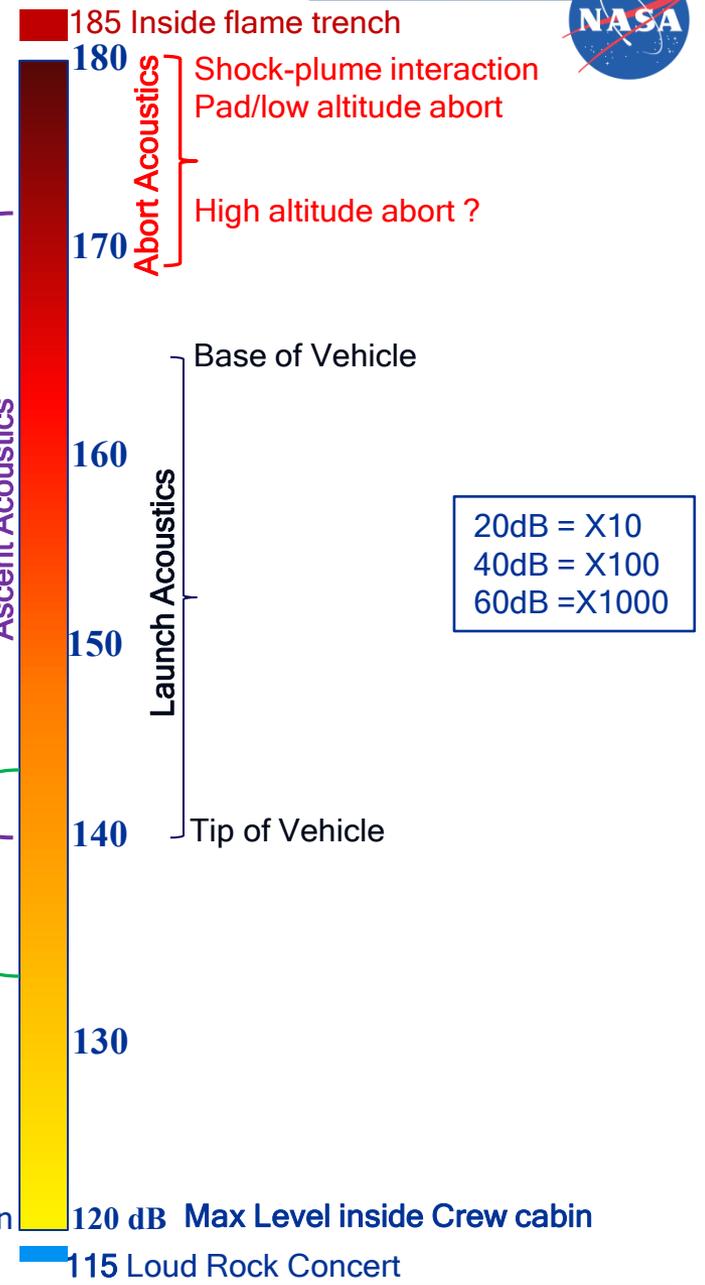


Transonic Oscillating shock

Protuberances, Separated flow regions

Smooth parts of vehicle

Level inside cargo compt, payload fairing





The end goal of acoustic analysis is to predict structural responses due to acoustic loads

3.1 Acoustic-Load Parameters

NASA SP-8072

To the extent required for design, the predicted acoustic loads shall be given as a function of position and time in terms of:

- Overall sound-pressure level
- Frequency spectrum
- Spatial correlation

2.2 Vehicle Loading

The minimum description of the loading on the vehicle, needed to estimate the structural response, is given in terms of the detailed distribution on the structure of the sound-pressure spectrum. A more detailed description also requires the spatial correlation pattern of the sound-pressure field to enable more exact vibration prediction. Such analyses are required for examining certain types of failures, such as the sonic fatigue of lightweight external panels.



Aeroacoustics : part of Fluids – Structure Interactions

NASA CR-1596: Himelblau, Fuller, Scharton, “Assessment of space vehicle aeroacoustic-vibration prediction & testing”

the displacement spectral density for location \mathbf{x} at each frequency f due to a spatially-distributed applied loading is

$$G_w(\mathbf{x}, f) = A^2 G_{pr}(f) \sum_{i=1}^{\infty} \sum_{k=1}^{\infty} \frac{\phi_i(\mathbf{x}) \phi_k(\mathbf{x}) H_i^*(f) H_k(f) j_{ik}^2(f)}{(2\pi)^4 f_i^2 f_k^2 M_i M_k} \quad (2)$$

Structural response $G_w(\mathbf{x}, f)$, Acoustic auto-spectrum $A^2 G_{pr}(f)$, area A , Mode shape $\phi_i(\mathbf{x}) \phi_k(\mathbf{x})$, Freq response including damping $H_i^*(f) H_k(f) j_{ik}^2(f)$, Modal mass $M_i M_k$

where the cross-joint acceptance function is given by

$$j_{ik}^2(f) = \left[A^2 G_{pr}(f) \right]^{-1} \iint_A G_p(\underline{\xi}, \underline{\xi}', f) \phi_i(\underline{\xi}) \phi_k(\underline{\xi}') d\underline{\xi} d\underline{\xi}' \quad (2a)$$

Acoustic cross-spectrum $G_p(\underline{\xi}, \underline{\xi}', f)$

- Modelling via splitting the problem into aero-acoustics and vibro-acoustics



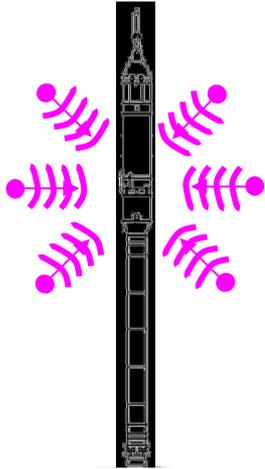
Separation of fluid dynamics and structural dynamics

- Aero-acoustics as a part of combined load

- **Forcing function** - Distribution of Auto and Cross-spectra of acoustic pressure fluctuations

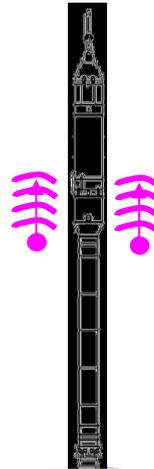
Diffused Acoustic Field

$$G_{12} = \bar{G}_d(f) \frac{\sin(k_0 d)}{k_0 d}$$



Progressive Wave Field

$$G_{12} = \bar{G}_p(f) e^{-c_d k_t d} [\cos(k_t d) - i \sin(k_t d)]$$



G_d = DAF autospectrum

G_p = PWF autospectrum

$k_t = \omega/U_t$ = trace wavenumber

$k_0 = \omega/c_0$ = acoustic wavenumber

d = separation distance

c_d = correlation decay coefficient

- **Prediction of Structural response** - forcing functions input to structural dynamics analyses - FEM, BEM, SEA models of the components, systems and subsystems of the vehicle.

Vibro-Acoustics tests for flight certification



Reverberant Acoustic Test Facility
NASA Plum Brook Station



One of the 25Hz
horns in the test
chamber



Mechanical Vibration Facility



Roadmap:

- Launch Acoustics
 - Description of launch pad
 - Prediction, CAA
 - Static fire test
 - Flight test
 - Identification of acoustic sources During Antares launch
 - by a microphone phased array
 - ▶ not discussed – Ignition over pressure (IOP)

- Ascent Acoustics
- Abort Acoustics

- Other minor sources (not discussed)
 - vent noise
 - pressure fluctuations during reentry, etc.



Why study launch acoustics?

- Very high acoustic level during launch creates high vibro-acoustics environment
 - ▶ All payloads, many parts of the vehicle, and ground op systems need to be designed, tested and qualified for this environment
 - ▶ The fluctuation levels influence the weight and the cost of the vehicle
- The acoustic suppression systems needs to perform optimally to provide relief

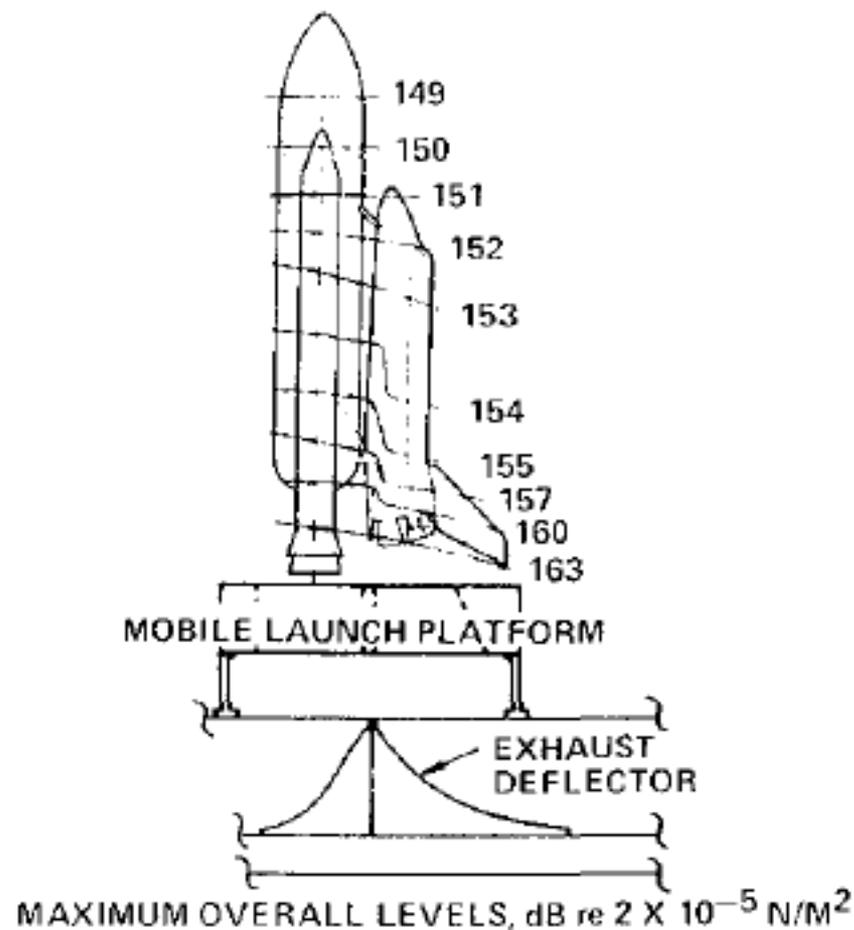
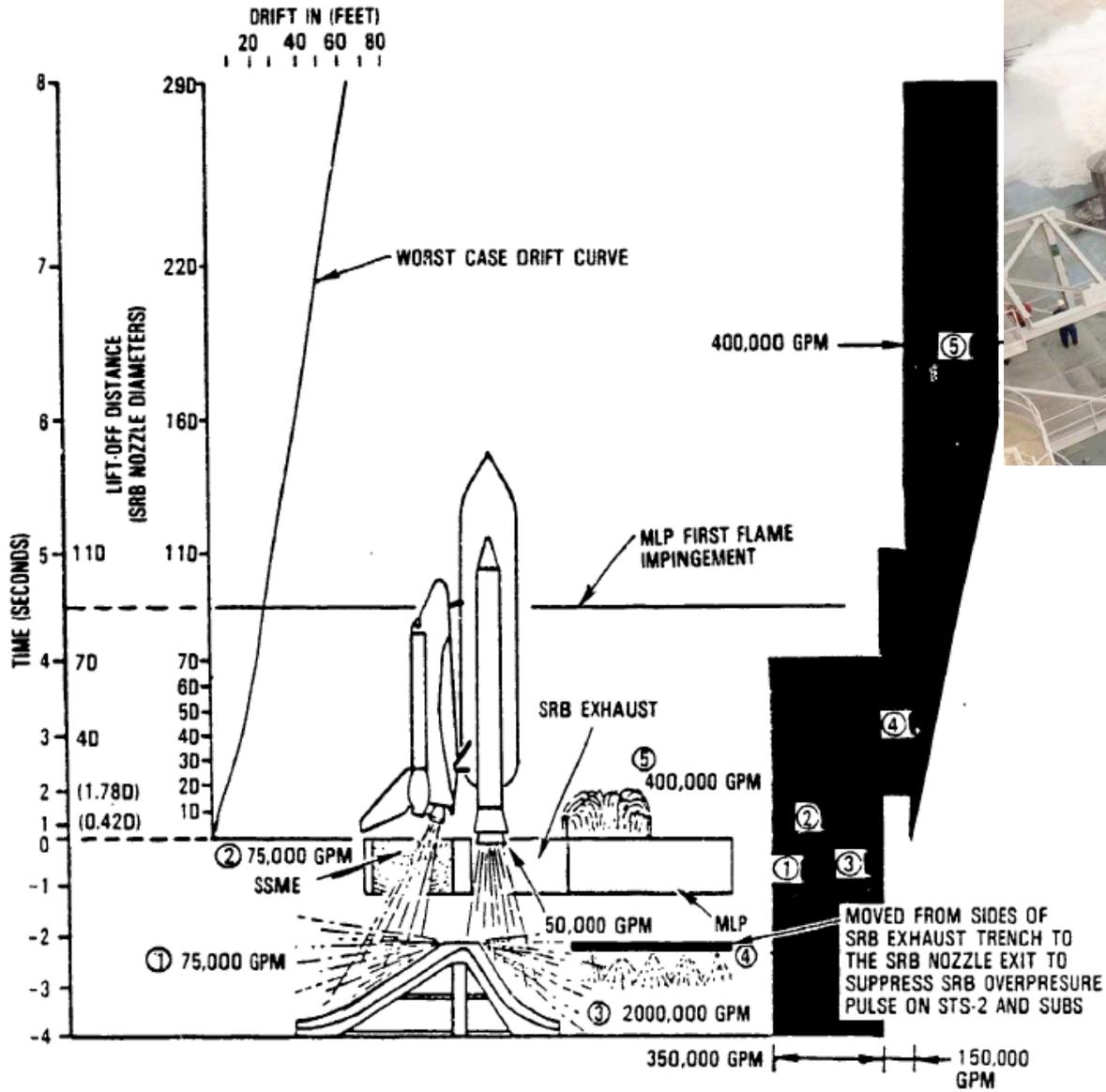


Fig. 2 Engine noise levels during Shuttle lift-off.



Launch pad design and acoustic suppression system



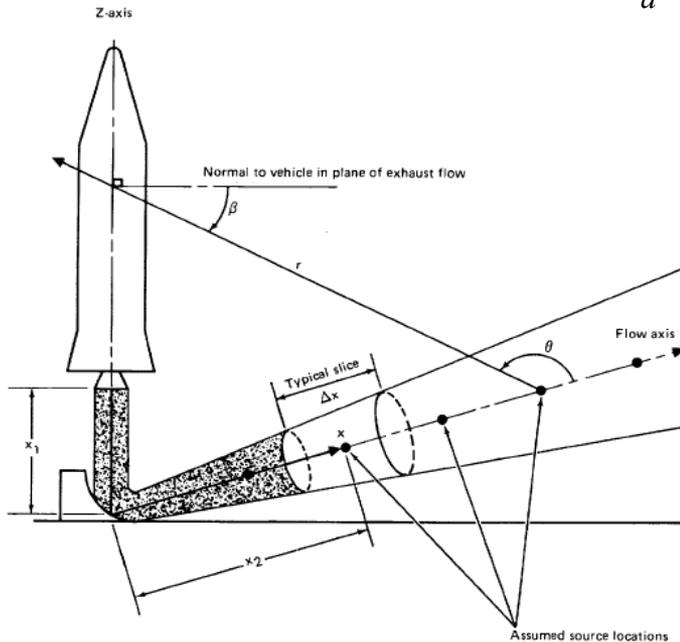
Shuttle Pad water injection

- Deflector
- Trench/Duct
- Mobile launch platform
- Service Tower
- Water flow systems
- Vehicle trajectory
 - elevation
 - drift

Prediction – NASA SP-8072, “Rocket Vehicle Liftoff Acoustics and Skin Vibration Acoustic Loads Generated by the Propulsion System” 1971

- There exists no prediction methodology from the fundamental equations
- Total acoustic power W_a is related to the mechanical power W_m generated by the rocket, $\eta =$ efficiency factor 0.2% to 0.8%

$$W_a = \eta W_m = \eta \sum_{\text{All nozzles}} 0.5 (\text{Thrust}) U_{\text{exit}}$$



Distributed source along plume path

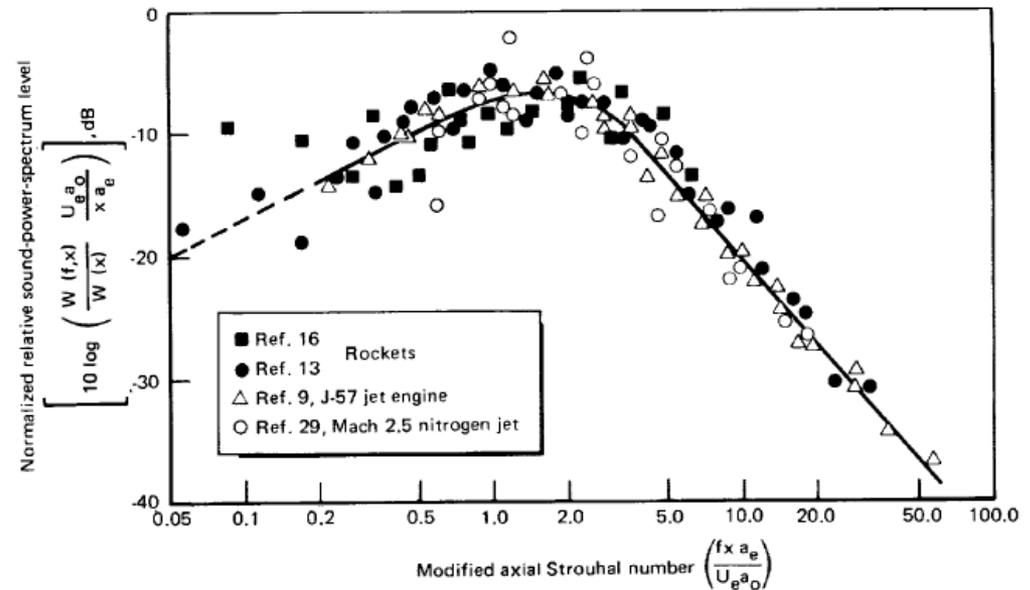
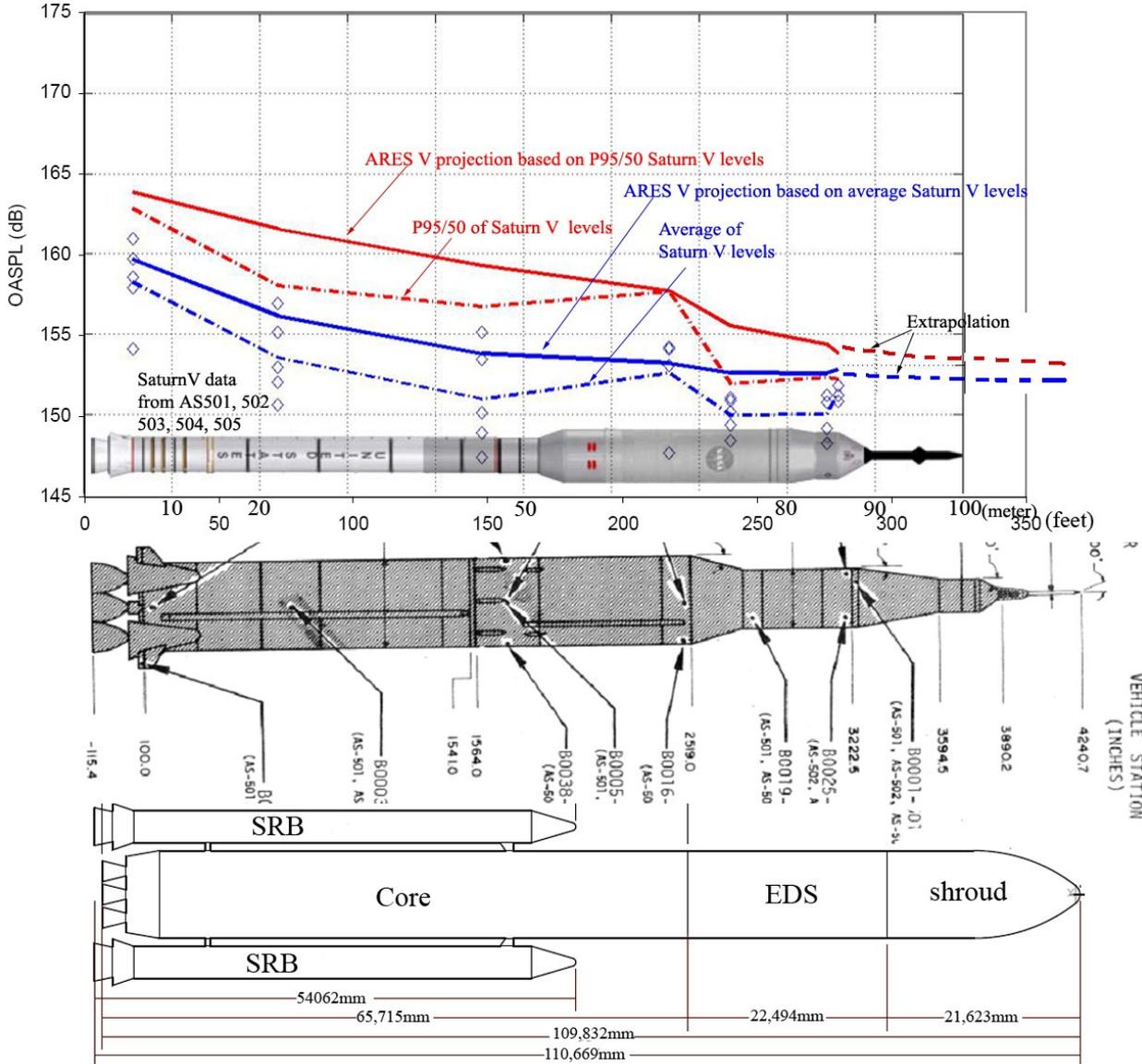


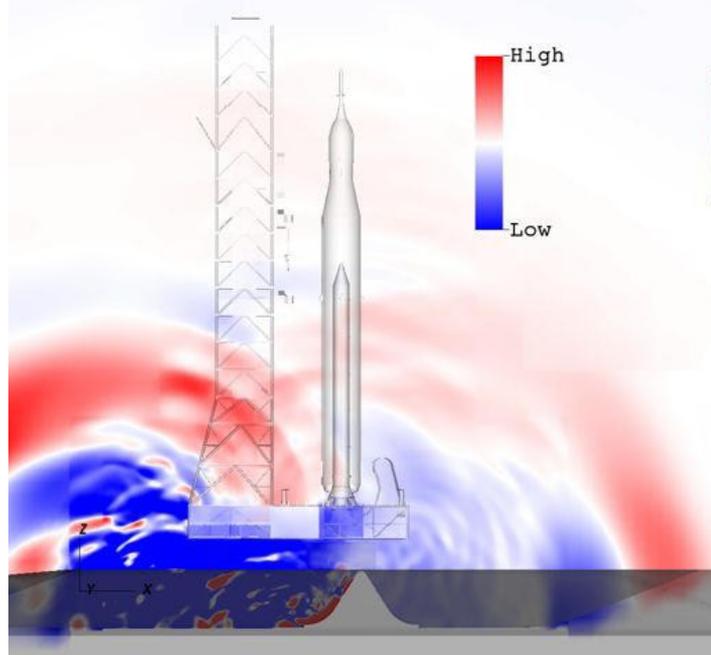
Figure 13. – Normalized relative power-spectrum level as a function of axial position along the flow for chemical rockets and jets.

Prediction - based on flight data from prior vehicles

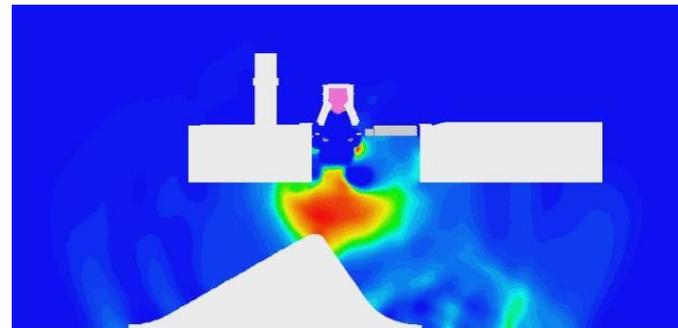
Acoustic data books

- Apollo – Saturn
- Space Shuttle
- Ares-IX
- Scaling based on engine thrust, and Strouhal frequency.

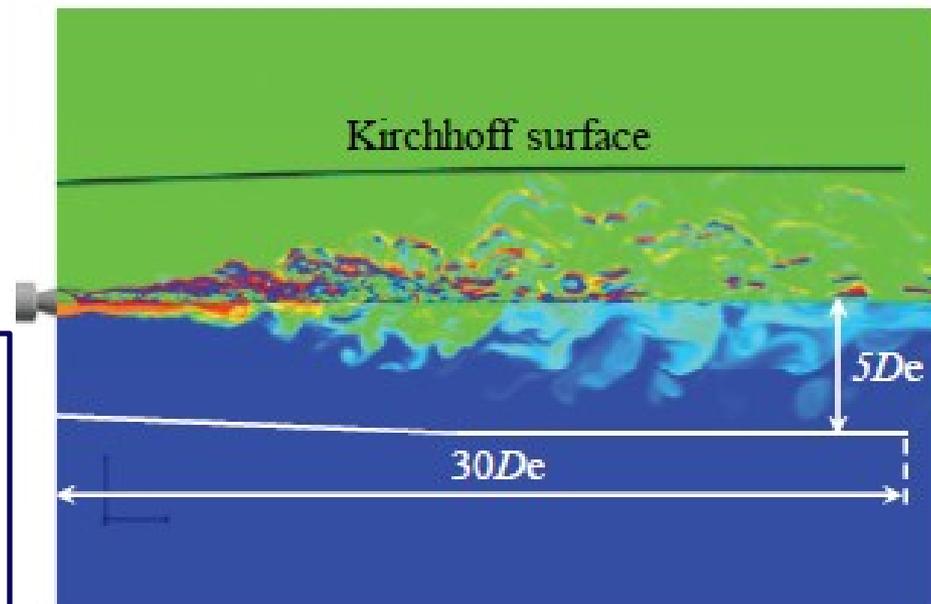




SLA Launch simulation, NASA Ames
LAVA code, Kiris et al, AIAA 2014-0070.



Pressure pulse after Ignition, J. West, MSFC



LES simulation: Fukuda et al, 2009
Effect of water injection: Fukuda et al, 2011

Challenges –

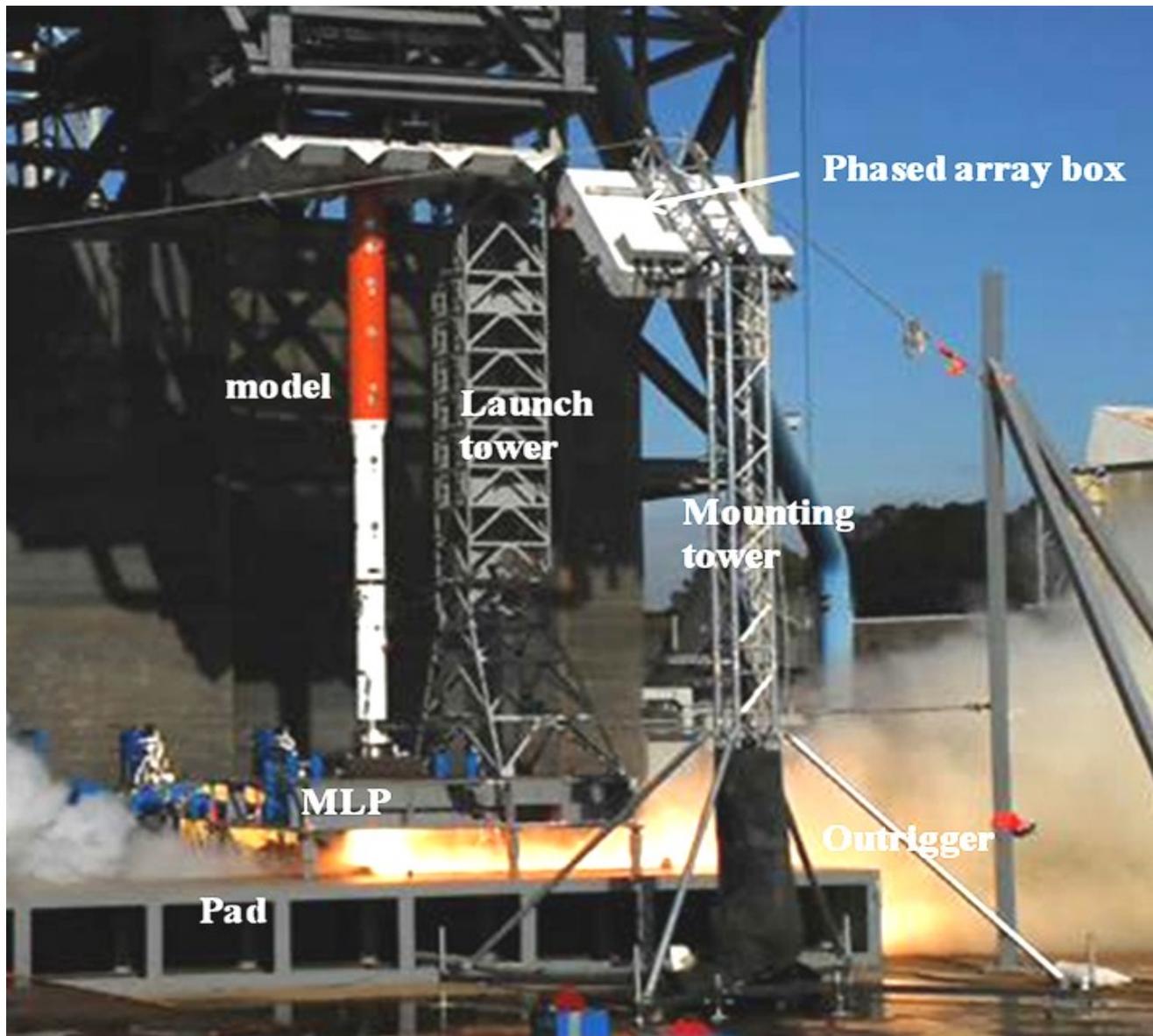
⇒ Complex geometry, high Re, multi-phase flow, multiple γ , multiple species

Paths for CAA simulation:

- RANS + acoustic analogy
- LES
- Need of experimental data for validation



Model scale static fire tests - ASMAT



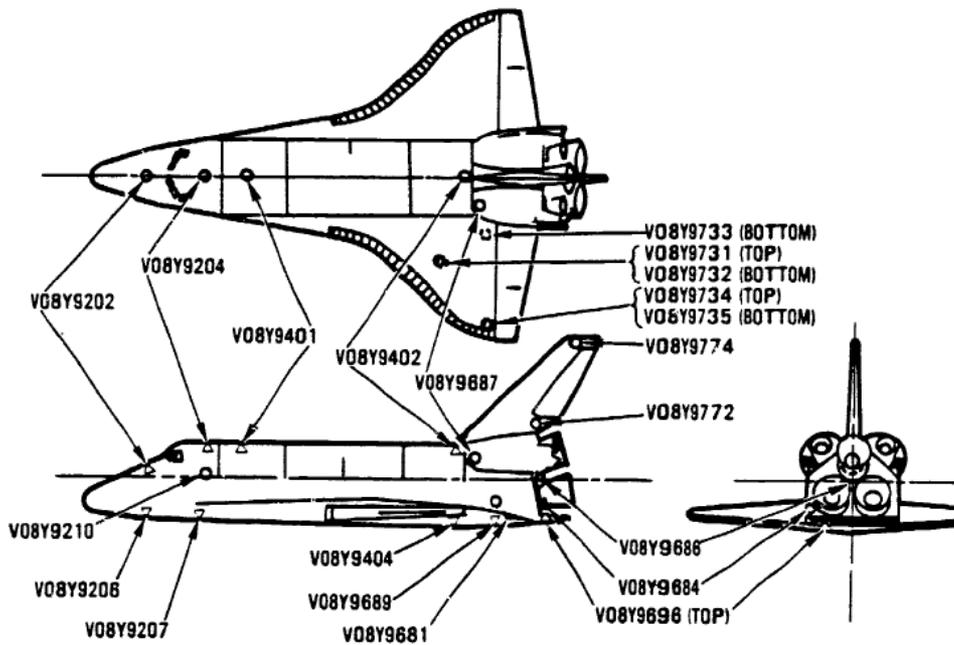
Static fire tests are the best means to determine

- launch environment
- water schedule
- pad modification

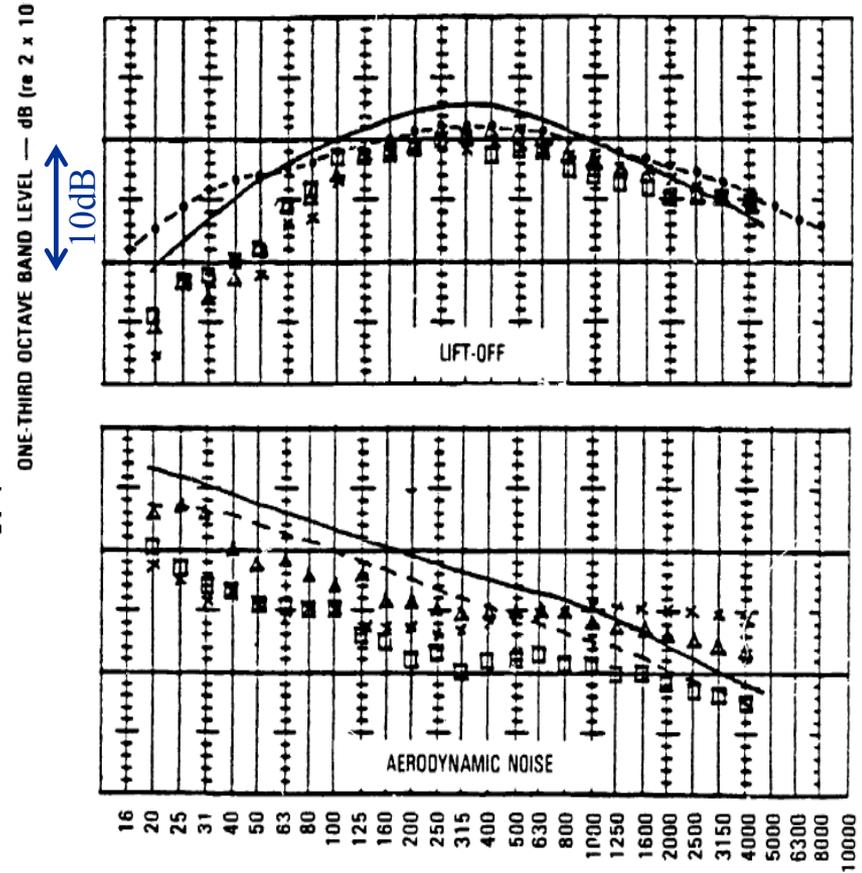
● 5% scale model of ARES I



Validation/adjustment from Flight sensors



External microphones on Orbiter



ONE-THIRD OCTAVE BAND CENTER FREQUENCIES—HERTZ

TEST PREDICTED ZONAL DESIGN LIMIT ————
 TEST PREDICTED ZONAL NOMINAL - - - - -
 FLIGHT DERIVED ZONAL - · - · - ·

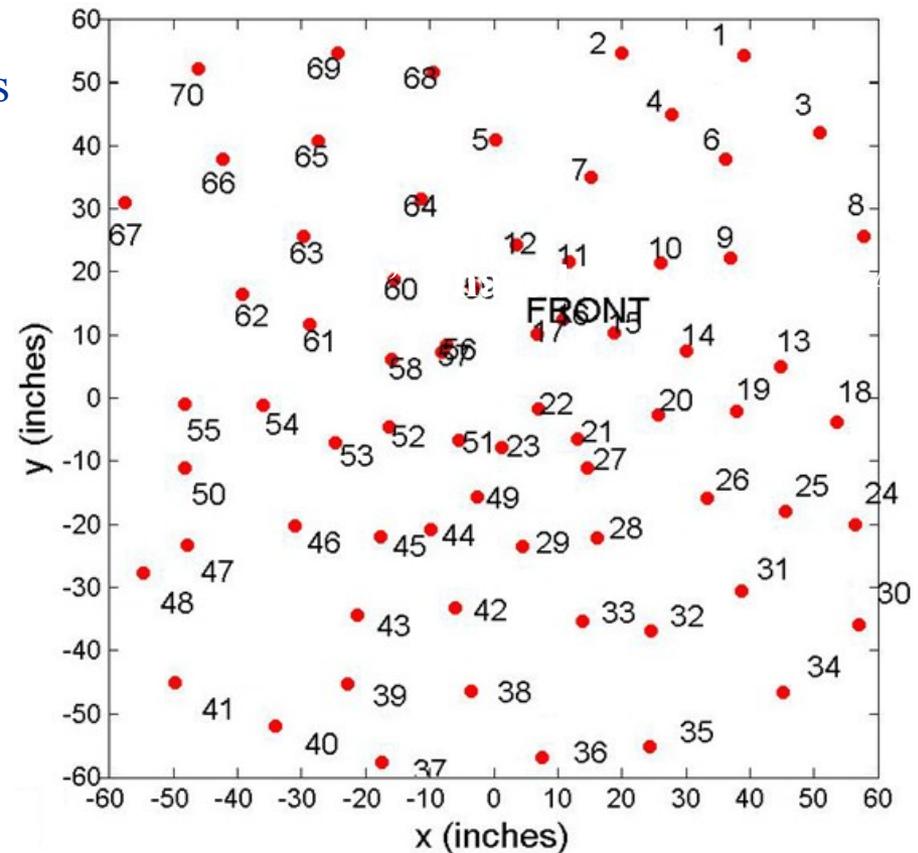
FLIGHT DATA:
 STS-1 ○○○○ STS-4 □□□□
 STS-2 ×××× STS-5 ▽▽▽▽
 STS-3 △△△△
 MEASUREMENT: V08Y9684A



What are the true sources of noise during liftoff?

- Use of microphone phased array

- Phased array – Acoustic camera, a tuned ear.
- Ubiquitous in Aeronautics, new in Space applications
- Need for a large size array for a full-scale vehicle application
- *Angular resolution of array* ~ $(\text{acoustic wavelength}) / (\text{array aperture})$
- Design of a brand new array
 - ▶ 10'X10' size, use 70 microphones
 - ▶ lighter weight
 - ▶ weather protection
 - ▶ debris protection
 - ▶ vibration isolation for camera



Microphone pattern for new 10' array



Evolution of phased array project

- Array validation in **Ames hybrid motor test**
 - ▶ revealed the need for solid state electronics
 - ▶ vibration isolation
 - ▶ need for rain protection

- Software

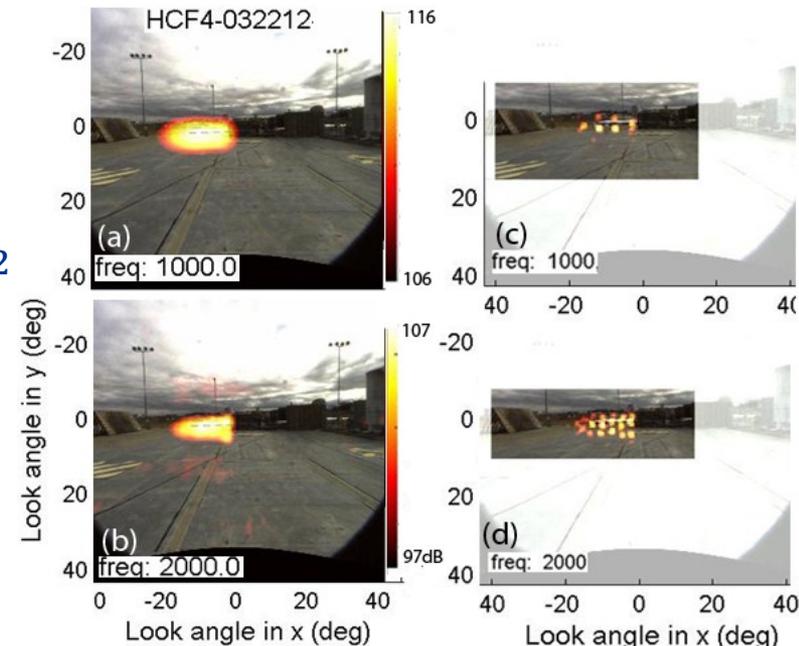
- ▶ Conventional beamform

$$b_{jj}(f) = w_{j,m}^\dagger G_{m,m'} w_{j,m'}$$

- ▶ Spectral Element Technique (SEM) provided most promise

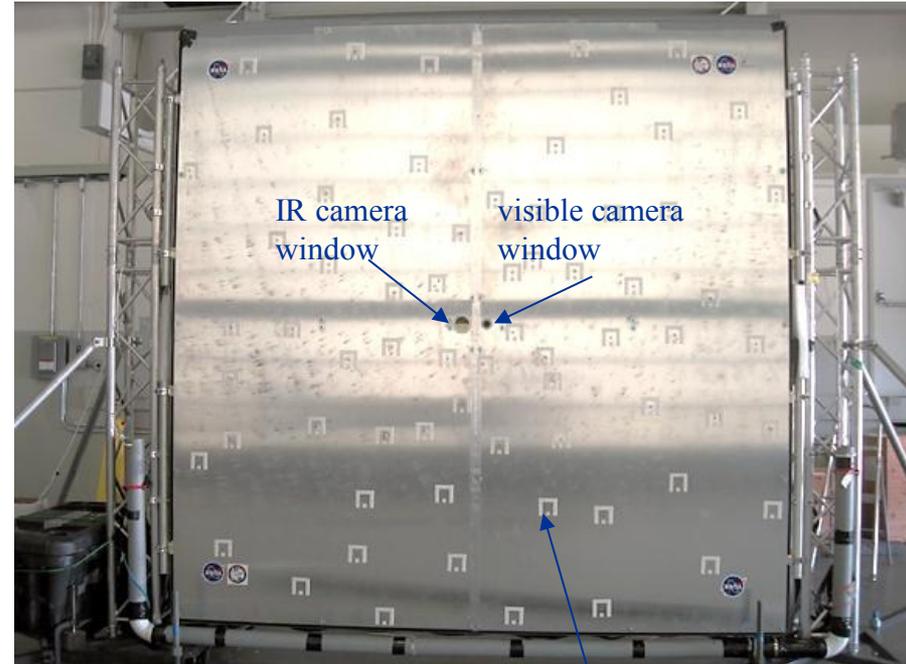
$$E(\alpha_j, f) = \sum_{m,m'=1}^J \left| G_{mm'} - \sum_{j=1}^N w_{j,m} \alpha_j^2 w_{j,m'}^* \right|^2$$

- All hardware shipped to **NASA Wallops**



Noise map during hybrid motor burn

Phased array set-up at Wallops pad 0A



(front view) Mylar cover for each microphone

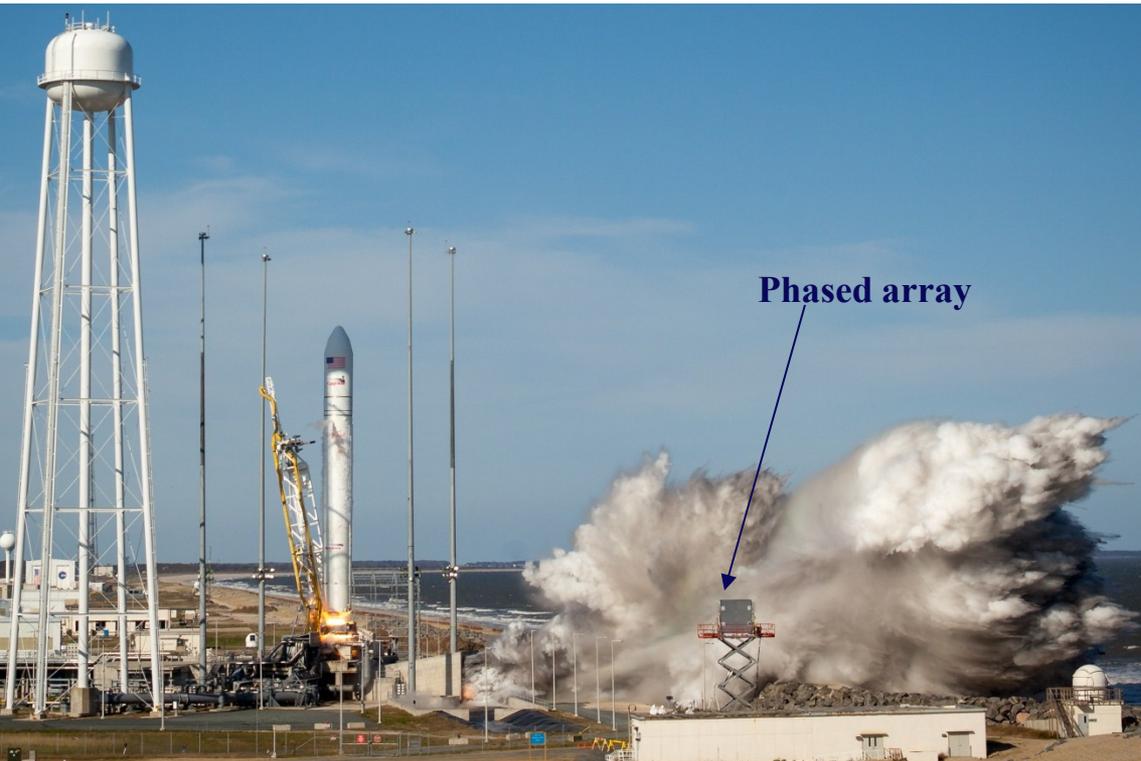
Instrumentations:

- 70 condenser microphones
- 1 visible band camera
- 1 long wave Infra-red camera
- 1 x-y accelerometer

The phased array was mounted on a scissor lift at south side of pad 0A, ~ 400' from the Antares Engine, & 40' above ground



Phased array in Antares A-one launch: April 21, 2013





◀ Water injection inside launch mount (on the top of the flame trench).

On-deck water injection using 4 Rain-bird heads ▶

- Water started to flow from 3 short and 1 long rainbirds





Initial Trajectory

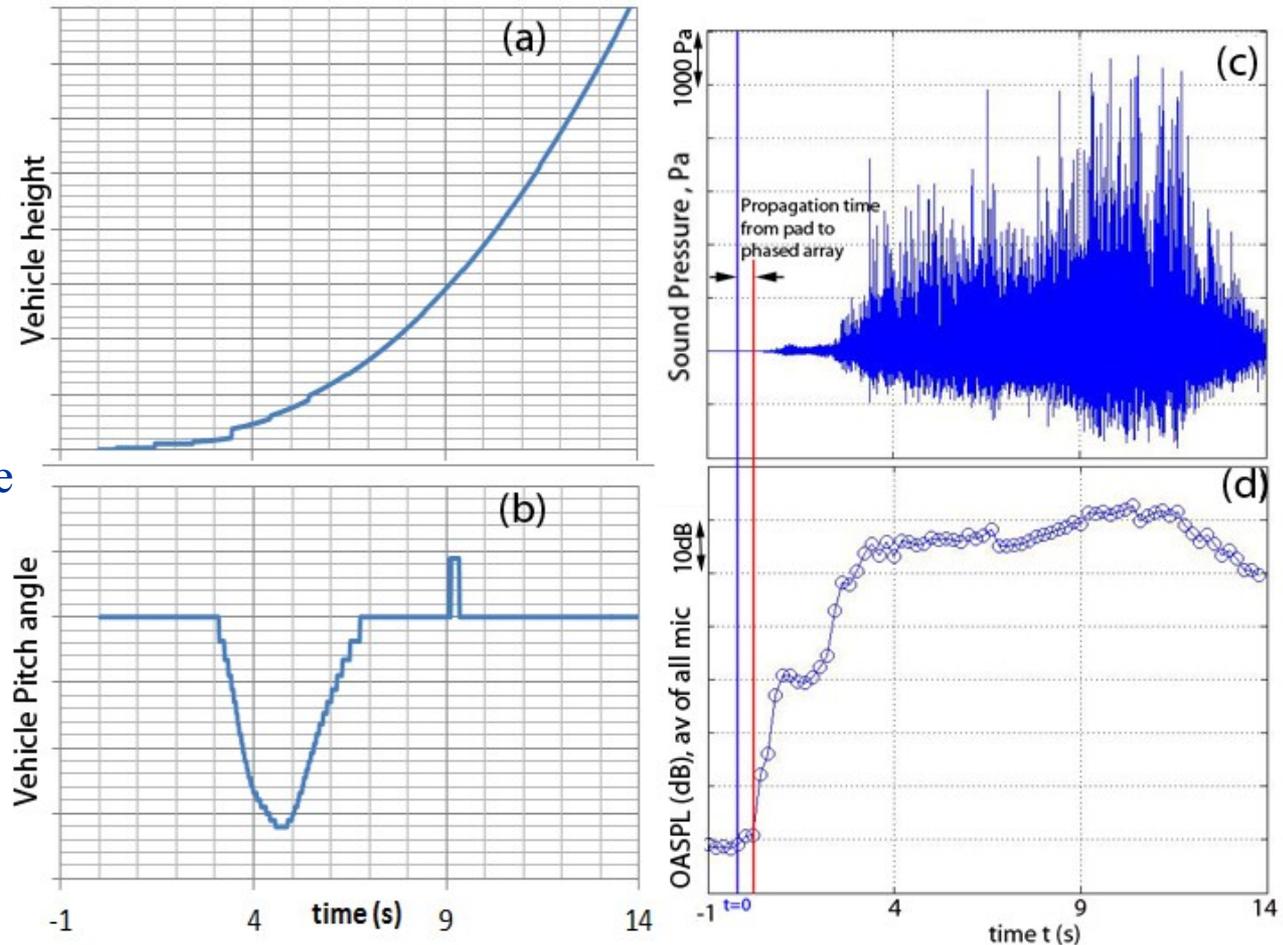
- Slow moving vehicle
- TEL avoidance maneuver to avoid contact with the service tower

Time dependent beam-forming:

- Microphone time signals were segmented into 0.2s wide segments

Propagation delay:

- Microphones received the launch events at a delayed time. ~ 0.4 s for sounds to propagate from the launch pad to the phased array.

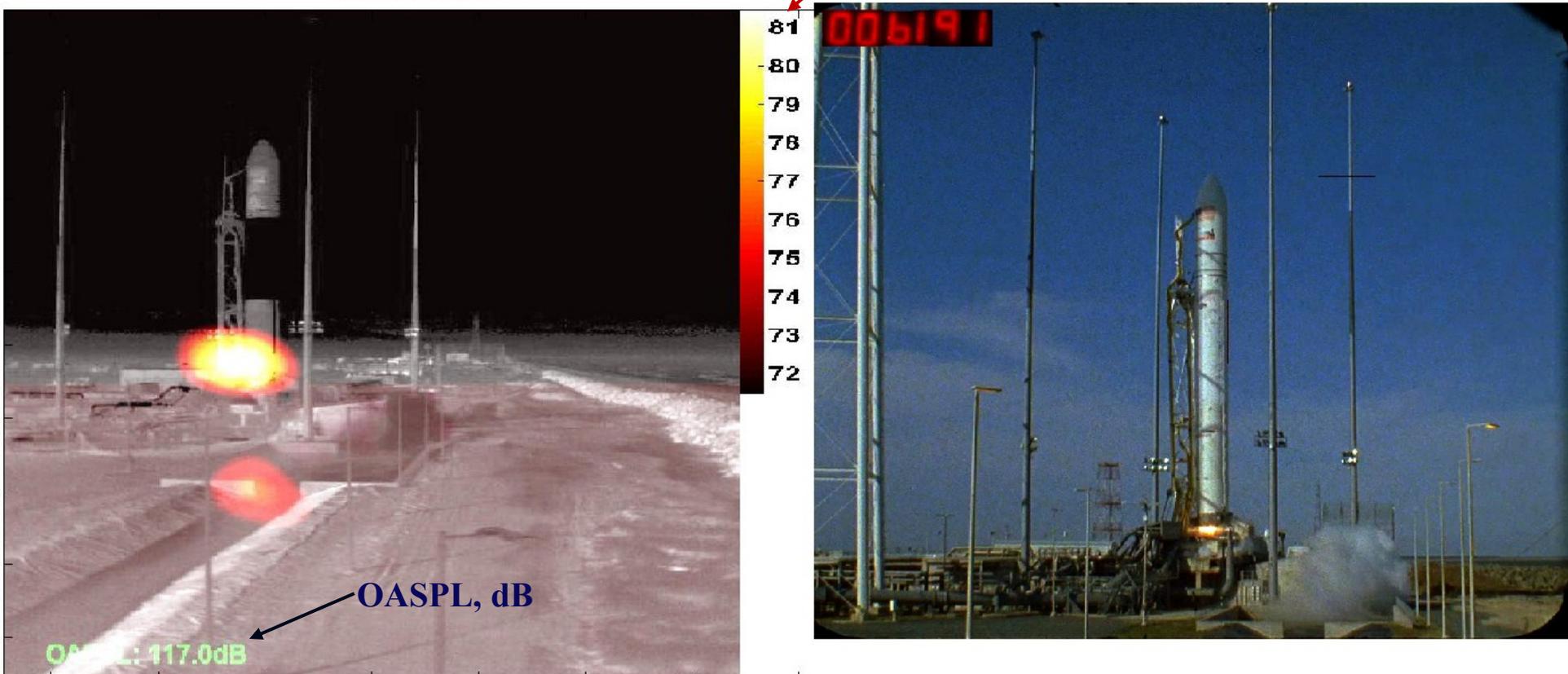




Noise source map at t+0.6s, conventional beam-form at 2kHz

Source strength at 2kHz in 80Hz wide band - *Auto-scaled*

freq: 2000.0 seg:10

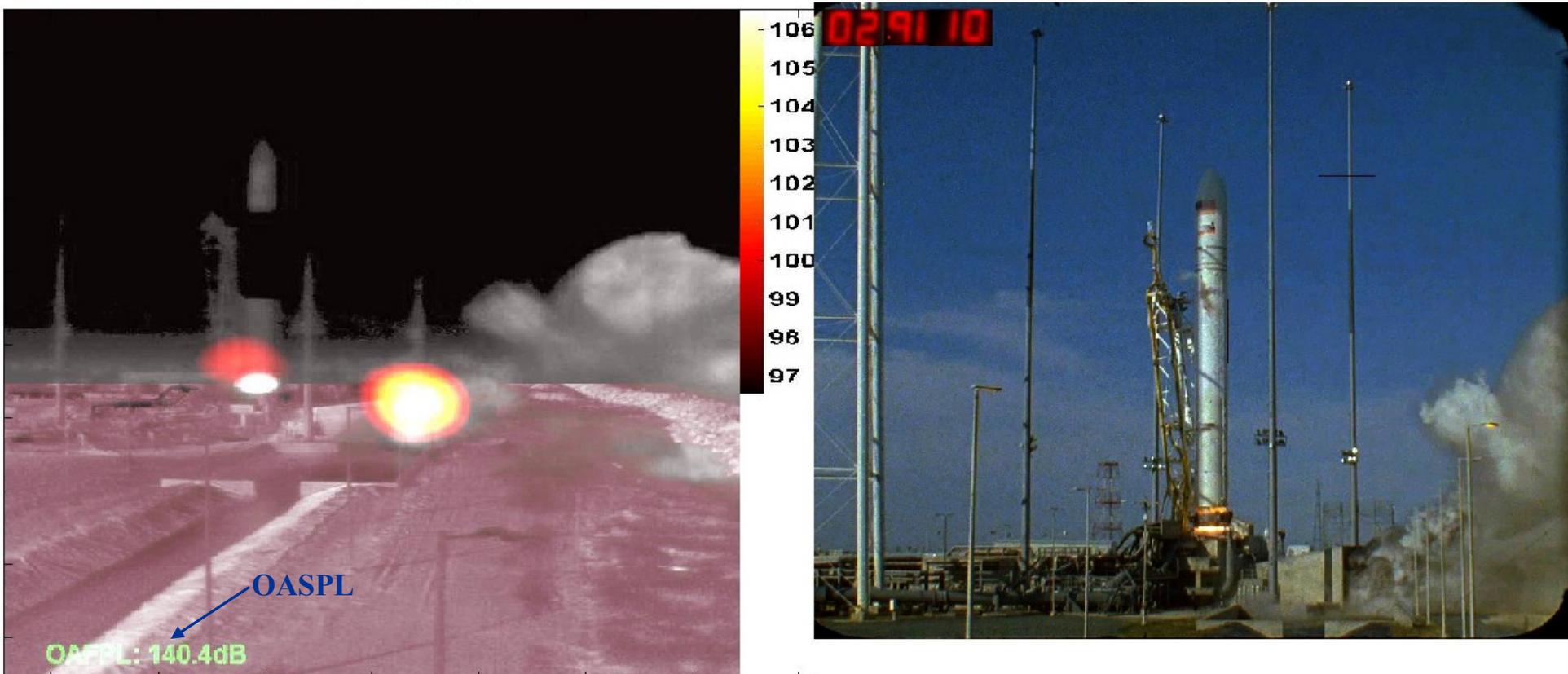


- Engine Ignition created noise source at launch mount
- Phased array, mounted 40' above ground, saw both the primary source and its image on ground



Noise source map at t+2.9s

freq: 2000.0 seg:21

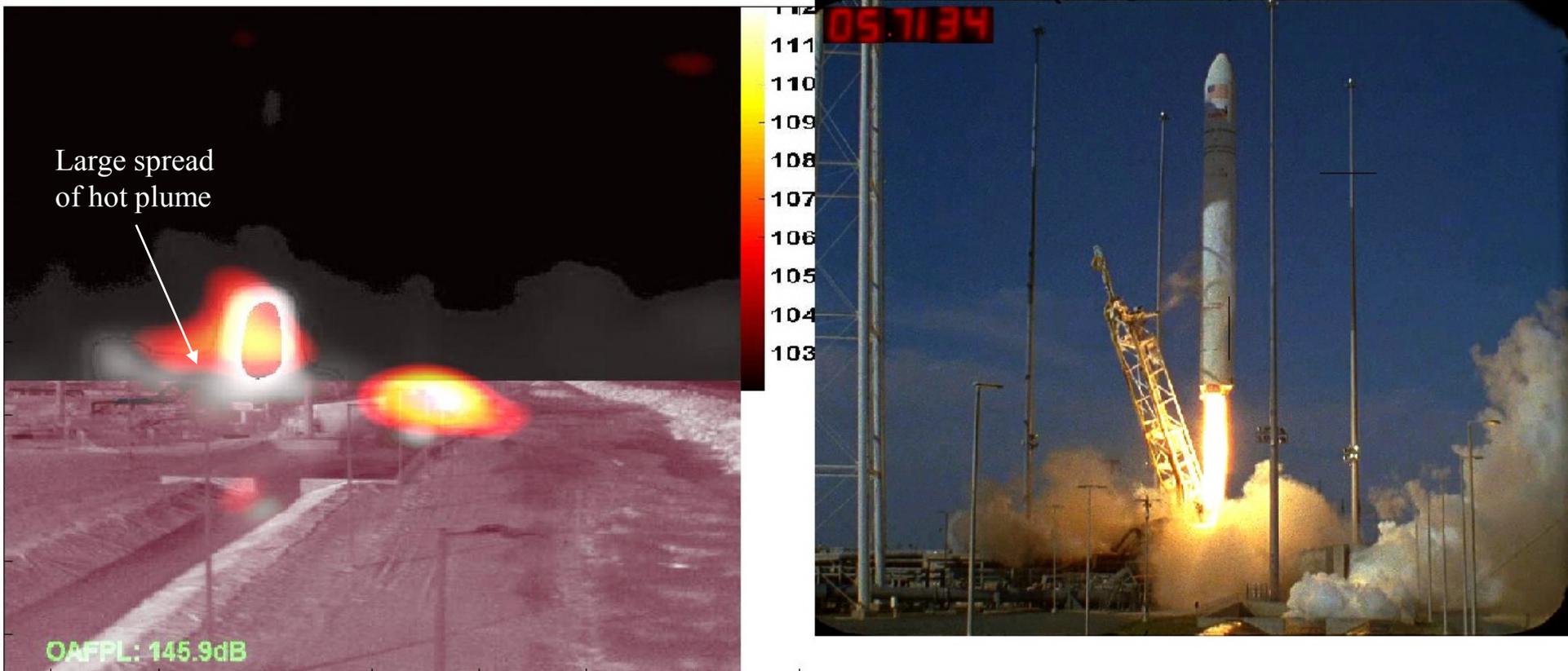


- The duct (trench) exhaust became the primary noise source as the hot plume started to come out (see movie).
- Effective cooling by duct water minimized the extent of the noise source – the OASPL was somewhat reasonable.
- Launch mount remained as a strong noise source.



Noise source map at t+5.7s

freq: 2000.0 seg:35

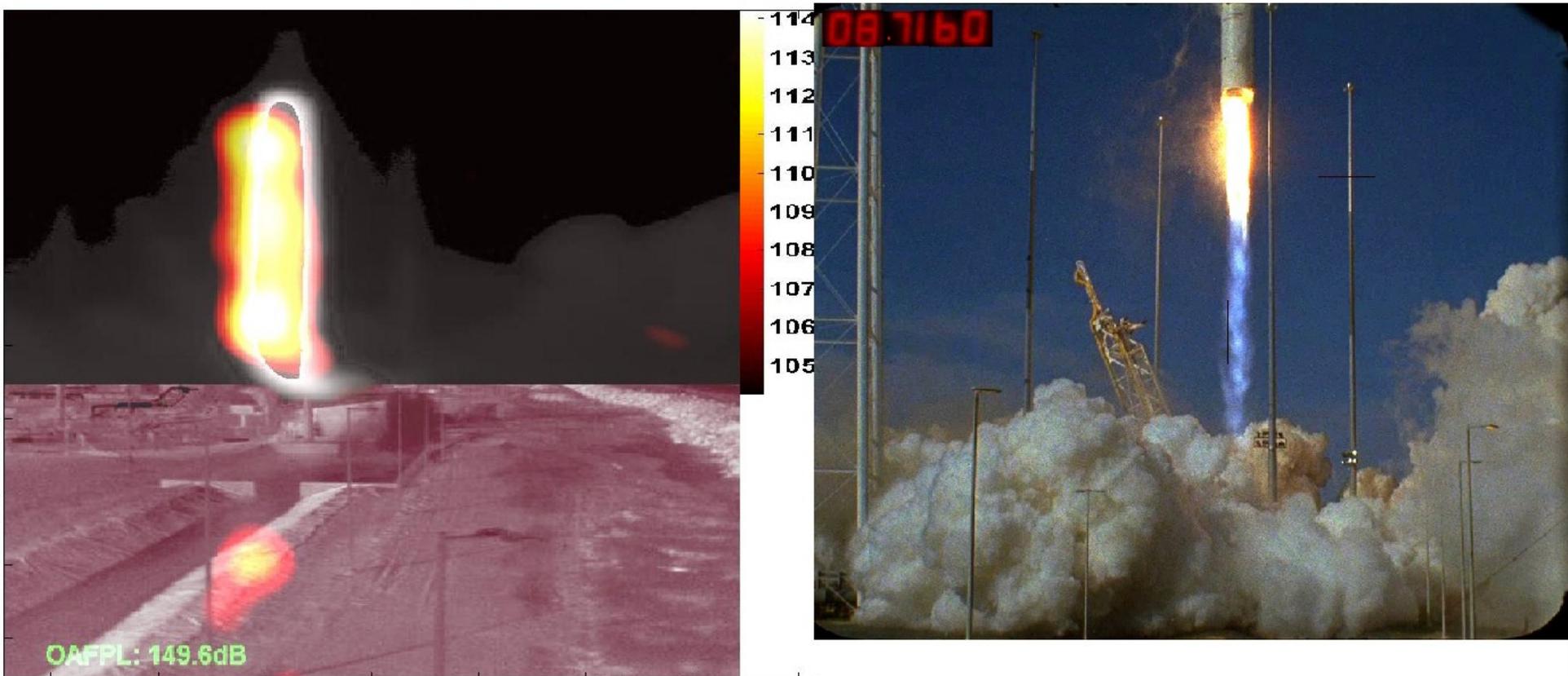


- Vehicle drifted even more towards east, caused heavy spreading of the hot plume over the pad, - Extended the size of the noise source.
- Start of flow from short 3 Rainbirds (not much water). No flow from 1 tall rainbird. Duct water in full force.



Noise source map at t+8.7s

freq: 2000.0 seg:50



- The long, exposed plume was the primary noise source.
- Still some impingement on the pad, yet the rainbird system had come to full force, and quenched the hot plume and the deck.
- From this time on, as the vehicle gained altitude and speed, the acoustic level on the vehicle was expected lower; however, ground service equipment did not see any decrease for another few seconds
- ground reflection



Optimization of Antares Water injection schedule

Hi Jay,

Yes the activation timing of the water deluge rainbirds was moved up from T+5s to T+3.8s.

Subject: Re: Antares Test Launch

Understood, thanks. Yes from a ground system standpoint, we also noted less ablative wear on the launch mount this time around, which is most likely attributable to faster water deluge activation. The phased array effort was indeed beneficial.

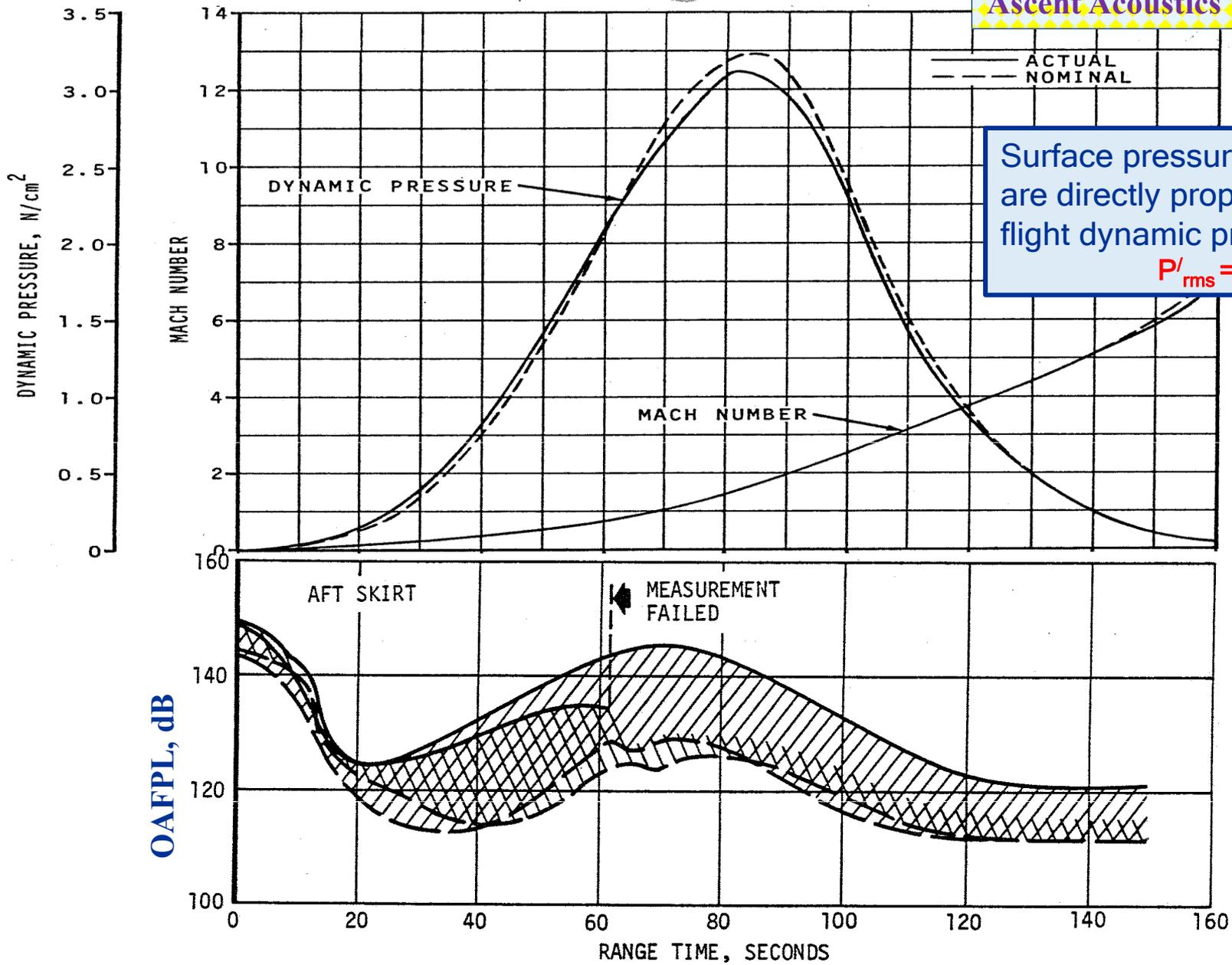


Ascent Acoustics

- o Vehicle trajectory and dynamic pressure
- o Buffet and acoustics
- o Prediction – empiricism and existing database, CFD
- o Wind tunnel tests
- o shape modification
- o Flight tests



AS-508



Surface pressure fluctuations are directly proportional to the flight dynamic pressure:
 $P'_{rms} = k q$

Figure 16-16. S-IVB Acoustic Levels During S-IC Burn

Prediction - Aerodynamics of Launch Vehicle

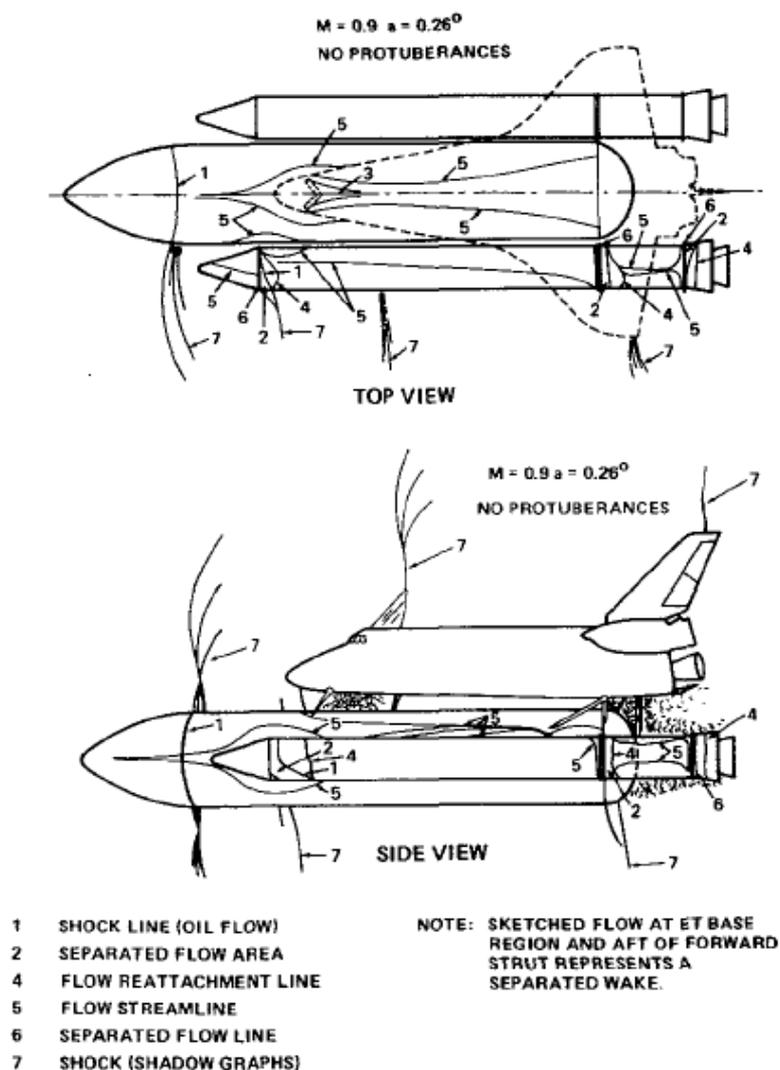


Fig 16 Shuttle aerodynamic flow field - Mach 0.9

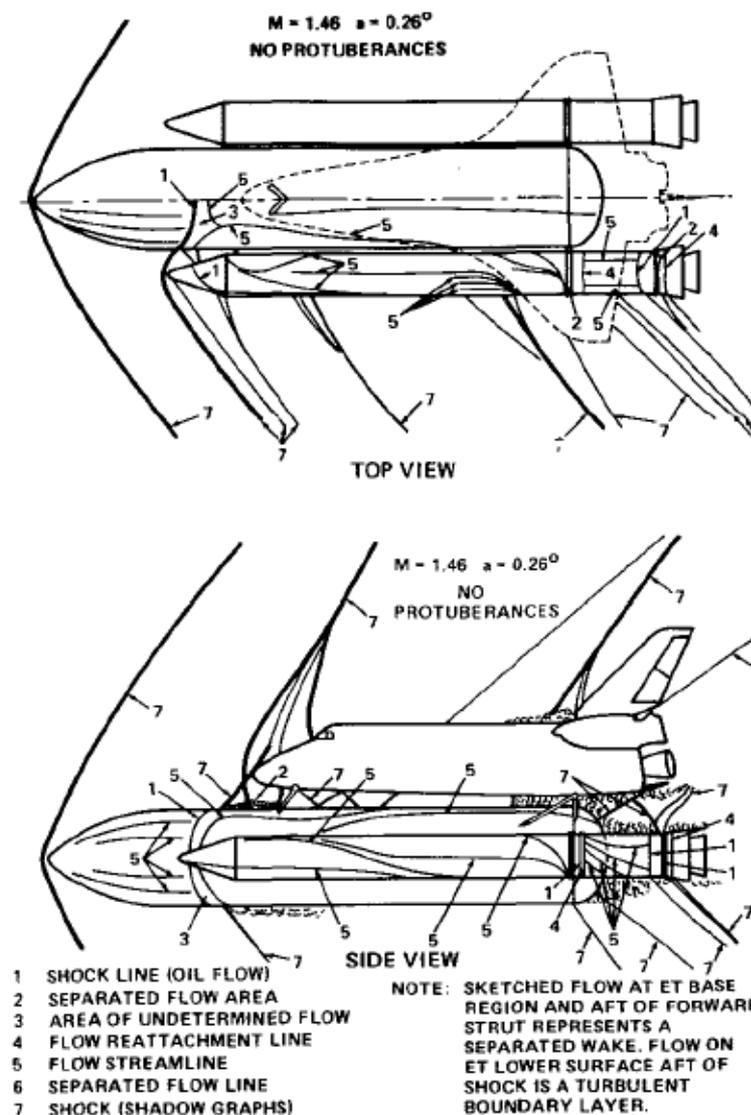


Fig 17 Shuttle aerodynamic flow field - Mach 1.46



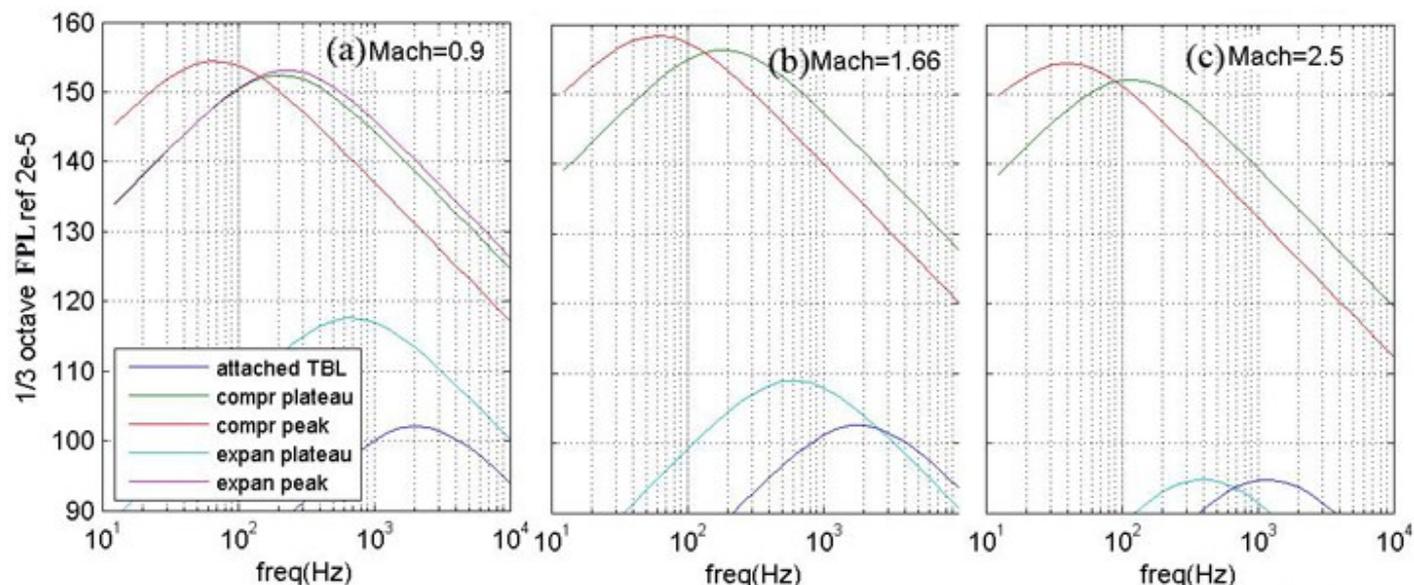
Prediction - steady state CFD to determine input parameters for empirical relations

Attached turbulent boundary layer:

$$p_{rms} = q \frac{0.01}{1 + M^2}$$

$$G(f) = \frac{4C\delta^* F^{1.433}}{U \left(1 + C^2 F^{2.867} \left(\frac{2\pi f \delta^*}{U} \right)^2 \right)} p_{rms}^2$$

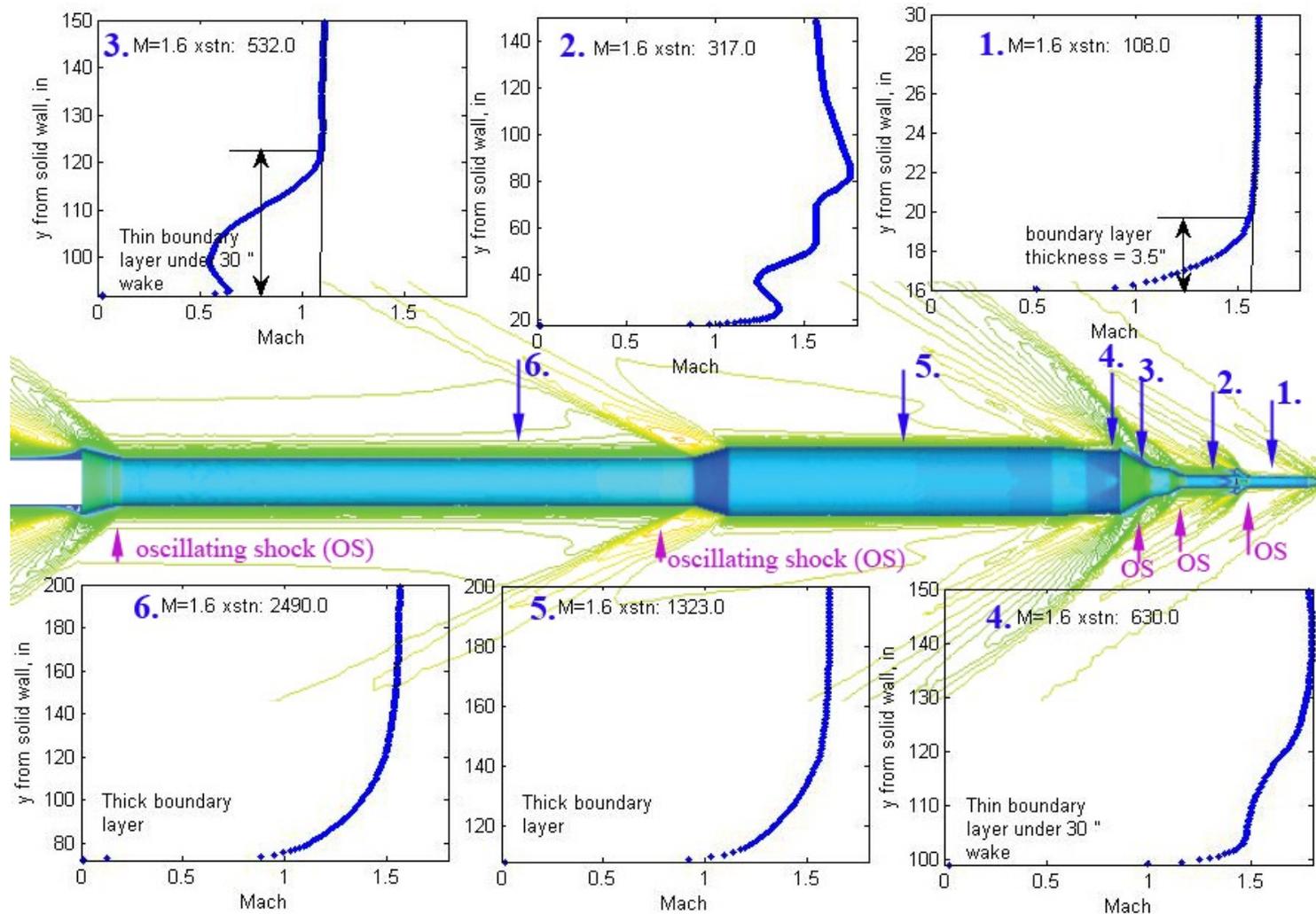
Use CFD database to determine boundary layer
Displacement thickness δ^*



Calculated auto-spectra using empirical relations

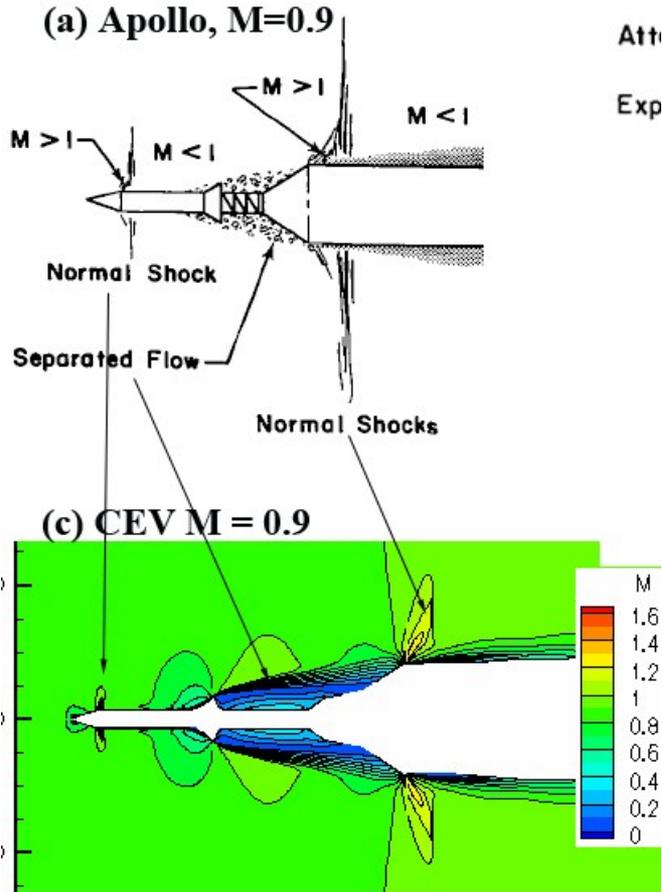


Prediction - steady state CFD to determine input parameters for empirical relations

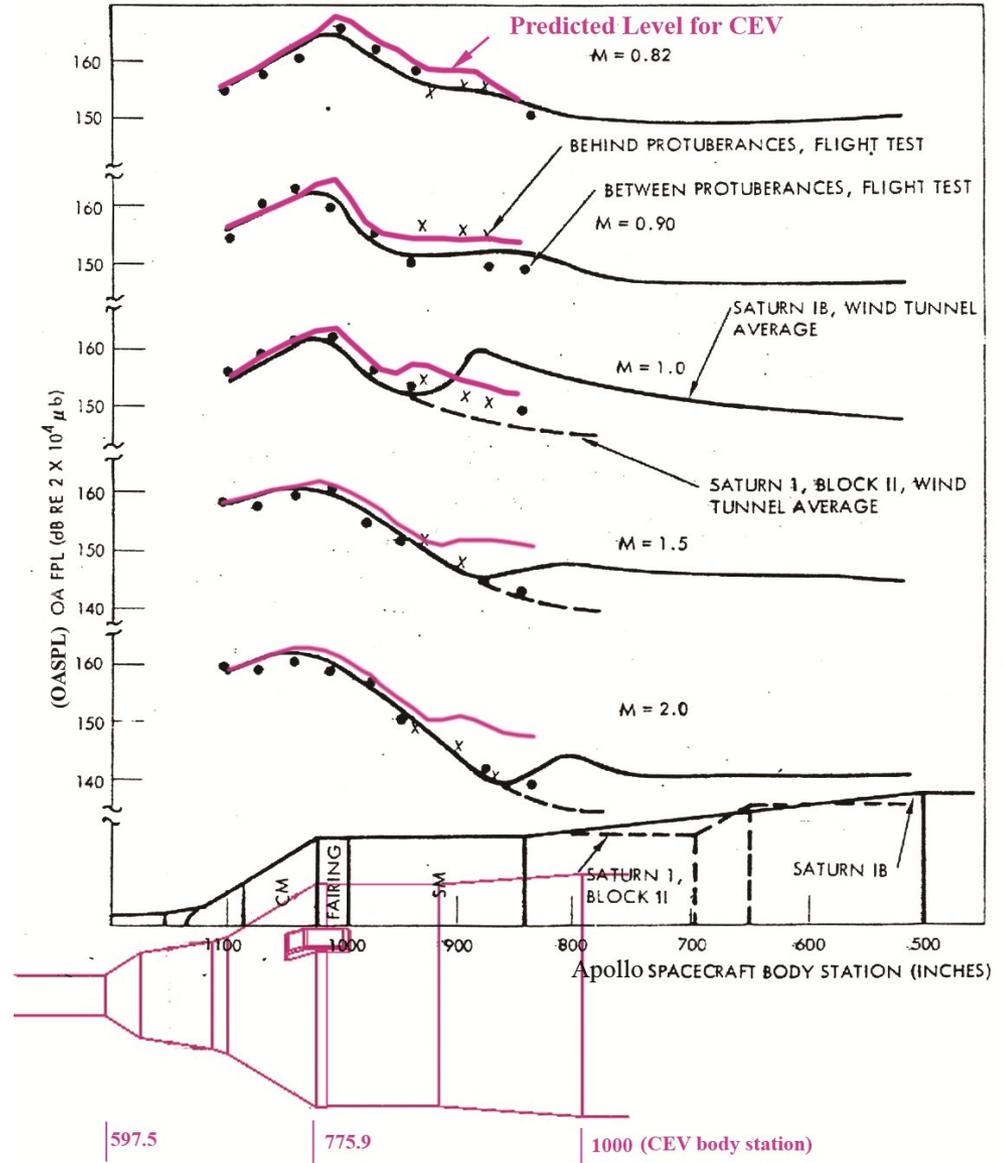


USM3D calculated flow-field over ARES IX at flight M = 1.6 (Source: Steve Bauer LaRC)

Prediction - based on flight data from prior vehicles



Att
Exp



- Falls apart when vehicle shape changes

Wind tunnel tests and scaling Laws



Space Launch System (SLS) test at NASA Ames Unitary

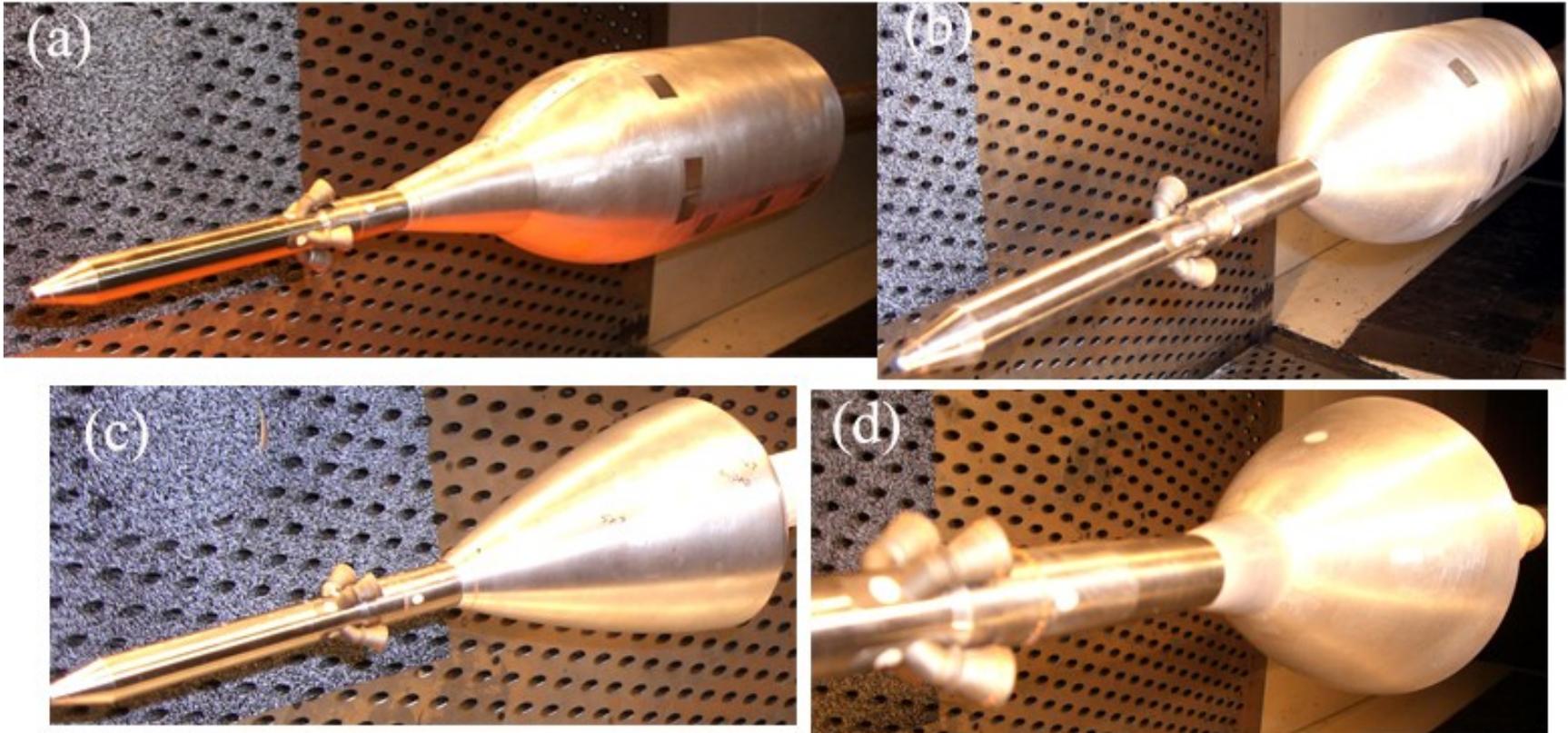
What to do if measured fluctuations are very high? – cost and weight penalty

Table 17. Rigid buffet model scaling laws.

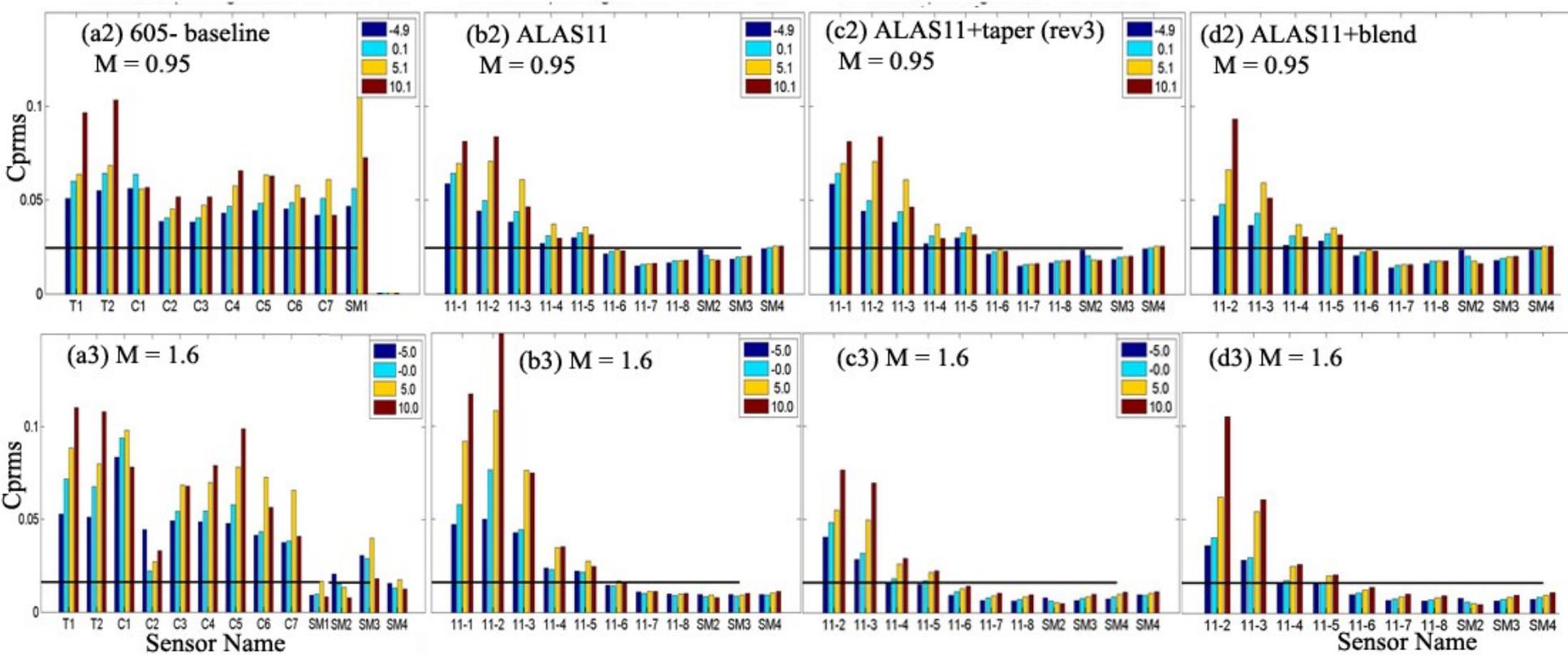
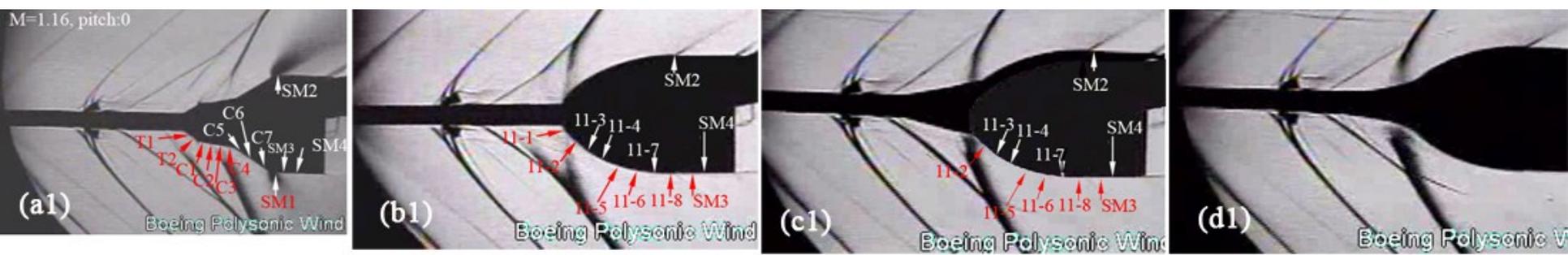
Quantity to be Scaled	Full-scale to Model-scale Relation
Pressure	$P_{fs} = P_{ms} \frac{Q_{fs}}{Q_{ms}}$
Force	$F_{fs} = F_{ms} \frac{Q_{fs}}{Q_{ms}} \left(\frac{D_{fs}}{D_{ms}} \right)^2$
Time	$T_{fs} = T_{ms} \frac{D_{fs}}{D_{ms}} \frac{V_{ms}}{V_{fs}}$
Frequency	$f_{fs} = f_{ms} \frac{D_{ms}}{D_{fs}} \frac{V_{fs}}{V_{ms}}$
Pressure PSD (psi ² /Hz)	$\phi_{fs}^{(P)} = \phi_{ms}^{(P)} \left(\frac{Q_{fs}^{(P)}}{Q_{ms}^{(P)}} \right)^2 \frac{D_{fs}}{D_{ms}} \frac{V_{ms}}{V_{fs}}$
Force PSD (lbf ² /Hz)	$\phi_{fs}^{(F)} = \phi_{ms}^{(F)} \left(\frac{Q_{fs}^{(F)}}{Q_{ms}^{(F)}} \right)^2 \left(\frac{D_{fs}}{D_{ms}} \right)^5 \frac{V_{ms}}{V_{fs}}$



Real Engineering – What if the acoustic levels are too high? MPCV Shape Optimization to Reduce Aero-acoustic environment

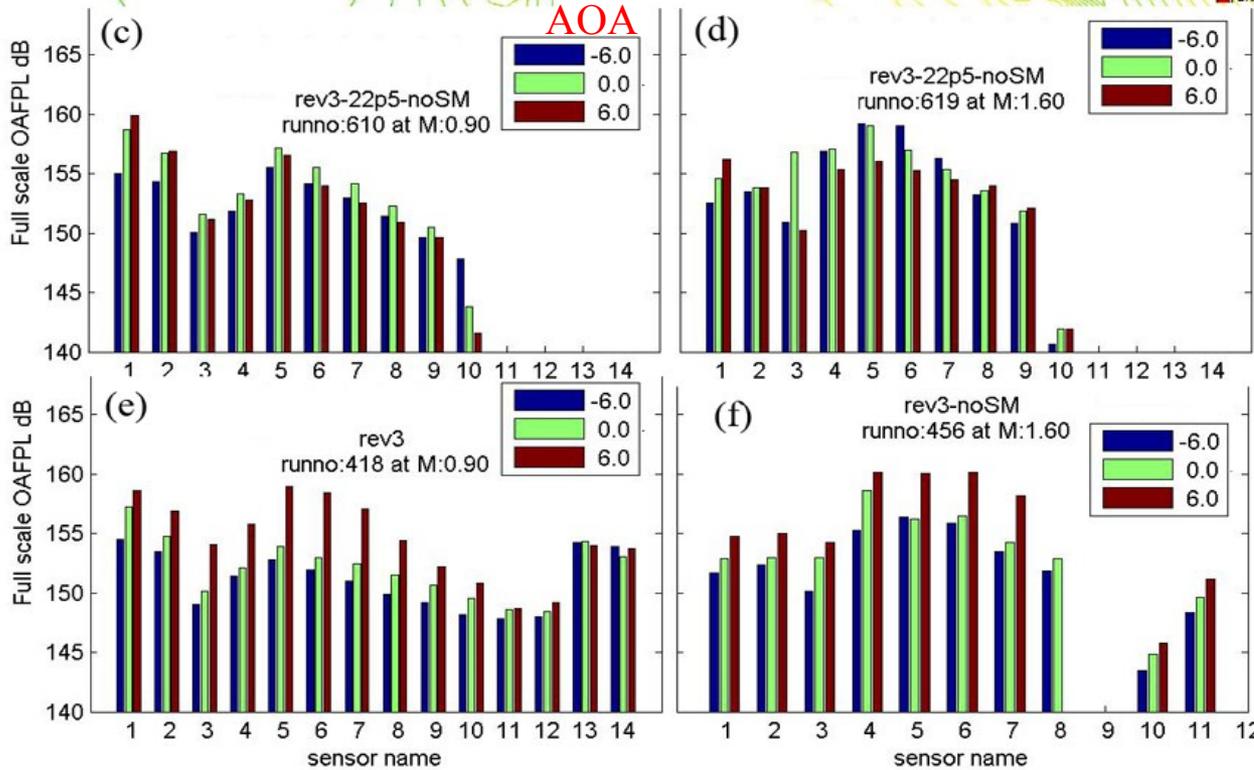
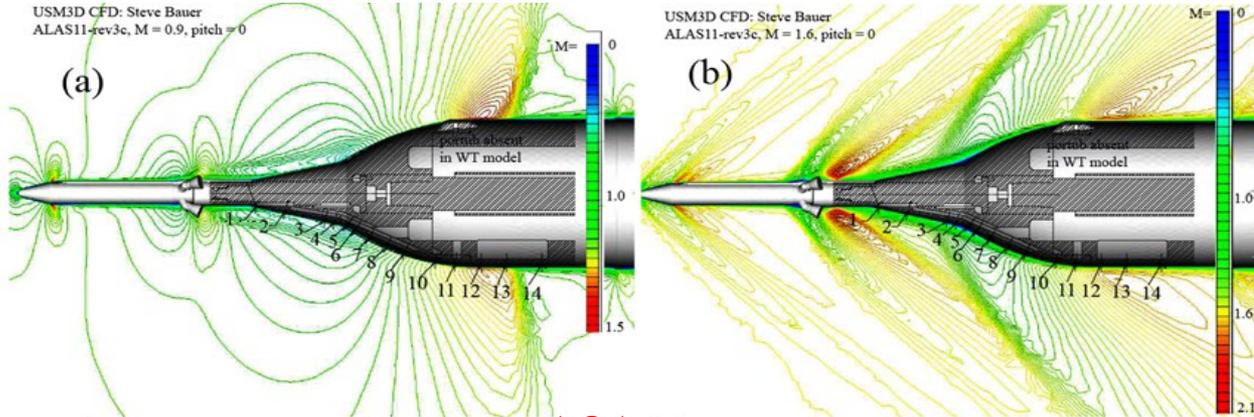


MPCV Shape Optimization to Reduce Acoustic environment





MPCV Shape Optimization to Reduce Acoustic environment





Comparison with Data from Flight Test – ARES-IX

Reed et al. AIAA 2011-174



Fig. 6 Transducers OAD819P, OAD920P, OAD921P, and OAD922P locations.

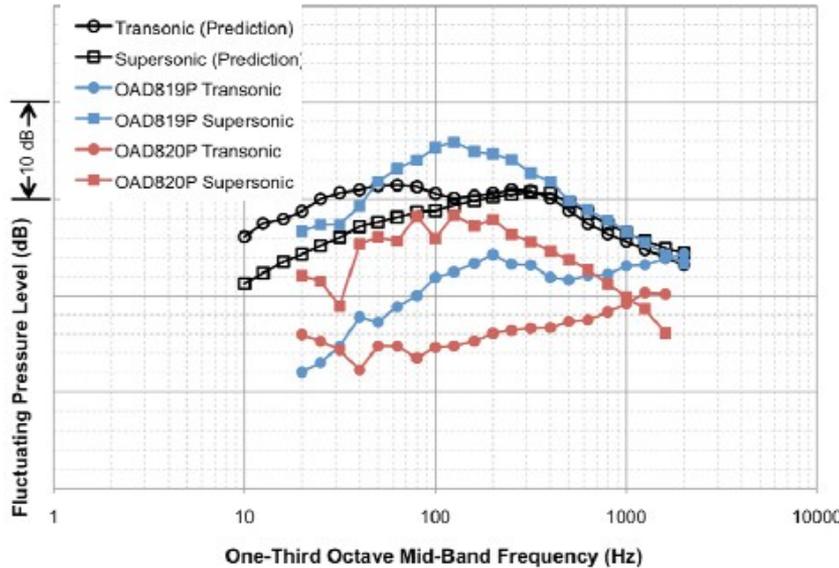
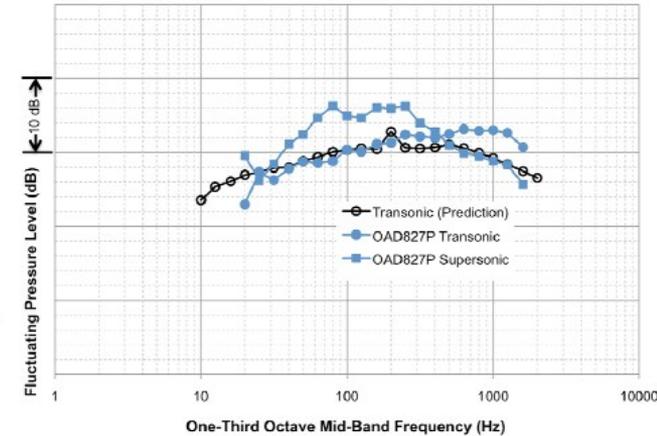


Fig. 9 Transducer OAD827P location.

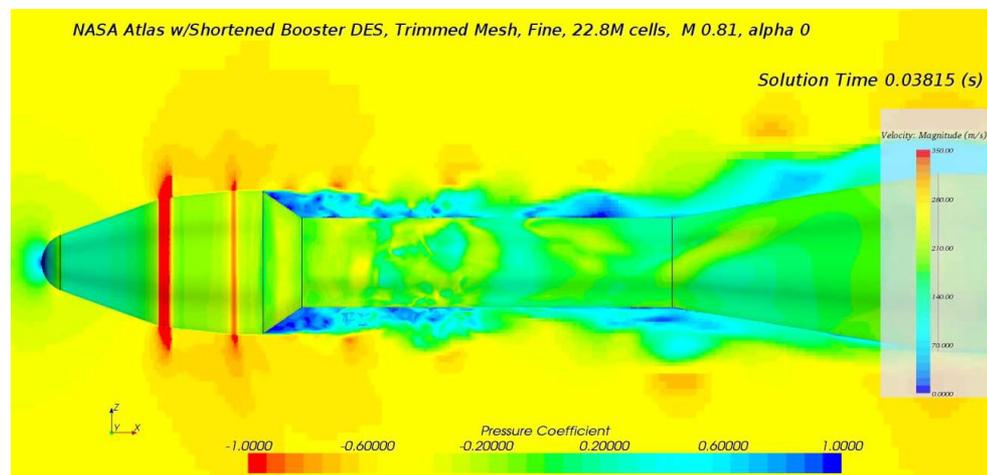


- In general reasonable comparison
- Discrepancies near changes in outer mold line geometries.
- zones near protuberances show poor comparison
- Data from supersonic part of the flight show poor comparison
- Flaws in the scaling laws?? Reynolds number effect?



Buffet – fluctuations in aerodynamic forces:

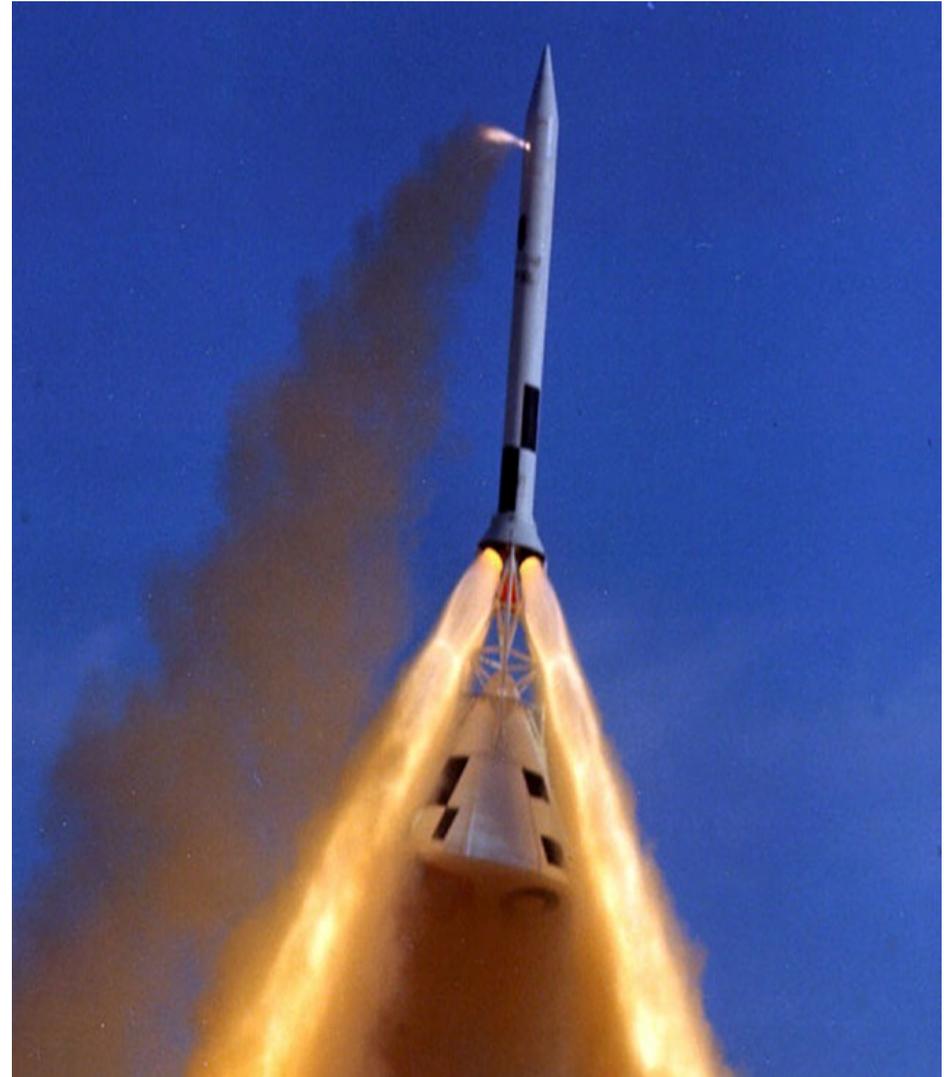
- Fluctuations in force = integration of pressure fluctuations
- Force fluctuations in 1-20Hz may cause coupling with global bending and/or torsional modes of the vehicle.
- May lead to catastrophic failures
- Typically occurs at transonic speed: $0.8 \leq M \leq 1.1$
- Primary cause: shock oscillation coupled with large separated flow.
- Mitigation - Restriction/Minimization of separated zones.
 - fixing oscillating shocks.



Matt Knapp, TLG Aerospace

Abort Acoustics

- o Problem definition
- o Wind tunnel simulation, CFD
- o Flight test

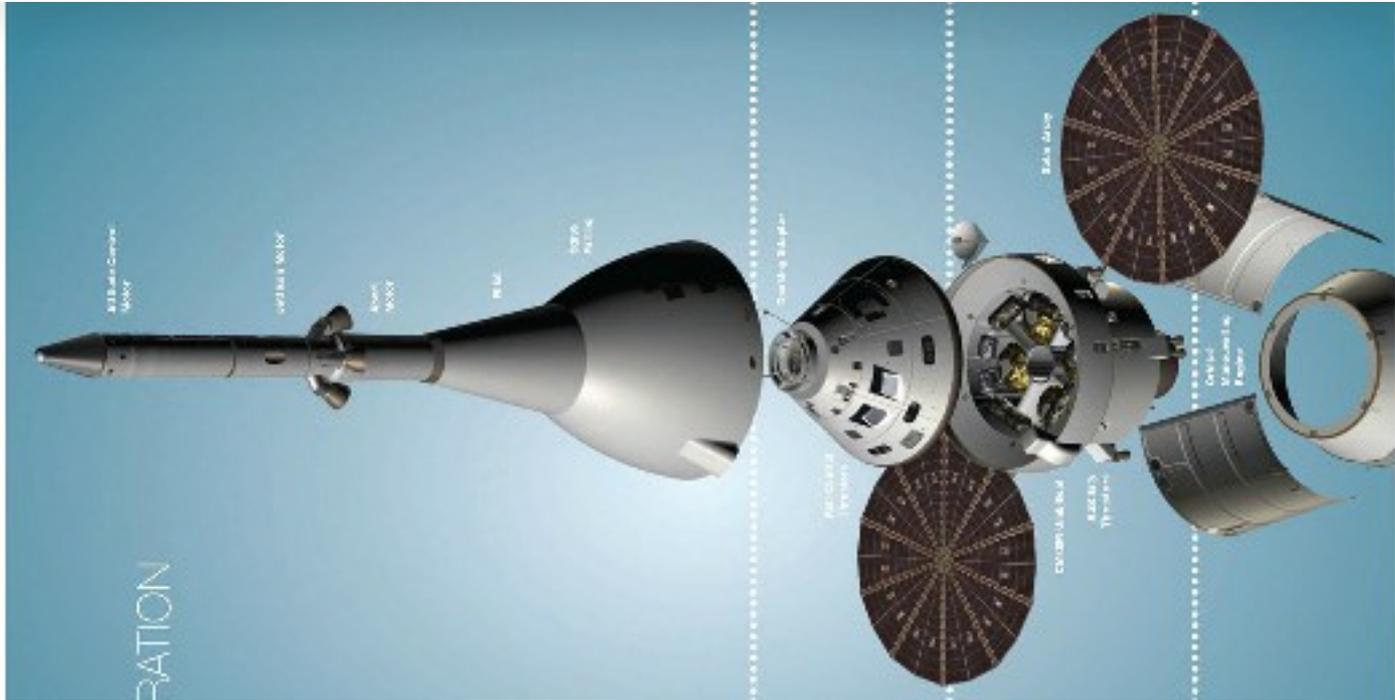


Apollo Abort test

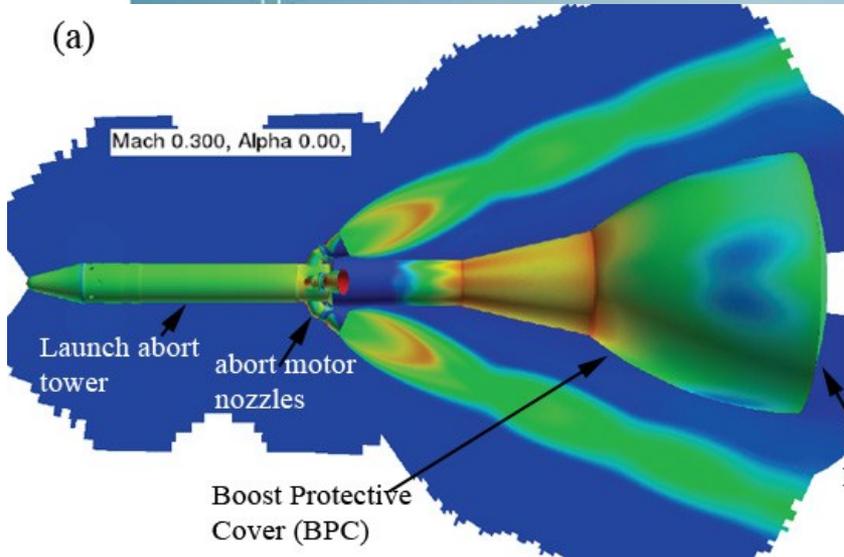


ORION/MPCV and the Launch Abort System

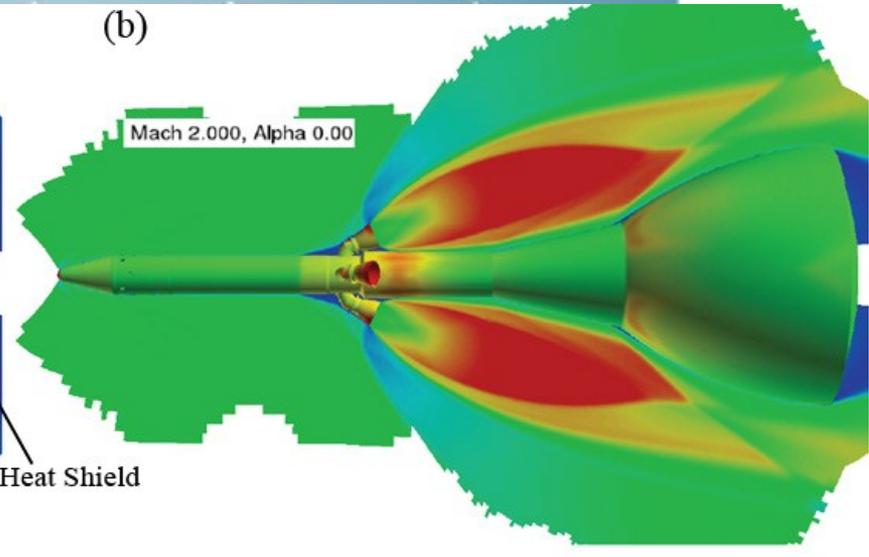
Abort Acoustics



(a)



(b)



Project Orion: Crew Exploration Vehicle (CEV)



Prediction –

- Initial prediction Based on SP-8072 – Not dependable
- No prior experience from Mercury or Saturn programs
- All microphones burnt out in one flight test



Measurement of plume-generated noise in the static test of MPCV launch abort motor ST1

Project Orion: Crew Exploration Vehicle (CEV)

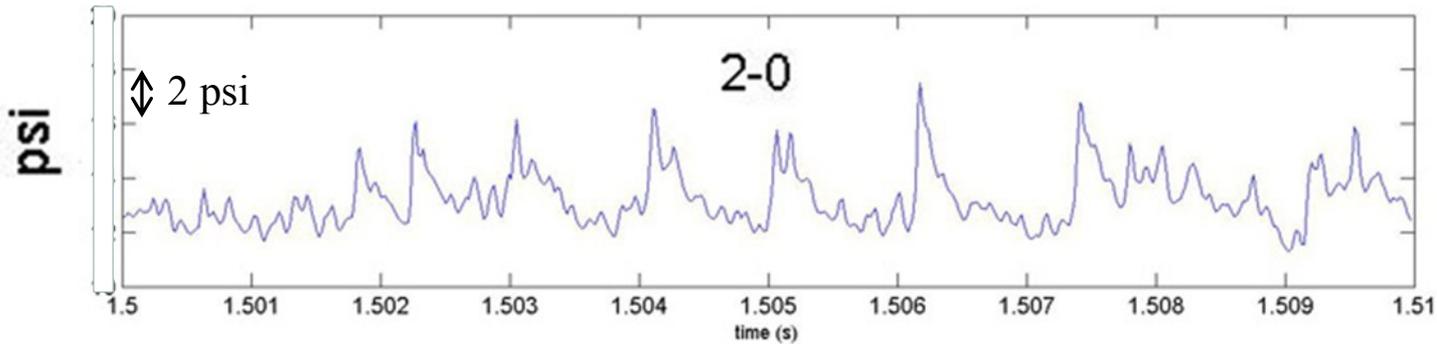
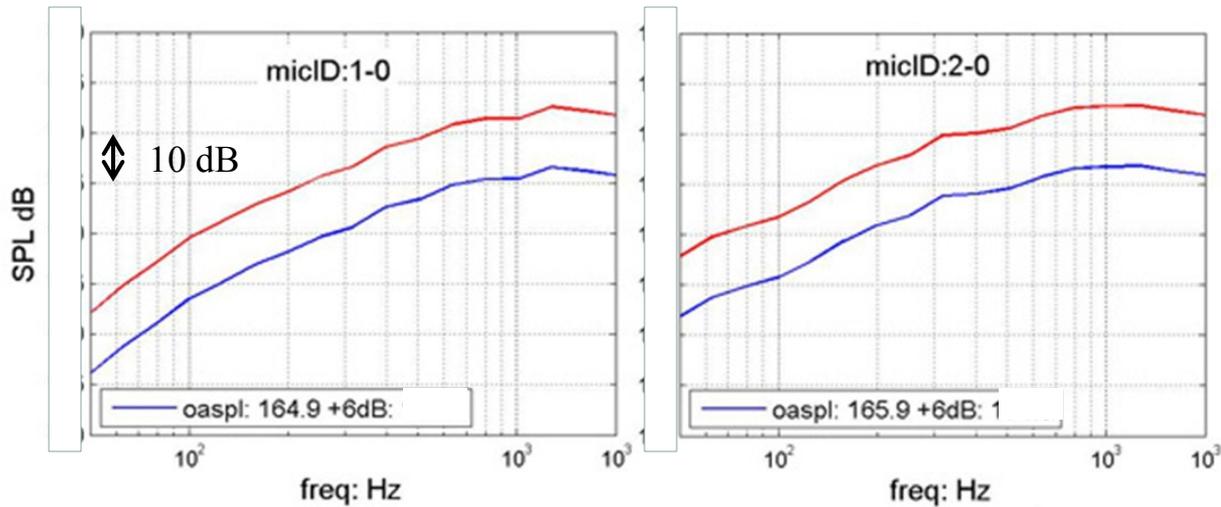




Results from ST1



- No prior aerospace structure was subjected to this high level of dynamic load



Very high level
High freq dominated
Non-linear, shock dominated



How to create acoustic environment for Abort?

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



Why hot-Helium?

Abort Acoustics



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

Pressure fluctuations at a point \mathbf{X} on LAV (Ffowcs-Williams, 1965):

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

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

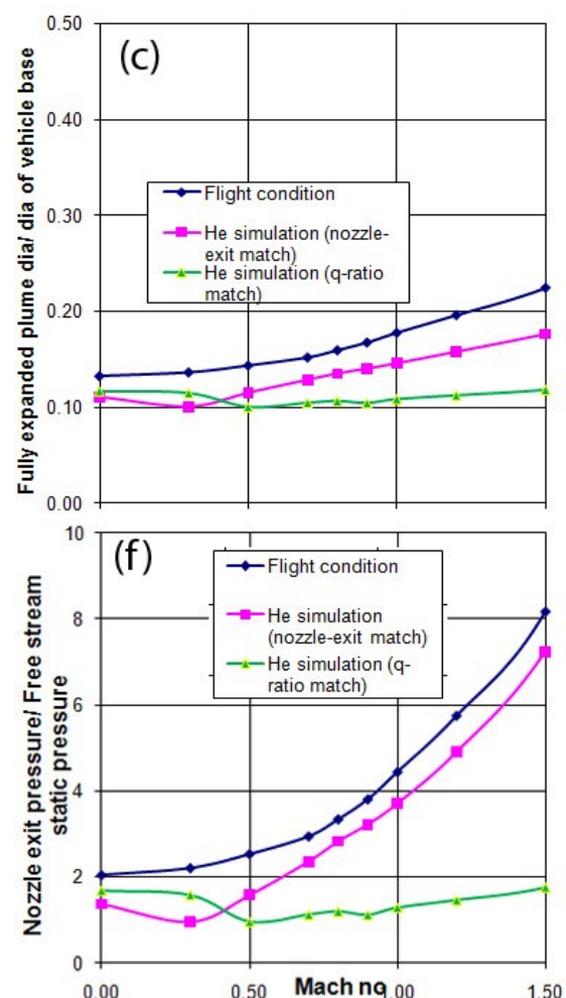
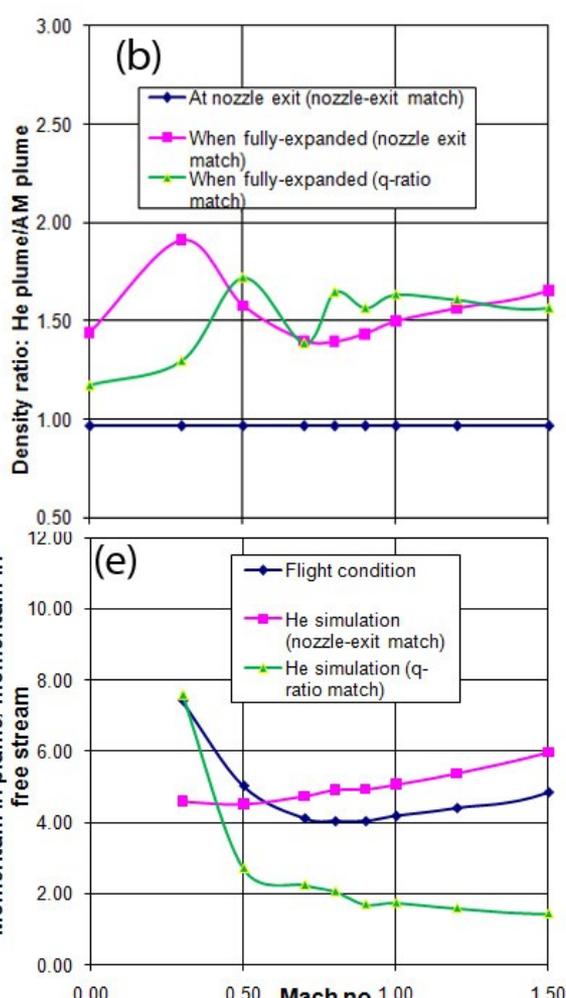
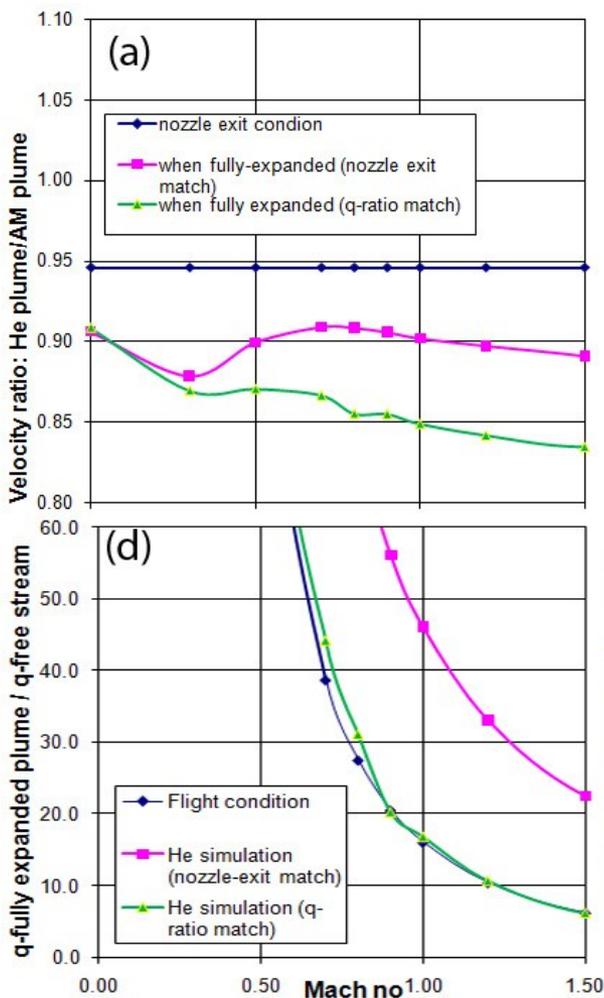
- Validation from prior small-scale tests:
 - SRM vs. He: Morgan & Young (1963)
 - Jet engine noise: Doty & McLaughlin (2001), Kinzie & McLaughlin (1999)
 - Papamoschou (2007), Greska & Krothapalli (2009)
- Practicality of operation:
 - Suitable in a wind tunnel .
 - Use of high fidelity model with all 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



Matching between wind tunnel and flight conditions



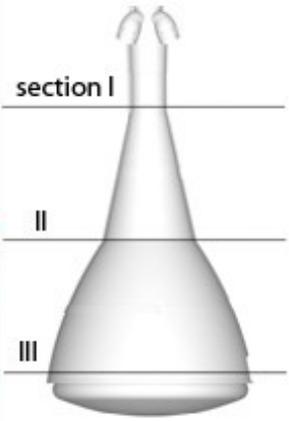
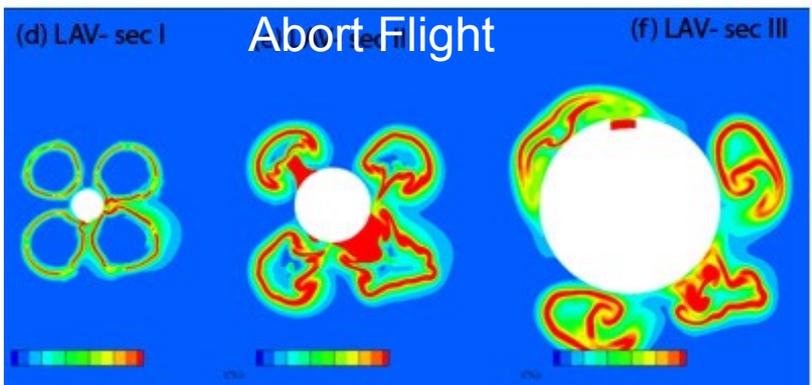
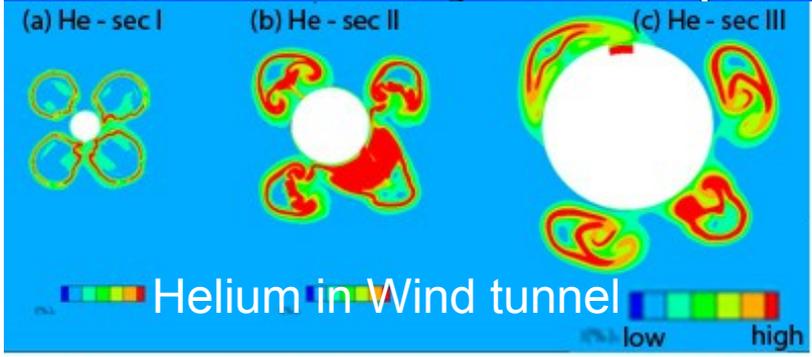
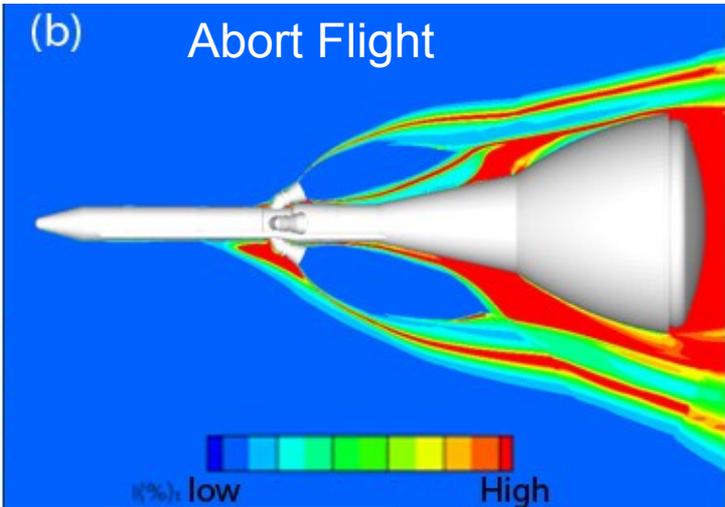
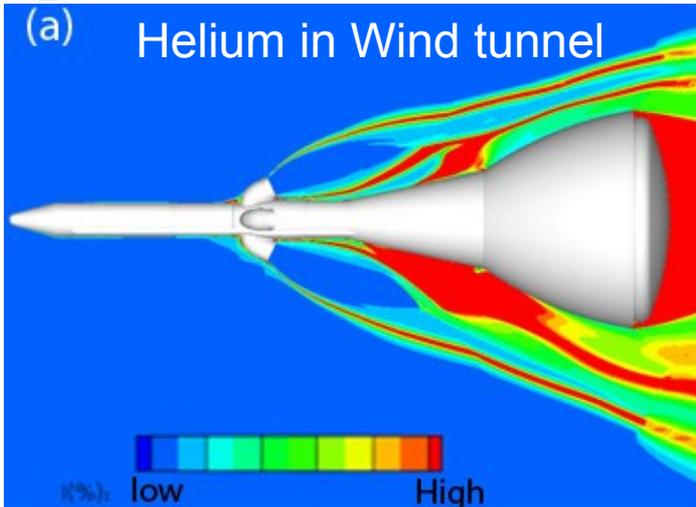
$$\frac{p_f}{p_t} = f \left(\frac{D_{er}}{D_{eh}}, \frac{D_{jr}}{D_{jh}}, \frac{\alpha_r}{\alpha_h}, \frac{\beta_r}{\beta_h}, \frac{M_{jr}}{M_{jh}}, \frac{M_{er}}{M_{eh}}, \frac{(p_e/p_a)_r}{(p_e/p_a)_h}, \frac{c_{jr}}{c_{jh}}, \frac{\rho_{jr}}{\rho_{jh}}, \frac{\rho_{er}}{\rho_{eh}}, \frac{U_{jr}}{U_{jh}},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





Abort initiated at M 1.6 : Influence of forward flight

Project Orion: Crew Exploration Vehicle (CEV)



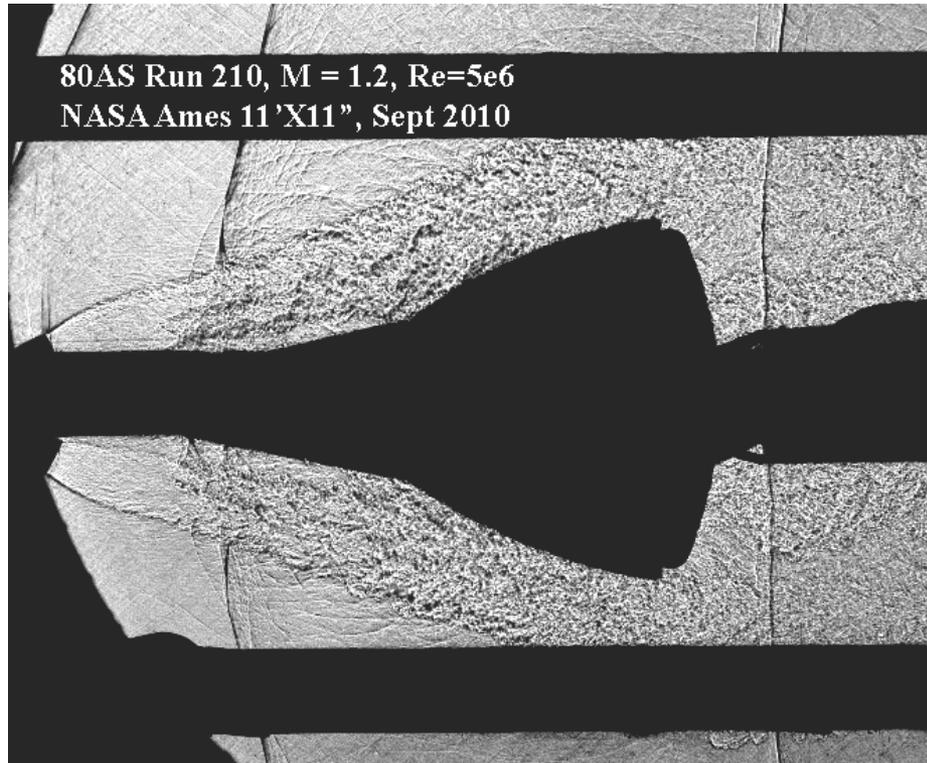
Distribution of turbulence intensity

$M_a = 1.6, \alpha = -10^\circ, \beta = -10^\circ$

CFD by: William J. Coirier, Kratos/DFI



Abort initiated at M 1.2 : Influence of forward flight



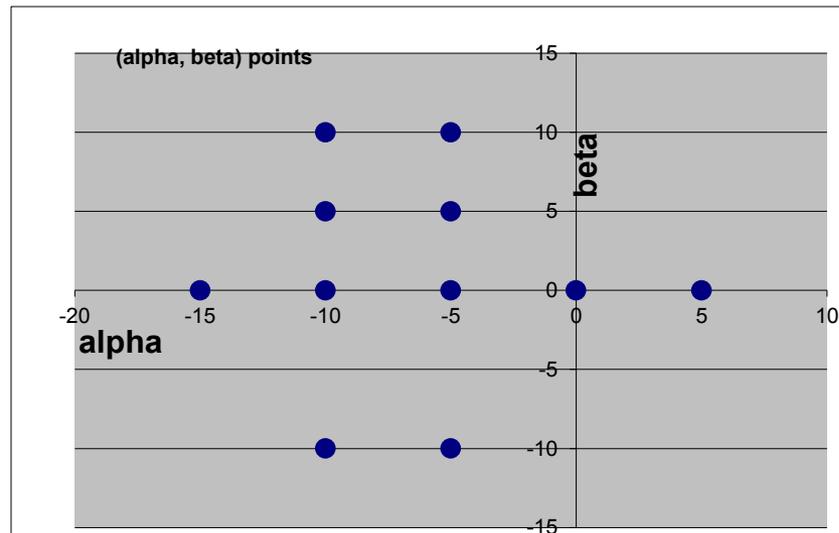
- Wind tunnel pressure fluctuations need to be scaled to flight condition
 - problem of two different ratios of dynamic pressures:

$$\frac{p'(\text{model})}{p'(\text{flight})} = f\left(\frac{\text{Dynamicpress}_{\text{tunnel}}}{\text{Dynamicpress}_{\text{flight}}}, \frac{\text{Dynamicpress}_{\text{Helium plume}}}{\text{Dynamicpress}_{\text{Rocket plume}}}\right)$$

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



- Test conducted in the NASA Ames 11-Ft Unitary Plan wind tunnel
- Mach Range 0.3 – 1.2
- Reynolds Number: 2×10^6 - 5.0×10^6 /foot,
- He pressure at Model Plenum: 300psi to 600psi
- He temperature at Model Plenum: 660F to 700F
- Internal piping for 11 different model attitudes:





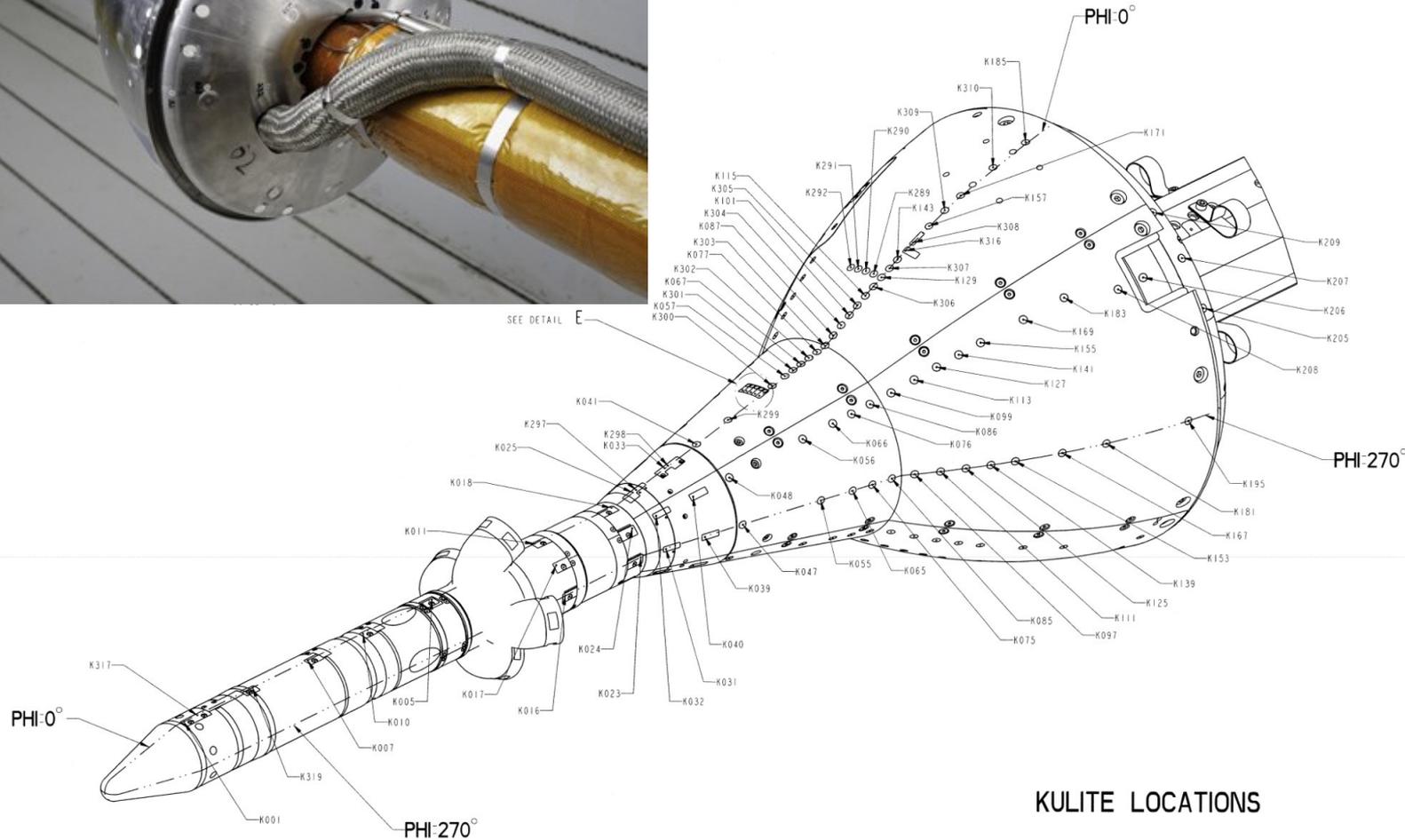


Abort Acoustics





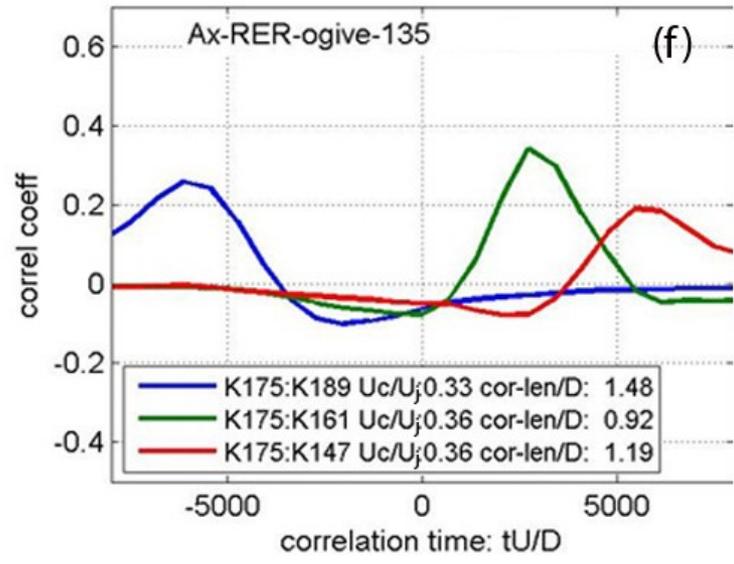
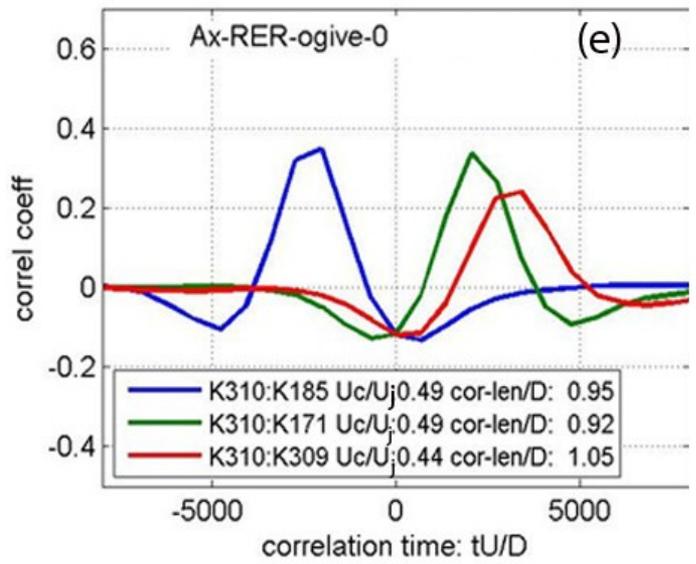
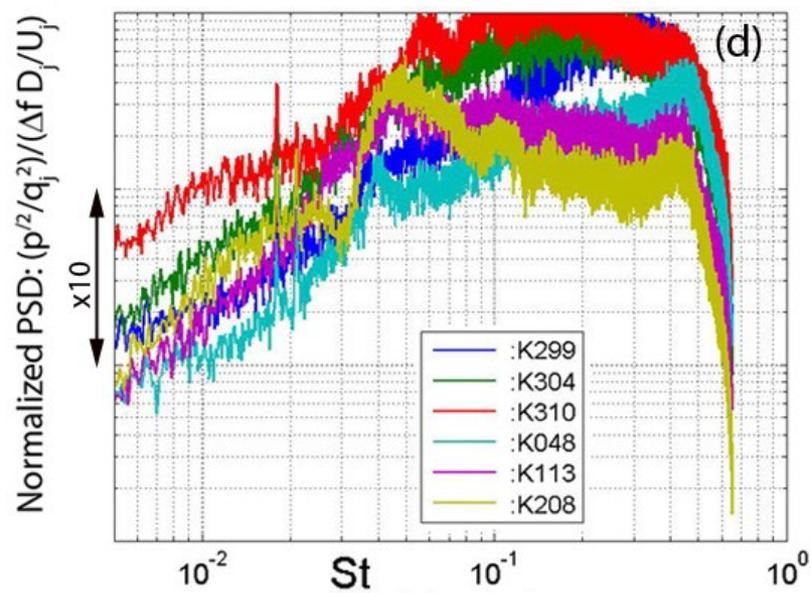
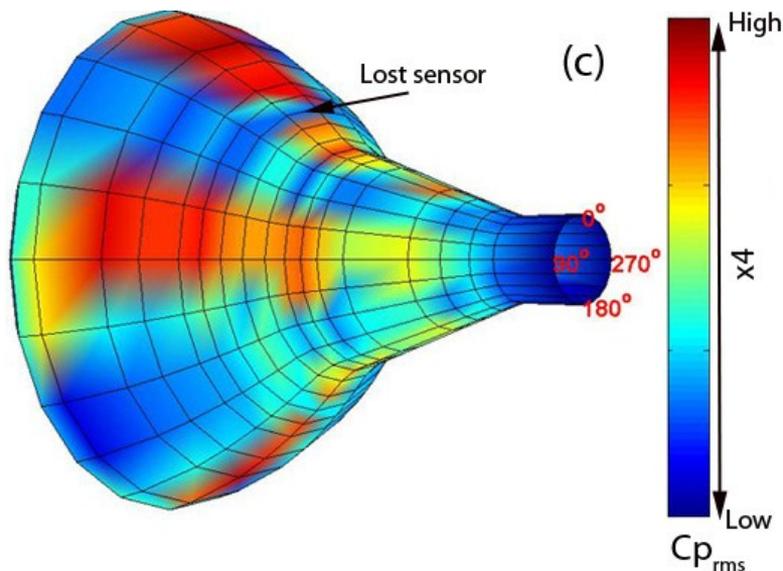
- 6% scaled of LAV 606 F.1
- Continuous active cooling of the model core
- Subjected to very large temperature cycle – periodic heating and cooling.
- 237 Kulite sensors

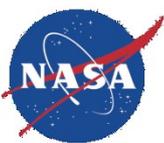


KULITE LOCATIONS



Sample Result: Run 184: $M = 0.3$, $Re = 3e6$, $\alpha=0$, $\beta=0$



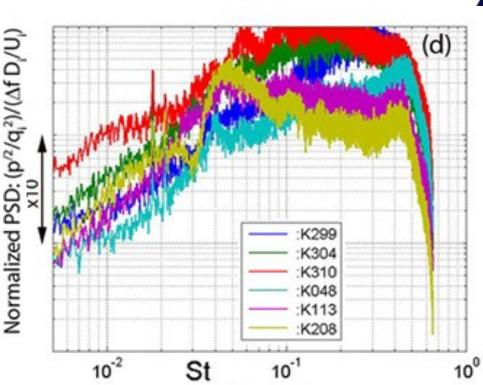
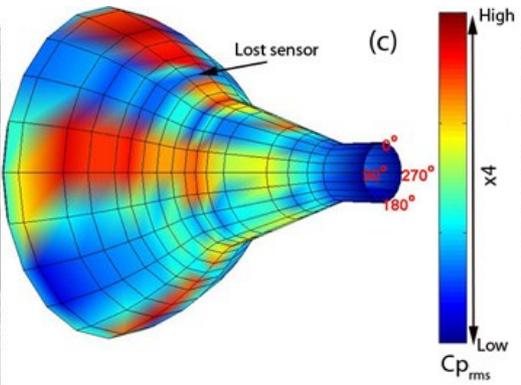
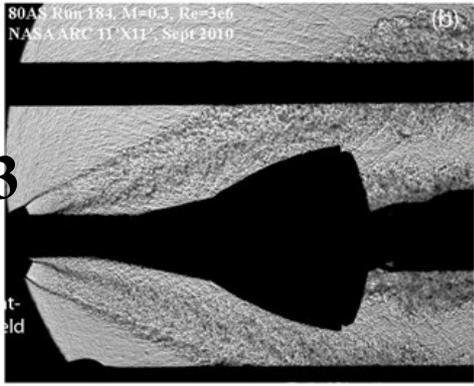


Effect of Forward Flight

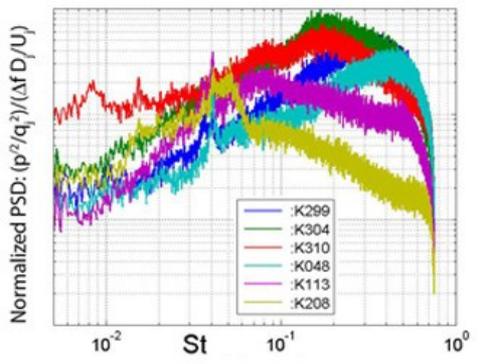
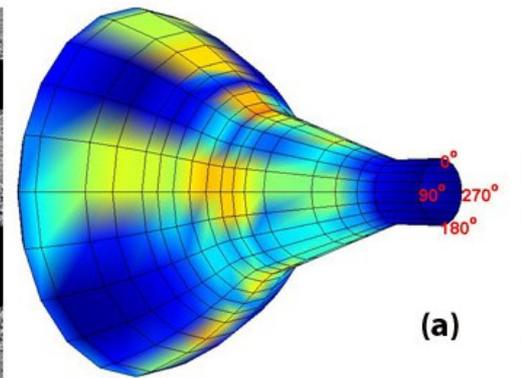
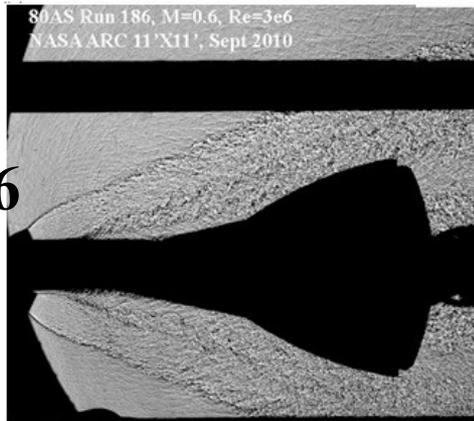
Abort Acoustics



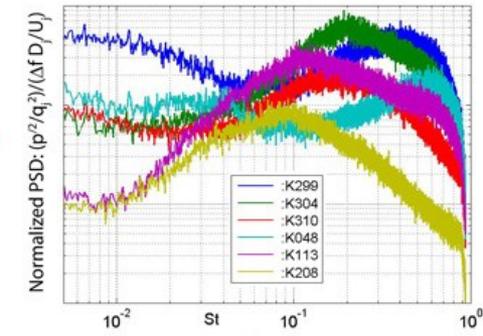
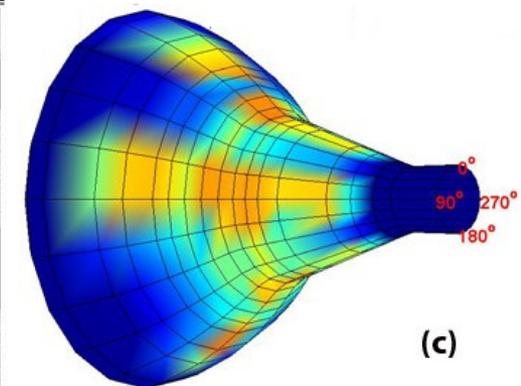
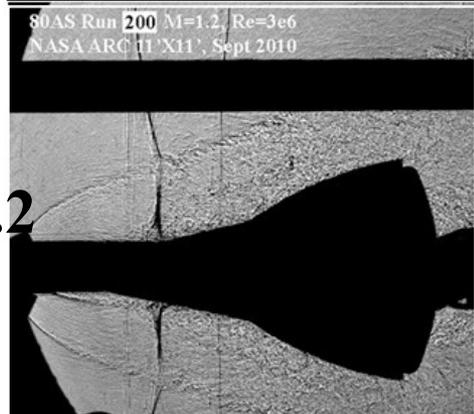
M = 0.3



M = 0.6



M = 1.2



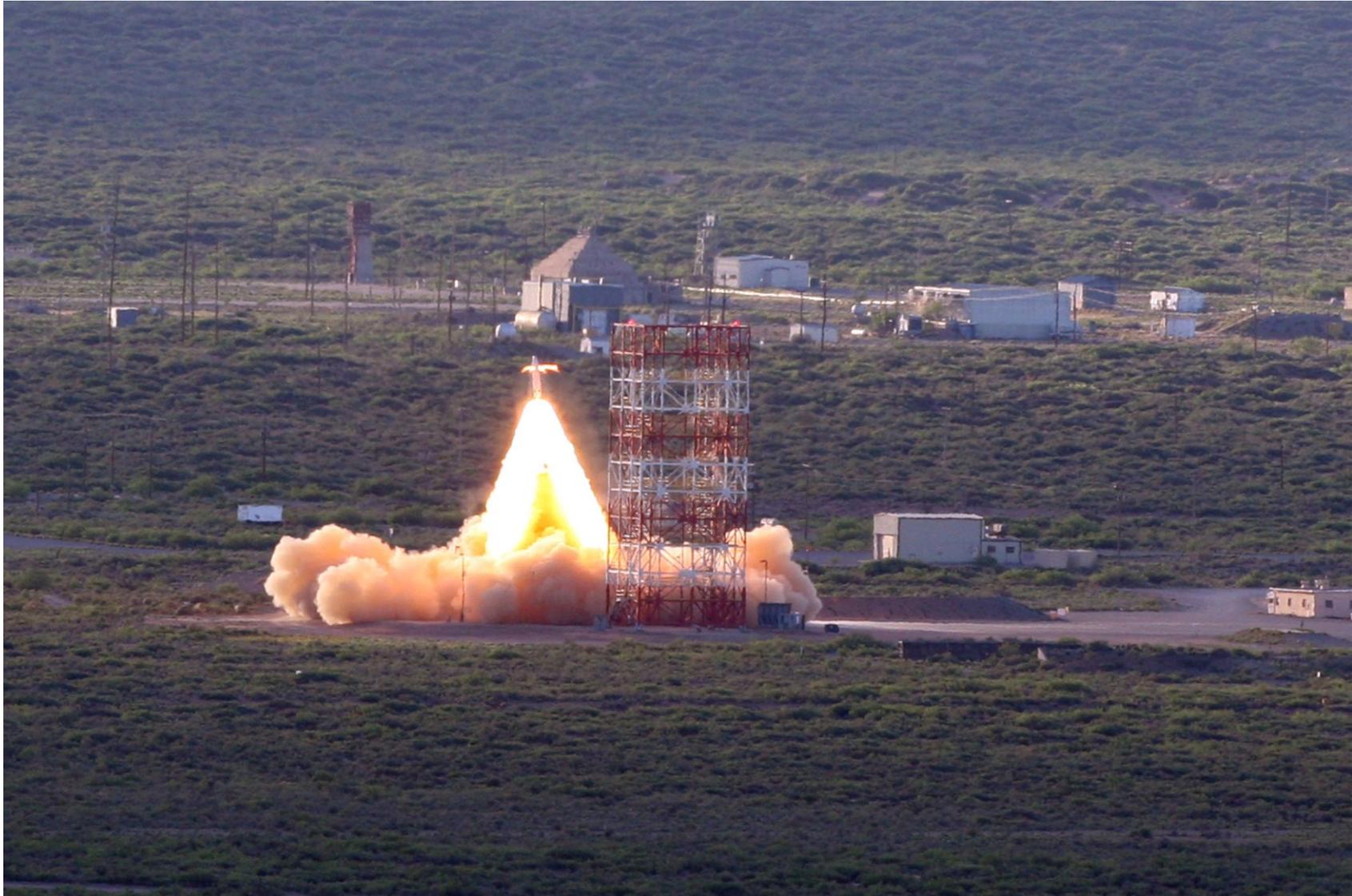


July 2010

Pad Abort-1 is a NASA flight test of a system that could be used to rescue a crew and its spacecraft in case of emergencies at the launch pad.

www.nasa.gov







Comparison with Pad Abort 1 flight data

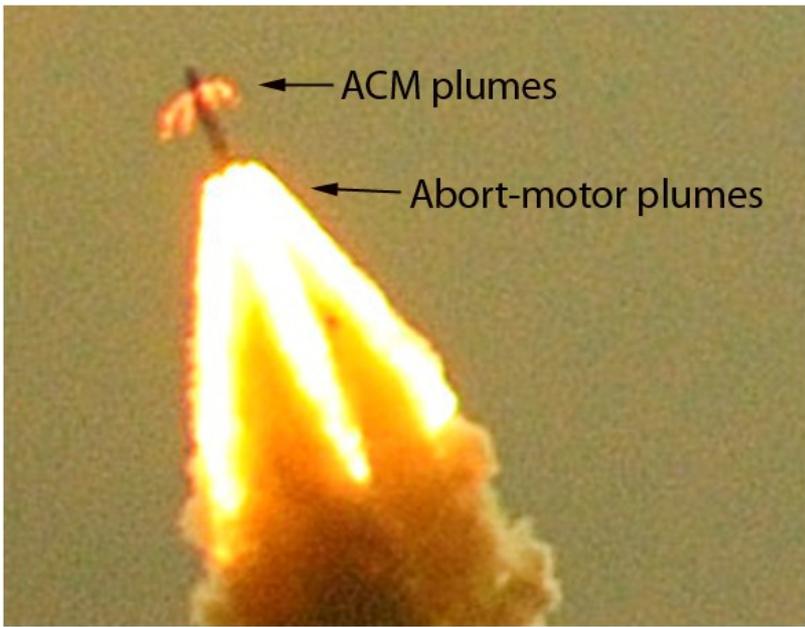
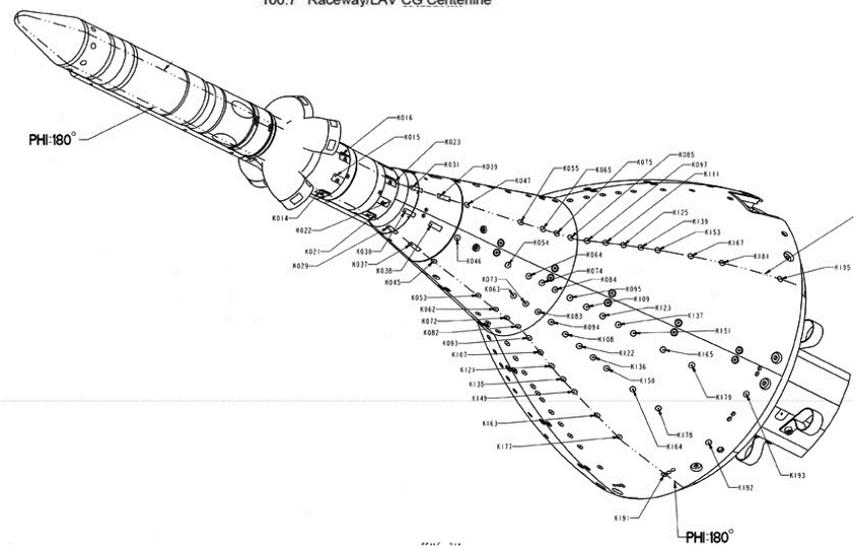
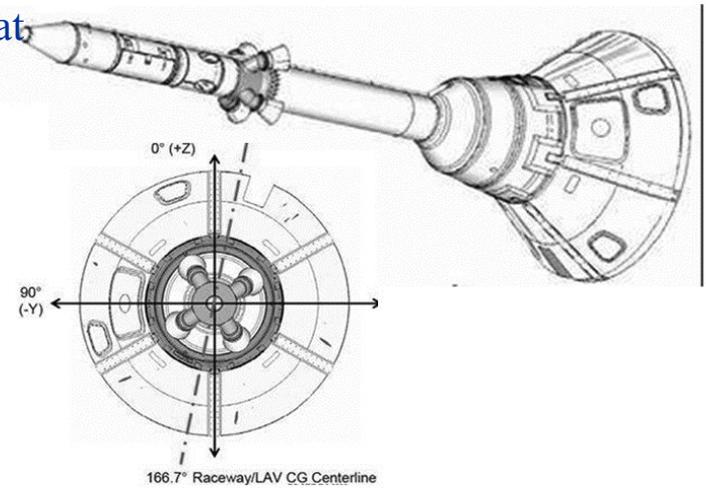


Pad Abort test flight PA1:

- Happened on 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

● Not exactly apple-to-apple comparison

- Older, slimmer profile
- **Flight:** transient data, **wind tunnel:** steady state
- Wind tunnel: No Attitude Control Motor



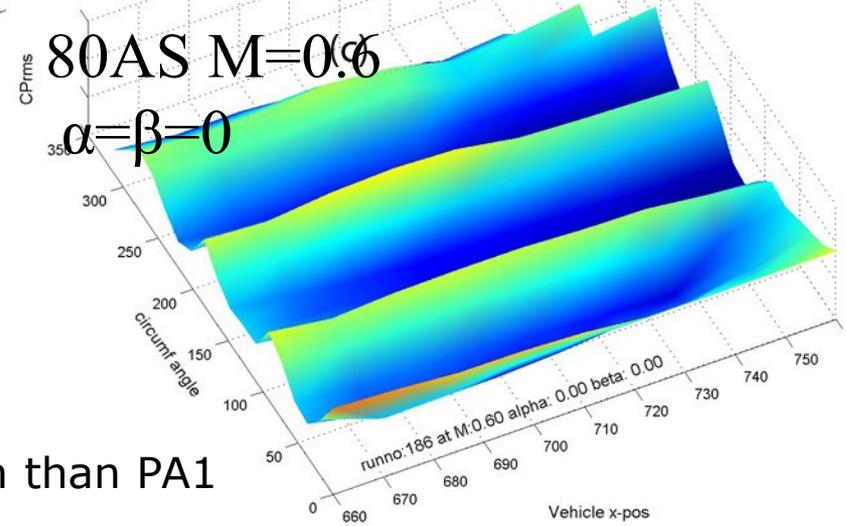
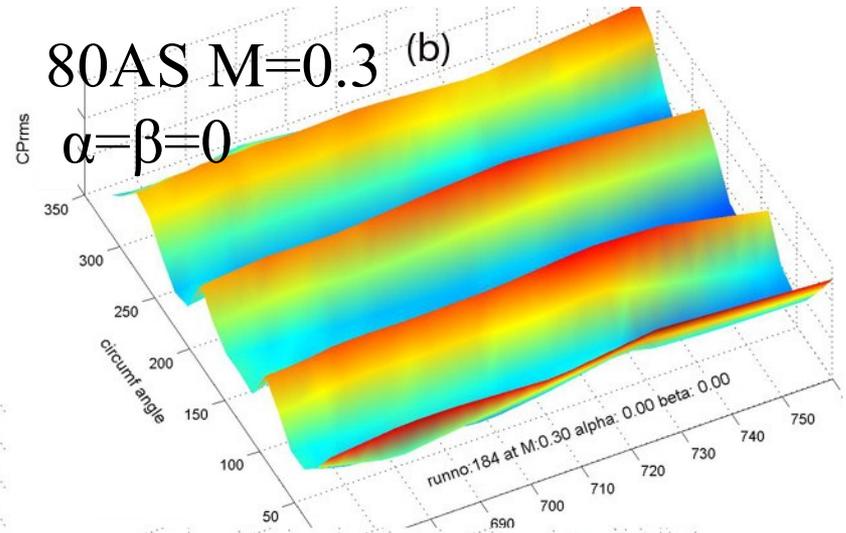
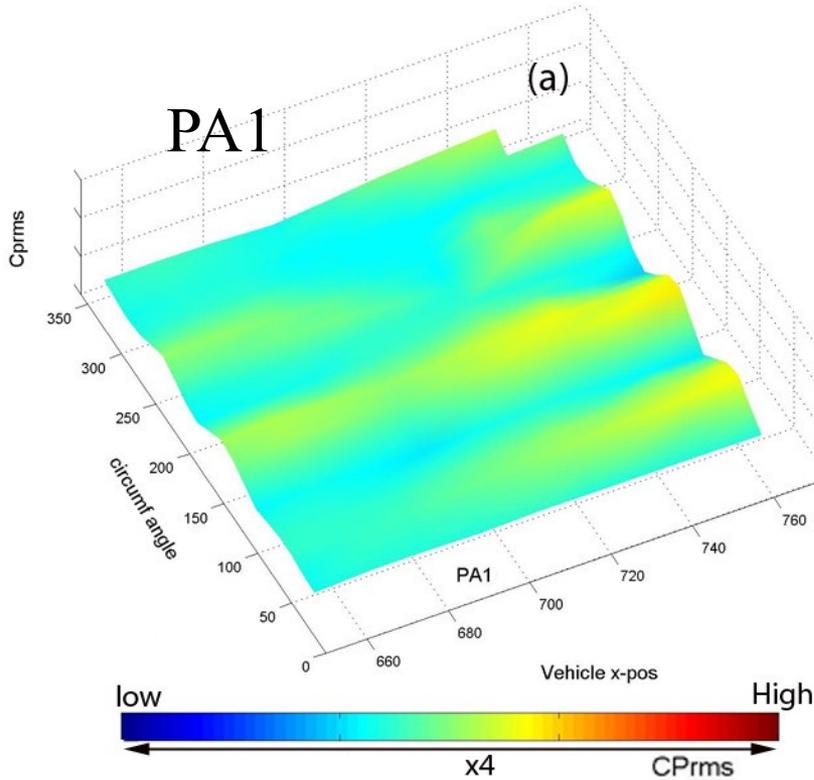


Comparison with PA1 flight data

Abort Acoustics



Project Orion: Crew Exploration Vehicle (CEV)



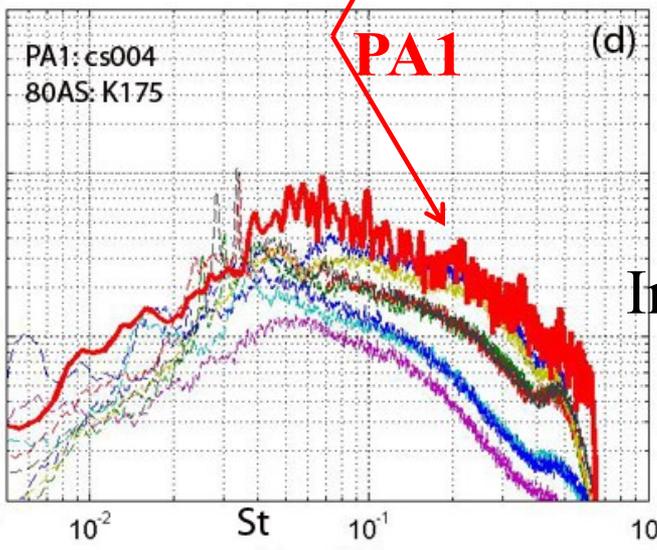
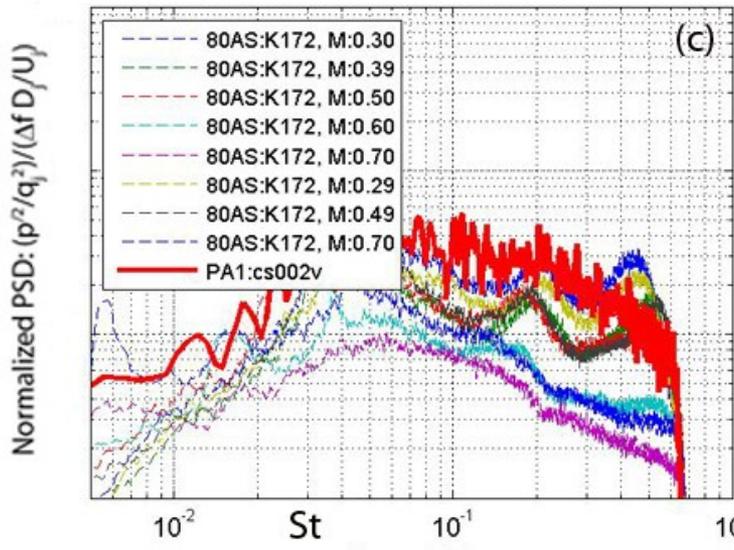
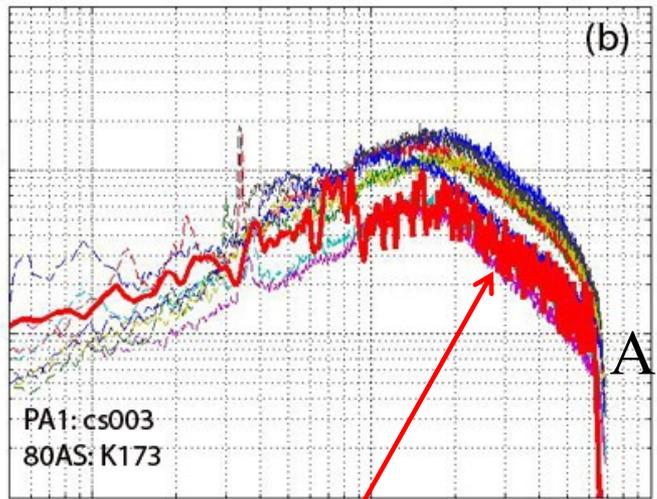
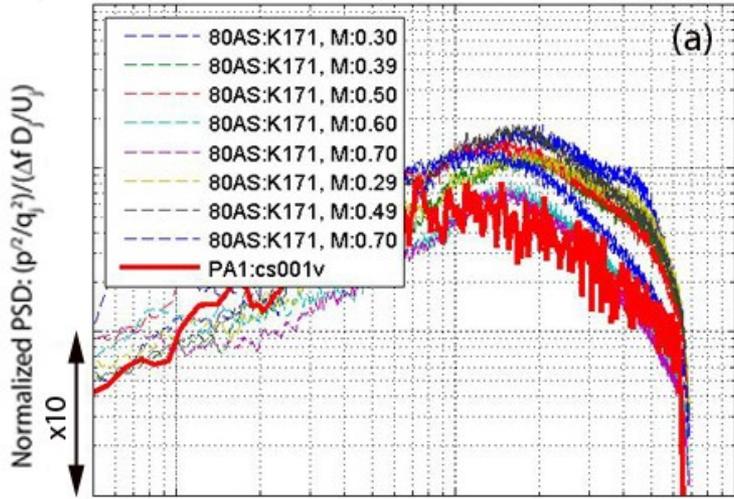
- 80AS show wider crest-trough variation than PA1
 - PA1 flew with non-zero α , β
 - PA1 had ACM induced turbulence



Comparison with PA1 flight data – q scaling



Project Orion: Crew Exploration Vehicle (CEV)



Along Plume axes

In Between Plume



Existing uncertainties:

- Scaling laws for abort initiated at transonic/supersonic flight
- Increment in environment due to scattering of plume by vehicle induced shock waves

Expecting further validation from another flight test

- Ascent Abort 2 (AA2) – Abort initiated at $M \sim 1.1$



Basics

- For launch vehicles aeroacoustics is a part of fluid-structure interaction problem
- Separation into Aeroacoustics and Vibro-acoustics
- Aeroacoustics = surface pressure fluctuations
- Forcing functions for vibro-acoustic calculations
 - overall level – extremely high
 - auto-spectra
 - cross-spectra
- Need for direct solution of fluid-structure interaction.

Launch Acoustics

- Complexity of launch pad – acoustic suppression systems
 - deflector and trench design
 - vehicle trajectory and drift
 - amount of water injection and timing schedule
- Prediction via NASA SP-80672 & limitations
 - ignores plume impingement, water injection, vehicle drift
- Prediction via flight data from prior launch vehicles
 - very large spread, different for a new vehicle
- Limited ability of CAA
- Use of a microphone phased array for direct identification of noise sources
 - Very different description of noise sources that SP-8072



Ascent Acoustics

- Source- turbulent flow over vehicle surface, local flow separation, unsteady shocks
 - dynamic pressure and vehicle trajectory
- Prediction – identification of local flow separation and transonic/supersonic shock wave.
 - Improvement of empiricism via input from CFD
 - Future need for less empiricism - CFD ?
 - Data from prior flight experiences
- Wind tunnel test - validation/verification
- Change of vehicle OML to reduce ascent acoustics– MPCV experience
- Limitations observed from flight data

Abort Acoustics

- Lack of prior experience and database
- Creation of database from Static Fire test – spectral trends, shock amplitude
- Challenge of simulating hundreds of abort scenario within a reasonable budget
 - Hot helium to simulate rocket plume
 - similarity parameters
 - scaling problems
 - Increasing Flight Mach shows a reduction in overall levels, but increases low freq content.
 - Plume impingement generally reduces level of pressure fluctuations
- Comparison with flight data from Pad Abort 1:
 - Not an apple-to-apple comparison: different shape, transient flight vs steady simulation
 - Nonetheless, comparable overall level and the spectral shape
- Unique, one-of-a-kind test provides aeroacoustics environment for the design and qualification testing of ORION/MPCV Launch Abort Vehicle.



BACKUP



Summary:

- **Unobstructed plume: noise sources are distributed along the plume**
- **In a launch configuration: locations where plume impinges on solid surfaces are the primary sources**
 - ▶ Current Lift-off models (SP8072) does not account for impingement
 - Need investments in changing/updating these models
 - ▶ Minimization of plume impingement will attenuate liftoff environment
 - By reduce vehicle drift in early part of liftoff
 - Possibly by increasing the MLP hole size
- Open/Uncovered part of the trench are noise sources
 - Closing the trench as much as possible will reduce liftoff environment
- Water injection in the hole & trench is effective in reducing trench generated noise
- On-Deck water (Rainbird) is partially effective in noise source mitigation
- Microphone phased-array is an ideal tool to study all launch acoustic environments
 - Results from the current study are expected to help SLS pad design

Future work:

Looking for opportunities to use phased-array in full-scale launch



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12. Panda, J., James, G. H., Burnside, N. J., Fong, R. K., Fogt, V. A. & Ross, J. C., "Use of Heated Helium to Measure Surface Pressure Fluctuations on the Launch Abort Vehicle During Abort Motor Firing," AIAA paper 2011-2901.
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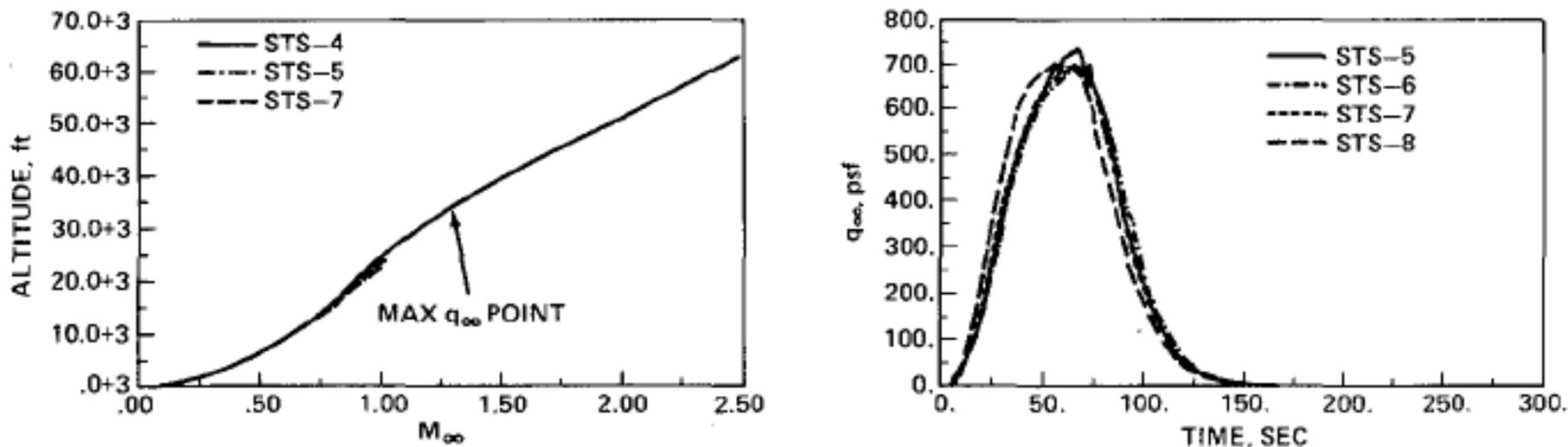


Fig 4 Typical ascent flight trajectories

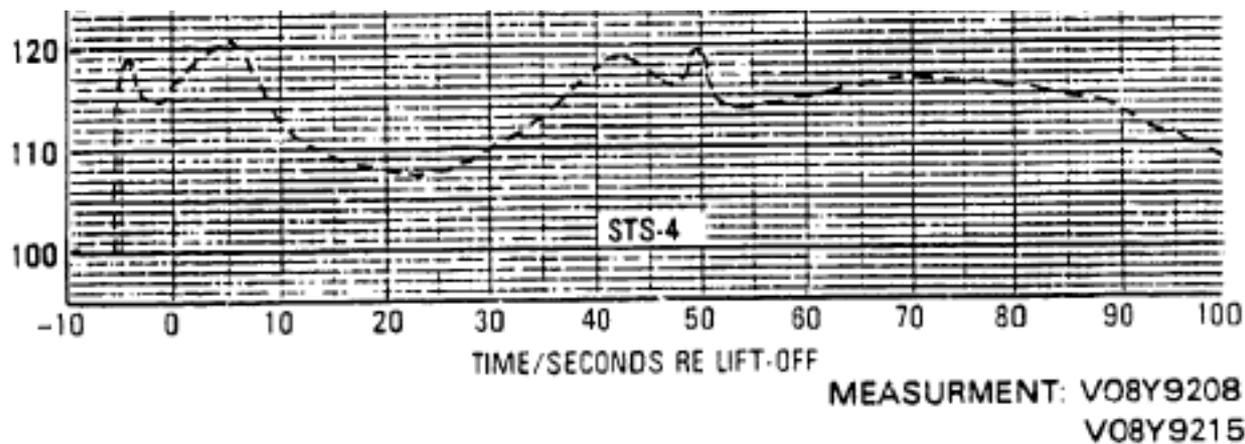
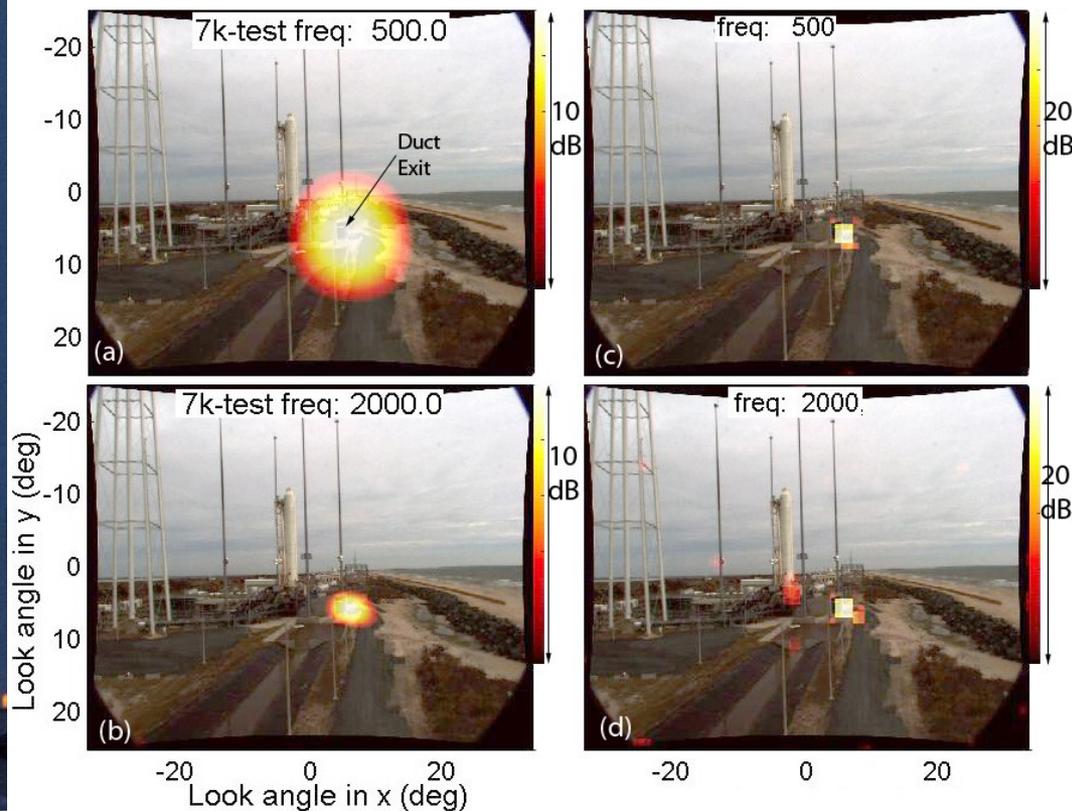
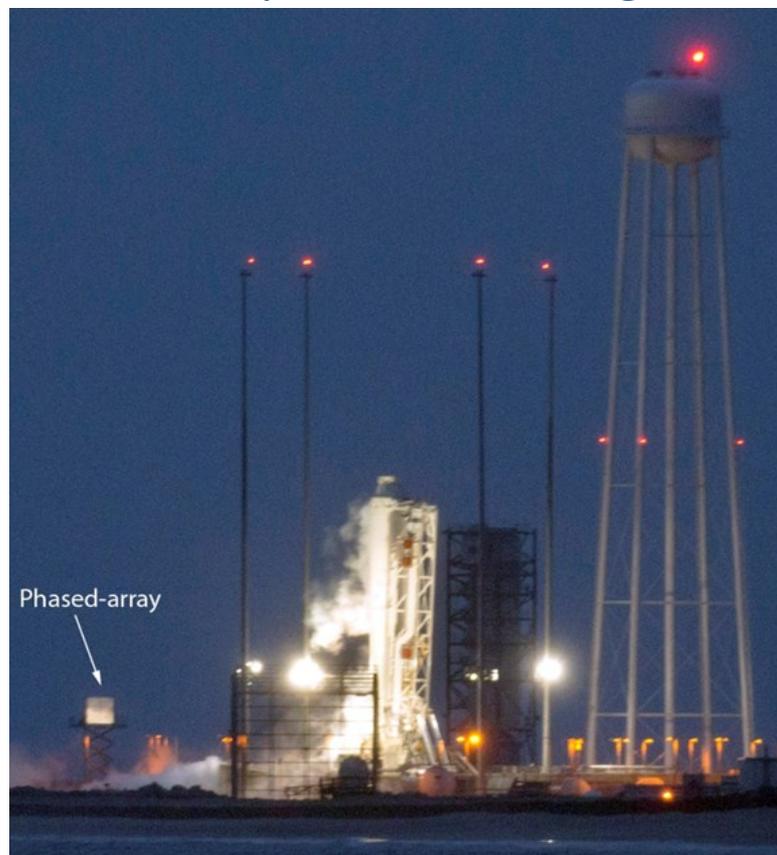


Figure 1.3-2. STS Aero/Acoustic Noise Level Time History - Crew Cabin - Flight Deck



Phased array in Antares Engine Test: Feb 22, 2013



Summary of results from Engine Test:

- The primary noise source was the duct exit
- Plume out of the duct exit was NOT a primary source - very large amount of water pumped at the duct inlet quenched the flame
- Noise generated during impingement on the deflector, and general mixing inside the duct, emerged out of the duct exit.
- First time application of phased array in full-scale engine test