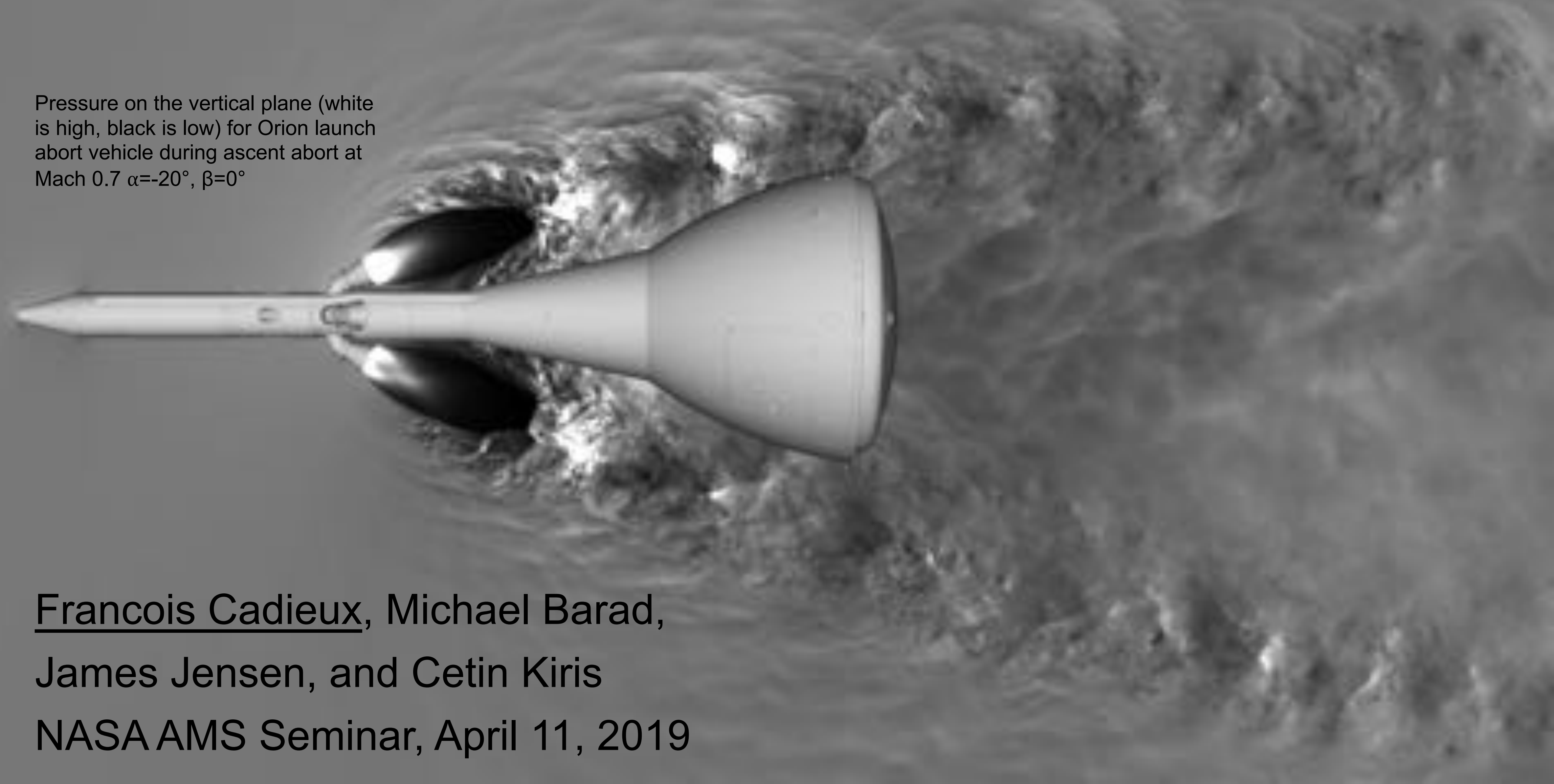
Orion Launch Abort Acoustics



Pressure on the vertical plane (white is high, black is low) for Orion launch abort vehicle during ascent abort at Mach 0.7 α=-20°, β=0°

Francois Cadieux, Michael Barad,
James Jensen, and Cetin Kiris

NASA AMS Seminar, April 11, 2019

National Aeronautics and Space Administration

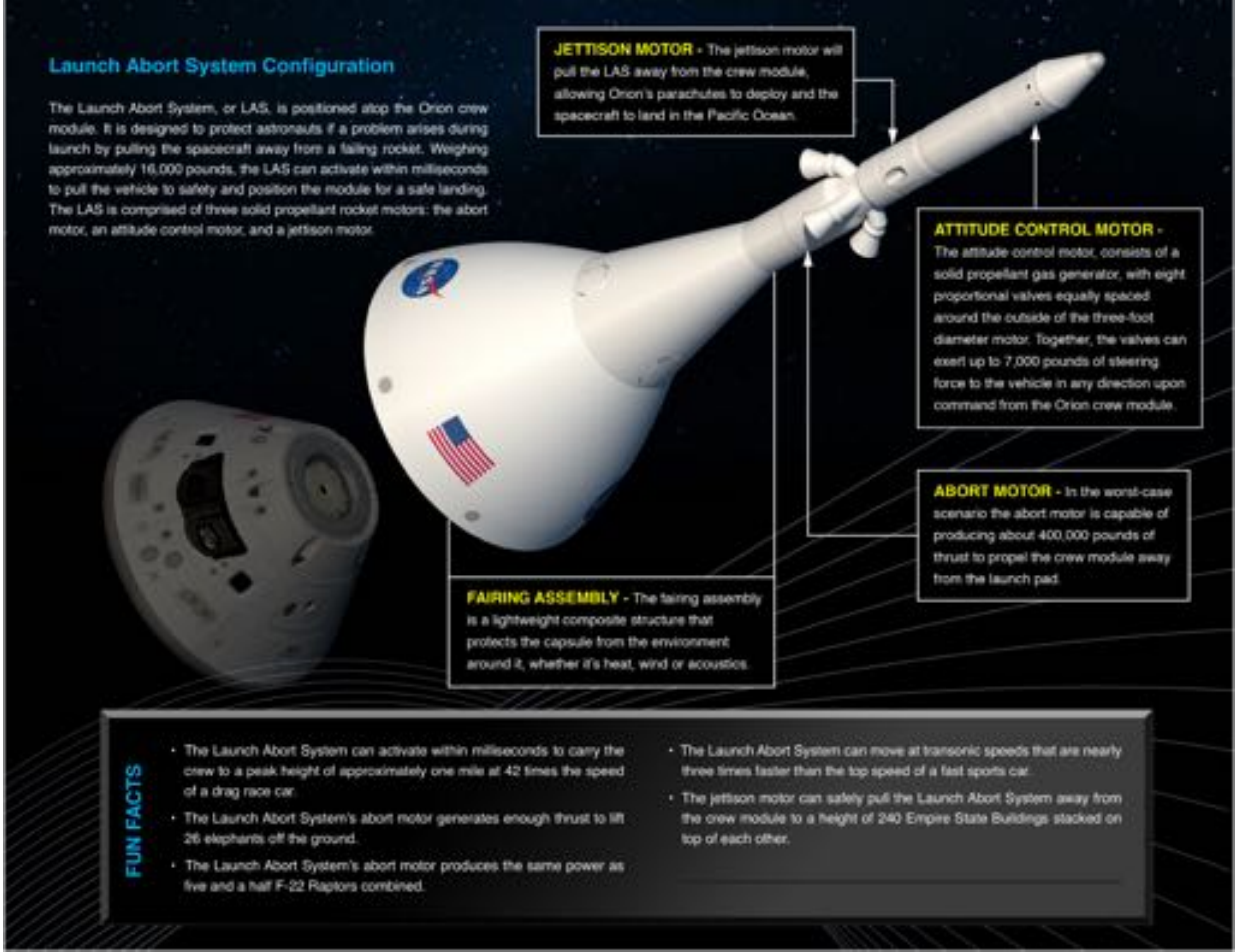
ORION

Launch Abort System (LAS)

NASAfacts

Ensuring Astronaut Safety

NASA is developing technologies that will enable humans to explore new destinations in the solar system. America will use the Orion spacecraft, launched atop the Space Launch System rocket, to send a new generation of astronauts beyond low-Earth orbit to places like an asteroid and eventually Mars. In order to keep astronauts safe in such difficult, yet exciting missions, NASA and Lockheed Martin collaborated to design and build the Launch Abort System.



Launch Abort System Configuration

The Launch Abort System, or LAS, is positioned atop the Orion crew module. It is designed to protect astronauts if a problem arises during launch by pulling the spacecraft away from a failing rocket. Weighing approximately 16,000 pounds, the LAS can activate within milliseconds to pull the vehicle to safety and position the module for a safe landing. The LAS is comprised of three solid propellant rocket motors: the abort motor, an attitude control motor, and a jettison motor.

JETTISON MOTOR - The jettison motor will pull the LAS away from the crew module, allowing Orion's parachutes to deploy and the spacecraft to land in the Pacific Ocean.

ATTITUDE CONTROL MOTOR - The attitude control motor, consists of a solid propellant gas generator, with eight proportional valves equally spaced around the outside of the three-foot diameter motor. Together, the valves can exert up to 7,000 pounds of steering force to the vehicle in any direction upon command from the Orion crew module.

ABORT MOTOR - In the worst-case scenario the abort motor is capable of producing about 400,000 pounds of thrust to propel the crew module away from the launch pad.

FAIRING ASSEMBLY - The fairing assembly is a lightweight composite structure that protects the capsule from the environment around it, whether it's heat, wind or acoustics.

FUN FACTS

- The Launch Abort System can activate within milliseconds to carry the crew to a peak height of approximately one mile at 42 times the speed of a drag race car.
- The Launch Abort System's abort motor generates enough thrust to lift 26 elephants off the ground.
- The Launch Abort System's abort motor produces the same power as five and a half F-22 Raptors combined.
- The Launch Abort System can move at transonic speeds that are nearly three times faster than the top speed of a fast sports car.
- The jettison motor can safely pull the Launch Abort System away from the crew module to a height of 240 Empire State Buildings stacked on top of each other.

Using HPC To Keep Astronauts Safe

1. Perform time-accurate, scale-resolving computational fluid dynamics (CFD) simulations to predict transient pressure loads in various sections of the Orion Launch Abort Vehicle (LAV)
2. Collaborate with Orion Loads and Dynamics team to use these predictions along with wind tunnel data, ground test measurements, and flight tests to reduce risk of structural failure due to vibrations for a wide range of launch abort scenarios: pad abort, subsonic/transonic/supersonic ascent abort

Outline

1. Pre-test CFD support for Orion abort motor qualification ground test (QM-1)
2. Post-test CFD validation
3. Using CFD to account for missing LAV in QM-1 test
4. Investigation into ascent abort scenarios
5. Wind tunnel CFD validation and scaling to flight conditions
6. Using CFD to reduce uncertainty at high angles of attack

Methodology

- Selected Launch, Ascent, and Vehicle Aerodynamics (LAVA) solver
  - Cartesian grid paradigm with adaptive mesh refinement (AMR)
  - 5th order weighted essentially non-oscillatory (WENO5) convective flux
  - explicit 4th order Runge-Kutta (RK4) time integration with CFL ~ 0.5
- Used immersed boundary representation of geometry with slip walls
- Motor modeled with exhaust mixture and time-varying total pressure and temperature conditions inside chamber provided by contractor’s ballistics simulation (and then fixed operating point from test measurements)
- Synthetic eddy method (SEM) used to seed turbulence inside combustion chamber (turned off in later simulations)

ST1 test at Orbital ATK facility in Utah

Grid Refinement Study

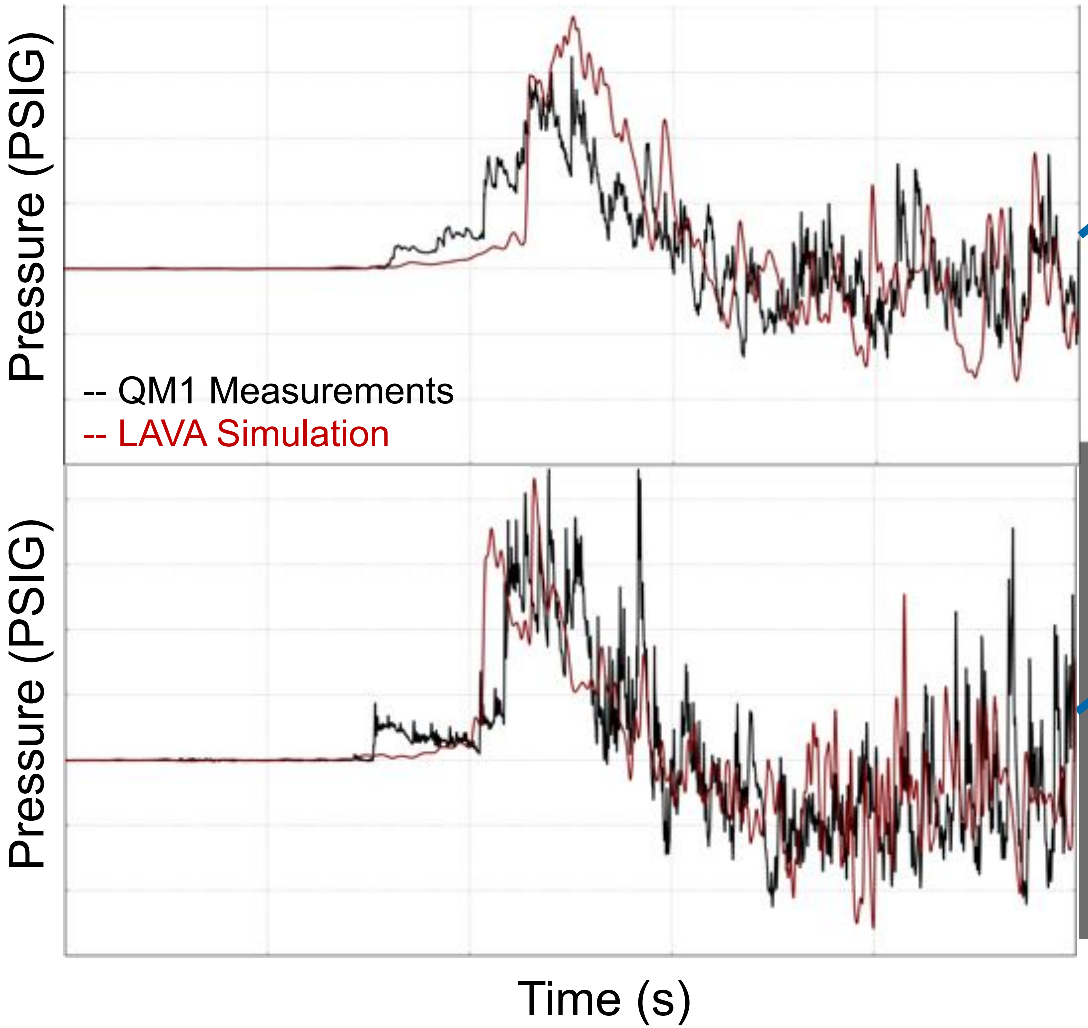
- Halved the finest grid spacing until we matched ignition over-pressure (IOP) from ST1 abort motor ground test data
- Obtained good match with ~0.02 nozzle diameters (D) cubes
- Fixed minimum mesh size on volumes around plumes and vehicle/test stand
- Used AMR with re-gridding every 10 steps (dt ~ 1.6×10^{-6} seconds) to follow regions of high vorticity and pressure gradient magnitude with a cap on number of cells per level and total of 380 million cells

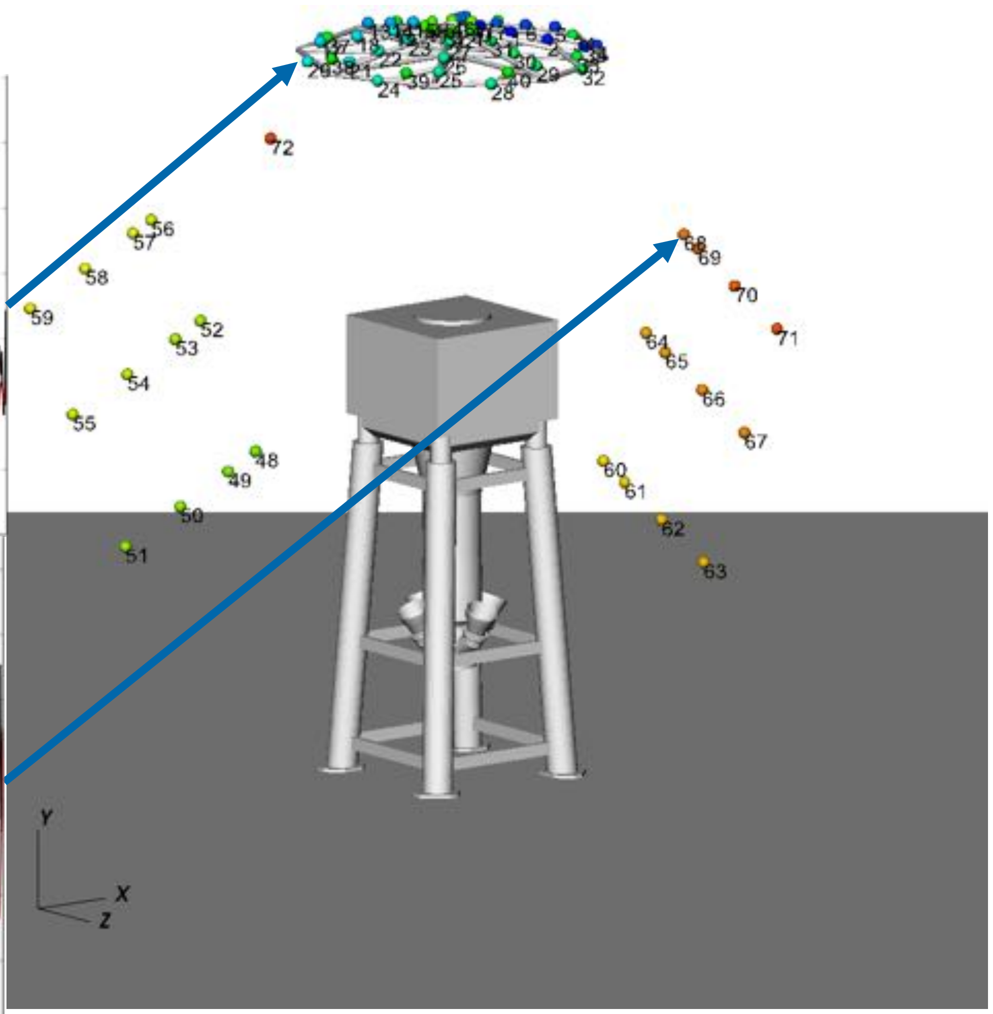
Predict Loads for QM-1 Abort Motor Test

Rendering of the Orion Launch Abort System (LAS) qualification ground test (QM1) simulated using LAVA Cartesian with adaptive mesh refinement (AMR). Video showcases the turbulent structures resolved in the plumes colored by gauge pressure. Each pixel turning from blue to white to red indicates a source of acoustic waves that can impinge on the apparatus and cause vibrations. We provided loads on heat shield fixture and crane to help test designers ensure safety of the test and reduce risk in data collection.

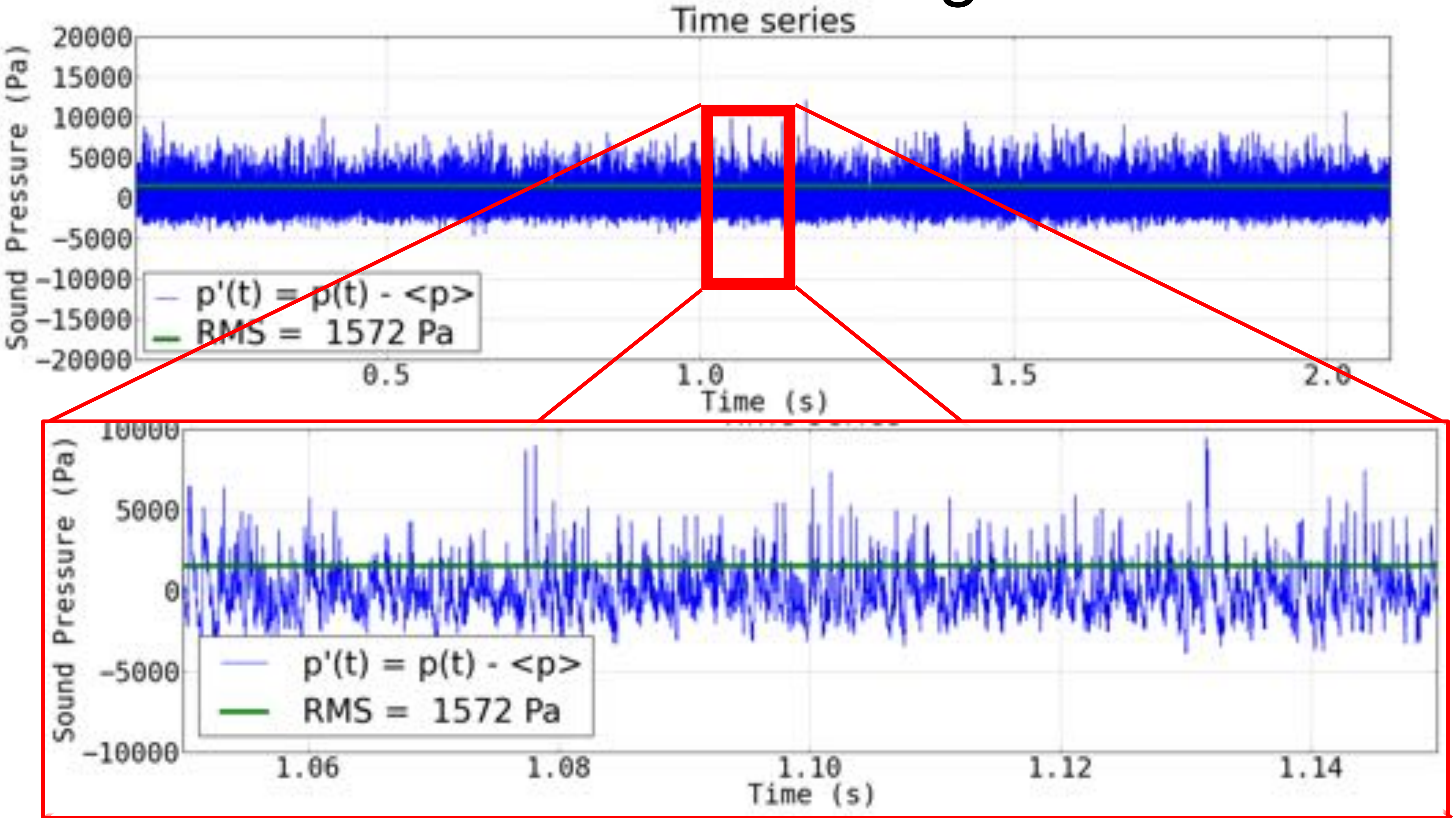
Post QM-1 Abort Motor Test Validation

Ignition Overpressure (IOP) versus Time

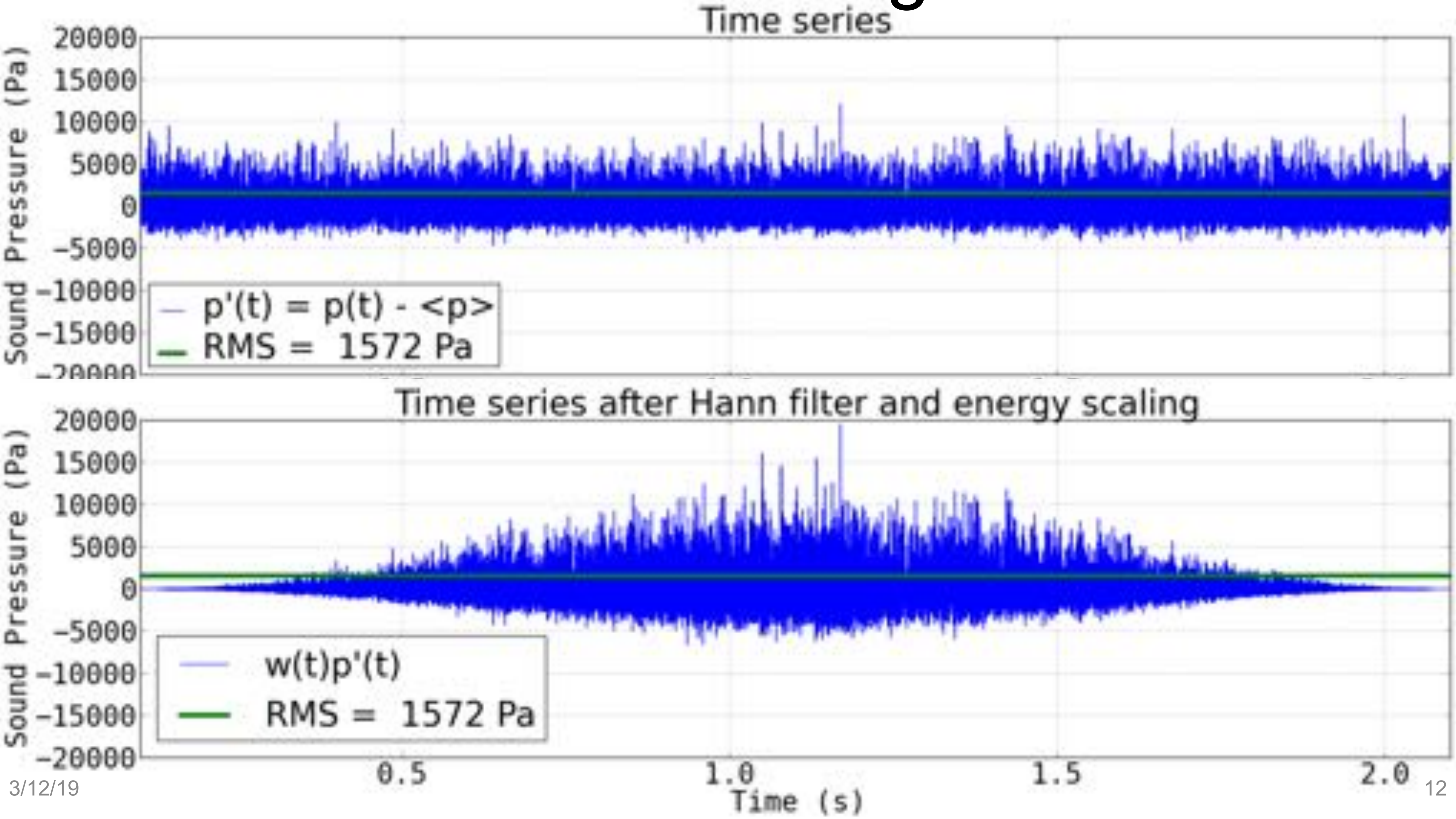




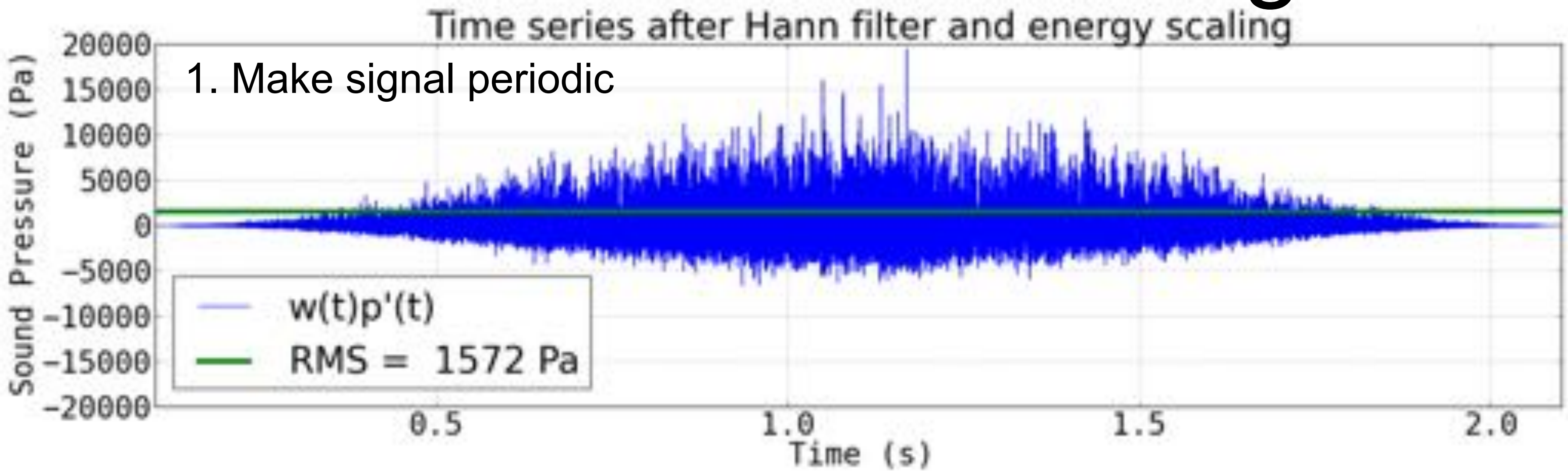
Acoustics Post-Processing



Acoustics Post-Processing



Acoustics Post-Processing

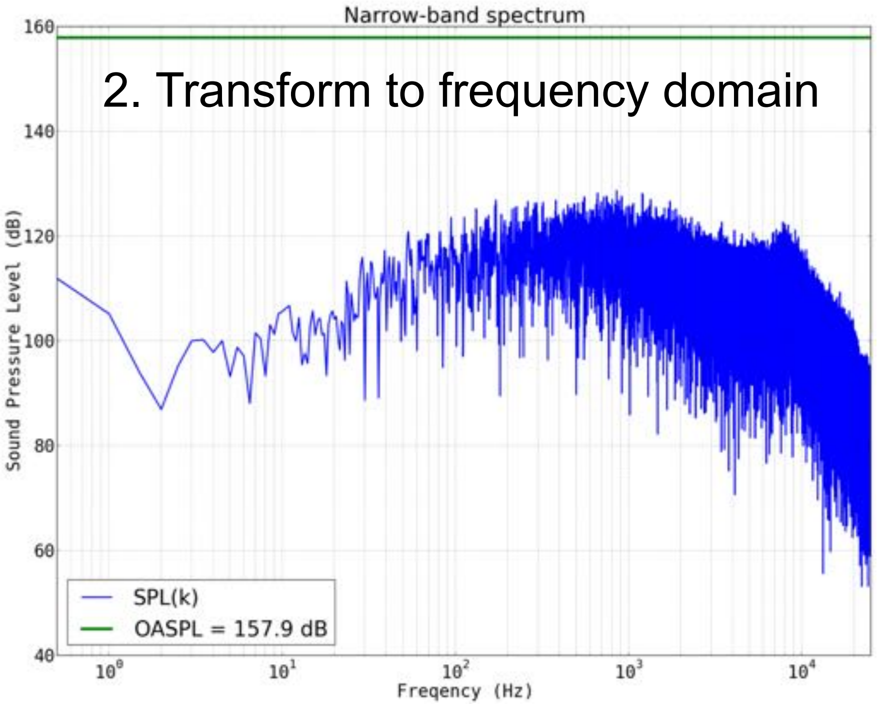


1. Make signal periodic

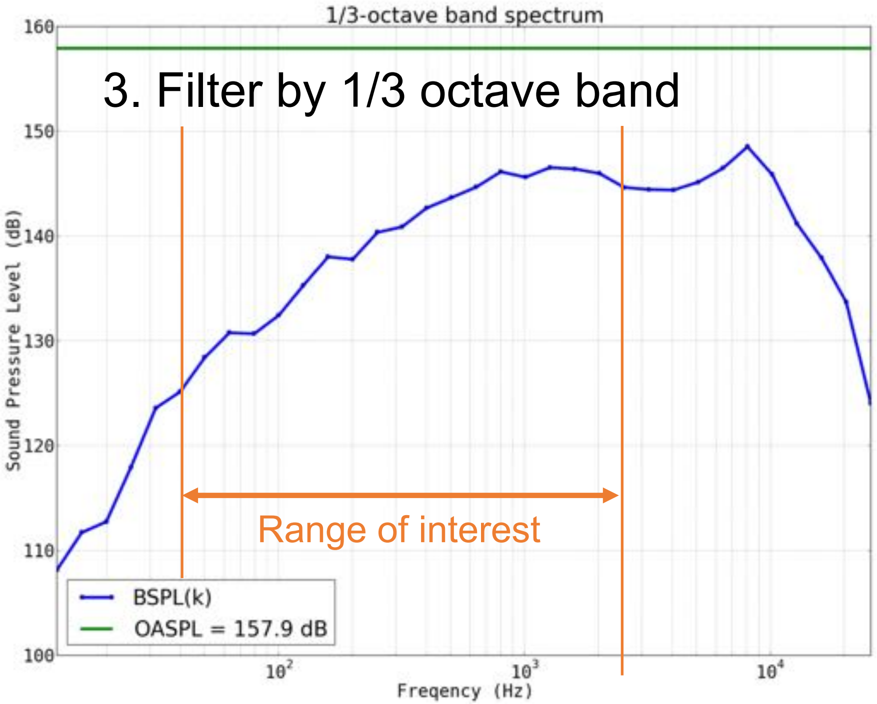
Overall Sound Pressure Level (OASPL)

$$\mathrm{OASPL} = 10 \log\left(\frac{(RMS)^2}{p_{ref}^2}\right)$$

→ OASPL = 157.9 dB



2. Transform to frequency domain



3. Filter by 1/3 octave band

$$\mathrm{SPL(k)} = 10 \log\left(\frac{P(k)\,\Delta f}{p_{ref}^2}\right)$$

$$\mathrm{BSPL}(\hat{k}) = 10 \log\left(\frac{\sum_{k=k_s(\hat{k})}^{k_e(\hat{k})} P(k)\,\Delta f}{p_{ref}^2}\right)$$

$$\mathrm{OASPL} = 10 \log\left(\frac{\sum_{k=0}^{N} P(k)\,\Delta f}{p_{ref}^2}\right)$$

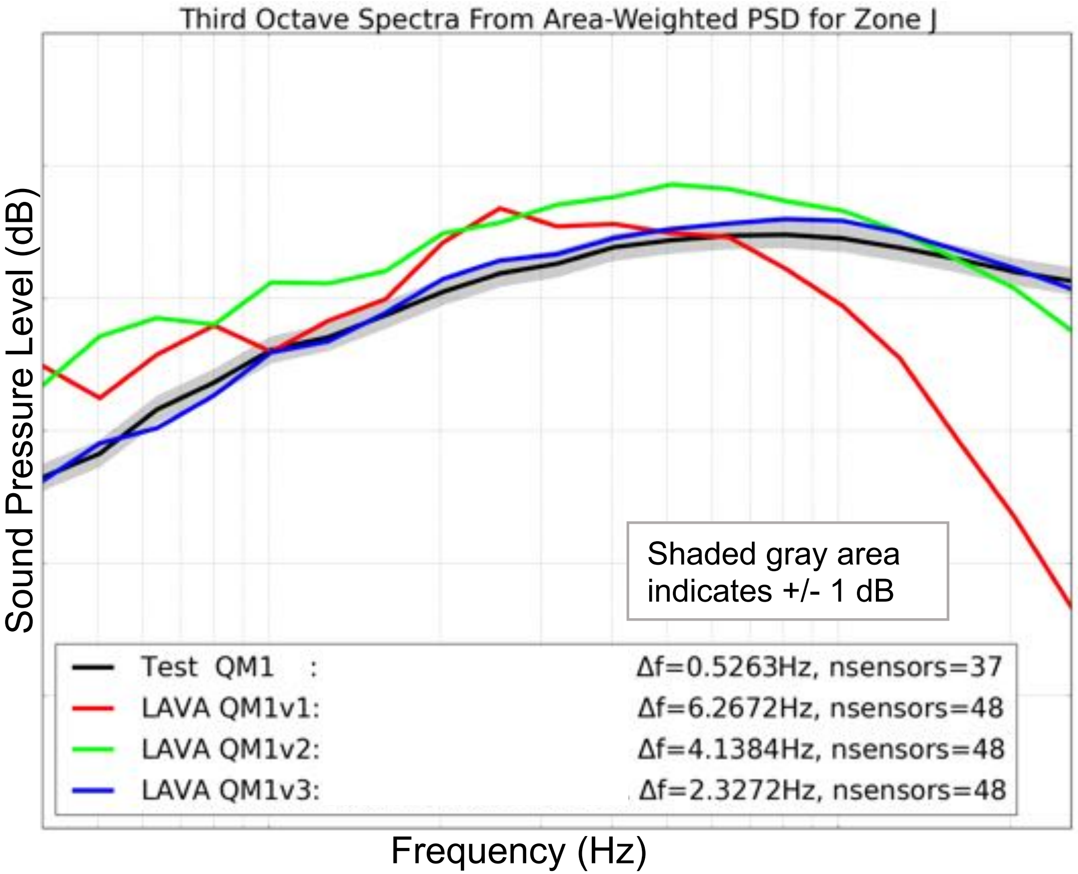
$$\mathrm{OASPL} = 10 \log\left(\frac{\sum_{\hat{k}=0}^{N} \sum_{k=k_s(\hat{k})}^{k_e(\hat{k})} P(k)\,\Delta f}{p_{ref}^2}\right)$$

where

P(k) is the power spectral density (Pa^2/Hz) at frequency k (Hz)

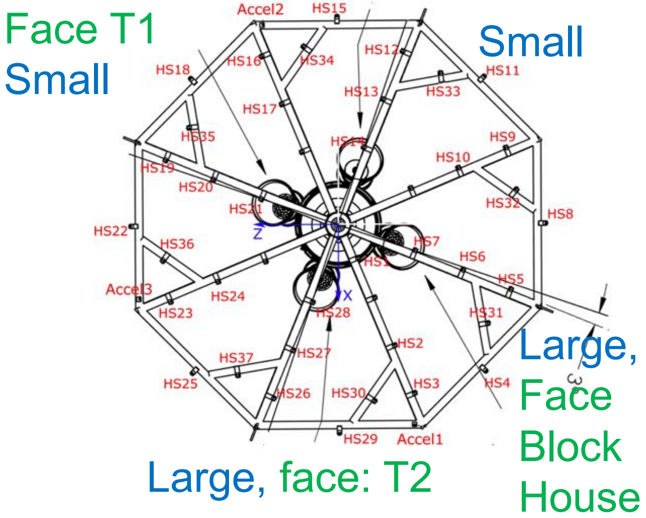
Post QM-1 Abort Motor Test Validation

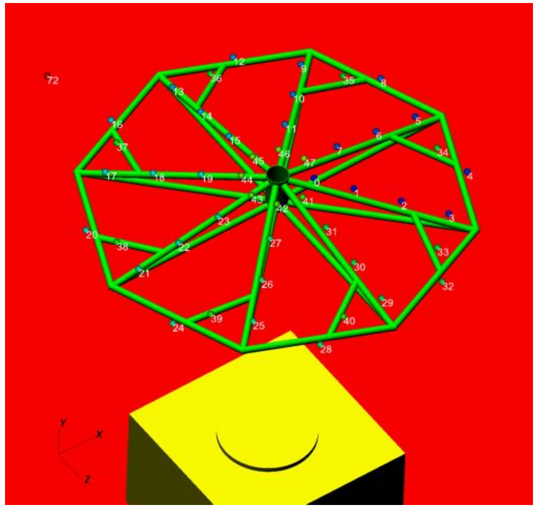
Heat Shield Area-Weighted Kulite Acoustics



- QM1v1 had insufficient resolution in heat shield region to capture content beyond 1 kHz
- QM1v2 used target thrust from ballistics as motor boundary condition (18% higher than measured in QM1 Test)
- QM1v3 used the measured thrust, improved refinement regions with no AMR, and no SEM

Heat Shield Kulite Sensors (microphones)

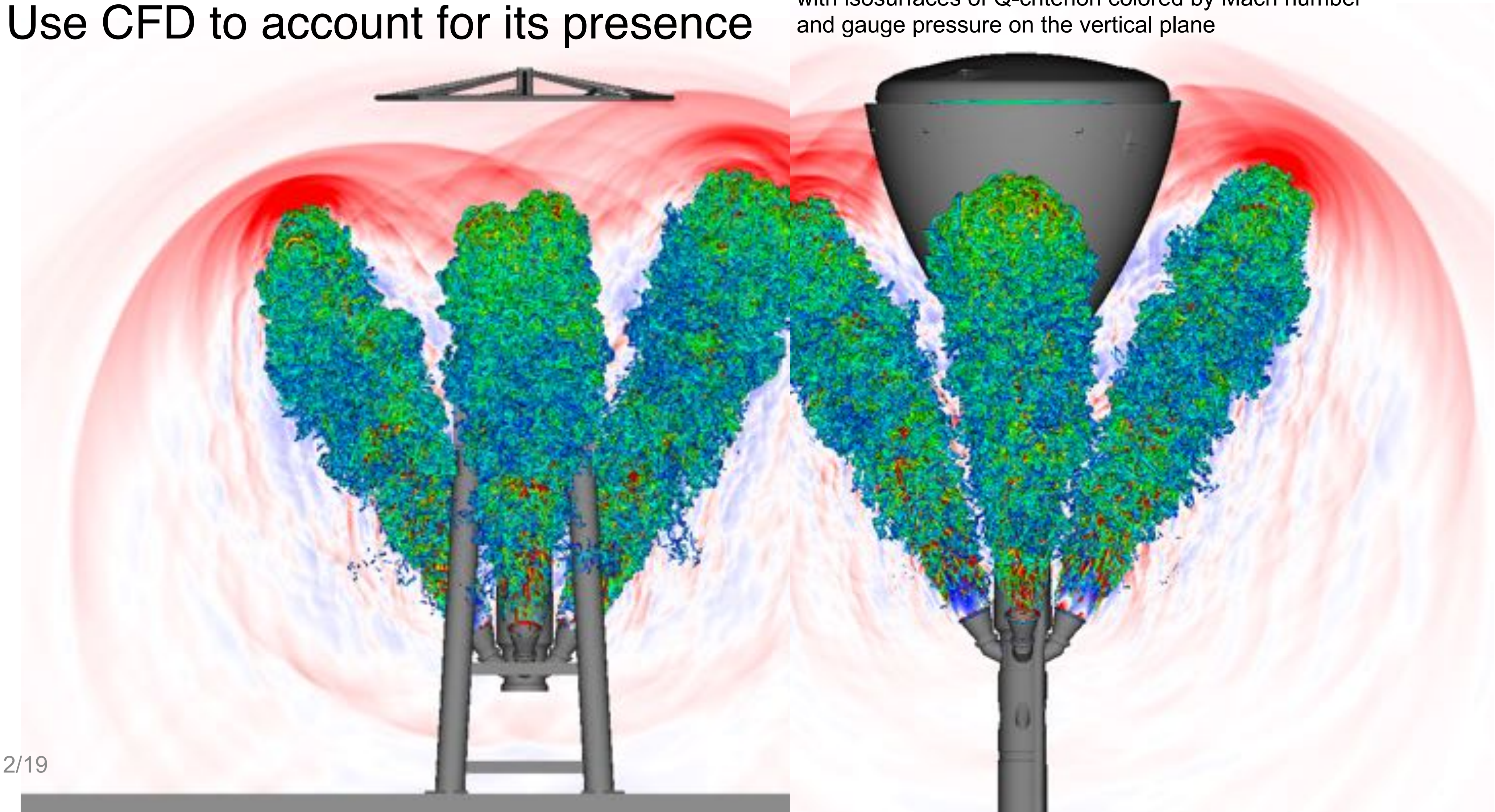




Launch Abort Vehicle Simulations

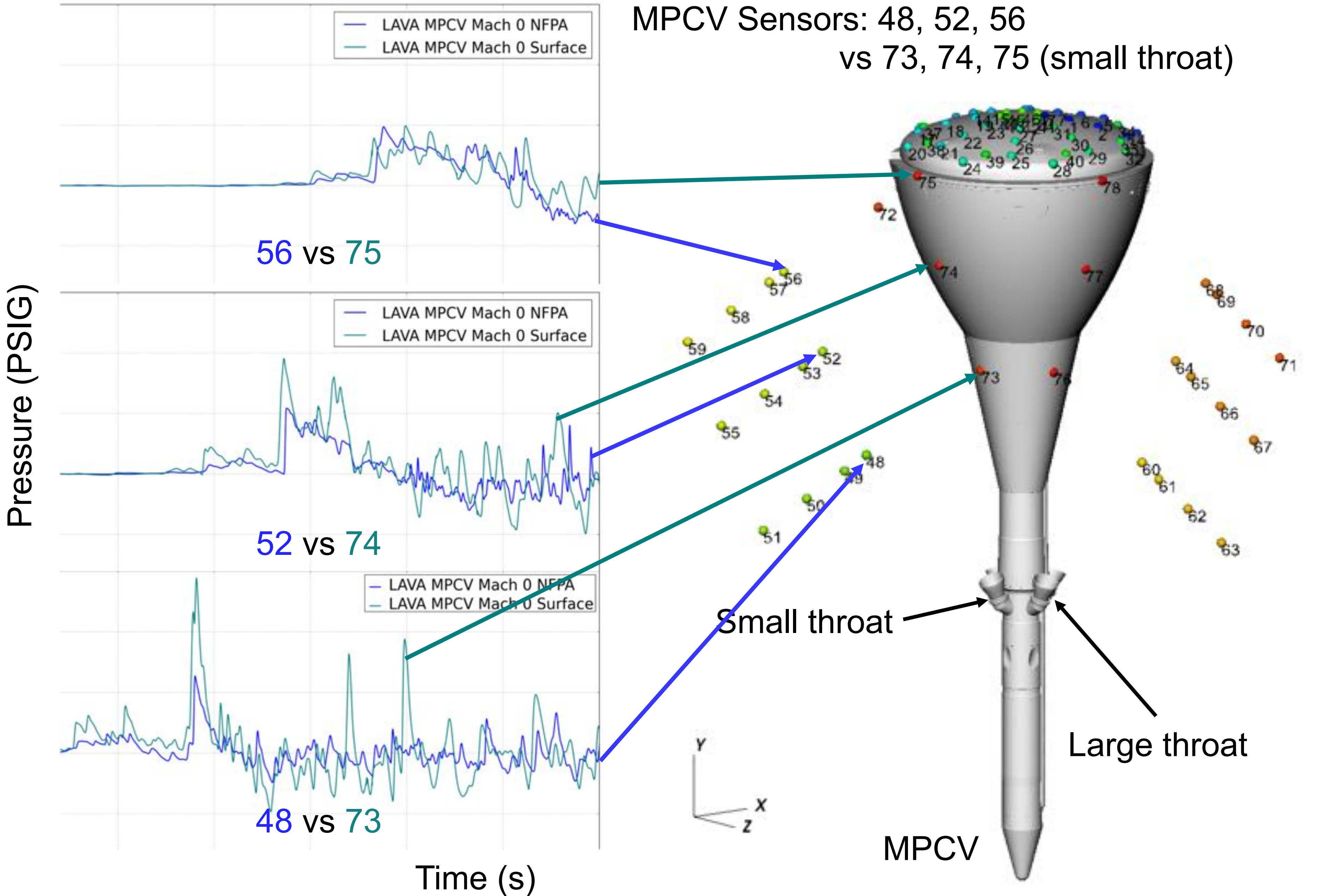
- LAV was missing from QM1 test
- Use CFD to account for its presence

Renderings of QM1 test and LAV pad abort simulations with isosurfaces of Q-criterion colored by Mach number and gauge pressure on the vertical plane



Pressure Doubling on LAV Surface

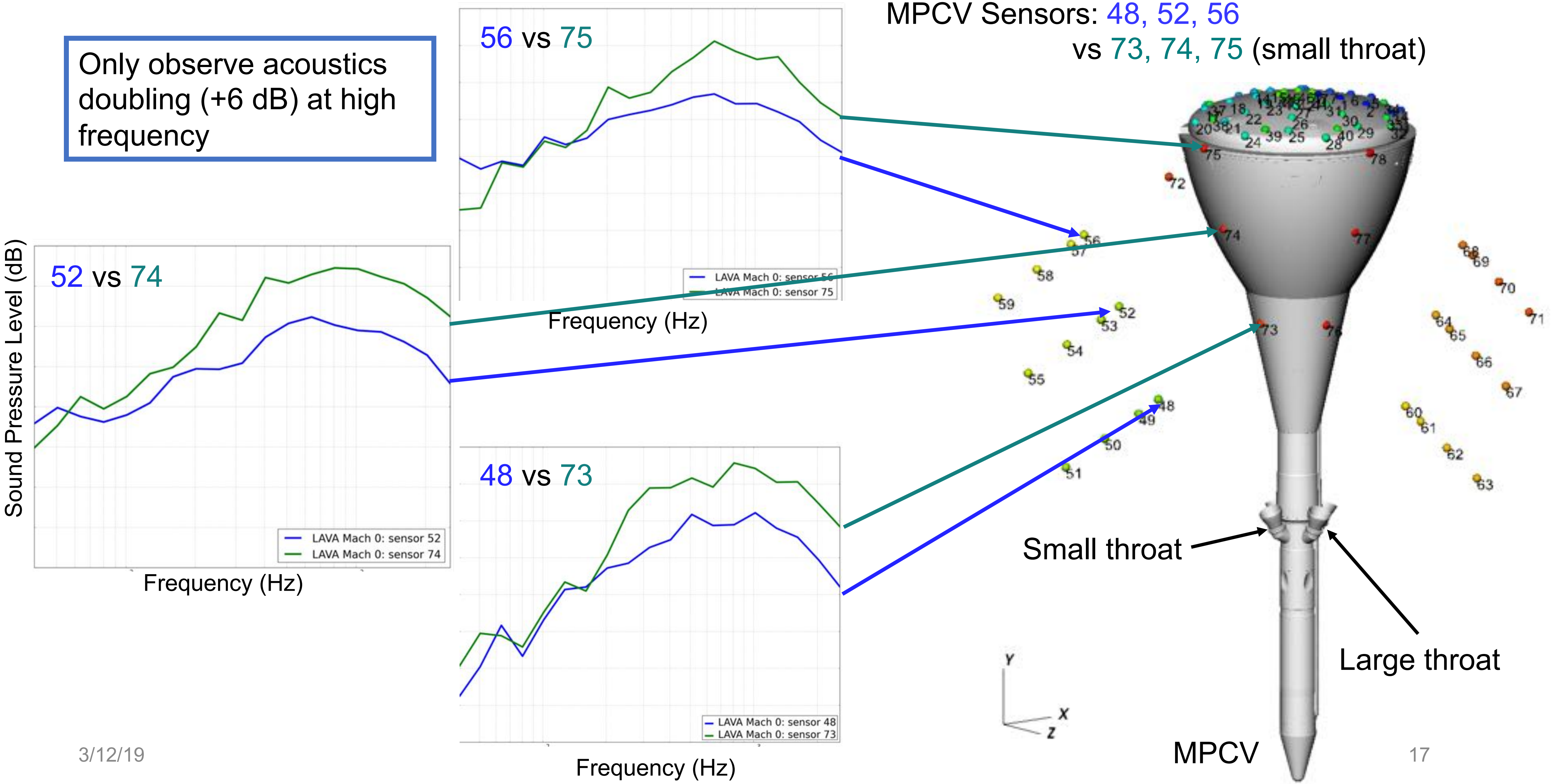
MPCV Sensors: 48, 52, 56
vs 73, 74, 75 (small throat)



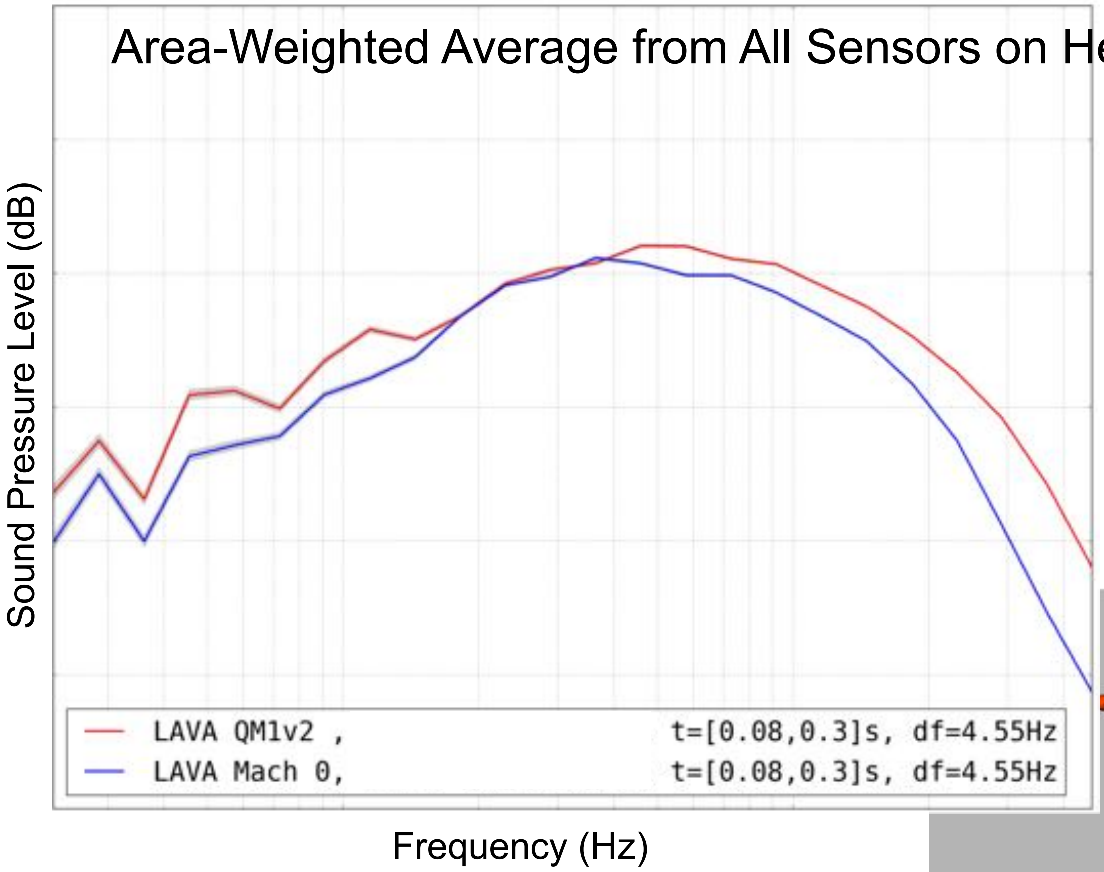
Acoustics Doubling on LAV Surface

Only observe acoustics doubling (+6 dB) at high frequency

MPCV Sensors: 48, 52, 56
vs 73, 74, 75 (small throat)



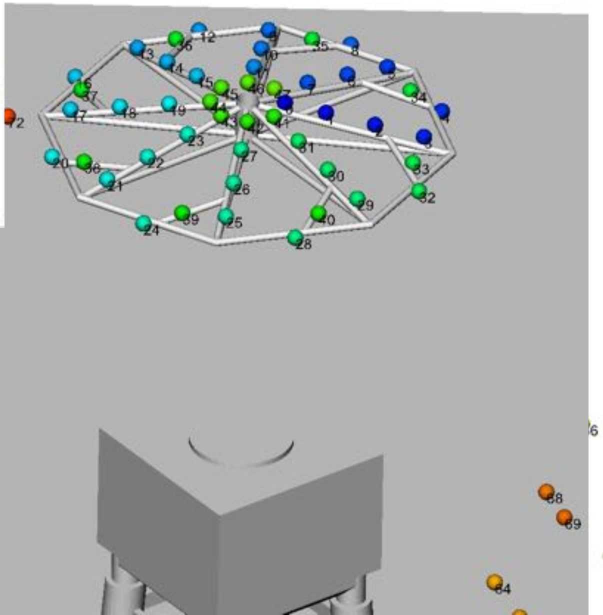
Changes in Heat Shield Acoustics



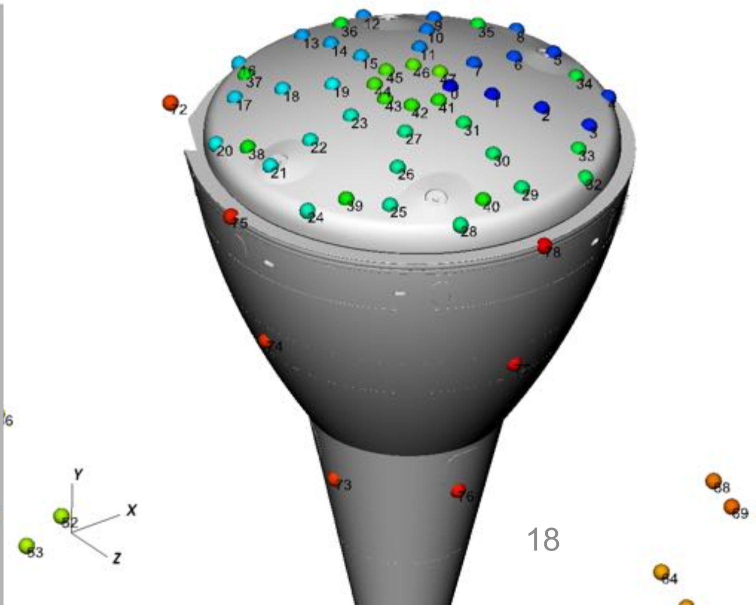
Area-Weighted Average from All Sensors on Heat Shield

Heat shield sees small reduction in levels due to shielding from the LAV

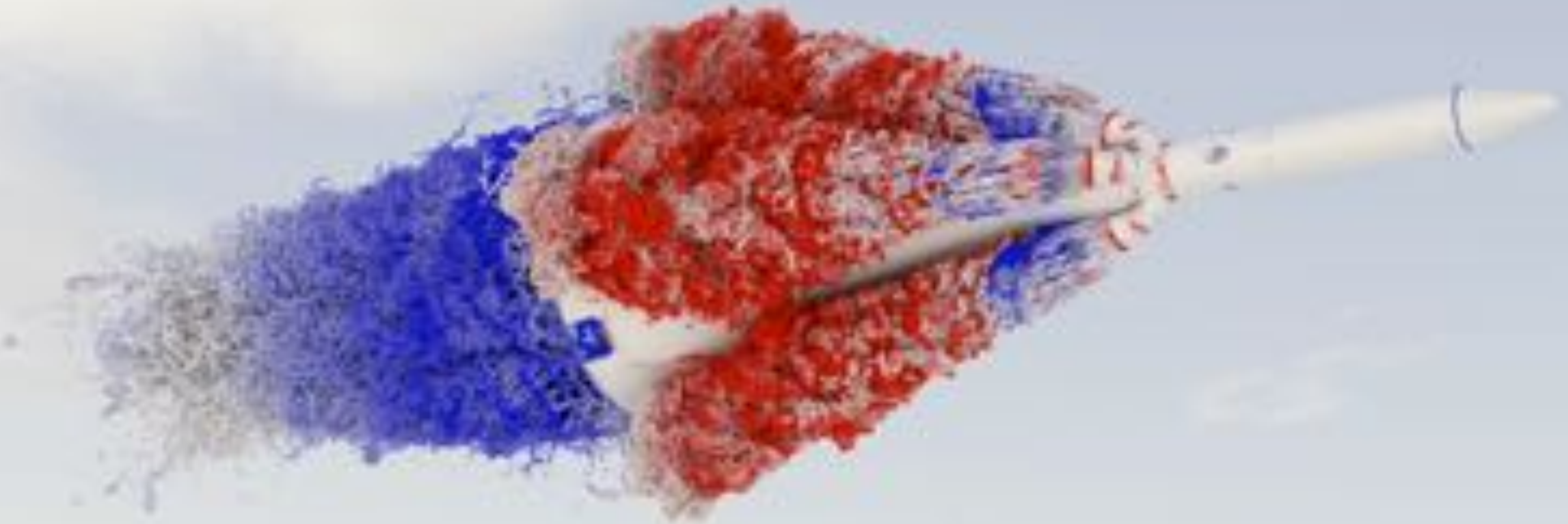
QM1



LAV Mach 0



Extrapolating From Ground Test to Flight



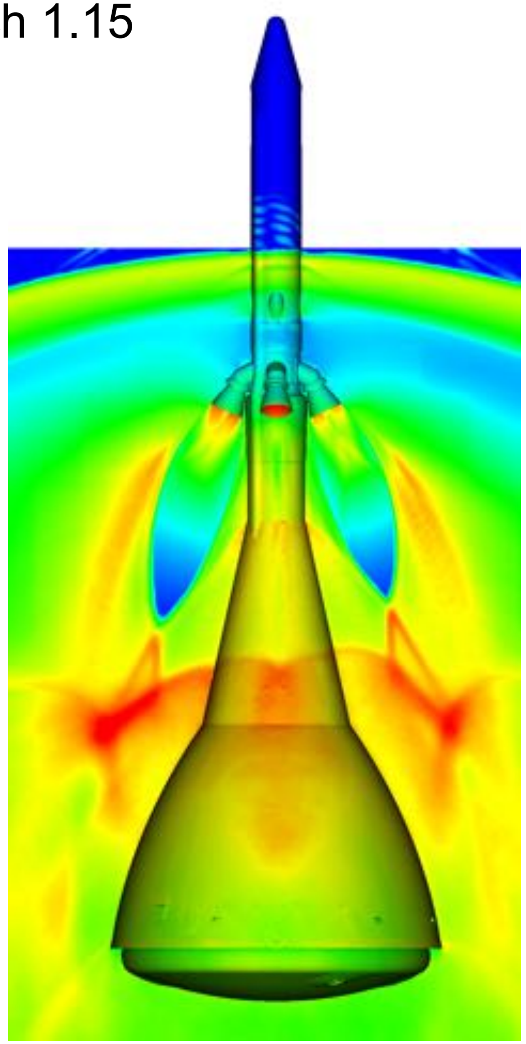
Rendering of the Orion Launch Abort Vehicle (LAV) during an ascent abort simulation where the vehicle is traveling at transonic speeds when abort is triggered. Video showcases the turbulent structures resolved in the plumes colored by gauge pressure. Each pixel turning from blue to white to red indicates a source of acoustic waves that can impinge on the apparatus and cause vibrations. The delta difference in unsteady loads between the QM-1 and LAV at different flight conditions is used to determine vehicle detailed design requirements.

Ascent Abort Scenarios

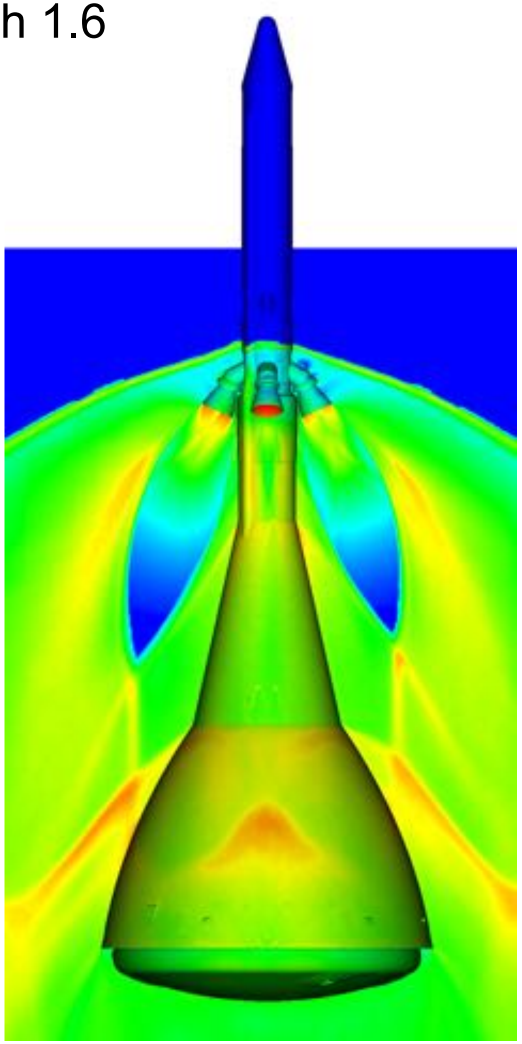
Effect of Mach Number on Overall Sound Pressure Level

Mach 0

Mach 1.15



Mach 1.6

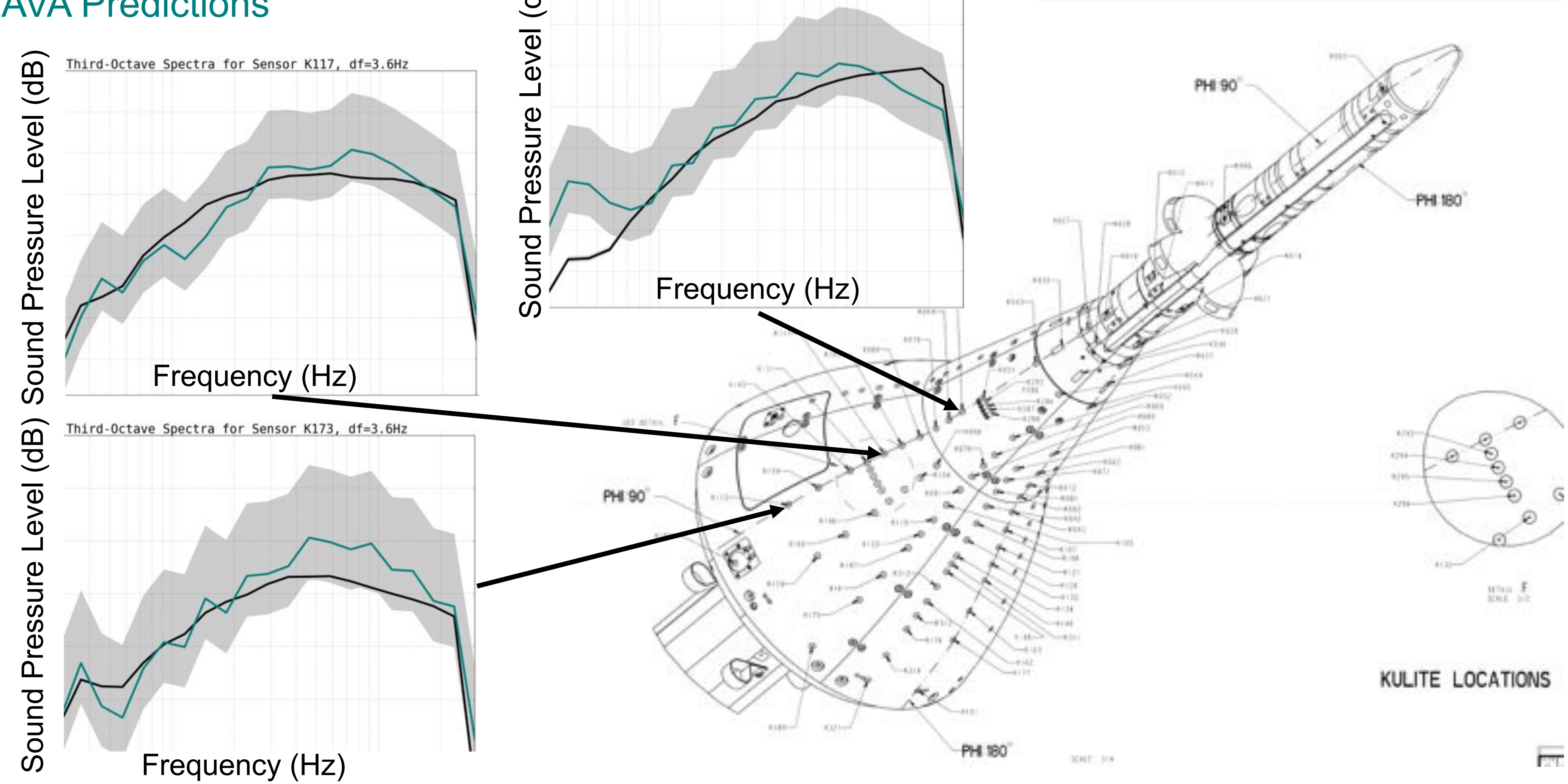


Wind Tunnel Experimental Validation

Shaded gray area indicates uncertainty in simulation results due to short integration time (0.09 s) vs experiment (5.00 s)

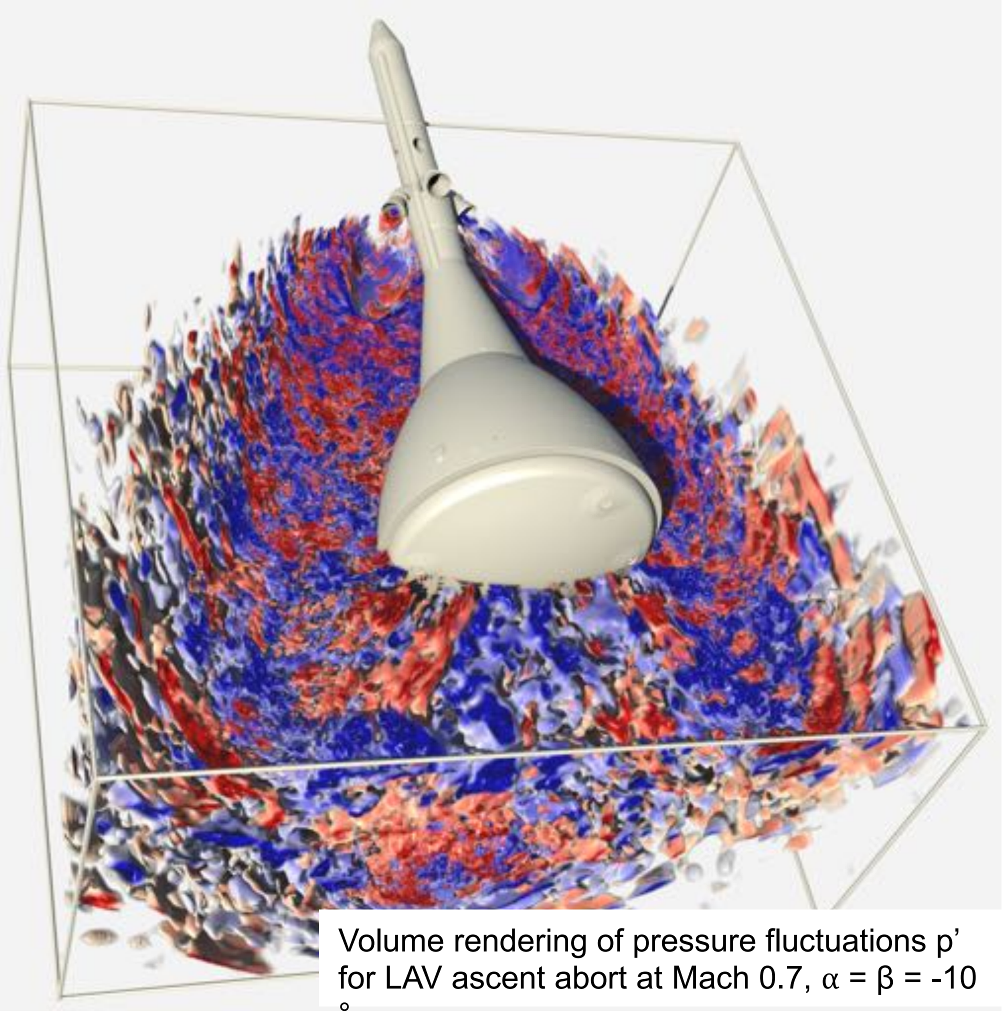
-- Wind Tunnel Measurements

-- LAVA Predictions



Acoustic Visualization Technique

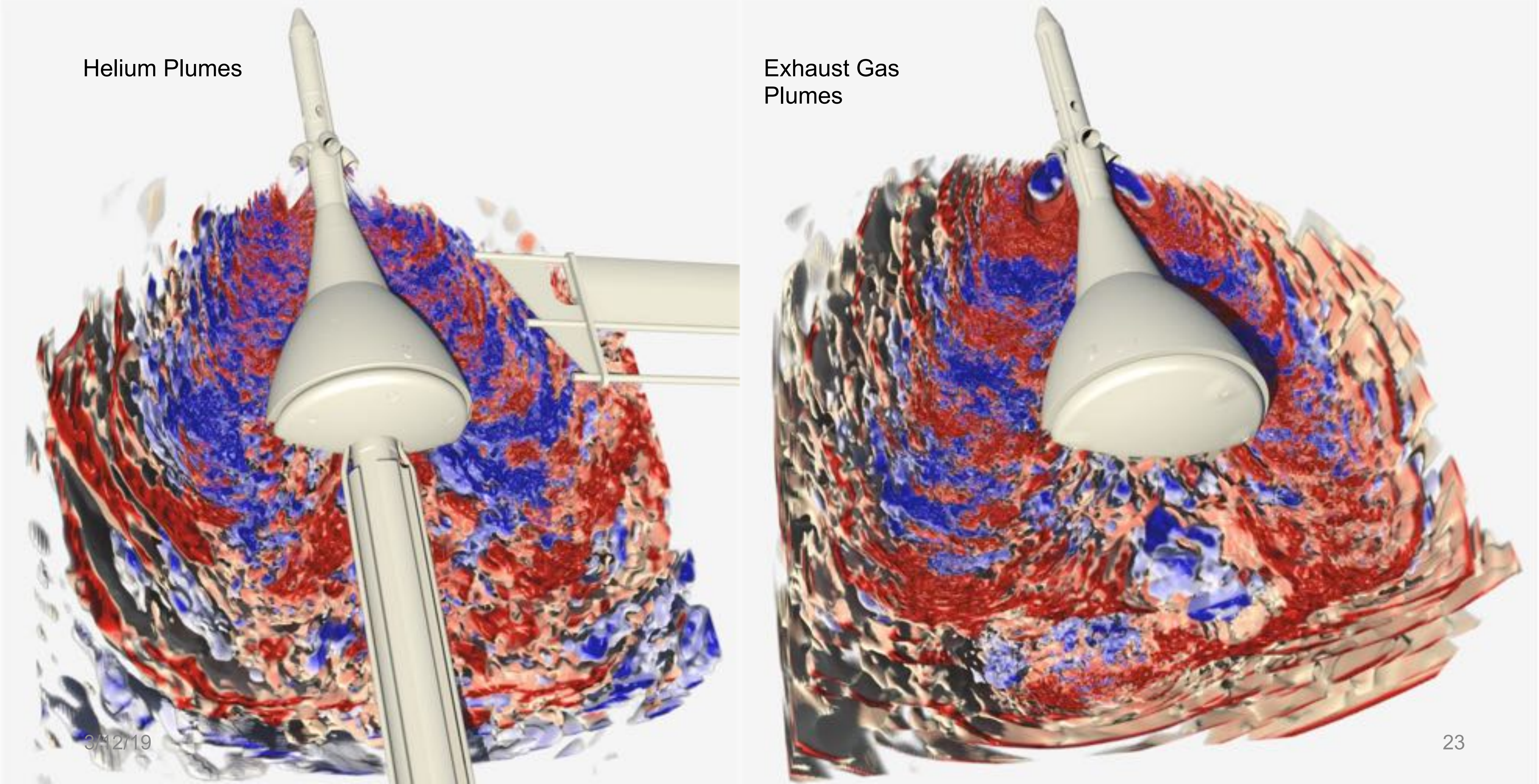
1. Interpolate pressure from adaptive-mesh-refinement solution onto evenly-spaced mesh box shown on right
2. Accumulate time average of pressure at every point on that box
3. Compute p’ = p – <p> at every point and every time step
4. Render volume of p’ using a smooth transfer function that looks like |p’|>Δp, where Δp is set by user



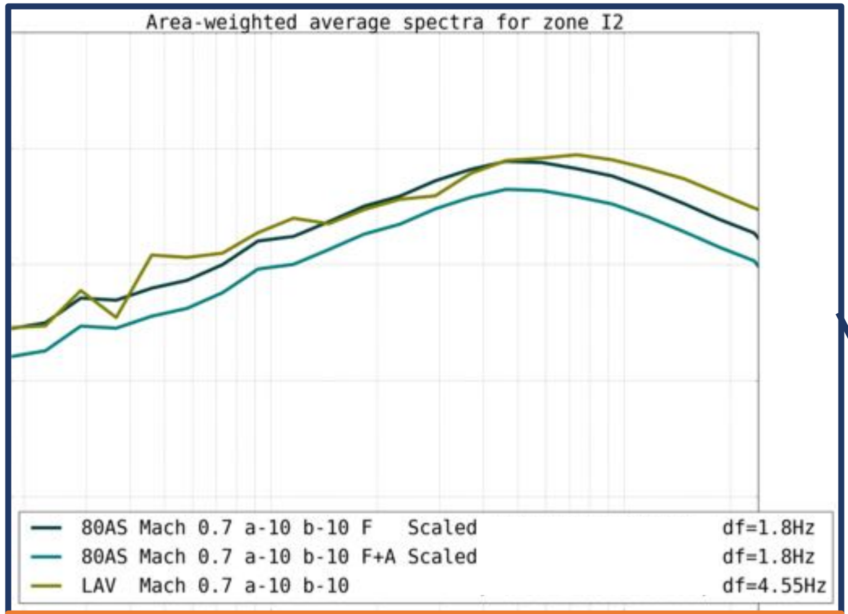
Volume rendering of pressure fluctuations p’ for LAV ascent abort at Mach 0.7, $\alpha = \beta = -10$ °

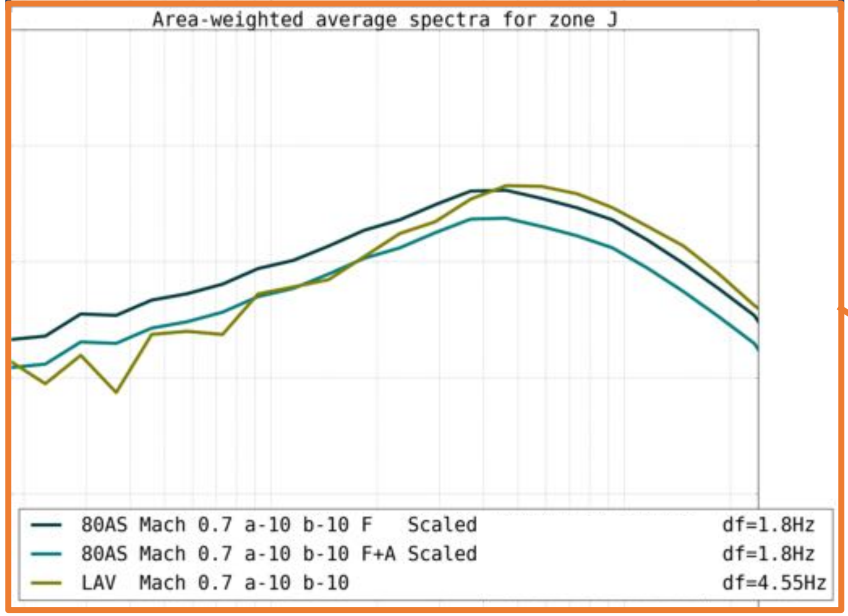
From Wind Tunnel To Flight

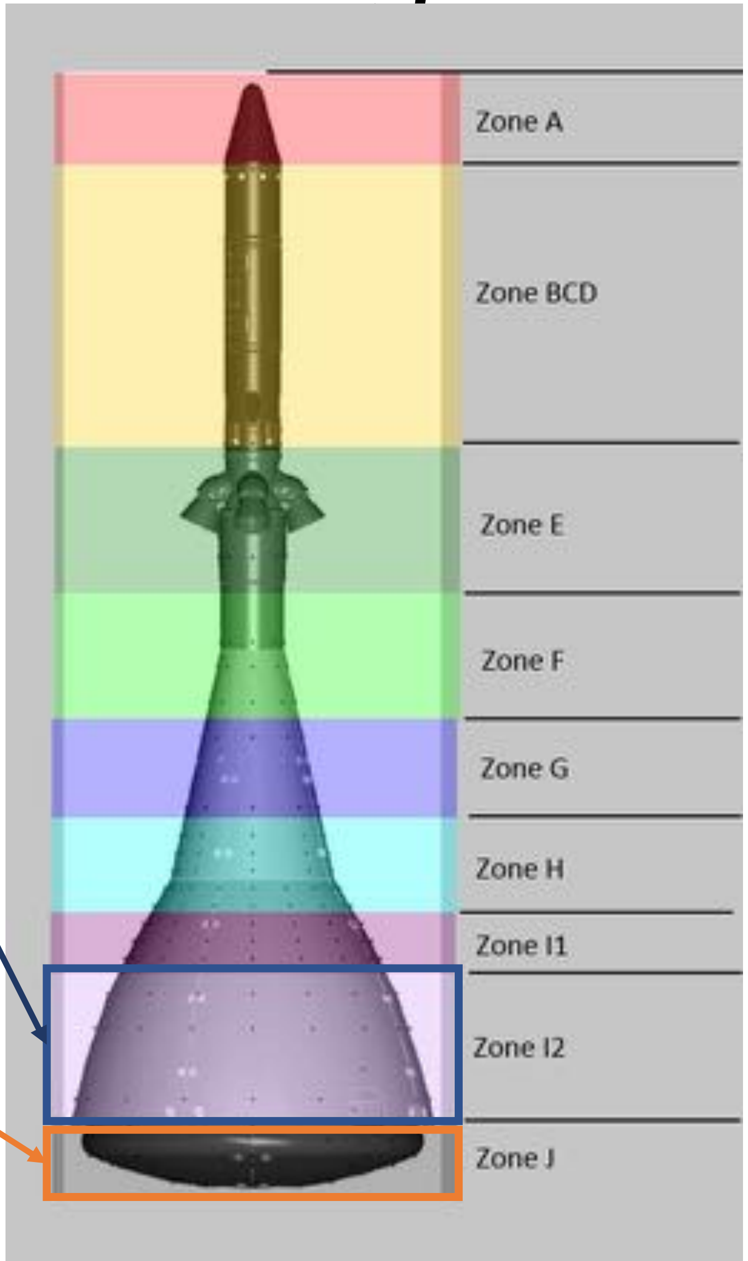
Volume rendering of p’ clipped at vertical plane for wind tunnel (left) and LAV (right) simulations for Mach 0.7, $\alpha = \beta = -10$ °



Acoustics from Wind Tunnel to Flight


Area-weighted average spectra for zone I2

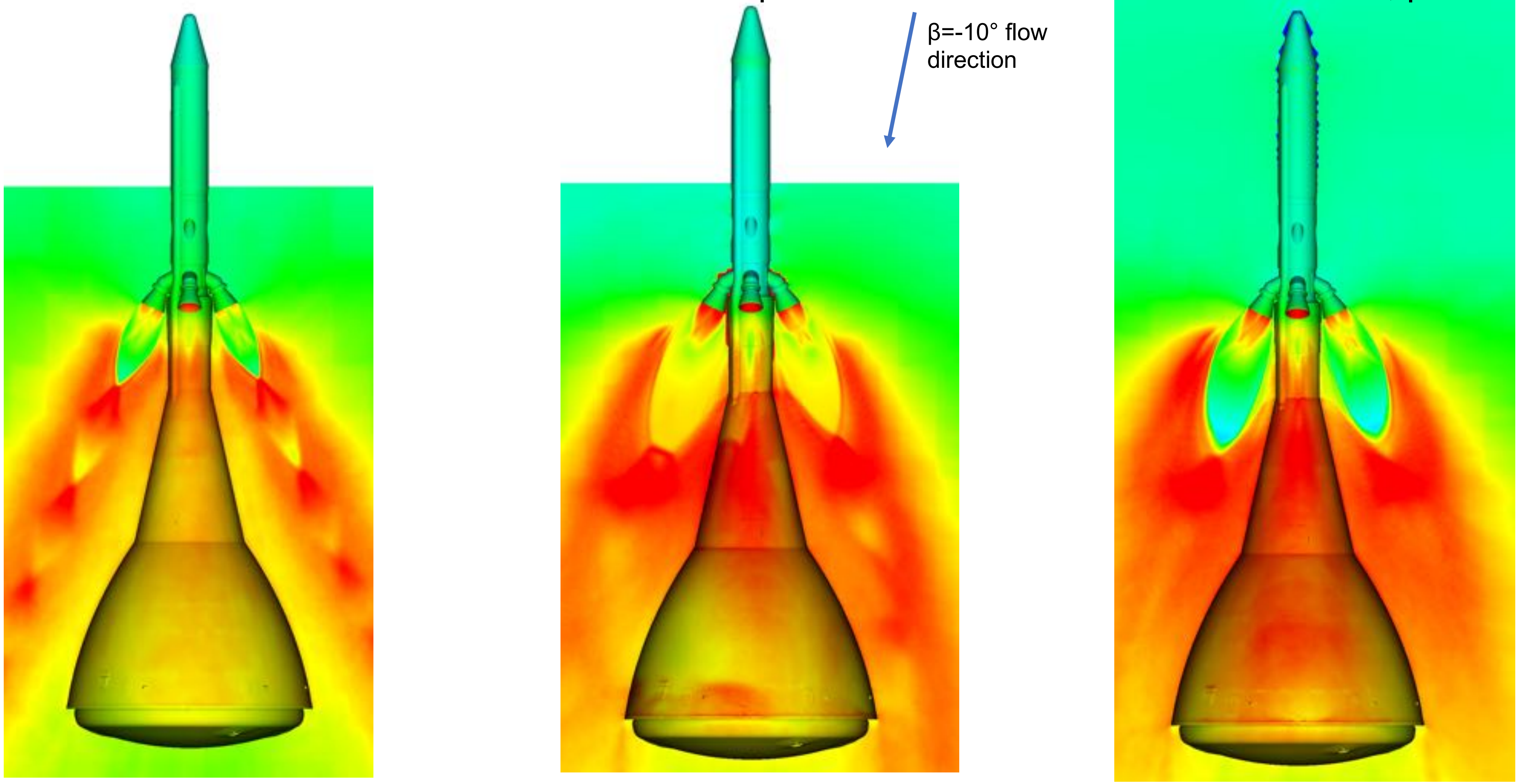

Area-weighted average spectra for zone J



Exploring High Angles of Attack

Volume rendering of temperature for LAV ascent abort at Mach 0.7, α = 20 °, β = 0 °

Effect of Angle of Attack on Acoustics



Mach 0

Mach 0.7 α=β=-10°

β=-10° flow direction

Mach 0.7 α=-20°, β=0°

Flow for α<0° is INTO the plane, β<0° is flow from right to left

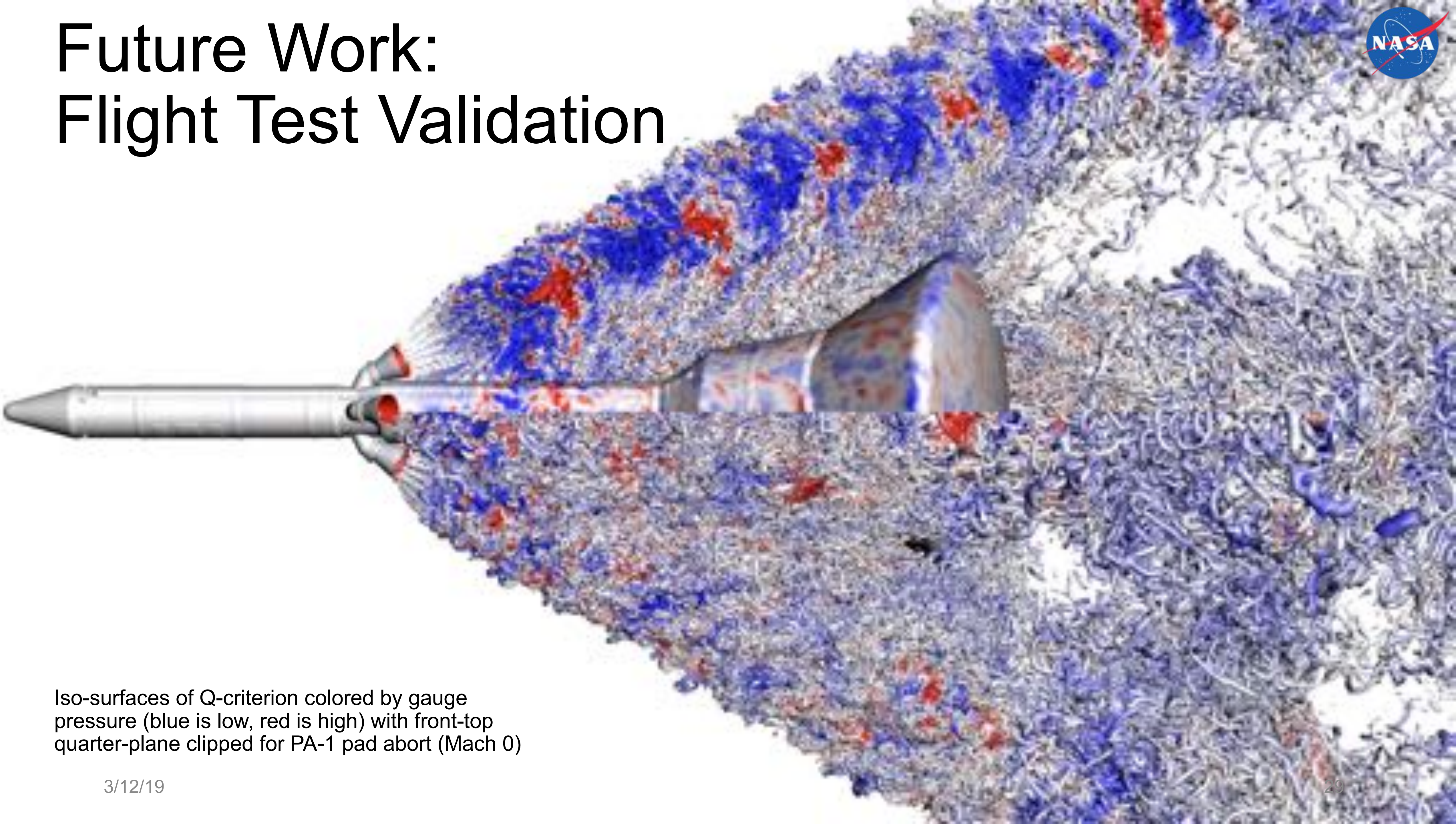
Lessons learned

- AMR has impact on turbulence spectrum and acoustics that is difficult to control and quantify → use it in initial simulation and then define fixed refinement zones
- Need finest level wherever sensors or an important surface is located and unbroken connection to source of sound, otherwise, the high frequency content is lost due to jumps in mesh resolution
- If IOP is not of interest, no point in covering it with mesh (it is harsh on CFL restriction)

Lessons learned (cont’d)

- Long time integration is key to obtaining smooth spectra that one can compare to experiments that are multiple seconds long → any algorithmic or parallel efficiency improvement that reduces turnaround time is worth implementing
- Robustness of immersed interface treatment and numerical flux is critical with Mach 3 plumes and thin nozzle lips
- Important to post-process the experimental data and CFD in the exact same way if possible to have apple-to-apples comparison, sometimes, we keep some differences intentionally but it’s important to know what the impact is on the comparisons

Future Work:
Flight Test Validation



Iso-surfaces of Q-criterion colored by gauge pressure (blue is low, red is high) with front-top quarter-plane clipped for PA-1 pad abort (Mach 0)

Summary

- Performed 10 scale-resolving simulations to support Orion Loads and Dynamics team and Orion project
- Helped enhance safety and reduce risk for QM-1 test
- Validated CFD with post-test data and wind tunnel test measurements
- Investigated effects of Mach number on acoustic environment
- Explored high angles of attack to reduce uncertainty in design process

Acknowledgements

- NASA Orion Loads and Dynamics team:
  - Quyen Jones
  - Jayanta Panda
  - Vincent Fogt
  - Kenneth Fiorelli
- NAS Visualization Team:
  - Timothy Sandstrom
- NAS Supercomputing Facility
- LAVA Team:
  - Jeffrey Housman for providing insights and lessons learned on jet acoustics

Questions?

Pressure on the vertical plane (white is high, black is low) for LAV ascent abort at Mach 0.7 $\alpha=-20°$, $\beta=0°$

APPENDIX

HPC Resources

1. Each simulation ran for roughly 30 days on 3000-4000 cores
2. Each simulation creates roughly 100 TB of volume data, and 100 GB of surface data (vehicle and cut planes)
3. Could use more cores for faster turnaround time, but beyond 5000 cores we start to see diminishing efficiency due to too few points per core
4. Actively working to refactor code to increase parallel efficiency and strong scaling

LAVA Simulations

Run status

Case	Current Duration [s]	Acoustics Interval [s]	Currently running?
QM1v1	0.2280	0.148	no
LAV Mach 0	0.5020	0.422	no
LAV Mach 1.15	0.3730	0.293	no
LAV Mach 1.6	0.3220	0.242	no
QM1v2	0.3210	0.241	no
LAV Mach 0.7 α=-10, β=-10	0.3700	0.290	no
80-AS Mach 0.7 α=-10, β=-10	0.090*	~0.60*	no
LAV Mach 0.7 α=20, β=0	0.3410	0.261	no
QM1v3	0.5235	0.430	no
PA-1 Mach 0	0.5953	0.476	no

*With plume scaling, we have ~0.6 seconds of “flight” data

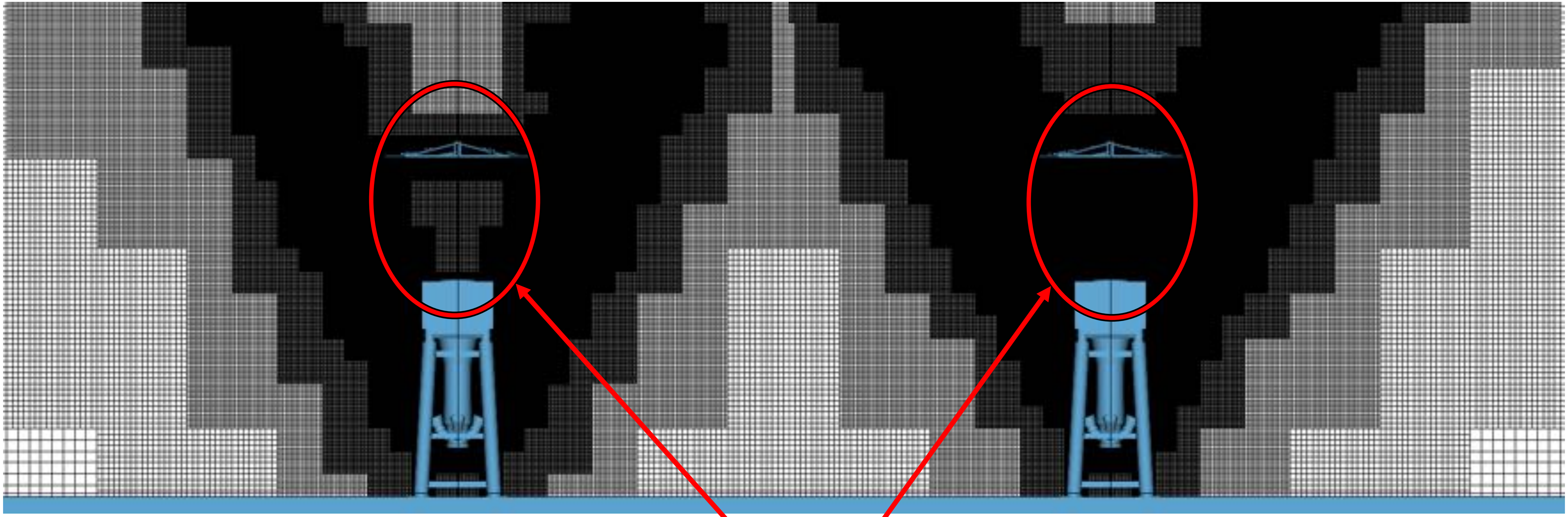
LAVA Simulations

Numerical Methodology

Parameter	Previous	Latest	Benefit
Convective flux	5th order WENO	5th order WENO	-
Time integration	Explicit 4th order Runge-Kutta	Explicit 4th order Runge-Kutta	-
Time step	Fixed Courant Friedrichs Lewy number (CFL) = 0.5 → dt ~ 1.6×10^{-6} seconds	Fixed Time Step dt ~ 1.6×10^{-6} seconds → CFL ~ 0.5	-
Inter-level time integration	Composite: all levels of the mesh are updated at each step, with the same dt	Subcycled: only finest mesh level is updated at each step, the next finest is updated every other step with a dt twice as large	Better parallel efficiency & scaling (faster)
Adaptive Mesh Refinement (AMR)	Grid is adjusted every 10 steps to follow vorticity and pressure gradients	None – grid is user-defined	No re-gridding overhead, better capture turbulent pressure fluctuations
Total mesh size ($\times 10^6$)	~350	600-800	Similar resources and turnaround time
Motor Boundary Condition	Time-varying total conditions from ballistics (including IOP)	Fixed total conditions from experiment at 0.2 seconds	Faster to reach stationary state (reduces turnaround time)
Synthetic Eddy Method	Turbulence injected upstream of splitter (SEM)	None	No spurious noise near nozzles

LAVA Simulations

Numerical Methodology



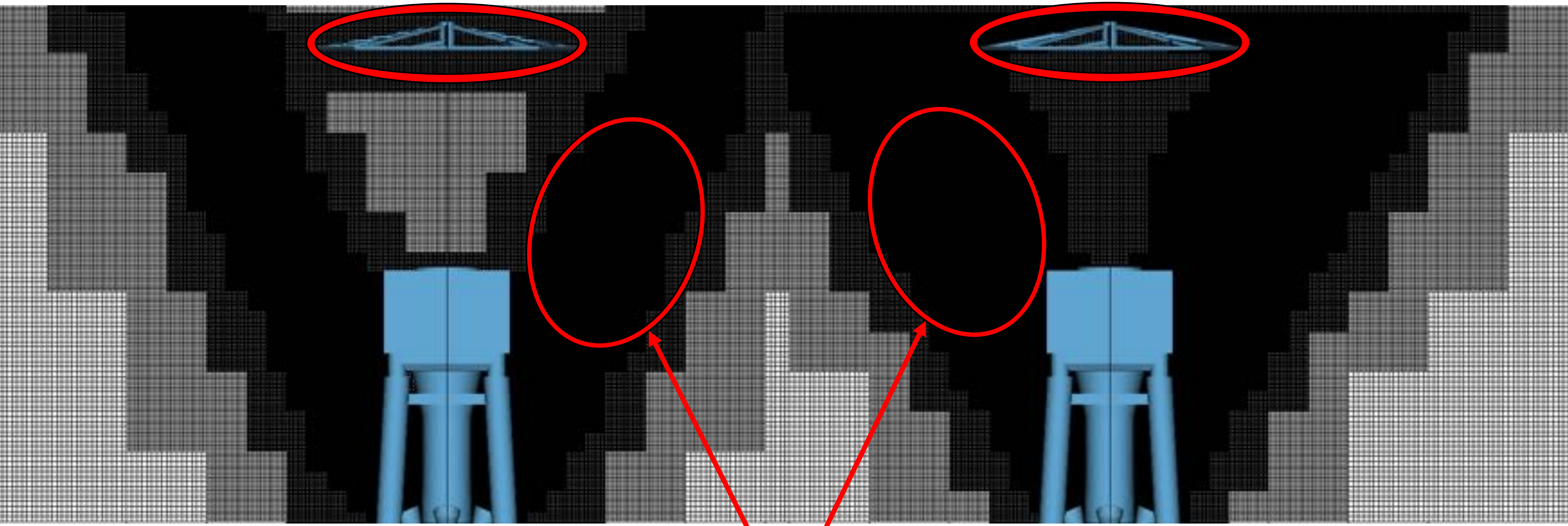
AMR Adapted grid from QM1v2

Fixed grid from QM1v3

Filled in region below and around heat shield with finer mesh

LAVA Simulations

Numerical Methodology



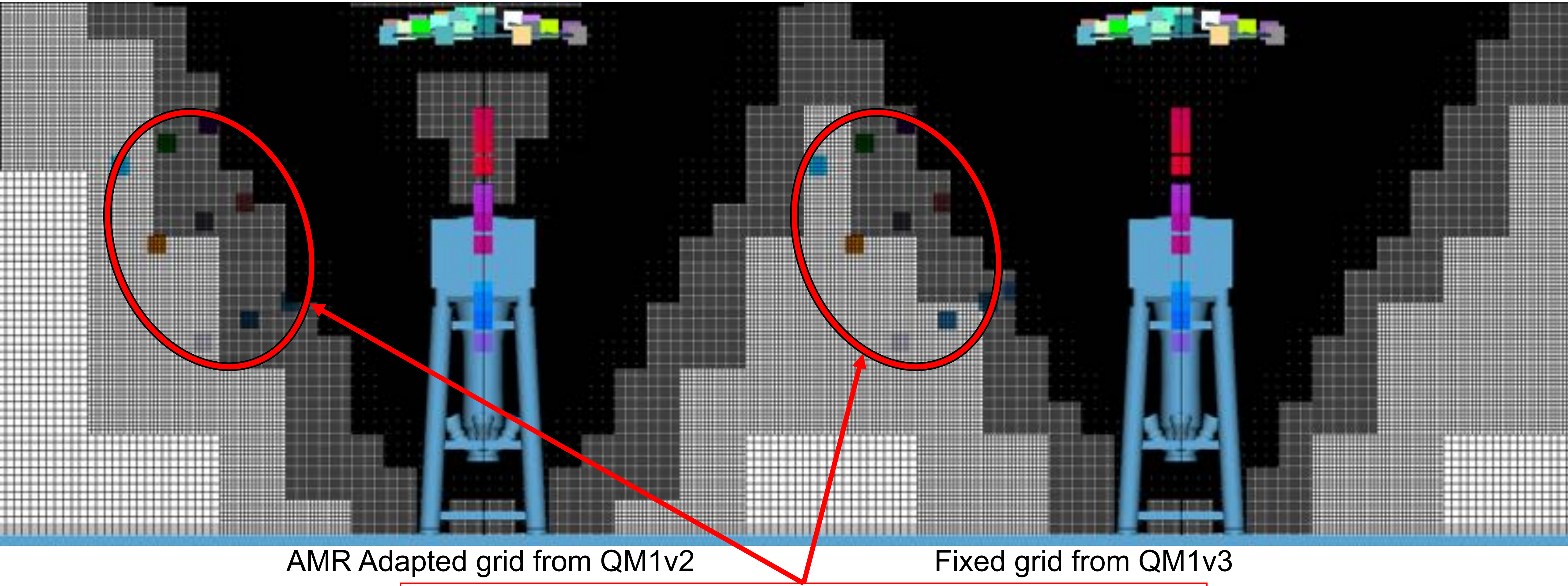
AMR Adapted grid from QM1v2

Fixed grid from QM1v3

Larger region of fine mesh around plume and heat shield

LAVA Simulations

Numerical Methodology



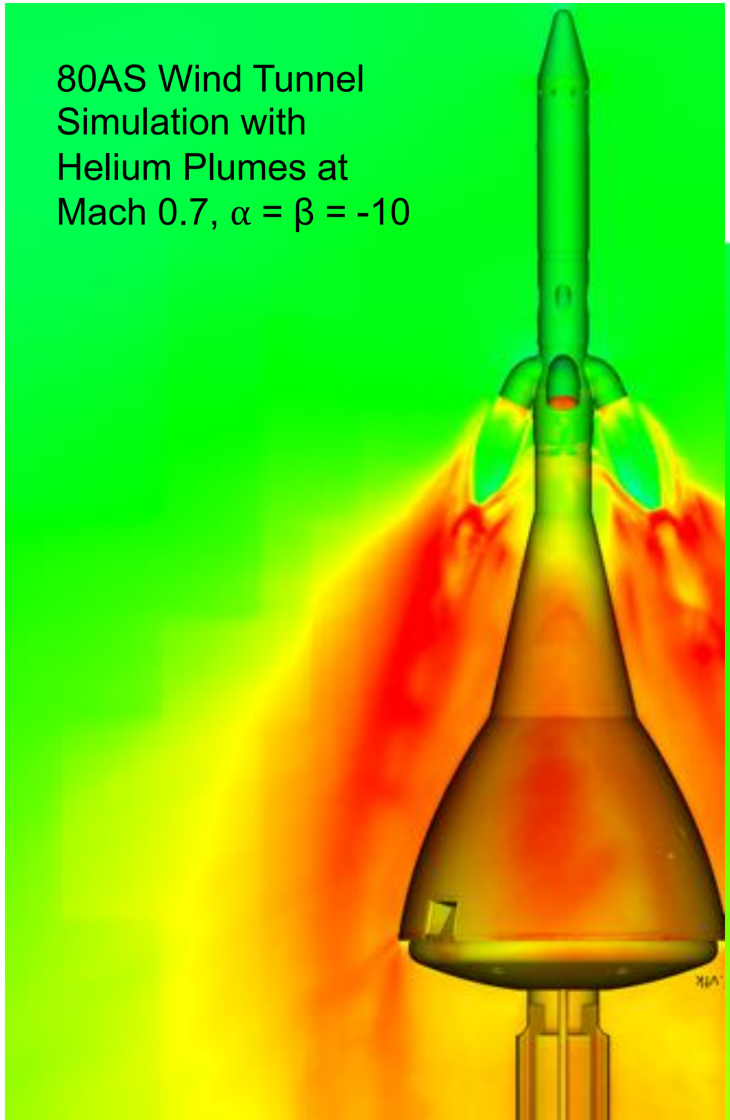
AMR Adapted grid from QM1v2

Fixed grid from QM1v3

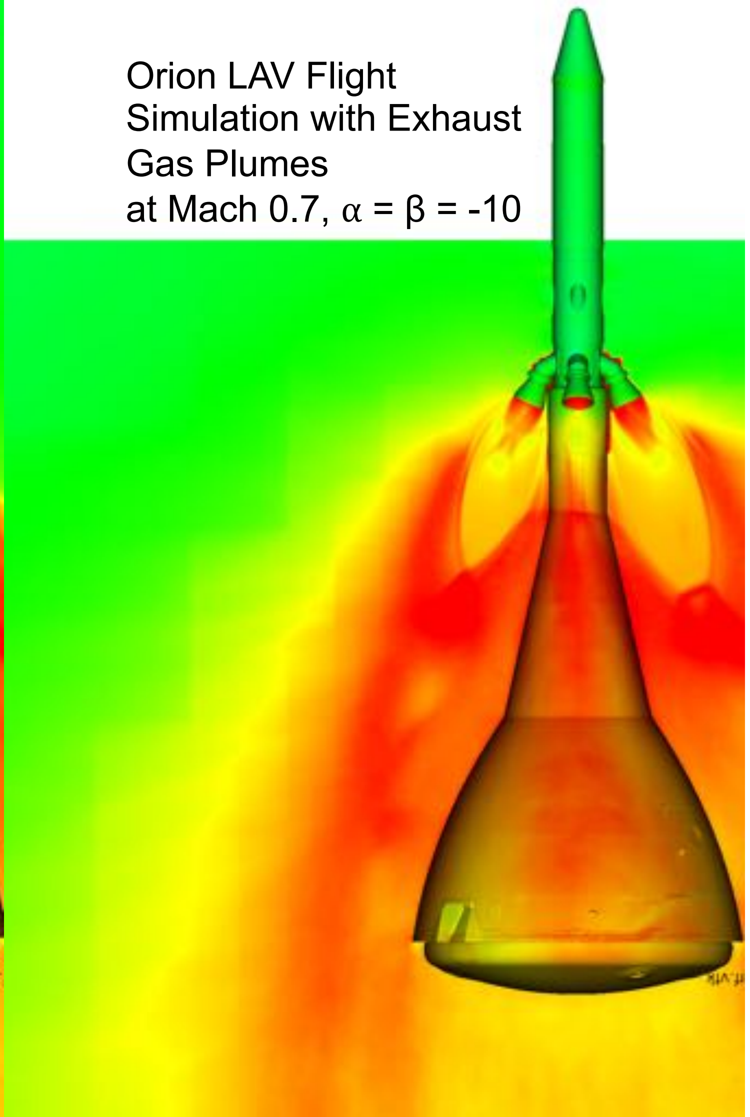
But NFPA sensors and inner ring heat shield sensors are still not all covered by finest mesh
→ reduces max freq resolved by factor of 2 for those sensors

From Wind Tunnel To Flight

Overall Sound Pressure Level



80AS Wind Tunnel
Simulation with
Helium Plumes at
Mach 0.7, α = β = -10



Orion LAV Flight
Simulation with Exhaust
Gas Plumes
at Mach 0.7, α = β = -10