Predicting Orion Pad Abort Vibrations to Keep Astronauts Safe

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Snapshot from a simulation of the Orion launch abort vehicle pad abort 1 flight test. Passive particles are seeded at the nozzles and colored by velocity magnitude: white is fast, dark orange is slow.

Image Credit: Timothy Sandstrom

National Aeronautics and Space Administration

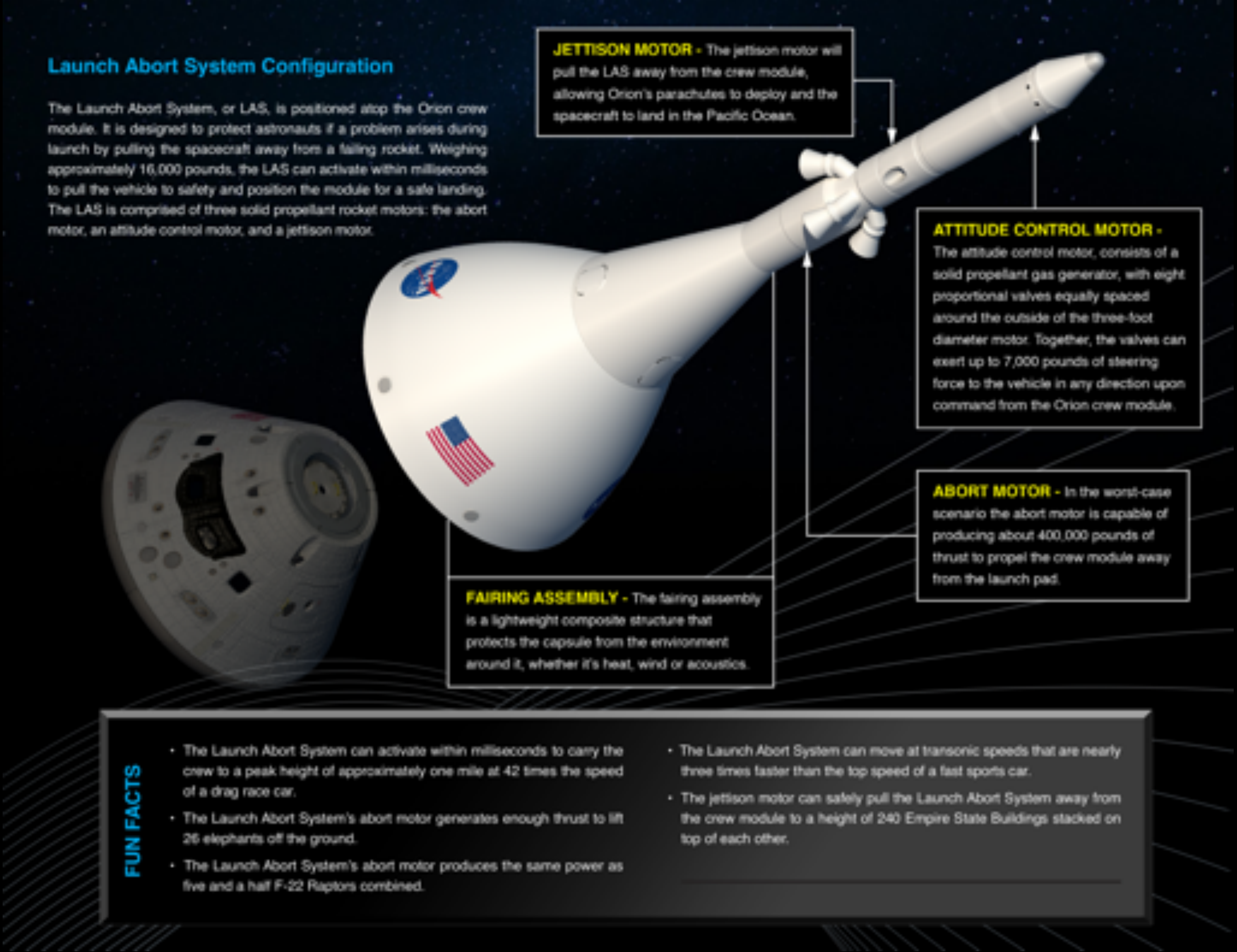
ORION

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

- Perform computational fluid dynamics (CFD) simulations to predict Orion LAS surface vibrations for various abort scenarios

- Collaborate with the Orion Loads and Dynamics team to validate CFD and combine with wind tunnel, ground and flight test data to reduce uncertainty

- Impact the fairing assembly design:
  - Reduce risk of structural failure due to vibrations
  - Minimize structural weight

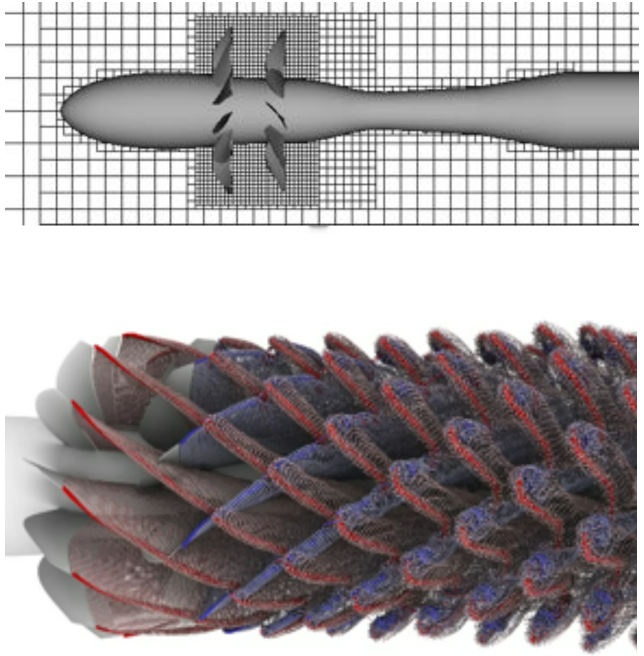
Initial Project Requirements

Predict transient pressure loads and acoustics on the apparatus ahead of the Qualification Motor 1 (QM-1) ground test to ensure the safety of the test and reduce risk in data collection

Picture Credit: Jayanta Panda

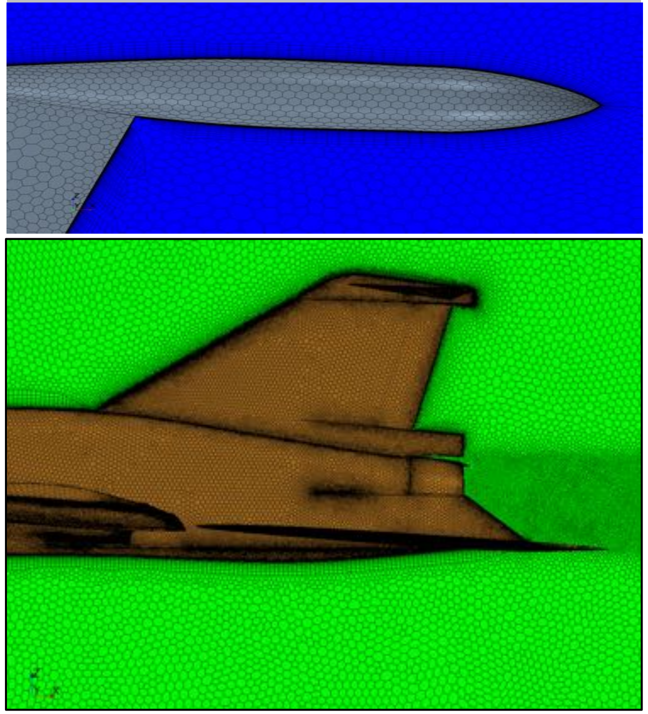
CFD Grid Paradigms

Structured Cartesian AMR



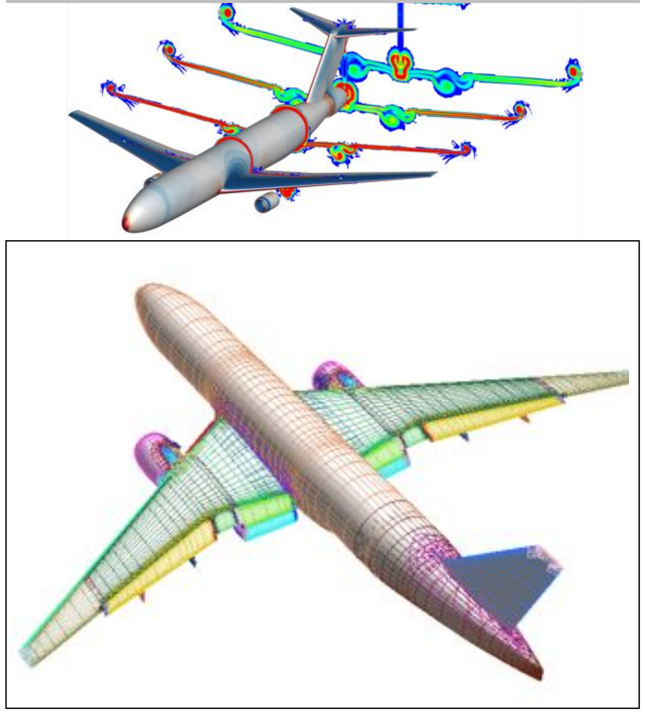
- Essentially no manual grid generation
- Highly efficient Structured Adaptive Mesh Refinement (AMR)
- Low computational cost
- Reliable higher order methods
- Non-body fitted -> Resolution of boundary layers inefficient

Unstructured Arbitrary Polyhedral



- Partially automated grid generation
- Body fitted grids
- Grid quality can be challenging
- High computational cost
- Higher order methods yet to fully mature

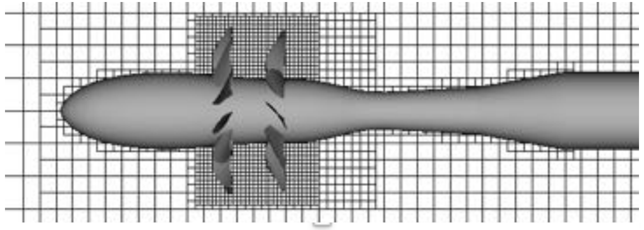
Structured Curvilinear



- High quality body fitted grids
- Low computational cost
- Reliable higher order methods
- Grid generation largely manual and time consuming

Why Cartesian AMR?

Structured Cartesian AMR

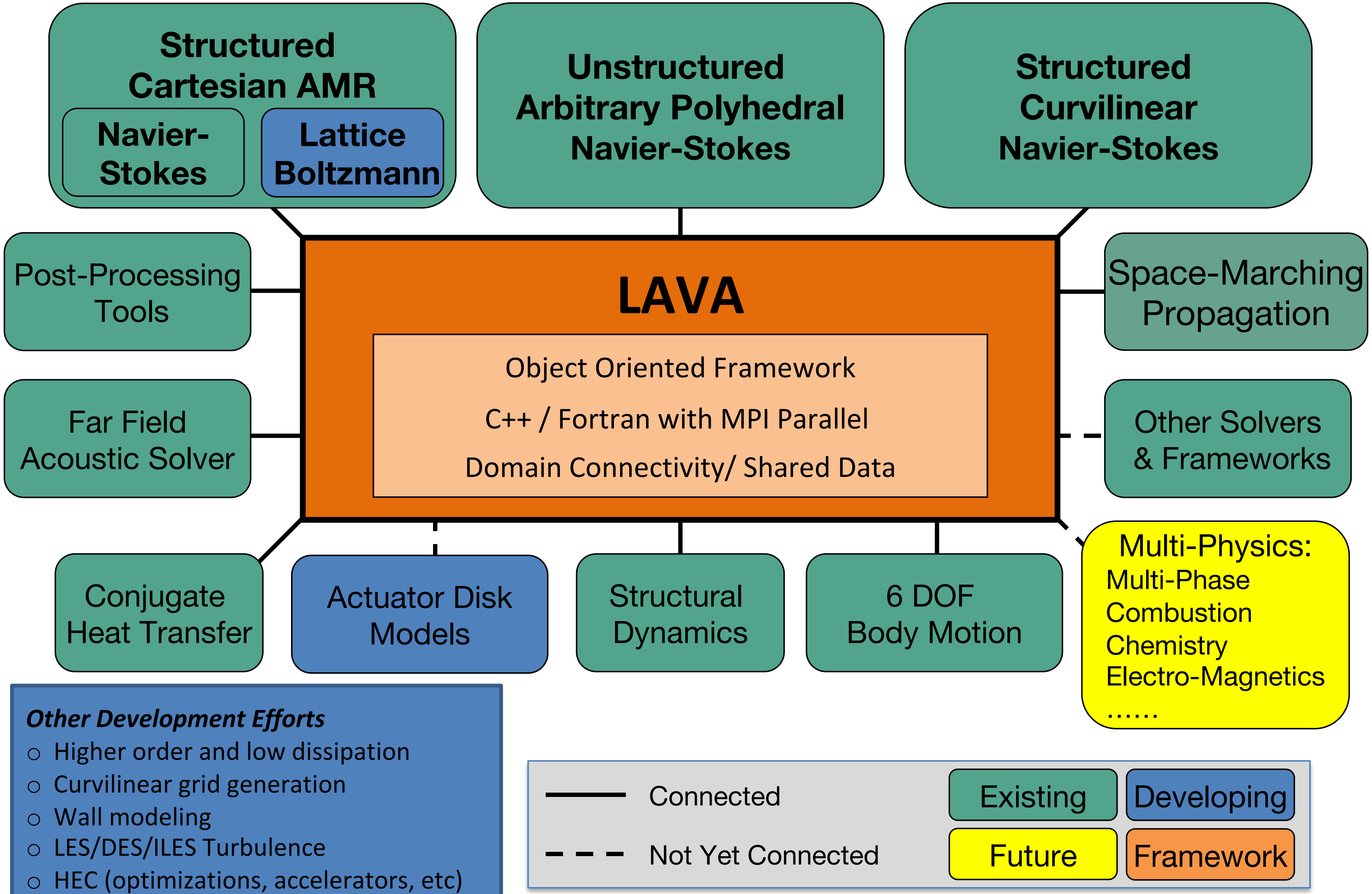


- Essentially no manual grid generation
- Highly efficient Structured Adaptive Mesh Refinement (AMR)
- Low computational cost
- Reliable higher order methods
- Non-body fitted -> Resolution of boundary layers inefficient

Predict transient pressure loads and acoustics on structures for QM-1 abort motor ground test:

- Simulate complex geometry over large domain
  - ✓Automatic mesh generation and immersed boundary representation
- Track ignition overpressure (IOP) wave as it propagates
  - ✓On-the-fly solution-based adaptive mesh refinement (AMR)
- Capture high Mach number turbulent plume acoustics
  - ✓Robust high-order scheme in space and time
  - ✓Near-isotropic cells are best for predicting jet noise
  - ✓Boundary layers do not play critical role for the quantities of interest for this project
- Short turnaround time for decision making
  - ✓Automatic grid generation means we can get started immediately
  - ✓Block-structured framework increases computational efficiency

Launch, Ascent, and Vehicle Aerodynamics
LAVA Framework



Structured Cartesian AMR

Navier-Stokes

Lattice Boltzmann

Unstructured Arbitrary Polyhedral Navier-Stokes

Structured Curvilinear Navier-Stokes

Post-Processing Tools

Far Field Acoustic Solver

LAVA

Object Oriented Framework

C++ / Fortran with MPI Parallel

Domain Connectivity/ Shared Data

Space-Marching Propagation

Other Solvers & Frameworks

Conjugate Heat Transfer

Actuator Disk Models

Structural Dynamics

6 DOF Body Motion

Multi-Physics:
Multi-Phase
Combustion
Chemistry
Electro-Magnetics
……

Other Development Efforts
- Higher order and low dissipation
- Curvilinear grid generation
- Wall modeling
- LES/DES/ILES Turbulence
- HEC (optimizations, accelerators, etc)

——— Connected

– – – Not Yet Connected

Existing

Developing

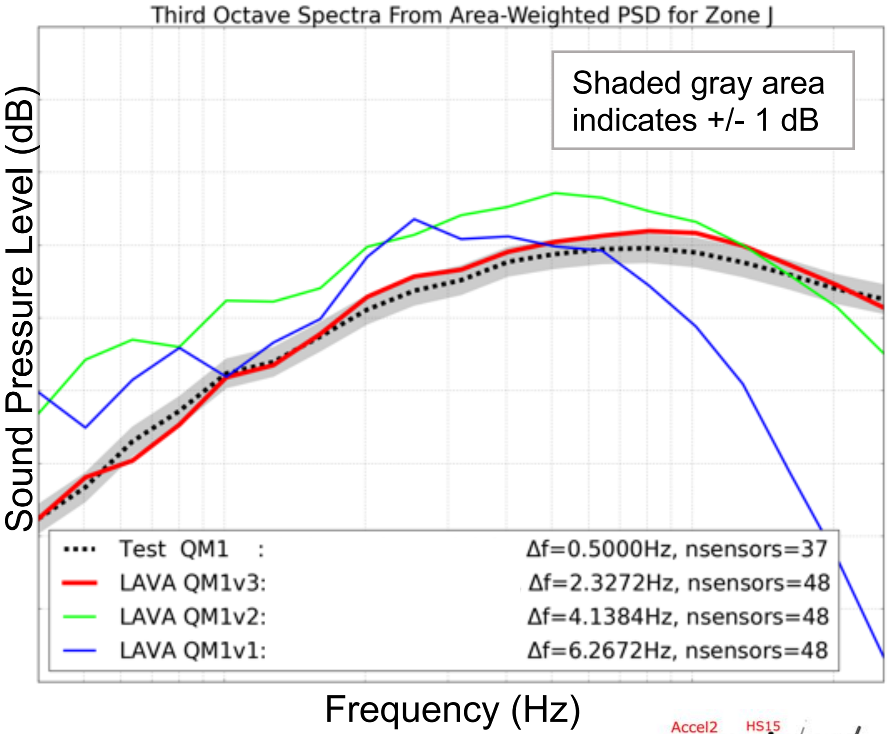
Future

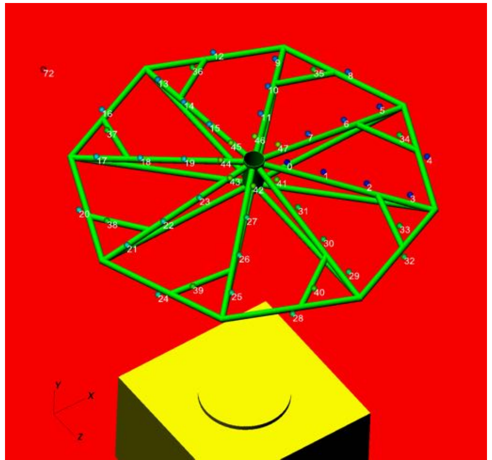
Framework

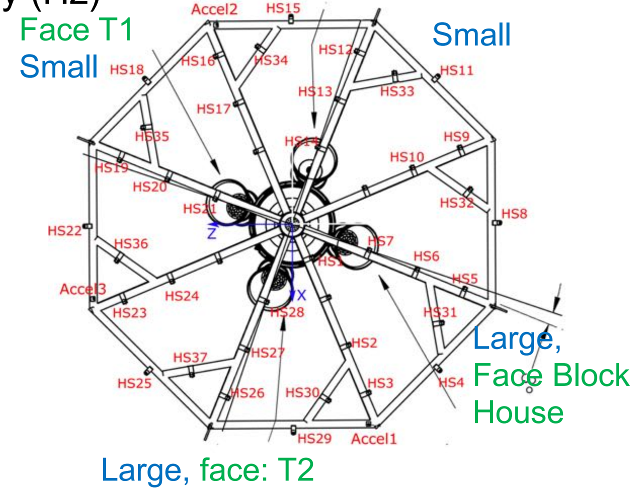
Kiris at al. AIAA-2014-0070 & AST-2016

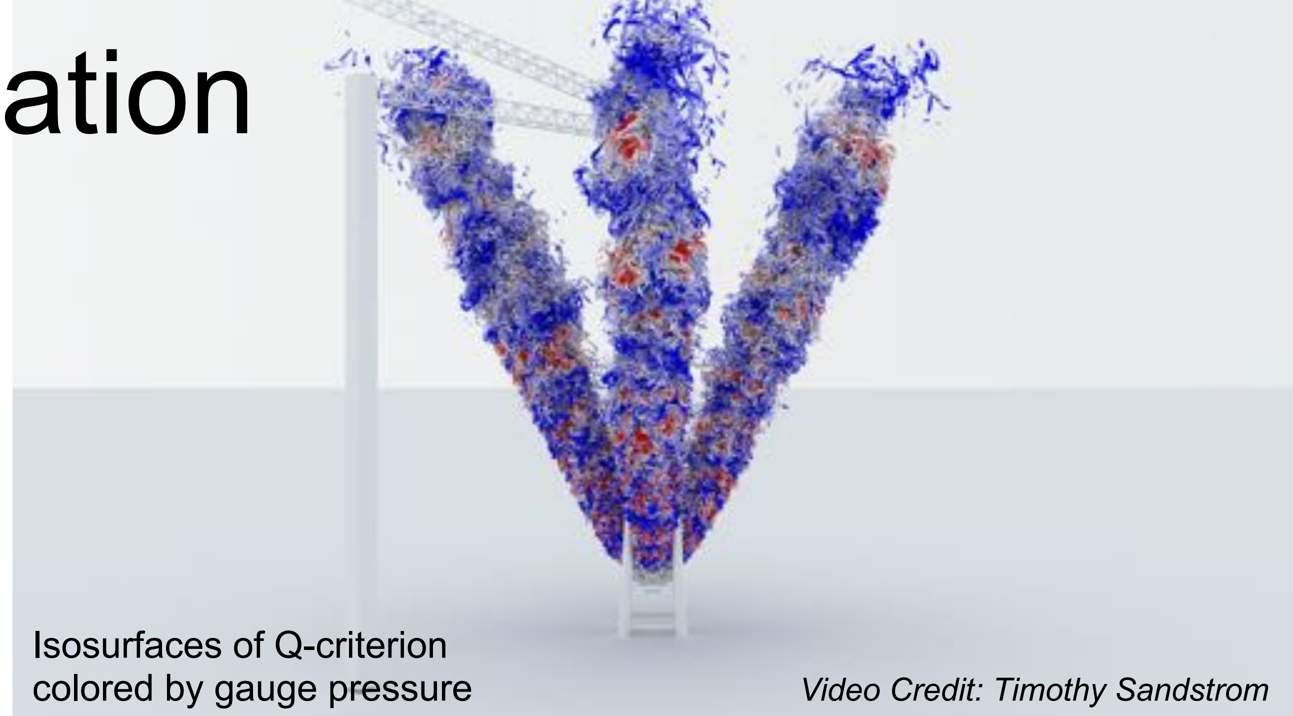
QM-1 Ground Test Validation

Heat Shield Area-Weighted Kulite Acoustics


Third Octave Spectra From Area-Weighted PSD for Zone J



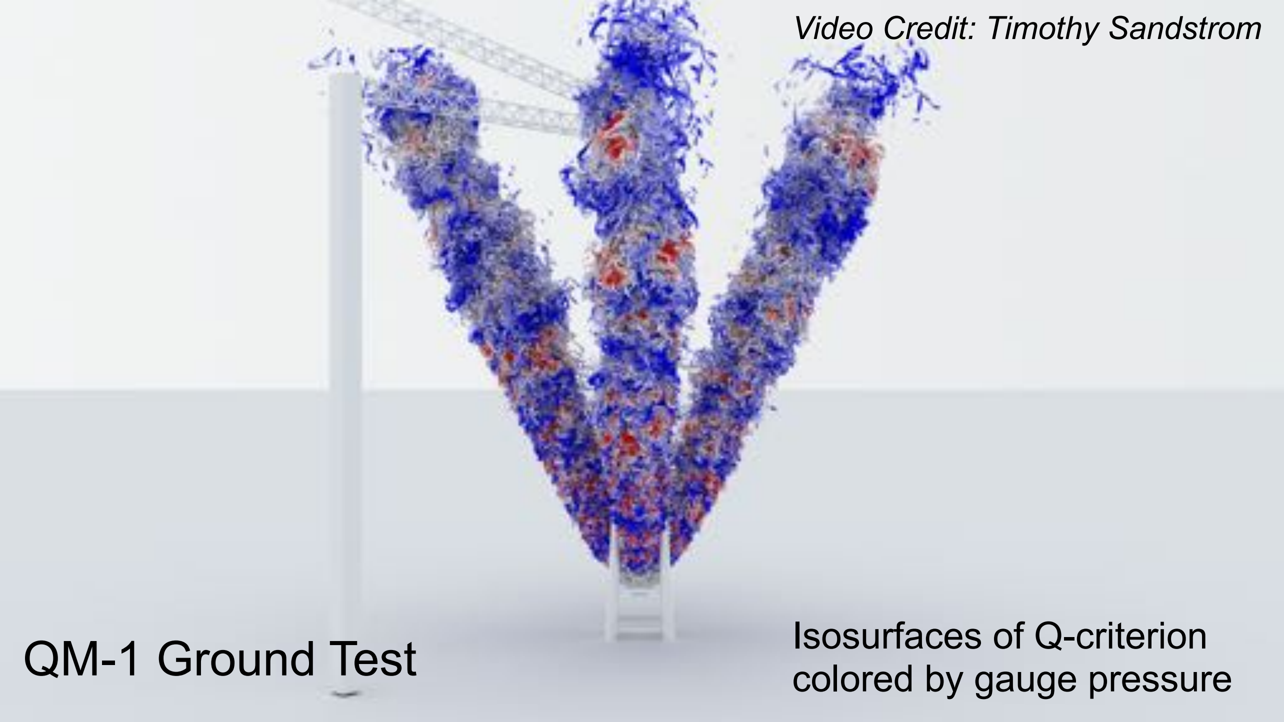



Isosurfaces of Q-criterion colored by gauge pressure

Video Credit: Timothy Sandstrom


Picture from QM-1 Test

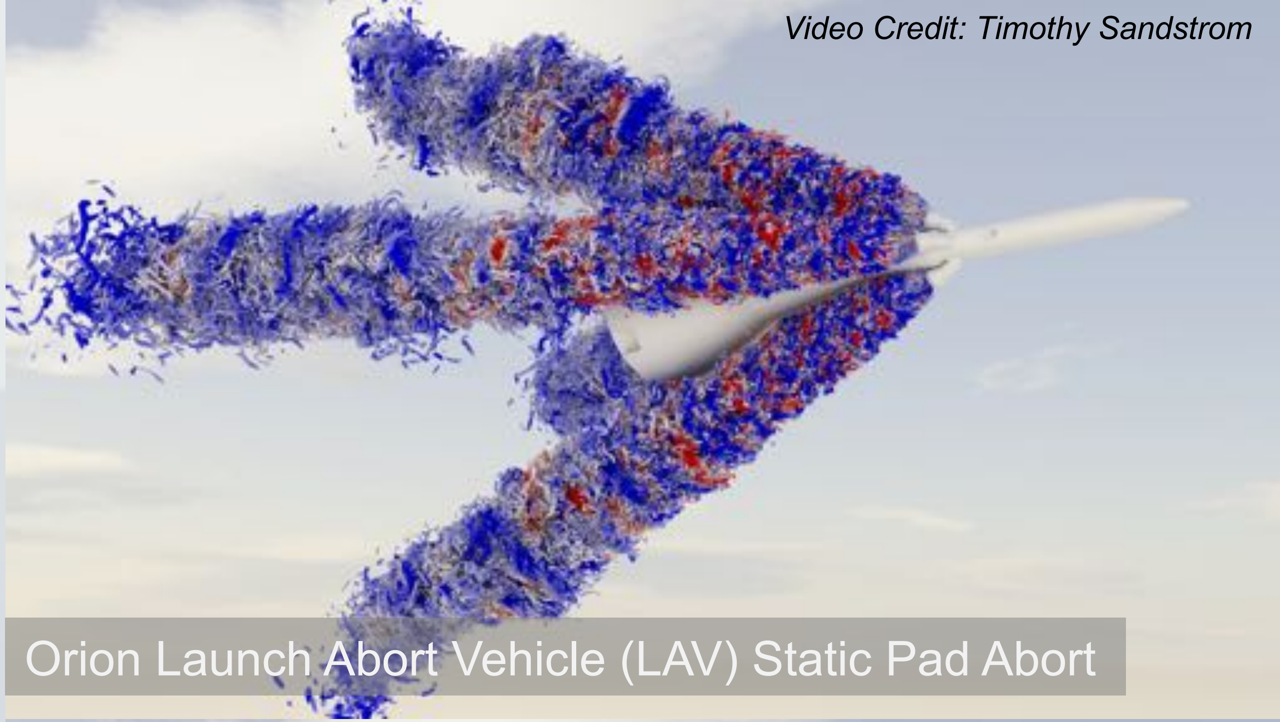
HPC Resources	
Wallclock time (days)	18
Number of nodes	80
Node type	Skylake
Total number of cores	3,200
Time simulated (seconds)	0.38
Volume data (TB)	100



Video Credit: Timothy Sandstrom

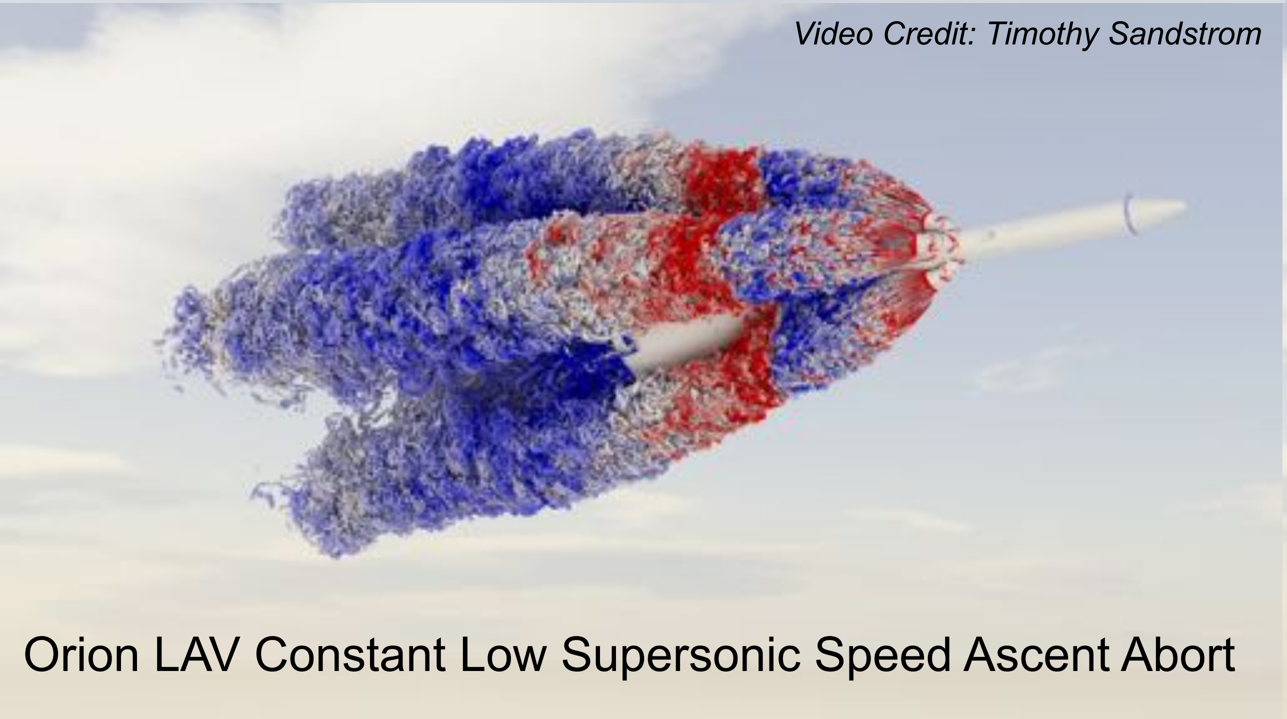
QM-1 Ground Test

Isosurfaces of Q-criterion
colored by gauge pressure



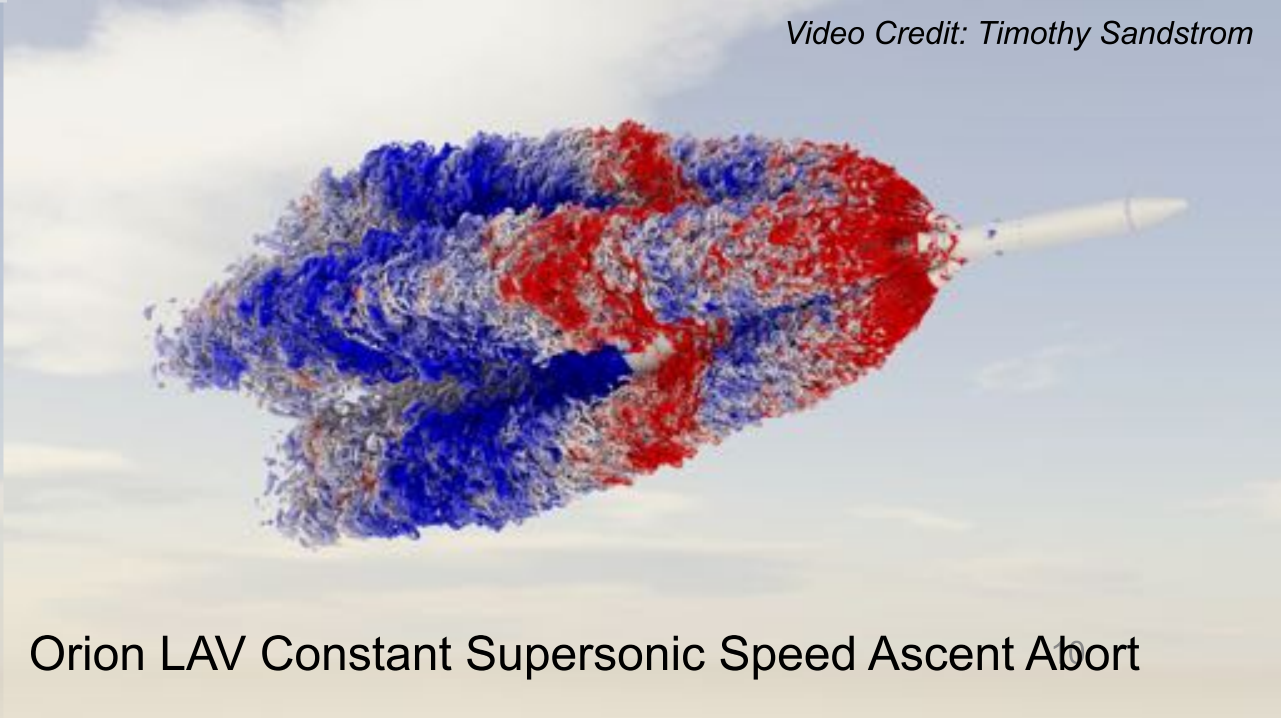
Video Credit: Timothy Sandstrom

Orion Launch Abort Vehicle (LAV) Static Pad Abort



Video Credit: Timothy Sandstrom

Orion LAV Constant Low Supersonic Speed Ascent Abort



Video Credit: Timothy Sandstrom

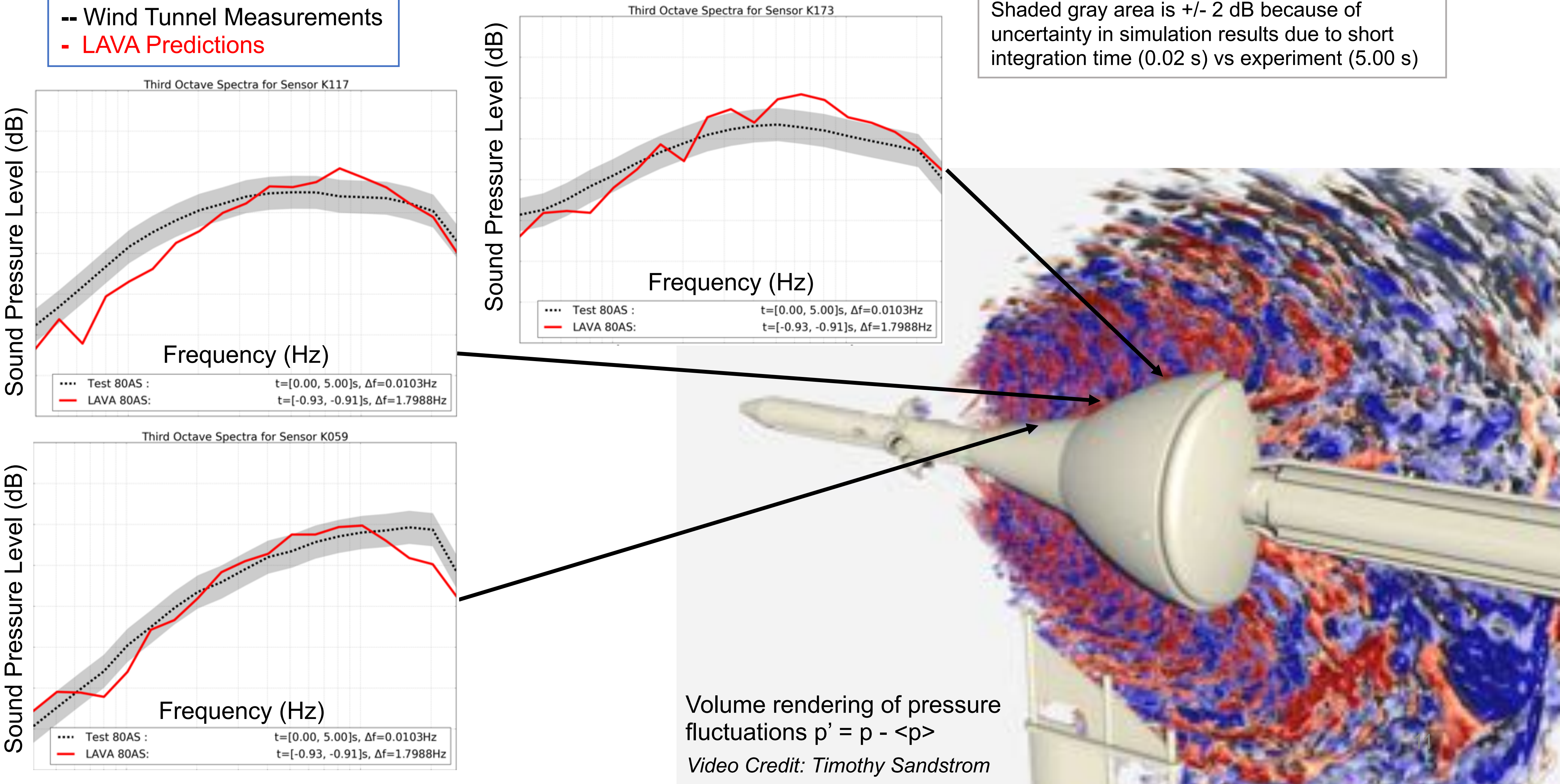
Orion LAV Constant Supersonic Speed Ascent Abort

Wind Tunnel Experimental Validation

Transonic ascent abort at moderate angle of attack and side slip

-- Wind Tunnel Measurements
- LAVA Predictions

Shaded gray area is +/- 2 dB because of uncertainty in simulation results due to short integration time (0.02 s) vs experiment (5.00 s)

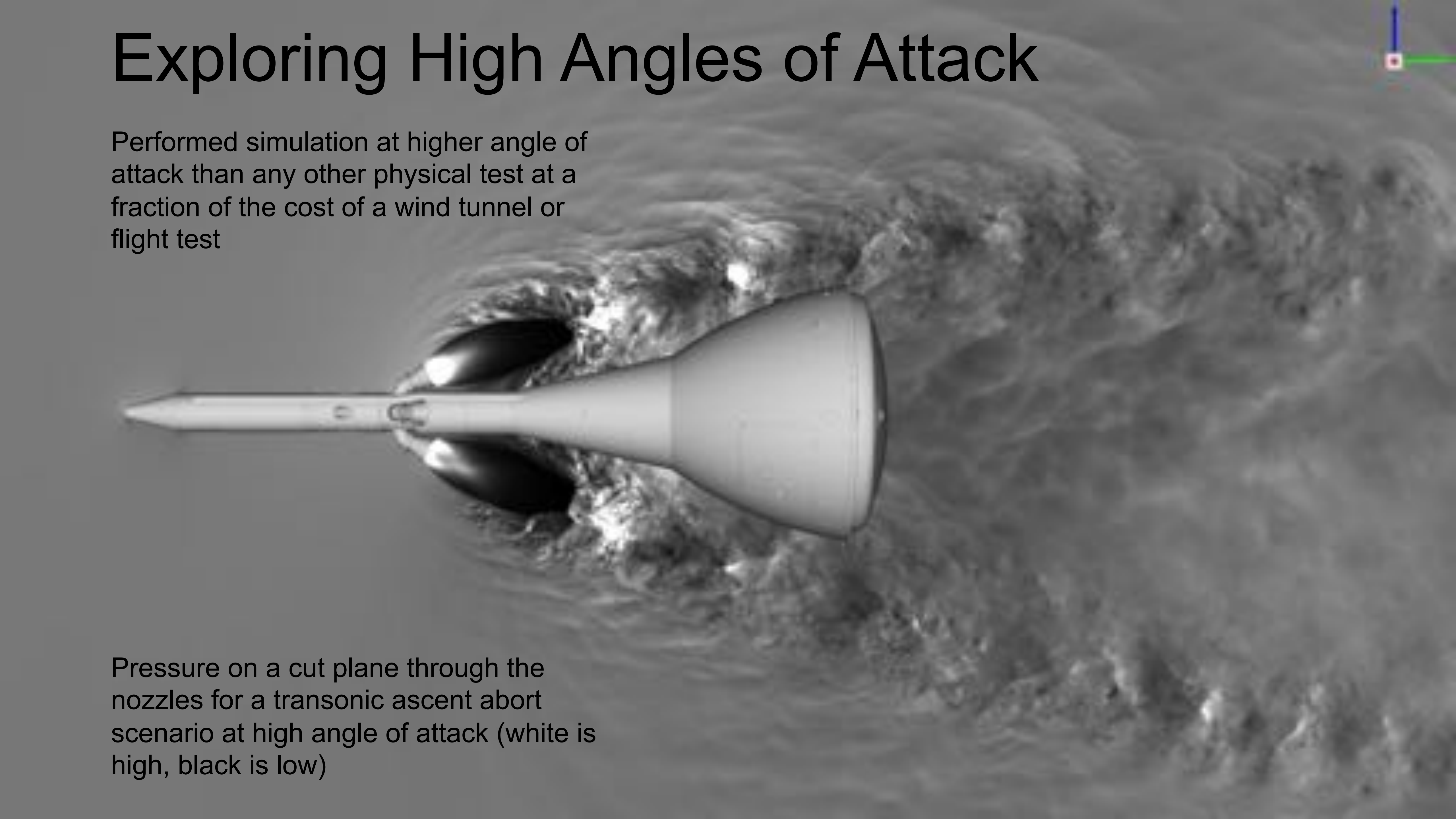


Volume rendering of pressure fluctuations p’ = p - <p>

Video Credit: Timothy Sandstrom

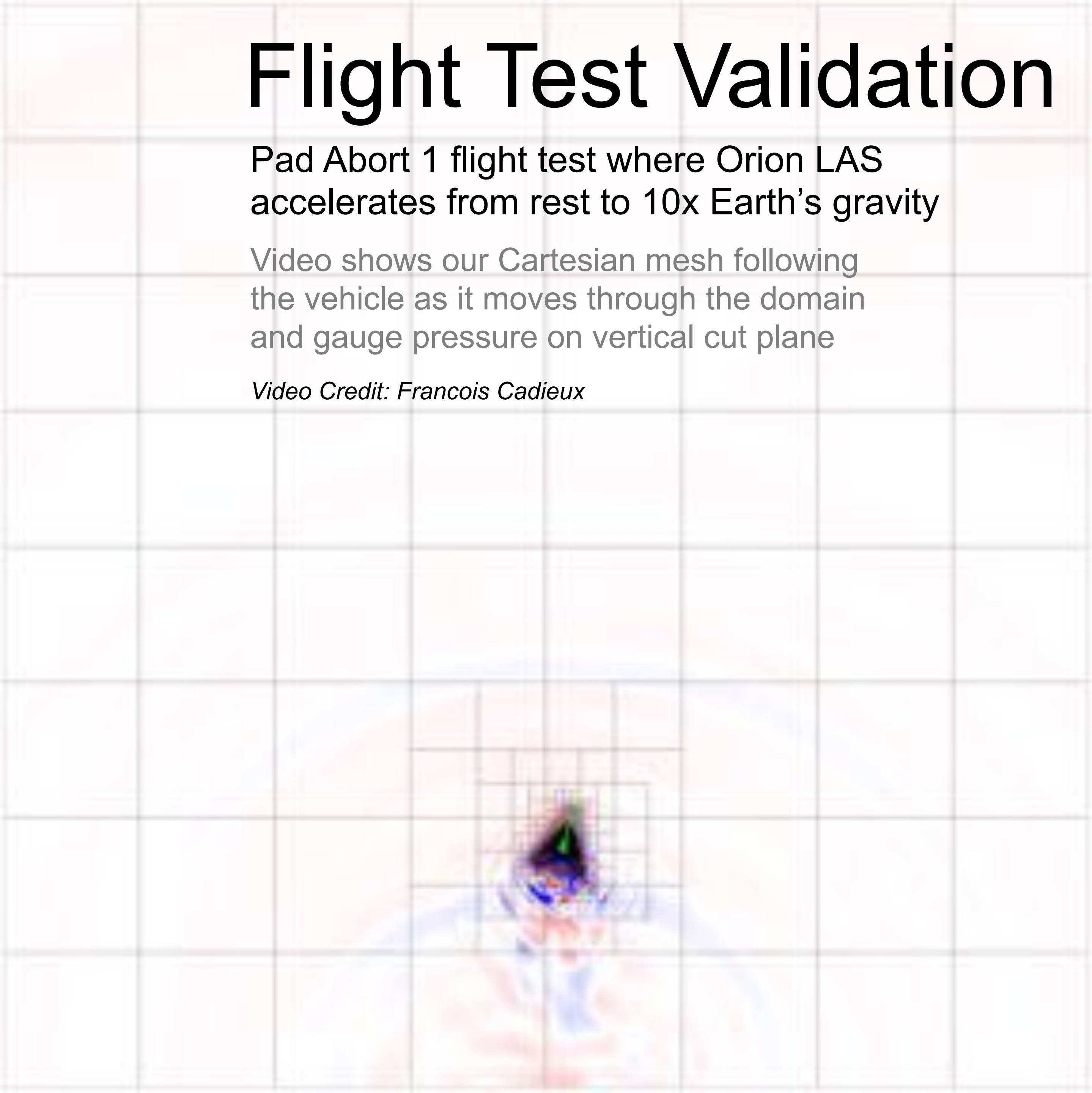
Exploring High Angles of Attack

Performed simulation at higher angle of attack than any other physical test at a fraction of the cost of a wind tunnel or flight test



Pressure on a cut plane through the nozzles for a transonic ascent abort scenario at high angle of attack (white is high, black is low)

Flight Test Validation



Pad Abort 1 flight test where Orion LAS accelerates from rest to 10x Earth's gravity

Video shows our Cartesian mesh following the vehicle as it moves through the domain and gauge pressure on vertical cut plane

Video Credit: Francois Cadieux

HPC Resources		
	Static	**Moving**
Wallclock time (days)	18	45
Number of nodes	100	400
Node type	Skylake	Skylake
Total number of cores	4,000	16,000
Number of time steps	280,500	572,000
Time simulated (seconds)	0.44	1.25
Volume data (TB)	100	200
Surface and Cut Plane data (GB)	200	600

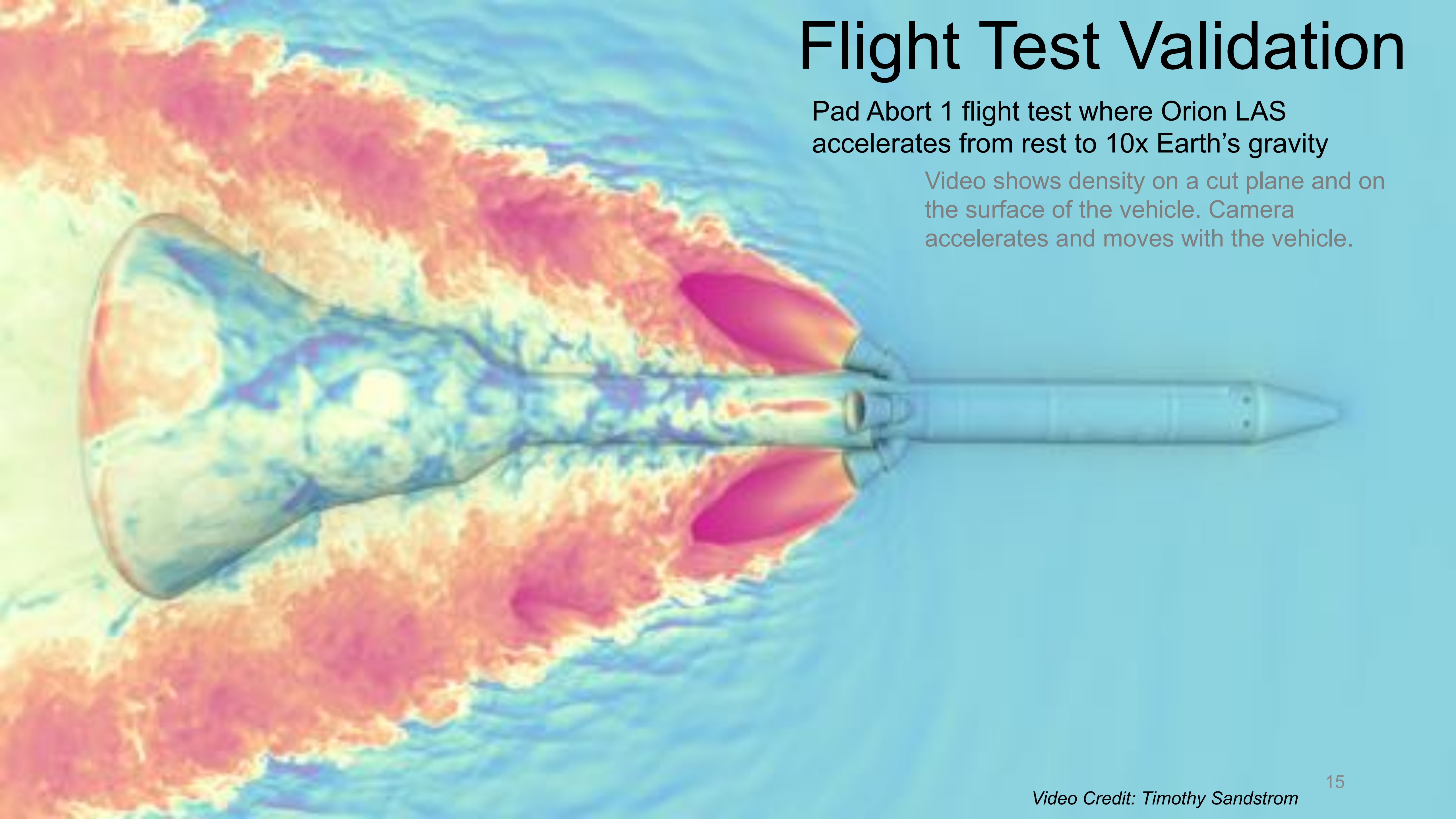
Video Credit: *Timothy Sandstrom*

Flight Test Validation

Pad Abort 1 flight test where Orion LAS accelerates from rest to 10x Earth’s gravity

Video shows passive particles seeded at the nozzle colored by velocity magnitude: white is fast, dark orange is slow

Flight Test Validation



Pad Abort 1 flight test where Orion LAS accelerates from rest to 10x Earth’s gravity

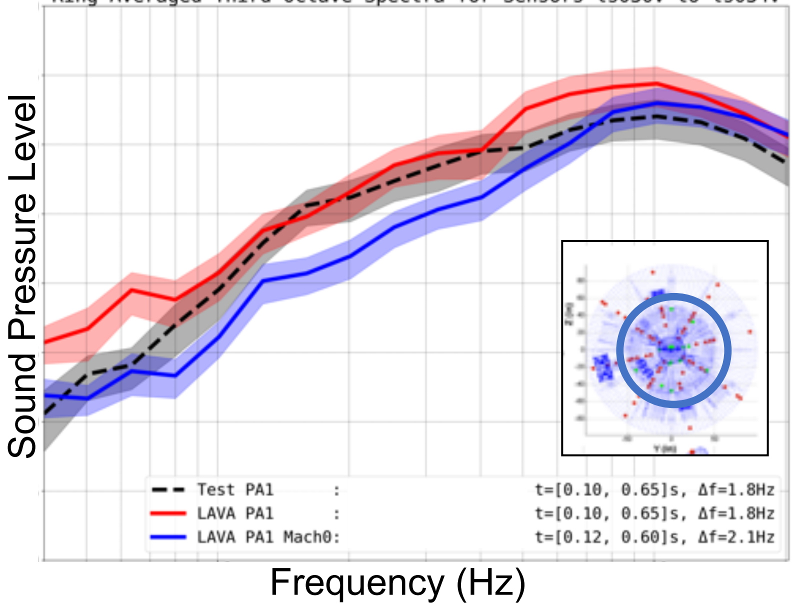
Video shows density on a cut plane and on the surface of the vehicle. Camera accelerates and moves with the vehicle.

Video Credit: Timothy Sandstrom

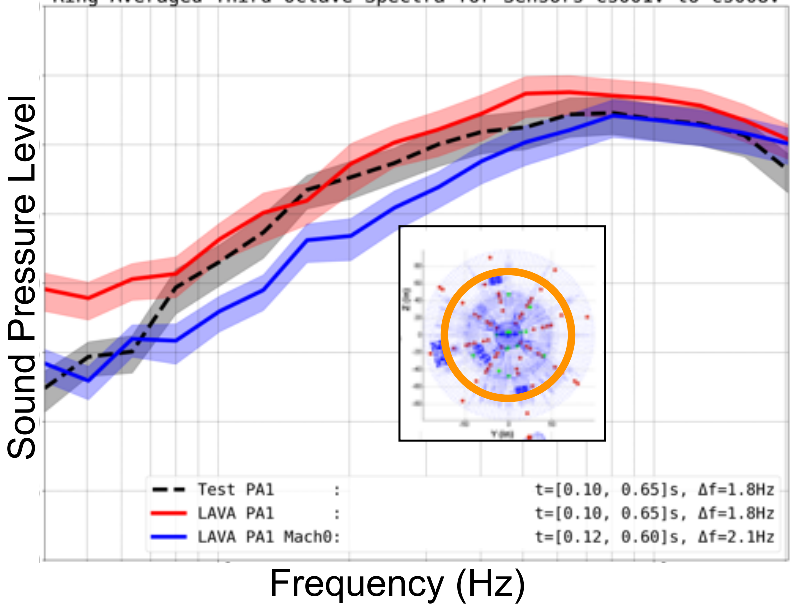
Flight Test Validation

Pad Abort 1 flight test where Orion LAS accelerates from rest to 10x Earth's gravity

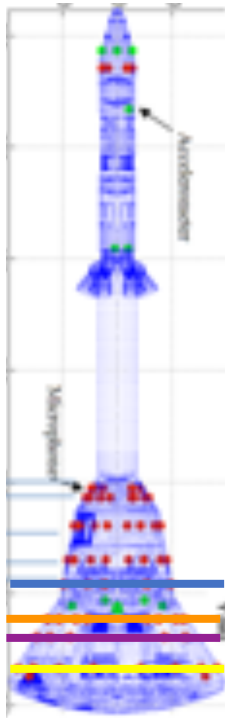
Ring-Averaged Third Octave Spectra for Sensors ls030v to ls034v



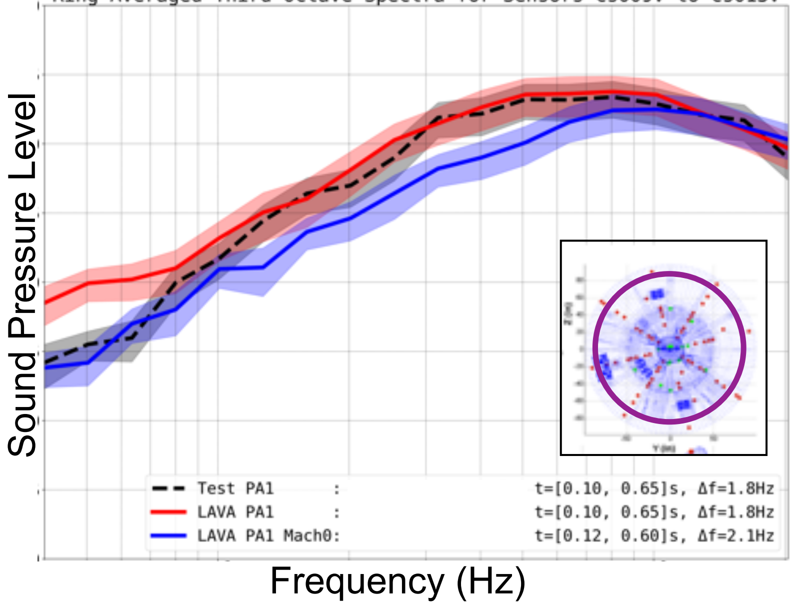
Ring-Averaged Third Octave Spectra for Sensors cs001v to cs008v



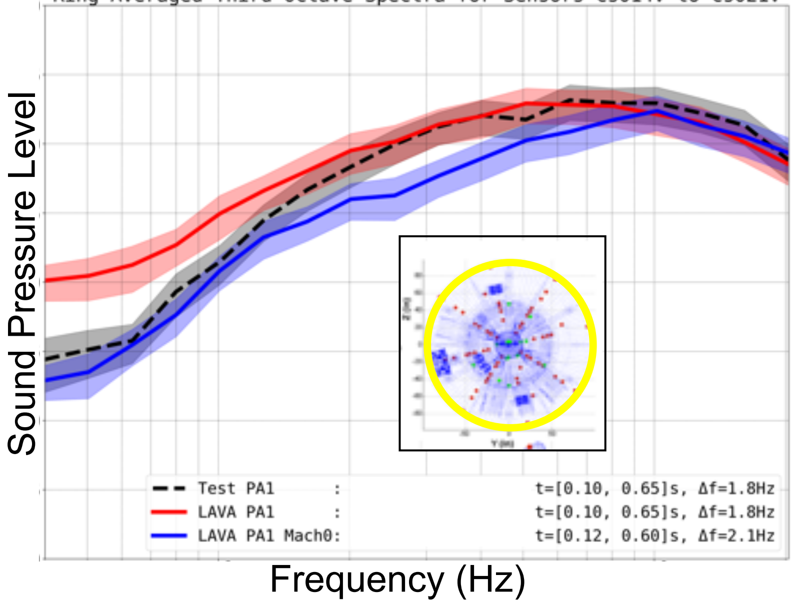
-- Flight Test Measurements
- LAVA Predictions
- No Accel LAVA Predictions



Ring-Averaged Third Octave Spectra for Sensors cs009v to cs013v



Ring-Averaged Third Octave Spectra for Sensors cs014v to cs021v



Shaded regions are approx. +/- 2 dB because of statistical uncertainty

HPC Impact

High parallel efficiency algorithms tailored to many-core architecture

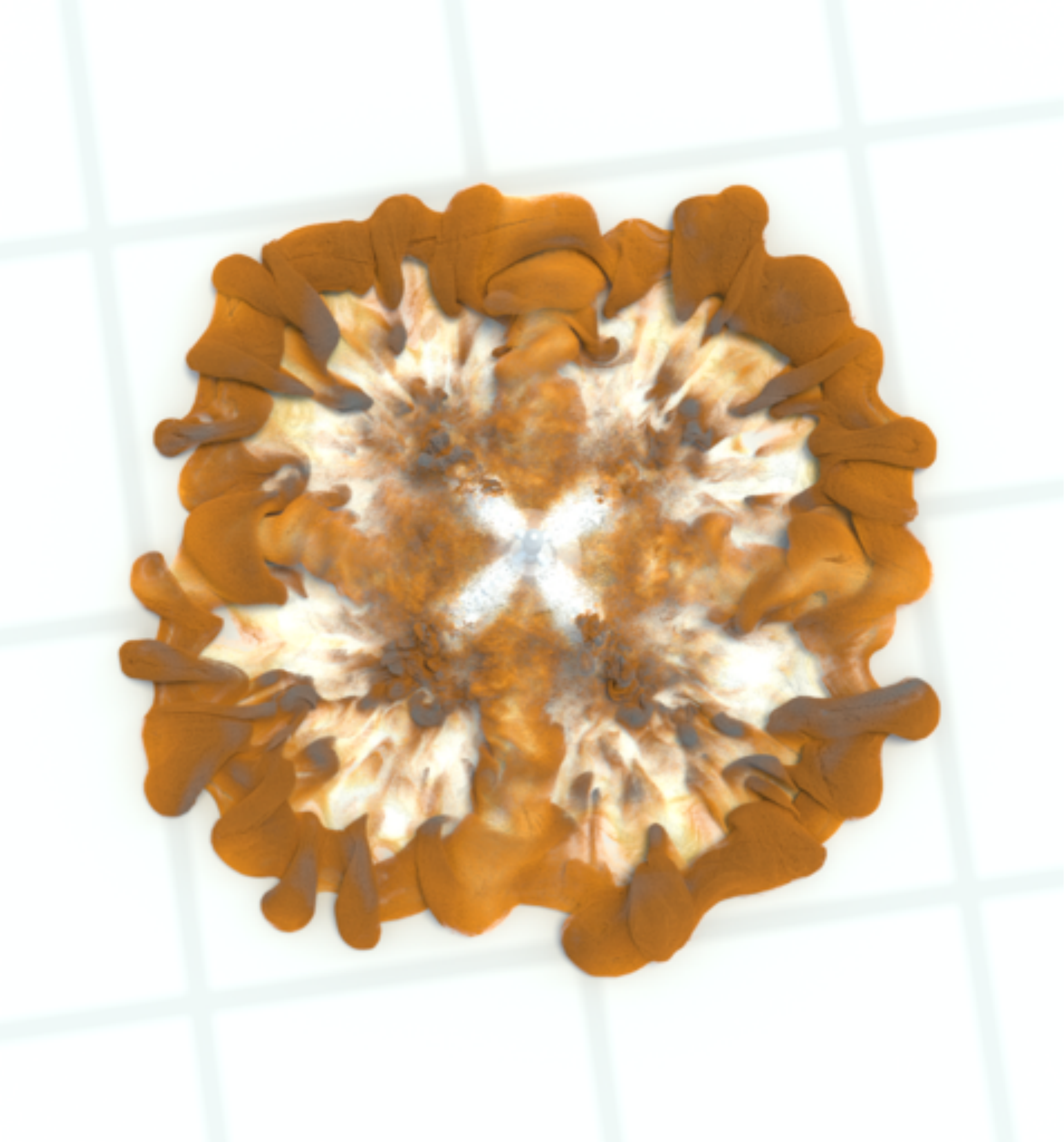
+

High space and time resolution through high-order schemes

+

Capability computing resources (high # of cores over many days)

Perform *unprecedented* scale-resolving simulations that help enhance safety and reduce risk for the Orion Launch Abort System



Summary

- Performed 11 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, wind tunnel test measurements, and flight test record
- Investigated effects of vehicle altitude, velocity, and angle of attack on acoustic environment for ascent abort scenarios
- Explored impact of acceleration on unsteady surface pressure

Acknowledgments

- This work is funded by NASA Orion project
- Computer resources provided by NASA Advanced Supercomputing (NAS) Facility
- NASA Orion Loads and Dynamics team:
  - Quyen Jones
  - Jayanta Panda
  - Vincent Fogt
  - Kenneth Fiorelli
- NAS Visualization Team:
  - Timothy Sandstrom
- LAVA Team:
  - for providing insights and lessons learned from other projects

Backup Slides

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) for a wide range of launch abort scenarios: pad abort, subsonic/transonic/supersonic ascent abort
2. Collaborate with Orion Loads and Dynamics team to combine:
   - CFD predictions
   - wind tunnel experiments
   - ground test measurements
   - flight test measurements

   To better characterize and reduce uncertainty in the acoustic environment
3. In the context of optimizing the design of the LAV fairing assembly:
   - Minimize Orion LAV fairing assembly structural weight
   - Reduce risk of structural failure due to vibrations

Initial Project Requirements

Predict transient pressure loads and acoustics on near field plume acoustics towers, heat shield cage structure, and crane ahead of QM-1 abort motor ground test (June 2017)

Picture from ST1 abort motor ground test

CFD Requirements

Predict transient pressure loads and acoustics on structures for QM-1 abort motor ground test:

- Simulate complex geometry over large domain and long integration time for acoustics
- Track ignition overpressure (IOP) wave as it propagates
- Capture high Mach number turbulent plume acoustics
  - Turbulent jet shear layers responsible for majority of acoustics
  - Combustion noise is minimal
- Short turnaround time for decision making

Numerical Methodology

- Solve multi-species Navier-Stokes equations (no turbulence/subgrid scale model) with
  - 5th order weighted essentially non-oscillatory (WENO5) convective flux [1]
  - 2nd order centered viscous flux
  - explicit 4th order Runge-Kutta (RK4) time integration with CFL ~ 0.5
- Used immersed boundary method [2,3] 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)

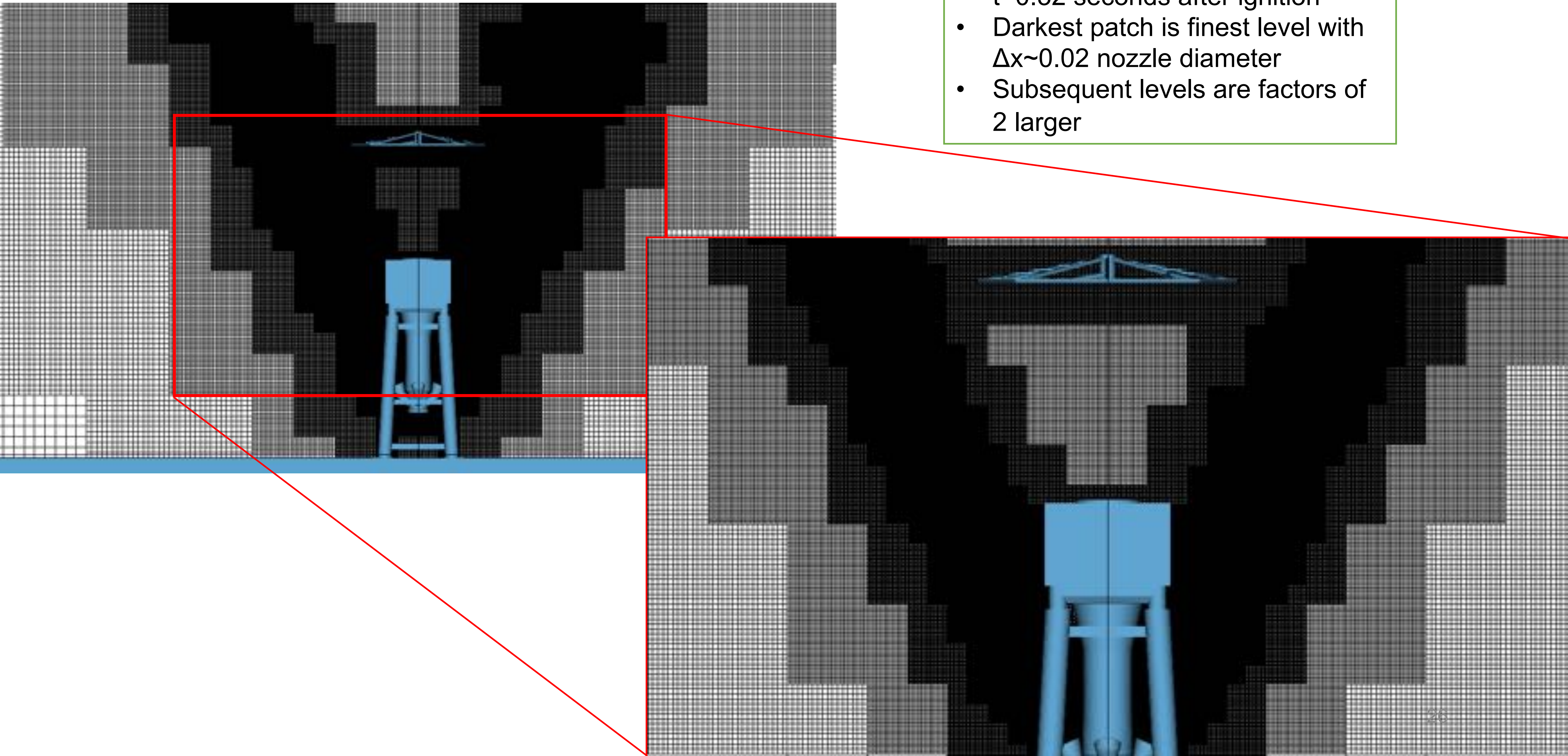
[1] Brehm, Christoph, et al. "A comparison of higher-order finite-difference shock capturing schemes." *Computers & Fluids* 122 (2015): 184-208.
[2] Brehm, C., and Hermann F. Fasel. "A novel concept for the design of immersed interface methods." *Journal of Computational Physics* 242 (2013): 234-267.
[3] Mittal, Rajat, et al. "A versatile sharp interface immersed boundary method for incompressible flows with complex boundaries." *Journal of computational physics* 227.10 (2008): 4825-4852.

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 maximum mesh spacing on volumes around plumes and vehicle/test stand to ~0.04 D
- Used AMR with re-gridding every 10 steps ($\Delta t \sim 1.6\text{x}10^{-6}$ 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

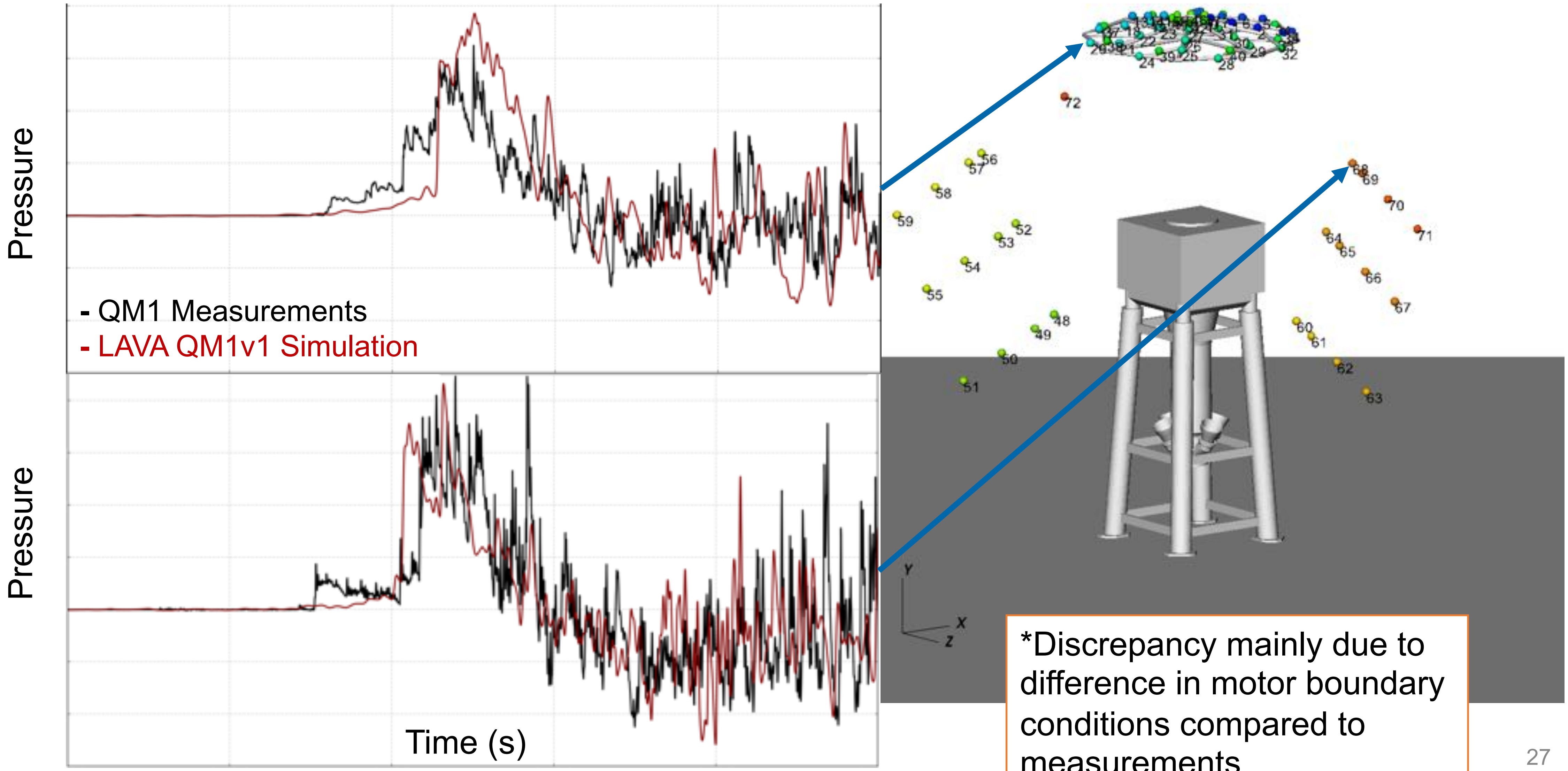
Example of AMR Mesh

- Taken from QM1v2 simulation at t=0.32 seconds after ignition
- Darkest patch is finest level with Δx~0.02 nozzle diameter
- Subsequent levels are factors of 2 larger



Post QM-1 Abort Motor Test Validation

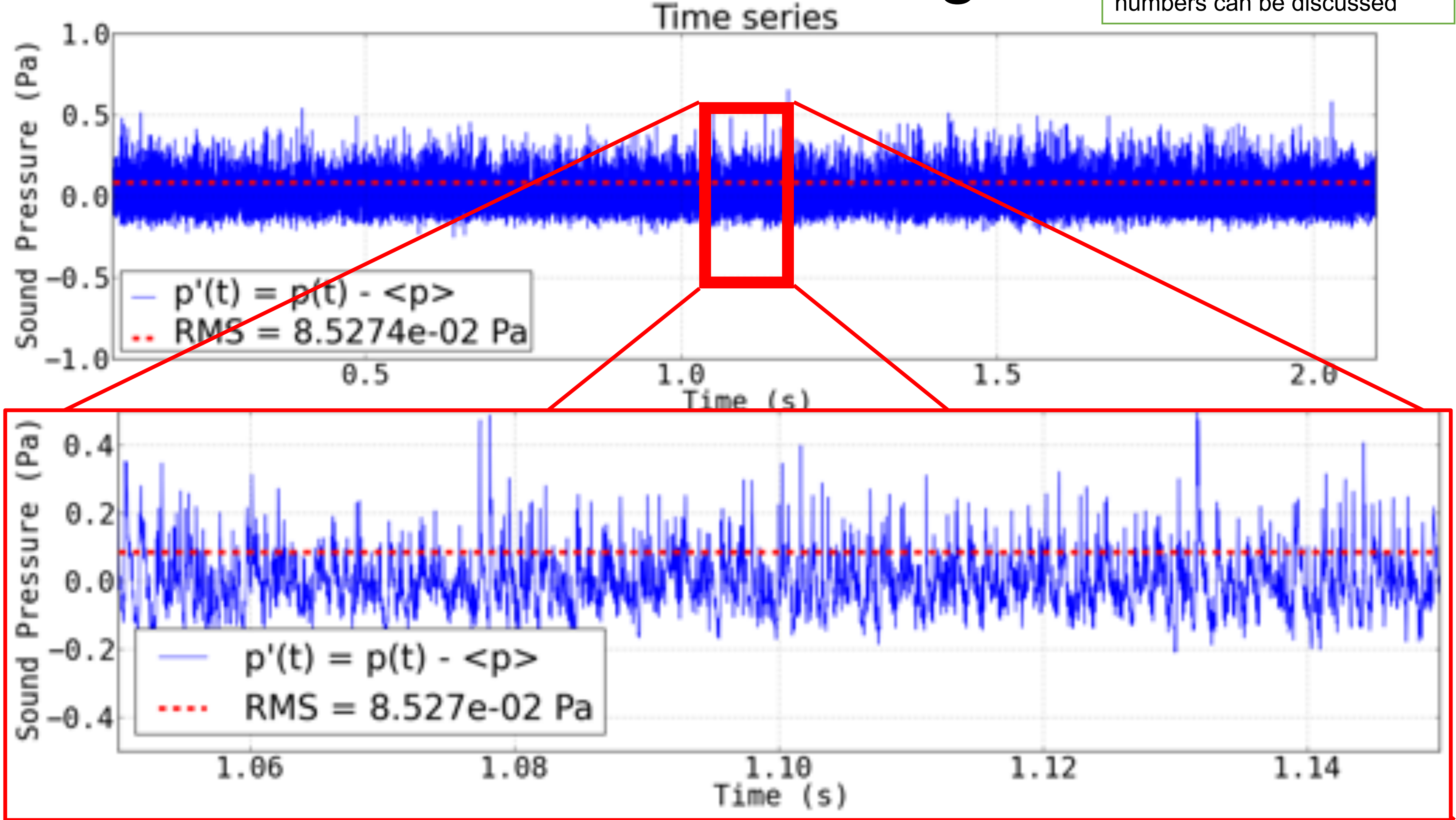
Ignition Overpressure (IOP) versus Time



*Discrepancy mainly due to difference in motor boundary conditions compared to measurements

Acoustics Post-Processing

*Signal from a QM1 Kulite has been arbitrarily scaled so numbers can be discussed



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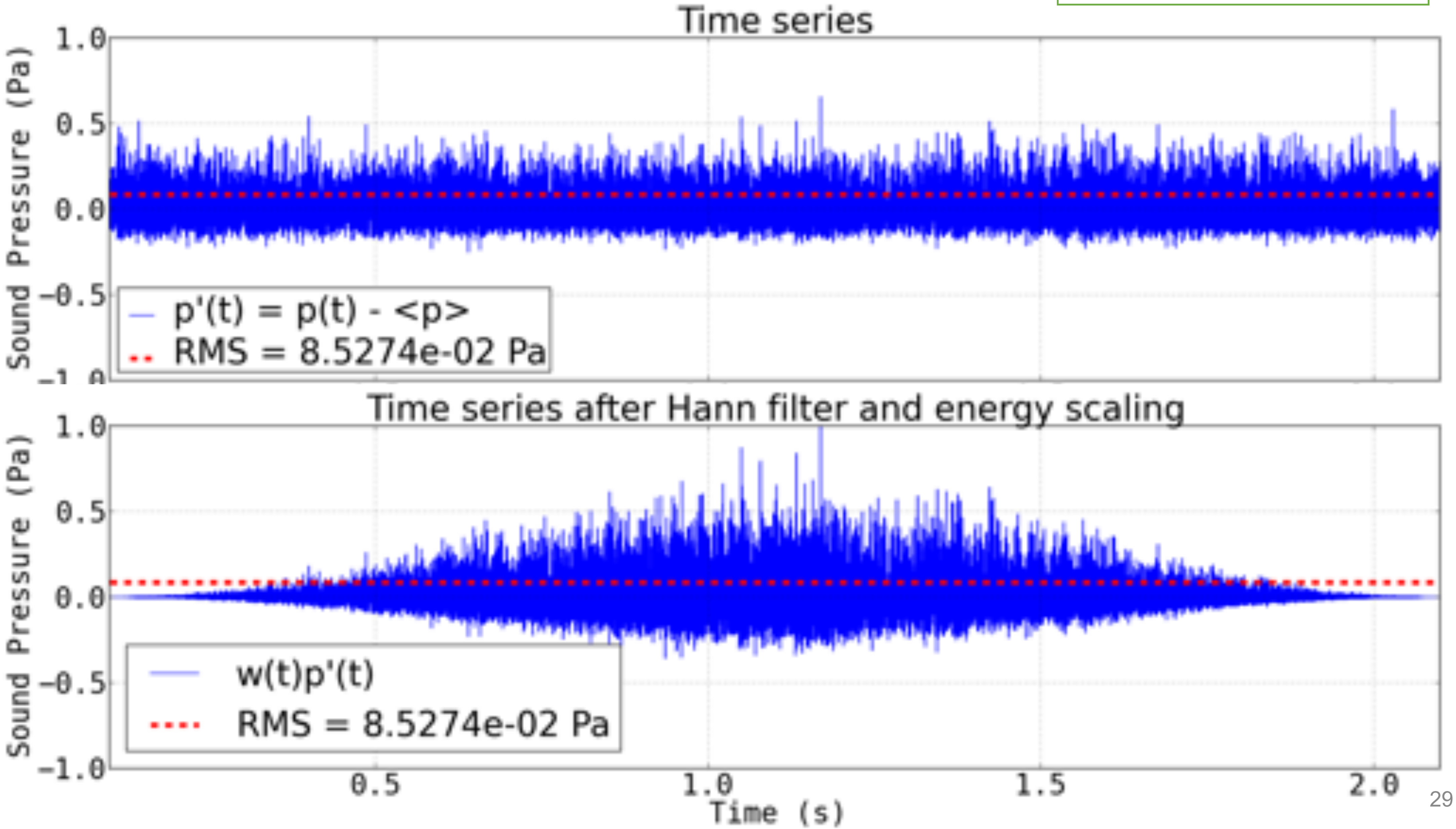

Acoustics Post-Processing

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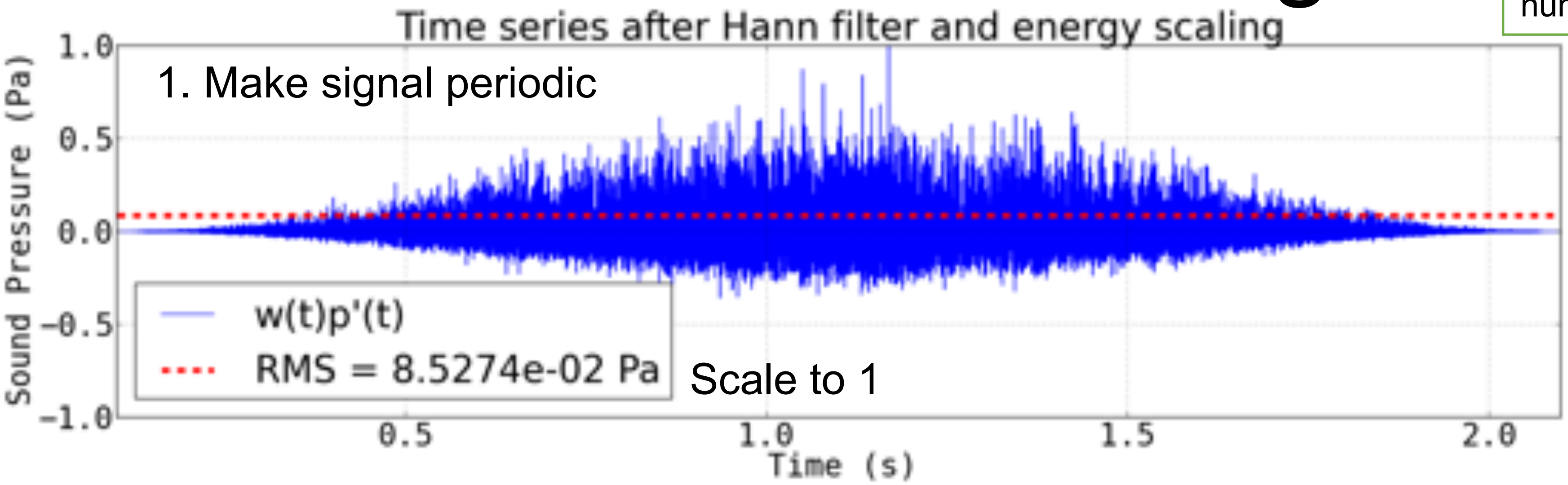

Time series after Hann filter and energy scaling

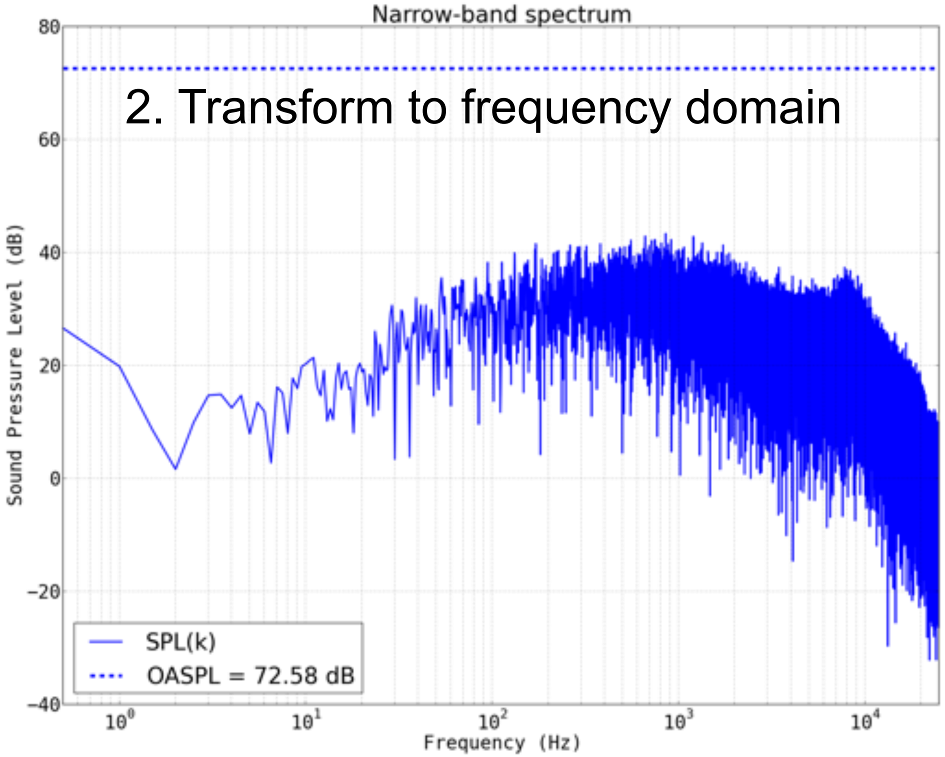
1. Make signal periodic

Scale to 1

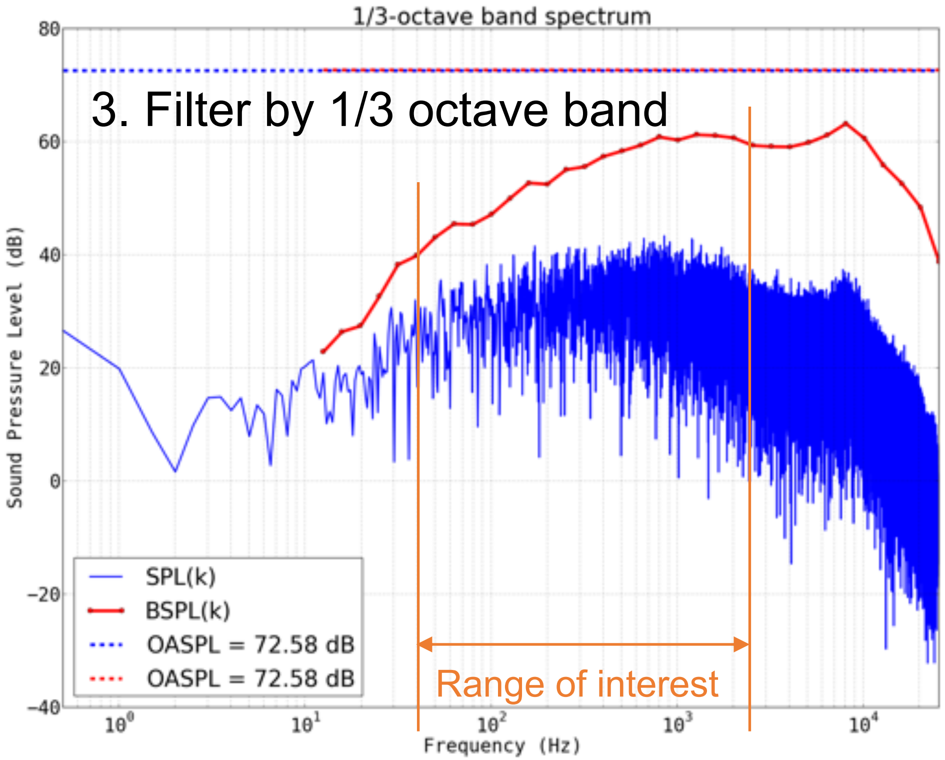
Overall Sound Pressure Level (OASPL)

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

→ OASPL = 72.58 dB


Narrow-band spectrum

2. Transform to frequency domain


1/3-octave band spectrum

3. Filter by 1/3 octave band

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

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

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

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

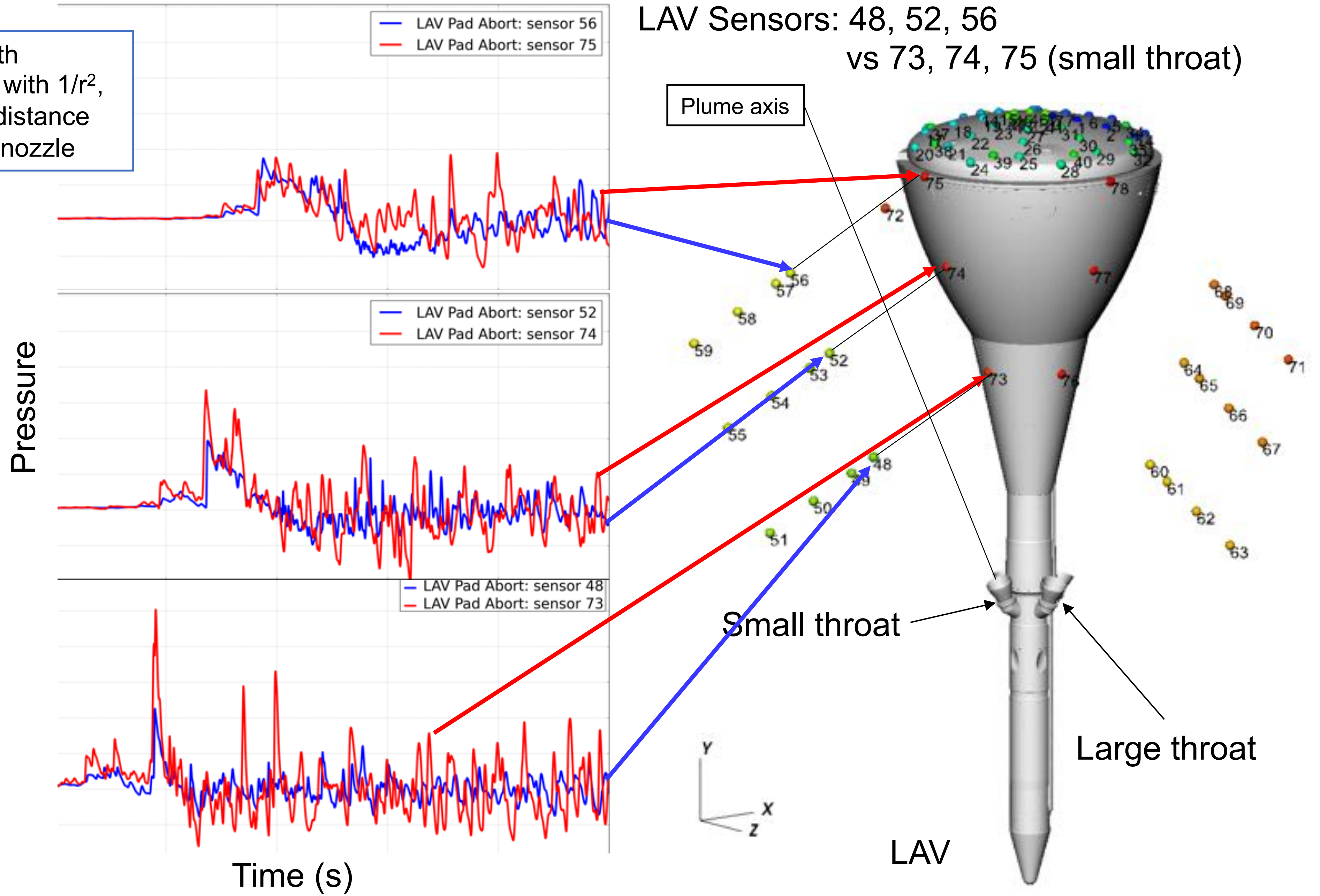
where

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

Pressure Doubling on LAV Surface

IOP strength diminishes with $1/r^2$, where r is distance away from nozzle

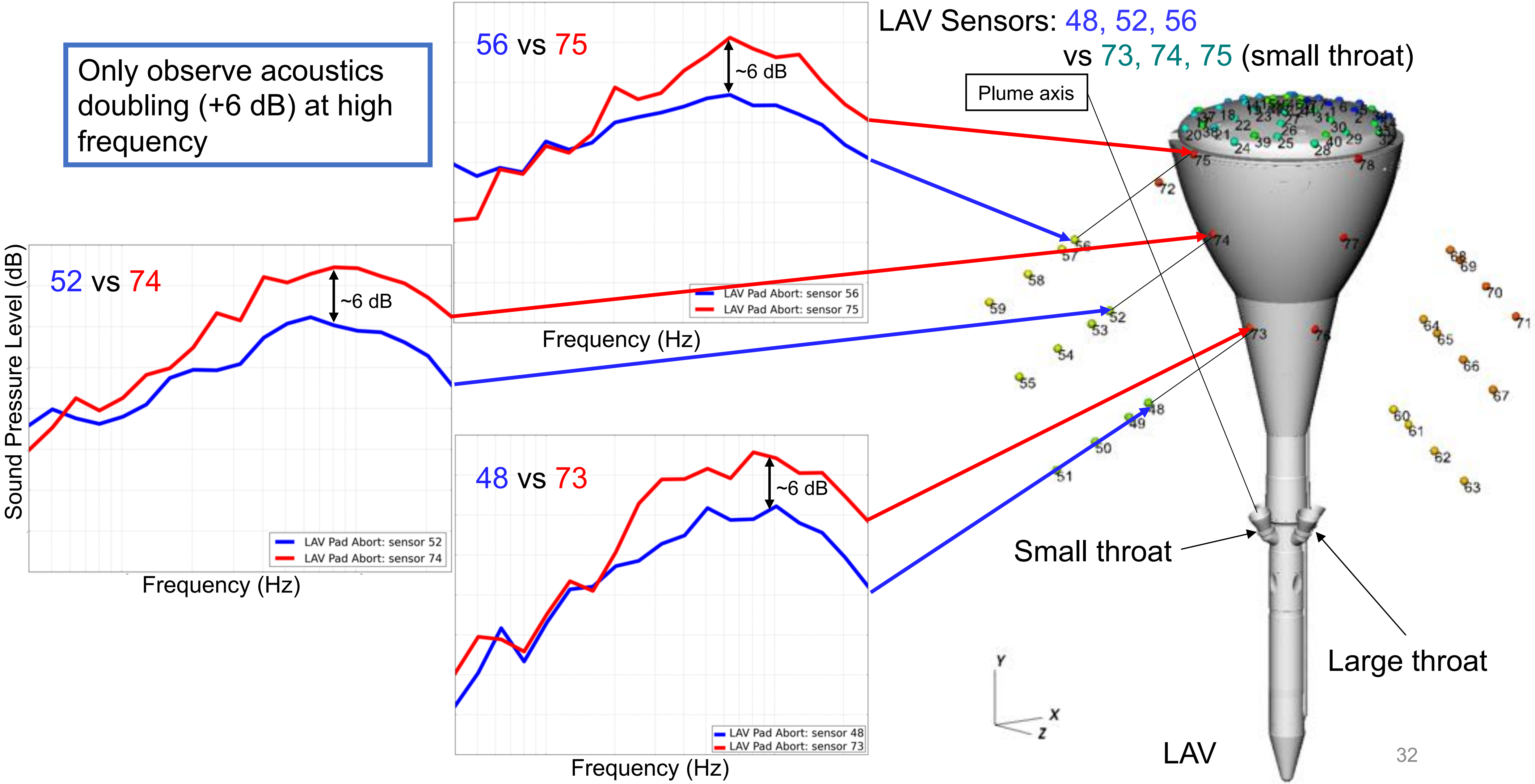
LAV Sensors: 48, 52, 56
vs 73, 74, 75 (small throat)



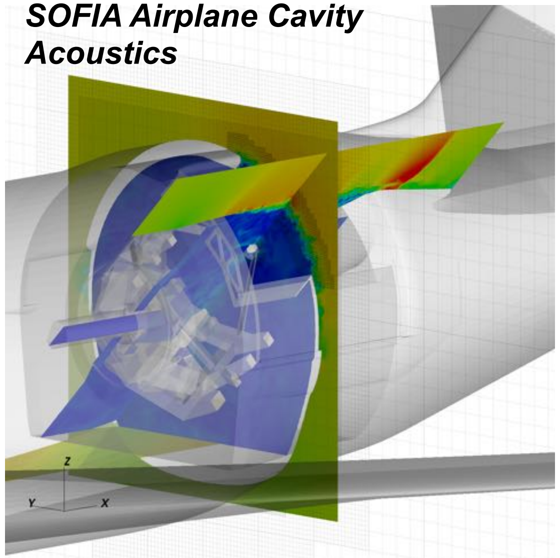
Acoustics Doubling on LAV Surface

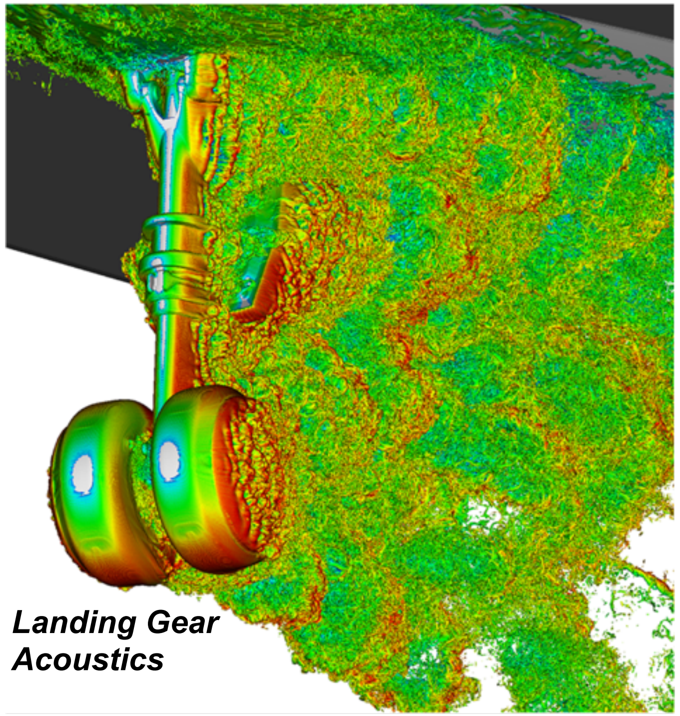
Only observe acoustics doubling (+6 dB) at high frequency

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



Previous LAVA Cartesian AMR Applications

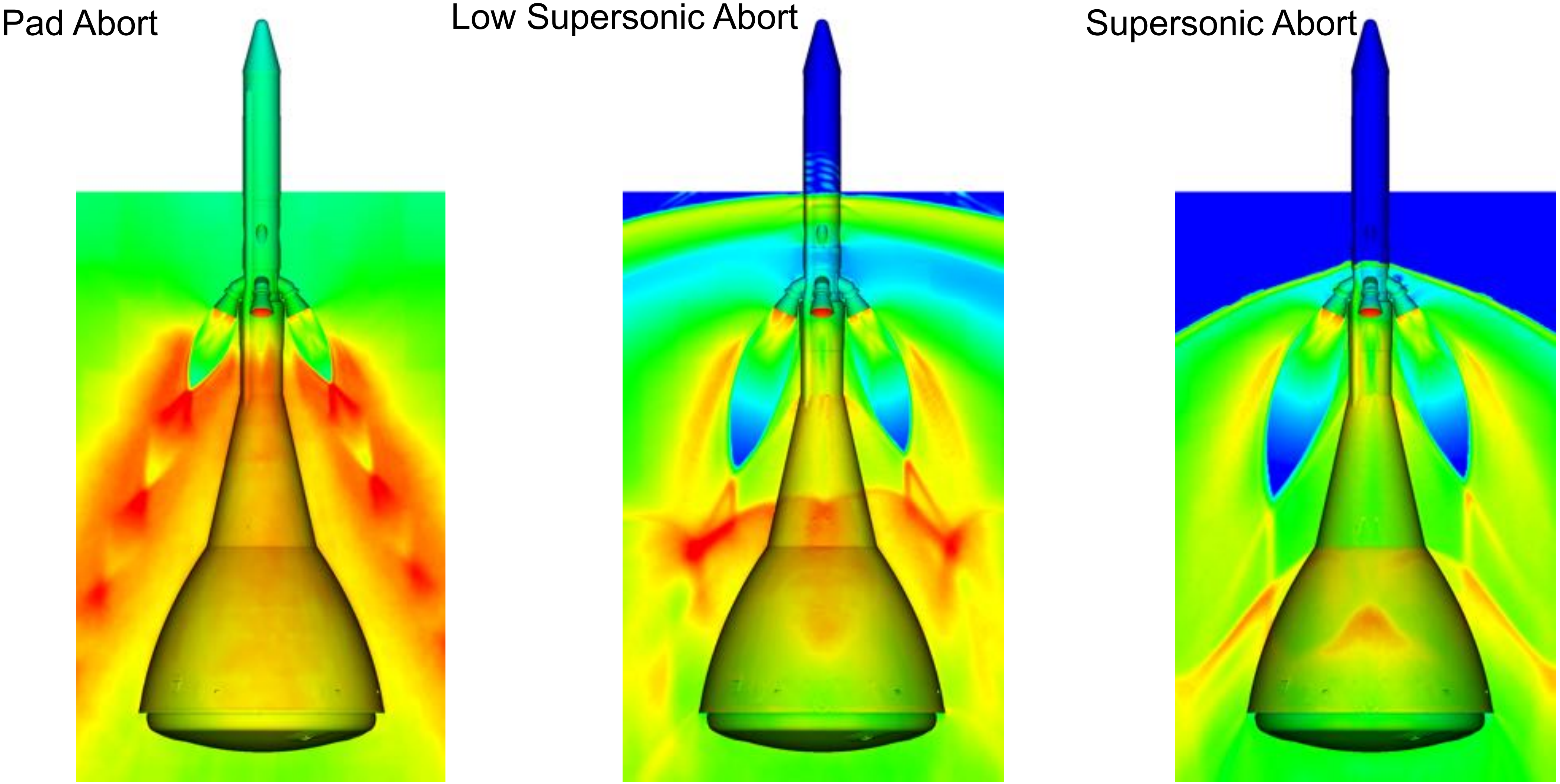

SOFIA Airplane Cavity Acoustics


Landing Gear Acoustics

Kennedy Space Center Launch Pad 39B Flame Trench Redesign

Investigating Ascent Abort Scenarios

Effect of velocity and altitude on Overall Sound Pressure Level



Pad Abort

Low Supersonic Abort

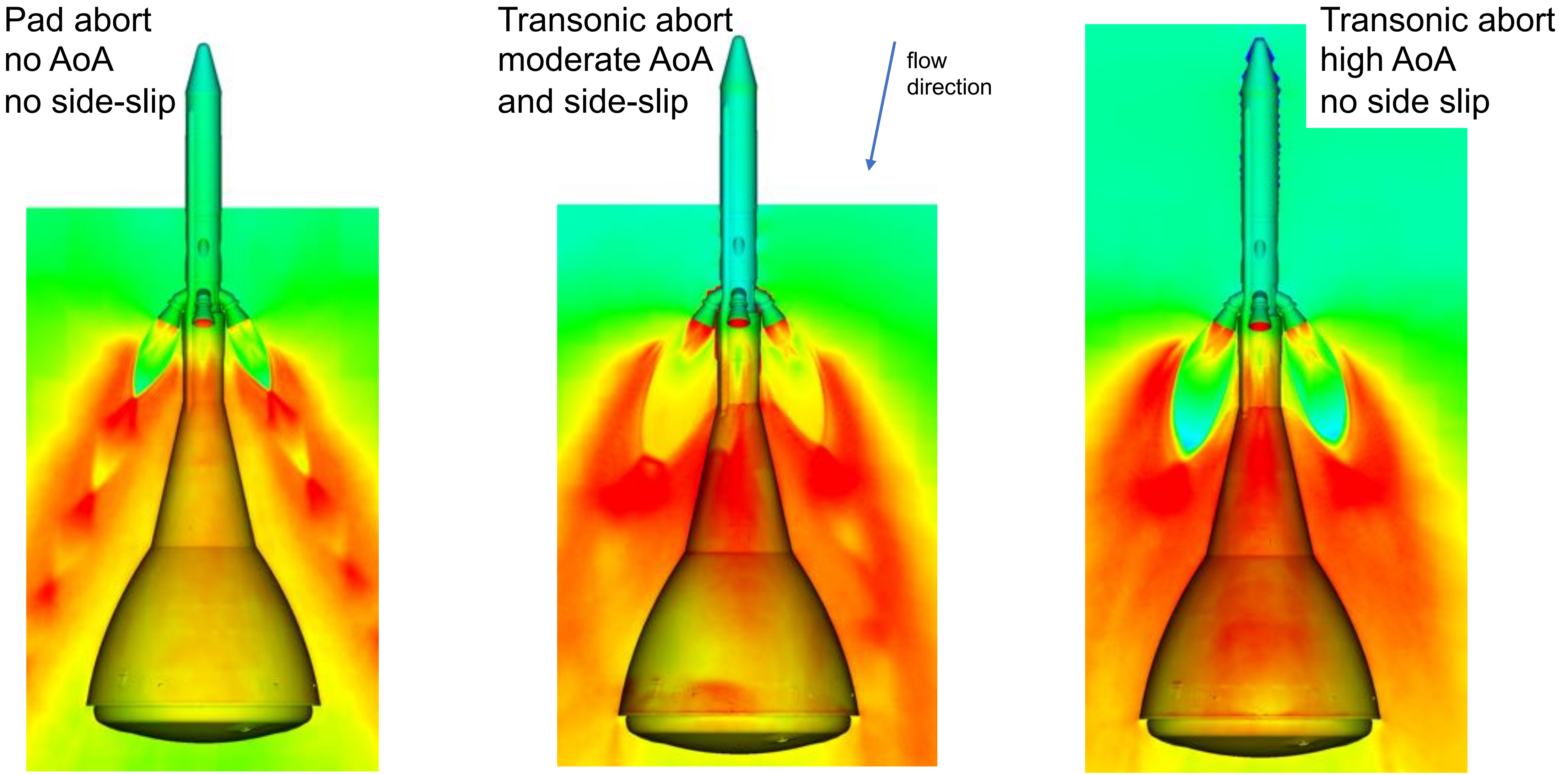
Supersonic Abort

Colormap is the same across all plots (blue is low, red is high)

Exploring High Angles of Attack

Volume rendering of temperature for LAV transonic ascent abort at high angle of attack

Effect of Angle of Attack on Acoustics



Flow for AoA is INTO the plane, side-slip is flow from right to left

*Colormap is the same on all plots

Success Factors

Convergence of following efforts made this possible:

- High parallel efficiency algorithms tailored to many-core architecture
- Capability computing resources (high # of cores over many days)
- High effective space and time resolution through high-order schemes
- Adaptive mesh refinement technology

Lessons Learned: Keys to Success

- High-order space-time scheme to reduce resolution req’s
- Solution-adaptive mesh refinement for capturing IOP
- Uninterrupted fine cells from turbulent shear layer (noise source) to vehicle/sensors of interest to capture acoustics
- Fixed refinement volumes in regions where acoustics are of interest is better than solution-based AMR → tradeoff between capturing IOP and acoustics
- High parallel efficiency/scalability to enable long integration time for converging to smooth acoustic spectra

→ Even for other grid paradigms, much of the mesh would need to be near-isotropic and solved with a small time step…