



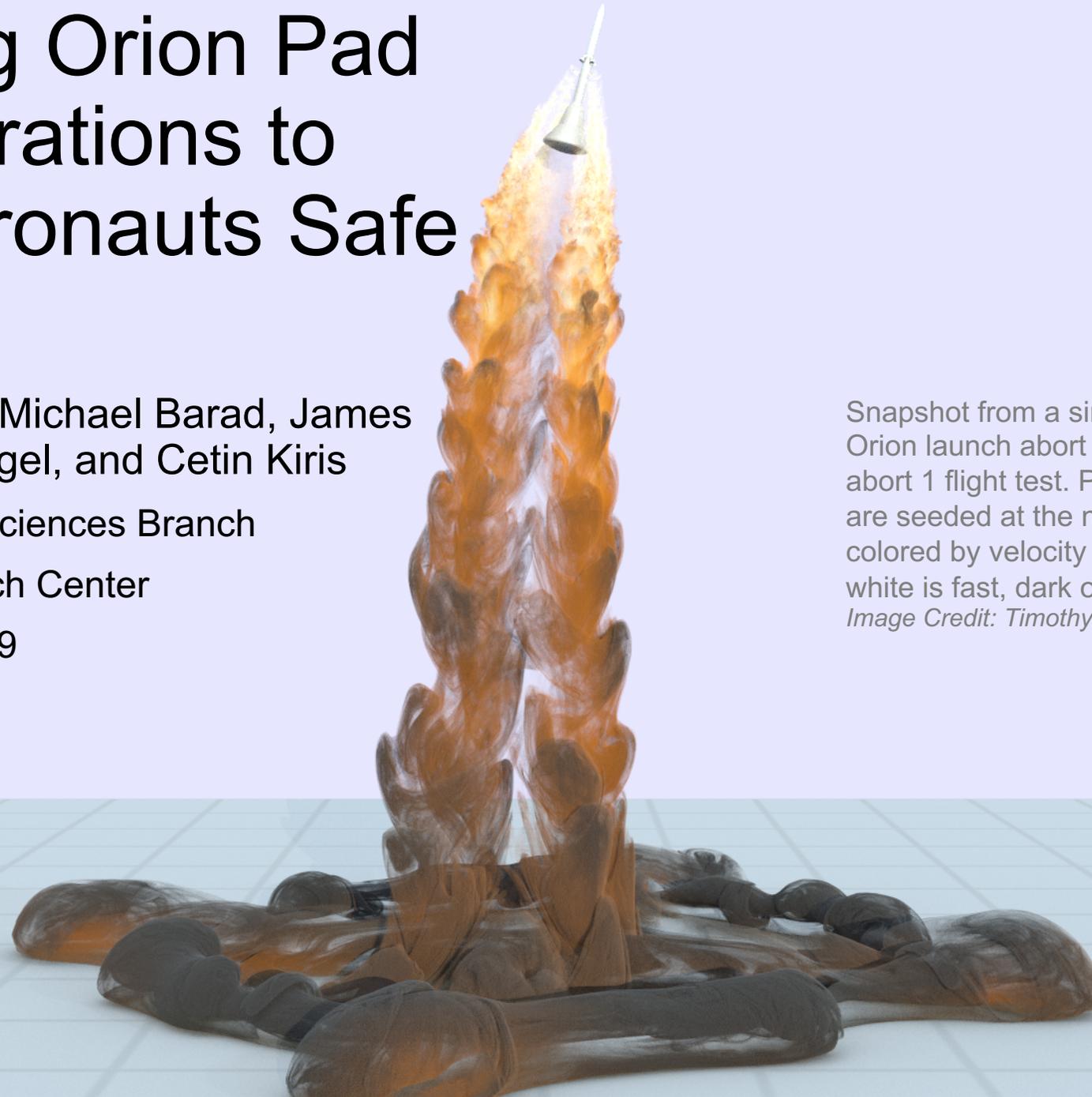
Predicting Orion Pad Abort Vibrations to Keep Astronauts Safe

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Supercomputing 2019

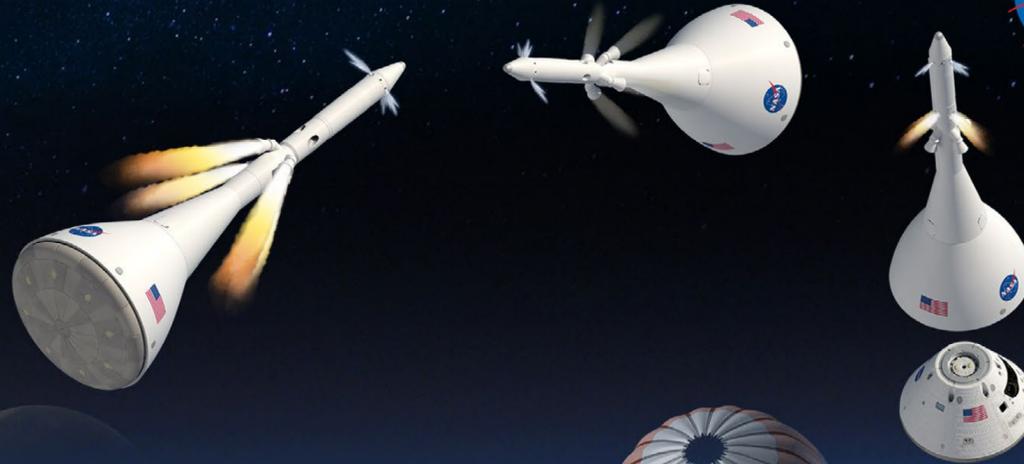


Snapshot from a simulation of the Orion launch abort vehicle pad abort 1 flight test. Passive particles are seeded at the nozzles and colored by velocity magnitude: white is fast, dark orange is slow.
Image Credit: Timothy Sandstrom



ORION

Launch Abort System (LAS)



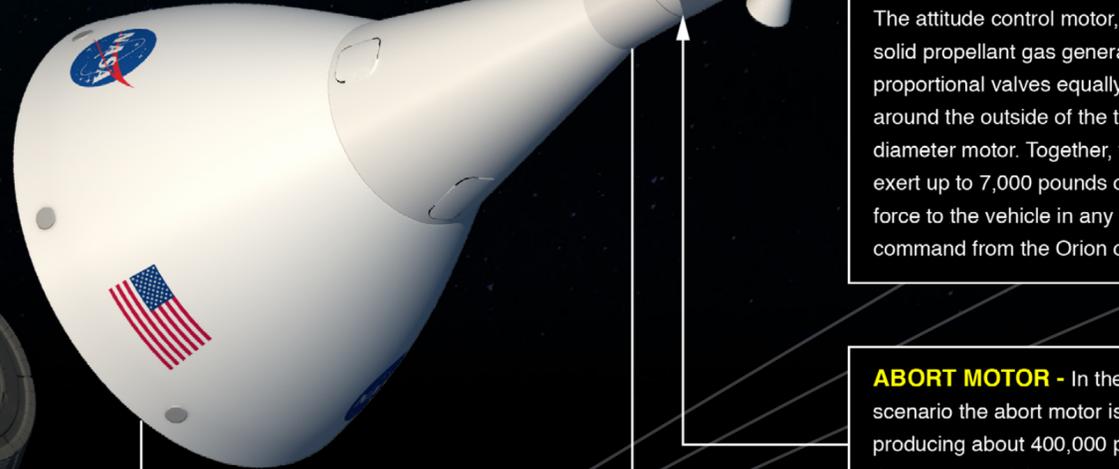
NASAfacts

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.

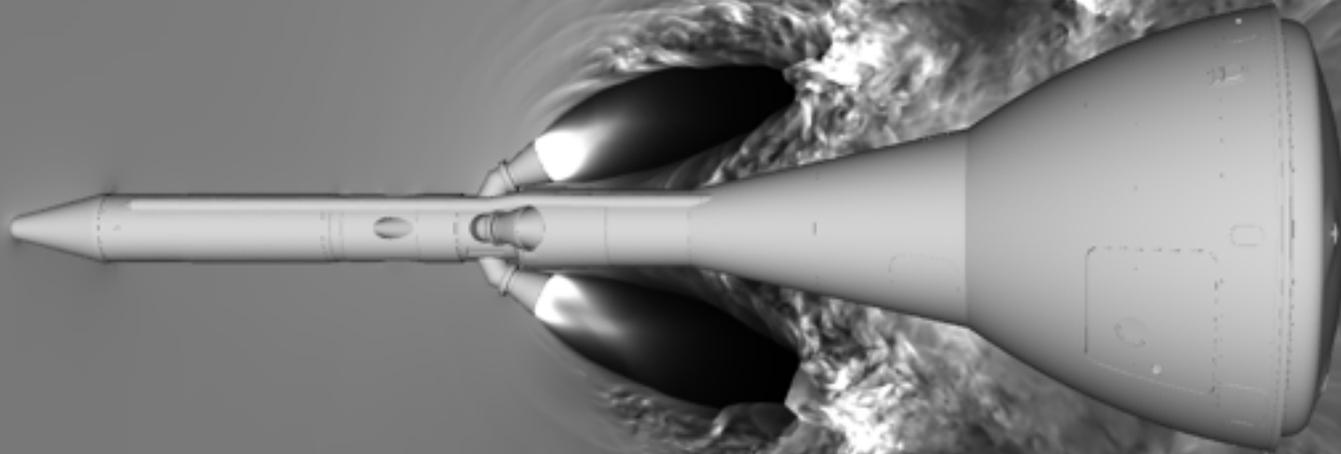
FAIRING ASSEMBLY - The fairing assembly is a lightweight composite structure that protects the capsule from the environment around it, whether it's heat, wind or acoustics.

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

Near-Field Plume Acoustics (NFPA) Towers 1 & 2

Crane

Heat Shield Measurement Apparatus

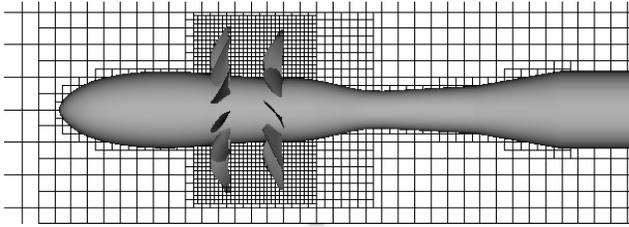
Crane

NFPA

CFD Grid Paradigms

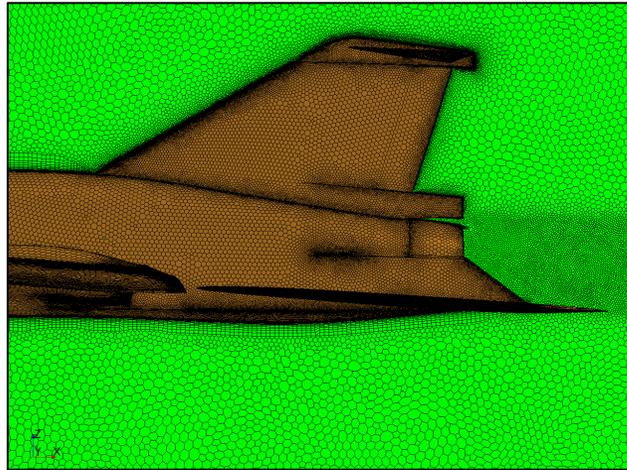
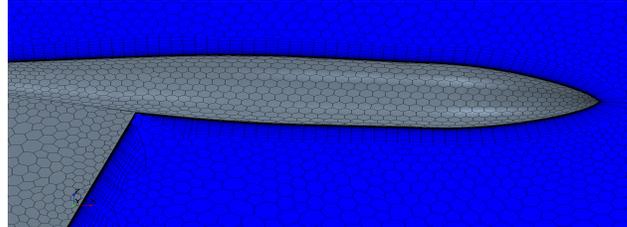


**Structured
Cartesian AMR**



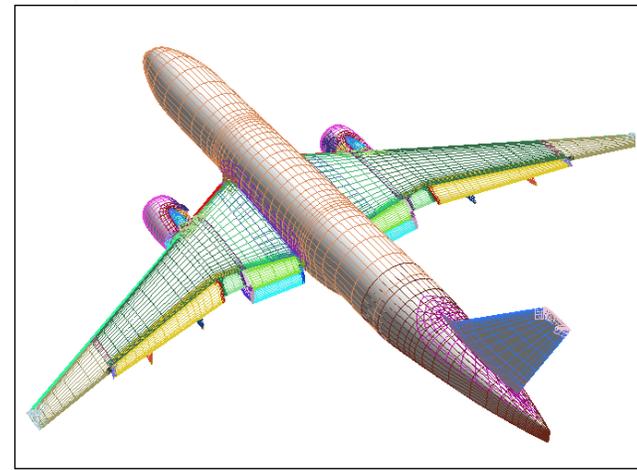
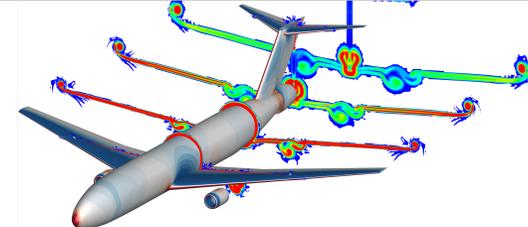
- Essentially no manual grid generation
- Highly efficient Structured Adaptive Mesh Refinement (AMR)
- Low computational cost
- Reliable higher order methods
- Non-body fitted -> Resolution of boundary layers inefficient

**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

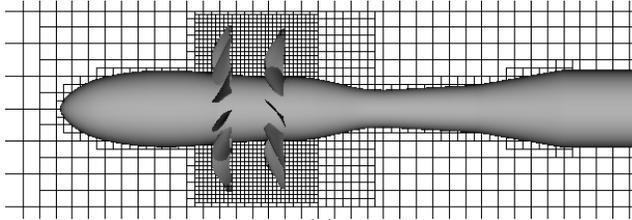
**Structured
Curvilinear**



- 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**

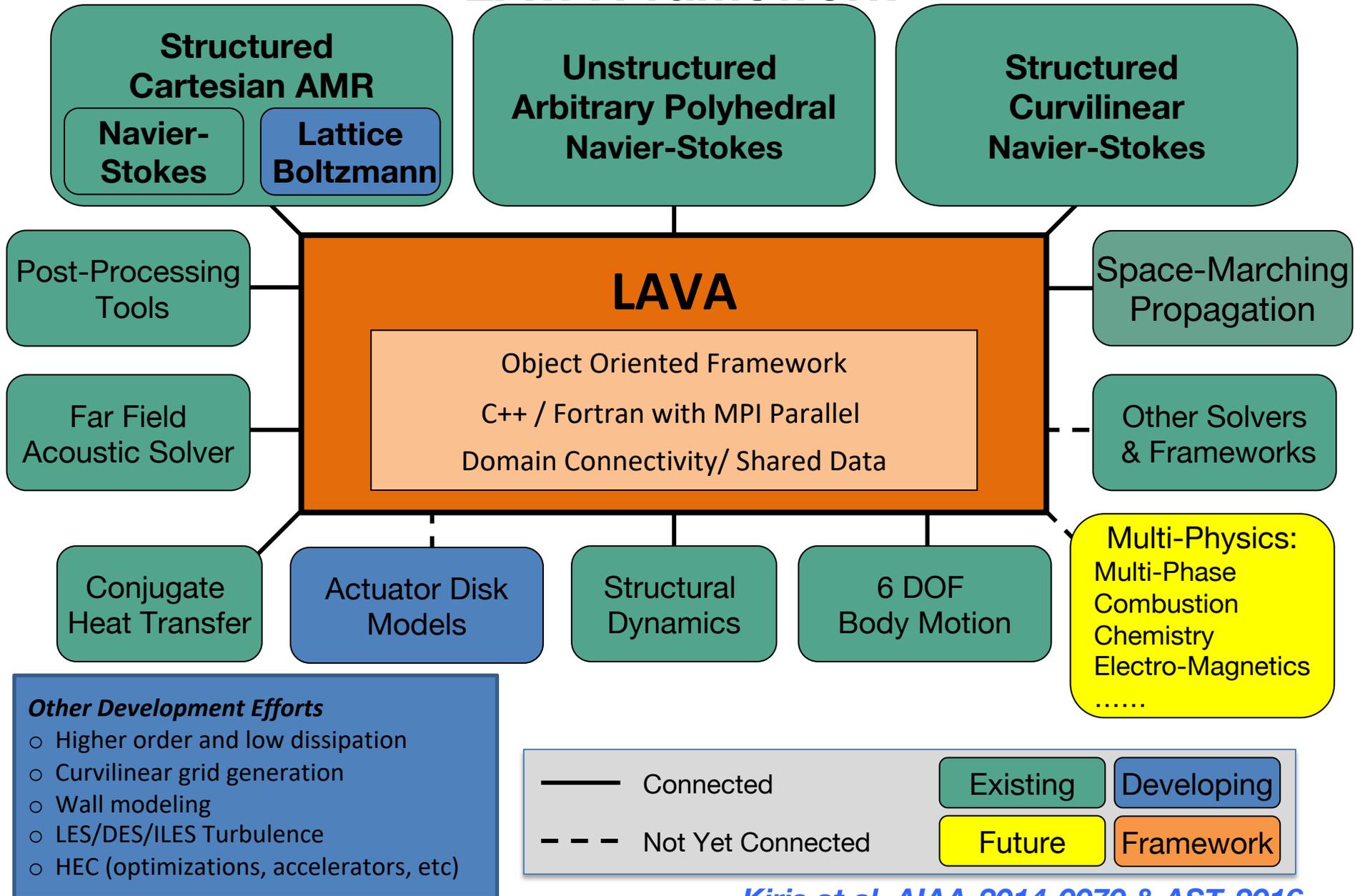
Predict transient pressure loads and acoustics on structures for QM-1 abort motor ground test:

- 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

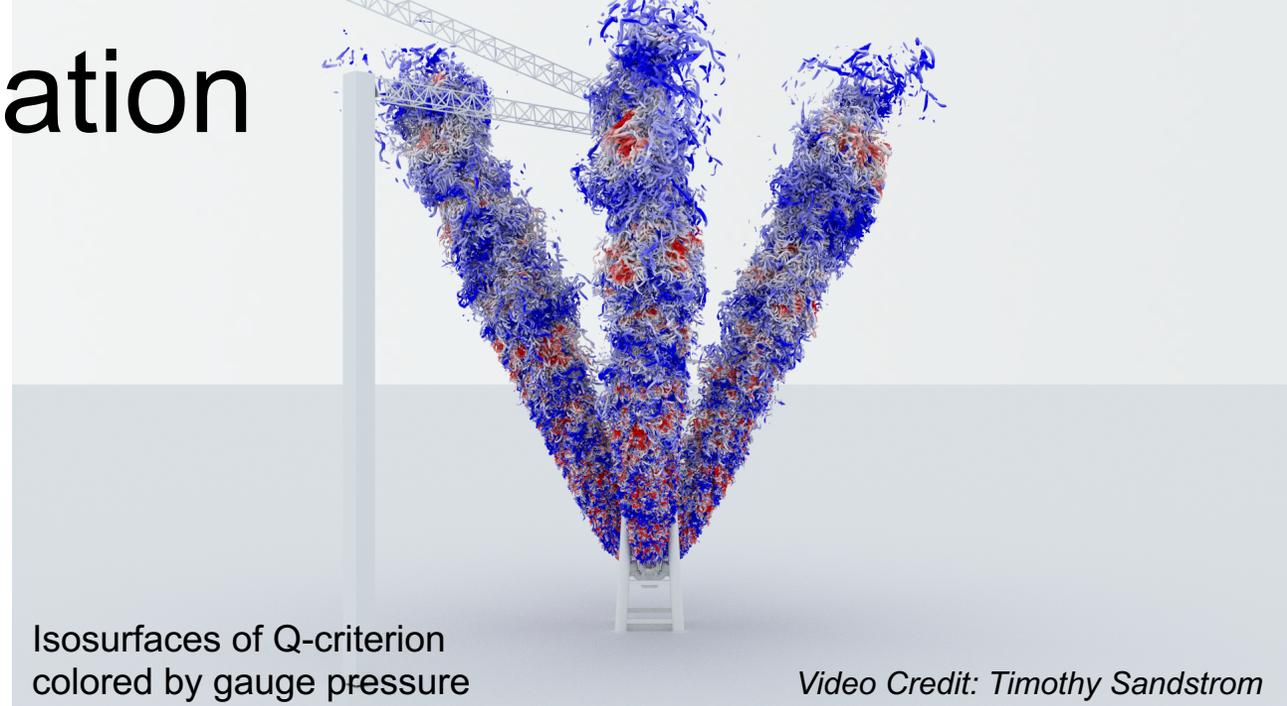
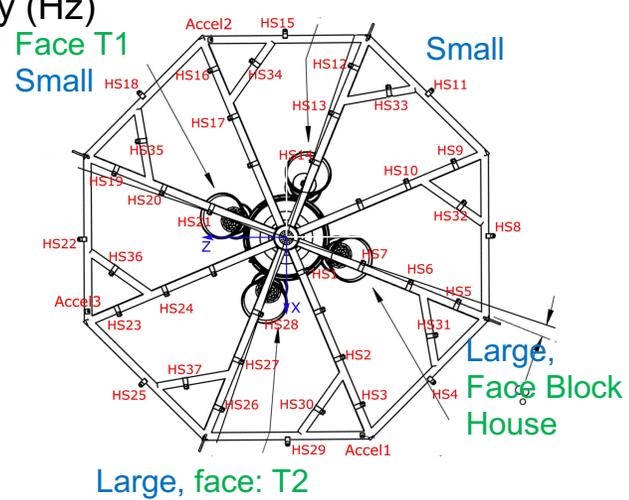
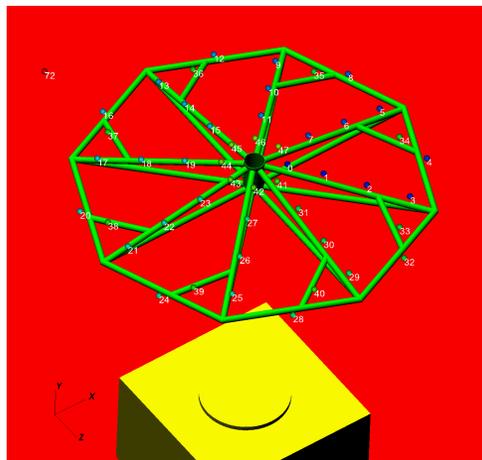
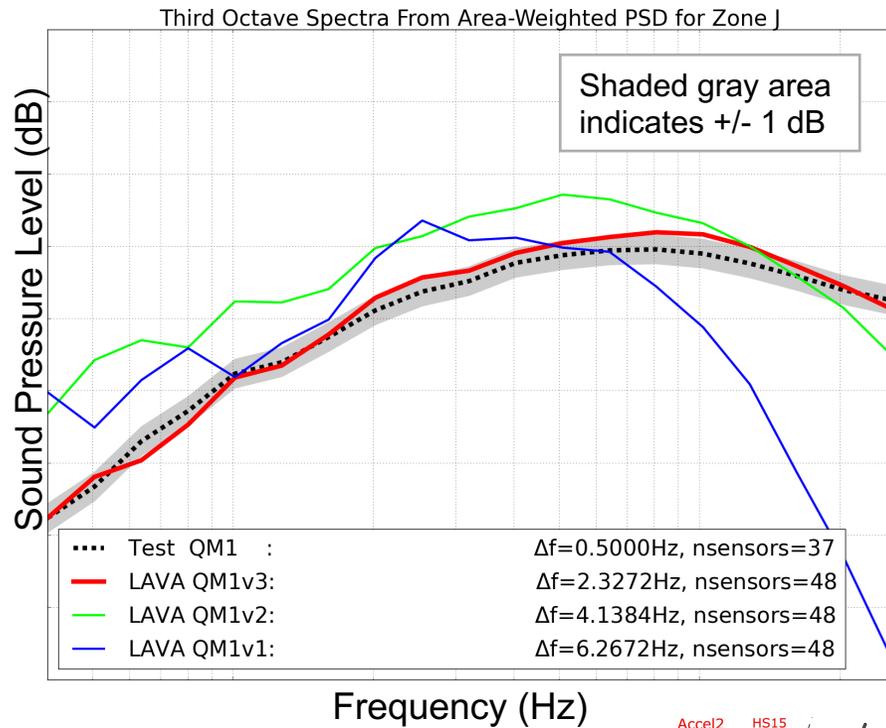


LAVA Framework

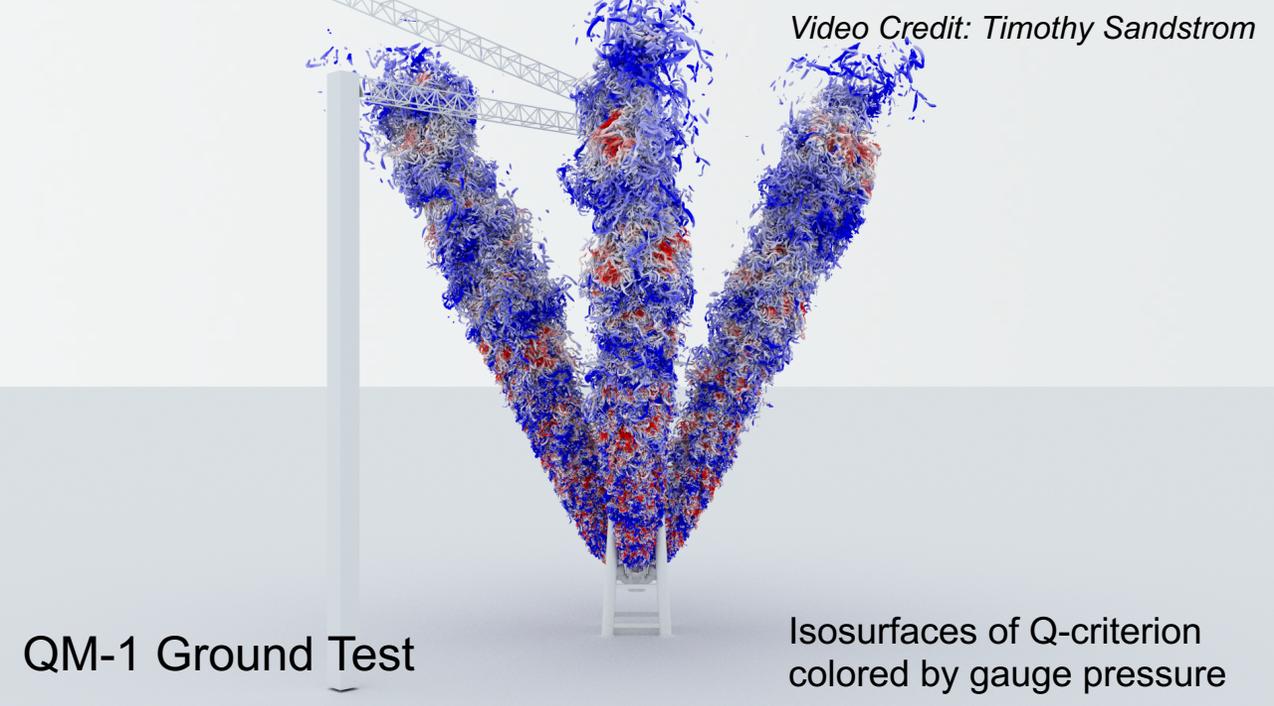


QM-1 Ground Test Validation

Heat Shield Area-Weighted Kulite Acoustics



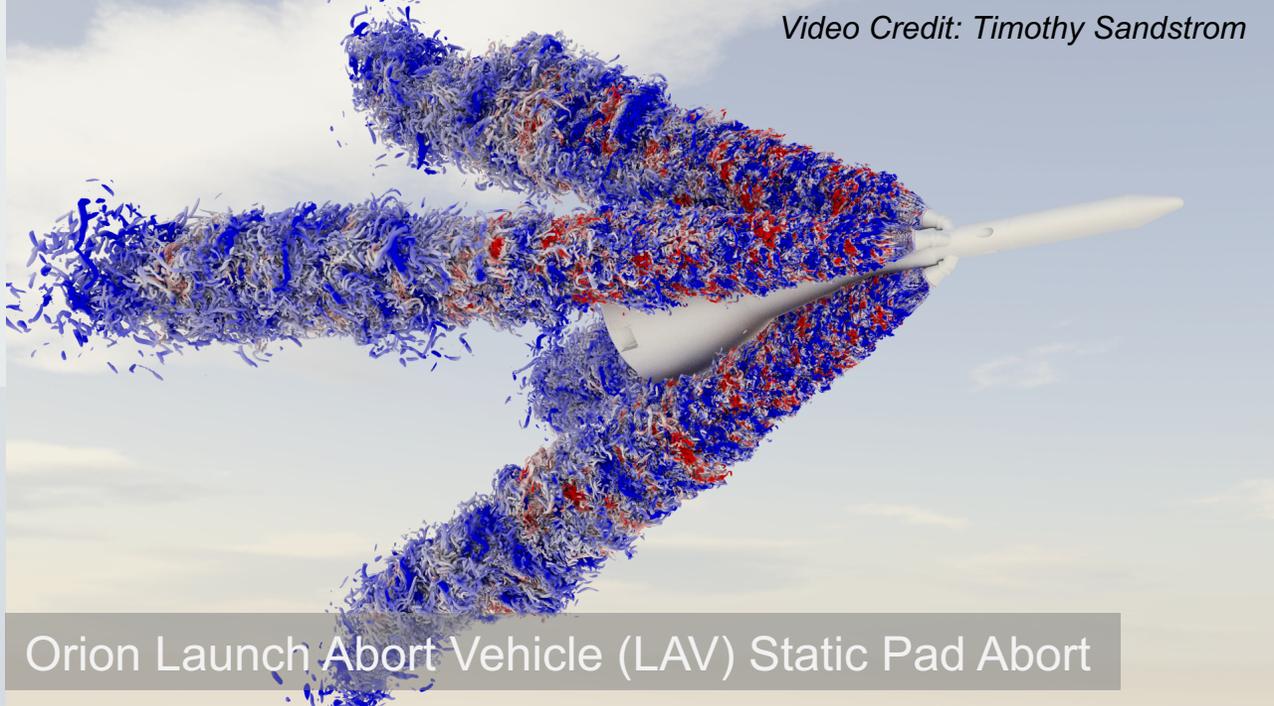
HPC Resources	
Wallclock time (days)	18
Number of nodes	80
Node type	Skylake
Total number of cores	3,200
Time simulated (seconds)	0.38
Volume data (TB)	100



Video Credit: Timothy Sandstrom

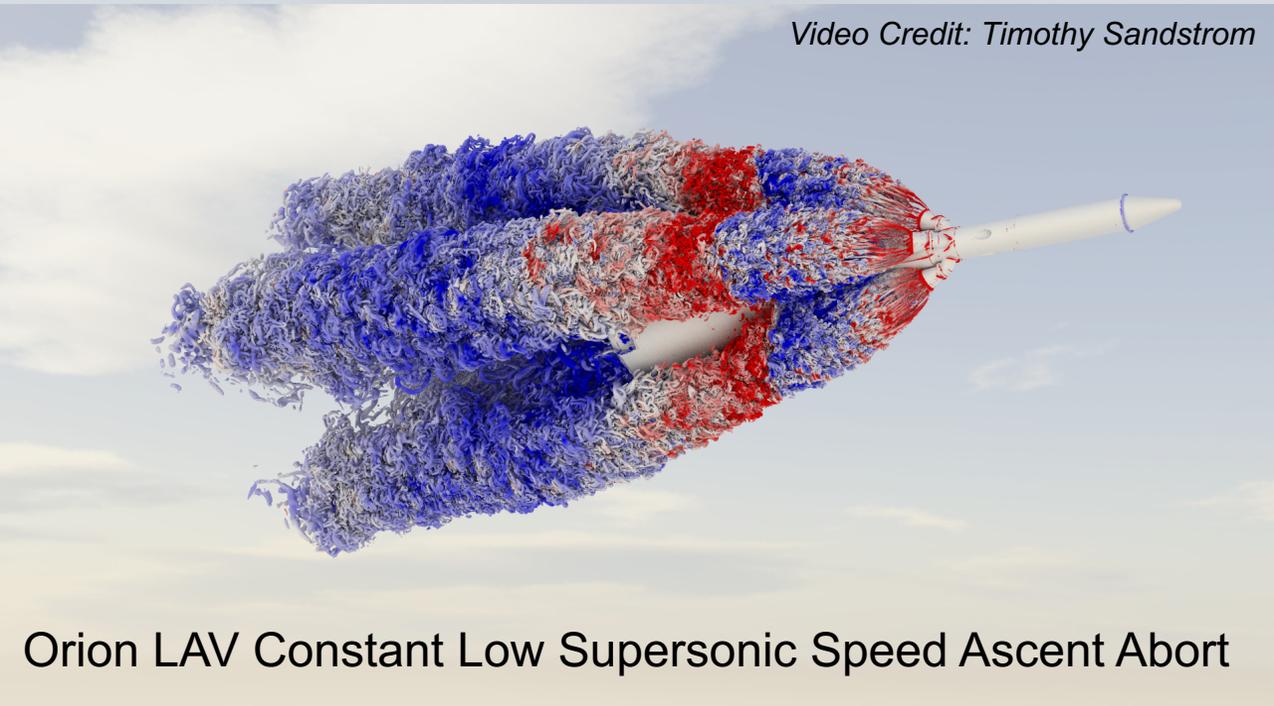
QM-1 Ground Test

Isosurfaces of Q-criterion colored by gauge pressure



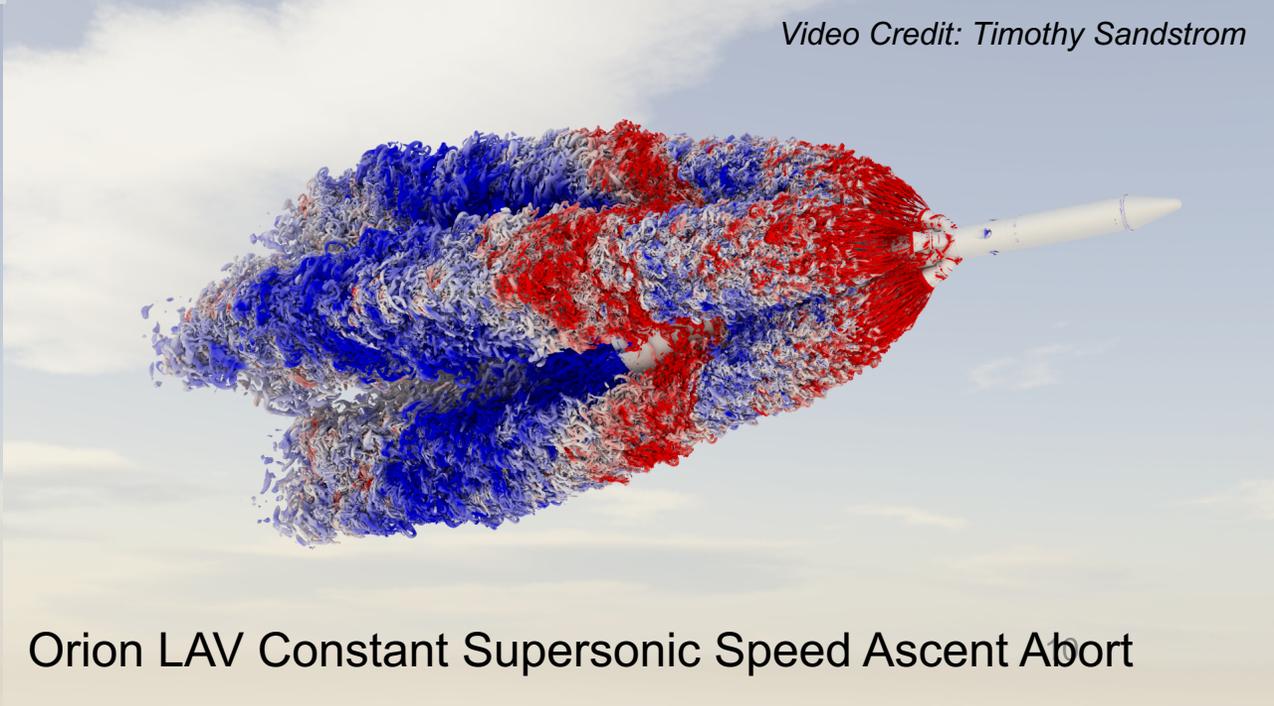
Video Credit: Timothy Sandstrom

Orion Launch Abort Vehicle (LAV) Static Pad Abort



Video Credit: Timothy Sandstrom

Orion LAV Constant Low Supersonic Speed Ascent Abort



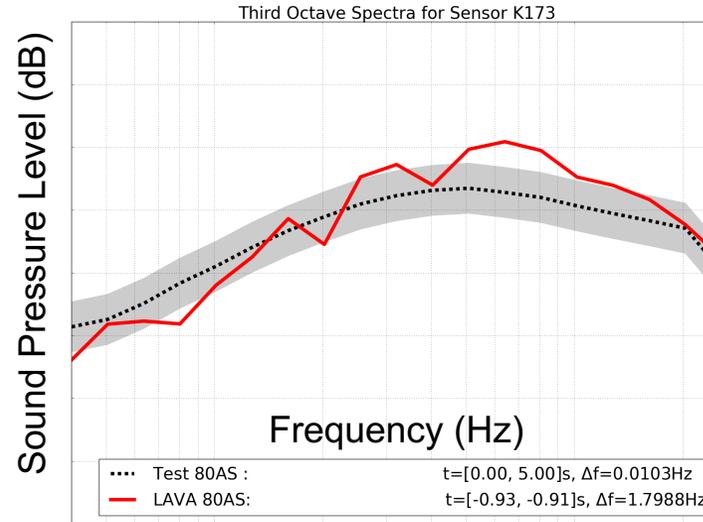
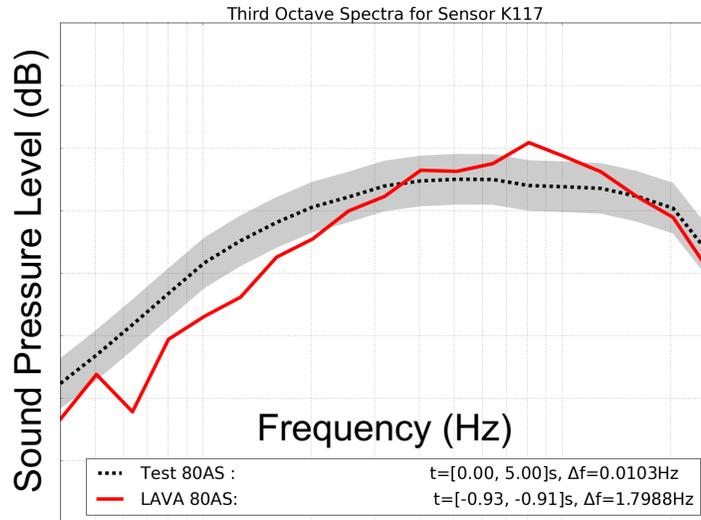
Video Credit: Timothy Sandstrom

Orion LAV Constant Supersonic Speed Ascent Abort

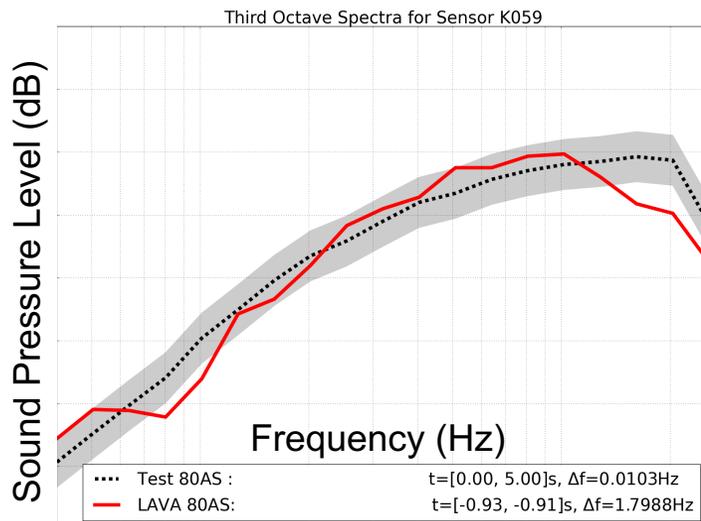
Wind Tunnel Experimental Validation

Transonic ascent abort at moderate angle of attack and side slip

- Wind Tunnel Measurements
- LAVA Predictions

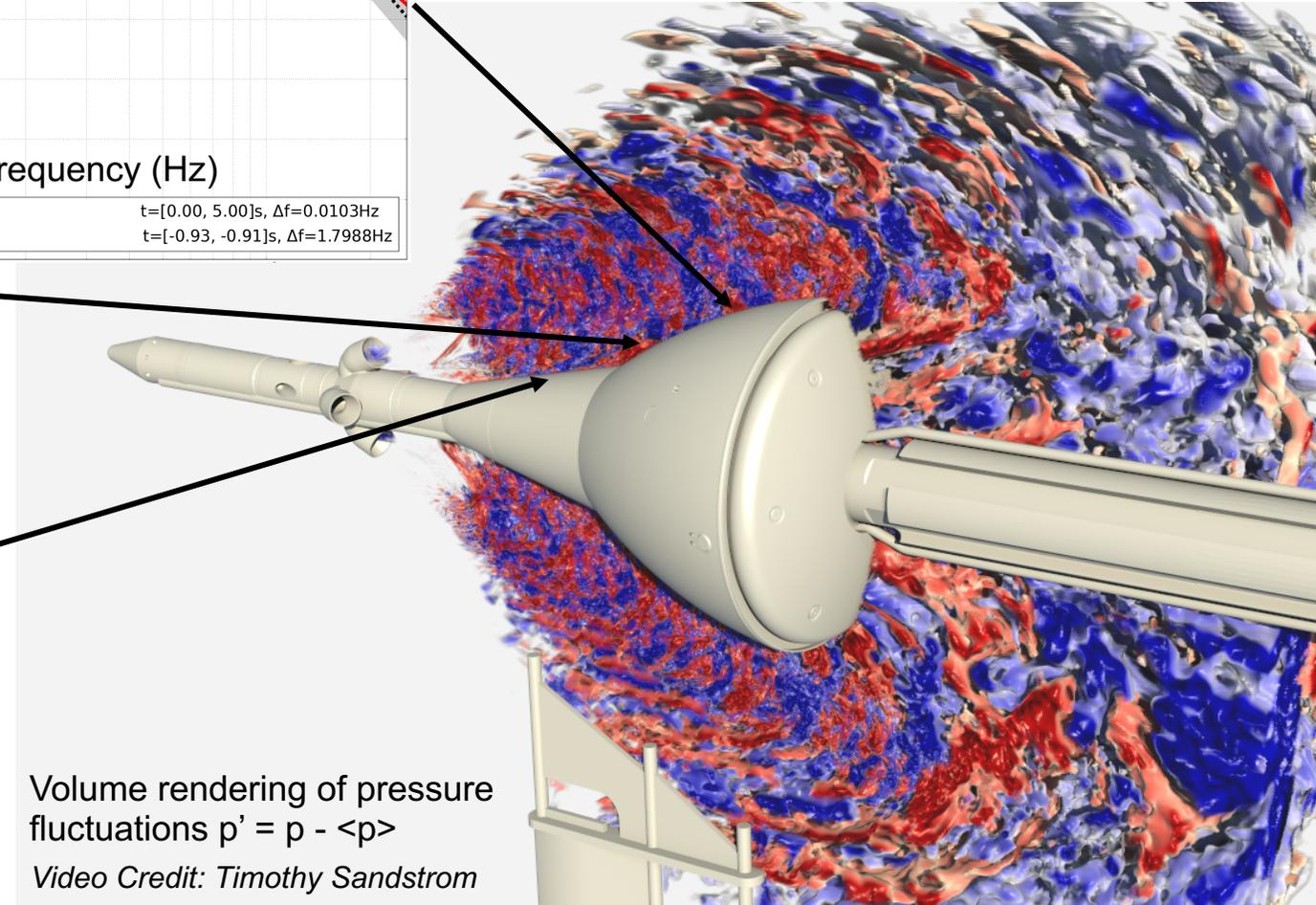


Shaded gray area is +/- 2 dB because of uncertainty in simulation results due to short integration time (0.02 s) vs experiment (5.00 s)

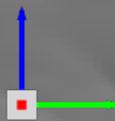


Volume rendering of pressure fluctuations $p' = p - \langle p \rangle$

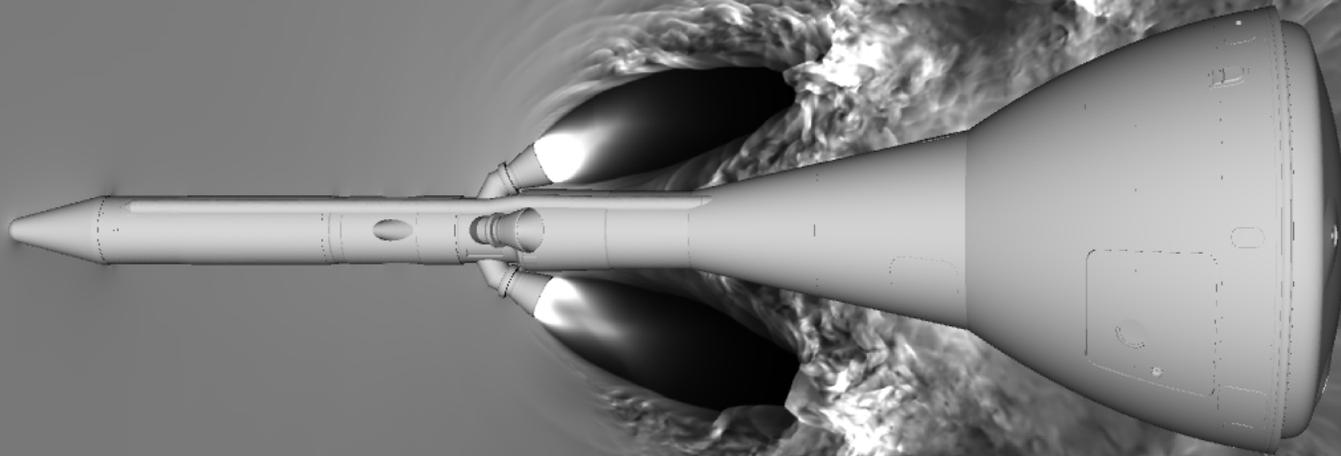
Video Credit: Timothy Sandstrom



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)

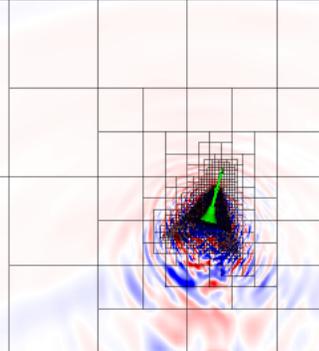


Flight Test Validation

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

Flight Test Validation

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

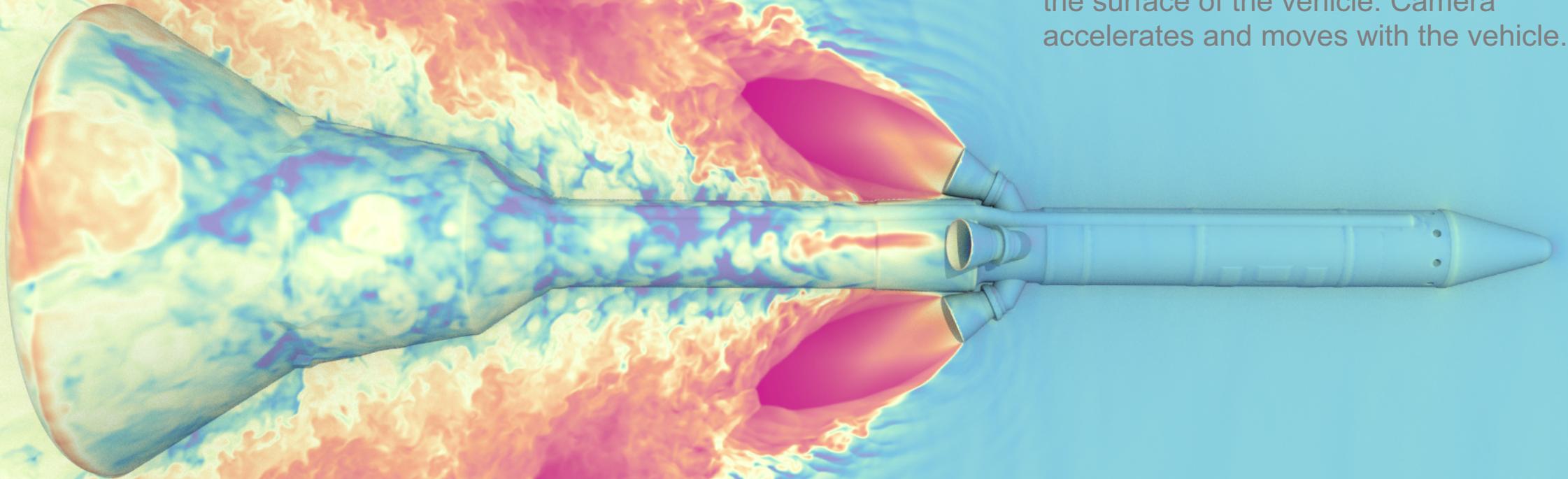
Video shows passive particles seeded at the nozzle colored by velocity magnitude: white is fast, dark orange is slow



Flight Test Validation

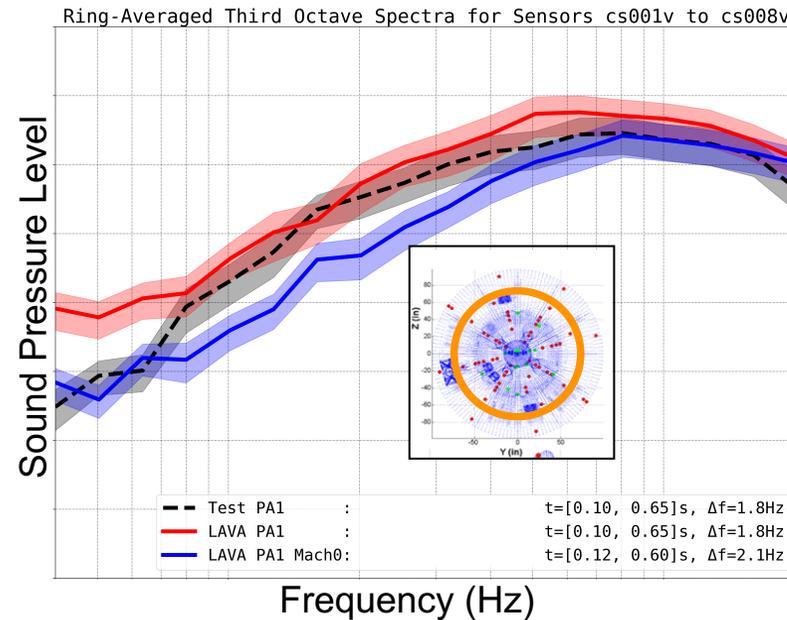
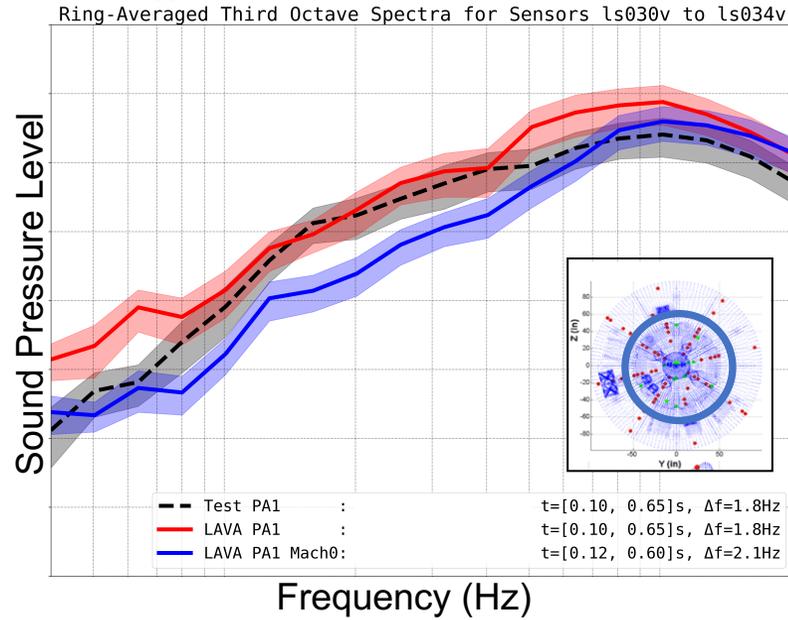
Pad Abort 1 flight test where Orion LAS accelerates from rest to 10x Earth's gravity

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

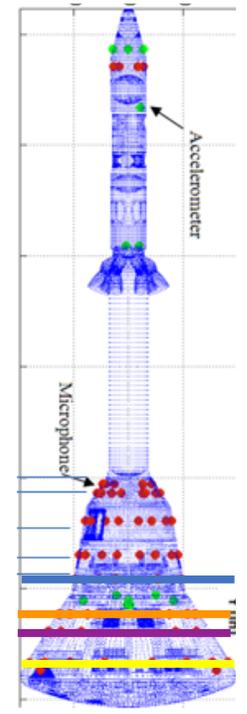
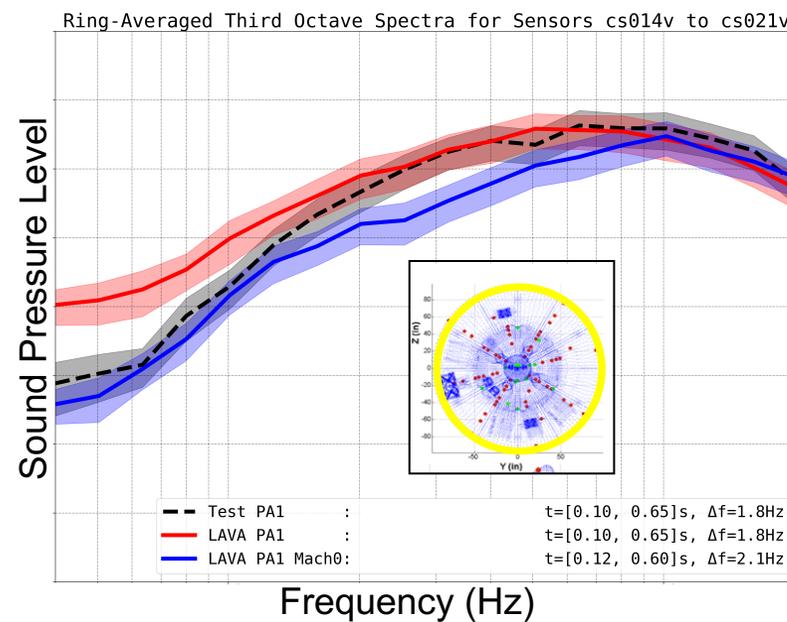
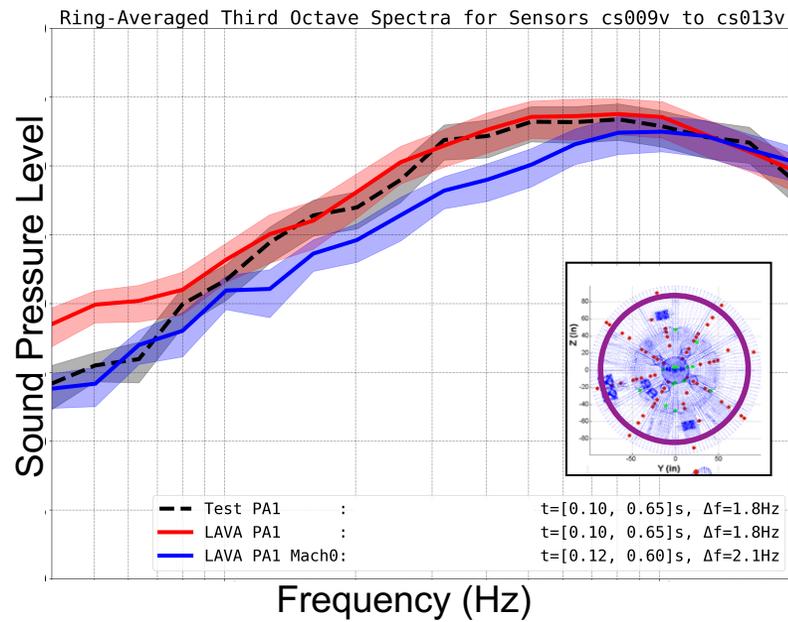


Flight Test Validation

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



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



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

HPC Impact

High parallel efficiency algorithms tailored to many-core architecture



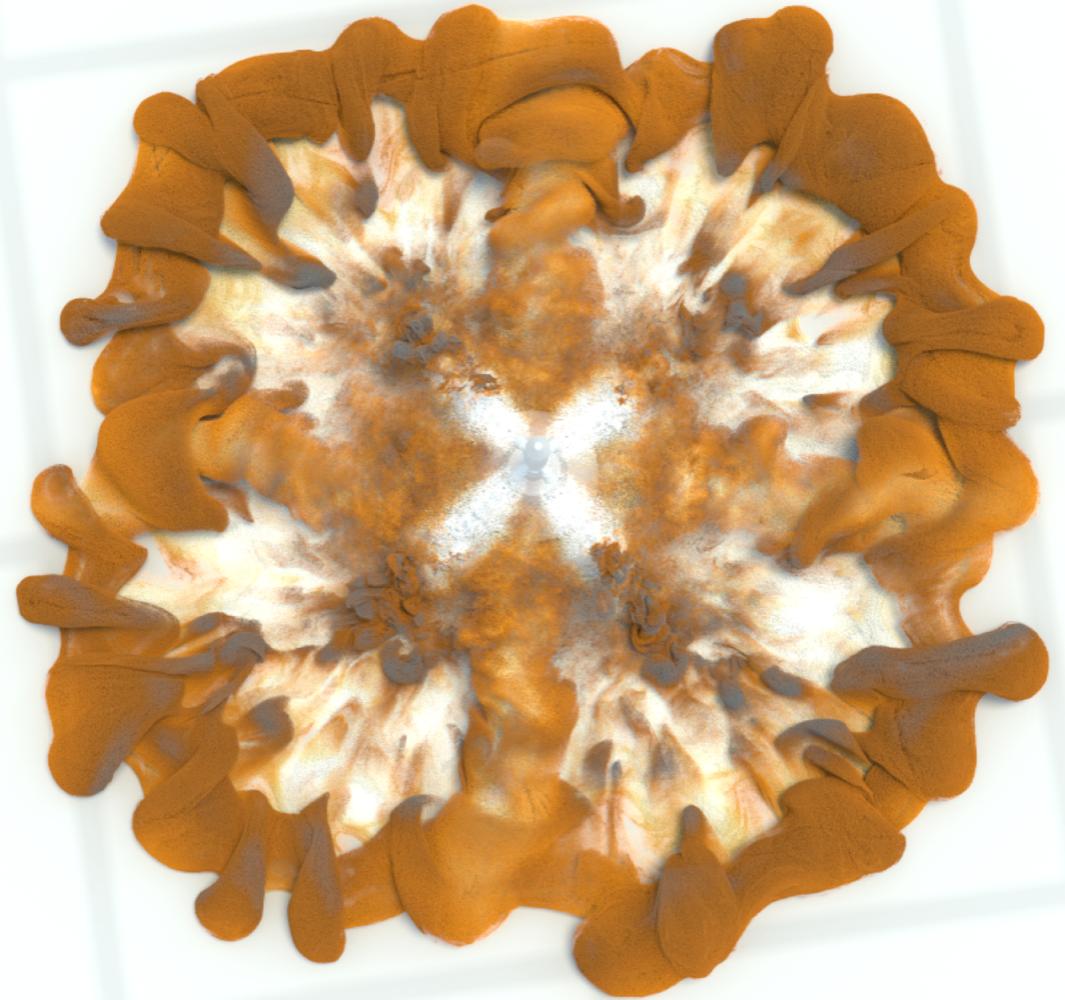
High space and time resolution through high-order schemes



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

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- NAS Visualization Team:
 - Timothy Sandstrom
- LAVA Team:
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