Predicting Aircraft and Spacecraft Acoustics*

* partially funded by NASA's HEOMD and ARMD projects

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Supercomputing 2018 (SC18) Conference,
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Outline

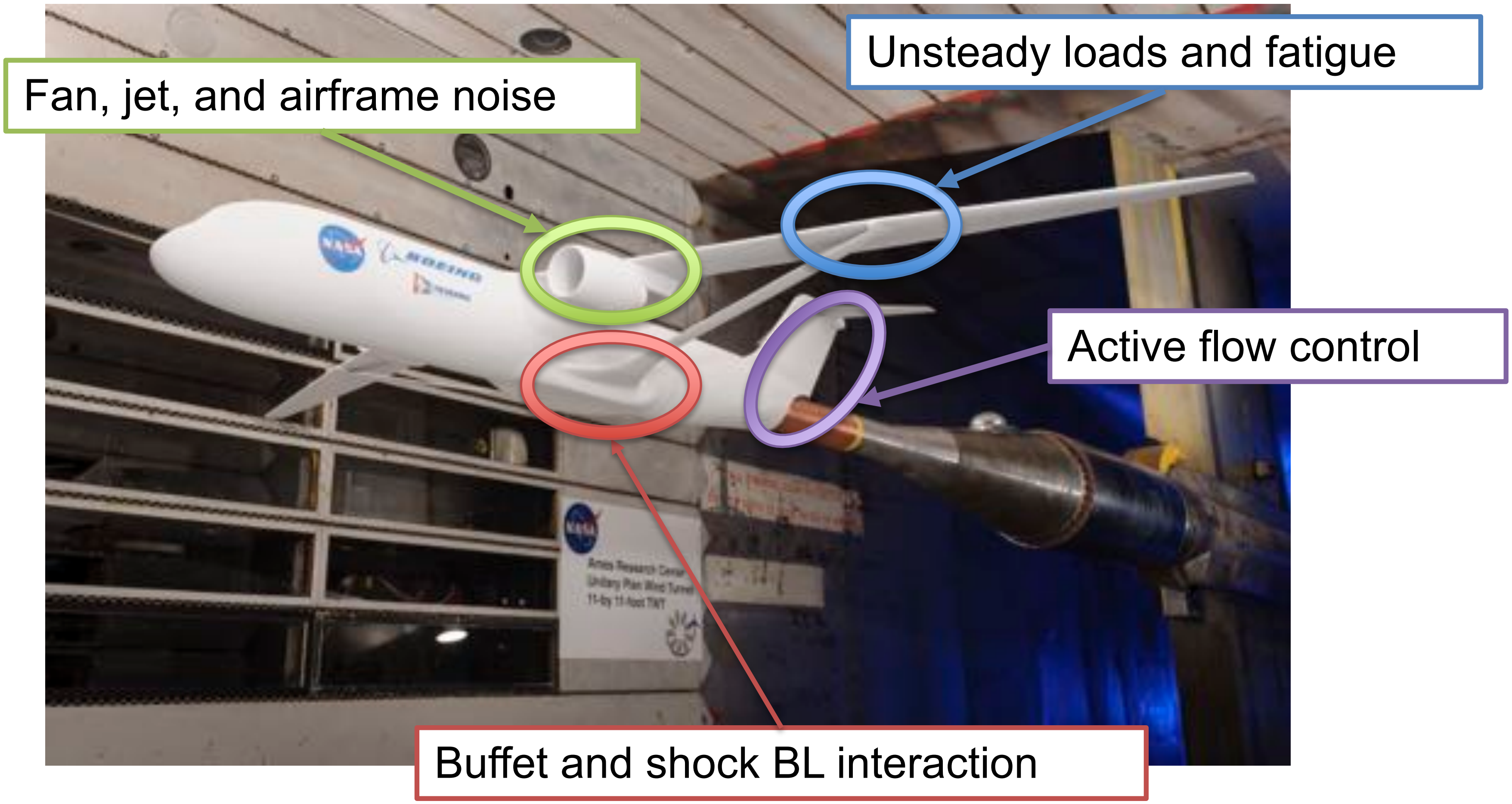
- **Motivation**
- **LAVA Framework**

- **Launch: Kennedy Space Center Infrastructure Redesign**
  - Ignition over-pressure waves
- **Ascent: Orion Multi-Purpose Crew Vehicle Launch Abort System**
  - Transient pressure loads
- **Vehicle Aerodynamics: Low-Boom Flight Demonstrator**
  - Jet noise
- **Propeller Noise: Small UAS Acoustics**
  - Validation for moving geometry and tonal noise computation – Lattice Boltzmann
- **Fan Noise**
  - R4 Source Diagnostic Test - Toward Fan Broadband Noise Prediction

Motivation

✓ **Increase predictive use of computational aerosciences capabilities for next generation aviation and space vehicle concepts.**

- The next frontier is to use wall-modeled and/or wall-resolved large-eddy simulation (LES) to predict:



Challenges in Computational Aero-Acoustics

✓ Grid Generation

- Structured Cartesian, Unstructured Polyhedrals, Structured Curvilinear; each paradigm has its own pros and cons → flexibility to pick best suited approach
- Remains a bottleneck → automation and solution-adaption

✓ Resolving/Modeling Turbulent Scales

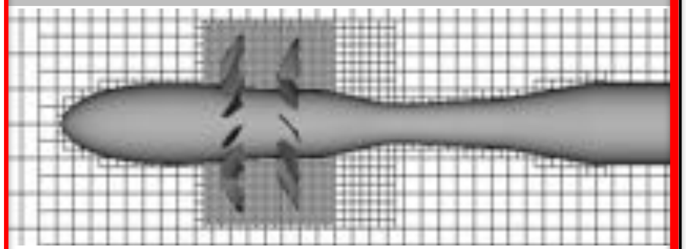
- Resolving thin wall-bounded turbulence is too computationally costly for most aerospace applications → hybrid methods & wall-models
- Resolving all relevant scales of turbulent motion away from walls is also prohibitive → Higher order less dissipative numerics & subgrid-scale modeling

✓ Computational Requirements

- Space and time resolution requirements for acoustics problems are demanding.
- Explore revolutionary approaches to reduce computational time to reach converged statistics and spectra like Lattice-Boltzmann

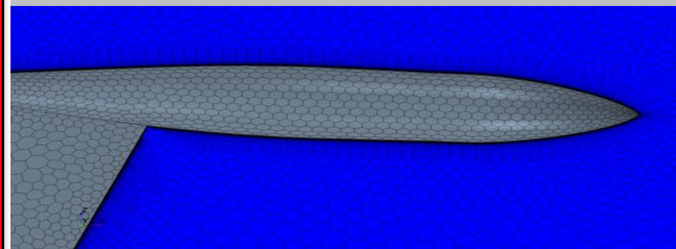
Computational Grid Paradigms

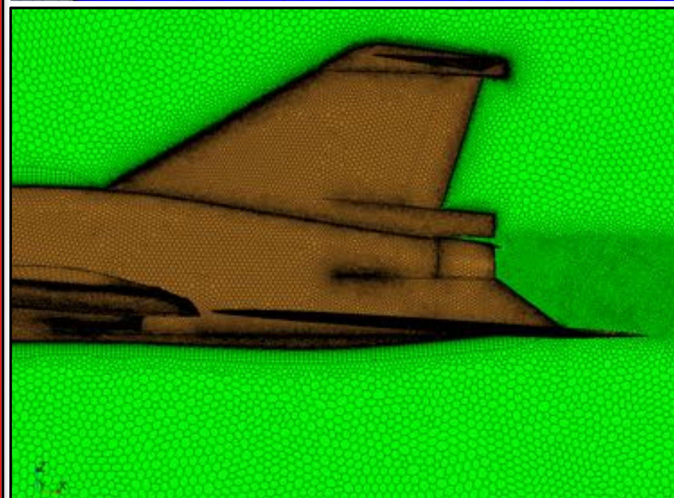
Structured Cartesian AMR



- 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

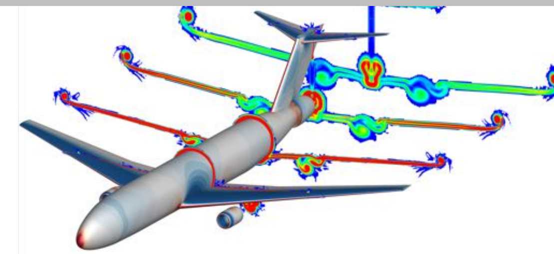
Unstructured Arbitrary Polyhedral

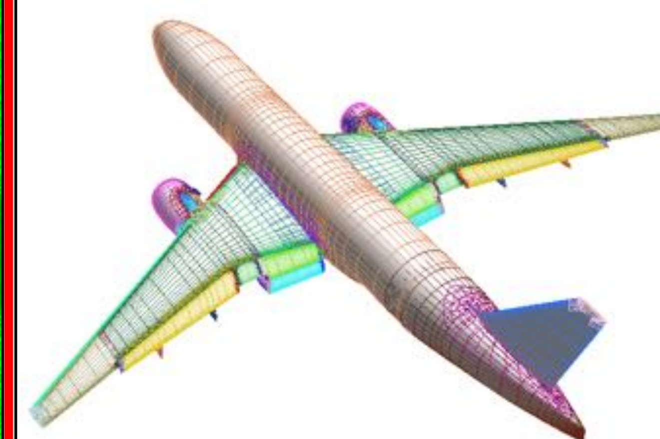




- Partially automated grid generation
- Body fitted grids
- Grid quality can be challenging
- High computational cost
- Higher order methods yet to fully mature

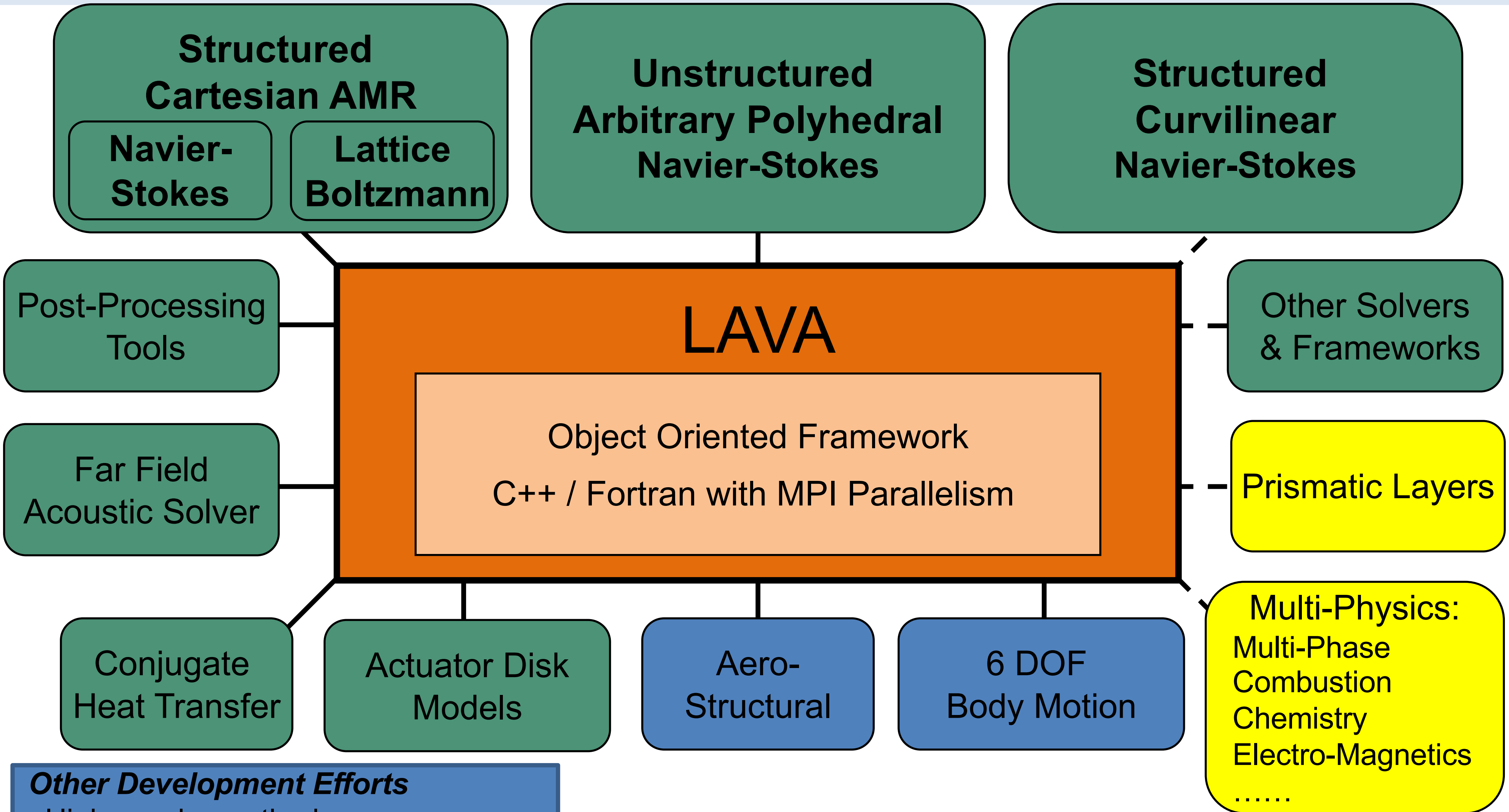
Structured Curvilinear



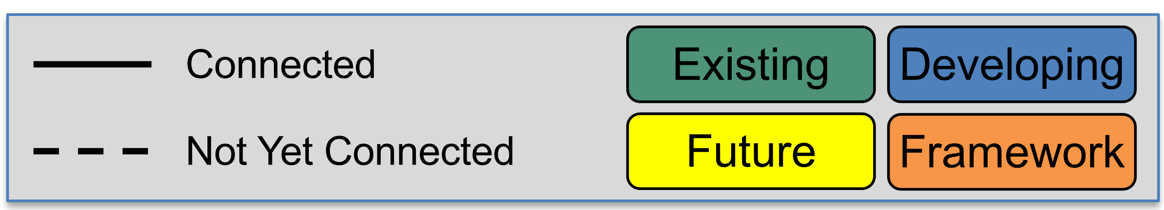


- High quality body fitted grids
- Low computational cost
- Reliable higher order methods
- Grid generation largely manual and time consuming

Launch, Ascent, and Vehicle Aerodynamics
LAVA Framework



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



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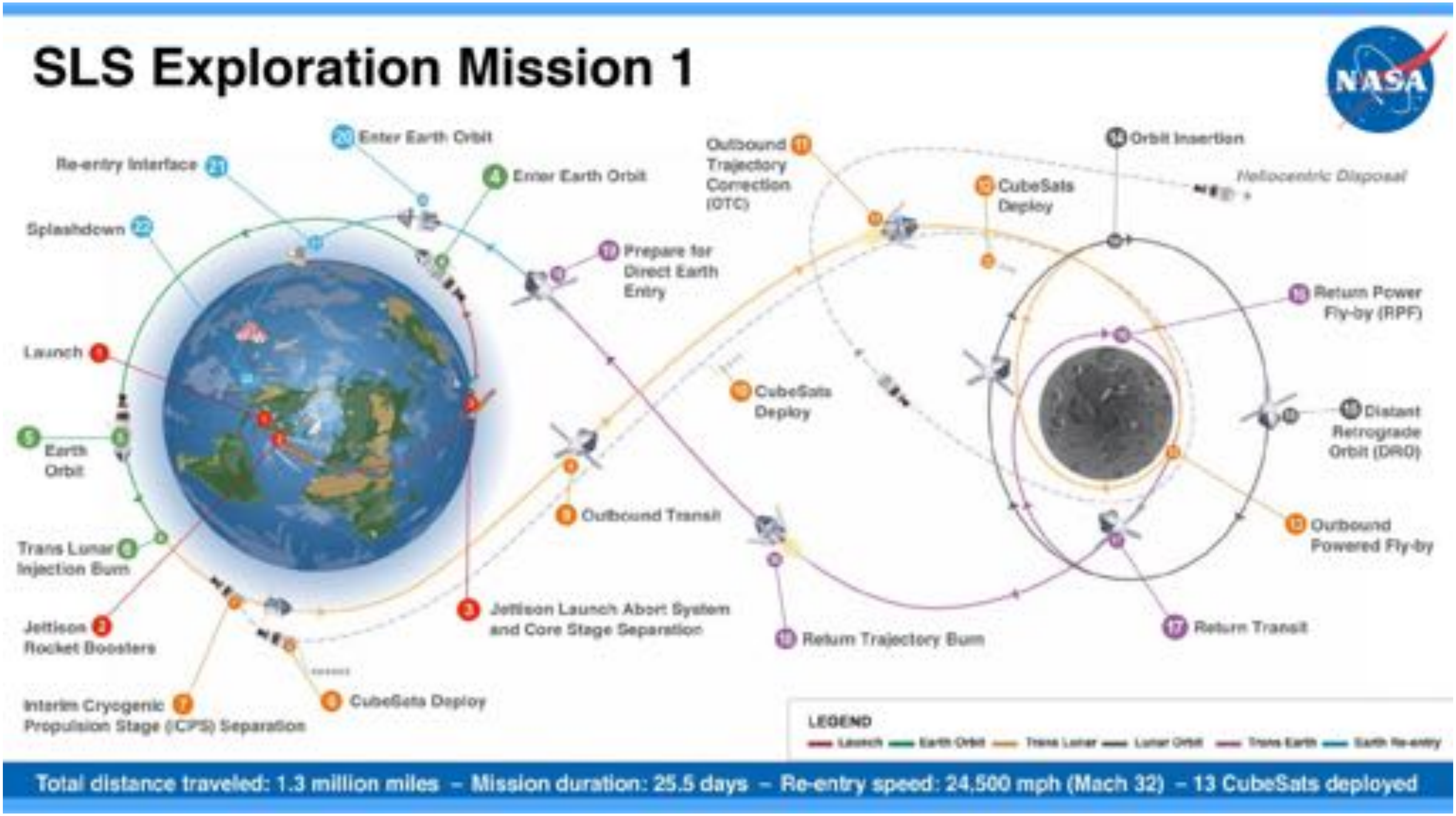
Launch Environment Simulations



Kennedy Space Center’s Pad 39B

https://www.youtube.com/watch?v=9matDigB2w4

After many years of harsh rocket launches, the Main Flame Deflector (MFD) at Kennedy Space Center has been upgraded in anticipation of flights of NASA’s next generation Space Launch System.

The new MFD has a much easier to maintain shingled steel surface.

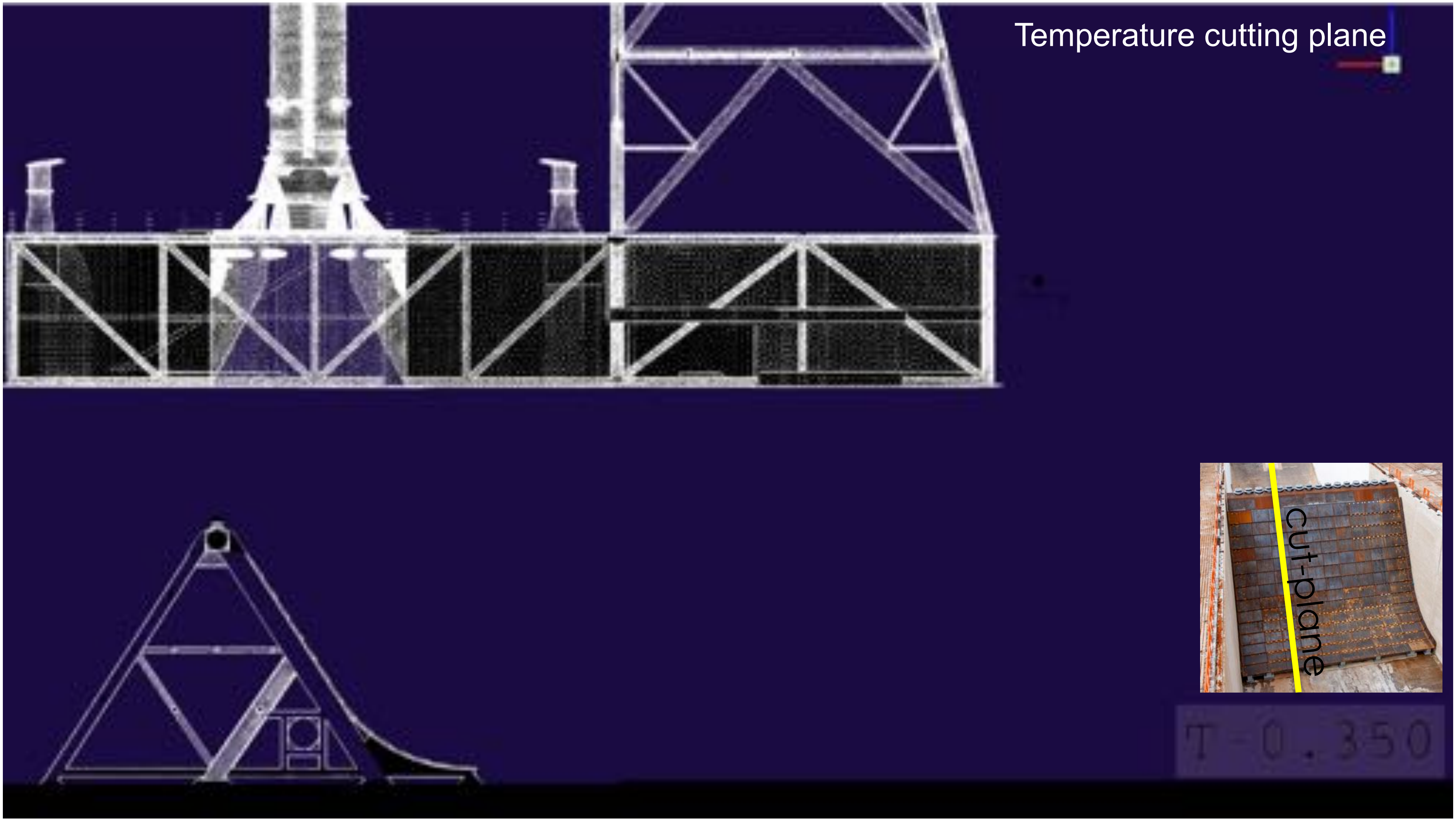
Flame Trench Redesign

Gaps between the MFD and the trench wall, and the gaps between the steel plates of the MFD itself could allow hot plume gases and strong acoustic waves to affect structures under the MFD.

High-resolution computational fluid dynamics (CFD) simulations have been carried out to help identify thermal, pressure, and flow environments on and around the geometrically complex MFD.

Lessons Learned: Launch Environment

- Robustness is critical
- Compare early and often to any relevant experimental data
- Use the best tool for the deliverable



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National Aeronautics and Space Administration

ORION

Launch Abort System (LAS)

NASAfacts

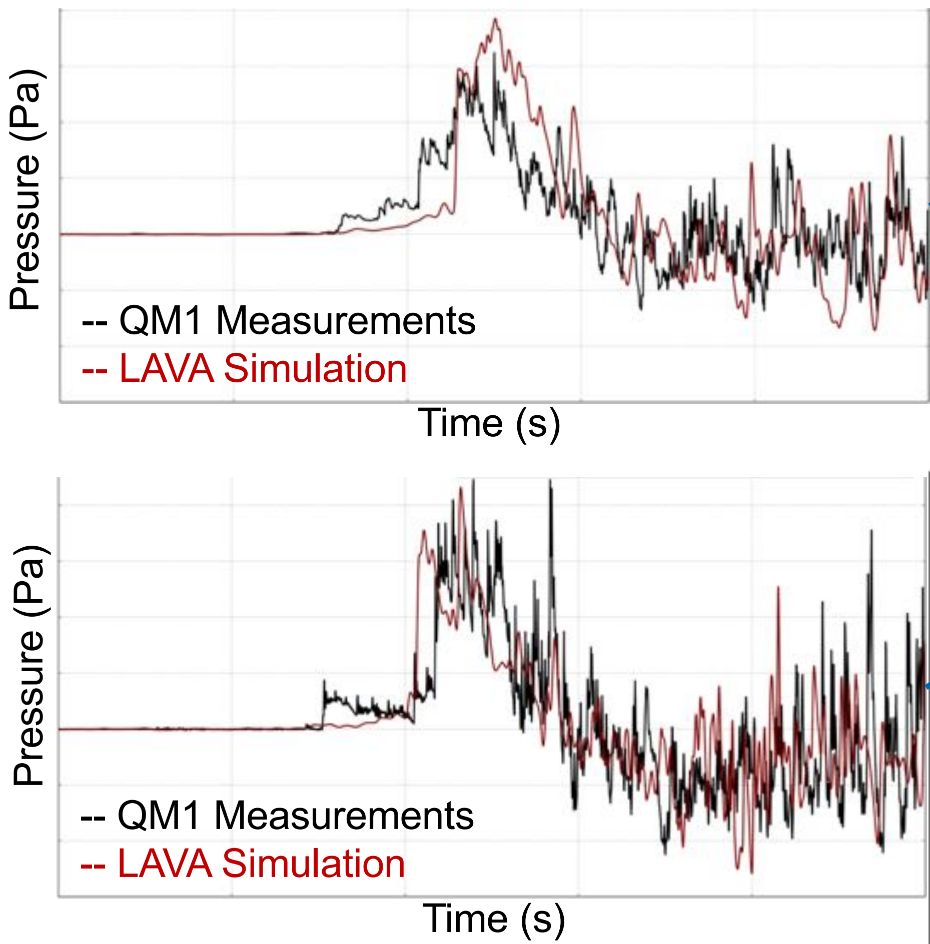
Ensuring Astronaut Safety

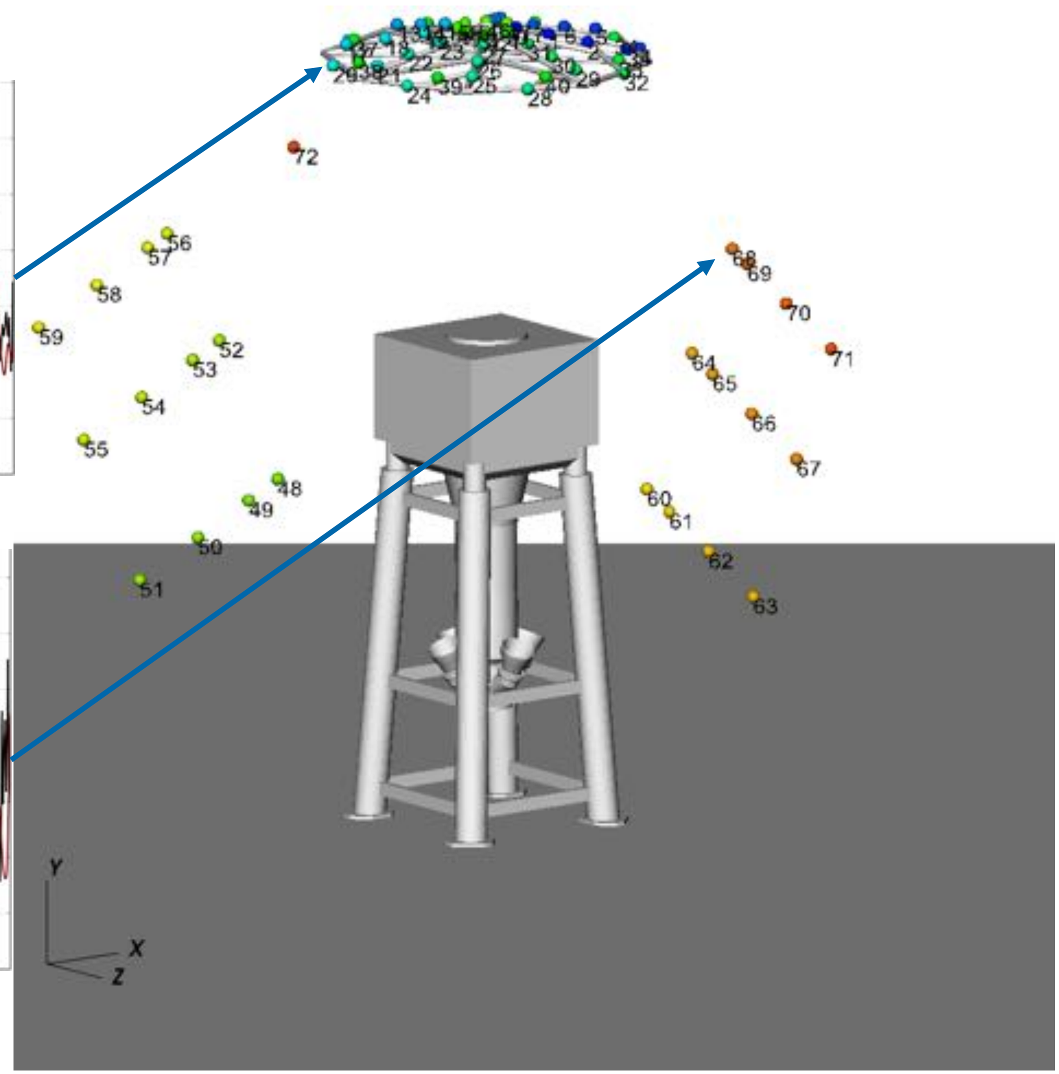
NASA is developing technologies that will enable humans to explore new destinations in the solar system. America will use the Orion spacecraft, launched atop the Space Launch System rocket, to send a new generation of astronauts beyond low-Earth orbit to places like an asteroid and eventually Mars. In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

ST1 Launch Abort Motor Test

Post Abort Motor Test Validation

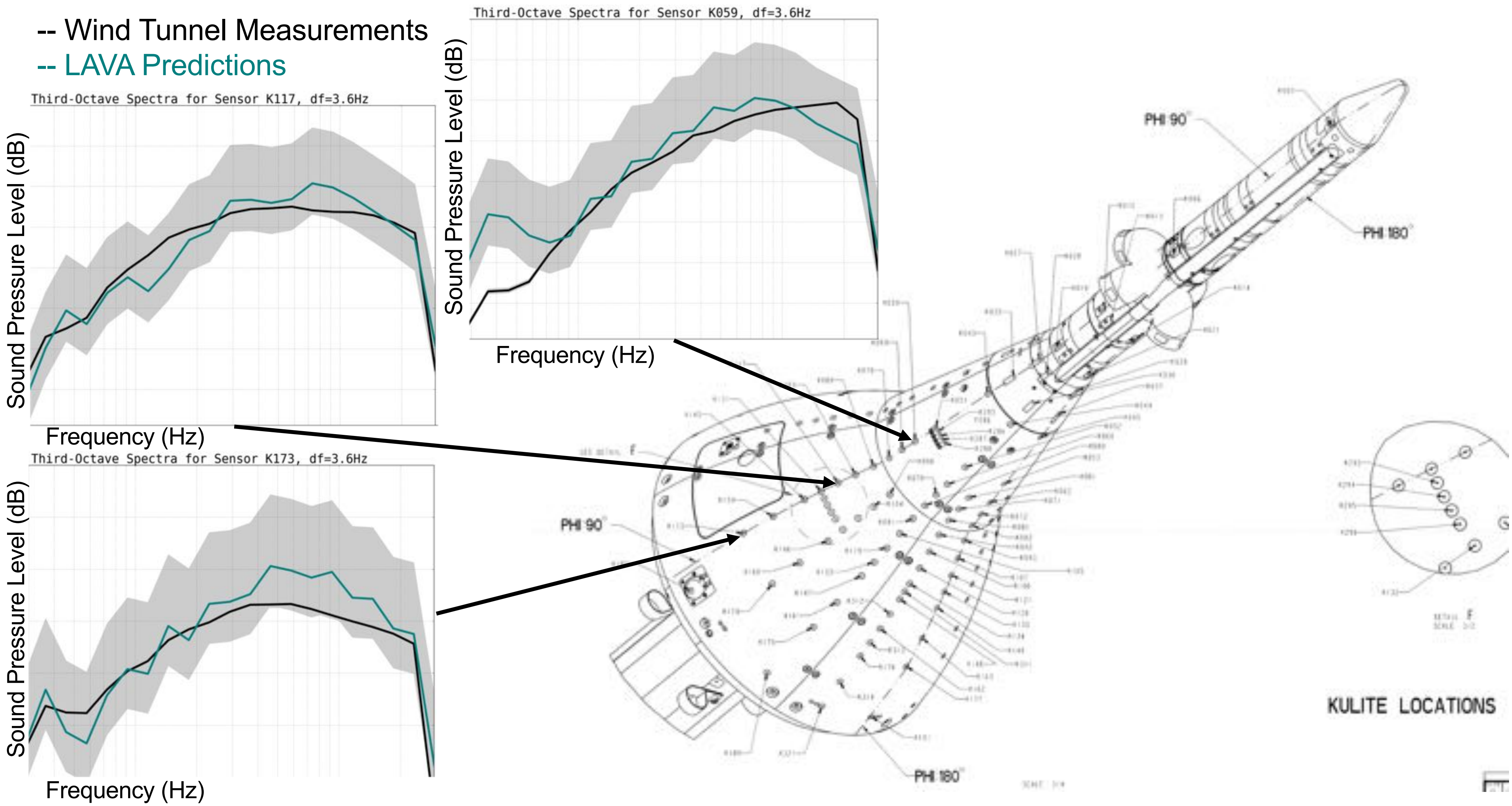
Ignition Overpressure (IOP) versus Time





Wind Tunnel Validation

-- Wind Tunnel Measurements
-- LAVA Predictions



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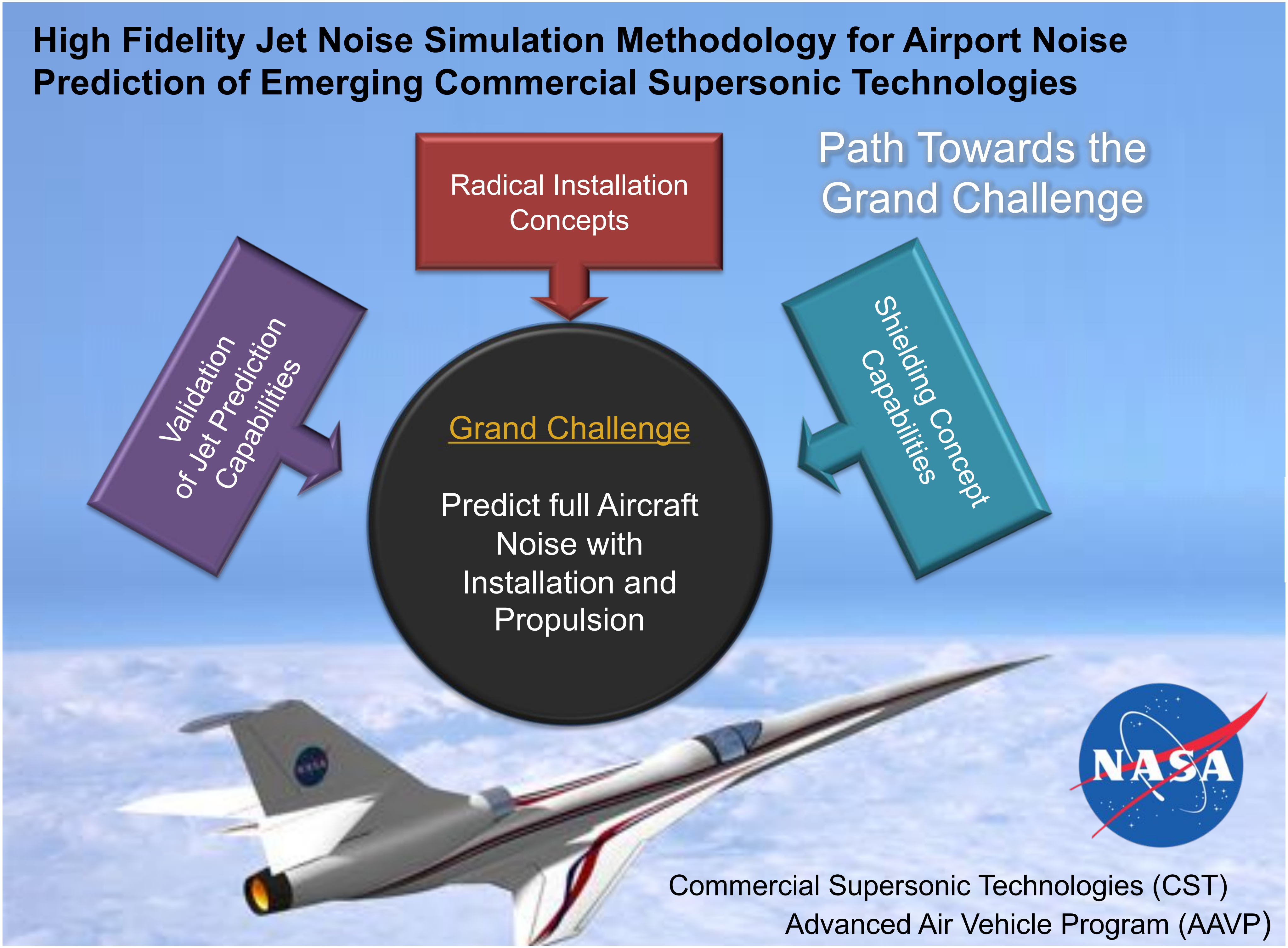
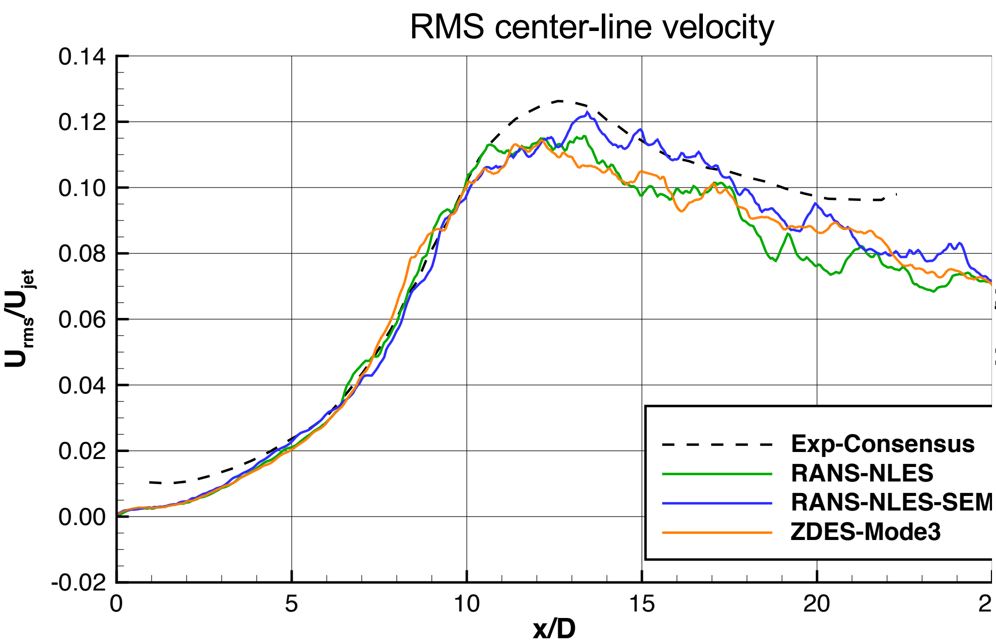
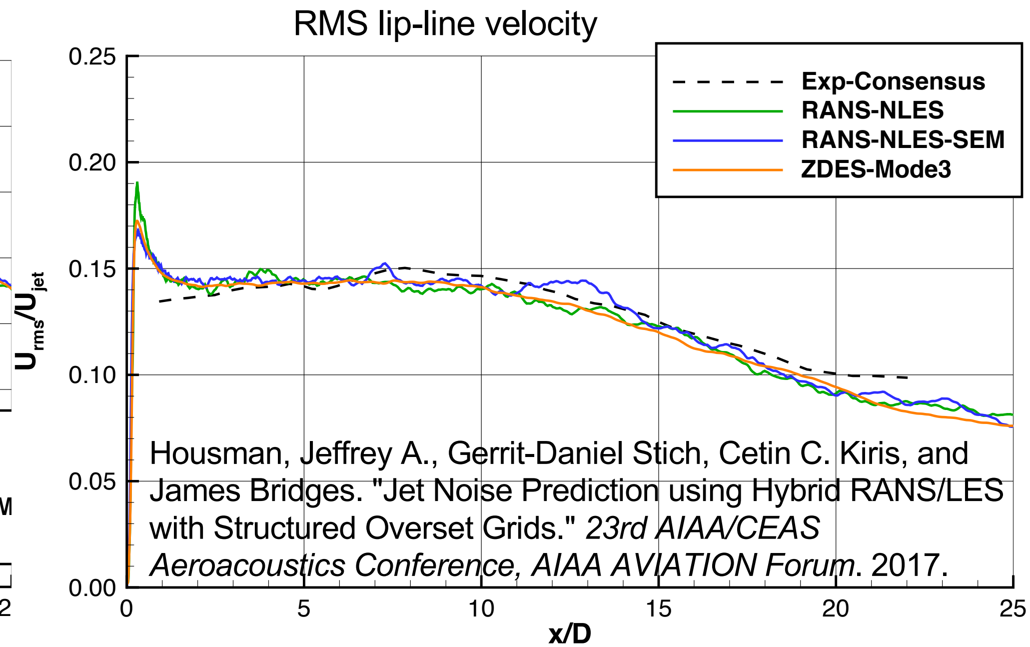
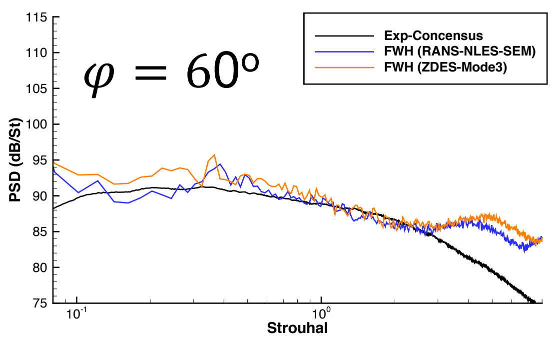

High Fidelity Jet Noise Simulation Methodology for Airport Noise Prediction of Emerging Commercial Supersonic Technologies
Path Towards the Grand Challenge
Radical Installation Concepts
Validation of Jet Prediction Capabilities
Shielding Concept Capabilities
Grand Challenge
Predict full Aircraft Noise with Installation and Propulsion
NASA
Commercial Supersonic Technologies (CST)
Advanced Air Vehicle Program (AAVP)

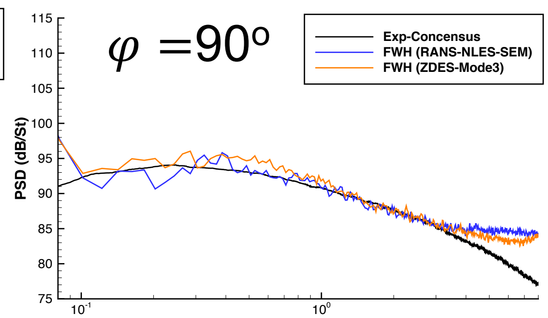
SP 7 Round Jet – Farfield Results

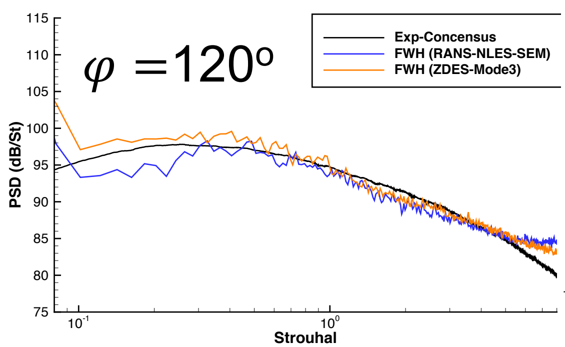


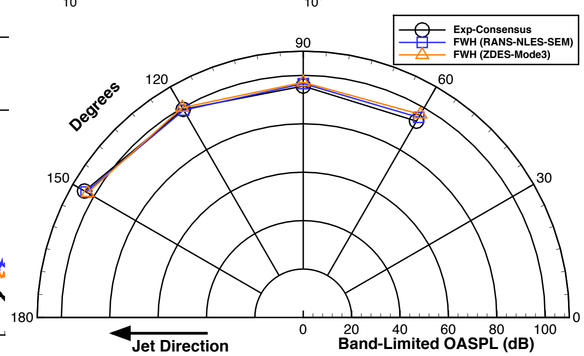


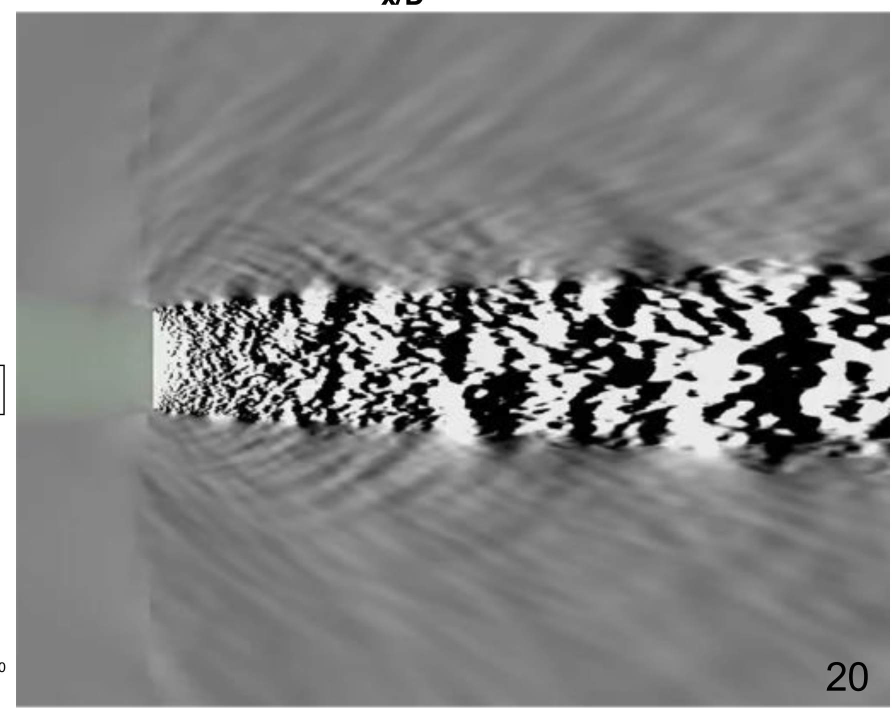
Housman, Jeffrey A., Gerrit-Daniel Stich, Cetin C. Kiris, and James Bridges. "Jet Noise Prediction using Hybrid RANS/LES with Structured Overset Grids." *23rd AIAA/CEAS Aeroacoustics Conference, AIAA AVIATION Forum*. 2017.







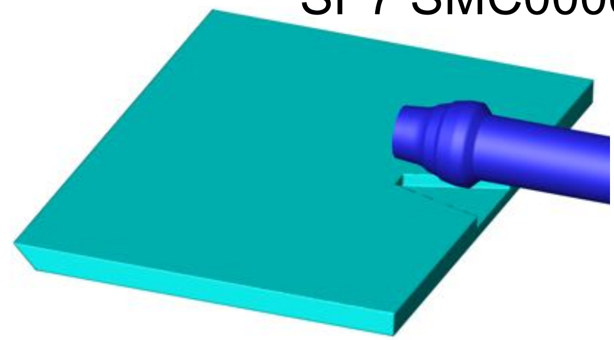




First Step Towards Radical Installation Concepts

Initial Validation → Shielding Concept

SP7 SMC0000

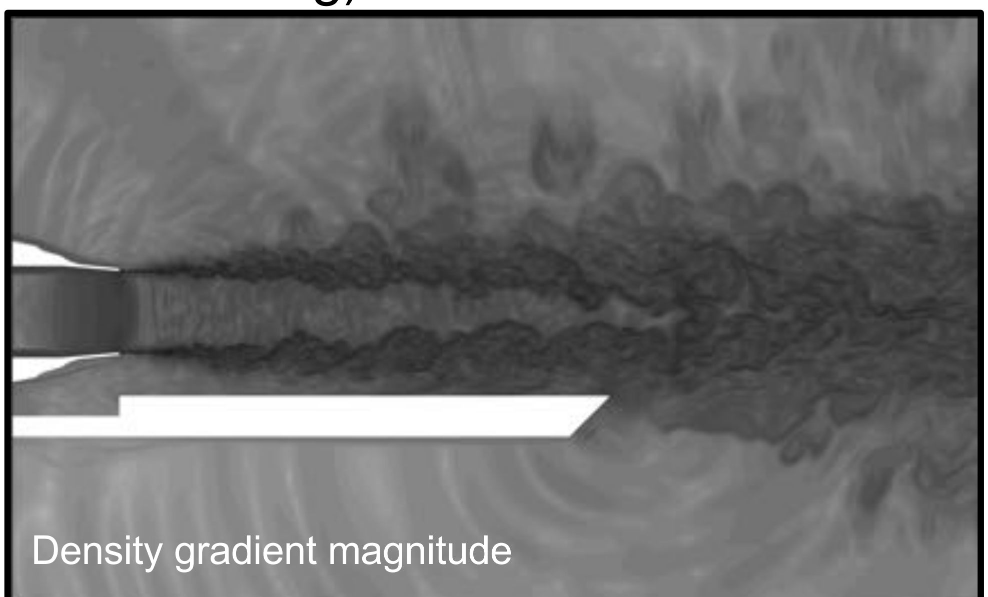


Objective:

- ✓ Moving towards radical installation concepts.
- ✓ Jet-surface interaction noise is difficult to predict.

Approach:

- ✓ Assess Jet Surface Interaction Noise with ZDES (Mode 3).
- ✓ Improve Post-Processing tools to gain better understanding of the sound generation and shielding physics (permeable and impermeable FWH, beamforming)

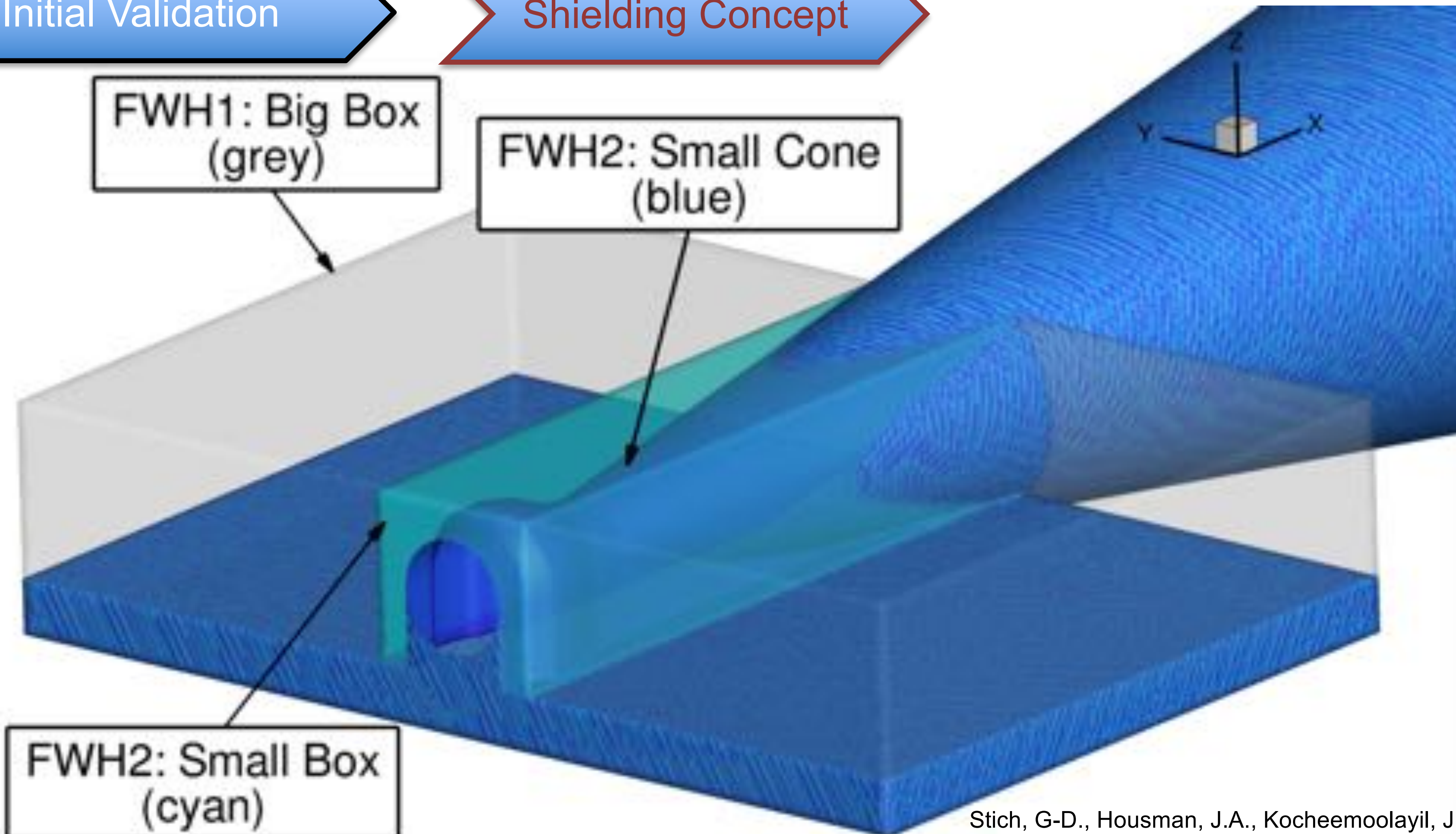


Density gradient magnitude

Establishing Best Practices for FWH Surface

Initial Validation

Shielding Concept



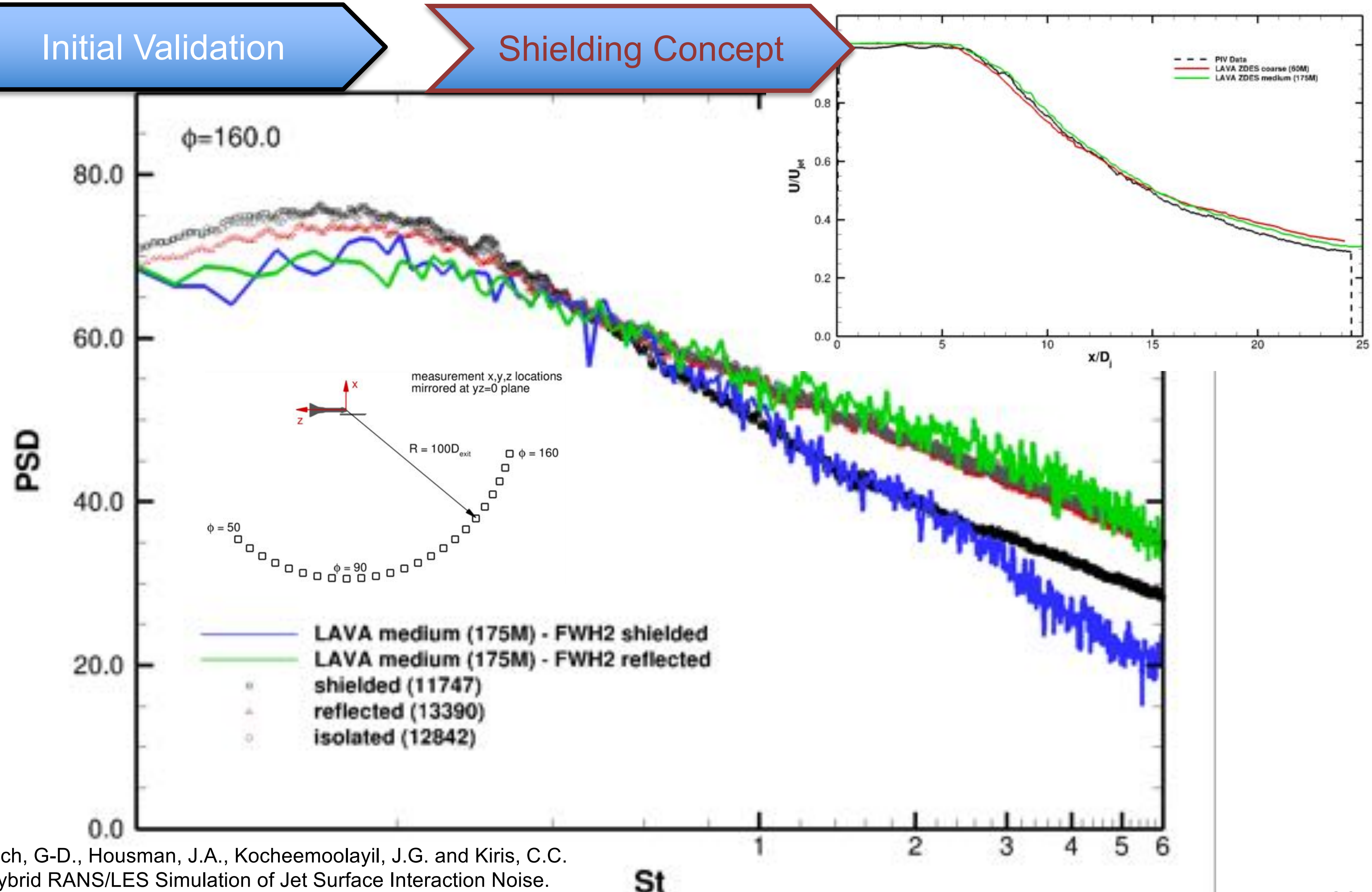
Stich, G-D., Housman, J.A., Kocheemoolayil, J.G. and Kiris, C.C. .Hybrid RANS/LES Simulation of Jet Surface Interaction Noise. AIAA-CEAS 2019. Delft. Netherlands.

- ✓ Choice of FWH surface not trivial.
- ✓ Conflicting requirements on resolution and inclusion of all relevant sound generation and shielding physics.

Capturing Shielding Effects

Initial Validation

Shielding Concept



Stich, G-D., Housman, J.A., Kocheemoolayil, J.G. and Kiris, C.C. .Hybrid RANS/LES Simulation of Jet Surface Interaction Noise. AIAA-CEAS 2019. Delft. Netherlands.

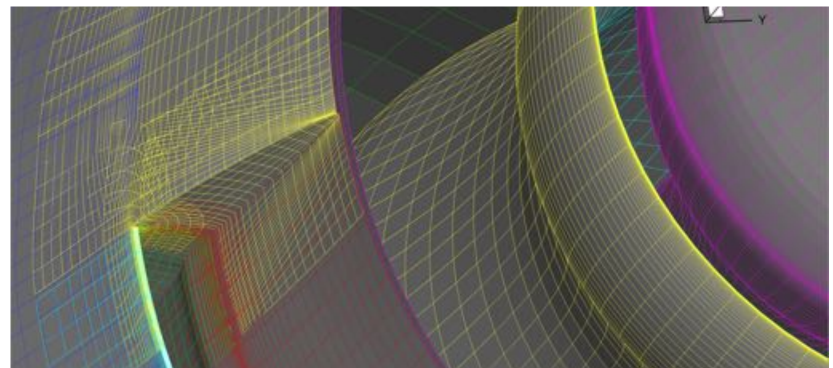
Next Step Towards Radical Installation Concepts

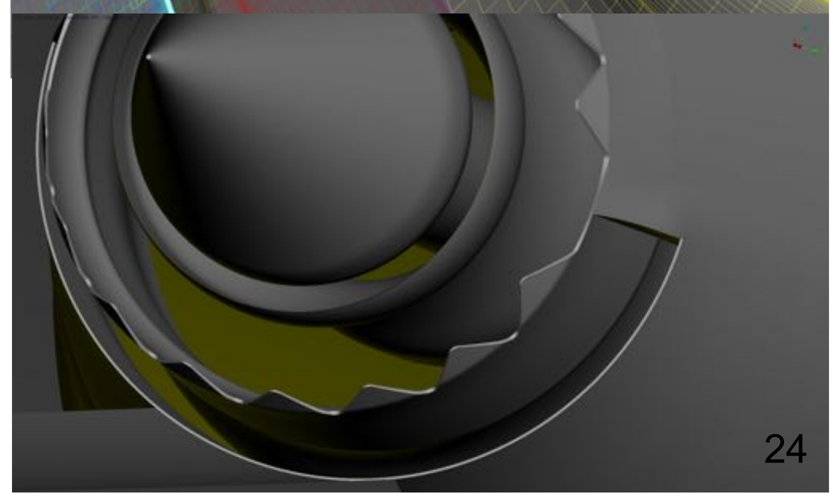
Initial Validation → Shielding Concept → Radical Installation Concepts

Objective:

- ✓ Significantly increase complexity (last step before “grand challenge”).
- ✓ Multi-stream nozzle with shielding and installation effects.
- ✓ Comparison with comprehensive experimental database.

Picture taken from:
NASA Test Report: Top-Mounted Propulsion Test 2017 (TMP17)

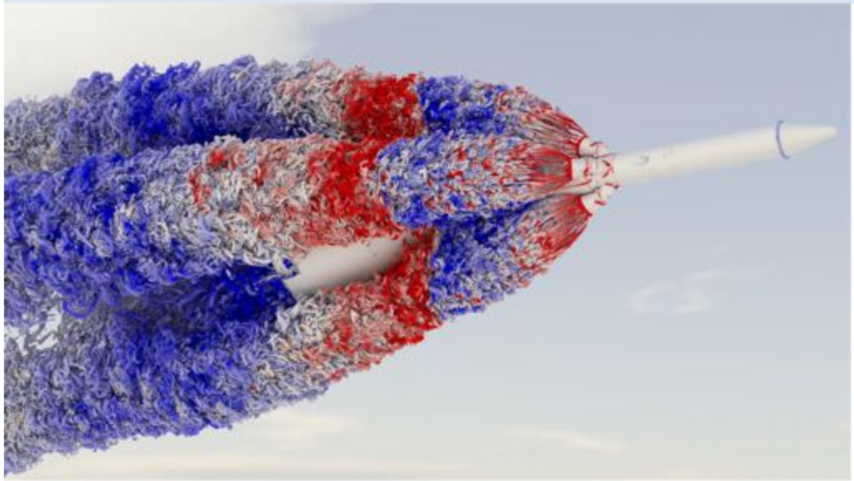




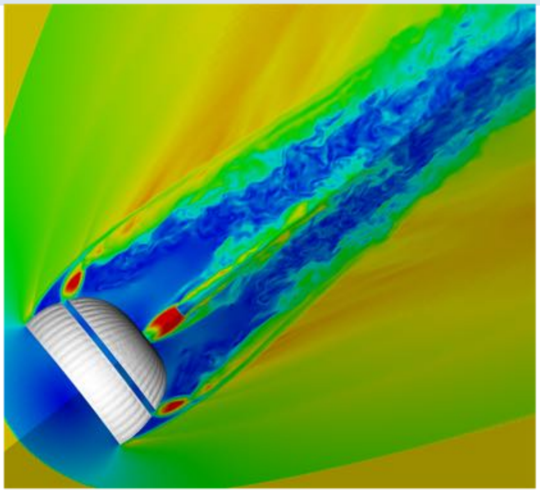
Lessons Learned: Jet Noise

- Mesh quality makes a big difference
- Use lowest dissipation convective flux that is stable
- Resolve turbulent boundary layer structures inside the nozzle
- Understand effect of FWH surface shape and triangle size

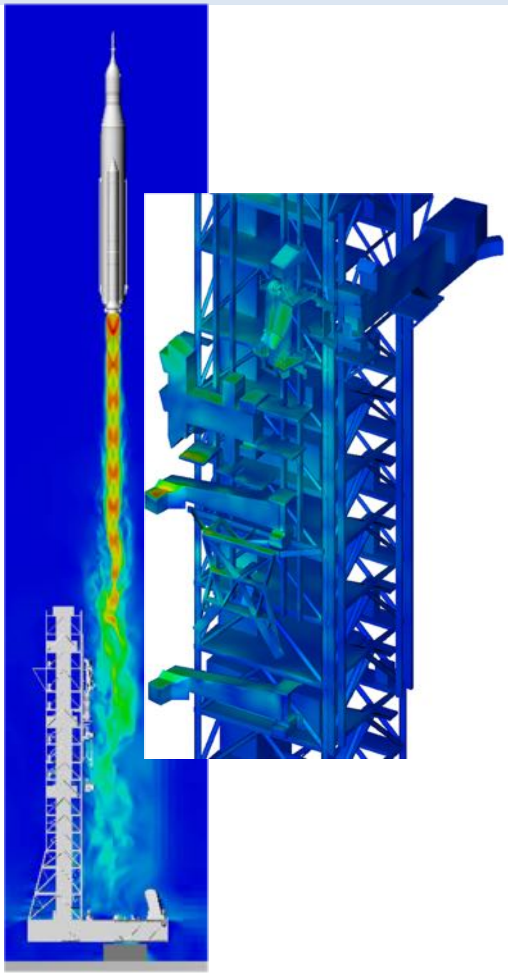
Aero-Acoustics With Cartesian Navier-Stokes



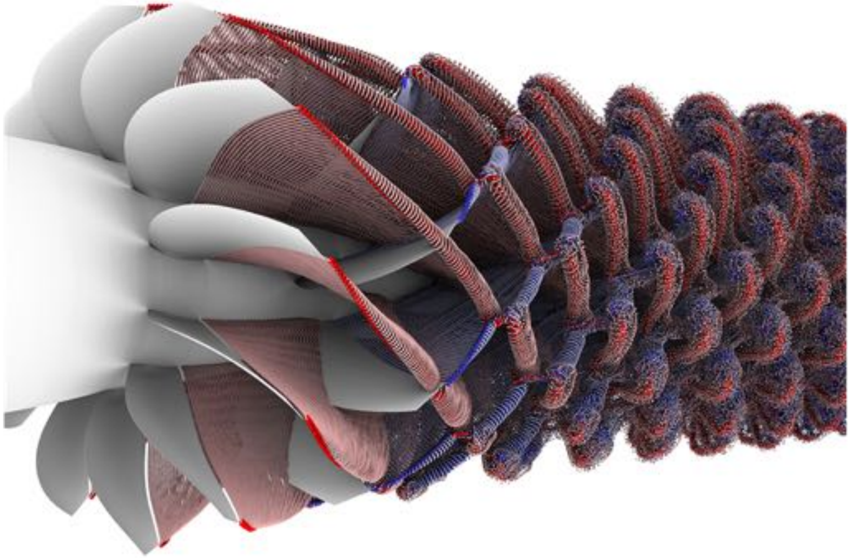
Launch Abort System Analysis for Orion
350 million cells, 28 days of wall time (2000 cores)



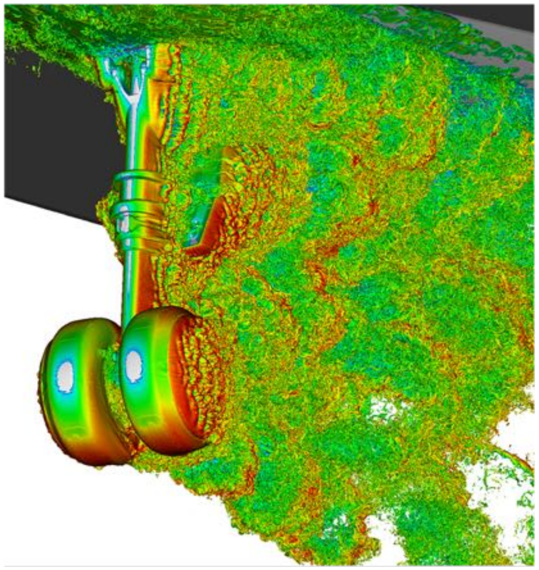
Low Density Supersonic Decelerator
200 million cells, 3 days of wall time (2000 cores)



Launch Environment
200 million cells, 7 days of wall time (1000 cores)



Contra-Rotating Open Rotor Propulsion
360 million cells, 14 days (1400 cores)



Landing Gear
298 million cells, 20 days of wall time (3000 cores)

Challenges in Computational Aero-Acoustics

✓ **Computational Requirements**

- Space-time resolution requirements for acoustics problems are demanding
- LAVA Cartesian infrastructure has been re-factored into Navier-Stokes (NS) and Lattice Boltzmann Method (LBM)
  - 10-50 times speed-up can be achieved with LBM vs NS-WENO without any compromise in accuracy or robustness

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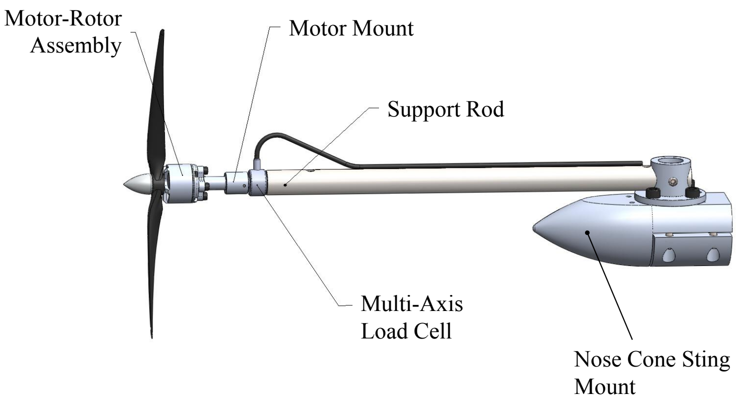
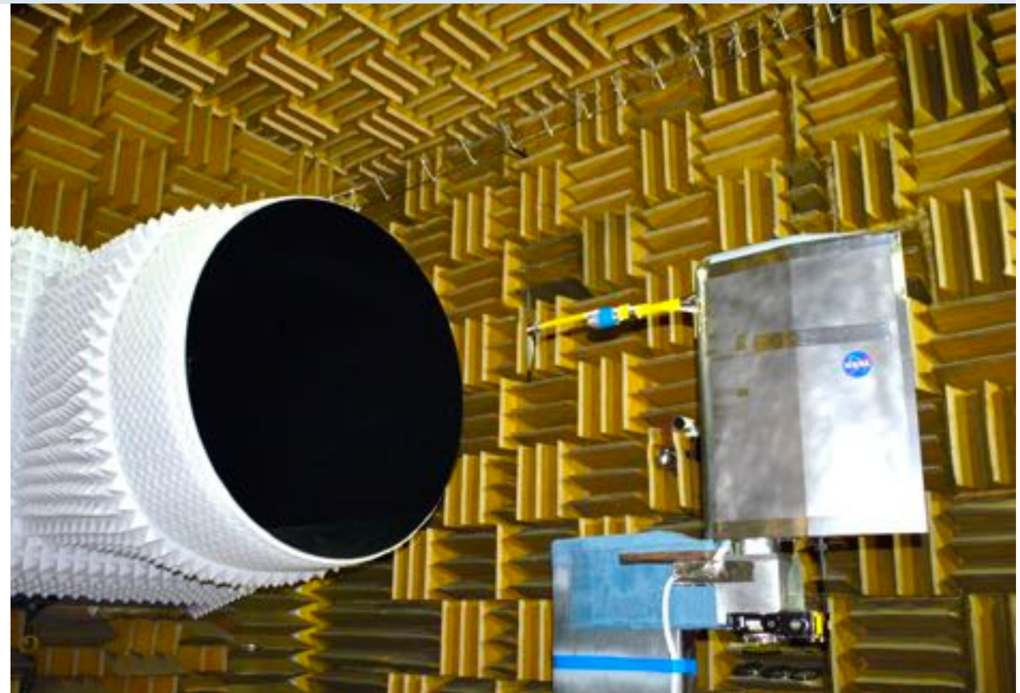
Picture credit: NASA / Lillian Gipson
NASA
Towards Urban Air Mobility (UAM)
High-Fidelity Modeling and Optimization Method Development
NASA Revolutionary Vertical Lift Technology Rotary Project (RVLT)

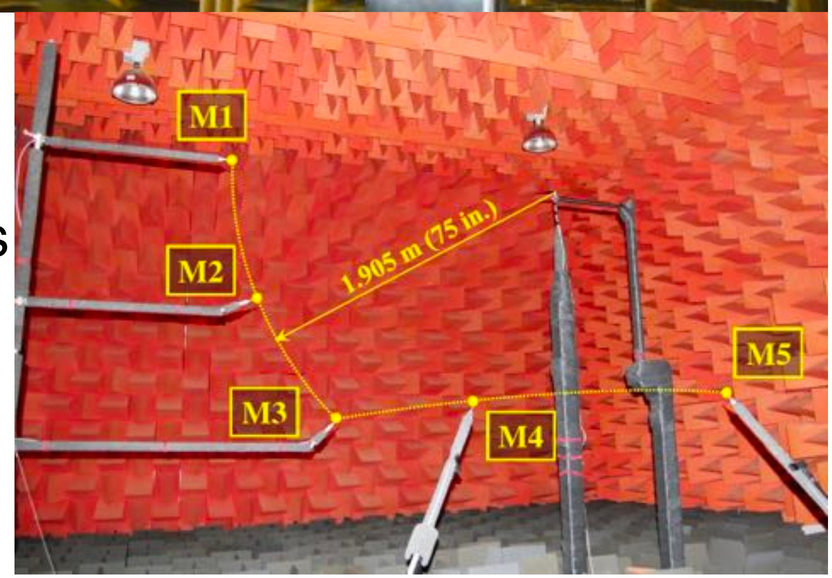
Isolated UAS Rotor in Hover Validation

Zawodny and Haskin **(AIAA-2017-3709)**	
Rotor Span R	0.1905 [m]
Microphones (M1-M5)	10R
Considered RPM	5400



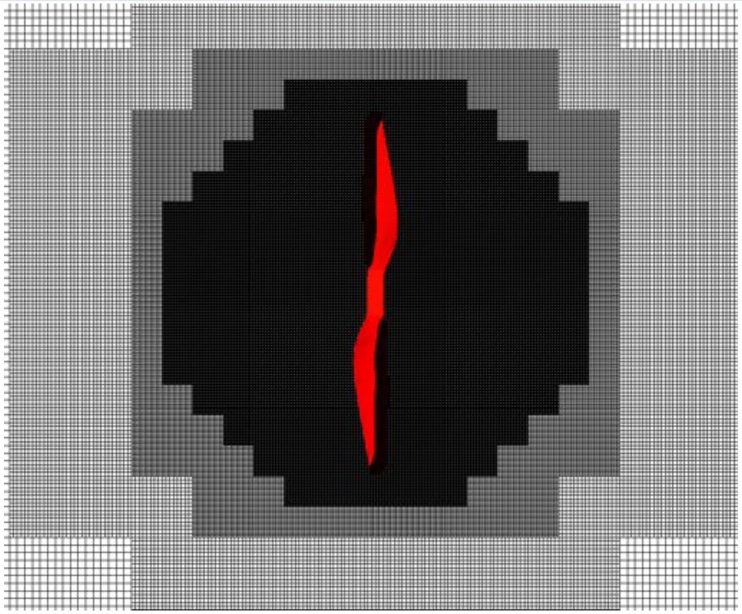


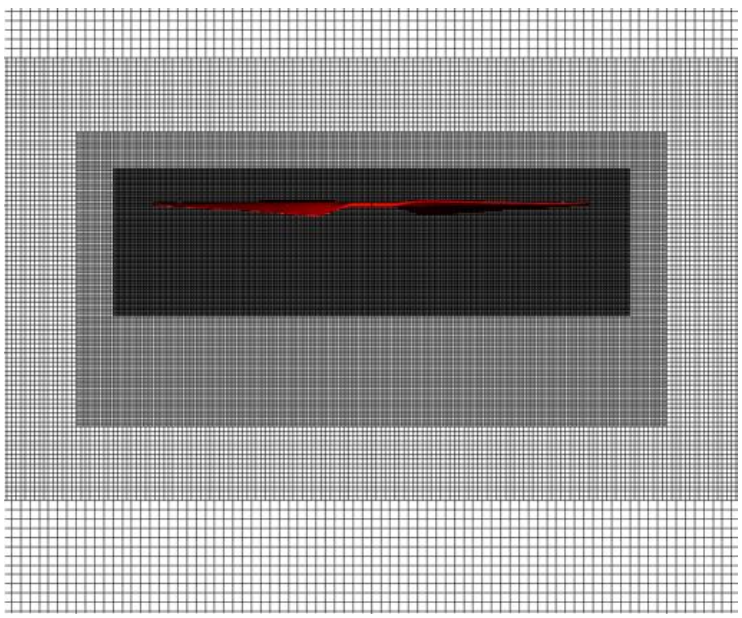
- ✓ Experiments conducted at NASA Langley LSAWT as well as in the Structural Acoustics Loads and Transmission (SALT) anechoic chamber.
- ✓ Motor-Rotor Assembly as well as Mount and Support structure not considered in simulations.



Experimental Data from Zawodny and Haskin AIAA-2017-3709

LAVA Cartesian Methods



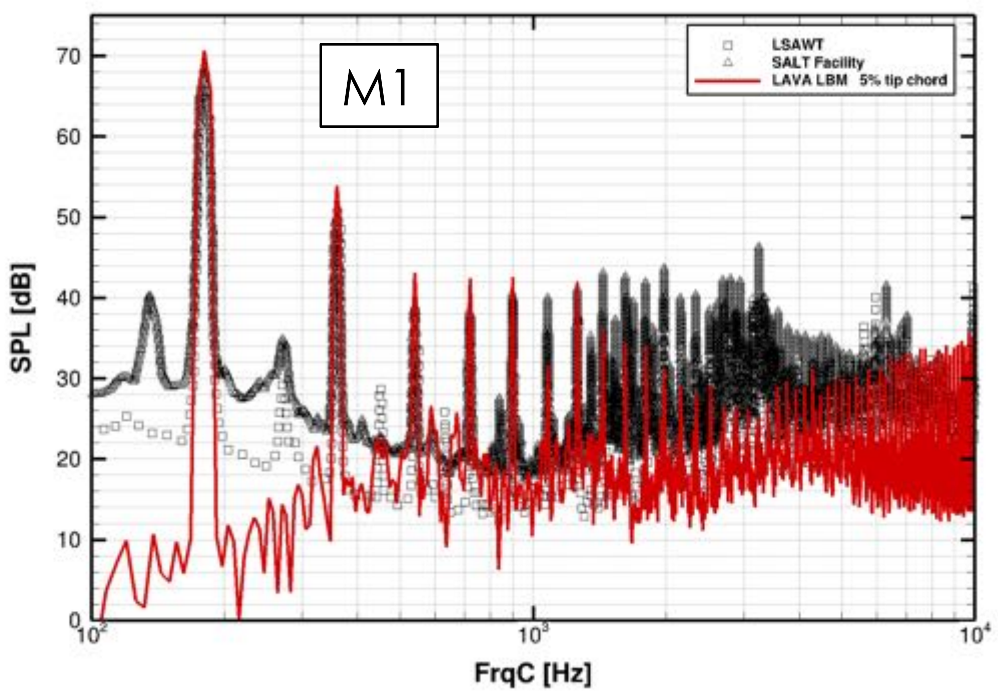


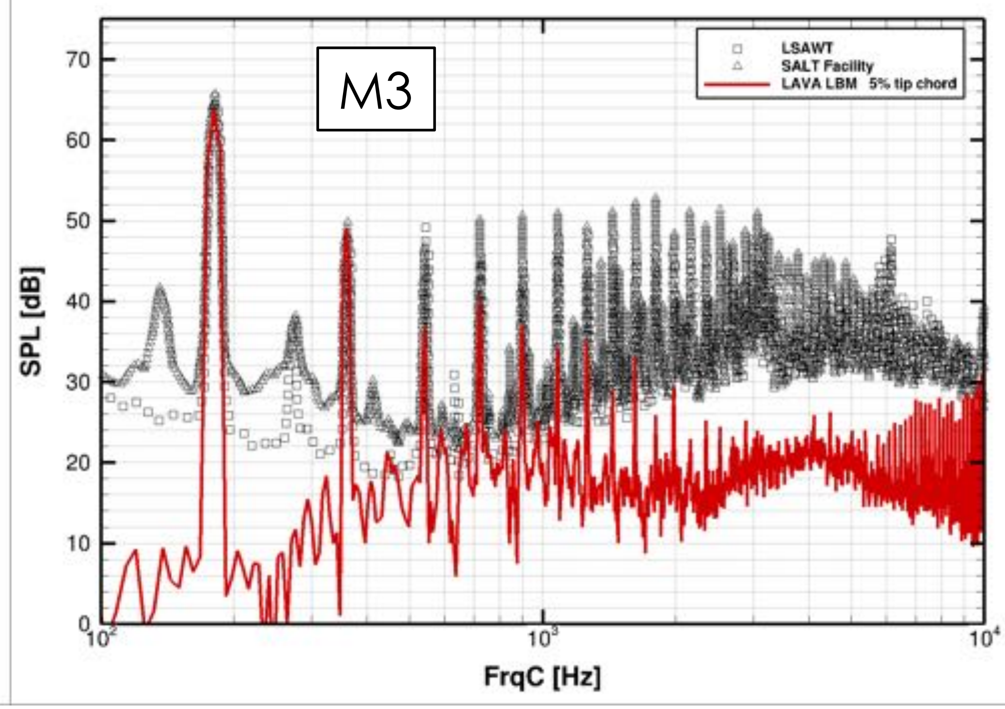
Lattice Boltzmann (LBM – EMRT)	Navier-Stokes (NS – WENO6)

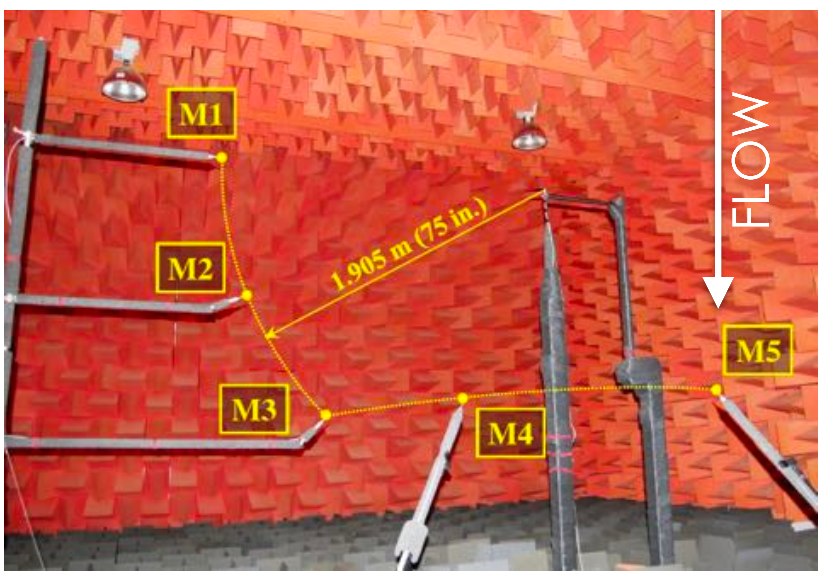
- ✓ Refinement ratio of 2:1
- ✓ Very Coarse : 40% tip chord (8lev)
- ✓ Coarse : 20% tip chord (9lev)
- ✓ Medium : 10% tip chord (10lev)
- ✓ Fine : 5% tip chord (11lev)

Isocontour of Q-criterion colored by Pressure.
Navier-Stokes Simulation on medium Cartesian mesh.

Lattice Boltzmann Method
Farfield Noise – SPL Spectrum for Observer M1 & M3

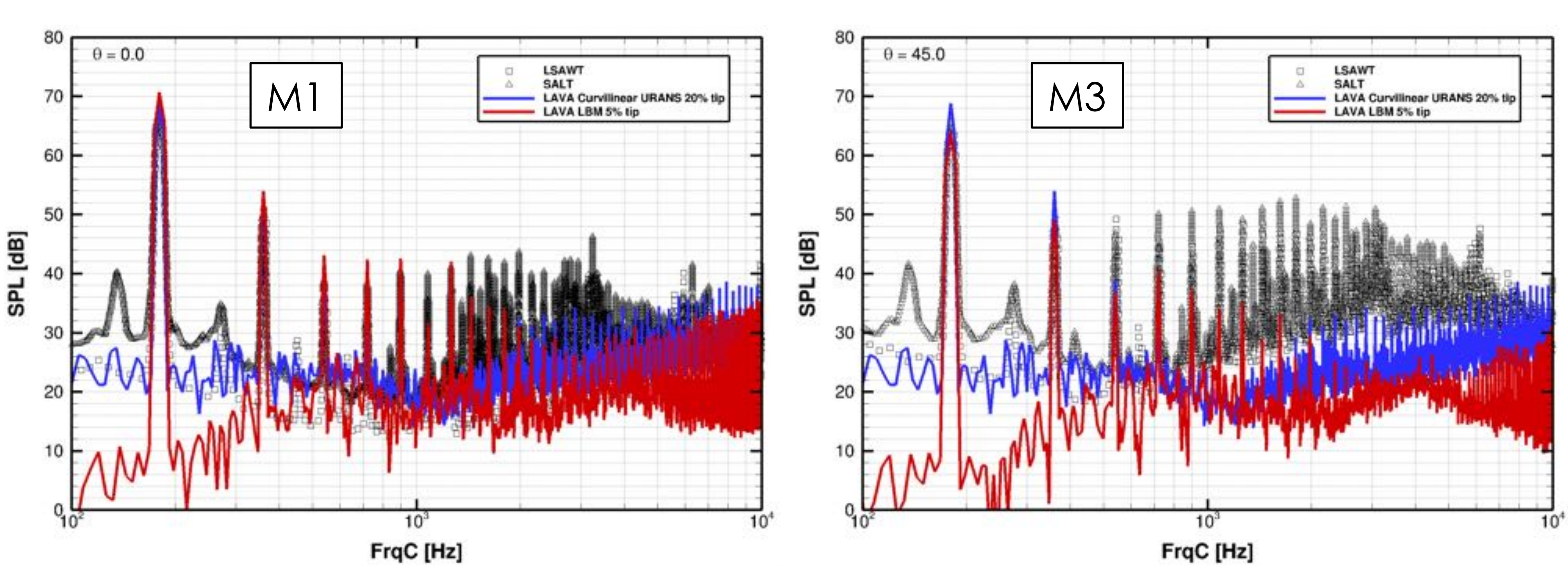






- ✓ Excellent agreement with BPF1-BPF5 for M1 (0.0°) microphone location
- ✓ Excellent agreement with BPF1 & BPF2 for M3 (45.0°)
- ✓ Different FWH formulations (permeable and impermeable) currently under investigation

Comparison between the Approaches



- ✓ Consistent prediction using all three approaches
- ✓ Computational efficiency and complete absence of manual volume mesh generation key advantage of LBM
- ✓ Manual meshing efforts increase significantly upon considering installation effects (e.g. full Quadcopter or tiltwing urban air taxis)

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Aircraft Noise Reduction (ANR)

High Fidelity Acoustic and Performance Simulation of NASA R4 Noise Source Diagnostics Test (SDT)

R4 Source Diagnostic Test
Toward Fan Broadband Noise Prediction

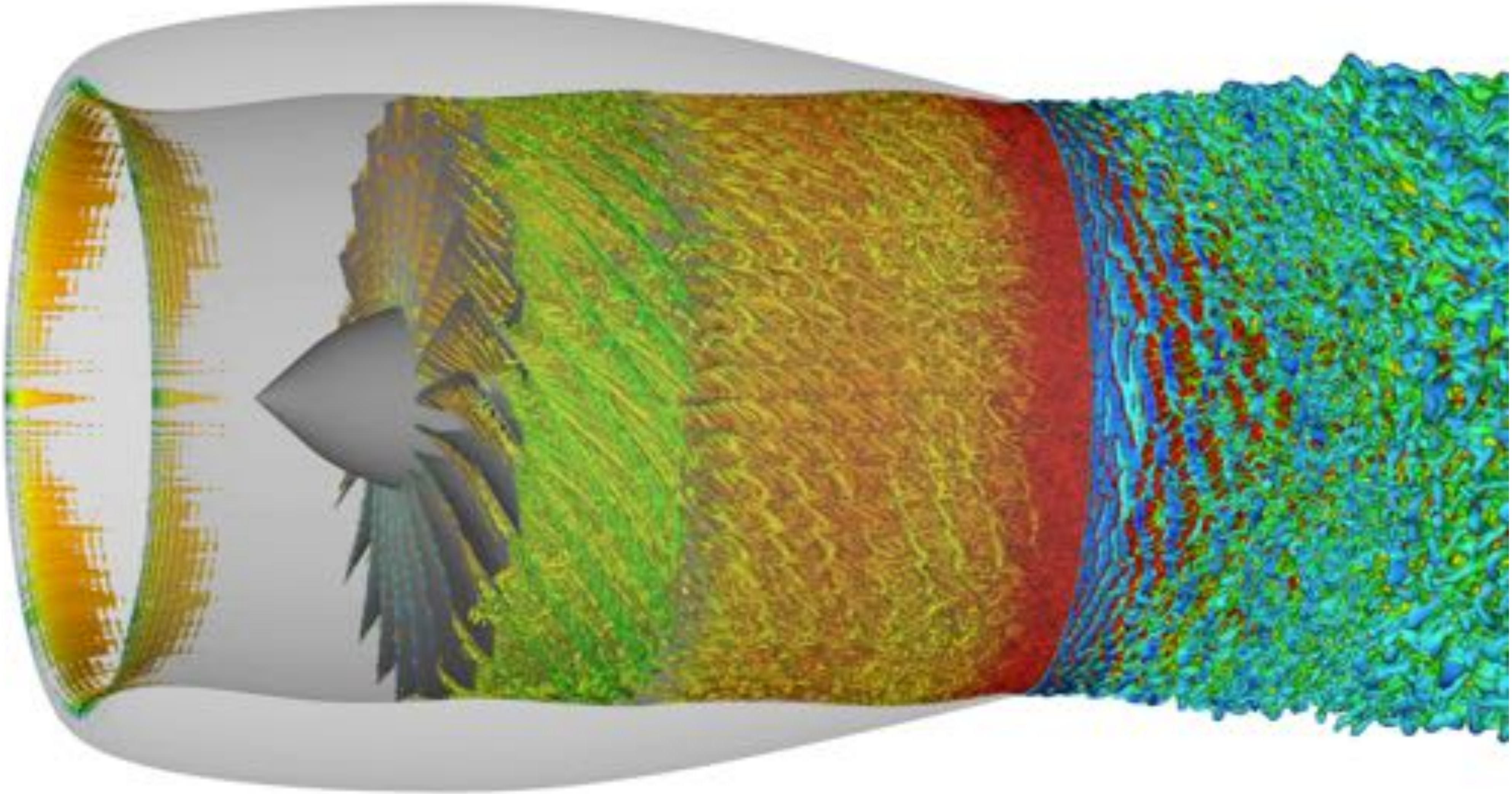
- ✓ Fan Noise Workshop Realistic Case 2 (RC2v2) at approach speed (7808 RPM) with baseline OGV design with goal to compare to hot-wire, LDV, and microphone test data
- ✓ LAVA Cartesian with fixed isotropic refinement zones from fan to exhaust
- ✓ Running two cases:
  - 6th order adaptive WENO [1]
  - 2nd order Kinetic-Energy Preserving (KEP) flux [2] with JST Artificial Dissipation [3]
- ✓ Moving geometry with immersed boundary representation
  - Impose slip boundary condition with 2nd order ghost cell method with ghost-in-fluid for thin geometry
- ✓ Coarse grid:
  - Min cell size = 2 mm
  - Number of degrees of freedom = 84M
- ✓ Medium grid:
  - Min cell size = 1 mm
  - Number of degrees of freedom = 387M

[1] Hu, X. Y., Q. Wang, and Nikolaus Andreas Adams. "An adaptive central-upwind weighted essentially non-oscillatory scheme." *Journal of Computational Physics* 229.23 (2010): 8952-8965.
[2] Yuichi Kuya, Kosuke Totani, Soshi Kawai. "Kinetic energy and entropy preserving schemes for compressible flows by split convective forms." *Journal of Computational Physics* 375 (2018): 823-853
[3] Jameson, Antony. "Origins and further development of the Jameson–Schmidt–Turkel scheme." *AIAA Journal* (2017): 1487-1510.

Summary

LAVA scale-resolving simulations impact NASA applications by providing:

- Flexibility with respect to mesh paradigms
- Cutting-edge hybrid RANS LES and WM-LES capabilities
- Fast-enough turnaround time to be included in design cycle



Cartesian Navier-Stokes Simulation of R4 SDT Fan Noise: iso-surfaces of q-criterion colored by Mach number (preliminary)