The Next Frontier of Modeling and Simulation at NASA: *Successes and Challenges*

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OUTLINE

- **Introduction**
  - *NASA Advanced Supercomputing Division at NASA Ames Research Center*
  - *Computational Aerosciences Branch at NASA Advanced Supercomputing Division*

- **Challenges in Modeling and Simulation**

- **NASA Space Vehicle Applications**
  - *Launch Environment*
  - *Orion Launch Abort Vehicle*

- **NASA Aeronautics Applications**
  - *X-57 Electric Aircraft Concept Aerodatabase*
  - *Flow Solver Refactoring for the Aerodatabase Generation*
  - *X-59 Low Boom Flight Demonstrator Aerodatabase*
  - *Jet Noise Simulation for of Emerging Commercial Supersonic Technologies*
  - *Noise Prediction for Emerging Markets Urban Aur Mobility (Quadcopter)*
  - *Airframe Noise Prediction (Landing Gear)*
- **Summary**

NASA Advanced Supercomputing (NAS)
High-End Computing Capability (HECC) Project

NASA's Premier Supercomputer Center

Resources have broad mission impact across all of NASA's Missions

Over 500 science & engineering projects with more than 1,500 users

(hosted by the NASA Advanced Supercomputing (NAS) Division at Ames)

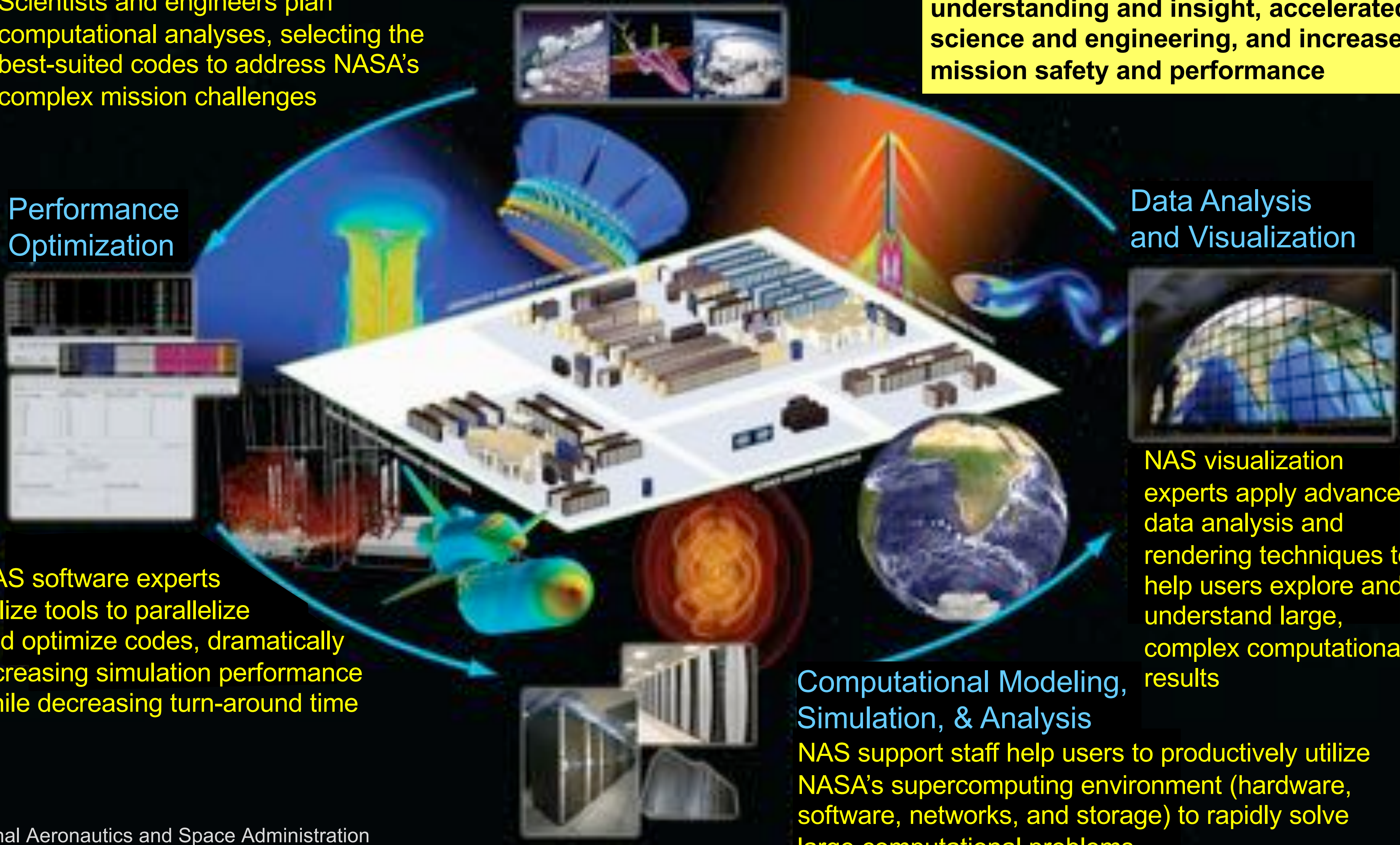
Computing Systems

- **Pleiades** – 7.09 PF peak
  - 241,324 cores, 11,207 nodes
  - InfiniBand Interconnect, hypercube topology
  - GPU racks – NVIDIA V100: 83 nodes – 0.65 PF peak
  - #31 on TOP500 (#14 in US); 06/2019 list
- **Electra** – 8.32 PF peak
  - 124,416 cores; 1152 Broadwell-based nodes, 2304 Sky-lake-based nodes
  - Modularized container-based approach – PUE ~1.03
  - #37 on TOP500 (#15 in US); 06/2019 list
- **Aitken** – 3.69 PF peak
  - 46,080 cores; 1152 Cascade Lake-based nodes
  - Modularized container-based approach

Storage – Global File Systems

- 7 Lustre File systems: 50 PB
- Archive tape system capacity:1 EB

NASA Advanced Supercomputing (NAS)



NASA Mission Challenges

Outcome: Dramatically enhanced understanding and insight, accelerated science and engineering, and increased mission safety and performance

Scientists and engineers plan computational analyses, selecting the best-suited codes to address NASA's complex mission challenges

Performance Optimization

NAS software experts utilize tools to parallelize and optimize codes, dramatically increasing simulation performance while decreasing turn-around time

Computational Modeling, Simulation, & Analysis

NAS support staff help users to productively utilize NASA's supercomputing environment (hardware, software, networks, and storage) to rapidly solve large computational problems

Data Analysis and Visualization

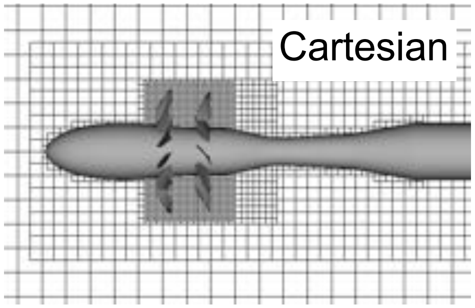
NAS visualization experts apply advanced data analysis and rendering techniques to help users explore and understand large, complex computational results

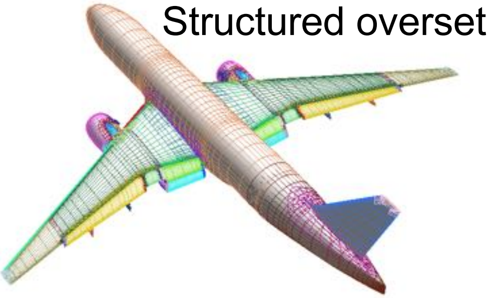
NASA Advanced Supercomputing (NAS)

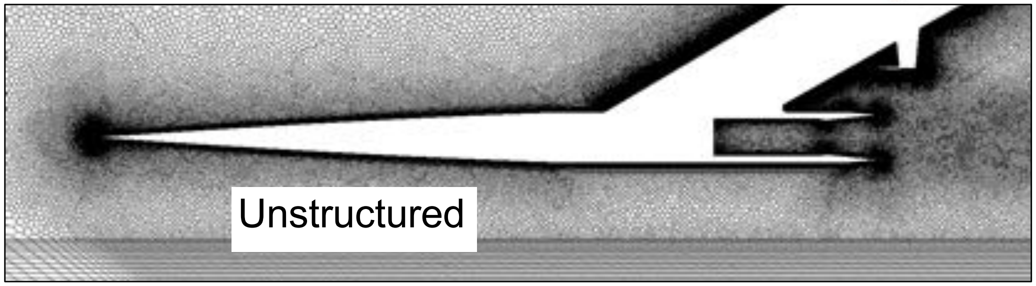
Computational Aerosciences

Aerodynamic Simulation System

- Geometric complexity and fast turn around time
- Flexible meshing: Cartesian, unstructured, structured

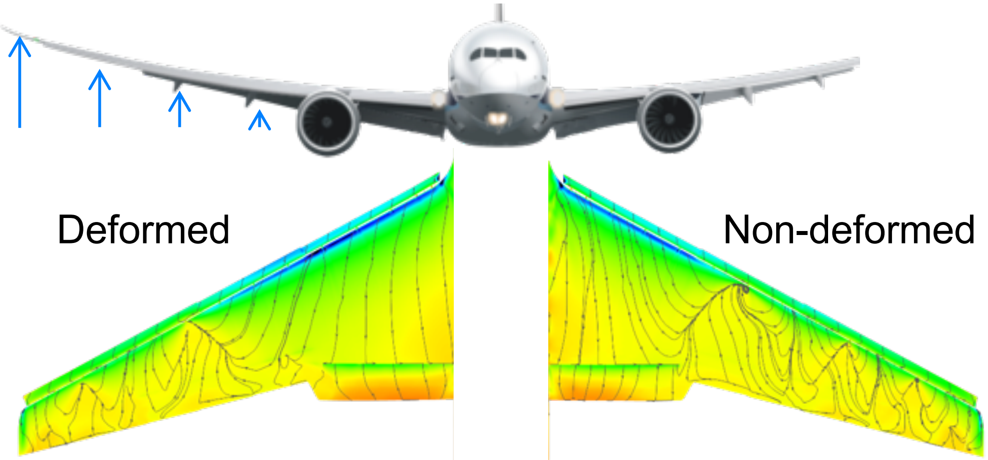




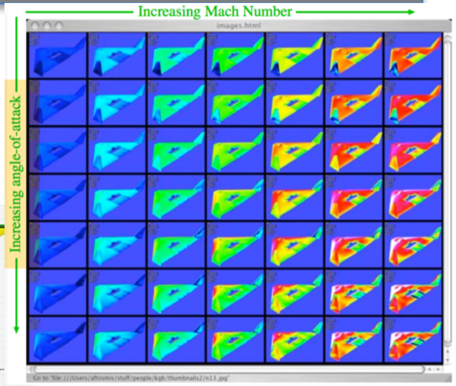


Aerostructural Simulation & Design

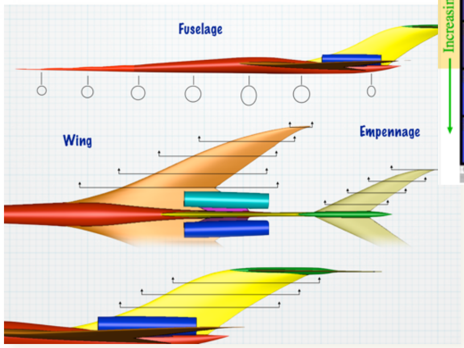
- Wing shape varies throughout mission profile
- Aero-structural coupling for design process



Automated Aero-Database

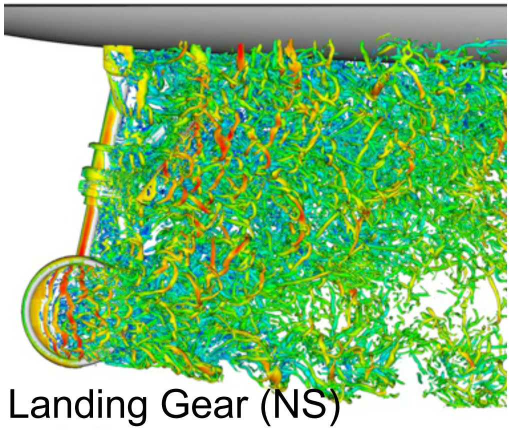


Shape Optimization and Design

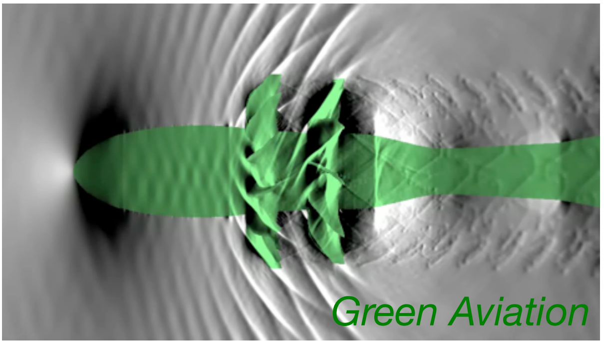


Aeroacoustics Simulation

Enhanced CAA Capability



Landing Gear (NS)

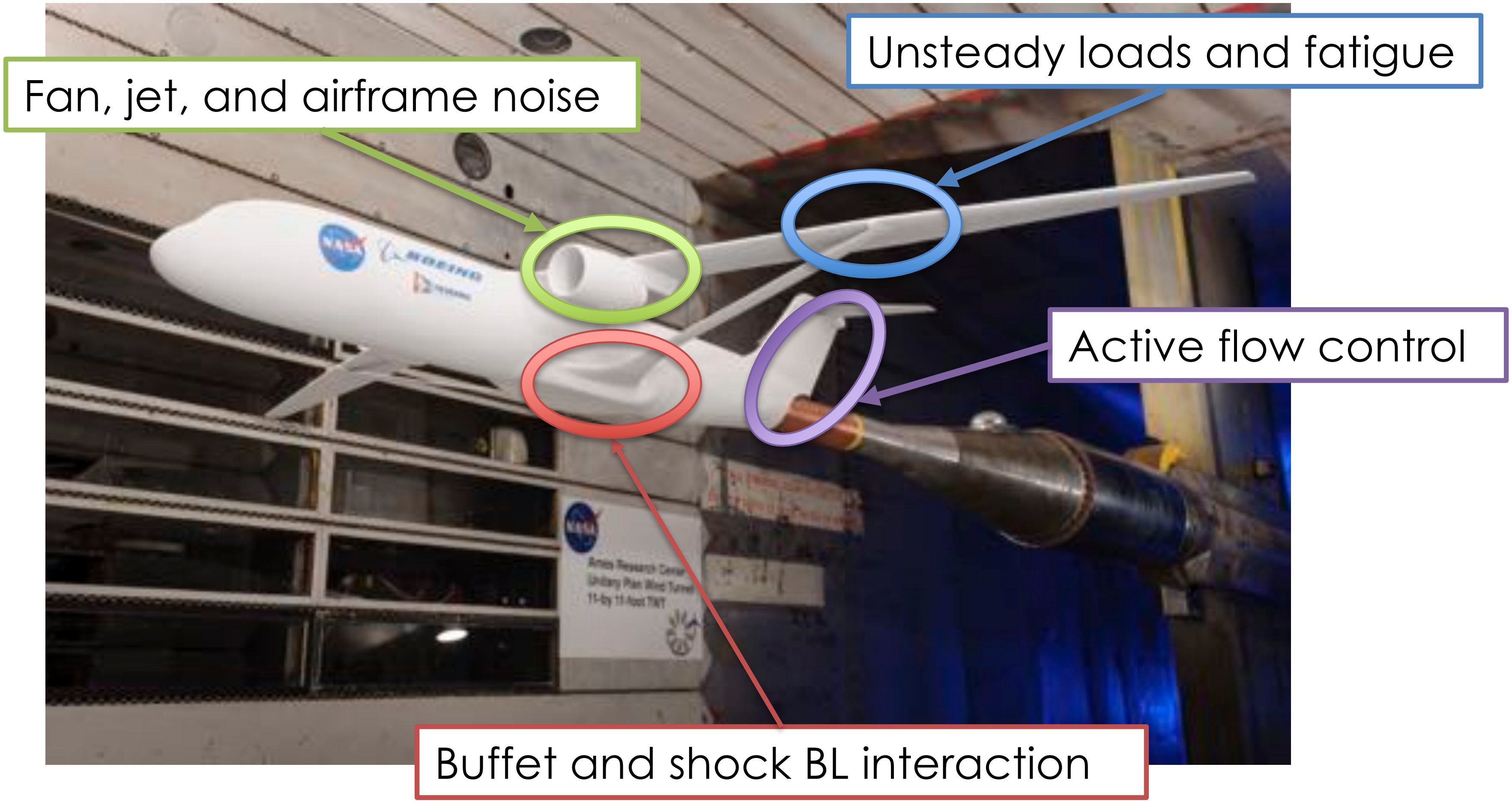


Contra-rotating Open Rotor

Next Frontier of Modeling and Simulation

✓ **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 Aerosciences

✓ **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**

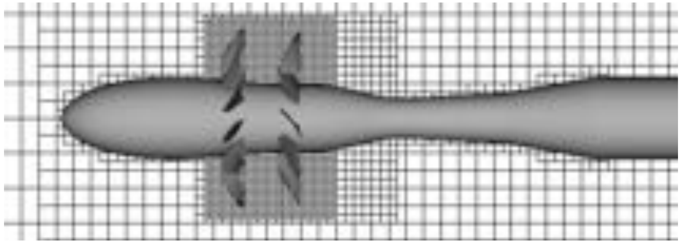
- Resolving thin wall-bounded turbulence is too computationally costly for most aerospace applications → hybrid methods & wall-models
- Resolving all relevant scales of turbulent motion away from walls is also prohibitive → Higher order less dissipative numerics & subgrid-scale modeling

✓ **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

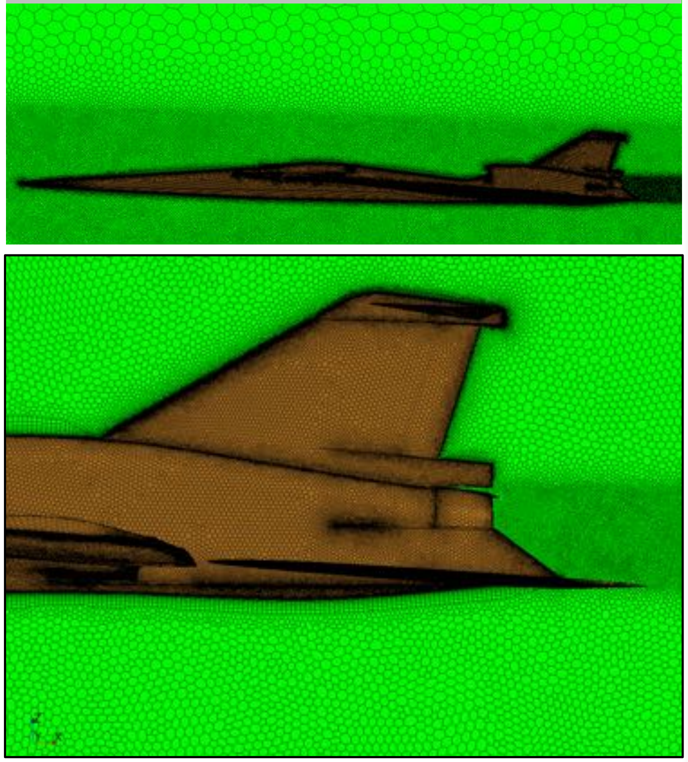
Computational Grid Paradigms in LAVA

Structured Cartesian AMR



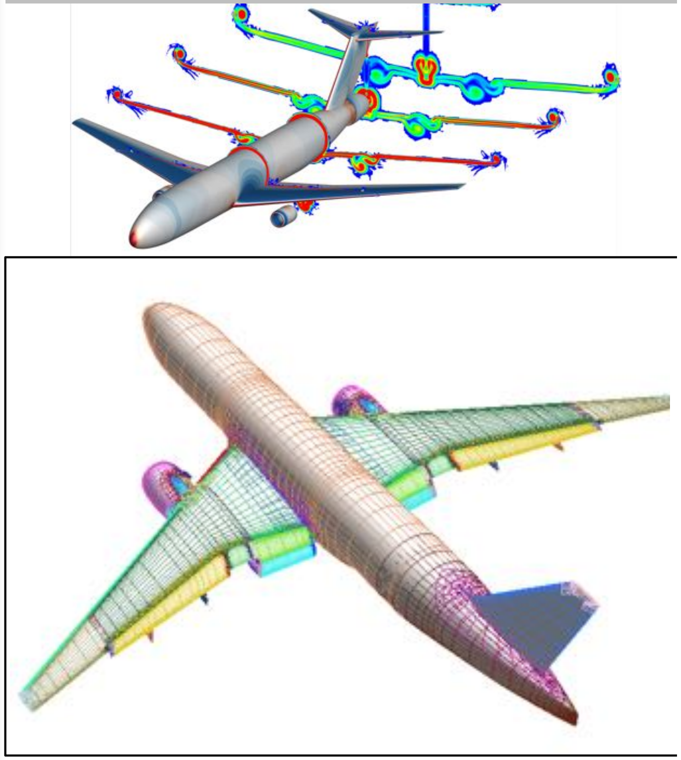
- Essentially no manual grid generation
- Highly efficient Structured
- Adaptive Mesh Refinement (AMR)
- Low computational cost
- Reliable higher order methods
- Non-body fitted -> Resolution of boundary layers inefficient

Unstructured Arbitrary Polyhedral



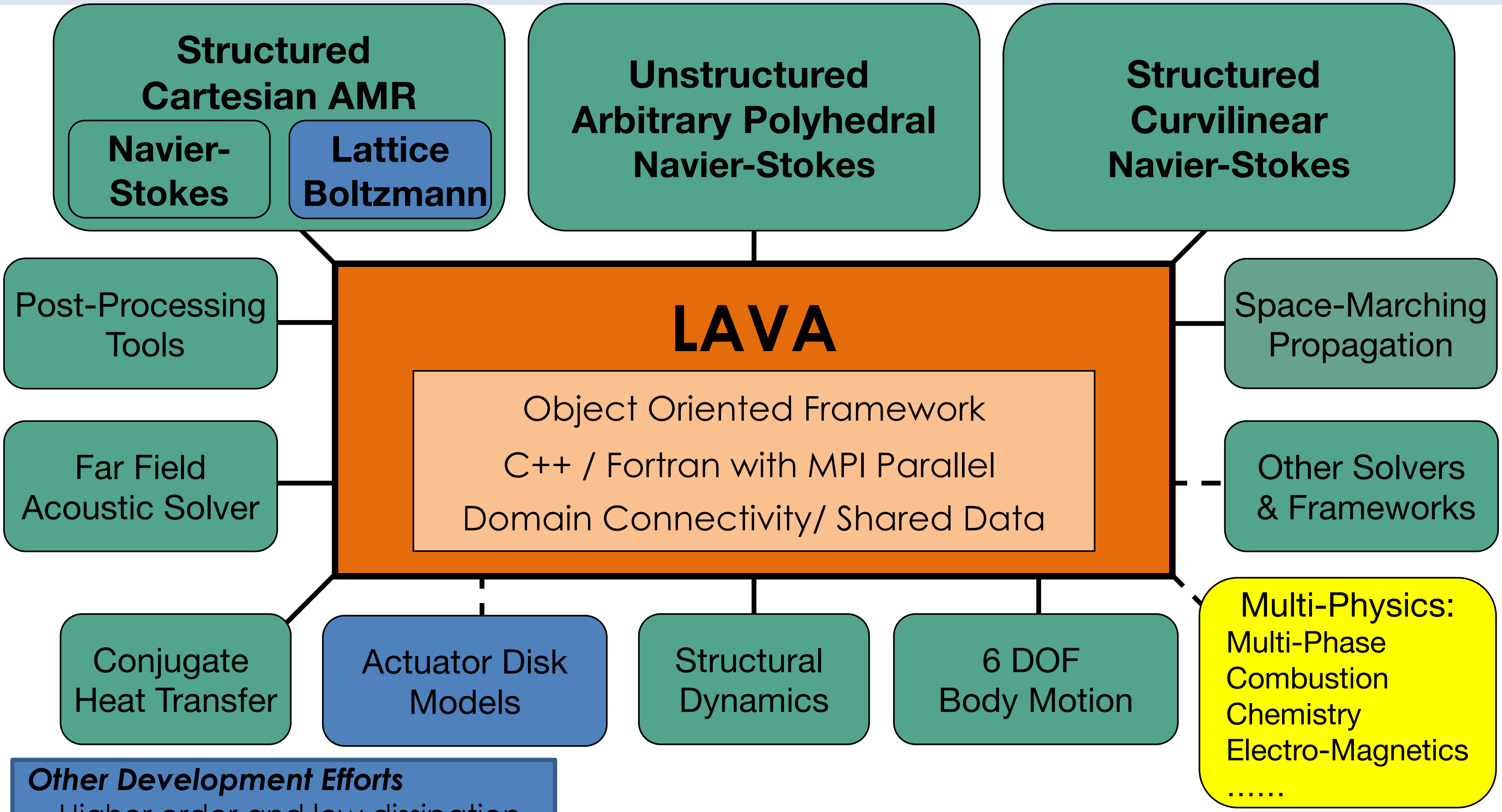
- Partially automated grid generation
- Body fitted grids
- Grid quality can be challenging
- High computational cost
- Higher order methods yet to fully mature

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



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

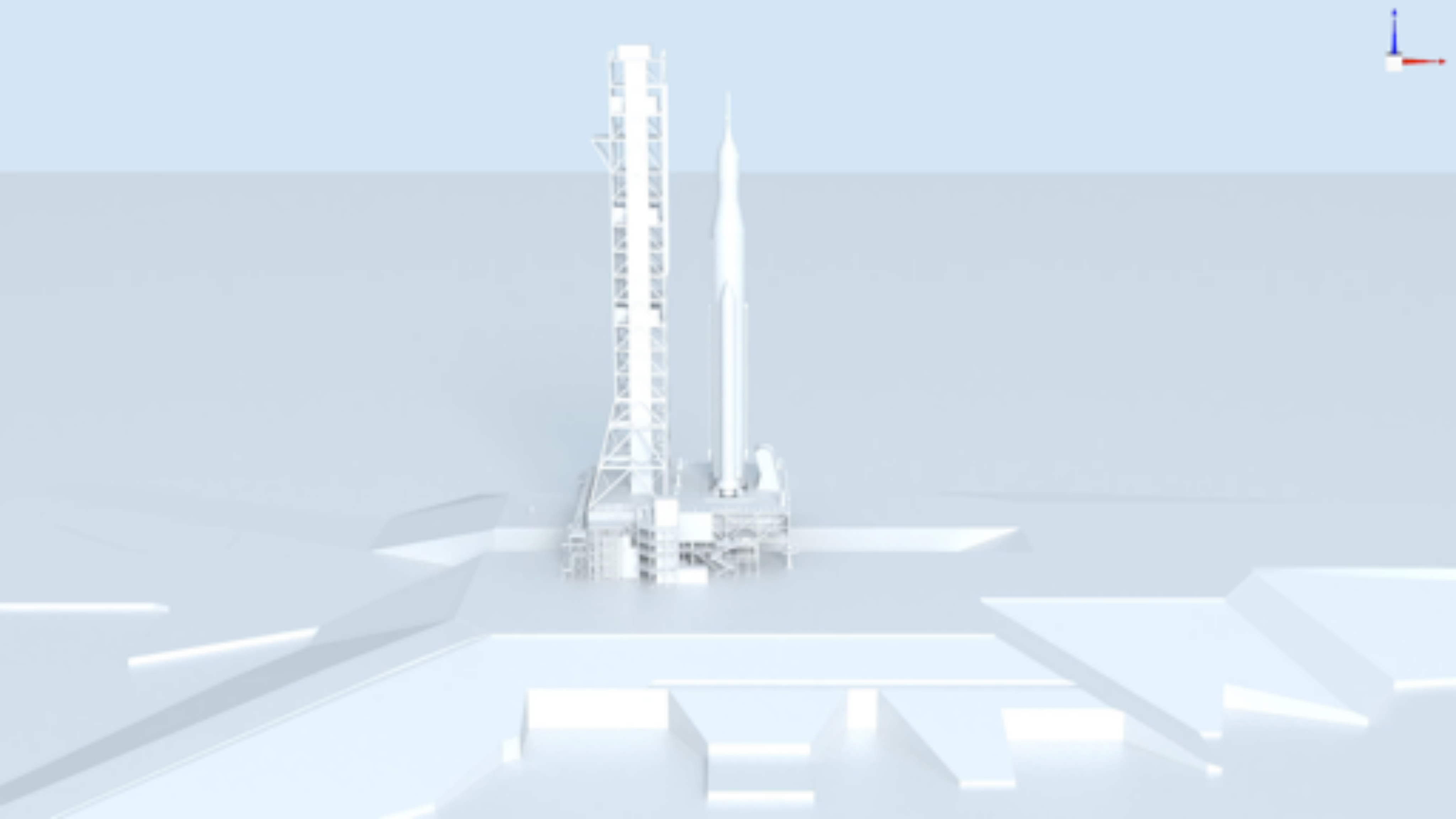
🟦 Developing

🟨 Future

🟧 Framework

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

Launch Environment



Visualization of geometry used in LAVA Cartesian simulation

Kennedy Space Center’s Pad 39B

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

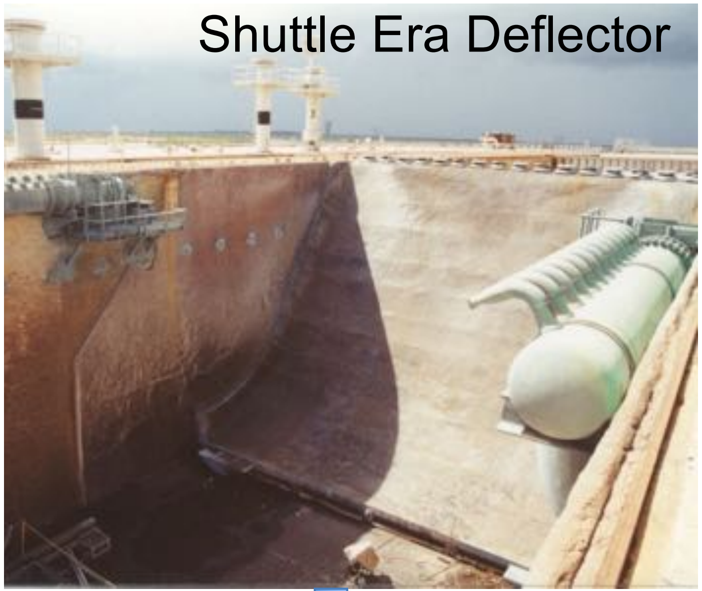
After many years of harsh rocket launches, the Main Flame Deflector (MFD) at Kennedy Space Center has been upgraded in anticipation of flights of NASA’s next generation Space Launch System.

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.

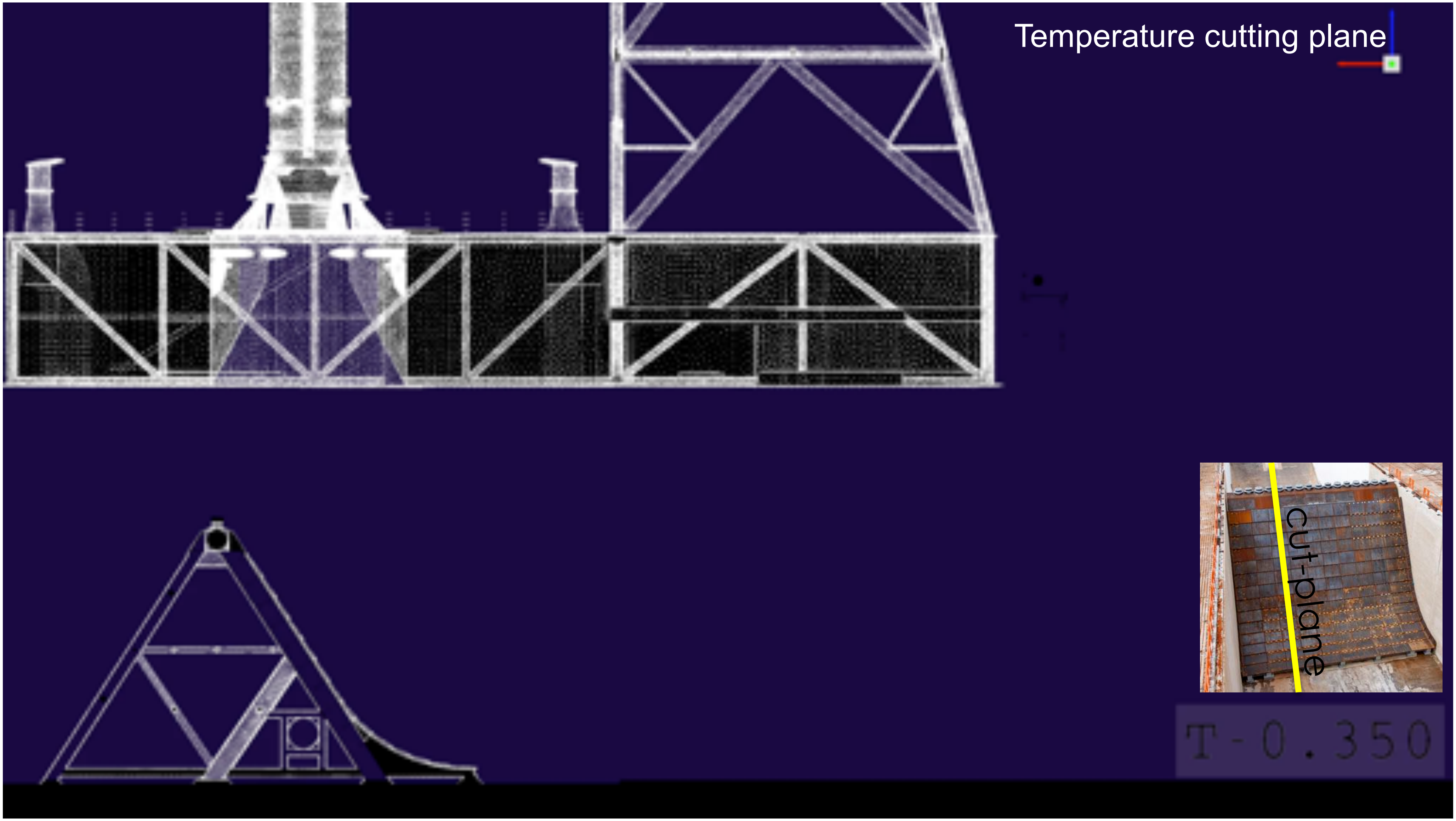


Shuttle Era Deflector

New Deflector

Lessons Learned: Launch Environment

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



Cartesian Grid IOP Simulations

Temperature cutting plane passing through an SRB centerline. Plume is clipped. Green people shown for scale.

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.

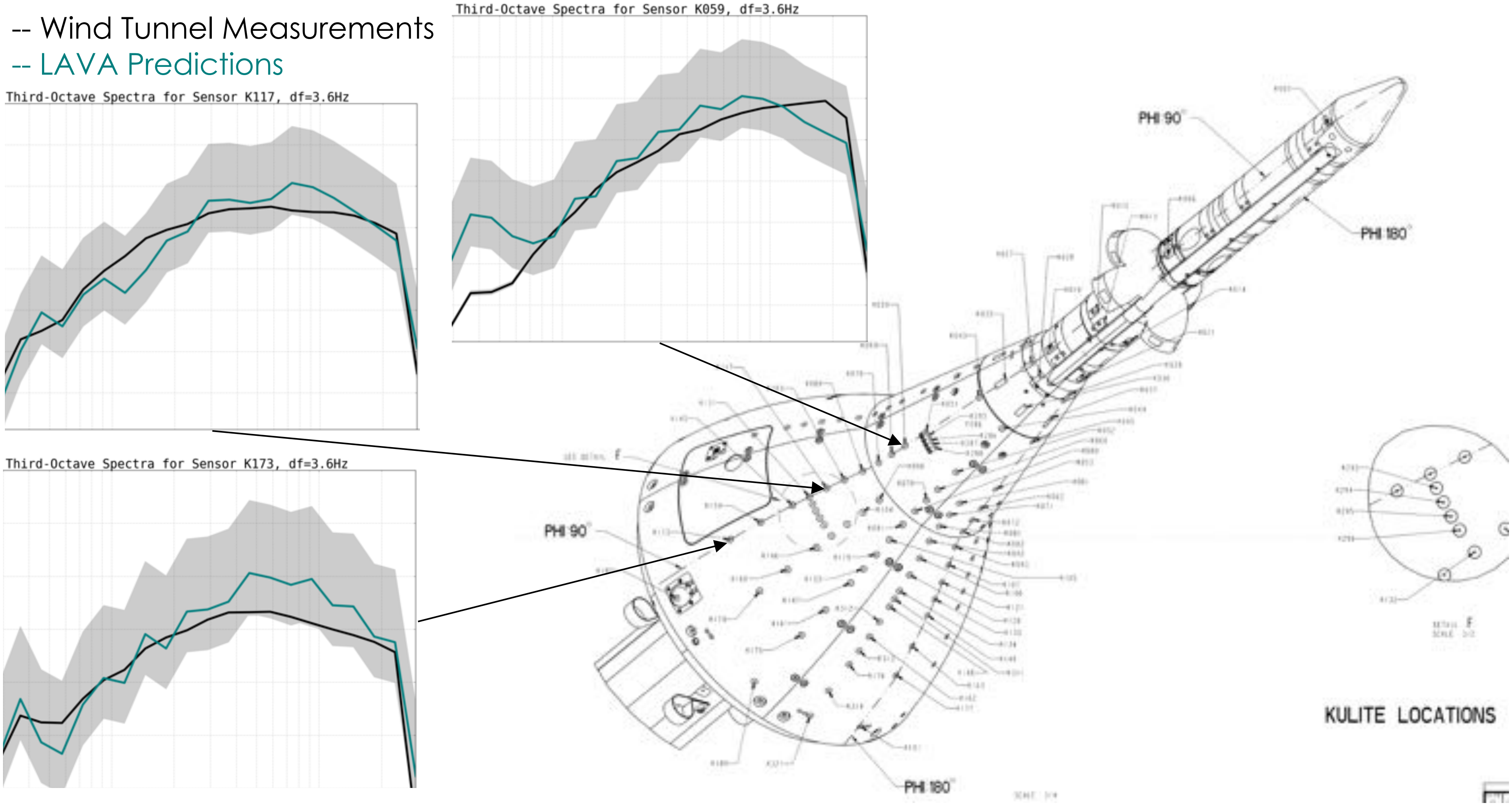
Launch Abort System Ascent Abort Simulation

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.

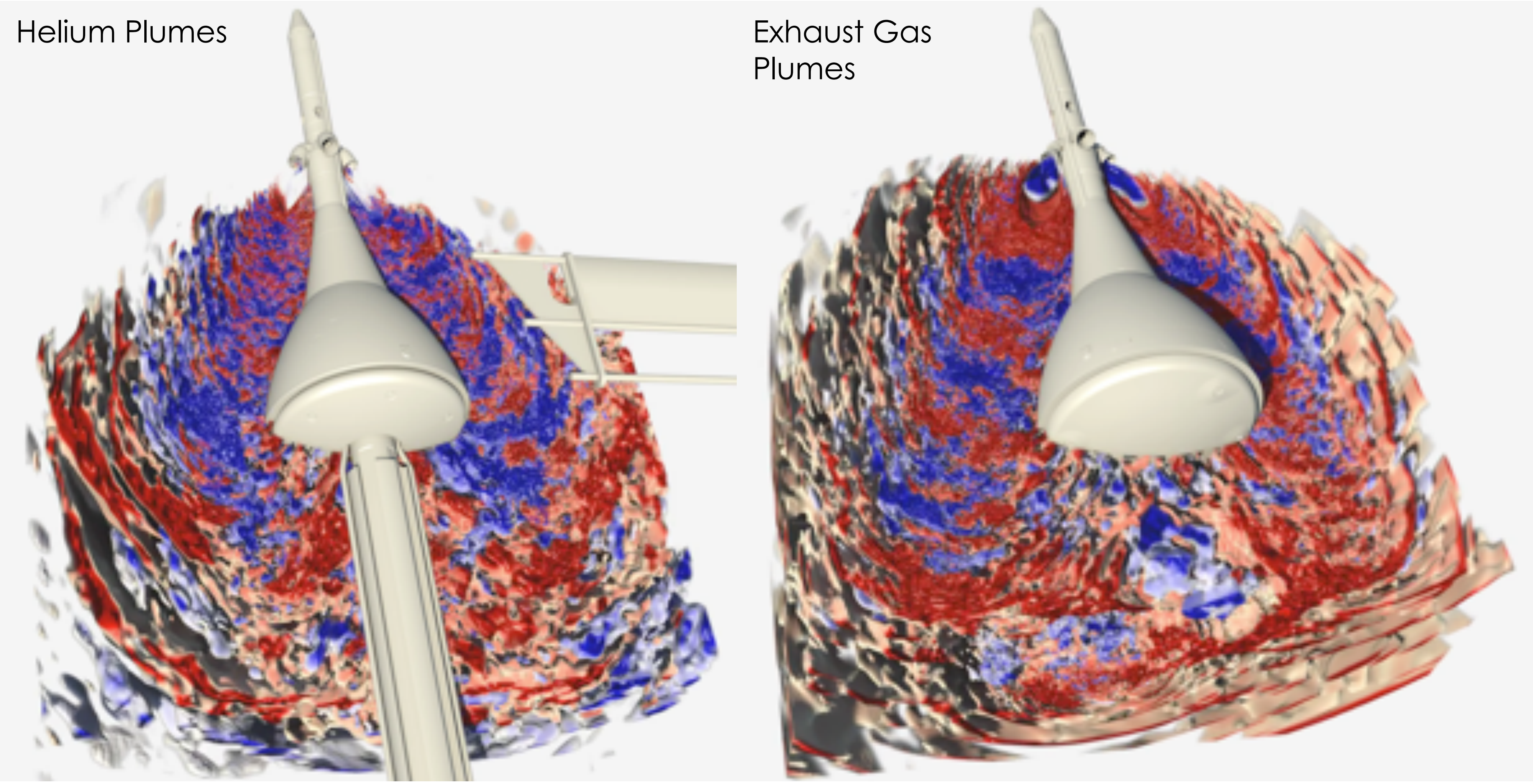
Validating Acoustics Against Wind Tunnel

-- Wind Tunnel Measurements

-- LAVA Predictions



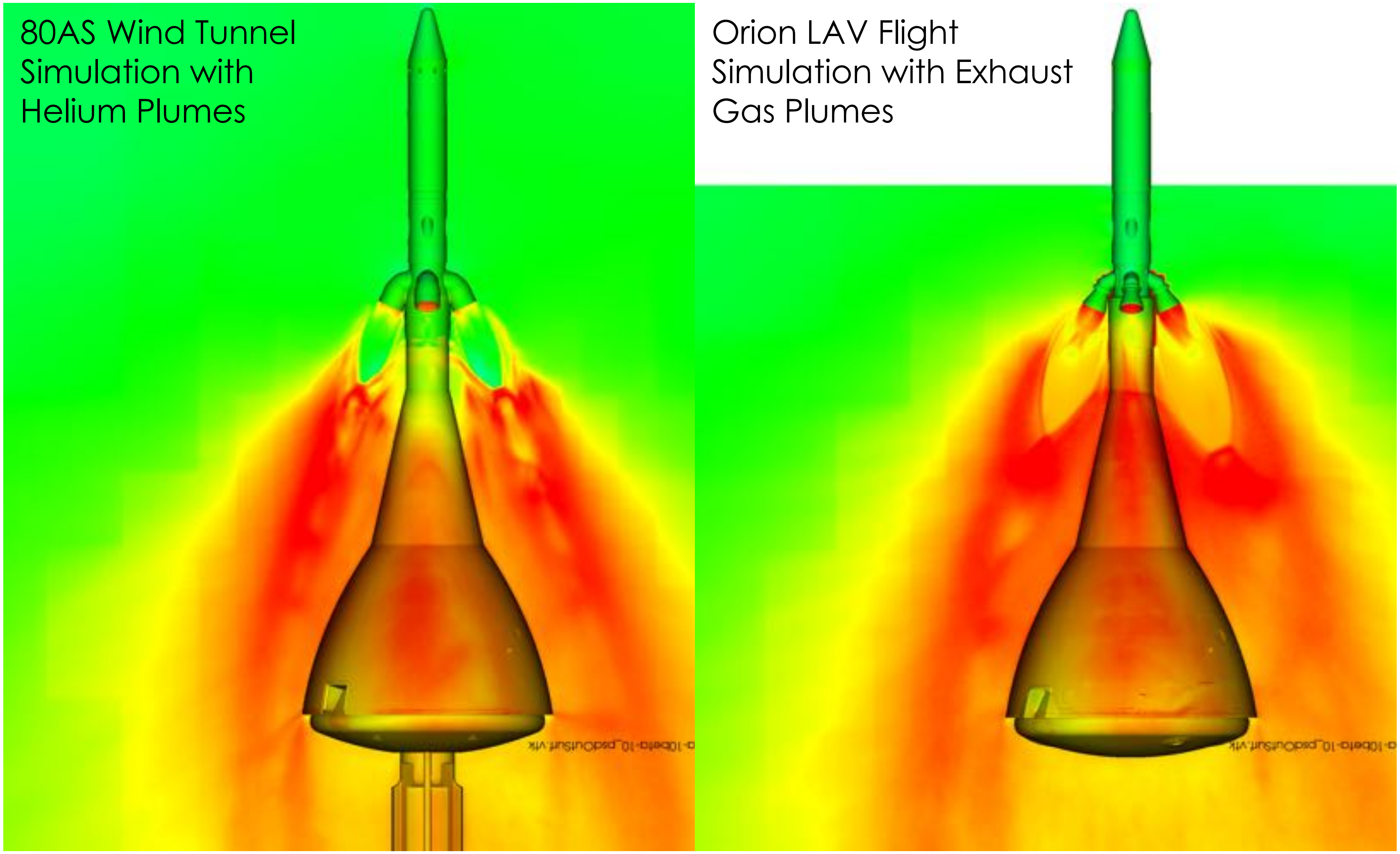
From Wind Tunnel To Flight



Volume rendering of p’ clipped at symmetry plane for 80AS wind tunnel (left) and LAV flight (right) simulations for ascent abort at Mach 0.7, $\alpha = \beta = -10$ °

From Wind Tunnel To Flight

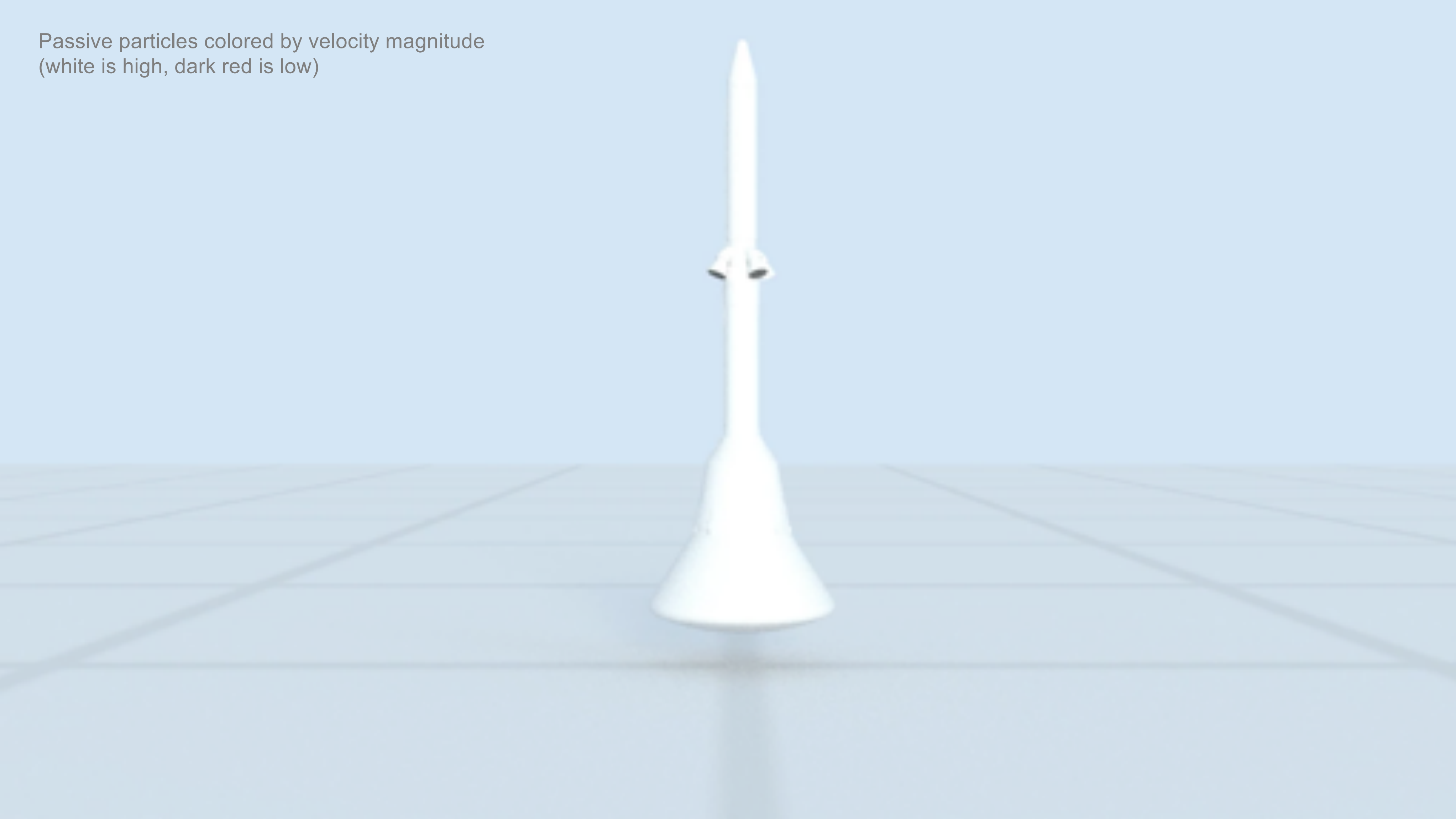
Overall Sound Pressure Level



80AS Wind Tunnel Simulation with Helium Plumes

Orion LAV Flight Simulation with Exhaust Gas Plumes

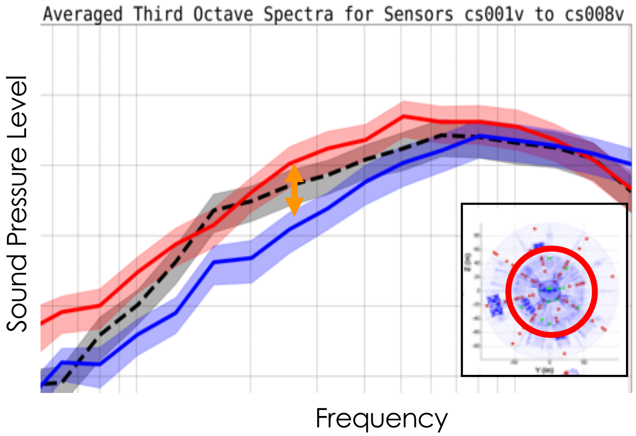
Orion Launch Abort Acoustics

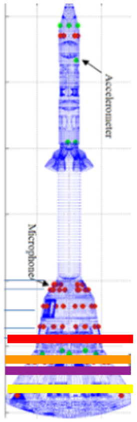


Predicting Surface Fluctuating Pressures For Accelerating Vehicle with LAVA Cartesian Navier-Stokes

SIMULATING PA-1 FLIGHT TEST

- LAVA team continues to collaborate with Orion Loads and Dynamics team at JSC to help characterize the vibro-acoustic environment of the Orion Launch Abort Vehicle (LAV) for launch and ascent abort scenarios
- Recently completed a simulation where the vehicle accelerates and banks to reproduce in PA-1 flight test trajectory from ignition until 1.25 seconds into the flight
- CFD predictions were validated with flight test data and in conjunction with other CFD simulations, results will help the Orion team better understand the effects of acceleration and angle of attack on surface fluctuating pressure levels

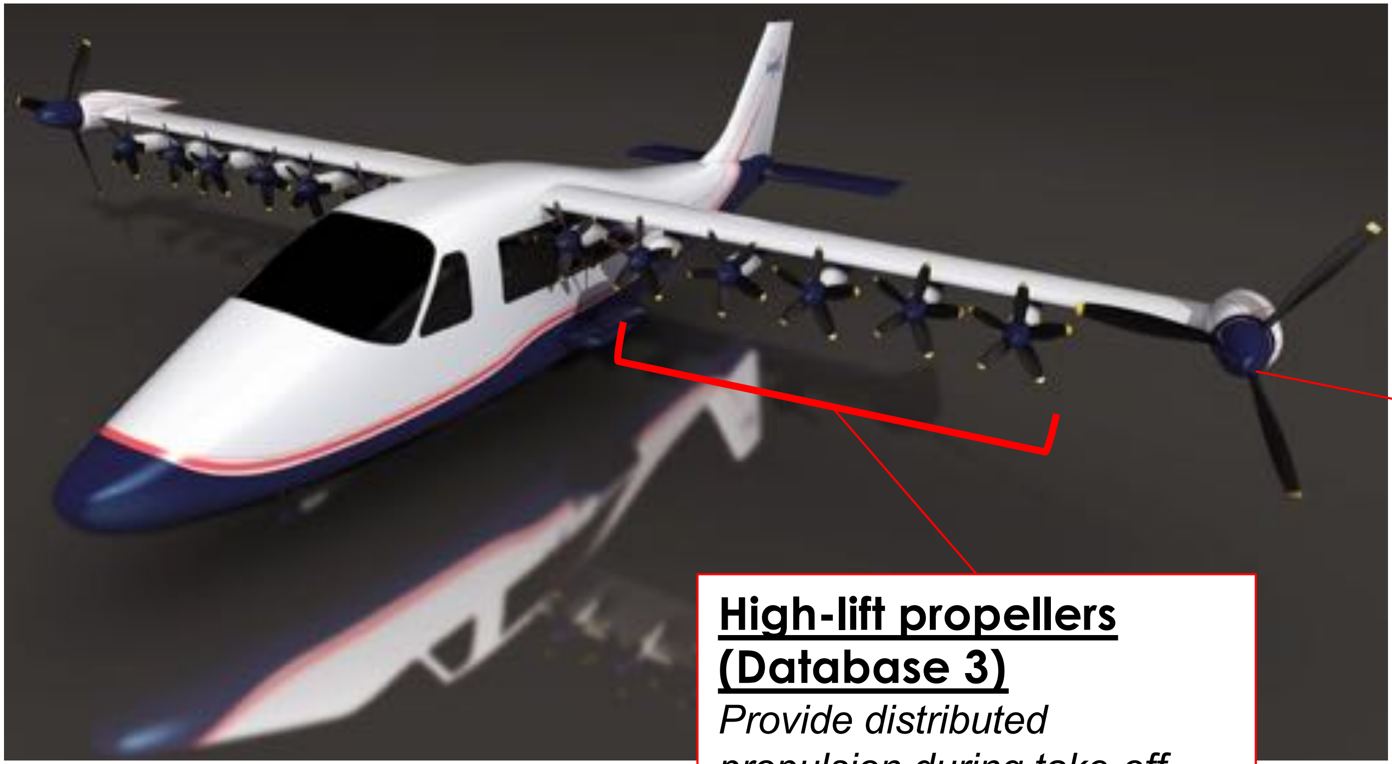




Passive particles colored by velocity magnitude (white is high, dark red is low).

X-57 Maxwell CFD Overview

- **NASA has developed the X-57 Maxwell electric aircraft concept to achieve a 5X reduction in energy consumption compared to conventional aircraft propulsion**
- **Research teams at NASA have performed CFD analysis to create multiple aerodynamic databases. These will be used to design aircraft control systems and the aircraft flight simulator.**
    - Database 1 (188 simulations): Power-off (no thrust)
    - Database 2 (205 simulations): Cruise propellers powered-on
    - Database 3 (1,936 simulations): High-lift propellers powered-on



Cruise propellers (Database 2)

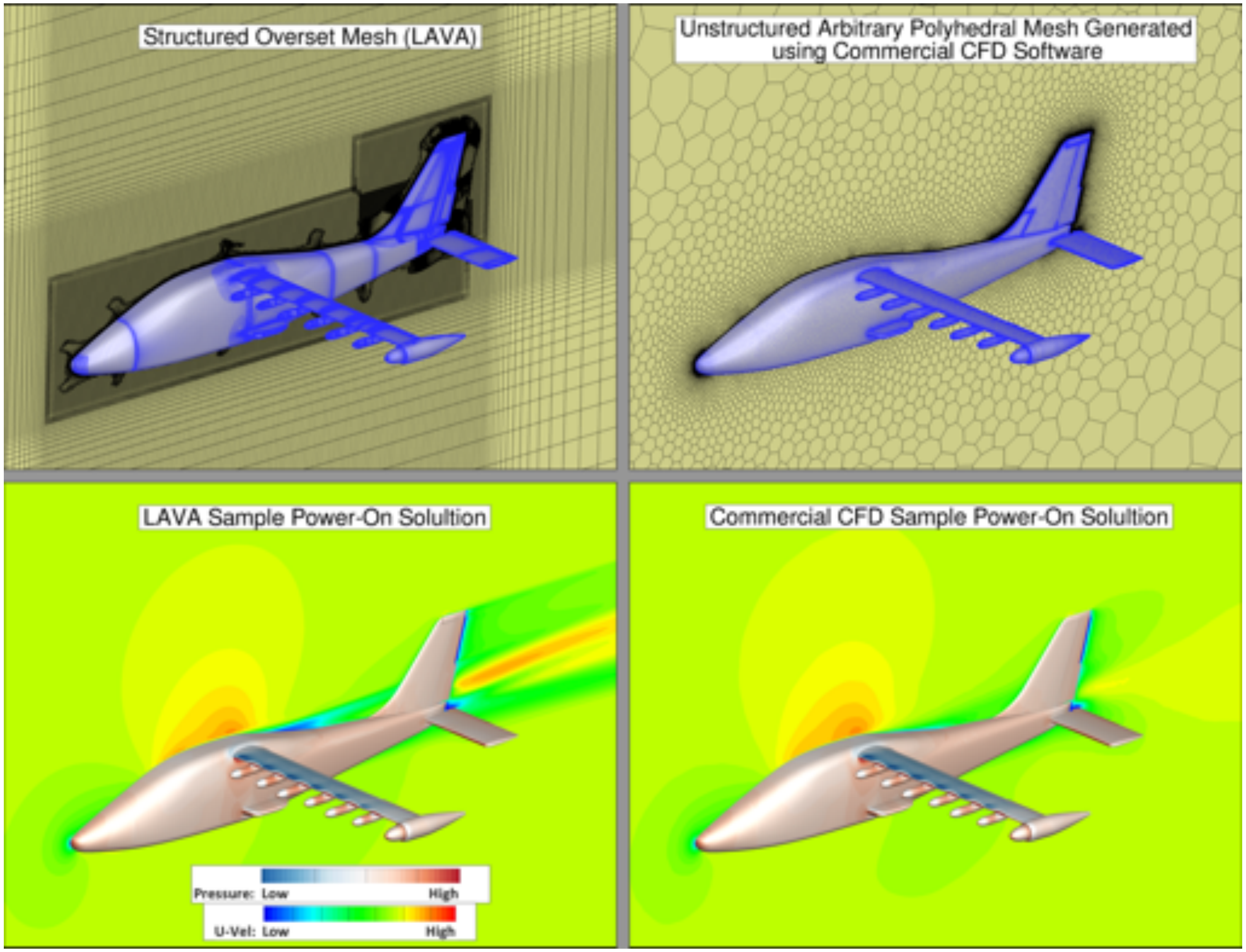
Provide main thrust during cruise

High-lift propellers (Database 3)

Provide distributed propulsion during take-off and landing

Using CFD to Generate an X-57 Aerodynamic Database

- The Launch Ascent Vehicle Aerodynamics (LAVA) and commercial CFD codes (such as ANSYS, Star-CCM+, etc.) have been used to generate computational meshes and simulate desired flight conditions
- To date, 1,200+ steady-state RANS simulations have been run to understand performance and impacts of distributed propulsion technology.
- Typical mesh size ~ 120 Million points

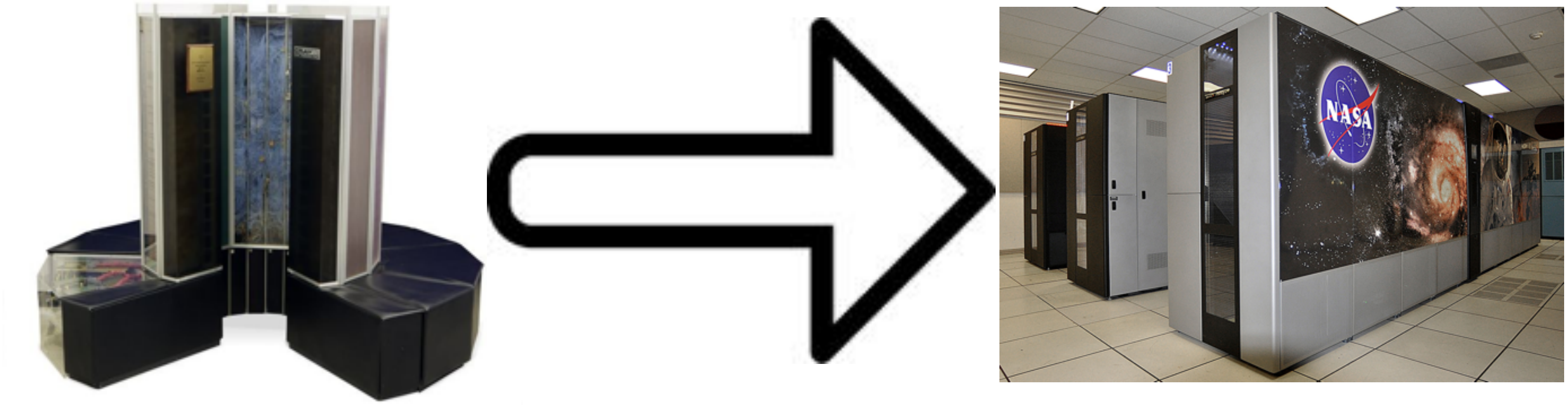


Example structured overset and unstructured polyhedral meshes (top) and sample CFD solution obtained from these meshes (bottom)

Refactoring Flow Solver for Aerodatabase Generation

The curvilinear solver in LAVA

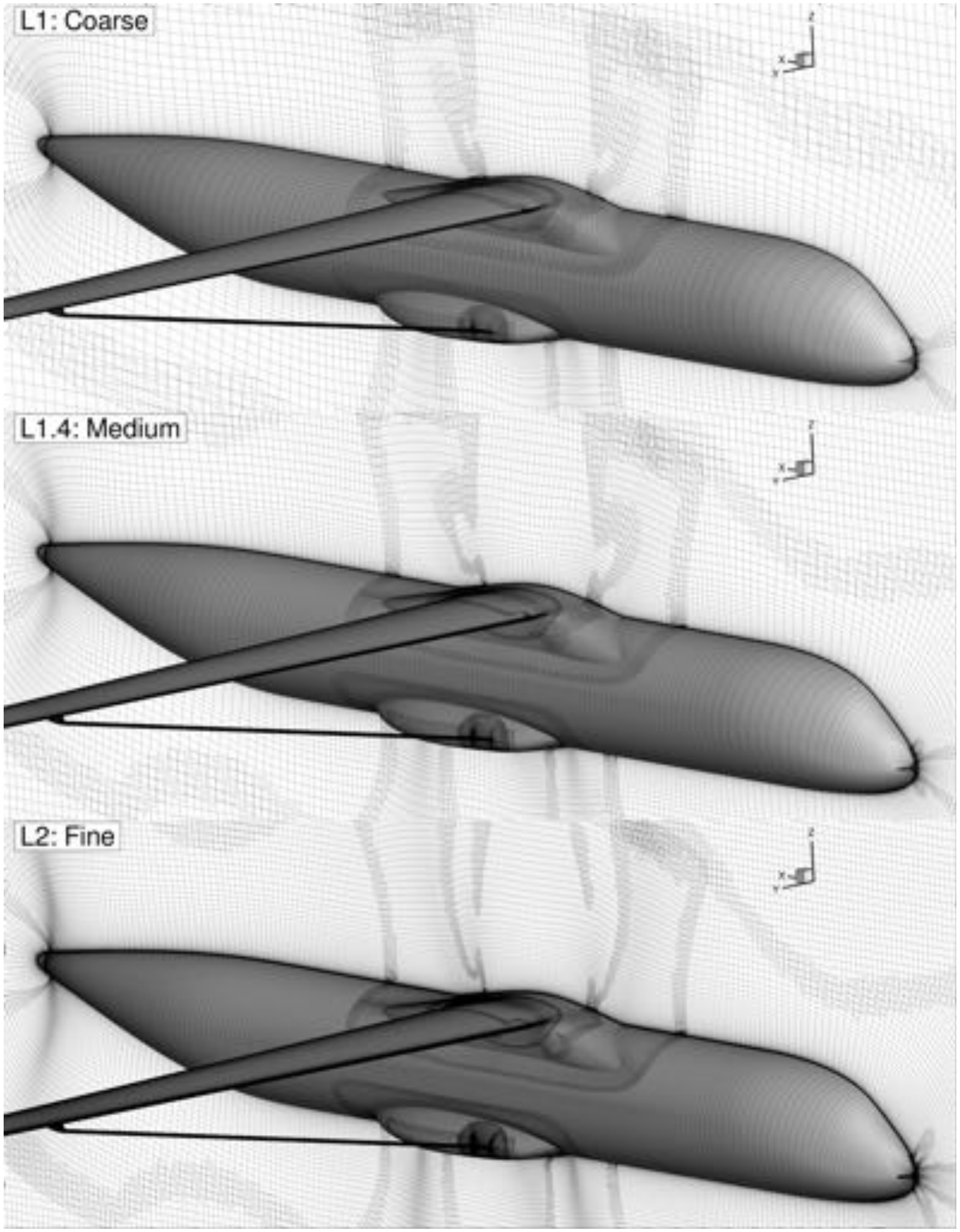
- Last major code structure overhaul to support “scalar processors” in the early 2000’s
- Computer architectures are now vastly different than in the year 2000
- Most common compute nodes (eg. Pleiades, Electra) have dozens of compute cores in a cache-coherent shared memory system
- The flat-MPI parallel approach typical of CFD codes at the turn of the century no longer matches the multi-level compute hierarchy
- Overall goal is to vastly improve the computational efficiency of the flow solver while retaining the same discretization



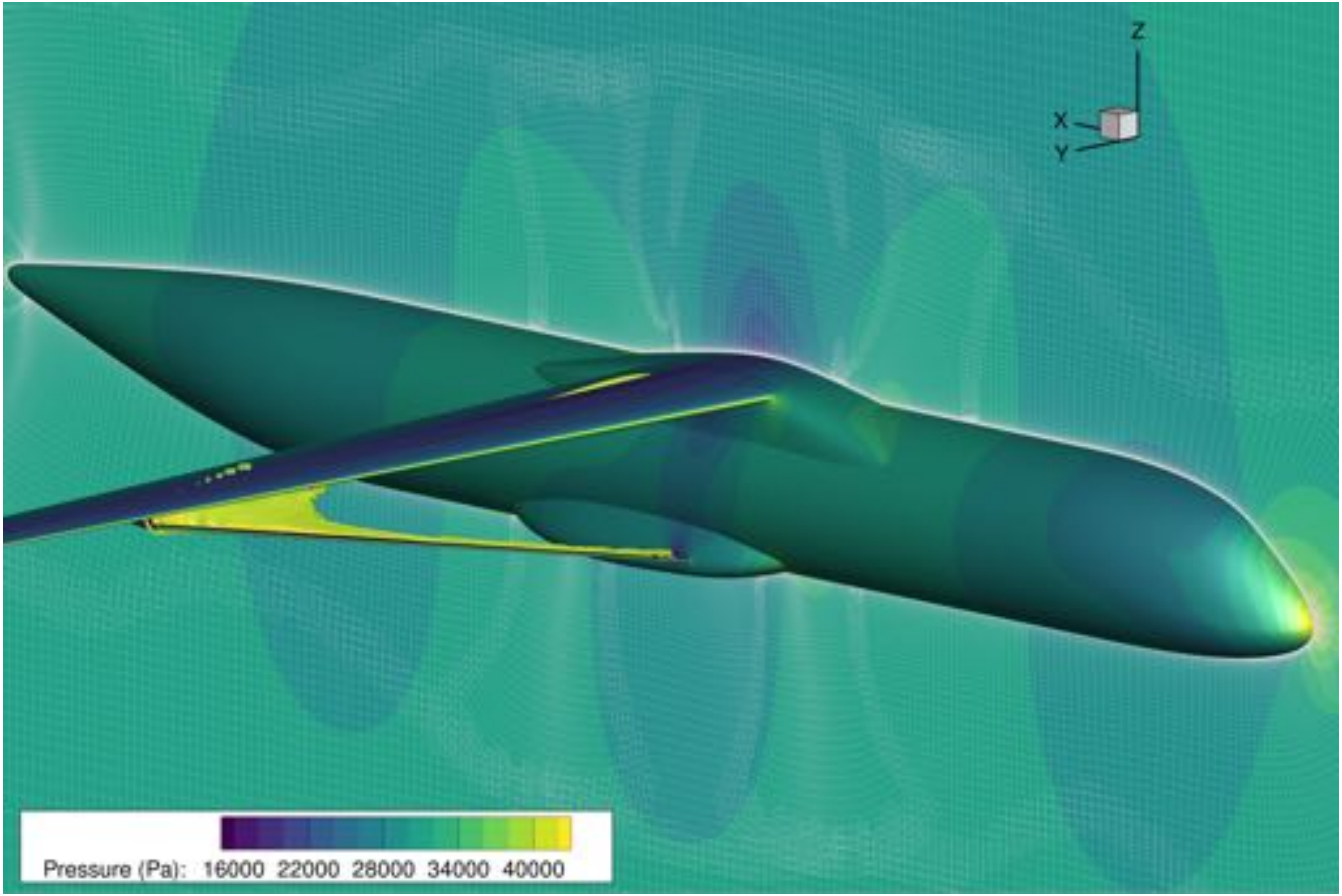
Test Case: PADRI – Truss-Braced Wing

- Generic strut-braced wing configuration
- Cruise Mach number of 0.72
- Similar to Boeing Truss-Braced Wing, but fully open-source geometry
- Three mesh levels tested

Mesh Level	Grid Nodes
L1	7.7 M
L1.4	19.7 M
L2	58.4 M

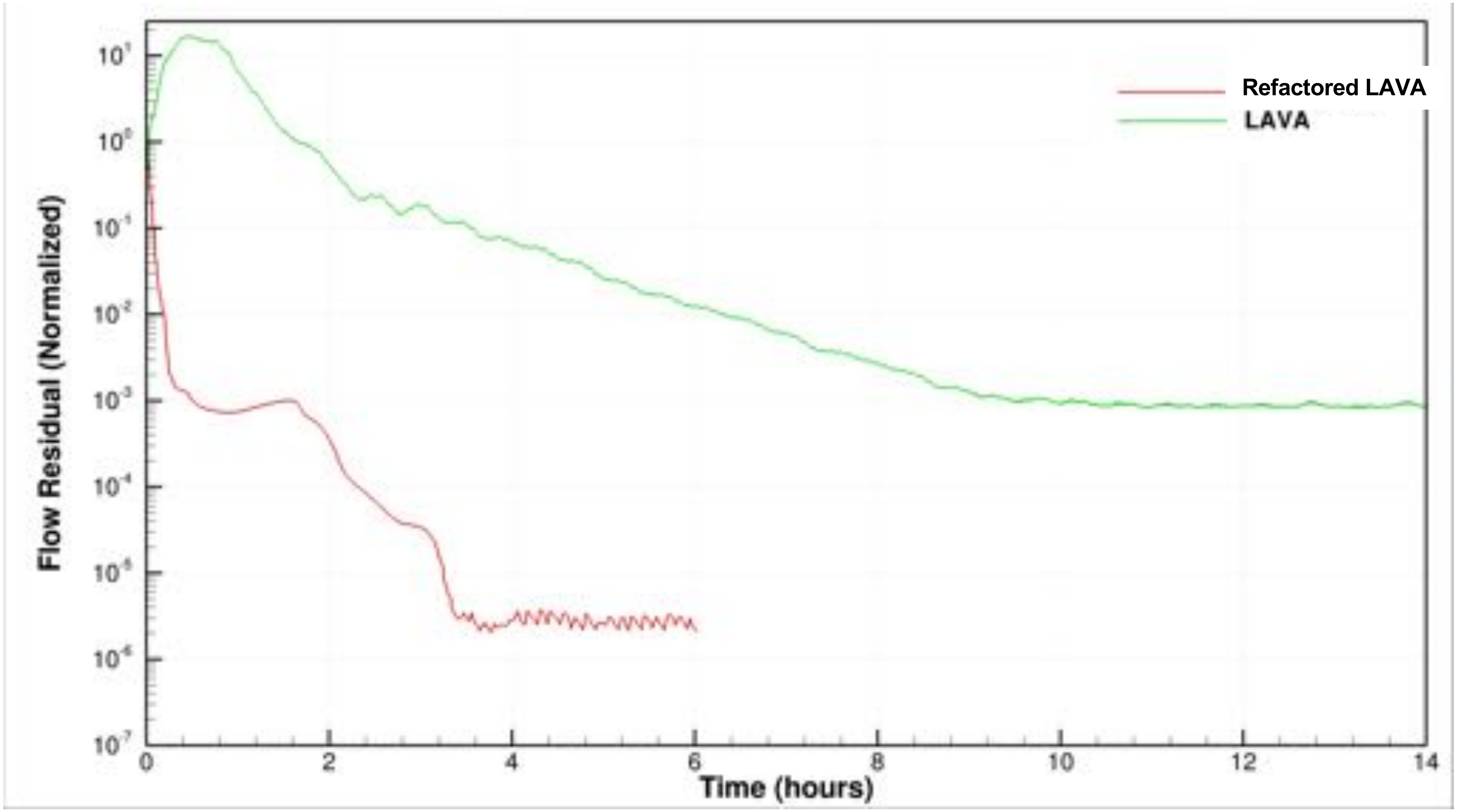


Solution: PADRI – Truss-Braced Wing



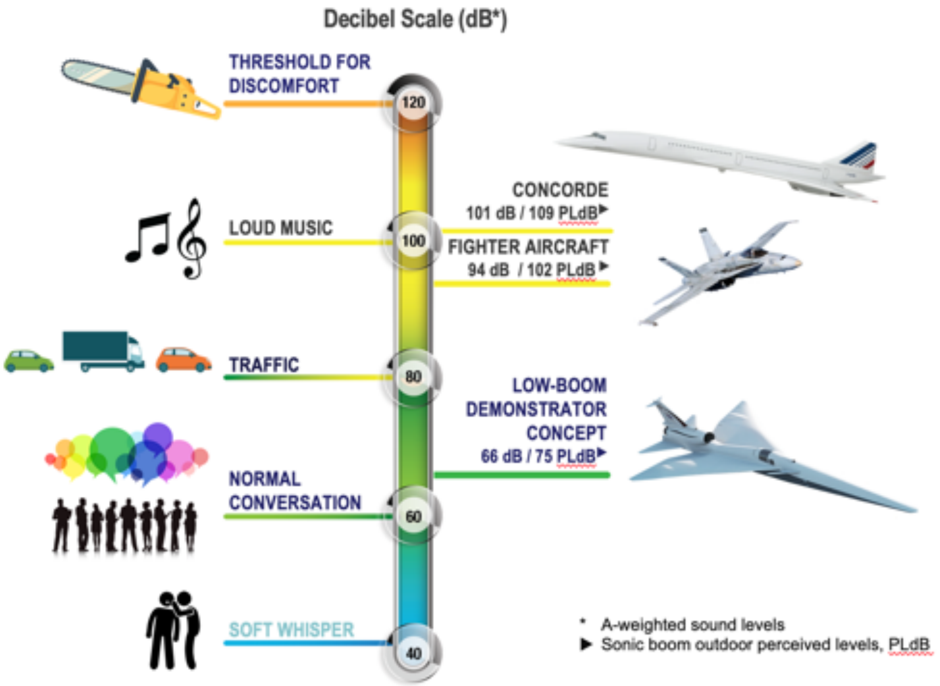
Speed Up

- Lava code used 680 Cores x 14 hours = 314.2 SBU (Ivy bridge)
- Refactored LAVA used 40 cores x 6 hours = 9.5 SBU (Skylake)
- **> 33X reduction in compute resources**



X-59 Quiet Supersonic Technology (QueSST)

- First Flight will be in 2021
- Community Testing to begin in 2022



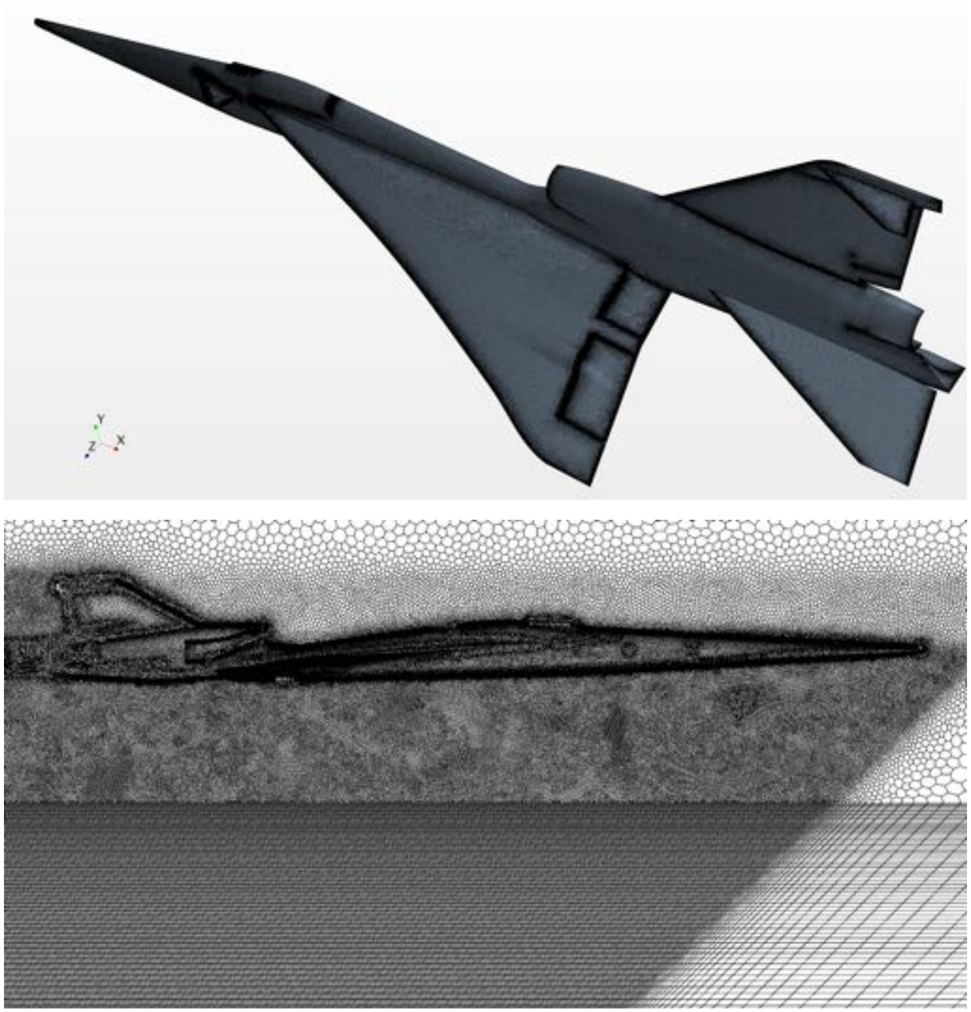
* A-weighted sound levels
▸ Sonic boom outdoor perceived levels, PLdB

- Supersonic flight is currently banned by the FAA due to the excessive noise produced by flying faster than M=1
- Want to build a database of community response to quiet (>75 PLdB) supersonic aircraft designs using a demonstrator aircraft (X-59 QueSST)

Credit: Lockheed Martin Corporation

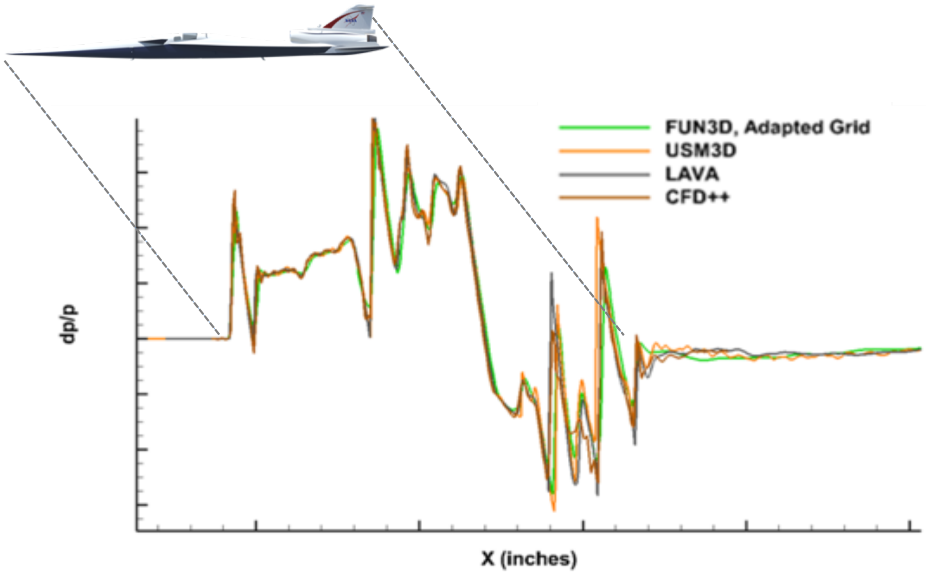
CFD Simulations of X-59 QueSST

Grid Generation

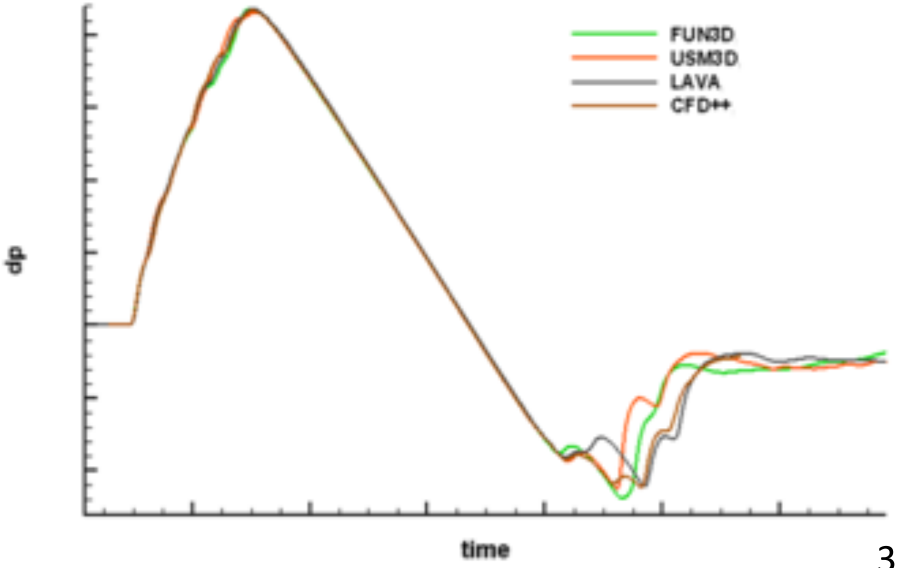


- Generated using a combination of commercial tools

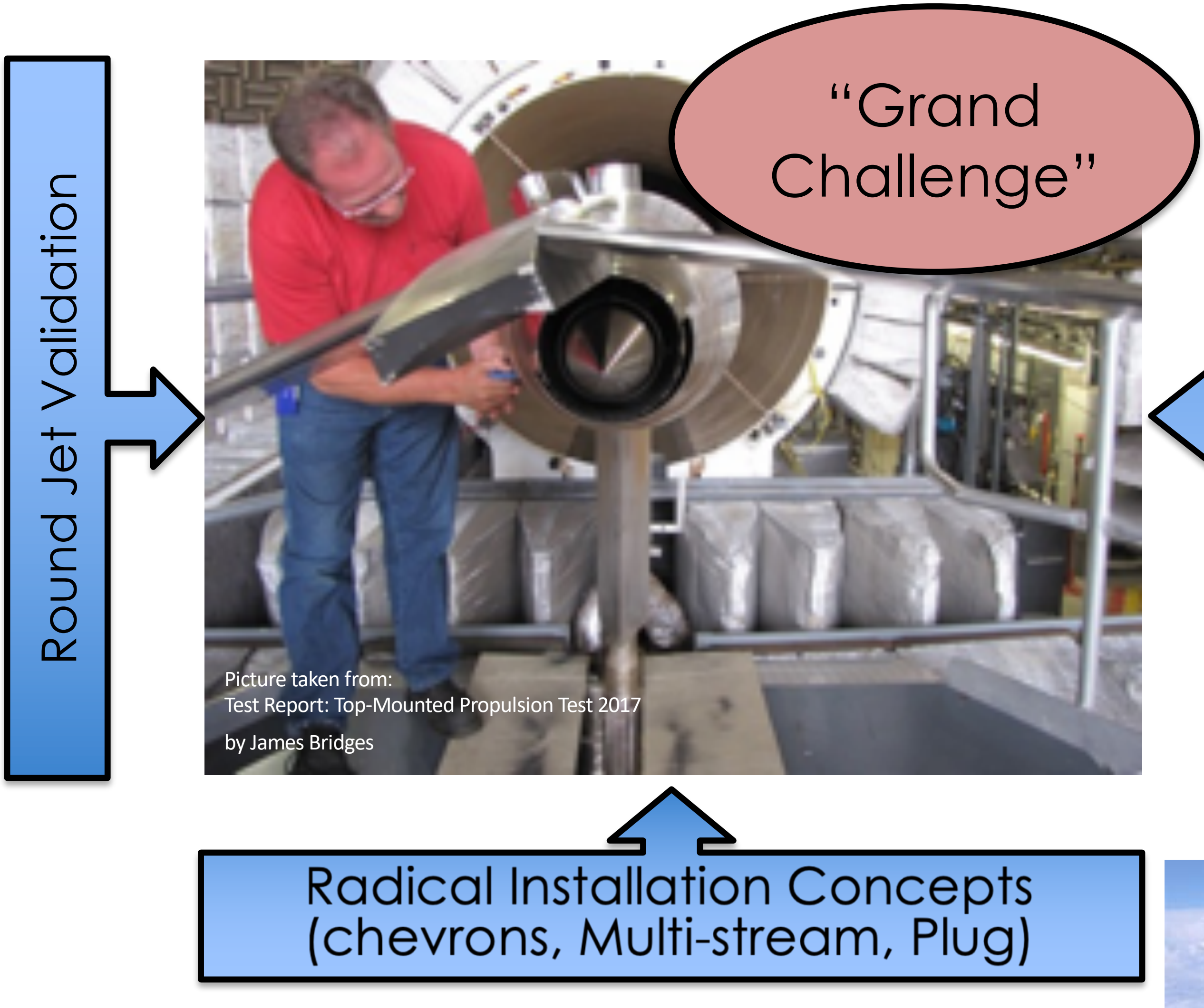
Near-field Pressure Signature



Loudness on the Ground



Jet Noise Simulation for of Emerging Commercial Supersonic Technologies



Round Jet Validation

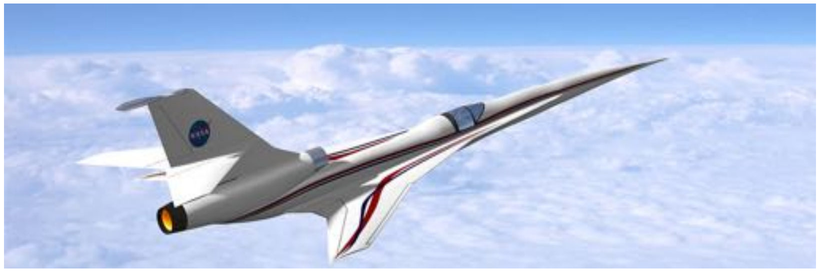
“Grand Challenge”

Shielding Concepts

Picture taken from:
Test Report: Top-Mounted Propulsion Test 2017
by James Bridges

Radical Installation Concepts (chevrons, Multi-stream, Plug)

- Novel jet noise reduction concepts for the LBFD require evaluation
- Scale-resolving simulations combined with experiments result in better understanding
- Simulation are required to be accurate, robust, and efficient



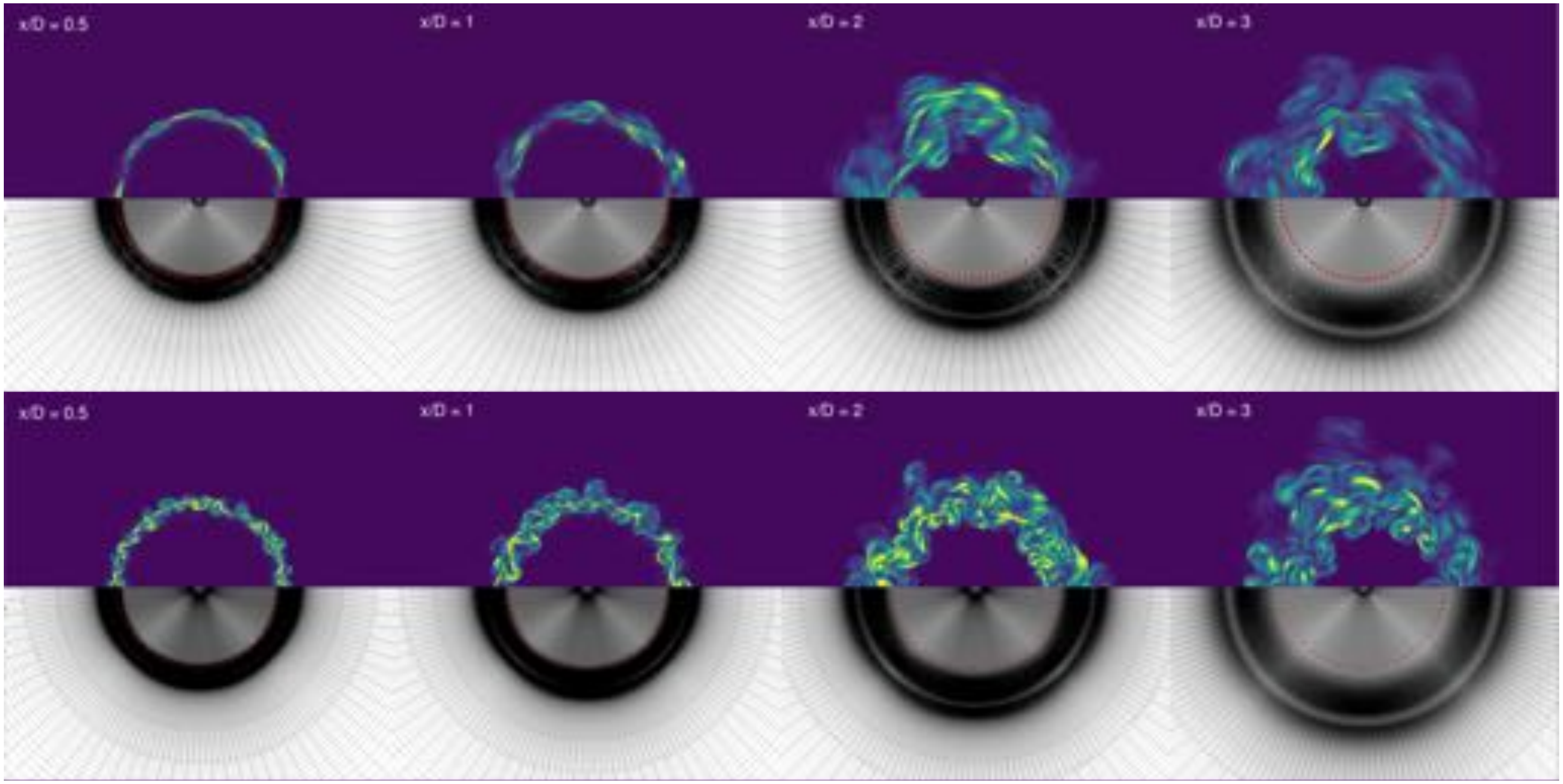
LBFD concept

Advanced Zonal RANS/LES Modeling
Hybrid RANS/LES of Jet Surface Interaction Noise

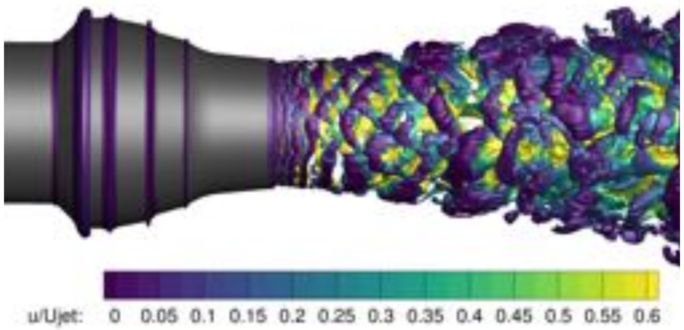
Round Jet
SP7 $M_{jet} = 0.9$

Coarse (90M)

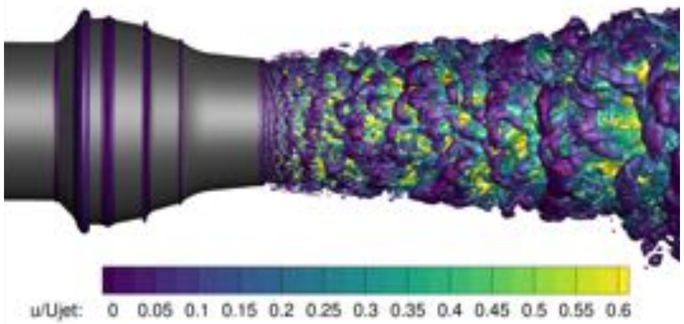
Fine (210M)



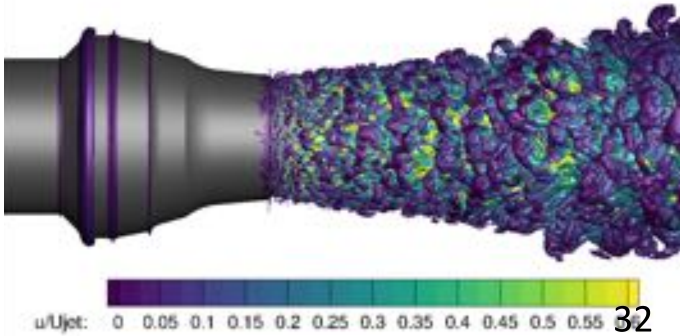
Coarse (90M)



Medium (120M)

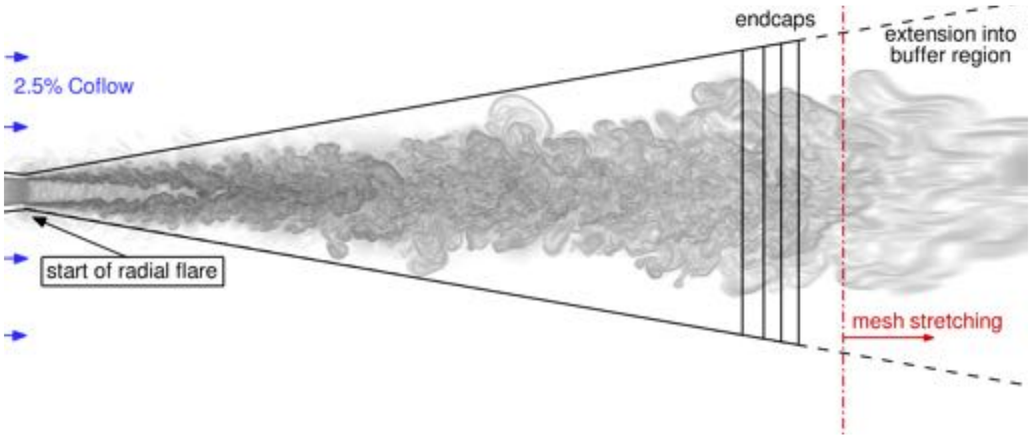


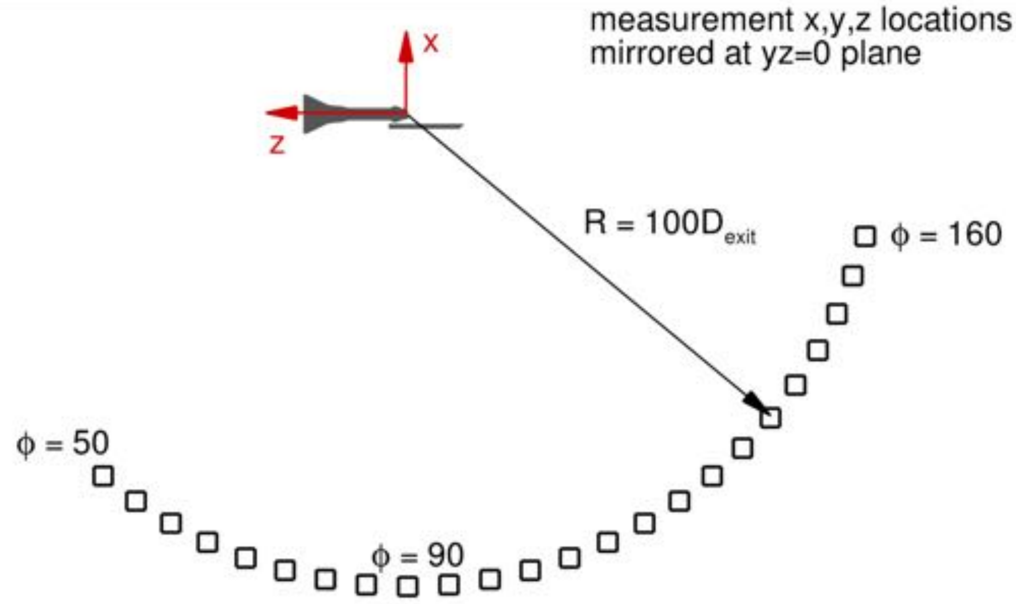
Fine (210M)



Advanced Zonal RANS/LES Modeling
Hybrid RANS/LES of Jet Surface Interaction Noise

Far-field acoustic propagation

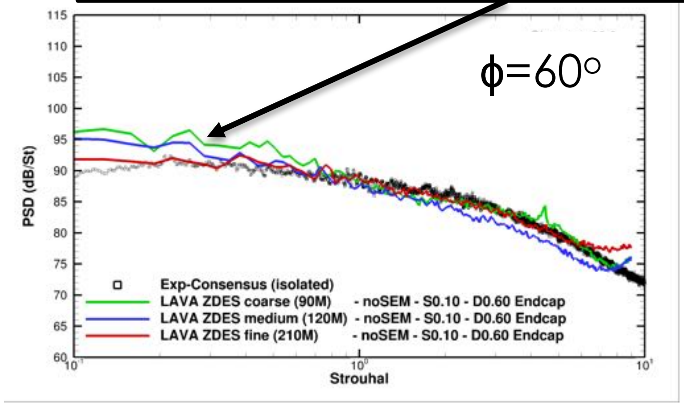


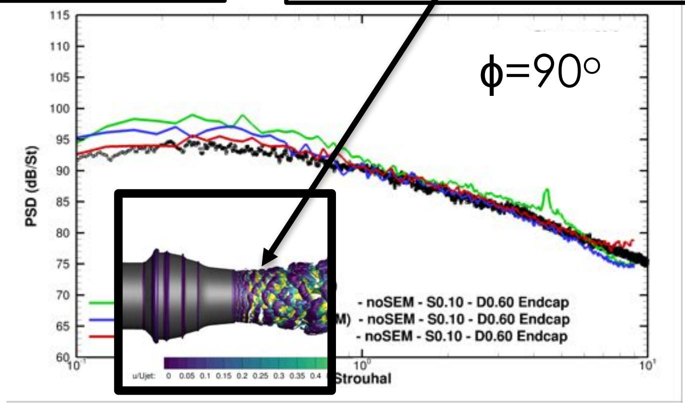


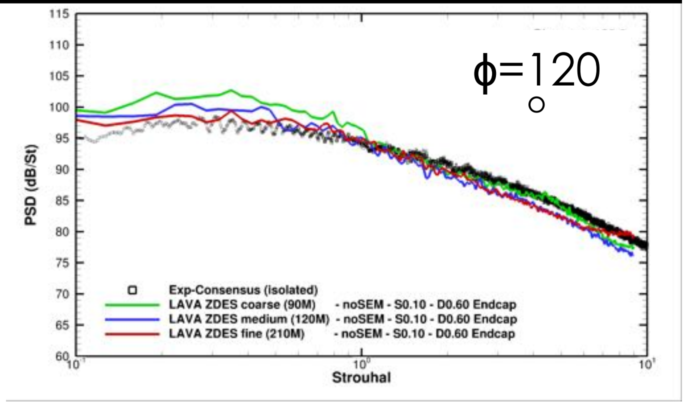
PSD comparisons at 100 nozzle diameters from the exit

coarse 5dB over-prediction for St < 0.7

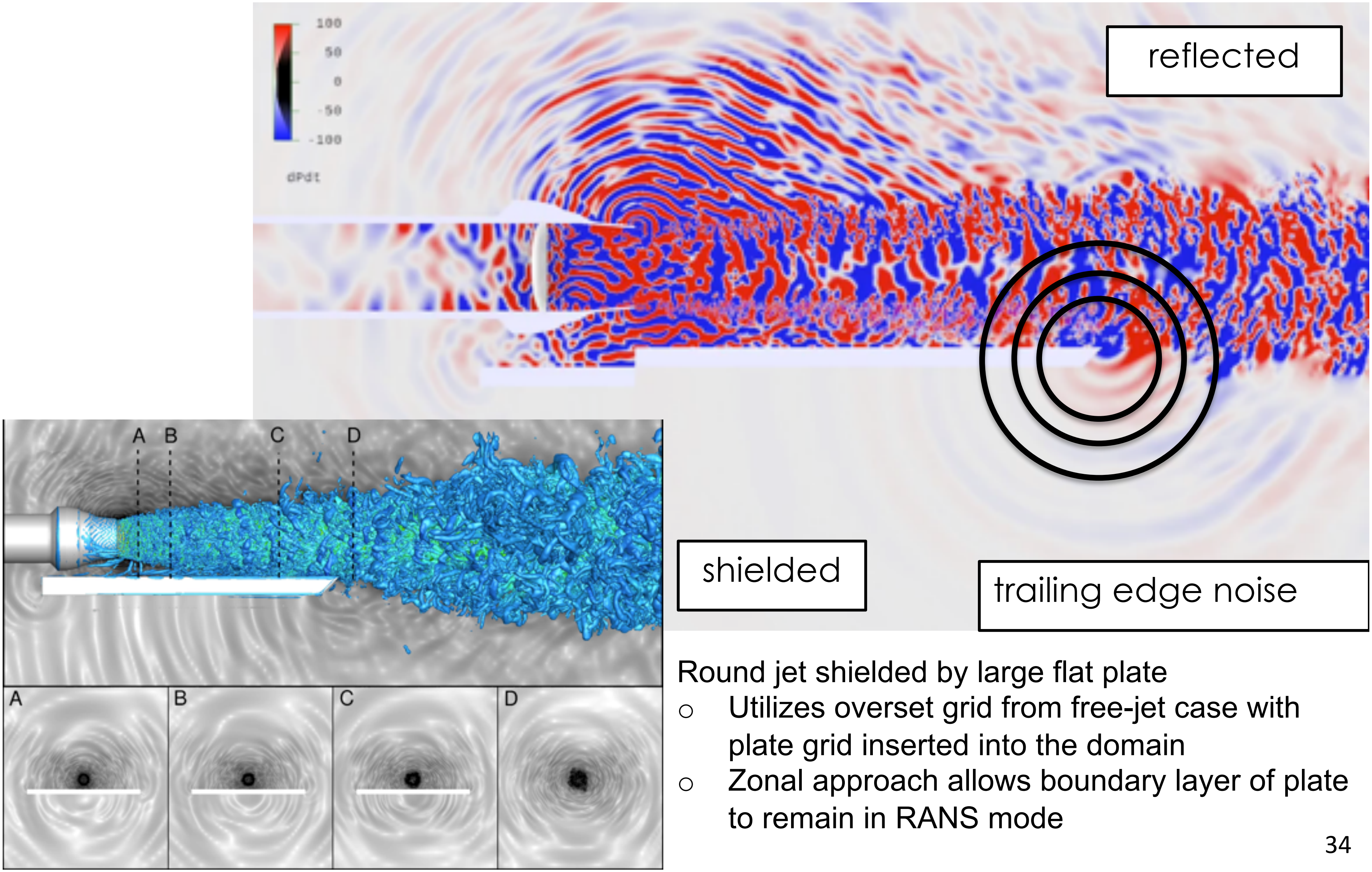
Delay in breakdown of 2D structures at nozzle exit





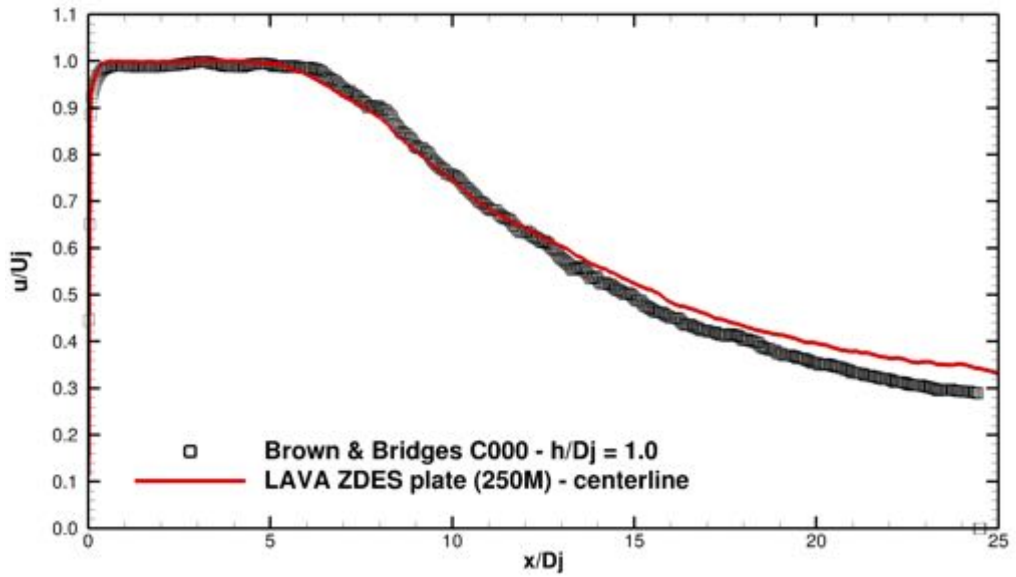


Advanced Zonal RANS/LES Modeling
Hybrid RANS/LES of Jet Surface Interaction Noise

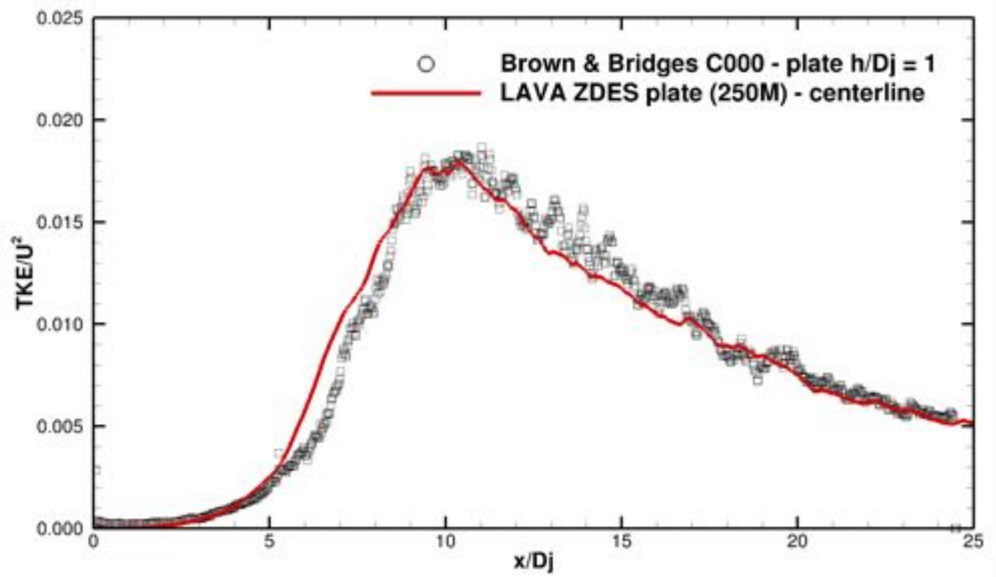


Round jet shielded by large flat plate
- Utilizes overset grid from free-jet case with plate grid inserted into the domain
- Zonal approach allows boundary layer of plate to remain in RANS mode

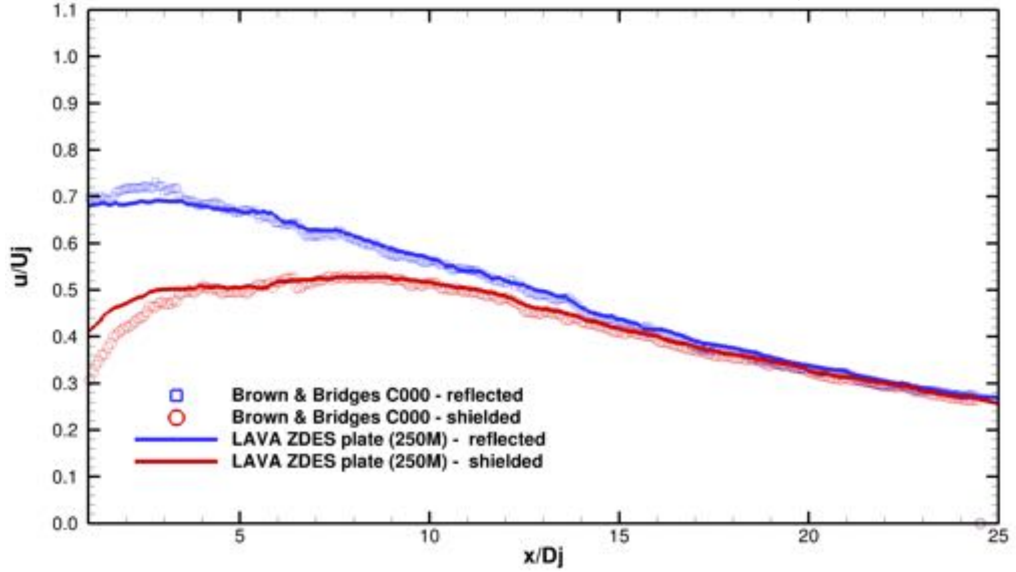
Advanced Zonal RANS/LES Modeling
Hybrid RANS/LES of Jet Surface Interaction Noise



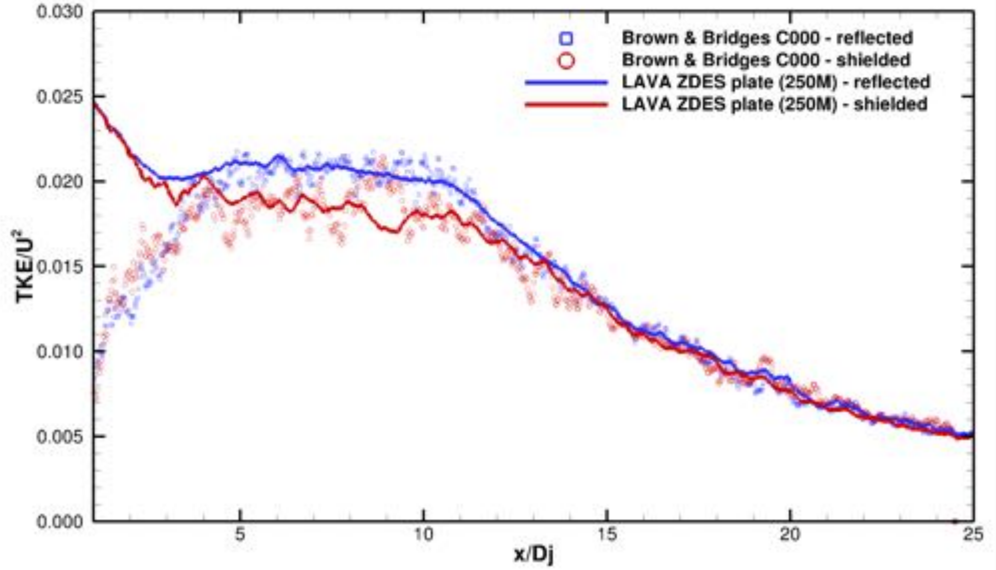
Centerline Axial Velocity



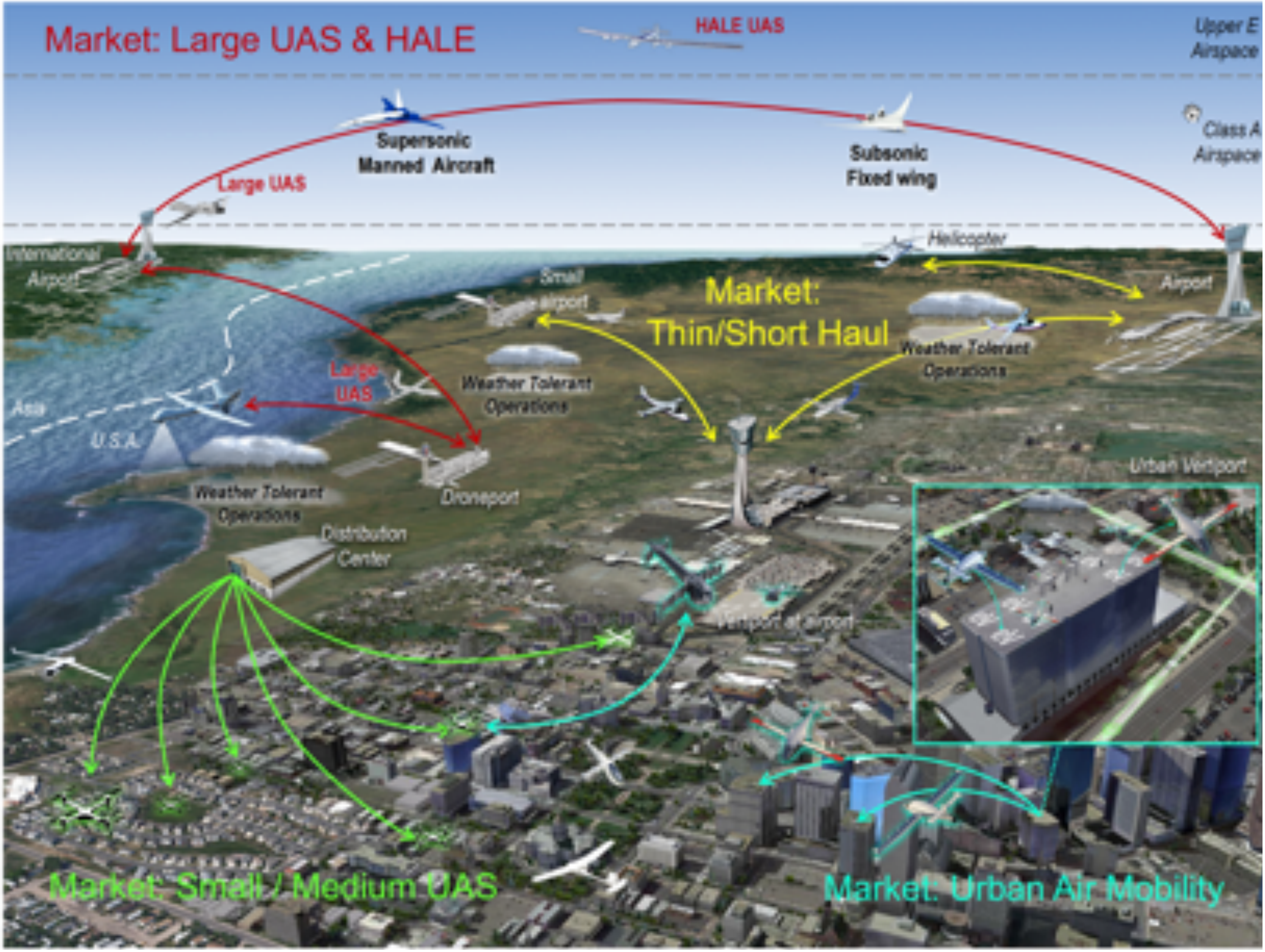
Centerline Resolved TKE



Lipline Axial Velocity



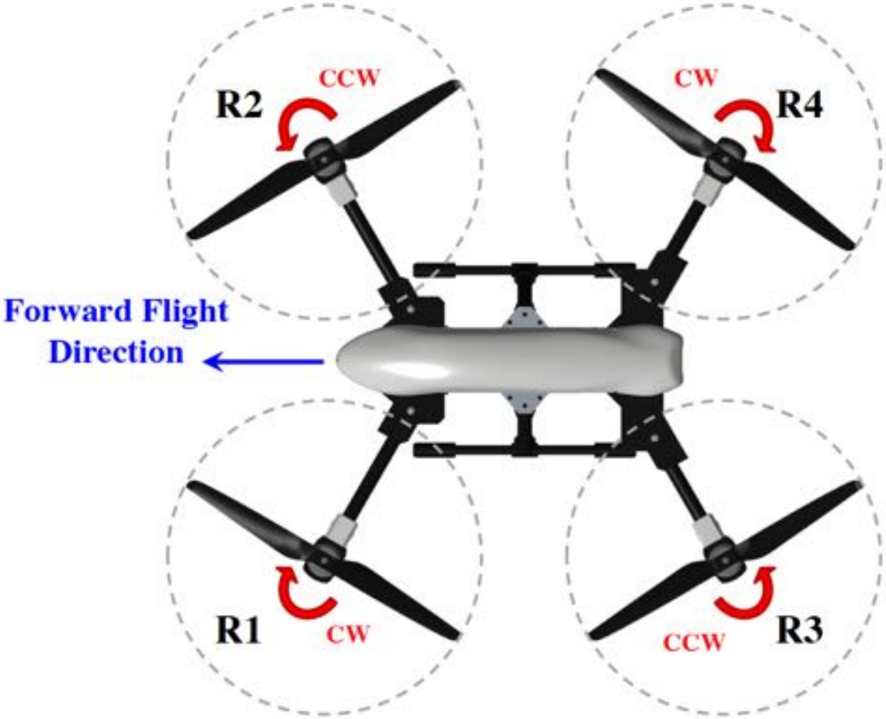
Lipline Resolved TKE

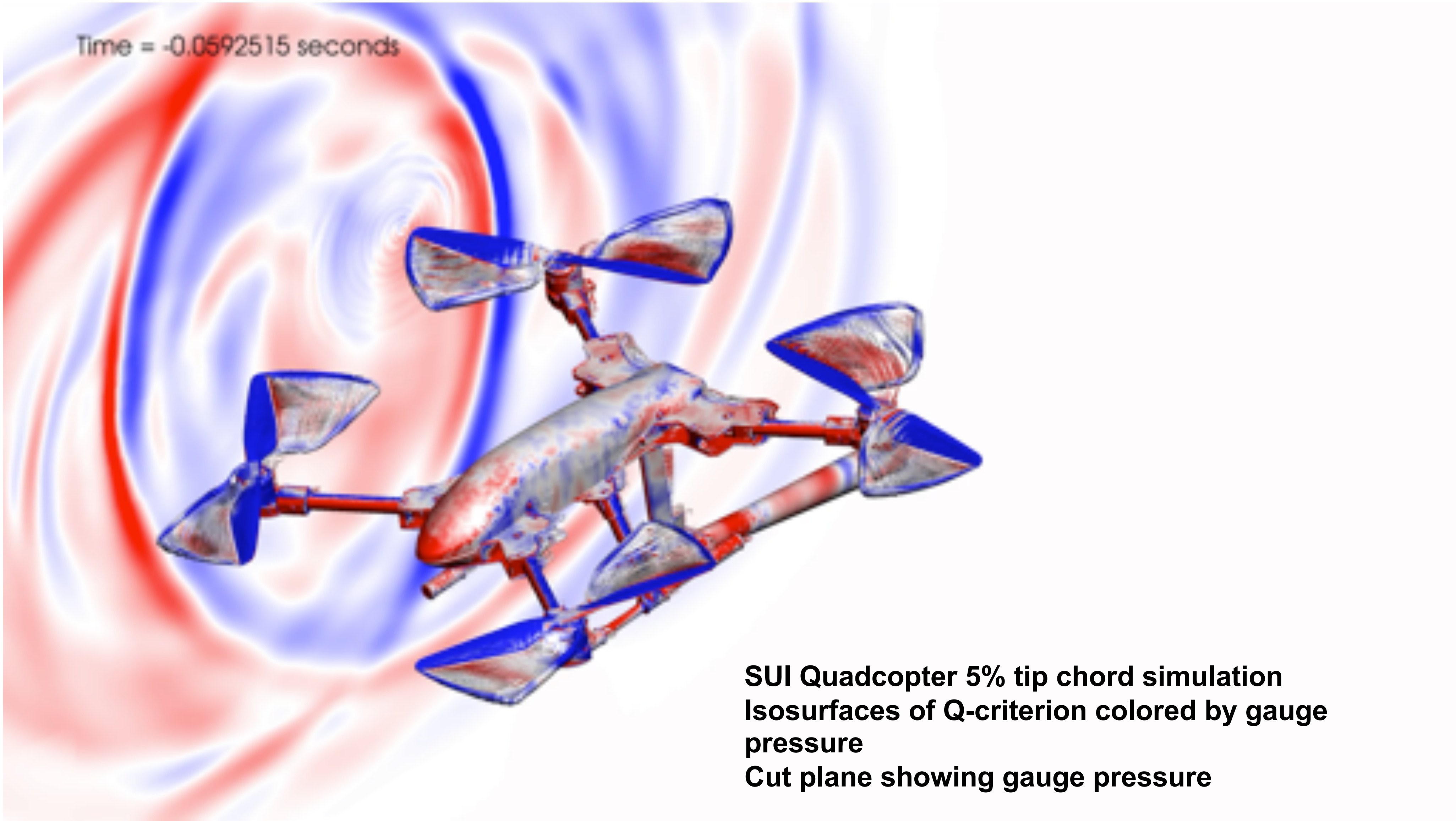

Market: Large UAS & HALE
HALE UAS
Upper E
Airspace
Supersonic
Manned Aircraft
Subsonic
Fixed wing
Class A
Airspace
Large UAS
International
Airport
Helicopter
Small
airport
Market:
Thin/Short Haul
Airport
Weather Tolerant
Operations
Large
UAS
Weather Tolerant
Operations
Asia
U.S.A.
Weather Tolerant
Operations
Droneport
Distribution
Center
Urban Vertiport
Vertiport at airport
Market: Small / Medium UAS
Market: Urban Air Mobility

Predicting SUI Quadcopter Noise During Forward Flight with LAVA Lattice Boltzmann Method

- Goals: Establish best practices for multi-rotor and vehicle interaction noise predictions, validate predictions, and assess accuracy/resources

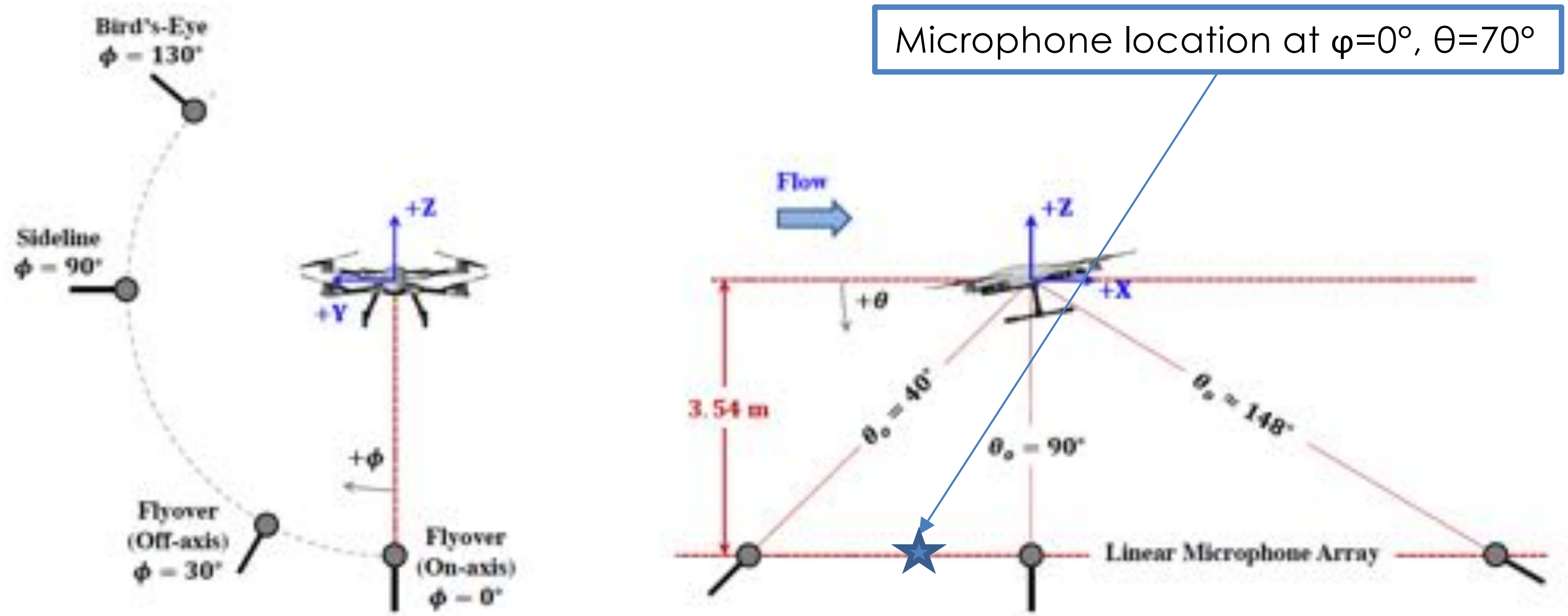
Mach = 0.045, AoA = -10 degrees





SUI Quadcopter 5% tip chord simulation
Isosurfaces of Q-criterion colored by gauge pressure
Cut plane showing gauge pressure

OBSERVER LOCATIONS



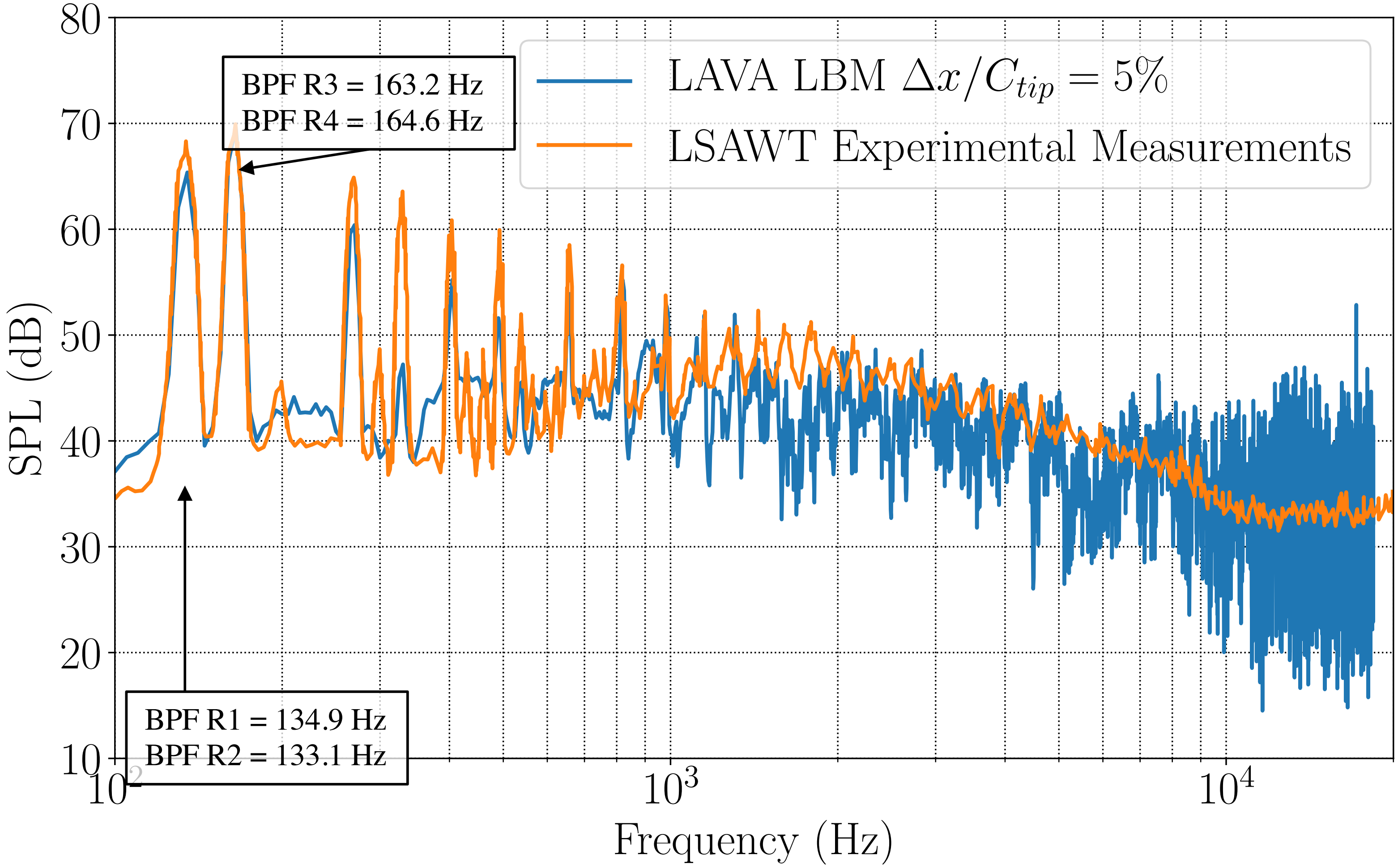
Microphone location at φ=0°, θ=70°

(a) Azimuthal (ϕ) locations of array surveys

(b) Polar (θ) locations of flyover microphones

Fig. 4 – Linear microphone array survey orientations: (a) upstream view of azimuthal plane (flow is into page), (b) profile view of polar plane (flyover configuration). (Note: images not drawn to scale)

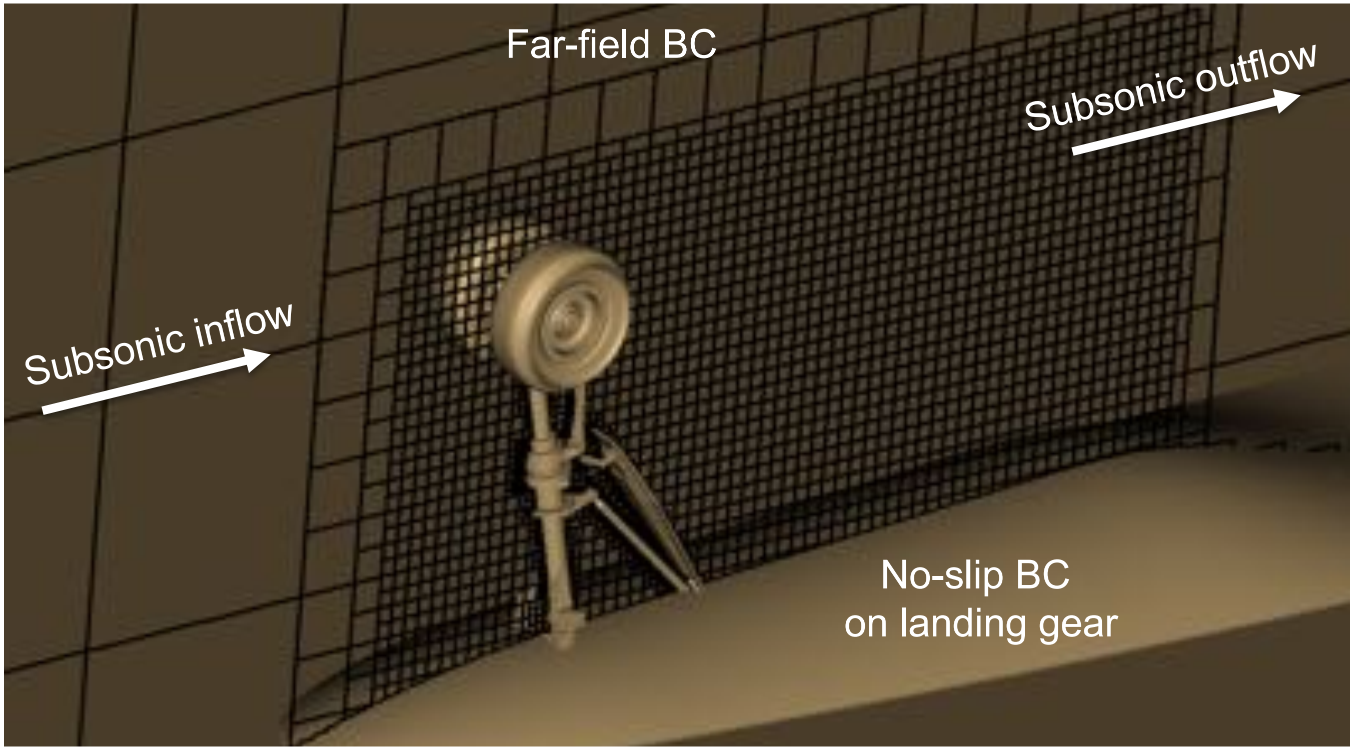
Computed vs Experiment - FWH Spectra at (ϕ,θ) = (0°,70°)



- LBM is costly compared to URANS to get thrust and tones…
- But LBM can predict broadband noise due to wake turbulence which is both difficult and more costly with other methods

Cavity-Closed Nose Landing Gear

Cartesian AMR Grid Topology and Computational Setup for LBM

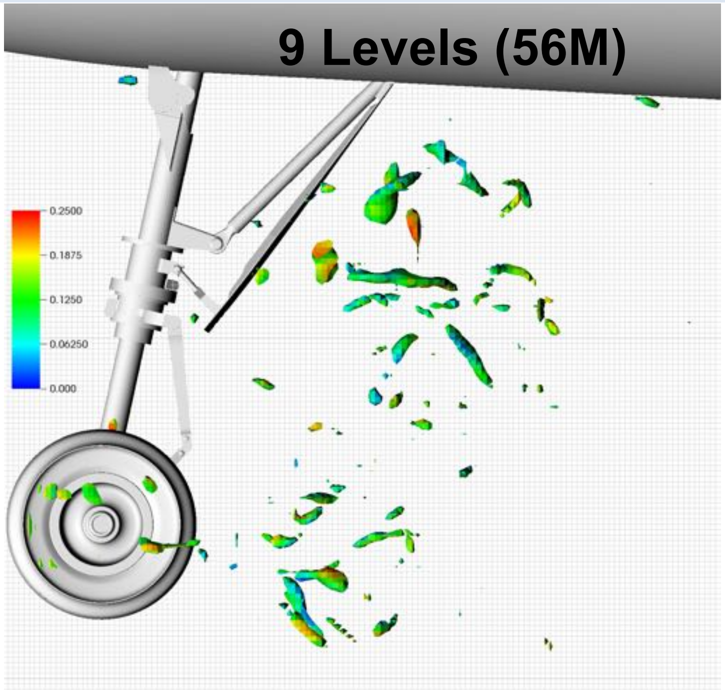


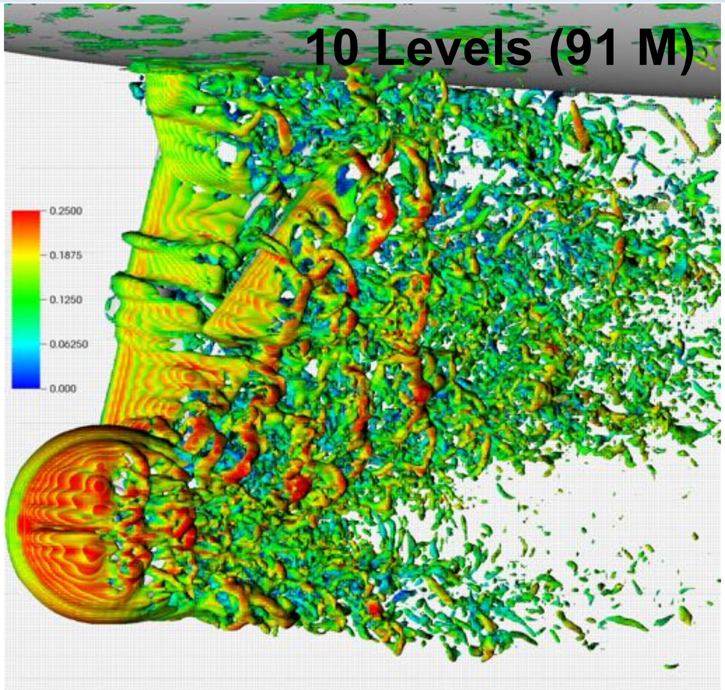
Mach = 0.166
Re = 66423 (D=D_{strut})
U_{ref} = 58.32 m/s
T_{ref} = 307.05 K
P_{ref} = 98605 Pa

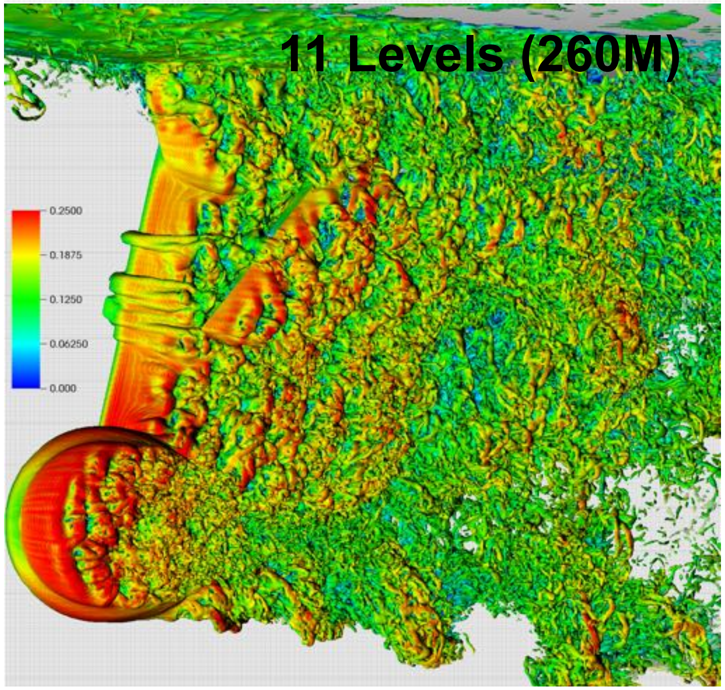
Setup follows the partially-dressed, cavity-closed nose landing gear (PDCC-NLG) noise problem from AIAA's Benchmark problems for Airframe Noise Computations (BANC) series of workshops. (Problem 4. Nose landing gear

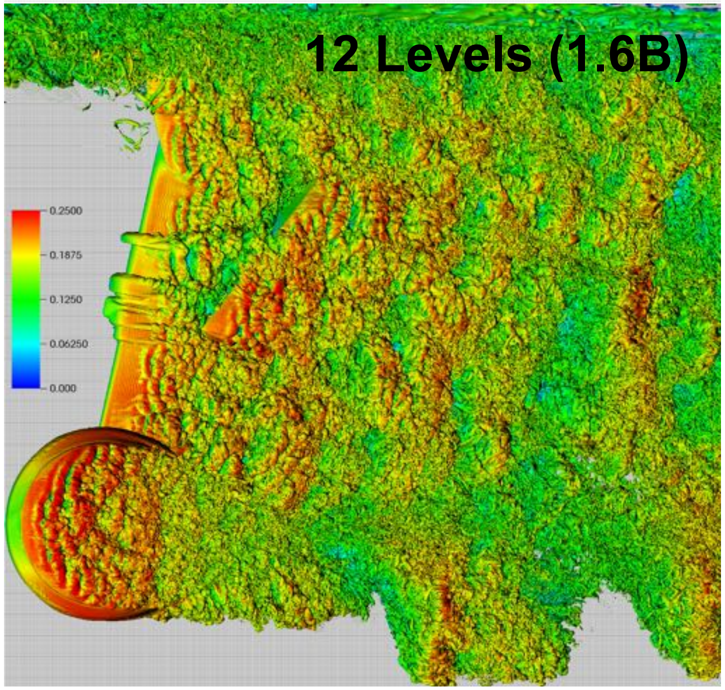
https://info.aiaa.org/tac/ASG/FDTC/DG/BECAN_files_/BANCIII.htm

Grid Sensitivity: Vorticity Colored by Mach

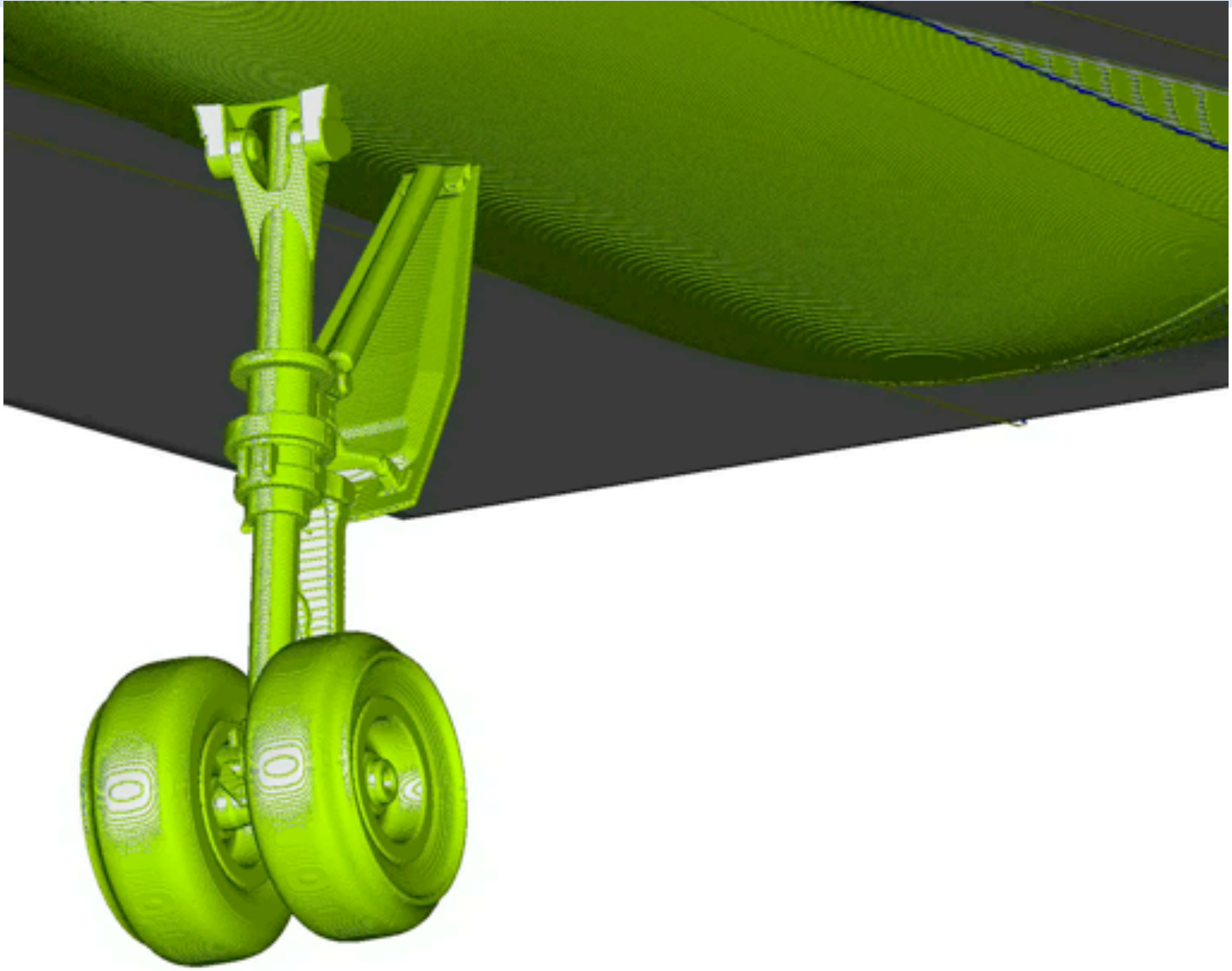

9 Levels (56M)


10 Levels (91 M)


11 Levels (260M)

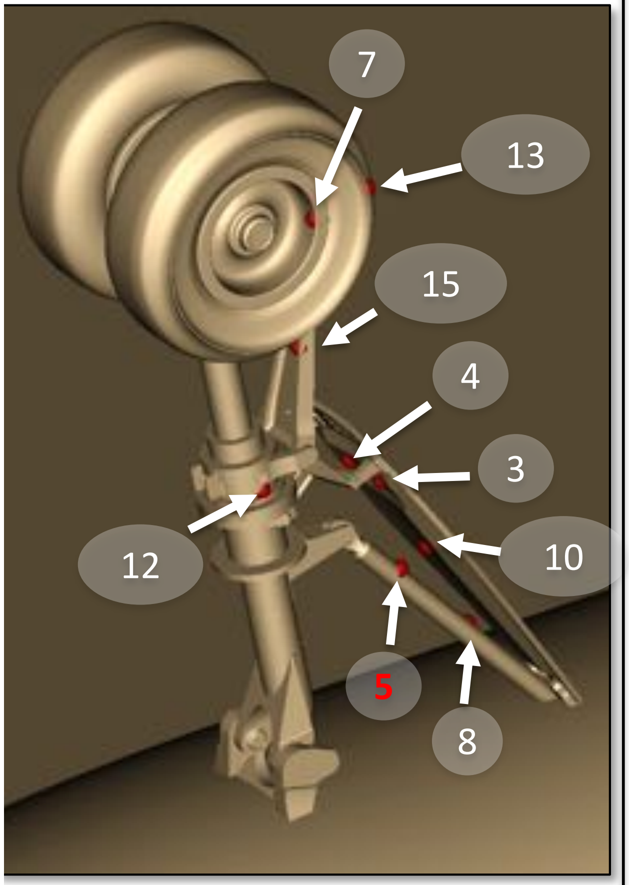

12 Levels (1.6B)

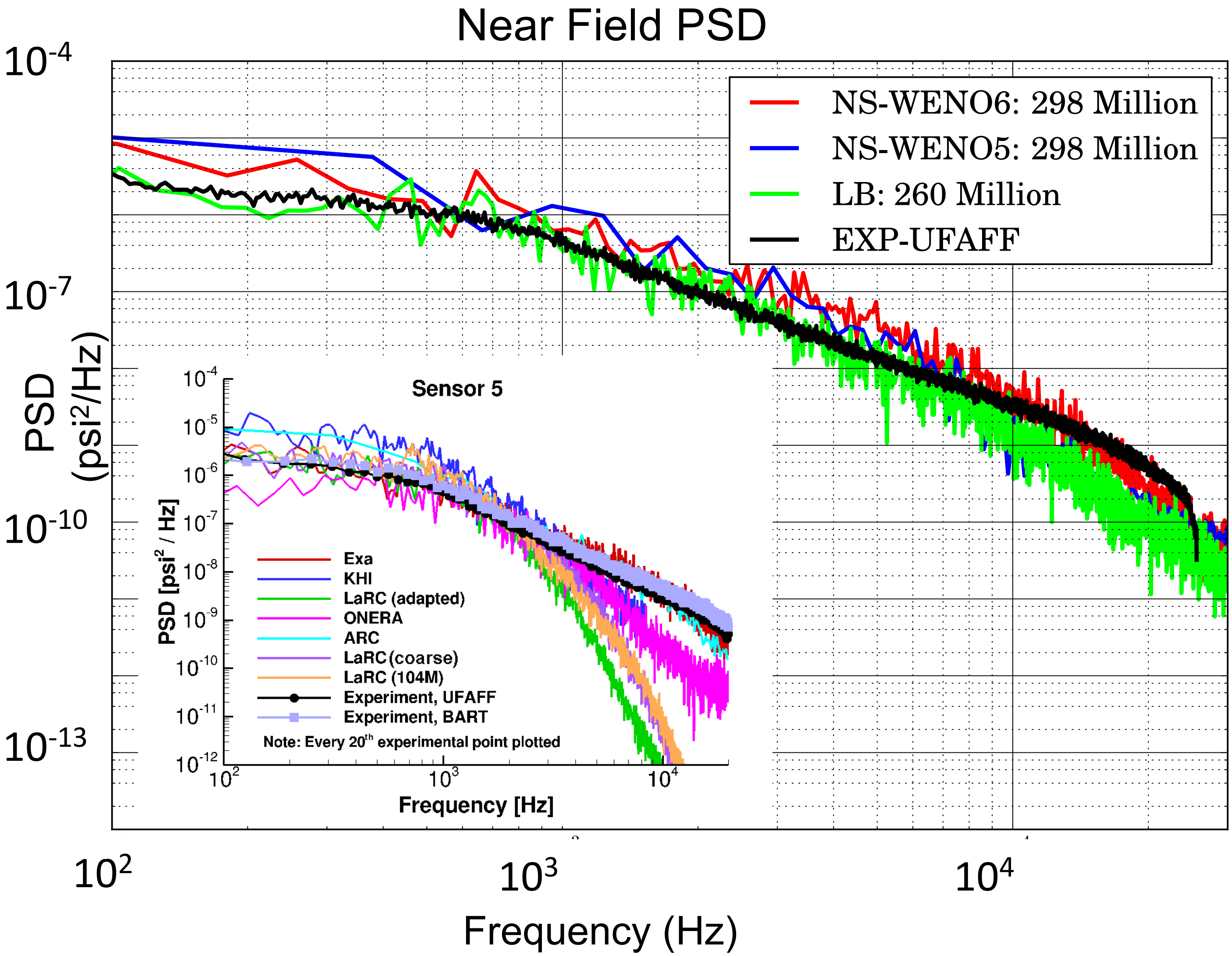
Isosurface of Vorticity Colored by Mach Number



Lattice Boltzmann vs Navier-Stokes - PSD

Channel 5





Challenges in Computational Aero-Acoustics

✓ Computational Requirements

- Space-time resolution requirements for acoustics problems are demanding.
- Resources used for Cartesian Navier-Stokes examples shown above:
  - Launch Environment: ~200 million cells, ~7 days of wall time (1000 cores)
  - Launch Abort System: 400 million cells, 40 days of wall time (2000 cores)
  - Contra-Rotating Open Rotor: 360 million cells, 14 days (1400 cores)
  - Landing Gear: 298 million cells, 20 days of wall time (3000 cores)

- Landing Gear Lattice Boltzmann: 298 million cells, 2 days of wall time (1400 cores)

- LAVA Cartesian infrastructure has been re-factored into Navier-Stokes (NS) and Lattice Boltzman Method (LBM).
  - 10-15 times speed-up can be achieved with LBM vs NS.
  - Existing LAVA Cartesian data structures and algorithms are utilized to reduce implementation effort.

Summary and Next Steps

Summary

- Demonstrated strong Computational Aeroerosciences capabilities focusing
  - Building in flexibility with respect to grid generation
  - Improving modeling of turbulent scales
  - Exploring revolutionary approaches such as Lattice-Boltzmann Method
- Demonstrated the power and importance of using scale resolving simulations during the design process for to guide a number of next-generation aerospace applications:
  - Launch Environment and Launch Abort System
  - Jet and aircraft noise
  - Fan and propeller noise
  - Landing gear noise

Next Steps

- Improve turbulent wall layer modeling and subgrid-scale modeling
- Optimize moving geometry capability
- Continue to integrate more multi-disciplinary capabilities: coupling structural dynamics, fluid-structure interaction

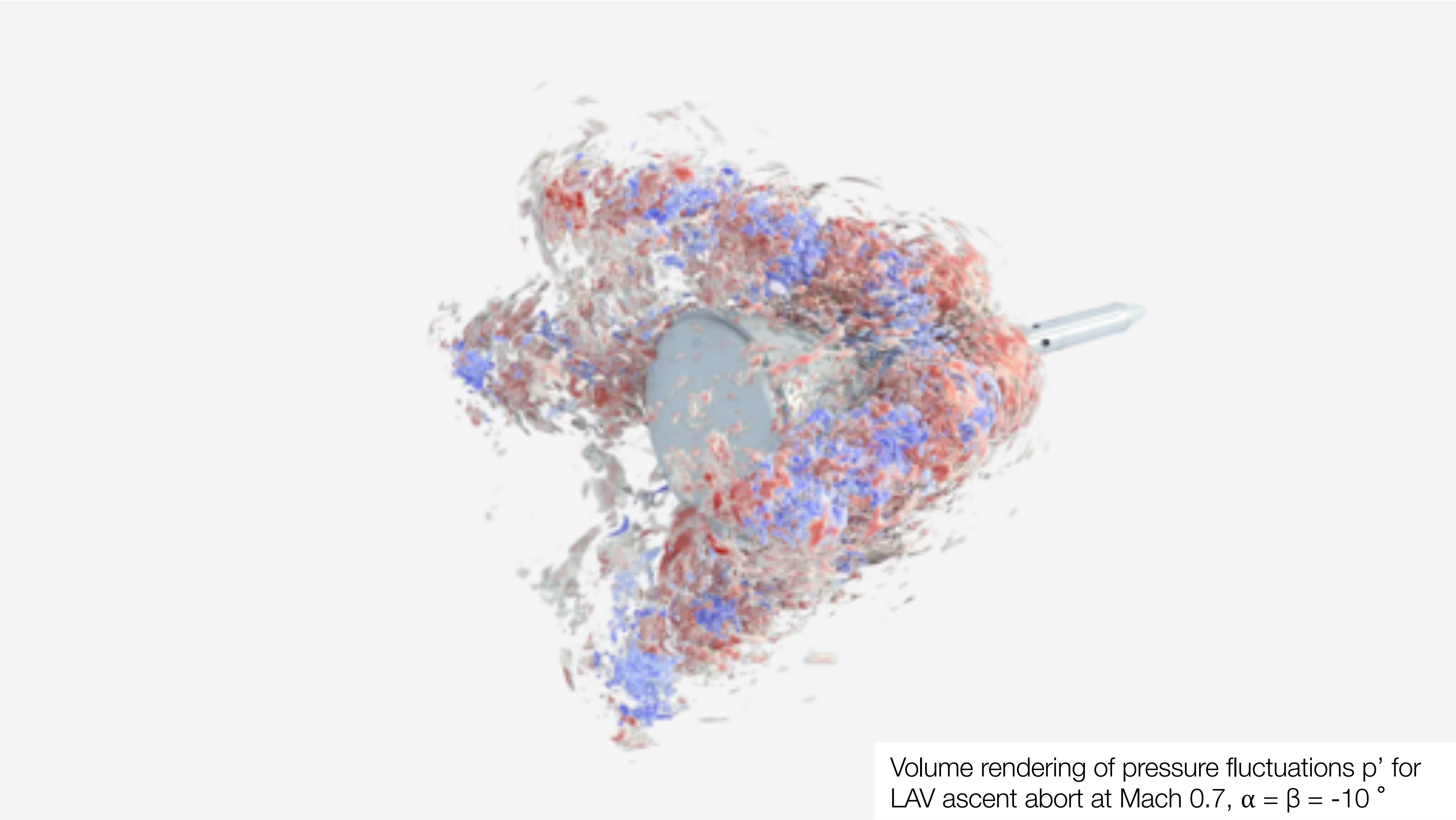
Acknowledgments

✓ This work was partially supported by the NASA ARMD and HEOMD projects

✓ LAVA team members in the Computational Aerosciences Branch at NASA Ames Research Center for many fruitful discussions

✓ Computer time provided by NASA Advanced Supercomputing (NAS) facility at NASA Ames Research Center

Questions?



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