# *Modeling and Simulation within Computational Aerosciences*

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NAS Tour
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# Role of Computational Aerosciences

✓ **Perform large-scale simulations for**

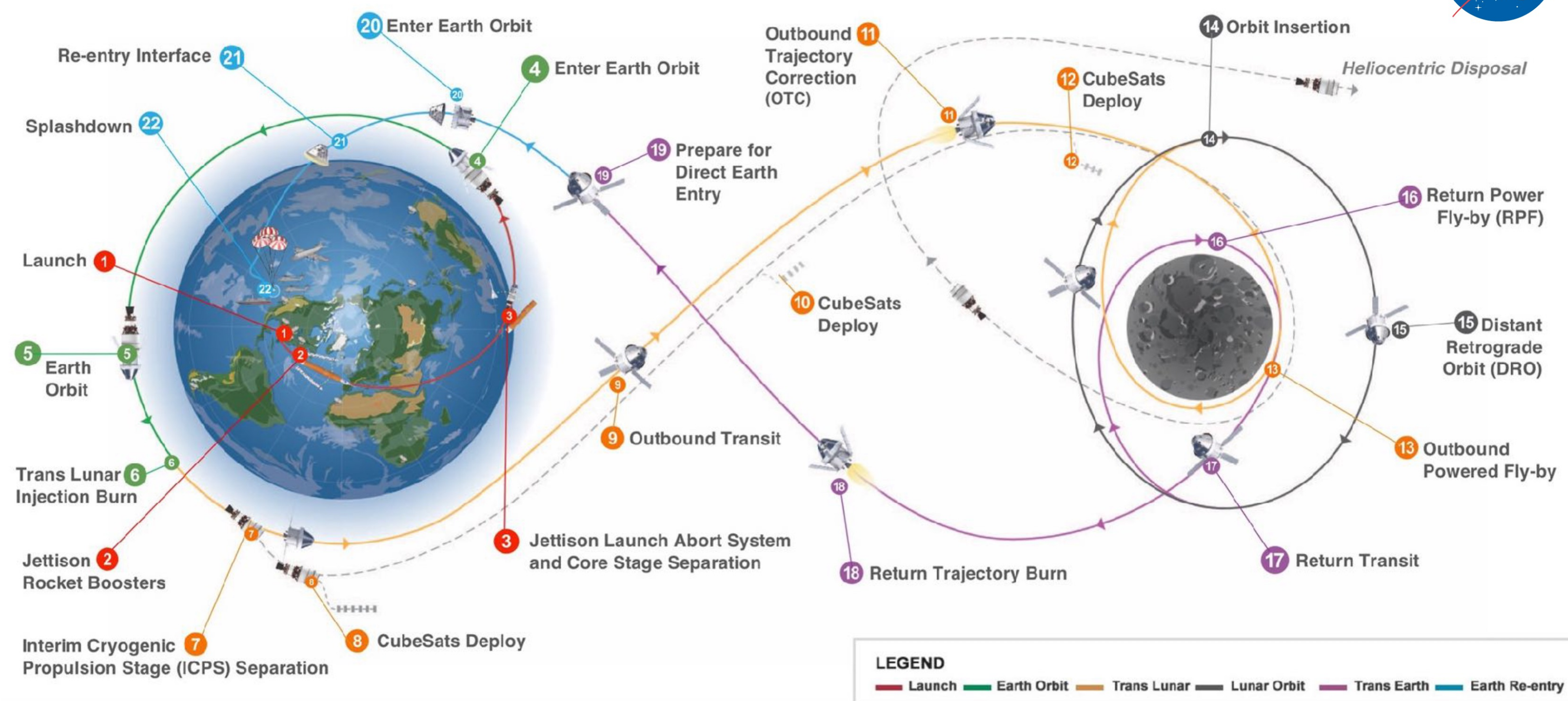
- Human Launch : Space Launch System (SLS), Orion, Commercial Crew - Databases and induced environments for ascent and abort, staging, debris, plume impingement, retro-propulsion, launch environment

✓ **Advance computational aerosciences predictive capabilities to support NASA's current and future missions/needs/requirements**

- Aerodynamic
- Aeroacoustics
- Aerostructures

✓ **Work with NASA High End Computing Capability (HECC) experts to adapt our toolsets for the next generation computing platforms**

# SLS Exploration Mission 1

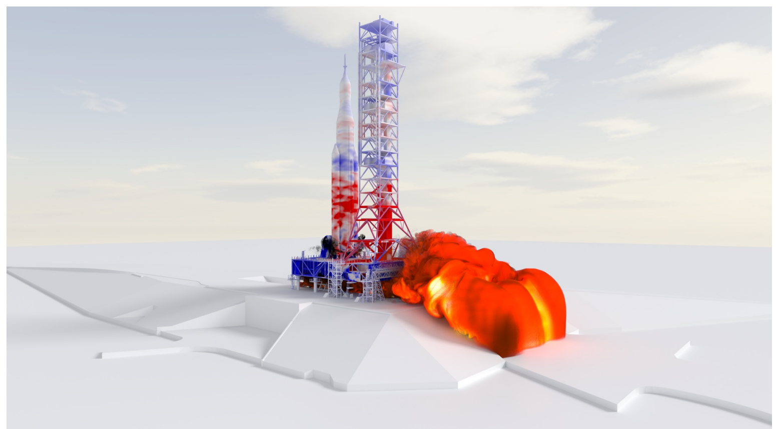



Total distance traveled: 1.3 million miles – Mission duration: 25.5 days – Re-entry speed: 24,500 mph (Mach 32) – 13 CubeSats deployed

# Multiphysics Prediction Capability for Launch Environment

*Photographs of a test of the NASA Kennedy Space Center (KSC) water deluge system which is used to suppress the immense sound pressure levels felt by the vehicle and surrounding structures during ignition.*

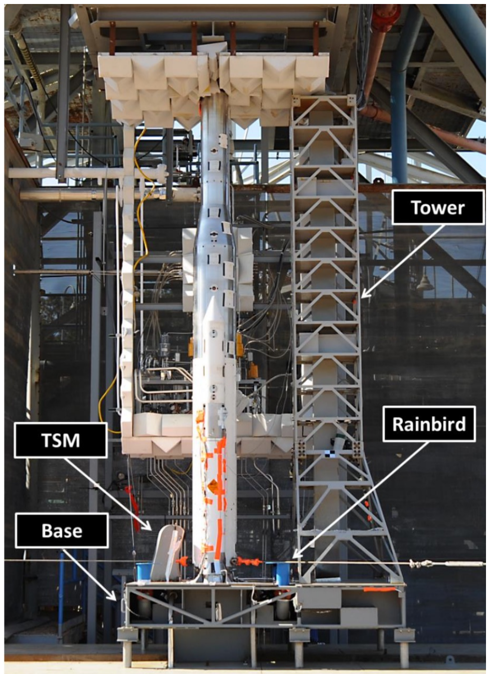
- ✓ Goal of this project was to develop a capability for high-fidelity full-scale time accurate simulations of the launch environment acoustics including the water-based sound suppression system.
- ✓ Novel and provably stable high-order method for multiphase flow developed and integrated into the LAVA Cartesian Adaptive Mesh Refinement (AMR) framework.



*Visualization of previous LAVA SLS launch environment simulation without water deluge system. Particles track the plume path and are colored by temperature (white hot, dark cool). Surfaces are colored by pressure (red high, blue low).*

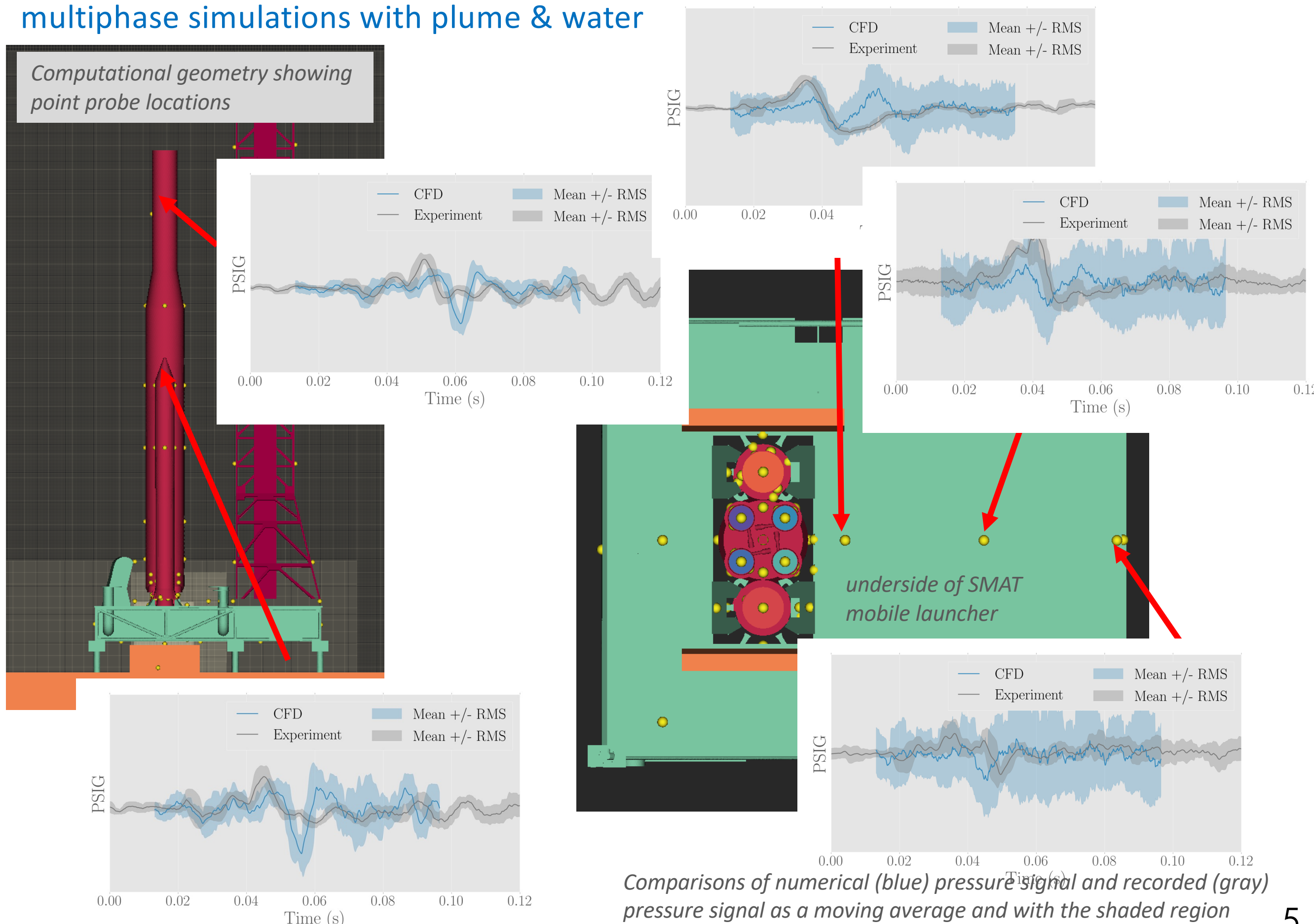
# Validation with the 5% Scale Model Acoustic Test (SMAT)

## multiphase simulations with plume & water




*Photograph of the Scale Model Acoustic Test (SMAT)*

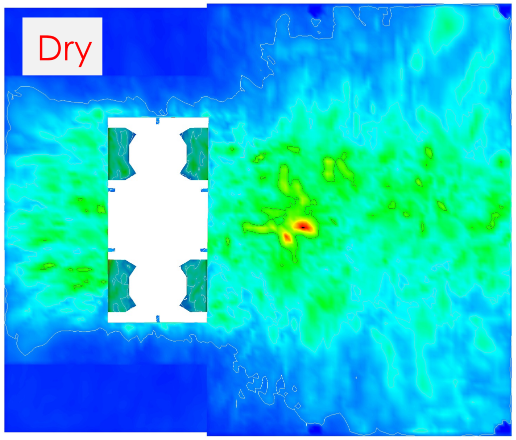
**"Ignition Overpressure Computational Fluid Dynamics Simulation of Scale Model Acoustic Test PC123-FA-HF-01" Peter A. Liever February 2017**

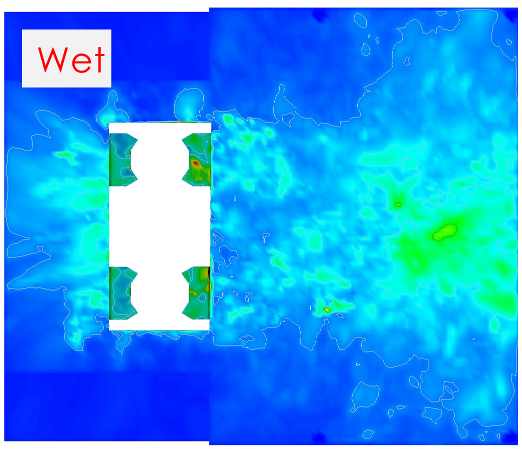



*Comparisons of numerical (blue) pressure signal and recorded (gray) pressure signal as a moving average and with the shaded region showing RMS.*

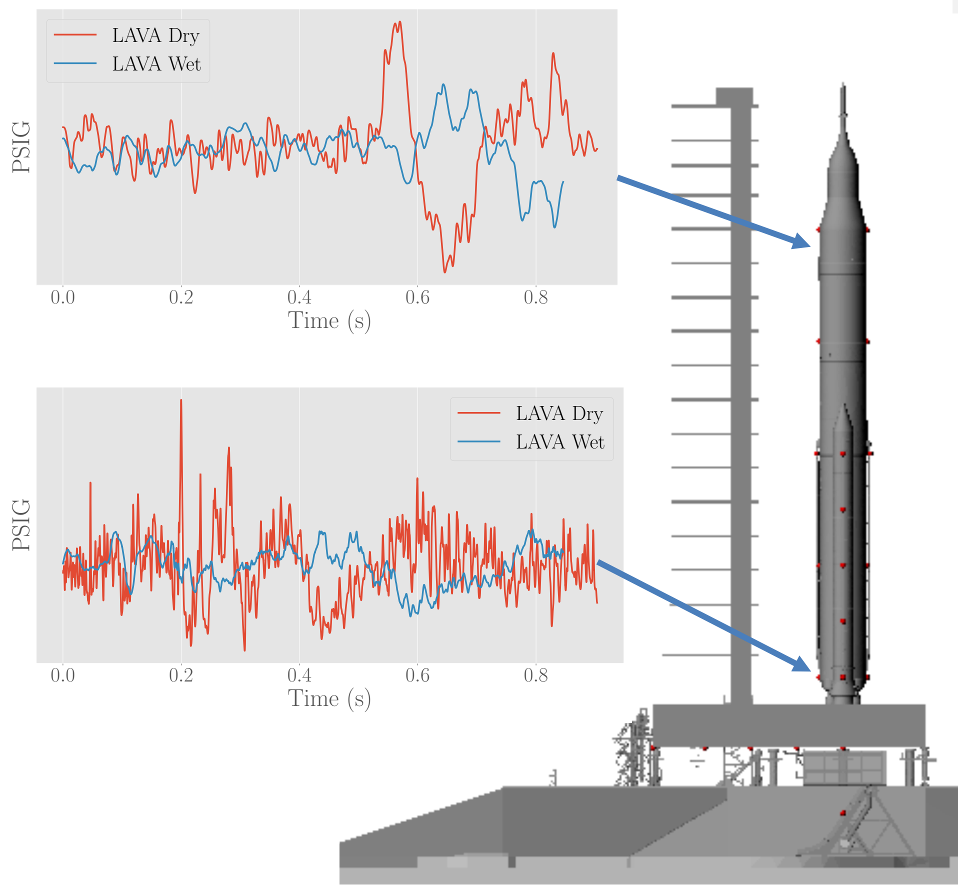
# Multiphase Simulations for Upcoming Artemis Flight at Launch Complex LC-39B

*Maximum gauge pressure felt on the underside of Mobile Launcher during the ignition of the SLS engines.*



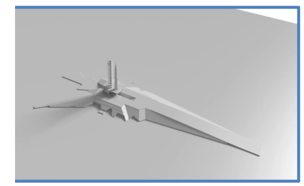



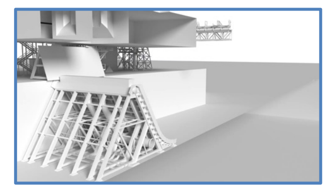

*Comparison of ignition overpressure wave for dry and wet case at two sensor locations on the vehicle.*




## Movies:

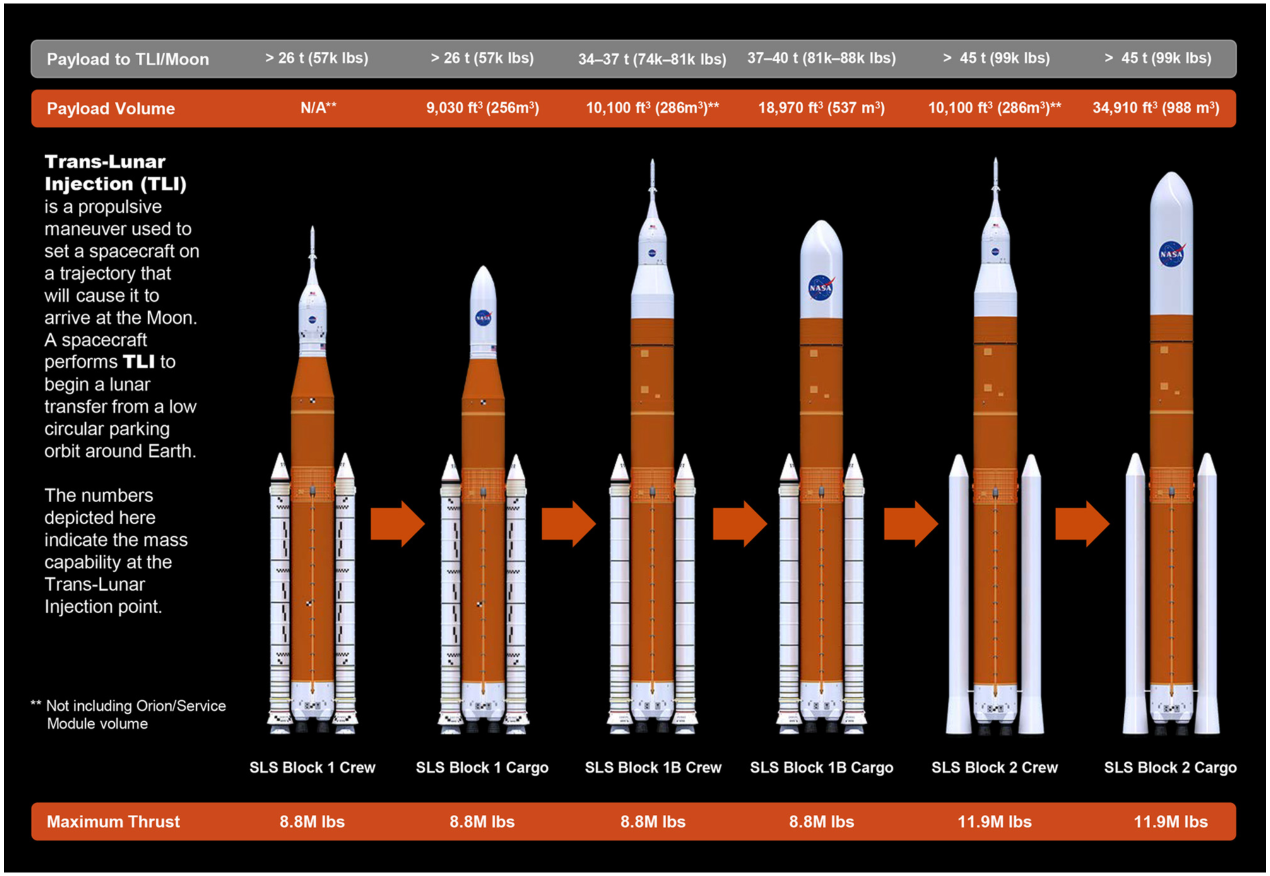
*Volume rendering of mass fractions. Liquid water is colored blue. Plumes are colored yellow to purple and water vapor is white.* Solid Rocket Boosters (SRBs) *starting indicate time T=0*



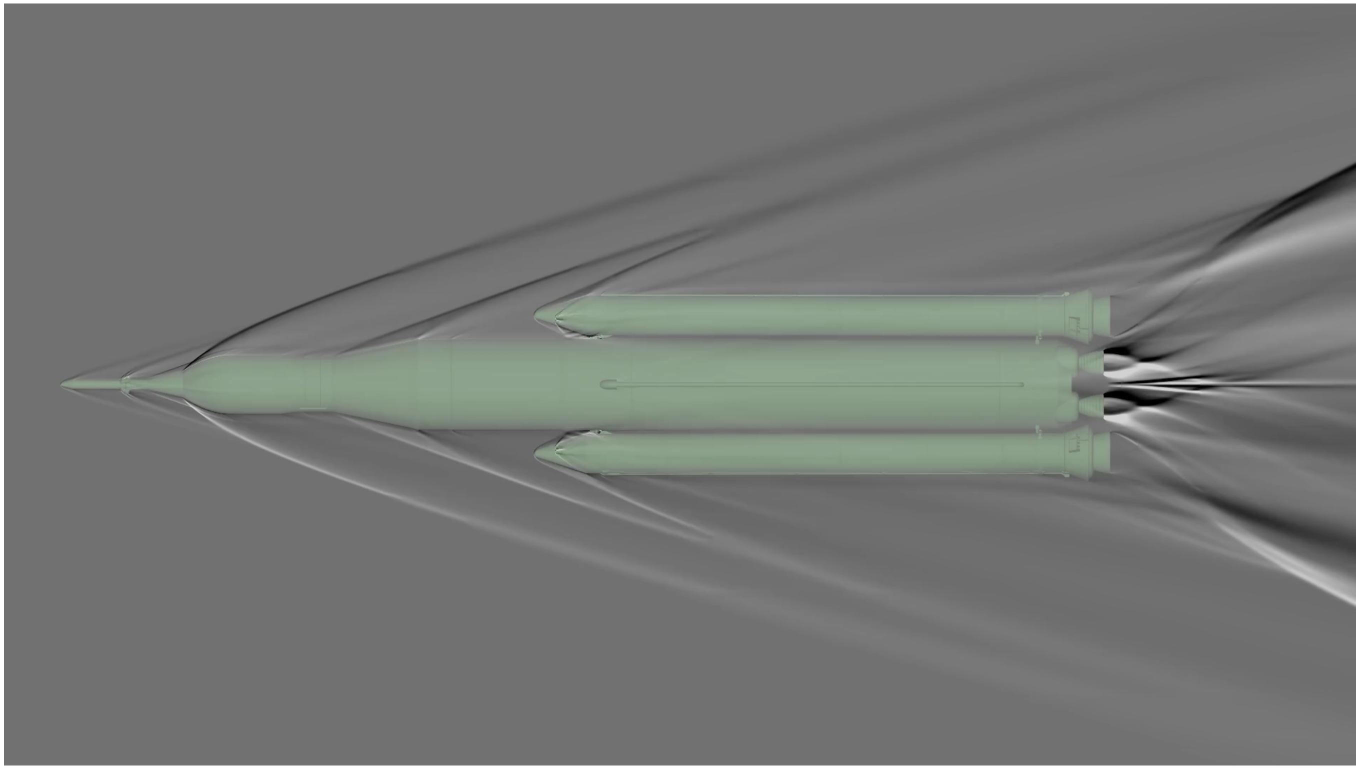


# Aerodynamic Databases

1. SLS Block 1 Crew
   - ~4000 ascent cases
   - ~40k booster separation cases (two analysis cycles)
2. SLS Block 1 Cargo (discontinued)
   - ~1000 ascent cases
3. SLS Block 1B Crew
   - ~1000 ascent cases
   - ~2500 booster sep cases
   - Next up: 10k more bsep
4. SLS Block 1B Cargo
   1. ~2000 ascent (2 payload fairings)
5. SLS Block 2 Crew
   - Next up: booster sep
   - Ascent coming soon
6. SLS Block 2 Cargo
   - No foreseeable tasking



# Space Launch Systems (SLS) – Stage Separation



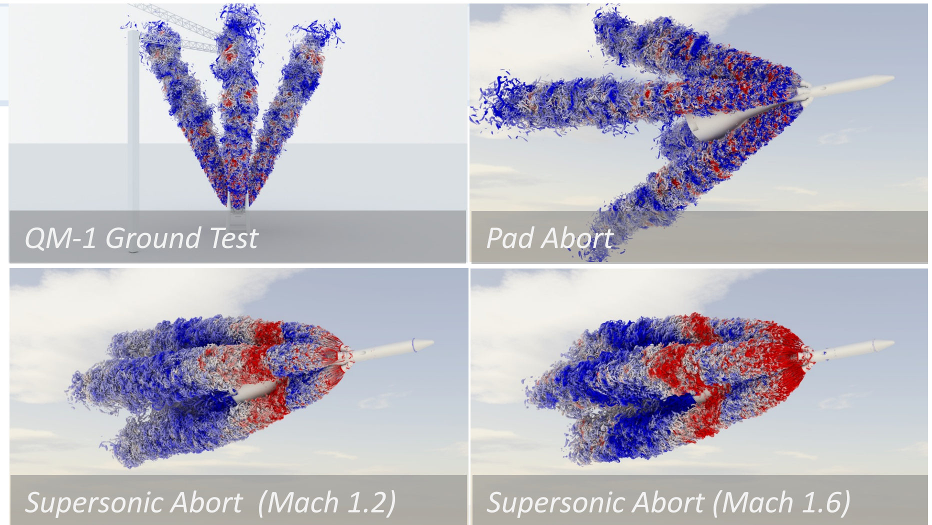
*SLS stage separation simulations showing numerical Schlieren*


**Ensuring Astronaut Safety**

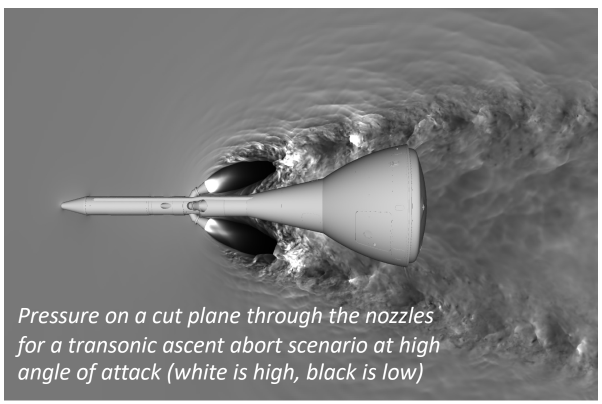
NASA is developing technologies that will enable humans to explore new destinations in the solar system. America will use the Orion spacecraft, launched atop the Space Launch System rocket, to send a new generation of astronauts beyond low-Earth orbit to places like an asteroid and eventually Mars. In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

# Predicting Orion LAS Acoustics: Wind Tunnel

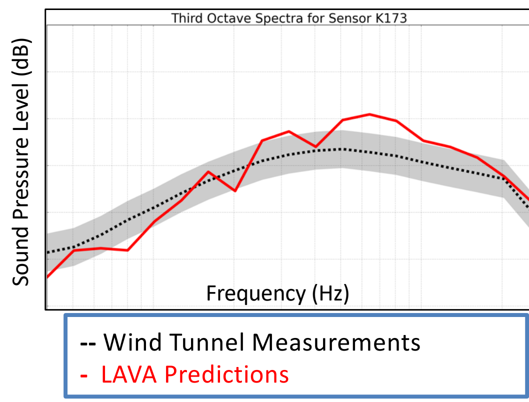
- ✓ Can Computational Fluid Dynamics (CFD) provide difference in vibration strength due to vehicle geometry difference with QM-1 test article? Yes, provided spatially varying expected delta-dB.
- ✓ Can CFD predict relationship between vibration strength and trajectory point obtained from wind tunnel test: altitude, velocity, angle of attack? Yes, validated predictions with wind tunnel data.
- ✓ Can CFD help reduce uncertainty in margins at high angle of attack? Yes

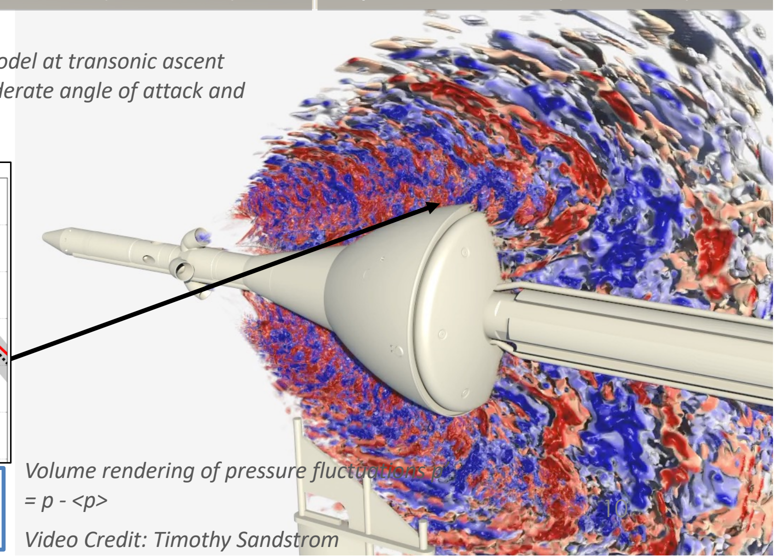



*Wind tunnel model at transonic ascent abort with moderate angle of attack and side slip*



*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)*



*Volume rendering of pressure fluctuations p' = p - <p>*

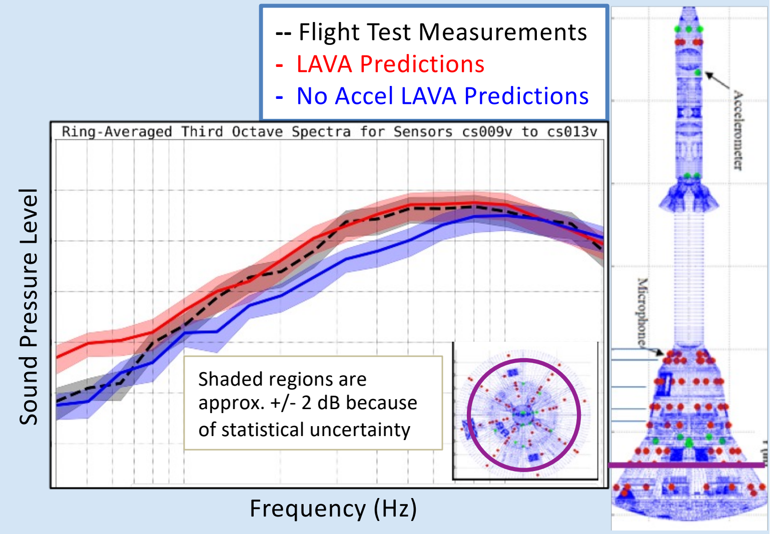
*Video Credit: Timothy Sandstrom*

# Flight Test Validation

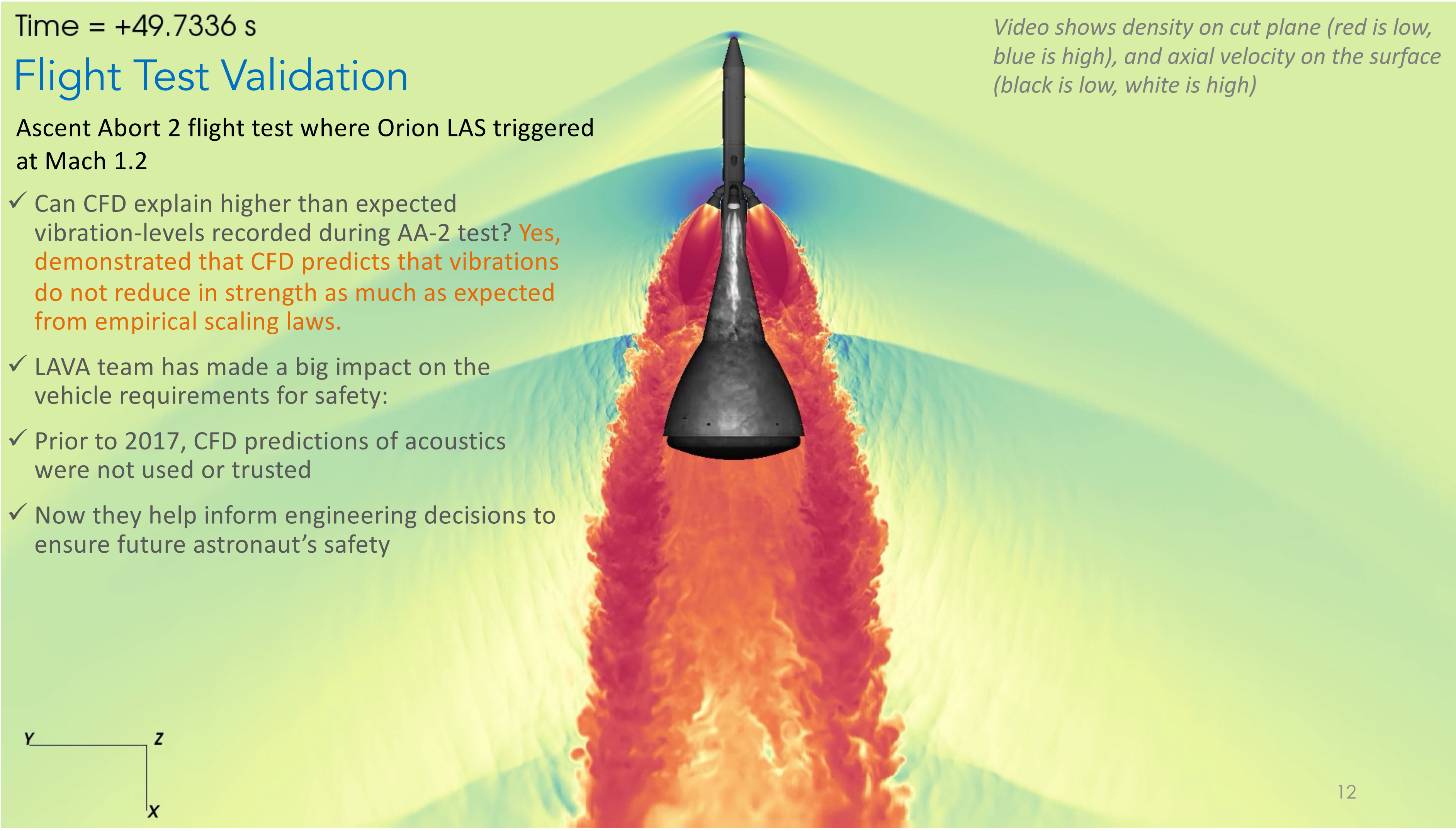
**Pad Abort 1 flight test where Orion LAS accelerates from rest to 10x Earth's gravity**

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

✓ Can CFD identify difference in vibration strength due to vehicle acceleration and change in attitude? Yes, provided spatially varying expected delta-dB.




*Video Credit: Timothy Sandstrom*




# Flight Test Validation

Ascent Abort 2 flight test where Orion LAS triggered at Mach 1.2

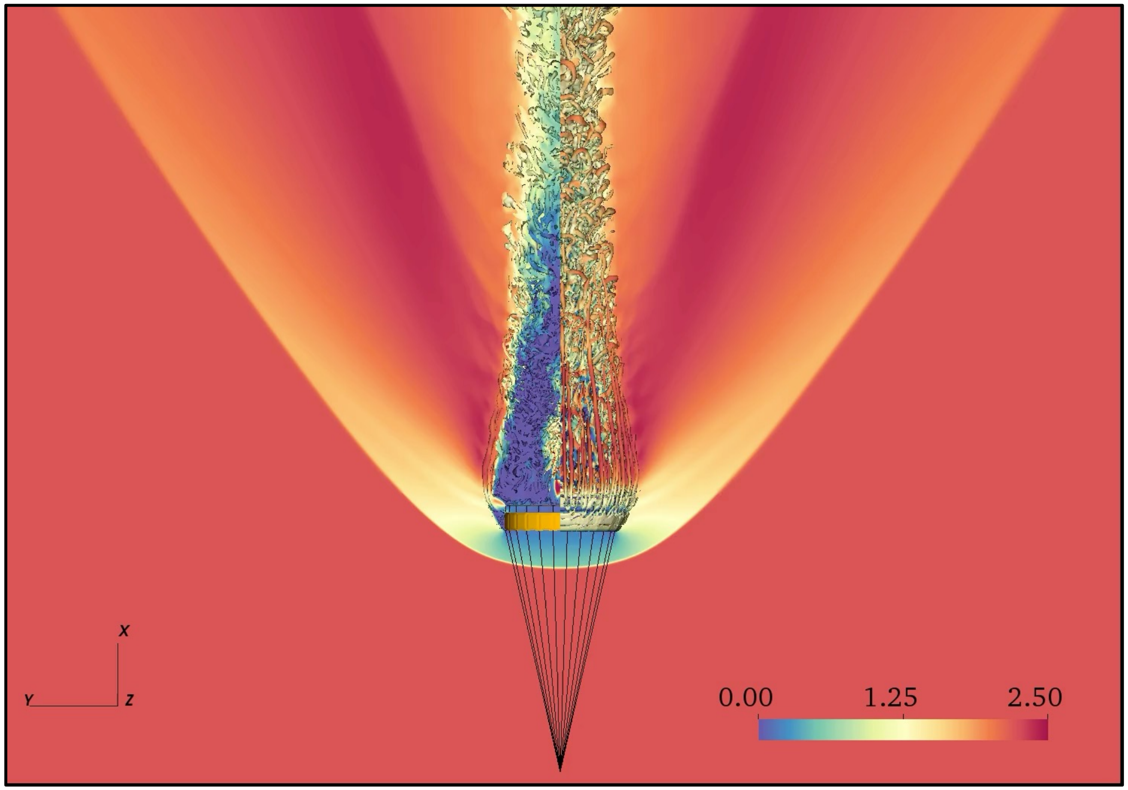
*Video shows density on cut plane (red is low, blue is high), and axial velocity on the surface (black is low, white is high)*

- ✓ Can CFD explain higher than expected vibration-levels recorded during AA-2 test? Yes, demonstrated that CFD predicts that vibrations do not reduce in strength as much as expected from empirical scaling laws.
- ✓ LAVA team has made a big impact on the vehicle requirements for safety:
- ✓ Prior to 2017, CFD predictions of acoustics were not used or trusted
- ✓ Now they help inform engineering decisions to ensure future astronaut's safety

# Supersonic Retro Propulsion (Mach 2.4)

*Volume rendering of exhaust mass fraction where yellow is 100% and black is 1%. Only the plumes on the left side of vehicle are rendered to elucidate the plume structure without obstruction*

# Supersonic Parachute/Fluid-Structure Interaction




*Pseudocolor contours of  Mach number shown on a cut plane through the center of the domain for the impermeable parachute in M = 2.2 flow and iso-contours of Q-criterion colored by Mach number*

# Role of Computational Aerosciences

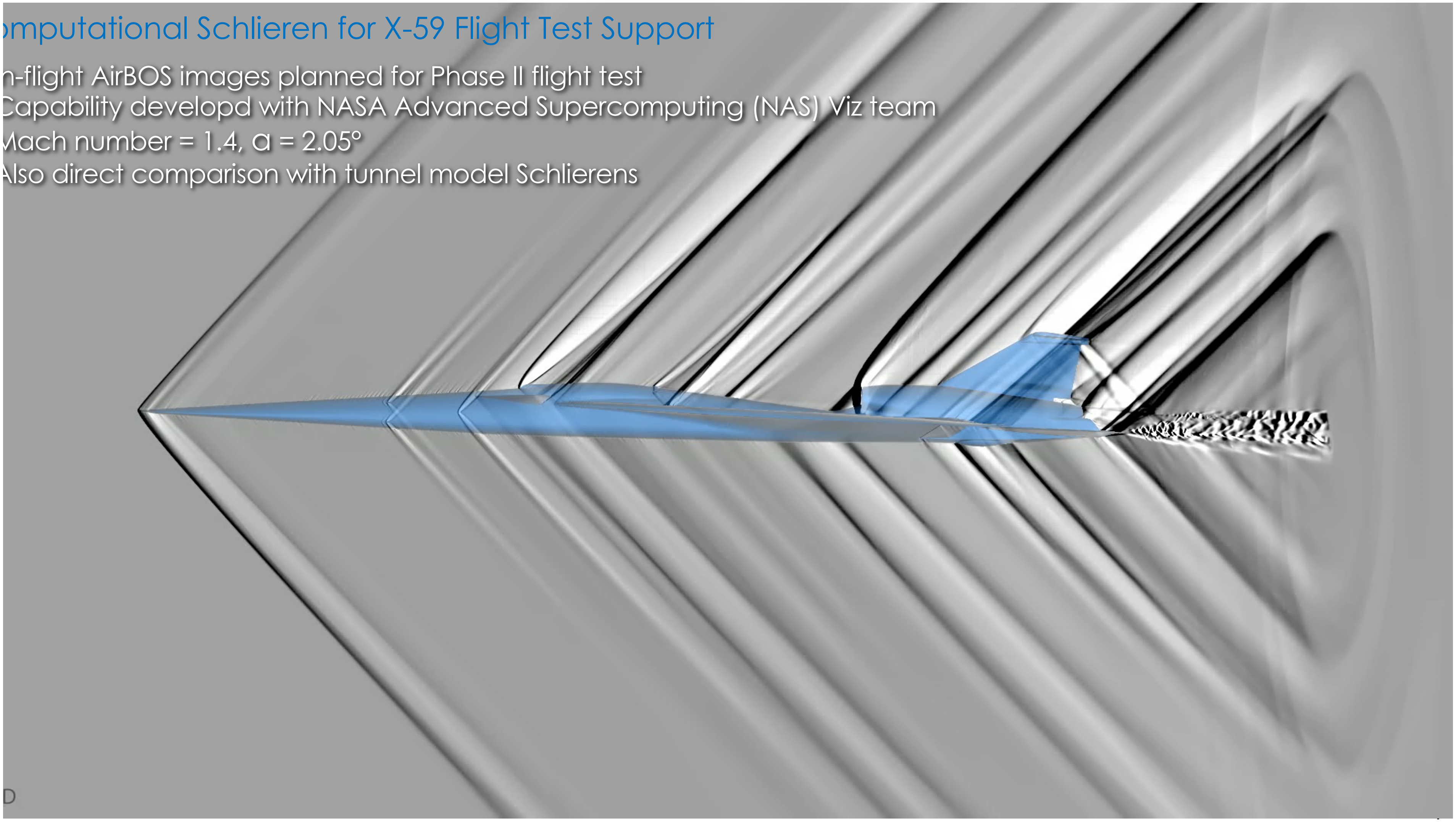
✓ **Perform large-scale simulations for**

- Sustained Atmospheric Flight : aerodynamic/aeroacoustic/aerostructural performance prediction, vehicle design, noise prediction, airframe/propulsion integration, safety analysis

✓ **Advance computational aerosciences predictive capabilities to support NASA's current and future missions/needs/requirements**

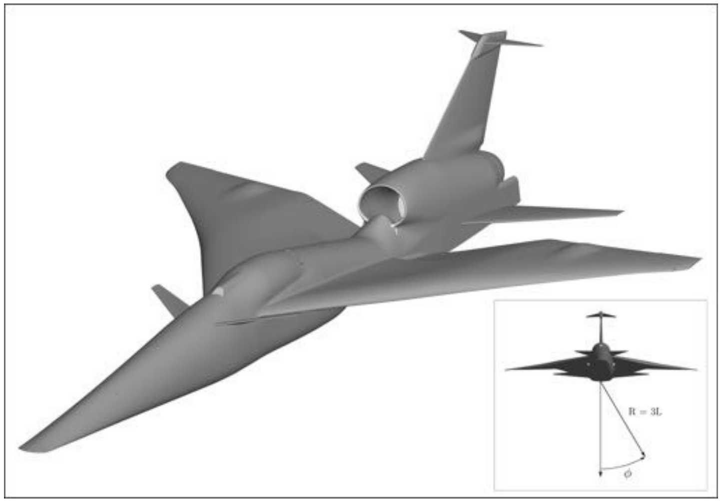
- Aerodynamic
- Aeroacoustics
- Aerostructures

✓ **Work with NASA High End Computing Capability (HECC) experts to adapt our toolsets for the next generation computing platforms**

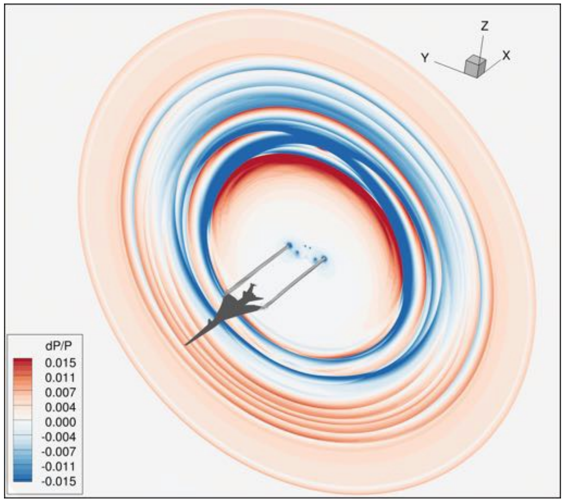

omputational Schlieren for X-59 Flight Test Support
n-flight AirBOS images planned for Phase II flight test
Capability developd with NASA Advanced Supercomputing (NAS) Viz team
Mach number = 1.4, α = 2.05°
Also direct comparison with tunnel model Schlierens
D

# X-59 Low Boom Flight Demonstrator Analysis

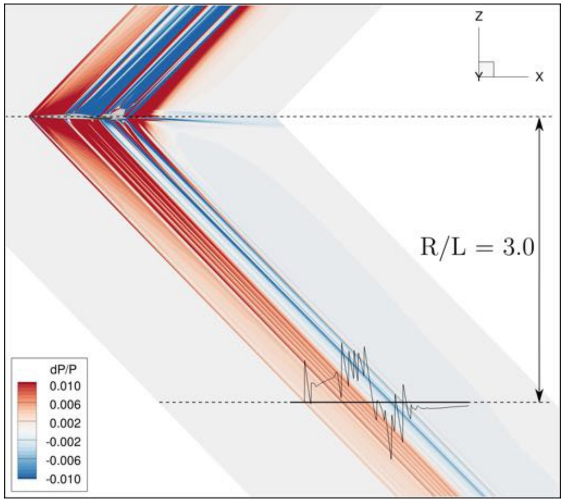
- ✓ LAVA Curvilinear is used to simulate numerous flight conditions and aircraft configurations for the X-59 Quiet Supersonic Aircraft program, generating databases of aerodynamic and noise predictions
- ✓ Refactorization of the LAVA Curvilinear flow solver has enabled near-field and far-field ground noise predictions to be generated with up to a 10X computational cost reduction
- ✓ A recently development space-marching routine coupled with the CFD solver has reduced the required CFD computational domain size, leading to simulation cost reduction



*X-59 Low-Boom Flight Demonstrator aircraft*




*Pressure disturbance contours shown, with wingtip vortices depicted in gray*

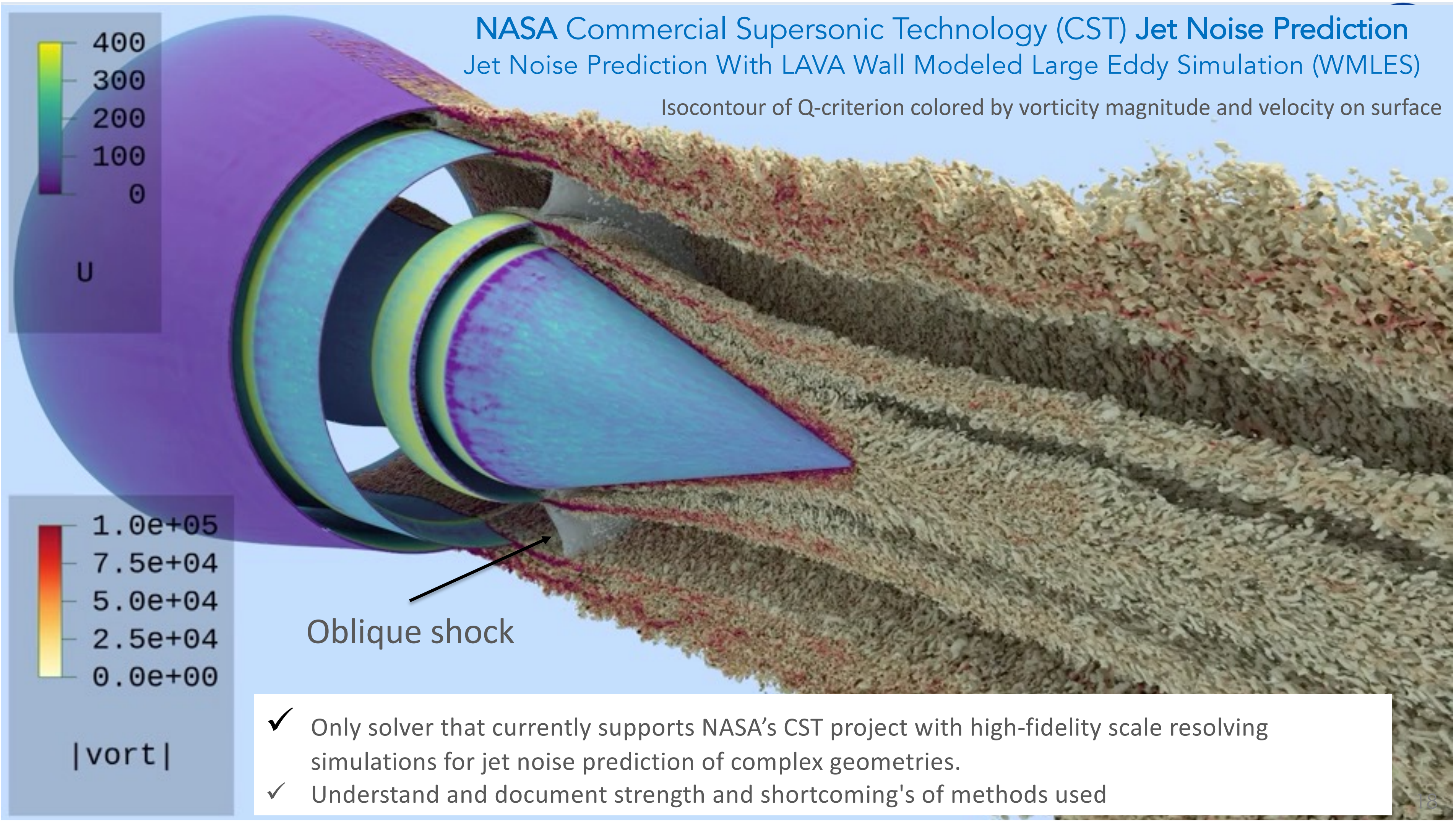



*Pressure disturbance contours on symmetry plane with sample nearfield boom signature*

## NASA Commercial Supersonic Technology (CST) **Jet Noise Prediction**

### Jet Noise Prediction With LAVA Wall Modeled Large Eddy Simulation (WMLES)

Isocontour of Q-criterion colored by vorticity magnitude and velocity on surface

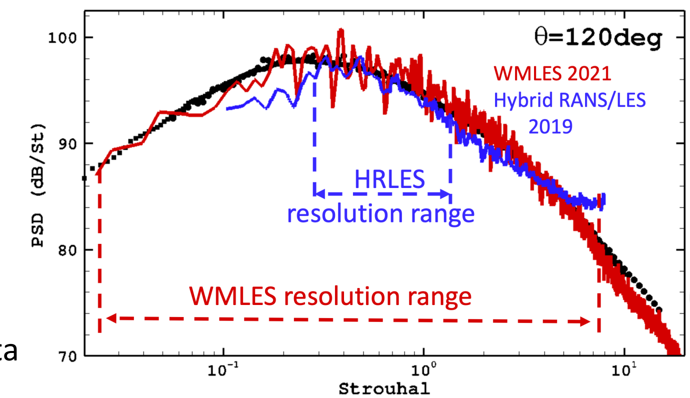


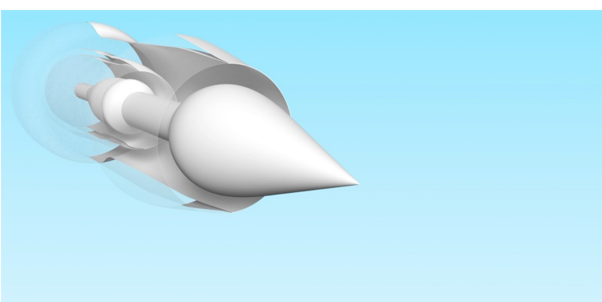

- ✓ Only solver that currently supports NASA's CST project with high-fidelity scale resolving simulations for jet noise prediction of complex geometries.
- ✓ Understand and document strength and shortcoming's of methods used

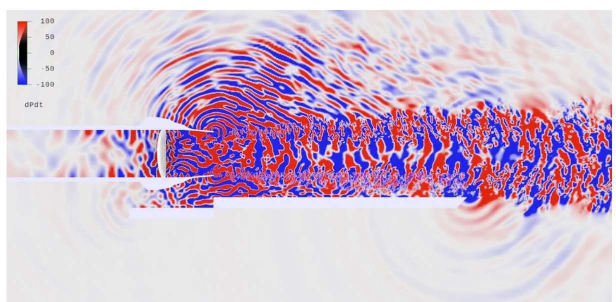
# Prediction of Jet Noise with LAVA Wall-Modeled LES (WMLES)

- **WMLES successfully applied to the prediction of jet noise within NASA CST**
  - Significant improvements in turnaround time (63x) compared to Hybrid Reynolds Averaged Navier Stokes (RANS)/Large Eddy Simulation (LES)
  - Improvements have enabled simulations previously not feasible
- **A first of it's kind database was generated utilizing WMLES within LAVA for NASA CST's Prediction Uncertainty Reduction (PUR) technical challenge.**
  - A total of 20 high-fidelity scale-resolving simulations performed
  - Each simulation takes around 24hr and generates 100 terabytes (TB) of data
  - Excellent agreement with experiments within 1 decibels (dB) (comparable to experimental rig-to-rig uncertainty)

Improved resolution range for far-field noise



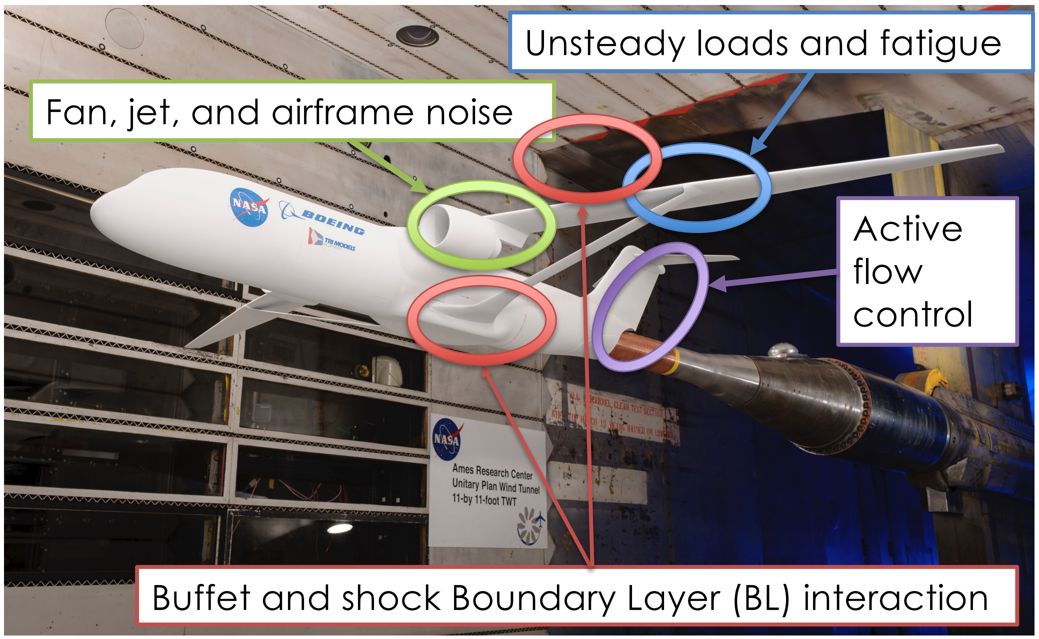


multi-stream heated jet

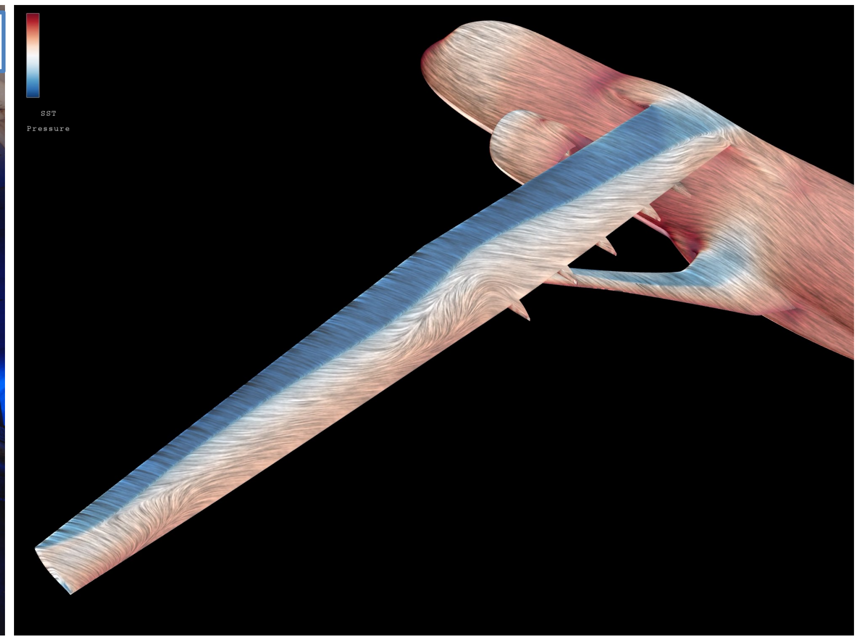

jet surface interaction noise

| Path towards a robust, reliable and fast WMLES solver for jet noise database generation | |
|---|---|
| **November 2019** | |
| Hybrid RANS/LES | 6.5 days [100 Broadwell] |
| 63 x speedup | |
| **Today** | |
| WMLES + Optimized Code & Best Practices & Scaling | 150 minutes [100 Rome] |

# Sustained Atmospheric Flight

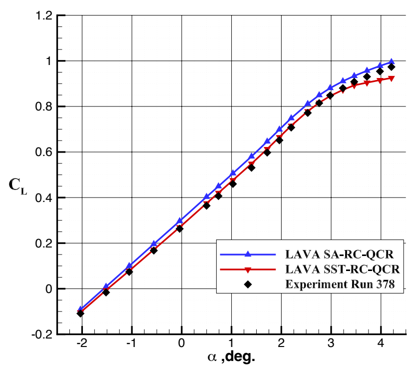
- ✓ **Increase predictive use of computational aerosciences capabilities for next generation vehicles**
  - The next frontier is to use scale resolving simulations to predict:

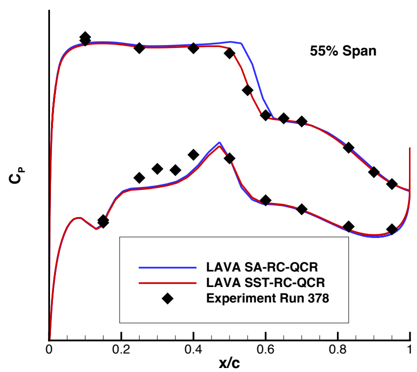


# Transonic Truss Braced Wing Simulations

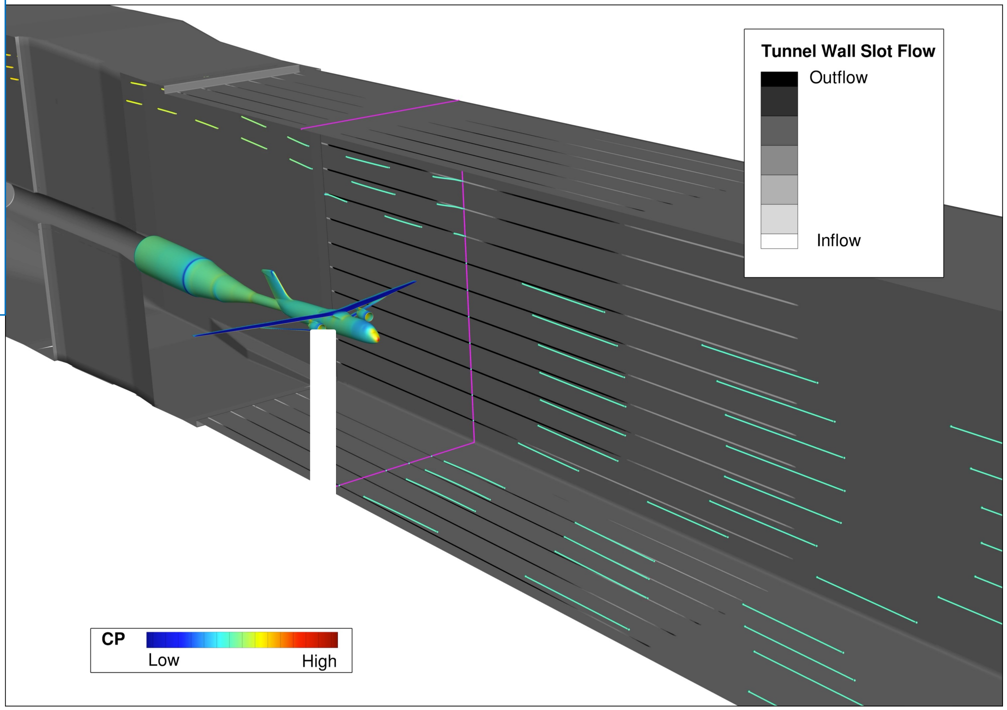
- Ran various studies to develop best practices and gain an understanding of the sensitivities of the model.
  - Grid adaption, grid refinement, component buildup, wall spacing, cavity / base correction, turbulence model & corrections, and time-step ramping, convective scheme discretization, starting conditions, and more.
- Refactorization of LAVA allowed for better and faster convergence and more accurate results
  - 12 to 27 times Standard Billing Unit (SBU) reduction.
  - Verified consistent results against original LAVA
- Presented paper (AIAA 2021-1531) at SciTech 2021 and received AIAA Applied Aerodynamics Best Paper Award.



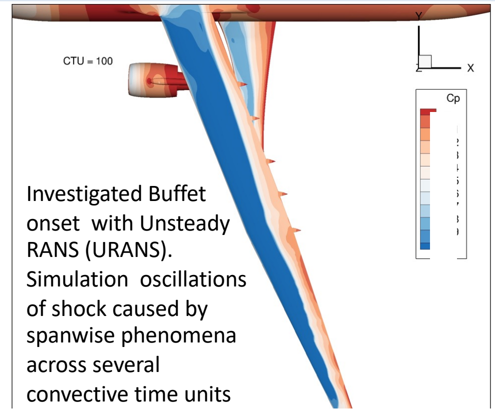

Using SST, lowered difference in $C_L$ relative to experiment from 5.8% to 1.1% near the cruise condition.

Visualizing inflow / outflow of particle paths in and out of porous wall Boundary Conditions (BC) for Wind tunnel simulations.

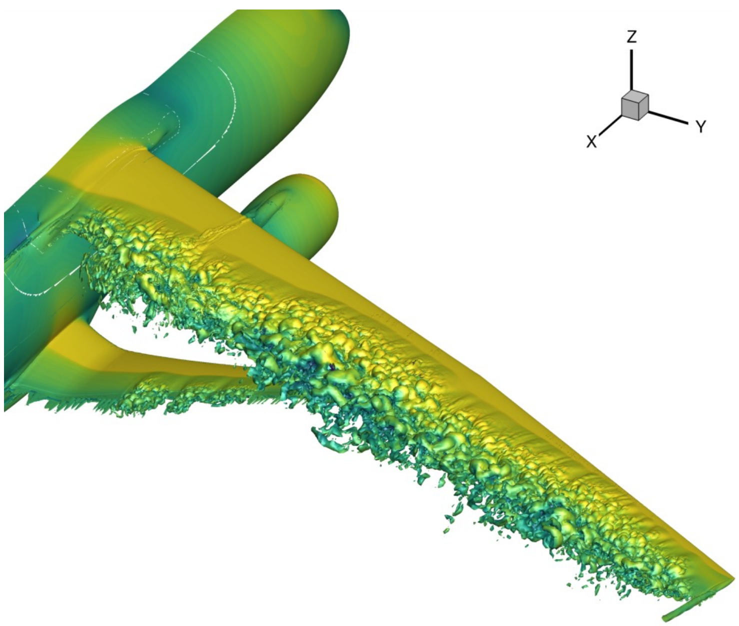


# Transonic Truss Braced Wing (TTBW) Simulations

- Refined meshing best practices for HRLES on the TTBW as well as performing Cartesian immersed boundary wall-modeled LES (WMLES) to investigate buffet.
- Will use these tools as well as transition model and more to work on scale resolving simulation to investigate high lift devices, deep stall, and aeroelasticity




Investigated Buffet onset with Unsteady RANS (URANS). Simulation oscillations of shock caused by spanwise phenomena across several convective time units




Visualization of vorticity magnitude colored by u-velocity for a scale-resolving Hybrid RANS-LES (HRLES) simulation at 6 deg AoA

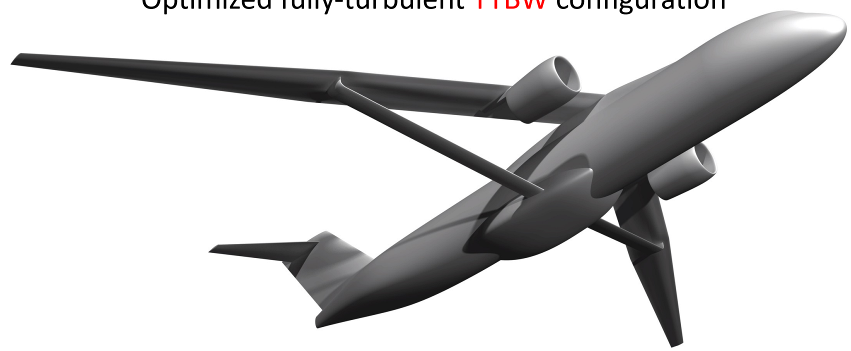

WMLES on Cartesian grid to simulate buffet on TTBW

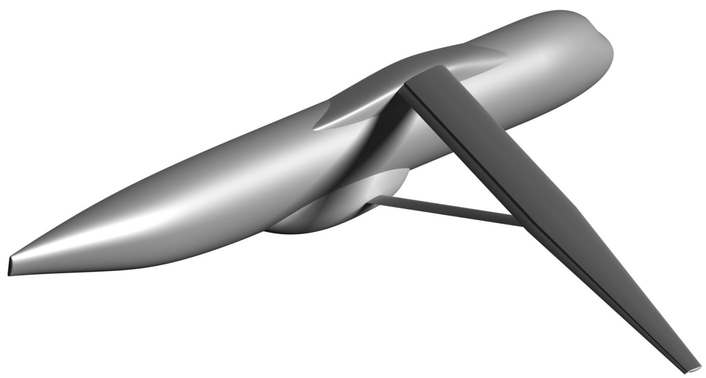
# NASA TTBW: Conceptual Design and Aerodynamic Shape Optimization

A Transonic Truss-Braced Wing (TTBW) single-aisle aircraft configuration has been designed and optimized, which serves as a platform for evaluating tools and technologies for next-generation aircraft concepts:

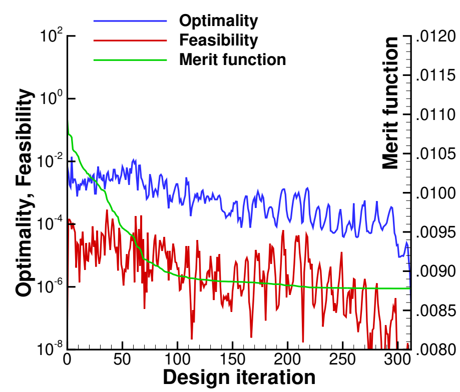
1. Cruise-slotted (CS) airfoil TTBW (TTBW-CS)
2. Natural-laminar-flow (NLF) TTBW (TTBW-NLF)
3. Tail-cone thruster (TCT) TTBW (TTBW-TCT)

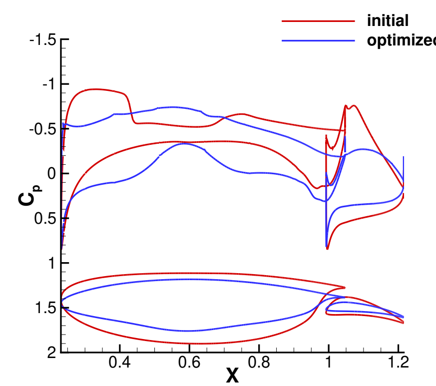
Optimized fully-turbulent TTBW configuration





Baseline TTBW-CS configuration for high-fidelity shape optimization




Drag-minimization of a cruise-slotted infinite swept wing to determine best practices for TTBW-CS optimizations

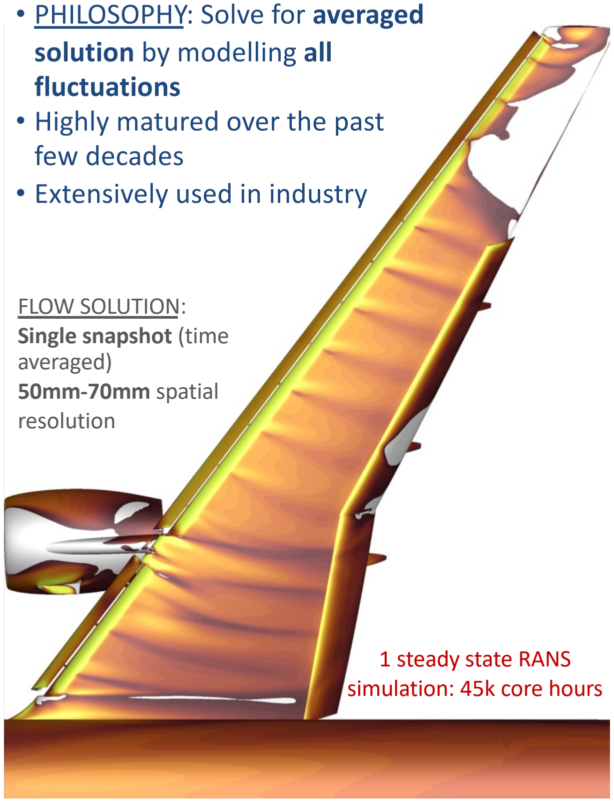
# Scale resolving simulations: Certification and Qualification by Analysis

## REYNOLDS AVERAGED NAVIER STOKES (RANS)

1980s - Present

- PHILOSOPHY: Solve for **averaged solution** by modelling **all fluctuations**
- Highly matured over the past few decades
- Extensively used in industry

FLOW SOLUTION:
**Single snapshot** (time averaged)
**50mm-70mm** spatial resolution

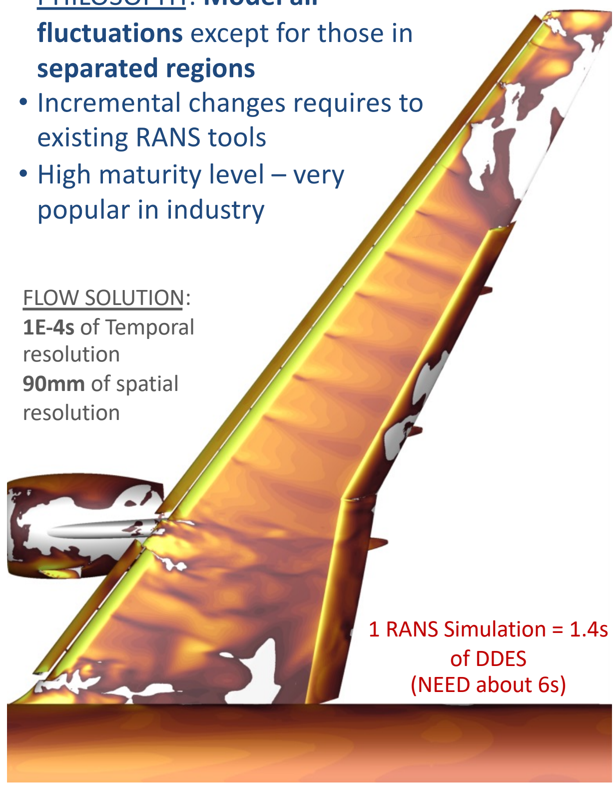



## DELAYED DETACHED EDDY SIMULATIONS (DDES)

1990s - Present

- PHILOSOPHY: **Model all fluctuations** except for those in **separated regions**
- Incremental changes requires to existing RANS tools
- High maturity level – very popular in industry

FLOW SOLUTION:
**1E-4s** of Temporal resolution
**90mm** of spatial resolution

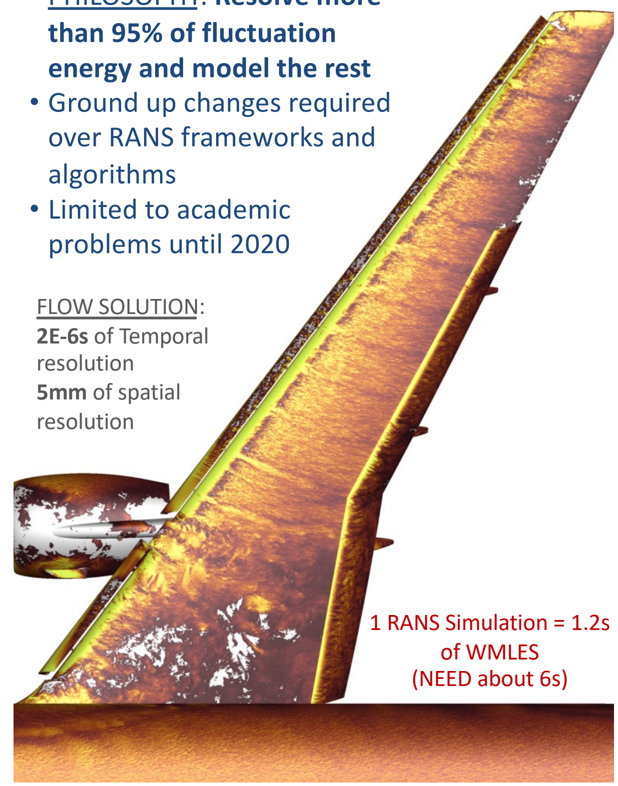



## LARGE EDDY SIMULATIONS (WMLES)

2020 - Present

- PHILOSOPHY: **Resolve more than 95% of fluctuation energy and model the rest**
- Ground up changes required over RANS frameworks and algorithms
- Limited to academic problems until 2020

FLOW SOLUTION:
**2E-6s** of Temporal resolution
**5mm** of spatial resolution



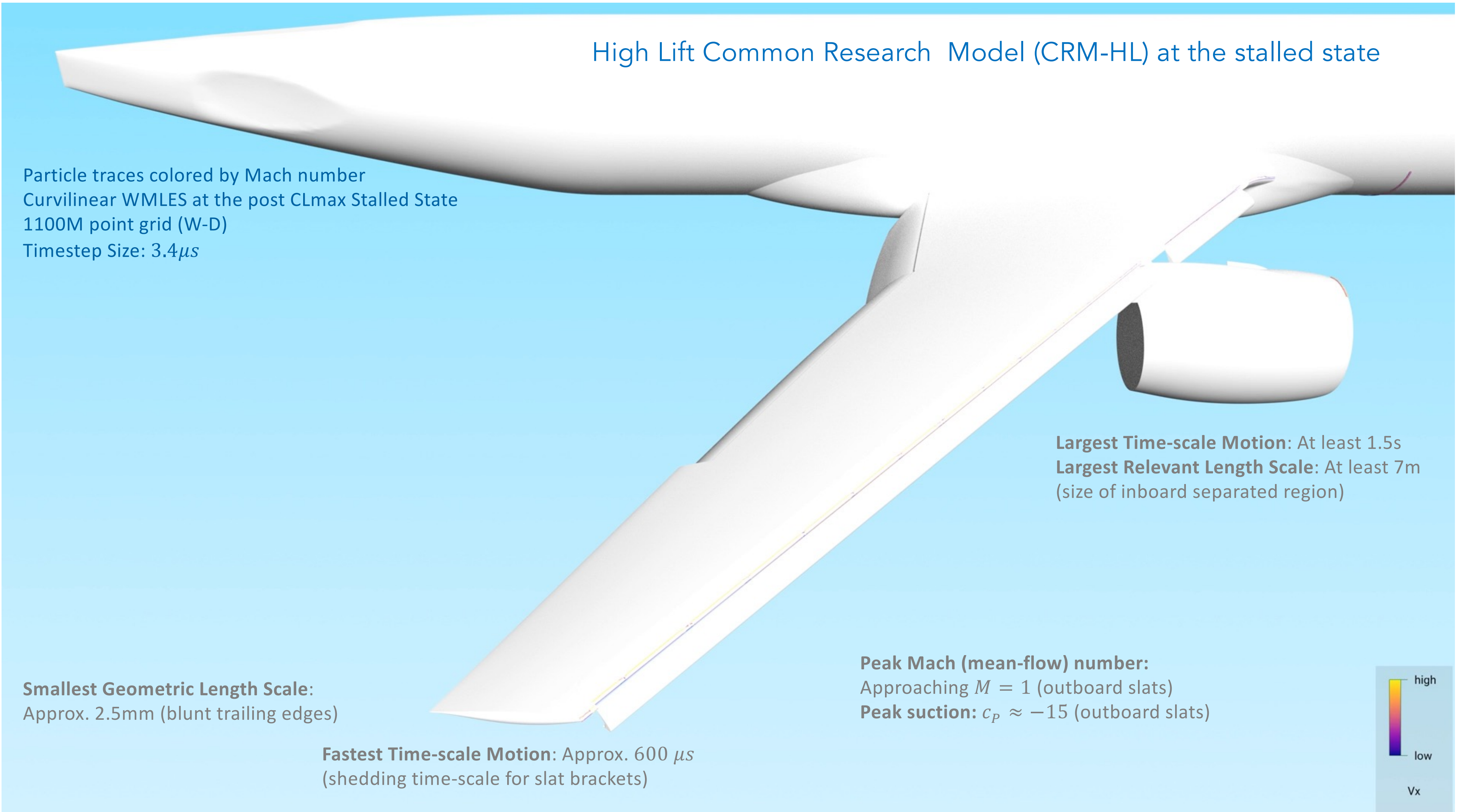
# High-Lift Common Research Model: $C_{L\max}$ prediction


1) "***High-Lift Common Research Model: RANS, HRLES and WMLES perspectives for CLmax prediction using LAVA***" by Kiris et. al. AIAA Scitech Forum 2022 DOI: 10.2514/6.2022-1554

2) "***A Reynolds-Averaged Navier-Stokes Perspective for the High Lift-Common Research Model Using the LAVA***" by Duensing et. al. AIAA Aviation Forum 2022. DOI: 10.2514/6.2022-3742 and AMS Seminar https://www.nas.nasa.gov/pubs/ams/2022/05-26-22.html

3) "***A Hybrid RANS-LES Perspective for the High Lift-Common Research Model Using the LAVA***" by Browne et. al. AIAA Aviation 2022 Forum . DOI: 10.2514/6.2022-3523 and AMS Seminar https://www.nas.nasa.gov/pubs/ams/2022/06-02-22.html

4) "***A Wall Modeled LES Perspective for the High Lift-Common Research Model Using the LAVA***" by Ghate et. al. AIAA Aviation 2022 Forum . DOI: 10.2514/6.2022-3434 and AMS Seminar https://www.nas.nasa.gov/pubs/ams/2022/06-09-22.html

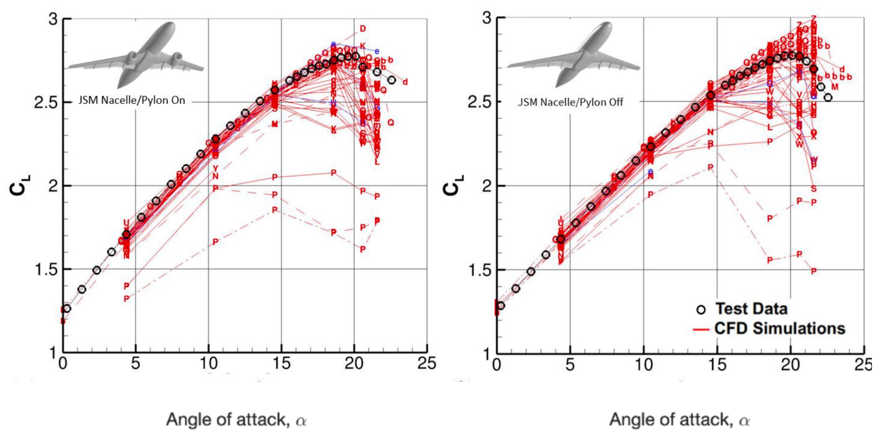

High Lift Common Research Model (CRM-HL) at the stalled state
Particle traces colored by Mach number
Curvilinear WMLES at the post CLmax Stalled State
1100M point grid (W-D)
Timestep Size: 3.4$\mu s$
Largest Time-scale Motion: At least 1.5s
Largest Relevant Length Scale: At least 7m
(size of inboard separated region)
Peak Mach (mean-flow) number:
Approaching $M = 1$ (outboard slats)
Peak suction: $c_p \approx -15$ (outboard slats)
Smallest Geometric Length Scale:
Approx. 2.5mm (blunt trailing edges)
Fastest Time-scale Motion: Approx. 600 $\mu s$
(shedding time-scale for slat brackets)
high
low
Vx

# Scale resolving simulations for Certification and Qualification by Analysis

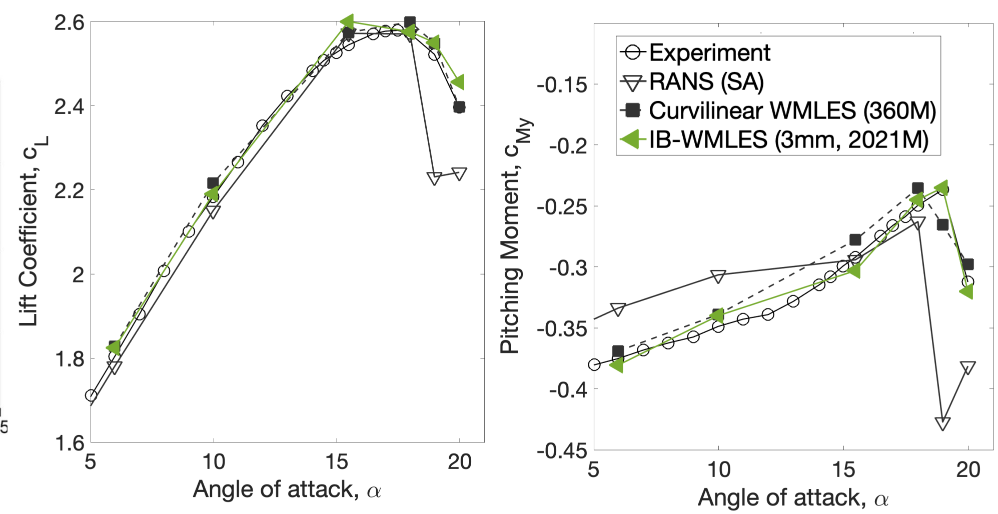
## High-Lift Configuration

- ✓ Systematic assessment **of RANS vs DDES vs WMLES** performed for the 4th High-Lift Prediction Workshop HLPW4
- ✓ Unlike cruise conditions, in high-lift configurations, substantial shortcomings in RANS simulation
- ✓ In-board, corner flow at the fuselage-wing juncture primary challenge for accurate prediction of aerodynamics
- ✓ LAVA scale resolving simulations appear to very cost competitive to legacy RANS models and show improvements over RANS predictions

**RANS from AIAA HLPW3**



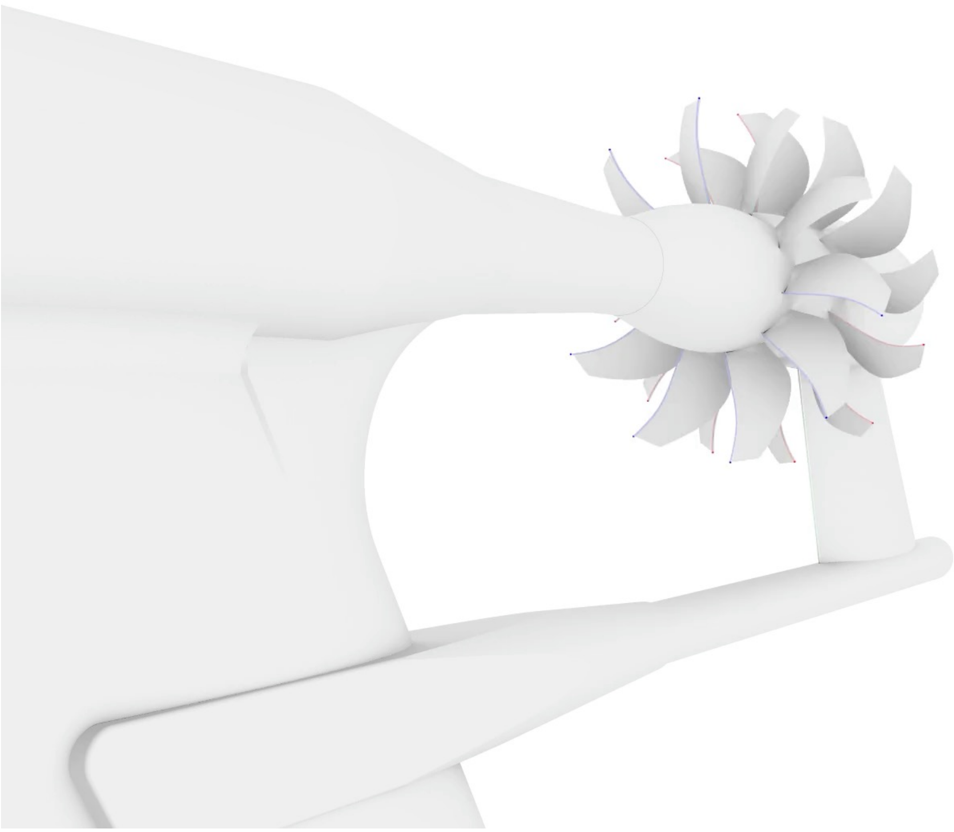

**LAVA WMLES from HLPW4**




**LAVA is the only NASA in-house capability to contribute in the HLPW4 with RANS, HRLES, and WMLES simulations**

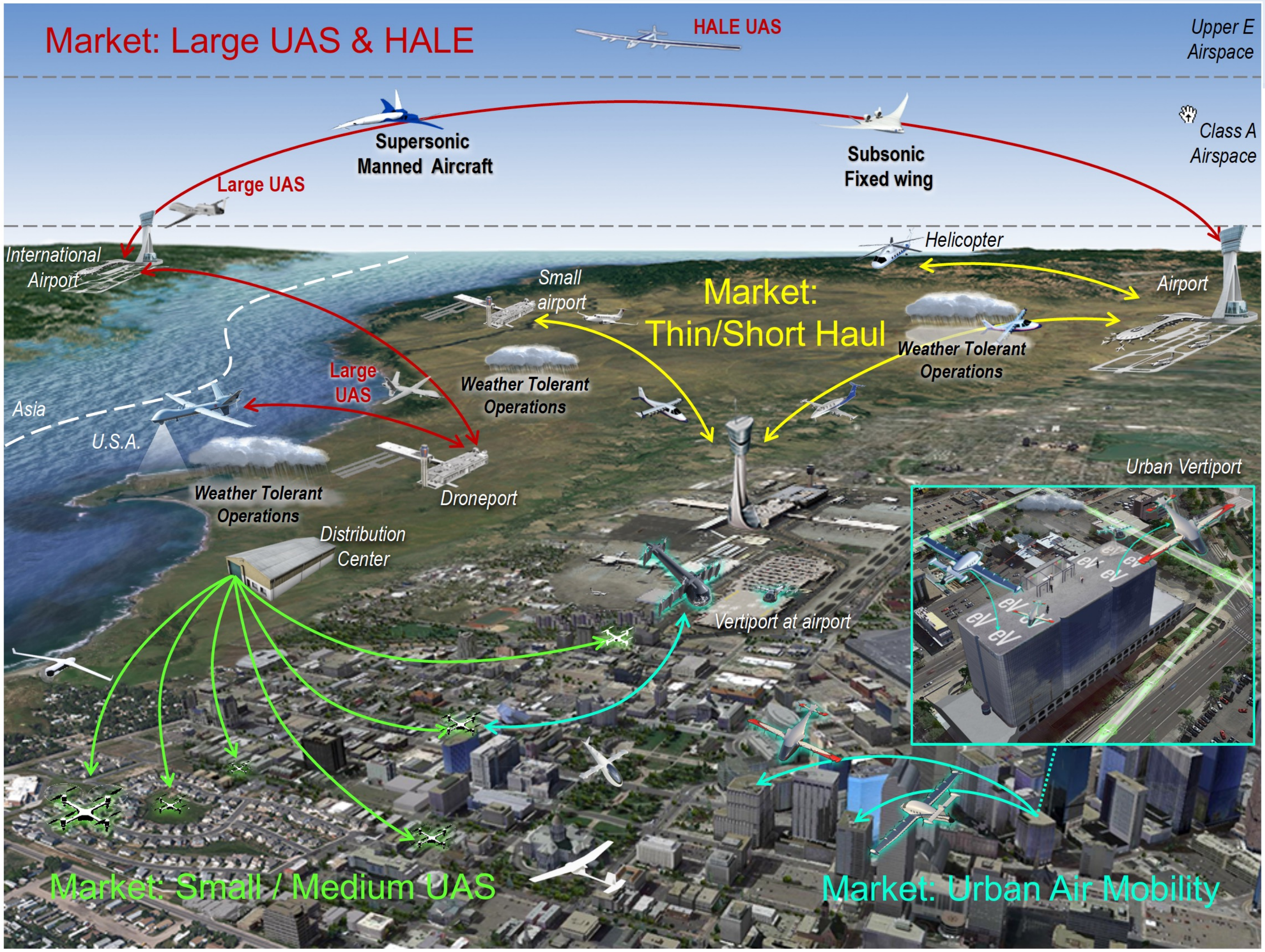

Iso-surfaces of Q-criterion
$\alpha = 19.98°$, Cartesian WMLES
3mm, 2010M point mesh

# Open-Rotor Acoustics

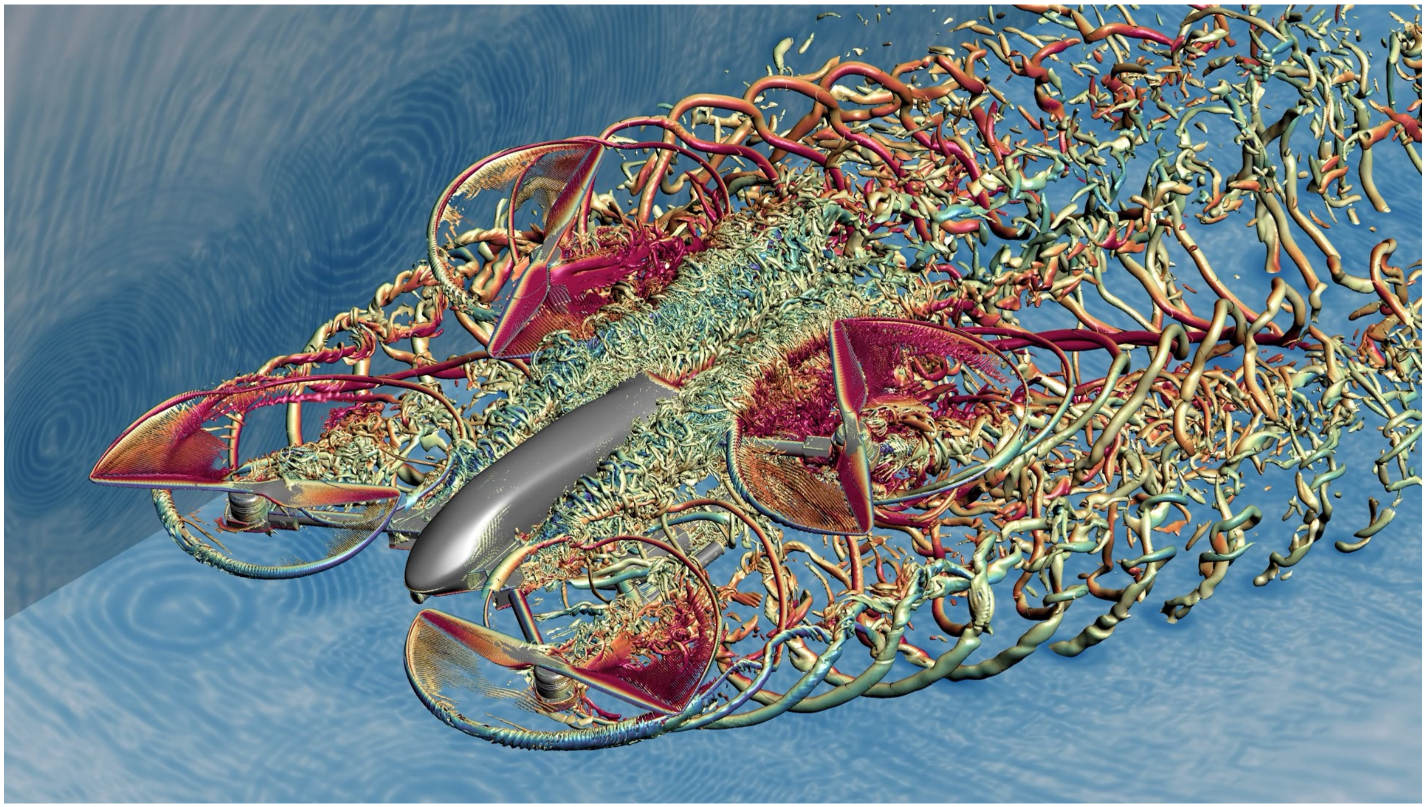


**UAS**: Unmanned Aerial Systems

**HALE**: High Altitude Long Endurance



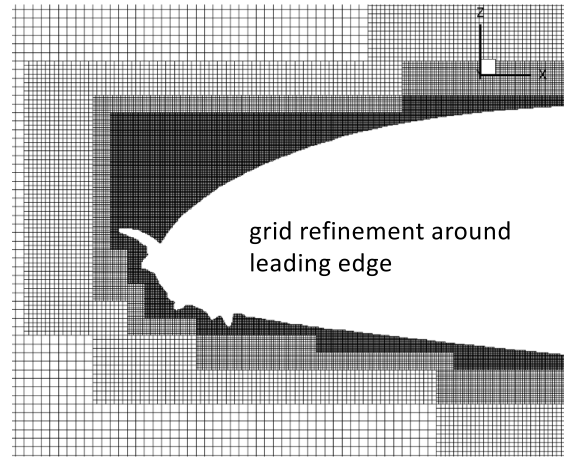
# Urban Air Mobility – Noise Prediction

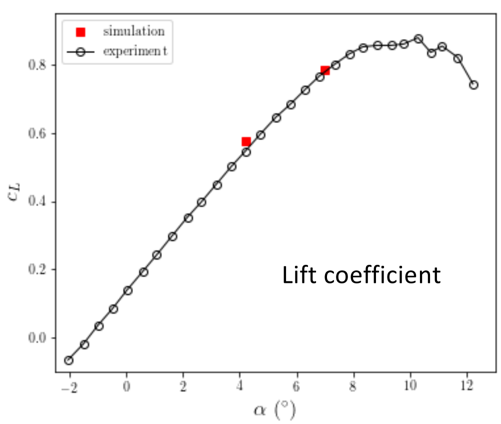


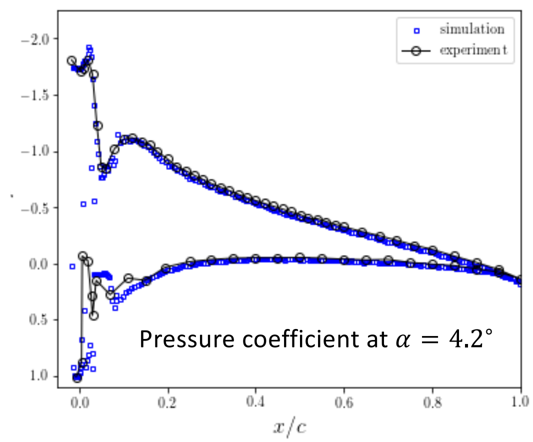
*Isosurfaces of Q-criterion colored by vertical velocity and cut plane colored by logarithm of pressure gradient magnitude*

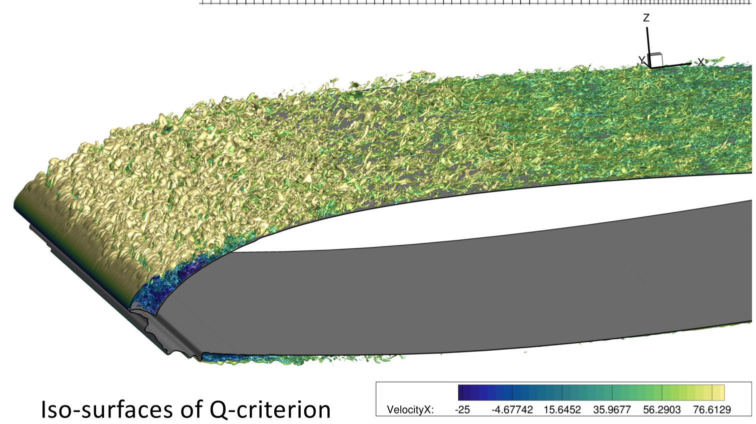
# WMLES to Predict Iced Aircraft Aerodynamics

- The LAVA team initiated a development activity to predict flow around an iced aircraft.
- Immersed boundary method with wall-stress boundary conditions from equilibrium wall model
- EG1164 case: full scale 72-inch-chord NACA 23012 with horn ice *[Broeren, Andy P., et al. 2010]*
- Reynolds number: 15.9 million; Mach number: 0.12
- Volume mesh: 143.7 million Cartesian cells with finest grid spacing ~0.9 mm
- Simulation can be completed using 200 Skylake nodes within 4 hours of wall-clock time for each angle of attack



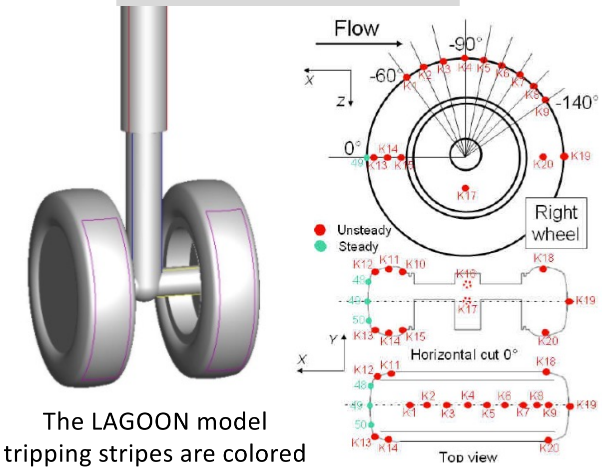




Iso-surfaces of Q-criterion

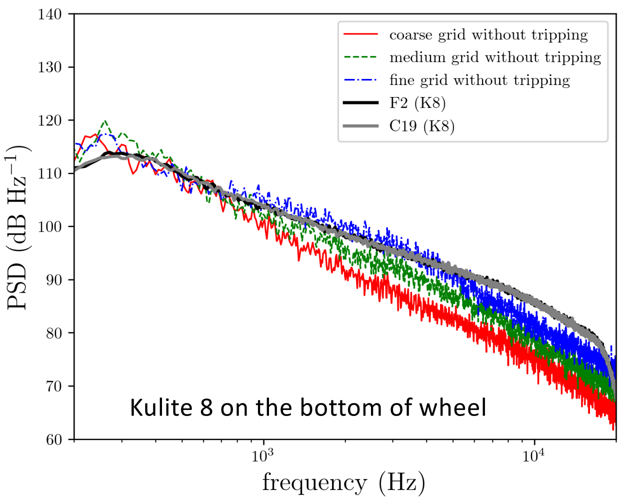
# WMLES to Predict Landing Gear Acoustics

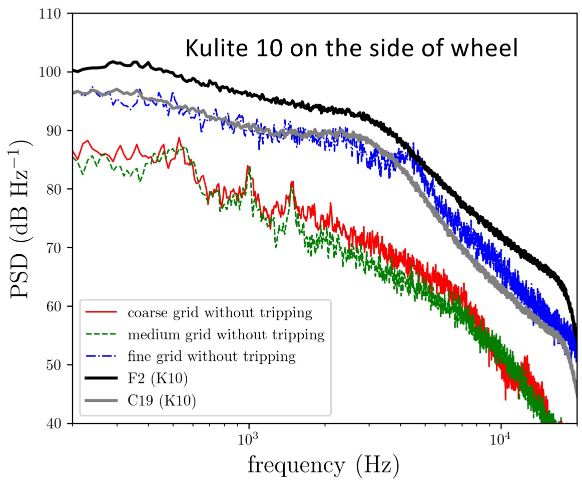
- BANCIII benchmark LAGOON landing gear problem *[Manoha & Caruelle 2015]*
- 2-wheel landing gear (LG) which is a 1:2.5 nose LG for an Airbus A320 aircraft
- Reynolds number: 1.55 million; Mach number: 0.23
- The irregular shape of the landing gear with the struts and axle is challenging for body-fitted meshing, especially for a fully-dressed landing gear
- Laminar to transition tripping stripes imposed on wheels, axle and struts to model the actual flow past a real nose landing gear
- Detailed experimental results from F2 and C19zwind tunnels

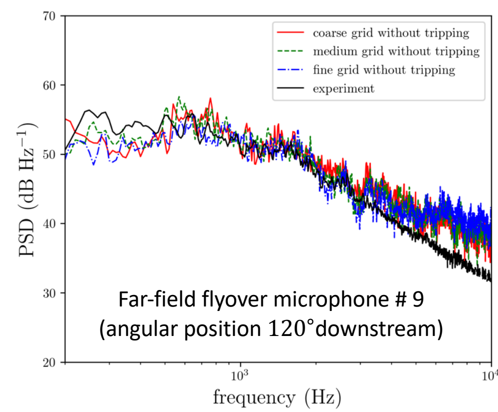
27 Kulites on the geometry




The LAGOON model
tripping stripes are colored



# X-57 Maxwell Aerodynamic Database Generation

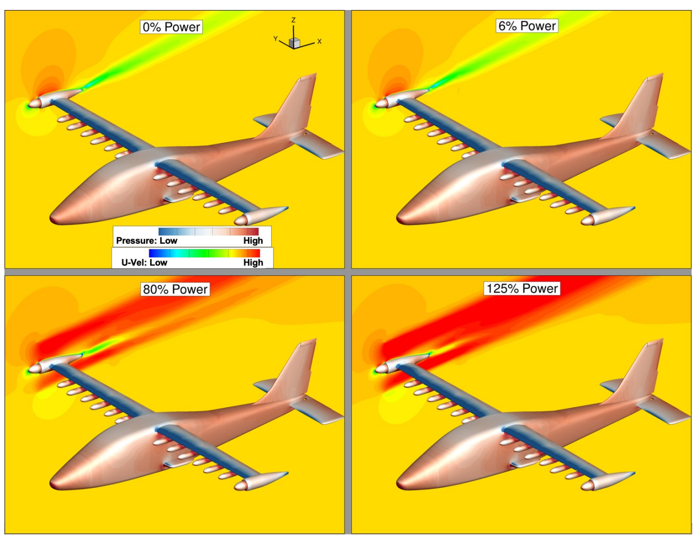
✓ The LAVA Curvilinear CFD flow solver has enabled the efficient generation of large-scale aerodynamic databases, quantifying the distributed propulsion effects on NASA's all-electric X-57 aircraft

- Over 2800 steady simulations for powered and unpowered flight conditions (left image)
- Over 40 time-accurate forced oscillation simulations to quantify dynamic stability characteristics (right image)

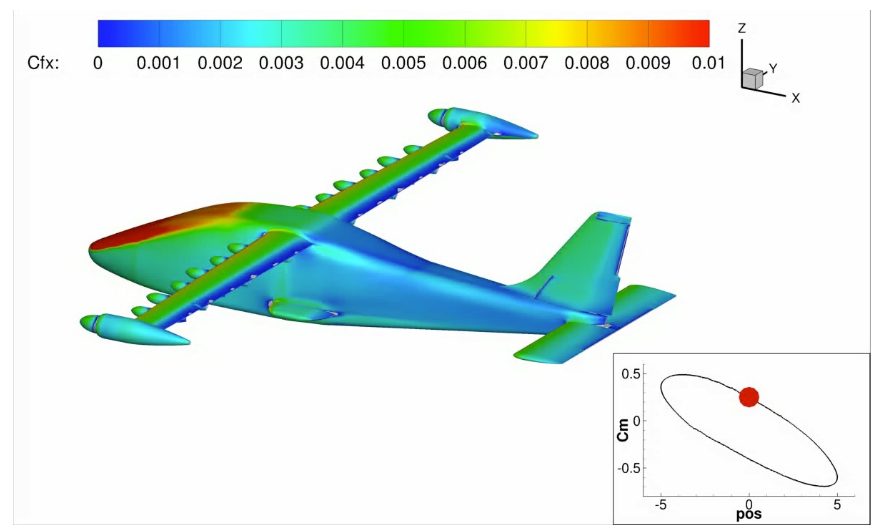
✓ Results are essential to accurately construct the piloted flight simulator, necessary to train X-57 pilots for safe flight

✓ Refactorization of the LAVA Curvilinear flow solver has resulted in a 9-12X reduction in simulation cost

- Large-scale database completion time has been reduced from years to months




*Surface pressure and streamwise velocity shown on planar slice for various database cruise power conditions.*




*Skin friction and pitching moment as a function of pitch angle for an unsteady forced pitch oscillation simulation.*

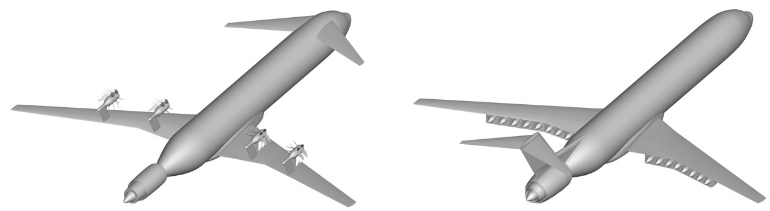
# Subsonic Single Aft-Engine (SUSAN) Aircraft Design and Support

- The **SUSAN Electrofan** hybrid-electric regional transport aircraft is being developed in a collaborative effort between ARC, GRC, LaRC, and AFRC.
- The LAVA group is contributing to the aircraft design from multiple fronts
    1. **Conceptual design** and sizing
    2. **High-fidelity steady RANS CFD** to investigate Propulsion Airframe Integration (PAI)
    3. **Aerodynamic shape optimization** to maximize benefits of Boundary Layer Ingestion (BLI)
- LAVA contributions have helped to quantify overall **aerodynamic performance**, design the **aircraft propulsion** systems, and perform **design trade studies** to develop a feasible and efficient aircraft

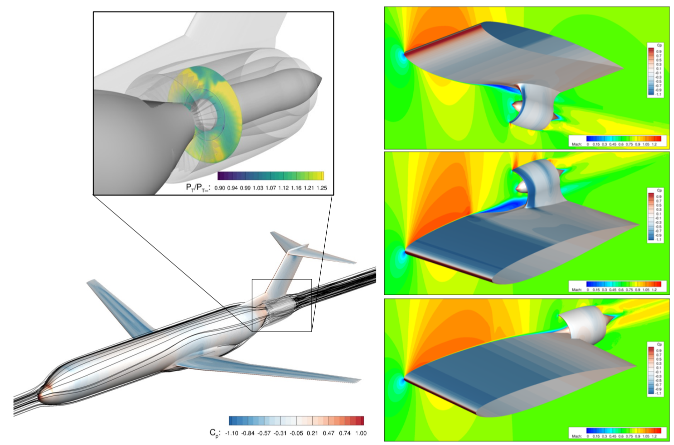
Artistic rendering of current proposed SUSAN aircraft configuration during takeoff.

Initial concept

Current concept



Evolution of SUSAN Electrofan aircraft concept.



RANS simulations using the LAVA Curvilinear CFD solver inform design choices and quantify performance of the current Tail-Cone Thruster (TCT, left image) and proposed Distributed Electric Propulsion (DEP, right image) system designs.

# Aircraft Cabin Air Flow Modeling & Simulations

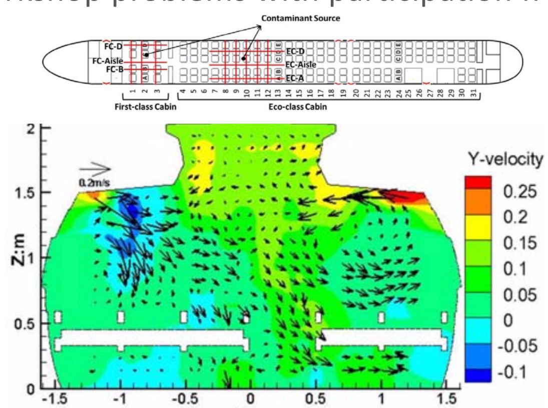
**Explore adoption of a Cabin Air Common Research Model (CA-CRM)**

- To serve as a test bed for simulation strategy development, verification and validation
- Commonly accessible to and contributed by NASA/DLR/NRC, the aviation industry, and the academia
- Essential to gain confidence in the modeling and simulation of both:
  1. Cabin air flow environment
  2. Cough/Sneeze etc. events (and the interaction with background flow / other passengers)
- Will provide essential insight into the appropriate physical/computational model fidelity
- Will aid cabin air simulations to be better integrated into the aviation industry design workflow
- Will increase confidence level of current practices using commercial software such as ANSYS, STAR-CCM+, etc.

**Potential starting points may already exist**

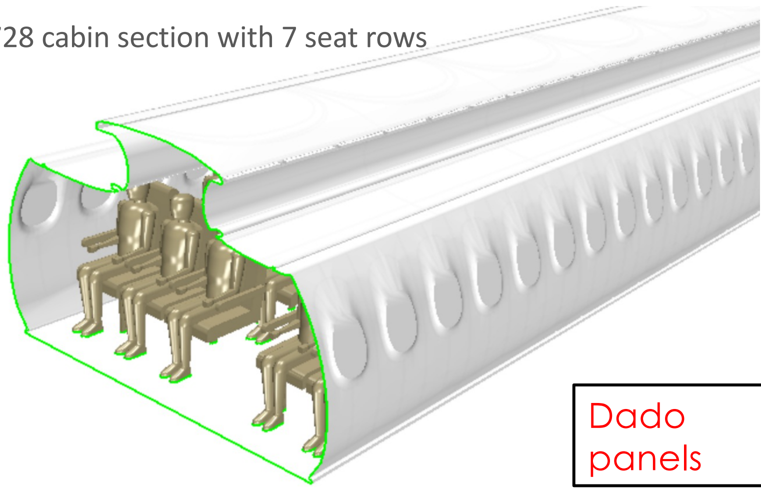
- DLR agreed to share Do728 data and geometry - Collaborating with: Daniel Schmeling, Christian Bauer, Andrei Shishkin, Mikhail Konstantynov
- Experimental and numerical studies could be made available through workshop problems with participation from academia and the industry

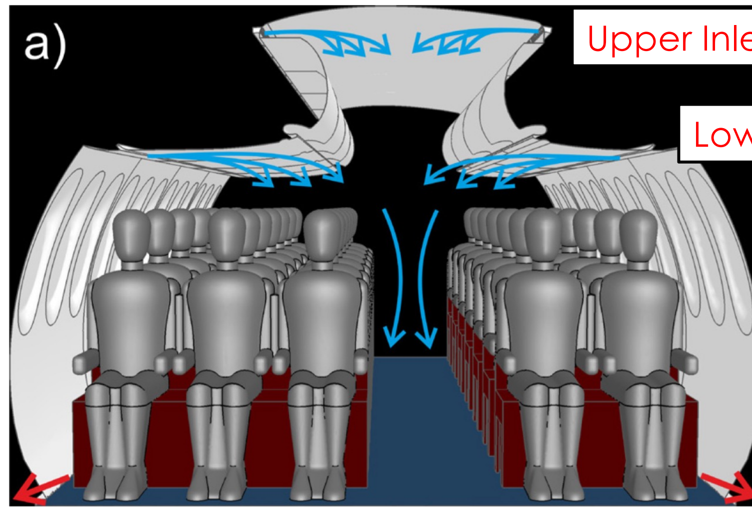
Source: Lin et al 2014 [Ref 4]

# Aircraft Cabin Air Flow Modeling & Simulations – Boundary Conditions

Do 728 cabin section with 7 seat rows



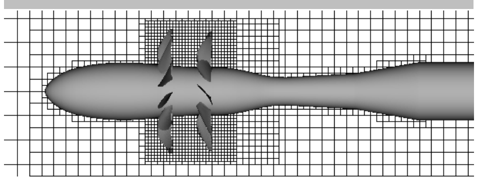


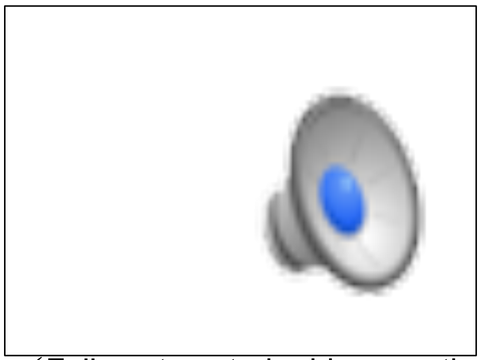

- Need coordination with the experimental team at DLR to identify a target test case to simulate
- Boundary conditions need to be well defined:
  - ➢ Inlets: Mass or volumetric flow rate, air temperature
  - ➢ Outlets: Back pressure
  - ➢ Cabin surfaces: can likely be assumed adiabatic due to ground level test
  - ➢ Mannequins: Surface temperature

J. Bosbach et al. **ALTERNATIVE VENTILATION CONCEPTS FOR AIRCRAFT CABINS**

# Grid Paradigms in CFD

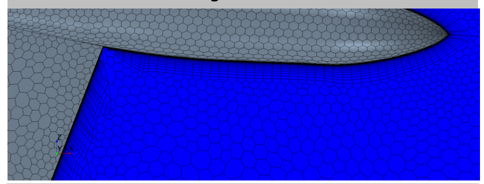
### *Structured Cartesian AMR*

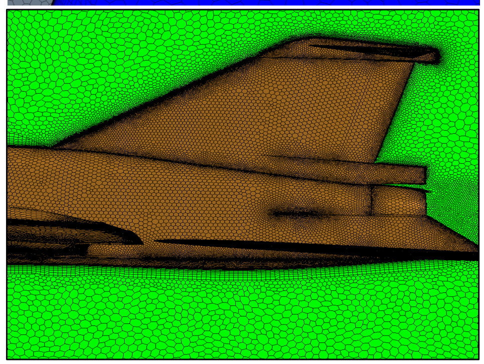




- ✓ Fully-automated grid generation
- ✓ Highly efficient Adaptive Mesh Refinement (AMR)
- ✓ Low computational cost
- ✓ Reliable higher order methods
- ✗ Non-body fitted → Resolution of boundary layers challenging

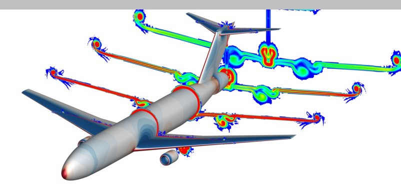
### *Unstructured Arbitrary Polyhedral*

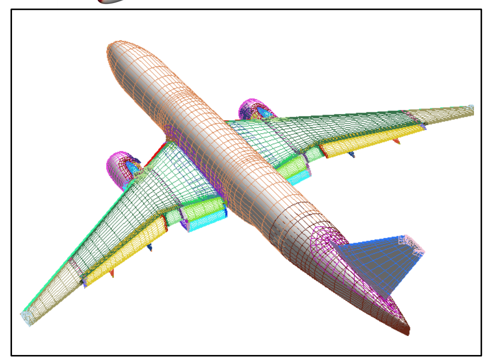




- ✓ Partially automated grid generation
- ✓ Body fitted grids
- ✗ Grid quality can be challenging
- ✗ High computational cost
- ✗ Higher order methods yet to fully mature

### *Structured Curvilinear*





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

ort



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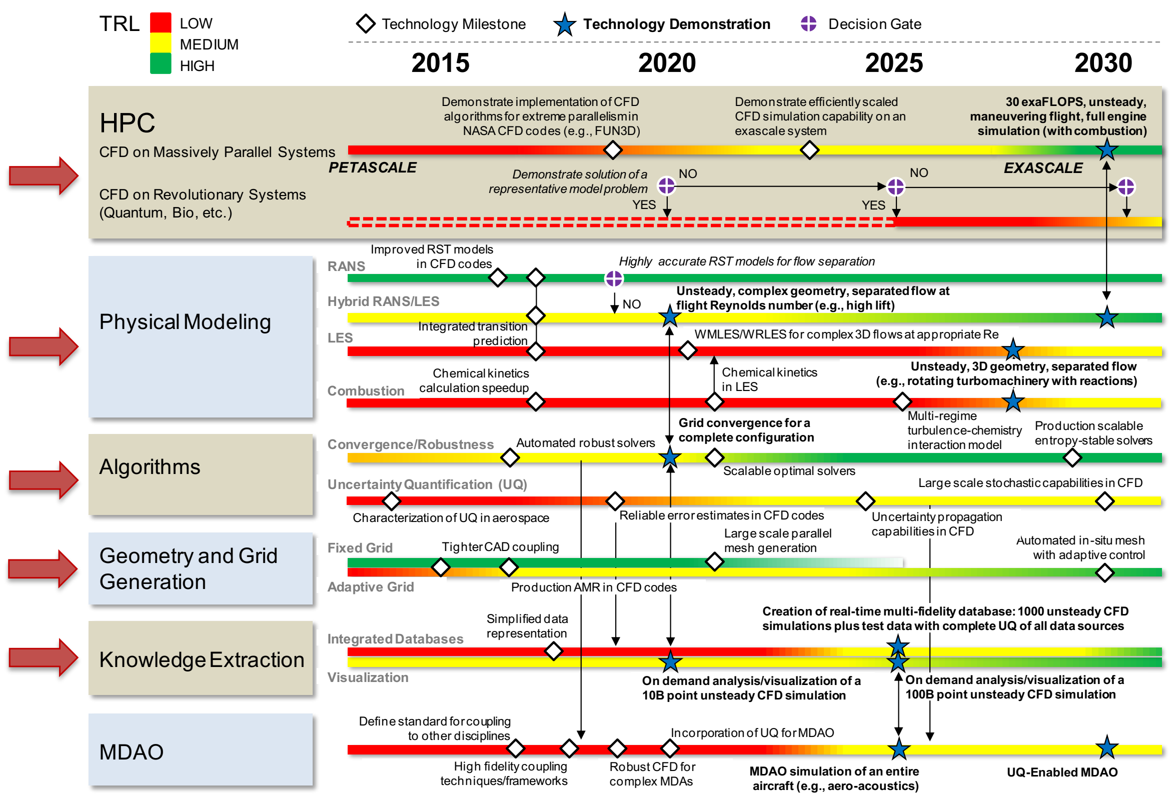
# CFD 2030 Technology Development Roadmap




CFD Vision 2030 Study report published in 2014