

# Advancing NASA Software for Sonic Boom Prediction

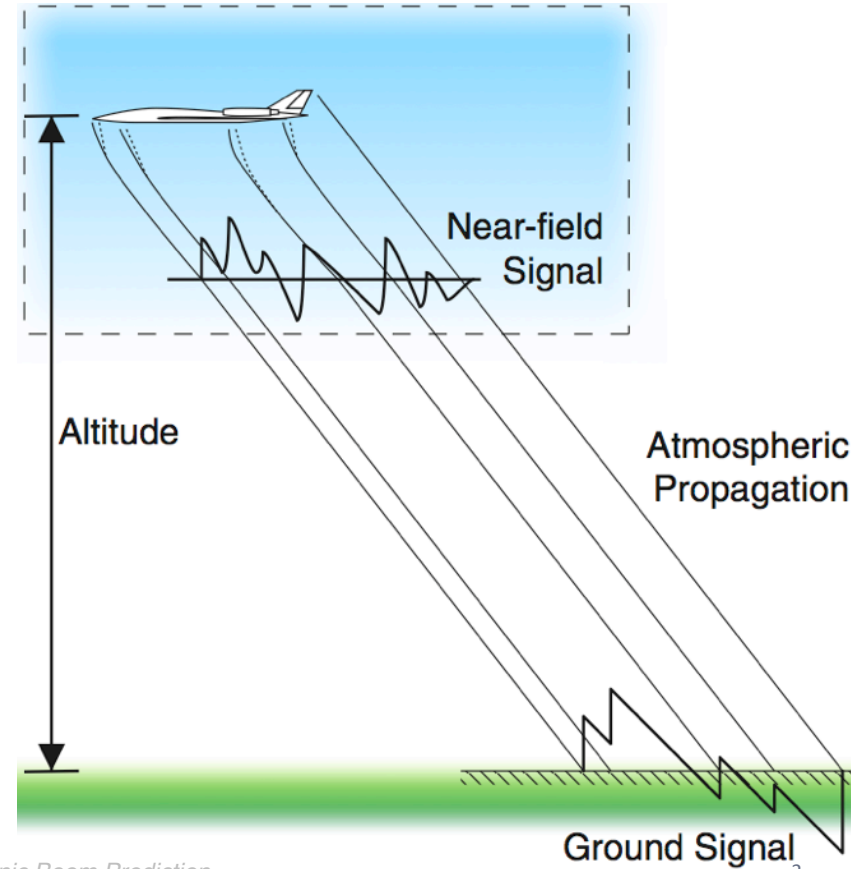
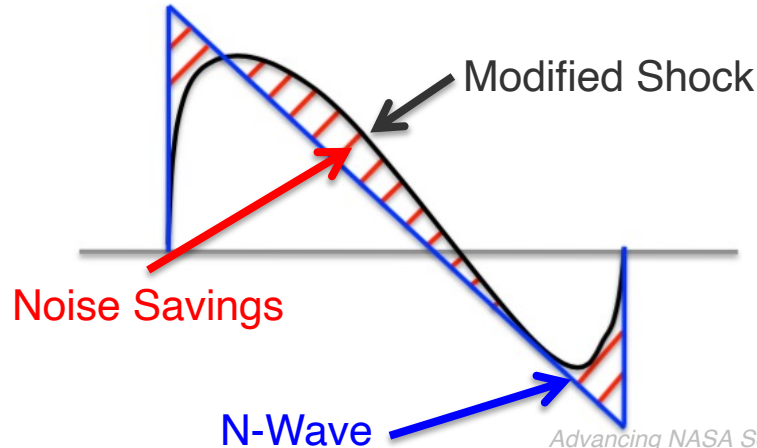
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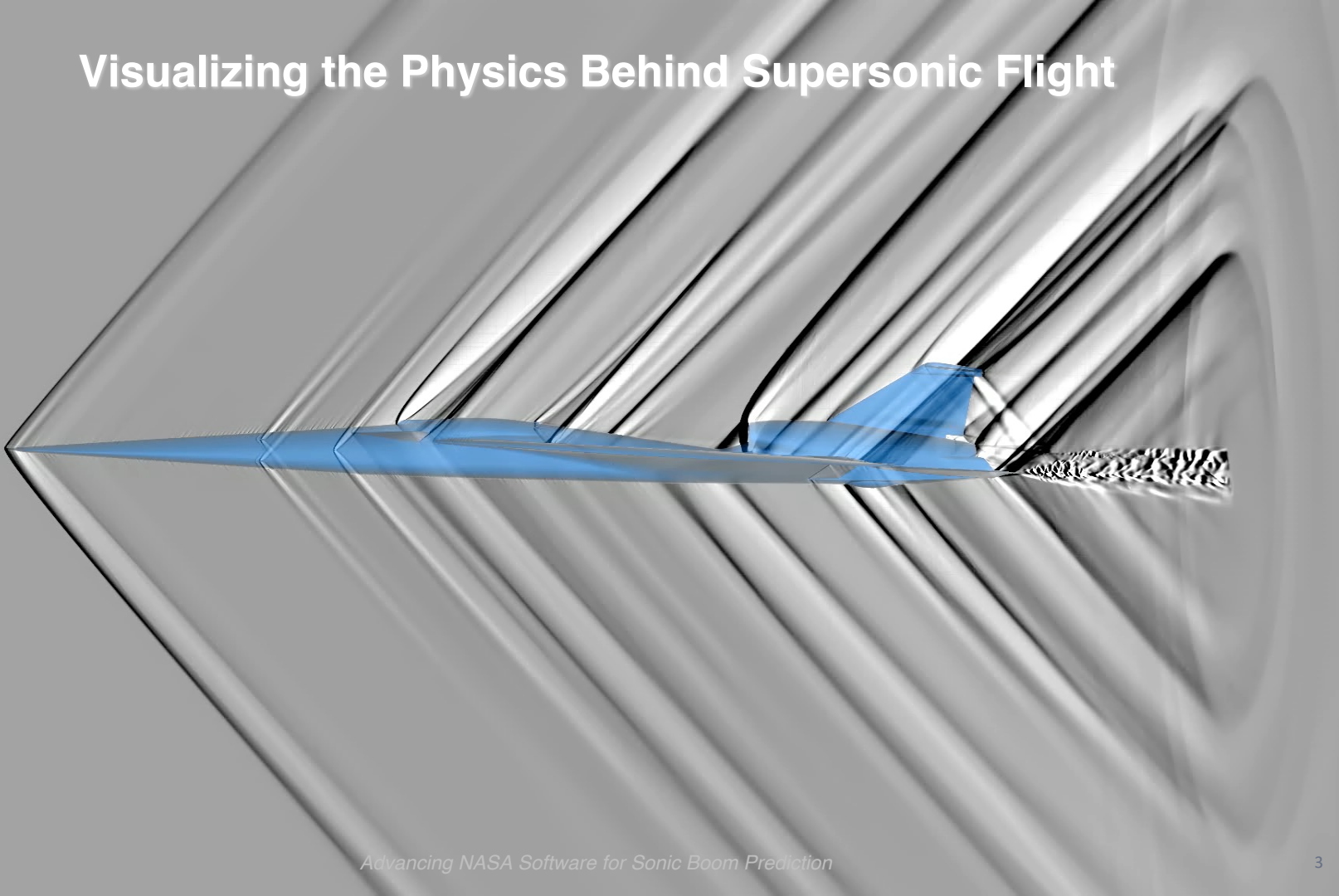
*Supercomputing 2022, Dallas, TX*

# Why Is Sonic Boom Reduction of Interest?

- **FAA regulations currently ban flying at supersonic speeds which produces excess noise**
- **Compression and expansion waves produced by the airframe combine to produce an N-Wave (very loud) pressure signature**



# Visualizing the Physics Behind Supersonic Flight



# How Does NASA Contribute to Sonic Boom Research?



- **Develop and analyze supersonic aircraft designs to study the noise associated with supersonic flight**
- **Quiet SuperSonic Technology (QueSST) Project Mission<sup>1</sup>**
  - Design and build the X-59 research aircraft
  - Fly the X-59 over populated areas to gather human feedback to noise generated



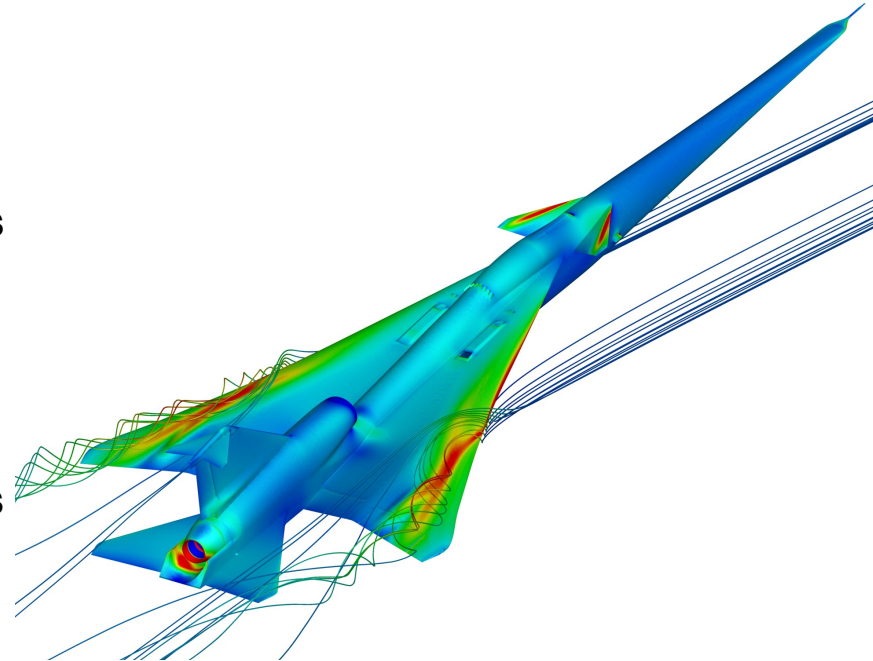
<sup>1</sup><https://www.nasa.gov/X59>

Image source: <https://www.nasa.gov/image-feature/nasa-s-x-59-quesst-airplane-takes-shape-at-lockheed-martin-skunk-works>

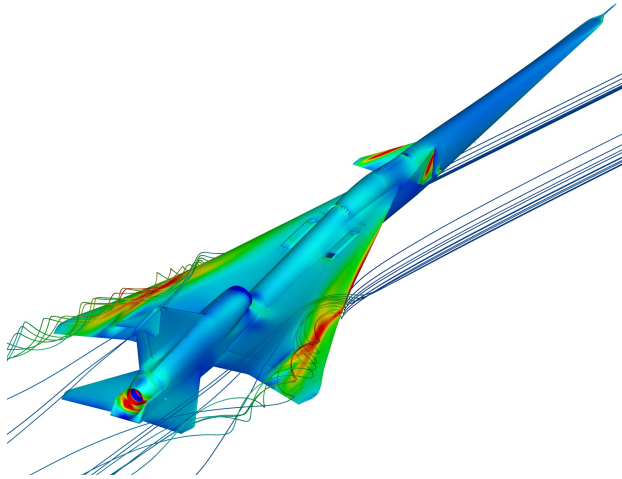
# How Can Simulations Help in this Pursuit?



- **Computational simulations (i.e., computational fluid dynamics (CFD)) can be used to quantify aircraft performance for a vast range of flight conditions**
- **Results can be utilized by other analysis tools (e.g., flight planning software)**
- **Complete flow field can be analyzed and understood**
- **This presentation will focus on advancements related to two solver frameworks**
  - Launch Ascent and Vehicle Aerodynamics (LAVA)
  - Cart3D

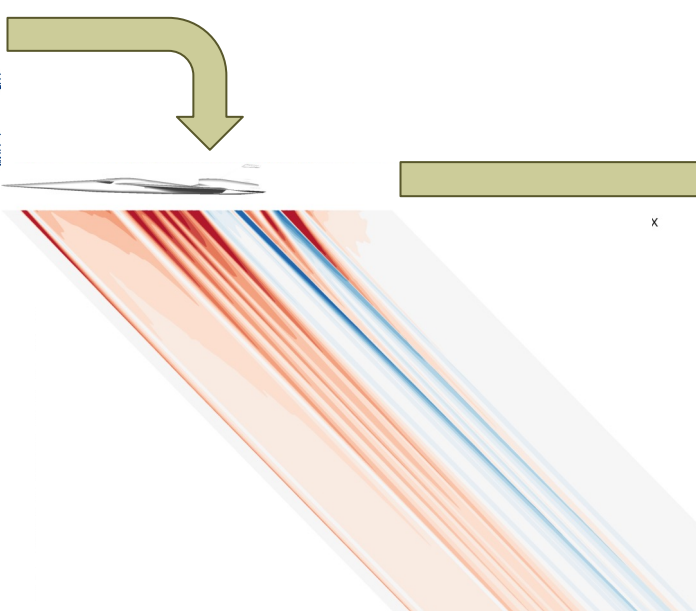


# Method to Predict Sonic Booms Using Simulations



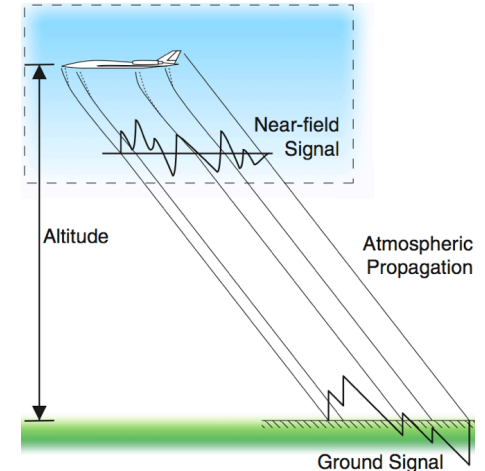
## Step 1: Computational Fluid Dynamics (CFD)

*Used to make near-body flow predictions*



## Step 2: Space Marching

*Takes near-body flow predictions and "marches" them away from aircraft*

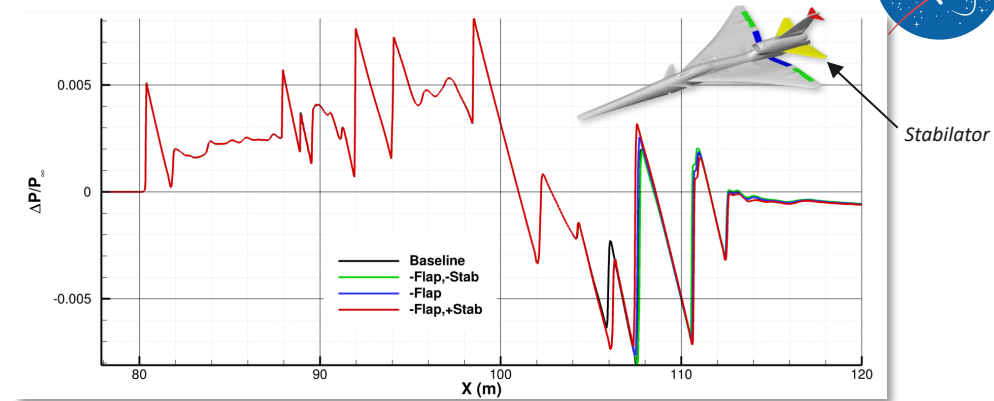
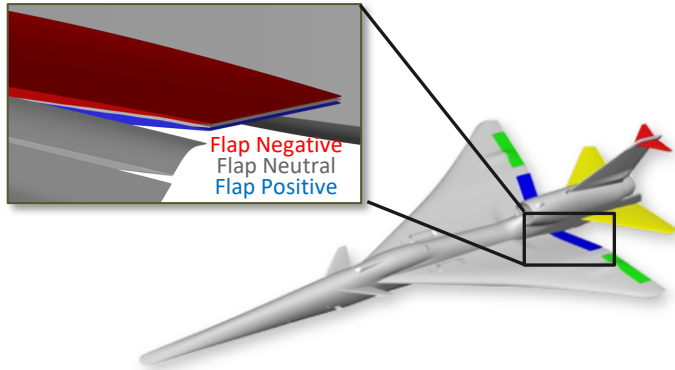


## Step 3: Pressure Signal Propagation

*Couples with space marching to propagate signals to ground level*

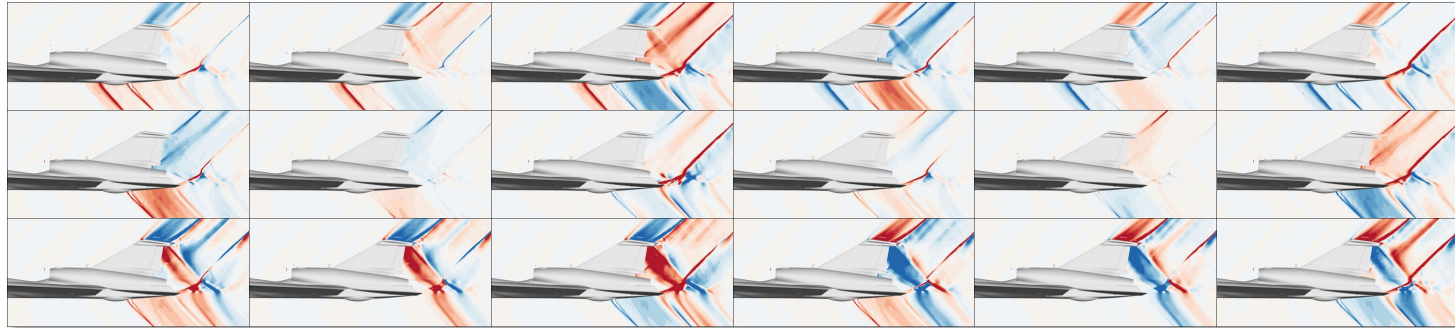
*Ground noise can be predicted using this three step method*

# Challenges Associated with Sonic Boom Simulation



**Geometry:** *Highly complex geometry with multiple moving parts*

**Solution Sensitivity:** *Slight changes to simulation or aircraft parameters affect ground noise predictions*

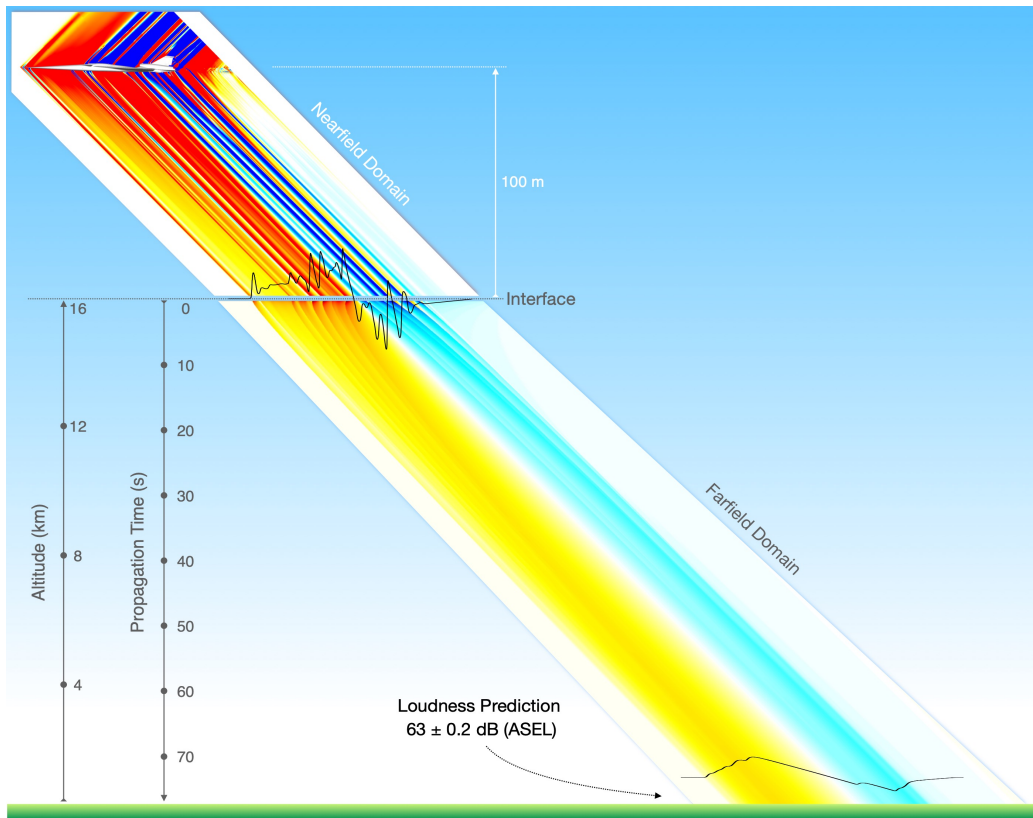


**Computational Cost:** *Fully characterizing aircraft boom performance requires thousands of high-fidelity simulations*

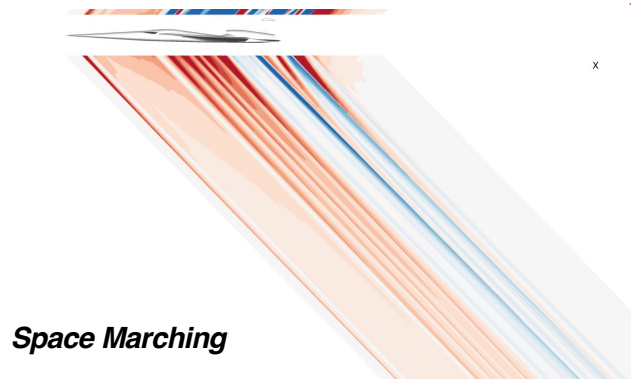




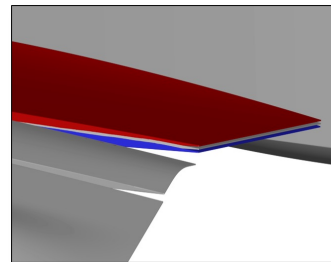
# How Have We Addressed Supersonic Modeling Challenges?



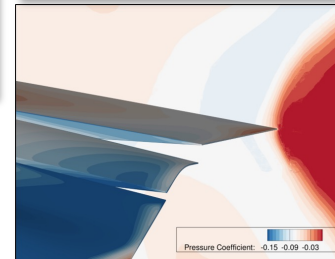
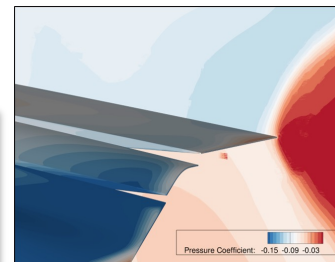
**Ground Noise Error Control**



**Space Marching**



**Automation of Database Generation Process**



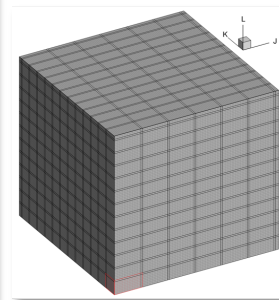
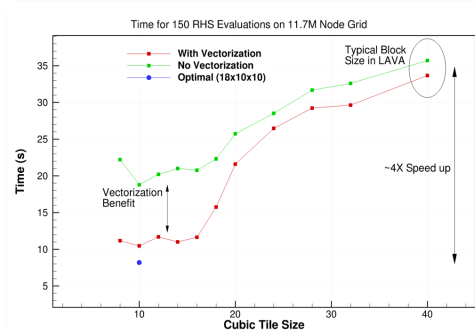
# Accelerating the CFD: Refactoring the LAVA Solver



- Last major code restructuring took place at the turn of the century to support scalar processors
- Current refactoring of the Launch Ascent and Vehicle Aerodynamics (LAVA) solver aims to better match code structure to modern hardware:
  - Each processor is a shared memory cluster that can directly access all memory on the node
- **Algorithmic Improvements:**
  - “Doing less total work”
- **“Computer Science” improvements:**
  - “Doing the same amount of work faster”



**Aitken Supercomputer<sup>1</sup>:** Total cores: 308,224, Total memory: 1.27 PB, 13.12 Pflop/s theoretical peak

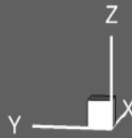


**Algorithmic Improvements:** Tiling decomposes computational grids such that a single core will be used to solve on hundreds of tiles.

<sup>1</sup>Image source:

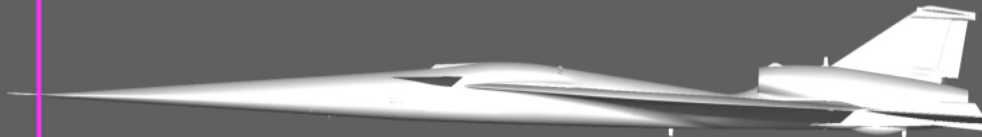
[https://www.nasa.gov/pubs/stories/2020/feature\\_aitken\\_expansion\\_fall\\_2020.html](https://www.nasa.gov/pubs/stories/2020/feature_aitken_expansion_fall_2020.html)

# Accelerating the CFD: Refactoring the LAVA Solver



|             | Original CFD | Refactored CFD |
|-------------|--------------|----------------|
| Time (hrs.) | 5.5          | 1.5            |
| CPU-hrs.    | 8,250        | 1,800          |

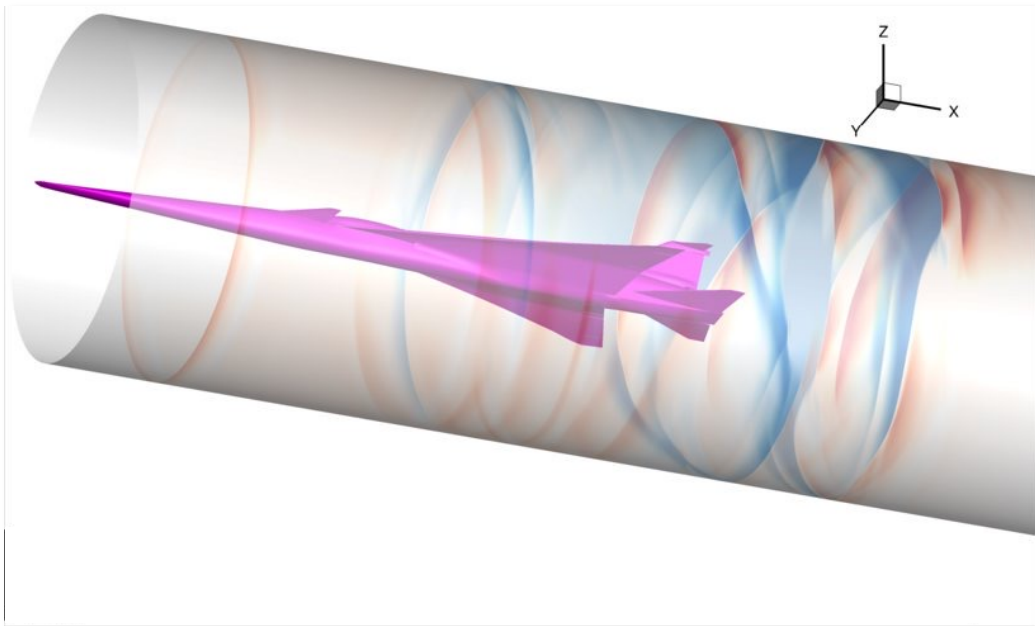
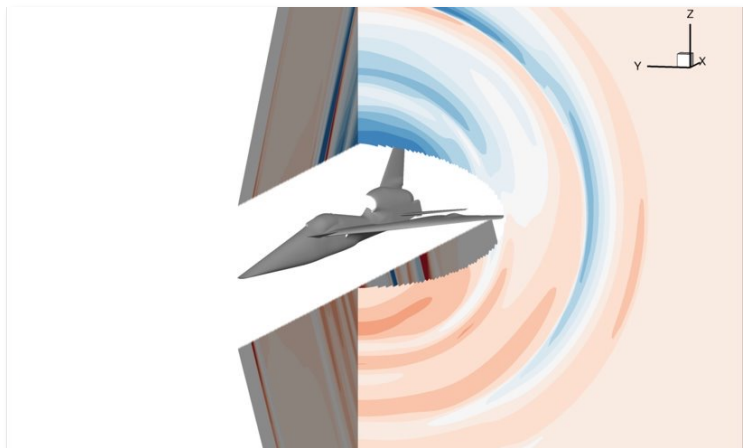
*Pressure disturbance (blue = low, red = high) along aircraft axial stations.*



- Solver refactorization alone decreased computational cost of X-59 simulations by 5X
- Algorithmic changes produced essentially identical solutions compared to previous solver versions

# Reducing the CFD Cost through Space Marching

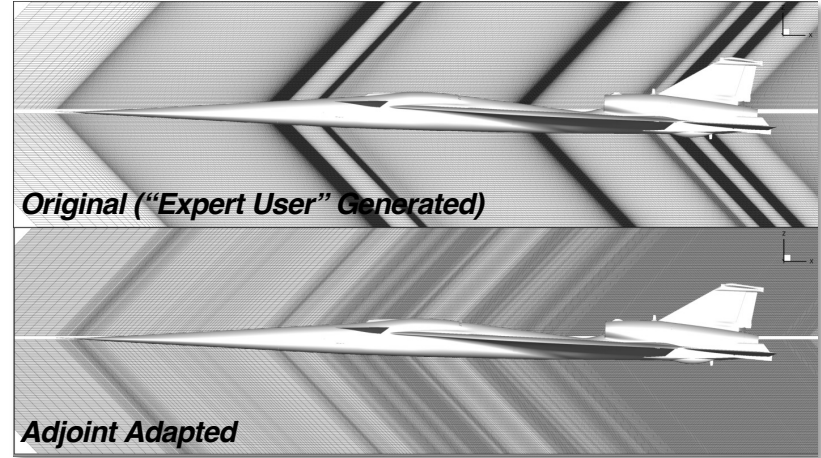
- Solves a different set of underlying equations computed on a standard laptop or workstation
- Marches solution extracted near CFD domain boundary to “mid-field” location
- CFD domain size can be substantially reduced to near-body location
- 2X savings in computational resources is estimated



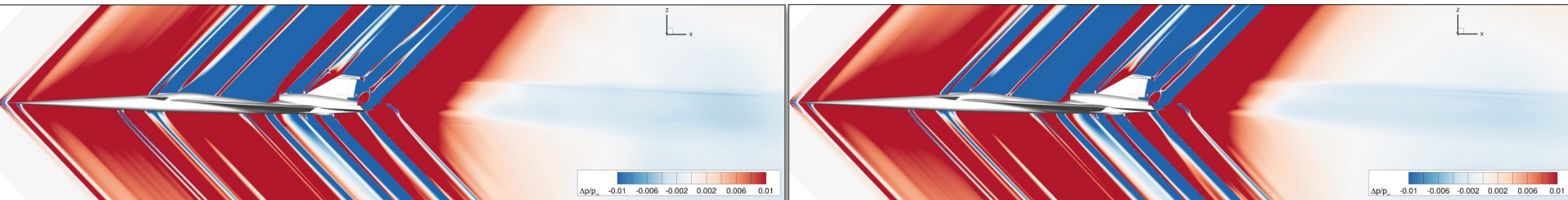
Pressure disturbance (blue = low, red = high) visualization near the X-59 in the space marching domain (left) and at the CFD solution extraction location (right).

# Implementing Mesh Adaptation Procedures

- Automation of off-body grid redistribution has been developed
- Minimization of resource requirements for a desired level of accuracy is desirable
- Adaptation targeting error in the output quantities of interest has been shown to resolve significant flow features with a 2X cost savings



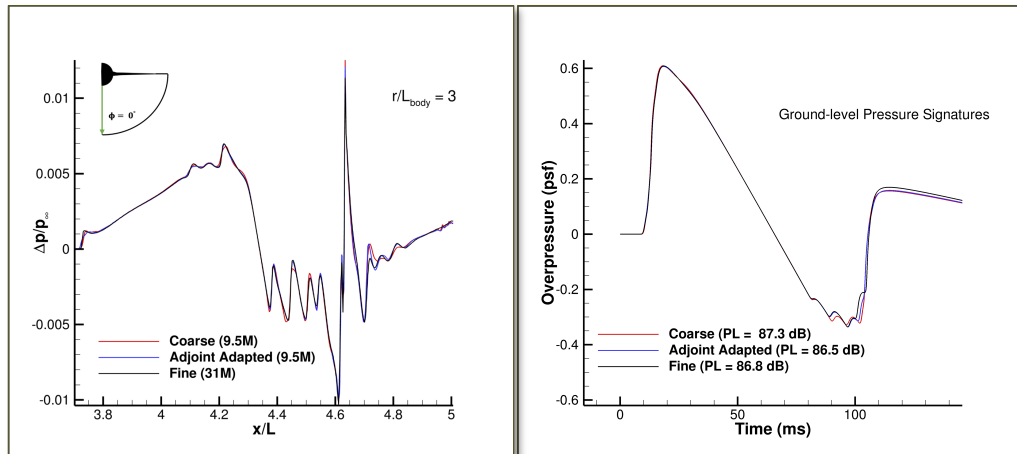
*Mesh adaptation applied to the X-59*



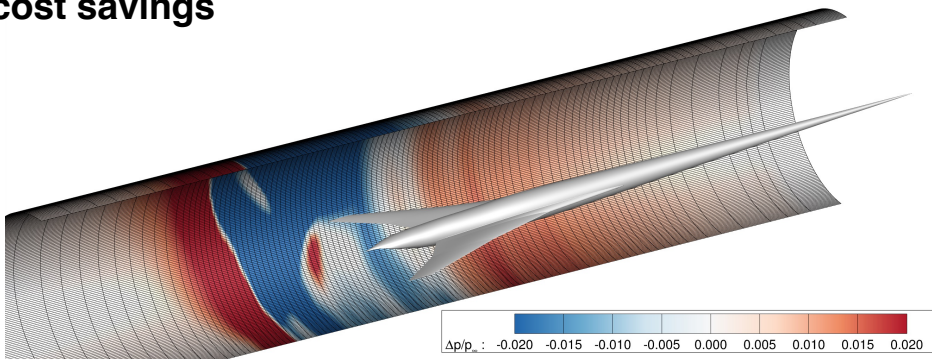
*Pressure disturbance (blue = low, red = high) visualization for the original (left) and adjoint adapted (right) computational grids.*

# Implementing Mesh Adaptation Procedures

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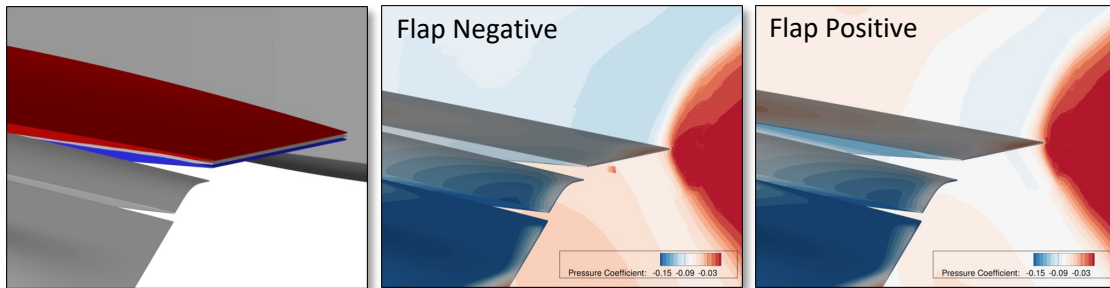
Nearfield (left) and ground (right) pressure signature comparisons



Pressure disturbance (blue = low, red = high) solution for a supersonic body using mesh adaptation

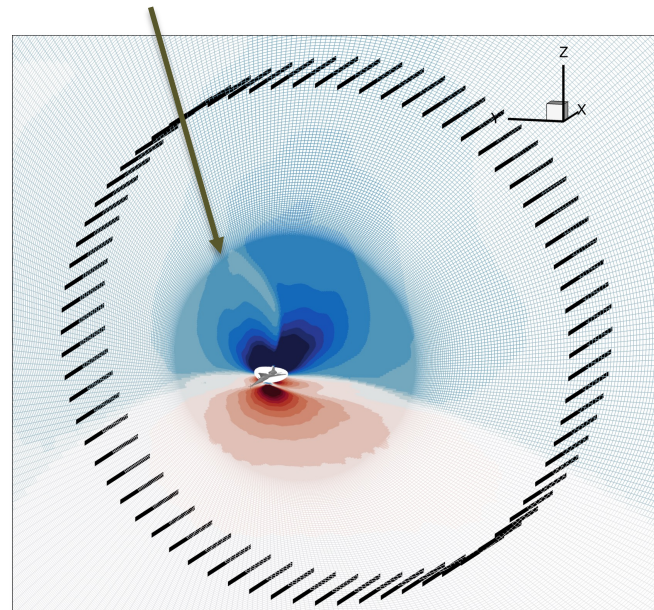
# Automation of Database Generation Process

- **Essential for database generation that consists of  $O(1000)$  solutions**
- **Minimizes manual intervention during simulation workflow**
  - Rapid computational mesh regeneration and simulation job submission
  - Efficient data extraction between propagation steps
  - Automatic line pressure signature extractions



Pressure coefficient (*blue* = low, *red* = high) shown on aircraft near flap surfaces

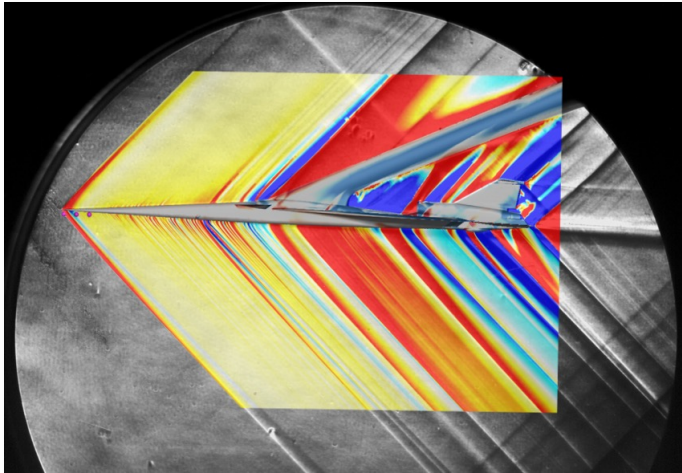
Effect of asymmetric aileron deflection



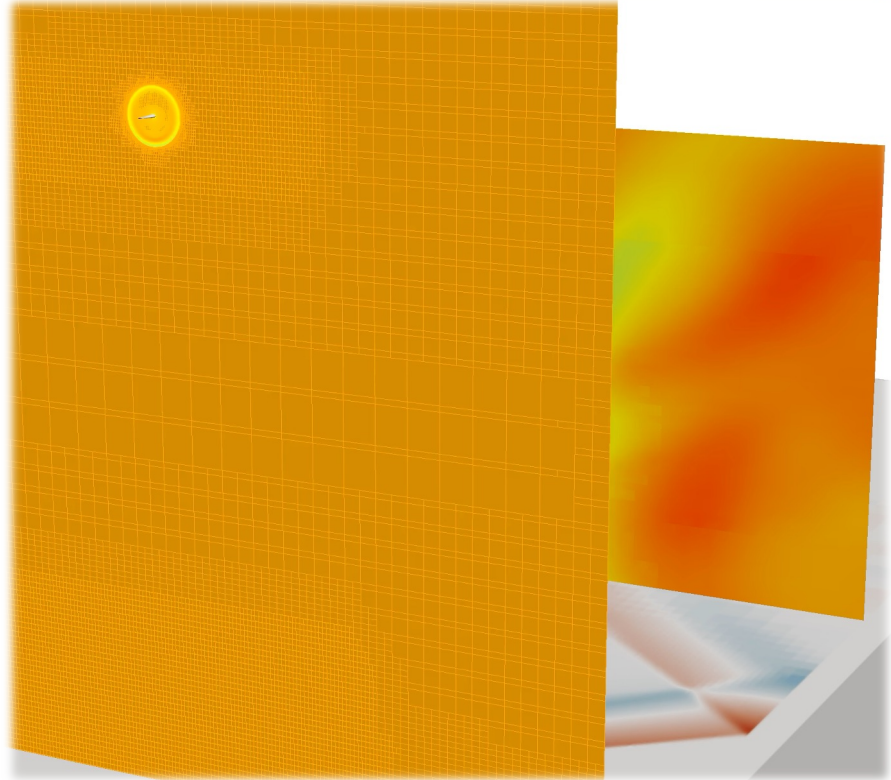
Pressure disturbance (*blue* = low, *red* = high) shown on off-body grid points

# Modeling Wind Tunnel Effects

- Simulations that incorporate wind tunnel components can be used to compute effects of tunnel hardware
- Crucial for CFD validation against experimental measurements
- Differences in X-59 predictions and measurements have been minimized



Comparison of Cart3D CFD solution to experimental Schlieren images

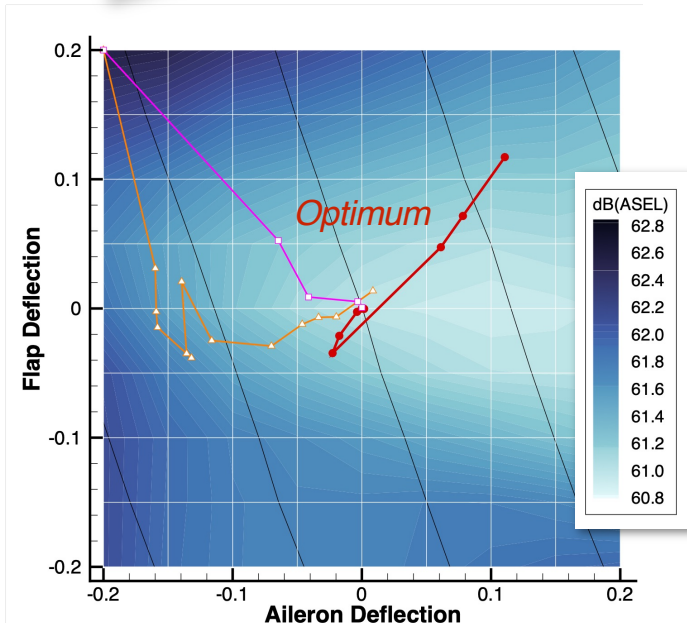
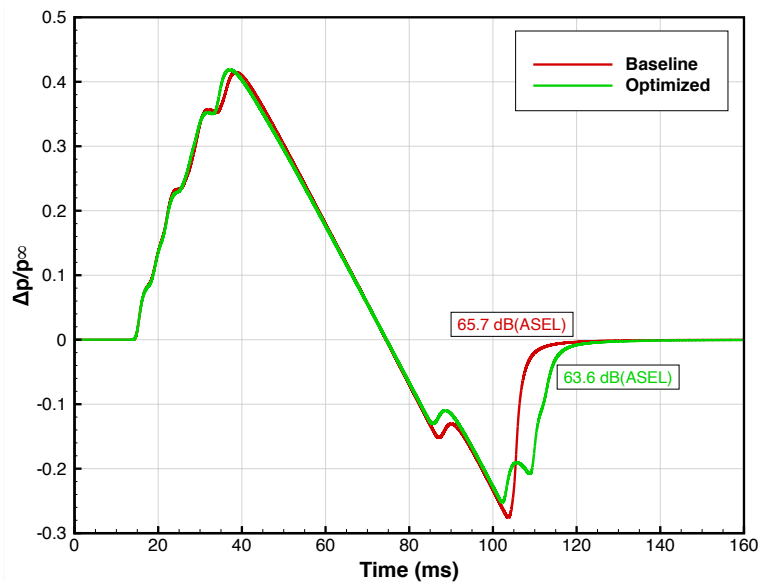
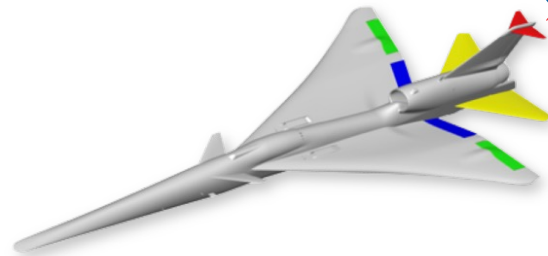


Pressure contours (*blue* = low, *red* = high) shown on geometries with Mach number (*blue* = low, *red* = high) shown on cutting plane

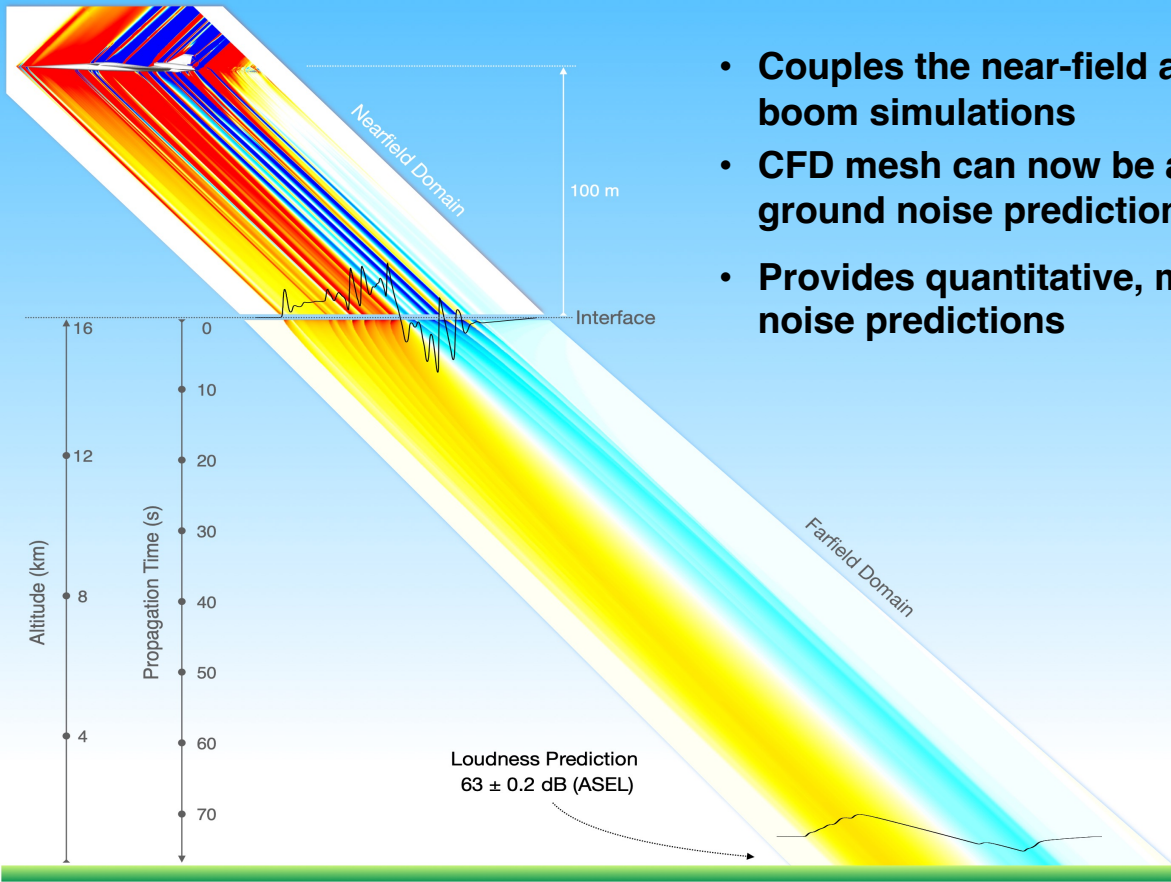
# Optimizing the Design to Minimize Ground Noise



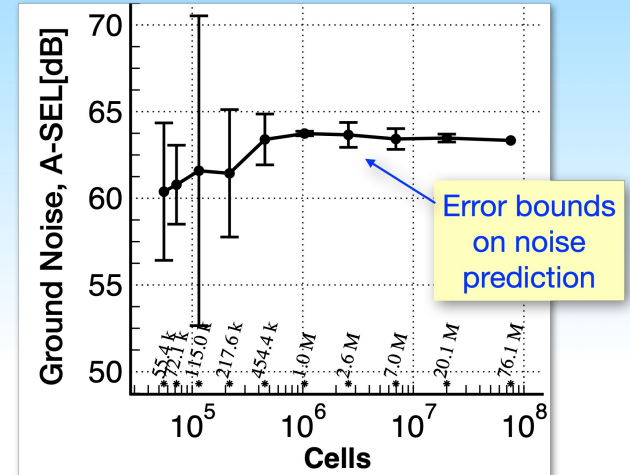
- Minimization of ground noise is performed by optimizing control surface deflections
- All optimizations satisfy lift requirement while converging to lowest loudness
- Ground loudness predictions (below) show potential to reduce noise by about 2 dB



# Controlling Error for Sonic Boom Calculations

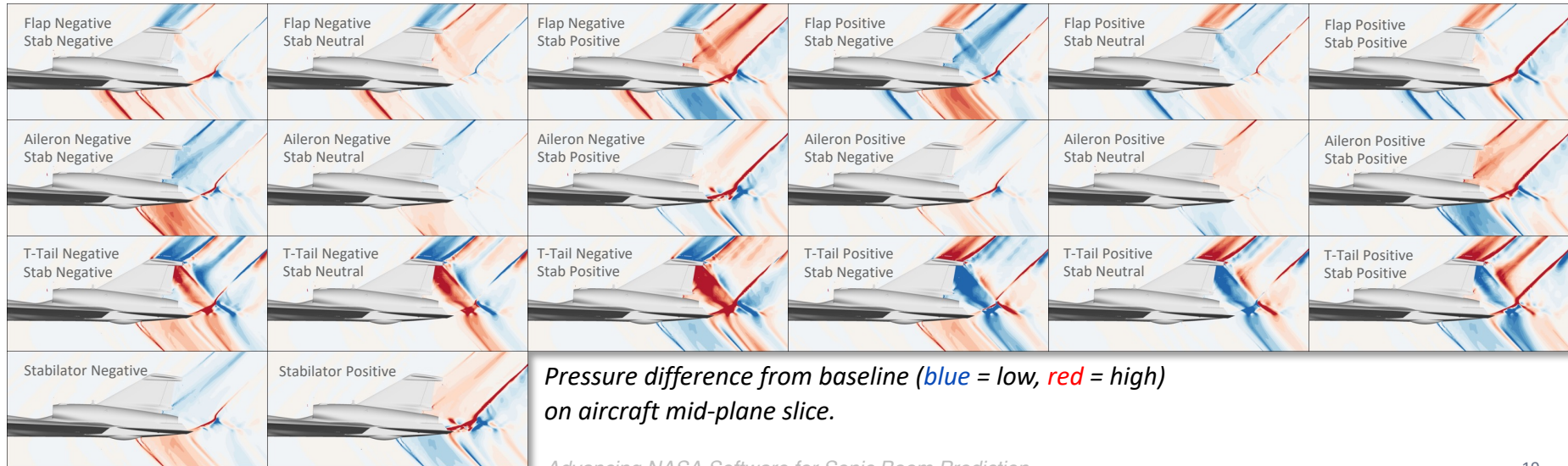


- Couples the near-field and far-field predictions used in sonic-boom simulations
- CFD mesh can now be adapted to minimize the error in the ground noise predictions
- Provides quantitative, meaningful error bounds on ground noise predictions



# How Does HPC Play a Role?

- **Development of boom databases requires thousands of CFD simulations, each requiring thousands of CPU-hours on NASA's HPC systems**
- **Database simulations make predictions across numerous flight conditions**
  - Freestream flow conditions
  - Control surface deflections



# How Does HPC Play a Role?

- **CFD simulations are the most computationally expensive aspect of supersonic boom prediction**
- **Example CFD simulation resources are summarized for the X-59, which were all run on at the NASA Advanced Supercomputing (NAS) facilities**
  - 1,500 CPUs (node types vary)
  - Eight (8) hours wall-clock time
- **Recent advancements to LAVA have ushered in substantial savings (~20X) over the last five years**
  - CFD solver refactorization (5X)
  - Space marching capability (2X)
  - Adjoint-based mesh redistribution (2X)

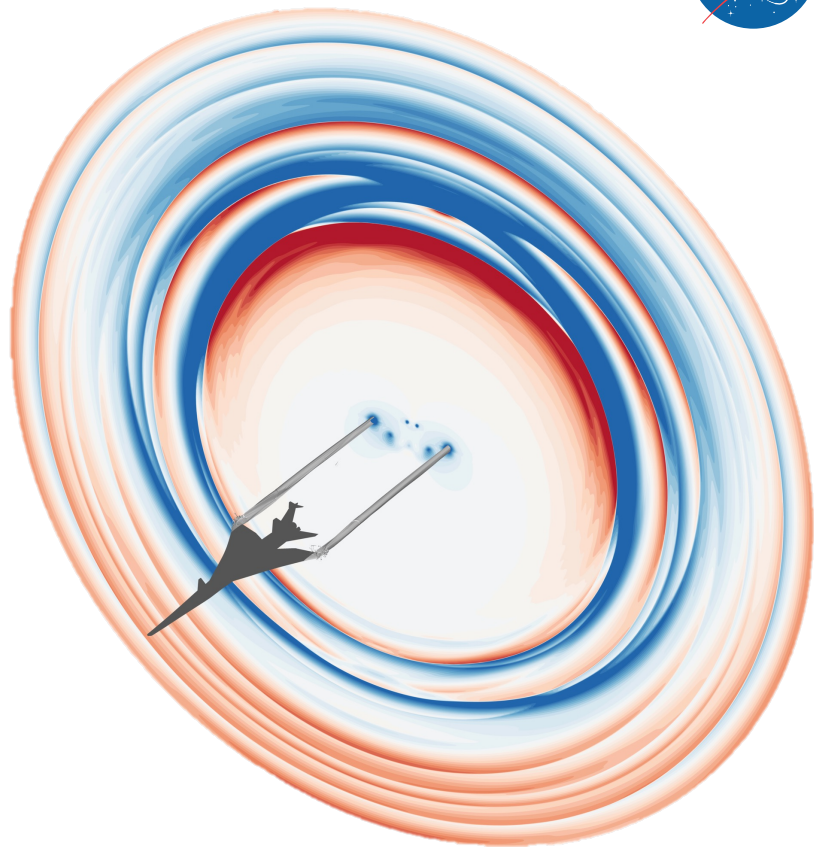


*Pleiades supercomputer at NASA Ames Research Center<sup>1</sup>*

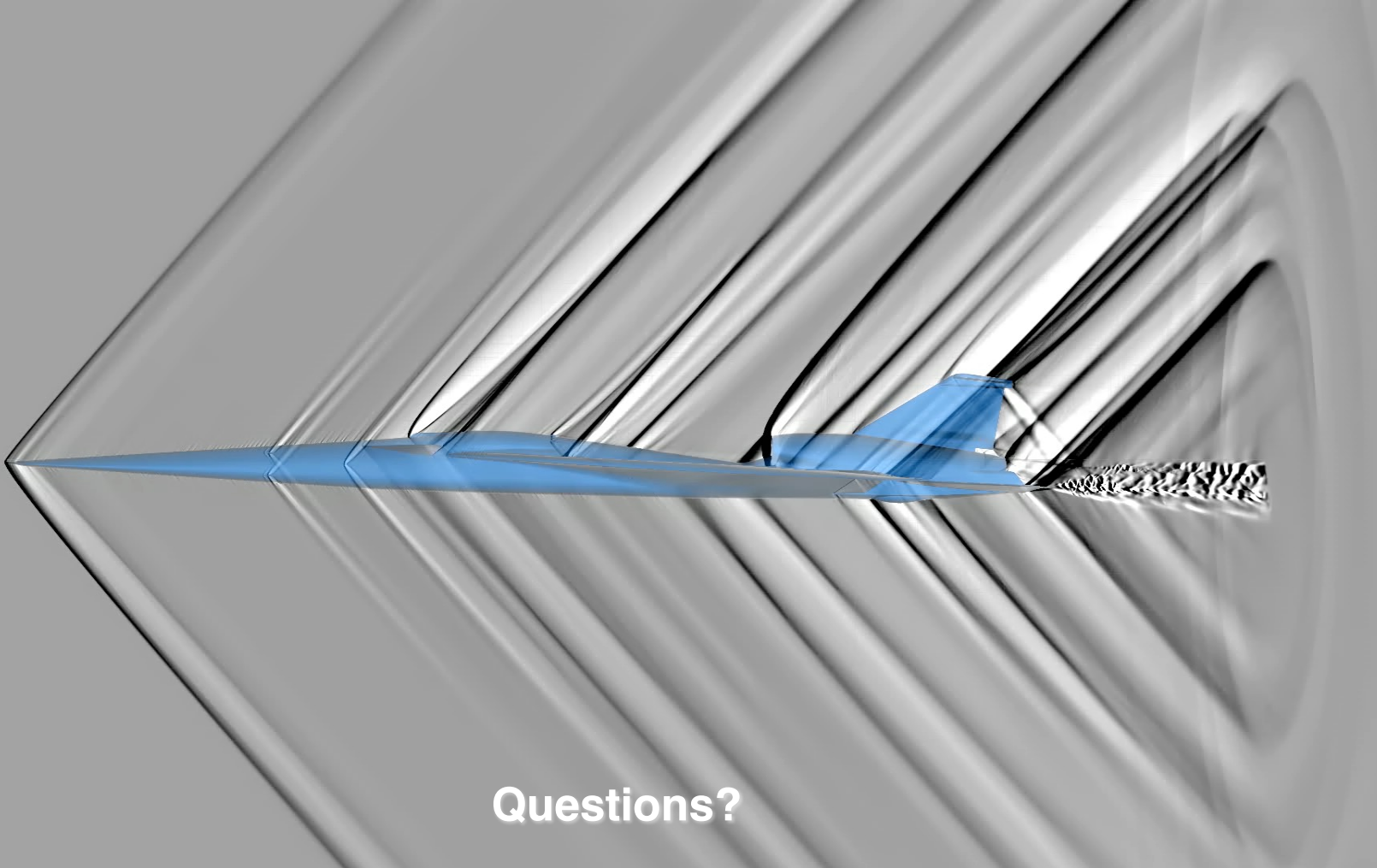
<sup>1</sup>Image source:  
<https://www.nas.nasa.gov/hecc/resources/pleiades.html>

# Acknowledgements

- This work was funded by the NASA Advanced Air Vehicles Program's Commercial Supersonic Technologies (CST) Project
- Special thanks to Scott Neuhoﬀ, Jeffrey Housman, Chase Ashby, James Jensen, Gaetan Kenway, Brandon Lowe, and other LAVA Team members for their technical contributions and valuable insight
- Computing resources provided by NASA Advanced Supercomputing (NAS) division at NASA Ames Research Center



<sup>1</sup>Image source:  
<https://www.nasa.gov/hecc/resources/pleiades.html>



**Questions?**