Lattice Boltzmann for Airframe Noise Predictions

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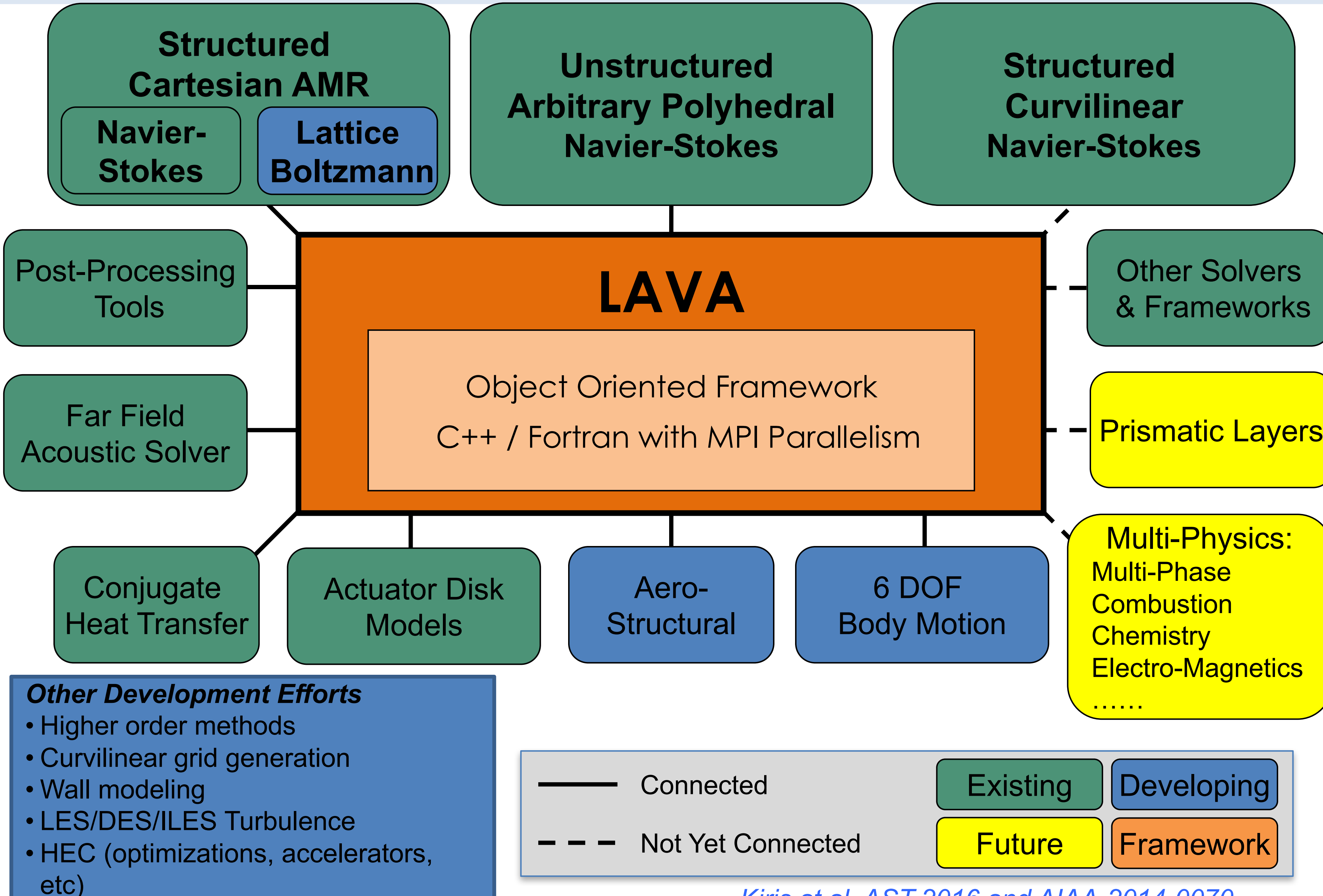
Objective

✓ **Increase predictive use of High-Fidelity Computational Aero-Acoustics (CAA) capabilities for NASA's next generation aviation concepts.**
  - CFD has been utilized substantially in analysis and design for steady-state problems (RANS).
  - Computational resources are extremely challenged for high-fidelity unsteady problems (e.g. unsteady loads, buffet boundary, jet and installation noise, fan noise, active flow control, airframe noise, etc)

✓ **Need novel techniques for reducing the computational resources consumed by current high-fidelity CAA**
  - Need routine acoustic analysis of aircraft components at full-scale Reynolds number from first principles
  - **Need an order of magnitude reduction in wall time to solution!**

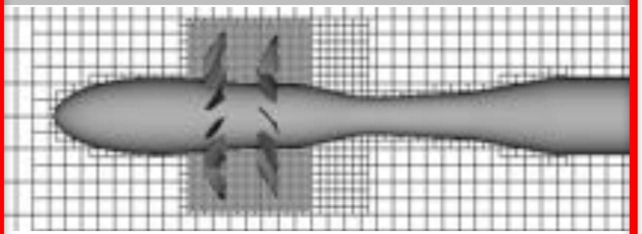
LAVA Framework



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

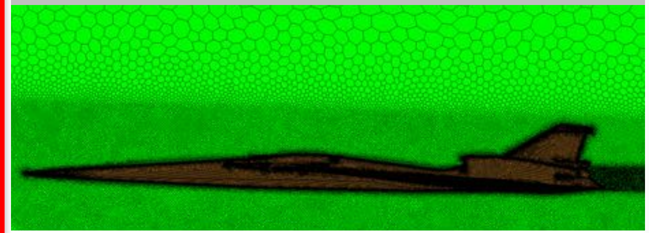
Computational Grid Paradigms

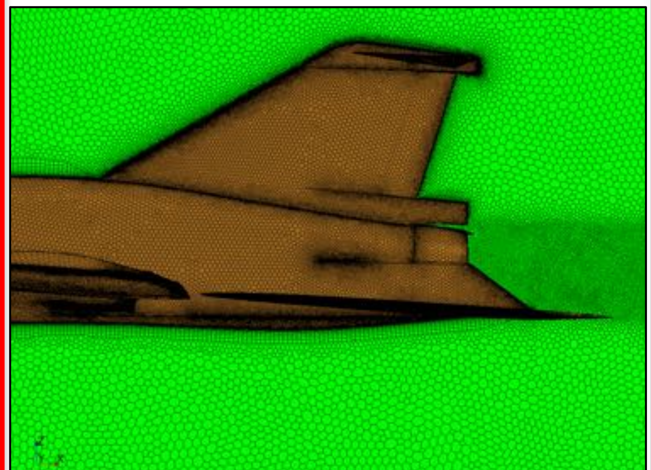
Structured Cartesian AMR



- 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

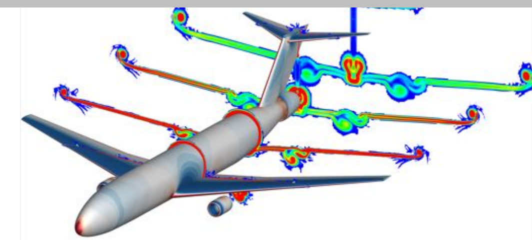
Unstructured Arbitrary Polyhedral

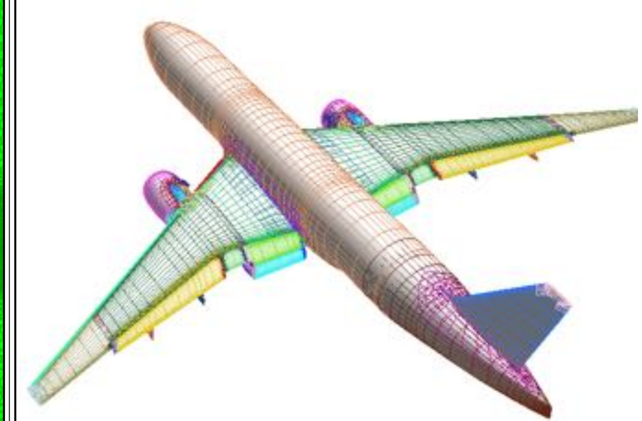




- Partially automated grid generation
- Body fitted grids
- Grid quality can be challenging
- High computational cost
- Higher order methods yet to fully mature

Structured Curvilinear



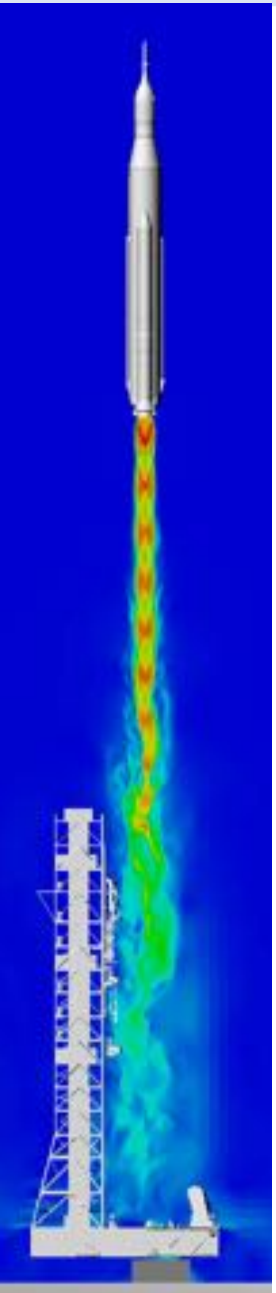


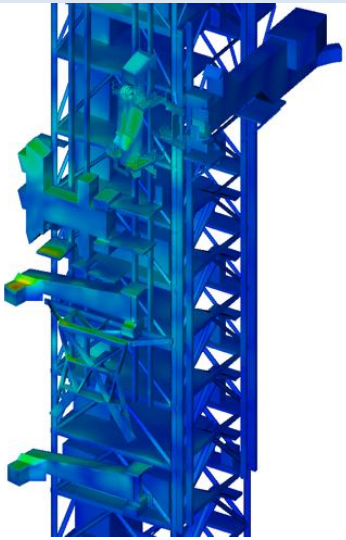
- High quality body fitted grids
- Low computational cost
- Reliable higher order methods
- Grid generation largely manual and time consuming

LAVA Cartesian Navier-Stokes Methods

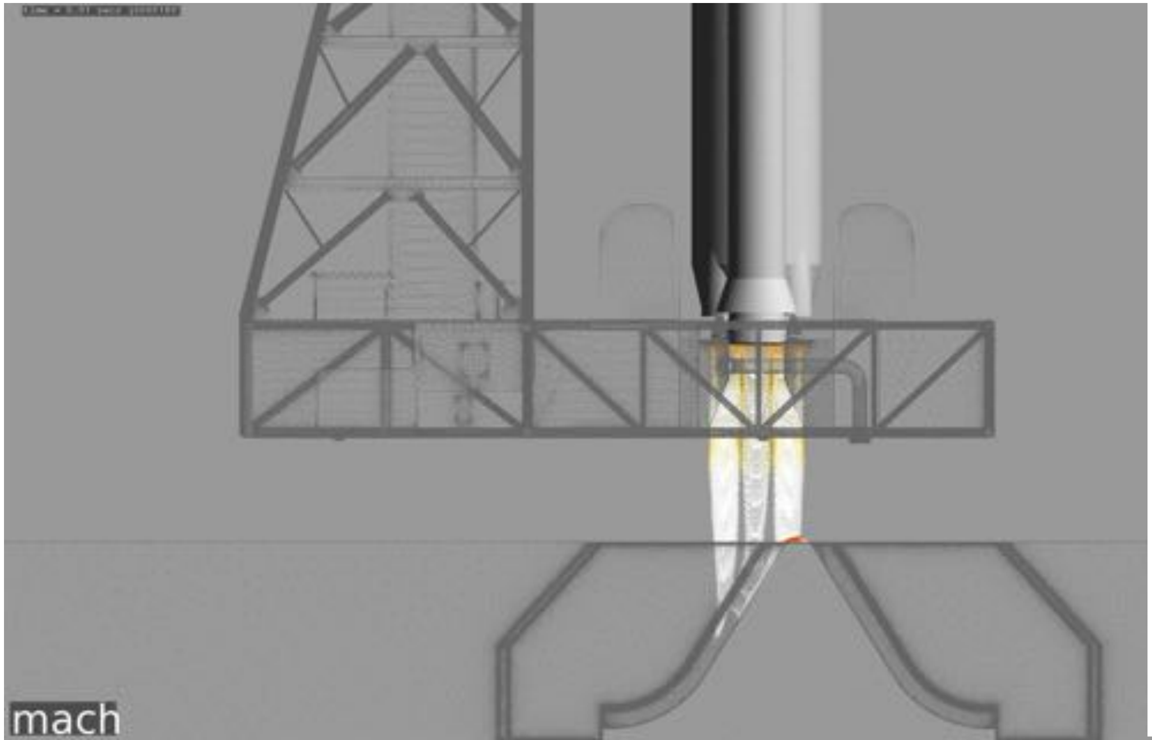
- 5^{th} and 6^{th} order WENO spatial discretization
- Higher-order immersed boundary method
- 4^{th} order explicit Runge-Kutta time stepping
- Structured Adaptive Mesh Refinement: Locally tracking gradients in flow field with finer mesh (shocks, shear layers, etc). Using Chombo for AMR data structures.
- The LAVA team has had many successful uses of this methodology for mission critical NASA applications.
- This approach has been a work-horse for quick turnaround projects with complex geometry and unsteady flow-fields.

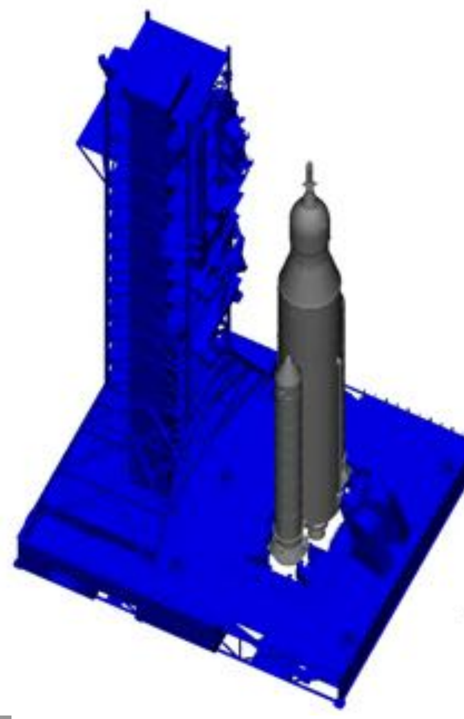
Recent LAVA Cartesian Navier-Stokes Successes: Launch Environment at NASA's Kennedy Space Center



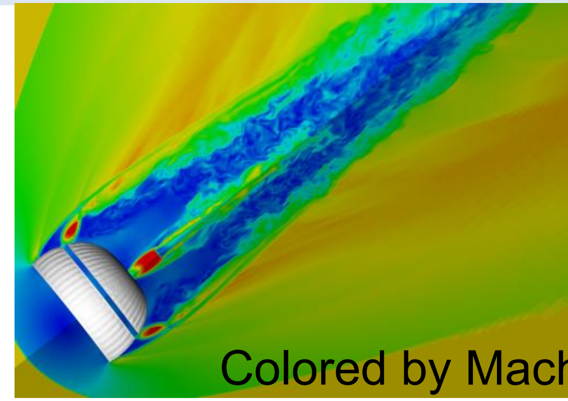


- Pressure and thermal analysis of plume impingement on main flame deflector
- Containment analysis of plume in flame trench
- Numerous vehicles were analyzed on the pad, including SLS and commercial vehicles
- Drift analysis with plume impingement:
  - unsteady CFD with fixed vehicle
  - time-averaged SLS plume swept past pad and tower following 4000 trajectories





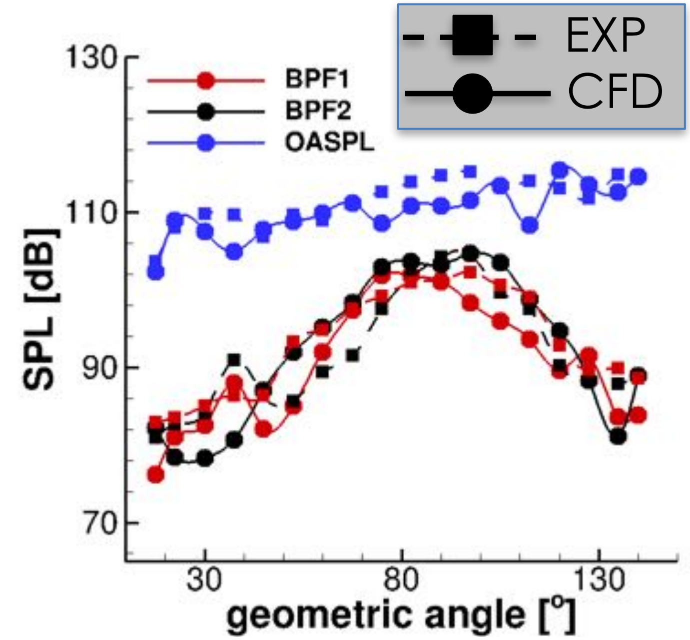
Recent LAVA Cartesian Navier-Stokes Successes: Low Density Supersonic Decelerator: Parachute Simulations



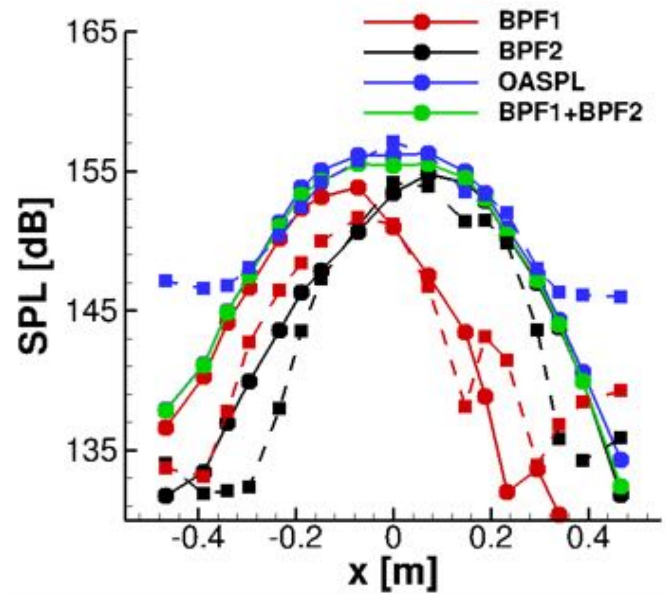
Passive particle visualization: colored by Mach number

Recent LAVA Cartesian Navier-Stokes Successes: Contra-Rotating Open Rotor

Passive particle visualizations: colored by seed location



Low Speed

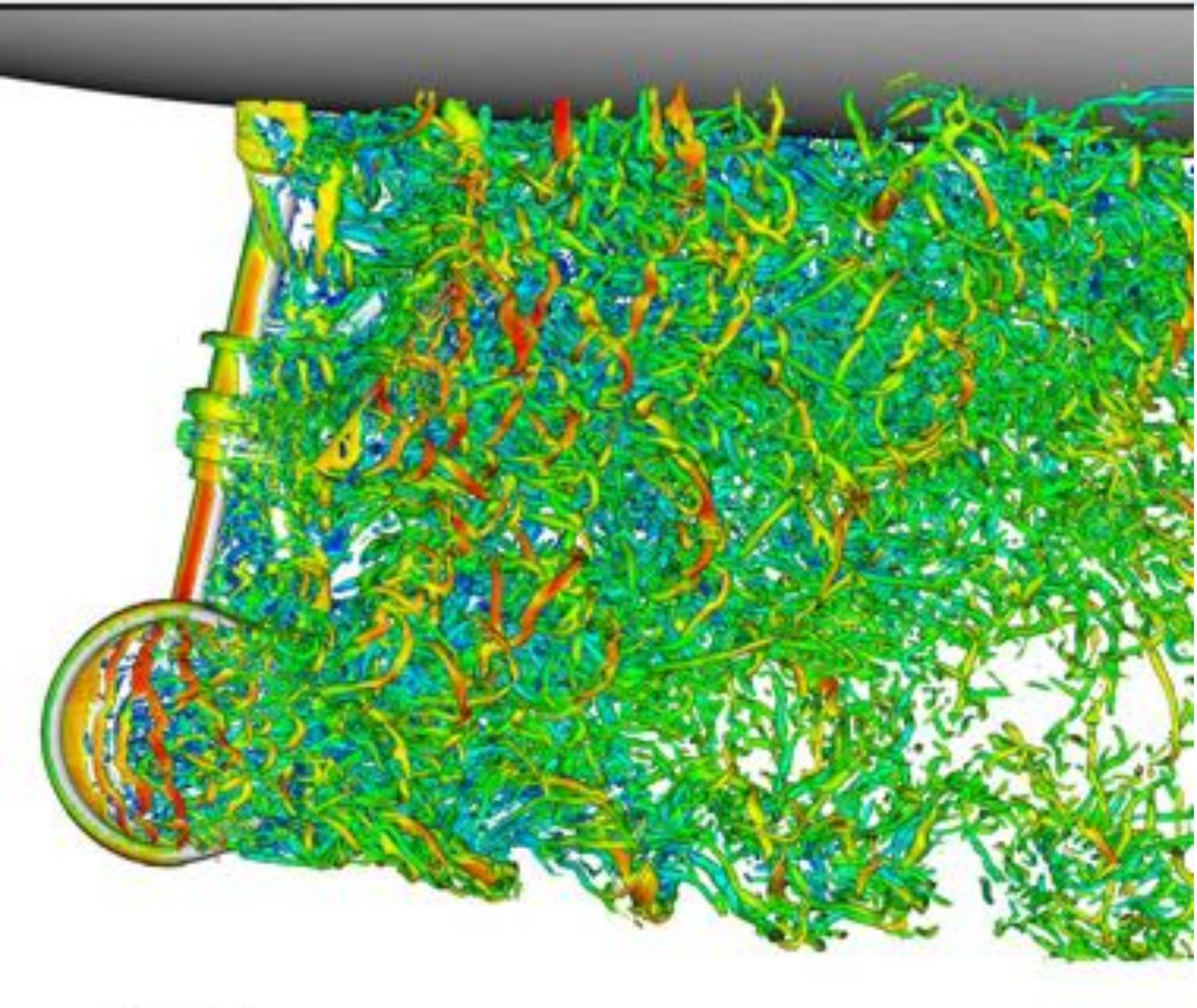


High Speed

Recent LAVA Cartesian Navier-Stokes Successes: Launch Abort System for NASA's Orion MPCV

Simulation of recent
QM-1 LAS experiment

Recent LAVA Cartesian Navier-Stokes Successes: Landing Gear for AIAA BANCIII Workshop



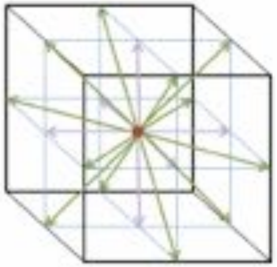
Challenges in Computational Aero-Acoustics

✓ 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)
  - Parachute: 200 million cells, 3 days of wall time (2000 cores)
  - Contra-Rotating Open Rotor: 360 million cells, 14 days (1400 cores)
  - Launch Abort System: 400 million cells, 28 days of wall time (2000 cores)
  - Landing Gear: 298 million cells, 20 days of wall time (3000 cores)
- LAVA Cartesian infrastructure has been re-factored into Navier-Stokes (NS) and Lattice Boltzman Method (LBM).
  - 10-50 times speed-up can be achieved with LBM vs NS-WENO.
  - Existing LAVA Cartesian data structures and algorithms are utilized to reduce implementation effort.

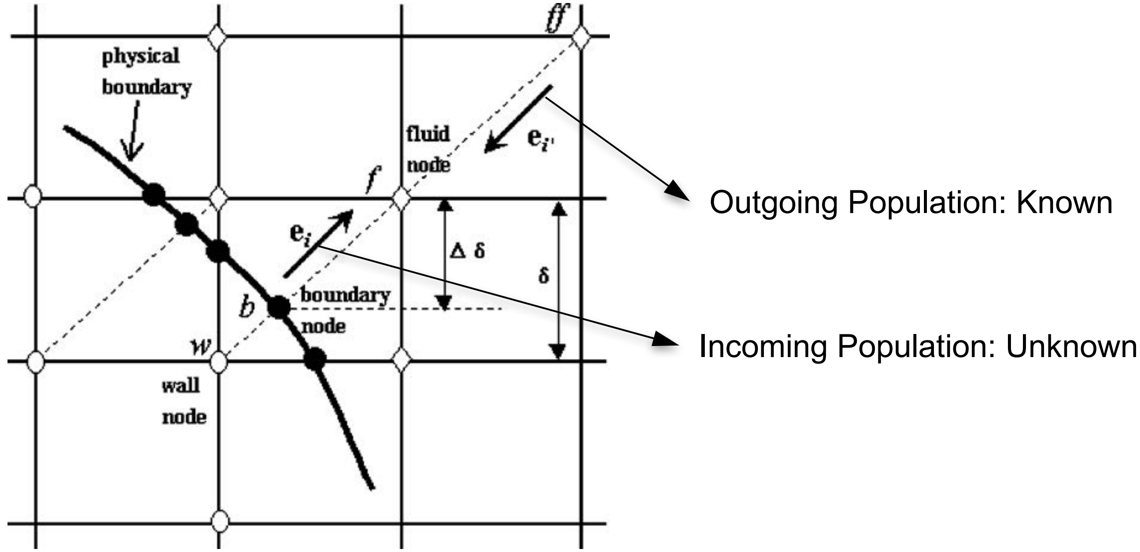
LAVA LBM: Governing Equations

$$\underbrace{f_i(\vec{x} + c\vec{e}_i \Delta t, t + \Delta t) - f_i(\vec{x}, t)}_{\text{Streaming}} = \underbrace{\frac{1}{\tau}(f_i(\vec{x}, t) - f_i^{eq}(\vec{x}, t))}_{\text{Collision}}$$



- **Physics:**
  - Governs space time evolution of Density Distribution Functions
  - Equilibrium distribution functions are truncated Maxwell-Boltzmann distributions
  - Relaxation time related to kinematic viscosity
  - Pressure related to density through the isothermal ideal gas law
  - Lattice Boltzmann Equations (LBE) recover the Navier-Stokes equations in the low Mach number limit
- **Numerics:**
  - Extremely efficient ‘collide at nodes and stream along links’ discrete analog to the Boltzmann equation
  - Particles bound to a regularly spaced lattice collide at nodes relaxing towards the local equilibrium (RHS)
  - Post-collision distribution functions hop on to neighboring nodes along the lattice links (LHS) – Exact, dissipation-free advection from simple ‘copy’ operation
  - Macroscopic quantities such as density and momentum are moments of the density distribution functions in the discrete velocity space

LAVA LBM: Embedded Geometry

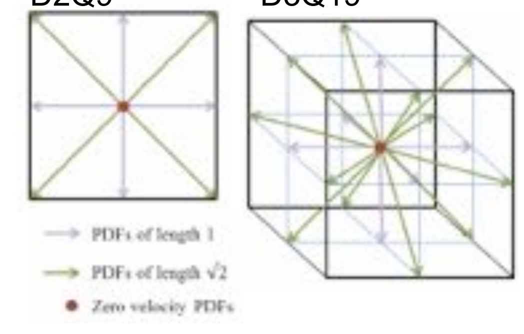


- Boundary conditions in LBM are simple rules that relate ‘incoming’ populations to ‘outgoing’ populations for lattice links intercepted by an embedded surface
- **Standard Bounce Back** (SBB): ‘Bounce-back’ rule realizes the no-slip boundary condition, but approximates the curved geometry by a series of small steps.
- **Linear Bounce Back** (LBB): Interpolated no-slip bounce-back rules (cf. Bouzidi et al. (POF, 01)) capture the curvature in geometry more accurately. Improved prediction of surface pressure fluctuations, critical for accurate acoustic predictions.
- **Halfway Bounce Back** (HBB) rule of A. C. Ladd (JFM, 94) generalized to be second-order accurate for arbitrary geometry (stationary and moving) and adapted for wall models using a generalized slip algorithm for realizing the appropriate momentum exchange.

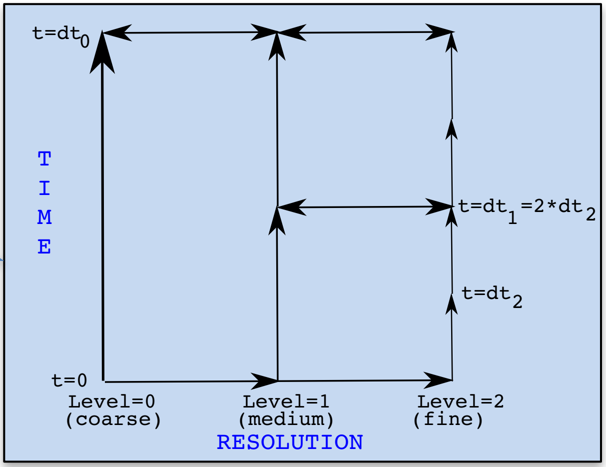
LAVA LBM: Progress

IMPLEMENTATION TO DATE:

- **Lattices**: including D2Q9, D3Q15, D3Q19, D3Q27, D3Q39 …
- **Collision Models**:
  - Bhatnagar-Gross-Krook (BGK)
  - Multi-Relaxation Time (MRT)
  - Entropic and positivity preserving variants of BGK
  - Entropic Multi-Relaxation Time (EMRT)
  - Regularized BGK
- **LES Model**: Smagorinsky sub-grid-scale
- **Wall Models:** Tamm-Mott-Smith boundary condition, filter-based slip wall model, or traditional equilibrium wall stress model
- **Parallelization**:
  - Structured adaptive mesh refinement (SAMR) based LBM requires parallel ghost cell exchanges:
    - Fine-fine for communication within levels
    - Coarse-fine for communication across levels
    - Efficient parallel I/O
- **Multi-Resolution with Recursive Sub-Cycling**
- **Boundary Conditions**:
  - No-slip and slip bounce back walls
  - Accurate and robust curved walls
  - Inflow/outflow, and periodic



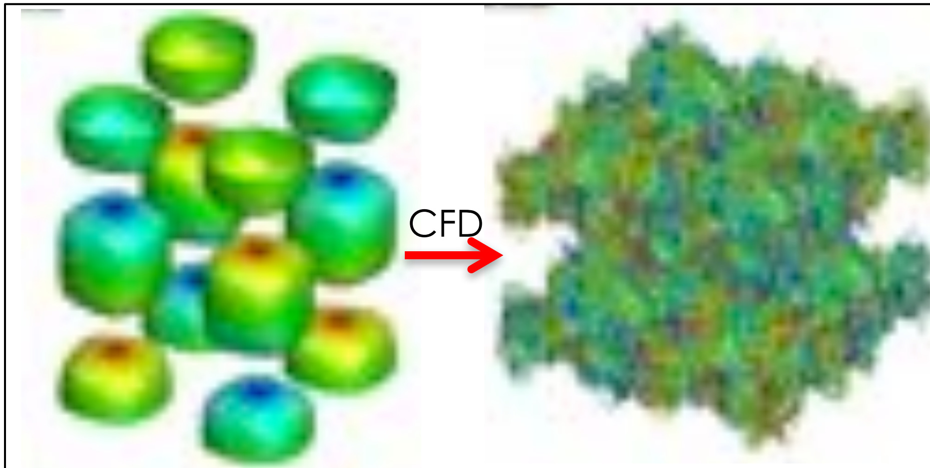
D2Q9 = 2D w/ 9-velocities…



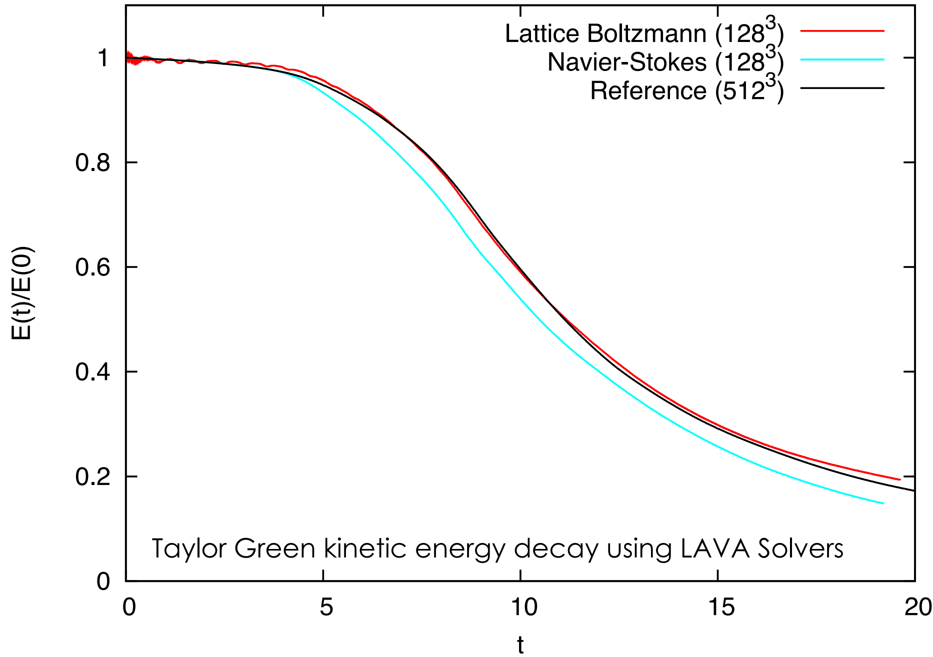
LAVA LBM: Verification and Validation

TURBULENT TAYLOR GREEN VORTEX BREAKDOWN TEST CASE:

- **Motivation**:
  - Simple low speed workshop case for testing high-order solvers
  - Illustrates ability of solver to simulate turbulent energy cascade
  - Periodic boundary conditions
- **Setup**:
  - Analytic initial condition
    - Mach = 0.1
    - Reynolds Number = 1600
  - Triply periodic flow in a box
- **Comparisons:**
  - LAVA's Lattice Boltzmann (LB) solver captures the turbulent kinetic energy cascade from large scales to small scales extremely well.
  - Performance compared to LAVA's Cartesian grid Navier-Stokes WENO solver showed a factor of 50 speedup.



Taylor Green vorticity breakdown. Image credit: 3rd International Workshop on High-Order CFD Methods (Beck et al)



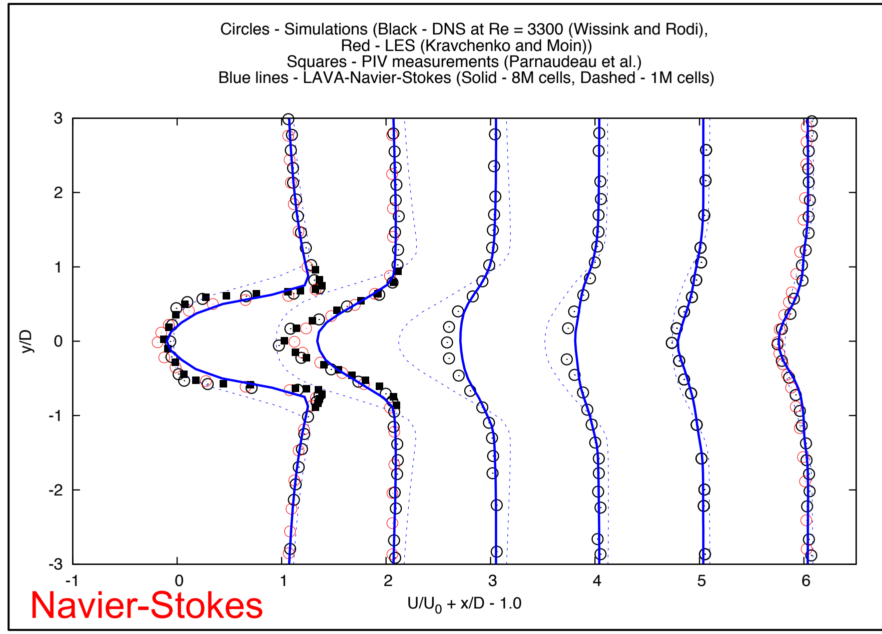
Taylor Green kinetic energy decay using LAVA Solvers

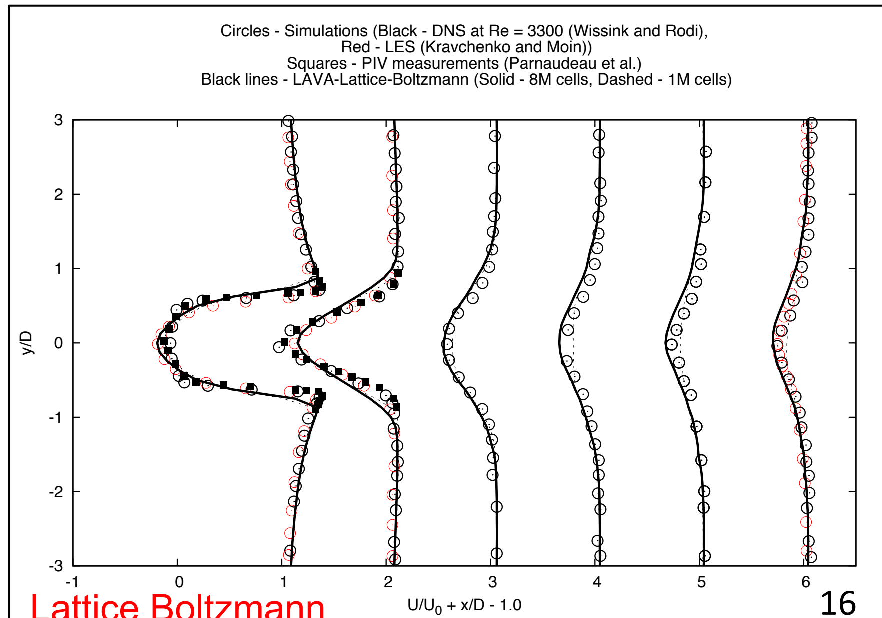
LAVA LBM: Verification and Validation

LES OF FLOW PAST A CYLINDER

- Well documented prototypical turbulent separated flow
- Detailed comparisons made with measurements and benchmark simulations

- **Setup:** Reynolds number = 3900
- **Comparisons:**
  - LBM at 1M and 8M compares well with DNS @ 400M (M = million points)
  - 20x speedup even with embedded geometry:
  - Excellent comparison with benchmark datasets (PIV, LES, DNS). DNS reference used Re=3300.
  - More accurate than high-order upwind biased NS schemes for identical resolution

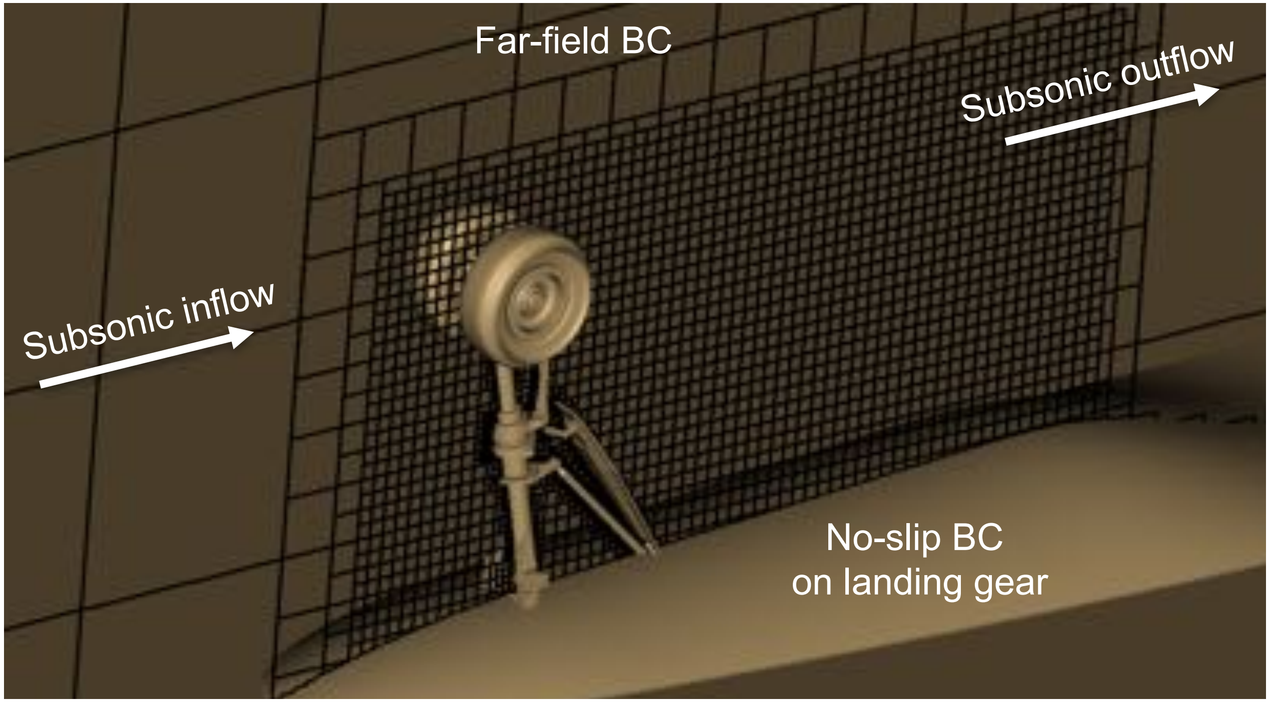




Lattice Boltzmann (passive particles for visualization)

Cavity-Closed Nose Landing Gear

Grid Topology and Computational Setup



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

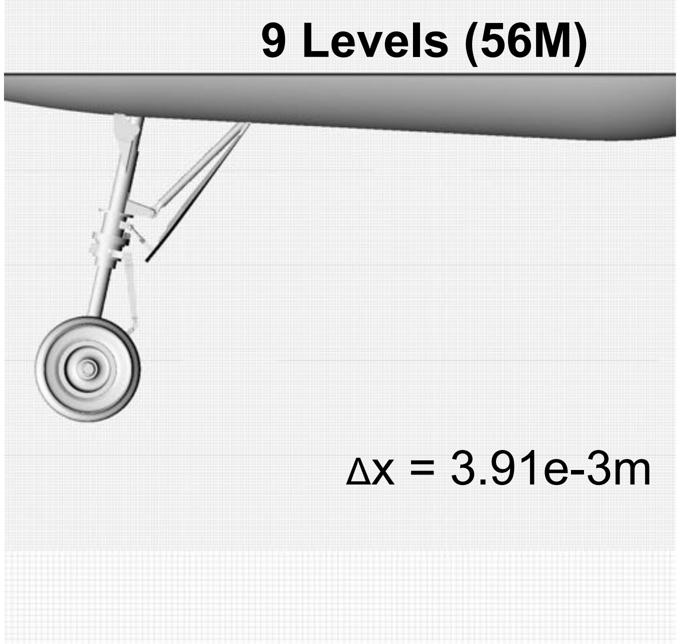
LAVA Cartesian options:

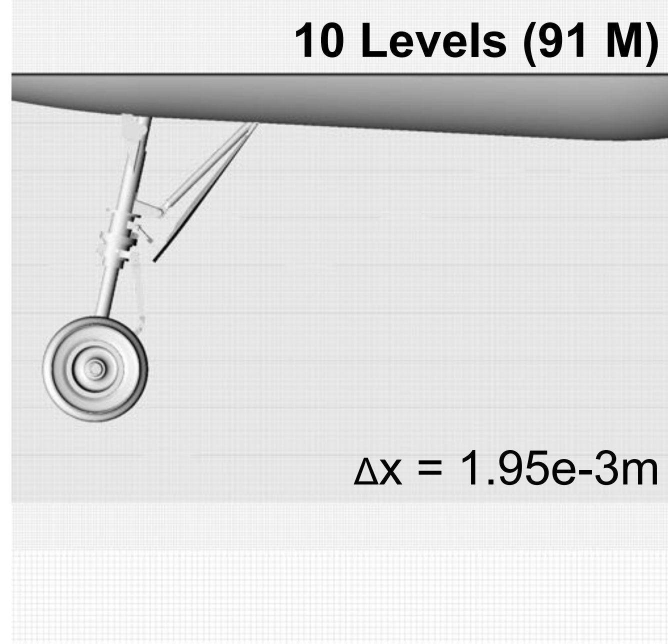
- LBM uses EMRT with D3Q27
- NS uses WENO5 or WENO6 (as noted)

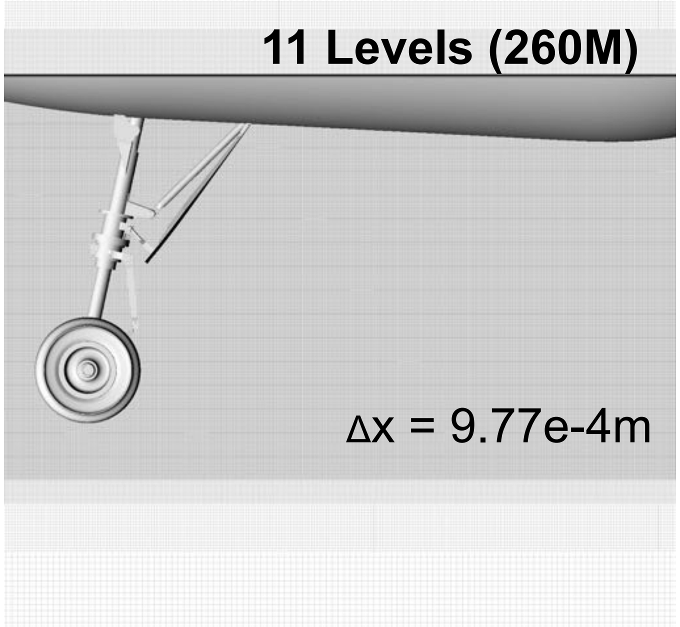
Setup follows the partially-dressed, cavity-closed nose landing gear (PDCC-NLG) noise problem from AIAA's Benchmark problems for Airframe Noise Computations (BANC) series of workshops. (Problem 4. Nose landing gear)

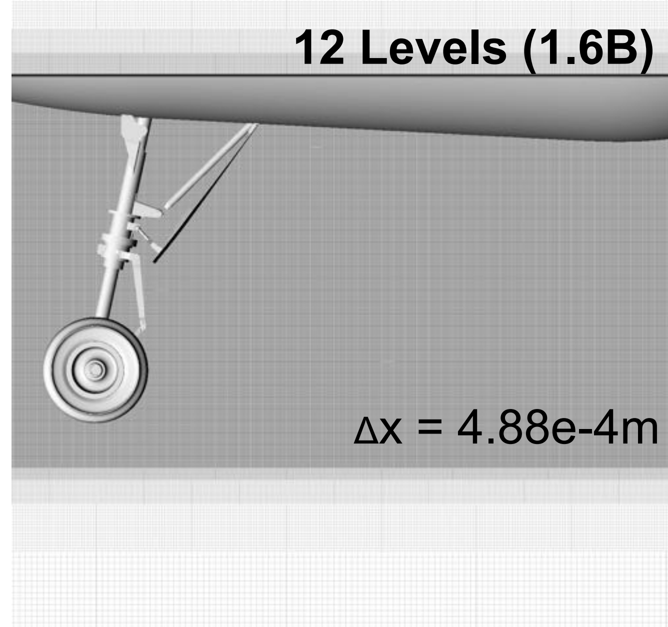
https://info.aiaa.org/tac/ASG/FDTC/DG/BECAN_files_/BANCIII.htm

Cartesian Grid Resolution

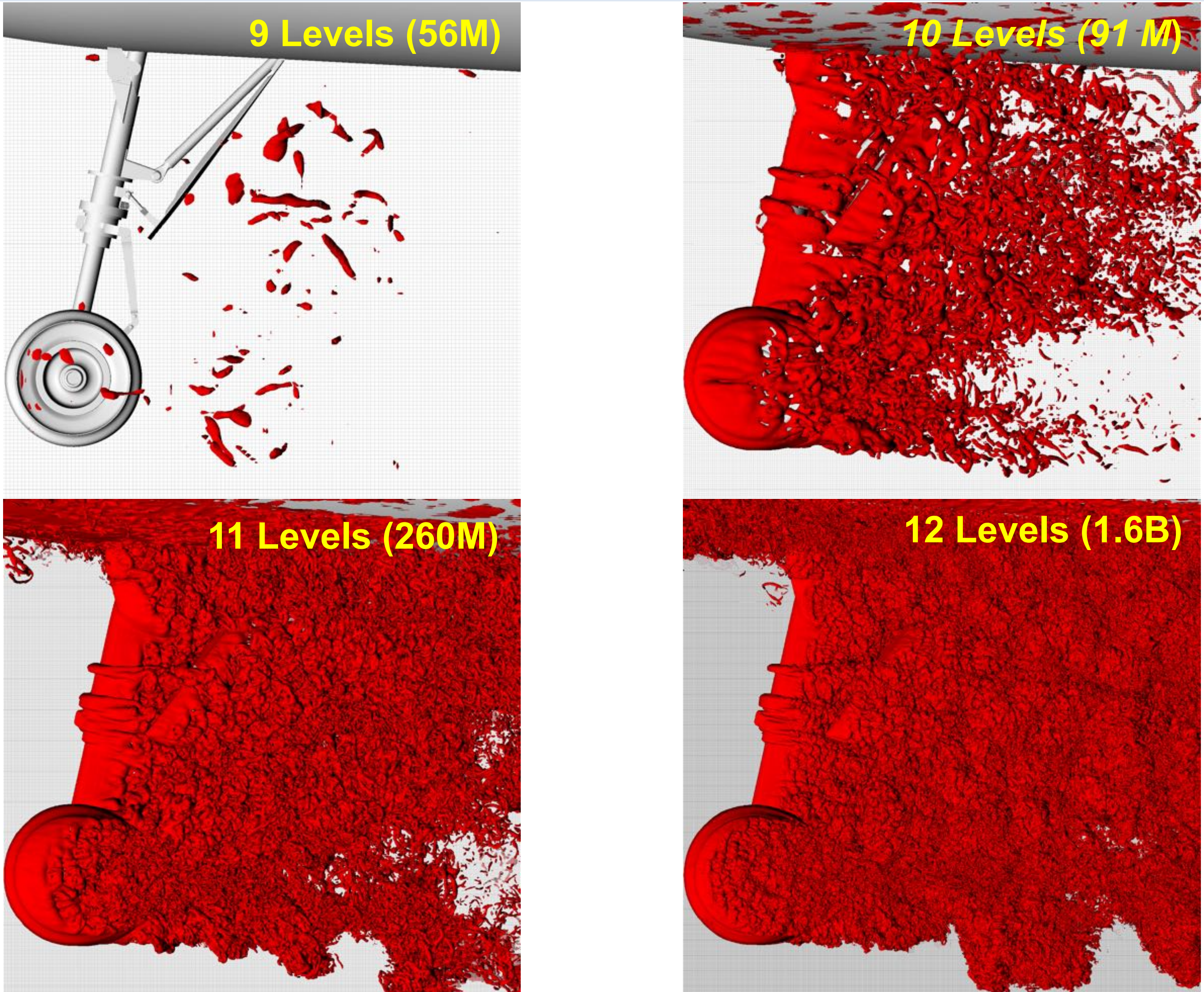




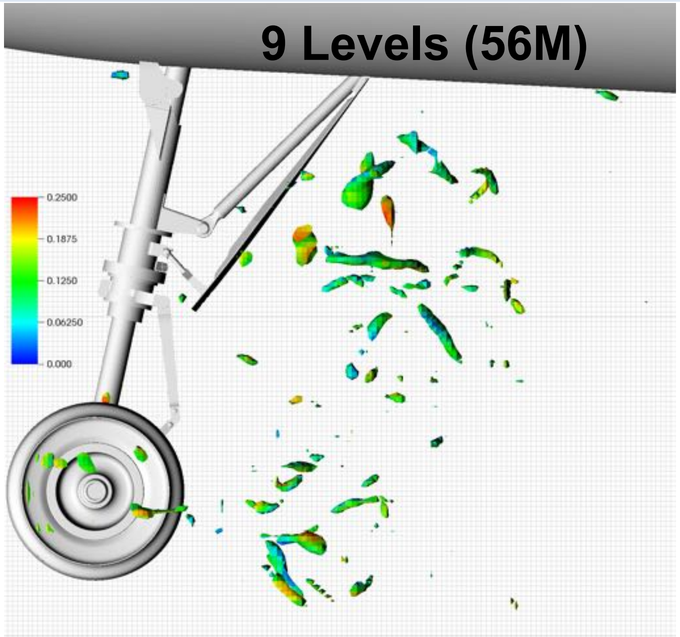


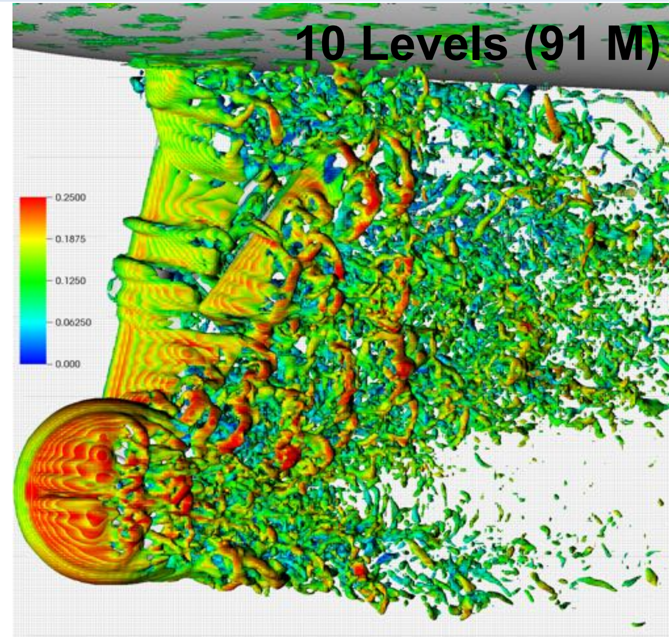


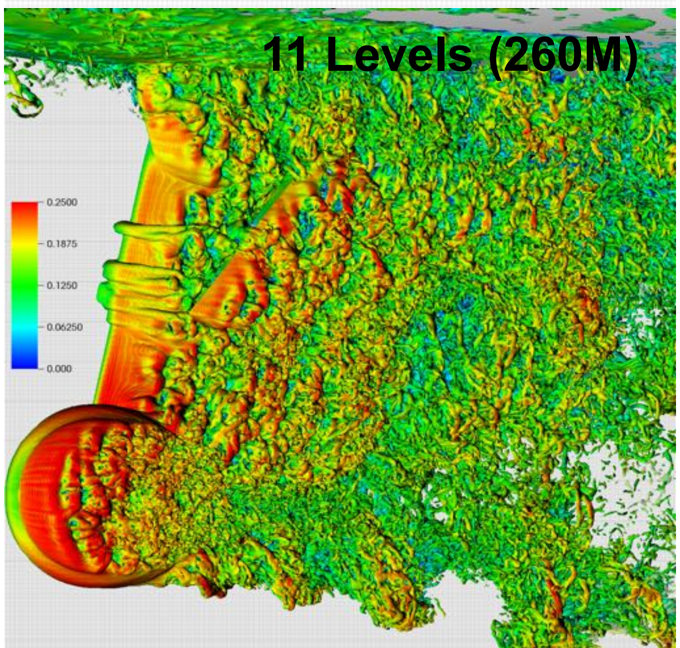
Grid Sensitivity: Vorticity @ 10000 [1/s]

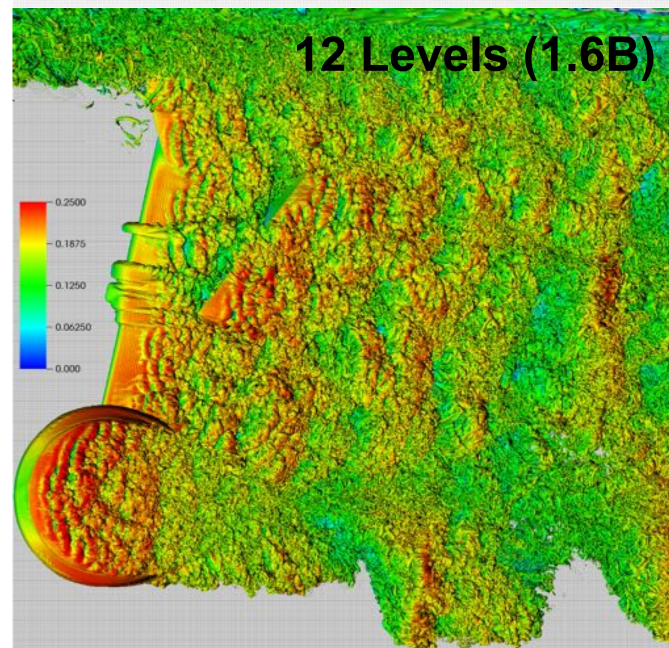


Grid Sensitivity: Vorticity Colored by Mach

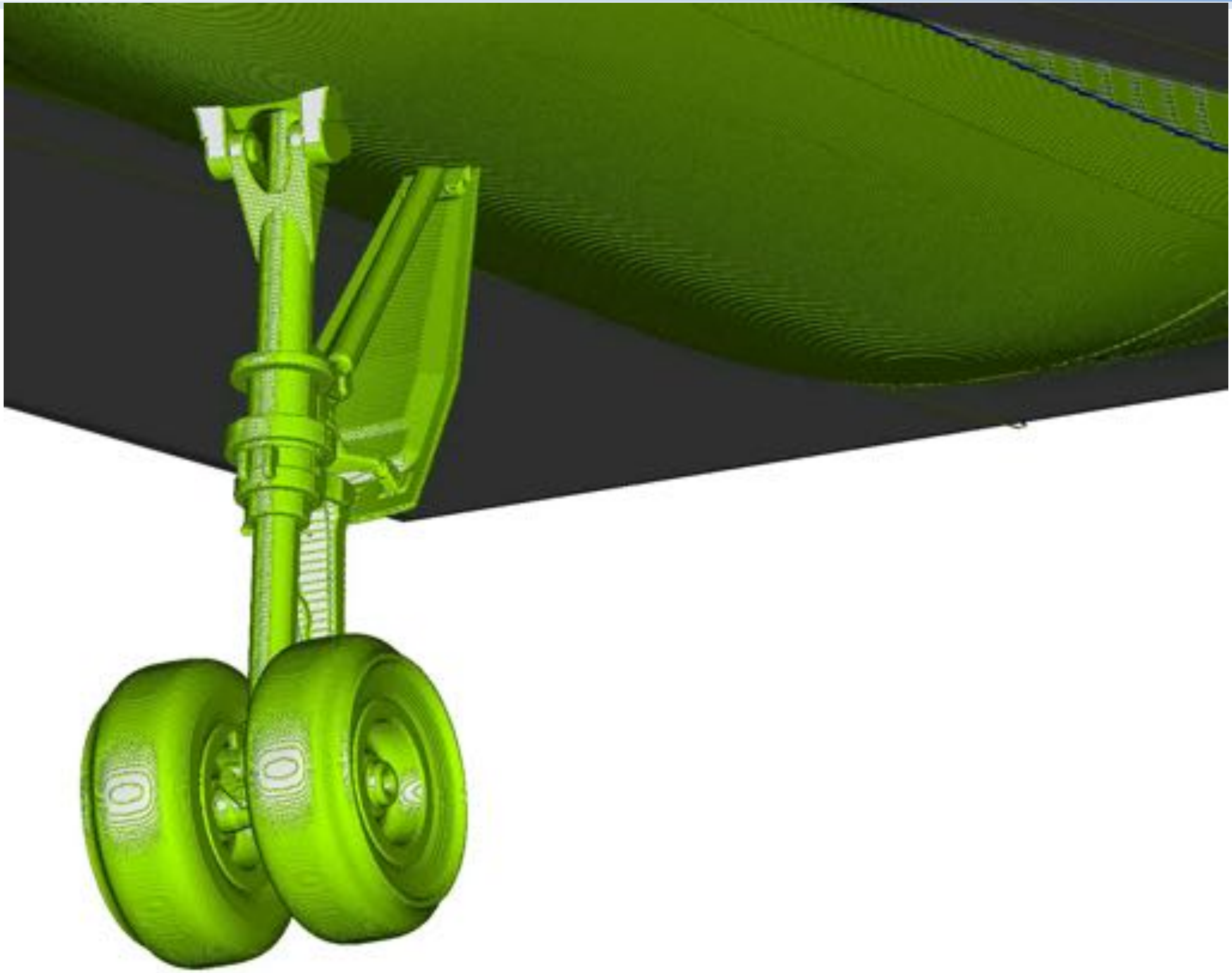








Vorticity Colored by Mach Number



LBM @ 1.6 billion: expense = 7.9 normalized wall time units (relative to 260M calc)

Velocity Magnitude (Center-plane)

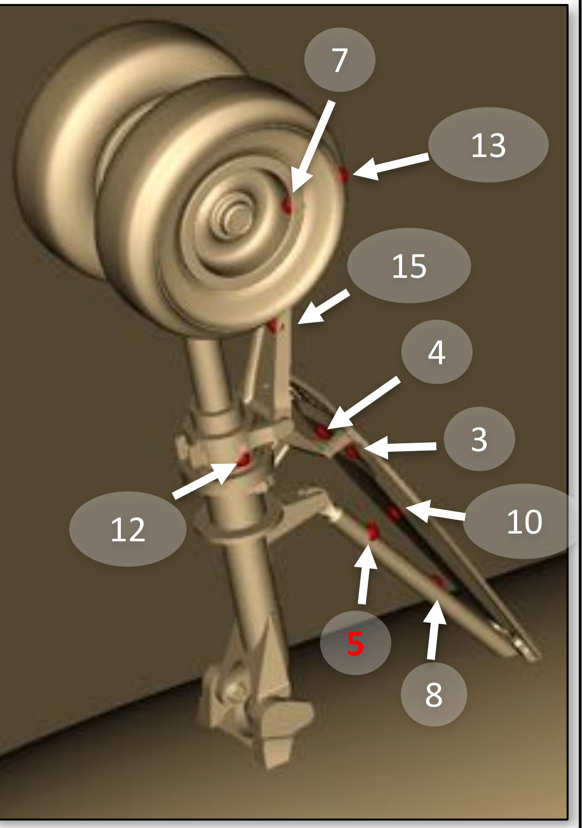
LBM @ 1.6 billion: expense = 7.9 normalized wall time units (relative to 260M calc)

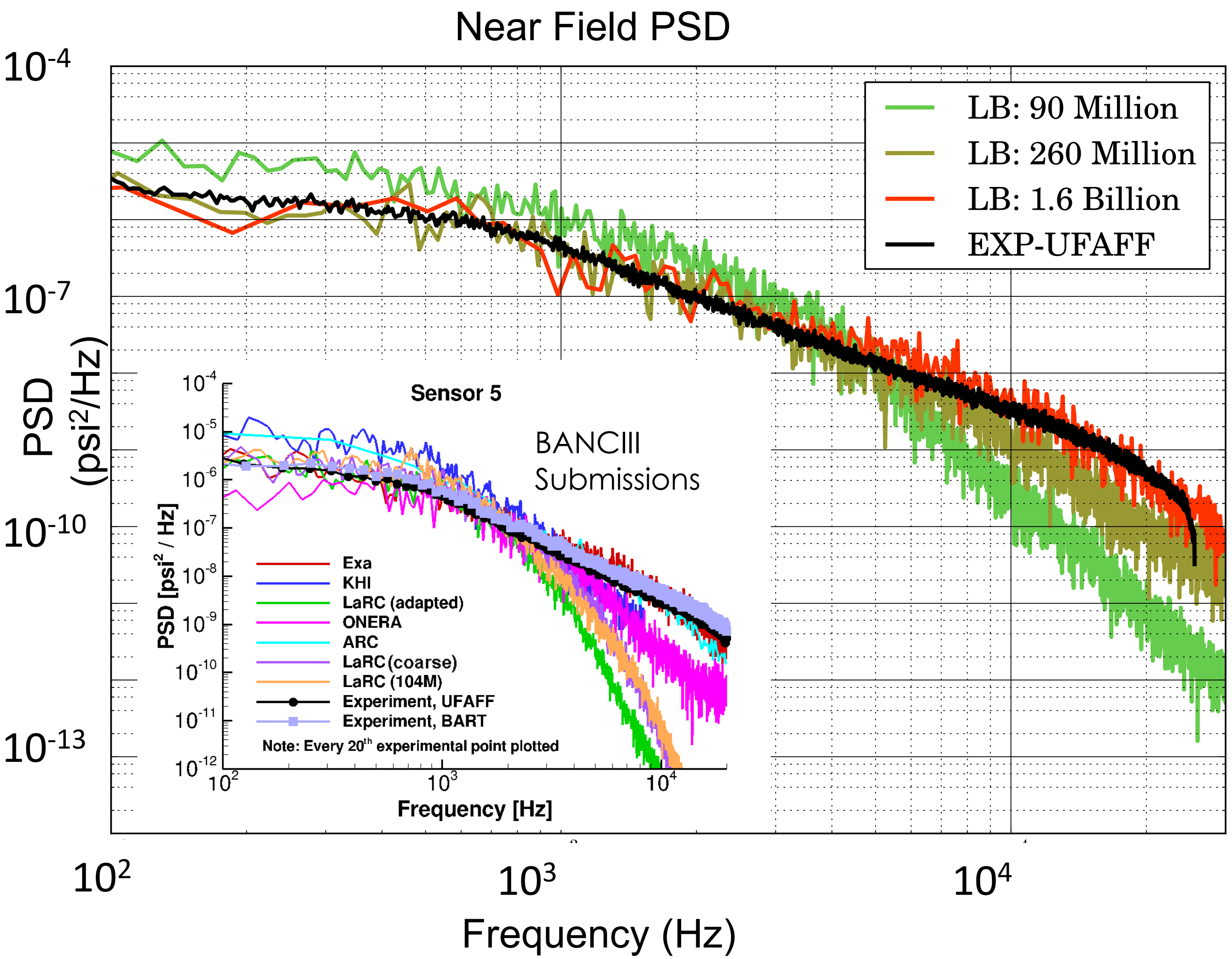
Passive Particle Colored by Mach

LBM @ 1.6 billion

Grid Sensitivity - PSD

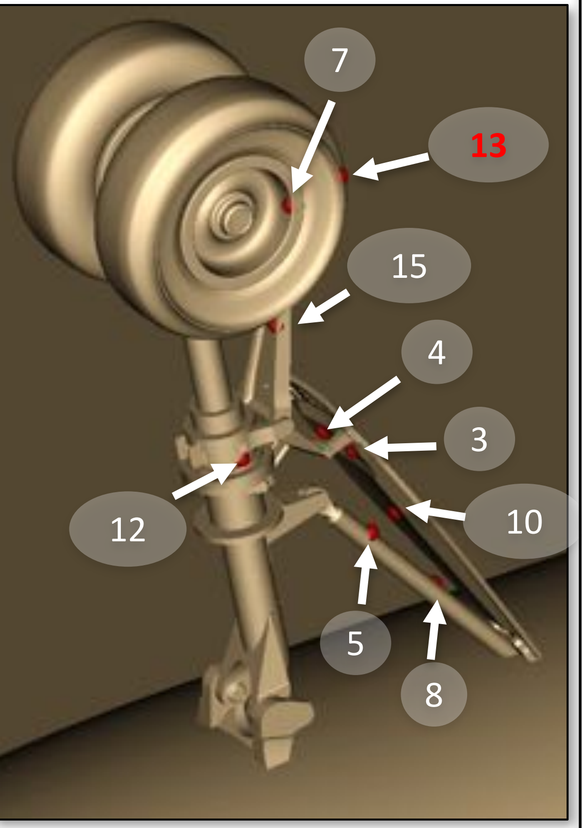
Channel 5: Upper Drag Link

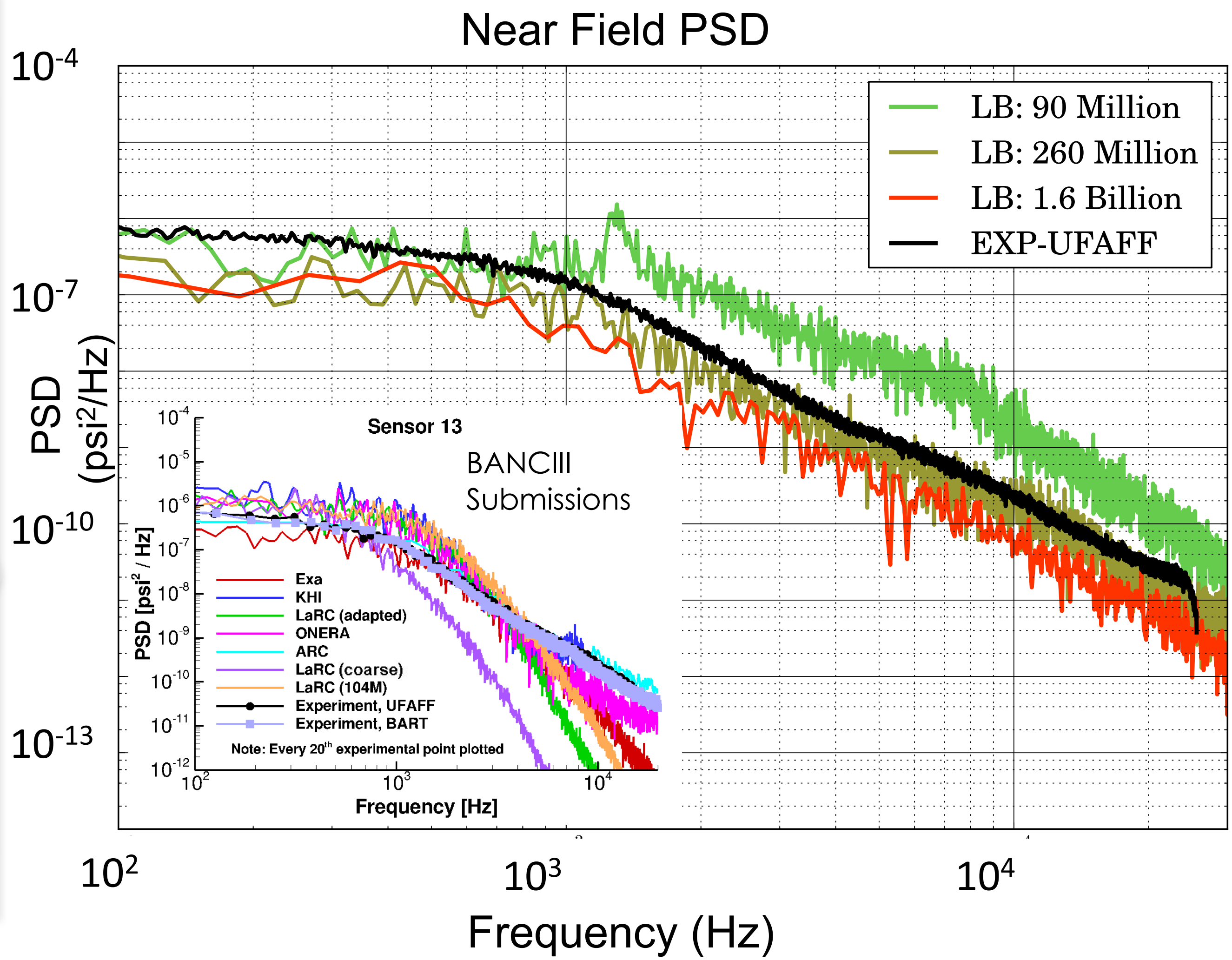




Grid Sensitivity - PSD

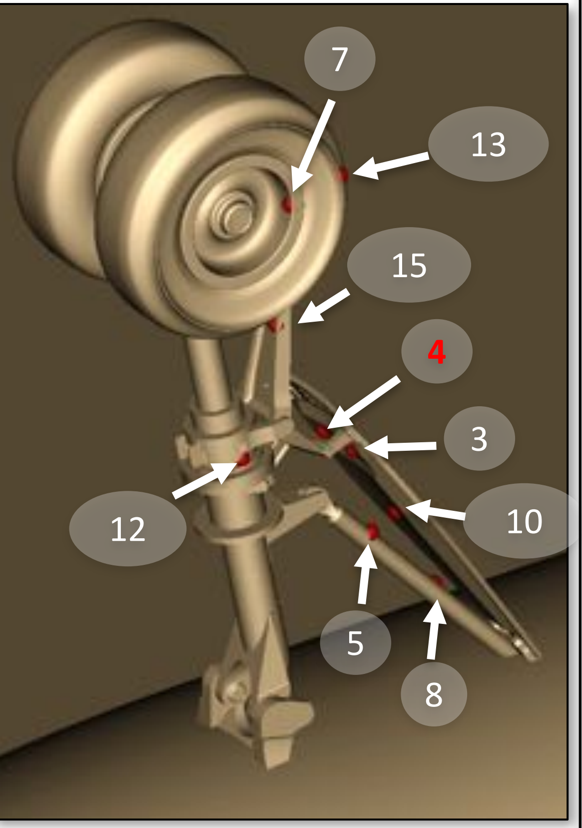
Channel 13: Outer Wheel

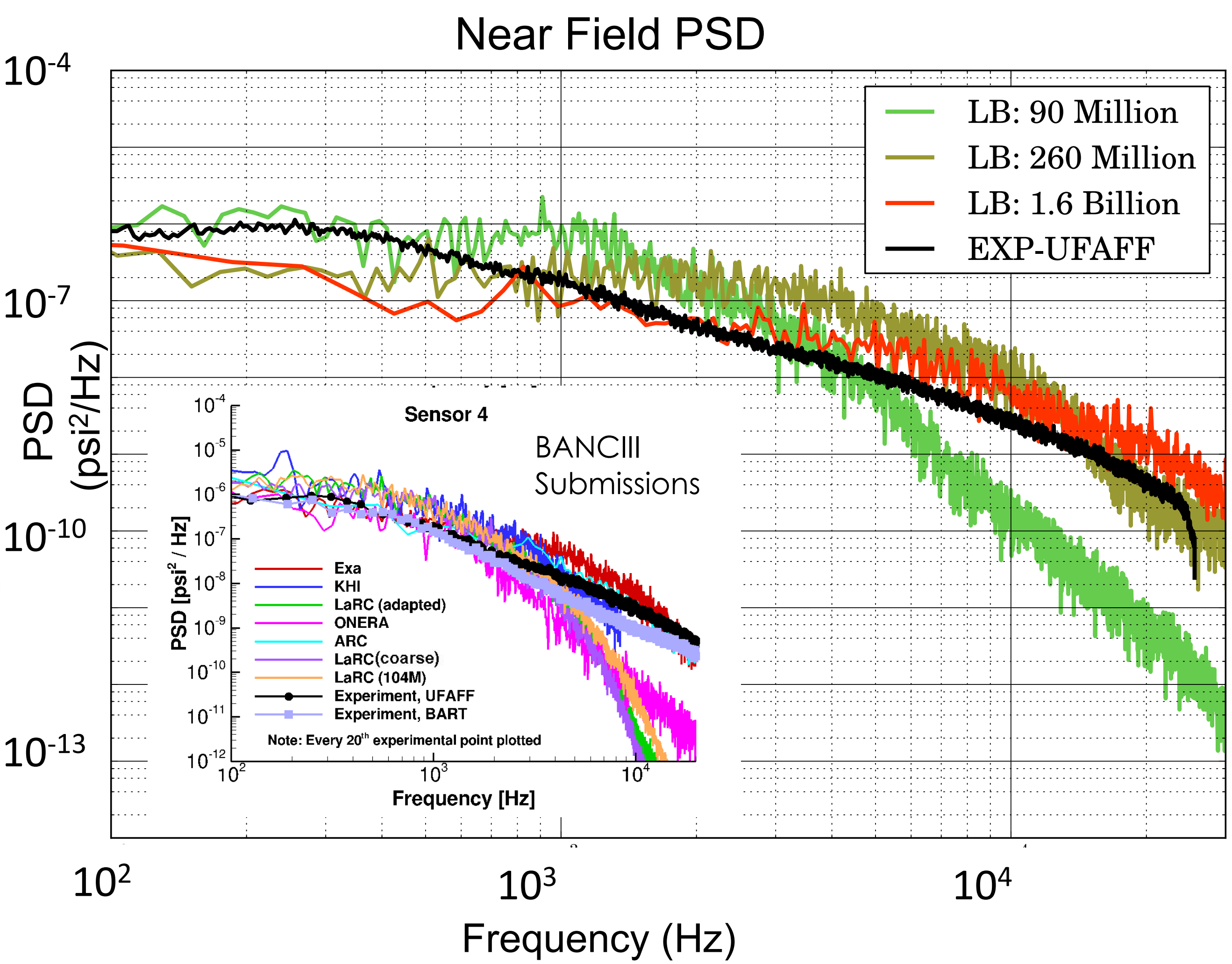




Grid Sensitivity - PSD

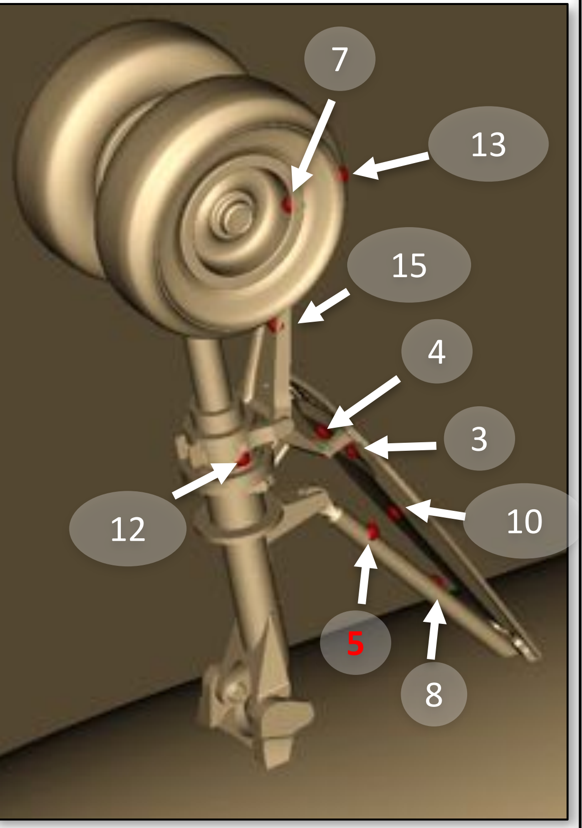
Channel 4: Upper Door

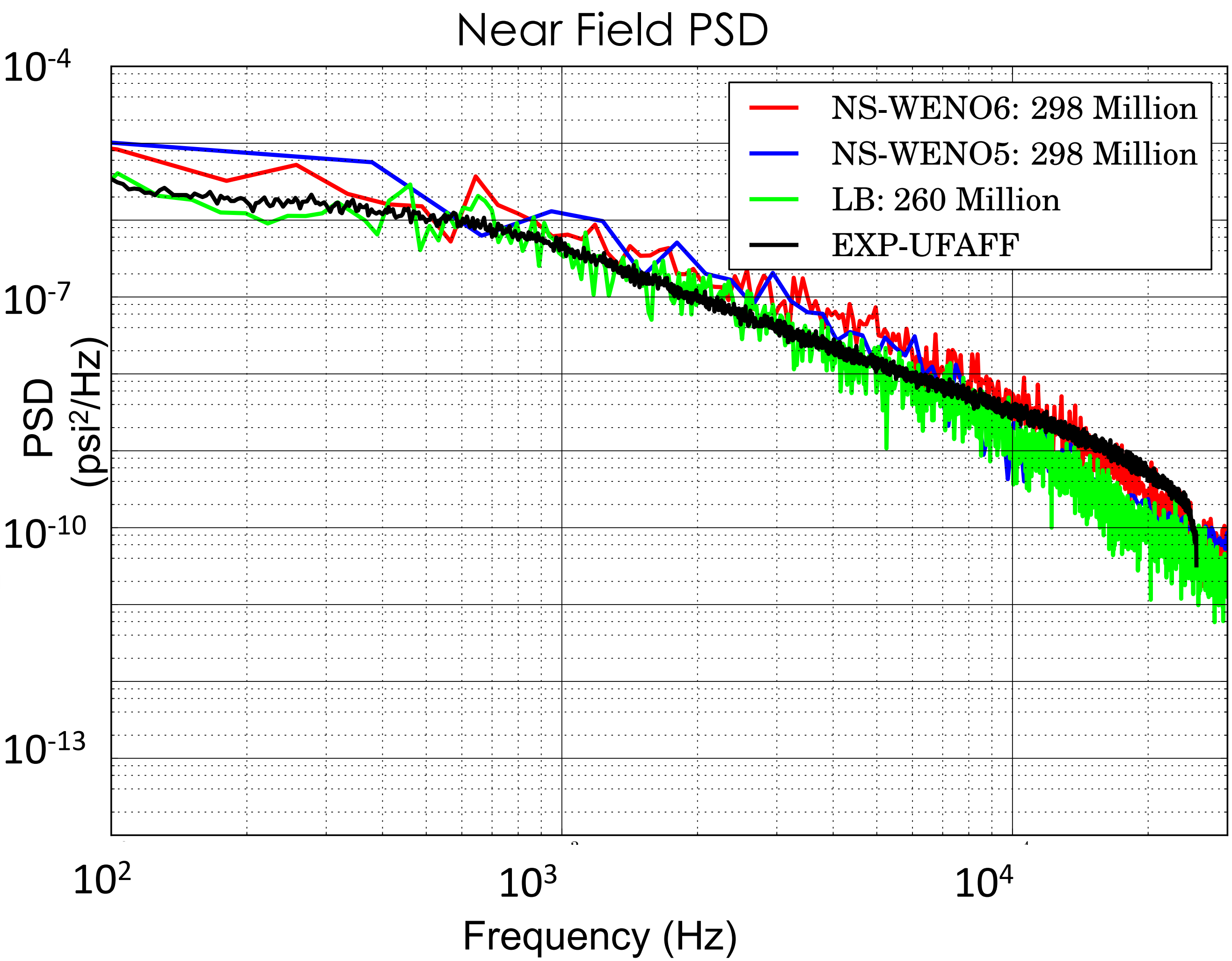




LBM vs NS - PSD

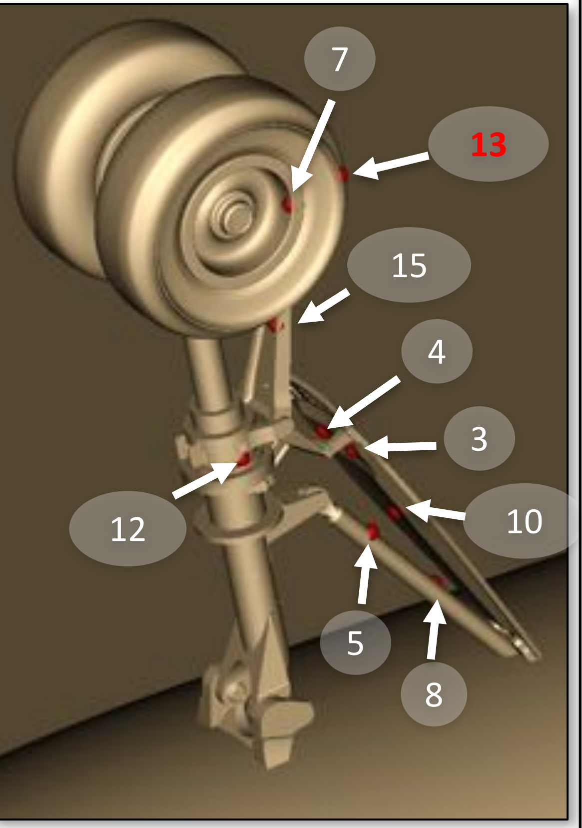
Channel 5: Upper Drag Link

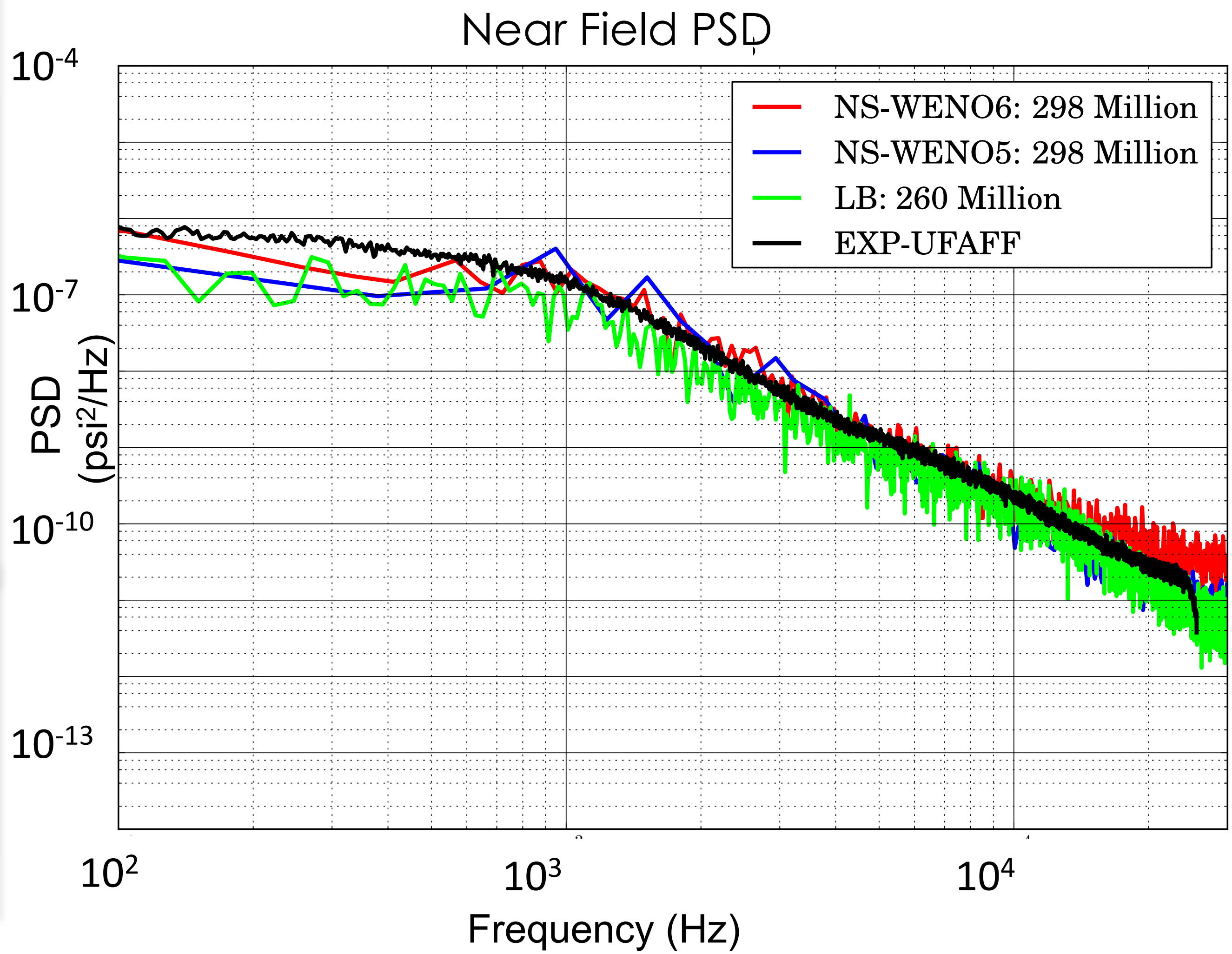




LBM vs NS - PSD

Channel 13: Outer Wheel



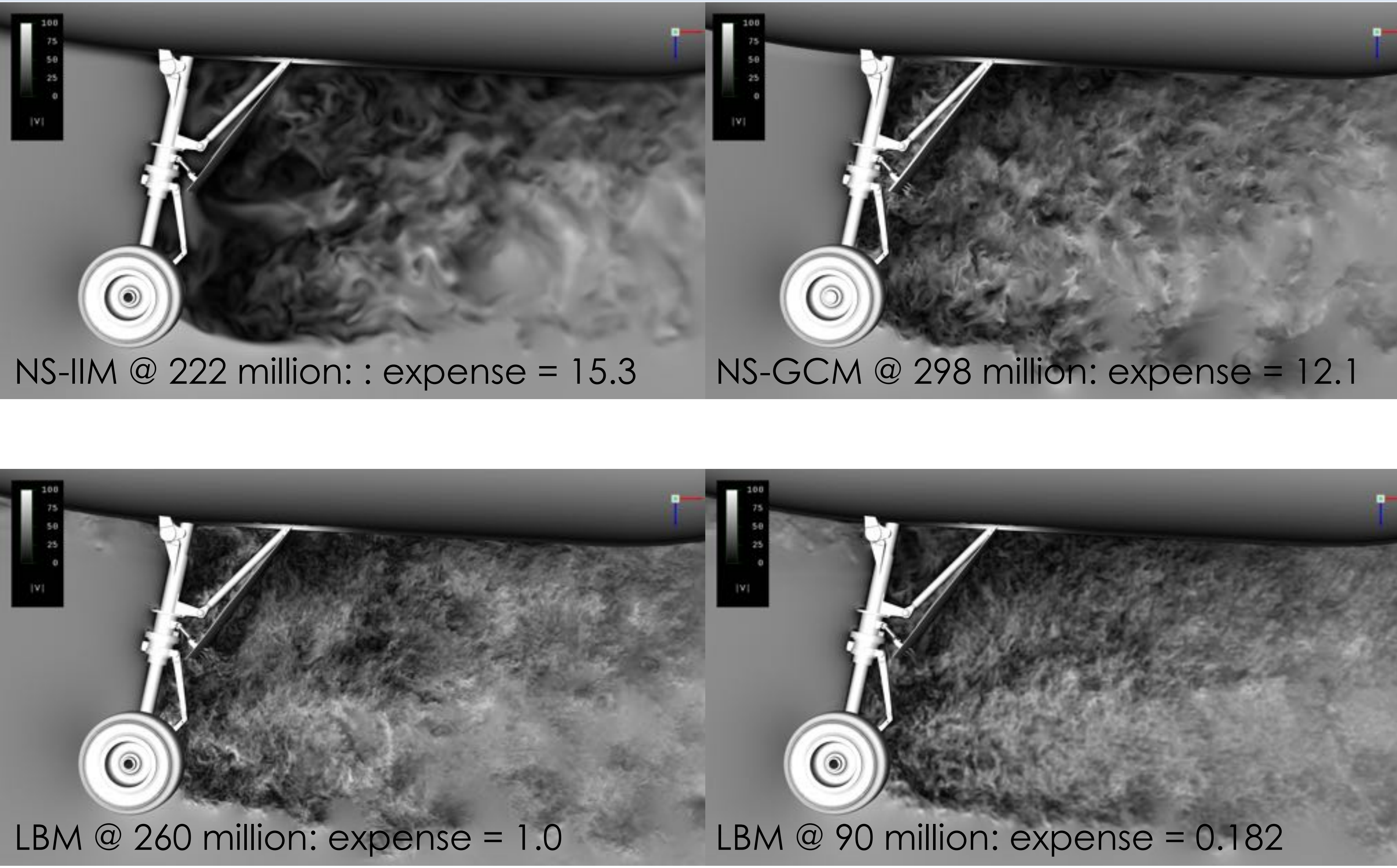


Grid and Performance Statistics

Method	CPU Cores (type)	Cells (million)	Wall Days to 0.19 sec	Core Days to 0.19 sec	Relative SBU Expense
NS-GCM	3000 (ivy)	298	20.5	61352	12.1
NS-IIM	9600 (has)	222	6.1	58490	15.3
LBM	1400 (bro)	260	2.25	3156	1

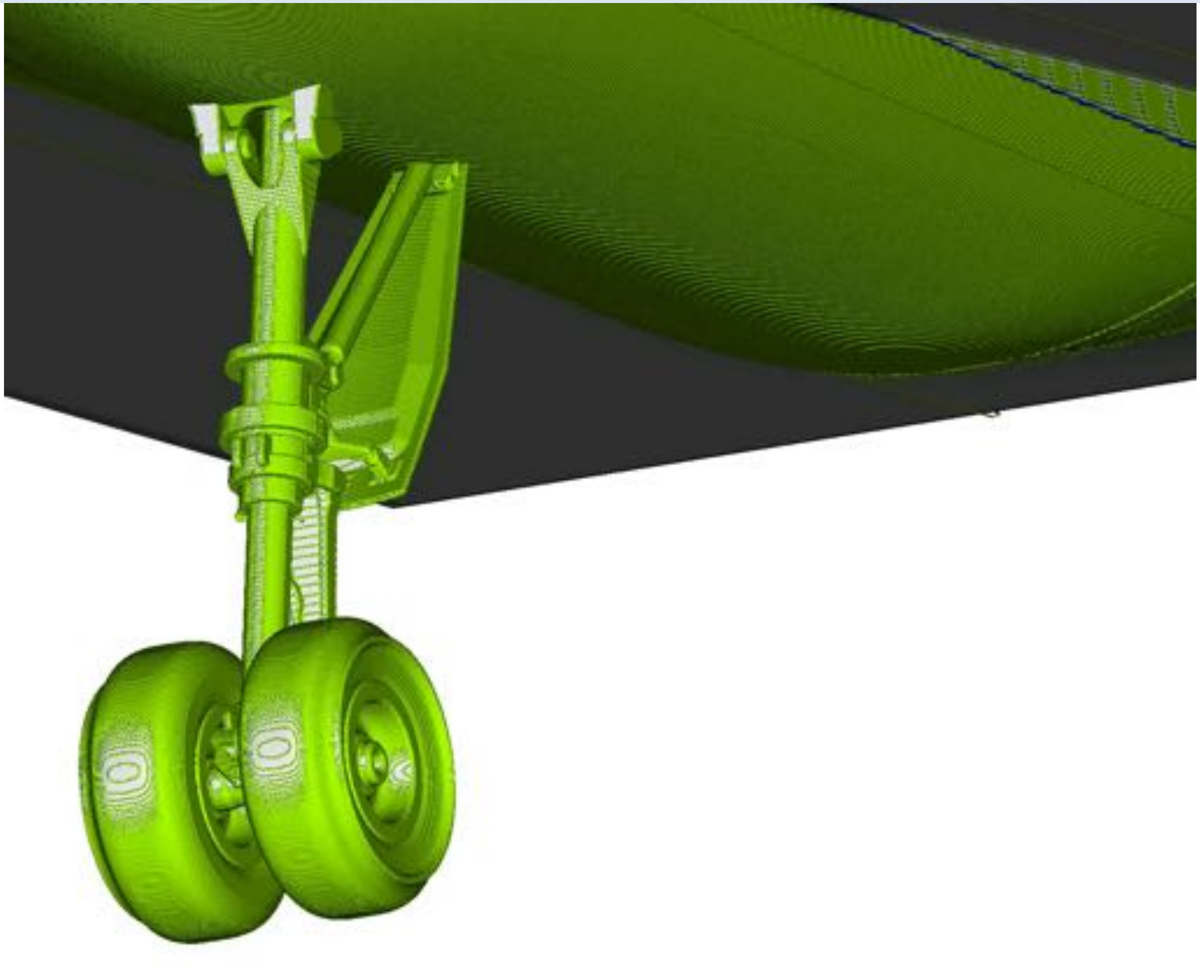
- For a comparable mesh size, LBM is 12-15 times faster (in CPU utilization) than Navier-Stokes with immersed boundaries, and is equally accurate. "Apples-to-apples" comparison with the exact same mesh & CPU-type is ongoing. Note: LBM code is not yet optimized, and we output volume data every 50 steps!
- LBM at 1.6 billion cells is ~2 times faster than NS at 298 million. This is a key enabler for unprecedented high resolution simulations.
- Performance details:
    - Both Cartesian Navier-Stokes and LBM are memory-bound (not compute-bound) algorithms, the latter much more so than the former. Because of this, FLOPS are essentially "free".
    - Non-linear, LBM collision operation where all the work happens is entirely local!! Data locality is critical to the computational efficiency of LBM relative to high-order Cartesian NS codes.

Velocity Magnitude (Center-plane)



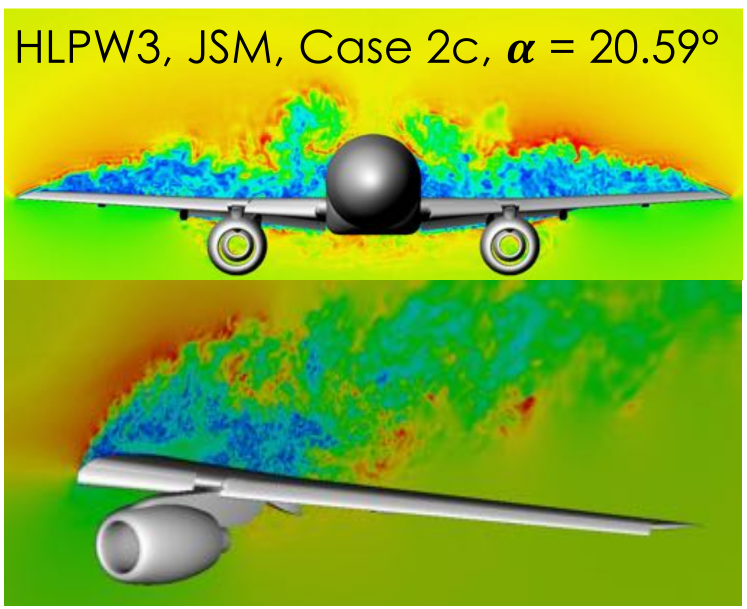
Summary

- Cartesian methods are very successful for the right problems
- Demonstrated the LBM approach on the AIAA BANC III Workshop Landing Gear problem IV.
    - Computed results compare well with the experimental data
    - 12-15 times speed-up was observed between LBM and NS calculations.
- LBM has better memory access and significantly lower floating point operations relative to WENO+RK4
- LBM has minimal numerical dissipation

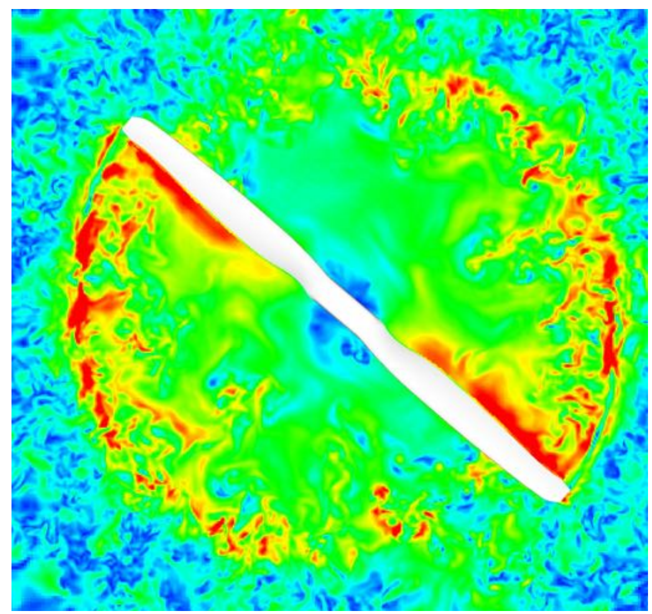


Next Steps

- Continue Verification & Validation efforts
- Improve wall modeling for arbitrarily complex geometry at high Reynolds numbers
- Moving geometry capability, including non-trivial motions (e.g. relative body, deformations, etc)
- Extend Mach number range to transonic and high speed flows
- Performance optimizations: serial and parallel



LAVA LBM full aircraft (in progress)



LAVA LBM moving geometry formulation (in progress)

Acknowledgments

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

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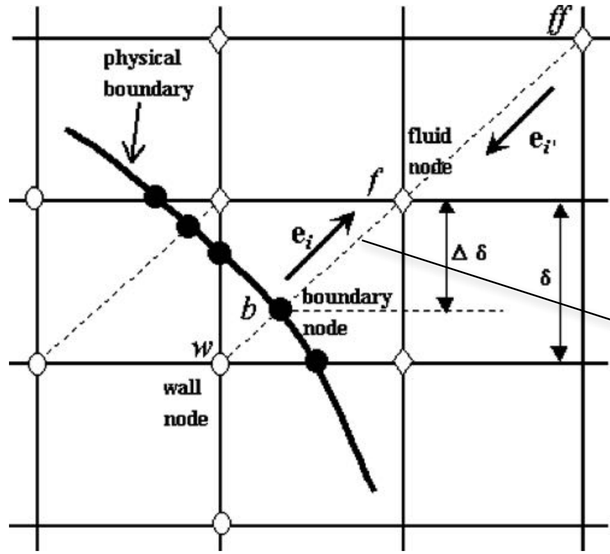
Questions ?

LAVA LBM: Wall Model



Broken links query surface triangulation for local slip/penetration velocity or wall shear stress computed dynamically by the wall model

- Accurate wall models are critical for Cartesian-grid approaches such as LBM
- **Filter-based slip wall model**: Follows the approach of Bose and Moin (POF, 2014). Adapted for LAVA LBM through a generalized slip algorithm. Traditional wall models based on law-of-the-wall hard to justify for the BANCIII landing gear noise simulation. Reynolds number is too low. Subcritical separation from wheels expected.
- **Traditional equilibrium and non-equilibrium wall models** (In progress): Follows the approach of Kawai and Larsson (POF, 2012) and Yang et al. (POF, 2015). Rules that express unknown incoming populations in terms of known outgoing populations modified to enforce momentum flux computed by the wall model.