Towards NASA's In House Lattice-Boltzmann Solver

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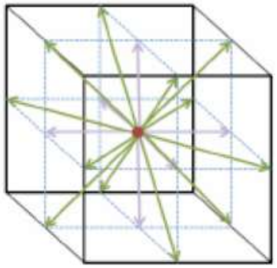
Challenges in Computational Aero-Acoustics

✓ 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 Boltzmann Method (LBM)
  - 10-50 times speed-up can be achieved with LBM vs NS-WENO without any compromise in accuracy or robustness

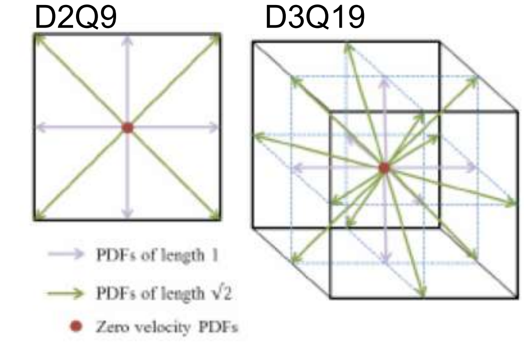
LAVA LBM: Governing Equations

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



- **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
  - Post-collision distribution functions hop on to neighboring nodes along the lattice links – 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

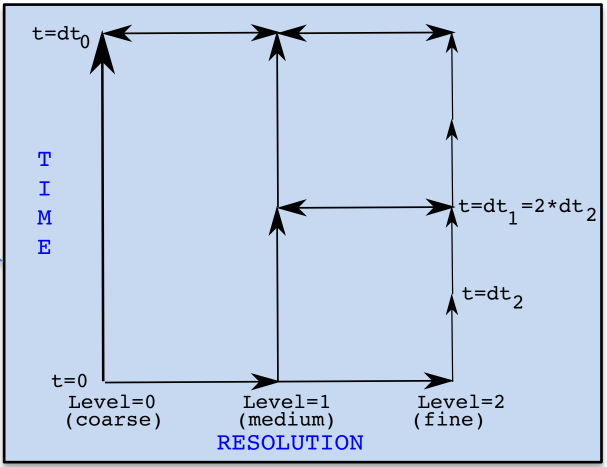
LAVA LBM: Progress



D2Q9 = 2D w/ 9-velocities…

Implementation to Date:

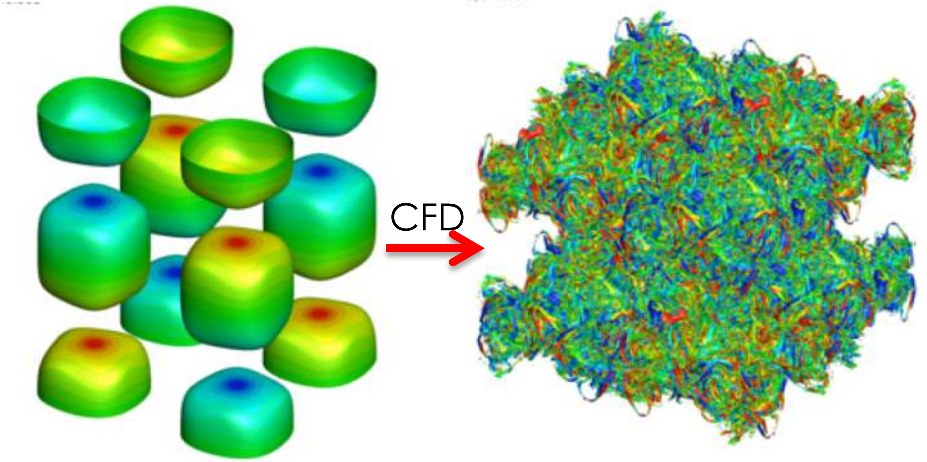
- **Lattices**: including D2Q9, D3Q15, D3Q19, D3Q27, D3Q39 …
- **Collision Models**:
  - Bhatnagar-Gross-Krook (BGK)
  - Multi-Relaxation Time (MRT)
  - Entropic and positivity preserving variants of BGK
  - Entropic Multi-Relaxation Time (EMRT)
  - Regularized BGK
- **Turbulence Models**: Smagorinsky, Vreman, Sigma and Spalart-Allmaras models
- **Wall Models:** Tamm-Mott-Smith boundary condition, filter-based slip wall model, Wall functions based on log law and power law
- **Parallelization**:
  - Structured adaptive mesh refinement (SAMR) based LBM requires parallel ghost cell exchanges:
    - Fine-fine for communication within levels
    - Conservative Coarse-fine interface treatment
    - Efficient parallel I/O
- **Multi-Resolution with Recursive Sub-Cycling**
- **Boundary Conditions**:
  - No-slip and slip bounce back walls
  - Accurate and robust curved walls (stationary and moving)
  - Inflow/outflow, and periodic



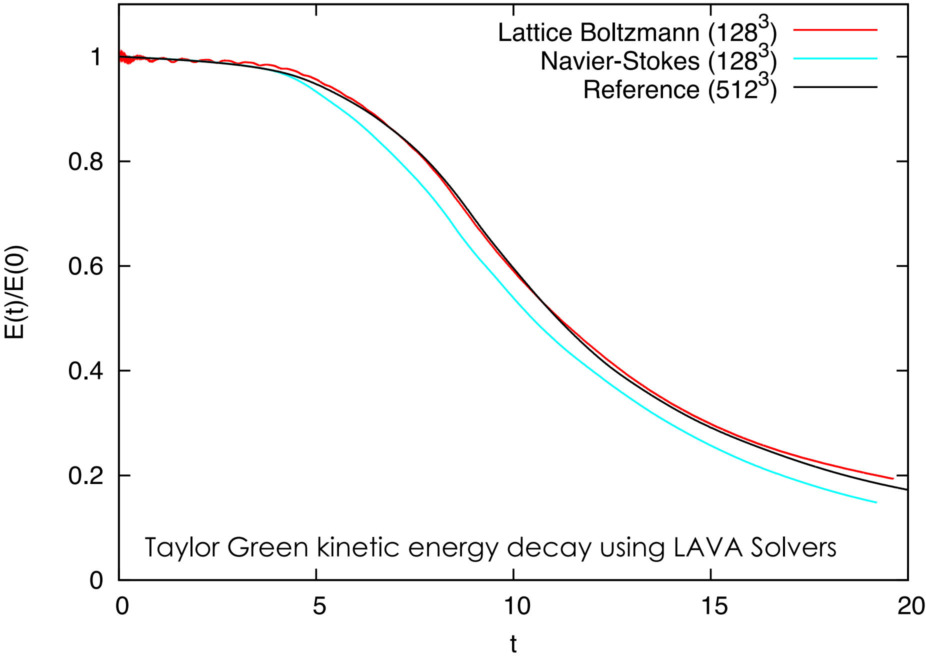
LAVA LBM: Verification and Validation

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)



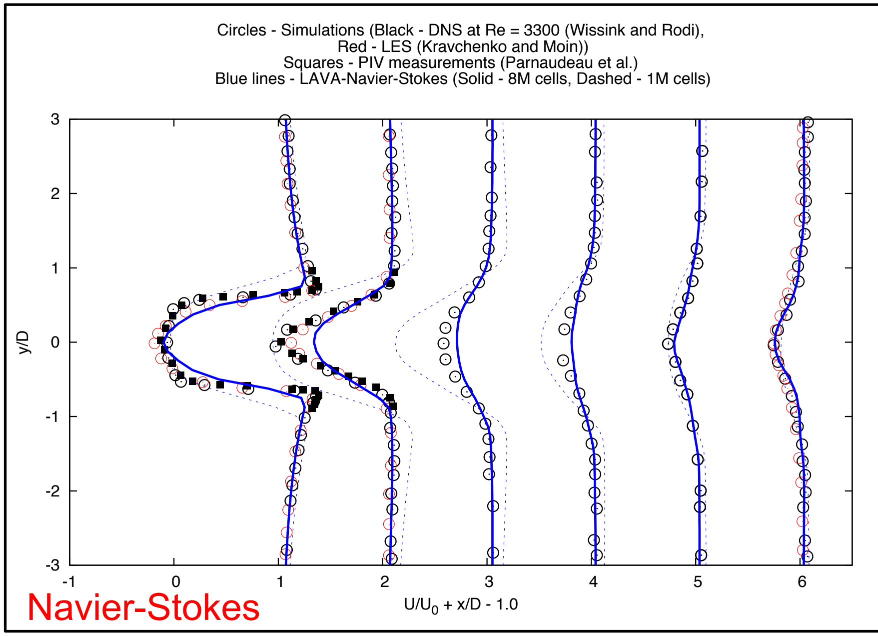
Taylor Green kinetic energy decay using LAVA Solvers

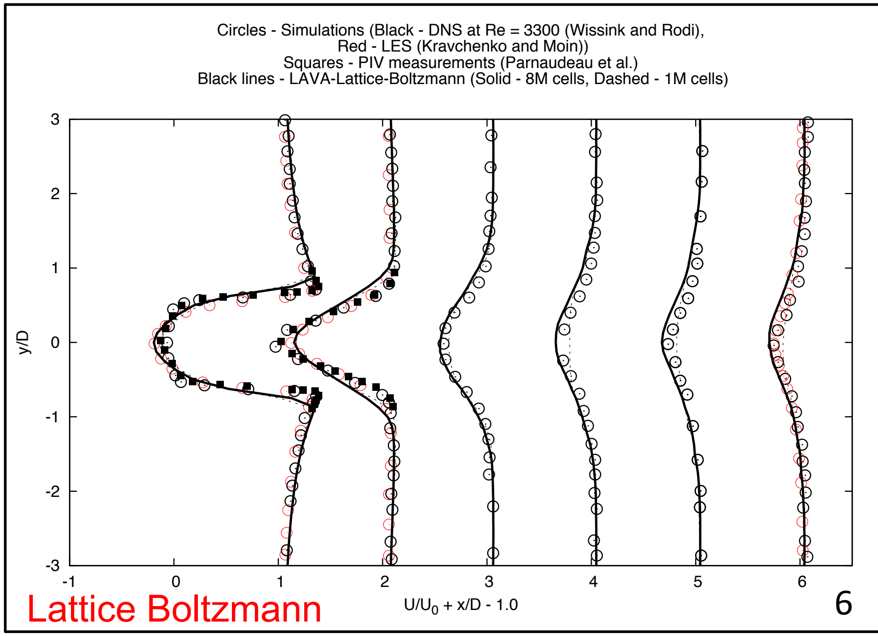
LAVA LBM: Verification and Validation

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
  - Good comparison with benchmark datasets (PIV, LES, DNS) even with just 8 lattice nodes across the cylinder
  - More accurate than high-order upwind biased NS schemes for identical resolution

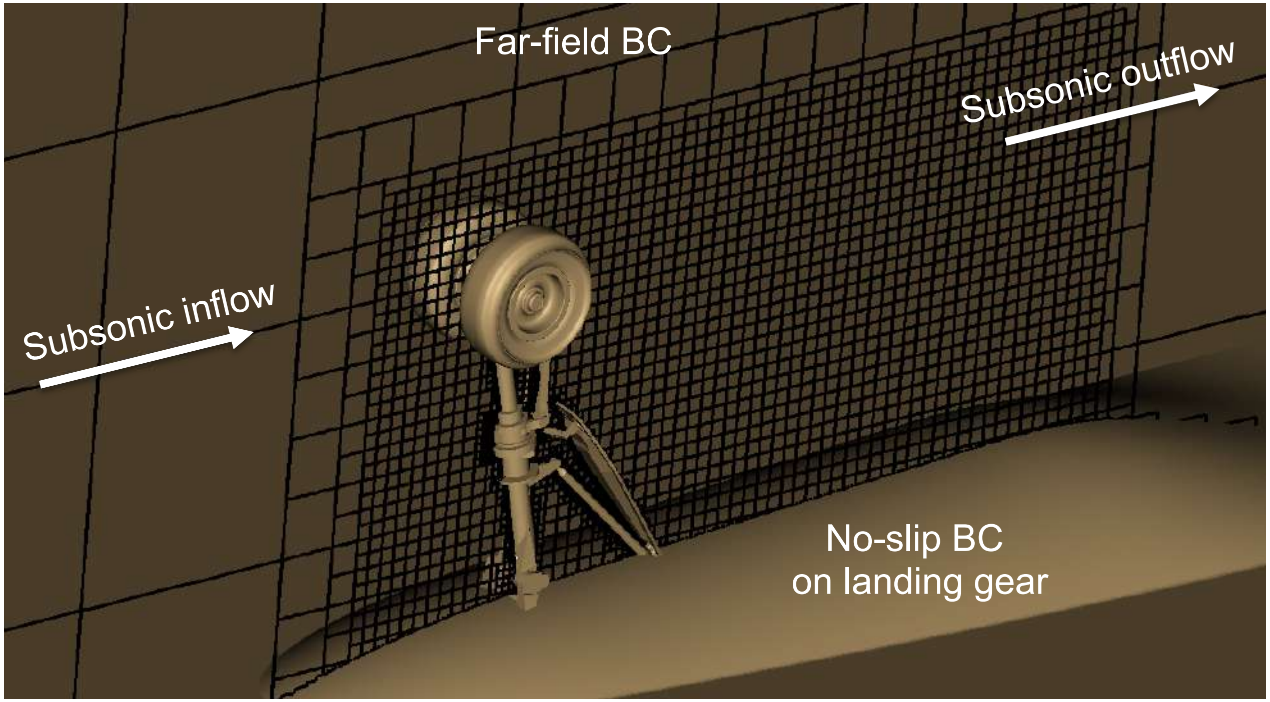
Lattice Boltzmann (passive particles for visualization)





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

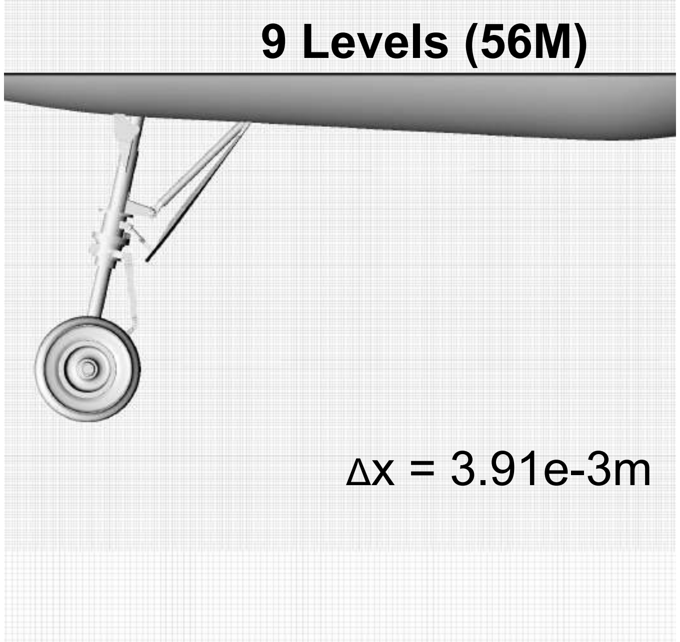
LAVA Cartesian options:

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

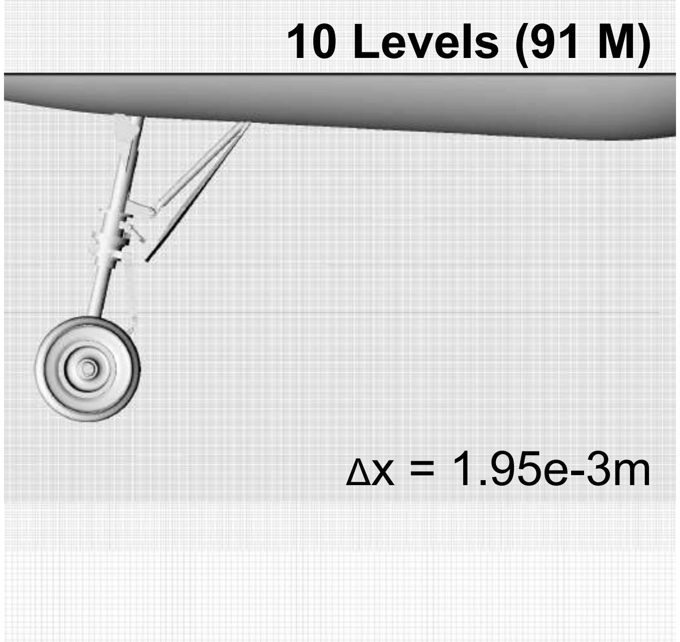
Setup follows the partially-dressed, cavity-closed nose landing gear (PDCC-NLG) noise problem from AIAA's Benchmark problems for Airframe Noise Computations (BANC) series of workshops. (Problem 4. Nose landing gear)

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

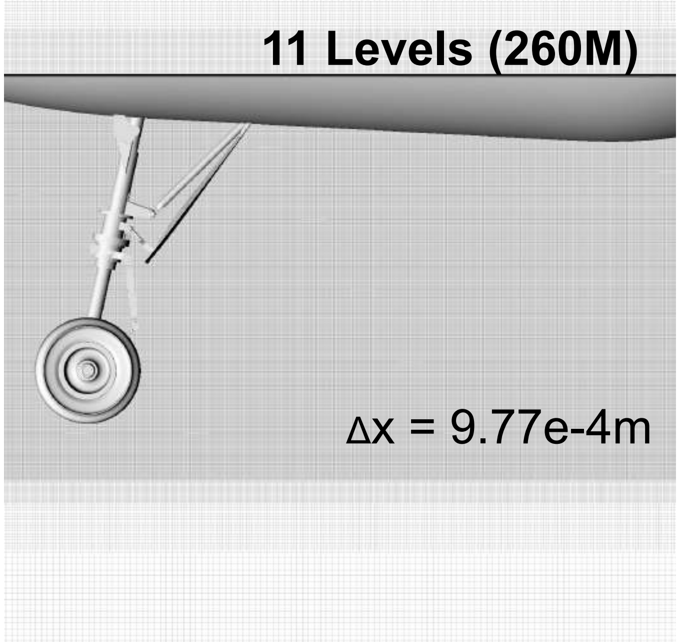
Cartesian Grid Resolution


9 Levels (56M)

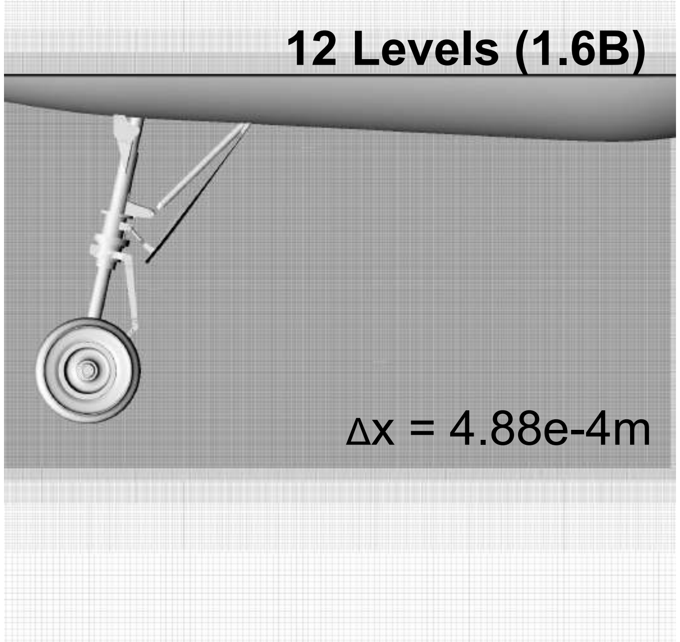
Δx = 3.91e-3m


10 Levels (91 M)

Δx = 1.95e-3m

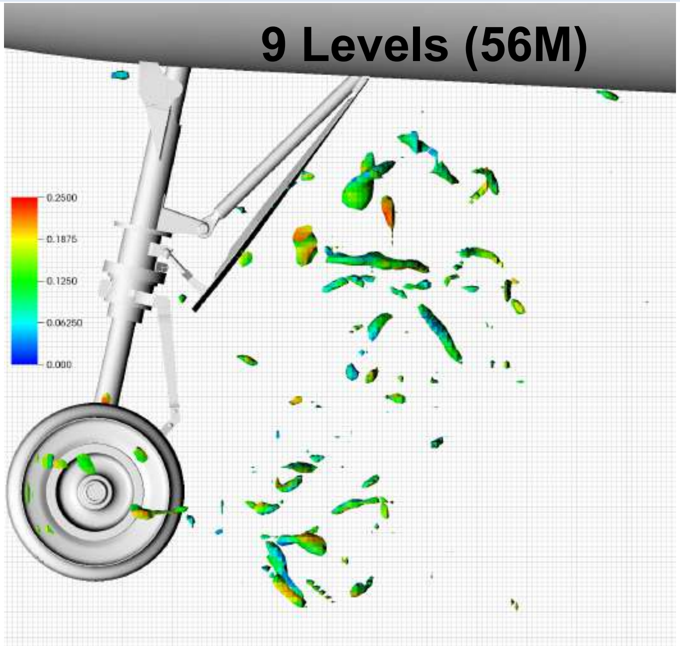

11 Levels (260M)

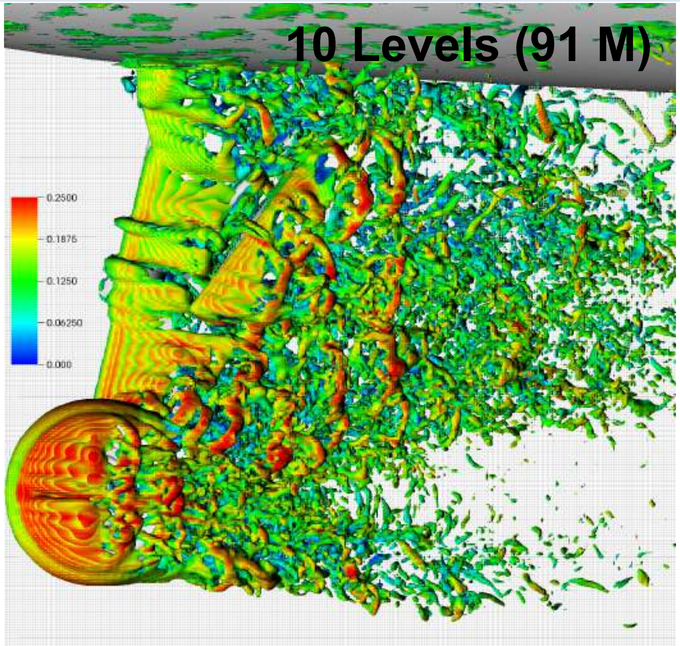
Δx = 9.77e-4m

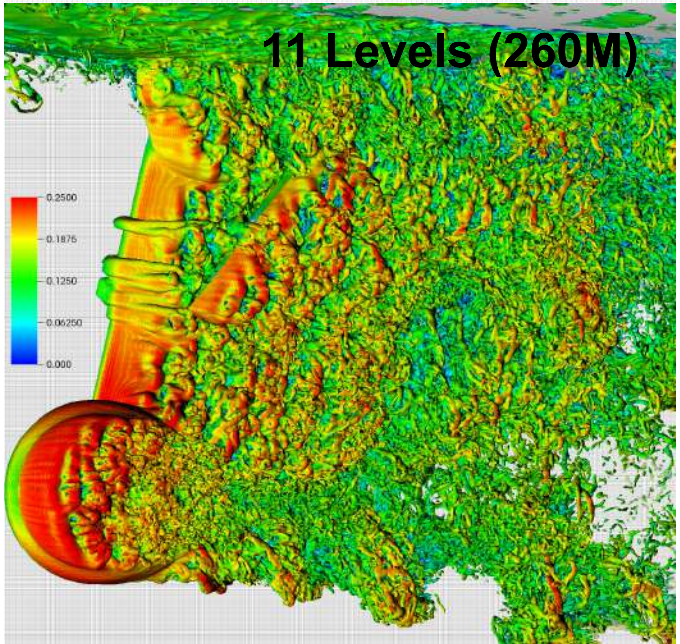

12 Levels (1.6B)

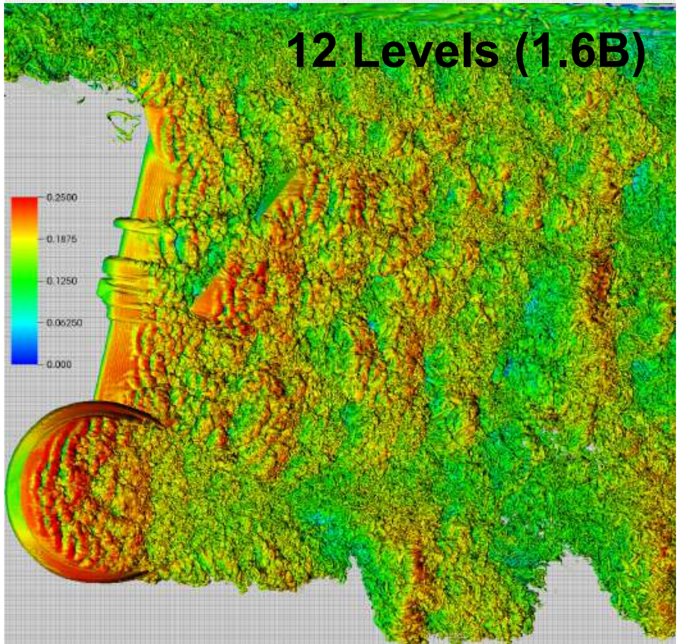
Δx = 4.88e-4m

Grid Sensitivity: Vorticity Colored by Mach


9 Levels (56M)


10 Levels (91 M)


11 Levels (260M)


12 Levels (1.6B)

Velocity Magnitude (Center-plane)

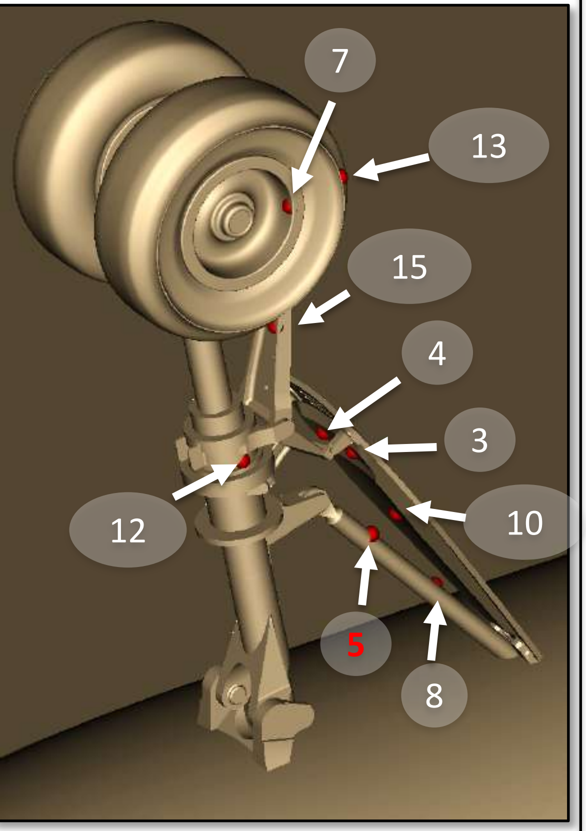
LBM @ 1.6 billion: expense = 7.9 normalized wall time units (relative to 260M calc)

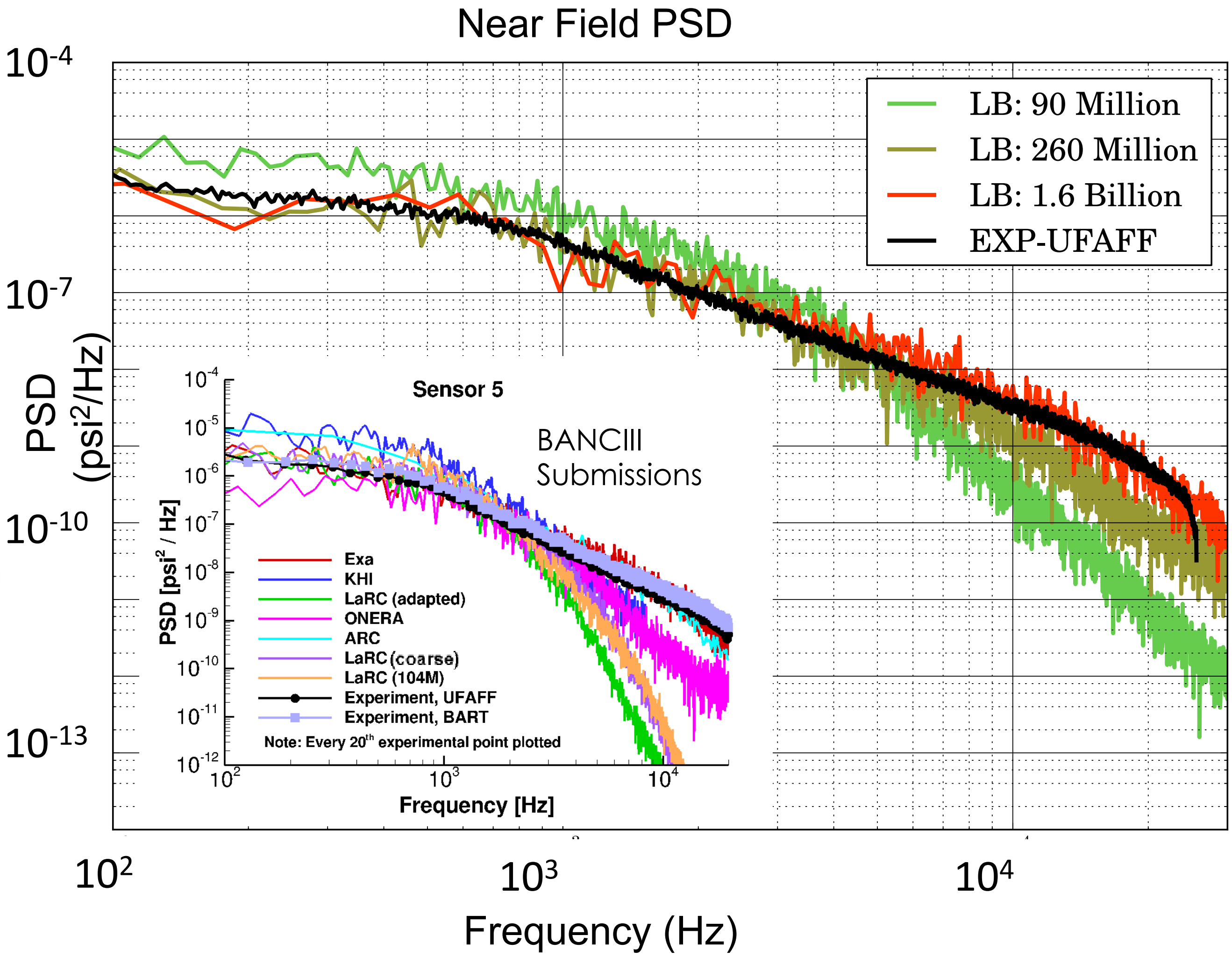
Passive Particle Colored by Mach Number

LBM @ 1.6 billion

Grid Sensitivity - PSD

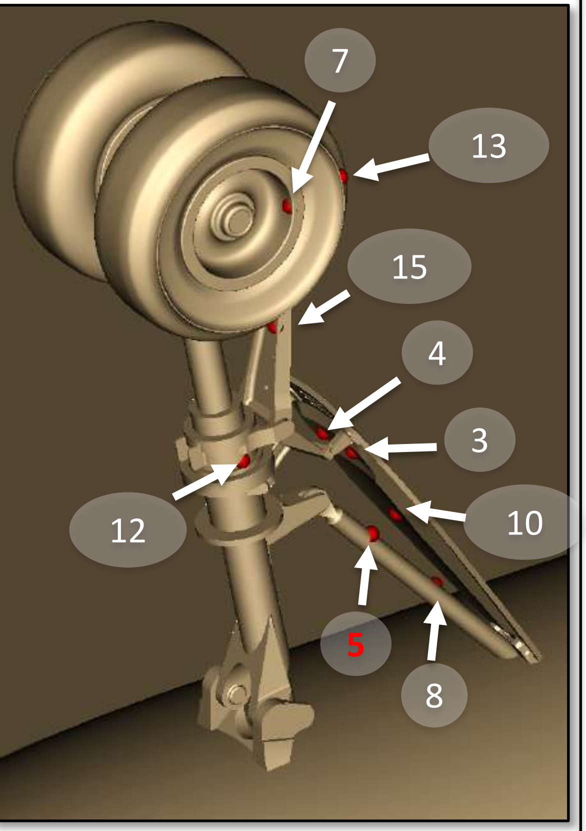
Channel 5: Upper Drag Link

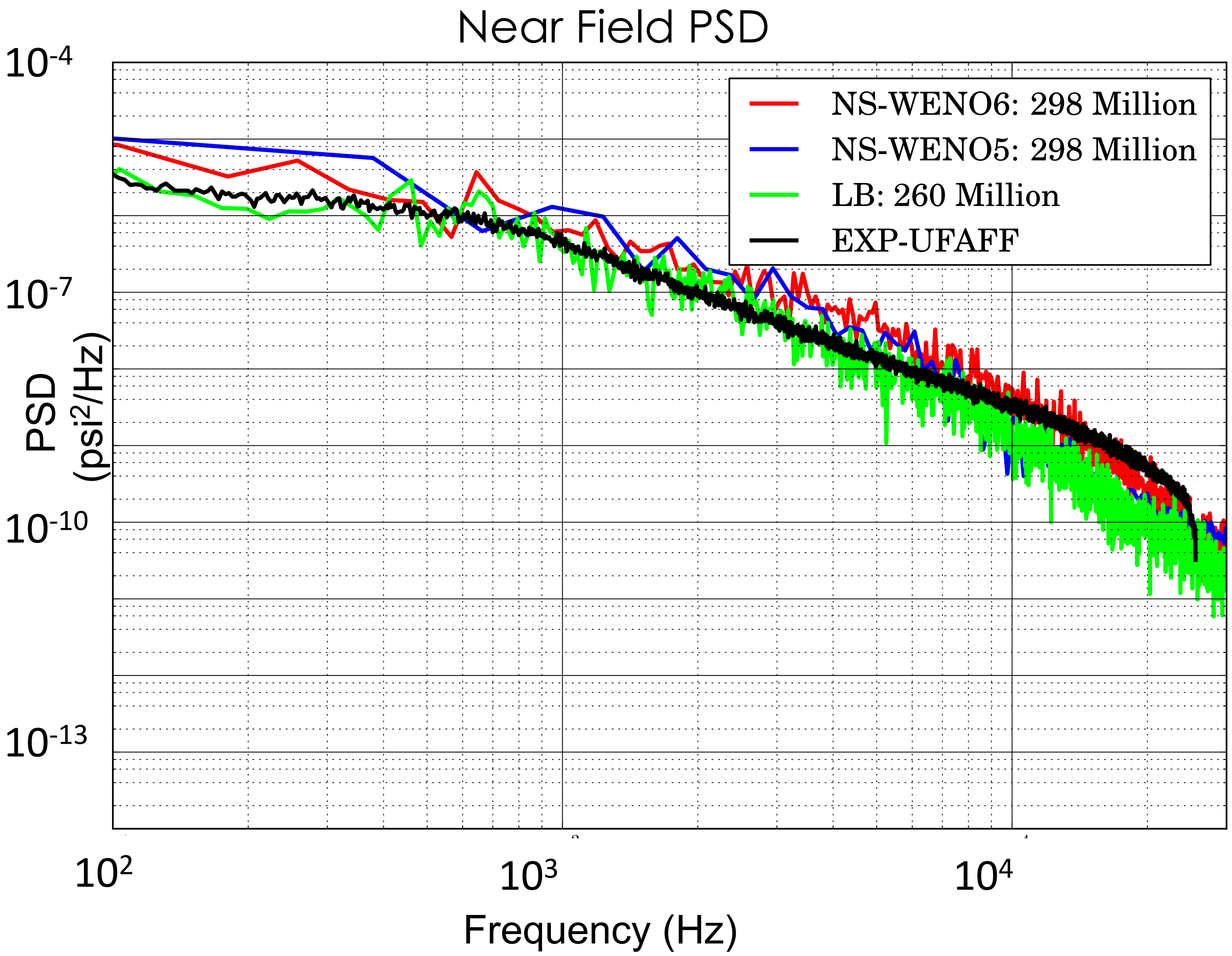




LBM vs NS - PSD

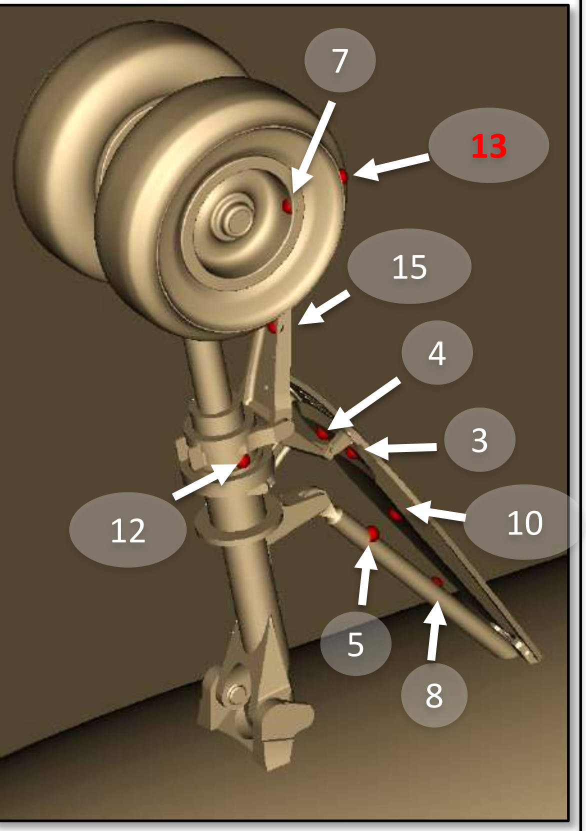
Channel 5: Upper Drag Link

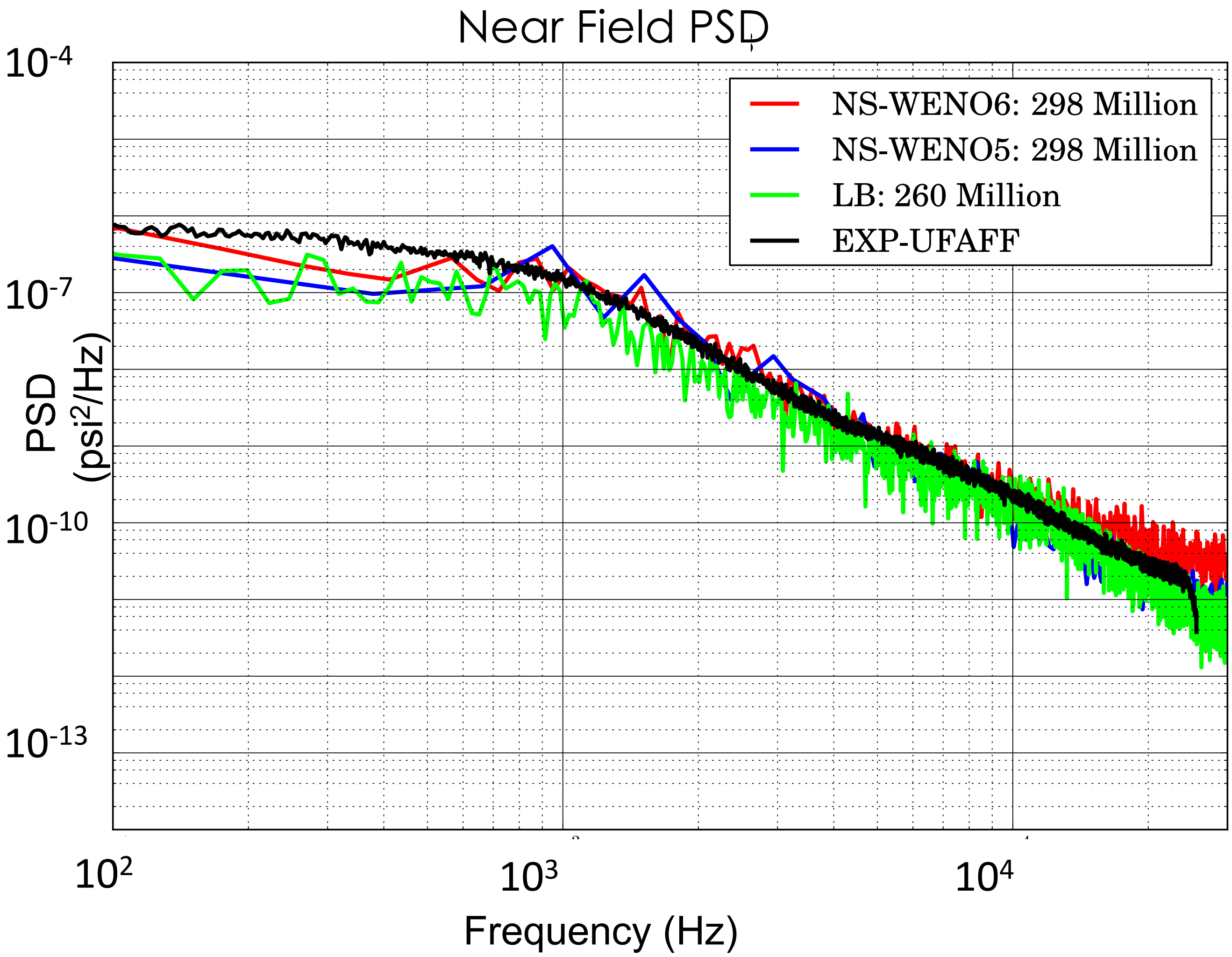




LBM vs NS - PSD

Channel 13: Outer Wheel



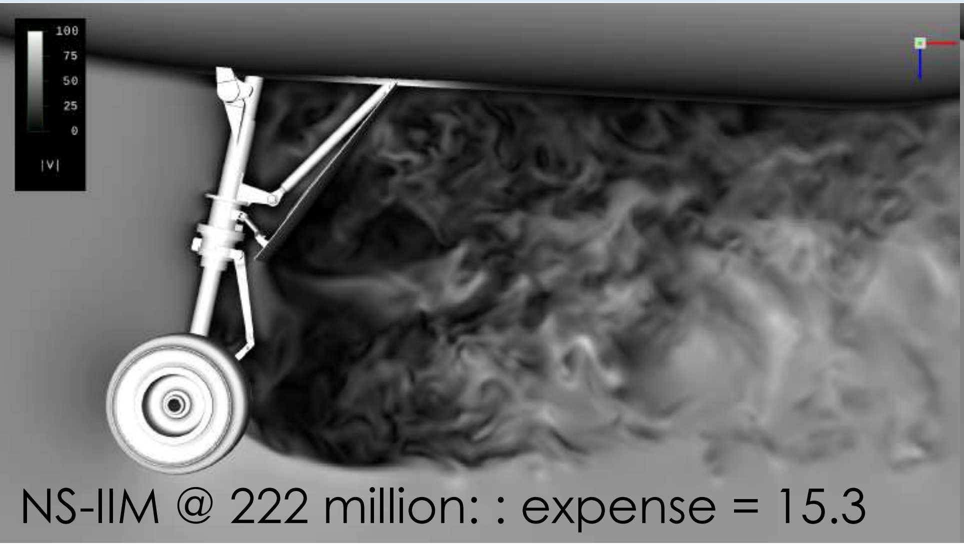


Grid and Performance Statistics

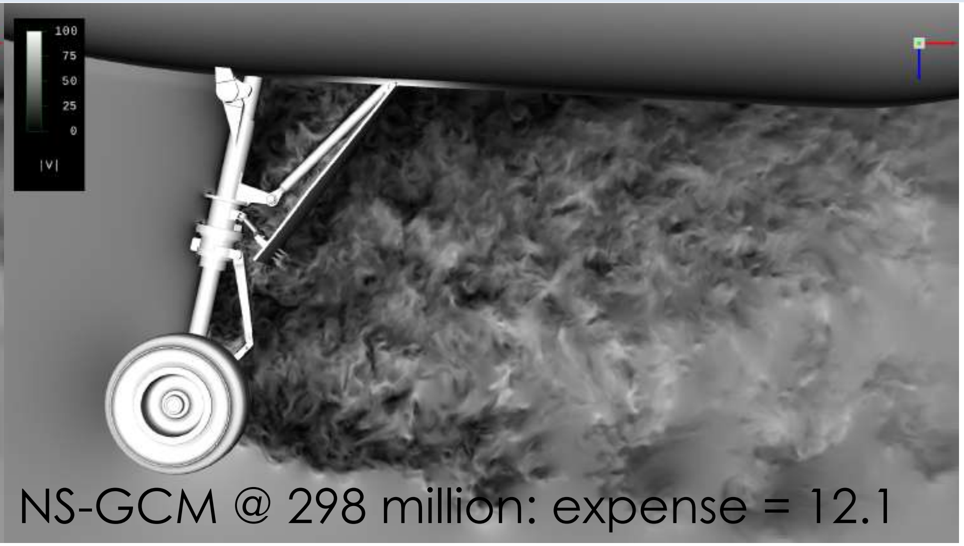
Method	CPU Cores (type)	Cells (million)	Wall Days to 0.19 sec	Core Days to 0.19 sec	Relative SBU Expense
NS-GCM	3000 (ivy)	298	20.5	61352	12.1
NS-IIM	9600 (has)	222	6.1	58490	15.3
LBM	1400 (bro)	260	2.25	3156	1

- For a comparable mesh size, **LBM is 12-15 times faster computationally than Navier-Stokes** 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.
  - 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.

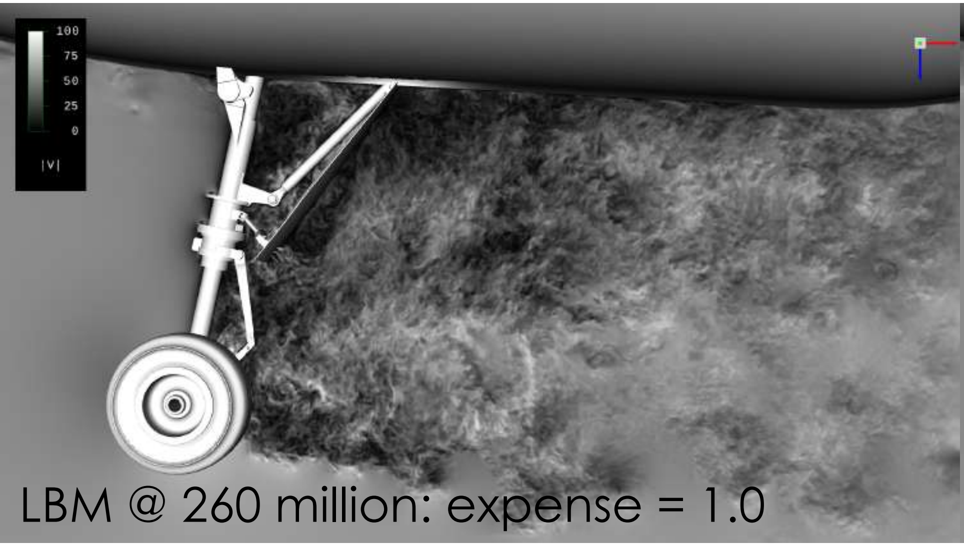
Velocity Magnitude (Center-plane)



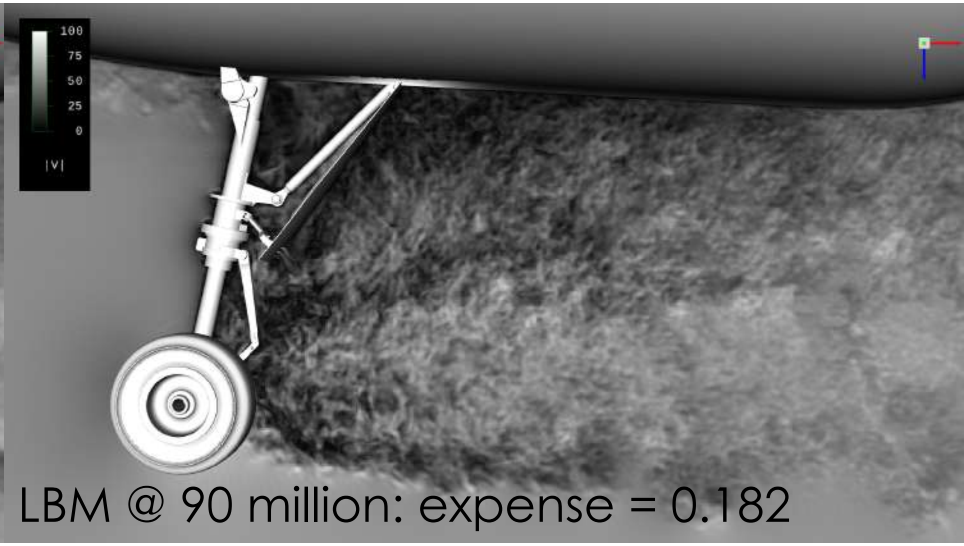
NS-IIM @ 222 million: : expense = 15.3



NS-GCM @ 298 million: expense = 12.1

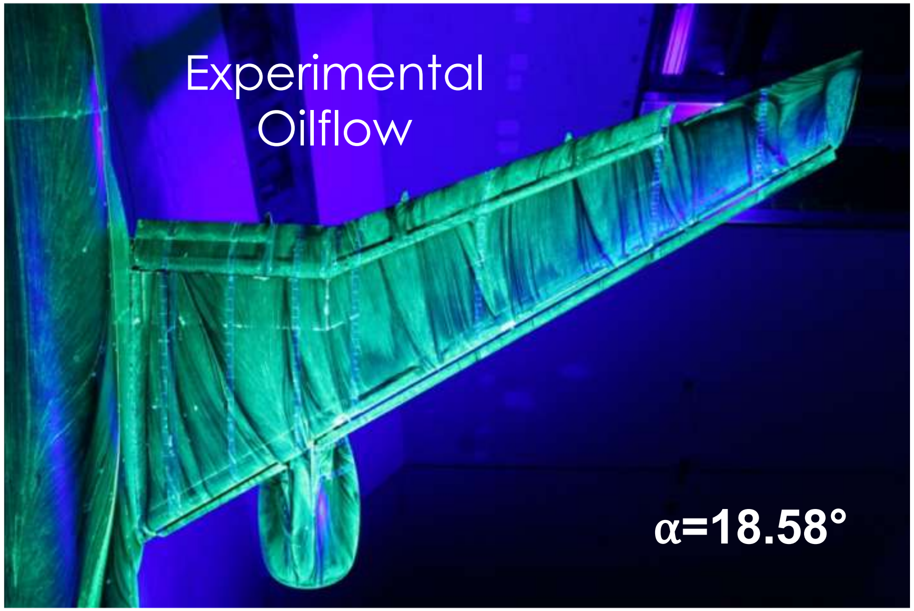


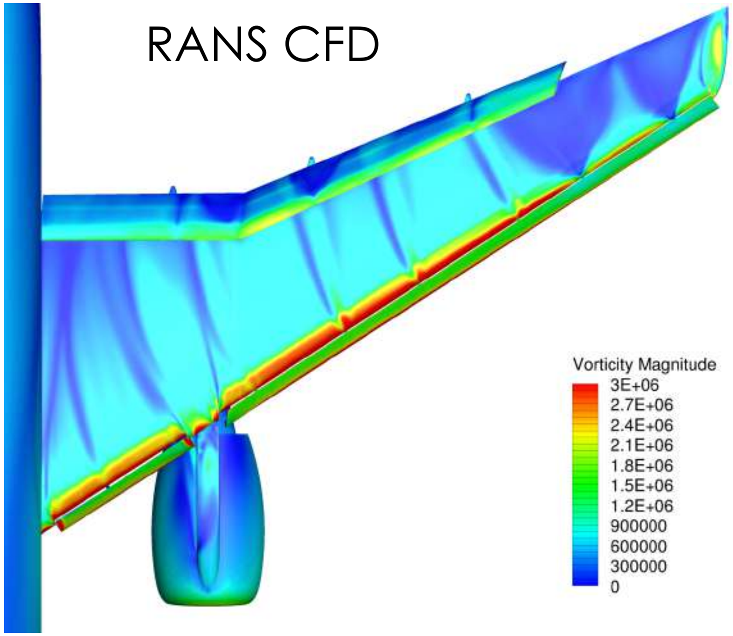
LBM @ 260 million: expense = 1.0

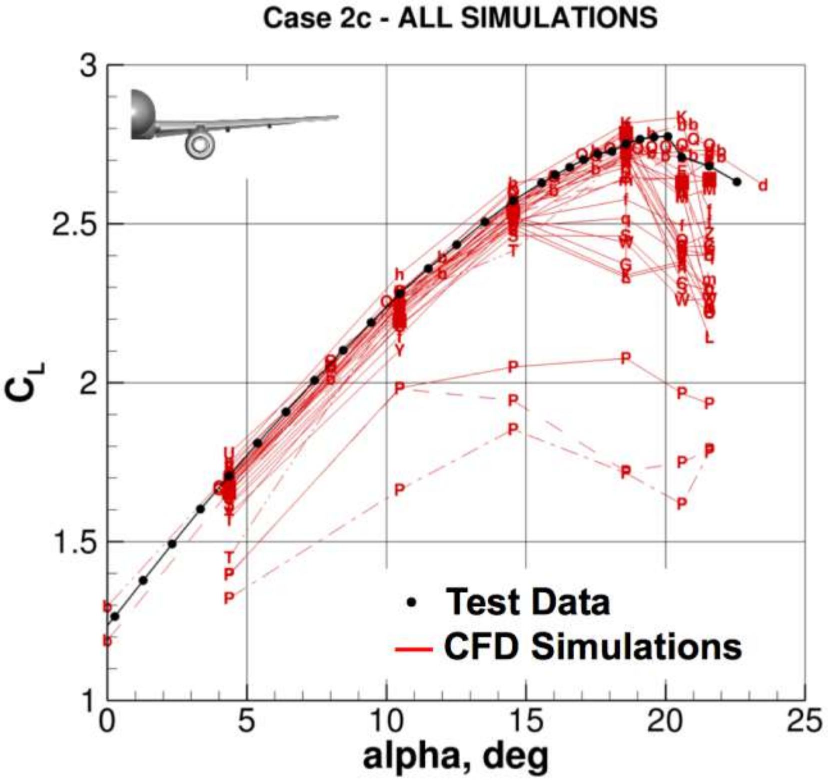


LBM @ 90 million: expense = 0.182

AIAA High Lift Prediction Workshop 3



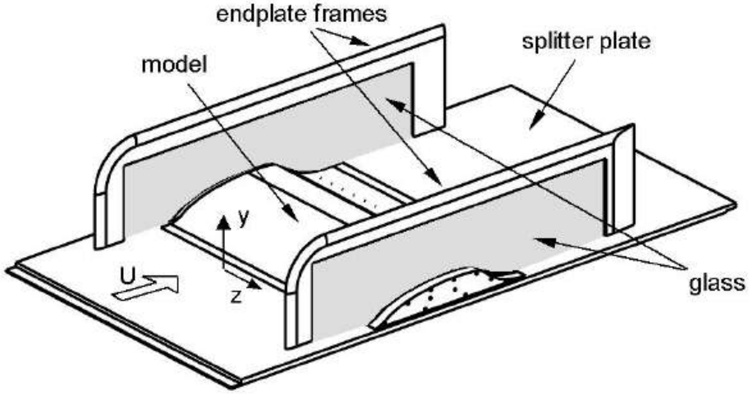




- RANS unreliable beyond 14°
- Higher fidelity approaches with fast turnaround times necessary

NASA 2-D Hump – Experimental Setup

- ✓ Assess ability of CFD solvers to predict flow separation from a smooth body (caused by adverse pressure gradient) as well as subsequent reattachment and boundary layer recovery.



Wall-resolved LES:

- ✓ Uzun, A. and Malik, M. (AIAA 2017-5308)

Wall-modeled LES:

- ✓ Iyer, P. and Malik, M. (AIAA 2016-3186)

Lattice Boltzmann Methods:

- ✓ Duda, B. and Fares, E. (AIAA 2016-1836)

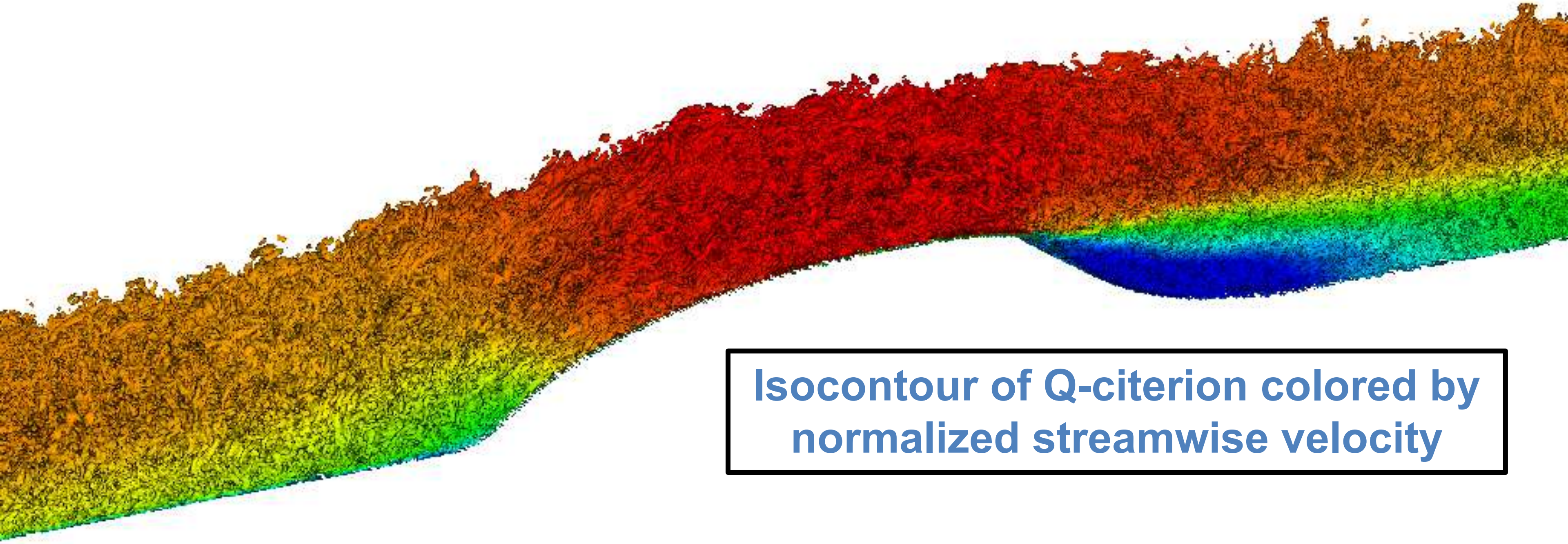
[1] Greenblatt et. Al. "Experimental Investigation of Separation Control Part 1: Baseline and Steady Suction". AIAA Journal, vol 44, no. 12, pp. 2820-2830, 2006

[2] Rumsey C, "Turbulence Modeling Resource", https://turbmodels.larc.nasa.gov

[3] Rumsey C, "CFD Validation of Synthetic Jets and Turbulent Separation Control", http://cfdval2004.larc.nasa.gov

Application of the Lattice Boltzmann Method

- ✓ Lattice: D3Q27
- ✓ Collision Model: EMRT
- ✓ Synthetic Eddy Method with scaled DNS Flat plate Data at x/c = -3.0

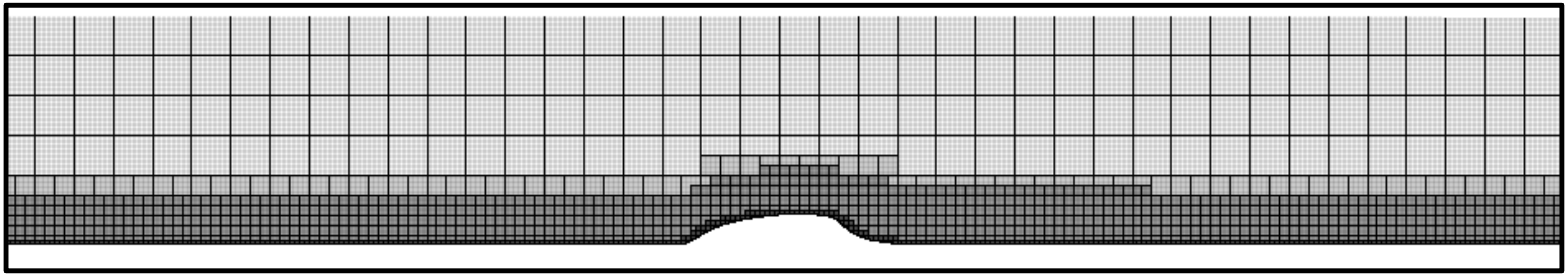


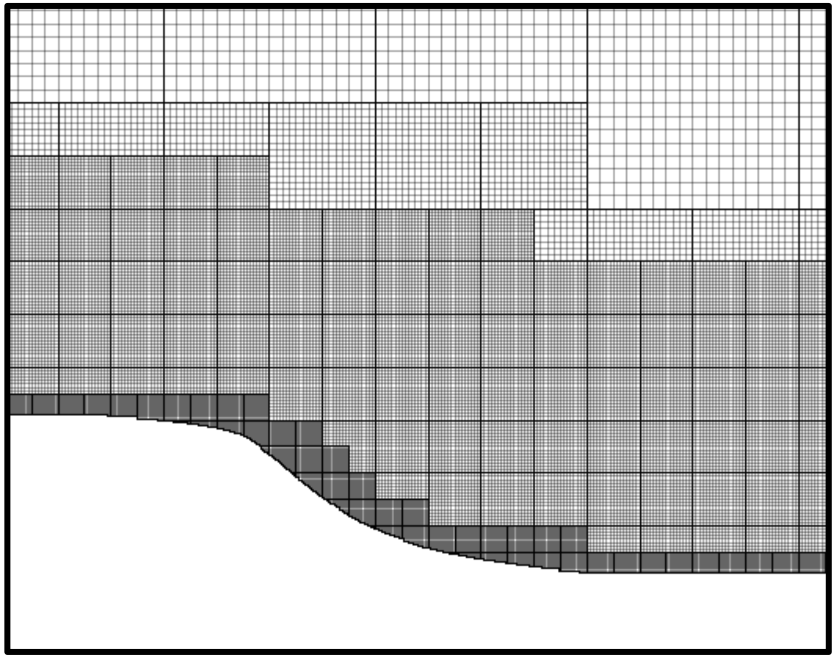
Isocontour of Q-citerion colored by normalized streamwise velocity

- ✓ Periodic BCs in spanwise direction (Side walls not modeled)

Application of the Lattice Boltzmann Method

- ✓ Local as well as adaptive mesh refinement well tested in our Cartesian framework.

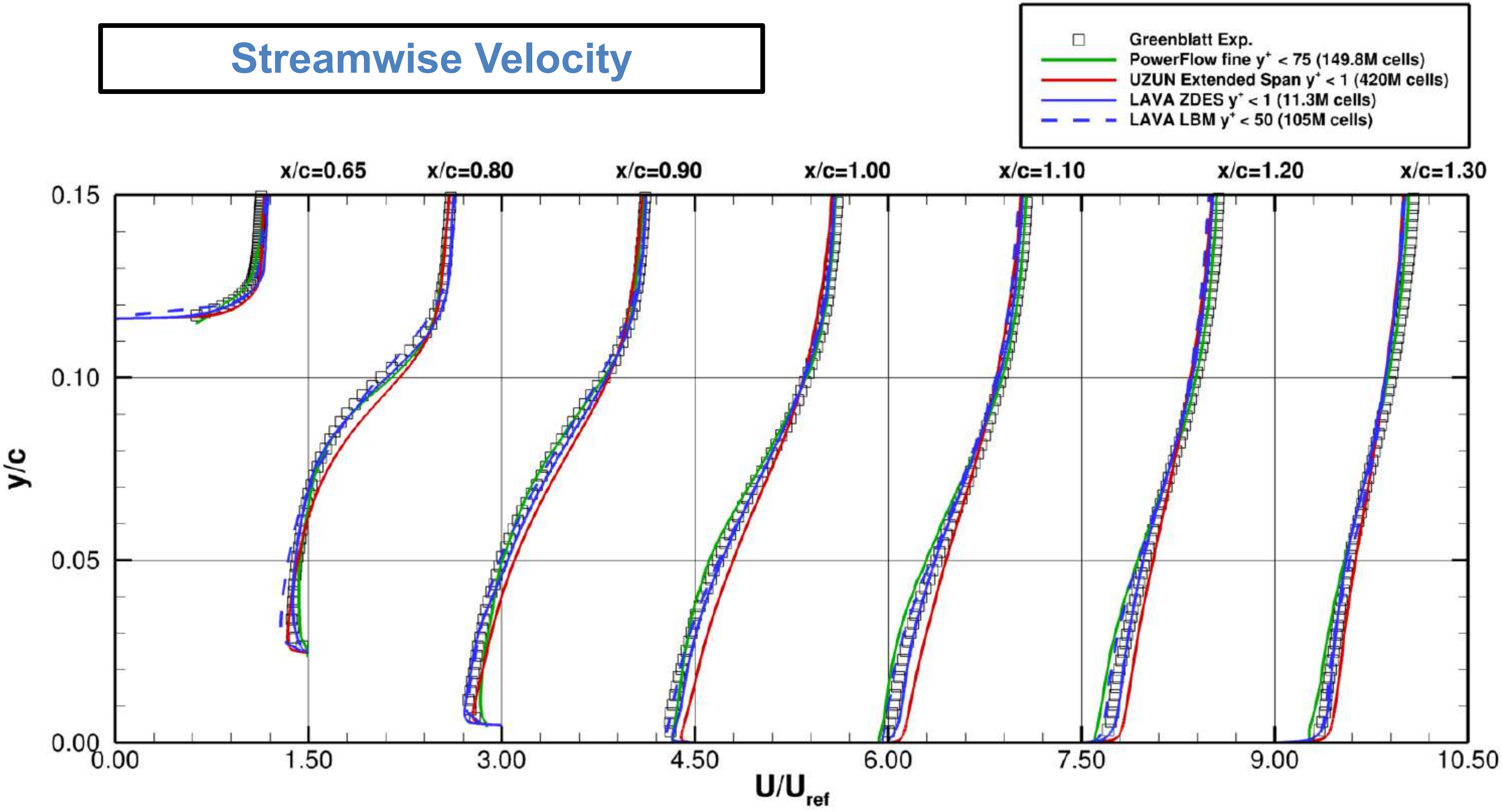




- ✓ 5 Refinement Levels
- ✓ Refinement ratio of 2:1
- ✓ Level 3 in regions of high vorticity
- ✓ Level 4 on all viscous walls
- ✓ Level 5 from x/c = -0.2 to 1.3
- ✓ **105 million points**
- ✓ Spanwise extent = 0.2c
- ✓ **$\Delta^+ \approx 50$ in viscous wall units**

NASA 2-D Hump – Application of Lattice Boltzmann

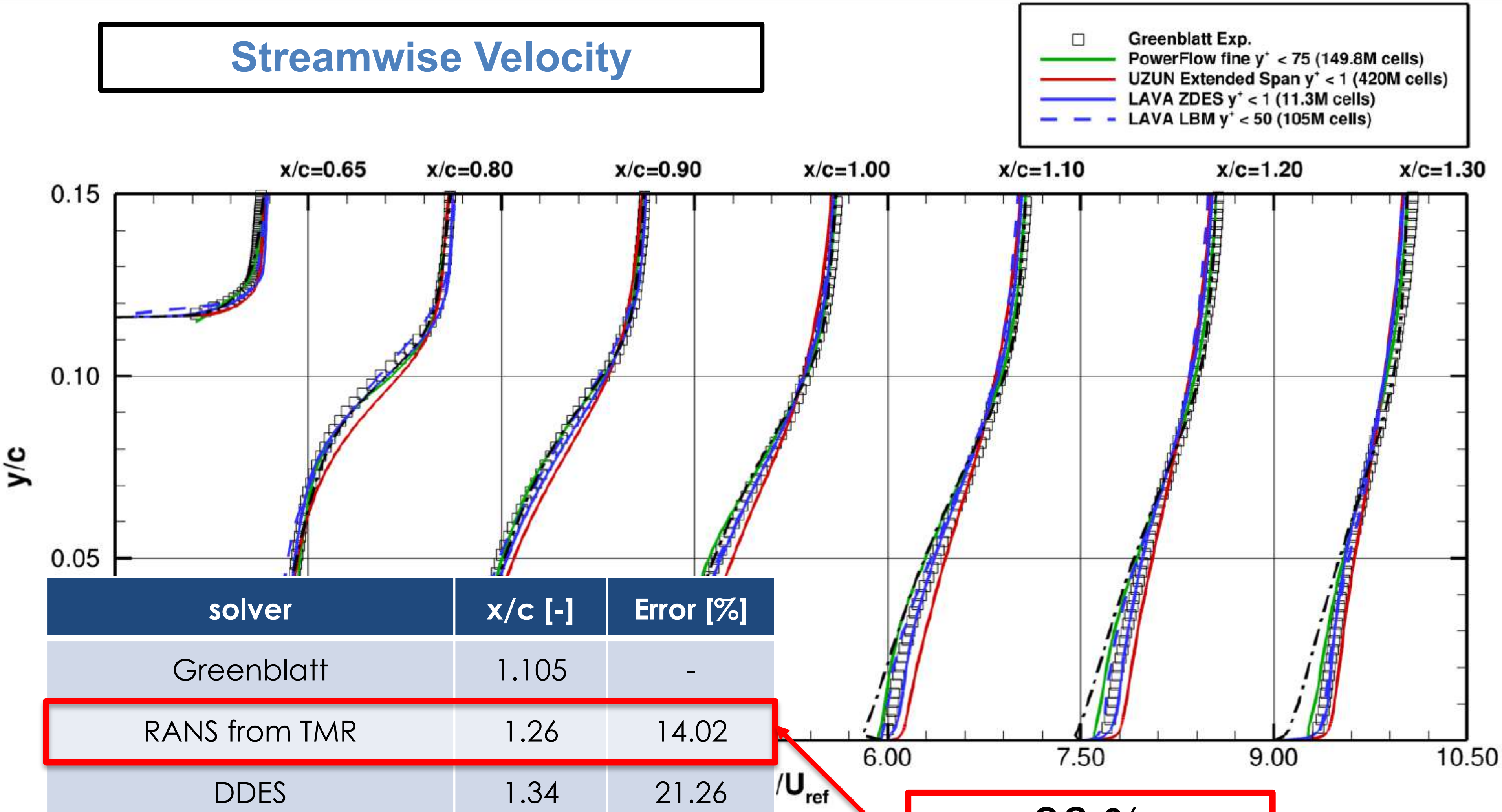
Streamwise Velocity



✓ Excellent agreement with measurements

NASA 2-D Hump – Application of Lattice Boltzmann

Streamwise Velocity

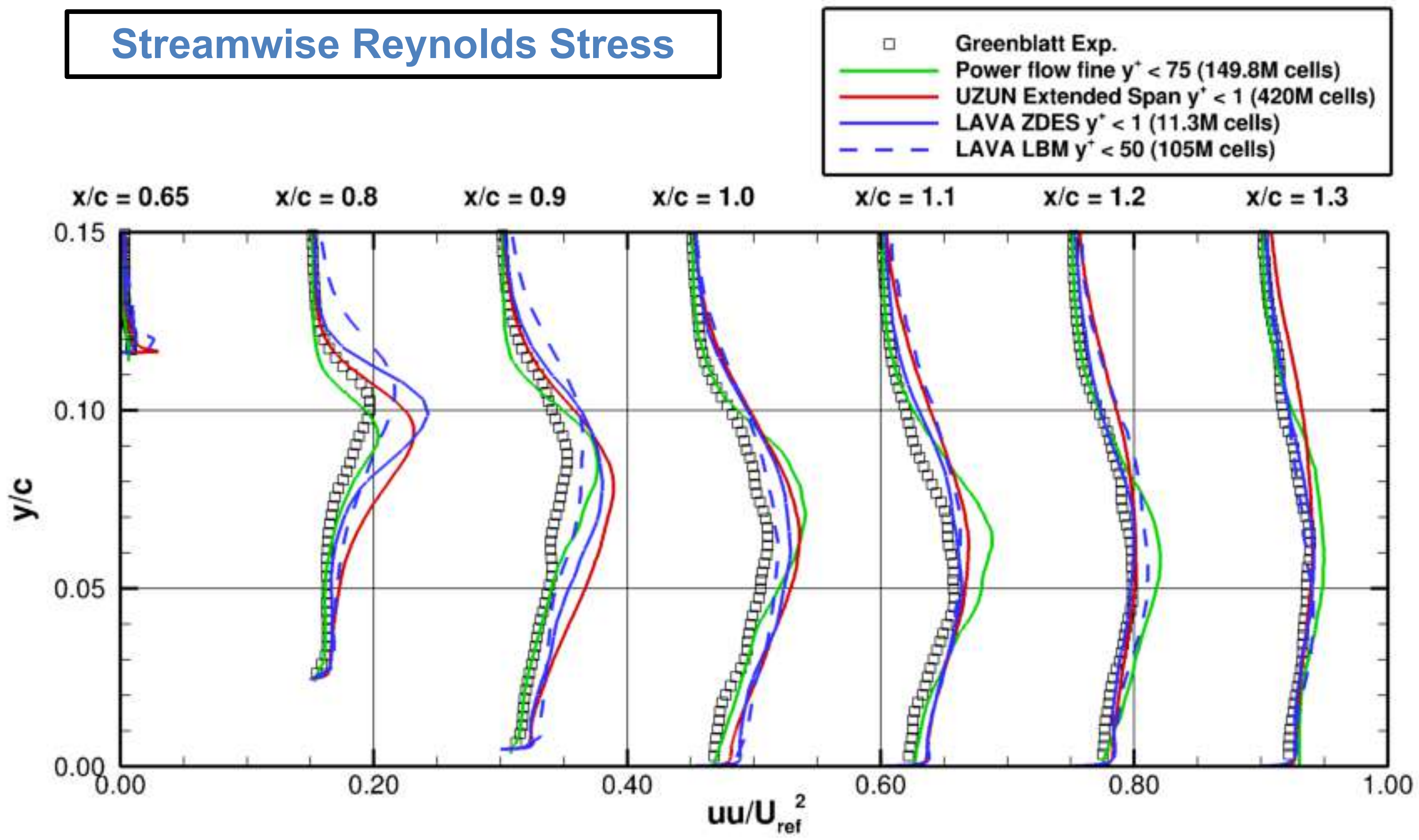


solver	x/c [-]	Error [%]
Greenblatt	1.105	-
RANS from TMR	1.26	14.02
DDES	1.34	21.26
DDES + SEM	1.23	11.31
ZDES + SEM	**1.11**	**0.45**

96 % improvement

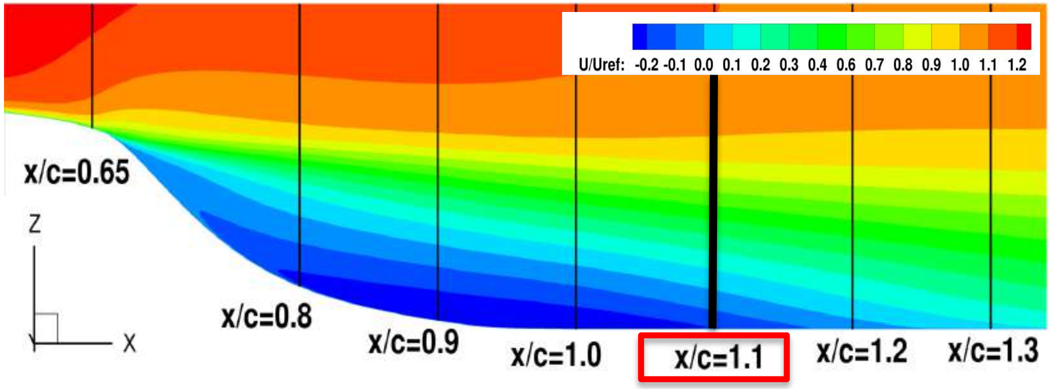
]

NASA 2-D Hump – Application of Lattice Boltzmann

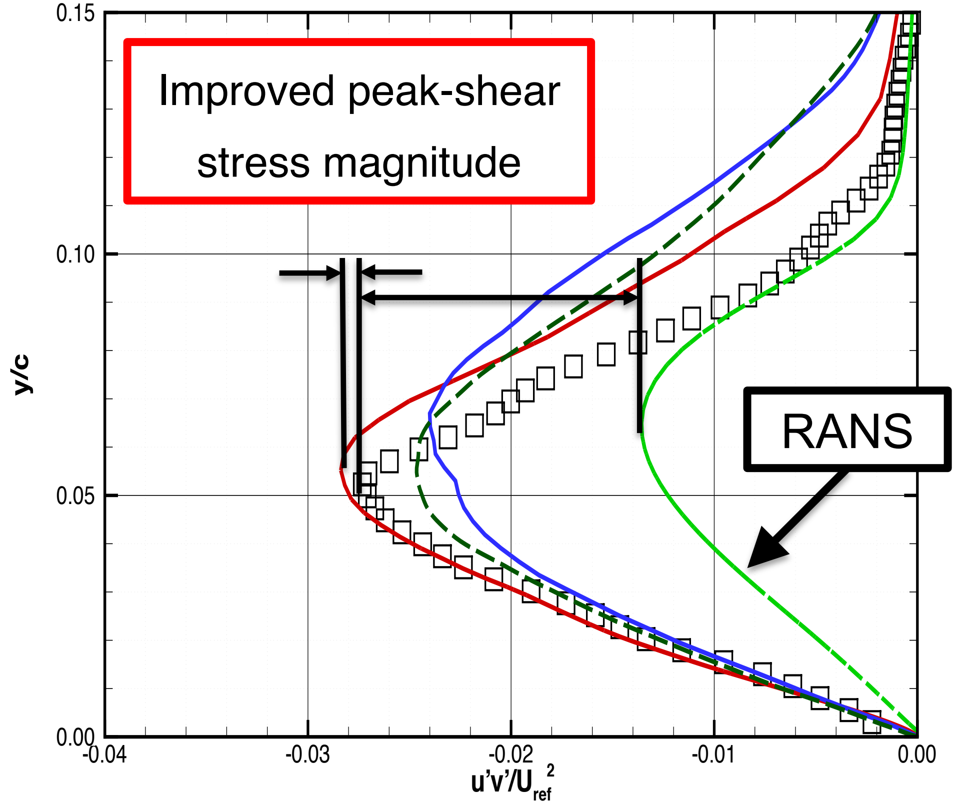


- ✓ Encouraging agreement with experiment for turbulence intensity profiles

NASA 2-D Hump – Application of Lattice Boltzmann



□ Greenblatt et.al.
LAVA ZDES Mode 3 $y^+ < 1$ (11.3M cells)
LAVA LBM $y^+ < 50$ (105M cells)
UZUN Extended Span $y^+ < 1$ (420M cells)
PowerFlow fine $y^+ < 75$ (148.9M cells)
PowerFlow periodic $y^+ < 75$ (148.9M cells)



Improved peak-shear stress magnitude

RANS

Picture credit: *NASA / Lillian Gipson*

Towards Urban Air Mobility (UAM)

High-Fidelity Modeling and Optimization Method Development

NASA Revolutionary Vertical Lift Technology Rotary Project (RVLT)

Isolated UAS Rotor in Hover Validation

Objective:

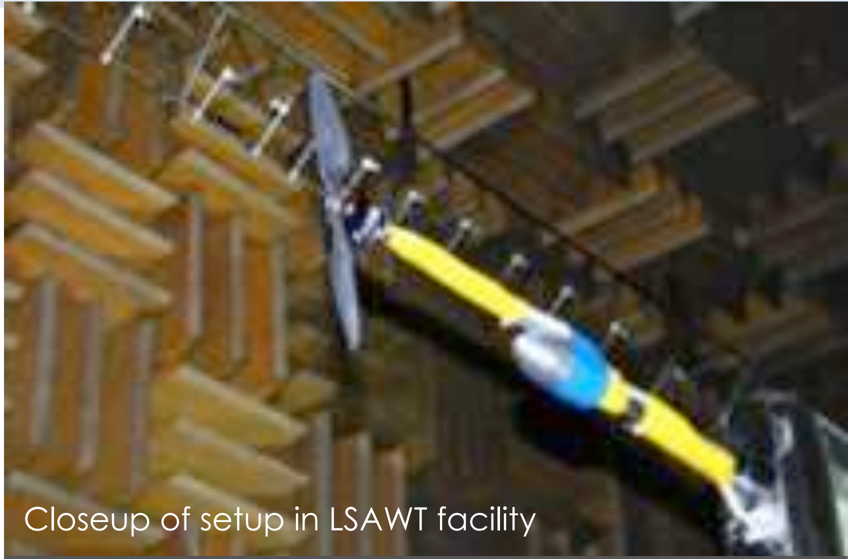
- ✓ Validate LAVA for RVLT applications
- ✓ Assess pros and cons of body-fitted/Cartesian Grid as well as Navier-Stokes/Lattice Boltzmann approaches

Computational Methodology :

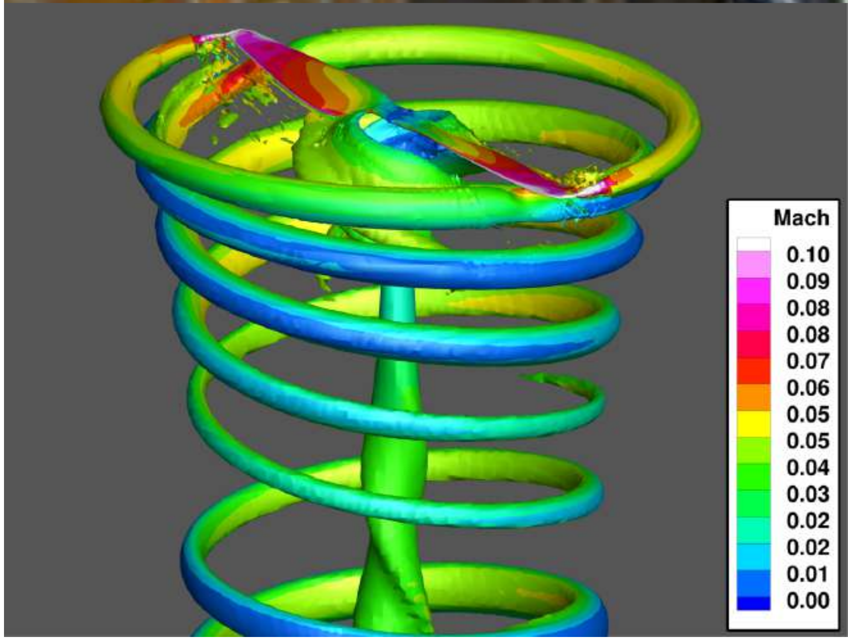
- ✓ Navier-Stokes (NS) URANS solver on Structured Overset Grid
- ✓ Navier-Stokes as well as Lattice Boltzmann (LB) on Cartesian Grid

Validation:

- ✓ Propeller Performance
- ✓ Far-field Acoustics



Closeup of setup in LSAWT facility

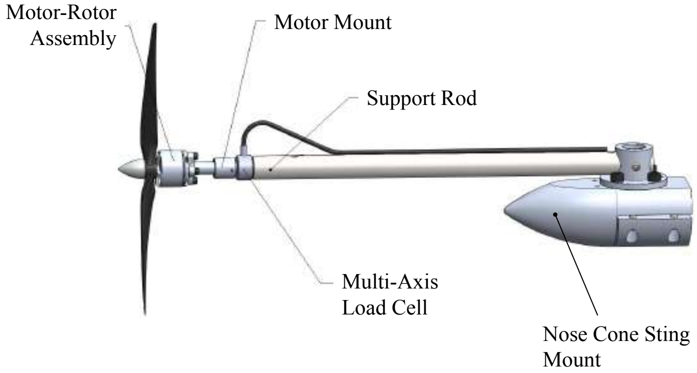


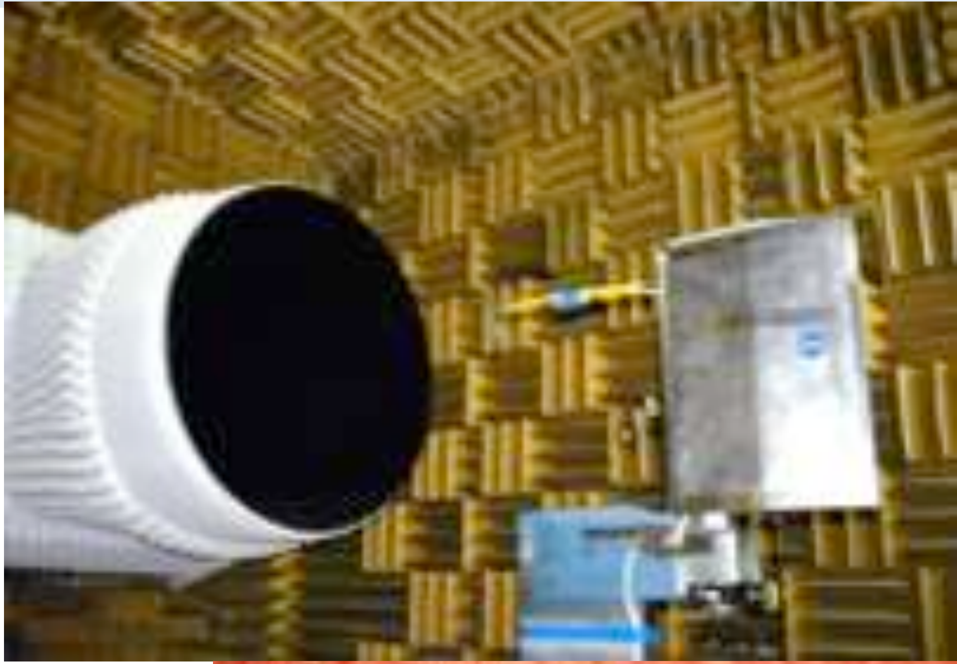
LAVA uRANS simulation at 5400 RPM

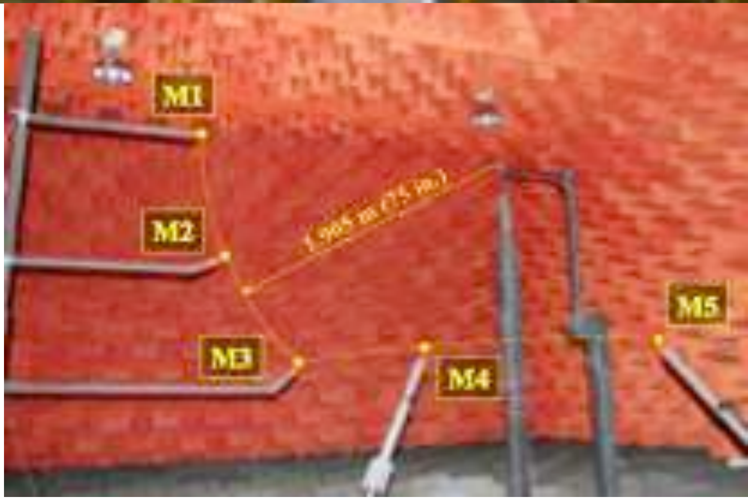
Experimental Data from Zawodny and Haskin AIAA-2017-3709

Isolated UAS Rotor in Hover Validation

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



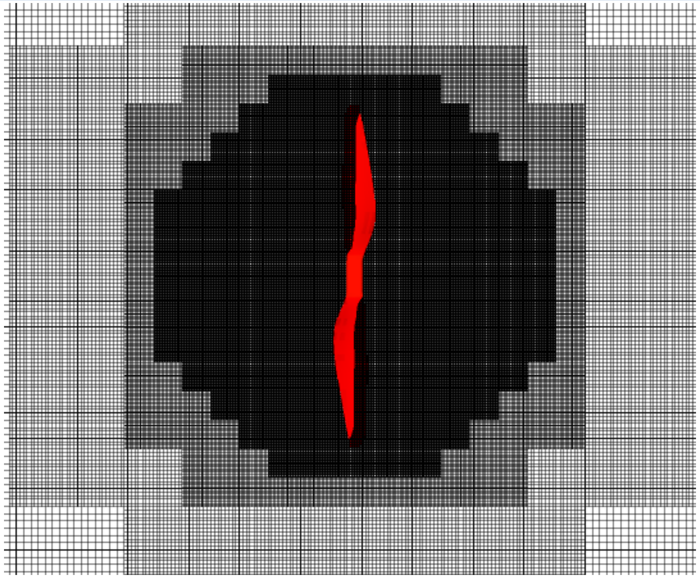




- ✓ Experiments conducted at NASA Langley LSAWT as well as in the Structural Acoustics Loads and Transmission (SALT) anechoic chamber.
- ✓ Motor-Rotor Assembly as well as Mount and Support structure not considered in simulations.

Experimental Data from Zawodny and Haskin AIAA-2017-3709

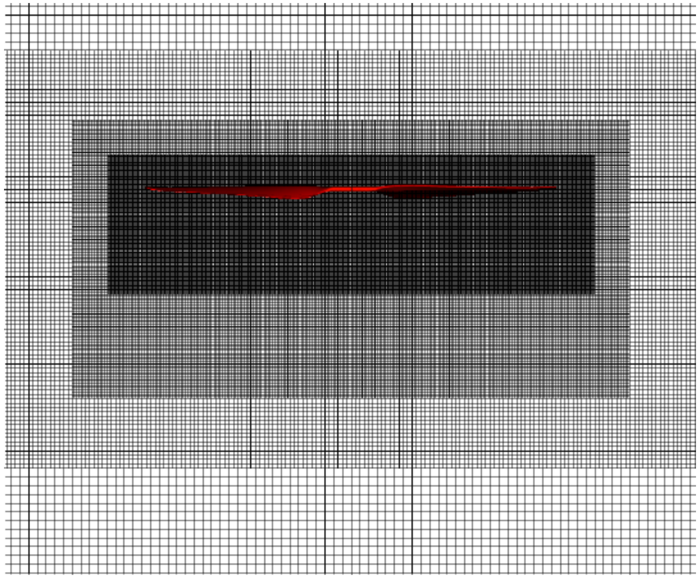
LAVA Cartesian Methods



Lattice Boltzmann
(LBM – EMRT)

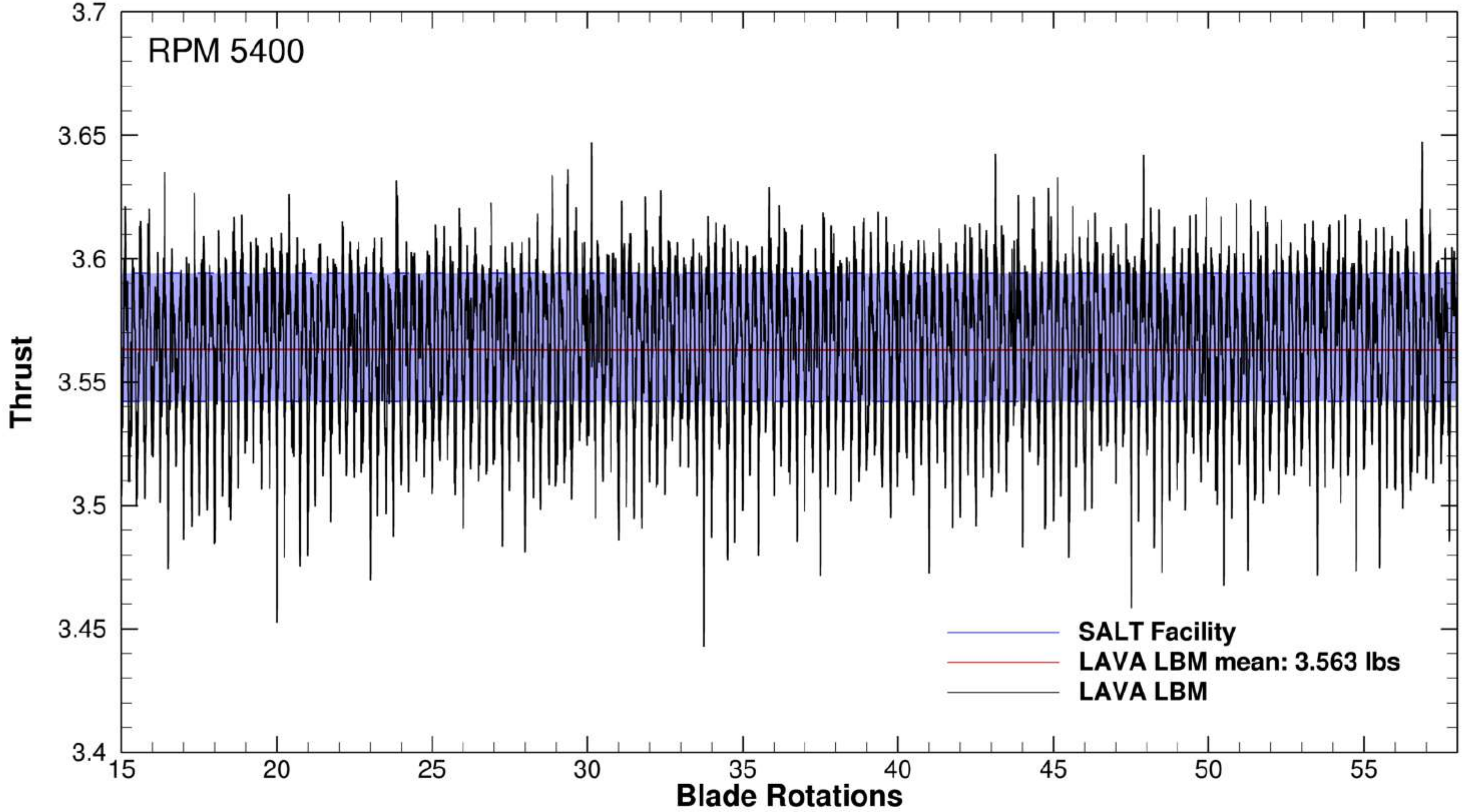
Navier-Stokes
(NS – WENO6)

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



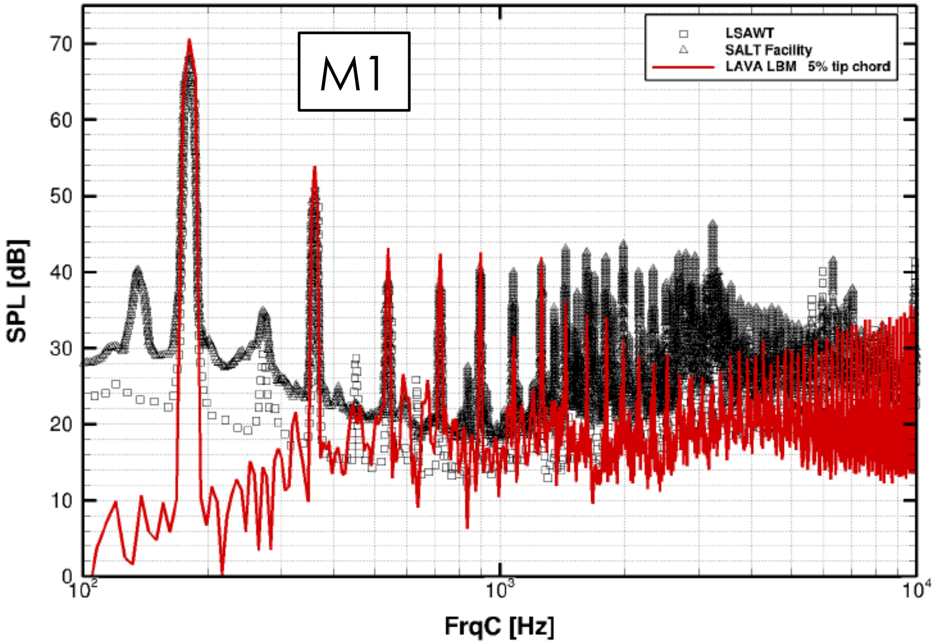
Isocontour of Q-criterion colored by Pressure. Simulation on medium Cartesian mesh.

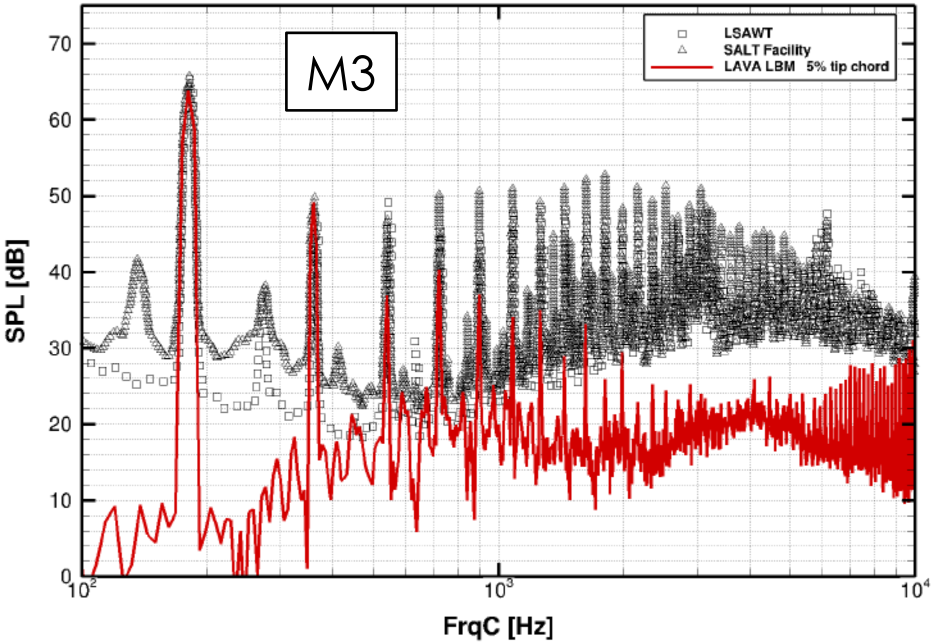
Lattice Boltzmann Method
Rotor Performance at 5400 RPM

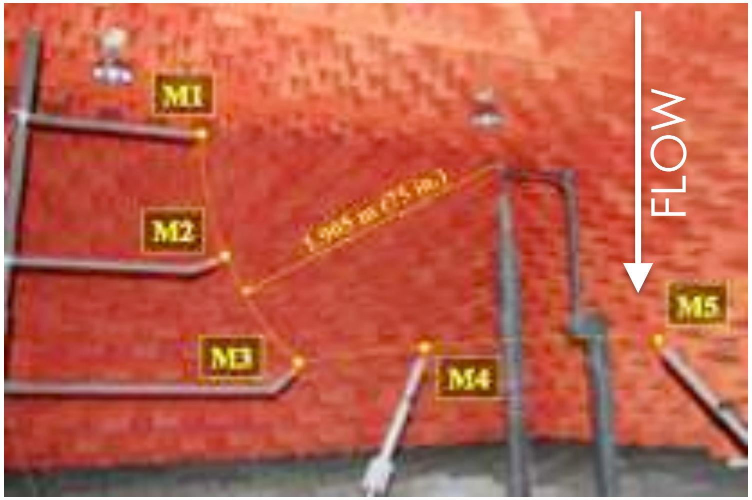


- ✓ Excellent agreement with experimental measurements
- ✓ Differences (< 1%) well within measurement uncertainty (highlighted in blue)

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

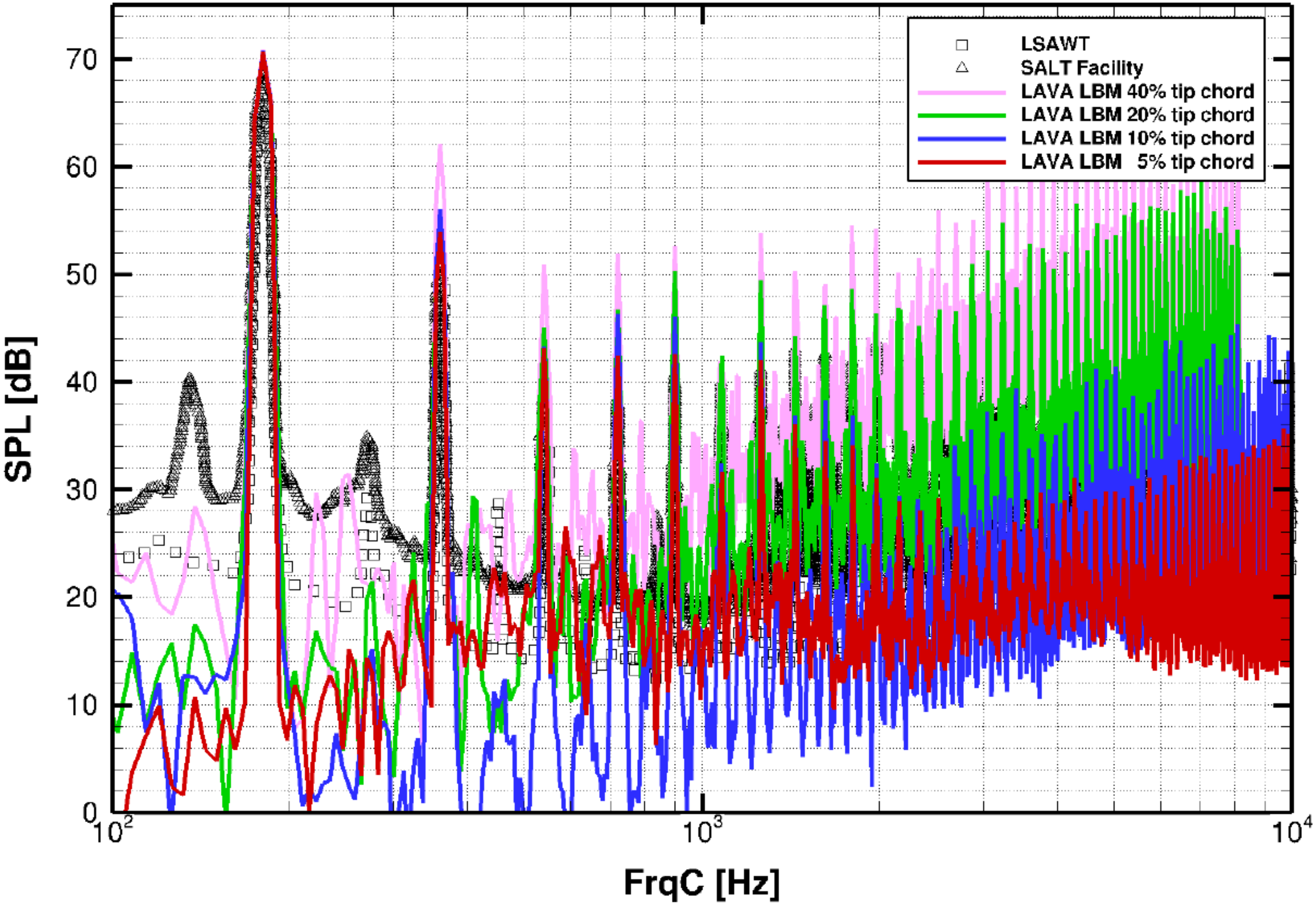






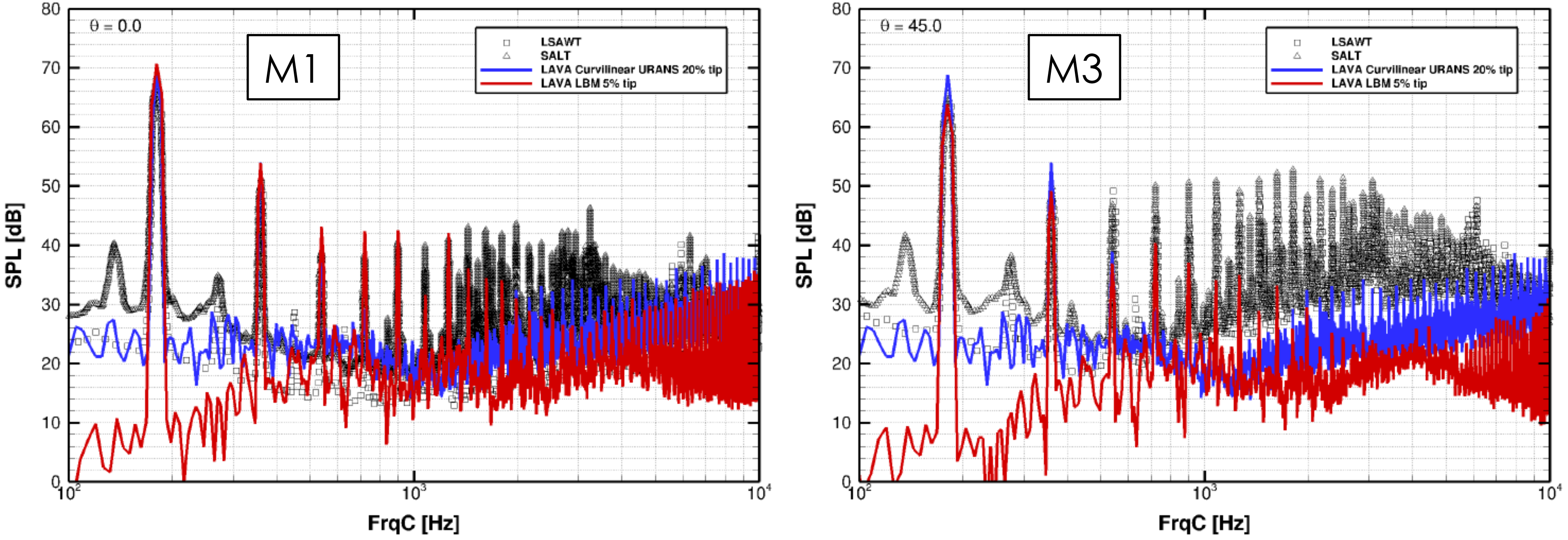
- ✓ Excellent agreement with BPF1-BPF5 for M1 (0.0°) microphone location
- ✓ Excellent agreement with BPF1 & BPF2 for M3 (45.0°)
- ✓ Different FWH formulations (permeable and impermeable) currently under investigation

Lattice Boltzmann Method
Farfield Noise – Mesh Refinement Study



- ✓ Consistent agreement for BPF1 on all mesh levels, BPF2 more sensitive.
- ✓ Good agreement for BPF 1 even on very coarse mesh.

Comparison between the Approaches



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

Summary

LAVA Lattice Boltzmann Solver has made significant progress towards becoming a work-horse for NASA mission critical applications:

- Ultra-high performance without any compromise in fidelity
- Completely automated workflow without labor intensive mesh generation

Acknowledgments

- ✓ This work was partially supported by the NASA ARMD’s Transformational Tools and Technologies (T^3), Advanced Air Transport Technology (AATT), Revolutionary Vertical Lift Technology (RVLT) projects

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

Questions?

Computational Resources for Wall Mounted Hump case

✓ All simulations performed on NASA Pleiades Cluster using Intel Xeon E5-2680v4

LAVA curvilinear ZDES Mode 3 : 240 CPUh/CTU
LAVA LBM-LES : 614 CPUh/CTU
Exa Powerflow LBM-VLES[1] : 540 CPUh/CTU

2.5x slower

very close to LAVA-LBM timings

LAVA curvilinear ZDES Mode 3 : $\Delta t = 1.8E^{-5}$
LAVA LBM-LES : $\Delta t = 4.6E^{-7}$

39x smaller

LAVA curvilinear ZDES Mode 3 : 11.3M grid points
Lattice LBM-LES : 105M grid points

9x more

[1] Duda and Fares. Apllication of a Lattice-Boltzmann Method to the Separated flow over the NASA hump. (AIAA-2016-1836)