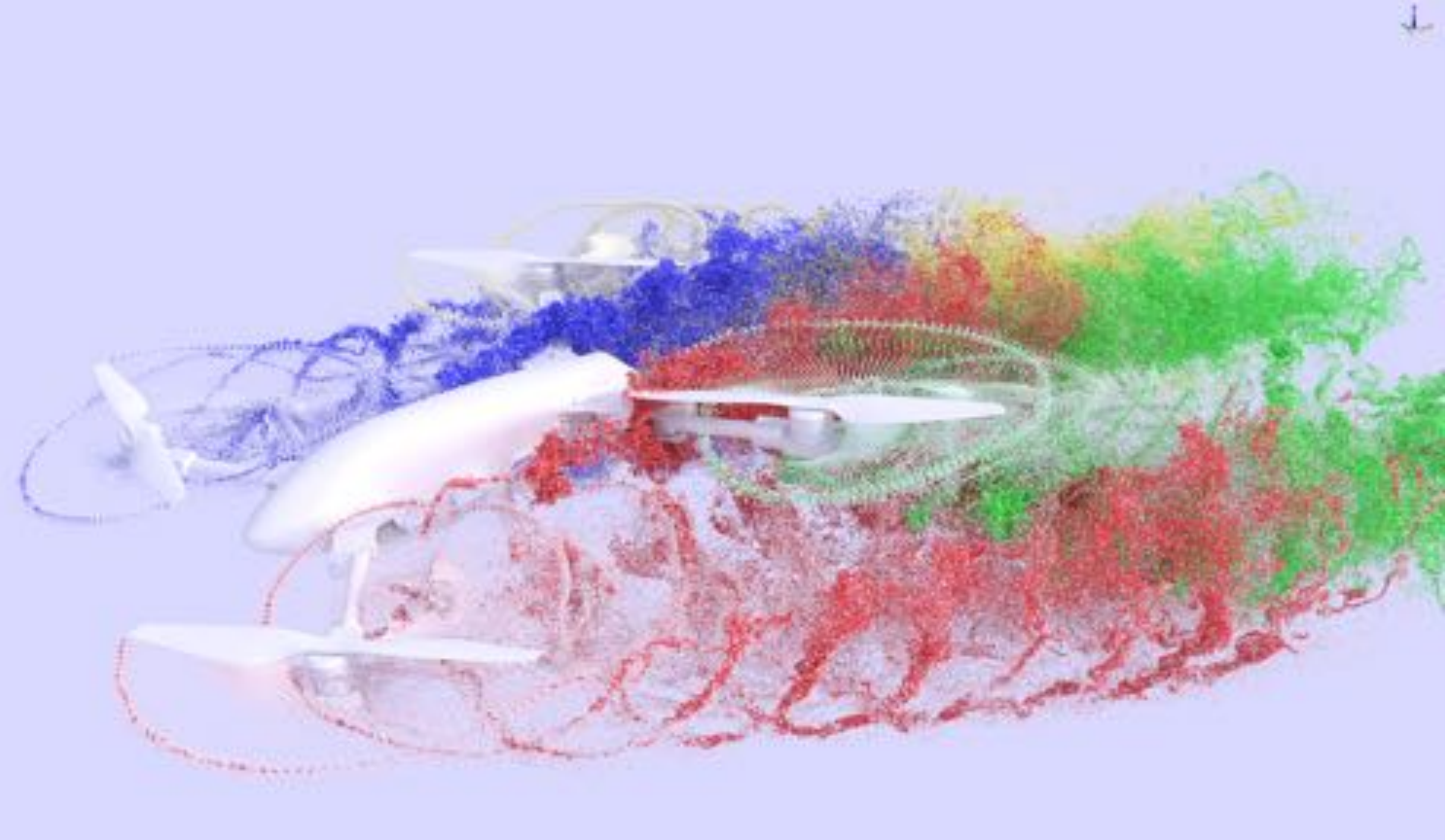


Predicting Quadcopter Drone Noise Using the Lattice Boltzmann Method

Francois Cadieux, Michael Barad, James Jensen, and Cetin Kiris

Computational Aerosciences Branch

NASA Ames Research Center

Supercomputing 2019

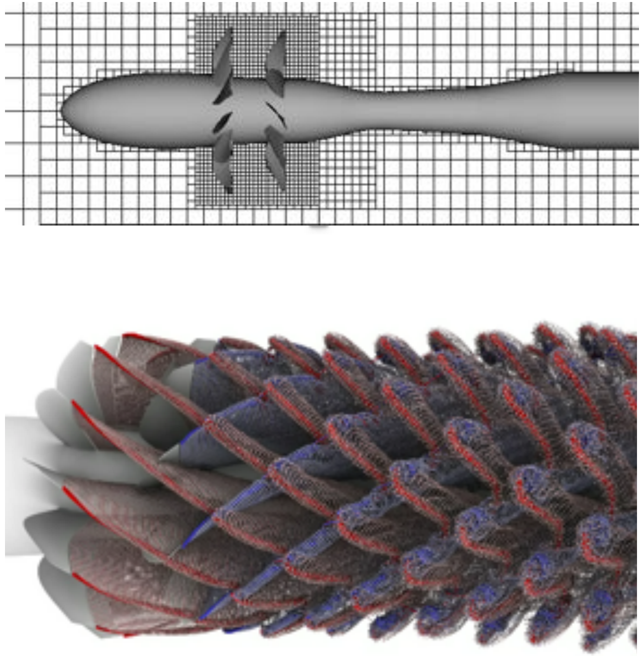
Motivation

- Community noise is a major concern for drone delivery of packages and for urban air mobility vehicles (air taxis)
- Rotor tonal noise is fairly well-understood and can be predicted accurately with simple tools
- Multi-rotor interaction and rotor-fuselage interaction is harder, but still within the realm of possibility
- Reliable and accurate predictions of broadband noise of a full multi-rotor vehicle have yet to be demonstrated

Picture credit: *NASA / Lillian Gipson*

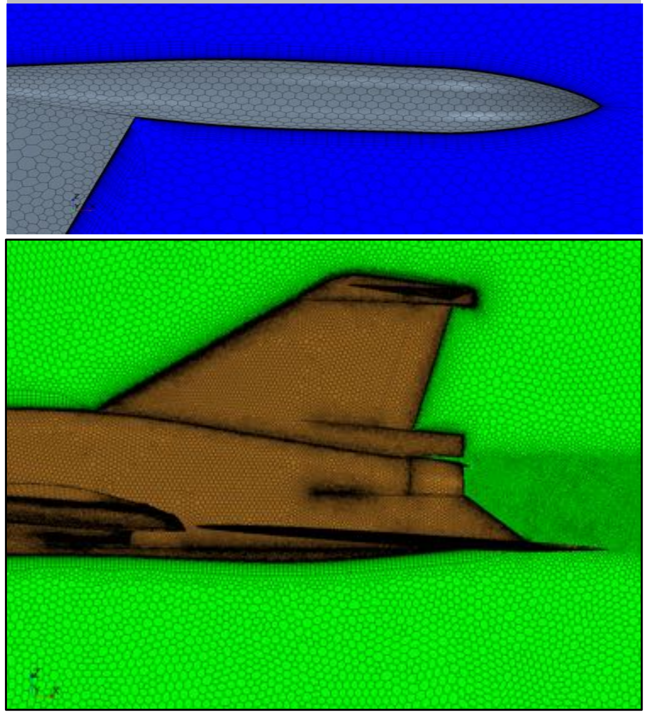
CFD Grid Paradigms

Structured Cartesian AMR



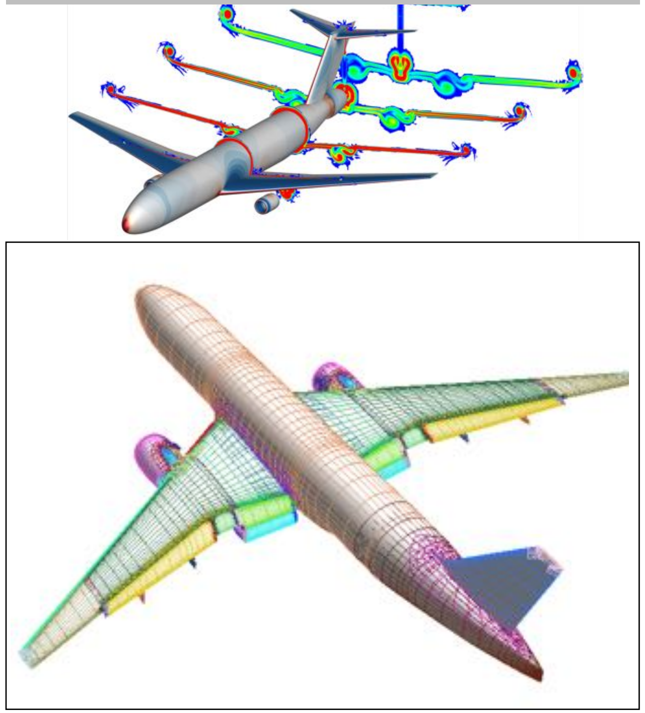
- Essentially no manual grid generation
- Highly efficient structured Adaptive Mesh Refinement (AMR)
- Low computational cost
- Reliable higher order methods
- Non-body fitted -> Resolution of boundary layers inefficient

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

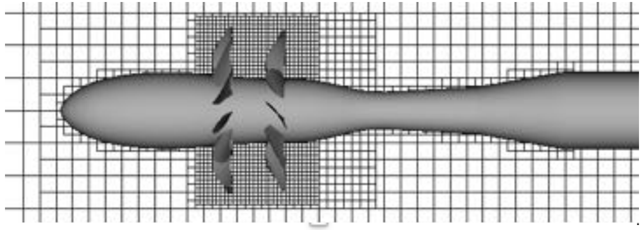
Structured Curvilinear



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

CFD Grid Paradigms

Structured Cartesian AMR

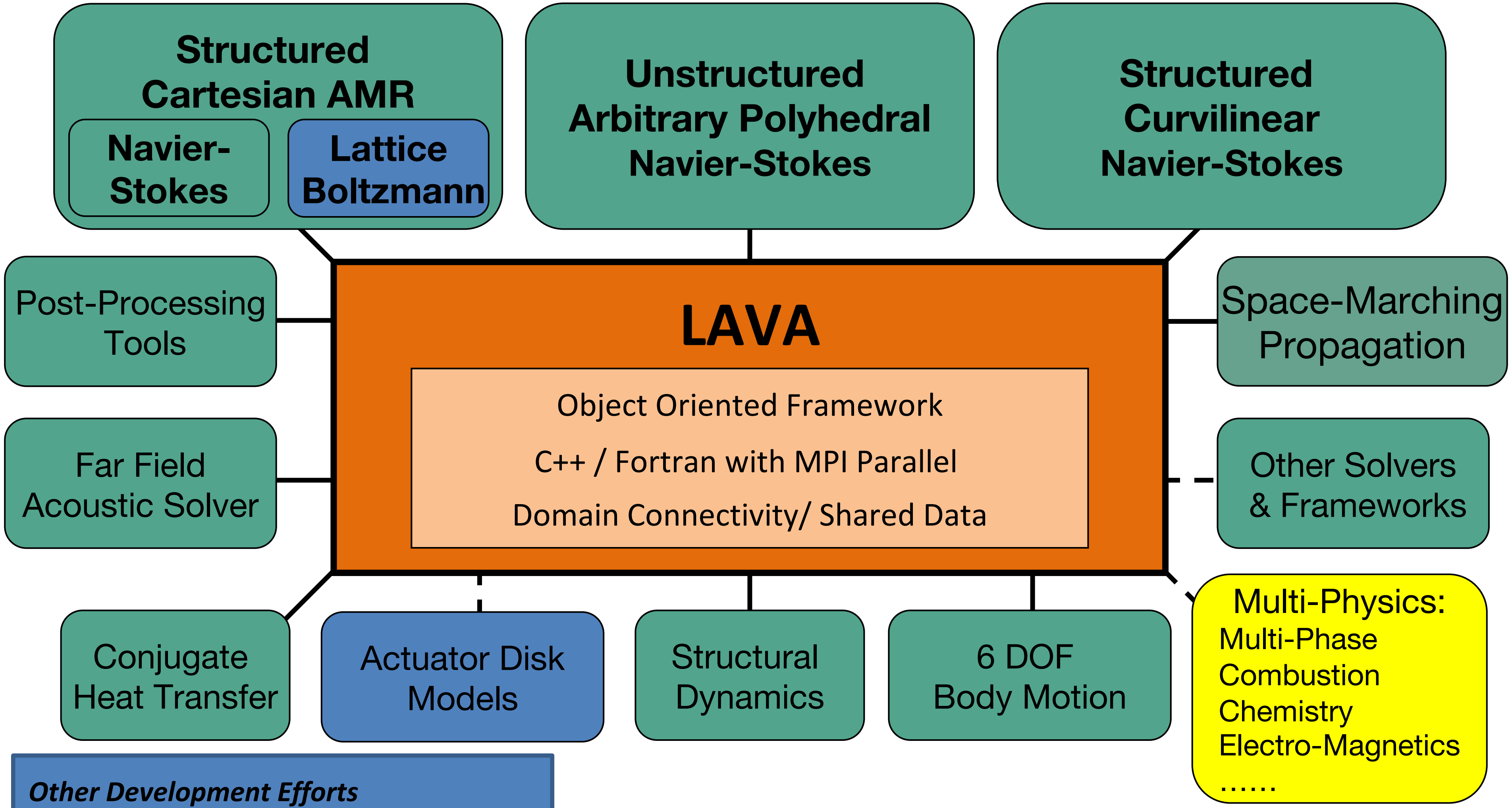


- Essentially no manual grid generation
- Highly efficient structured Adaptive Mesh Refinement (AMR)
- Low computational cost
- Reliable higher order methods
- Non-body fitted -> Resolution of boundary layers inefficient

Predict multi-rotor and rotor-fuselage interaction noise, including broadband noise for a quadcopter:

- Simulate complex vehicle without simplification
  - ✓ Automatic mesh generation and immersed boundary representation
- Track all sources of noise as they propagate
  - ✓ Adaptive mesh refinement (AMR) using on-the-fly statistics
- Capture acoustic waves from 135 Hz to 18 kHz
  - ✓ Low-dissipation high-resolution scheme (EMRT) can capture waves accurately with only 5 cells
  - ✓ Near-isotropic cells are best for predicting acoustics
  - ✓ Boundary layers do not play critical role in the quantities of interest for this project
- Short turnaround time for decision making
  - ✓ Automatic grid generation means we can get started immediately
  - ✓ Sub-cycling algorithm increases computational efficiency

Launch, Ascent, and Vehicle Aerodynamics
LAVA Framework



Structured Cartesian AMR

Navier-Stokes

Lattice Boltzmann

Unstructured Arbitrary Polyhedral Navier-Stokes

Structured Curvilinear Navier-Stokes

Post-Processing Tools

Far Field Acoustic Solver

LAVA

Object Oriented Framework

C++ / Fortran with MPI Parallel

Domain Connectivity/ Shared Data

Space-Marching Propagation

Other Solvers & Frameworks

Conjugate Heat Transfer

Actuator Disk Models

Structural Dynamics

6 DOF Body Motion

Multi-Physics:
Multi-Phase
Combustion
Chemistry
Electro-Magnetics
……

Other Development Efforts
- Higher order and low dissipation
- Curvilinear grid generation
- Wall modeling
- LES/DES/ILES Turbulence
- HEC (optimizations, accelerators, etc)

——— Connected

- - - Not Yet Connected

Existing

Developing

Future

Framework

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

Why Lattice-Boltzmann?

10X faster and extremely accurate*

No manual CFD mesh generation

Fast turnaround time

---

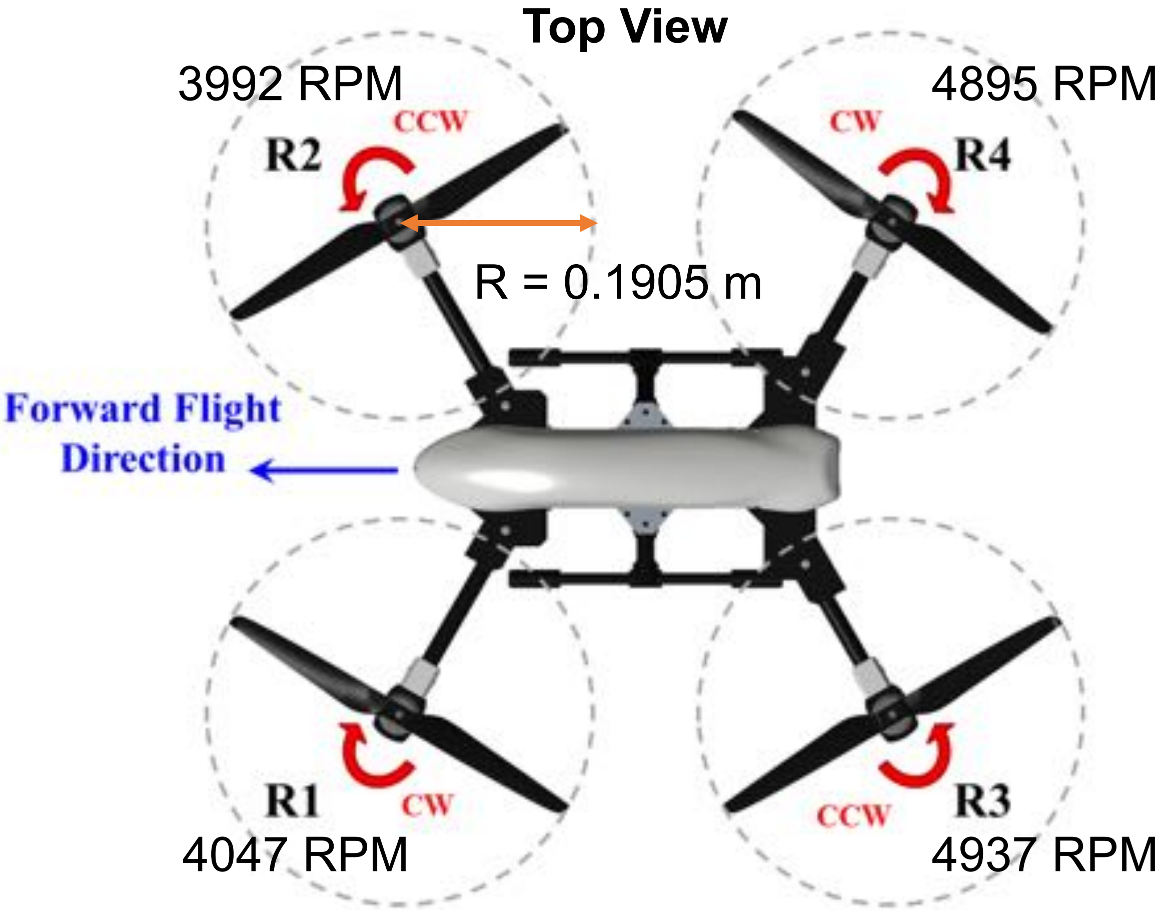
*to perform scale-resolving simulations of low Mach number flows

Objective

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

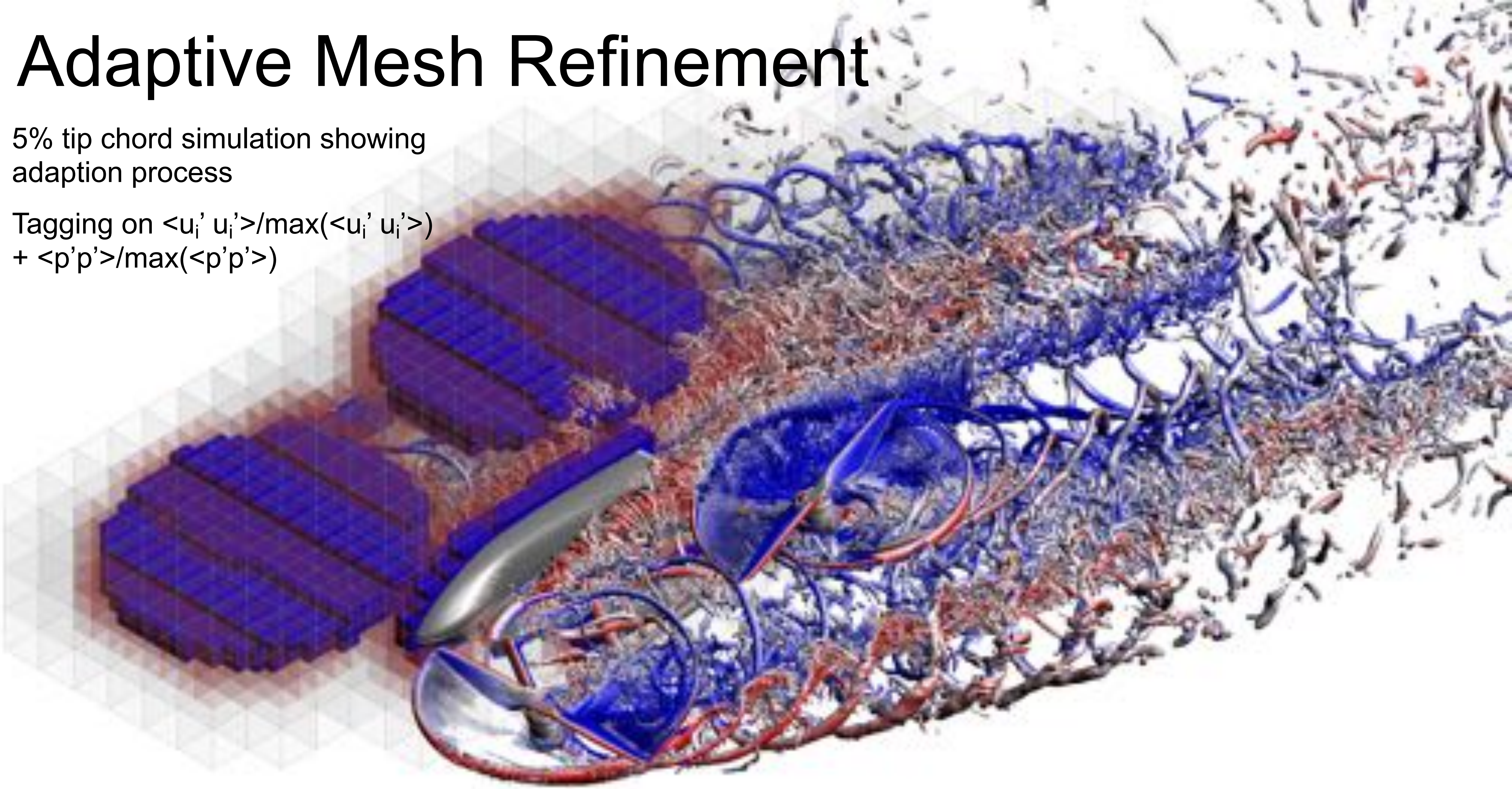
Zawodny, Nikolas, and Nicole Pettingill. "Acoustic wind tunnel measurements of a quadcopter in hover and forward flight conditions." *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*. Vol. 258. No. 7. Institute of Noise Control Engineering, 2018.

Mach = 0.045, AoA = -10°



Adaptive Mesh Refinement

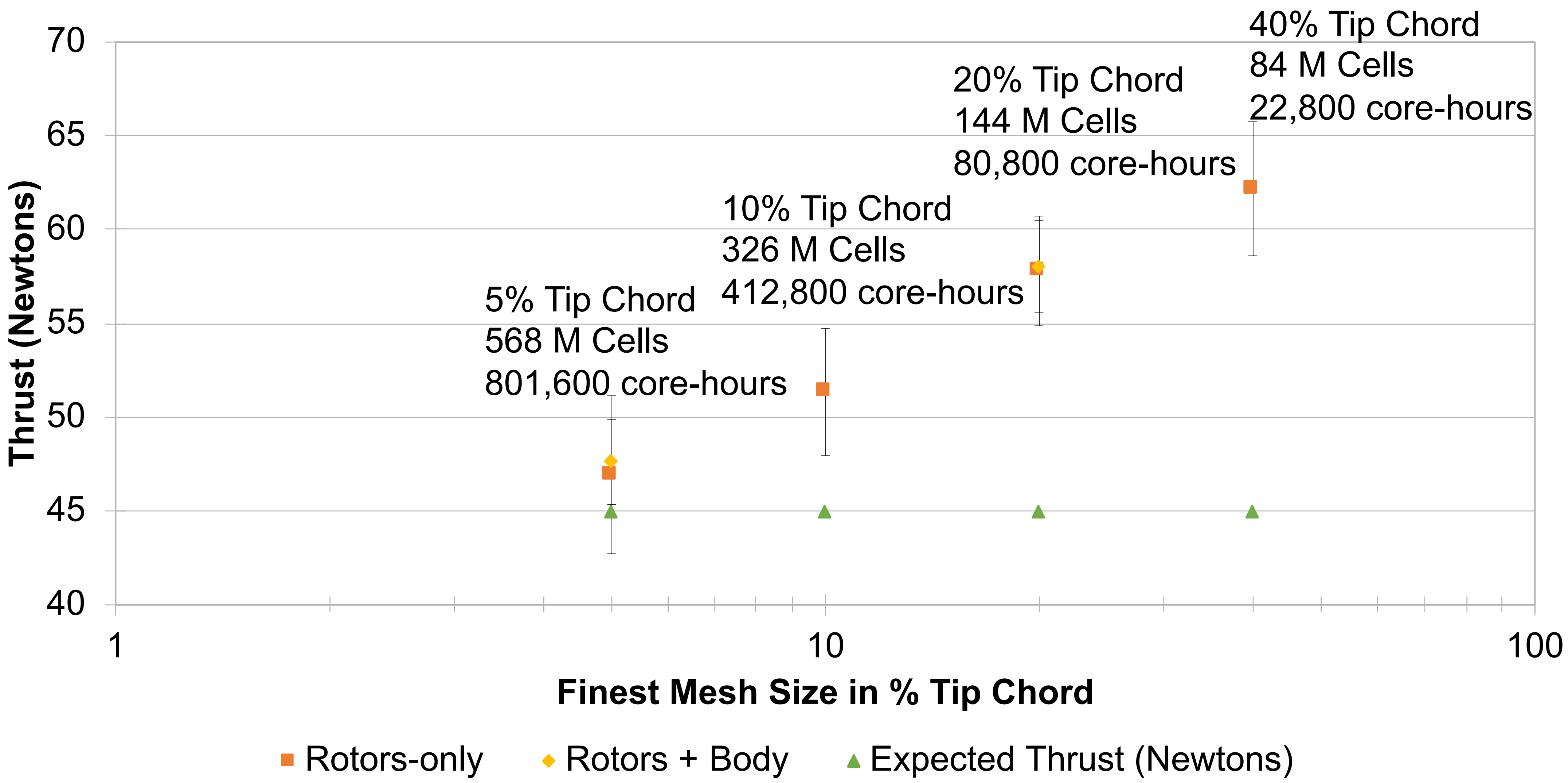
- 5% tip chord simulation showing adaption process
- Tagging on $\langle u_i' u_i' \rangle / \max(\langle u_i' u_i' \rangle) + \langle p'p' \rangle / \max(\langle p'p' \rangle)$

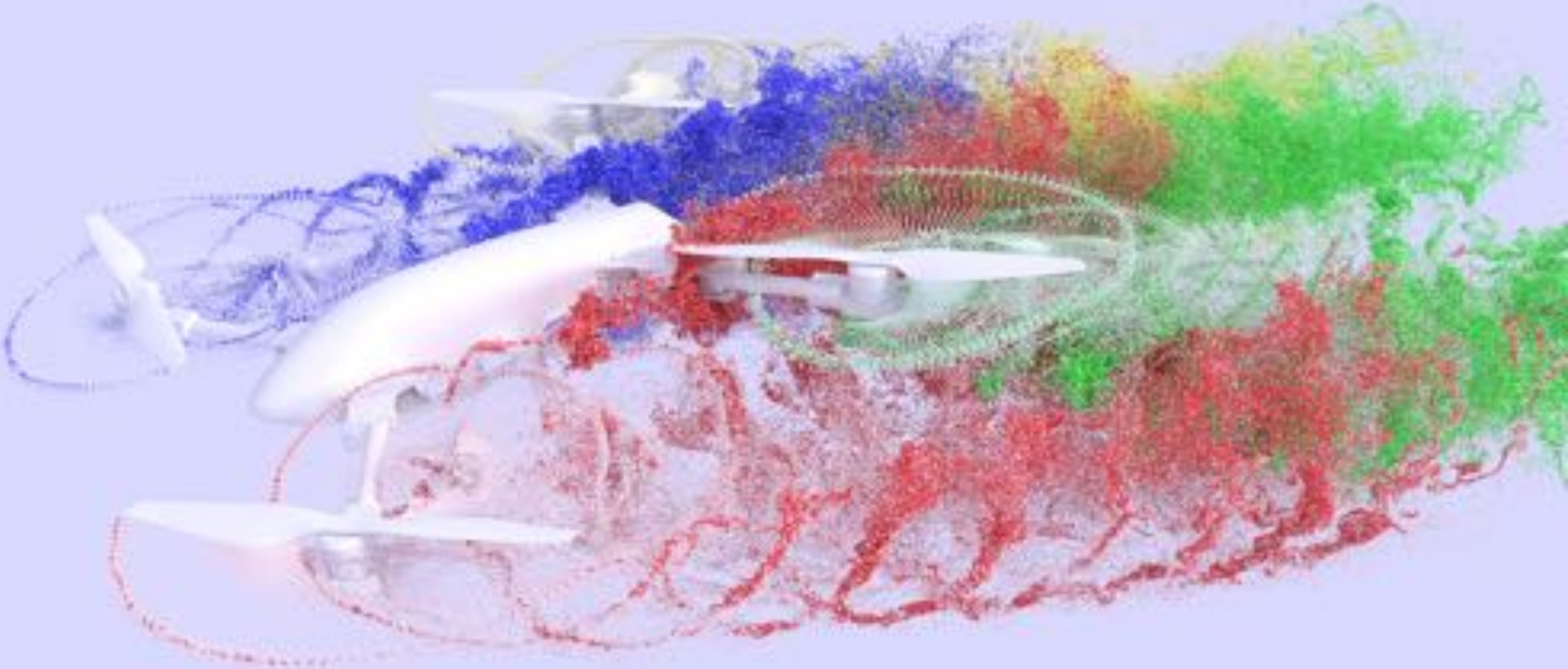


- Left: 3 finest mesh levels box distribution
- Boxes each contain 32^3 cells

- Right: Isosurfaces of Q-Criterion colored by vertical velocity

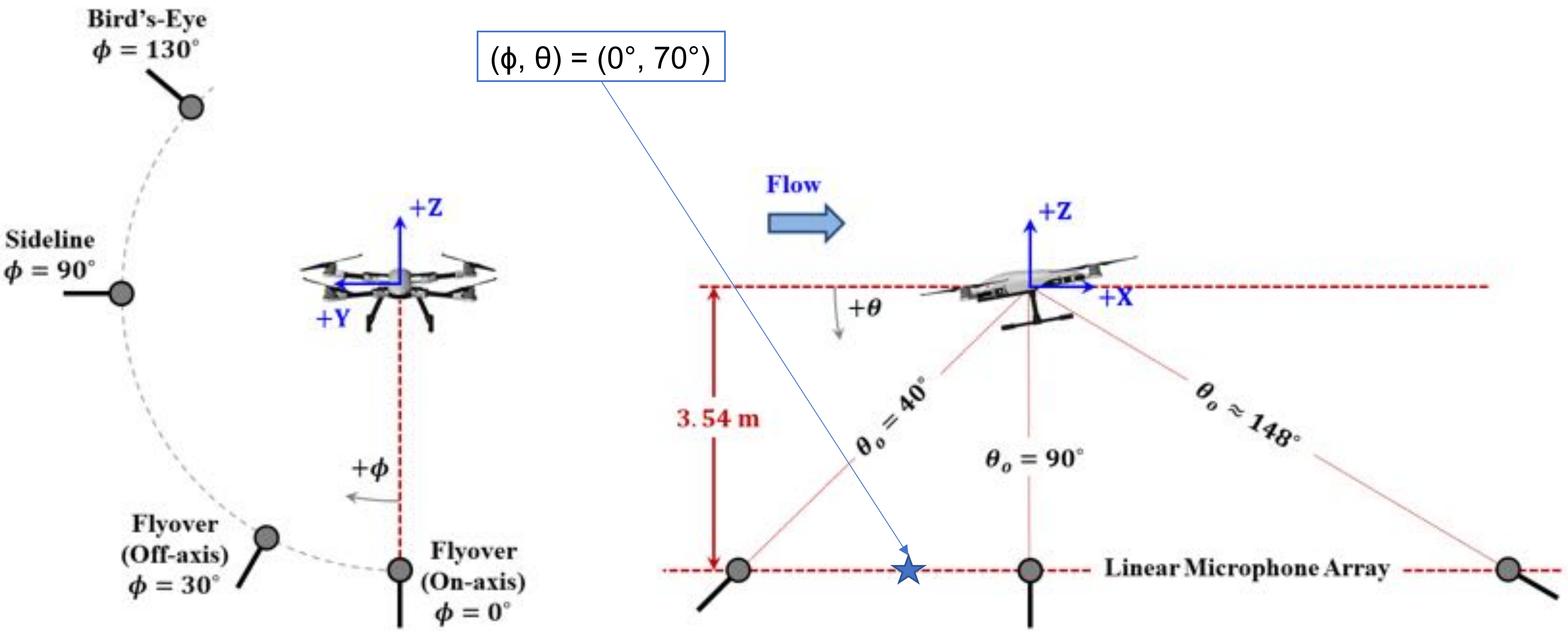
Mesh Convergence of Thrust





Animation Credit: Timothy Sandstrom

Microphone Location

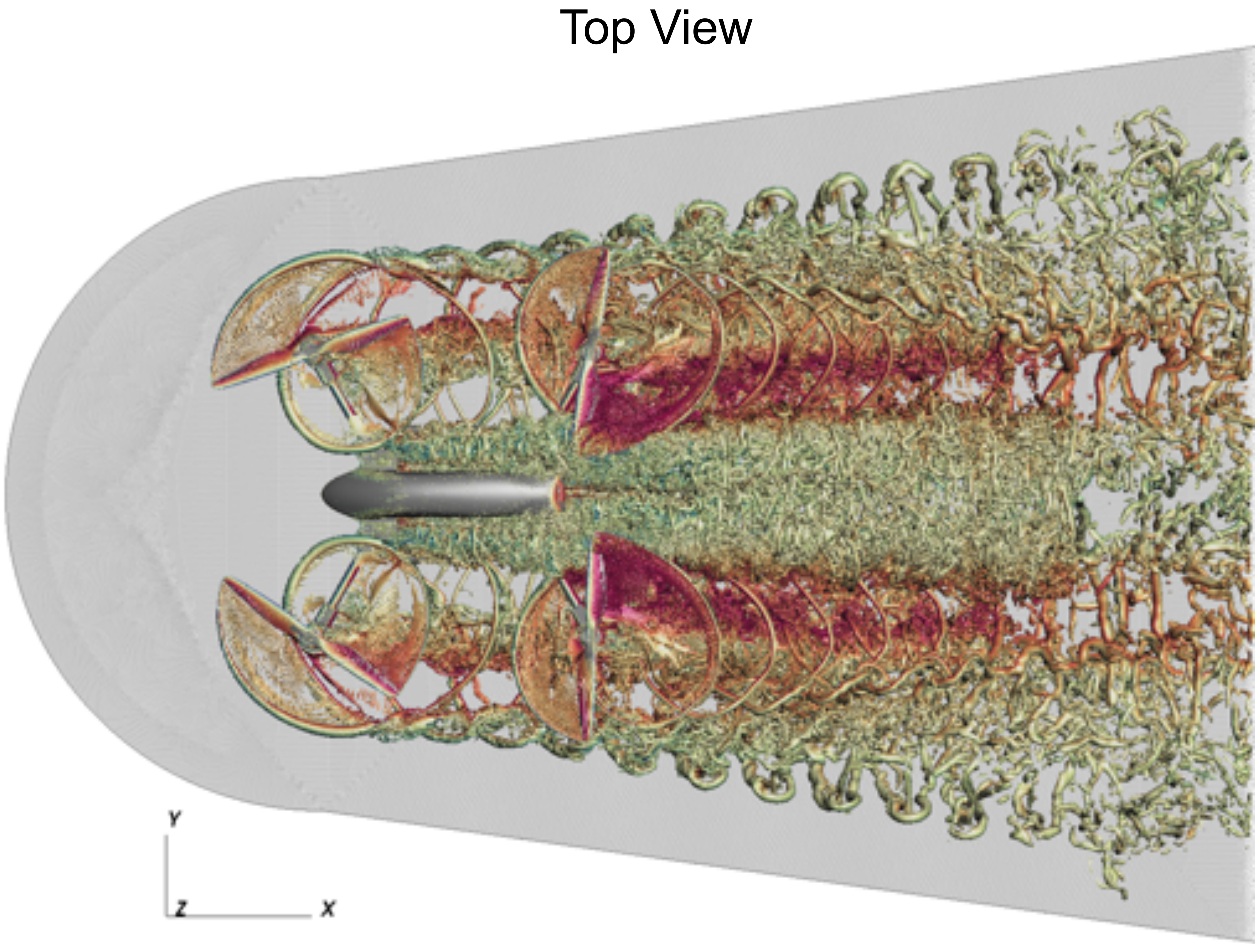


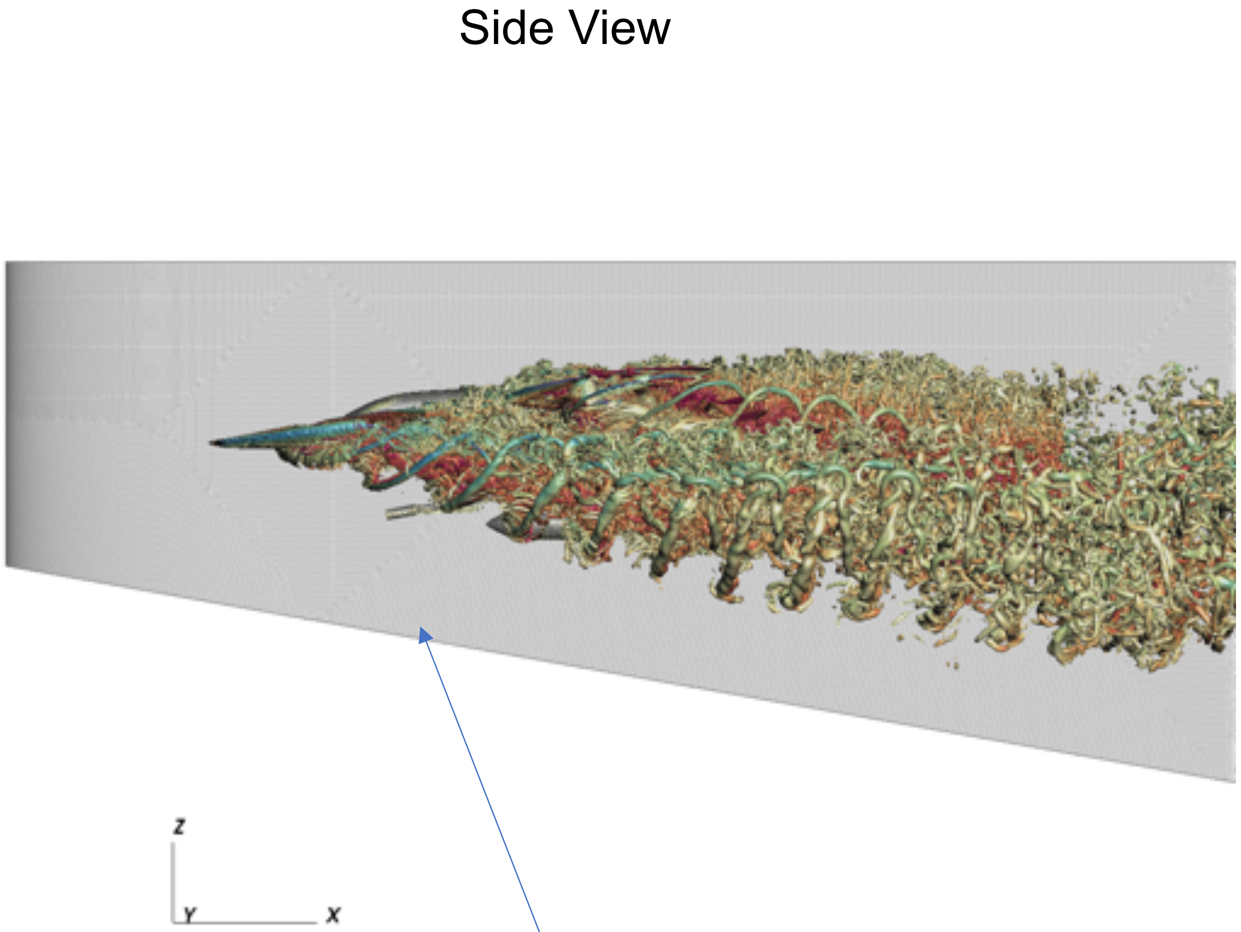
Front View

Side View

Zawodny, Nikolas, and Nicole Pettingill. "Acoustic wind tunnel measurements of a quadcopter in hover and forward flight conditions." *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*. Vol. 258. No. 7. Institute of Noise Control Engineering, 2018.

Far-Field Noise Propagation with FWH

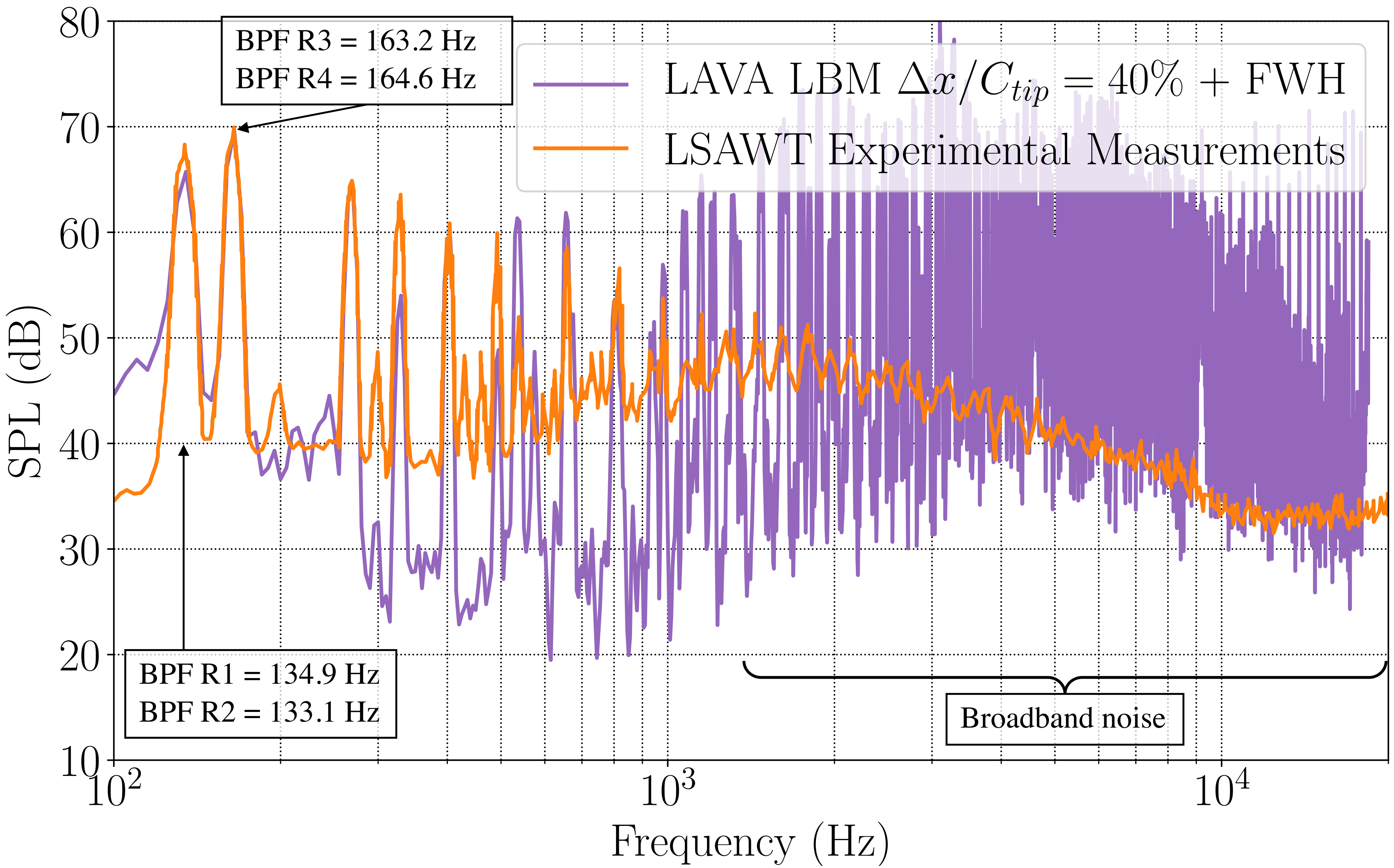




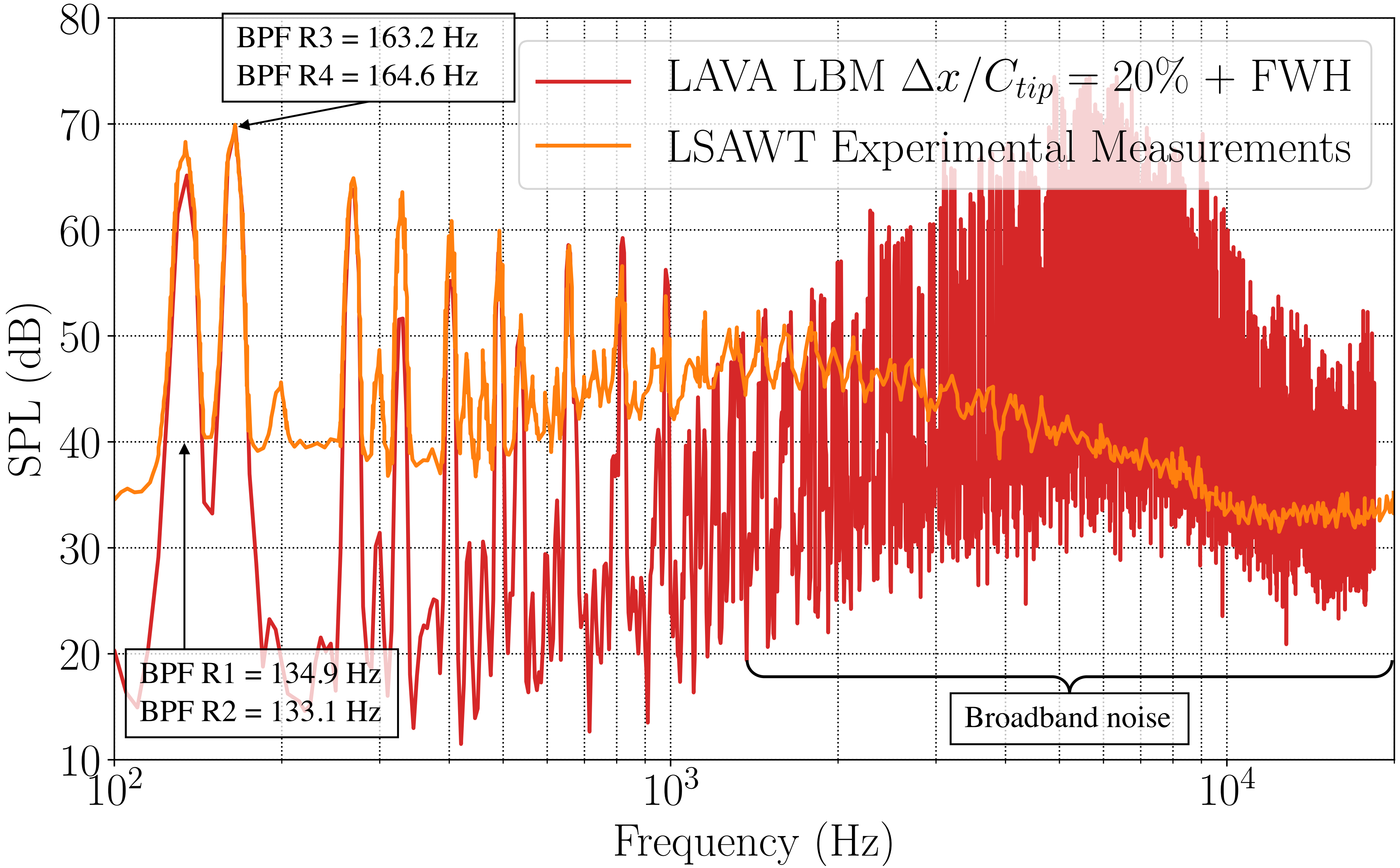
40% tip chord triangle edge length to capture up to 20 kHz

1.37 Million triangles

FWH Narrow-Band Spectra at (ϕ,θ) = (0°,70°)



FWH Narrow-Band Spectra at (ϕ,θ) = (0°,70°)



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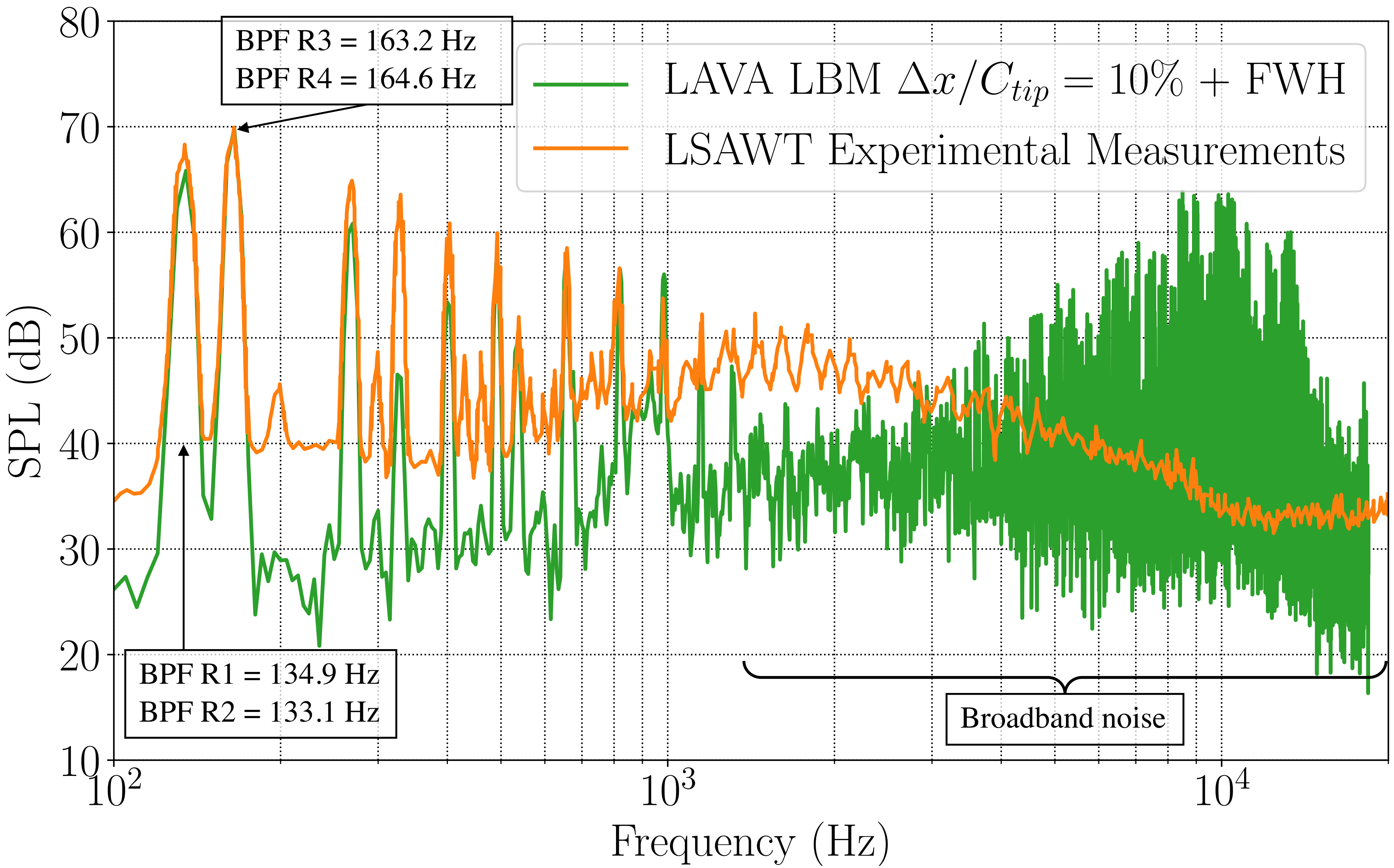

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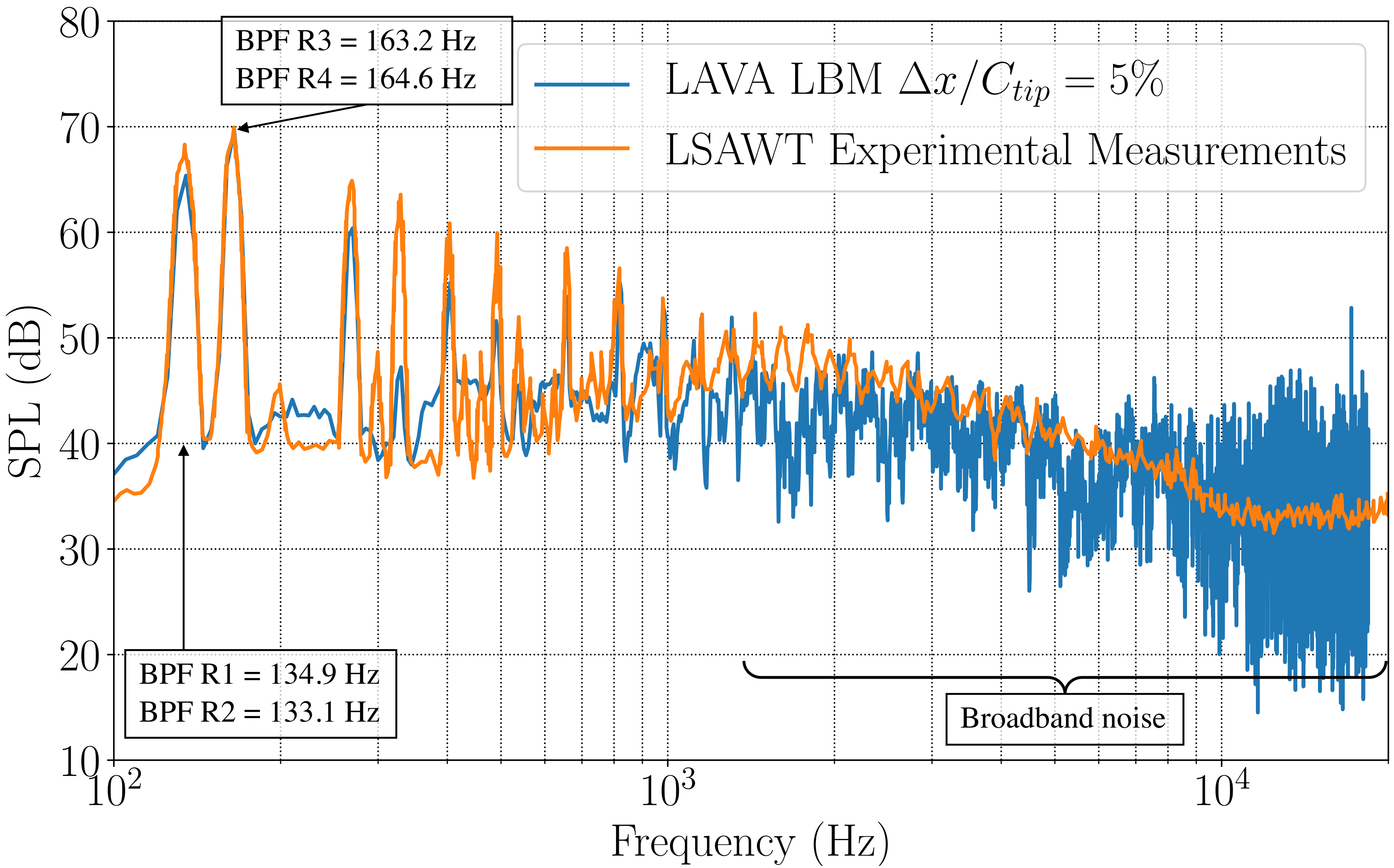
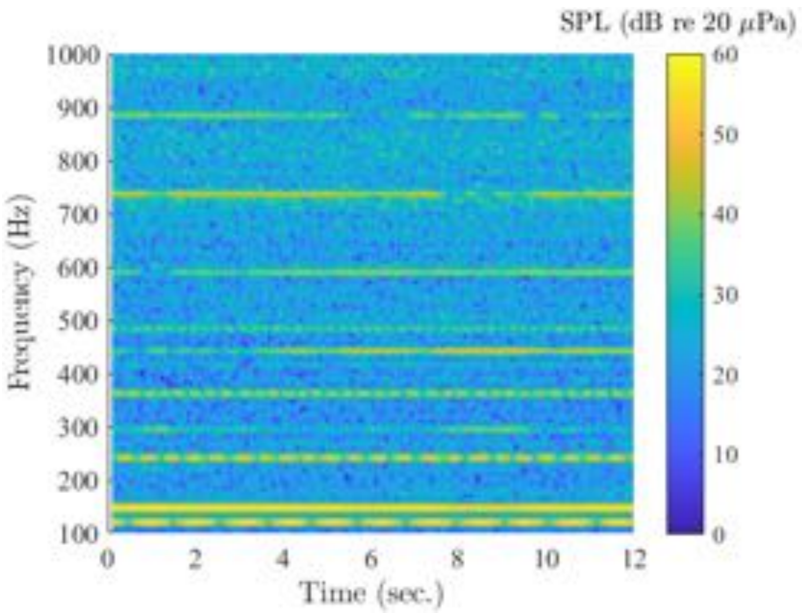
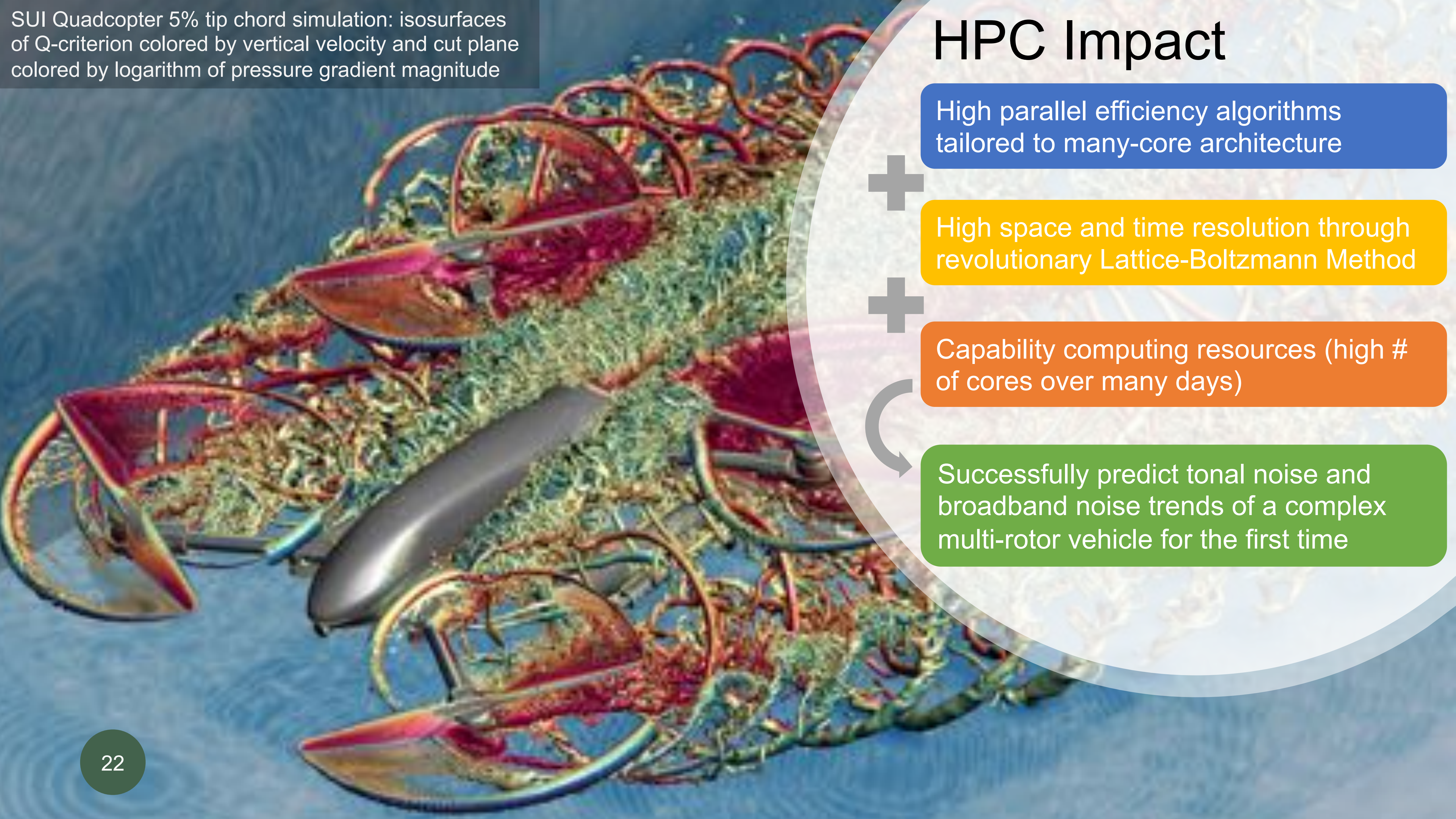


Source of discrepancies



- Simulations have all rotors rotating at fixed mean RPM measured in experiment
- But front rotors R1 and R2 rotation rate varied in time and were synchronized (same RPM) for significant portions of data collection
- Amplitude for 135Hz frequency associated with R1 and R2 oscillates significantly in spectrogram (left)



SUI Quadcopter 5% tip chord simulation: isosurfaces of Q-criterion colored by vertical velocity and cut plane colored by logarithm of pressure gradient magnitude

HPC Impact

High parallel efficiency algorithms tailored to many-core architecture

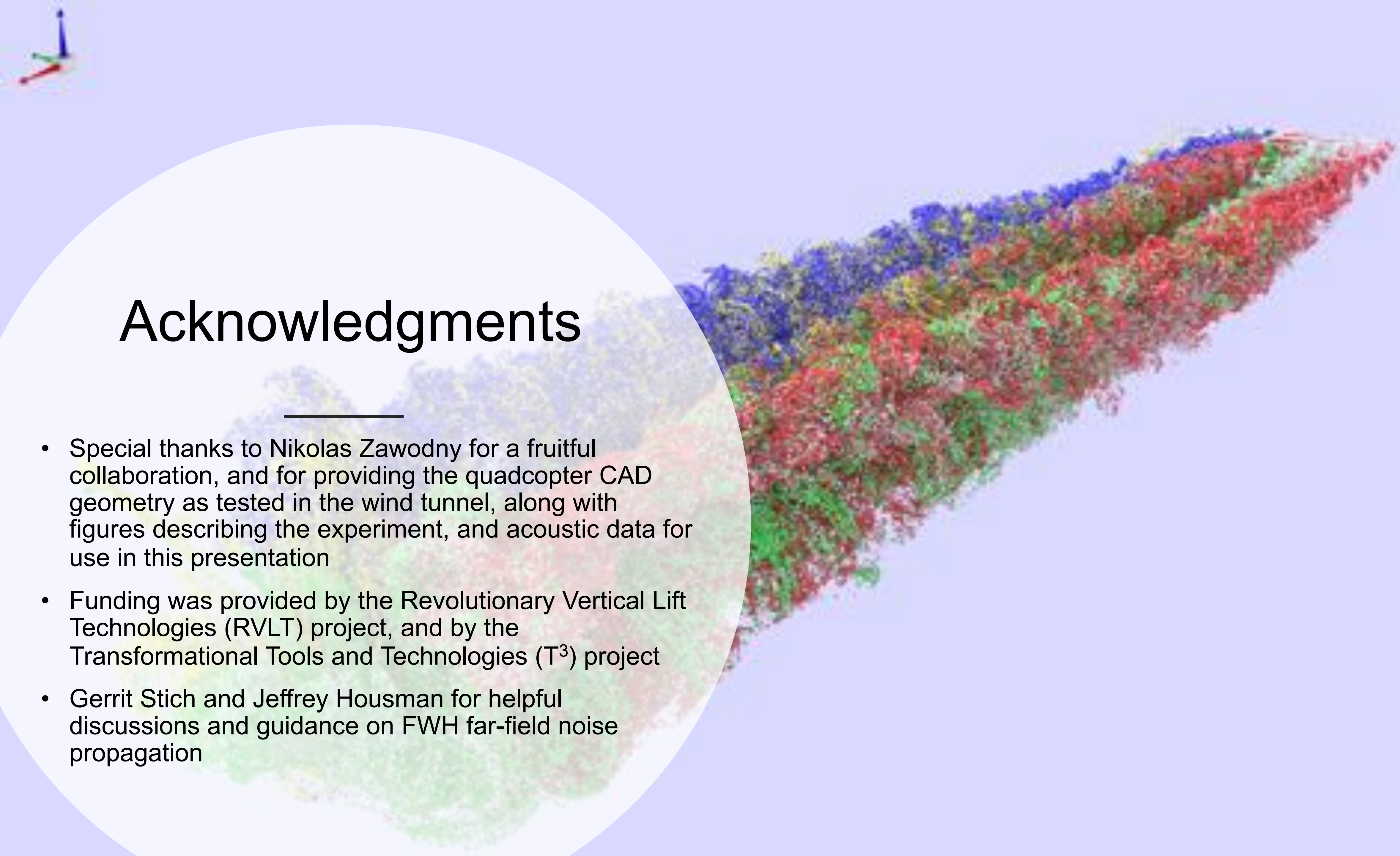
+

High space and time resolution through revolutionary Lattice-Boltzmann Method

+

Capability computing resources (high # of cores over many days)

Successfully predict tonal noise and broadband noise trends of a complex multi-rotor vehicle for the first time



Acknowledgments

- Special thanks to Nikolas Zawodny for a fruitful collaboration, and for providing the quadcopter CAD geometry as tested in the wind tunnel, along with figures describing the experiment, and acoustic data for use in this presentation
- Funding was provided by the Revolutionary Vertical Lift Technologies (RVLT) project, and by the Transformational Tools and Technologies (T^3) project
- Gerrit Stich and Jeffrey Housman for helpful discussions and guidance on FWH far-field noise propagation

Backup Slides

Conclusions

- Coupled with far-field acoustic propagation in the Launch, Ascent and Vehicle Aerodynamics (LAVA) framework, ***LBM successfully predicted tonal noise levels and captured broadband noise trends accurately for the first time***

- ***LBM is attractive because it is the only tool to demonstrate it can capture complex rotorcraft noise trends at high frequencies so far***, but it's rather expensive for aerodynamic performance and tonal noise

Challenges

- Fine-to-coarse transition affects acoustics because numerical dissipation is related to the grid size: even if the wave is well-represented in both the fine and the coarse grid, it experiences different effective viscosity similar to material porosity → so part of the wave might be reflected from the interface

- AMR is good as long as it converges in time average, otherwise, it will affect acoustics rather unpredictably

- FWH surface shape and placement is still based on experience rather than physics → need a tool to use simulation statistics to automatically design FWH surface based on solution and CFD mesh size

Numerical Methodology

- LBM with Entropic Multiple-Relaxation Time (EMRT) collision model
- Slip boundary condition on rotors and fuselage because we cannot afford to resolve tiny laminar and transitional boundary layers with Cartesian isotropic cells, and because from body-fitted RANS results we know the pressure forces dominate over viscous by nearly 3 orders of magnitude
- Set finest level of mesh on 4 cylinders to cover each rotor
- Regrid every ~45 degrees of slowest rotor to follow areas of high $\langle p'p' \rangle$ and $\langle u_i' u_i' \rangle$ based on on-the-fly statistics
- Set maximum mesh spacing to 40% tip chord resolution everywhere within the FWH surface to ensure we can capture waves up to 18 kHz

Acoustic Prediction Methodology

- Perform simulation for 4 revolutions of slowest rotor (~4000 RPM) to flush out transient, then continue an additional 0.4 seconds (~30 revolutions)
- Interpolate solution onto FWH surface triangulation and save it to disk at regular time interval allowing for ~10 to 20kHz maximum frequency
- Propagate to observers using fully parallelized FWH integrand in frequency domain for intervals of 0.2 seconds (df = 5 Hz) with 75% overlap using Hanning window (parameters chosen to match experiment)
- Compare to flow sensors at observer locations: their sampling frequency is limited to the frequency at which the mesh resolution level they are enclosed by is updated in the sub-cycling algorithm (meaning they can capture BPF and its first harmonic but not much more)

LBM Performance For Quadcopter

Simulation	Resolution (% tip chord)	# of cells	# of time steps performed	Wallclock time (hours)	Core Hours	Cells updated per second	Cells updated per second per core
Rotors + Body	40	8.37E+07	67793	28.5	22800	5.53E+07	6.91E+04
Rotors + Body	20	1.44E+08	135587	50.5	80800	1.07E+08	6.70E+04
Rotors + Body	10	3.26E+08	273408	129	412800	1.92E+08	5.99E+04
Rotors + Body	5	5.68E+08	542347	125.25	801600	6.83E+08	1.07E+05

*Performance is limited by output to disk (volume files are large and slow to write), and writing out surfaces of 1.3 Million triangles often is costly too