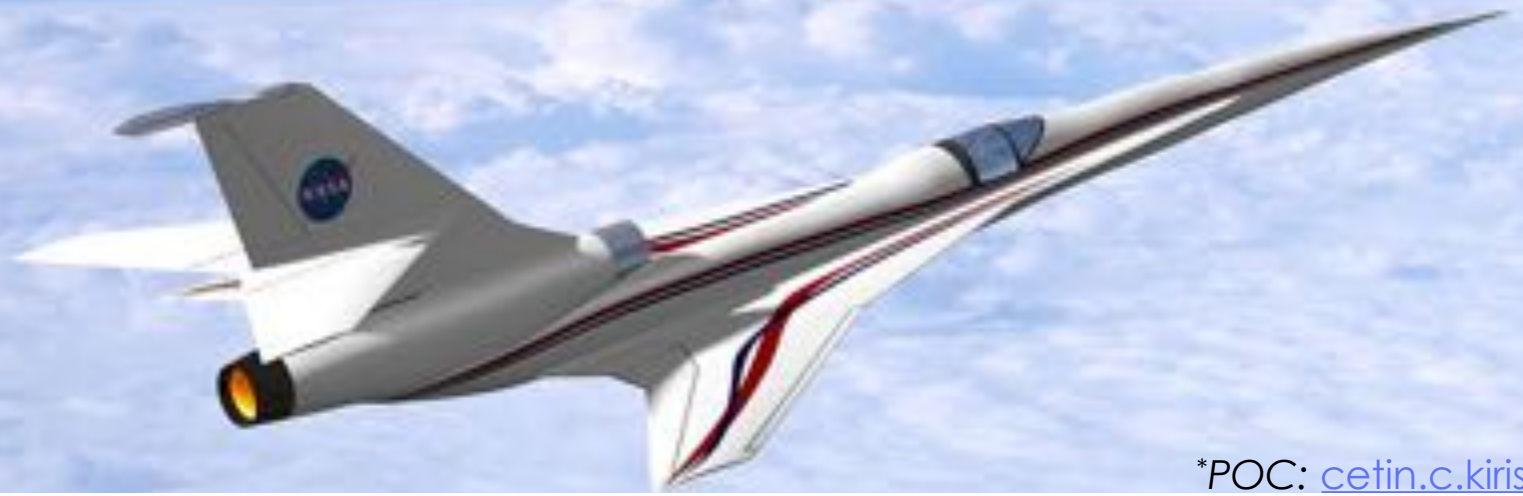
Jet Noise Predictions with Wall-Modeled LES*

Gerrit-Daniel Stich, Jeffrey Housman, Aditya Ghate, Cetin Kiris

Computational Aerosciences Branch
NASA Ames Research Center

Spring 2020 Acoustics Technical Working Group Meeting
VIRTUAL ZOOM Meeting April 7th & 8th , 2020



*POC: cetin.c.kiris@nasa.gov

NASA's Commercial Supersonic Technology (CST)



During take-off and landing engine noise is the dominant noise source

Jet noise mainly comes from high speed exhaust turbulence at the end of the nozzle as well as from the mixing of turbulent structures

- NASA initiated research activities towards Commercial Supersonic Technologies (CST)
- Within this project Three main Technical Challenges (TC) have been defined
  - TC 1.1 Low Boom Design Tools
  - TC 1.2 Sonic Boom Community Response Metric & Methodology
  - **TC 2.2 Low Noise Propulsion for Low Boom Aircraft**
- Develop an understanding of the effects of shielding surfaces on the aerodynamic noise sources from jet flows.

Picture Credit: NASA / Lockheed Martin

Integrated Propulsion Noise

Predicting Jet Noise for Full-Scale Low-Boom Flight Demonstrator



Integrated propulsion noise or jet surface Interaction noise (JSI) becomes increasingly more important with future aircraft designs

https://www.nasa.gov/topics/aeronautics/features/bridges_chevron_events.html

Alternative Nozzle Design Concepts

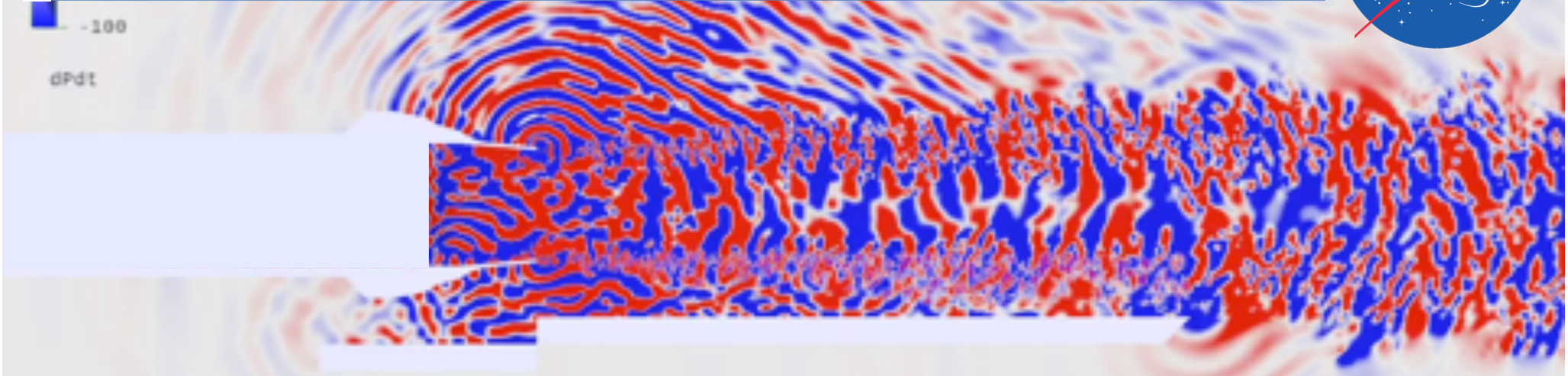


Photo credits: The Boeing Company / Bob Ferguson / NASA

One of the most recent noise-reducing technologies promoted through research processed by NASA and now making entrance on commercial jet engines are chevrons.

Role of Computational Aeroacoustics (CAA)

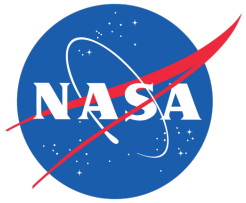
High-fidelity scale resolving simulations conducted at NASA's CST Project under the direction of James Bridges accurately capture physics of turbulence creating noise.



Determining where and how noise is created and how noise can be "shielded" from the observer could help reduce overall jet engine noise.

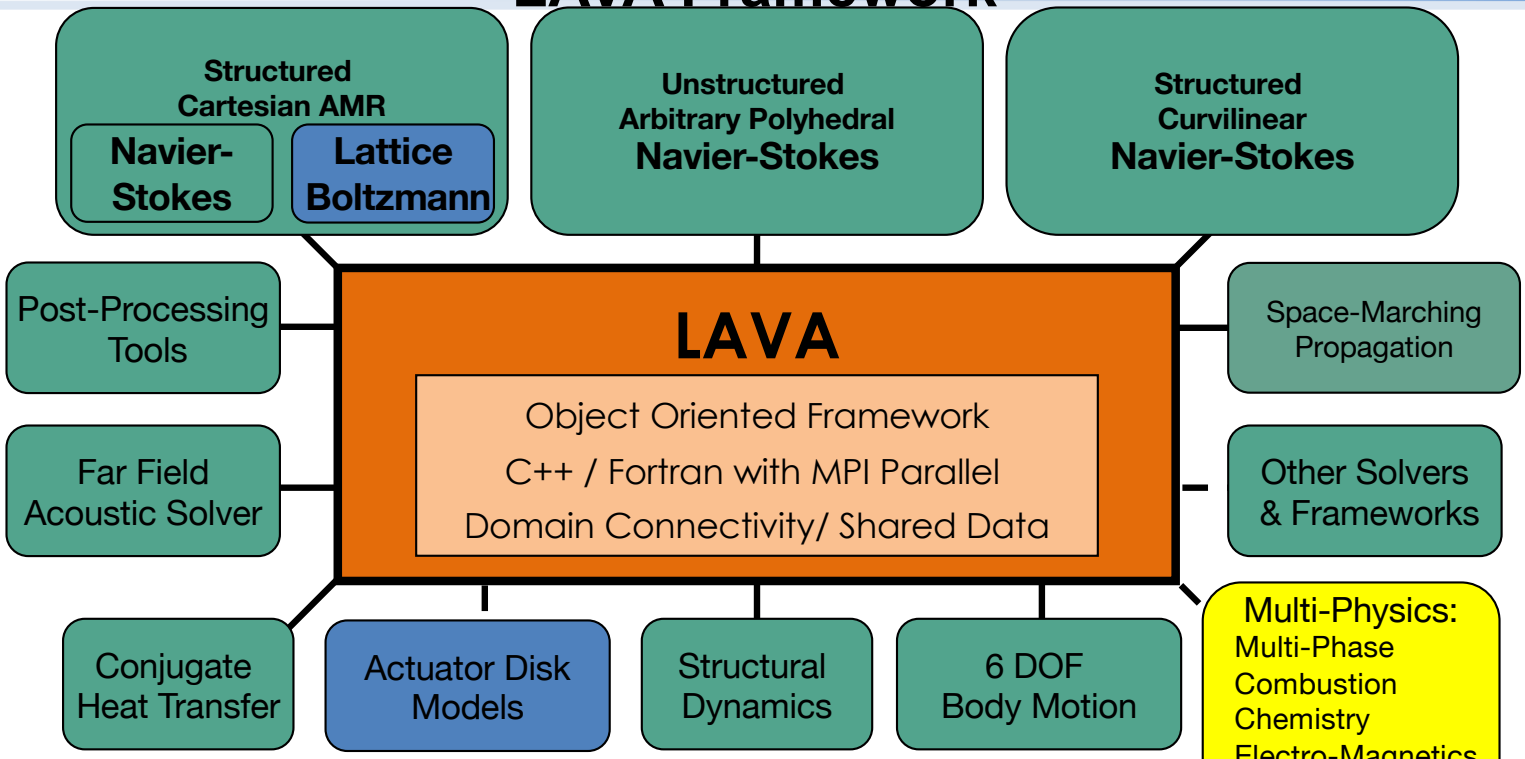
Flow Visualization by Timothy Sandstrom NASA Ames Research Center

Outline



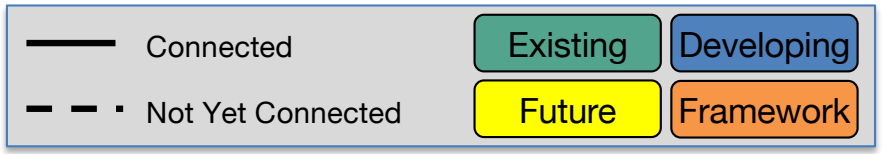
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Launch, Ascent, and Vehicle Aerodynamics
LAVA Framework



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

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



Wall-Modeled Large Eddy Simulation (WMLES)

inner layer ($y/\delta_0 \lessapprox 0.2$) modeled while outer layer resolved

LES domain extends all the way to the wall

Wall-stress Model (WSM)

$\vec{u}$, P

τ_w ; qw

LES

exchange of information at interface

RANS in near wall region X% of BL
LES in outside region

Hybrid RANS/LES

Analytical wall law

- Utilizes wall-functions like Musker's Law, Spalding , ….
- Takes $\vec{u}$ from LES to compute wall shear stress
- simple and negligible numerical effort

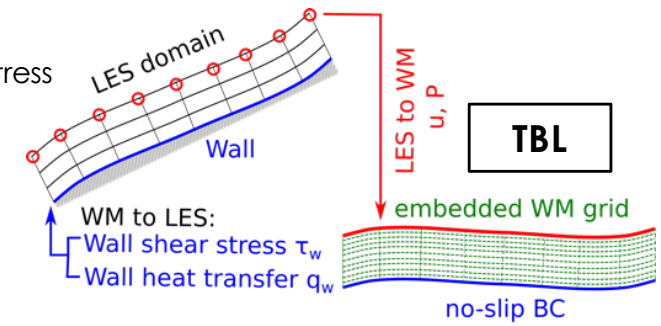
TBL equations PDE/ODE

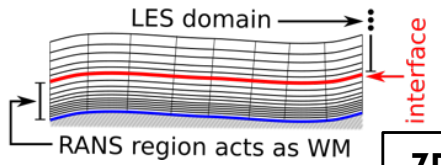
- Solves TBL equations in the BL
- Needs separate embedded grid
- Computationally more expensive
- Potential to include additional physics

Integral WM

- Integrate TBL equations vertically using given velocity profiles

$$Y_\tau^+ = U_1^+ + exp(-\kappa C)\left[exp(\kappa U_1^+) - 1 - \kappa U_1^+ - \frac{1}{2}\left(\kappa U_1^+\right)^2 - \frac{1}{6}\left(\kappa U_1^+\right)^3\right]$$





ZDES

- Grids require viscous wall-spacings $y^+ < 1$
- Require implicit time-stepping methods
  - Additional numeric complexity
  - Larger time-steps possible

Seamless Methods (DES, DDES,…)

- Transition location between RANS and LES not specifically set.
- Interface height and location defined by grid and solution

Zonal Methods (ZDES)

- User manually describes regions in which RANS and LES is used (requires experience and knowledge of problem)
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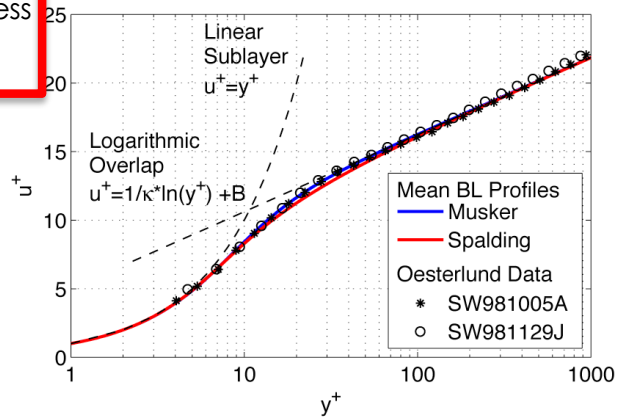
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$u^+ = f(y^+)$



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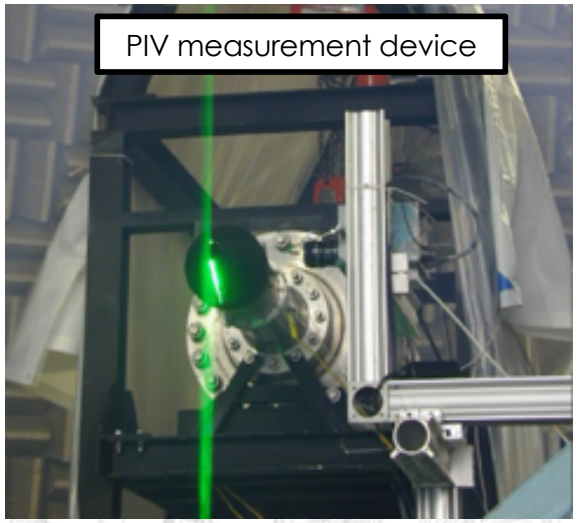
Experimental Setup
NASA Aero-Acoustics Propulsion Lab (AAPL)





- Baseline axisymmetric convergent Small Metal Chevron (SMC000) nozzle at Set Point 7 (SP7) with 12" extension

Bridges et. al. (NASA-TM-2011-216807)	SP7
Acoustic Mach number U_{jet}/c_∞	0.9
Jet temperature ratio T_e/T_∞	0.835
Nozzle pressure ratio p_t/p_∞	1.861
Nozzle Diameter D	0.0508 [m] 2.0 [inch]
Reynold number Re_D	1 Million
Reynolds number Re_τ	800
Boundary layer thickness	0.0128 D



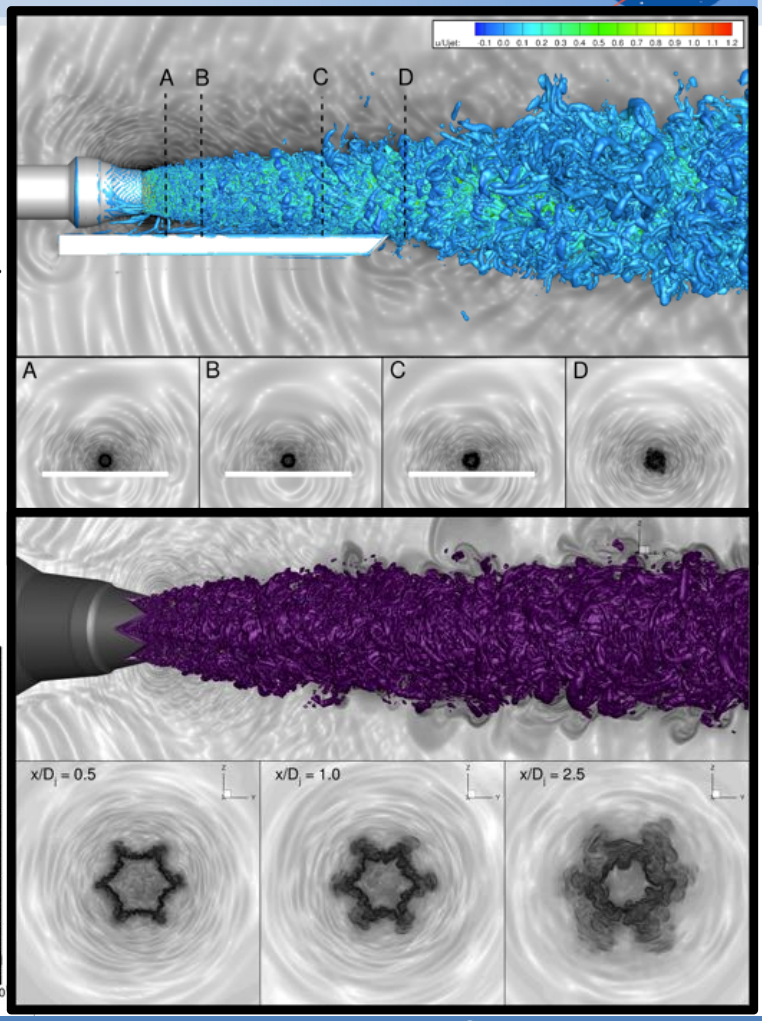
- 65" radius anechoic dome
- Located at Glenn Research Center (GRC)
- Small Hot Jet Acoustic Rig (SHJAR)
- Far-field acoustics, phased arrays, flow rakes, hotwire, schlieren, PIV, IR, Rayleigh, Raman, PSP

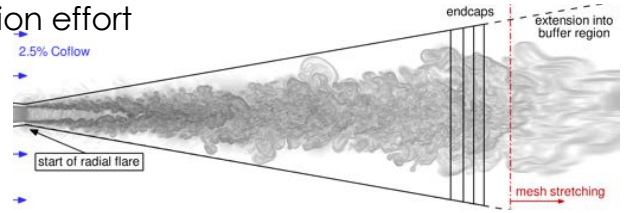
Outline

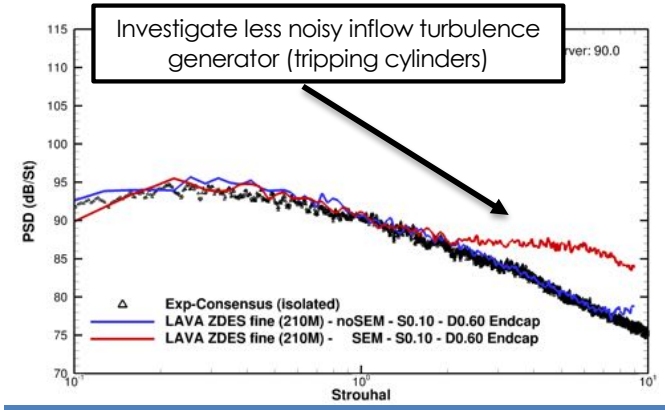
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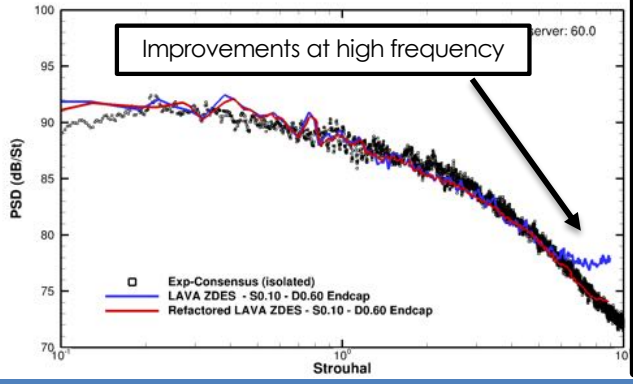
Jet Noise Predictions with Hybrid RANS/LES

- Validation of Jet noise prediction with Hybrid RANS/LES
  (Round Jet SMC000, Jet Surface Interaction, Chevron nozzle SMC001)
- Hybrid RANS/LES does excellent job in predicting near- and far-field results.
- Addition of multi-block capability in solver improved far-field results additionally.
- For increased geometric complexity hybrid RANS/LES approach has introduced additional difficulties:
  - increased manual mesh generation effort
  - cell aspect ratios
  - number of mesh points





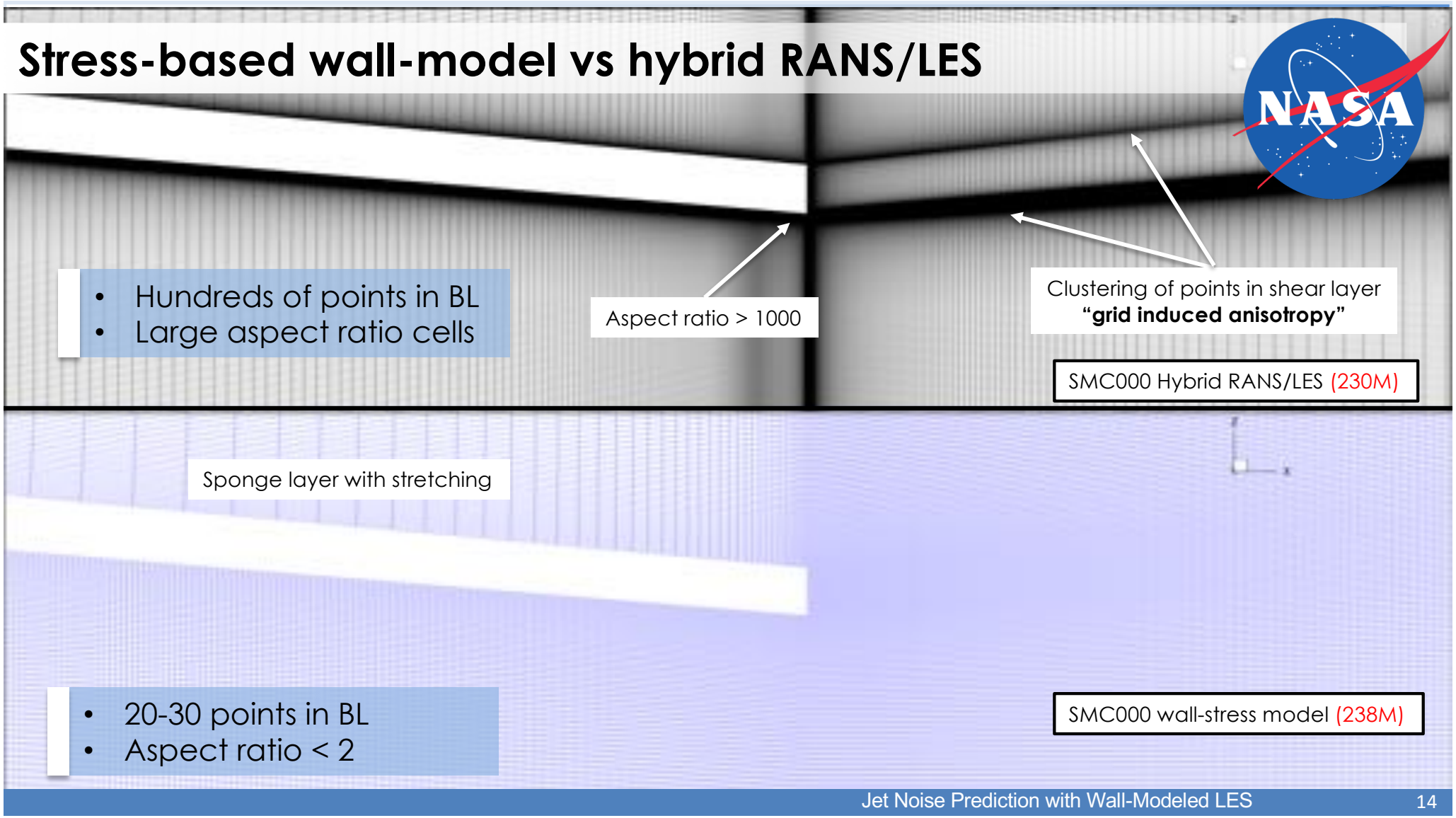




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Stress-based wall-model vs hybrid RANS/LES



- Hundreds of points in BL
- Large aspect ratio cells

- 20-30 points in BL
- Aspect ratio < 2

Stress-based wall-model vs hybrid RANS/LES

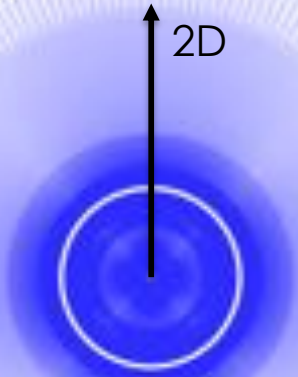
- #points in circ:
  771



SMC000 Hybrid RANS/LES (230M)

x/D = 0.0

- #points in circ:
  1441



SMC000 wall-stress model (238M)

- Significantly increased overall mesh resolution with same amount of total mesh points

Stress-based wall-model vs hybrid RANS/LES

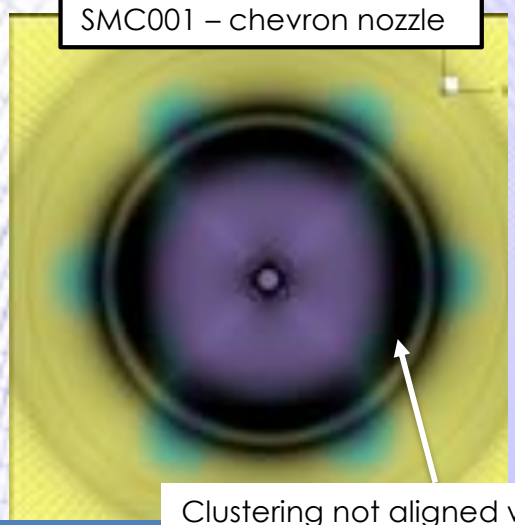
clustering of mesh points due to viscous wall spacing does not necessarily align with physics

"grid induced anisotropy"

SMC000 Hybrid RANS/LES (230M)

x/D = 2.0

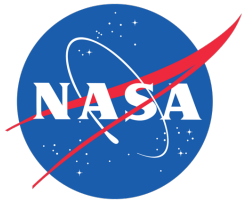
SMC001 – chevron nozzle



Clustering not aligned with solution

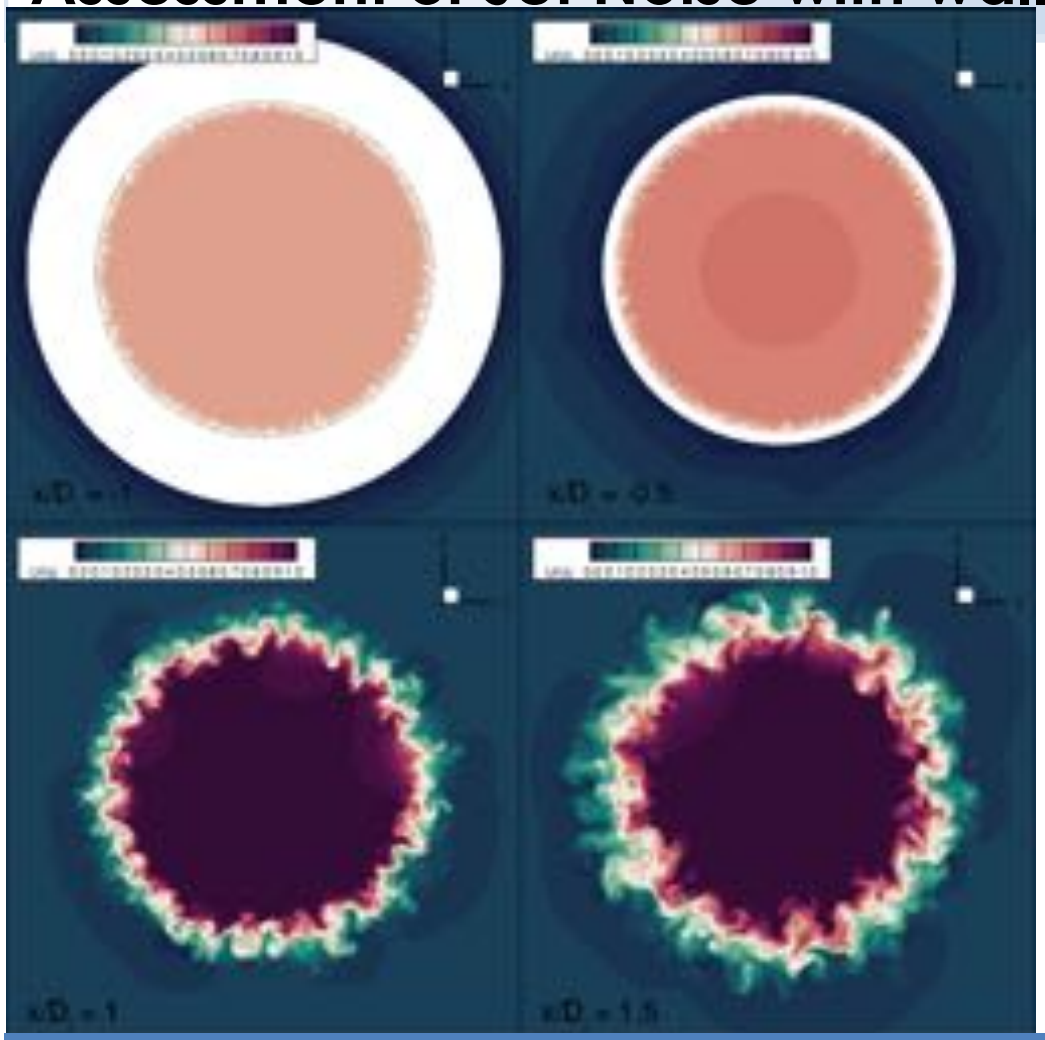
SMC000 wall-stress model (238M)

Outline



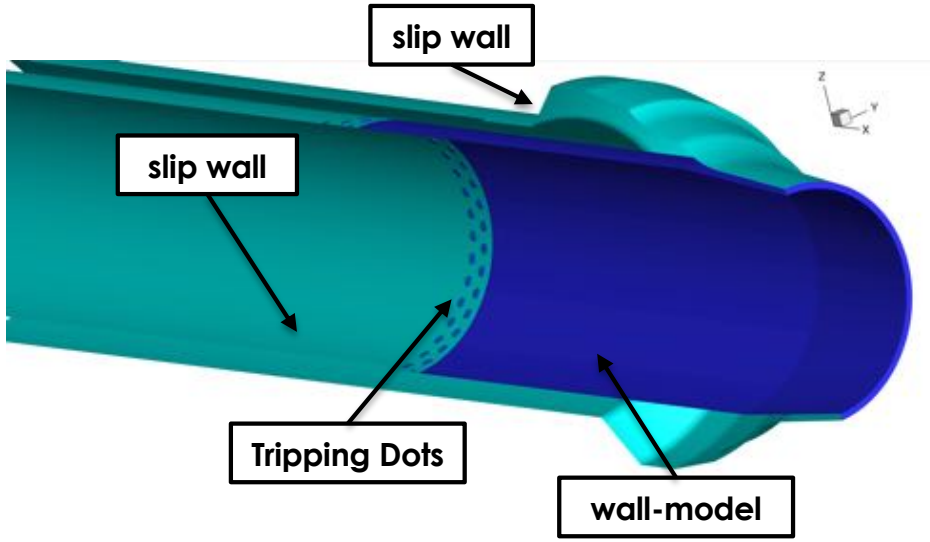
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Assessment of Jet Noise with wall-shear stress WM



- Stress-based equilibrium wall-model
- Explicit time-stepping method (RK3-TVD)
- Timestep size approx. 0.0004 dt^*c_{inf}/D (7.0e-8 s) (previous ZDES: 0.007 (1.0e-6))

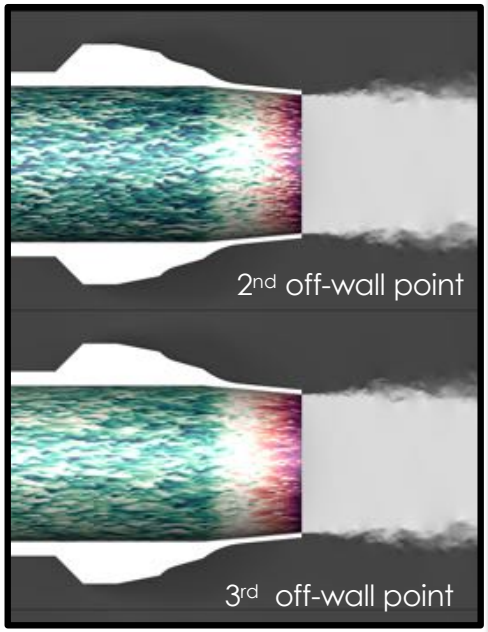
- Two rows of small tripping dots at x/D_j = -2.0
- Tripping dots resolved with immersed boundary method

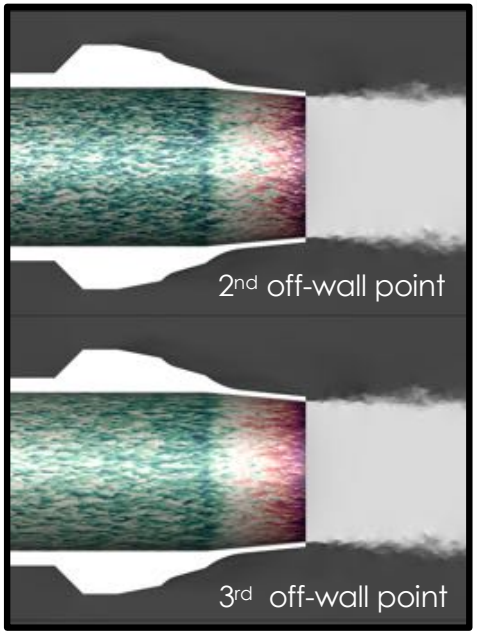


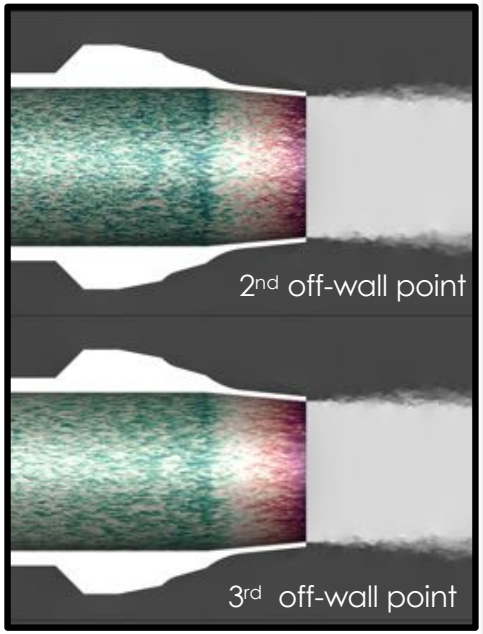
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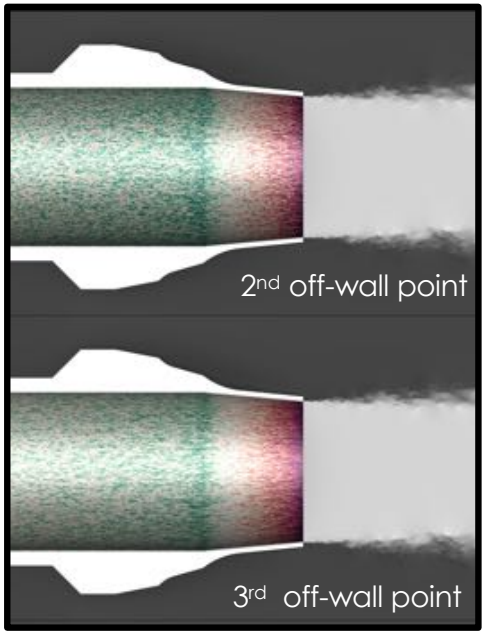
Influence of Dissipation on nozzle boundary layer

Upwind – 10%	Upwind– 5.0%	Upwind – 2.5%	Upwind - 0.2% inside 2.5% outside









- Elongated, coherent structures inside of nozzle.
- Artificially large azimuthal coherence because of numerical dissipation

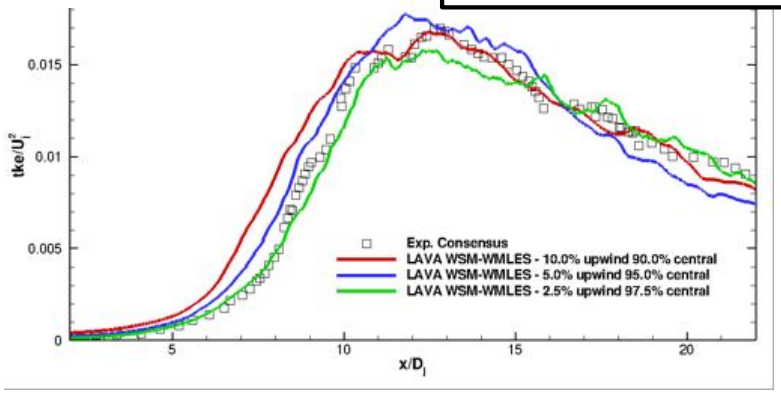
Reduced numerical dissipation results in reduction of azimuthal length scales (more realistic boundary layer turbulence)

- 0.2% upwind only within nozzle boundary layer and shear layer (up to 0.5D). 2.5% upwind in jet region.
- All sub-grid dissipation controlled by physics based sub grid scale (Sigma SGS) modeling

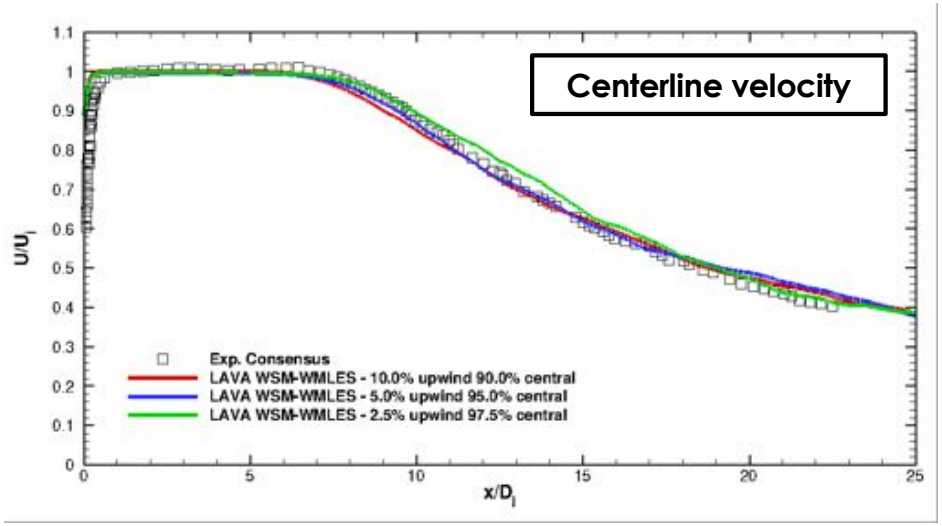
Assessment of Jet Noise with wall-shear stress wall-model

Near-Field Results

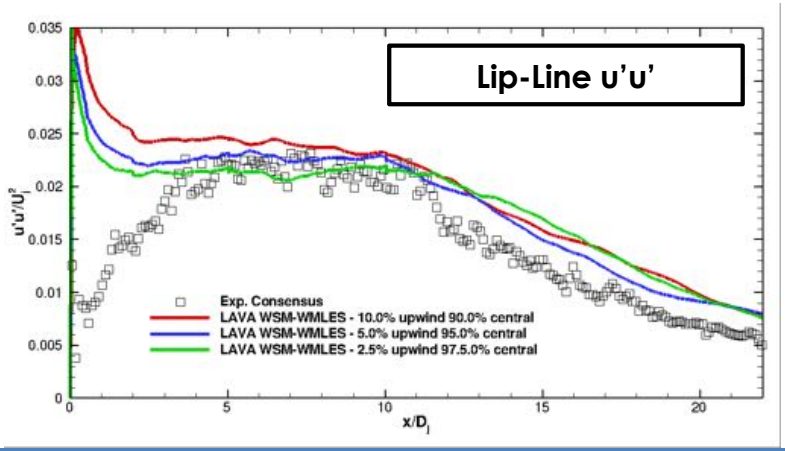
Centerline TKE



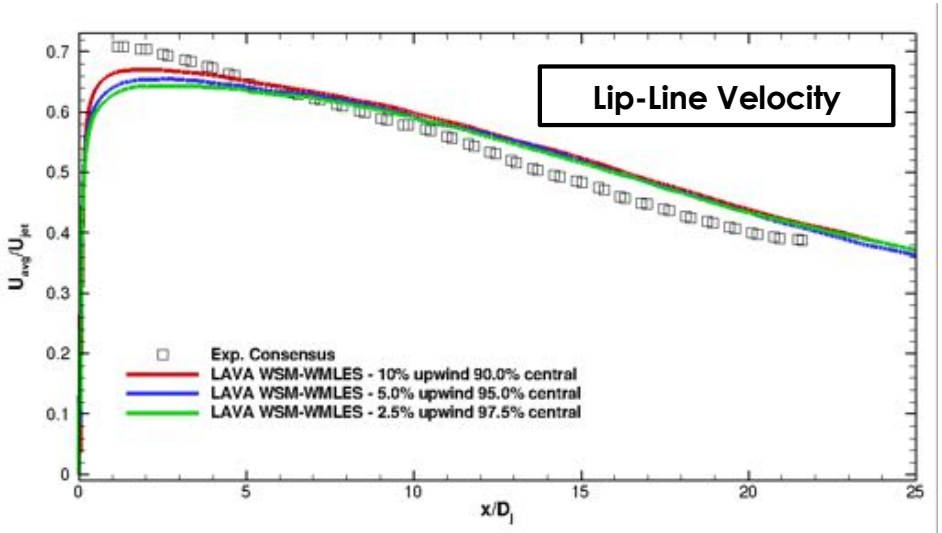
Centerline velocity



Lip-Line u'u'



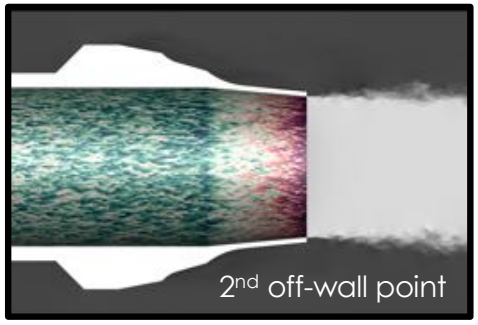
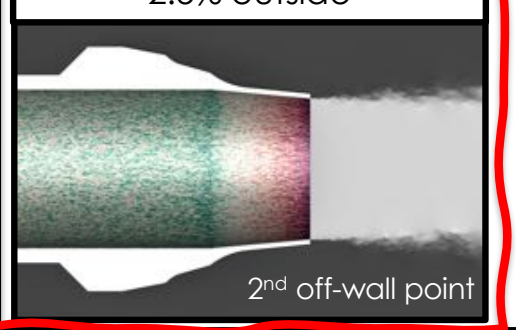
Lip-Line Velocity



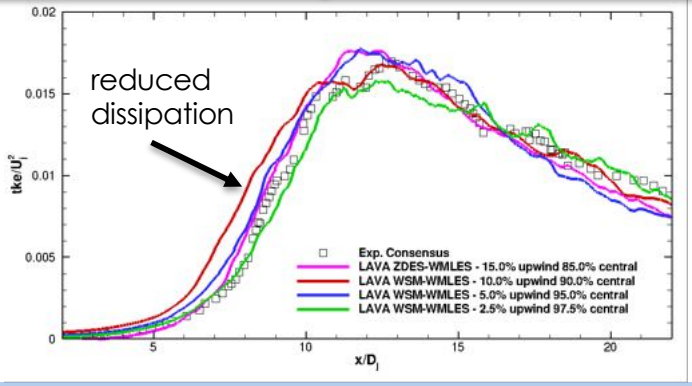
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Influence of Dissipation on nozzle boundary layer

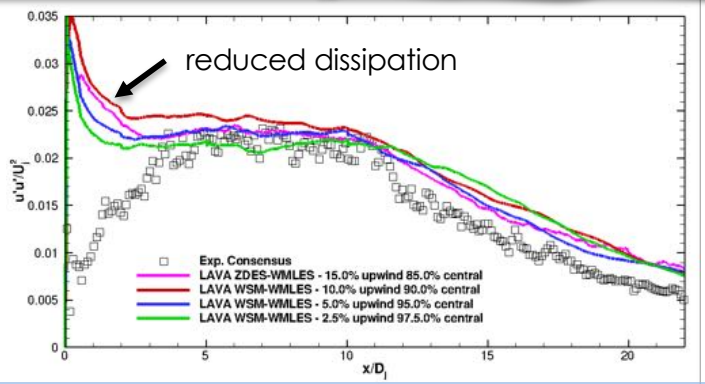
not run long enough yet

Upwind – 10%	Blending– 5.0%	Blending– 2.5%	Blending– 0.2% inside – 2.5% outside
			
2nd off-wall point	2nd off-wall point	2nd off-wall point	2nd off-wall point

Centerline TKE

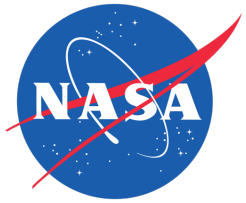


Lip-Line TKE



Artificial larger integral length scales in BL turbulence result in excessive and inaccurate entrainment in the jet shear layer formed at the lip of the nozzle. Lower dissipation values need for wall-shear stress model.

Outline



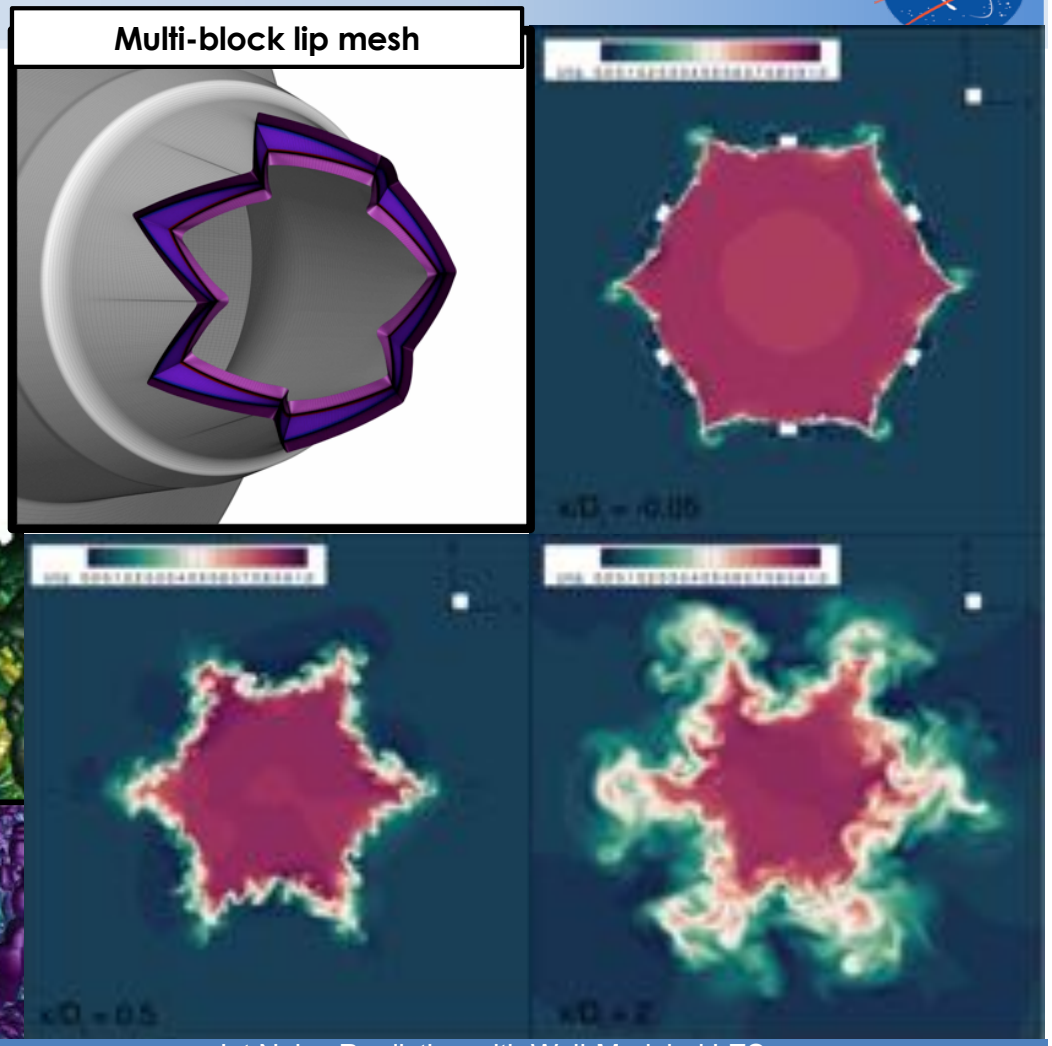
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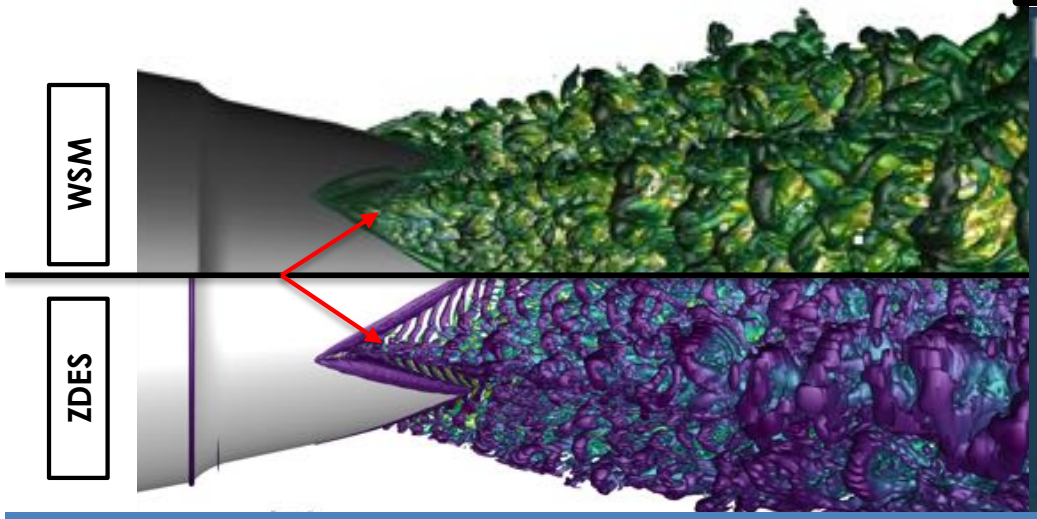
Next Steps: Assessment of noise from complex geometries WSM-WMLES

Chevron nozzle SMC001 SP7

Progress towards prediction of noise with wall-shear stress Model for complex geometries

- ❑ Started chevron SMC001 SP7 runs
- ❑ Improved delayed transition to 3D turbulent structures in nozzle shear-layer due to improved mesh quality





Refactored LAVA solver Framework

The Launch Ascent and Vehicle Aerodynamics (LAVA) solver framework has been refactored in order to increase performance and accuracy

Performance Improvements from Refactored LAVA Solver:

- **Speedup ~5x time accurate runs**: reduction on a 230M mesh point mesh from approx. 10 days across multiple long cluster jobs to less than 3 days on a single job *(reduced idle time in cluster queue)*

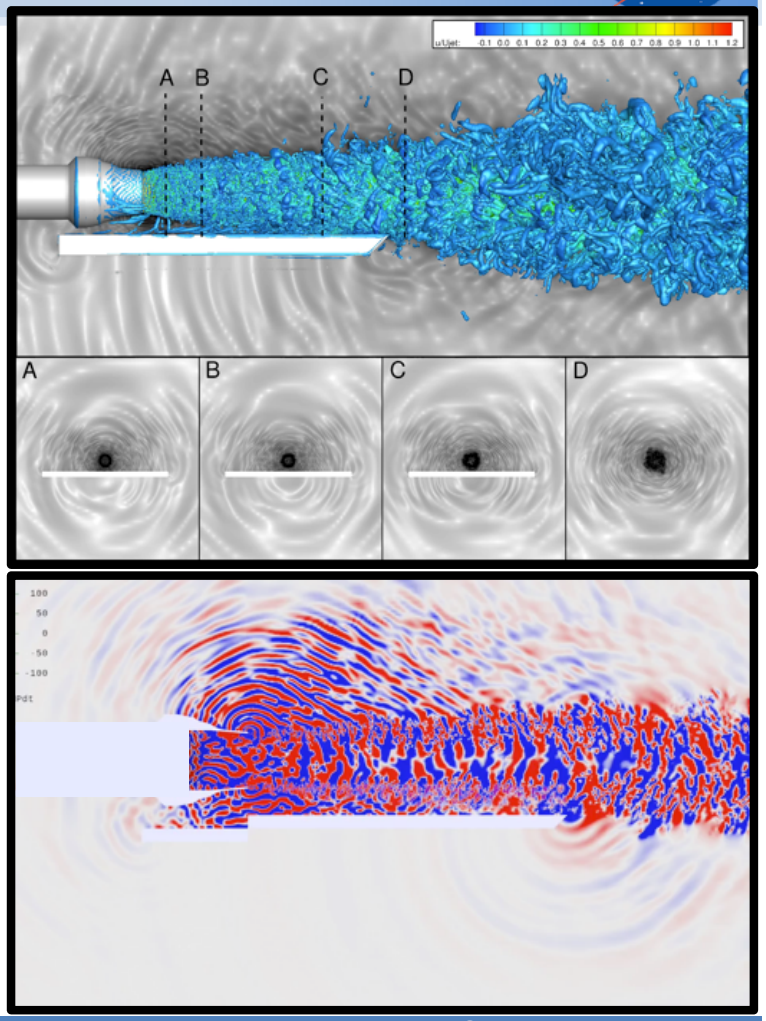
- **Added multiblock capability:** Higher mesh quality in critical flow regions results in better solution quality (see Fig 2)

- **Improved workflow:** preprocessing reduced from multiple hours to minutes with minimal user input

Implemented stress-based equilibrium wall-model

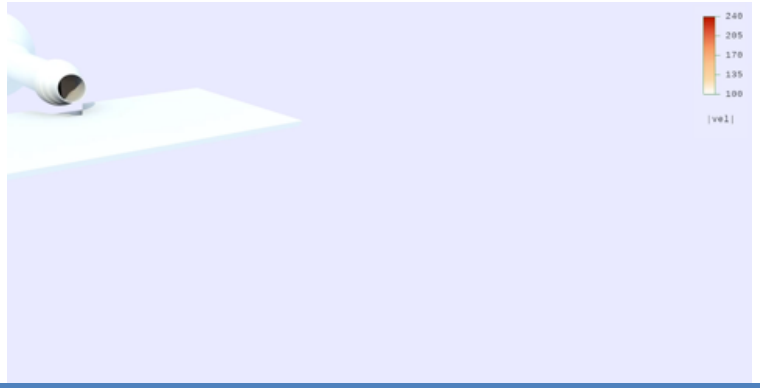
- Increased mesh quality and reduced mesh size with improved accuracy while adding less dissipation

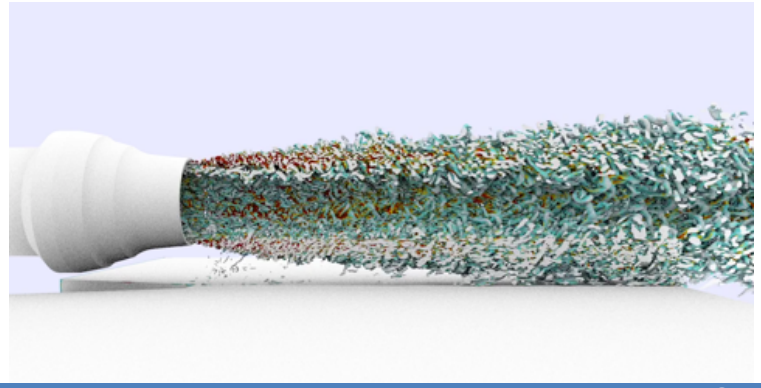
- **SMC000 3x speedup** with explicit scheme compared to implicit time-stepping while increasing space-time resolution. Jobs run within 30hr (additional to speedup mentioned above)



Summary

- Hybrid RANS/LES within the LAVA framework using structured curvilinear overlapping grids is successfully applied to predict jet noise.
- Good comparison with experiments for both near-field and far-field achieved for round-jet as well as surface interaction noise case.
- Wall-shear stress equilibrium wall-model was implemented within the LAVA framework
- Initial results with wall-shear stress equilibrium model look promising
- Significant speedup with refactored LAVA solver observed





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