

Wall-Modeled Large-Eddy Simulation of Jet Acoustics



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

Computational Aerosciences Branch
NASA Ames Research Center (ARC)



**Spring 2021 Acoustic Technical Working Group
Virtual Meeting , April 13th – 14th, 2021**

*Science And Technology Corporation (STC)

NASA's Commercial Supersonic Technology (CST)



Research activities to reduce propulsion noise has been supported by NASA's Commercial Supersonic Transport (CST) Project

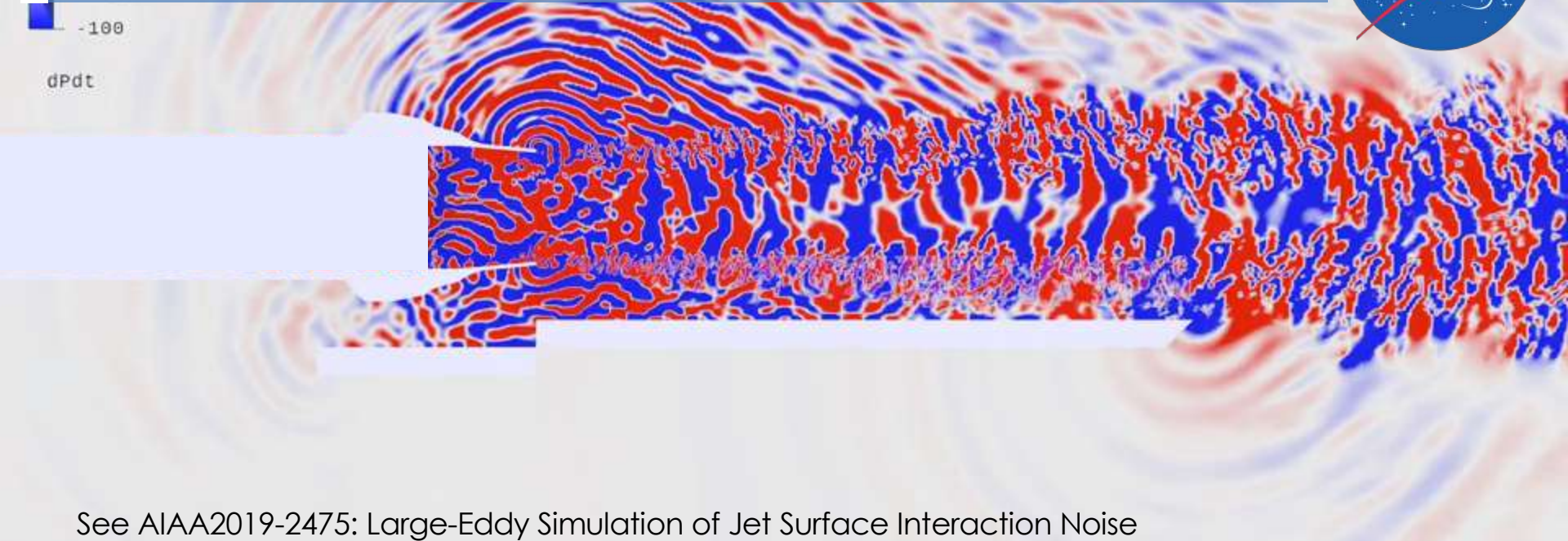
Jet noise is mainly produced by mixing of the turbulent high-speed jet exhaust with slower moving ambient air.

Goal: Providing scale-resolving simulations on full-scale low boom flight demonstrator

https://www.nasa.gov/sites/default/files/thumbnails/image/quesst_render_c.jpg

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.



See AIAA2019-2475: Large-Eddy Simulation of Jet Surface Interaction Noise

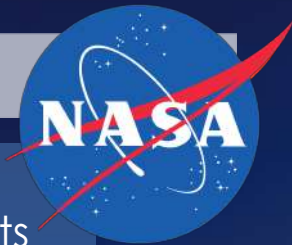
Determining where and how noise is created and how noise can be “shielded” from the observer could help reduce overall jet engine noise.

Flow Visualization by Timothy Sandstrom NASA Ames Research Center



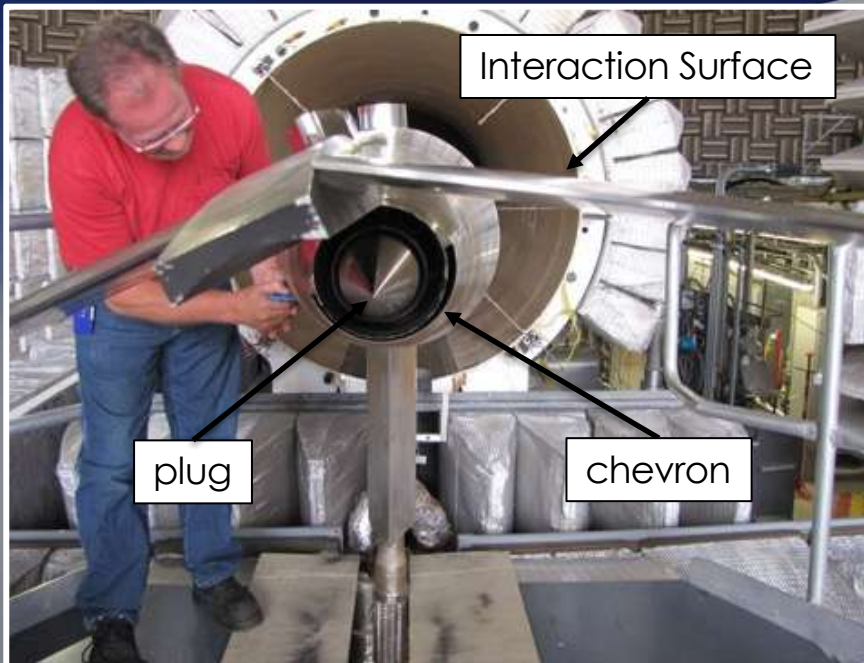
Objective for LAVA WMLES within CST Project

- Predict jet noise **accurately** and in **short enough turnaround time** to include analysis in future propulsion integration design
- **Understand** and document **uncertainties and shortcomings** of scale-resolving wall-modeled LES for jet noise simulations
- **Future Impact:** complement/replace wind tunnel and flight tests, reduction of associated costs, provides insight into noise reduction technology never-before available.



2017-2021: Progress Towards Full Aircraft Jet Noise Predictions

Perform systematic validation effort utilizing scale resolving Computational Fluid Dynamics (CFD) to evaluate aerodynamic for increasingly complex jets



ROUND JET VALIDATION

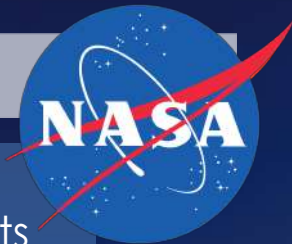
1

SHIELDING CONCEPTS

2

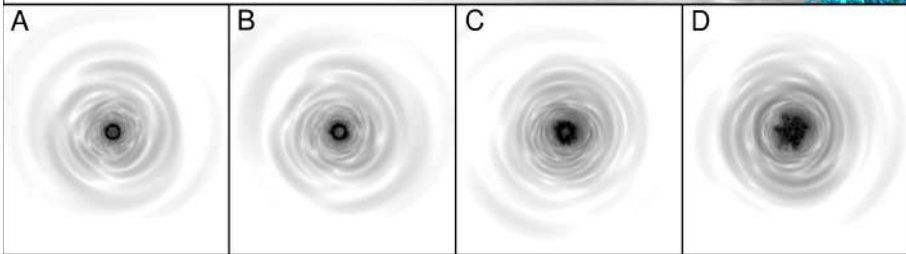
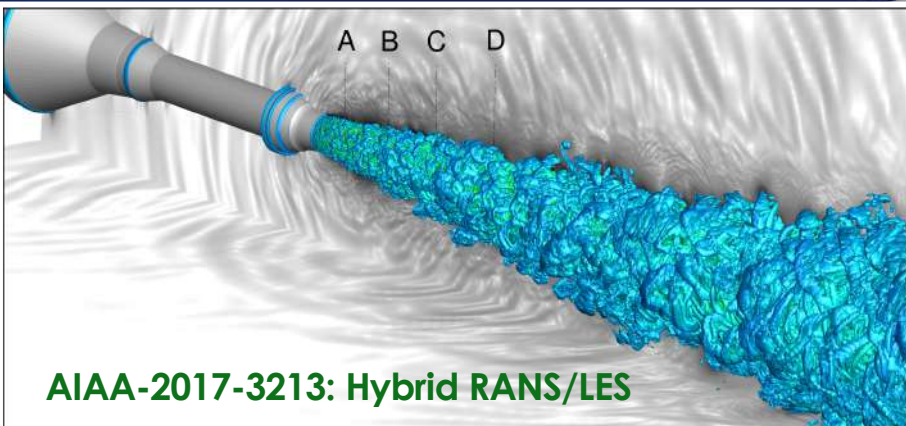
INCREASINGLY COMPLEX
GEOMETRY
(Chevron, Plug, Multi-stream)

3



2017-2021: Progress Towards Full Aircraft Jet Noise Predictions

Perform systematic validation effort utilizing scale resolving Computational Fluid Dynamics (CFD) to evaluate aerodynamic for increasingly complex jets



ROUND JET VALIDATION

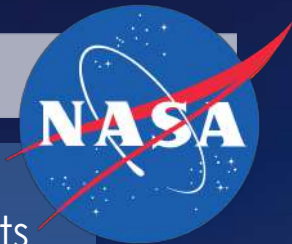
1

SHIELDING CONCEPTS

2

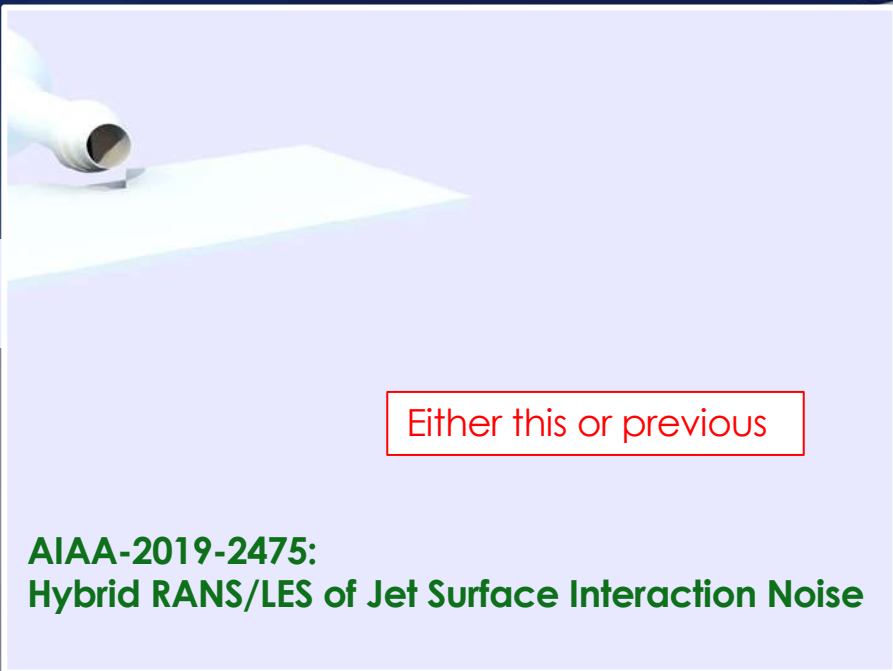
INCREASINGLY COMPLEX
GEOMETRY
(Chevron, Plug, Multi-stream)

3



2017-2021: Progress Towards Full Aircraft Jet Noise Predictions

Perform systematic validation effort utilizing scale resolving Computational Fluid Dynamics (CFD) to evaluate aerodynamic for increasingly complex jets



Either this or previous

AIAA-2019-2475:
Hybrid RANS/LES of Jet Surface Interaction Noise

ROUND JET VALIDATION

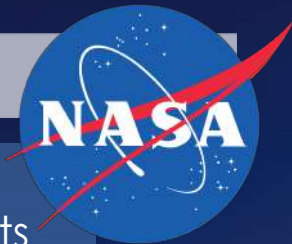
1

SHIELDING CONCEPTS

2

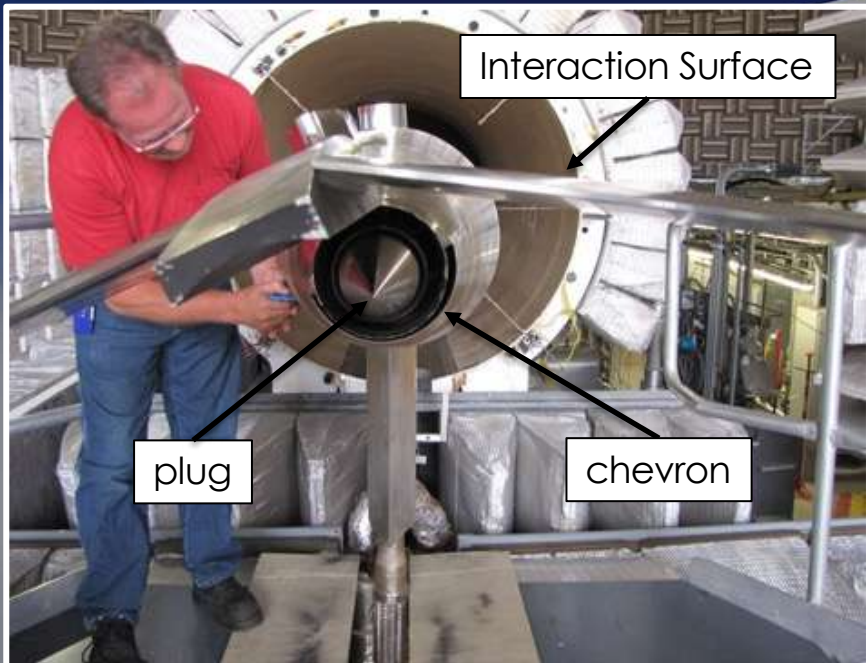
INCREASINGLY COMPLEX
GEOMETRY
(Chevron, Plug, Multi-stream)

3



2017-2021: Progress Towards Full Aircraft Jet Noise Predictions

Perform systematic validation effort utilizing scale resolving Computational Fluid Dynamics (CFD) to evaluate aerodynamic for increasingly complex jets



ROUND JET VALIDATION

1

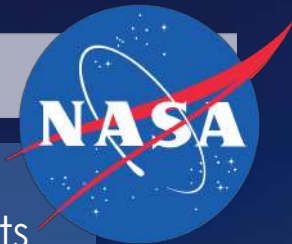
SHIELDING CONCEPTS

2

INCREASINGLY COMPLEX
GEOMETRY
(Chevron, Plug, Multi-stream)

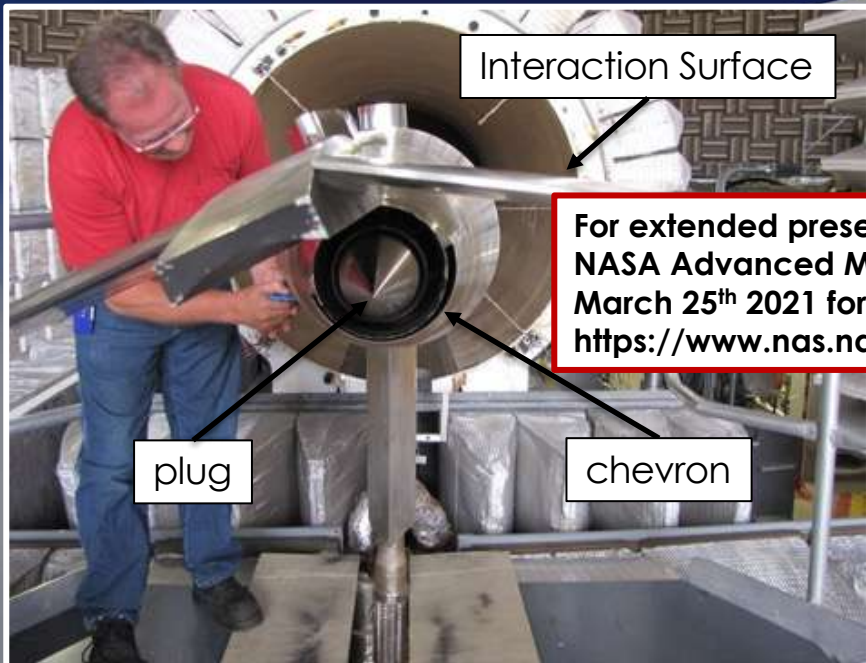
3

AIAA-2021-1185: WMLES chevron nozzle



2017-2021: Progress Towards Full Aircraft Jet Noise Predictions

Perform systematic validation effort utilizing scale resolving Computational Fluid Dynamics (CFD) to evaluate aerodynamic for increasingly complex jets



Interaction Surface

For extended presentation on this work please see:
NASA Advanced Modeling & Simulation Seminar
March 25th 2021 for details of this study:
<https://www.nas.nasa.gov/publications/ams/2021/03-25-21.html>

plug

chevron

INCREASINGLY COMPLEX
GEOMETRY
(Chevron, Plug, Multi-stream)

AIAA-2021-1185: WMLES chevron nozzle



Wall-Modeled Large-Eddy Simulation (WMLES)

Basic philosophy:

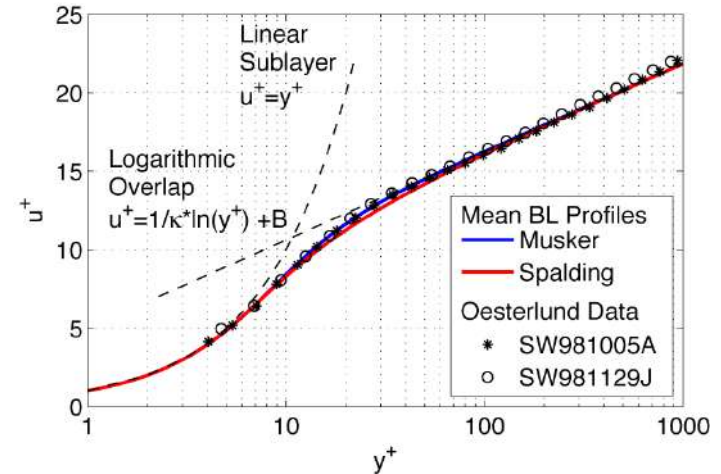
Would like to use LES everywhere but cannot resolve integral length scales for the inner-layer of a turbulent boundary layer at high Reynolds number; replace stiff-Dirichlet BCs with a wall-stress BC instead and compute the wall-stress using a wall function.

Analytical wall law:

- Utilize wall functions (e.g. Musker's Law) and compute wall shear-stress based on velocity from LES
- Computationally simple and inexpensive

$$u^+ = f(y^+)$$

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





Launch, Ascent, and Vehicle Aerodynamics (LAVA) Framework

- Utilized Curvilinear Structured Overset Solver within LAVA
- Equilibrium wall-model using Musker's wall-function
- Vreman subgrid scale model
- Convective flux discretization uses:
 - Primitive variable interpolation to the half points using blending between 4th order centered and 3rd order upwind with shock sensor
 - HLL Riemann solver
- Boundary layer tripping with use of immersed boundary method (cylinders)
- Time discretization using TVD-RK3 (Gottlieb et. al. 1998) at CFL 1.25

More details provided in [AIAA-2020-2735](#), [AIAA-2021-1185](#)



Experimental Setup

NASA Aero-Acoustics Propulsion Lab (AAPL)



- Baseline axisymmetric convergent Small Metal Chevron (SMC000) nozzle at Set Point 7 (SP7) and six chevron nozzle (SMC001)

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

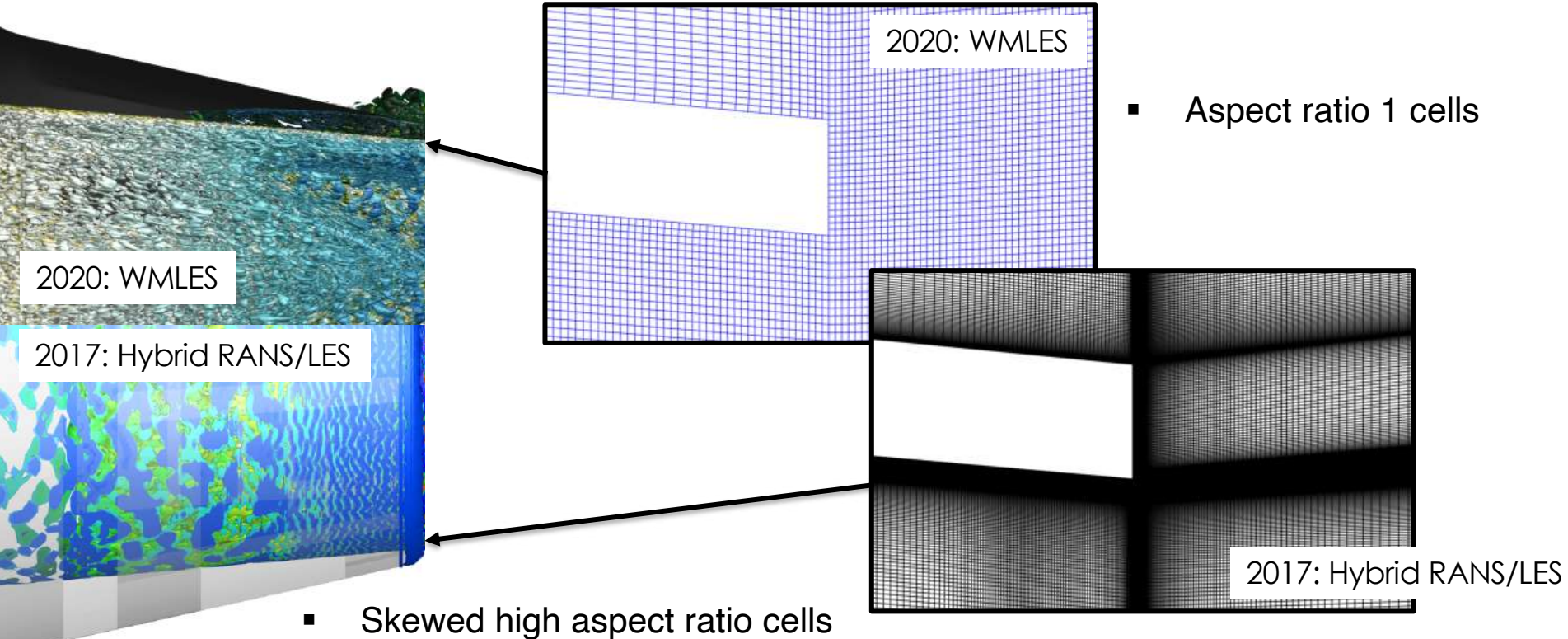
nozzle geometries



- 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

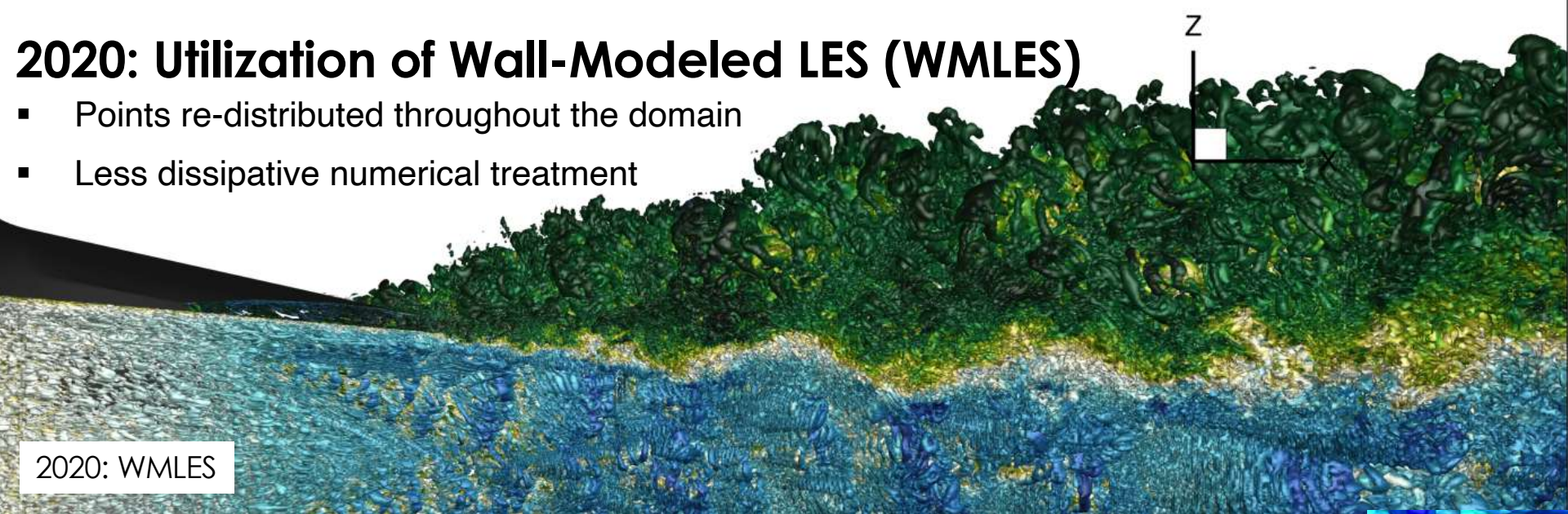
2020: Utilization of Wall-Modeled LES (WMLES)

- Points from resolving near-wall gradients distributed throughout the domain
- Improved aspect ratio (AR) allows "better" numerical treatment (less dissipation)

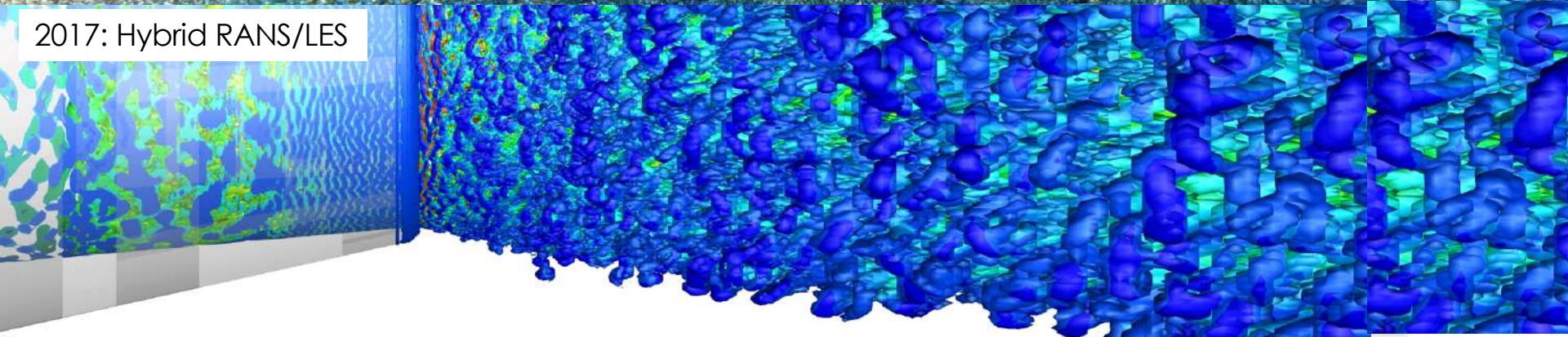


2020: Utilization of Wall-Modeled LES (WMLES)

- Points re-distributed throughout the domain
- Less dissipative numerical treatment



2020: WMLES

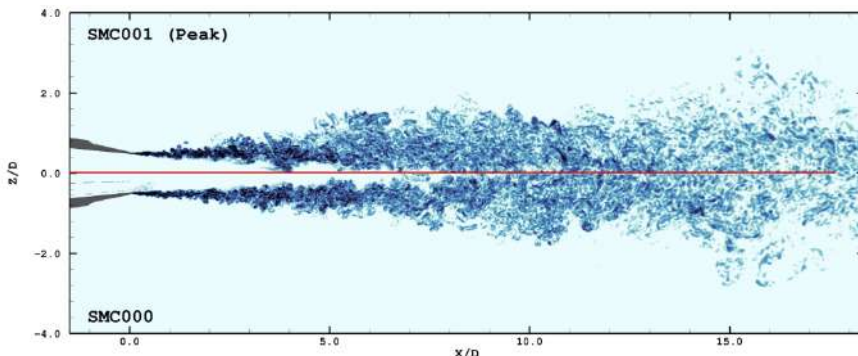
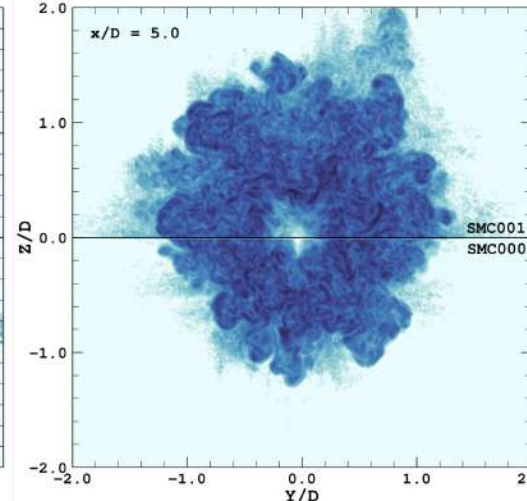
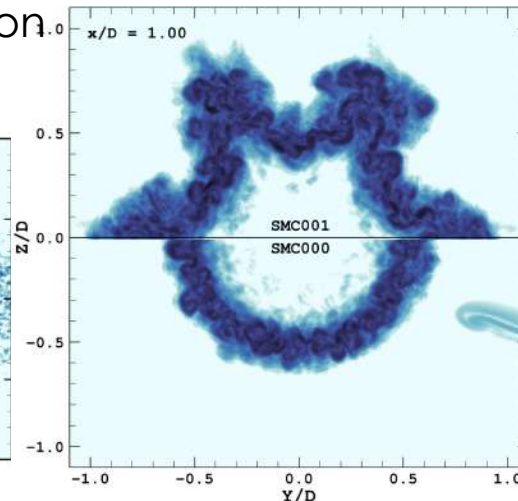
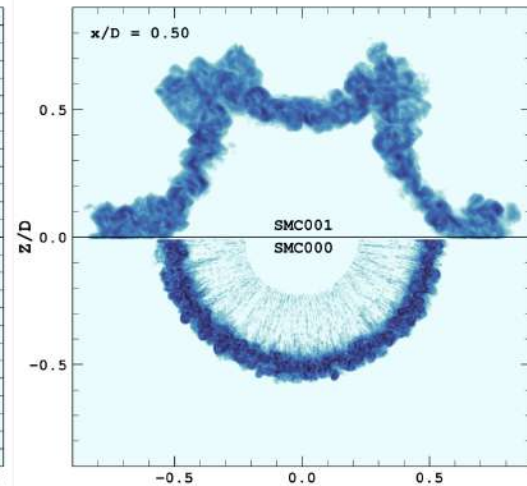
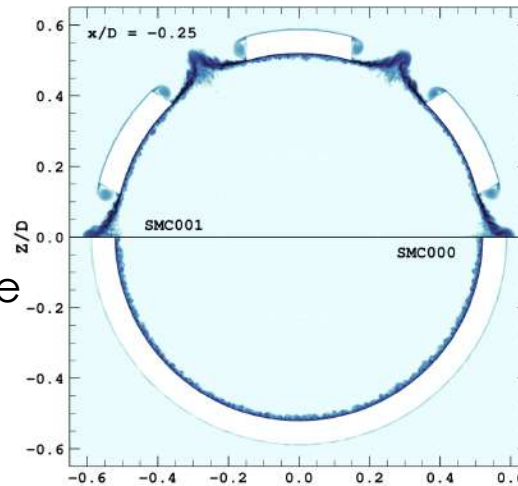


2017: Hybrid RANS/LES

Flow Field Comparison

SMC000 vs SMC001

- Vorticity magnitude for chevron nozzle (top) round-jet (bottom)
- Stronger jet spreading in chevron compared to round jet
- Vorticity roll-up at nozzle exit at chevron

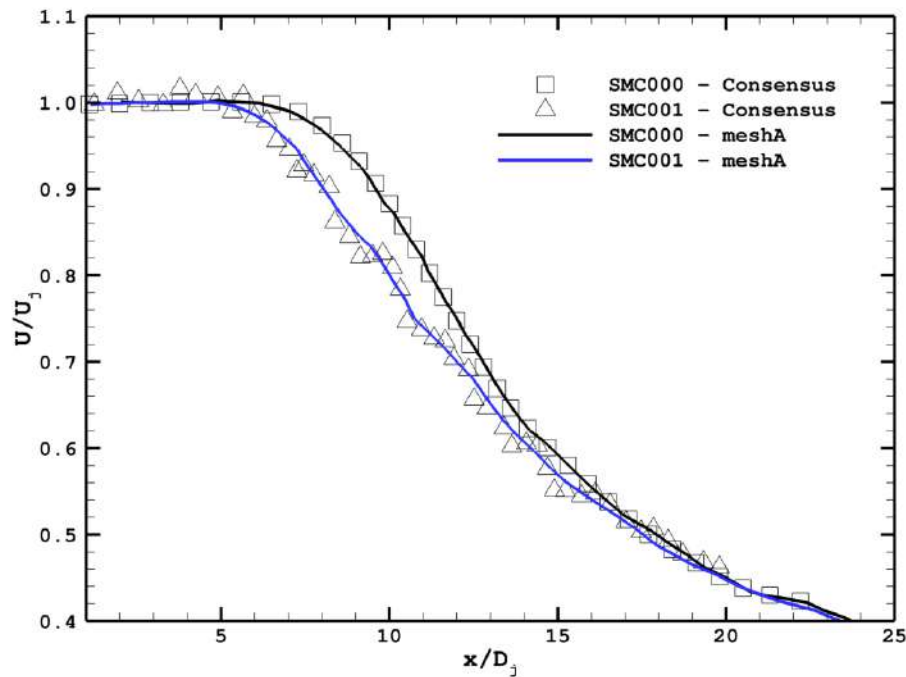


Near-Field Comparison: Centerline

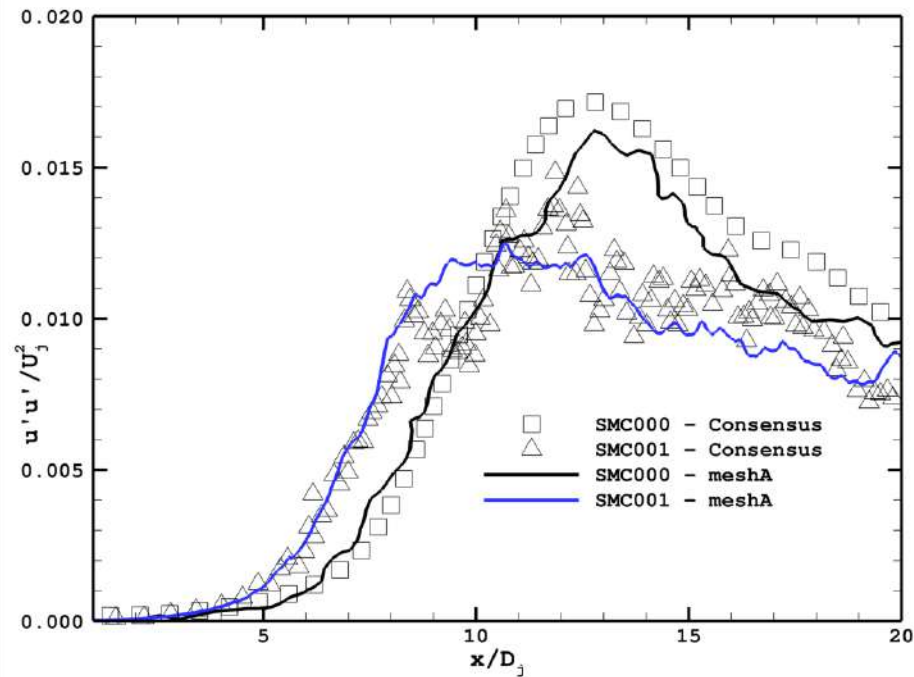
SMC000: Round
SMC001: Chevron



dimensionless streamwise velocity u/U_j



dimensionless variance $u'u'/U_j^2$

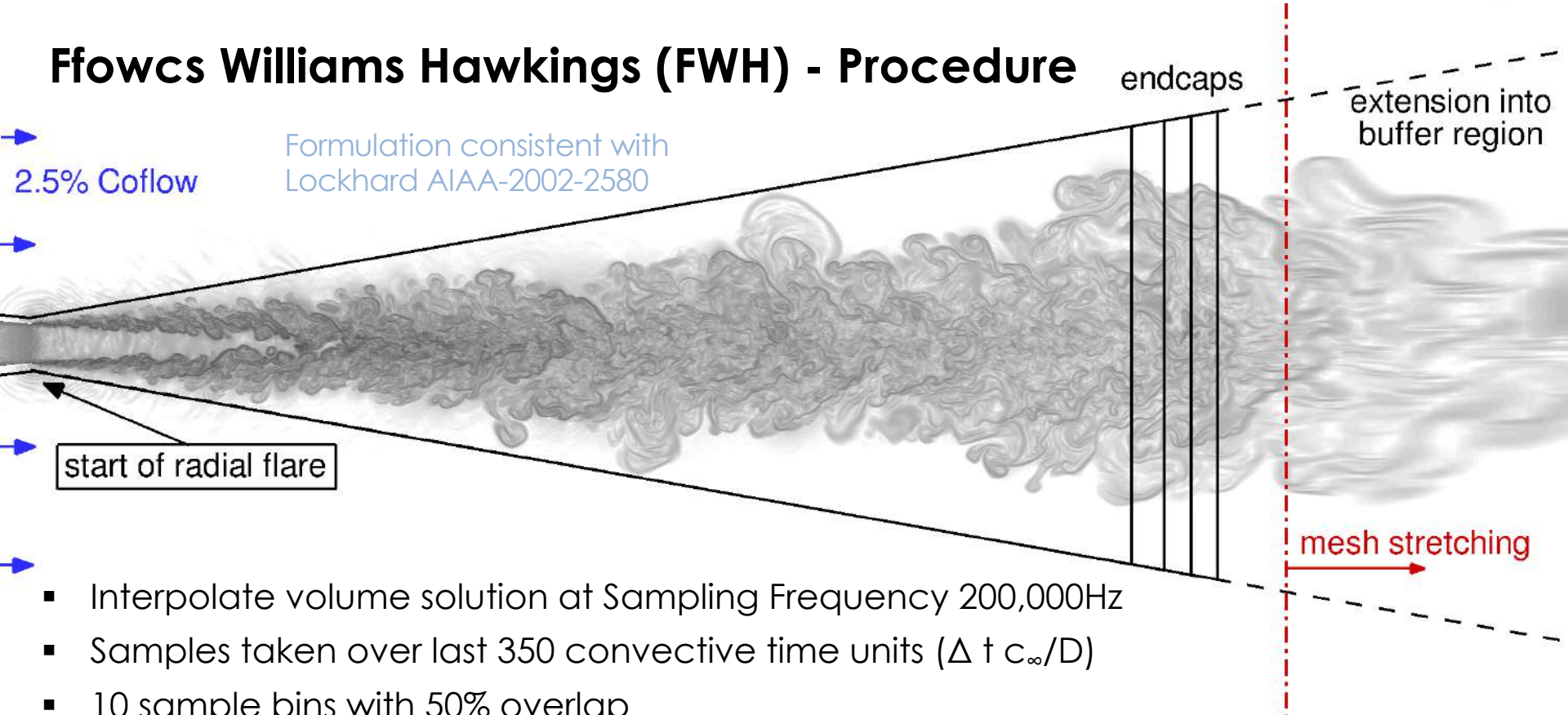


- Length of potential core predicted accurately ($U/U_j = 0.98$)
- Location and magnitude of normal stress agrees well with experiment

Fflowcs Williams Hawkings (FWH) - Procedure

2.5% Coflow

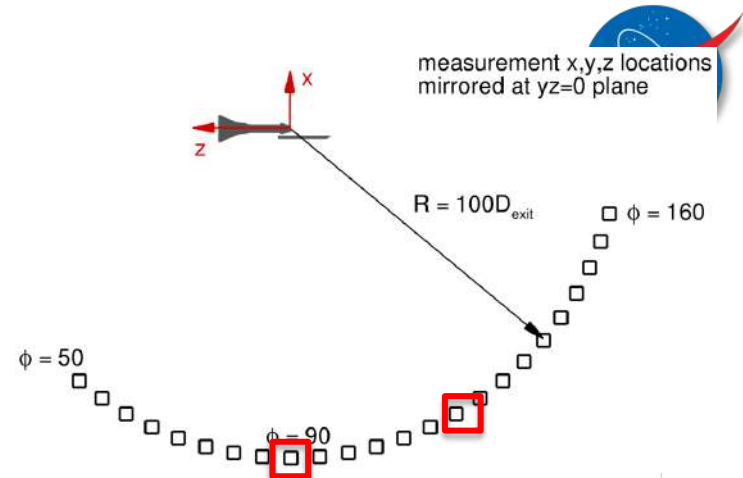
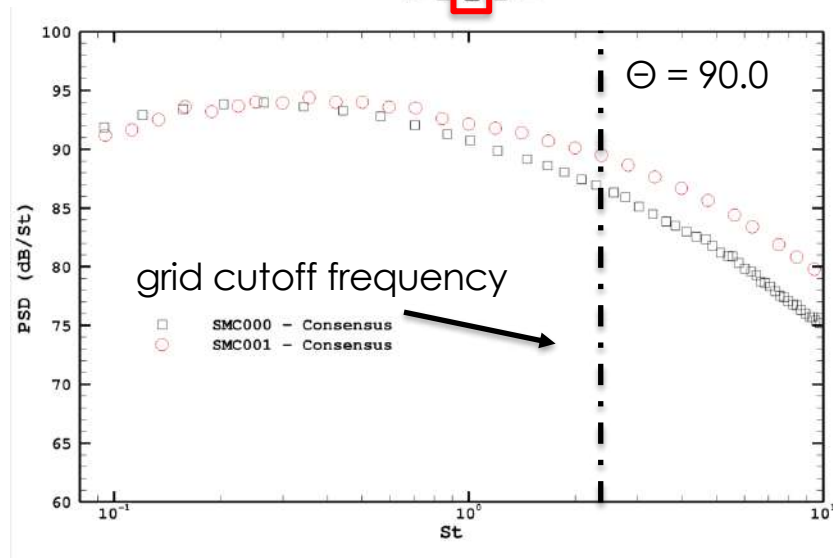
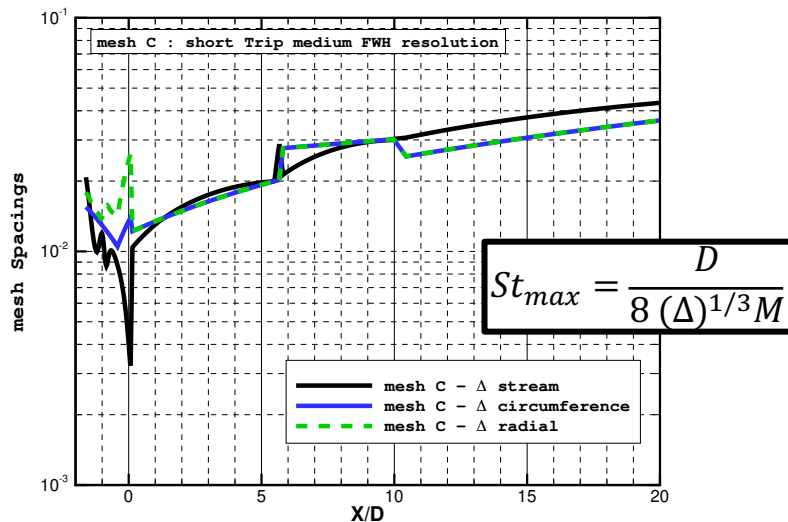
Formulation consistent with
Lockhard AIAA-2002-2580



- Interpolate volume solution at Sampling Frequency 200,000Hz
- Samples taken over last 350 convective time units ($\Delta t c_\infty/D$)
- 10 sample bins with 50% overlap
- Hanning window applied
- Averaged over 6 observers in azimuth

Far-field Noise Spectrum at 100D

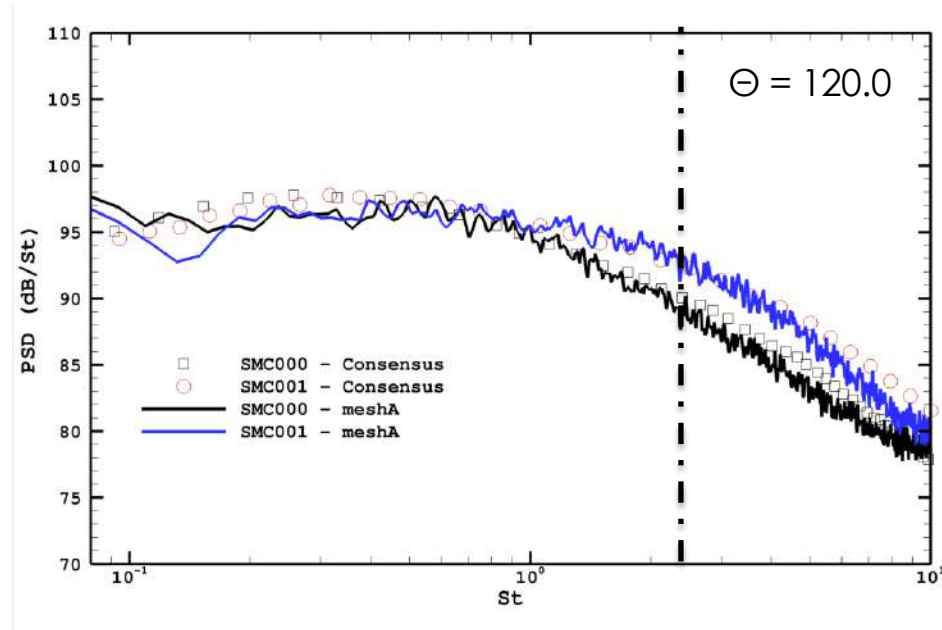
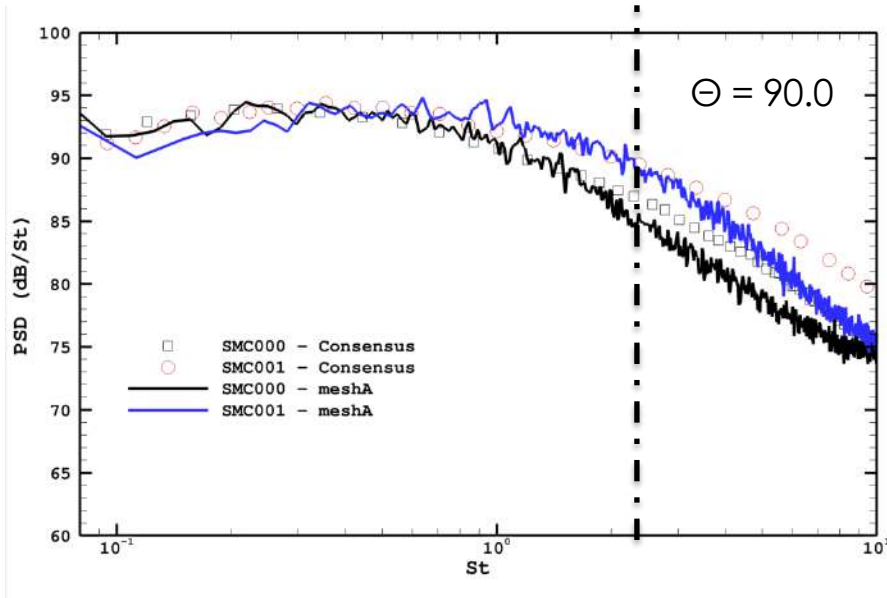
- Good agreement with microphone data until grid cutoff frequency
- Cutoff frequency estimated from mesh resolution along FWH surface assuming 8 pnts/wavelength



Far-field Noise Spectrum at 100D

SMC000: Round
SMC001: Chevron

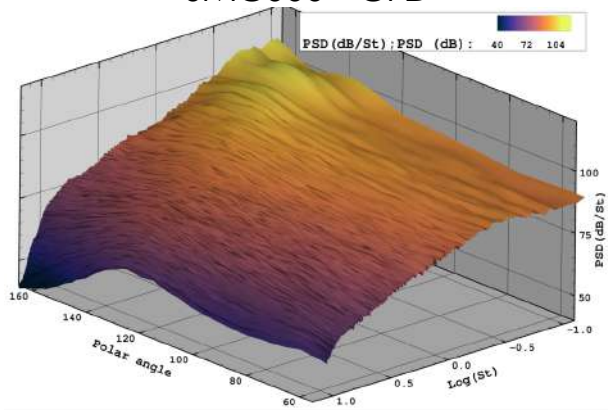
- Difference between round jet and chevron for $St > 1$ captured in simulation
- Slight underprediction of noise at lower frequencies
- Overall good agreement with experiment



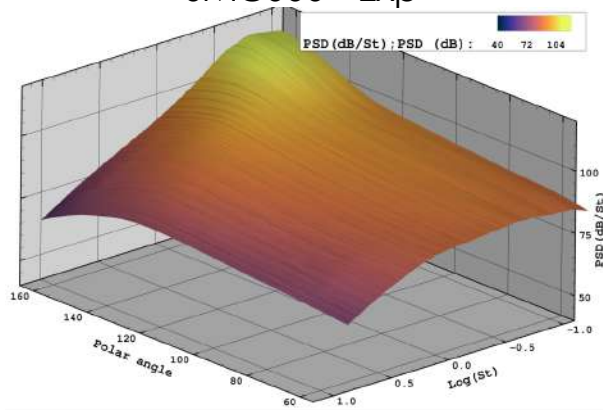
Far-field Noise Spectrum at 100D: Directivity



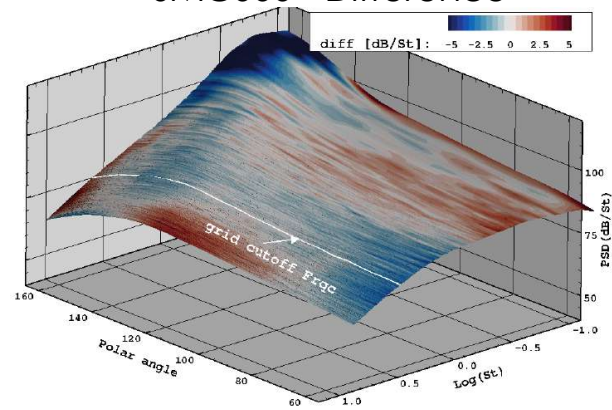
SMC000 - CFD



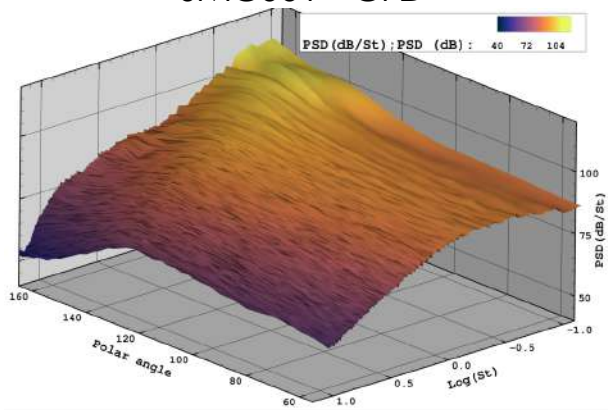
SMC000 - Exp



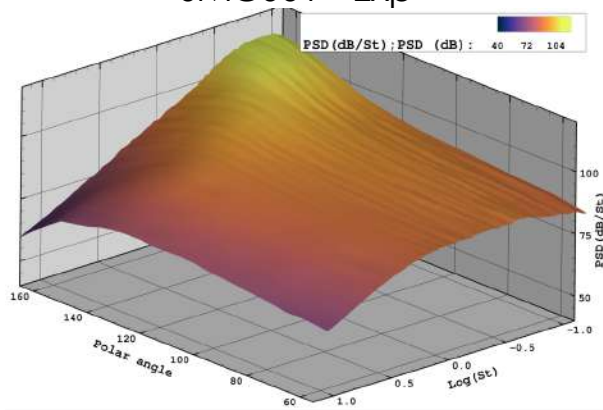
SMC000 - Difference



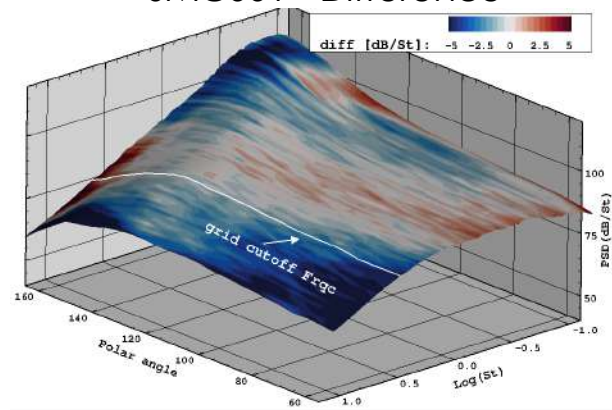
SMC001 - CFD



SMC001 - Exp



SMC001 - Difference



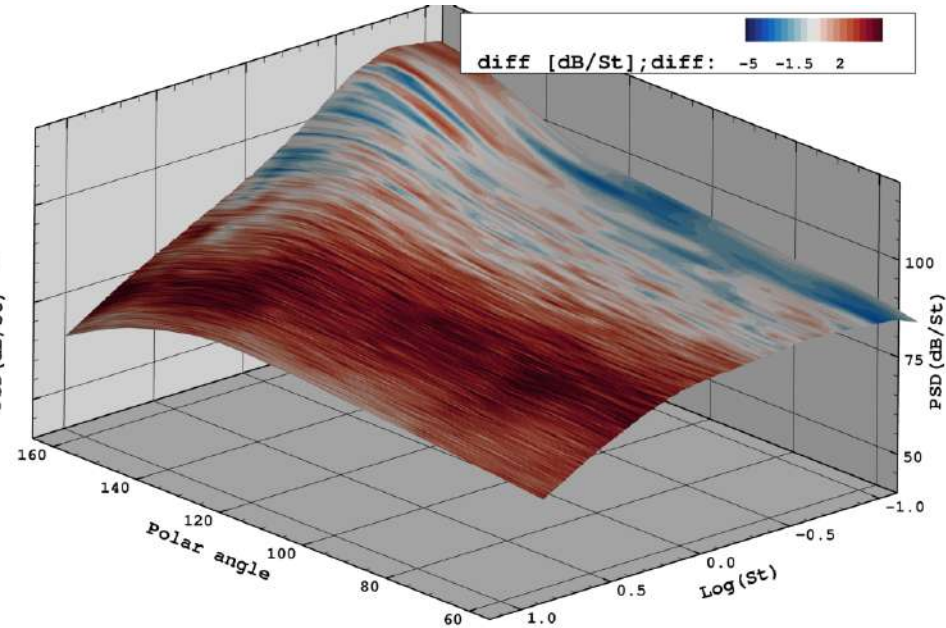
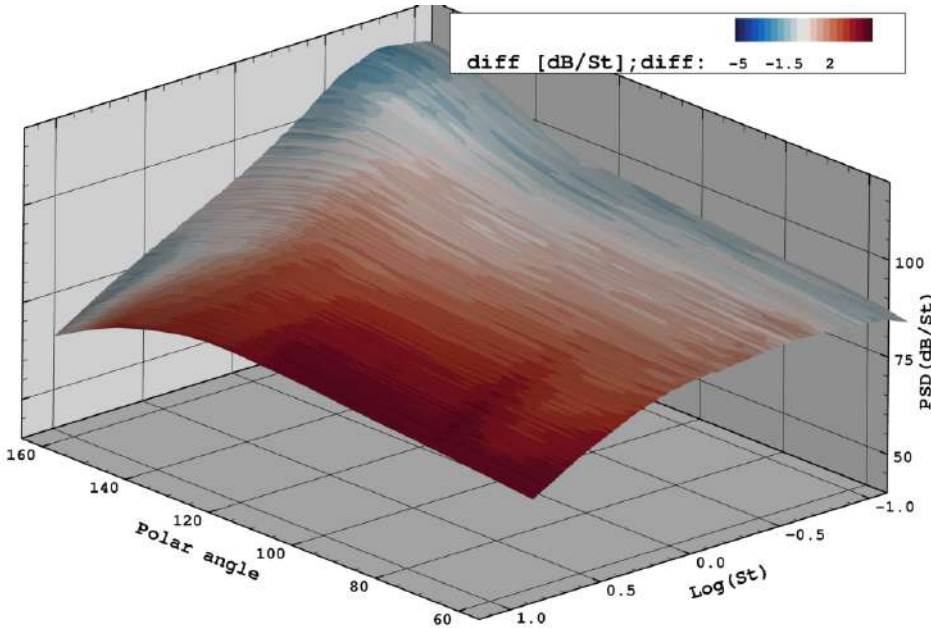
Far-field Noise Spectrum at 100D: Directivity

SMC000: Round
SMC001: Chevron



Difference SMC000 vs SMC001: Experiment

Difference SMC000 vs SMC001: CFD



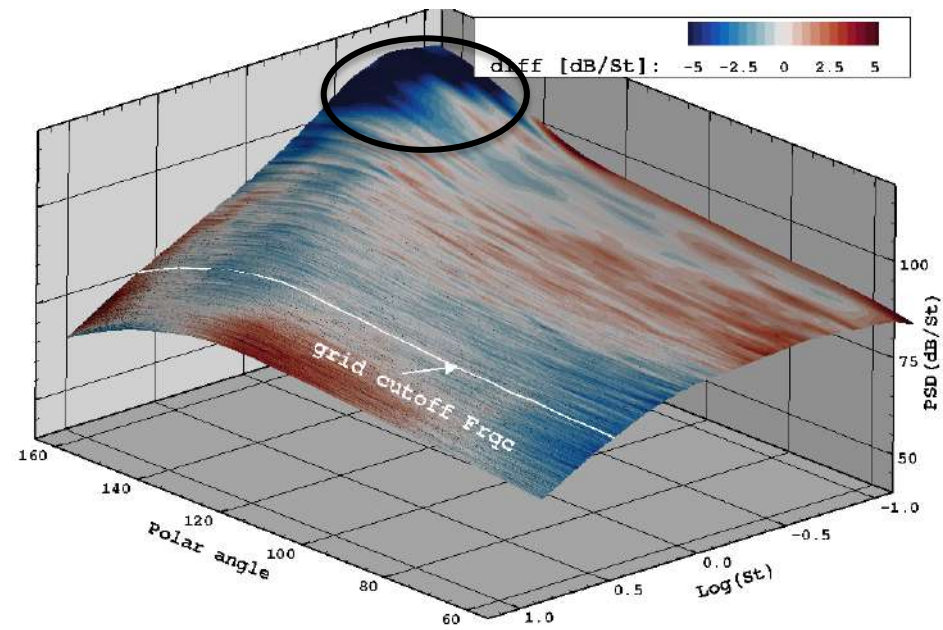
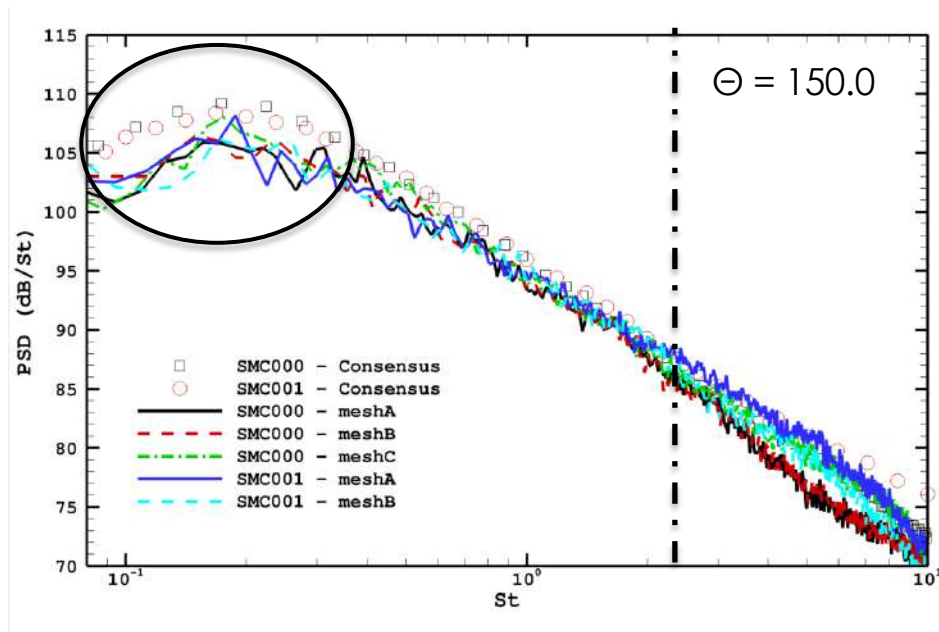
- Overall good agreement in prediction of noise reduction due to chevron nozzle
- Difference in PSD at very low frequencies and large angles due to statistical uncertainty of few data samples in signal

Far-field Noise Spectrum at 100D: Directivity

SMC000: Round
SMC001: Chevron



SMC000 – Difference CFD and Experiment



Prediction Uncertainty Reduction (PUR) (see Presentation by J. Bridges):

Reduce uncertainties in prediction of LTO noise to allow accurate assessment of environmental and economic impacts of commercial supersonic flight.



Timings and Code Improvements

Time savings due to algorithm, code improvements and development

Date	Method	Mesh size [10 ⁶]	$\Delta t/c^\infty$	CPU	Time/CTU [CPUh]	Time to solution 150 / 300 convective units	Speedup (November baseline)
November 2019	Hybrid RANS/LES (ZDES III)	225	0.007	60 Skylake (2400 cores)	995	3.2 day / 6.5 day	--
March 2020	Wall-stress WMLES	254	0.0005	60 Skylake (2400 cores)	430	26.8 hr / 2.3 day	2.8x
November 2020	Wall-stress WMLES	110	0.001	60 Skylake (2400 core)	69	4.3 hr / 8.6 hr	18x

CTU: Convective Flow Through Unit

* Timings include high frequency (sampling rate 200kHz) i/o output for solution

** Substantially better temporal resolution and spatial resolution (azimuth, stream) achieved compared to baseline November 2019



Timings and Code Improvements

Time savings due to algorithm, code improvements and development

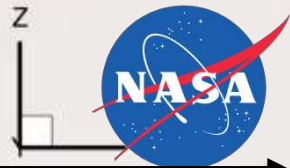
Date	Method	Mesh size [10 ⁶]	$\Delta t/c^\infty$	CPU	Time/CTU [CPUh]	Time to solution 150 / 300 convective units	Speedup (November baseline)
November 2019	Hybrid RANS/LES (ZDES III)	225	0.007	60 Skylake (2400 cores)	995	3.2 day / 6.5 day	--
March 2020	Wall-stress WMLES	254	0.0005	60 Skylake (2400 cores)	430	26.8 hr / 2.3 day	2.8x
November 2020	Wall-stress WMLES	110	0.001	60 Skylake (2400 core)	69	4.3 hr / 8.6 hr	18x
March 2021	Wall-stress WMLES	250	0.007	100 Rome (12800 core)	106	75min / 150 min	

CTU: Convective Flow Through Unit

* Timings include high frequency (sampling rate 200kHz) i/o output for solution

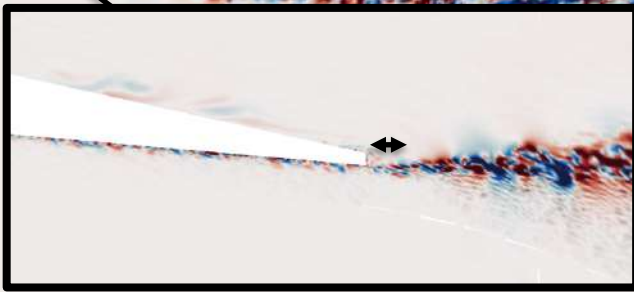
** Substantially better temporal resolution and spatial resolution (azimuth, stream) achieved compared to baseline November 2019

Comparison of Length and Time scales related to Eddy size

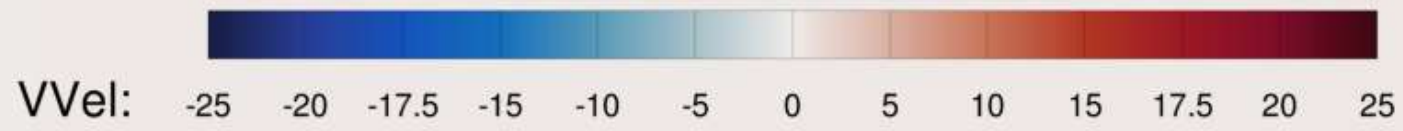


Domain size for jet 35D

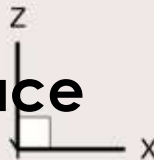
Length scale: 0.02D
Sweeping Timescale: 0.05 D/U



Length scale: 2.0D
Sweeping Timescale: 15.0 D/U



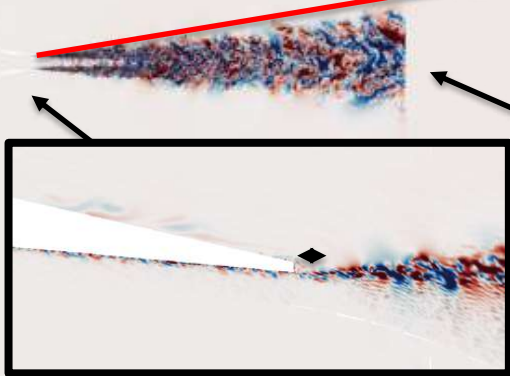
Far-field Noise Spectrum at 100D – Ends of the FWH surface



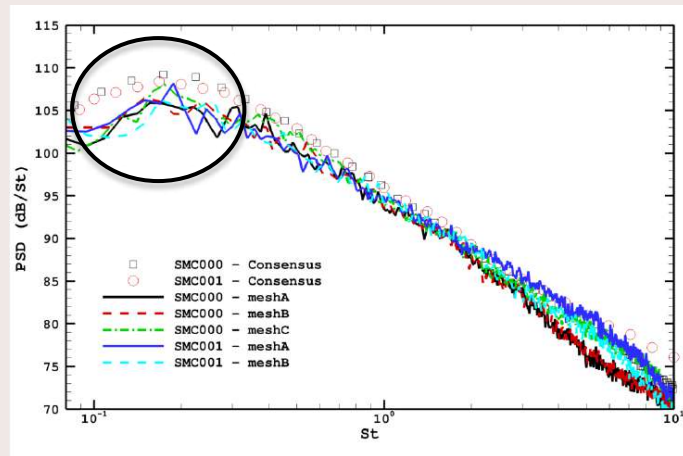
Domain size for jet 35D (standard size in literature)

Length scale: 0.02D
Sweeping Timescale: 0.05 D/U

165° observer

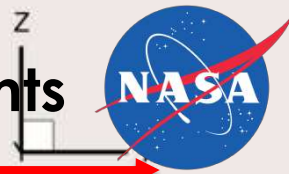


Length scale: 2.0D
Sweeping Timescale: 15.0 D/U



VVel: -25 -20 -17.5 -15 -10 -5 0 5 10 15 17.5 20 25

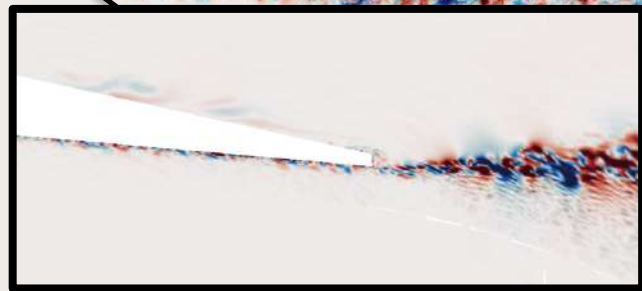
New Opportunities Enabled Through Code Improvements



Domain size for jet extended to $140D$

165 observer

Length scale: $0.02D$
Sweeping Timescale: $0.05 D/U$

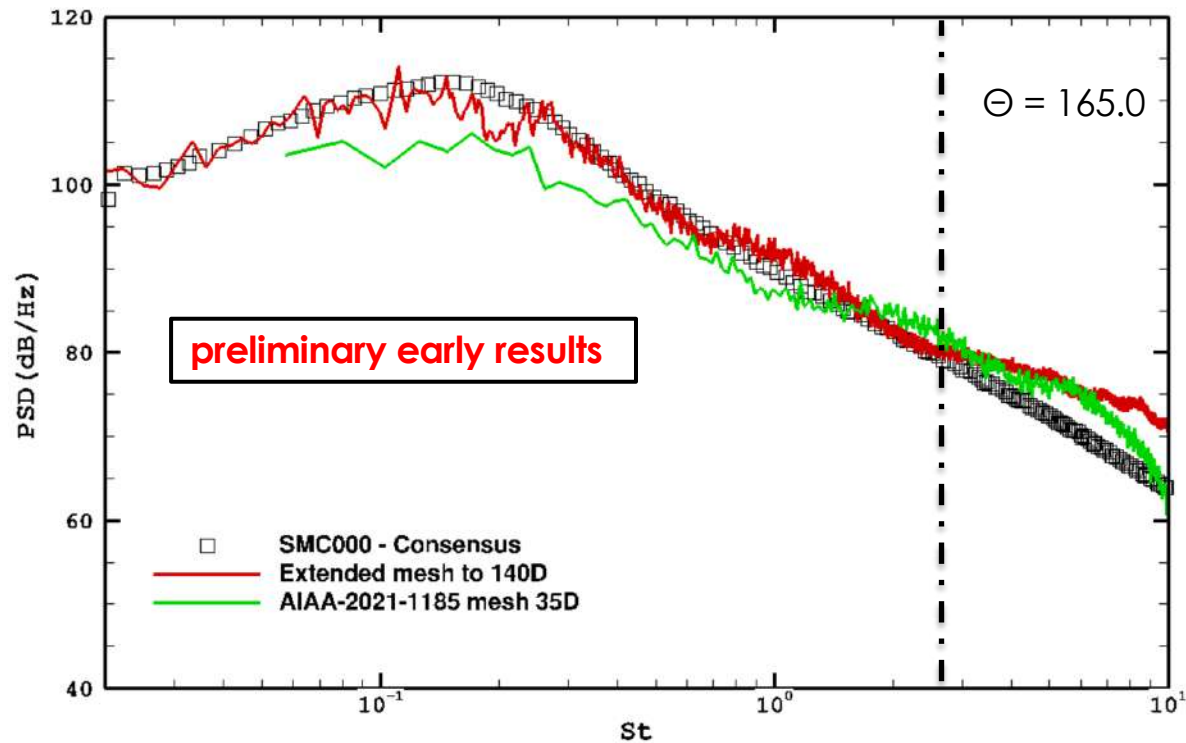


Length scale: $20.0D$
Sweeping Timescale: $522 D/U$



VVel: -25 -20 -17.5 -15 -10 -5 0 5 10 15 17.5 20 25

Far-field Noise Spectrum at 100D – Far Aft-Angles 165°

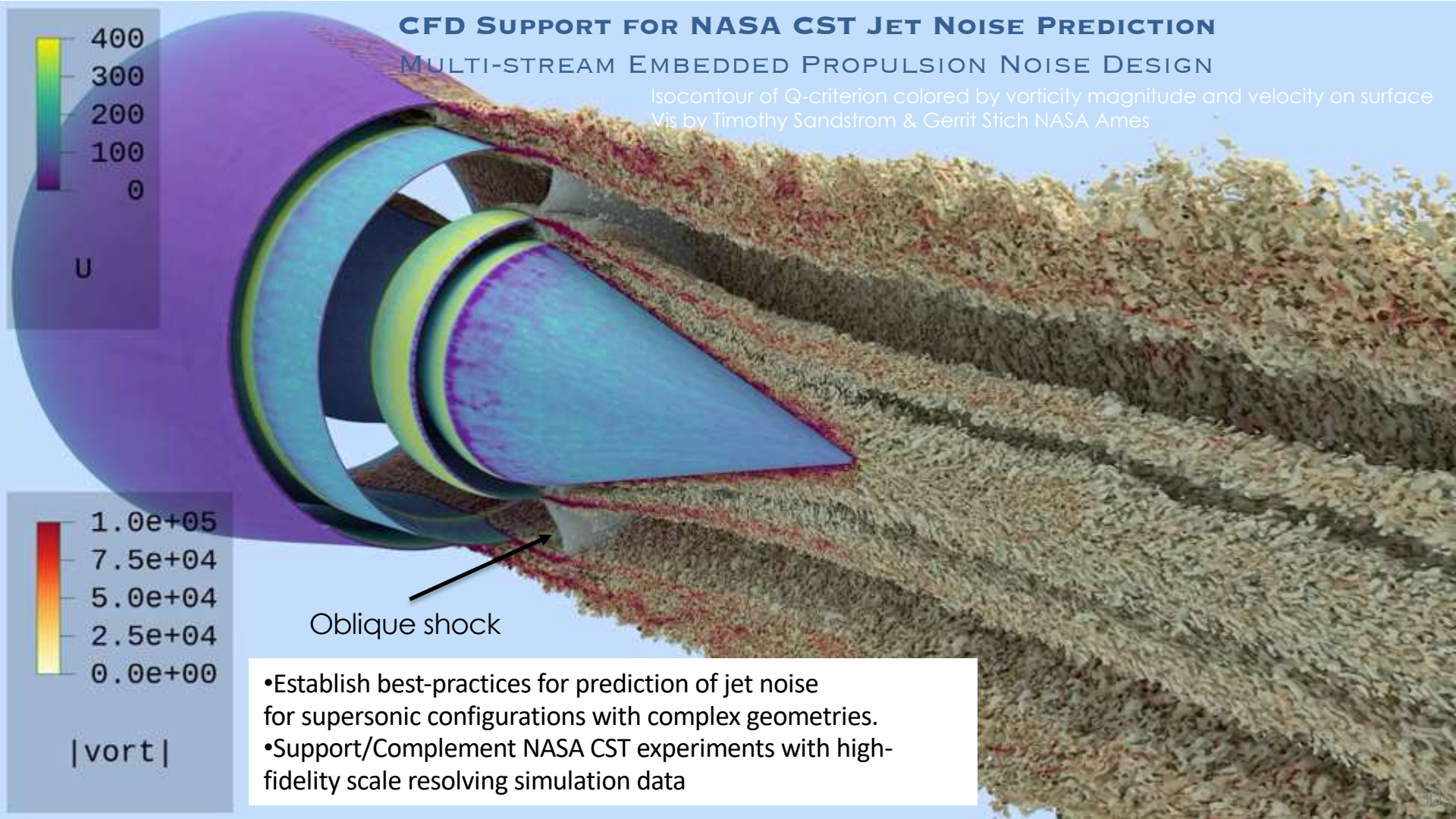


- ❑ Aft-angle peak noise seems to be improved with 140D domain vs 35D domain
- ❑ Extended domain enables comparison of FWH far-field noise with direct CFD noise at shallow aft angles
- ❑ Peaks in high frequency noise spectra due to hydrodynamic pressure fluctuations crossing through FWH
- ❑ Strong dependency on FWH surface triangulation
- ❑ More work necessary for concluding remarks

CFD SUPPORT FOR NASA CST JET NOISE PREDICTION

MULTI-STREAM EMBEDDED PROPULSION NOISE DESIGN

Isocontour of Q-criterion colored by vorticity magnitude and velocity on surface
Vis by Timothy Sandstrom & Gerrit Stich NASA Ames



- Establish best-practices for prediction of jet noise for supersonic configurations with complex geometries.
- Support/Complement NASA CST experiments with high-fidelity scale resolving simulation data



Conclusions and Future work

- ❑ Demonstrated capability to perform jet noise simulations with
 - A. **Good accuracy** compared to experiment for simple and more complex geometries
 - B. Showed and order of magnitude **improvement in overall turnaround time** (*from weeks to days to hours*)
- ❑ Improvement will enable database generation of jet noise flow simulations instead of few simulations per year (10 set points for SMC000)
- ❑ Additional insight can be found when comparing noise at far-aft angles with noise directly taken from CFD simulation at 165 observer
- ❑ Errors and shortcomings of WMLES for jet noise need to be **understood and documented further.**
- ❑ Systematic validation effort progressed further towards “Grand Challenge” configurations (TMP17, Plug20)



Acknowledgments

- ❑ This work was funded by the Commercial Supersonics Technology (CST) project
- ❑ The development of WMLES within the LAVA solver is funded by the Transformational Tools and Technology (T³) project under the Aeronautics Research Mission Directorate (ARMD).
- ❑ James Bridges and colleagues from NASA Glenn Research Center
- ❑ Computer time has been provided by the NASA Advanced Supercomputing (NAS) facility at NASA Ames Research Center.
- ❑ Gaetan Kenway for code optimizations and algorithm developments within LAVA
- ❑ Team members of LAVA group for helpful discussions and advice



Questions?

POC: Gerrit-Daniel.Stich@nasa.gov
Cetin.c.Kiris@nasa.gov