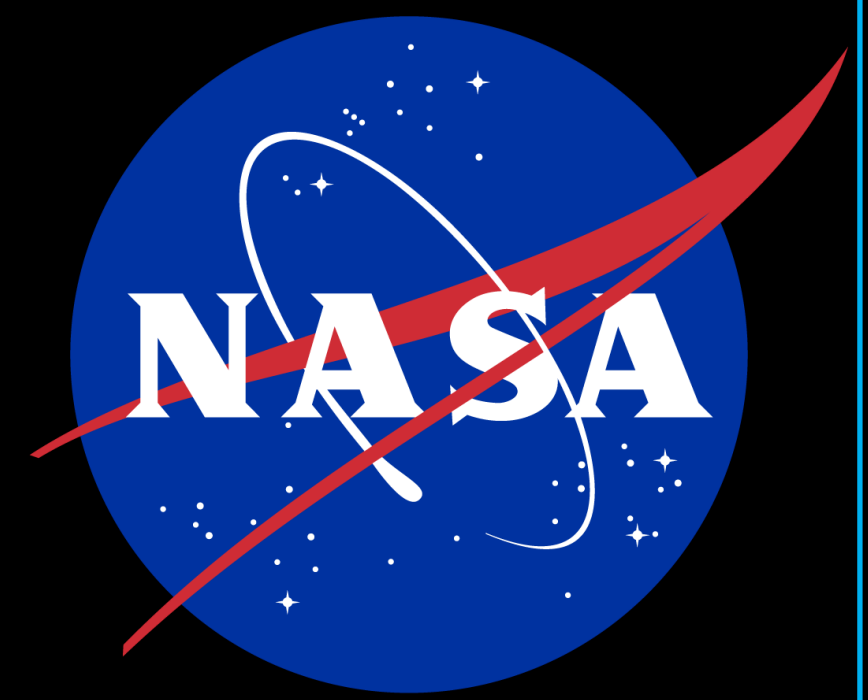


# Leveraging Large Eddy Simulations to Characterize Aeroacoustic Environments on Launch Vehicles

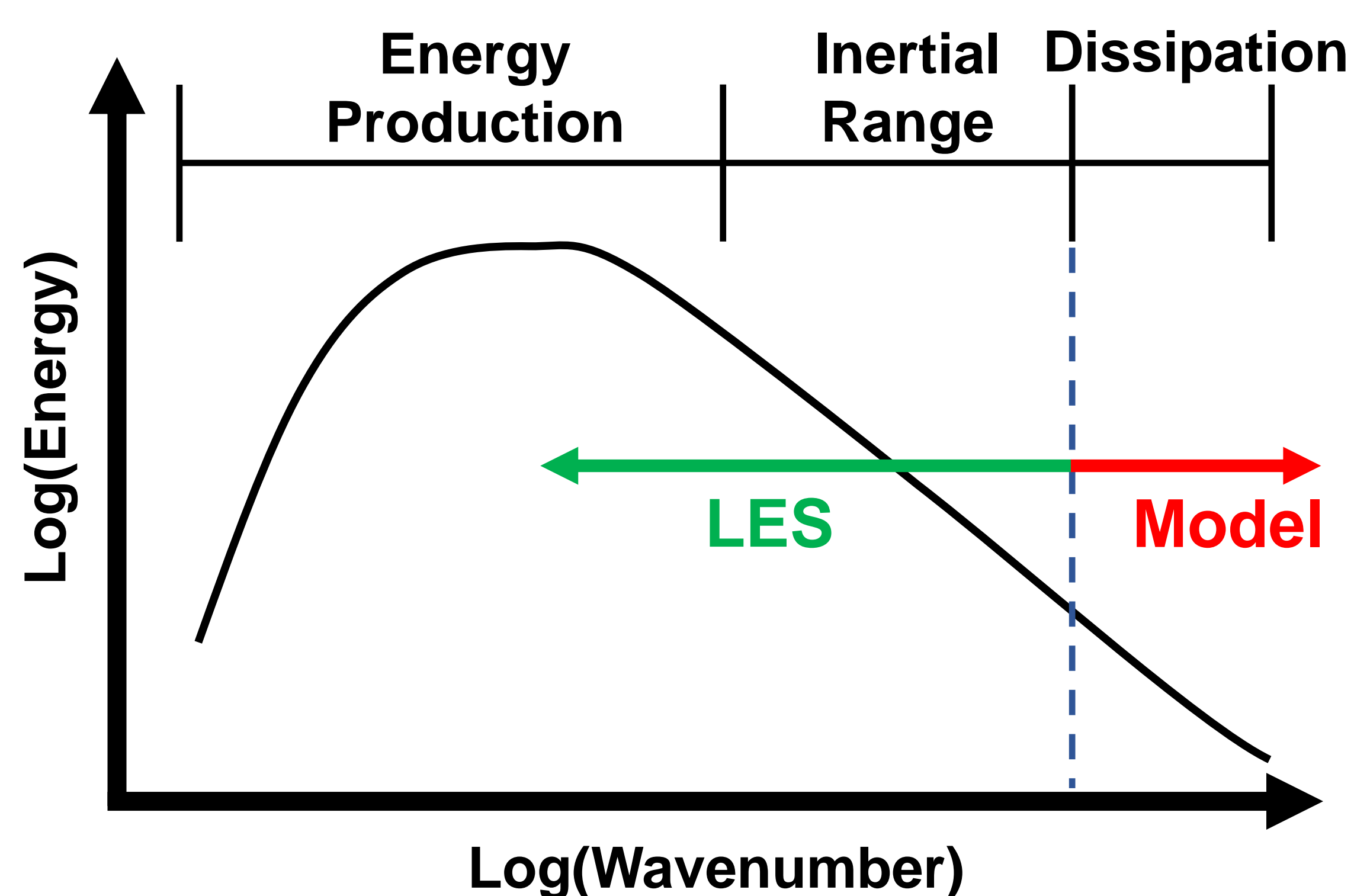


Jonathan Boustani, MSFC EV33/ESSCA/Mclaurin Aerospace  
Bryson Frank, MSFC EV33/ESSCA/Mclaurin Aerospace

## INTRODUCTION

NASA's Space Launch System (SLS) program has relied on multiple wind tunnel campaigns to predict expected aeroacoustic environments. Time, cost, Reynolds number matching, contamination from test section acoustics, and limitations in spatial resolution are all factors that impact the use of experimental data for development of launch vehicle environments. Methodological and computational advances over the last decade are enabling scale-resolving computational fluid dynamics (CFD) simulations to be completed that can address some of the challenges with conventional datasets, enabling more complete/accurate modeling of dynamic loading events on ascent.

These simulations are classified as so-called "Large-Eddy Simulations" (LES). As the name implies, these simulations seek to directly resolve the turbulence in the largest, most-energetic turbulent structures, or eddies, and the dissipation of the smallest eddies in the flow field is modeled. Like anything else, these simulations still must undergo rigorous testing and validation for the results to ultimately be trusted in the analysis of a launch vehicle. EV33 has begun to conduct some of this early-stage testing and validation to better support NASA missions in the future.

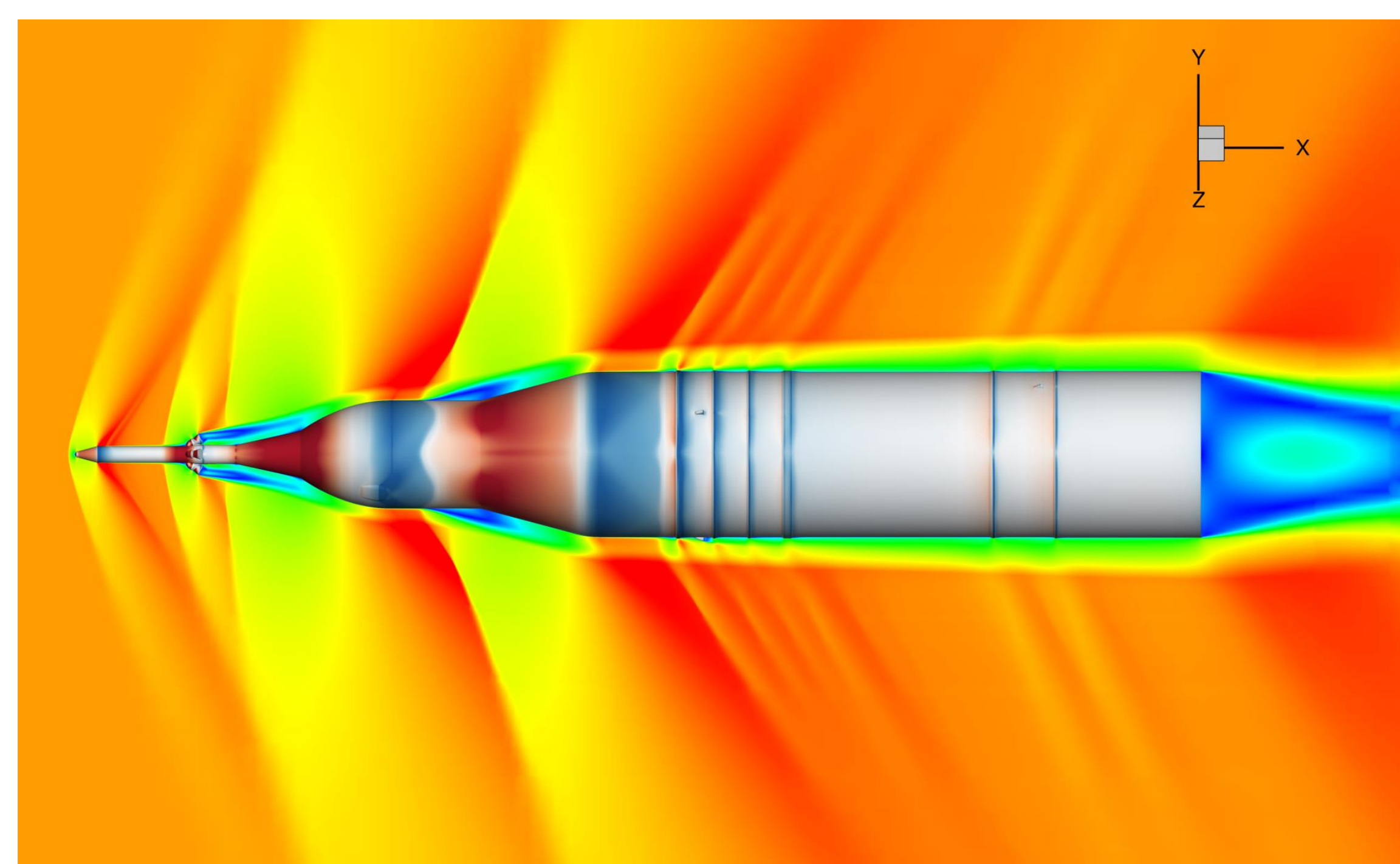


Caption: Turbulent energy spectrum showing the regions of LES (large scales) and modeled dissipation (small scales)

## RANS

Reynolds-averaged Navier-Stokes (RANS) simulations provide a steady-state, averaged solution of a flow field while modeling *all* turbulent scales. This approach is widely-used in industry due to its efficiency and suitability for a wide range of engineering problems.

A short-coming with RANS, however, is excessive dissipation due to modeling all length scales, and the lack of time-accurate resolution of moderate- to high-frequency phenomena.



Caption: Typical steady-state and averaged Mach number contours predicted by RANS on a 4%-scale Block-1B forebody.

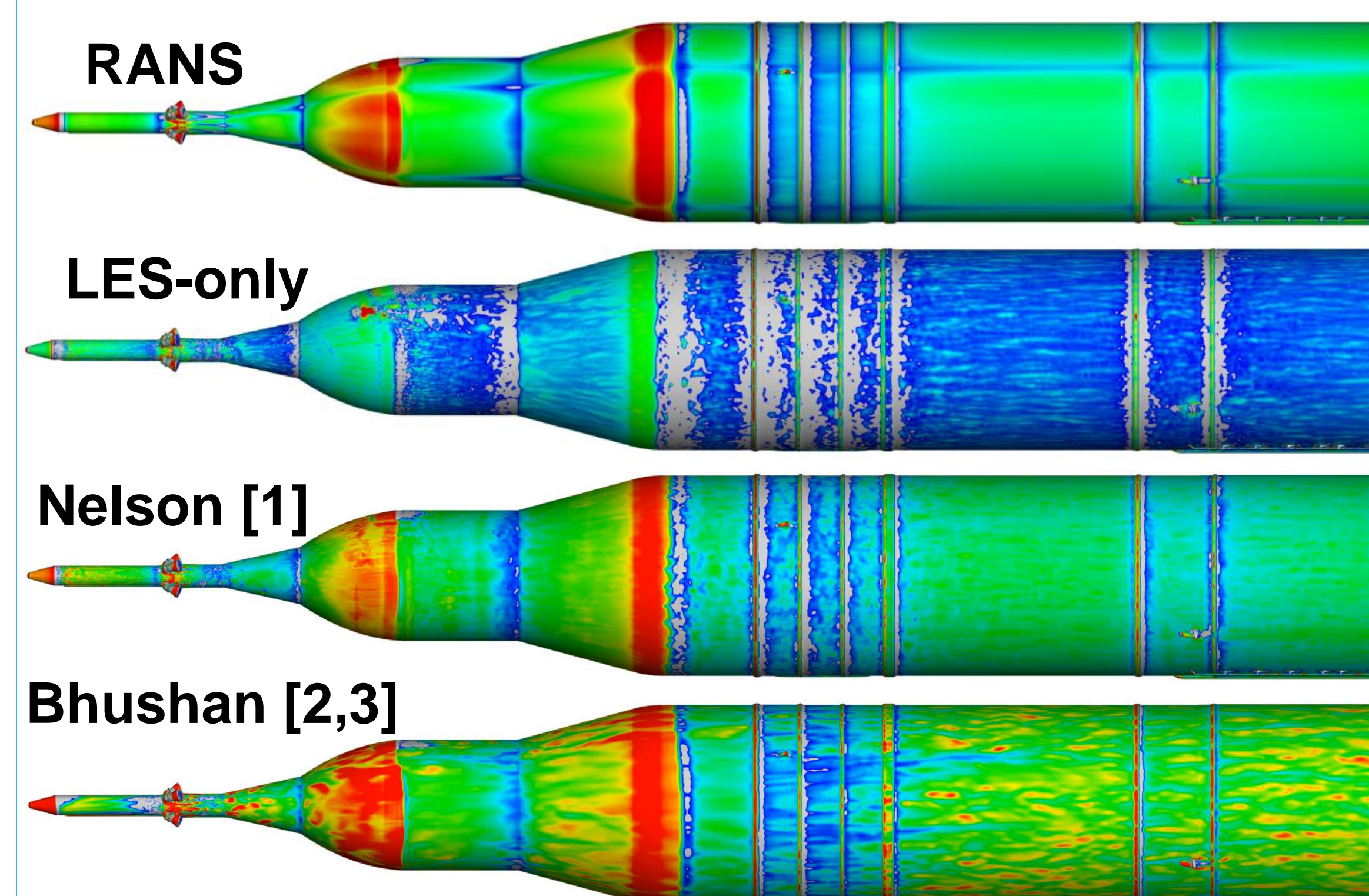
## Hybrid RANS-LES

Some of the short-comings associated with RANS simulations can be overcome by coupling RANS with LES. RANS does an excellent job at predicting attached turbulent boundary layers; thus, in such a hybrid method, RANS would be limited to the near-wall region. As the flow separates due to sharp geometric changes or adverse pressure gradients, the solution would transition to LES and begin to resolve the larger turbulent length scales associated with separated flow.

The smooth transition from RANS to LES is governed by a so-called shielding function, the design of which is itself an area of very active research. Members of EV33 using Loci/CHEM have so far considered shielding functions and hybrid RANS-LES (HRLES) schemes developed by Nelson and Nichols 2003 [1] and Bhushan and Walters 2015 [2,3].

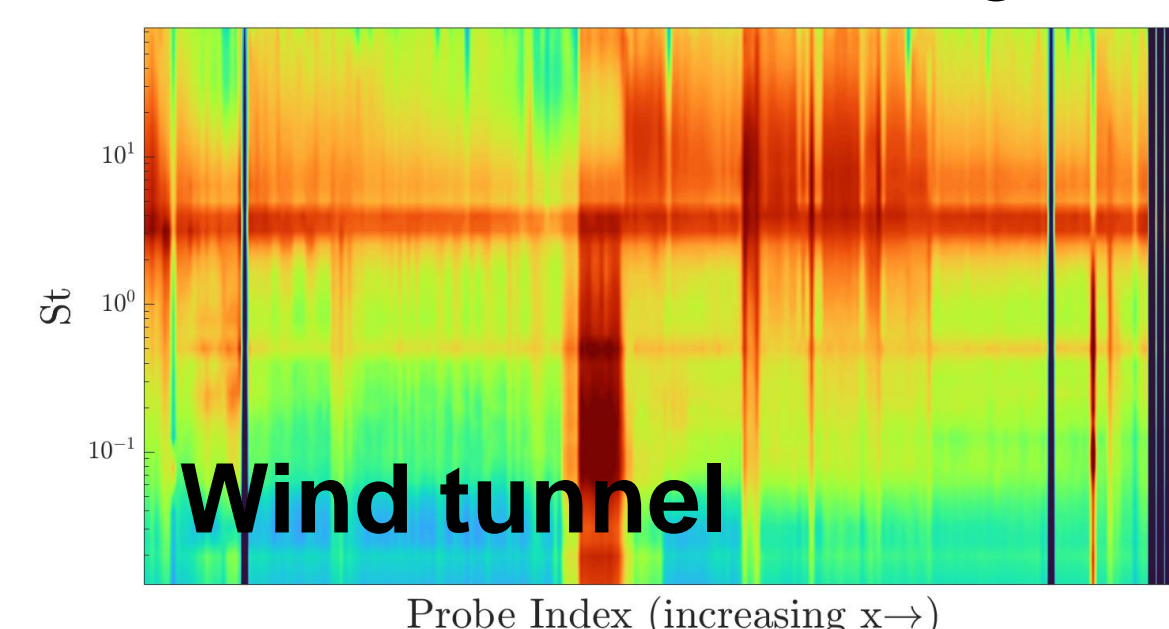
## Application to Aeroacoustics

Hybrid RANS-LES simulations of NASA's SLS Ascent Unsteady Aerodynamics wind tunnel Test (AUAT) were conducted by members of EV33. In this study, a 4%-scale Block-1B forebody was considered in free-air at  $M=0.84$ , neglecting tunnel effects. Comparison between the simulations and wind tunnel were made via analysis of fluctuating pressure level amplitude and frequency content.

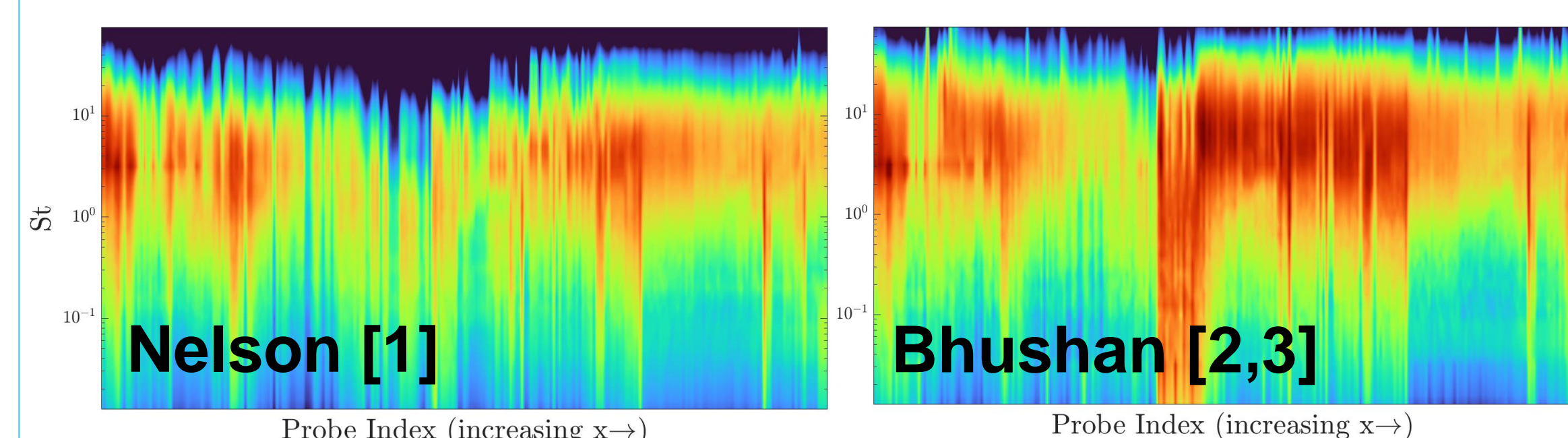


Caption: Surface contours of streamwise skin friction coefficient blanked for negative values for multiple schemes.

High-level comparisons of "bulk quantities" such as skin friction highlight the need for RANS to be conducted at the wall in order to model the smallest length scales.



Probe Index (increasing x→)

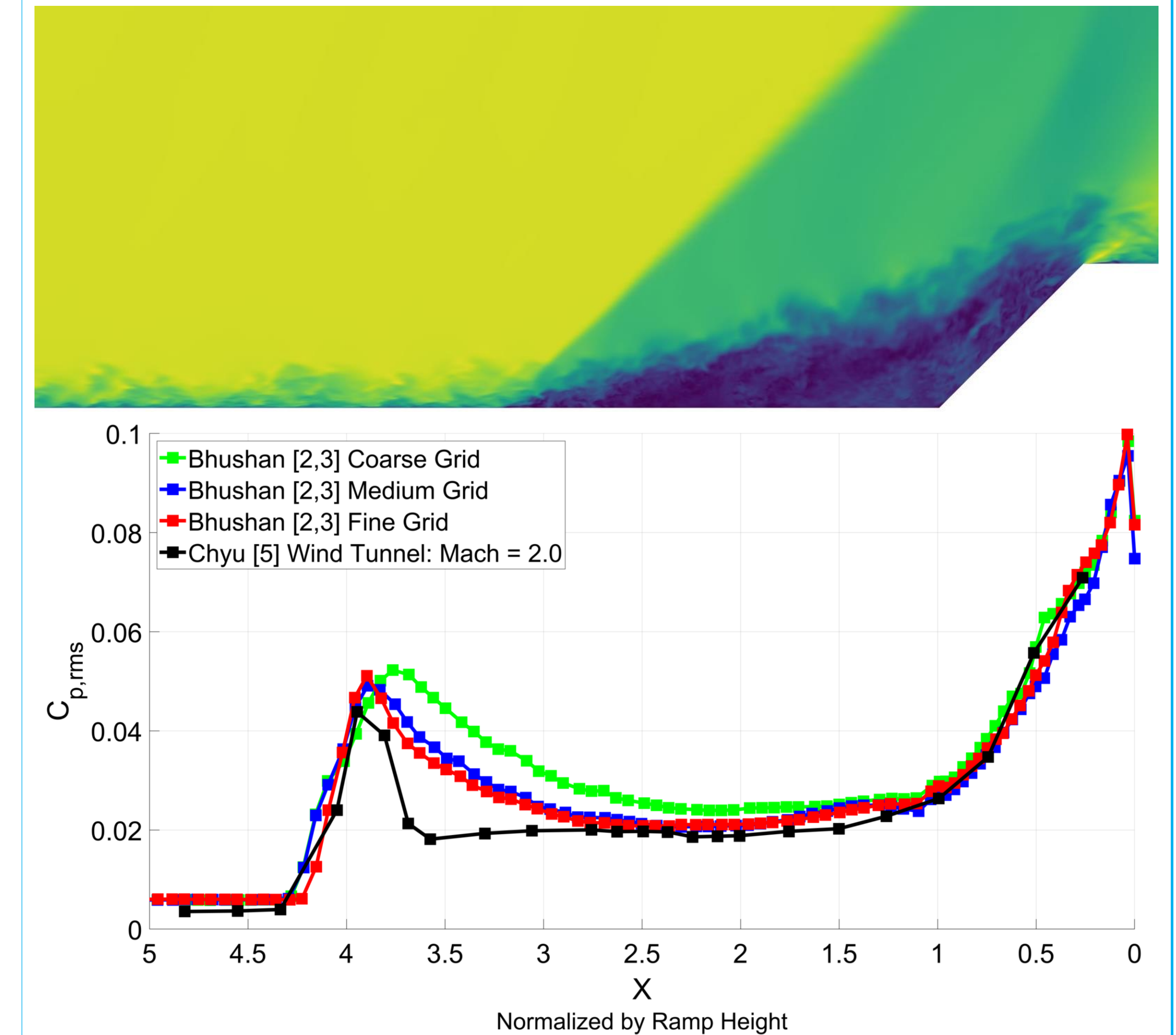


Caption: Spectrograms show areas where the CFD captures both the fluctuating pressure amplitude and frequency.

Another high-level comparison is obtained by computing spectrograms from the CFD and wind tunnel data. The method by Nelson and Nichols [1] fails to capture the separation over the shoulder of the USA, while the method by Bhushan and Walters [2,3] captures the location, amplitude, and frequency content well. More details can be found in Boustani *et al.* 2024 [4].

## Further Studies

Additional simulations are being performed on canonical geometries to further assess and inform the usage of these HRLES schemes on aeroacoustic environments. A compression corner geometry is being used to measure the effects of grid and timestep refinements on quantities such as separation location and  $C_{p,rms}$  in the separated flow region, and velocity profile and skin friction in the incoming boundary layer. Additional schemes such as the Improved Delayed Direct Eddy Simulation developed by Shur [5] and the Algebraic Wall Modeled LES model using the wall function developed by Nichols and Nelson [6] are also being examined.



Caption: Mach contours and the root-mean-square (RMS) of the pressure coefficient predicted by the Bhushan and Walters scheme [2,3] compared to tunnel data by Chyu and Hanly [7].

## CONCLUSION

Large-eddy simulations (LES) and recent advances in algorithms and computational hardware are enabling scale-resolving, time-accurate CFD simulations to support NASA missions. These simulations will provide spatial and temporal resolution of unsteady flow fields that are otherwise not possible with more conventional approaches such as steady-state RANS or unsteady RANS.

Members of EV33 are beginning to verify these methods and apply them to relevant wind tunnel problems that consider very unsteady flows. In addition to the compression corner and AUAT cases, the hammerhead Coe model is also being simulated and compared to available wind tunnel data.



Caption: Iso-surfaces of Mach number from a  $M=0.8$  simulation conducted with HRLES on the Coe hammerhead geometry.

## REFERENCES

- [1] Nelson, C. and Nichols, R., *16th Annual AIAA Computational Fluid Dynamics Conference*, 2003.
- [2] Bhushan, S. and Walters, D., *Physics of Fluids*, 2012.
- [3] Walters, D., Bhushan, S., Alam, M., and Thompson, D., *Thermal and Fluid Engineering Summer Conference*, 2015.
- [4] Boustani, J., Hall, L., and Steva, T. B., *AIAA SciTech 2024 Forum and Exposition*, 2024.
- [5] Shur, M., Spalart, P., Strelets, M., and Travin, A., *International Journal of Heat and Fluid Flow* 29, 2008.
- [6] Nichols, R., and Nelson, C., *AIAA Journal* Vol. 42, No. 6, 2004.
- [7] Chyu, W. and Hanly, R., *NASA Technical Note D-5440*, 1969.