VALIDATION OF HIGH-FIDELITY CFD/CAA FRAMEWORK FOR LAUNCH VEHICLE ACOUSTIC ENVIRONMENT SIMULATION AGAINST SCALE MODEL TEST DATA

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Overview

- During launch, the Space Launch System (SLS) - NASA's next generation heavy-lift launch vehicle - will experience high acoustic loads that emanate from interaction of the rocket plumes with the launch platform.
- Analytical methods based on scaling historical environments and sub-scale model test data are applied to define acoustic loads for vehicle design.
- Time-accurate Computational Fluid Dynamics (CFD) simulations of the integrated vehicle on the launch platform using NASA's supercomputing resources provide configuration specific simulation support.
- CFD modeling captures complex physics of ignition and liftoff flow transients, but lacks fidelity required to track high-frequency acoustic pressure fields.
- A new two-field Computational Aero-Acoustics (CAA) modeling capability has been developed that combines the robust liftoff CFD methods with high-fidelity acoustic field simulations capable of accurately propagating and preserving the high-frequency content of the acoustic wave field around the vehicle and launch complex.

Liftoff Acoustic Loads Environment

Ignition Overpressure (IOP)

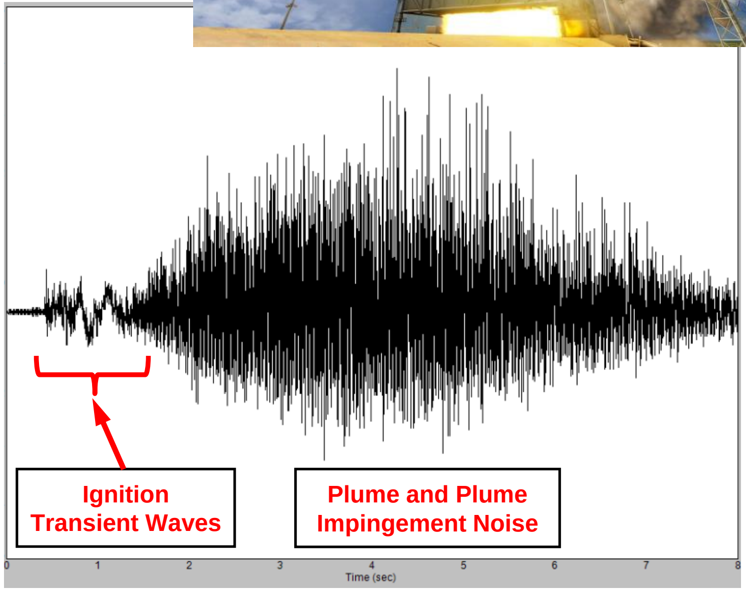
- Significant transient low-frequency pressure events during propulsion system start-up
- Caused by the rapid pressure rise rate and mass flow expulsion during of solid rocket motor

Liftoff Acoustics (LOA)

- Noise caused by the supersonic steady plume flow interaction with surrounding atmosphere and launch complex, persisting for 0 to 10 seconds as the vehicle lifts off
- Maximum noise loads occur late in the liftoff phase, as the vehicle rises to tower level and the plumes interact with pad
  - Noise plume reflecting from launch platform upward towards vehicle
  - Noise from plume impingement regions on launch platform

Launch acoustic loads are defined as design environment and applied in vehicle design process

Analytical methods anchored and scaled from historical launch vehicle databases and sub-scale model tests



Liftoff Acoustics Modeling Validation

- **ASMAT and SMAT Test Series**: Scaled model tests provide liftoff acoustic data for the launch vehicle and surrounding structures of the mobile launcher and exhaust trench.
- 5% scale models of vehicle, propulsion systems, ground structures, sound suppression water
- Obtain data for use in acoustic environments analytical modeling
  - ➢ Improve and formulate new liftoff acoustics environment analytical models
  - ➢ Provide high fidelity measurements suitable for CFD validation

ASMAT - Ares I Scale Model Acoustic Test

SMAT - Scale Model Acoustic Test

CFD Modeling of Liftoff Transients and Noise

CFD modeling capability has matured to model fully integrated vehicle and launch pad configuration with 3D transient flow analysis

- 200-500M cell mesh executed on 1000-3000 processors
- Time-accurate hybrid RANS/LES plume turbulence and acoustic source modeling
- Solid motor start-up transient flow simulations for IOP

CFD provides insight into complex 3D fluid dynamics of integrated vehicle launch pad environment to interpret physics and enhance engineering models

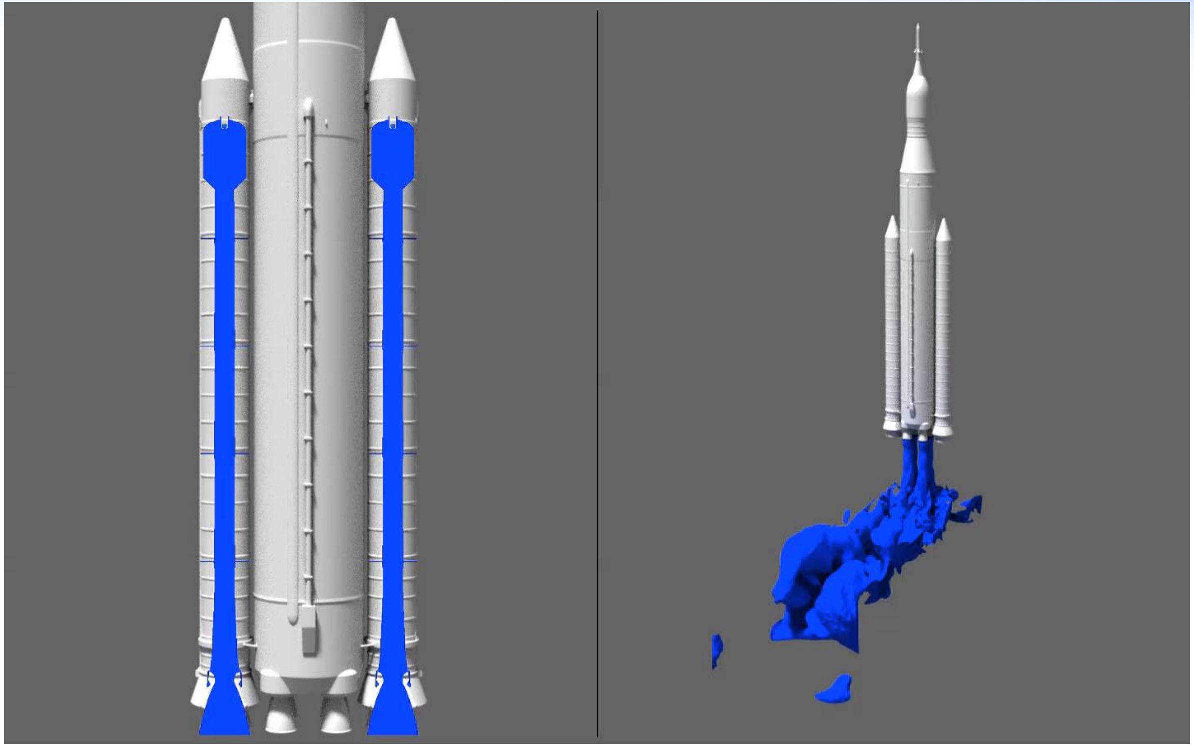
CFD offers design capability for designing/assessing mitigation measures

- Configuration changes (Mobile Launcher exhaust duct configuration, flame trench deflector placement, …)
- Targeted placement of sound suppression water towards acoustic source regions

The sub-scale liftoff acoustics experiments provide high quality validation for CFD models

Insight From Integrated Vehicle Simulations

- Integrated vehicle simulations directly address many liftoff acoustic environment uncertainties
- We can perform high fidelity CFD simulation of internal ballistics flow, nozzle start-up flow, and plume formation transients that increase realism of startup physics
- Transient flow simulations of integrated vehicle captures many 3D configuration and fluid dynamics effects
- CFD results provide baseline for improved empirical acoustic environment analysis tools



MSFC CFD Workhorse: Loci/CHEM CFD Framework

- **Loci Computational Framework**
  - Highly scalable automatic parallelization platform for computational field simulations
  - Developed by Mississippi State University
- **Loci/CHEM Density-based Navier-Stokes Solver Implemented in the Loci Framework**
  - Generalized unstructured grids
  - Multi-species mixing and reacting flow, finite rate, flamelet models
  - RANS, URANS, DES, Hybrid RANS/LES turbulence modeling
  - Lagrangian particle vaporization, condensation, combustion
  - Mesh deformation for fluid-structure deformation and fuel burn-back surface
  - Overset moving body with prescribed motion and 6-DOF
- **Extensively verified using Method of Manufactured Solutions Technique**
- **Production simulations typically 10M to 500M cells on 2000+ processors**

Acoustic Modeling Requires Higher Fidelity

- Existing mature, validated Loci/CHEM CFD modeling tailored to capturing essential physics: multi-phase plume interaction, turbulent LES, gas-water two-phase effects from sound suppression water, etc.
- CFD codes typically 2nd order, dissipative upwind algorithm for robustness in multi-species turbulent mixing and embedded shocks
- Robust plume flow modeling CFD algorithms are too dissipative for acoustic wave preservation in farfield
- Simply increasing mesh resolution not effective; acoustics propagation requires Computational Aero-Acoustic (CAA) solver with low dissipation and higher order accuracy for higher frequency noise

Solution: Implement two-field paradigm of CFD + CAA (Computational Aero Acoustics)

- Utilize existing CFD plume modeling fidelity to capture and resolve acoustics from sources originating from plumes, impingement, water suppression effects
- Hand-over to higher-order accuracy CAA solver and propagate acoustic pressure wave field from source regions
- Permits the use of the most appropriate physical and numerical modeling approaches for each

Which CAA Acoustic Modeling Approach?

- Two-field paradigms are the basis of many Computational Aero-Acoustic (CAA) methodologies currently applied:
  - Ffowcs Williams-Hawkings (FWH), Boundary Element Methods (BEM), Linearized Euler Equations (LEE), Kirchhoff Method, Acoustic Perturbation Equations (APE)
- Acoustic analogies methods such as FWH unable to accommodate wave interaction with bodies. The propagation of launch vehicle plume acoustic waves is heavily affected by the presence of the launch platform, flame trench and launch tower that block, reflect and diffract acoustic waves.
- Linearized methods (LEE, BEM, …) involve approximations ineffective at resolving nonlinearities in rocket plume acoustic propagation signature (strong Mach waves, wave impingement/reflection, …)
- Must perform acoustic field simulation on launch pad domain size: Requires higher order accuracy on reasonably coarse mesh resolving launch pad topology details

➢ **Need high accuracy, high resolution, low dissipation full Euler solver for unstructured mesh**

- **Suitable Discontinuous Galerkin (DG) solver available in Loci framework: Loci/THRUST**
- Implementation in highly efficient Loci framework optimized for NASA Pleiades supercomputer enables efficient CFD/CAA interface definition and CFD-to-CAA exchange during runtime

Overview of Loci/THRUST DG Solver

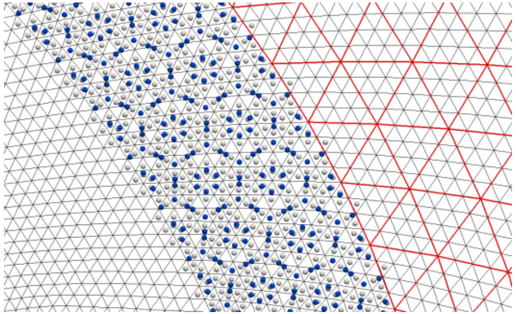
Loci/THRUST

- Unstructured Mesh Discontinuous Galerkin (DG) Solver
- Solves nonlinear Euler equations
- Up to 4^{th} order accurate in space and time
- Supports tet/hex/pyramid/prism unstructured mesh topology
- Supports higher order curved boundary mesh represented by nonlinear Bézier volumes
- Sponge layer farfield boundary conditions suppresses wave reflection
- Accuracy thoroughly verified through Method of Manufactured Solutions (MMS) and validated against acoustic benchmarks
- Developed in Loci computational framework
  - Massively parallel
  - Instant compatibility with Loci/CHEM CFD solver
  - Enables runtime coupling of CFD and CAA modules with acoustic interface exchange

CFD/CAA Coupling Through Overlapping Meshes

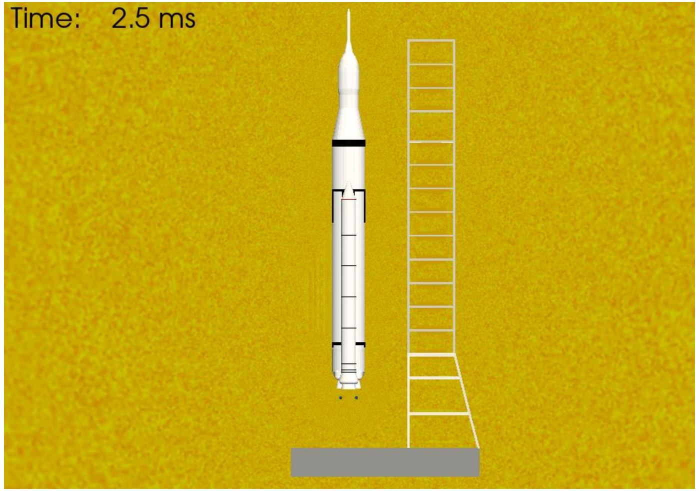
- Automated overset mesh hole-cutting performed in core during execution - introduces fringe cells receiving acoustic signal inflow from the CFD domain
- Spatial interpolation process to get CFD solution at CAA DG cell quadrature points
- Temporal interpolation process to ensure that spatially interpolated solution is temporally in sync with Runge-Kutta time level – high-order polynomial reconstruction used
- Simultaneous execution of CFD and CAA simulations on same set of cores
    - CFD: 2nd order implicit solver, DG: explicit 4th order space and time solver (Runge-Kutta)
    - Avoid execution of CFD solver at CAA time step - Advance CFD and CAA solution at respective optimal settings
    - Utilize temporal sub-stepping to advance CAA solution at partial timestep satisfying CFL limit
    - Selection automatically updated at each time step

3rd-Order Overset Coupling Example
CFD mesh (black) - CAA DG mesh (red)
DG Receptor Points (blue) - CFD Donor Points (grey)

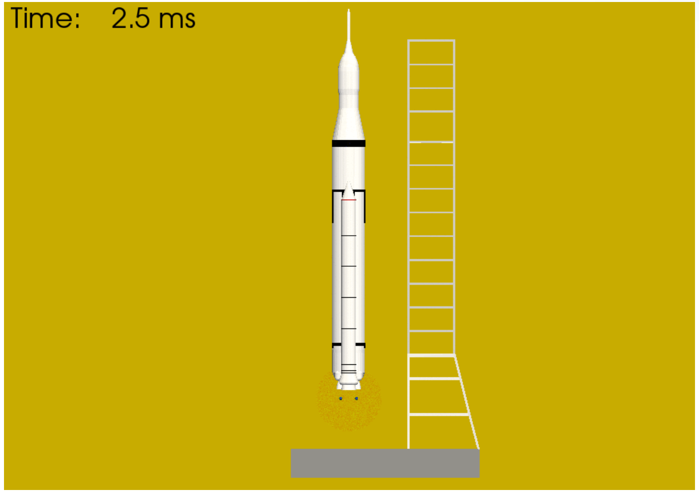


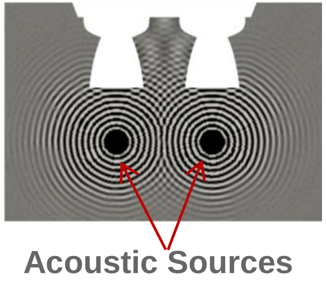
Concept Demo: Notional SLS Launch Environment

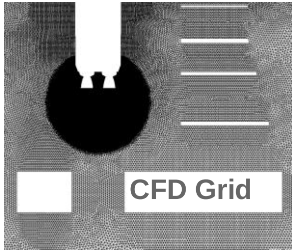
CFD
Loci/CHEM Only

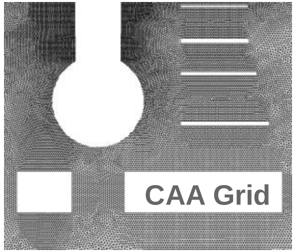


CFD/CAA
Loci/CHEM + Loci/THRUST (4th-Order)





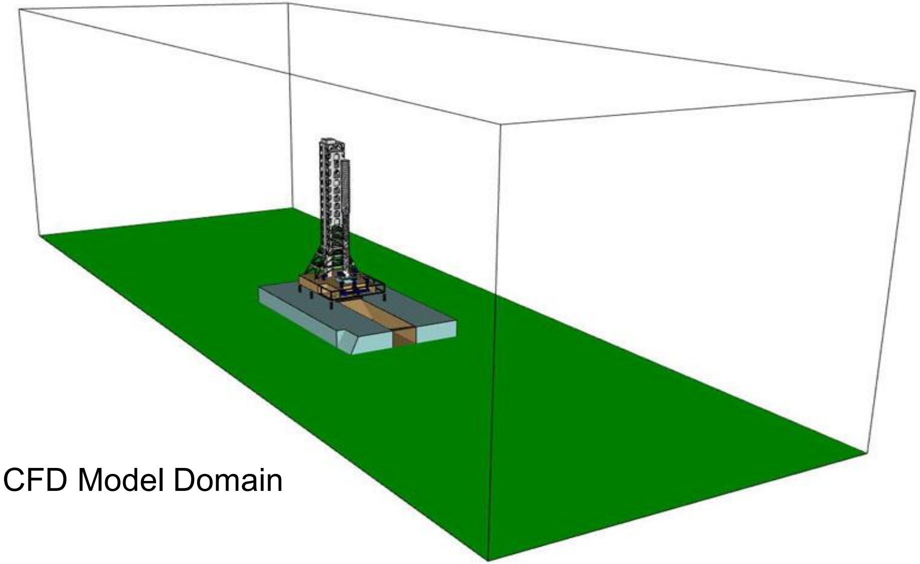




CAA Solution Preserves Waves And Captures Interference Effects With Structures

CFD/CAA Technology Application Testing

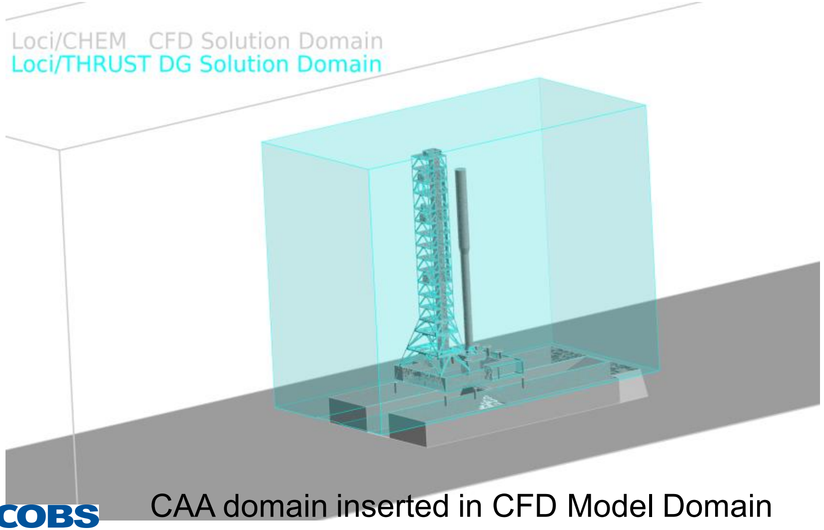
- Loci based CFD/CAA framework developed under NASA Small Business Research Project for MSFC
- Software thoroughly tested for higher order and acoustic benchmarks during development
- Software production version has recently been released to ER42 to perform application testing
- Simulate relevant production size case and establish scale-up to Pleiades supercomputer production
- Selected ASMAT case previously utilized for CFD liftoff validation
- Performed Test of CAA solver for 3rd order space/time



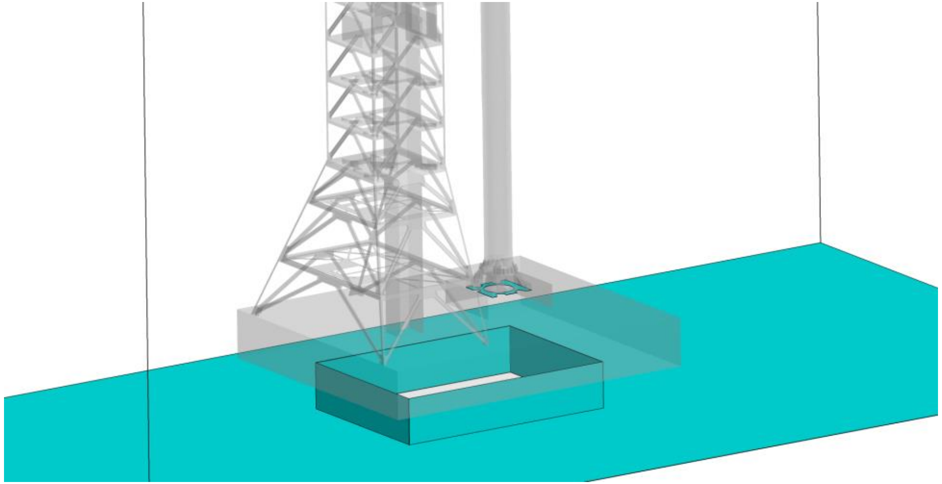
ASMAT Ignition CFD Model Domain

CFD/CAA Acoustic Solution for ASMAT

- Utilized existing CFD model of ASMAT ignition transients and acoustic modeling validation
- Embedded overset CAA solution domain
- CFD mesh: 378M cells – CAA mesh: 40M cells
- CAA acoustic domain extends from flame trench upper edge surface (‘pad level’) to tower top
- Wraps around launch platform ending close to plume region
- CAA domain inflows BCs receive pressure waves from flame trench upward flow, side flow under platform, and through launch mount opening around nozzle – interface through overset hole cutting process



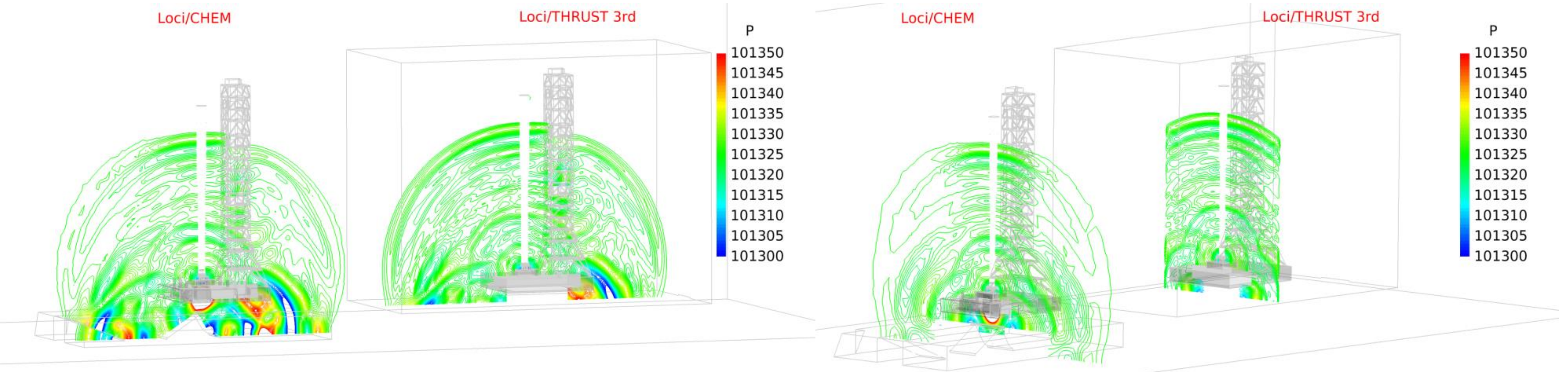
CAA domain inserted in CFD Model Domain



Interface boundaries designated for overset hole cutting interface

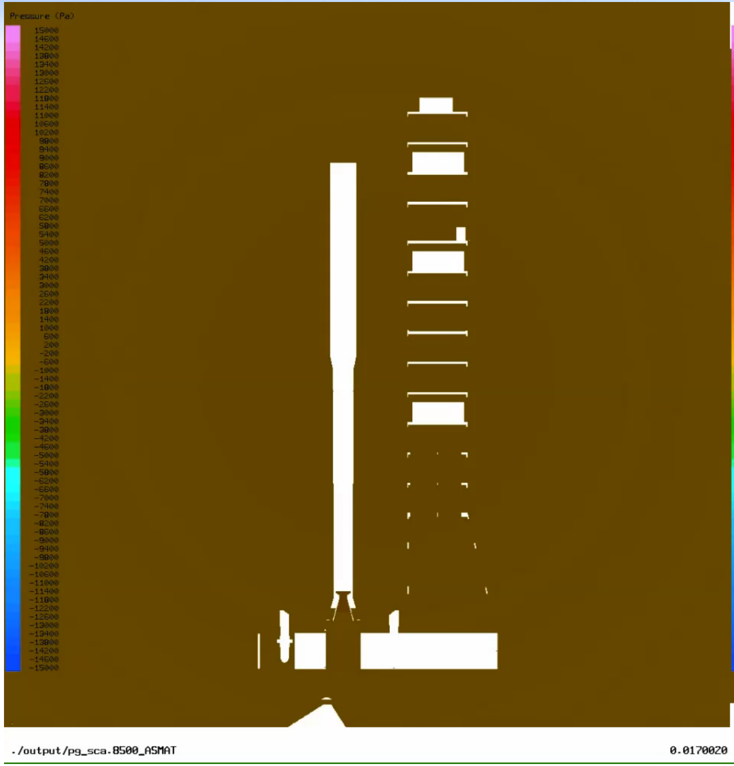
CFD/CAA Solution for ASMAT

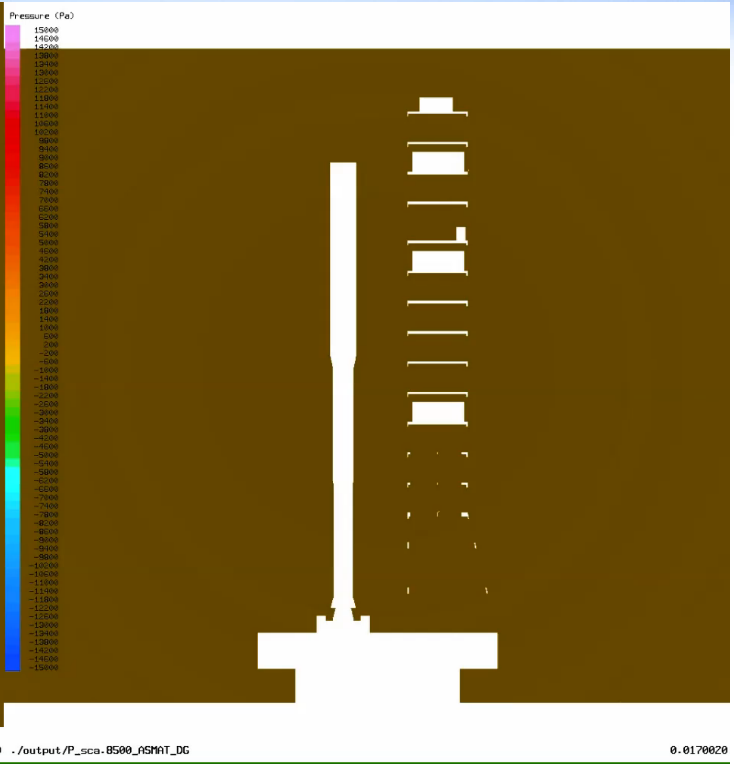
- Performed ignition transient simulation for first 25 milliseconds - sufficient for acoustic waves to travel from nozzle exit to upper regions of vehicle – covers ignition transient wave phase
- Motor start-up simulated with simplified motor start-up mass flow boundary condition – does not correctly impose internal motor flow dynamics at boundary condition location
- Validated acoustic signal frequency resolution and preservation : CFD - CAA - Experiment



End of simulation Snapshot: High Fidelity Signal Exchange Across CFD-to-CAA Overset Interface

CFD/CAA Solution for ASMAT





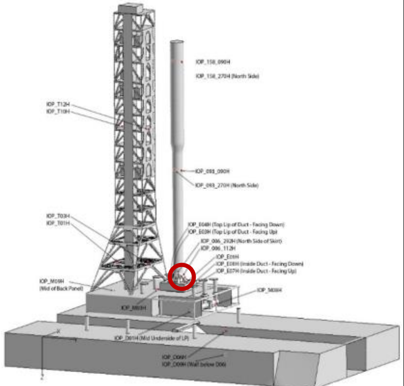
CFD: Loci/CHEM

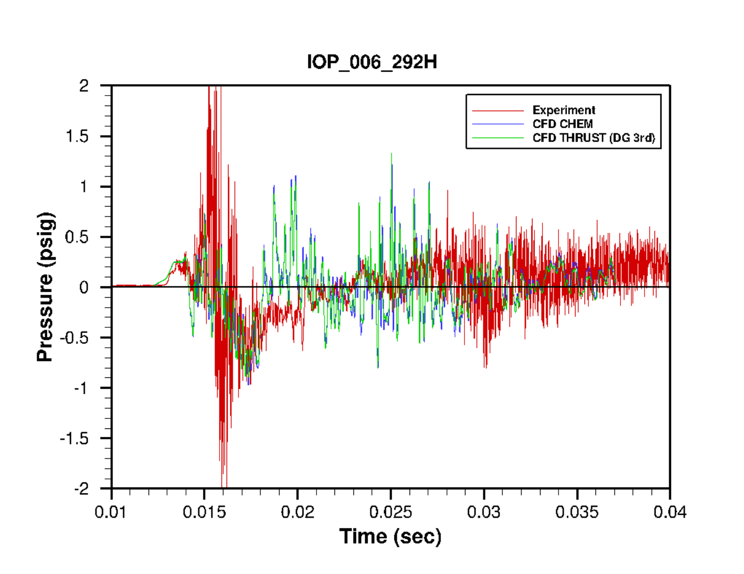
CAA: Loci/THRUST (3rd-Order)

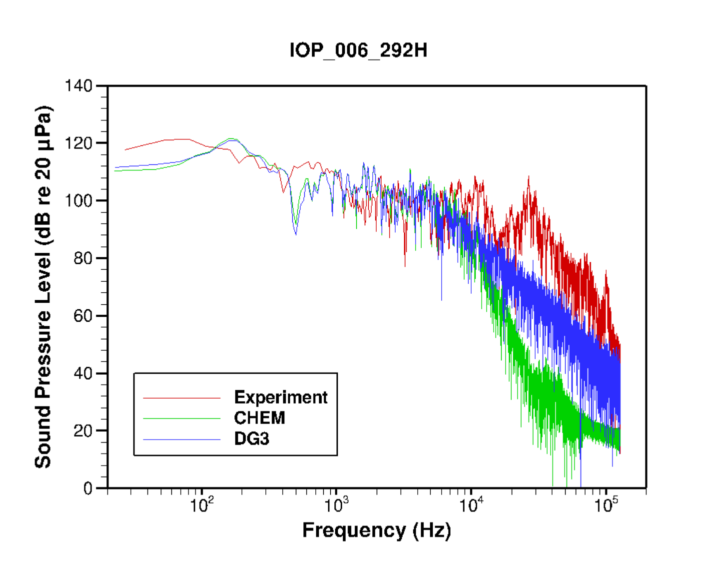
ASMAT CFD/CAA Solution Fidelity

Sensor At Vehicle Aft Skirt

- CFD and CAA mesh resolution sufficient to resolve and track signals up to 9,000 Hz
- Results confirm resolution over frequency range up to 9,000 Hz



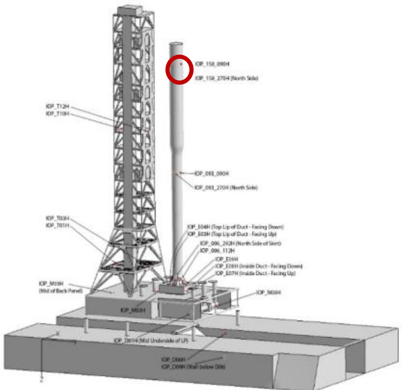


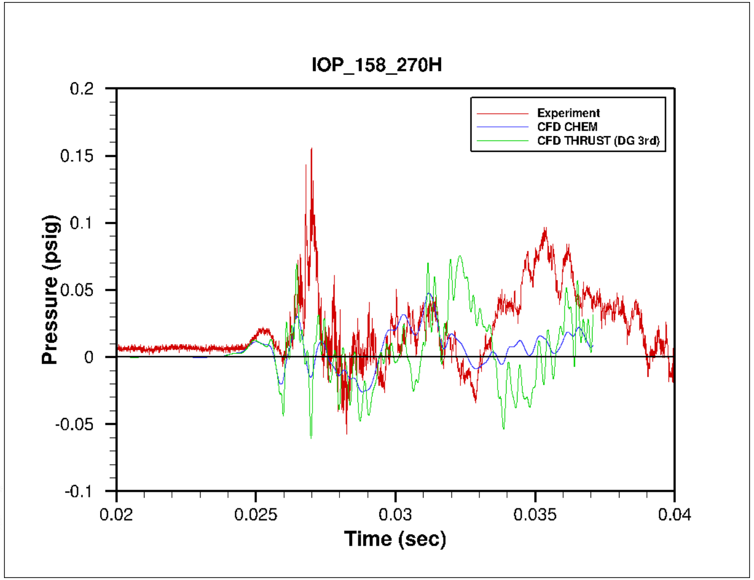


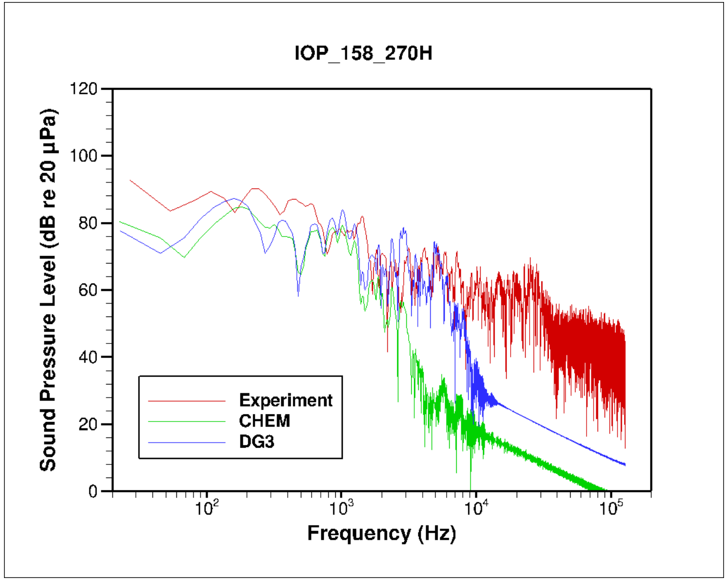
ASMAT CFD/CAA Solution Fidelity

Sensor At Top of Vehicle

- CFD mesh resolution sufficient to resolve and track signals up to 2,000 - 3,000 Hz
- CAA mesh resolution sufficient to resolve and track signals up to 9,000 Hz
- Results confirm CAA resolution over frequency range close to 8,000 Hz
- CFD resolution only accurate up to 1,000 Hz
- CFD algorithm dissipative nature loses signal content during long distance propagation







Computational Cost of CFD/CAA Acoustic Solution

- CFD mesh: 378M cells (unstructured viscous mesh)
- CAA mesh: 40M cells (unstructured Euler mesh)
  - Tailored to achieve comparable wave length resolution near vehicle

- CFD time step dt = 2e-6 sec (implicit solver)
- CAA performs 7 sub-steps (average) controlled by CFL stability limit (explicit solver)

- 1600 Ivy Bridge CPU processors, NASA Pleiades Supercomputer
- Simultaneous, coordinated execution of both CFD and CAA solver on all nodes
- Execution time: 75 sec per time step

- CFD solution: 40%
  - Identical to cost of stand-alone CFD simulation
- CAA solution (3rd order DG): 60%
  - Includes all additional CFD-CAA interface communication
  - Computational cost will increase for 4th order DG solution

- Additional CAA computational cost acceptable to achieve accurate acoustic field propagation

Conclusion

- Developed CFD based liftoff acoustic field prediction methodology to support MSFC mission of liftoff acoustic environment definition
- Inherent conflict between turbulent plume flow simulation robustness and acoustic field propagation accuracy. Two-field CFD/CAA software framework developed for liftoff acoustic field predictions
  - Robust Loci/CHEM CFD capability for plume transient flow and HRLES turbulence acoustic source modeling
  - High order (up to 4^{th}) Discontinuous Galerkin Euler solver for non-linear CAA
- Both modules embedded in Loci computational framework for extreme parallel efficiency
- Software application tested for scalability, efficiency towards realistic 3-D simulations
- Significant improvements in maintaining higher frequency acoustic signals with 3^{rd} order DG solver – Testing of 4^{th} order DG as soon as high order curved boundary BC implemented
- New capability enables characterization of acoustic field propagation at high frequencies over launch pad size domain distances
- High fidelity integrated in seamless liftoff acoustic environments simulation is now possible

Internal Ballistics Gas Dynamics CFD → Ignition Overpressure CFD → Farfield Acoustic CAA

Questions?