Inviscid and Viscous CFD Analysis of Booster Separation for the Space Launch System Vehicle

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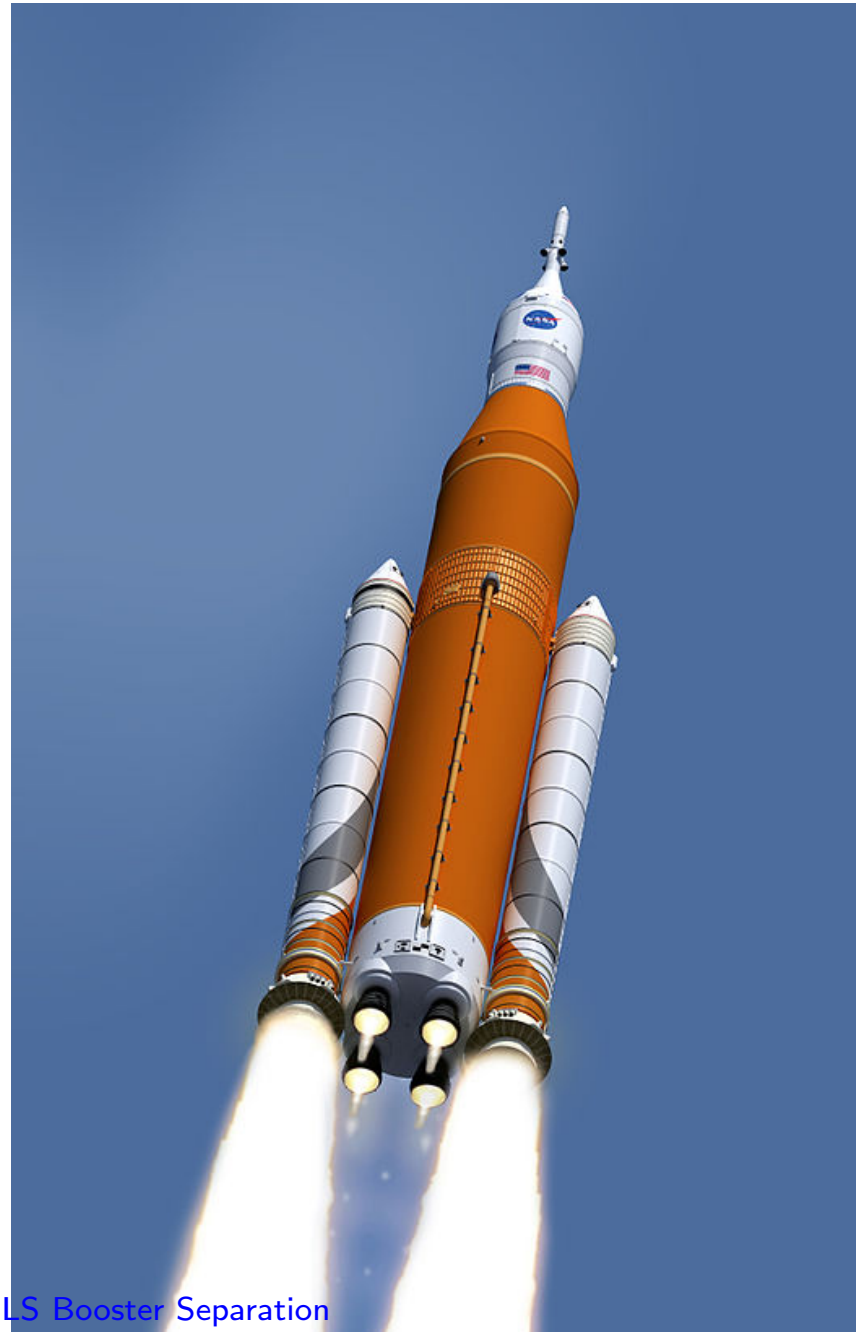
The Space Launch System

First *exploration*-class launch vehicle since Saturn V (and only the second ever)

10% more thrust at liftoff than Saturn V, but less mass to orbit in initial configuration

Largely built from Space Shuttle-derived hardware

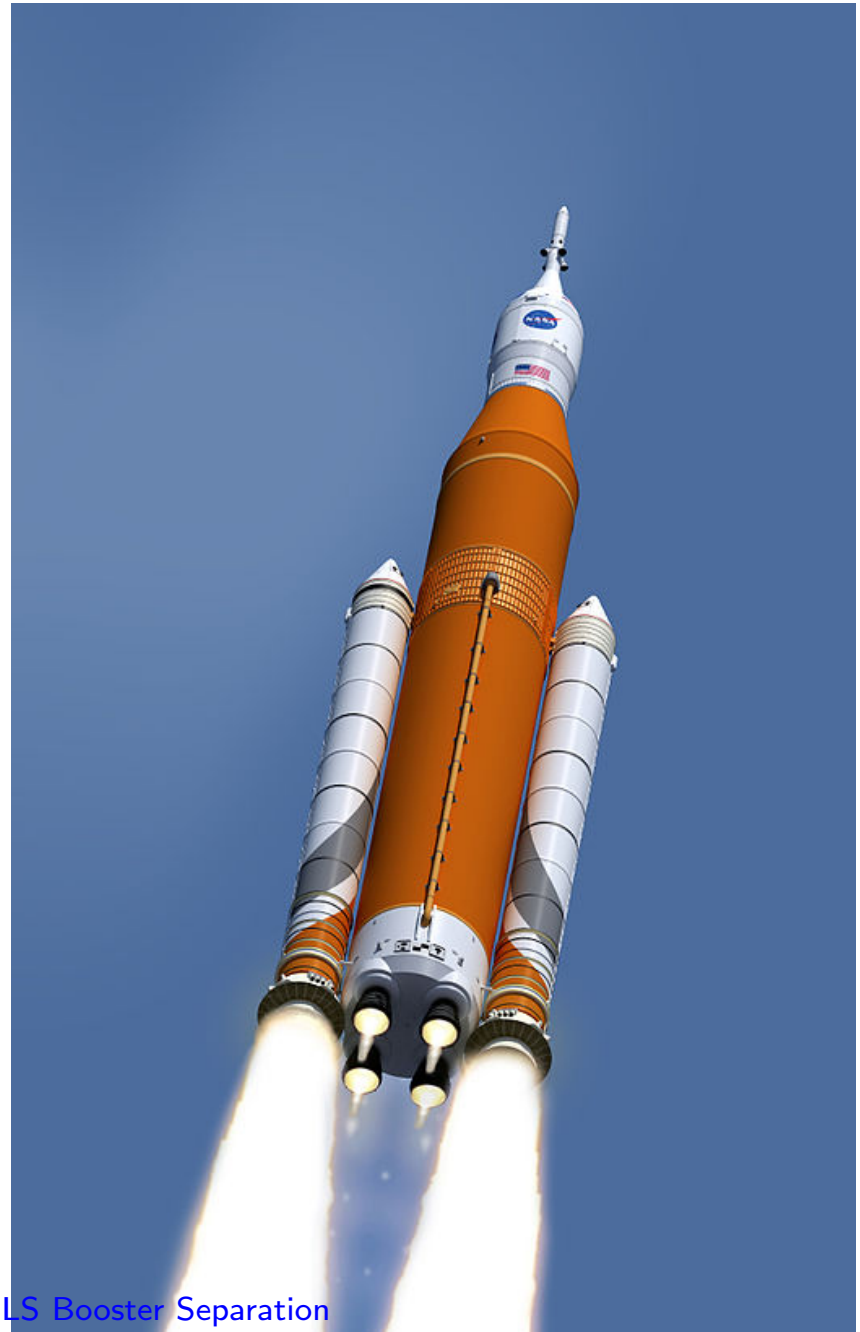
Capable of supporting crewed missions to lunar orbit and beyond



SLS Booster Separation

The Space Launch System

- Uses two Shuttle-like Solid Rocket Boosters for first 2 minutes or so
- These burn out long before the first core stage
- So we have to get rid of them during ascent
- And don't recontact the core



Space Shuttle SRB Separation Video



Objective

Requirements

- Deliver aerodynamic forces on three bodies (CORE, RSRB, LSRB) for all possible booster positions and flight conditions
- Flight certification database will be built on computational database
- Provide adequate validation and verification for UQ

Interactions with SLS Program

- Close interactions with NASA LaRC UPWT 1891 test
- Database implementation and uncertainty quantification by NASA LaRC Configuration Aerodynamics Branch
- Run matrix based on dispersed trajectory analysis from GN&C team using earlier aerodynamic database
- Primary figure of merit for this DB is size of uncertainty
- Success/failure determined by simulated probability of booster recontact



Approach

Quasi-Steady Force & Moment Database

- We need about 20,000 solutions to cover all conditions
- Each solution run at *fixed* conditions
- CFD with moving bodies is neither efficient nor accurate for this work

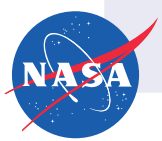
Data Sources

- Cart3D selected for database
  - Huge amount of cases; need efficiency
  - Extremely complex geometry; cut cells are great for this
- OVERFLOW used for flow understanding and code-to-code comparison
- Cart3D run on wind-tunnel geometry for code-to-reality

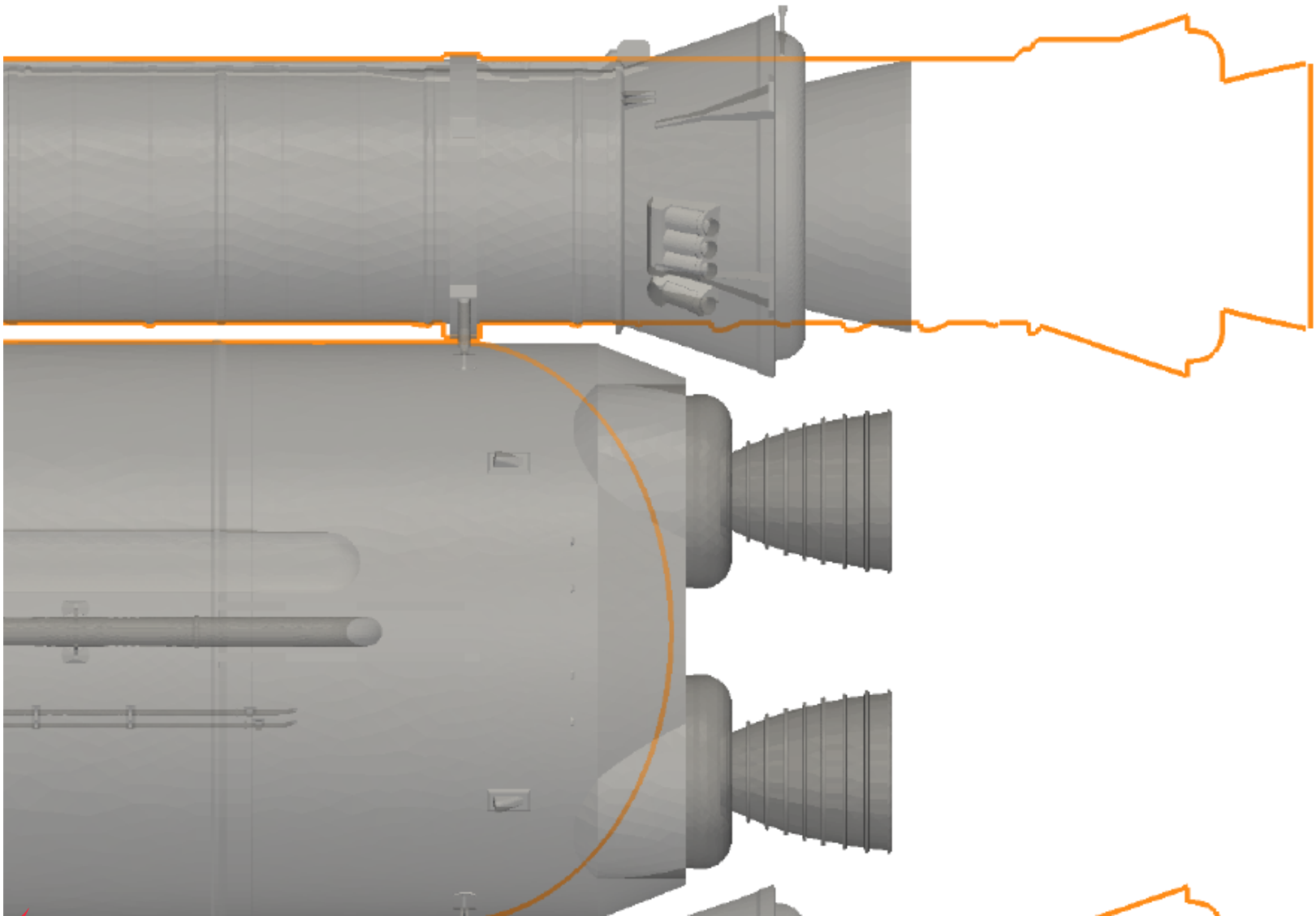
References

Cart3D: Aftosmis, M., Berger, M., and Adomavicius, G., "A Parallel Multilevel Method for Adaptively Refined Cartesian Grids with Embedded Boundaries," *38th Aerospace Sciences Meeting*, 2000, AIAA Paper 2000-0808.

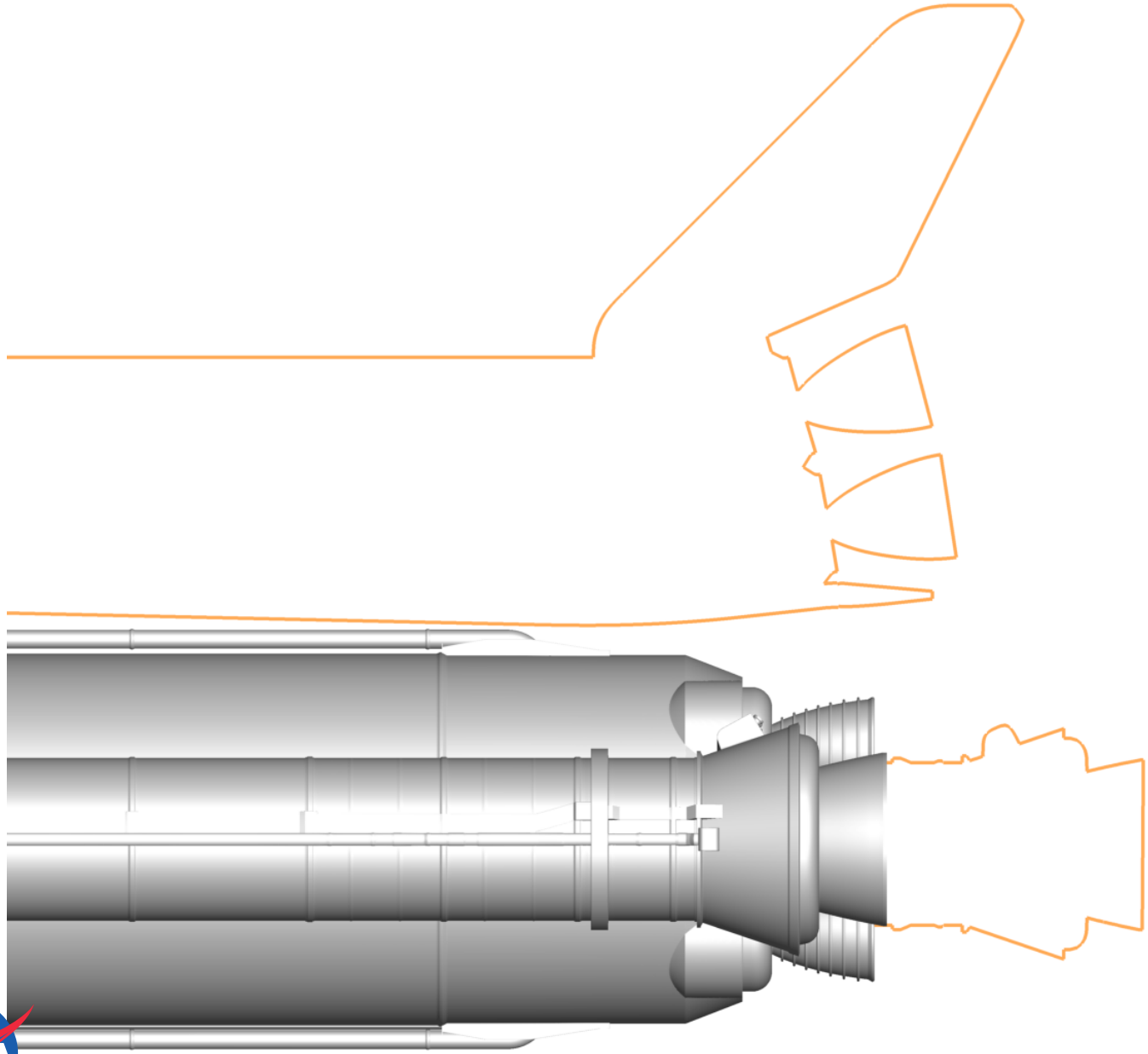
OVERFLOW: Nichols, R. H., Tramel, R. W., and Buning, P. G., "Solver and Turbulence Model Upgrades to OVERFLOW2 for Unsteady and High-Speed Applications," *36th AIAA Fluid Dynamics Conference*, 2006, AIAA Paper 2006-2824.



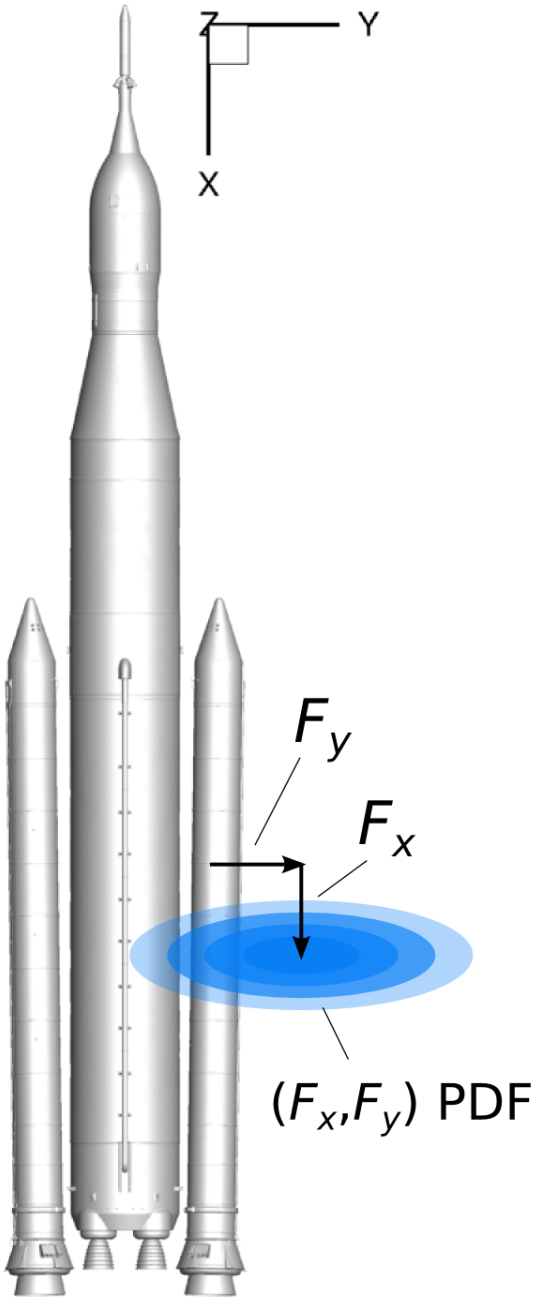
Why Is Separation So Difficult?



Why Is Separation So Difficult?



How Much Does Aero Matter?



Force & moment database must be delivered with uncertainties that ensure that the physical value is in the range of values delivered

This leads to a probability density function of force and moment values

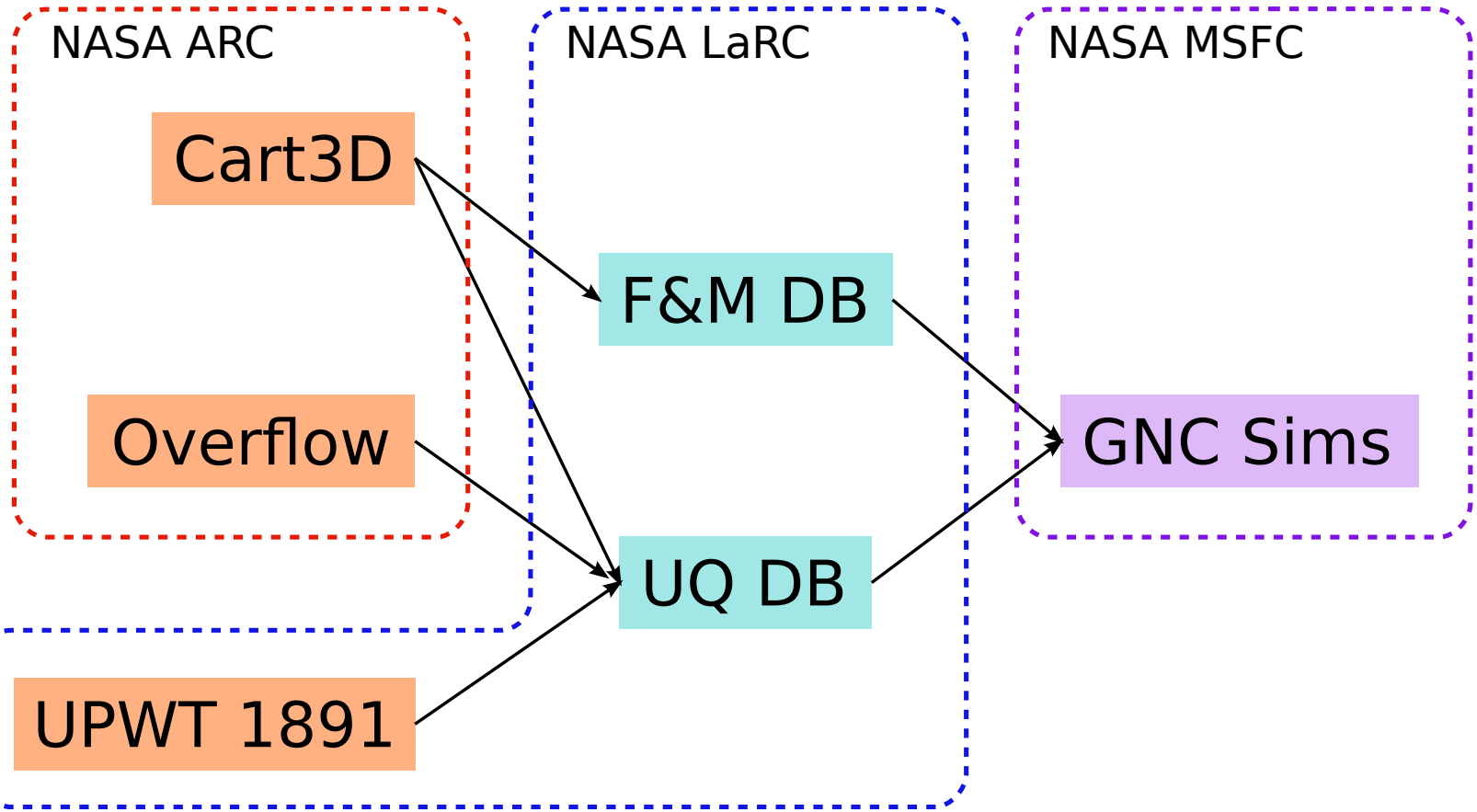
With large uncertainties, adverse aerodynamic forces are possible, and recontacts are predicted

This was the case with early aerodynamic models

Conservative uncertainties are a requirement because the success of the mission may depend on it!

Data Sources and Uses

- Two CFD solvers and one wind tunnel test
- Only Cart3D data goes directly into database
- Other two sources used for uncertainty model



List of Run Matrix Input Variables

Independent Variables

Variable	Symbol	Description
dx	Δx	Booster axial translation [ft]
dy	Δy	Booster lateral translation, away from core [ft]
dz	Δz	Booster translation in $+z$-direction [ft]
dpsi	$\Delta\psi$	Booster yaw angle relative to core body axes [deg]
dtheta	$\Delta\theta$	Booster pitch angle relative to core body axes [deg]
alpha	α	Angle of attack of the core [deg]
beta	β	Angle of sideslip of the core [deg]
CTBSM	$C_{T,BSM}$	Booster separation motor thrust coefficient

Scheduled Variables

Variable	Symbol	Description
t	*t*	Time since separation [s]
dphi	$\Delta\phi$	Booster roll angle relative to core body axes [deg]
mach	*M*	Core Mach number
q	*q*	Core dynamic pressure [psf]
CTCSE	$C_{T,CSE}$	Core stage engine thrust coefficient
CTSRB	$C_{T,SRB}$	Solid rocket booster thrust coefficient



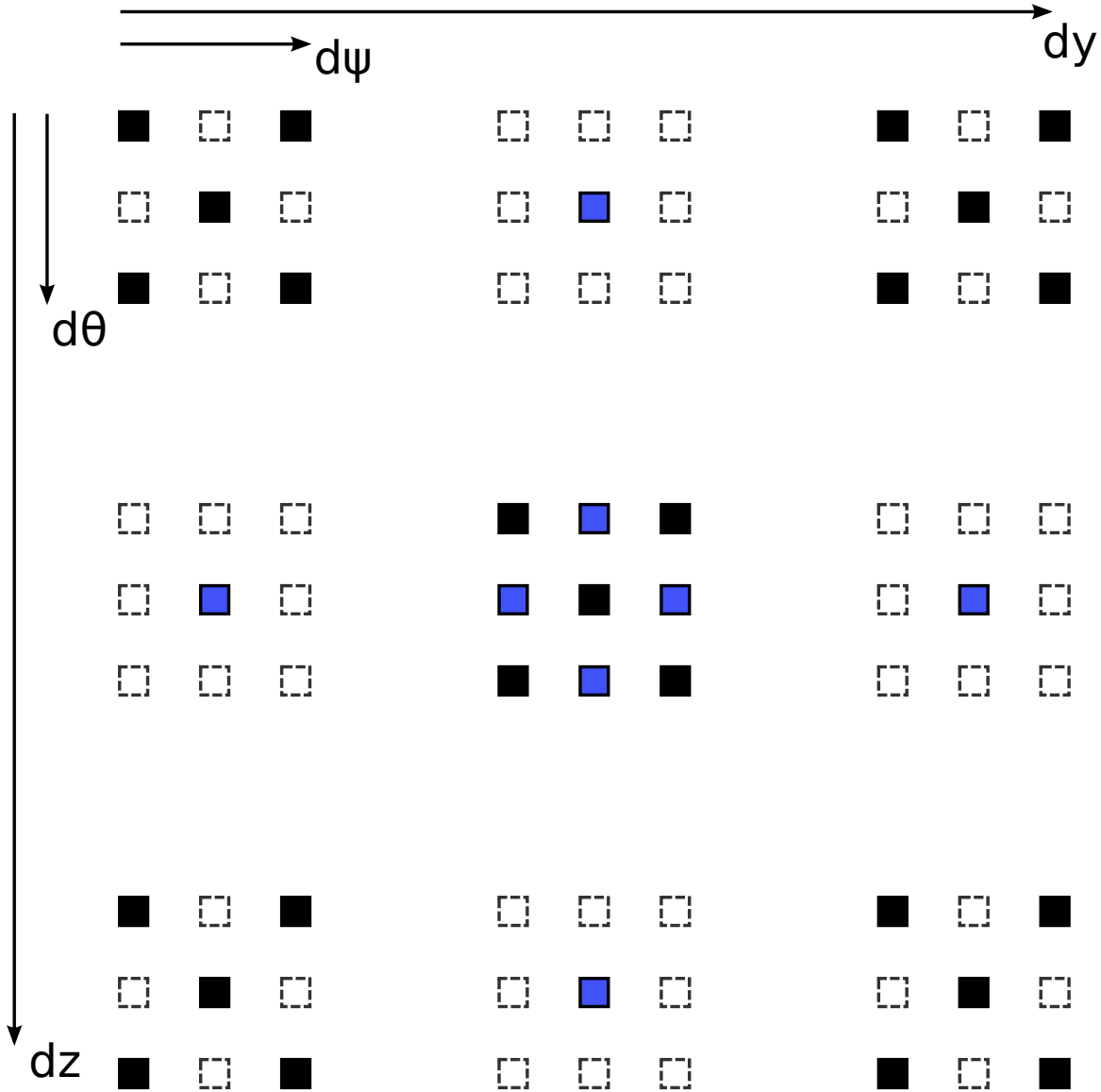
Star-Shaped High-Efficiency Run Matrix

Filled points are included in the matrix

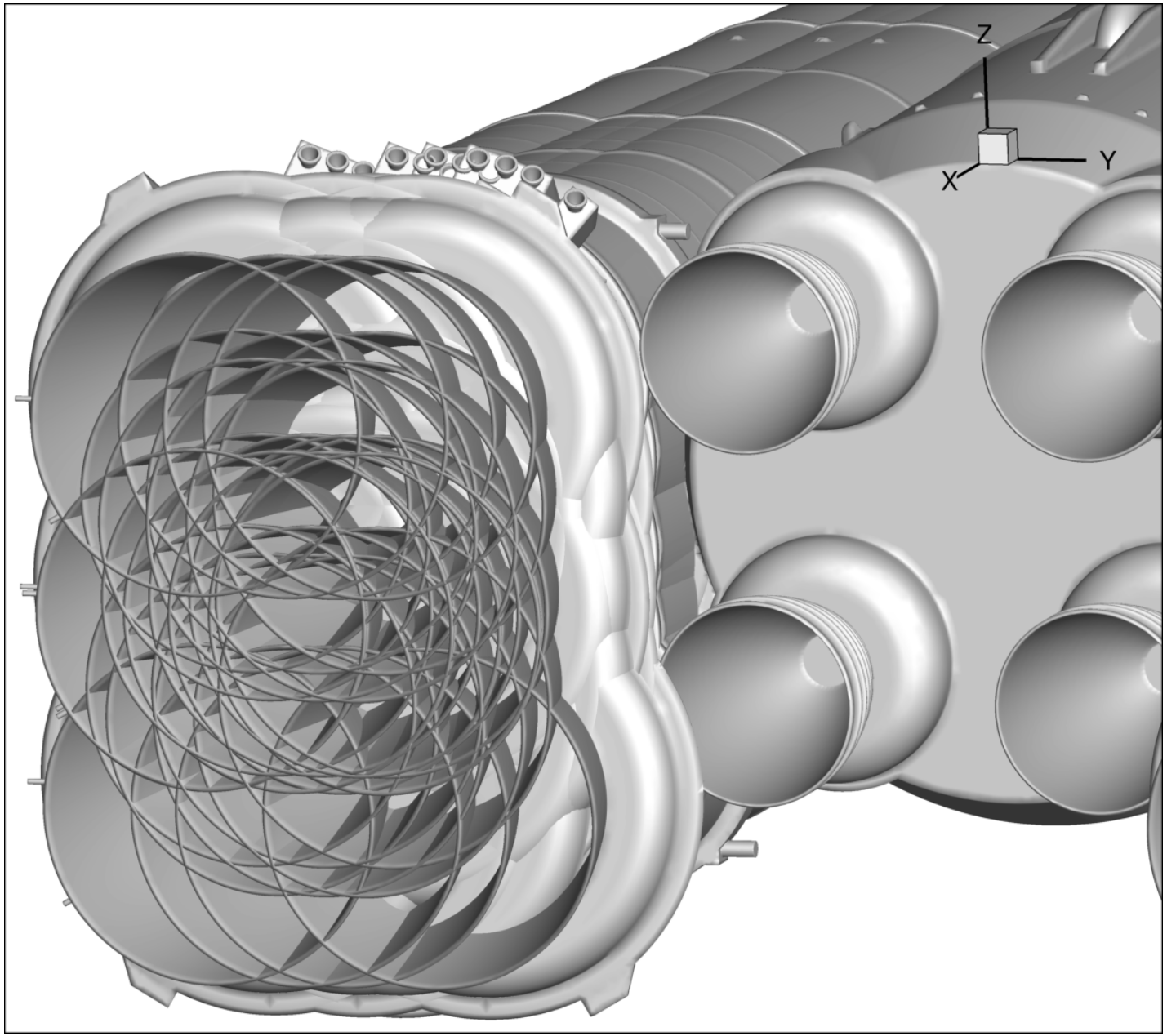
Open squares are not

Blue points are only included for α=0, β=0

5×5×5 regular points and 12 points for isolating low/high values of four variables

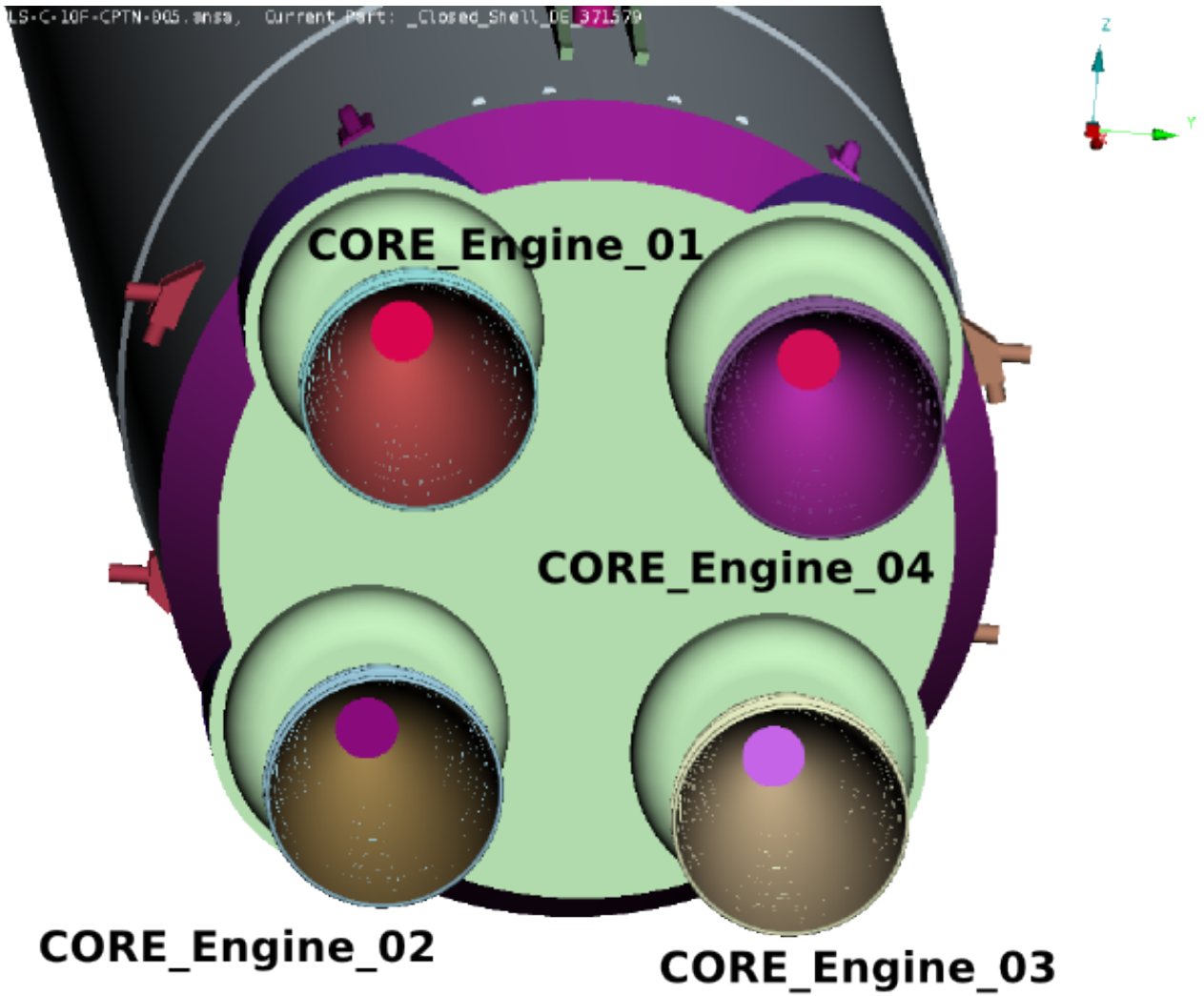


Run Matrix — Booster Position & Orientation



Considerations for Single Engine Failure

RS-25 (Core Stage Engine, CSE) Numbering



- Any one of these engines can fail with equal probability
- Because of near left-right symmetry, created separate database for failure of engine 3 or 4

Cart3D Inputs and Run Strategy

Iteration Control

- 5 adaptive mesh cycles, 500 iterations each
- $\geq$3000 more iterations on final mesh
- F&M in database averaged over last 2000 iterations

Output Function

$$J = C_Y + 0.5C_N + 0.5C_A + \sum_{i=1}^{13} w_i \frac{p(\mathbf{x}_i) - p_\infty}{p_\infty}$$

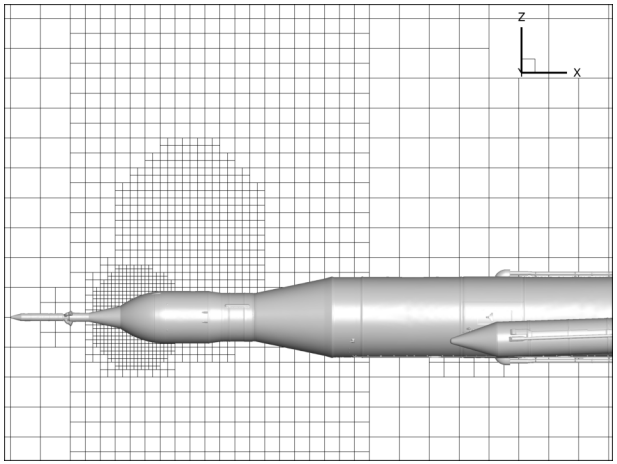
- Includes all forces except on base/nozzle surfaces
- Added some point sensors to help resolve forward BSM exhaust

Initial Mesh

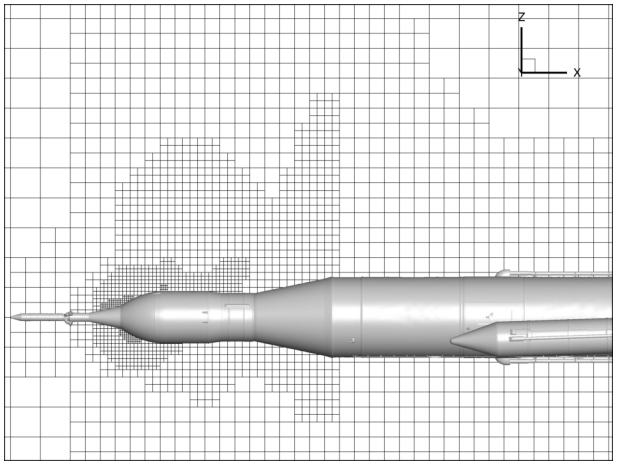
- Coarse (maxR=7) with several refinement boxes around crew vehicle and main engine/SRB exhaust plumes
- Highly refined on BSM nozzle interior surfaces (XLev=6)



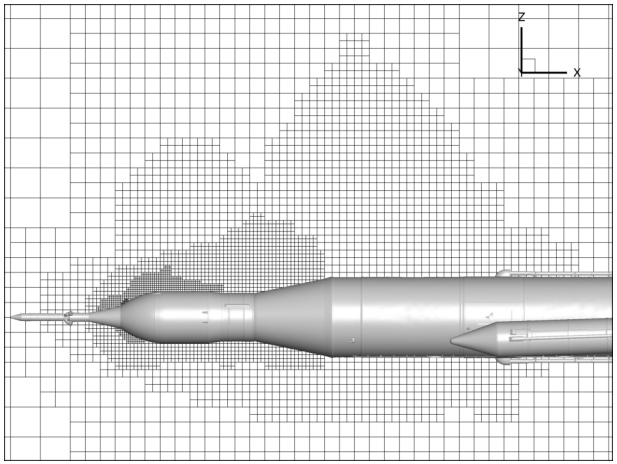
Adaptive Meshing Graphics



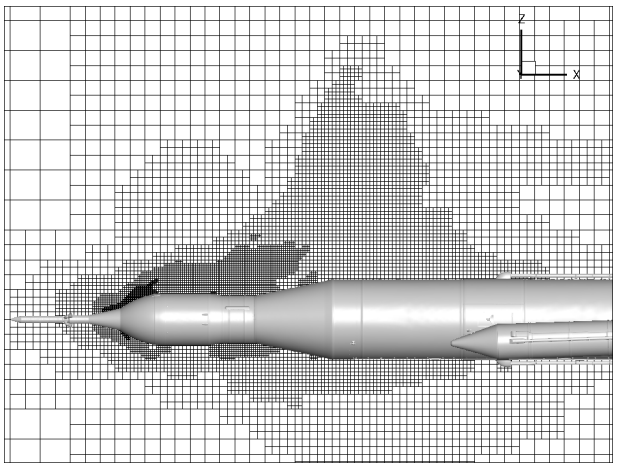
Original mesh
(∼140k cells)



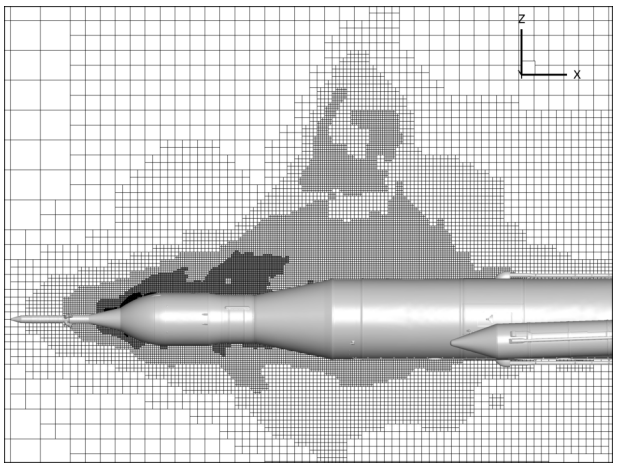
1 Adaptation cycle
(∼210k cells)



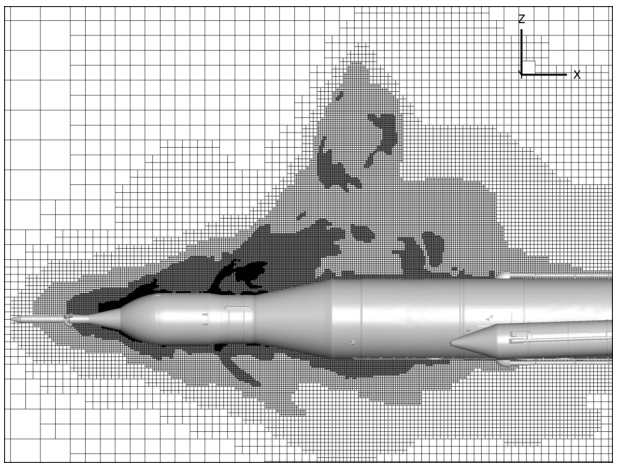
2 Adaptation cycles
(∼410k cells)



3 Adaptation cycles
(∼1.2M cells)



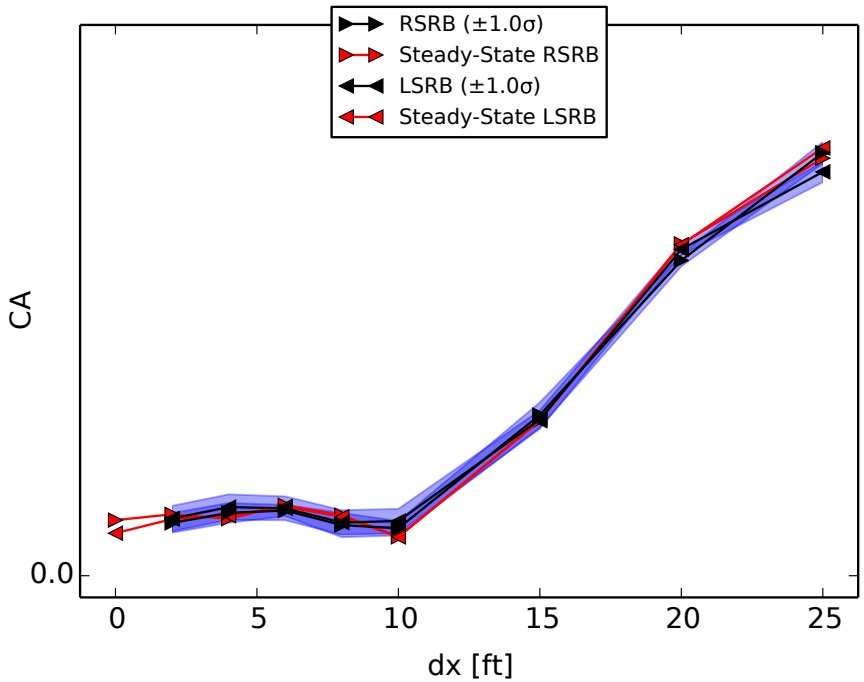
4 Adaptation cycles
(∼4.8M cells)



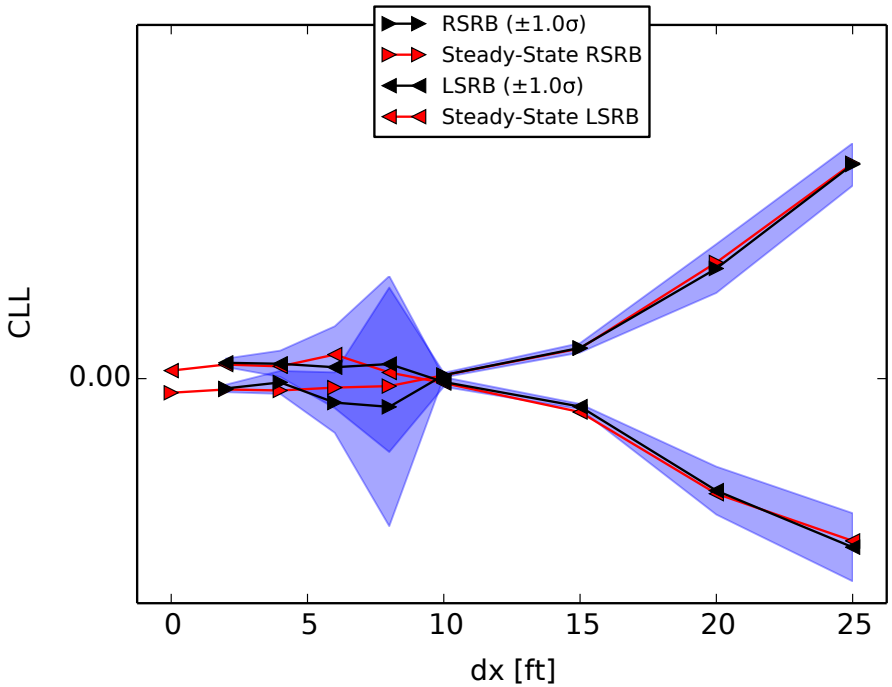
5 Adaptation cycles
(∼16M cells)

Time-Accurate Cart3D Comparison

Justification for Using Steady-State Cart3D



SRBs/*CA*



SRBs/*CLL*

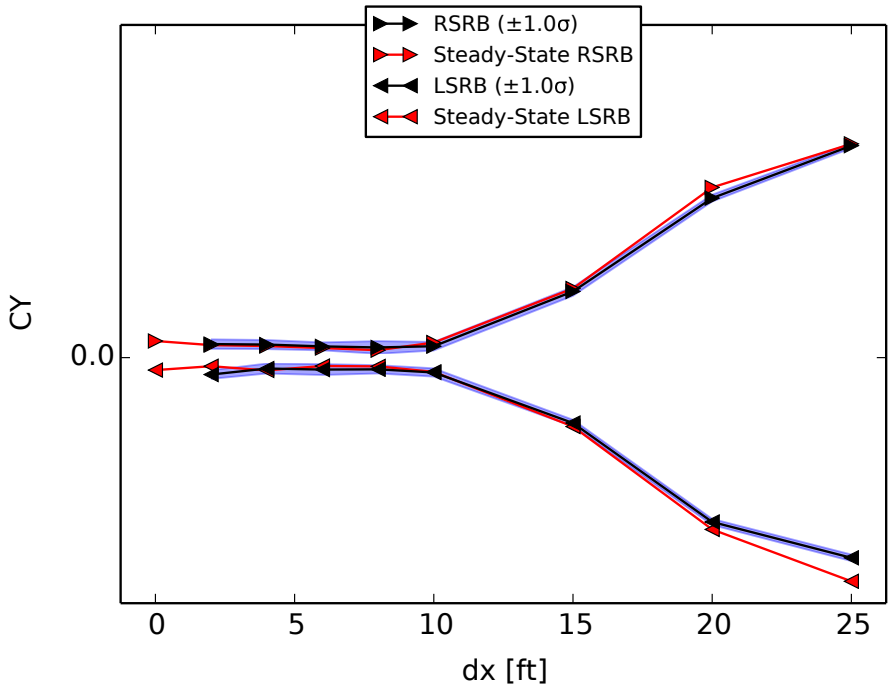
Black: time-accurate Cart3D solution

Red: steady-state Cart3D solution

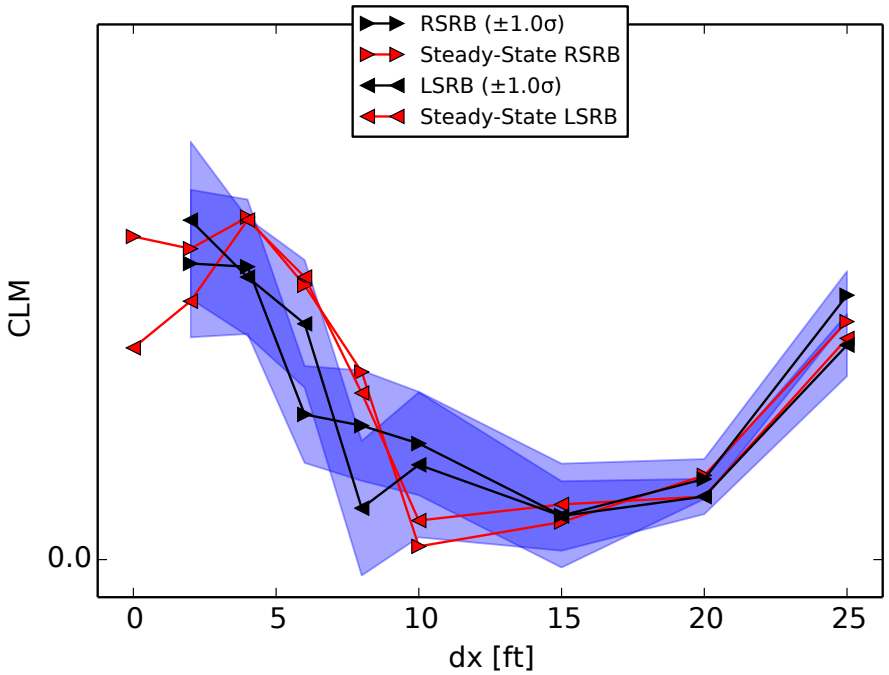
Blue band: Time-accurate one-sigma band based on iterative sampling error

Time-Accurate Cart3D Comparison

Justification for Using Steady-State Cart3D



SRBs/*CY*



SRBs/*CLM*

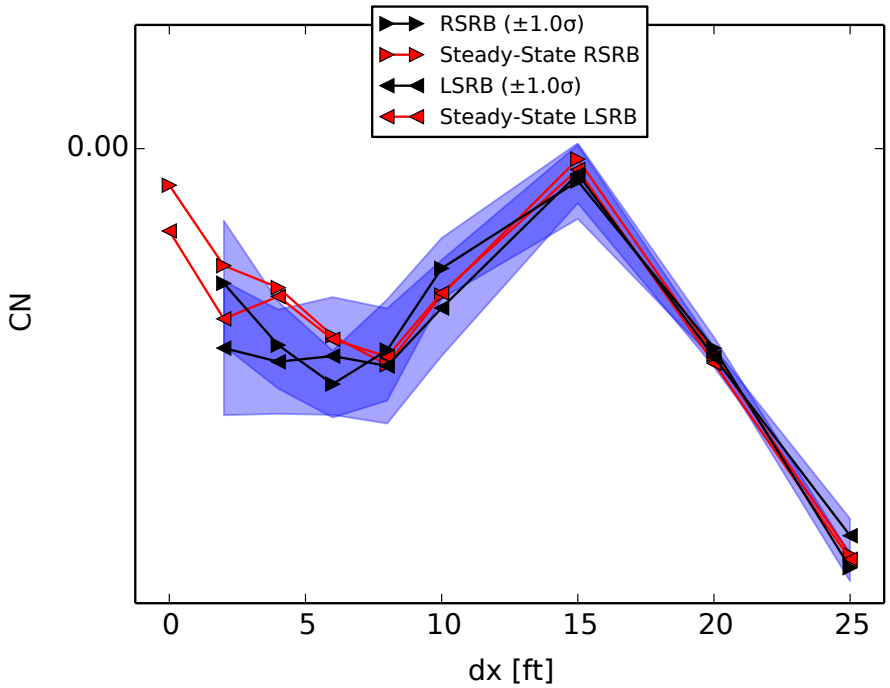
Black: time-accurate Cart3D solution

Red: steady-state Cart3D solution

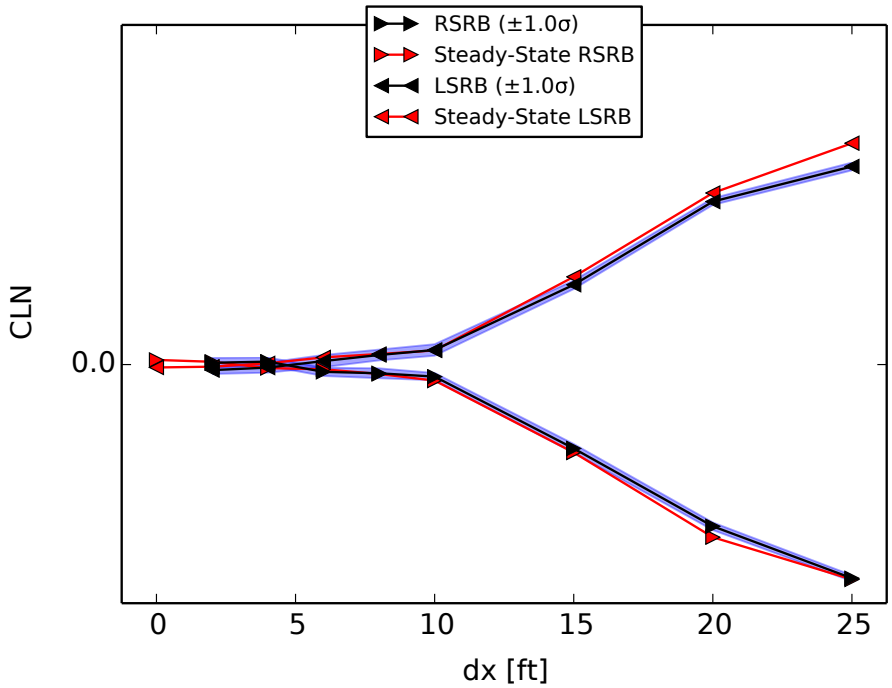
Blue band: Time-accurate one-sigma band based on iterative sampling error

Time-Accurate Cart3D Comparison

Justification for Using Steady-State Cart3D



SRBs/*CN*



SRBs/*CLN*

Black: time-accurate Cart3D solution

Red: steady-state Cart3D solution

Blue band: Time-accurate one-sigma band based on iterative sampling error

OVERFLOW Inputs and Strategy

Resources

- 25 Haswell nodes on NASA's *Pleiades*; using 24 cores per node
- 469 near-body zones with ∼160M grid points
- Off-body grid adaption to grow this to 250M grid points
- Over 250 cases, ∼4.6M core hours

Inputs

- 3rd-order HLLC upwind difference scheme
- SSOR implicit scheme (enhanced numerical stability in nozzle flow)
- Local time-stepping initially; time-accurate (2 subiters) at the end
- Spalart-Allmaras turbulence model

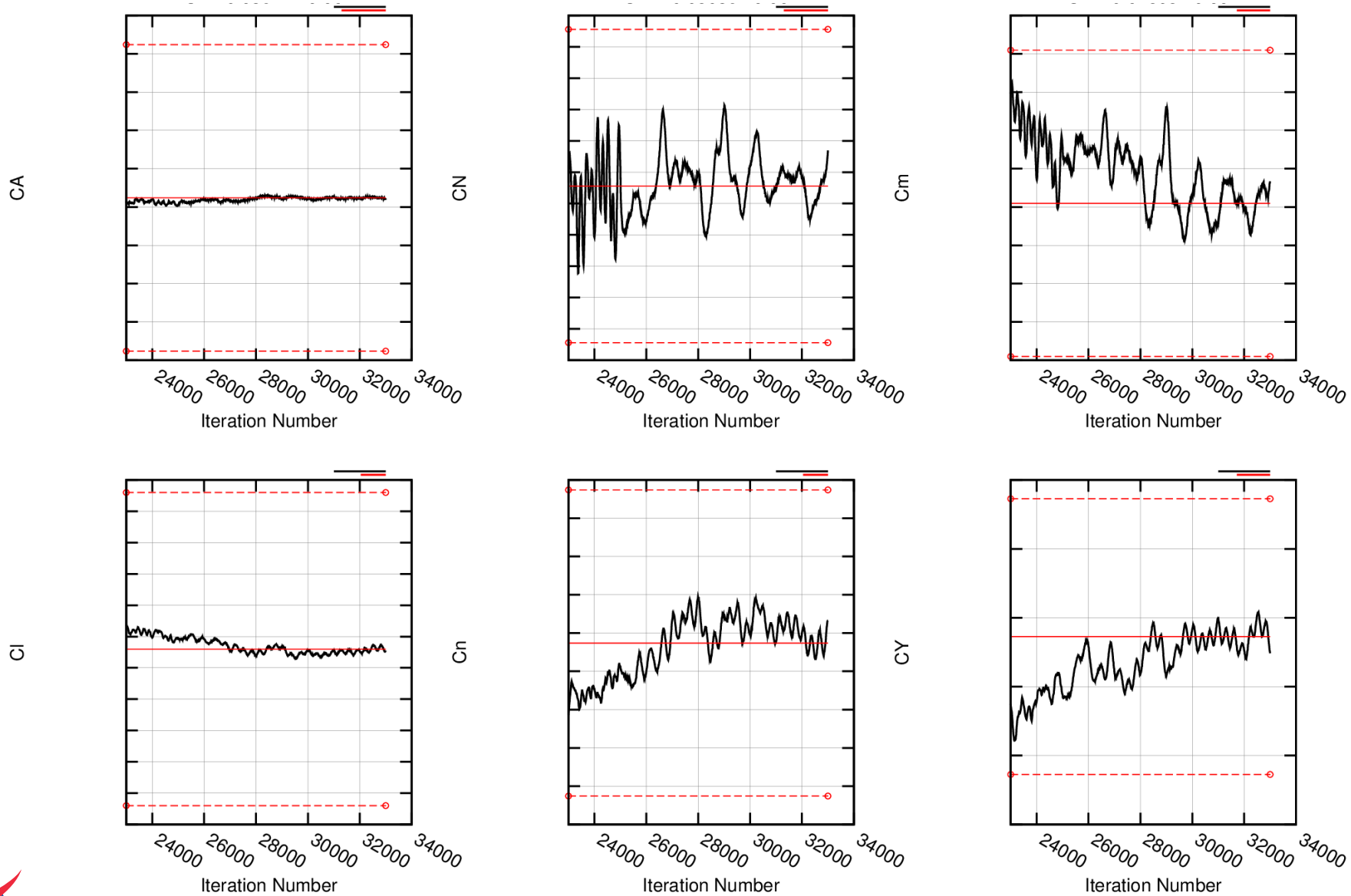
Strategy

- 20k steady-state iters + enough for clean average of 2k time-accurate
- Using *overlst* to control large run matrix and manage files



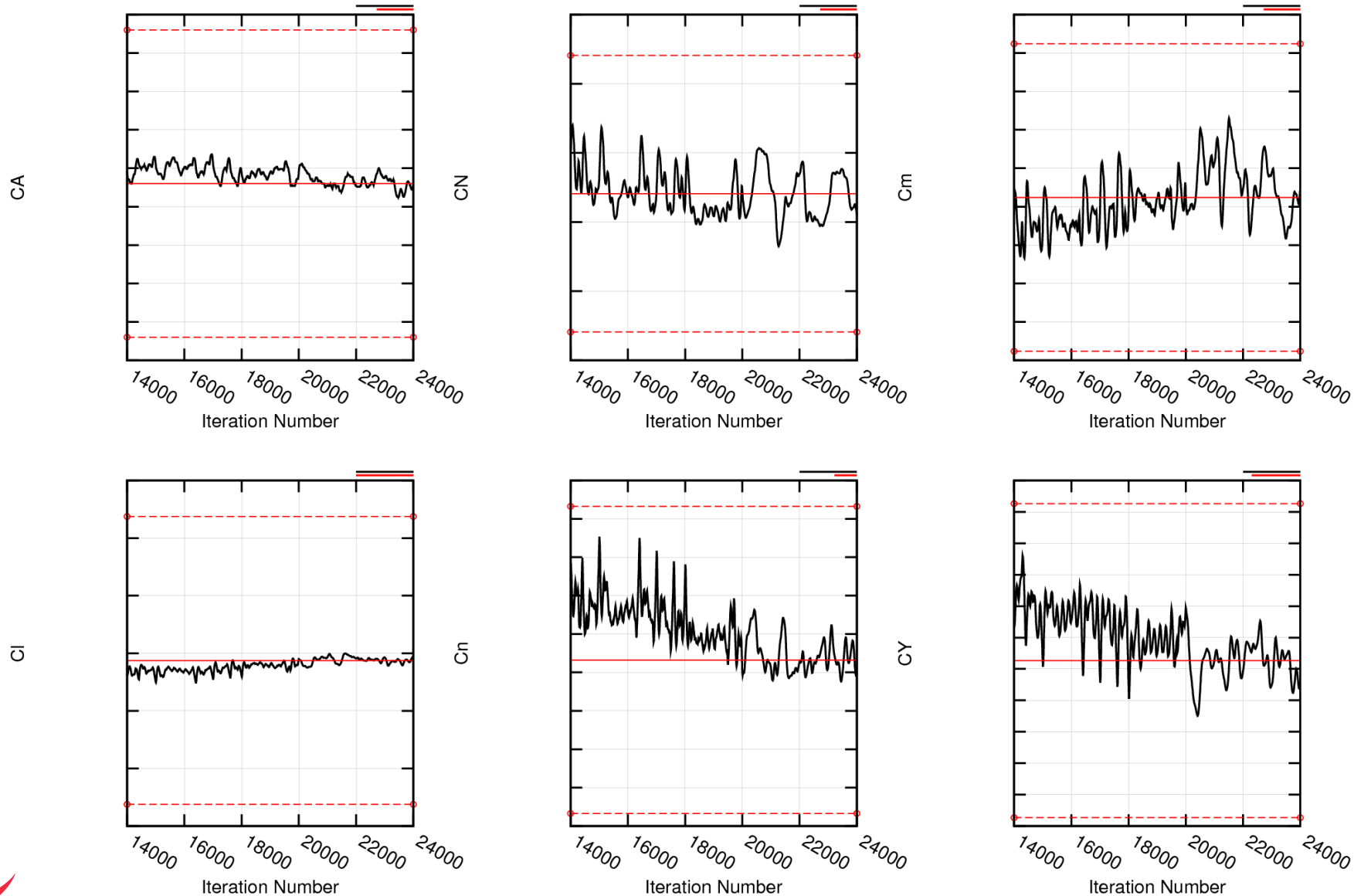
OVERFLOW Convergence Plots using `overlst`

BSM-on dx=10 ft

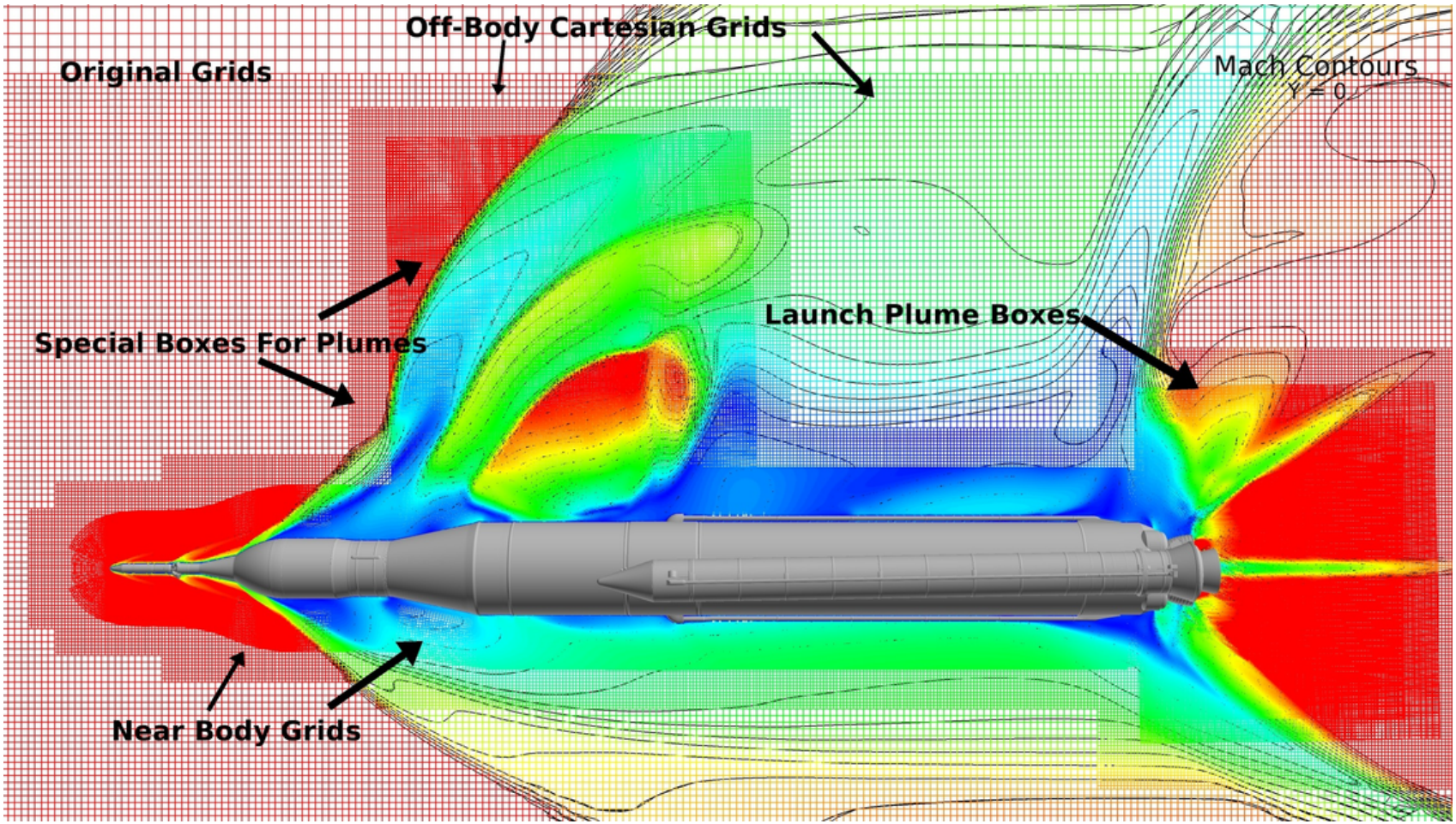


OVERFLOW Convergence Plots using `overlst`

BSM-off dx=8 ft

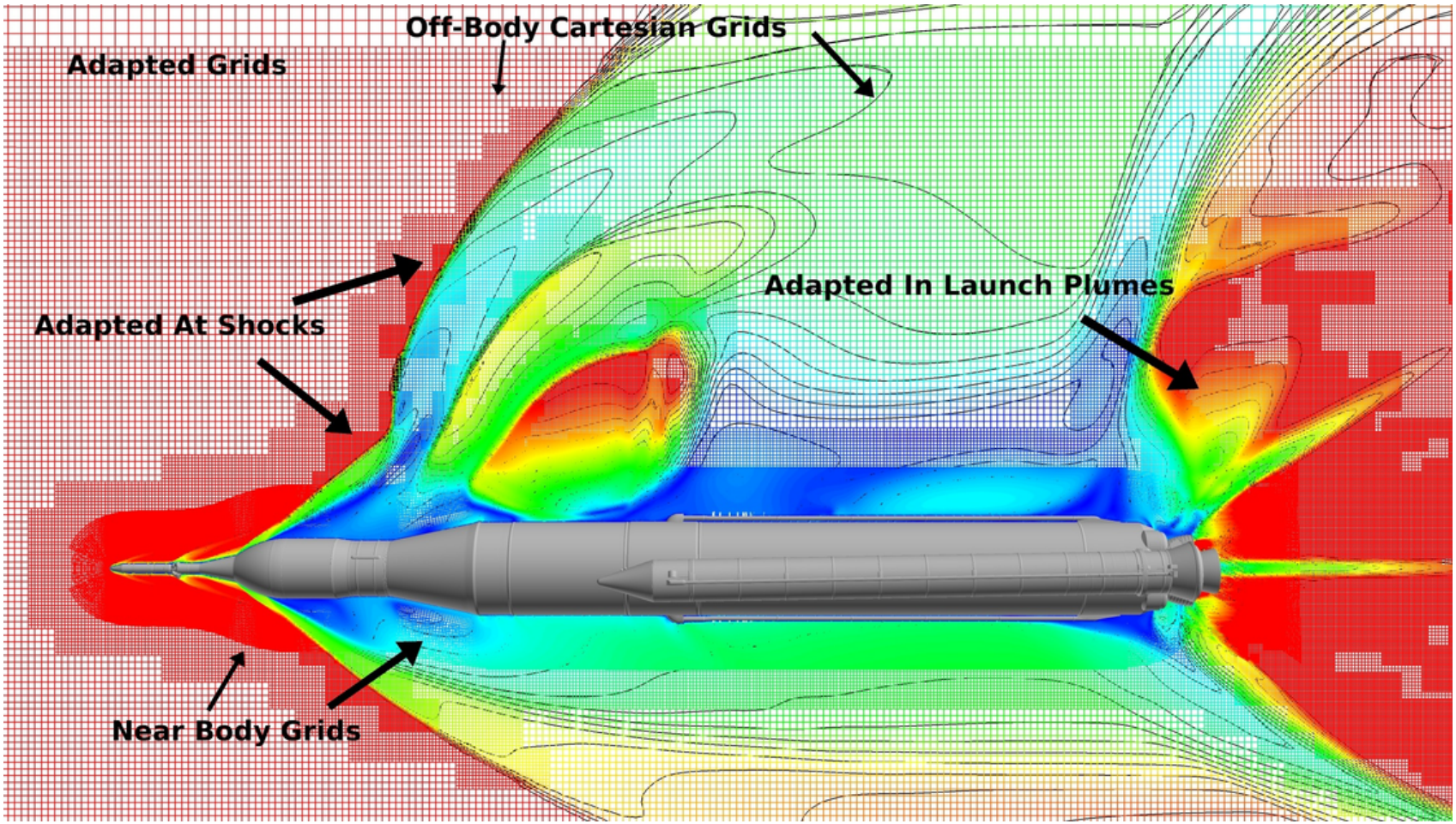


Manually Defined OVERFLOW SLS Grid System



BSM-on with Mach contours on $y = 0$ slice

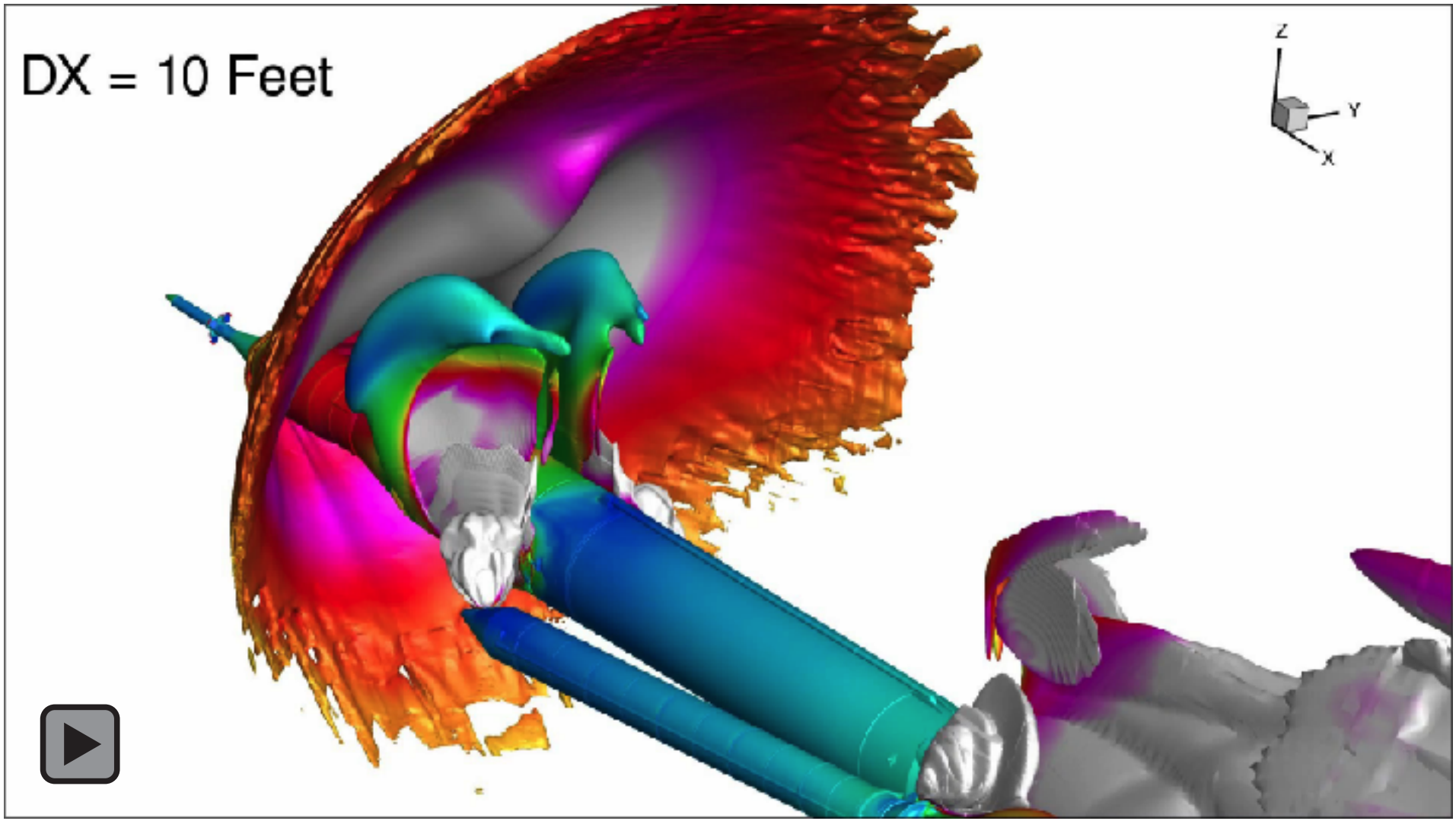
Adapted OVERFLOW SLS Grid System



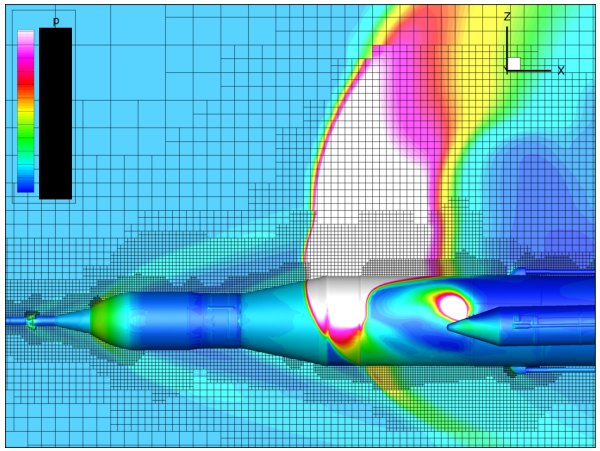
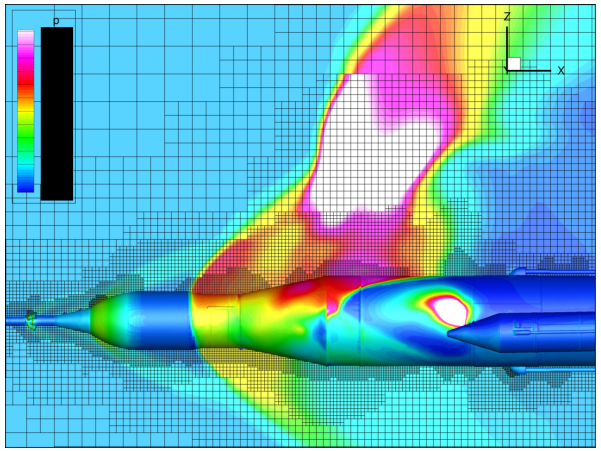
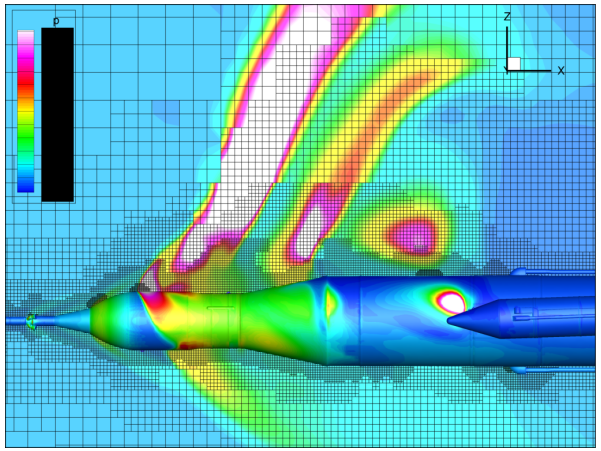
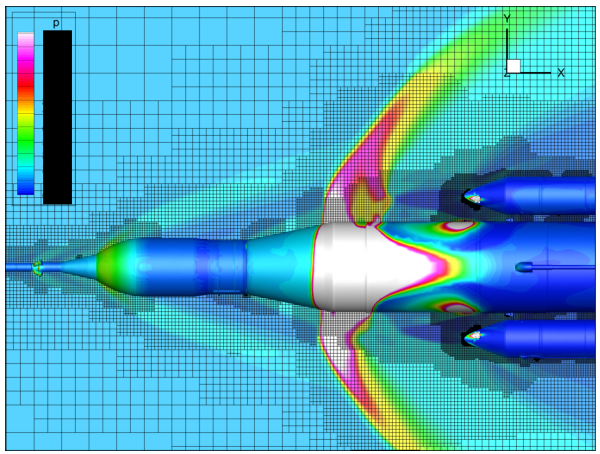
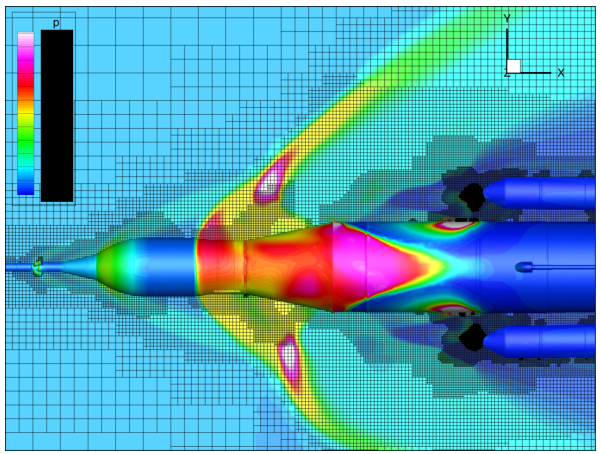
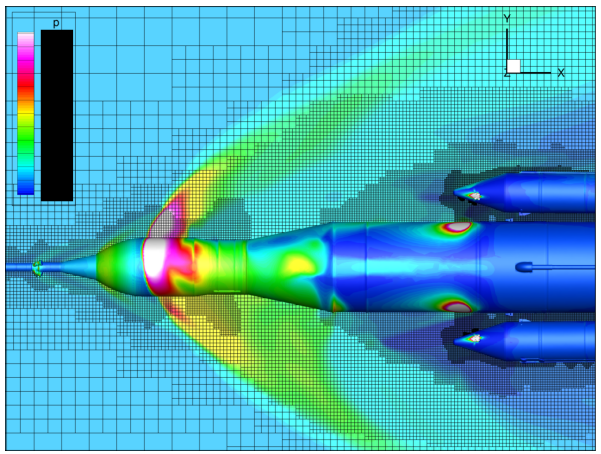
BSM-on with Mach contours on $y = 0$ slice

OVERFLOW Solution Highlighting BSM Plumes

Surfaces colored by static pressure



CDR Database: Lessons Learned

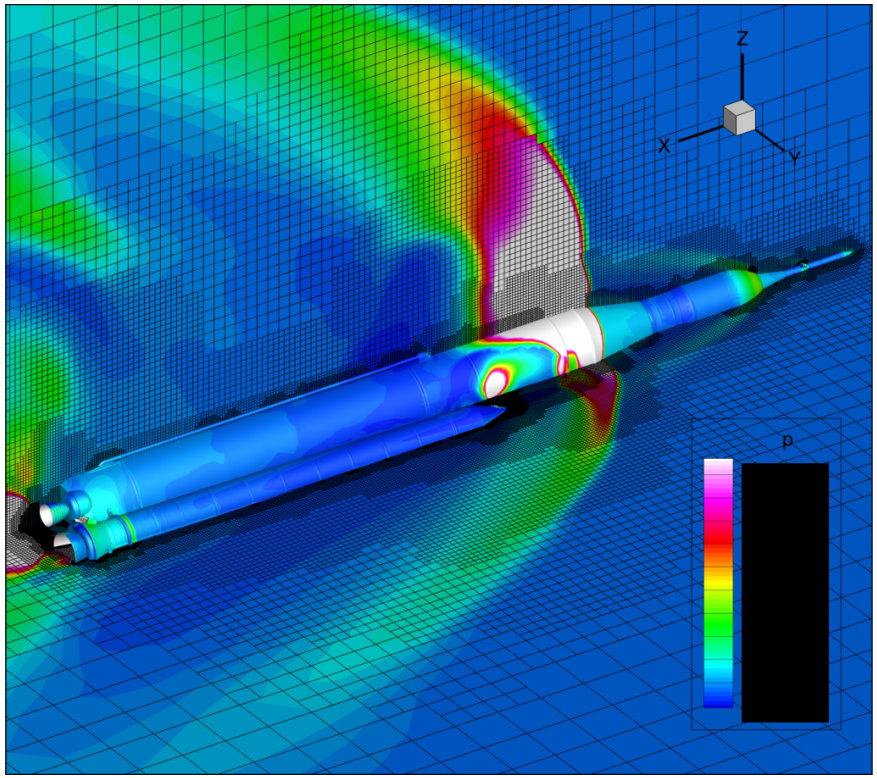







Shock position 3 | Shock position 2 | Shock position 1

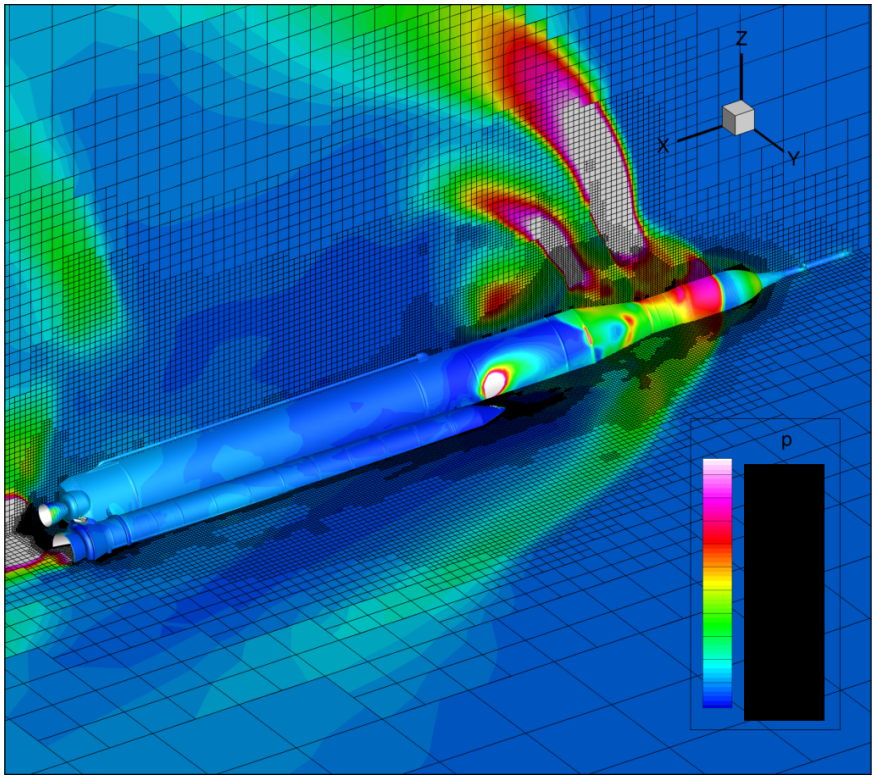
Results from Overflow viscous CFD: position 1 for all cases

Wind tunnel data in agreement, although possibility indicated of a shock position even farther forward

Improvements for Cart3D Inputs



Database solution

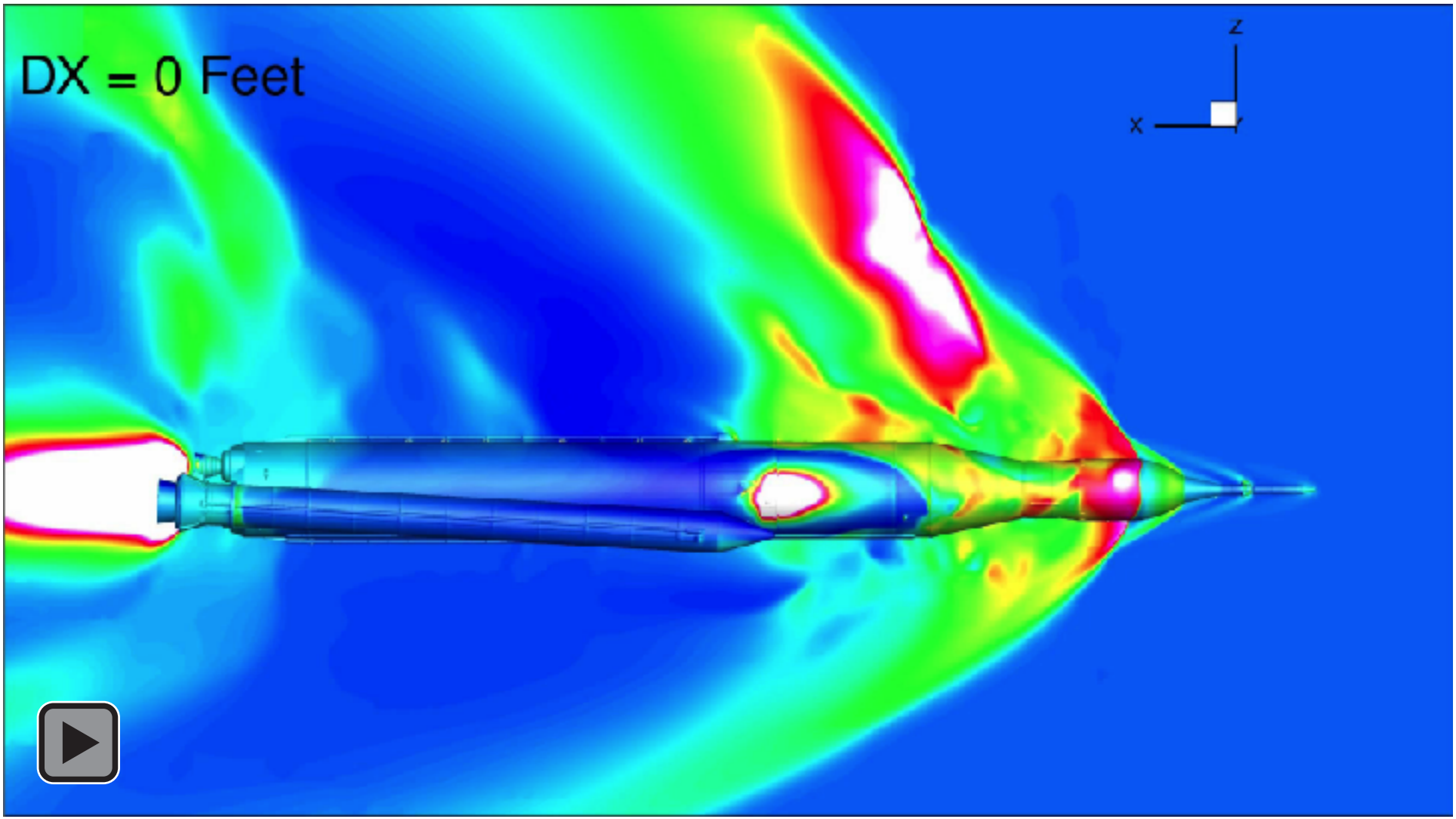


Improvement test run #31

- After database completion, much better understanding of solution quality
- Tried about 180 different Cart3D input strategies to improve results
- Essentially a flow separation—a viscous phenomenon
- High upstream resolution + vorticity allows inviscid solver to capture some of the effect

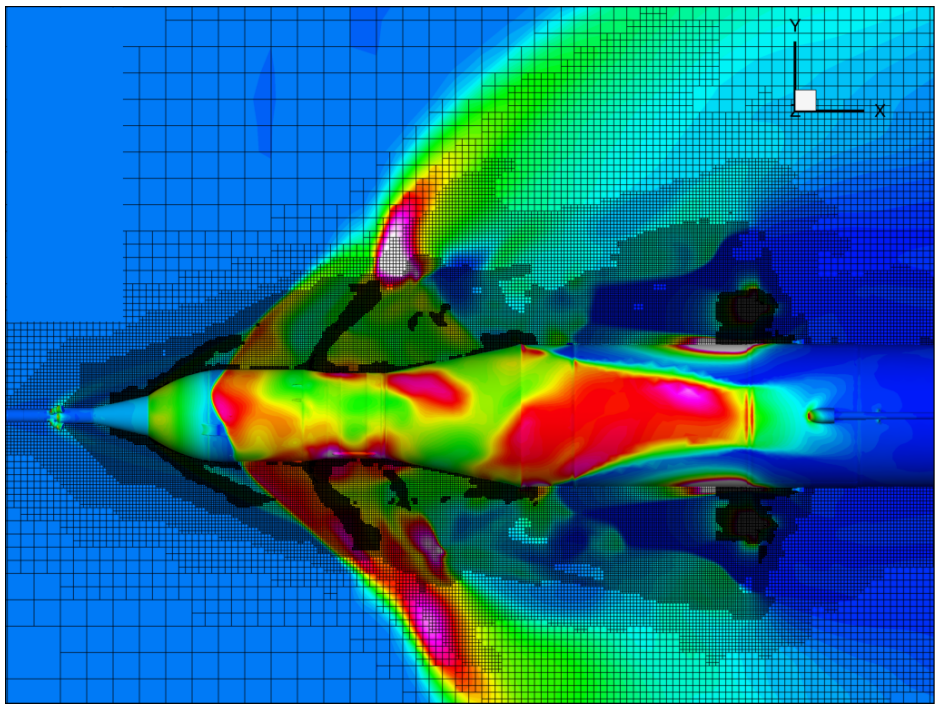
Videos of Two Cart3D Solutions

Surfaces colored by static pressure, $\mathrm{dx} = 0$ ft

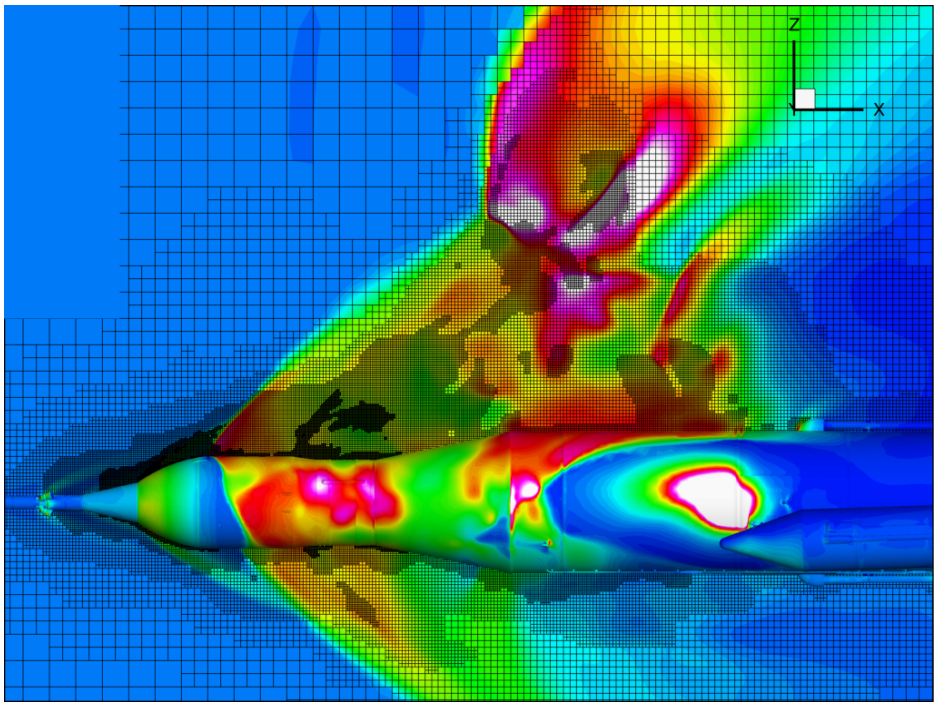


Sample Cart3D Static Pressure Slices

Taken at Last Iteration (No Averaging)



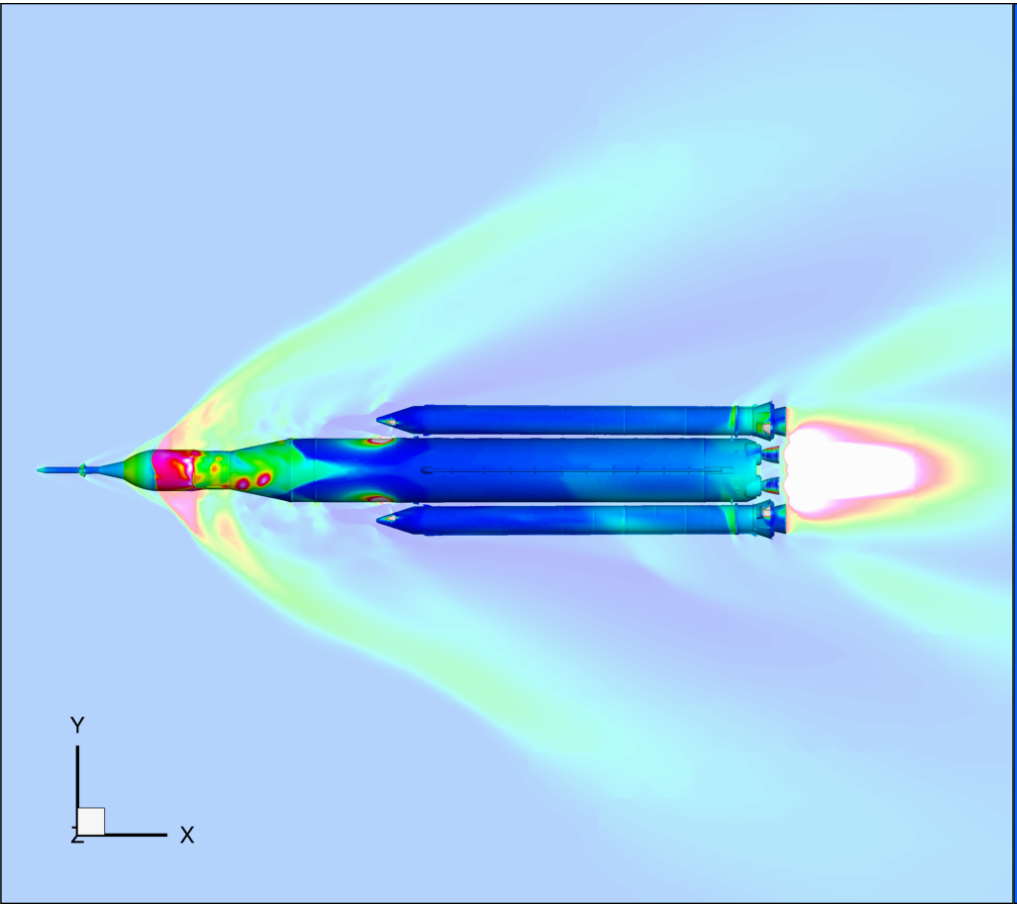
dx=6 ft, $z = 0$ slice



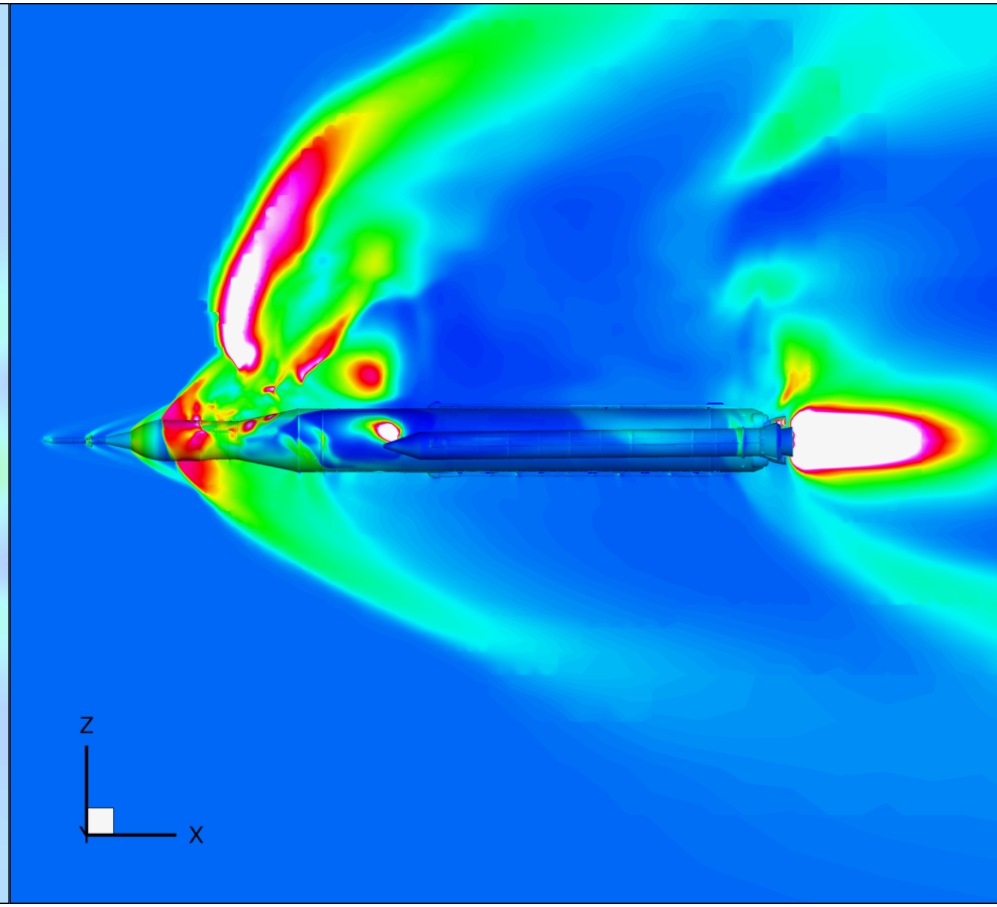
dx=6 ft, $y = 0$ slice

Nominal Trajectory Solutions

dx=2 ft (BSMs on)



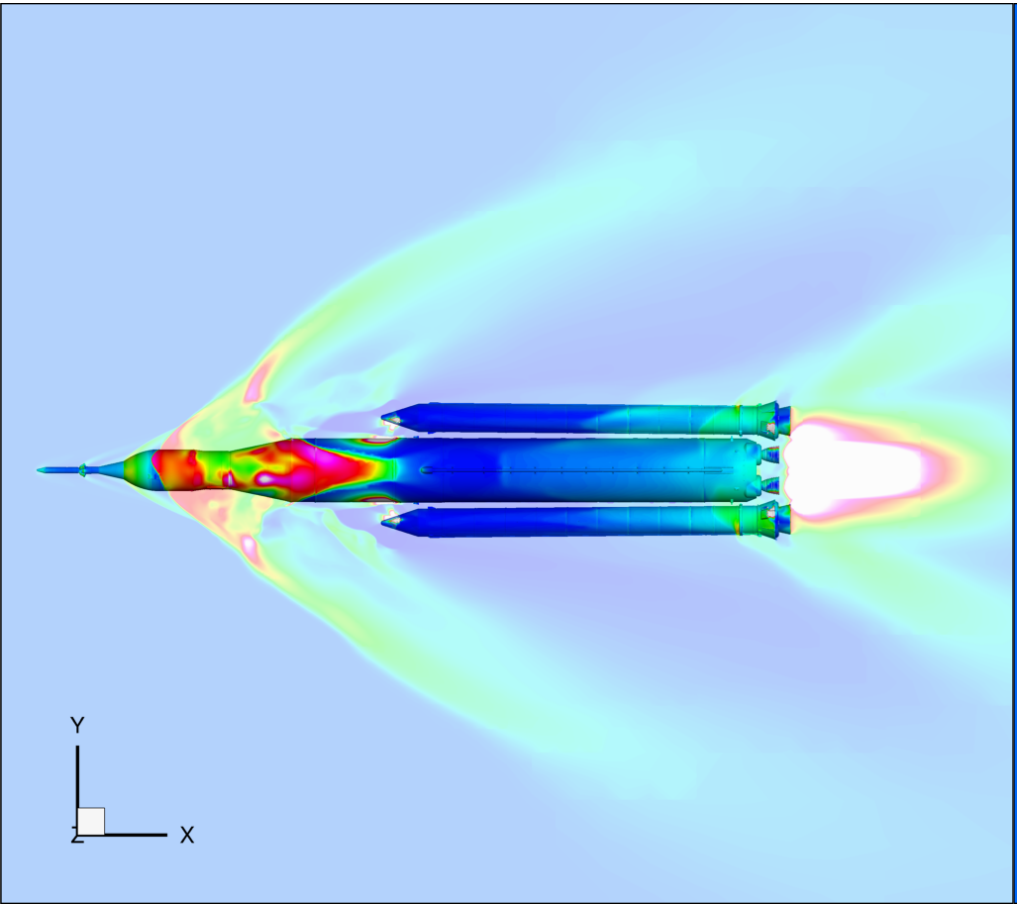
Translucent z=0 slice



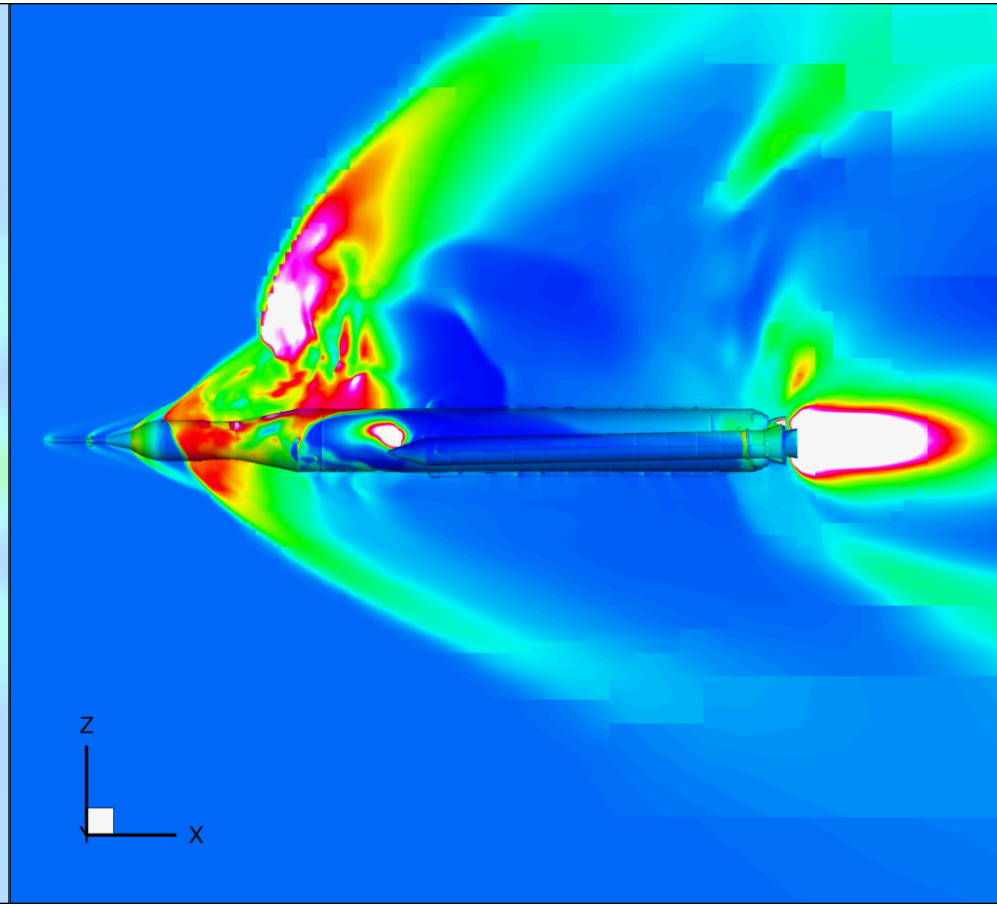
y=0 slice

Nominal Trajectory Solutions

dx=4 ft (BSMs on)



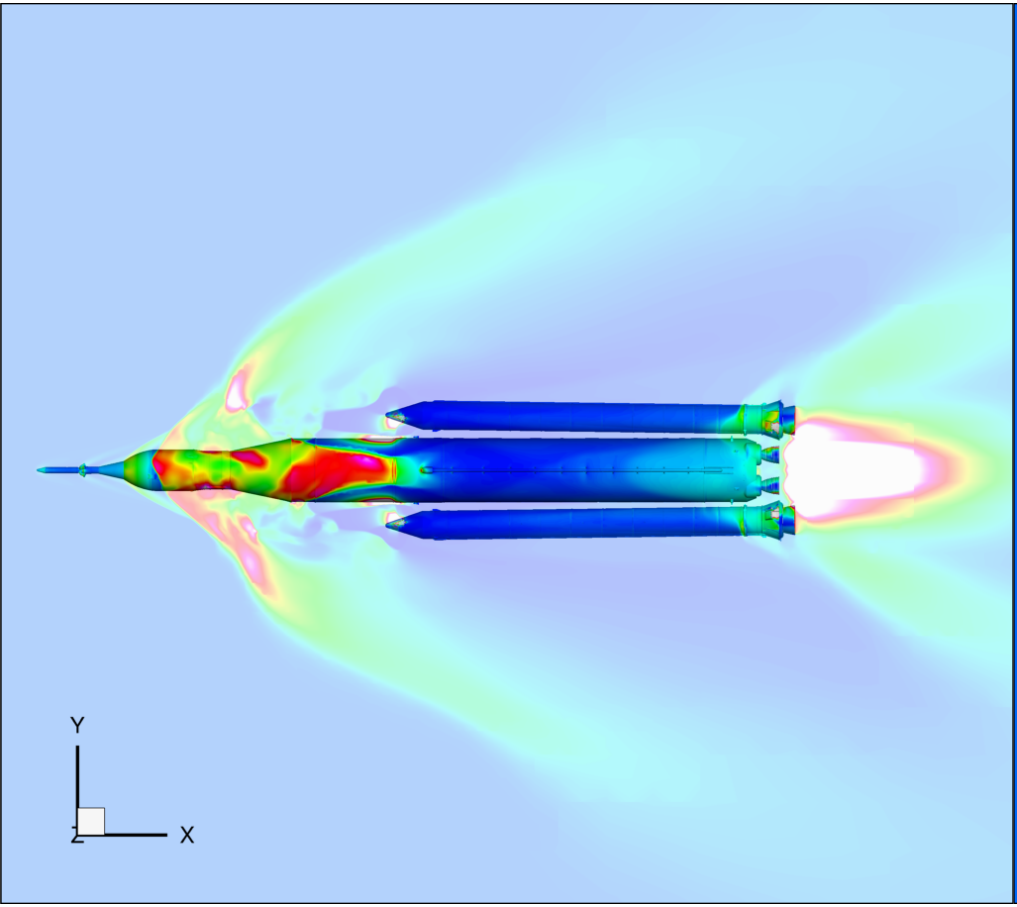
Translucent z=0 slice



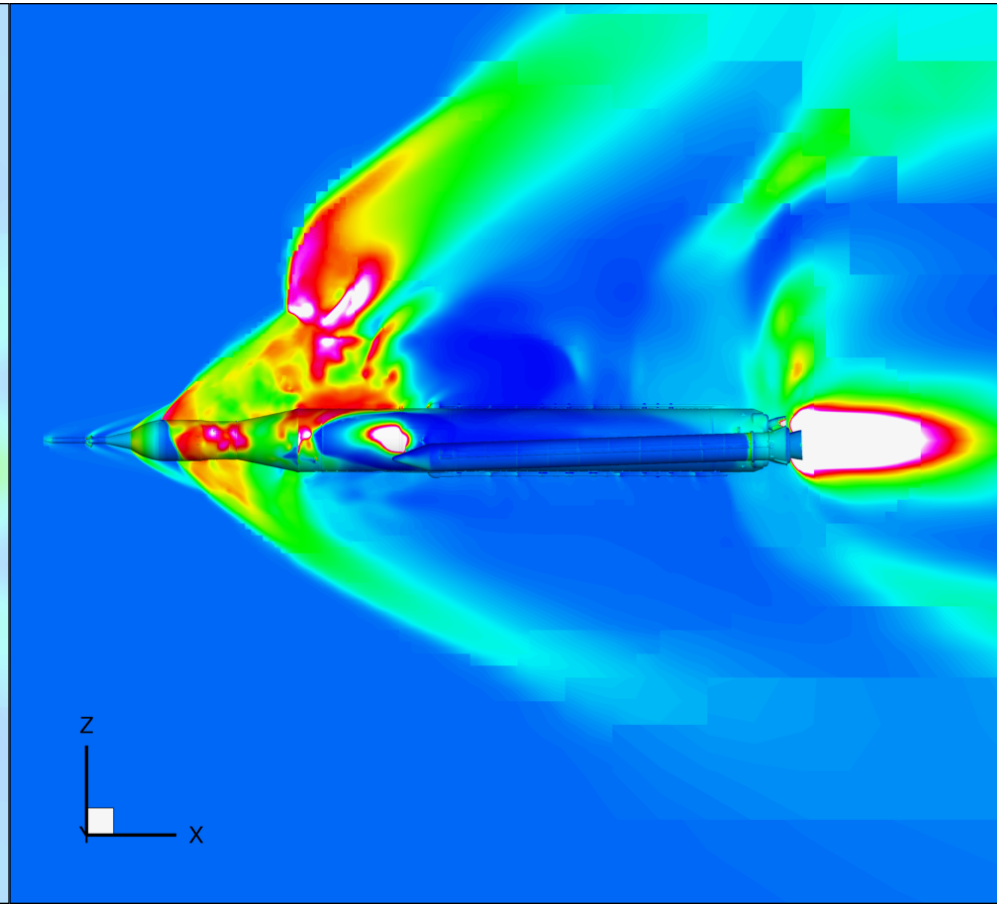
y=0 slice

Nominal Trajectory Solutions

dx=6 ft (BSMs on)



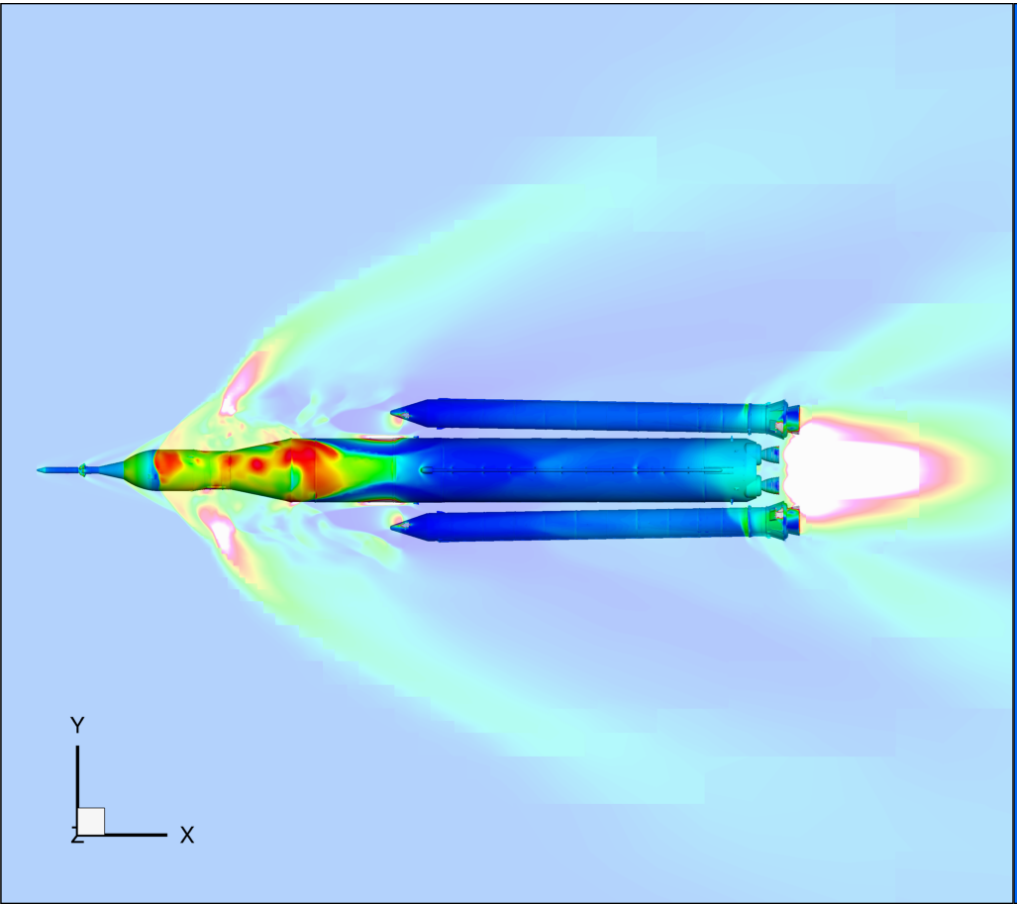
Translucent z=0 slice



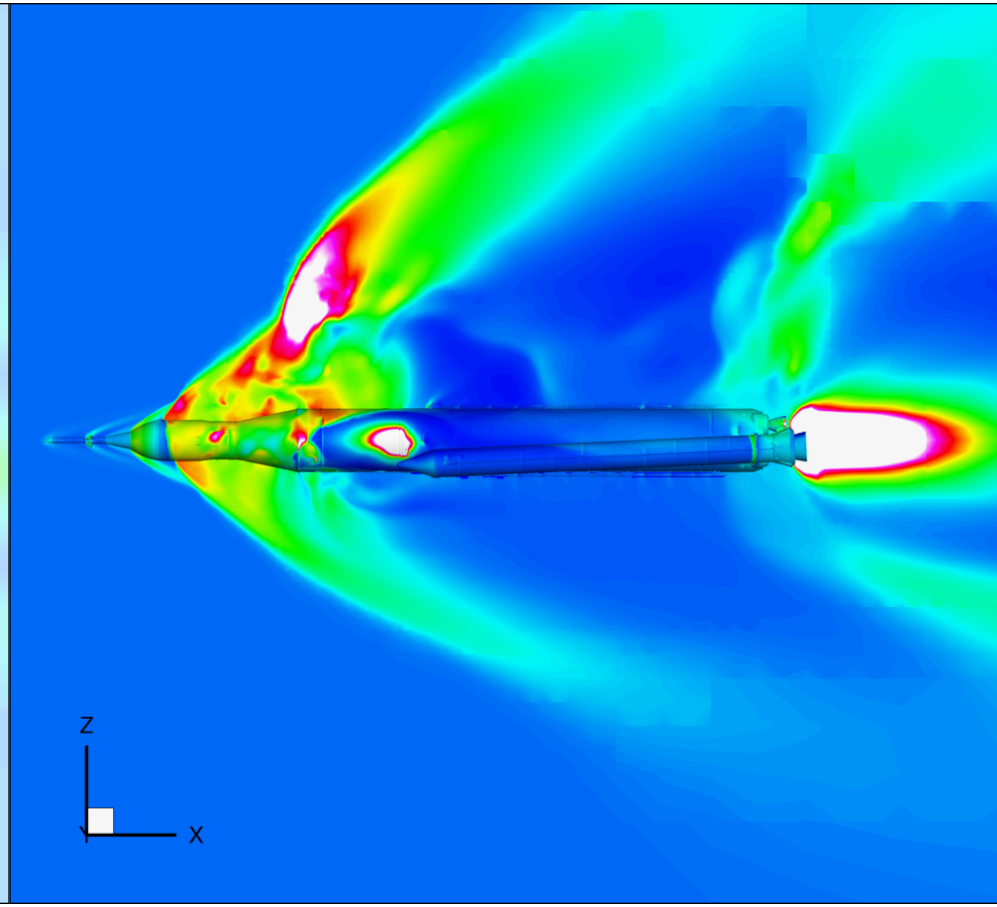
y=0 slice

Nominal Trajectory Solutions

dx=8 ft (BSMs on)



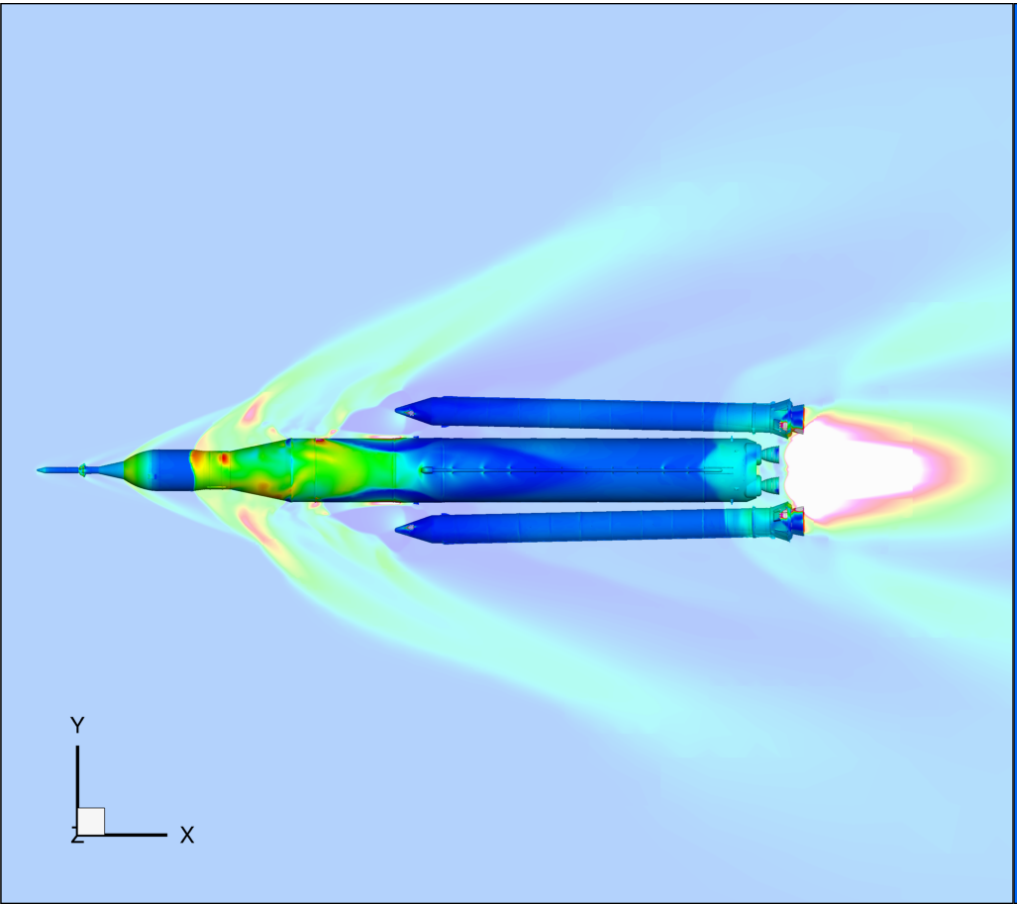
Translucent z=0 slice



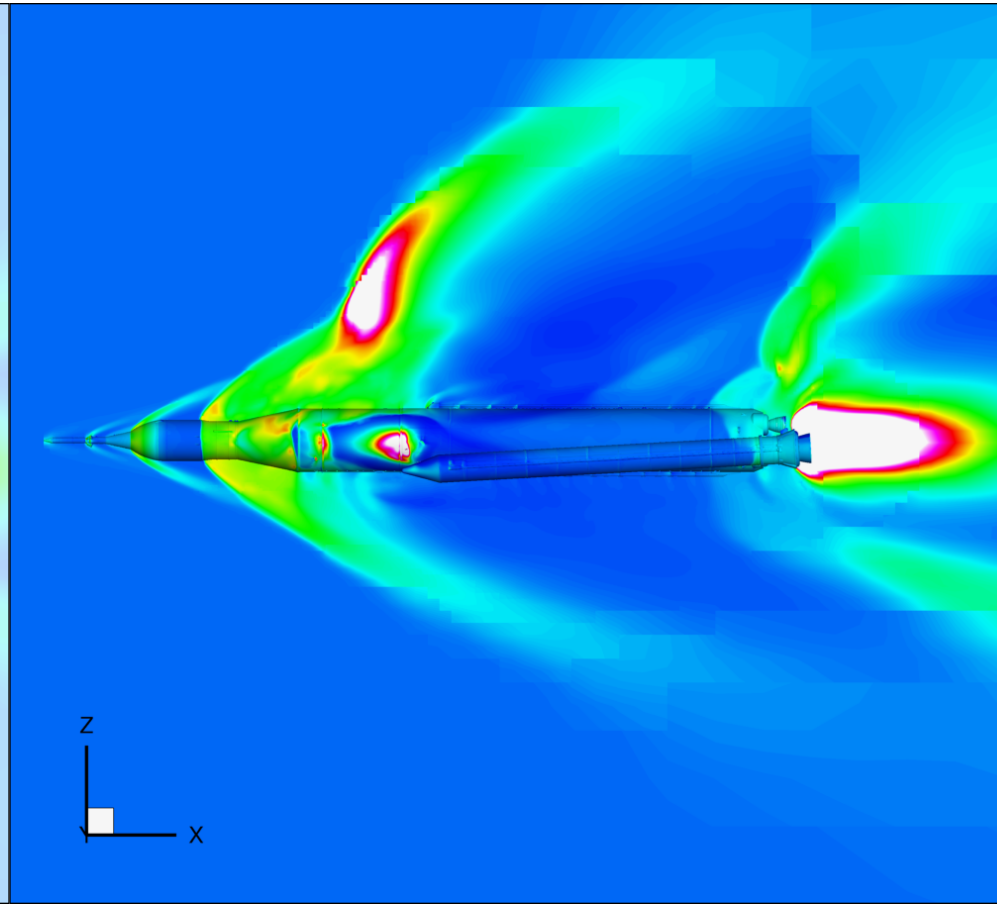
y=0 slice

Nominal Trajectory Solutions

dx=10 ft (BSMs on)



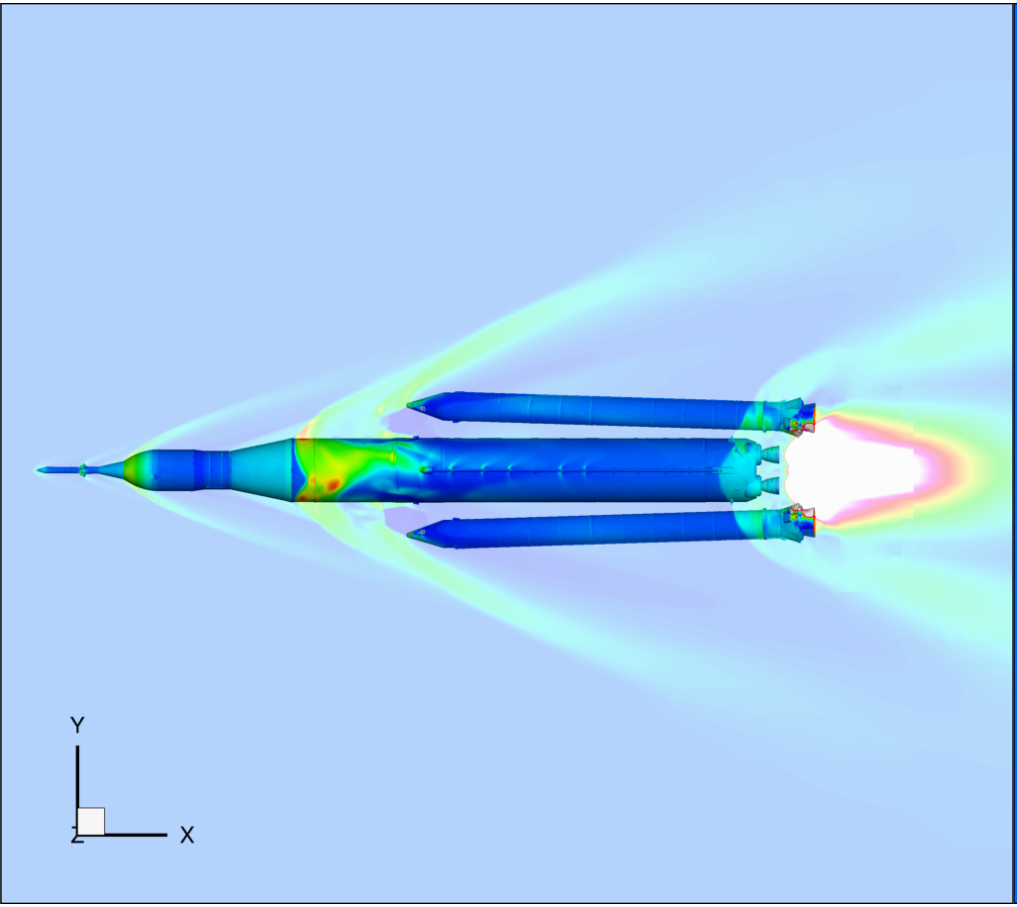
Translucent z=0 slice



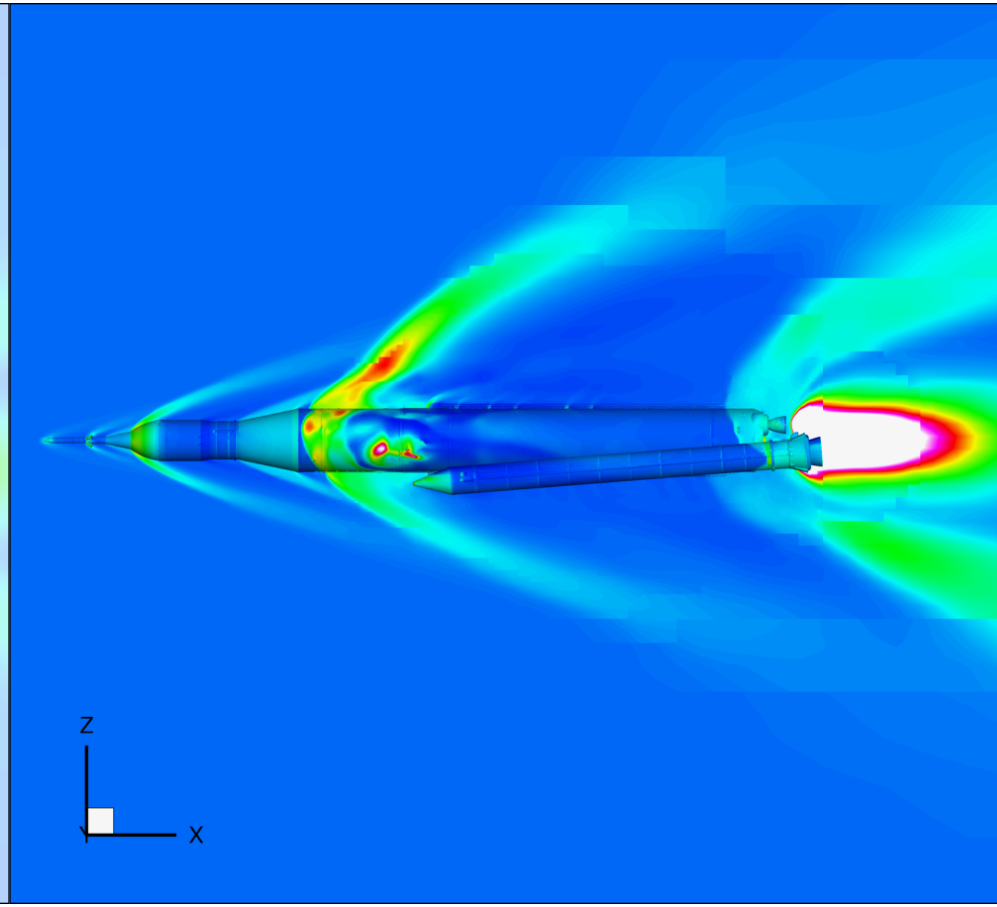
y=0 slice

Nominal Trajectory Solutions

dx=15 ft (BSMs tailing off)



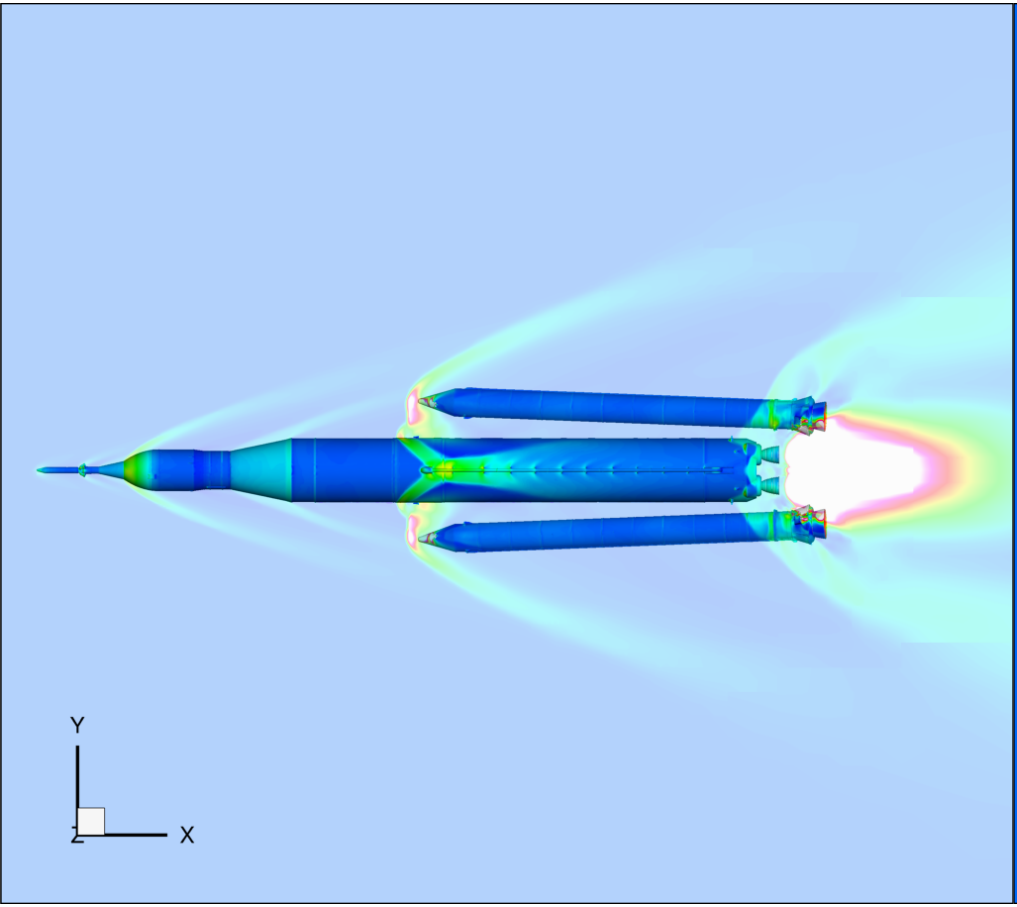
Translucent z=0 slice



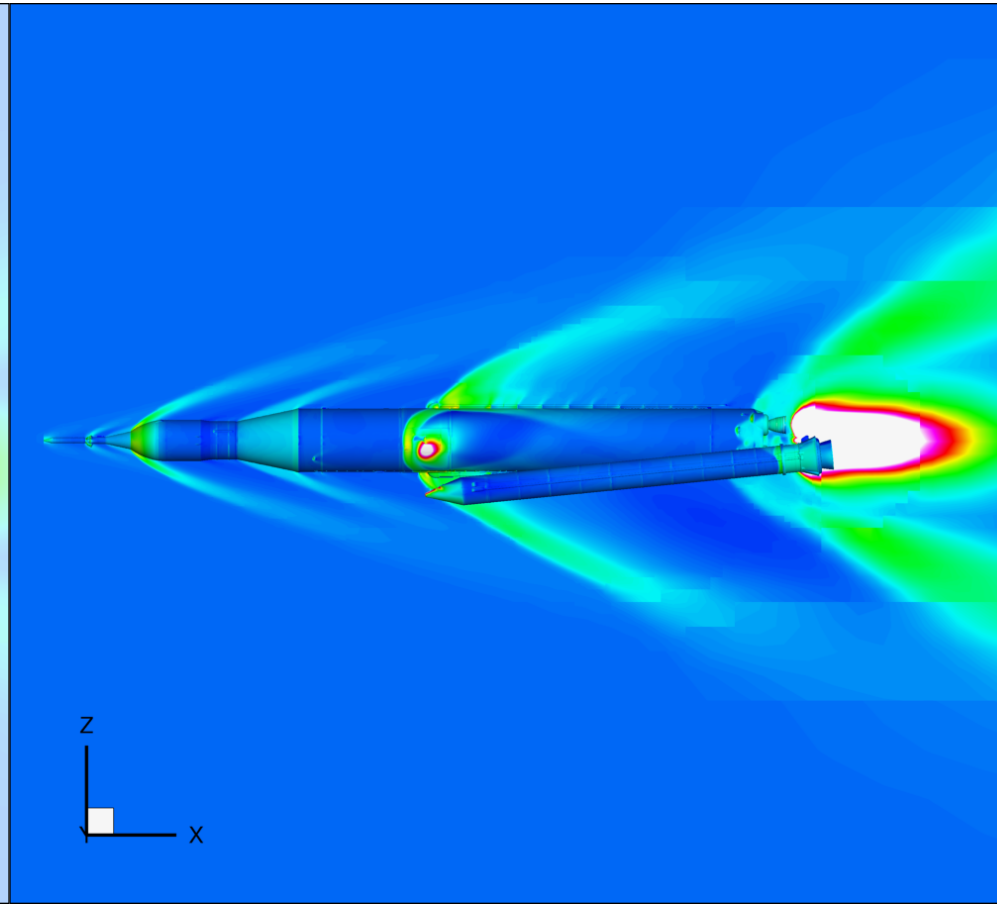
y=0 slice

Nominal Trajectory Solutions

dx=20 ft (BSMs tailing off)



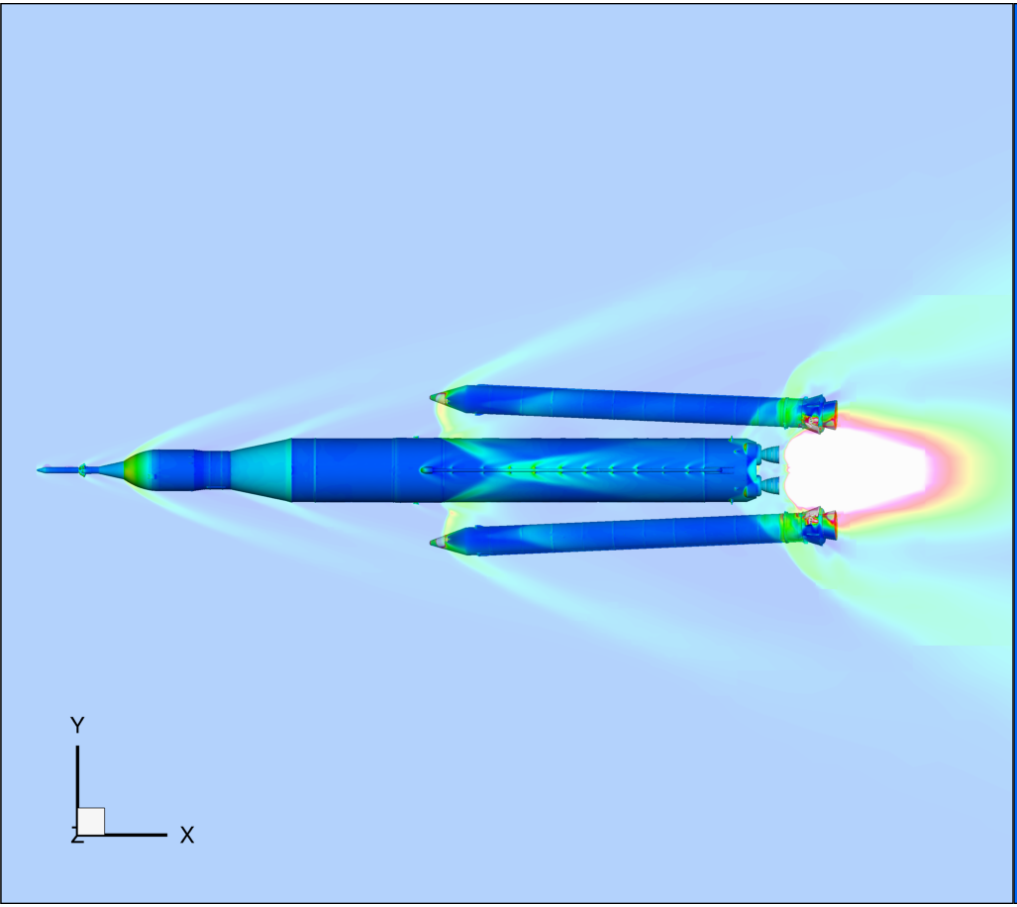
Translucent z=0 slice



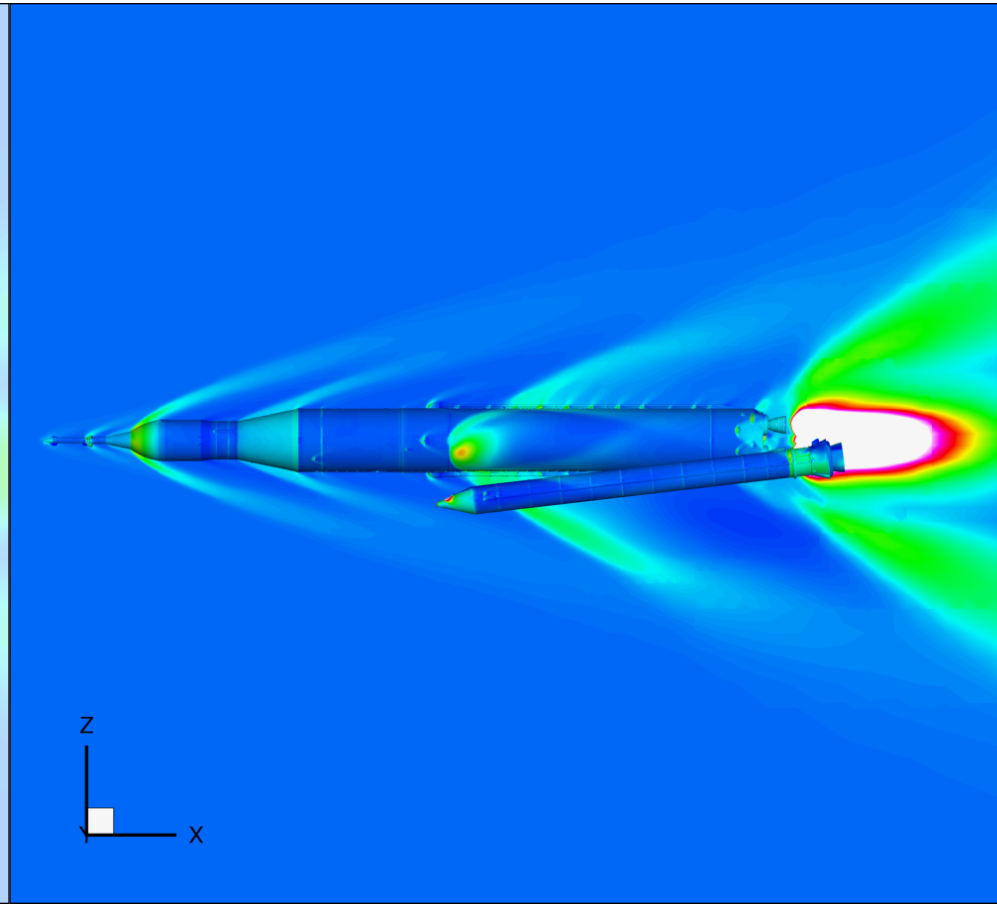
y=0 slice

Nominal Trajectory Solutions

dx=25 ft (BSMs tailing off)



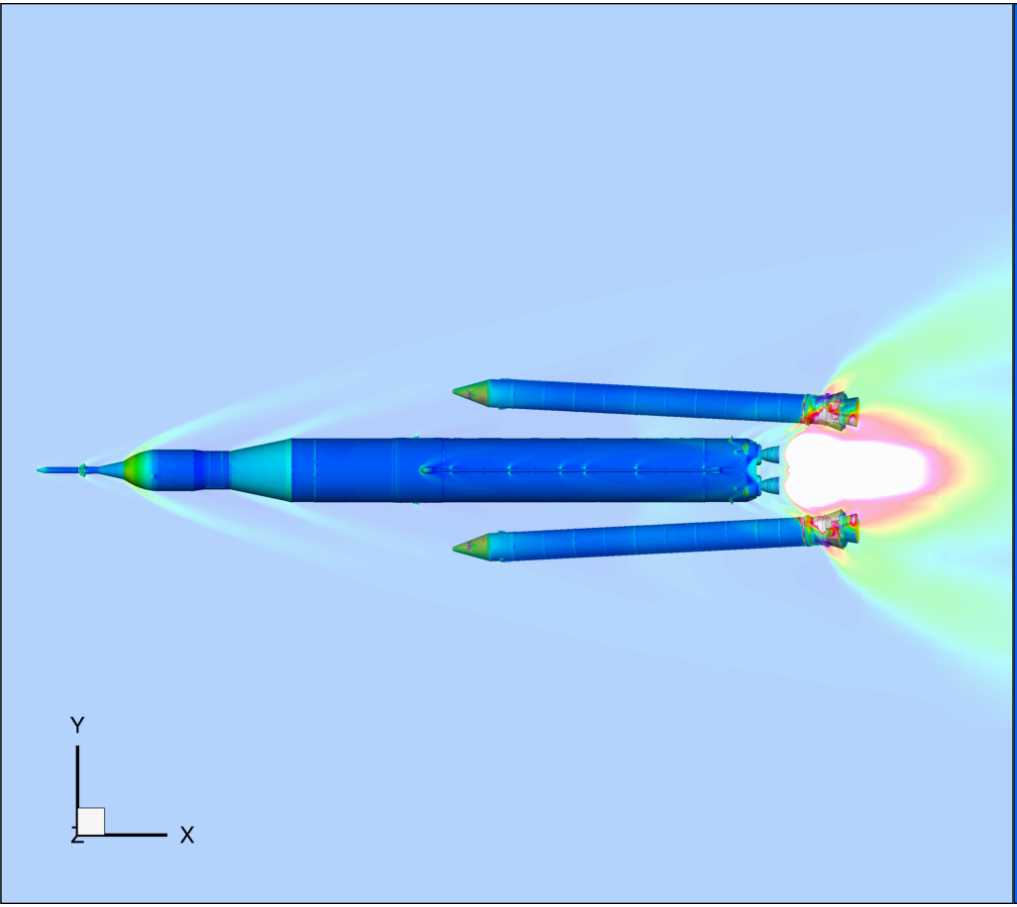
Translucent z=0 slice



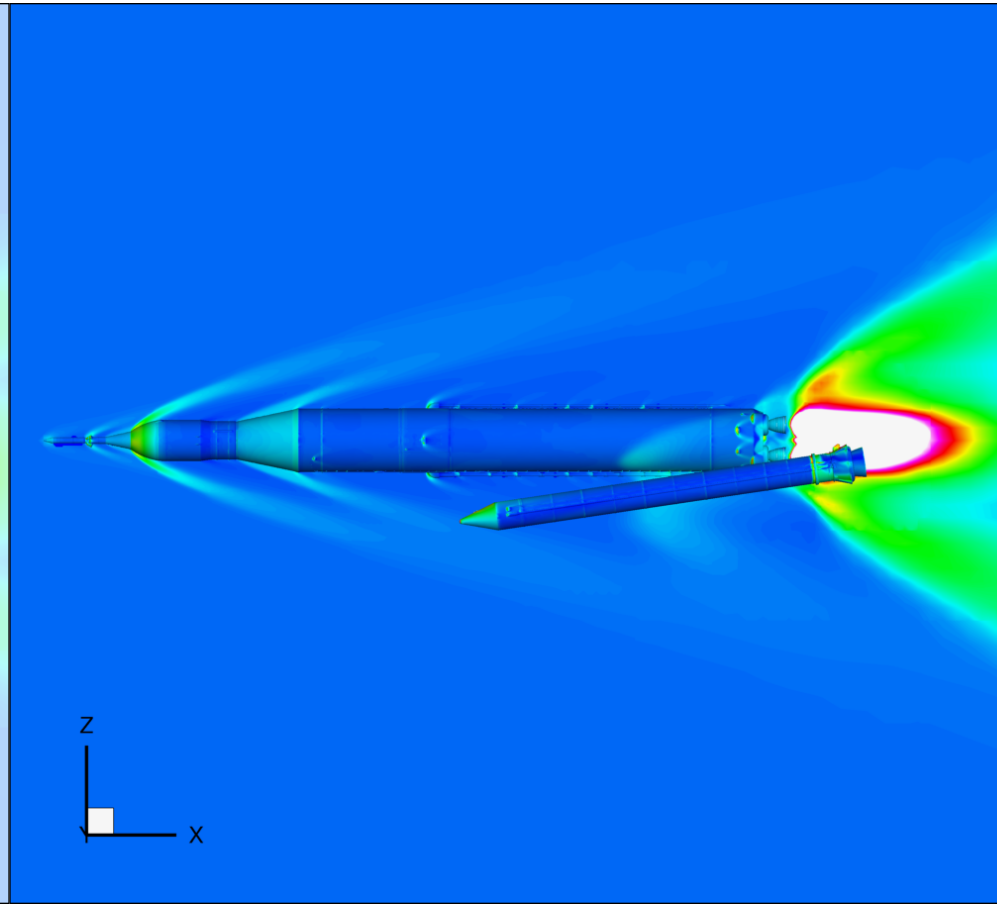
y=0 slice

Nominal Trajectory Solutions

dx=35 ft (BSMs off)



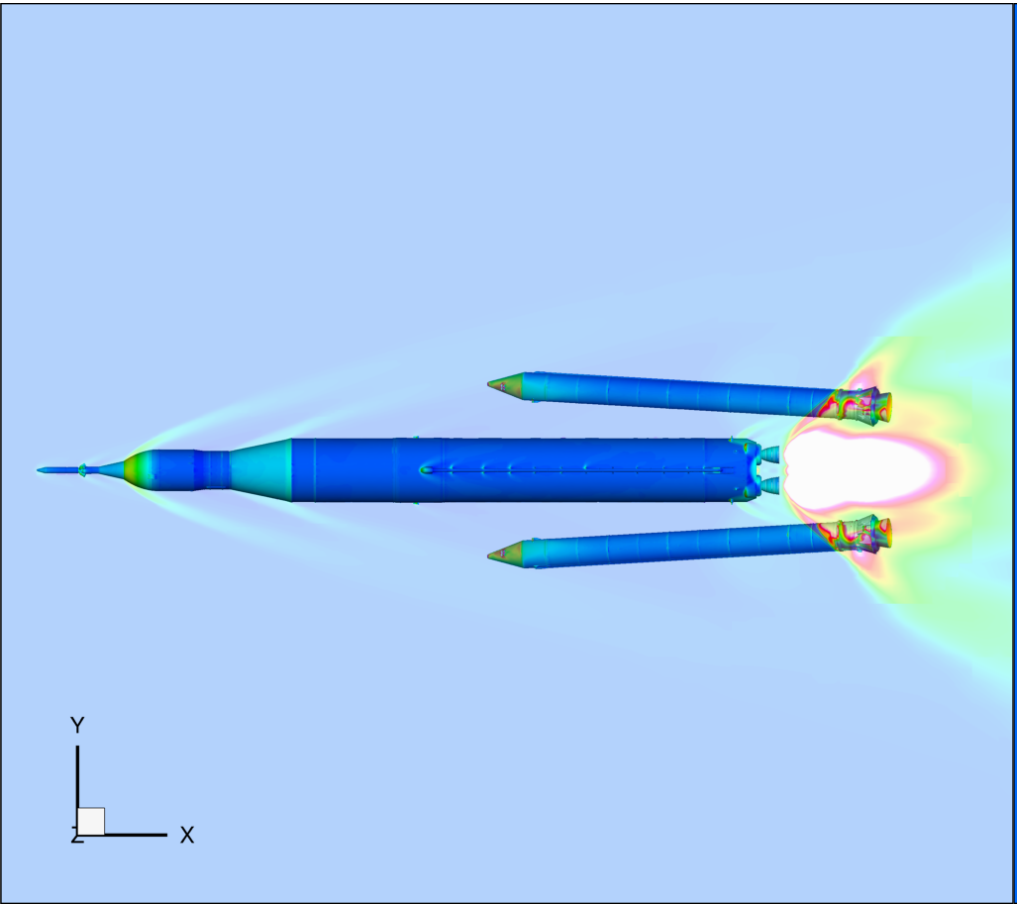
Translucent z=0 slice



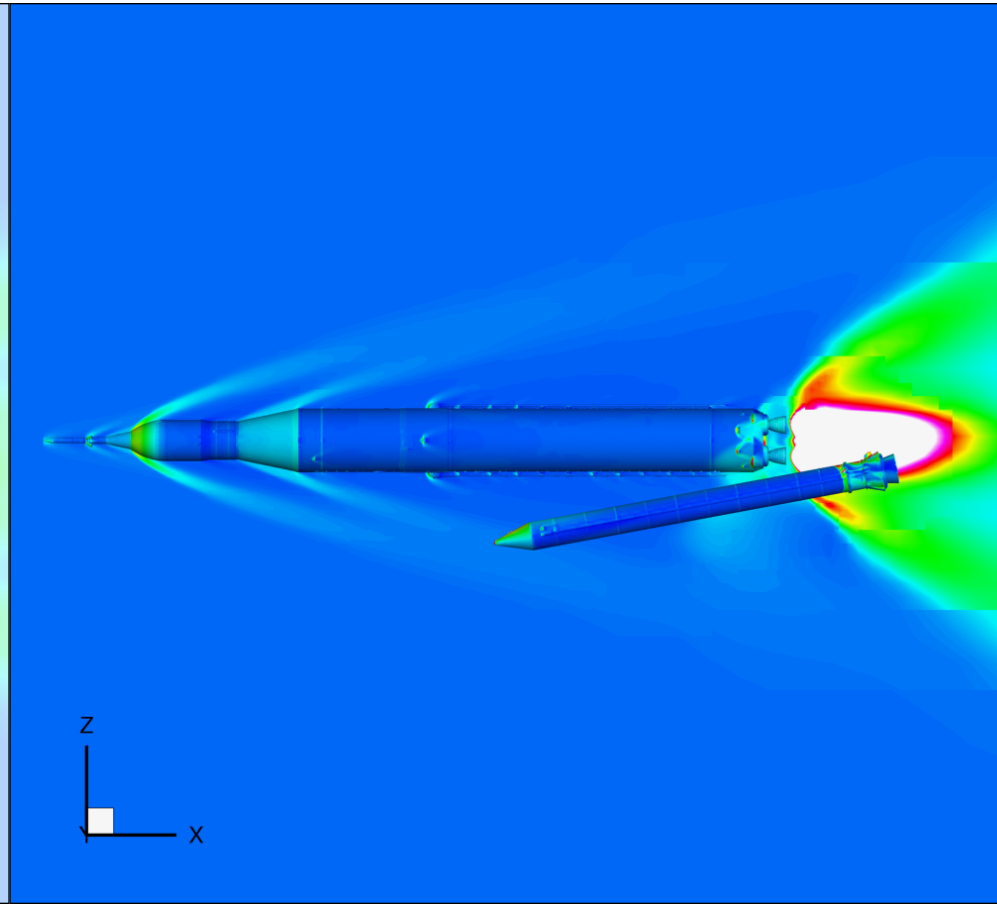
y=0 slice

Nominal Trajectory Solutions

dx=50 ft (BSMs off)



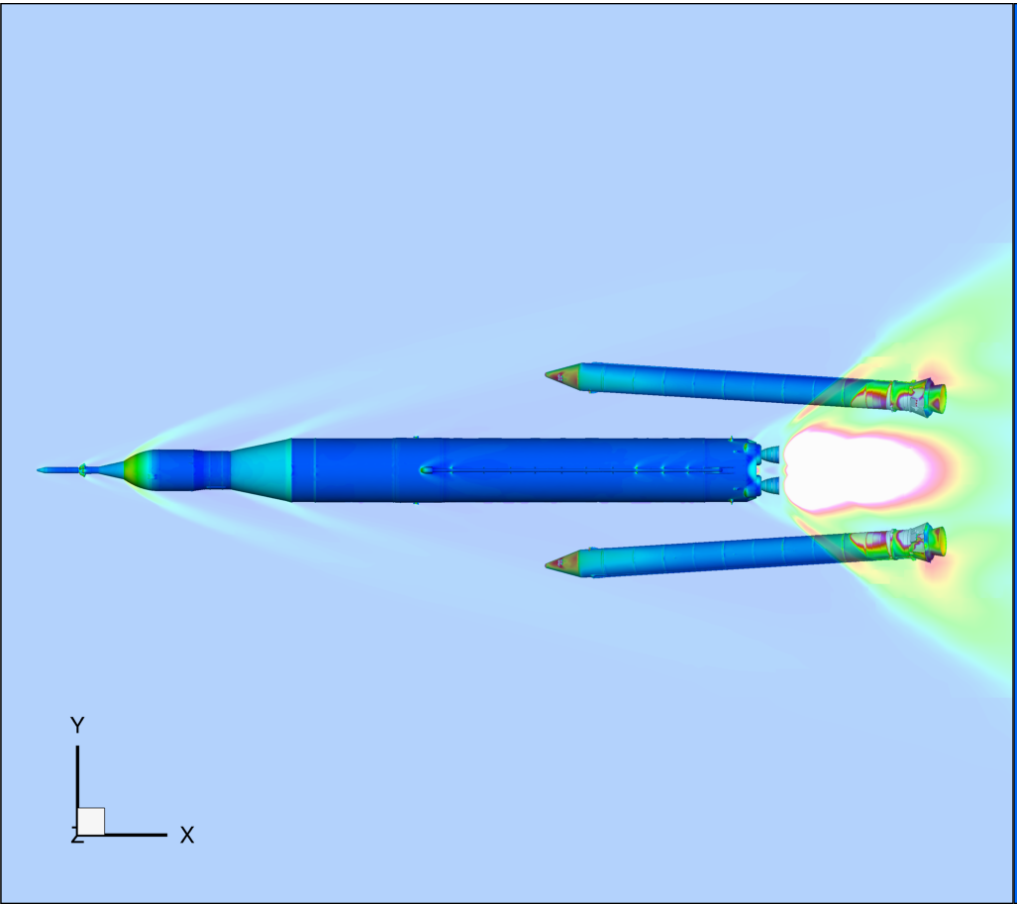
Translucent z=0 slice



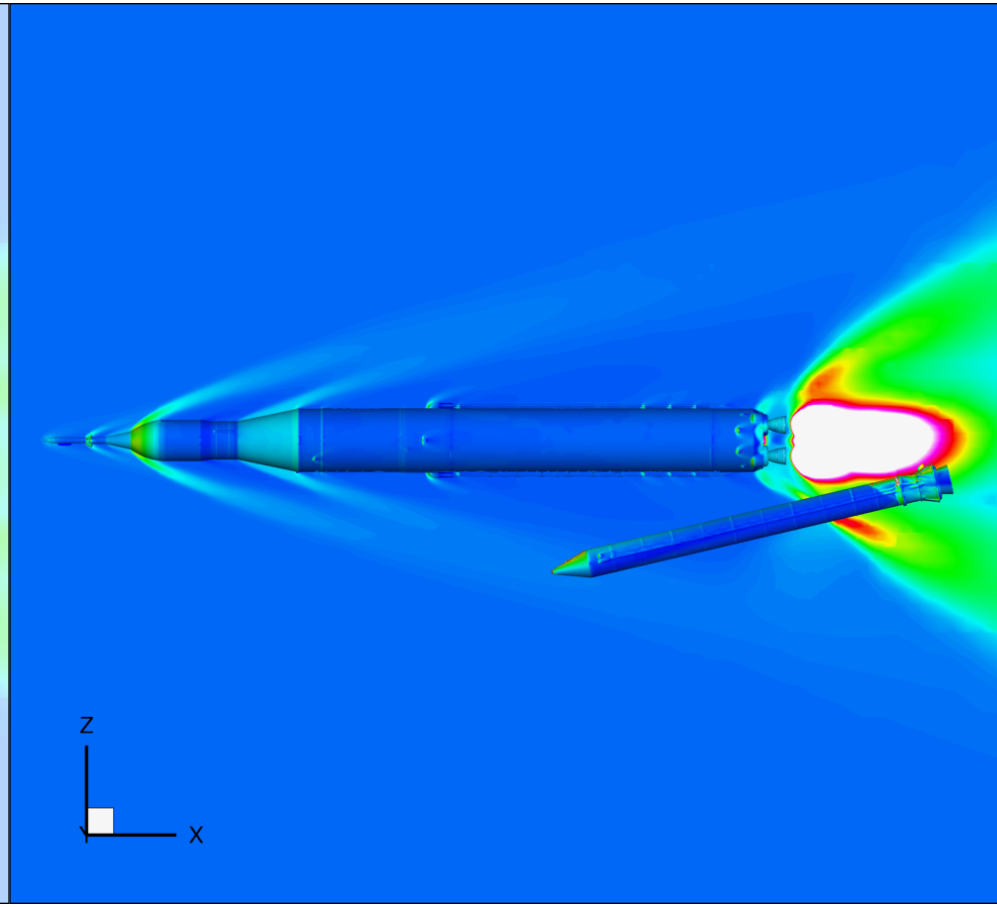
y=0 slice

Nominal Trajectory Solutions

dx=75 ft (BSMs off)



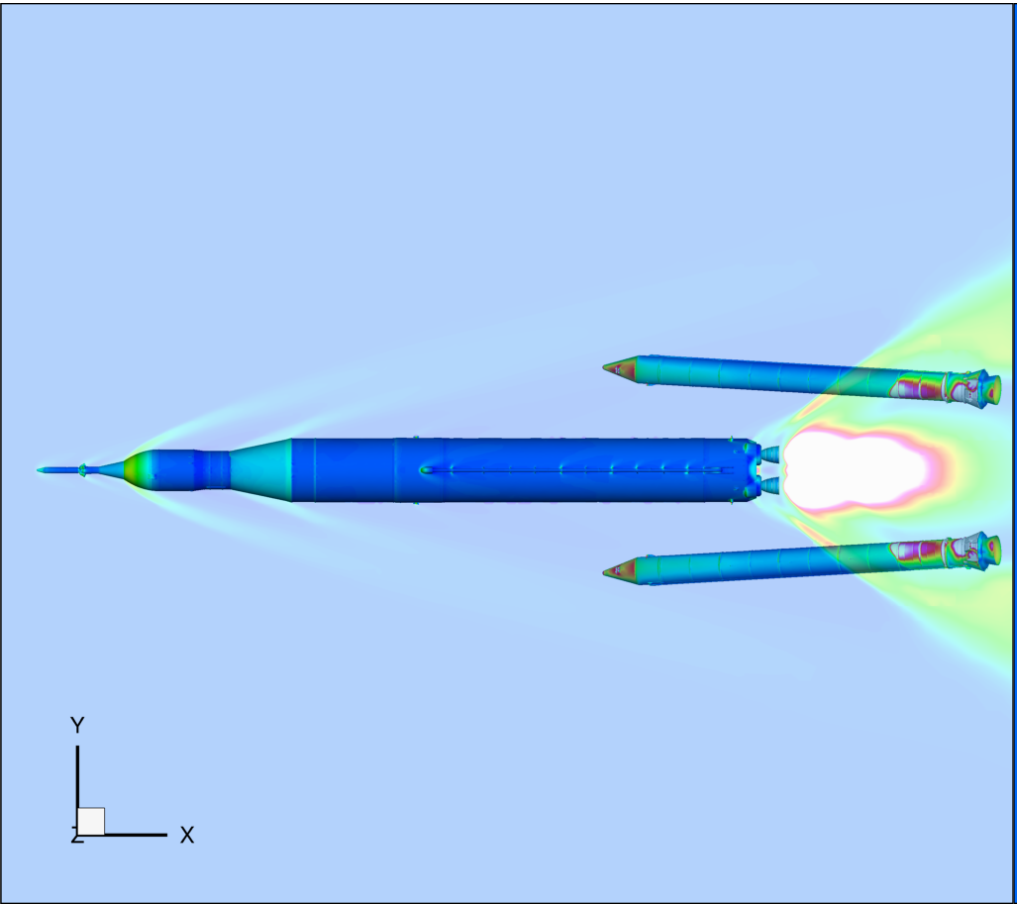
Translucent z=0 slice



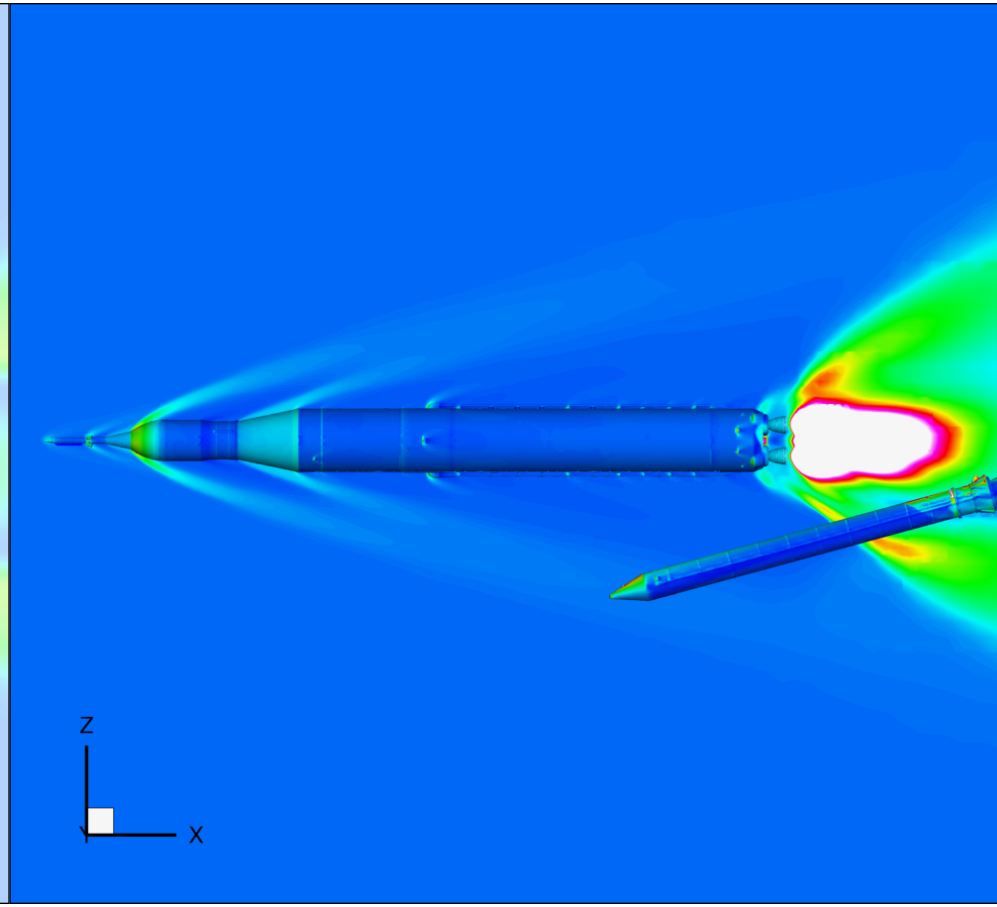
y=0 slice

Nominal Trajectory Solutions

dx=100 ft (BSMs off)



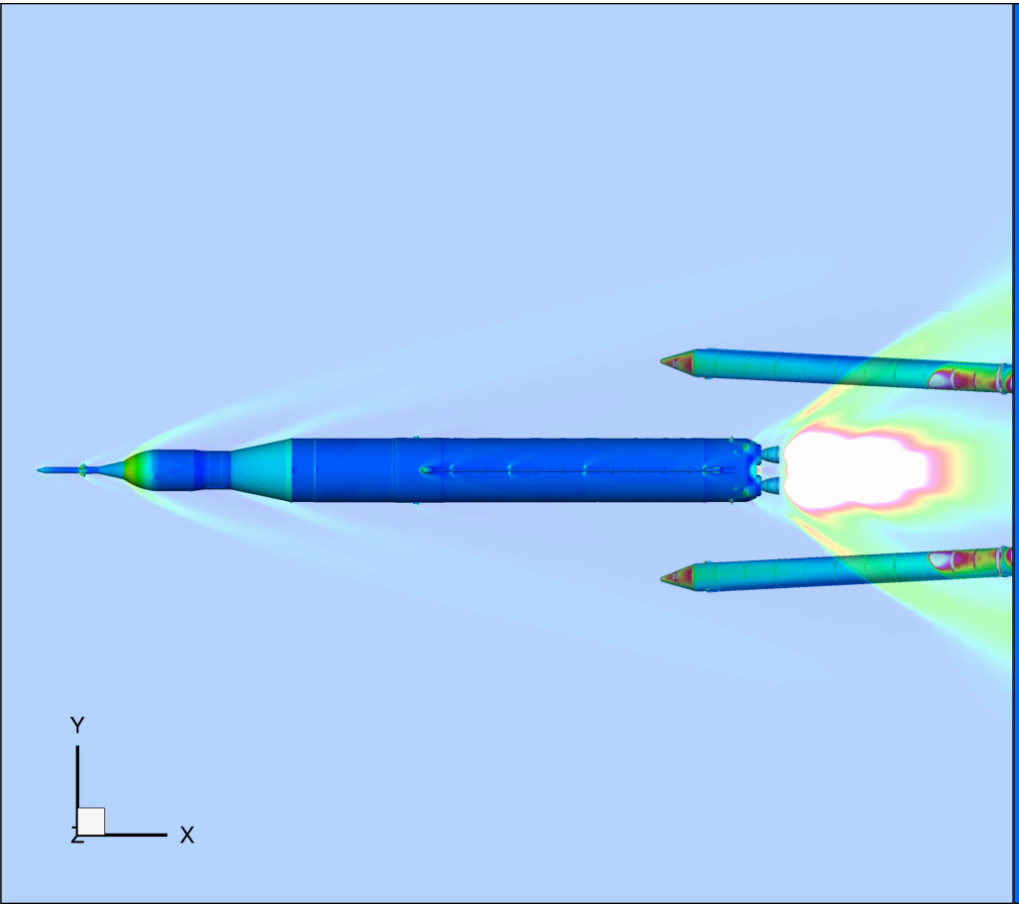
Translucent z=0 slice



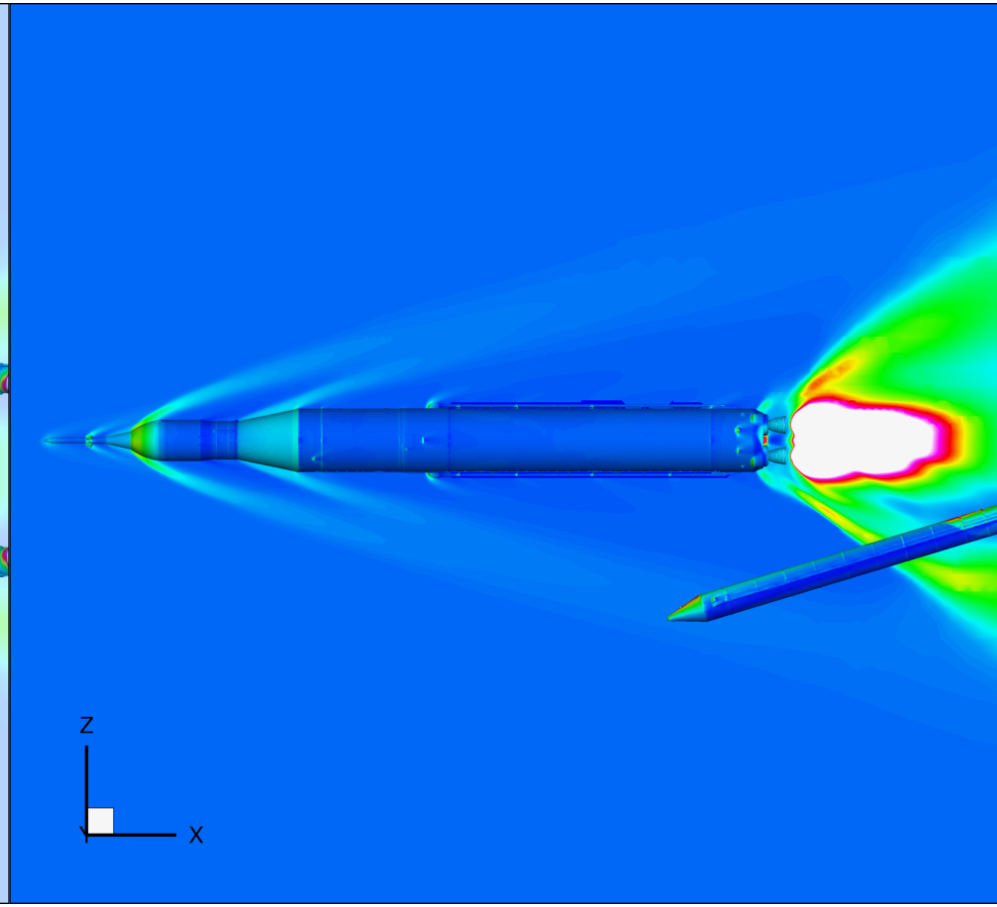
y=0 slice

Nominal Trajectory Solutions

dx=125 ft (BSMs off)



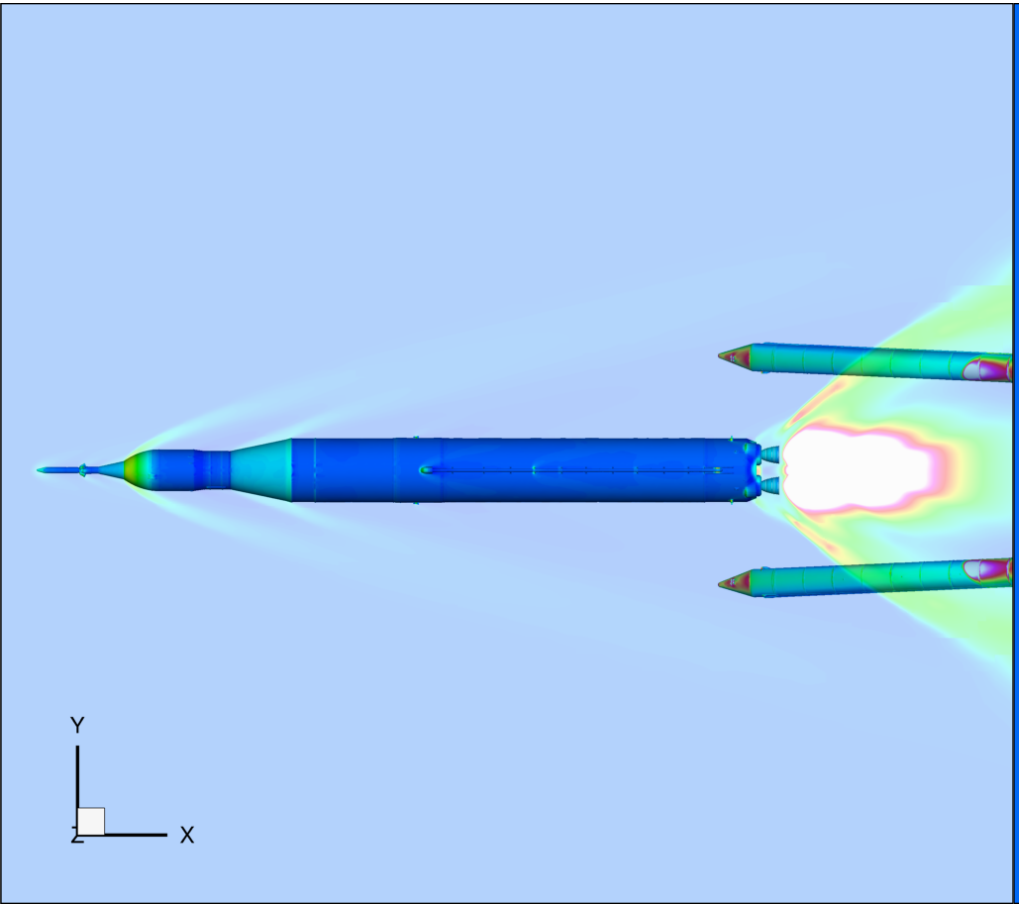
Translucent z=0 slice



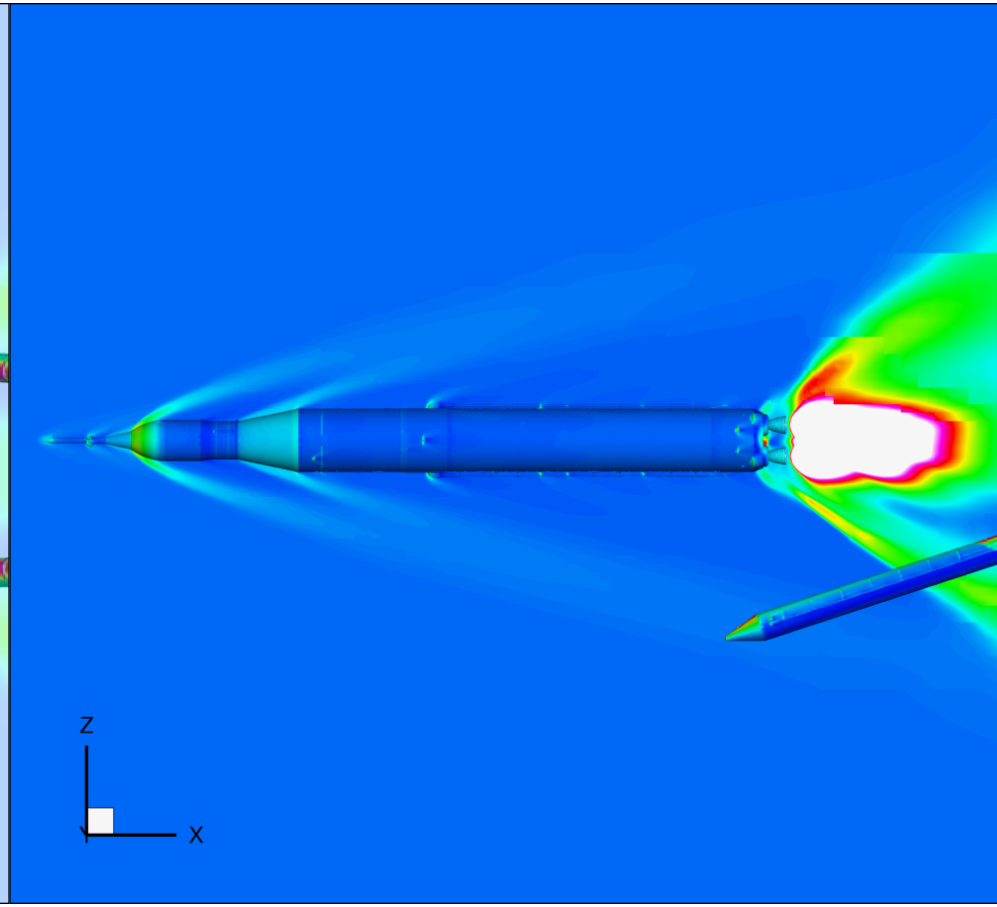
y=0 slice

Nominal Trajectory Solutions

dx=150 ft (BSMs off)



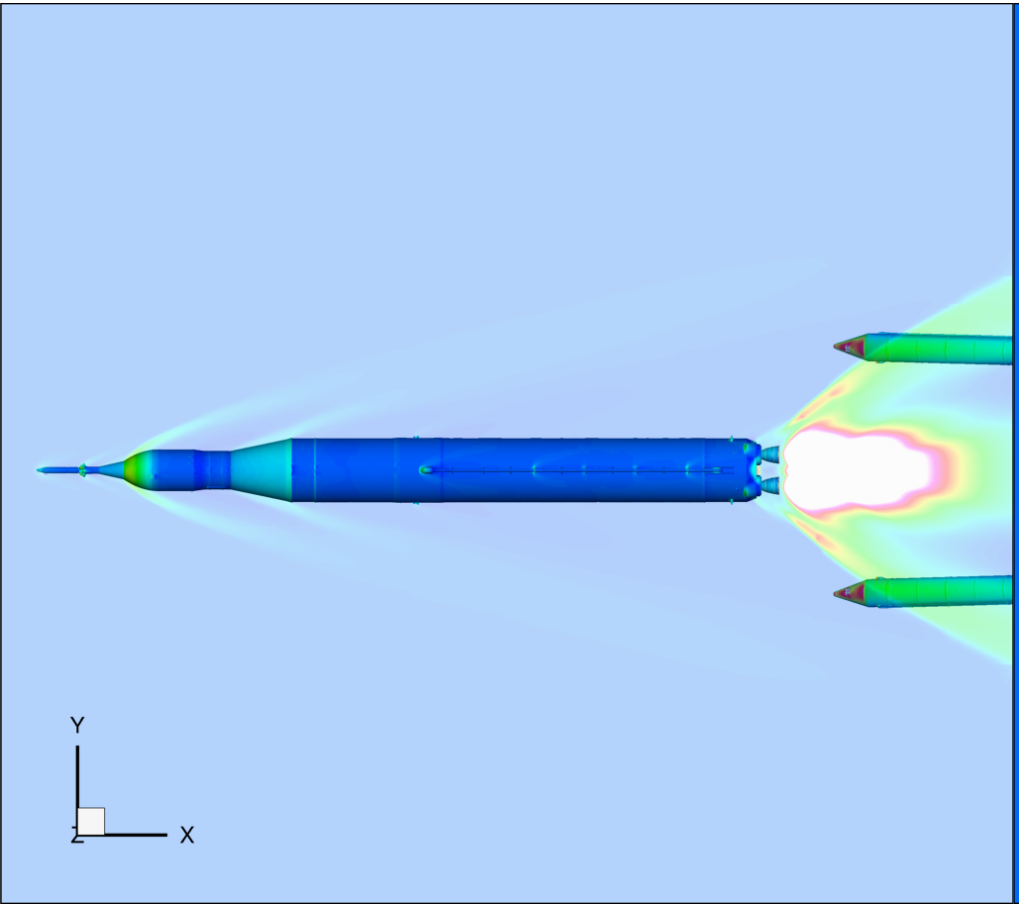
Translucent z=0 slice



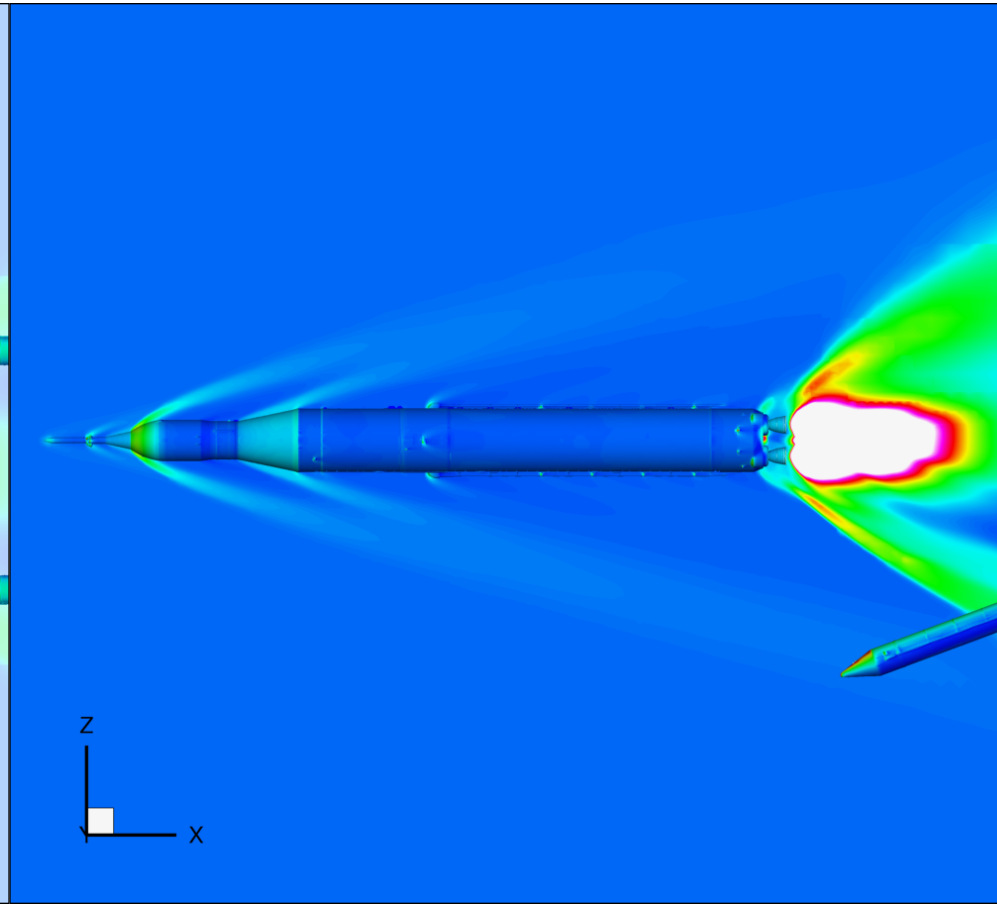
y=0 slice

Nominal Trajectory Solutions

dx=200 ft (BSMs off)



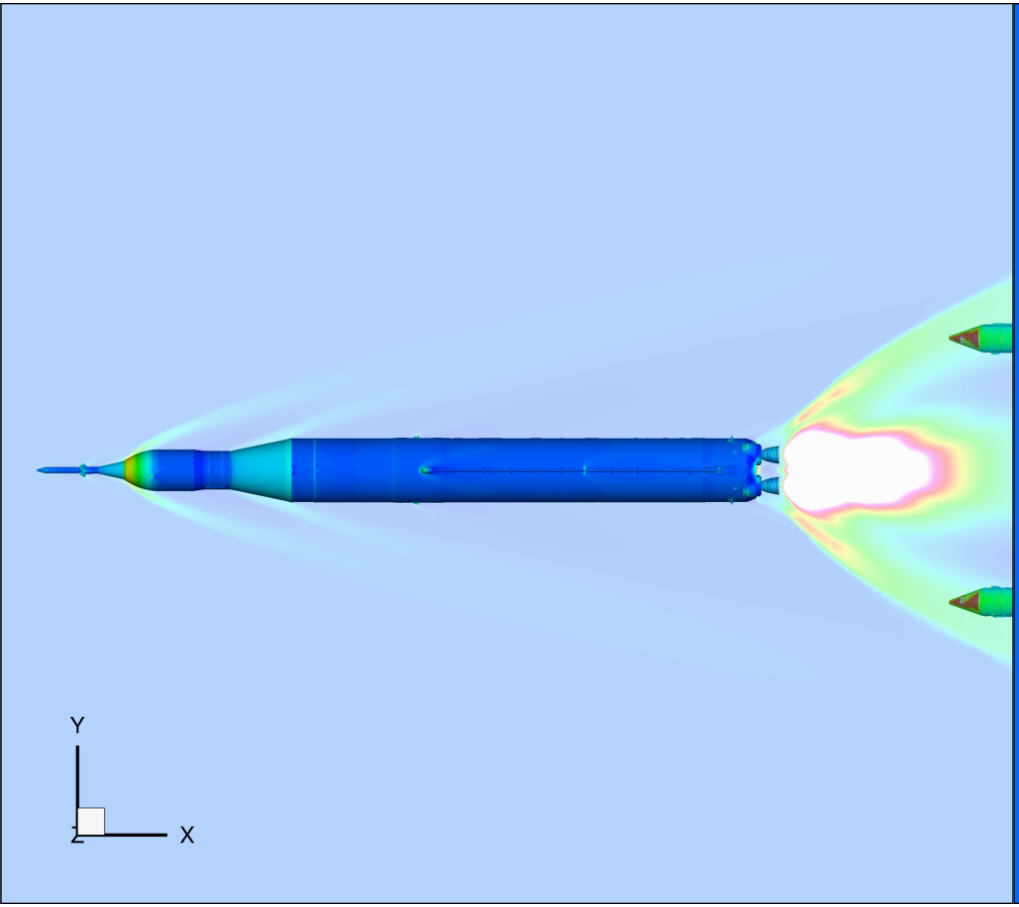
Translucent z=0 slice



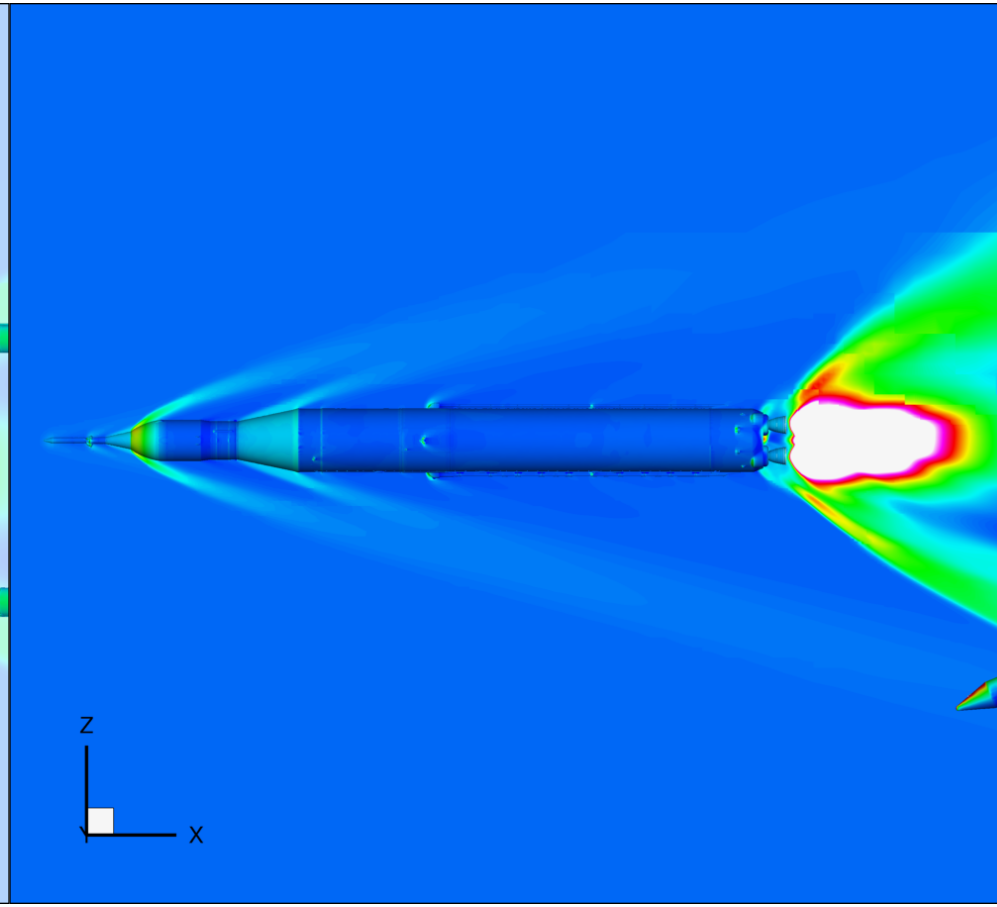
y=0 slice

Nominal Trajectory Solutions

dx=250 ft (BSMs off)

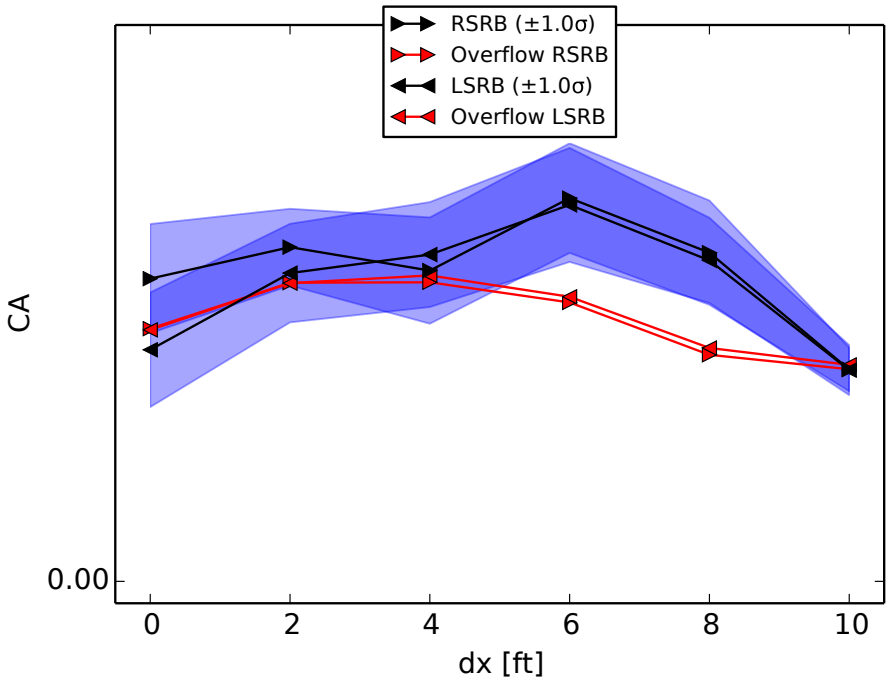


Translucent z=0 slice

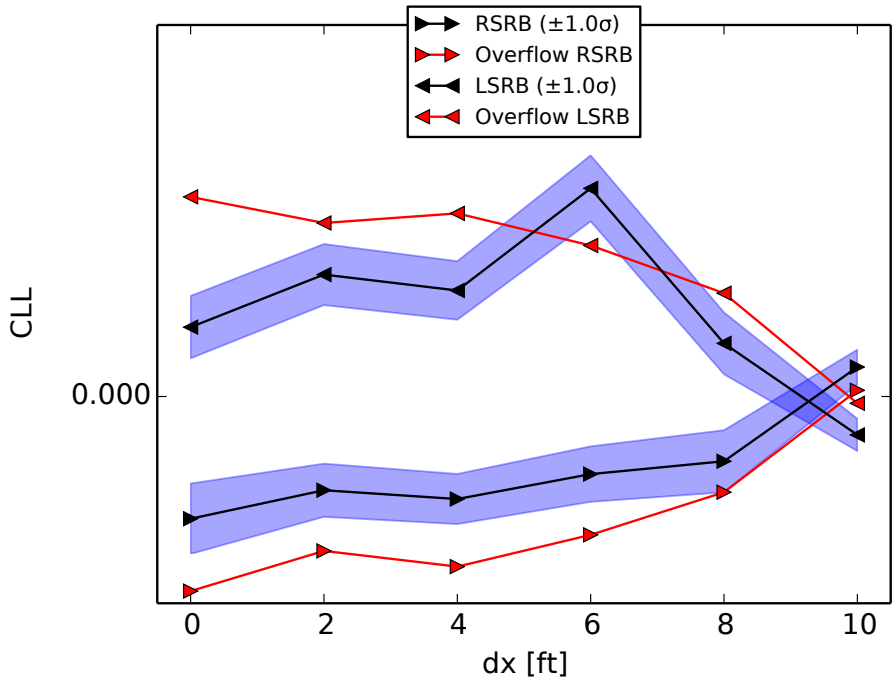


y=0 slice

Cart3D-to-OVERFLOW Comparison: SRBs, BSM-On



SRBs/*CA*



SRBs/*CLL*

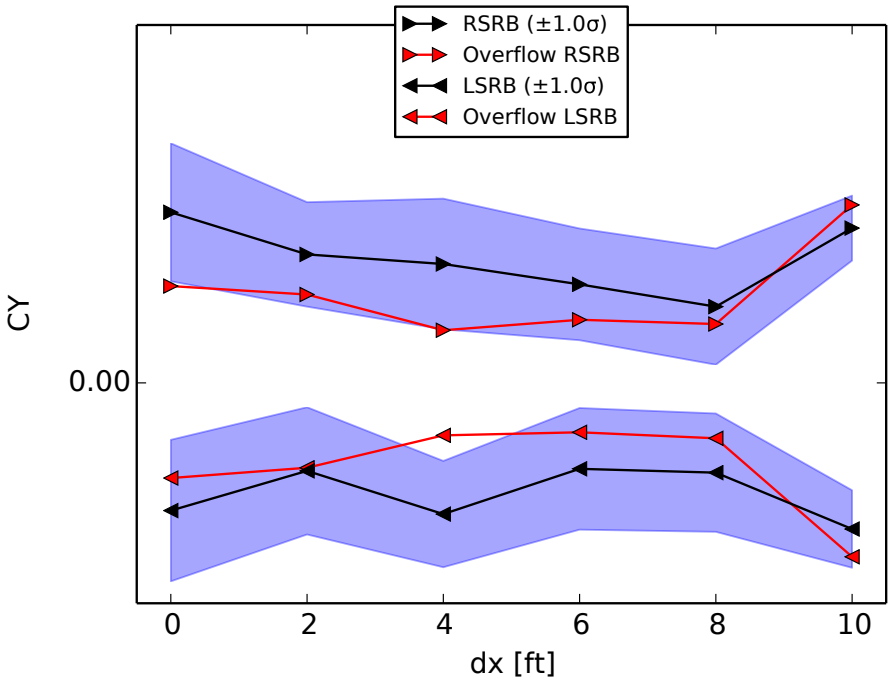
Black: steady-state Cart3D solution (Database)

Red: OVERFLOW solution

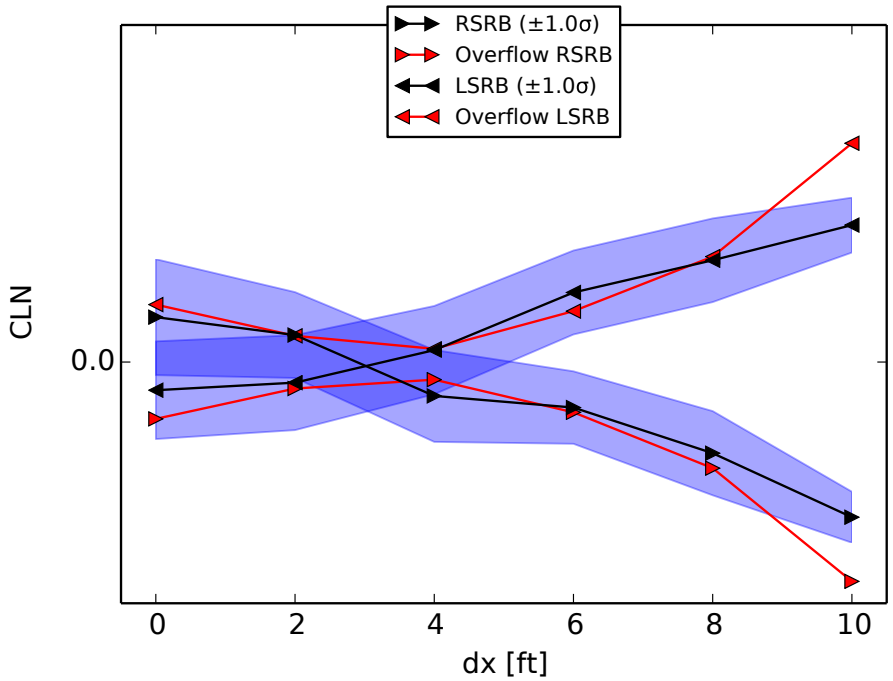
Blue band: Database one-sigma band based on iterative sampling error

Coefficient values are sensitive and not shown

Cart3D-to-OVERFLOW Comparison: SRBs, BSM-On



SRBs/*CY*



SRBs/*CLN*

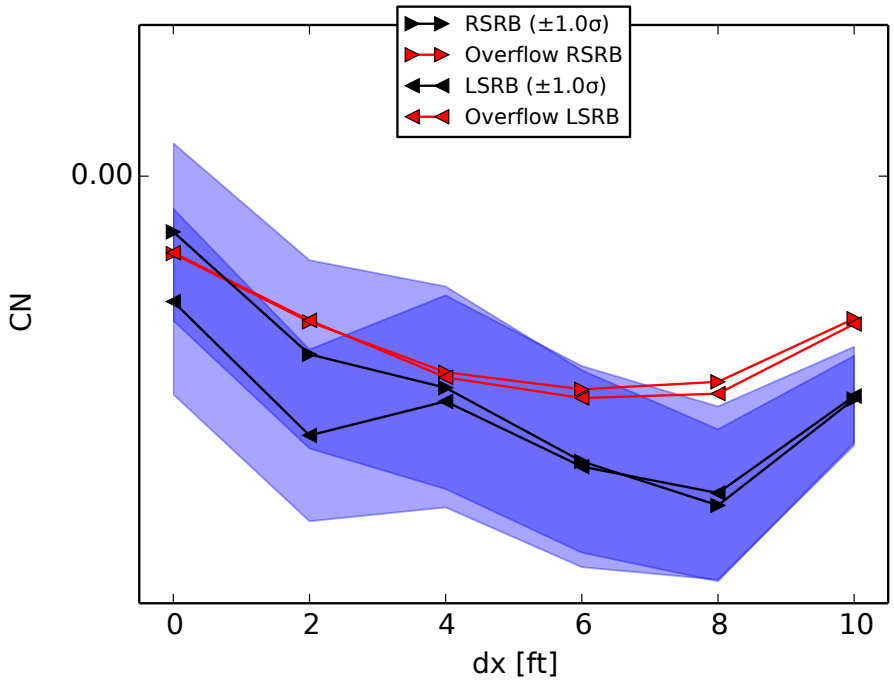
Black: steady-state Cart3D solution (Database)

Red: OVERFLOW solution

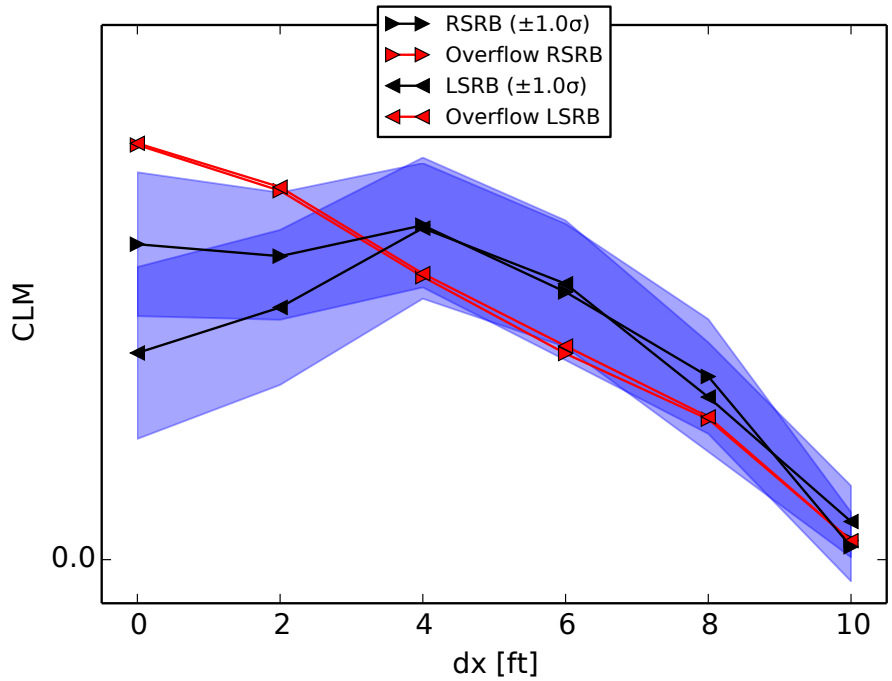
Blue band: Database one-sigma band based on iterative sampling error

Coefficient values are sensitive and not shown

Cart3D-to-OVERFLOW Comparison: SRBs, BSM-On



SRBs/*CN*



SRBs/*CLM*

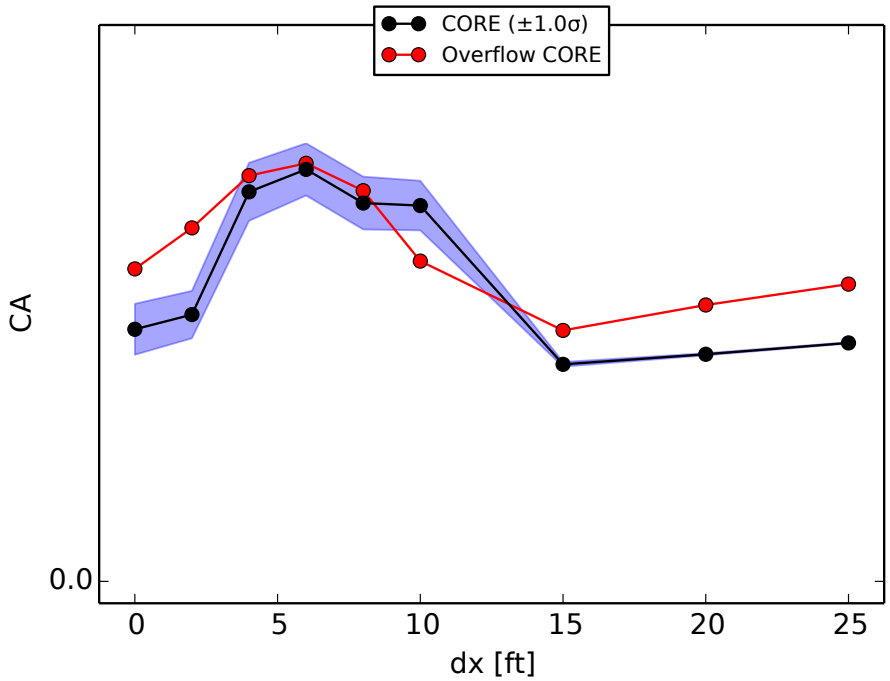
Black: steady-state Cart3D solution (Database)

Red: OVERFLOW solution

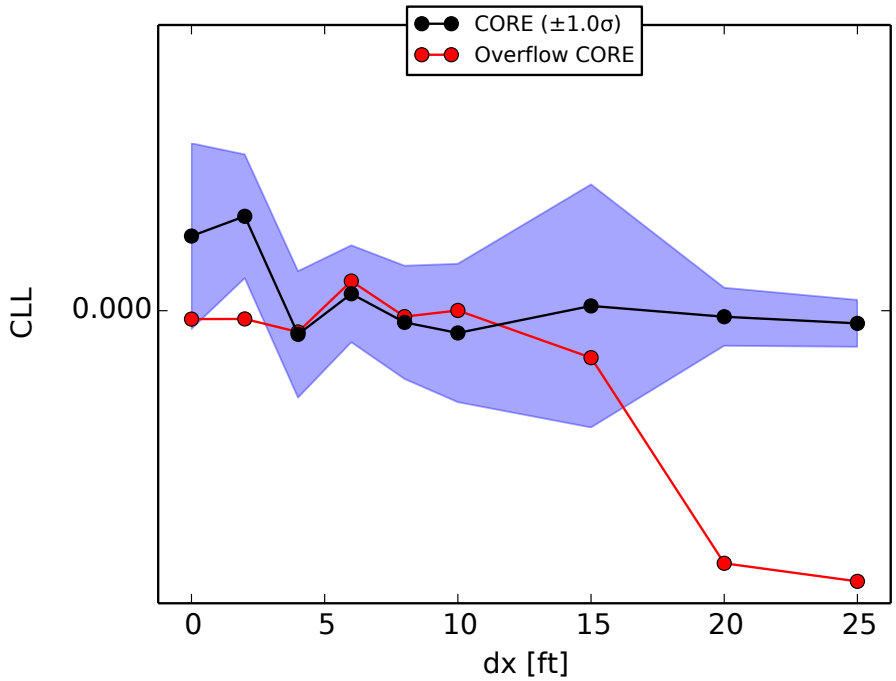
Blue band: Database one-sigma band based on iterative sampling error

Coefficient values are sensitive and not shown

Cart3D-to-OVERFLOW Comparison: CORE, BSM-On



SRBs/*CA*



SRBs/*CLL*

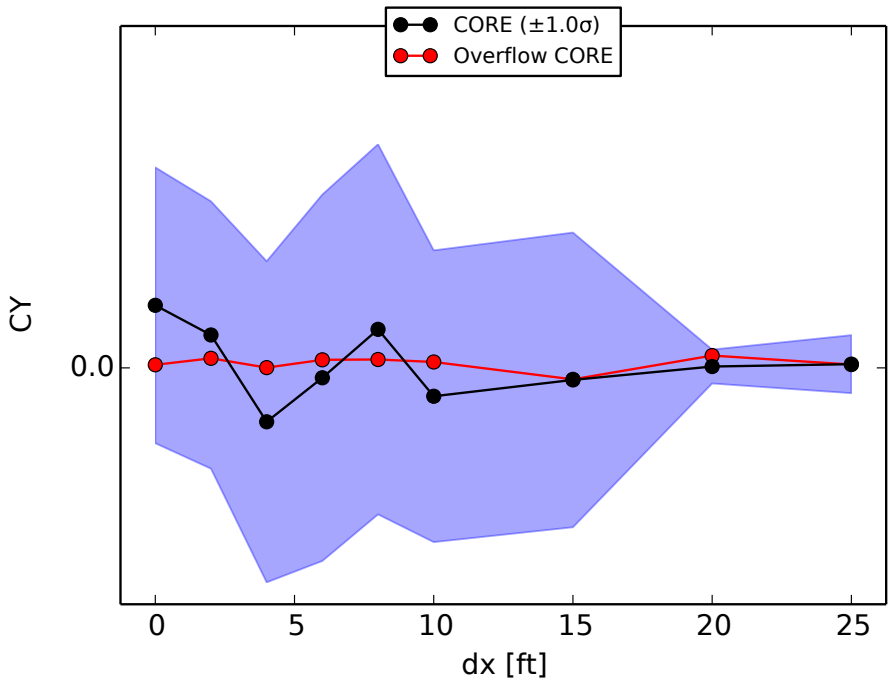
Black: steady-state Cart3D solution (Database)

Red: OVERFLOW solution

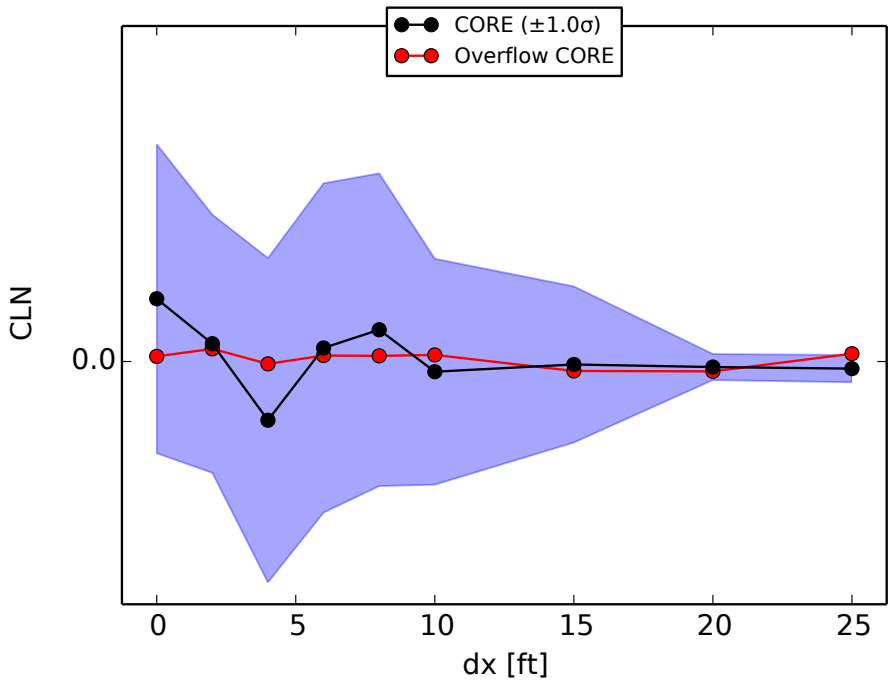
Blue band: Database one-sigma band based on iterative sampling error

Coefficient values are sensitive and not shown

Cart3D-to-OVERFLOW Comparison: CORE, BSM-On



SRBs/*CY*



SRBs/*CLN*

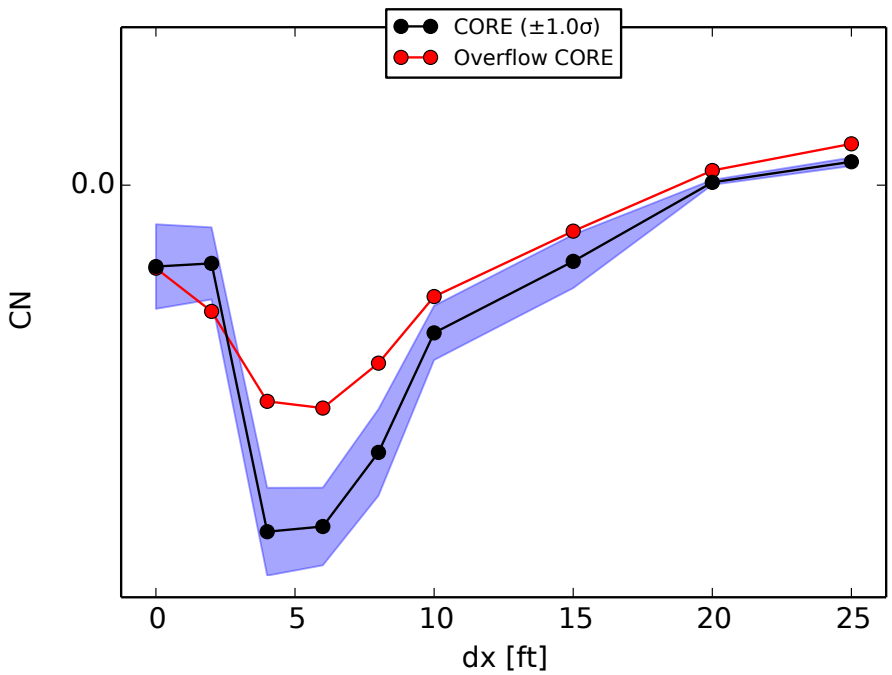
Black: steady-state Cart3D solution (Database)

Red: OVERFLOW solution

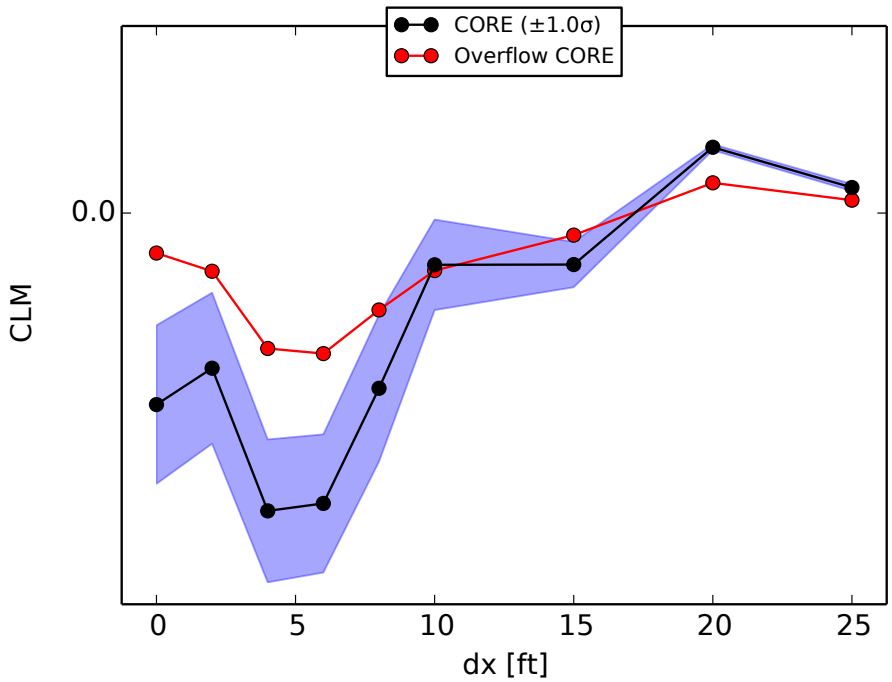
Blue band: Database one-sigma band based on iterative sampling error

Coefficient values are sensitive and not shown

Cart3D-to-OVERFLOW Comparison: CORE, BSM-On



SRBs/*CN*



SRBs/*CLM*

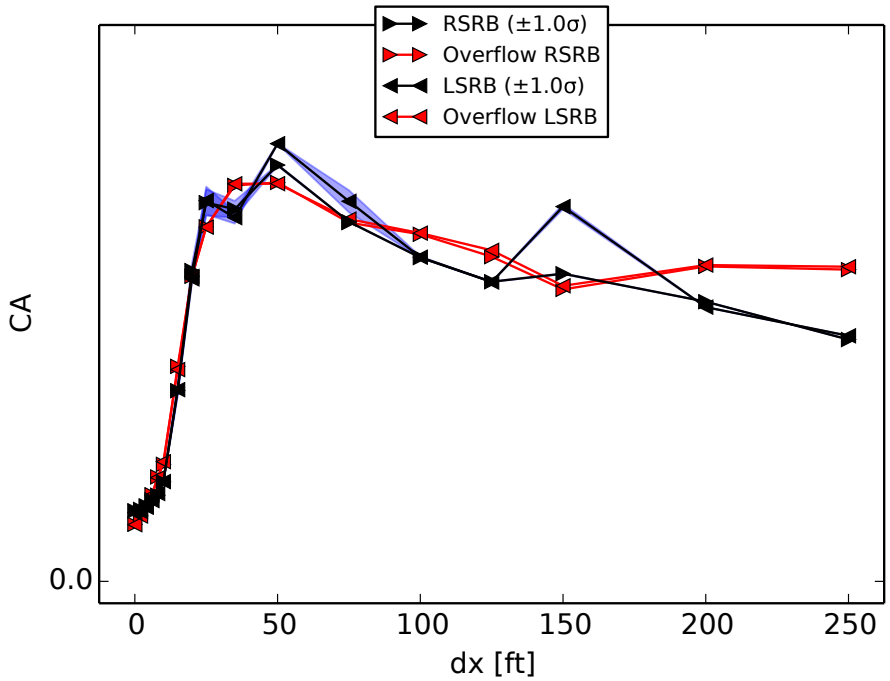
Black: steady-state Cart3D solution (Database)

Red: OVERFLOW solution

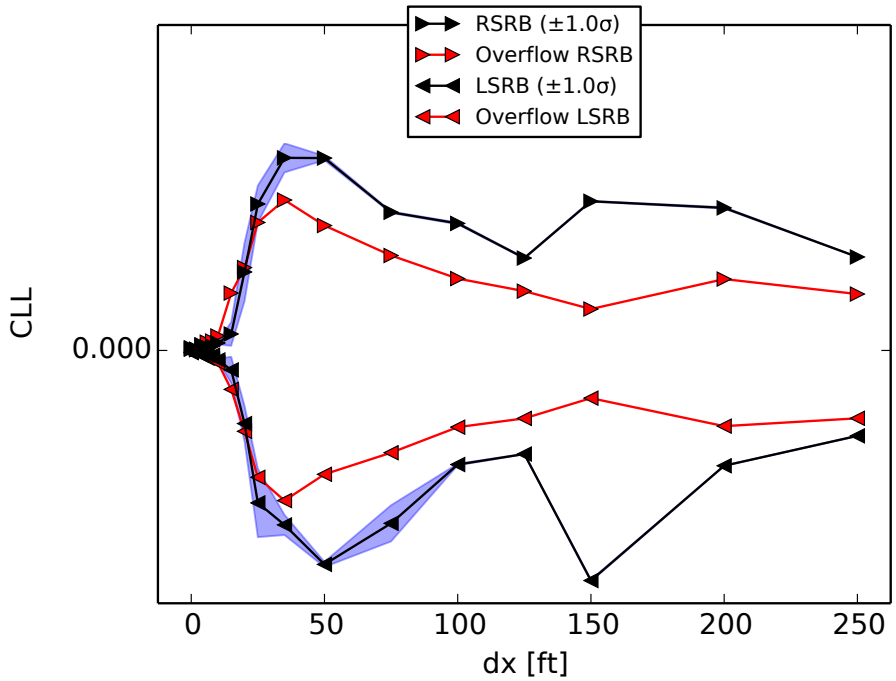
Blue band: Database one-sigma band based on iterative sampling error

Coefficient values are sensitive and not shown

Cart3D-to-OVERFLOW Comparison: SRBs, BSM-Off



SRBs/*CA*



SRBs/*CLL*

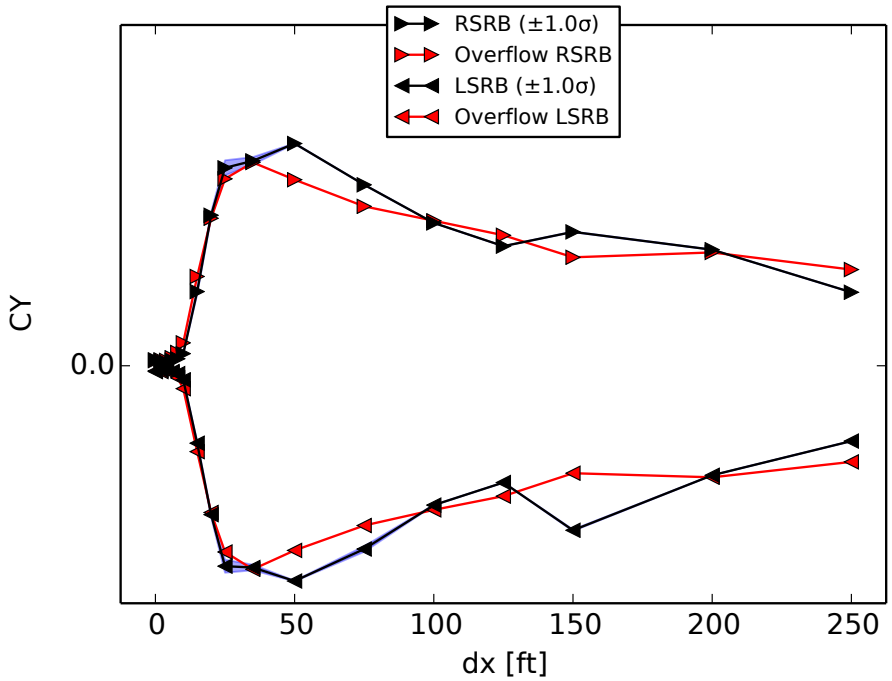
Black: steady-state Cart3D solution (Database)

Red: OVERFLOW solution

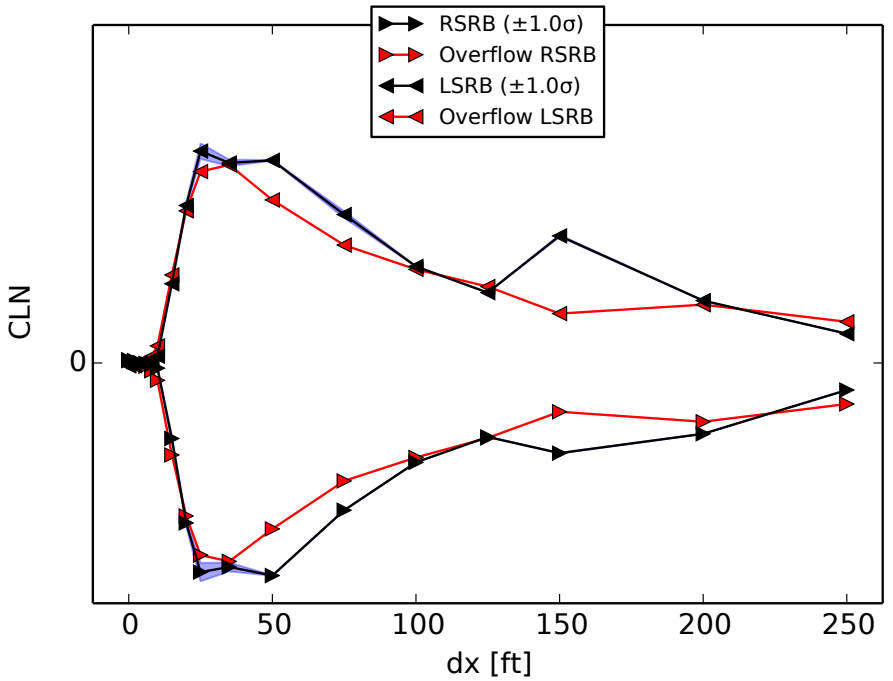
Blue band: Database one-sigma band based on iterative sampling error

Coefficient values are sensitive and not shown

Cart3D-to-OVERFLOW Comparison: SRBs, BSM-Off



SRBs/*CY*



SRBs/*CLN*

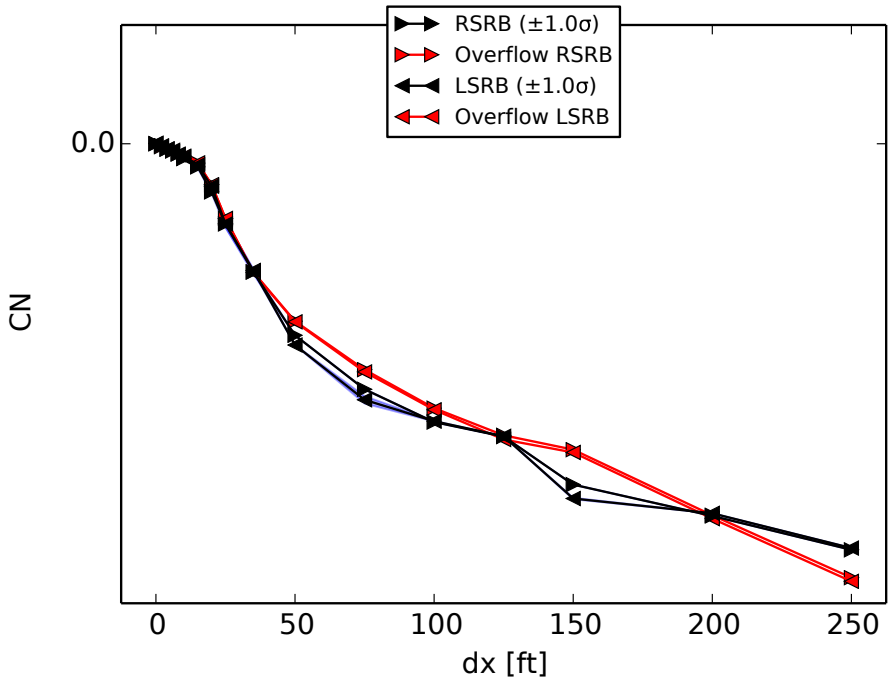
Black: steady-state Cart3D solution (Database)

Red: OVERFLOW solution

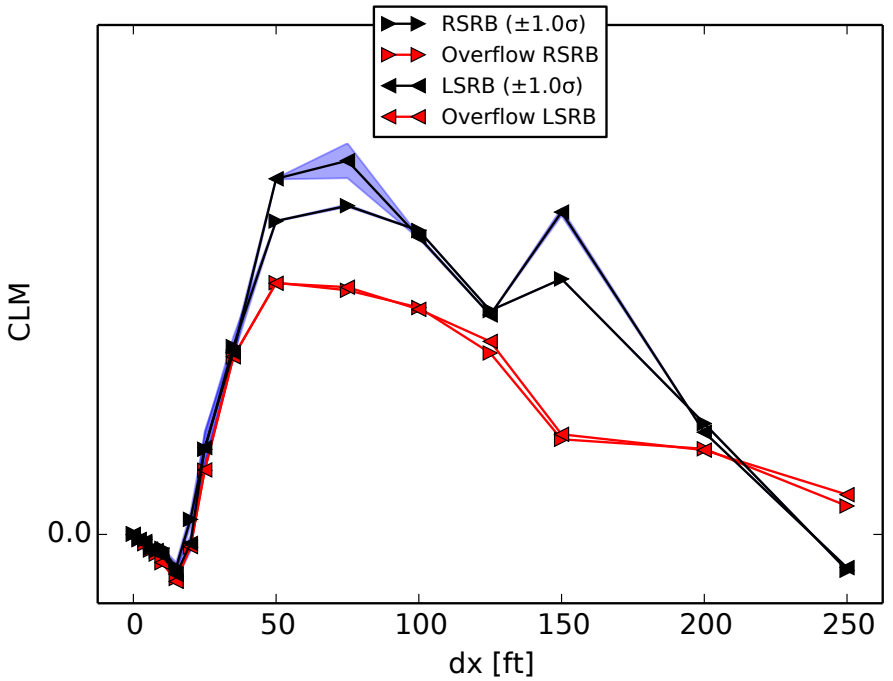
Blue band: Database one-sigma band based on iterative sampling error

Coefficient values are sensitive and not shown

Cart3D-to-OVERFLOW Comparison: SRBs, BSM-Off



SRBs/*CN*



SRBs/*CLM*

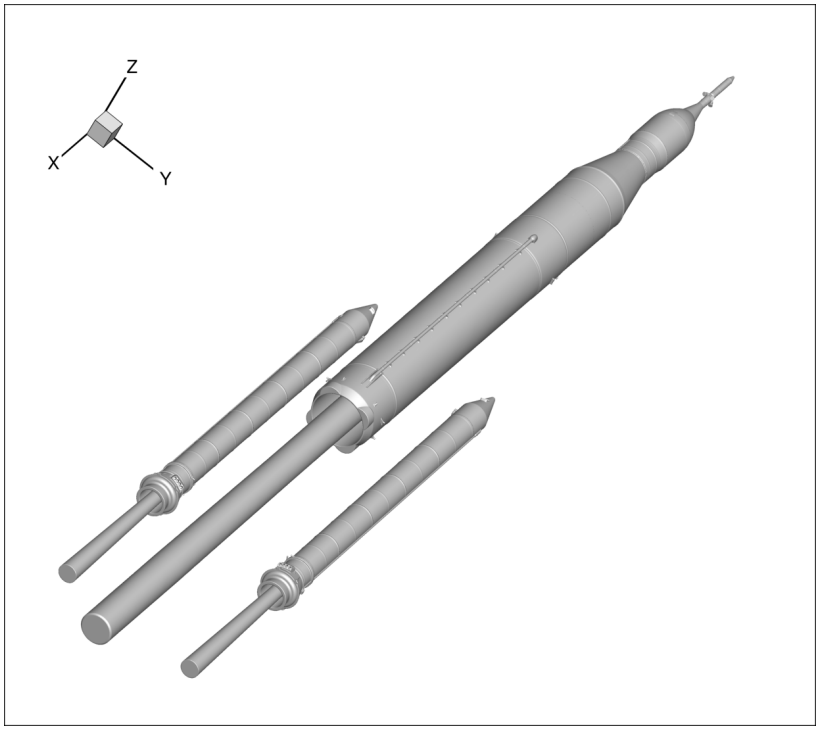
Black: steady-state Cart3D solution (Database)

Red: OVERFLOW solution

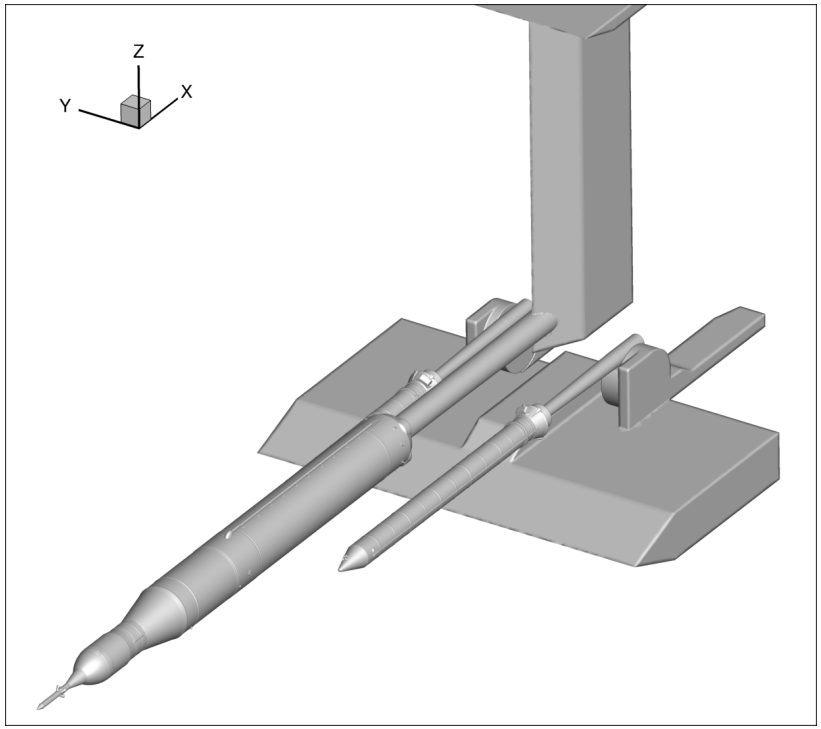
Blue band: Database one-sigma band based on iterative sampling error

Coefficient values are sensitive and not shown

Wind Tunnel Test at NASA LaRC UPWT

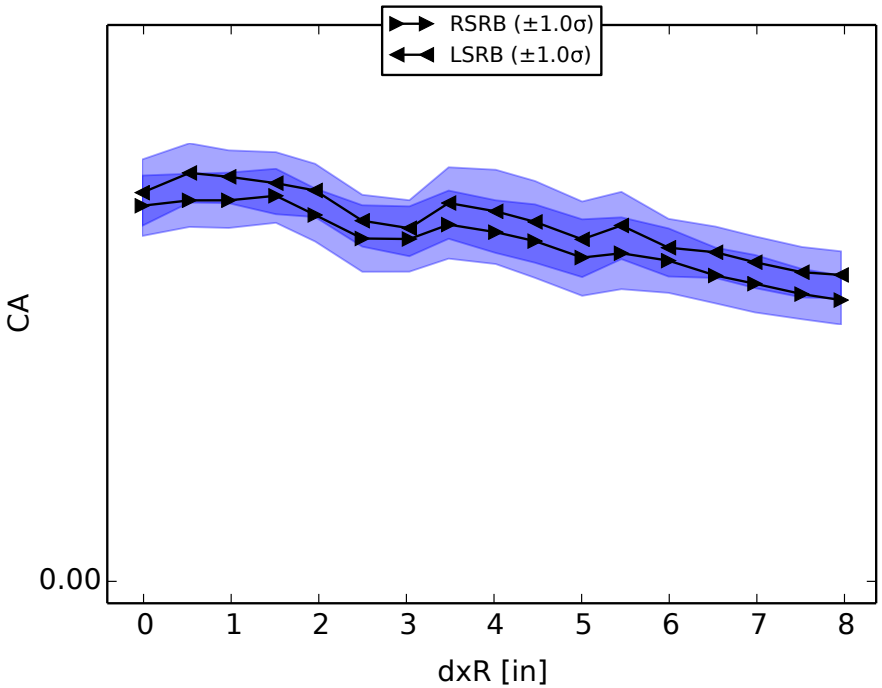


Surface without support hardware

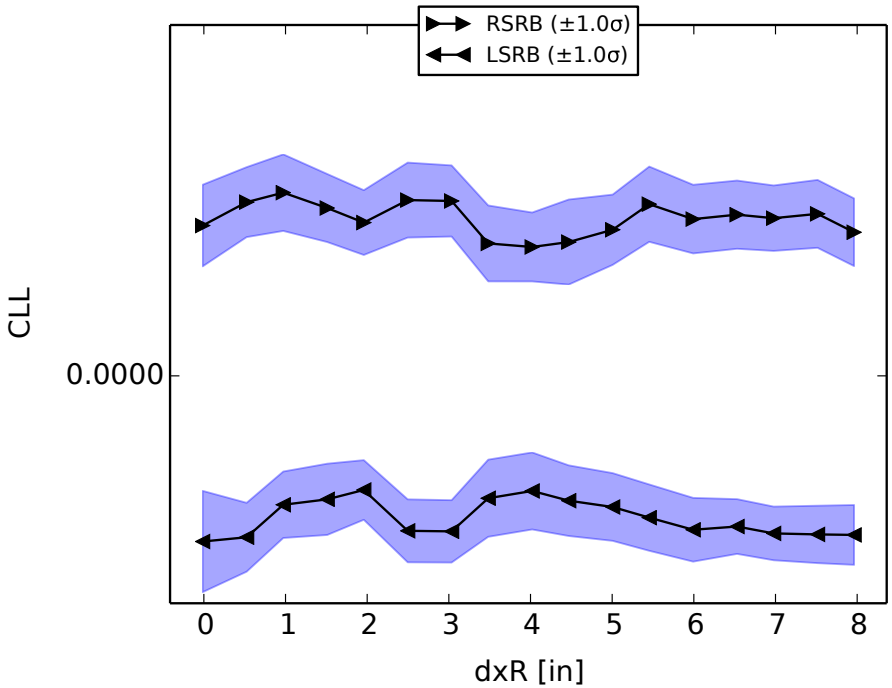


Surface including support hardware

Cart3D-to-Wind Tunnel Comparison: SRBs, BSM-On



SRBs/*CA*



SRBs/*CLL*

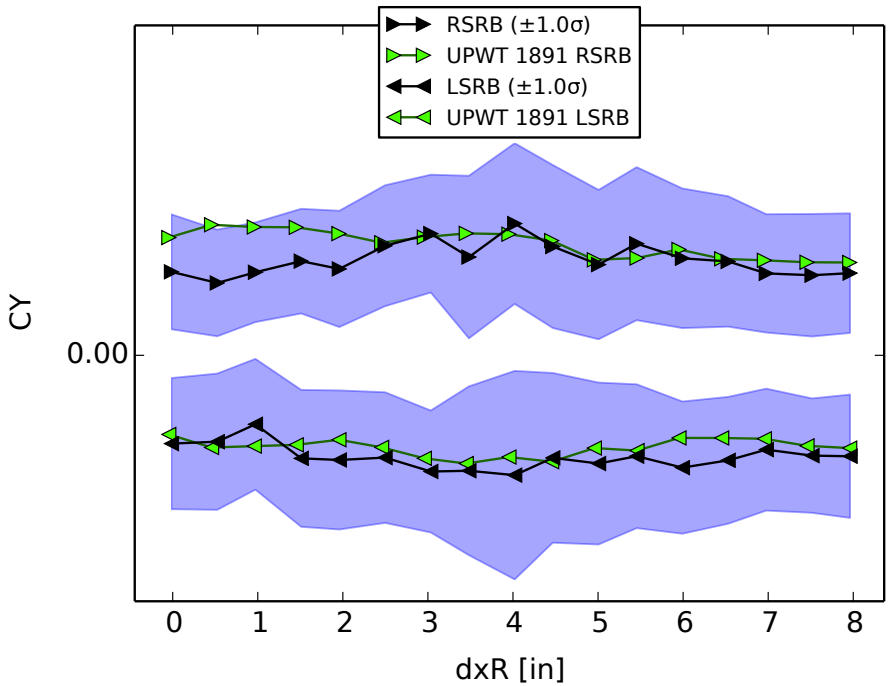
Black: statedy-state Cart3D solution (Database)

Green: UPWT 1891 experimental measurement

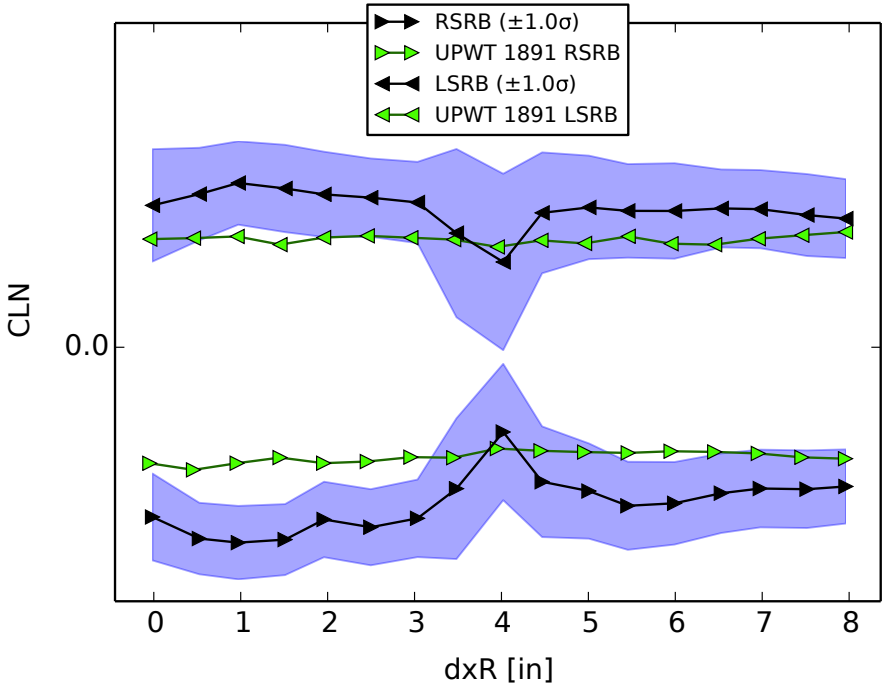
Blue band: Database one-sigma band based on iterative sampling error

Coefficient values are sensitive and not shown

Cart3D-to-Wind Tunnel Comparison: SRBs, BSM-On



SRBs/*CY*



SRBs/*CLN*

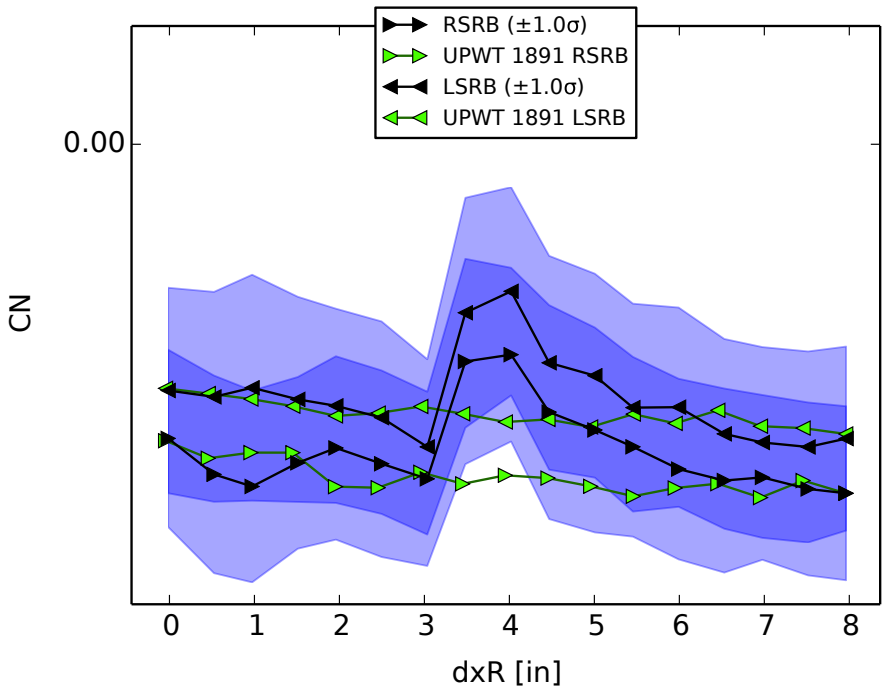
Black: statedy-state Cart3D solution (Database)

Green: UPWT 1891 experimental measurement

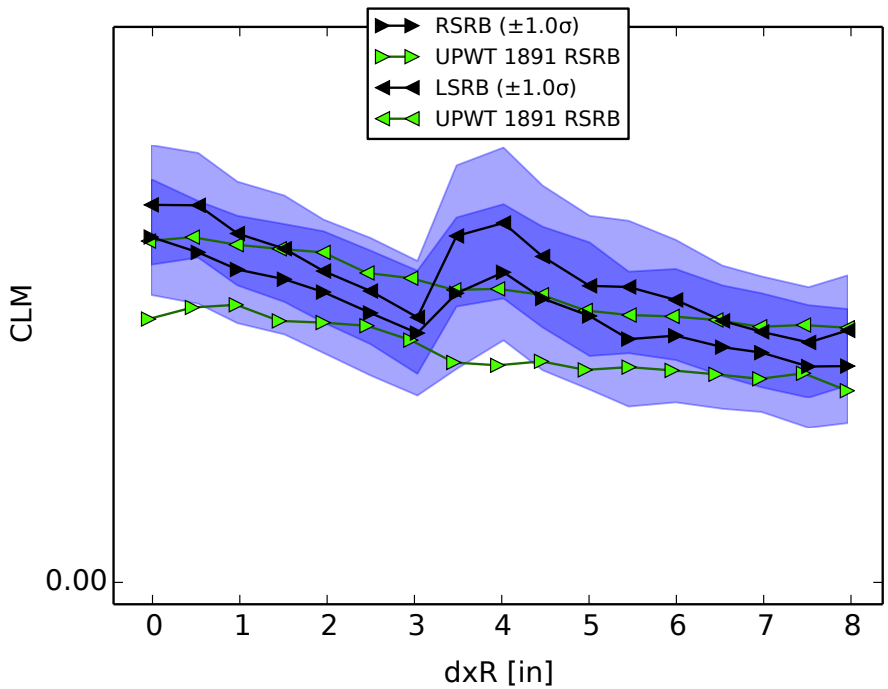
Blue band: Database one-sigma band based on iterative sampling error

Coefficient values are sensitive and not shown

Cart3D-to-Wind Tunnel Comparison: SRBs, BSM-On



SRBs/*CN*



SRBs/*CLM*

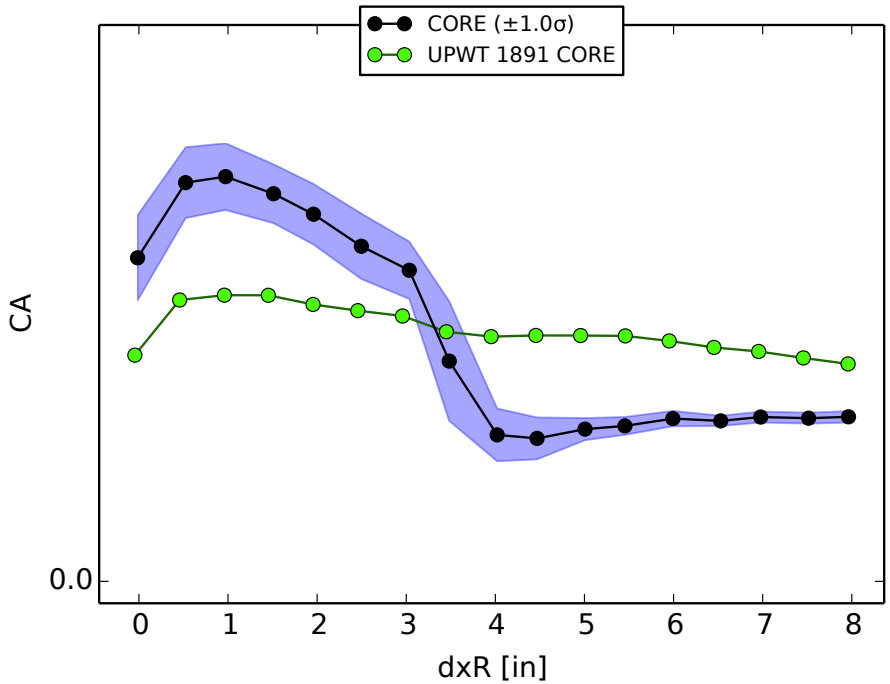
Black: statedy-state Cart3D solution (Database)

Green: UPWT 1891 experimental measurement

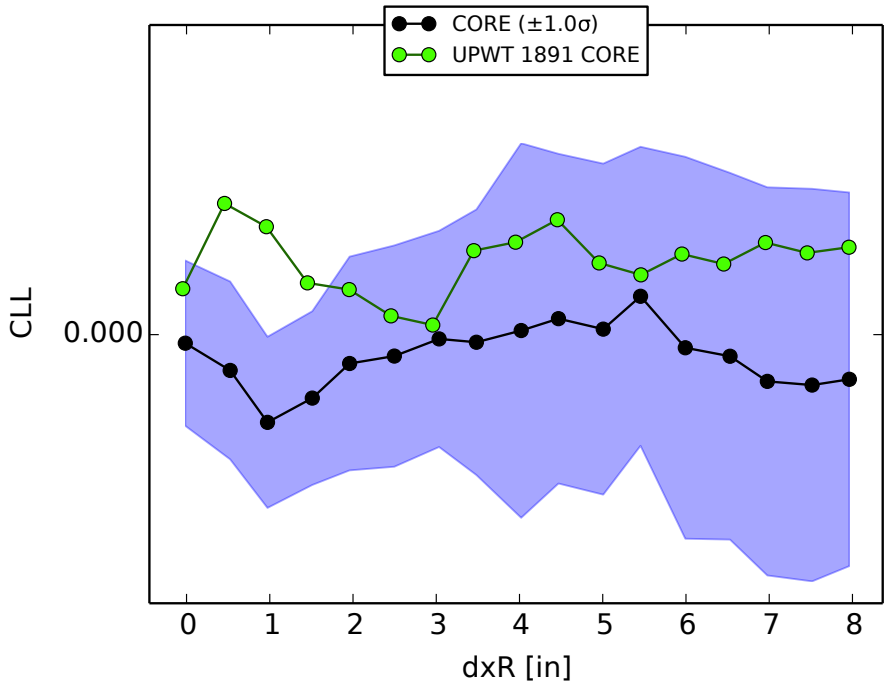
Blue band: Database one-sigma band based on iterative sampling error

Coefficient values are sensitive and not shown

Cart3D-to-Wind Tunnel Comparison: CORE, BSM-On



CORE/*CA*



CORE/*CLL*

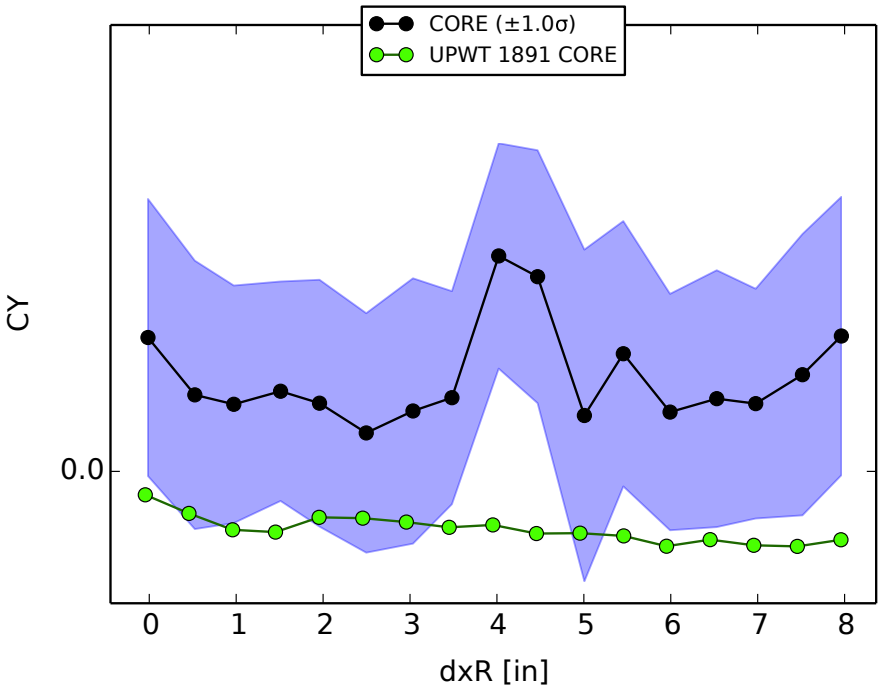
Black: statedy-state Cart3D solution (Database)

Green: UPWT 1891 experimental measurement

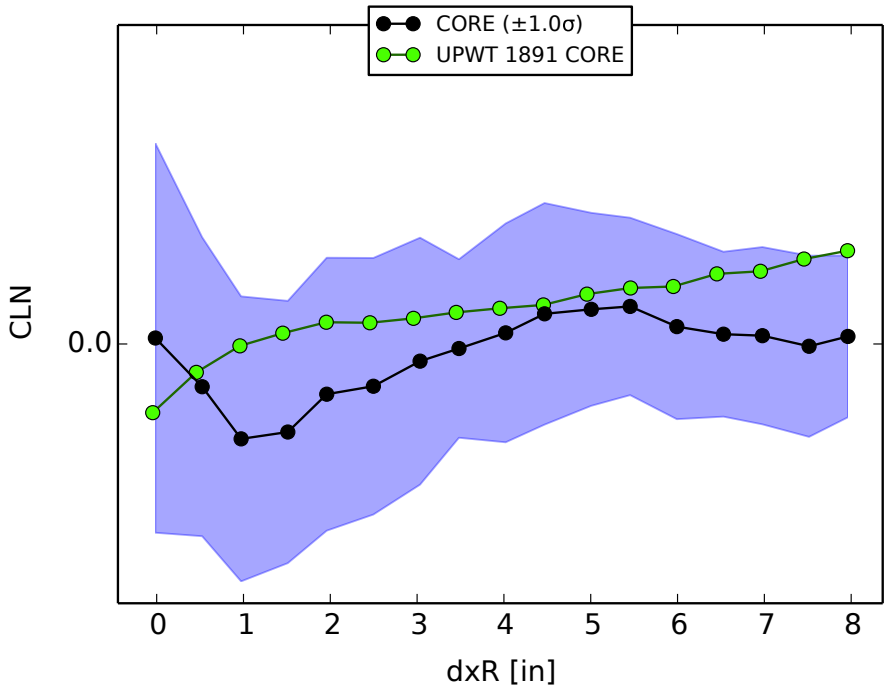
Blue band: Database one-sigma band based on iterative sampling error

Coefficient values are sensitive and not shown

Cart3D-to-Wind Tunnel Comparison: CORE, BSM-On



CORE/*CY*



CORE/*CLN*

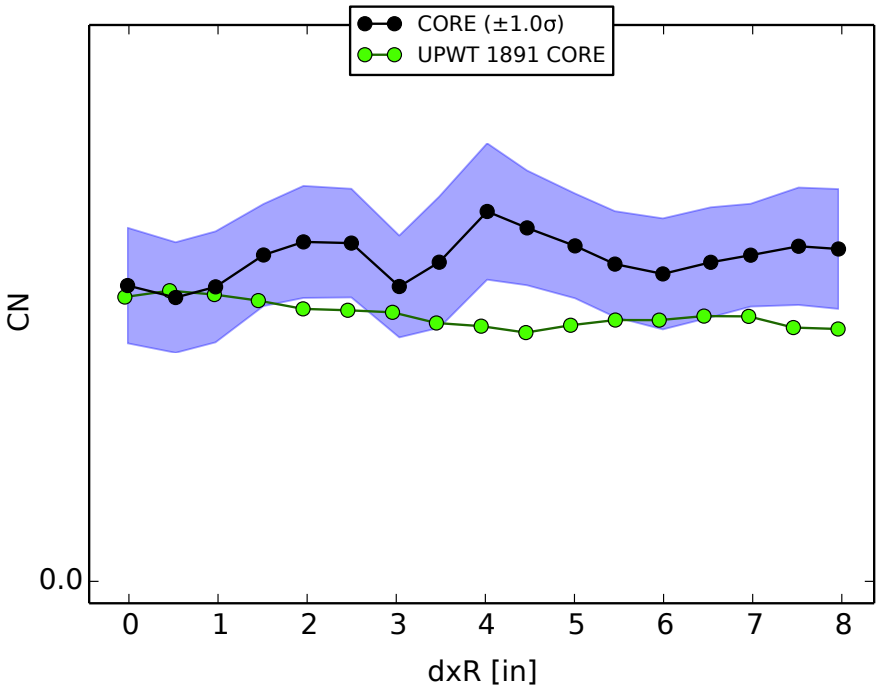
Black: statedy-state Cart3D solution (Database)

Green: UPWT 1891 experimental measurement

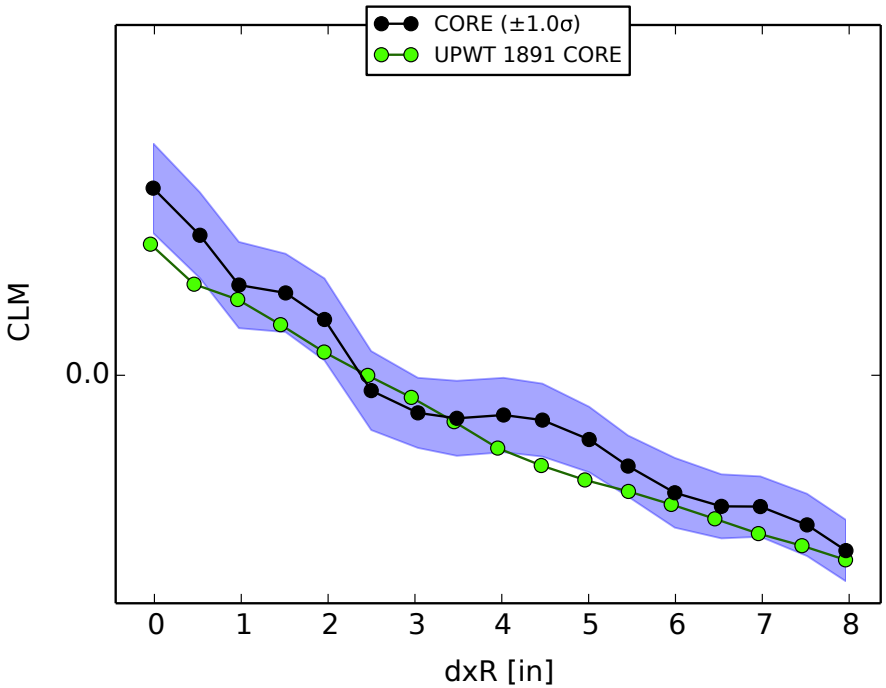
Blue band: Database one-sigma band based on iterative sampling error

Coefficient values are sensitive and not shown

Cart3D-to-Wind Tunnel Comparison: CORE, BSM-On



CORE/*CN*



CORE/*CLM*

Black: statedy-state Cart3D solution (Database)

Green: UPWT 1891 experimental measurement

Blue band: Database one-sigma band based on iterative sampling error

Coefficient values are sensitive and not shown

Conclusions

- Robust adaptive-meshing analysis for 20,000+ Cart3D simulations and 8-dimensional database
- OVERFLOW mesh adaption with complex flow and geometry
- Tested roughly 180 sets of Cart3D inputs before computing this database
- High-fidelity and experimental results used for uncertainty estimates and to evaluate Cart3D solution quality

- Uncertainties reduced (in critical first 10 ft) compared to preliminary aerodynamic databases
- Largest remaining source of uncertainty in current database is interpolation error



Acknowledgments

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- Dane Childers (NASA MSFC) GN&C customer of this data
- NASA LaRC SLS aerodynamics team, David Chan, Jeremy Pinier, Floyd Wilcox
- Previous NASA ARC SLS aerodynamics team members
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