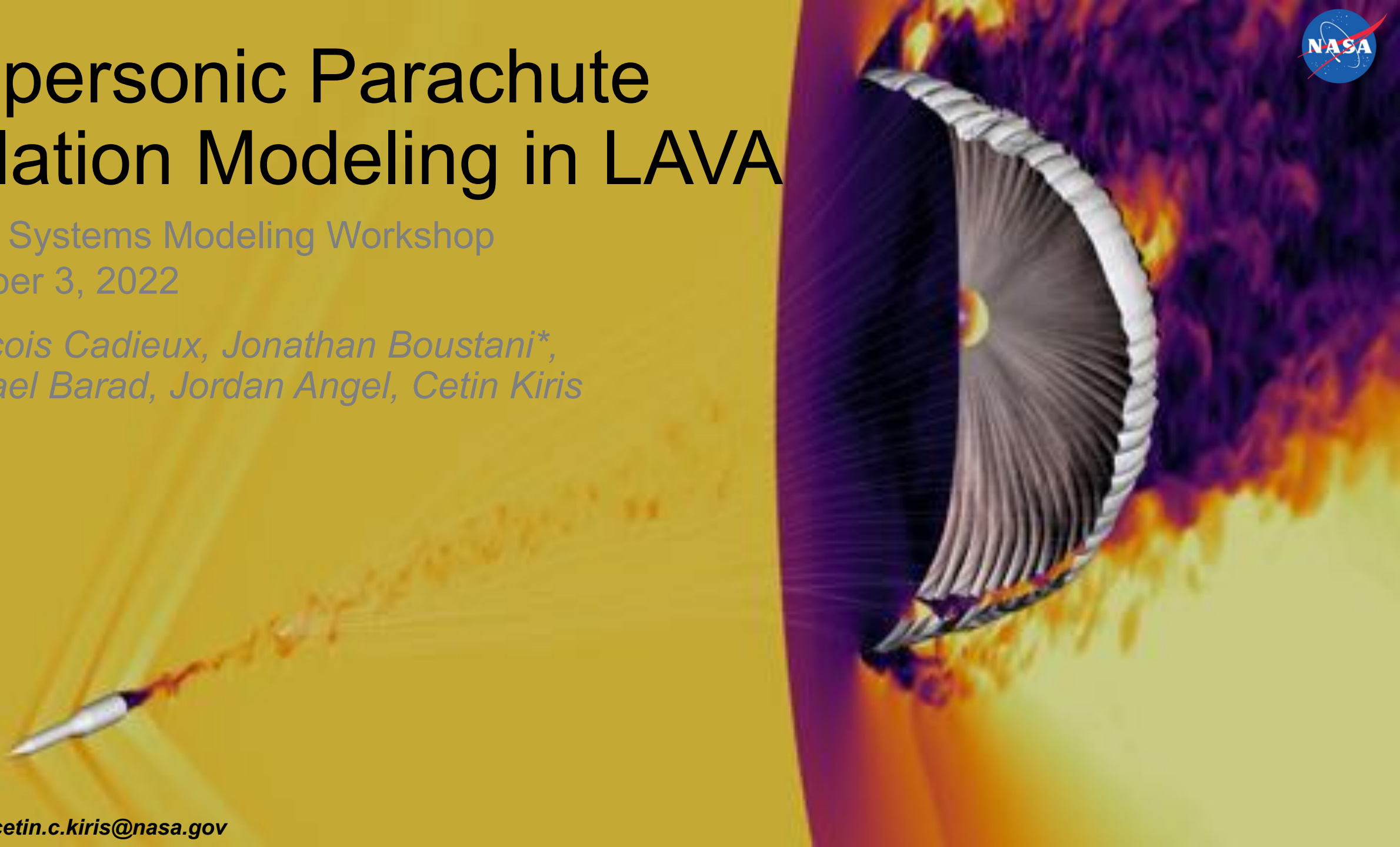




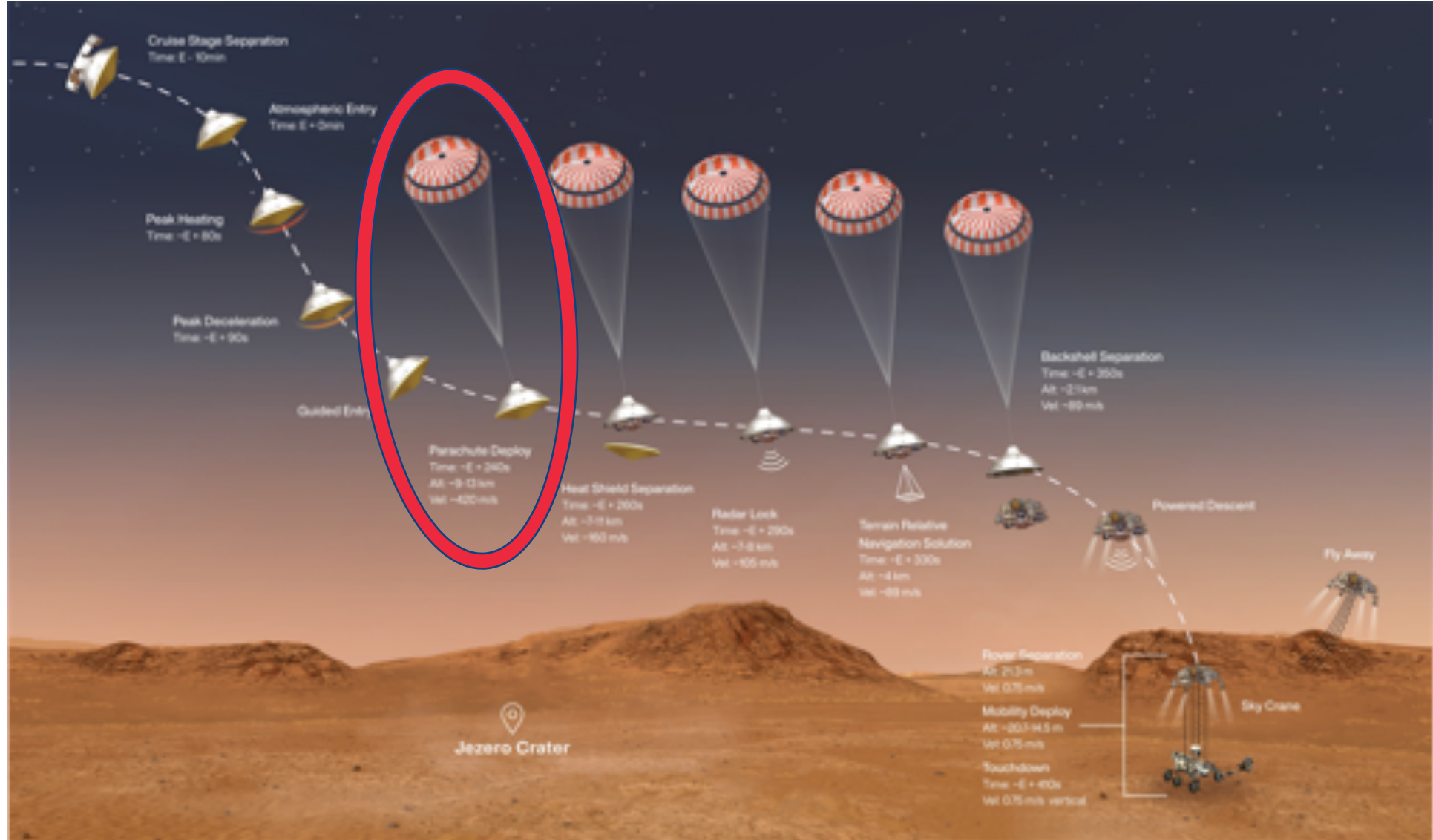
Supersonic Parachute Inflation Modeling in LAVA

Entry Systems Modeling Workshop
October 3, 2022

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Context: Perseverance Rover's EDL Profile



Problem Description

LDSD Parachute Failure

- Low Density Supersonic Decelerator project demonstrated that NASA & JPL could not predict the failure of a new parachute system design [1], or establish with confidence the cause of failure after the fact [2]



(NASA/JPL)

ASPIRE: 3 Successful Tests

- The Advanced Supersonic Parachute Inflation Research Experiments (ASPIRE) tested traditional parachutes intended for Mars landings (e.g. Perseverance) in supersonic conditions in the upper earth atmosphere

Fluid-Structure Interaction (FSI) Simulations

- FSI simulations could provide insight at much lower cost and eventually provide stress predictions across parachute system

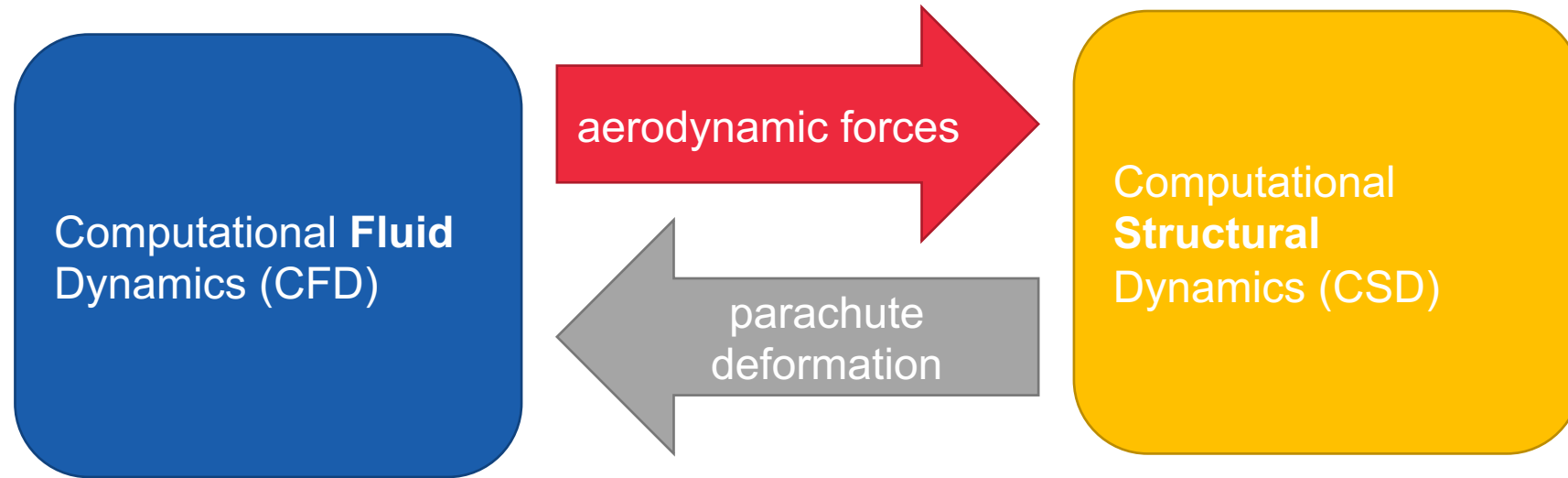
[1] Gallon, J., Witkowski, A., Clark, I. G., Rivellini, T., and Adams, D. S., "Low density supersonic decelerator parachute decelerator system," AIAA Aerodynamic Decelerator Systems (ADS) Conference, 2013, p. 1329

[2] Clark, I. G., Gallon, J. C., and Witkowski, A., "Parachute Decelerator System Performance During the Low Density Supersonic Decelerator Program's First Supersonic Flight Dynamics Test," 23rd AIAA Aerodynamic Decelerator Systems Technology Conference, 2015, p. 2130

Research Objectives



1. Develop in-house FSI capability to simulate supersonic parachute inflation

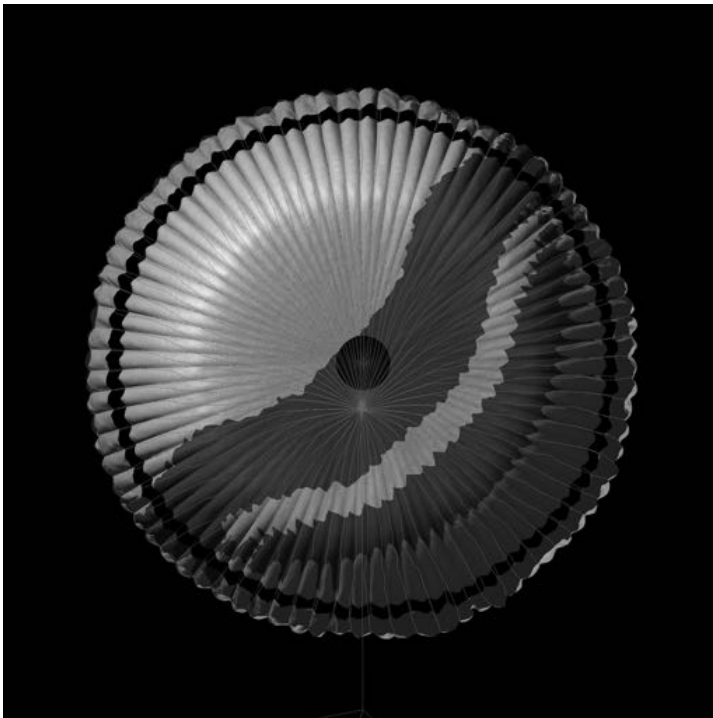


2. Validate FSI predictions with ASPIRE test measurements
3. Leverage FSI capability to help in design of next generation of parachutes using best practices established for ASPIRE

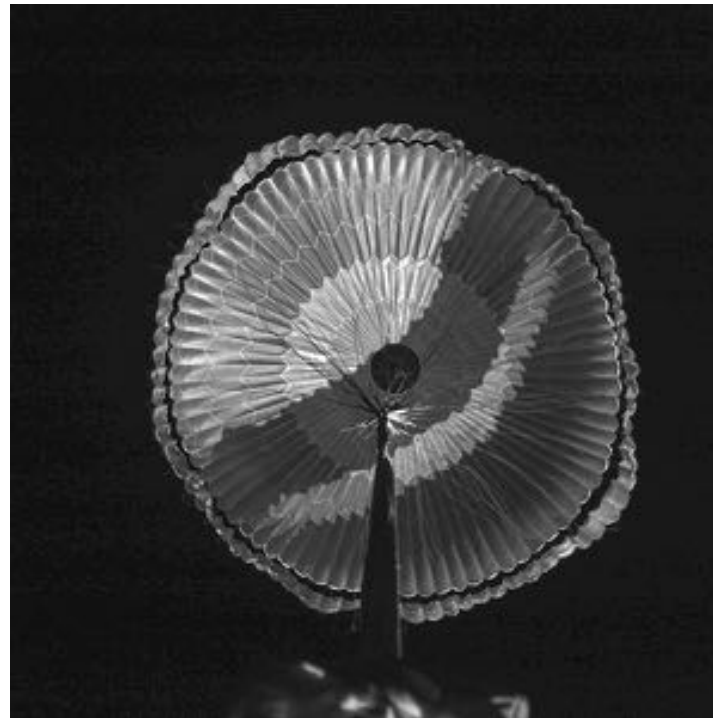
Review of FY21 Accomplishments



- ✓ Optimized LAVA structural dynamics code performance for FSI problems
- ✓ Developed, implemented, and validated a porosity model applied through immersed boundary condition in CFD to simulate PIA-C-7020D Type 1 parachute broadcloth
- ✓ Developed, implemented, optimized and validated a contact mechanics algorithm to handle both self contact, and contact with solid objects
- ✓ Performed simulations of the ASPIRE SR01 flight test to validate the new FSI capability



LAVA SR01 snapshot

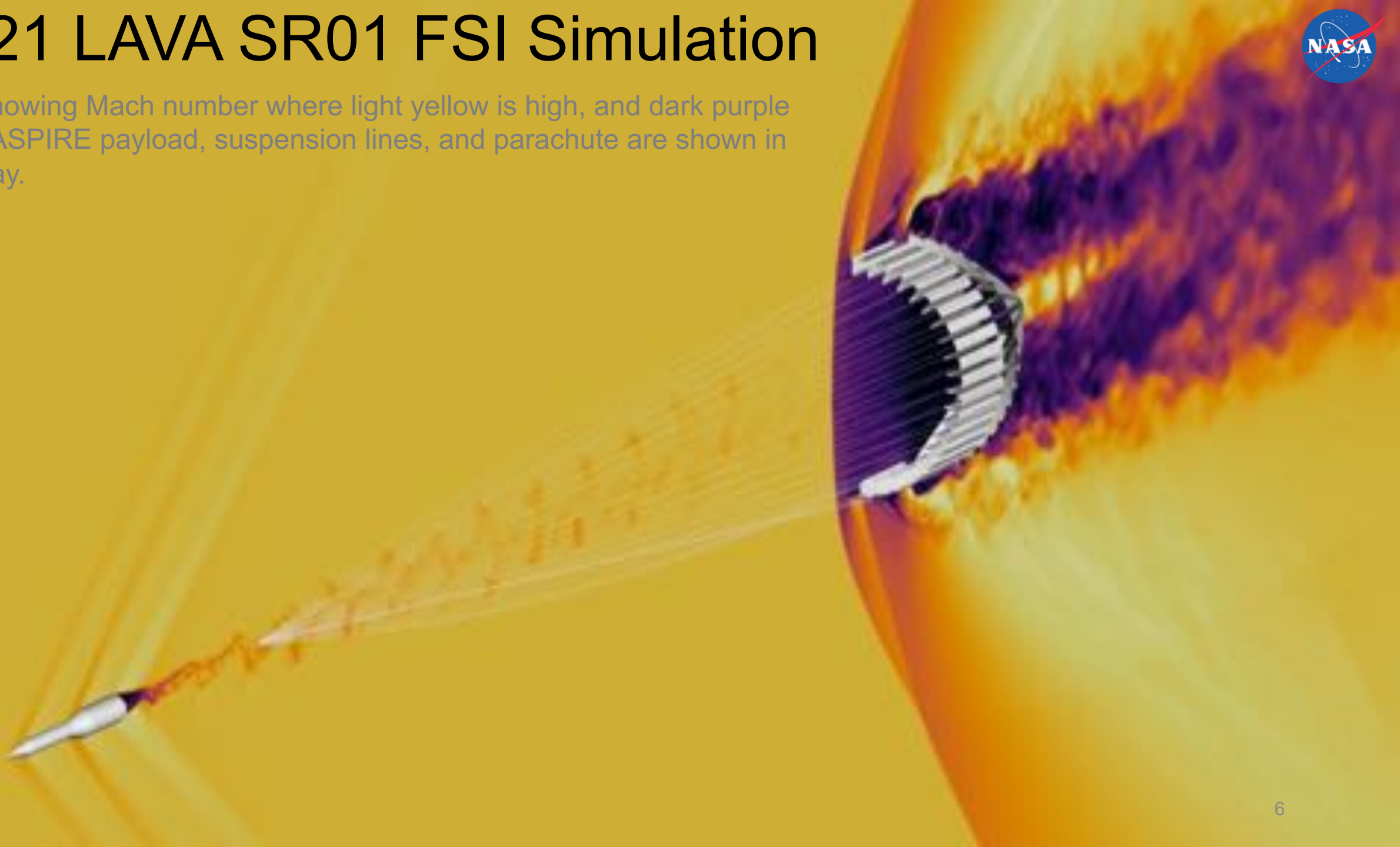


ASPIRE SR01 snapshot (NASA/JPL)

FY21 LAVA SR01 FSI Simulation



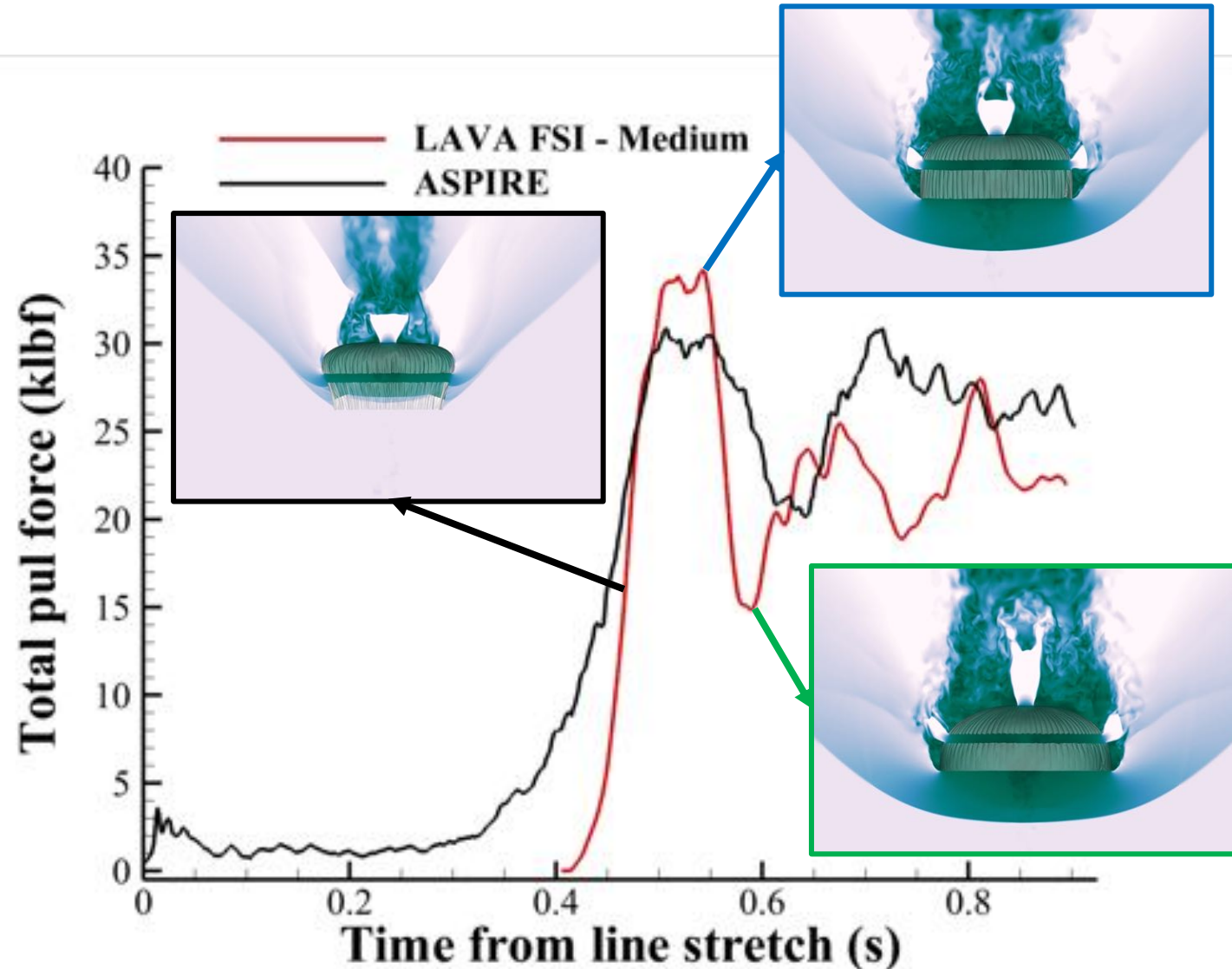
Slice showing Mach number where light yellow is high, and dark purple is low. ASPIRE payload, suspension lines, and parachute are shown in light gray.



FY21 Validation of ASPIRE SR01 FSI



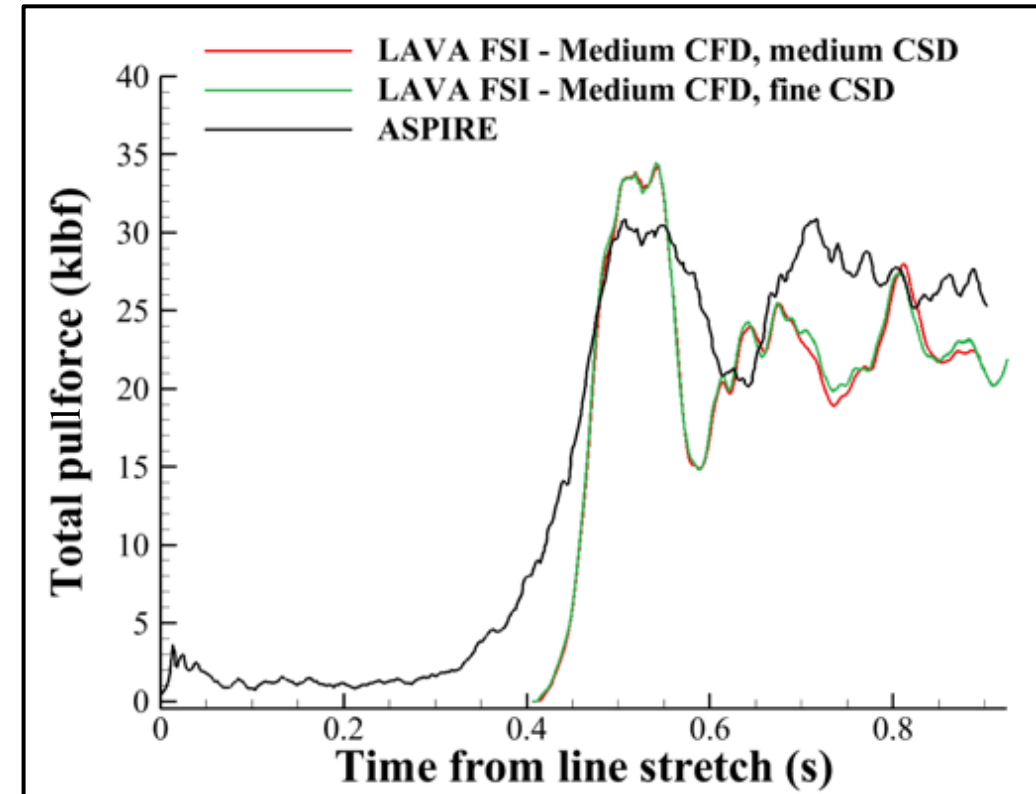
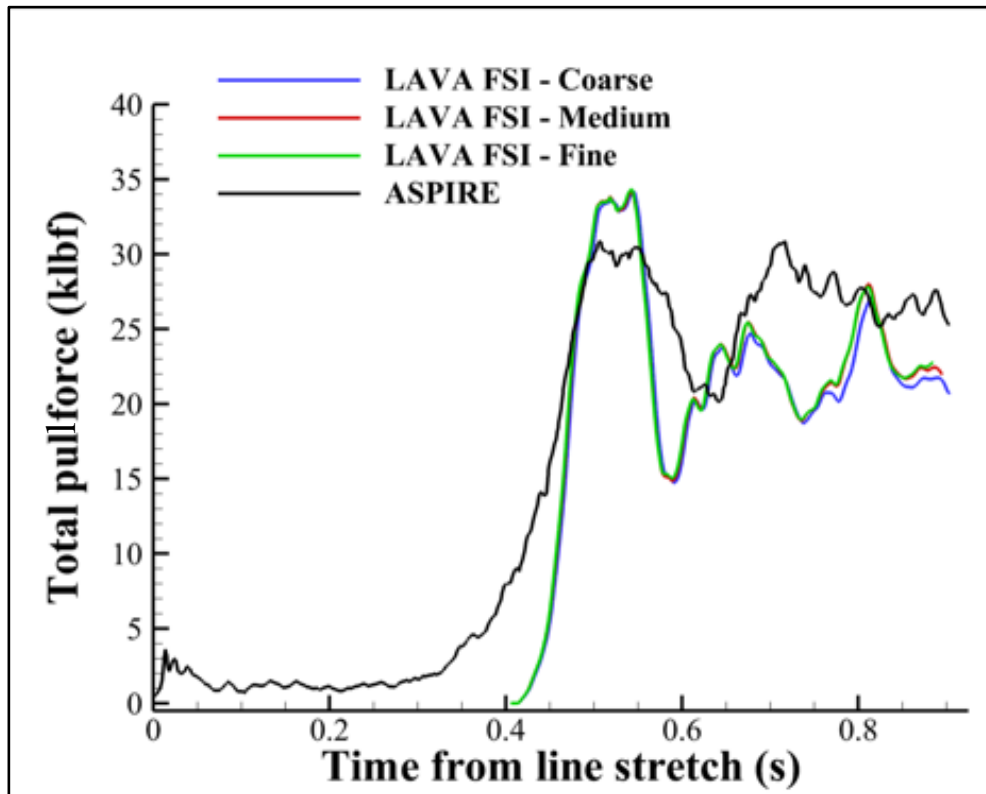
- ASPIRE payload had 3 load pins to measure the tension in the triple bridle as a function of time with a measurement uncertainty of about 6% of peak load (± 1.82 klbf)
- FSI simulation recorded the restoring force in the elements of each bridle to perform as close to apples-to-apples comparison of total pull force
- FSI shows qualitative behavior consistent with ASPIRE test
- FSI inflates faster and overpredicts inflation peak by ~10%
- FSI underpredicts trough and rebound peak by ~20%



FY21 Grid Convergence Results



- Performed consistent CFD grid convergence study using 3 grid levels & demonstrated 3rd order convergence rate and $< 1\%$ variation in predicted pull force
- Performed structural grid sensitivity study using one finer mesh by factor 0.7 for all edge lengths and demonstrated $< 1\%$ variation in predicted pull force



FY21 Sources of Uncertainty in FSI



As demonstrated by CFD and CSD grid refinement studies, FSI simulations are repeatable and show little discretization-related uncertainty. For more details, please refer to

Boustani, Jonathan, et al. "Fluid-structure interaction simulations of the ASPIRE SR01 supersonic parachute flight test." *Aerospace Science and Technology* 126 (2022): 107596.

We conclude that the discrepancy in predicted pull-force stems from **modeling errors**:

- Initial parachute shape: 3D parachute shape at line-stretch could not be reconstructed from flight data
- Parachute initial stress and velocity: assumed to be zero, causing impulse to the system
- Flow initial conditions: parachute loads never reach statistically stationary state in flight test (which was how we started SR02 FSI simulations)
- Material modeling:
 - Assumed all gore seams, disk and band leading and trailing edge had very strong Kevlar reinforcements but identical thickness due to lack of information
 - Similarly assumed all suspension lines, riser and bridles were made from same material with identical strength and thickness but recently learned this is not accurate
- Effects of deceleration: the parachute drag causes the whole system to decelerate abruptly during inflation

FY22: Improving Modeling Accuracy

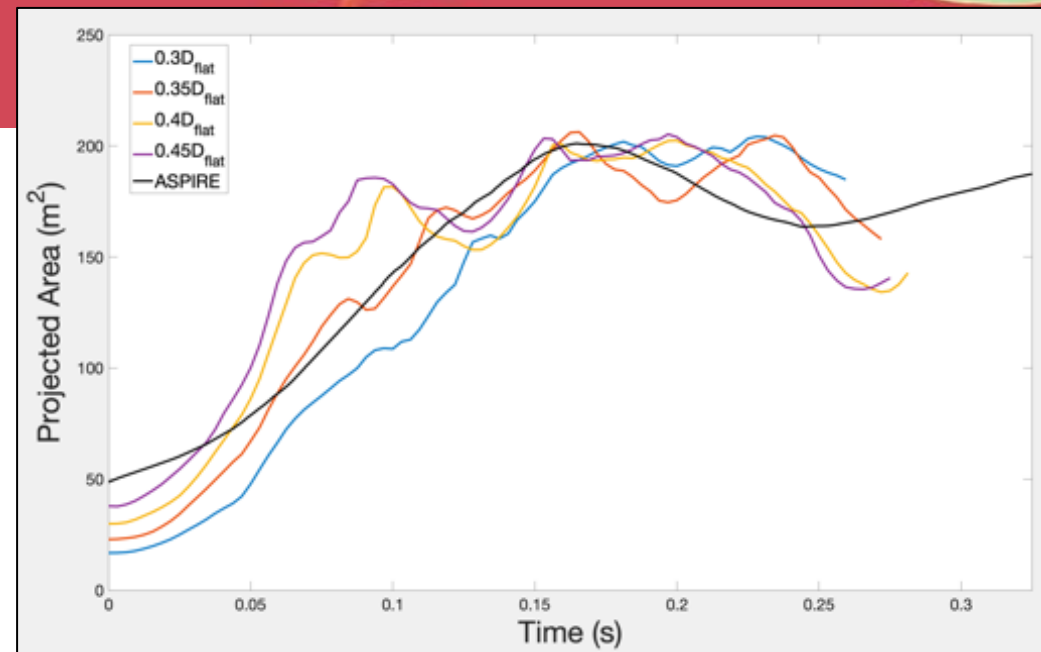
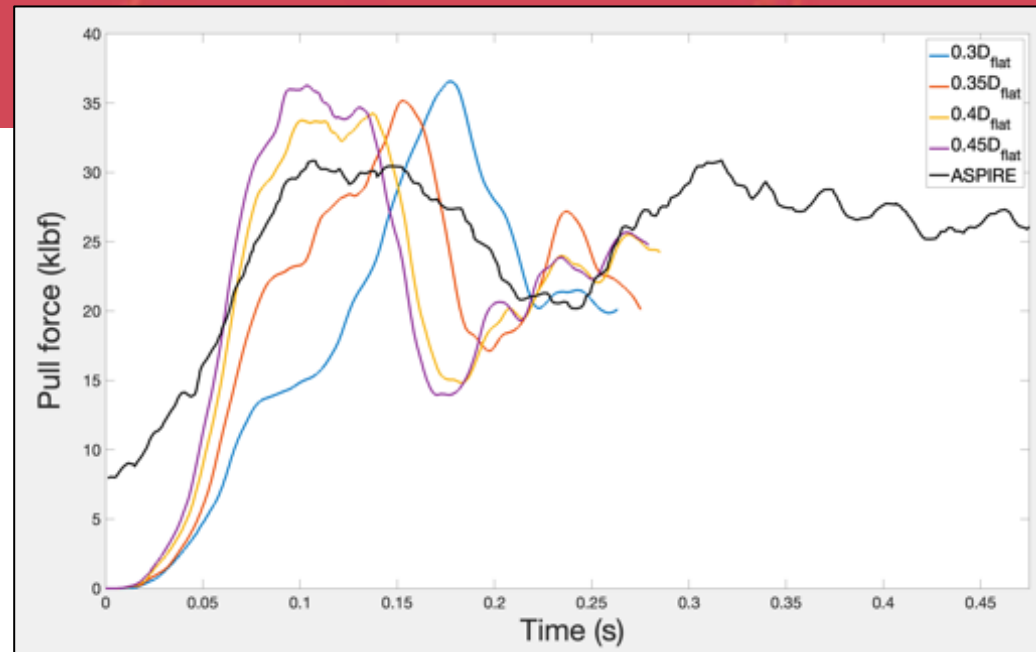
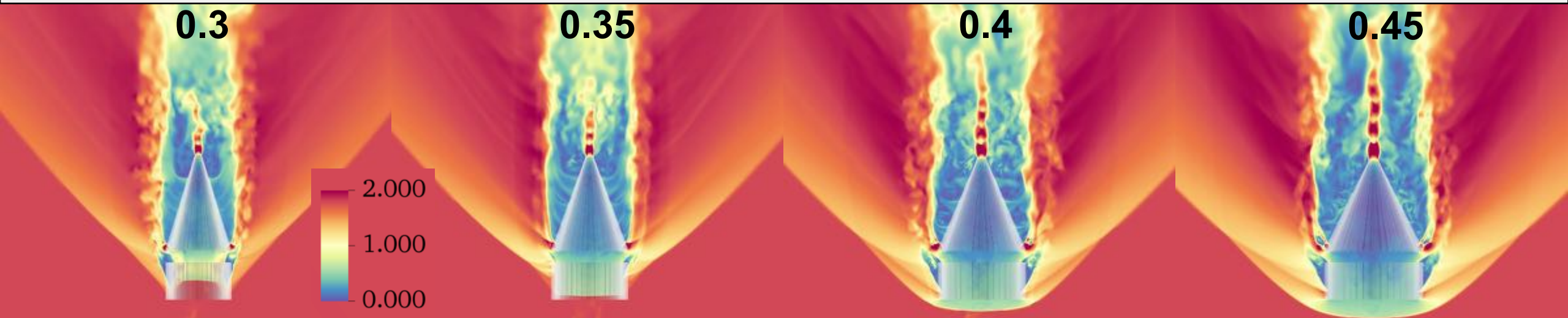


1. Analyze sensitivity of pull-force to initial parachute shape (from 40% of disk diameter down to 30%)
2. Investigate uncertainty and repeatability of flight tests to better contextualize FSI discrepancies with respect to flight test data
3. Develop free-flight capability to allow parachute system (parachute + payload) to decelerate and explore sensitivity of pull-force to inertial effects
4. Implement and verify consistent material models and properties for a more representative SR02/SR03 parachute system to enable code-to-code comparisons with JPL/Stanford team
5. Simulate ASPIRE SR03 flight test and quantify impact of modeling changes and improvements to best practices to validation metrics like pull-force and projected area (delayed to FY23)

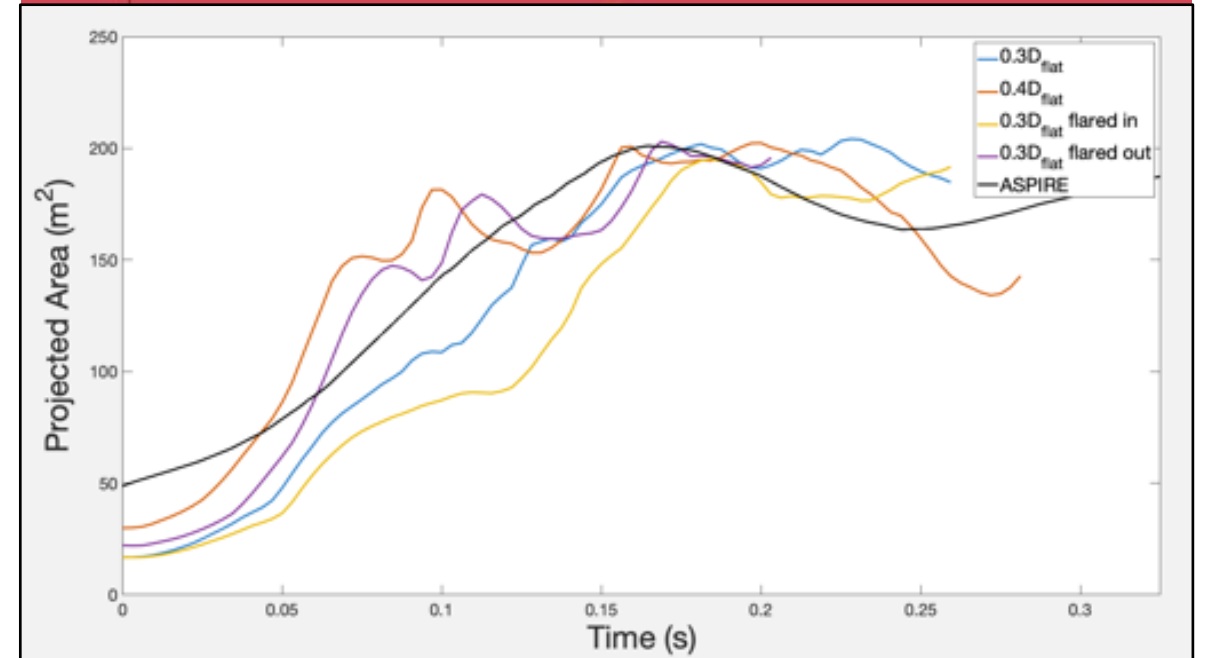
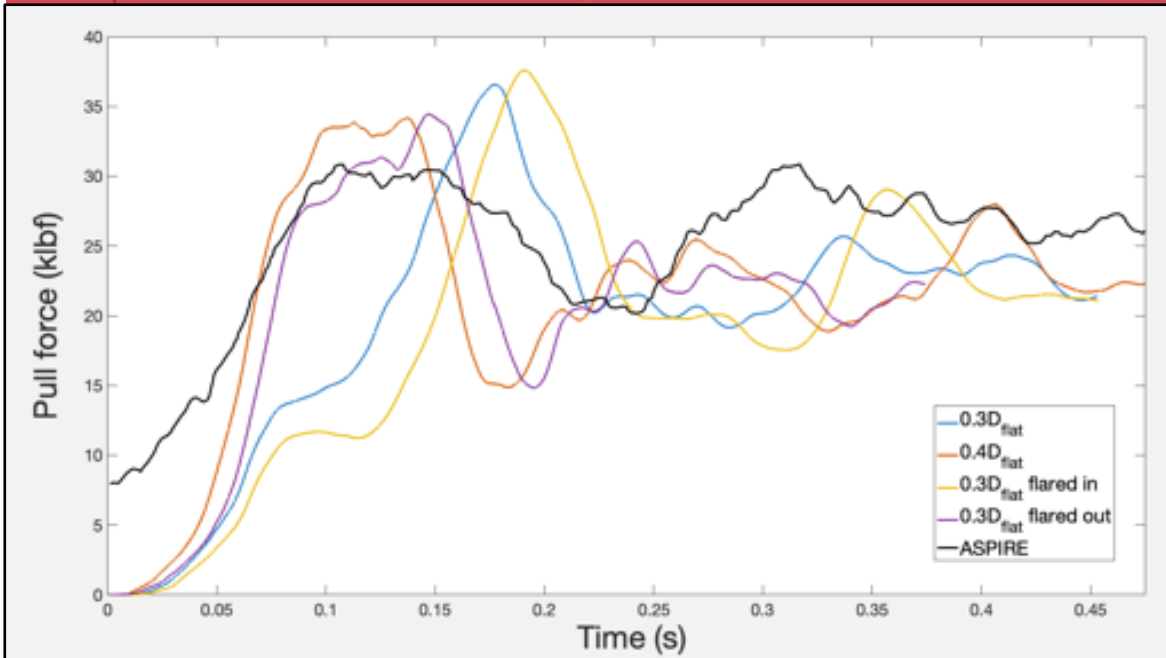
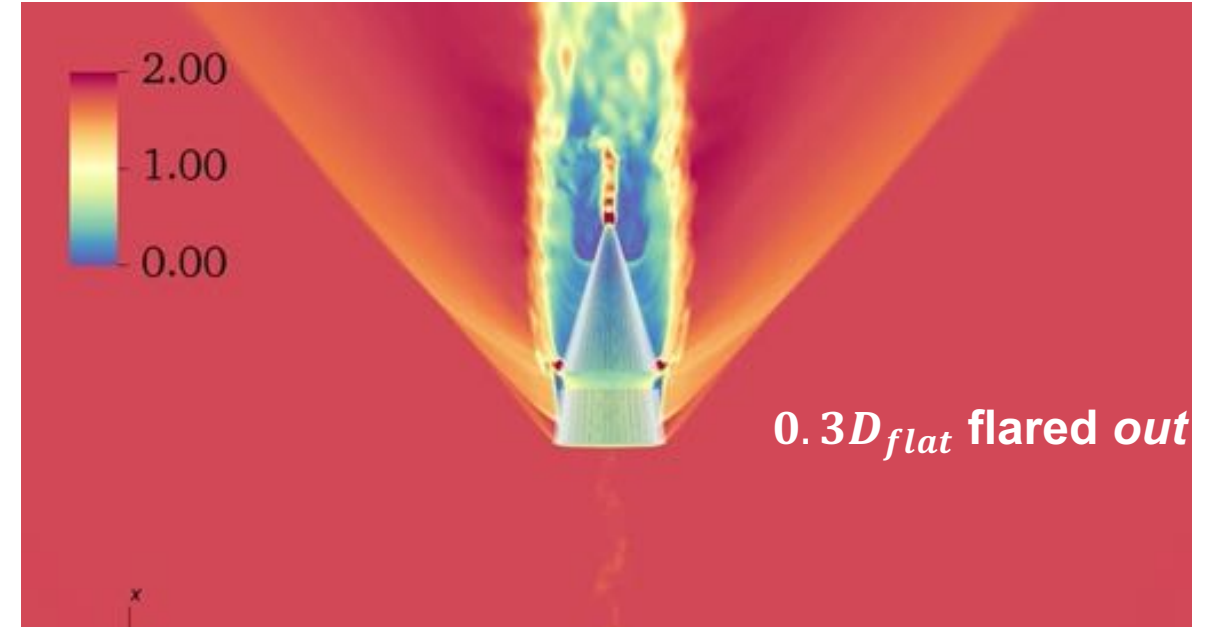
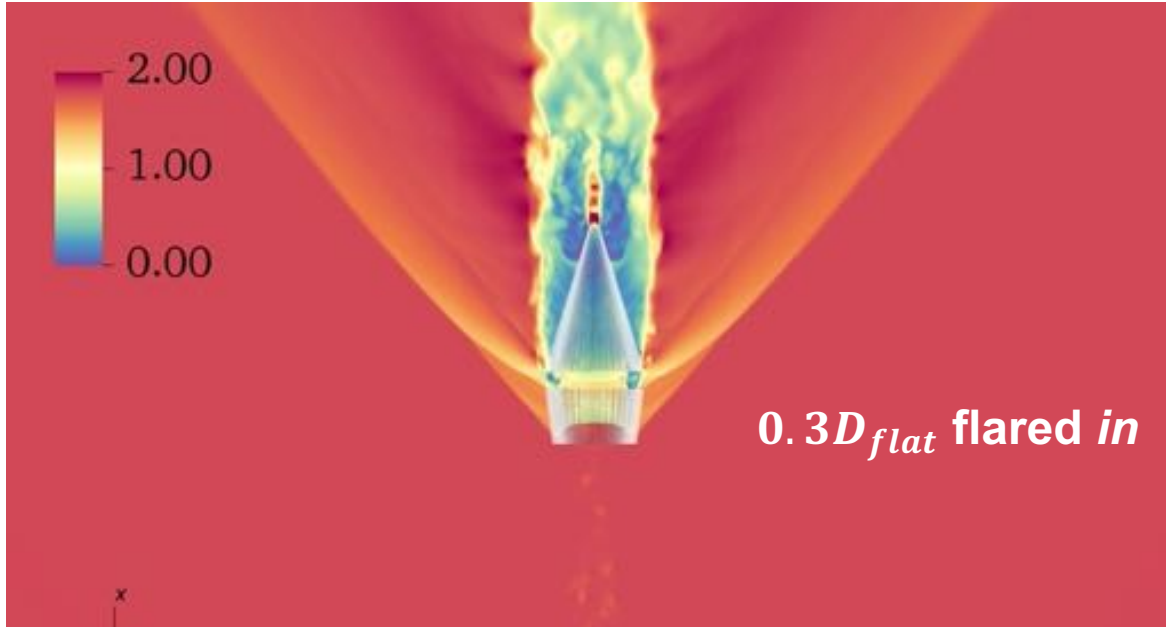
Effect of Initial Parachute Shape



Mach number on a cut-plane for the precursor static CFD simulations used as the initial condition for FSI simulations. The 0.3, 0.35, 0.4, 0.45 indicate the fraction of the “flat” disk diameter that the folded disk takes, e.g., $D_{folded} = 0.35 D_{flat}$, $D_{folded} = 0.4 D_{flat}$, etc.



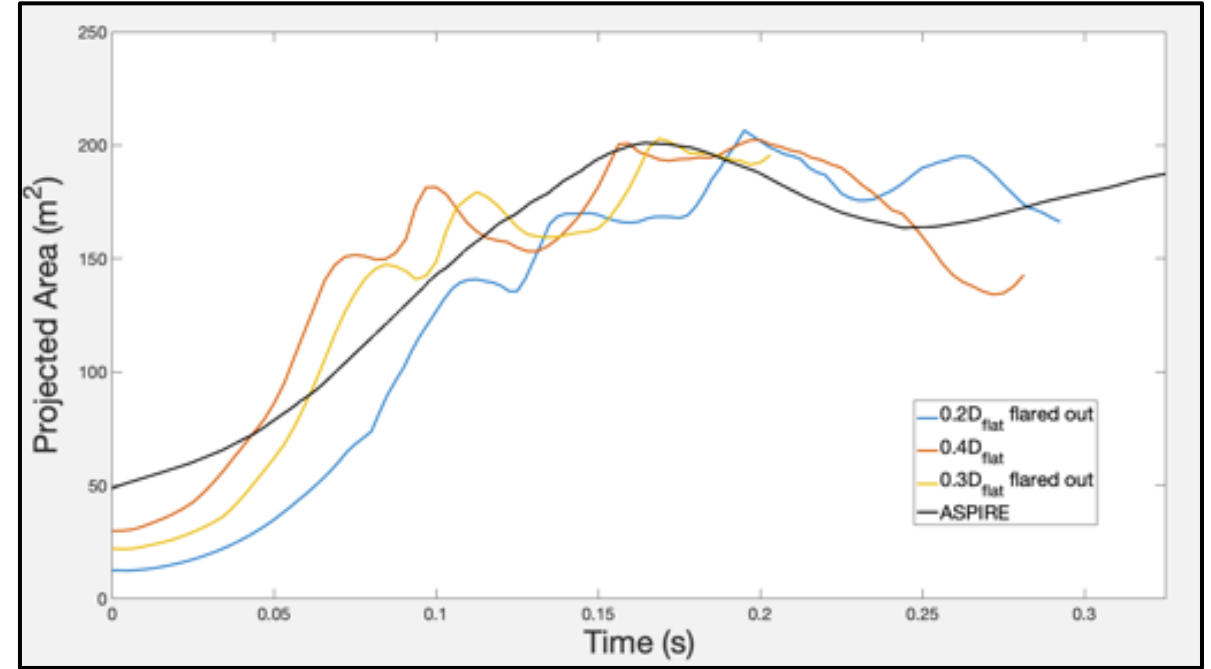
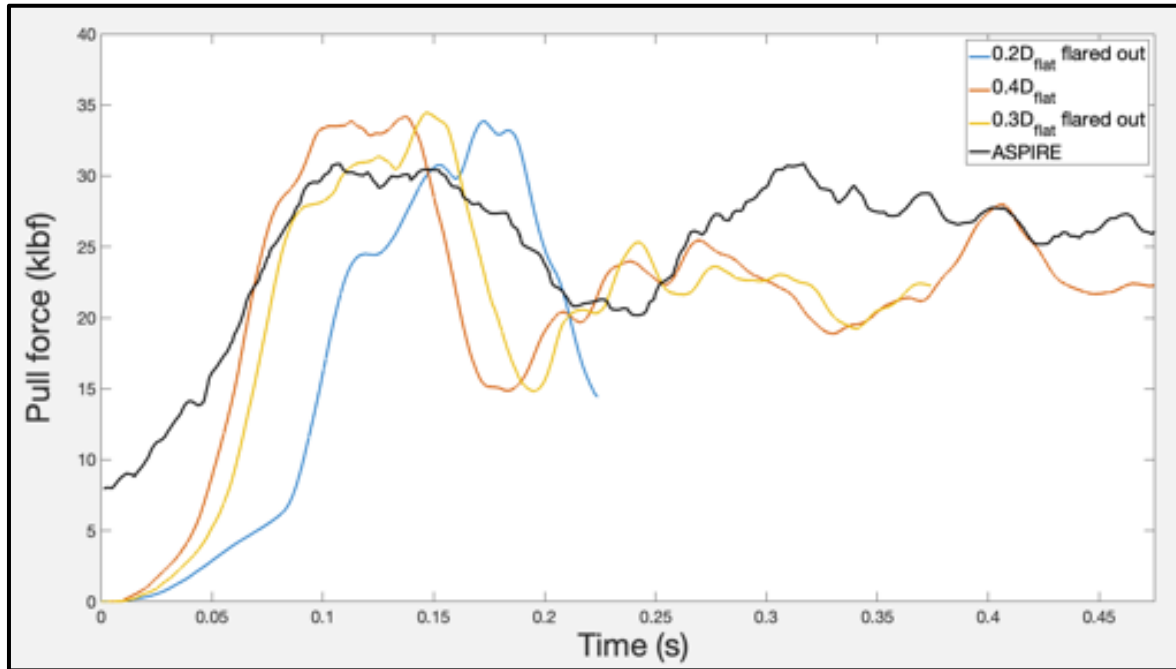
Effect of Initial Parachute Shape



Effect of Initial Parachute Shape



- Is smaller initial diameter with outward flare more representative of flight?
- 0.2 D with outward flare recovers 0.4 D peak pull-force, but slows inflation rate

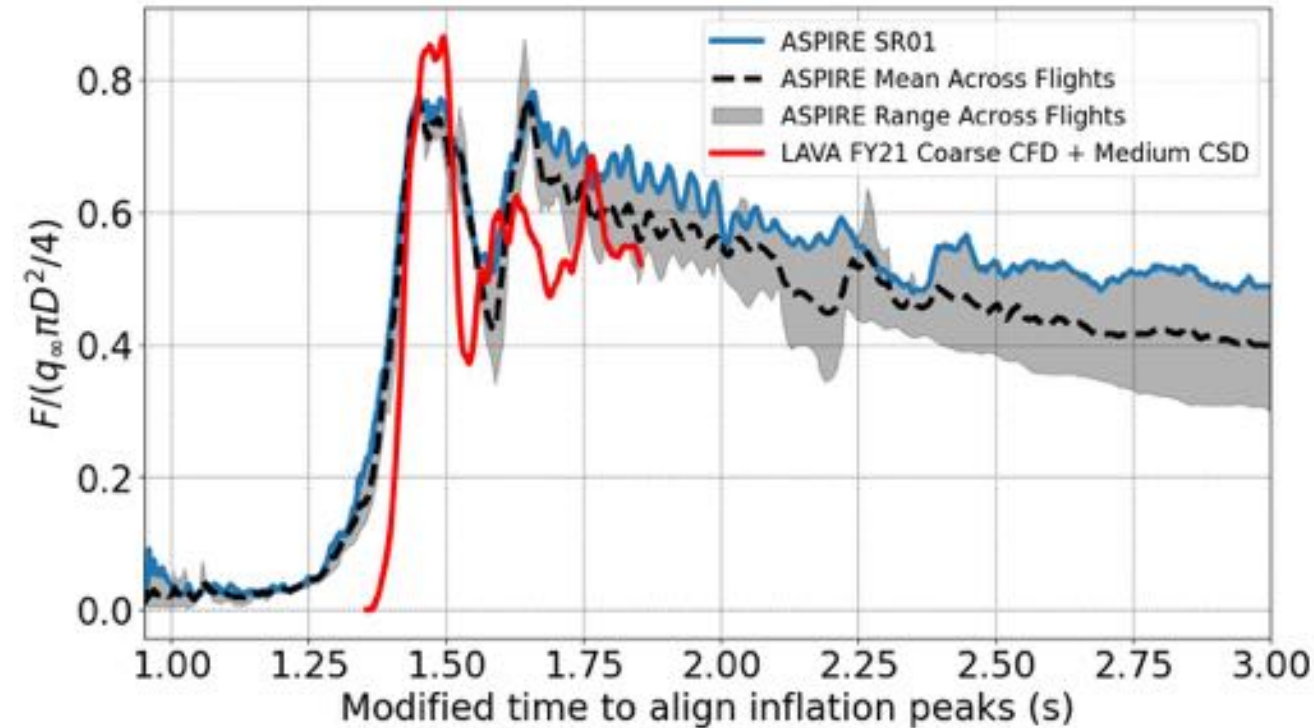


- So long as the bock shock is upstream of band at the start of FSI, the maximum pull-force is not very sensitive to initial shape
- Smaller initial diameter slows inflation rate which could be more representative, but is more challenging in terms of CFD resolution requirements

Investigating Flight Test Uncertainty



- Measurement uncertainty is not the same as uncertainty stemming from repeated tests
- ASPIRE project conducted 3 tests: SR01, SR02, and SR03:
 - Each test saw differences in parachute diameter, materials, construction, and release mechanism, along with significant increases in dynamic pressure when released
- We can gain information about flight test repeatability if we non-dimensionalize the pull-force by parachute area and dynamic pressure

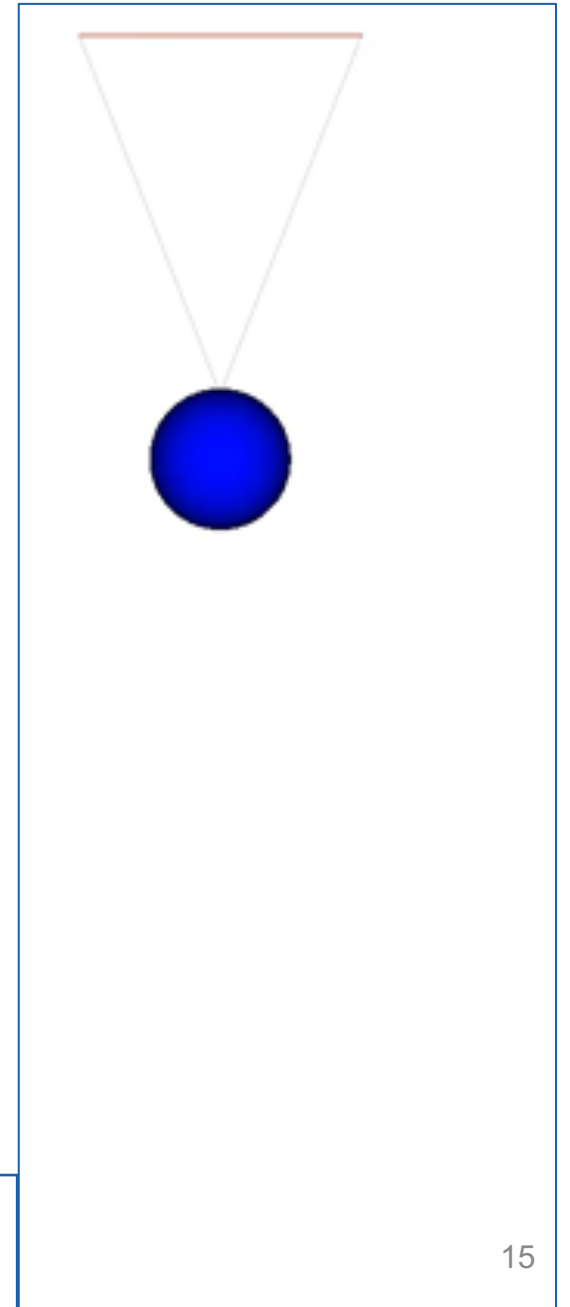


Non-Dimensional Drag Force	ASPIRE Average Across Flights	LAVA FSI Predictions FY21 Coarse CFD + Medium CSD Mesh	ASPIRE Percent Variation Across Flights (+/-)	Percent Difference Between LAVA and ASPIRE Average
Inflation Peak	0.773	0.865	3.42	+11.9
Rebound Peak	0.798	0.624	14.93	-21.8
Trough	0.409	0.372	42.10	-9.1

Free-Flight Capability To Model Deceleration



- Rigid body motion with input moments of inertia, mass, and center of gravity are allowed to move with respect to fixed Cartesian background grid according to forces acting on them (gravity, pressure loads from CFD)
- Leverages the same Runge-Kutta time integrators as CFD
- Coupling between payload and parachute is done through forces and displacements at shared nodes between bridle and payload rear surface
- Supports constrained formulation where inertial degrees of freedom can be “frozen” or ignored, e.g. to allow us to model only deceleration in vertical versus full 6 DOF motion
- Challenge: rigid body motion requires re-building BVH for surface triangulation and updating immersed boundary conditions at each RK sub-step (costly) for time accuracy

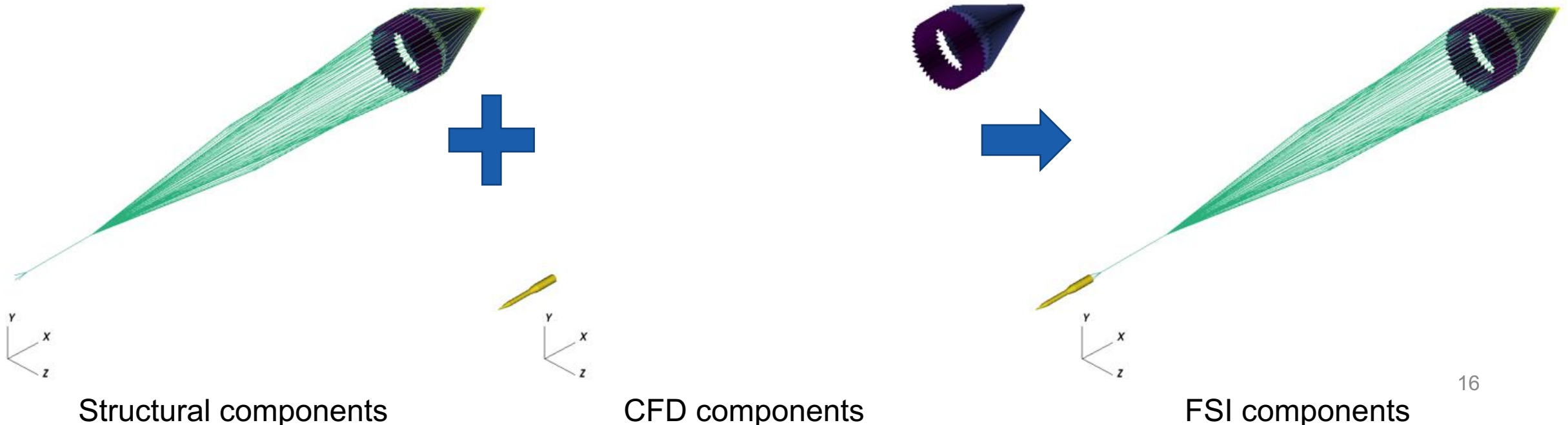


Demonstration of 6 DOF free-flight
parachute-payload coupling

Material Model Properties For SR02/03



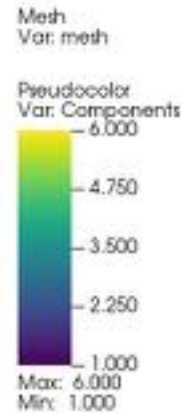
- Following release of more detailed JPL data on SR02/03 parachute construction and material properties, developed capability to handle different material properties on different parts of the canopy and suspension lines
- Developed repeatable parachute canopy structural mesh generation process
- Developed automated canopy CFD mesh generation with one-to-one node match to structural mesh to simplify load and displacement transfers between solvers
- Improved mesh generation for bridle, riser, suspension lines, gap lines, radials, and vent lines allowing each to be modeled with different material properties



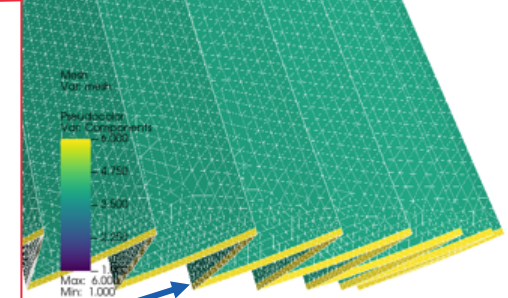
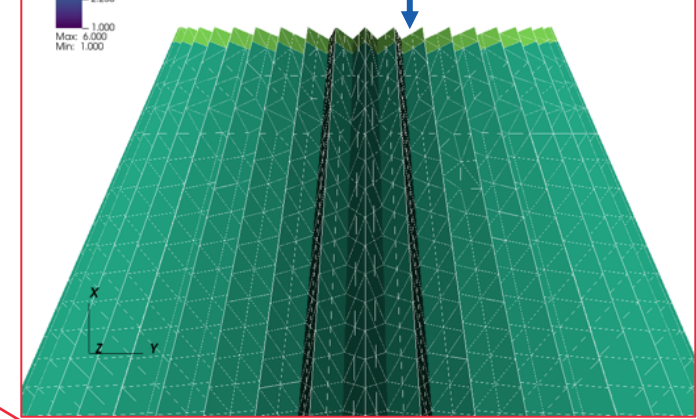
New Parachute Mesh



~275,000 triangles,
min edge length = 2.54 cm
max edge length = 5 cm



Disk trailing edge:
PIA-T-87130 Type VI
Class 9 Kevlar Webbing



disk leading edge & band
leading/trailing edge:
PIA-T-87130 Type VI
Class 9 Kevlar Webbing

Ongoing: Investigating Startup Procedure for FSI



Slice showing Mach number on *coarse* AMR mesh overlayed with high transparency where each box contains 16^3 cells. The payload and parachute system is light gray. The parachute is not “seen” by the CFD until $t=0.15$ s to flush out payload wake transients, at which point the mesh is adapted to reflect the presence of the static parachute. Approximately 0.05 seconds later, the coupled FSI simulation starts and the parachute deforms.

Forward Outlook



- Continue FSI simulations of the ASPIRE SR03 flight test with more detailed material properties recently published by JPL
- Explore the effects of flow and parachute initial conditions and try to reproduce JPL's recently published initialization procedure for code-to-code comparisons
- Investigate the effects of the full system's abrupt deceleration during inflation using newly developed free-flight capability

Iso-surfaces of q -criterion colored by total pressure showing detailed turbulent structures captured in fine mesh FSI simulations of FY21 ASPIRE SR01 flight. Payload and parachute system are shown in gray.

Acknowledgements



- This work is supported by the NASA Entry Systems Modeling (ESM) and the NASA Transformational Tools and Technologies (T³) projects
- Computational resources were provided by NASA Advanced Supercomputing (NAS) systems at NASA Ames Research Center

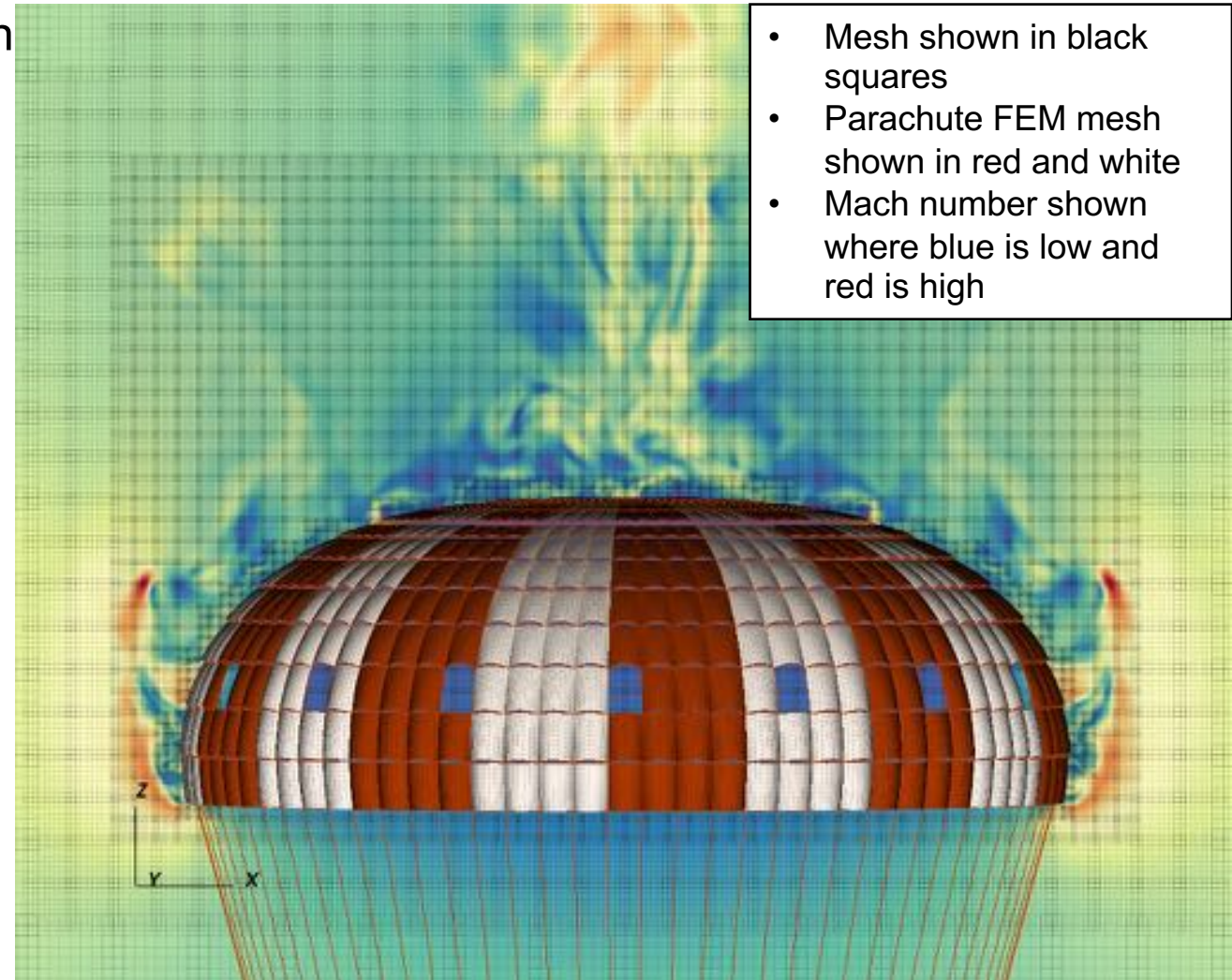
Special thanks to:

- Gaetan Kenway for helping to improve the parallel efficiency of the structural solver
- James Jensen for helping to develop new parachute canopy mesh generation procedure
- Timothy Sandstrom from NASA Ames Research Center for developing and maintaining an interface to the high-performance geometry kernels used in this work
- Michael Barnhardt and Aaron Brandis for insightful discussions on the sources of uncertainty in the ASPIRE flight data and for helping guide the focus of our development efforts

Modeling Single Orion CPAS Subsonic Parachute



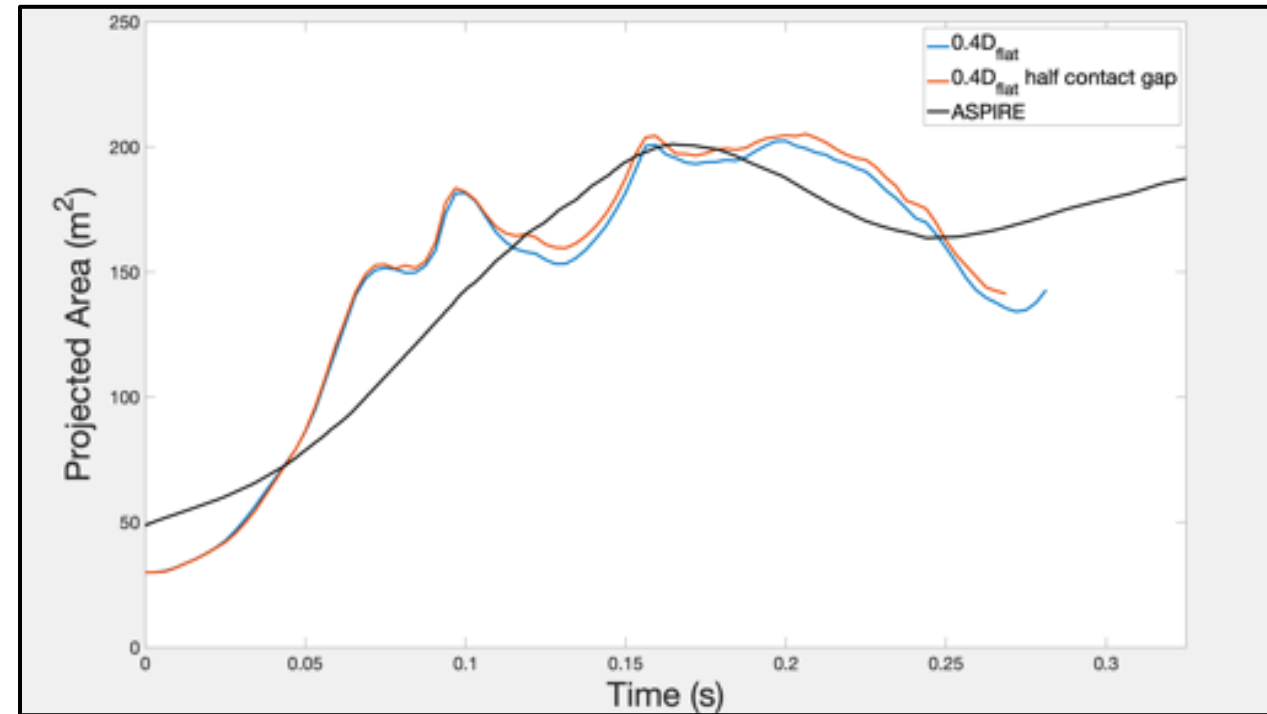
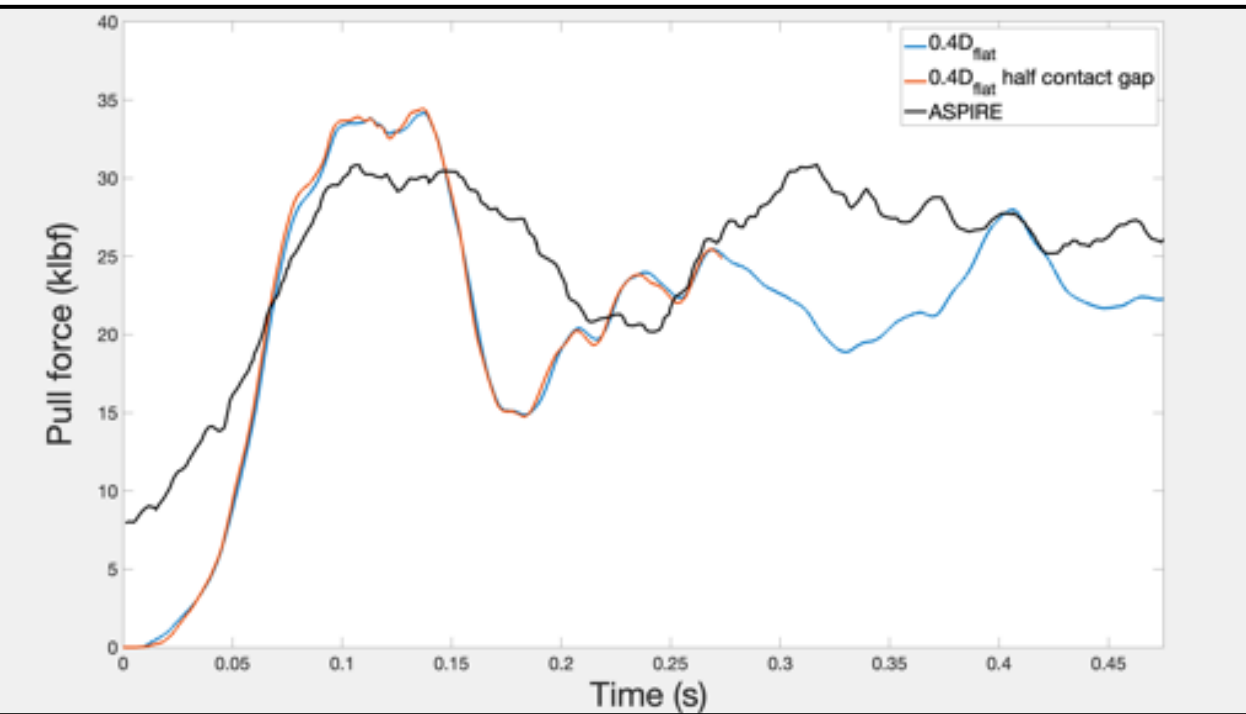
- Engineers want to know the ratio of tension on the vent lines near the hoop to the tension measured where the suspension lines meet the canopy: apply FSI capability to predict it
- Challenges:
 - low Mach number
 - long integration time
 - larger parachute diameter
 - canopy design has geometric porosity that is smaller than typical CFD mesh size (large range of relevant scales)
 - Has 3 regimes of operation with release of two reefing lines restricting parachute opening and forcing massive self-contact
- Progress:
 - Created a tool to go from LS-Dyna model to LAVA FSI-ready mesh
 - Started CFD-only simulation of static parachute at full-open
 - Waiting on material properties to start structural tests and then FSI simulations



Backup Slides

Sensitivity to Contact

- Contact algorithm has only one parameter: minimum allowable gap size for CFD
- Medium grid (2.4 cm) gap size is $\sim 5\Delta x$ and it is halved to investigate sensitivity



- Sensitivity to contact gap size is very minor

Motivation: Low Density Supersonic Decelerator



- Low density supersonic decelerator (LDSD) project aimed to test two novel technologies:
 - an inflatable decelerator
 - *a new Disksail parachute design* [1]
- Disksail parachute showed signs of damage early on during its inflation and ultimately was ripped apart
- Cause of failure still poorly understood today
- Leading hypothesis is that the new Disksail design itself caused more severe stresses than seen in previous disk-gap-band (DGB) parachutes [2]:
 - its larger shoulder region may have pulled the disk portion of the canopy flat earlier in the inflation process, causing the fabric to tear under the increased load



(NASA/JPL)

[1] Gallon, J., Witkowski, A., Clark, I. G., Rivellini, T., and Adams, D. S., "Low density supersonic decelerator parachute decelerator system," AIAA Aerodynamic Decelerator Systems (ADS) Conference, 2013, p. 1329

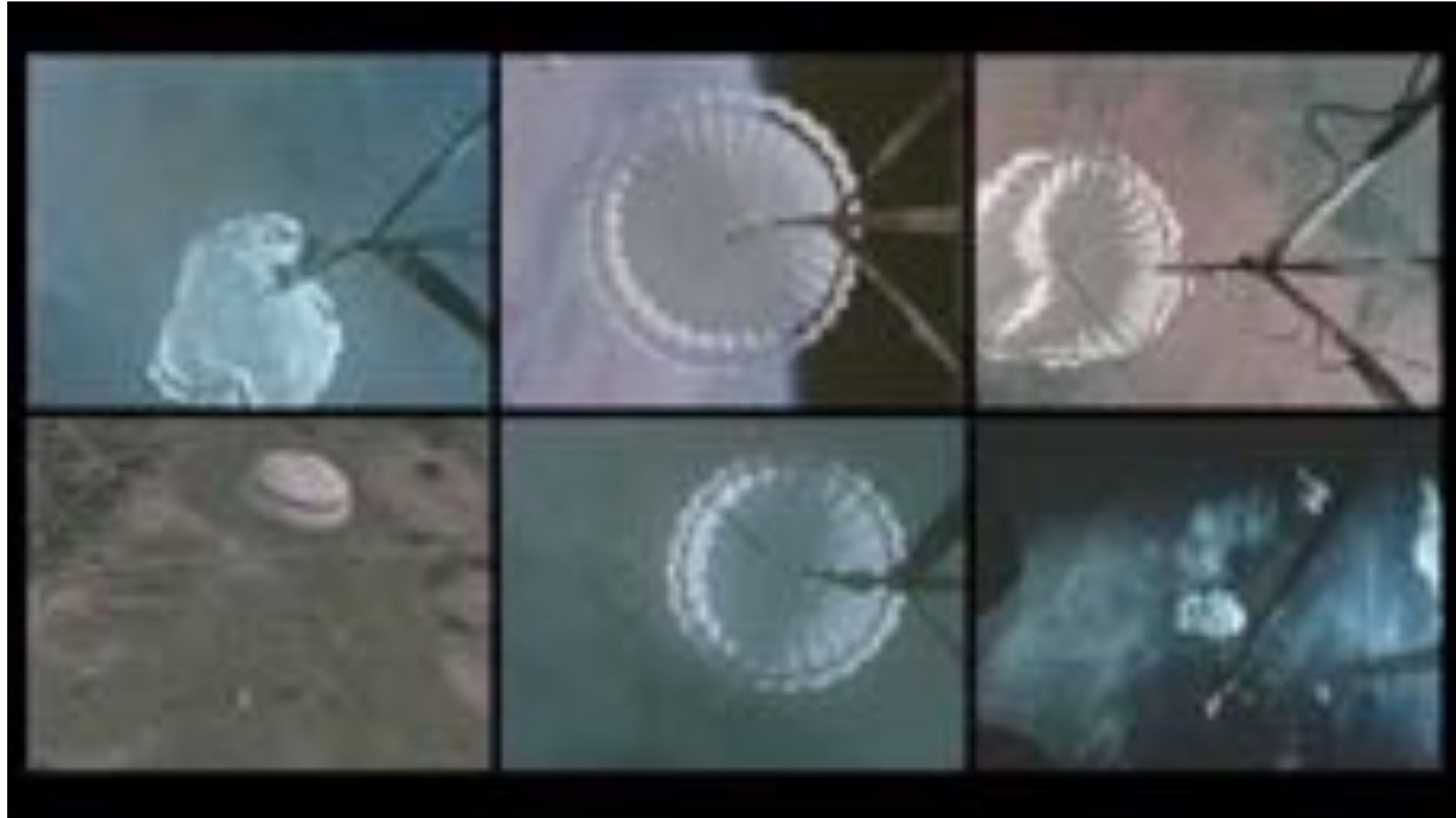
[2] Clark, I. G., Gallon, J. C., and Witkowski, A., "Parachute Decelerator System Performance During the Low Density Supersonic Decelerator Program's First Supersonic Flight Dynamics Test," 23rd AIAA Aerodynamic Decelerator Systems Technology Conference, 2015, p. 2130

Motivation: Low Density Supersonic Decelerator



NASA JPL: <https://youtu.be/9yRW hu0UGYw?t=74>

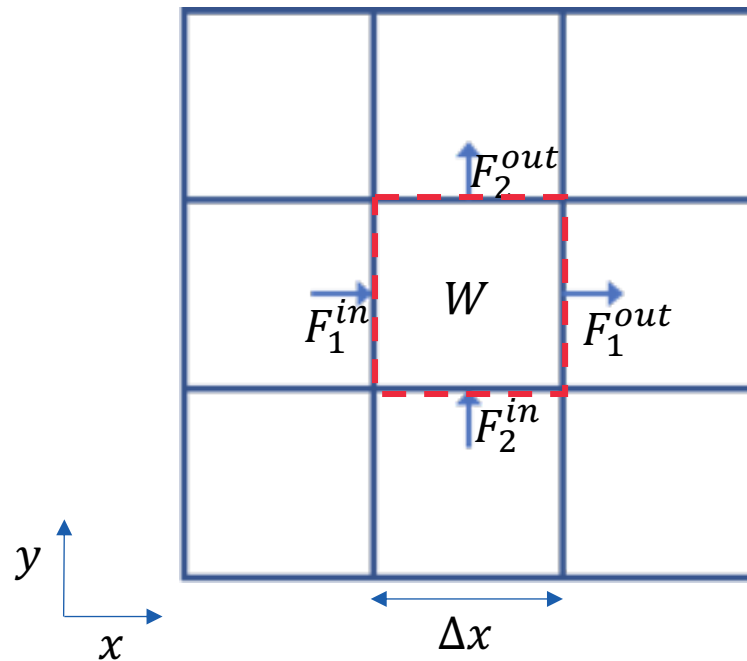
ASPIRE: Testing a Parachute for Mars



NASA JPL: <https://youtu.be/AcAgnQ9K7UY>

Quick Overview of Unsteady CFD

- Advance conservation of mass, momentum, and energy equations for a gas using fluxes through faces of a control volume (dashed red square) in time from $t \rightarrow t + \Delta t$ given initial and boundary conditions:



$$\frac{\partial W}{\partial t} = - \frac{\partial F_j}{\partial x_j} \quad W = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho E \end{bmatrix}$$

$$F_j = \begin{bmatrix} \rho u_j \\ \rho u_1 u_j + p \delta_{1j} \\ \rho u_2 u_j + p \delta_{2j} \\ (\rho E + p) u_j \end{bmatrix}^*$$

W : vector of conserved variables

F_j : flux in j direction

ρ : density

u : velocity in x direction

v : velocity in y direction

E : total energy

p : pressure

T : temperature

R : gas constant

c_v : specific heat at constant volume

$$p = \rho R T$$

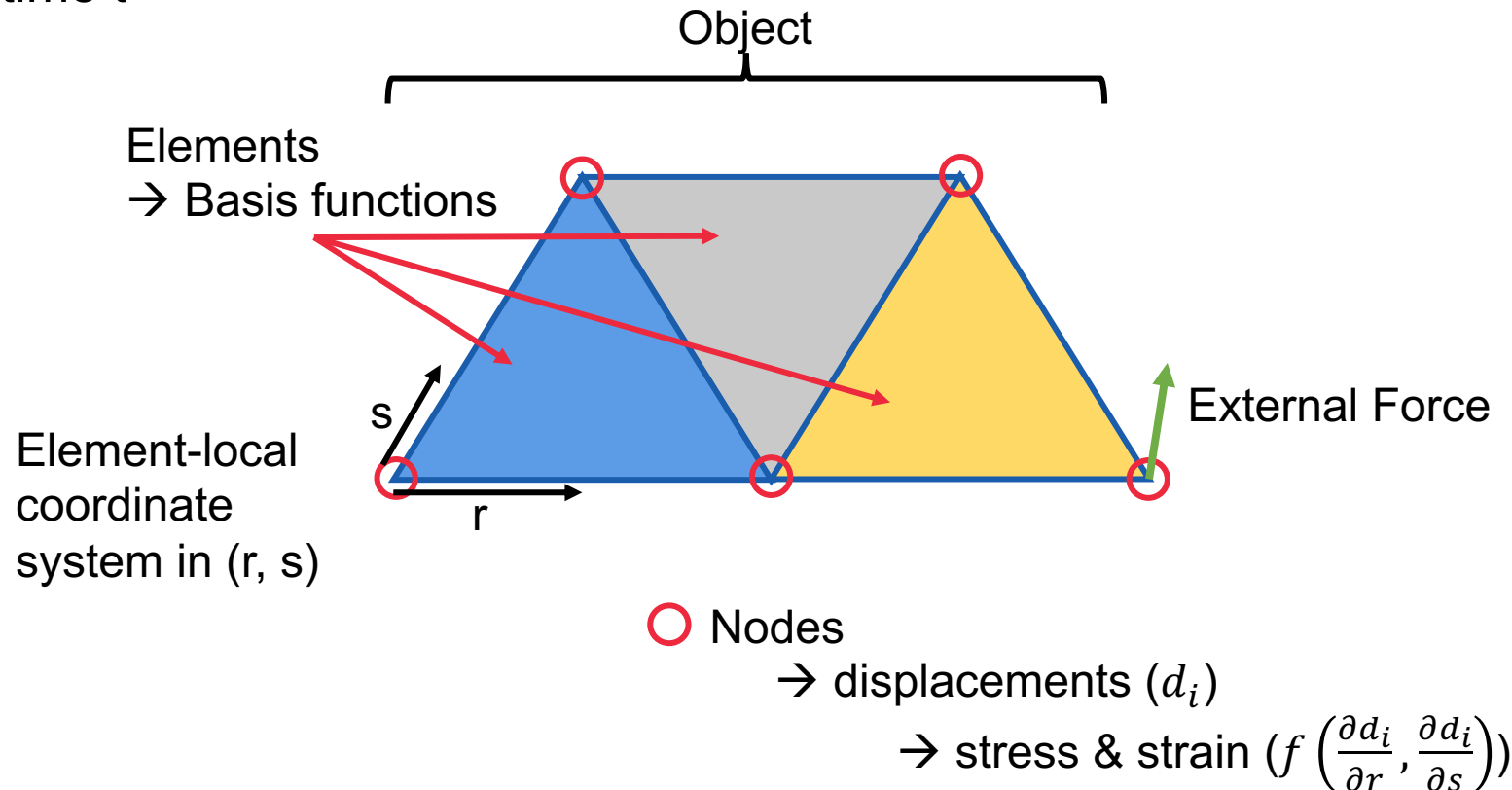
$$E = c_v T + \frac{1}{2} u_i u_i$$

*Viscous fluxes are neglected for simplicity

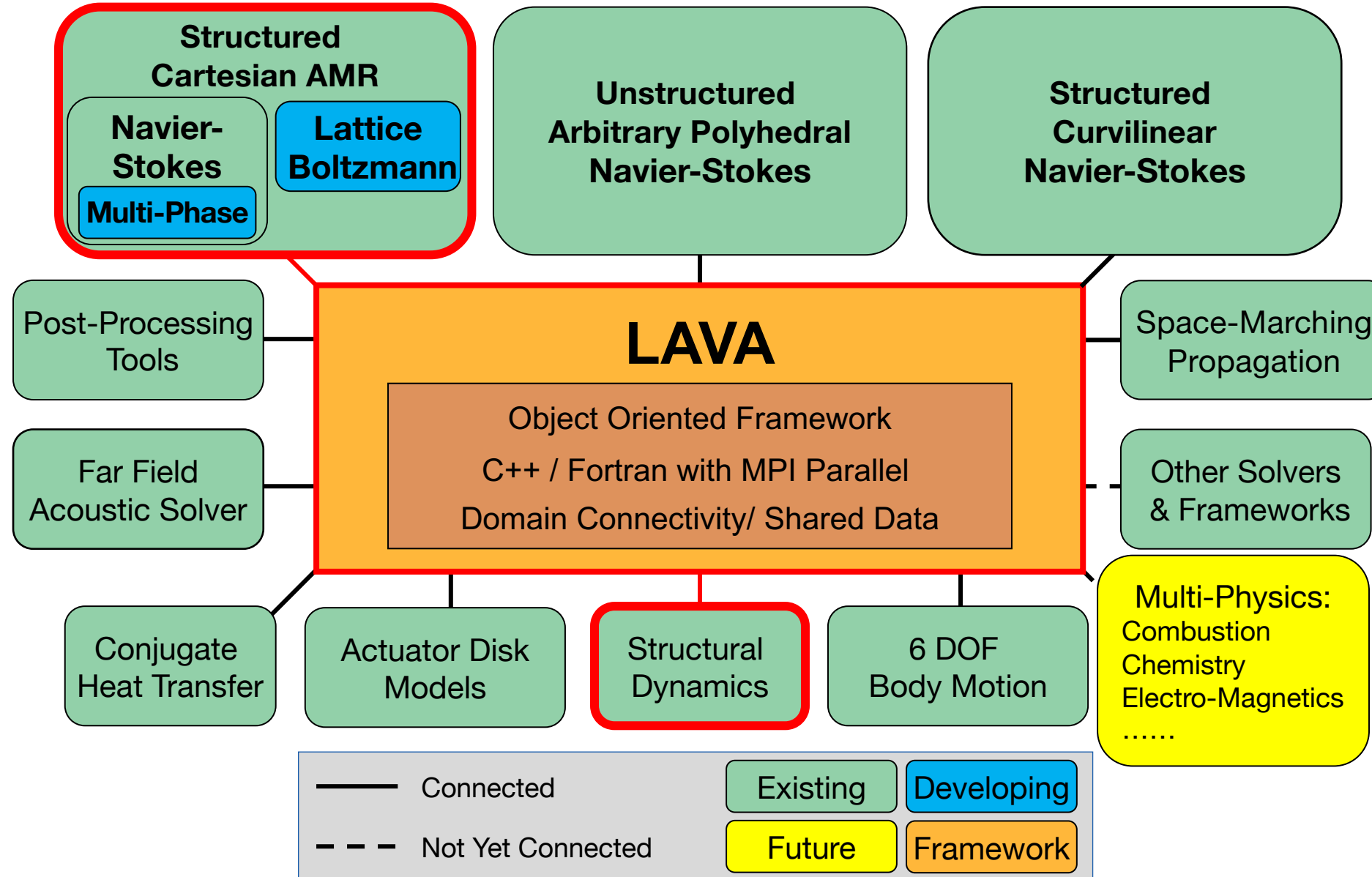
Quick Overview of Unsteady CSD



- Solve the equations of motion of nodes shared across finite elements (e.g. triangles) on an object for their displacements (d_i) to reach equilibrium between external forces and internal stresses (functions of gradients of d) at time $t + \Delta t$
- Given the object's material properties (e.g. thickness, density, Young's modulus, Poisson ratio) initial conditions, boundary conditions, and external forces acting on the nodes at time t



Launch, Ascent and Vehicle Aerodynamics



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

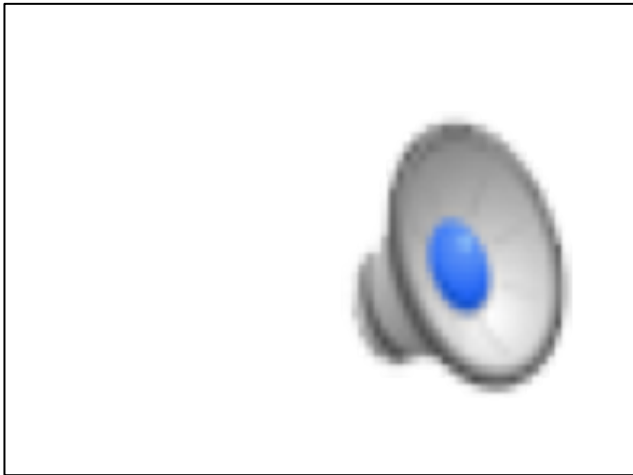
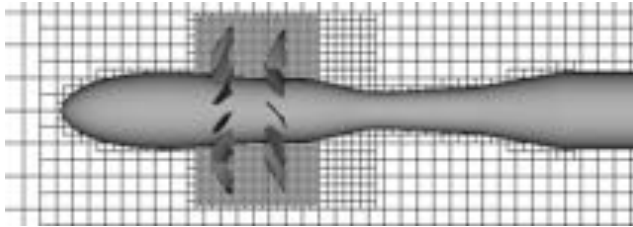
Other Development Efforts

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

CFD Approach



Structured Cartesian AMR

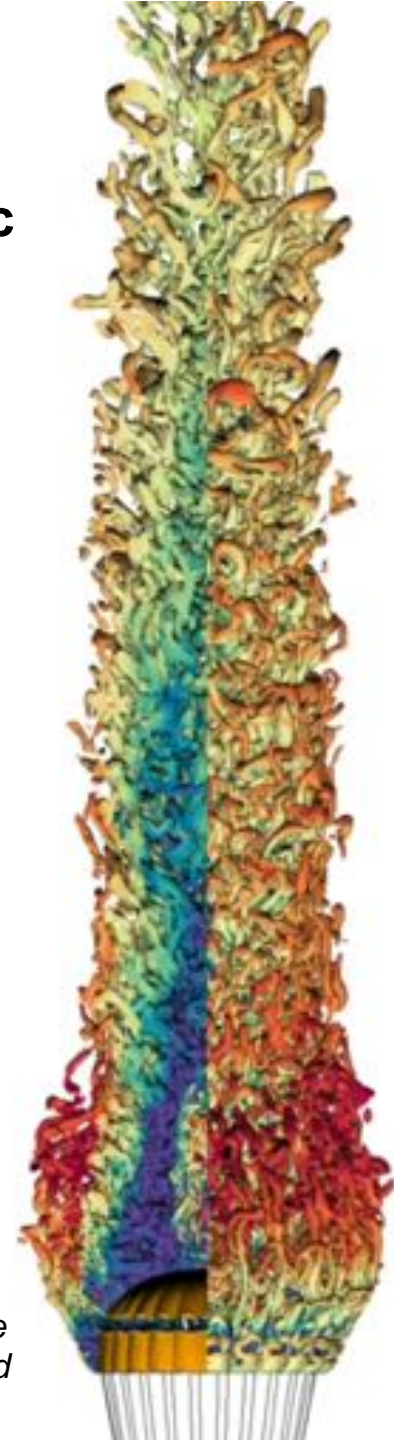


- Essentially no manual grid generation
- Highly efficient Structured Adaptive Mesh Refinement (AMR)
- Low computational cost
- Reliable higher order methods
- **Non-body fitted → Resolution of boundary layers challenging**

Requirements for Simulating Supersonic Parachute Inflation Process:

- ✓ Simulate inherently transient phenomenon in a time-accurate fashion efficiently
- ✓ Resolve moving bow shocks, payload and canopy wake
- ✓ Adapt grid to large deformations of parachute during inflation
- ✓ Thin attached boundary layers do not play a critical role in determining the inflation dynamics of the parachute: it is driven by ram drag, not viscous drag

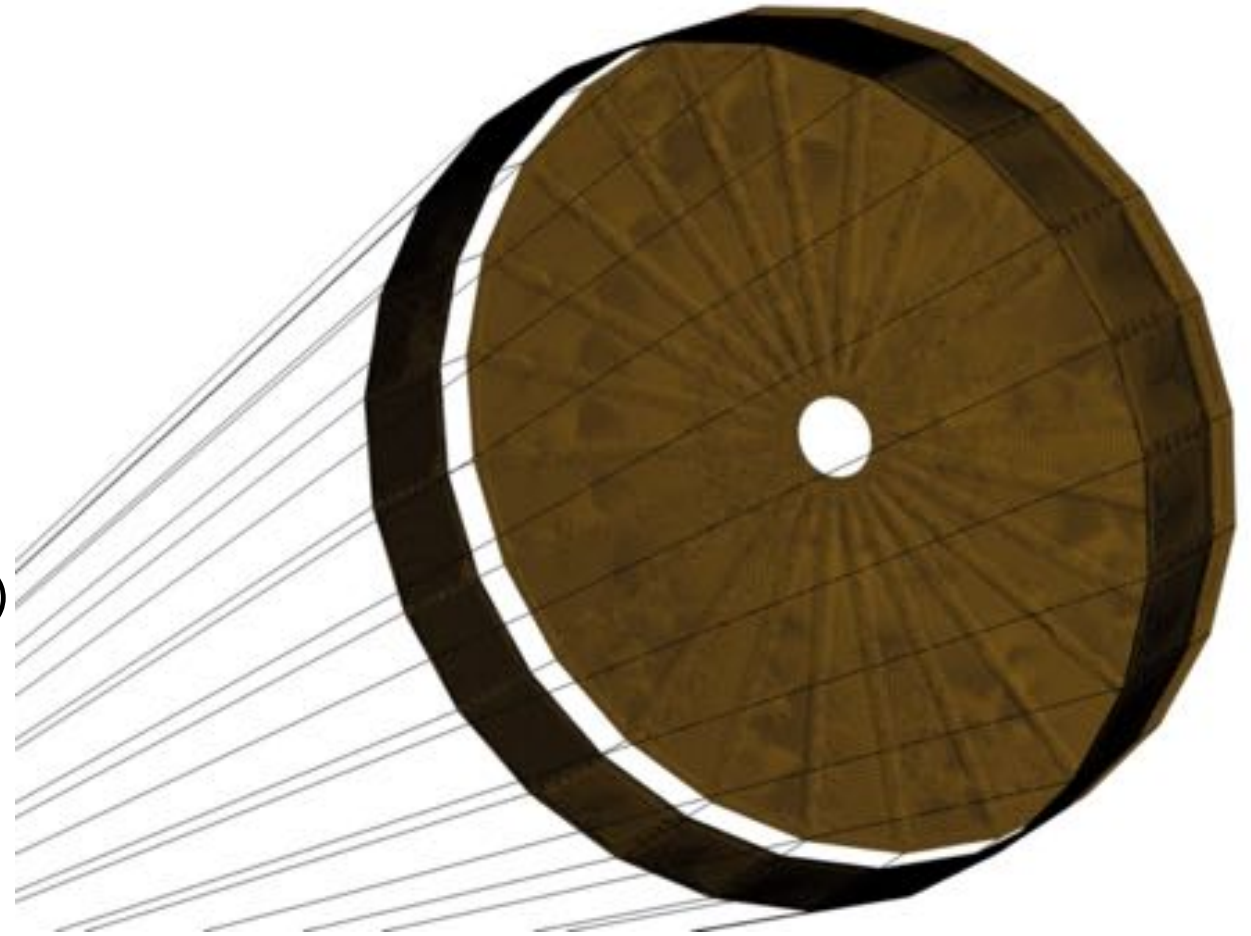
Isocontours of Q-criterion colored by Mach number where blue is lower and red is higher.



CSD Approach



- Use geometrically non-linear finite elements with Saint Venant-Kirchhoff hyper-elastic material model to handle parachute's large deformations
- Integrate equations in time using explicit second-order central scheme with high-frequency damping
- Leverage extended MITC3 triangular shell elements with 6 degrees of freedom (DOF) to alleviate shear-locking to model parachute fabric
- Model the suspension lines with Timoshenko beam elements with 6 DOF modified to allow for slack ("can't push on a rope")



Animation showing parachute structural mesh as it is deformed by a uniform outward pressure in a structural dynamics simulation (decoupled from CFD).

For more details, please refer to [3] and [4]:

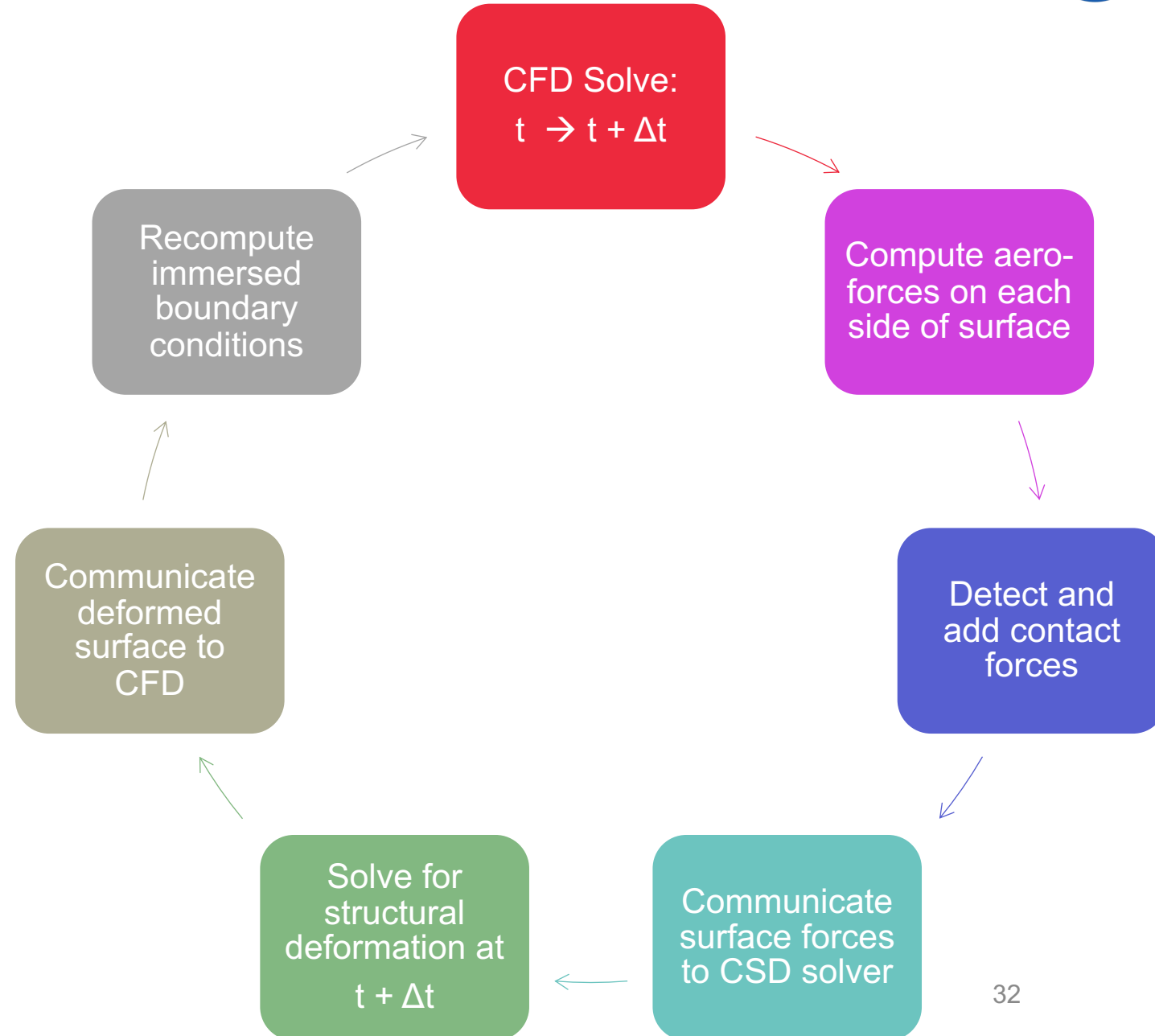
[3] Boustani, J., Cadieux, F., Kenway, G. K., Barad, M. F., Kiris, C. C., and Brehm, C., "Fluid-structure interaction simulations of the ASPIRE SR01 supersonic parachute flight test," *Aerospace Science and Technology*, 2022, p. 107596

[4] Boustani, Jonathan, et al. "Fluid-structure interactions with geometrically nonlinear deformations." *AIAA Scitech 2019 Forum*. 2019

CFD + CSD Coupling Approach



- Loose-coupling approach
- CFD time advancement limited by Courant–Friedrichs–Lewy ($CFL < 1$) condition
- CSD time advancement is sub-cycled with a smaller Δt to satisfy critical time step for structure if necessary



Modeling Contact For Parachute Inflation



It's not yet computational tractable to simulate the ASPIRE parachute as it rips out from its bag, so we start from a folded shape with 40% of its flat diameter, in which the 80 gores and 40 suspension lines are arranged like an accordion in 40 peaks and valleys

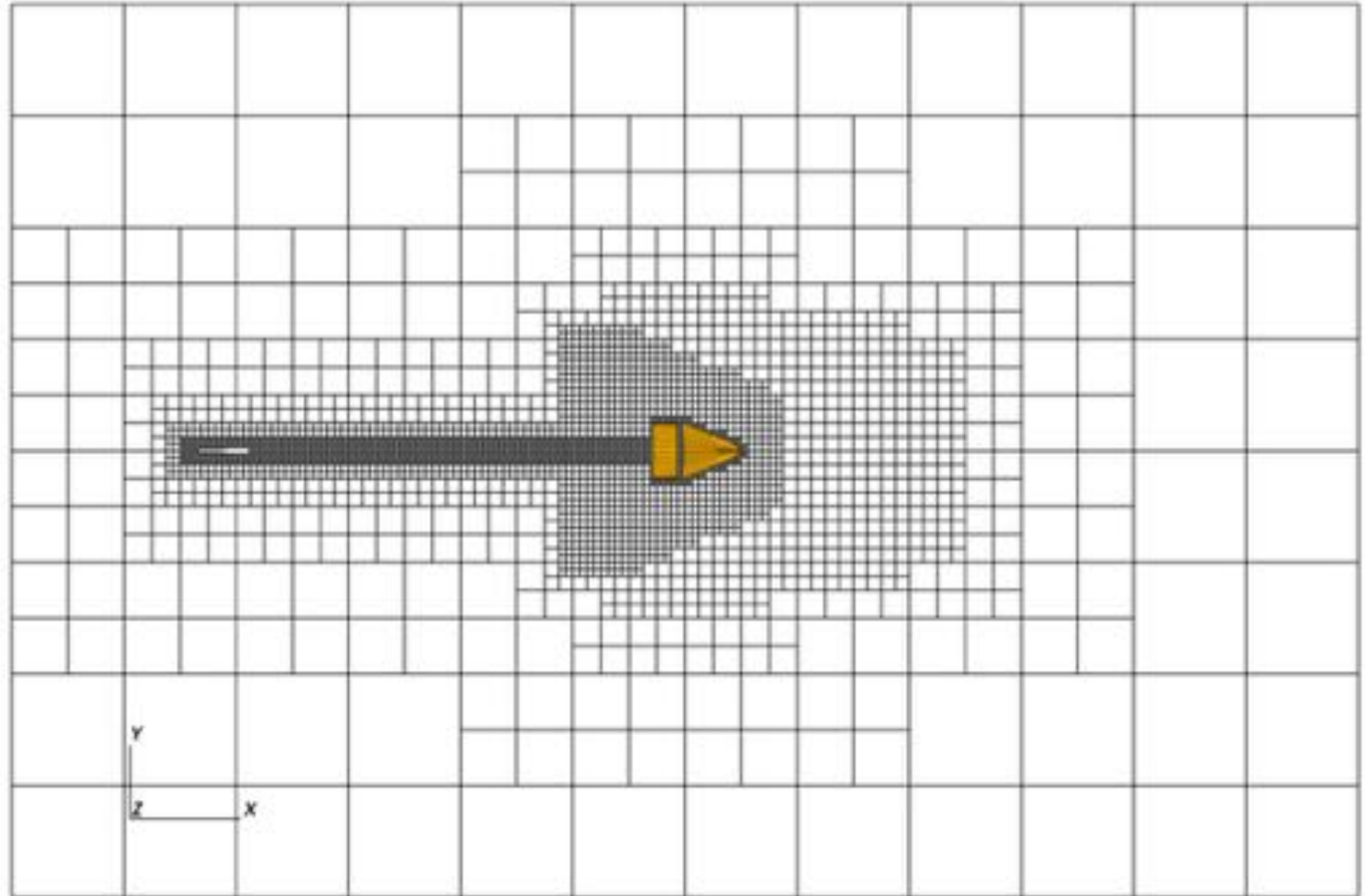


Animation showing parachute inflation from a structural-only simulation to evaluate the contact identification and enforcement algorithm. The CSD solver is exposed to a constant surface normal force.

Initial Cartesian AMR Grid For ASPIRE FSI

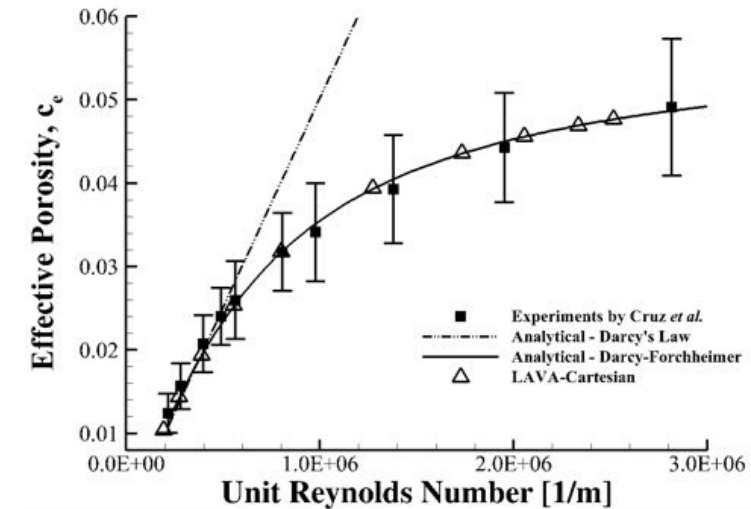
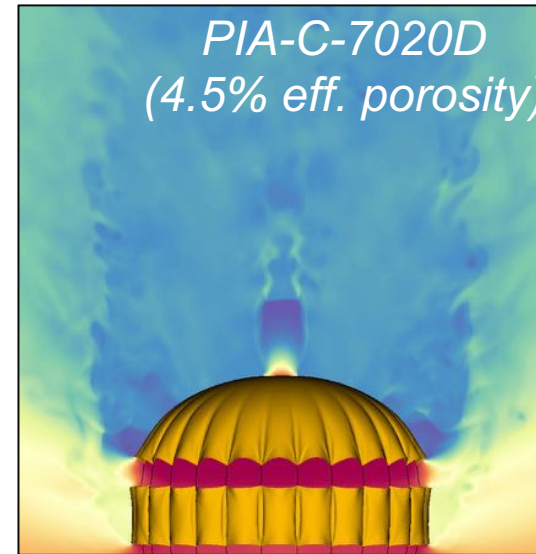
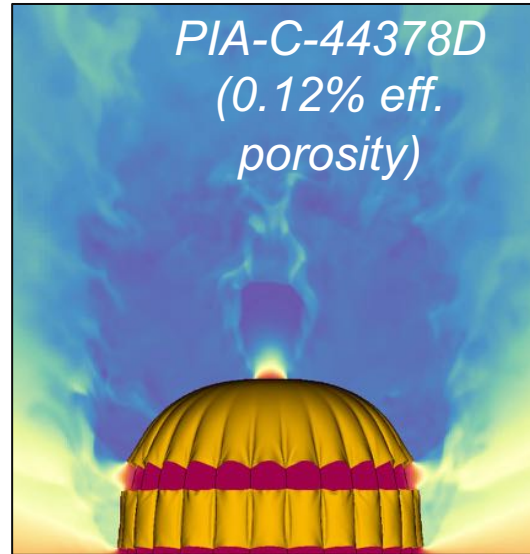
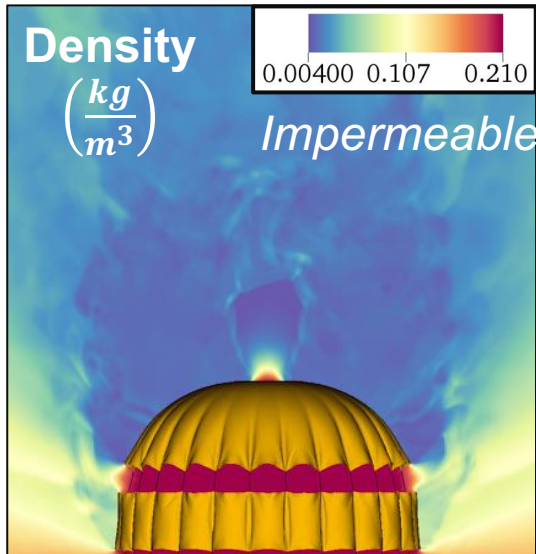


- Each box contain 16^3 cells
- AMR is used to ensure parachute canopy is surrounded by fine grid cells during inflation
- Finest cells have $\Delta x = 2.4cm$, and every subsequent level is twice larger in all directions



Modeling Parachute Porosity

- Obtain closed-form solution to Darcy-Forchheimer momentum equation through porous material (7.62×10^{-6} m thickness)
- Apply solution as a jump conditions in CFD to avoid requirement to resolve flow through the parachute's woven fibers (e.g. typical source term models)

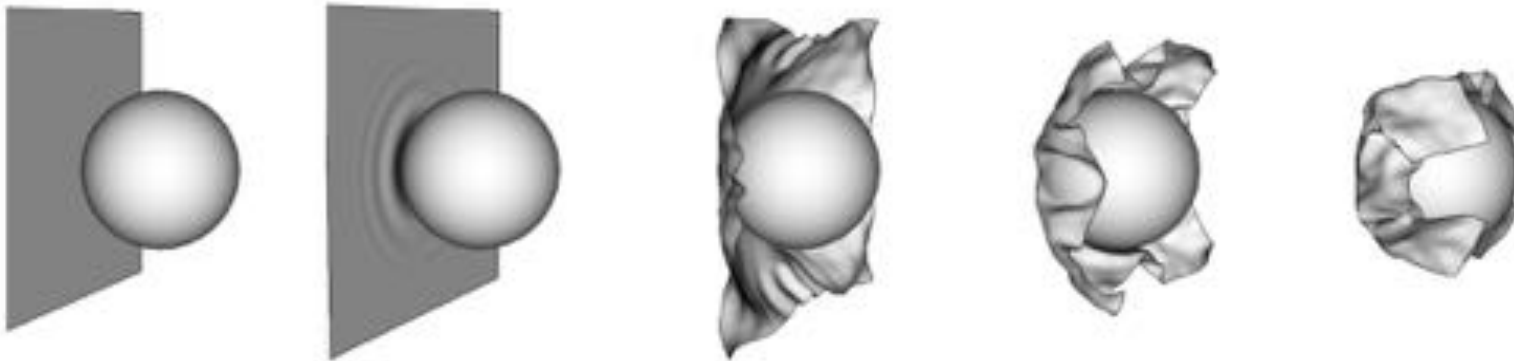


Comparison of results from experiments by Cruz *et al.* and simulations by LAVA-Cartesian for PIA-C-7020D Type I broadcloth.

- Higher porosity $\rightarrow$ weaker recirculation $\rightarrow$ more stable dynamics

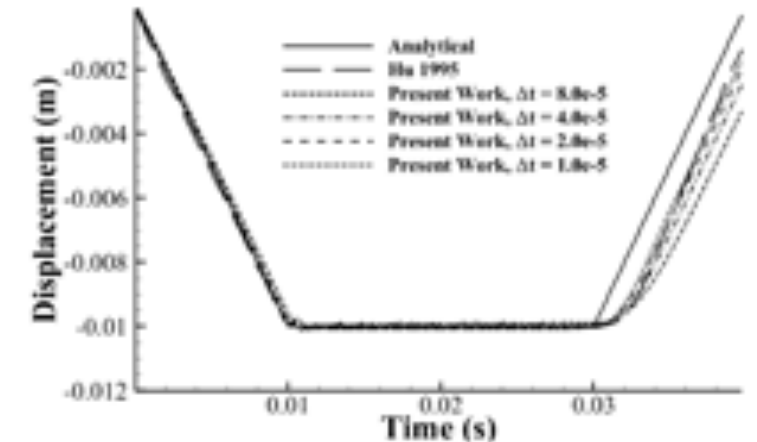
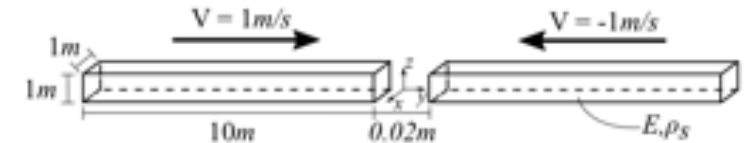
Modeling Contact Mechanics

- Before communicating aerodynamic forces to structural solver, identify triangles on surface who could soon come into contact by checking if ray traced from one triangle face pierces another within a given distance
- If a pair of triangles have velocities that will close the gap between them and cause contact to occur, we add a momentum force that models an elastic collision: this allows contact without surface (self-) intersections



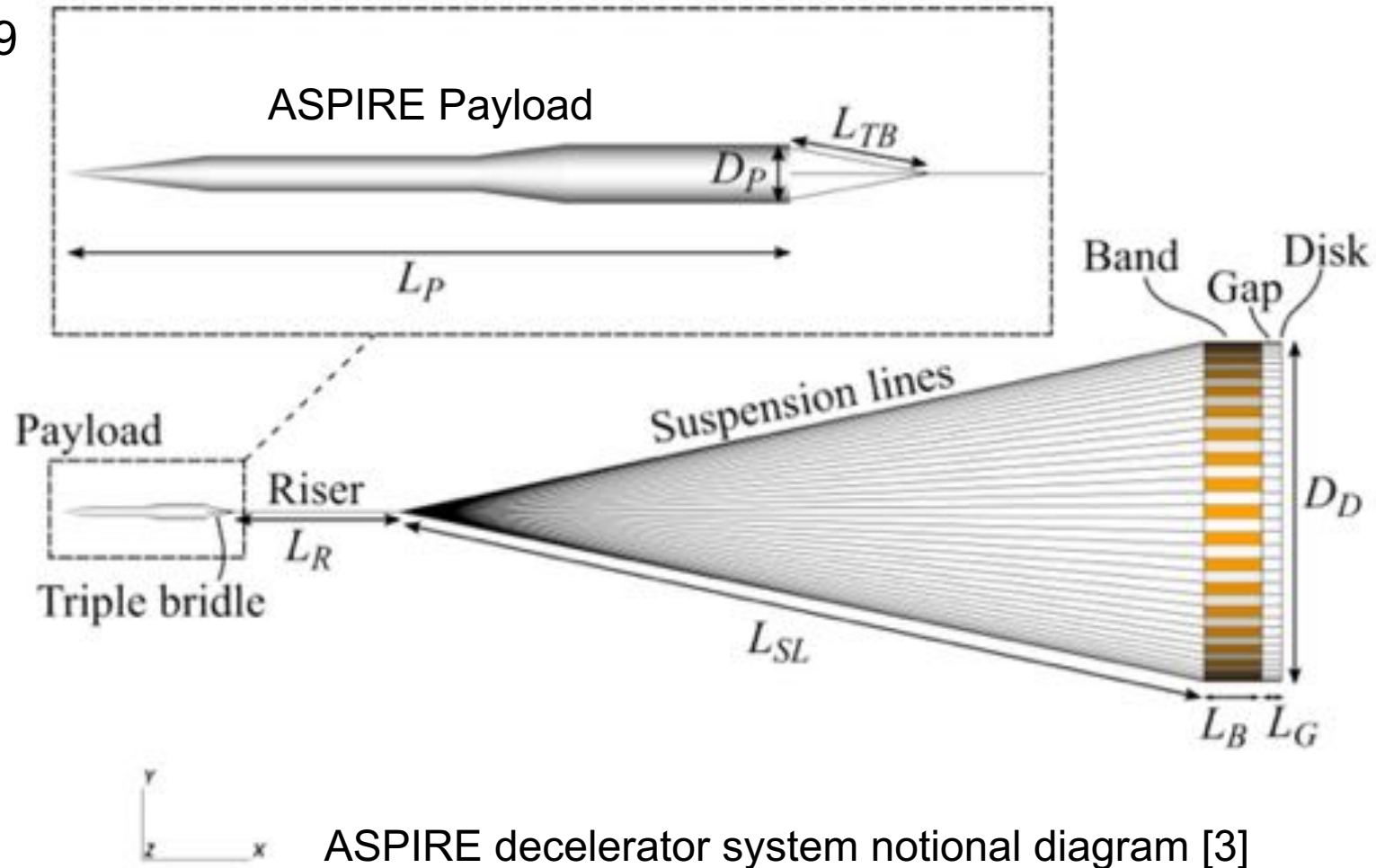
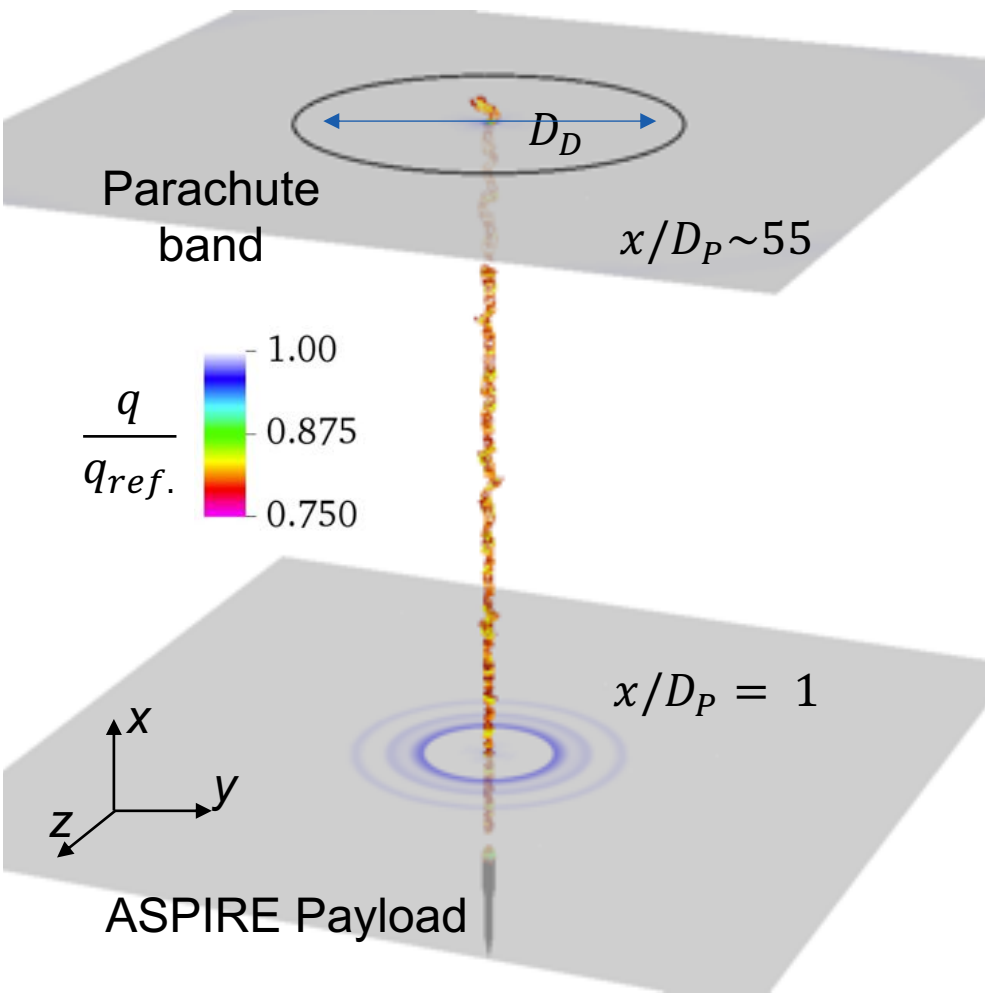
Snapshots in time of a test case demonstrating the contact identification and enforcement method

Setup and results from a canonical 1D contact problem



ASPIRE Payload Wake

- ASPIRE tests used a slender payload instead of blunt aero-shell like that of Mars 2020
- Freestream Mach number ~ 1.79

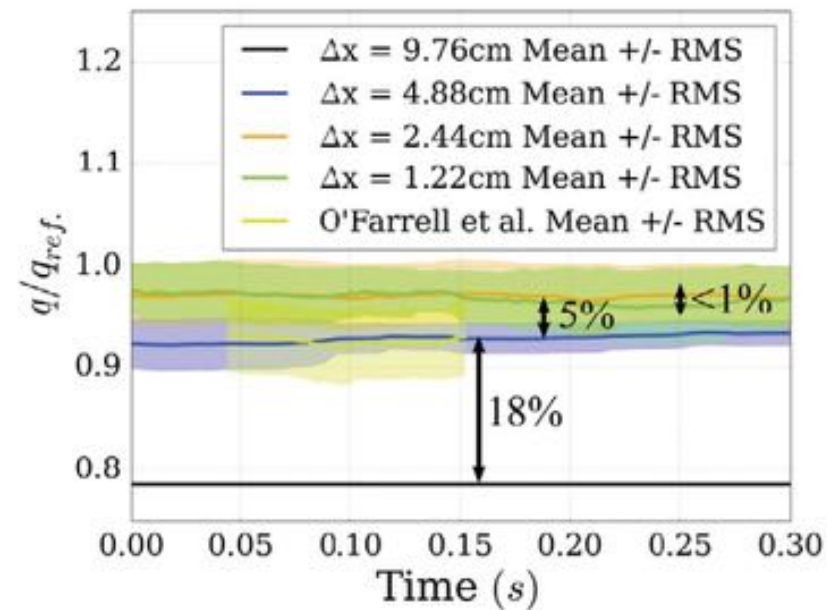


[3] Boustani, J., Cadieux, F., Kenway, G. K., Barad, M. F., Kiris, C. C., and Brehm, C., "Fluid-structure interaction simulations of the ASPIRE SR01 supersonic parachute flight test," Aerospace Science and Technology, 2022, p. 107596

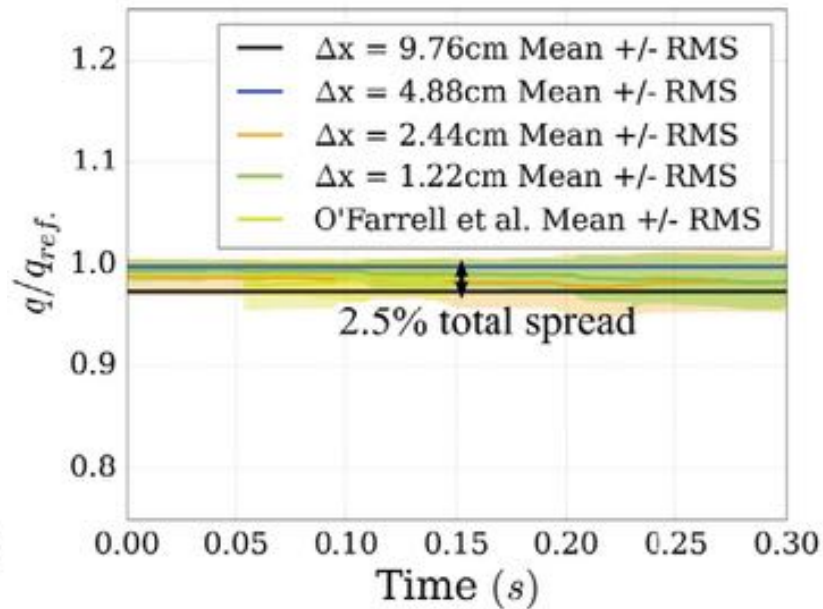
ASPIRE Payload Wake Deficit



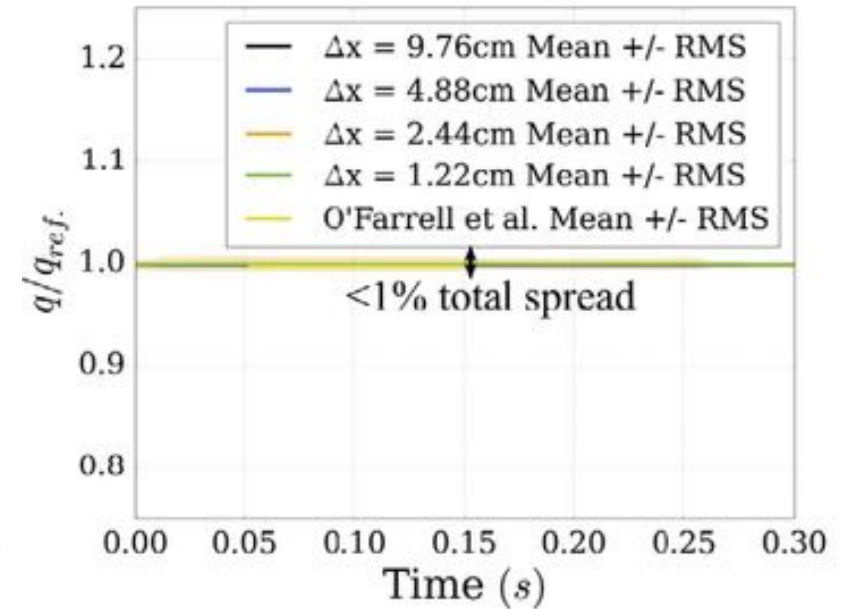
CFD Grid Convergence Study Results



$$x = 55 D_P, y = 0.5 D_P$$



$$x = 55 D_P, y = D_P$$



$$x = 55 D_P, y = 2 D_P$$

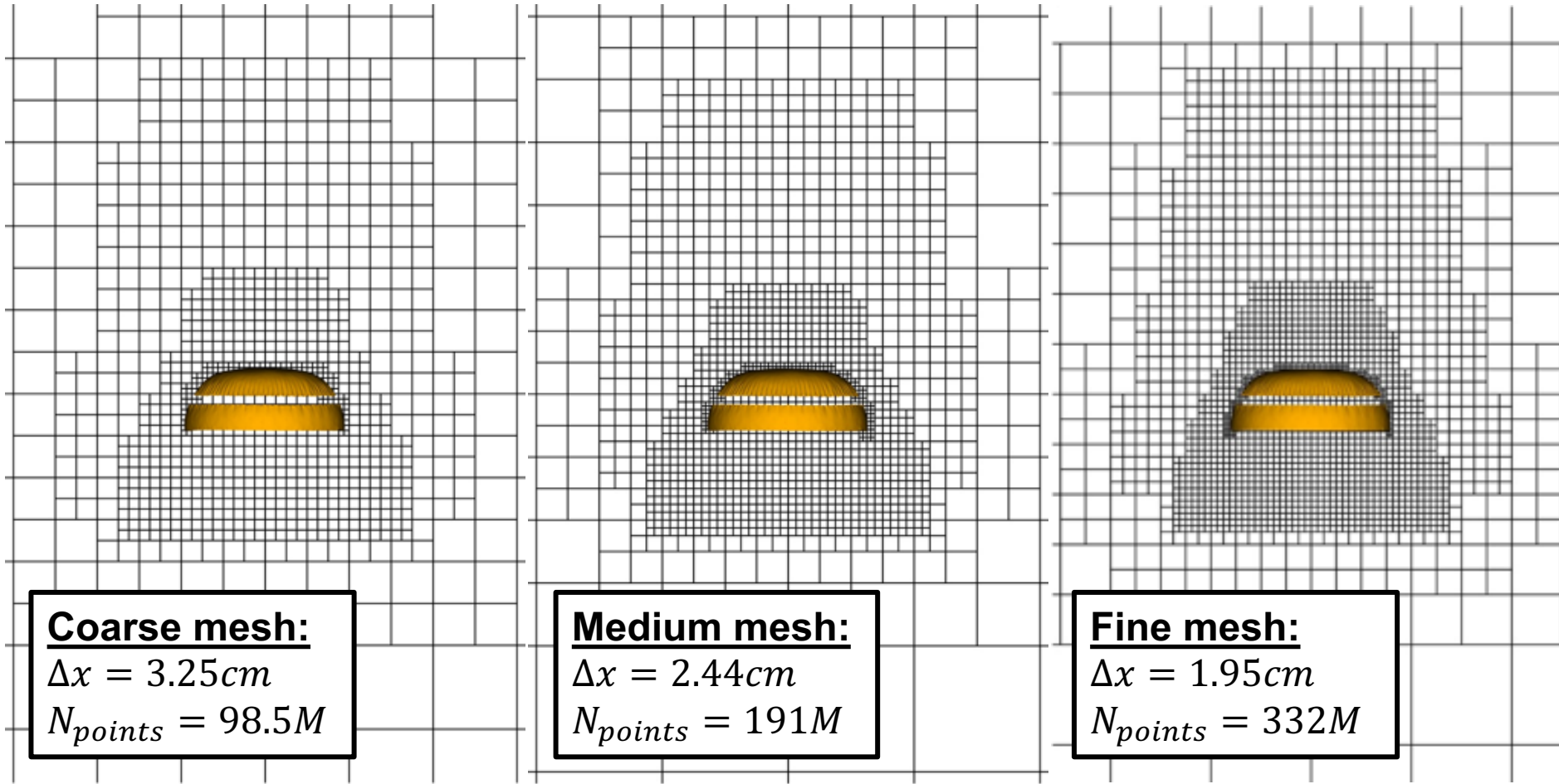
- Wake deficit is minor and very narrow
- < 1% change going from $\Delta x = 2.44 \text{ cm}$ to $\Delta x = 1.22 \text{ cm}$
- $\Delta x = 2.44 \text{ cm}$ is sufficient to capture wake deficit

ASPIRE Inflated Static Canopy

CFD Grid Convergence Study

Grids are uniformly refined by factors of $2^{1/3}$ so the total number of cells doubles each time

Same freestream conditions as experience during test when suspension lines first record tension (aka line-stretch event): Mach number ~ 1.79



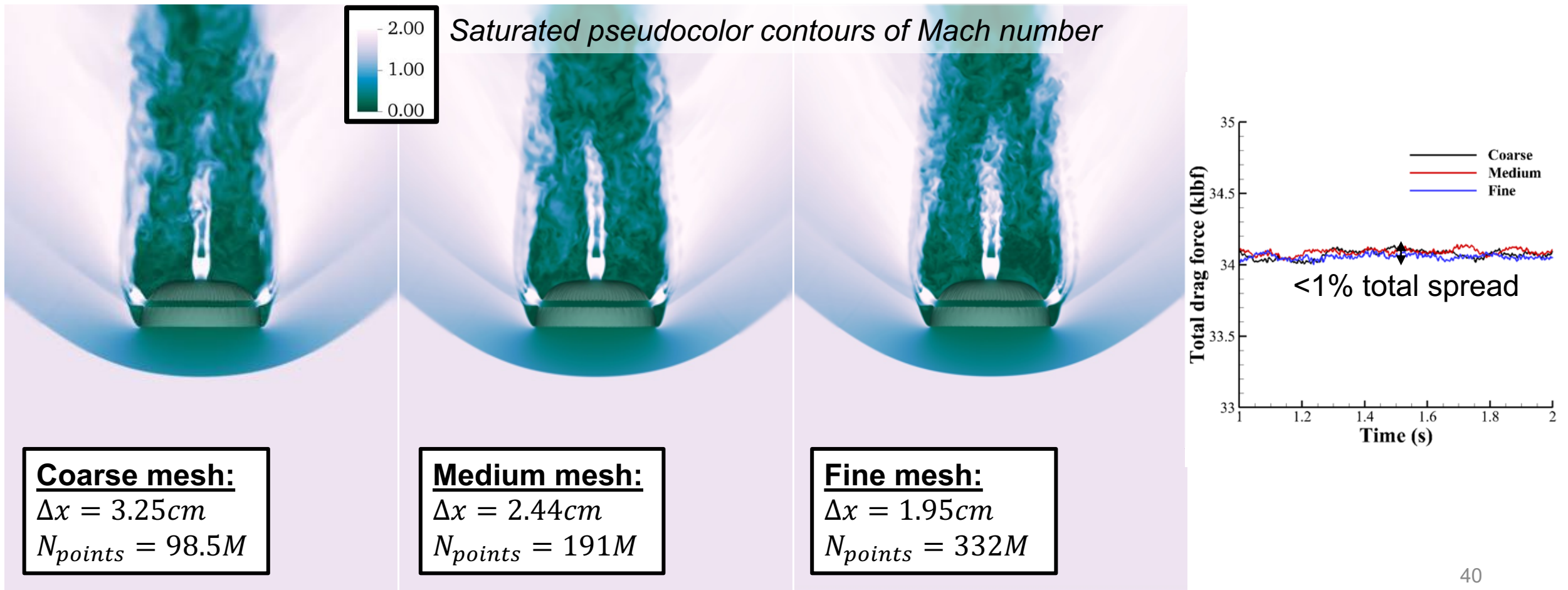
ASPIRE Inflated Static Canopy



CFD Grid Convergence Results

Integrated drag is already converged with $< 1\%$ difference between all resolutions tested

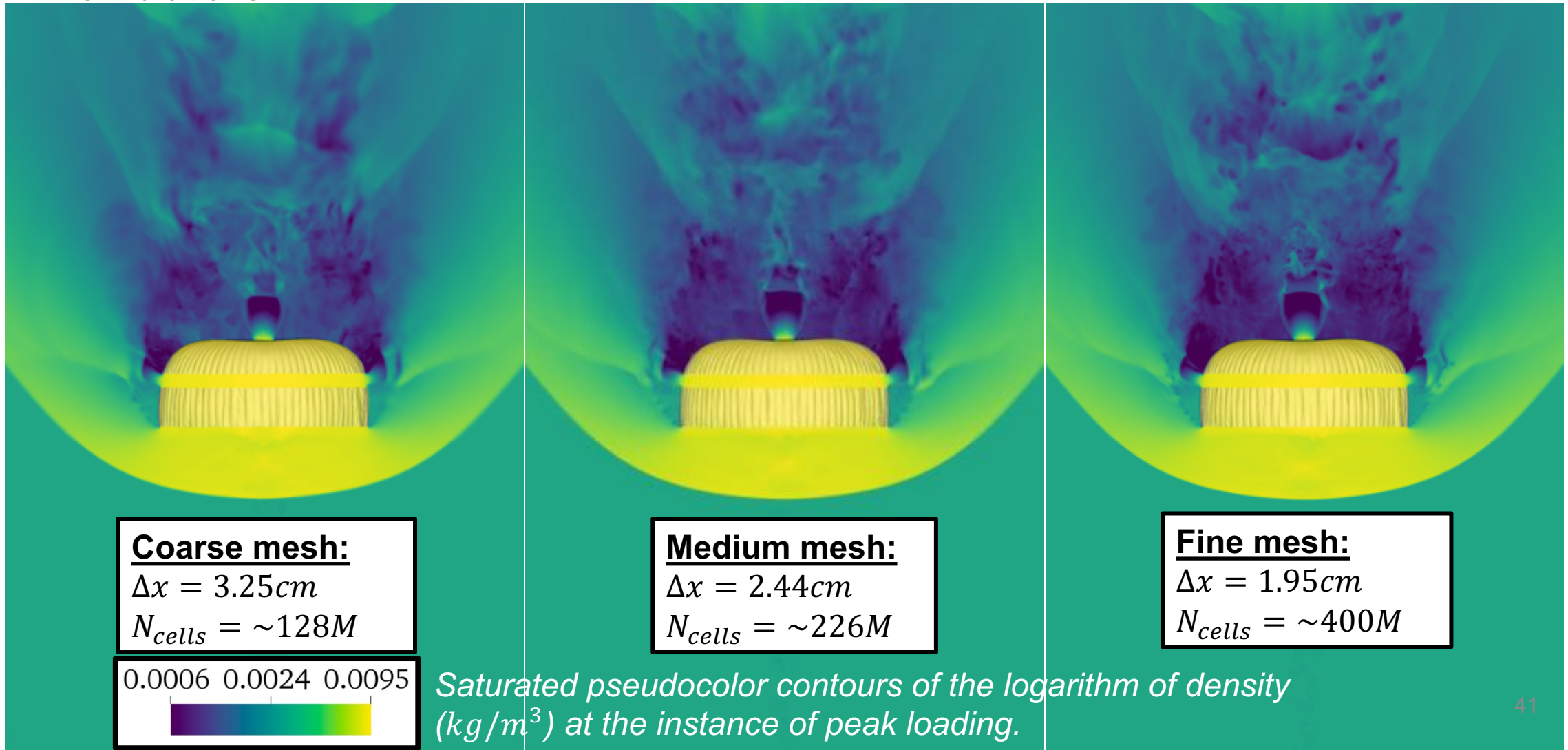
Only noticeable difference is the level of detail captured in wake turbulence



ASPIRE FSI Grid Convergence Study



- In order to ensure differences between FSI and flight test are not due to CFD resolution, we coarsen by $2^{1/3}$ and refine by $1/2^{1/3}$ every cell in the domain and perform two more simulations



Possible Sources of Error



1. Numerical Error

- Occurs whenever the spatio-temporal scales of motion in the problem simulated are not sufficiently resolved
- Reducing this error is a matter of reducing $(\Delta t, \Delta x)$ while still integrating a large enough time interval to capture phenomenon of interest
- Grid convergence studies can provide an estimate of converged value of a quantity of interest (e.g. pull-force) and a measure of uncertainty related to numerical error

2. Modeling Error

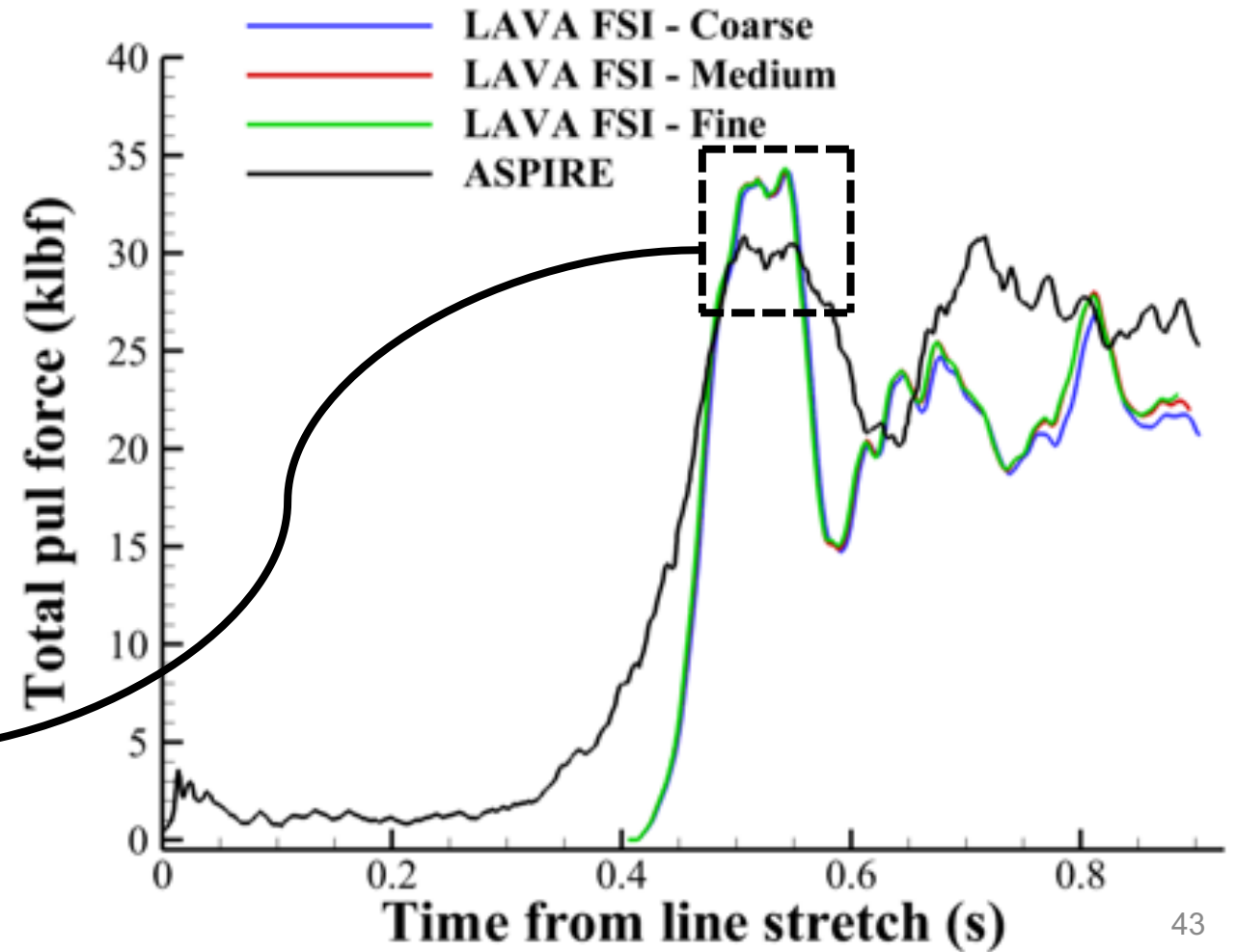
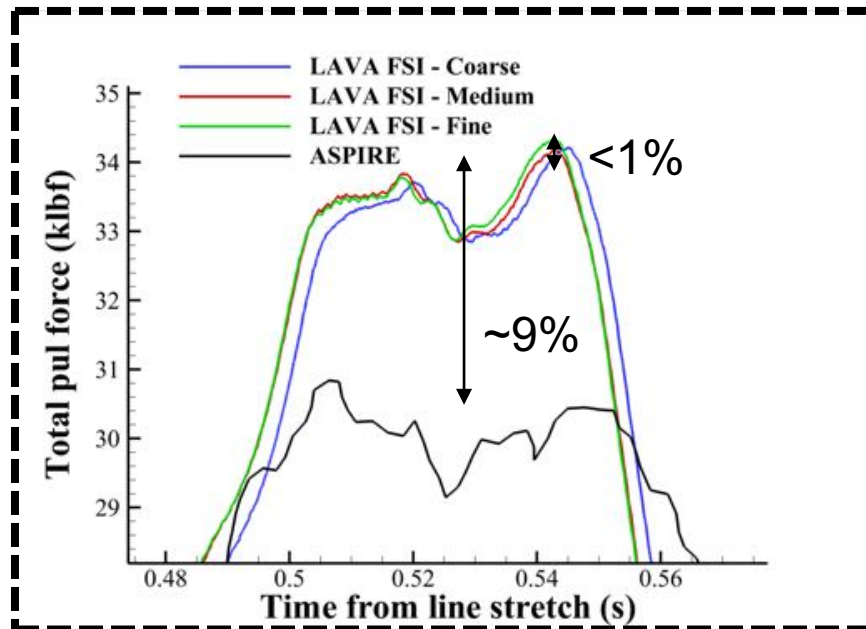
- Modeling error occurs every time a simplifying assumption is made that does not fully represent the underlying physics
- Bounding this error requires obtaining the degree of sensitivity of quantities of interest to assumptions made by either removing or changing them one at a time
- Expert knowledge of the problem is often required to identify the assumptions that are most likely to cause significant changes in the quantity of interest

Assessing numerical and modeling errors are both computationally costly!

ASPIRE FSI Grid Convergence Results



- Observed clear convergence behavior: Medium and Fine grid are on top of each other
- All 3 CFD grid resolutions predict inflation peak load within 1% of each other



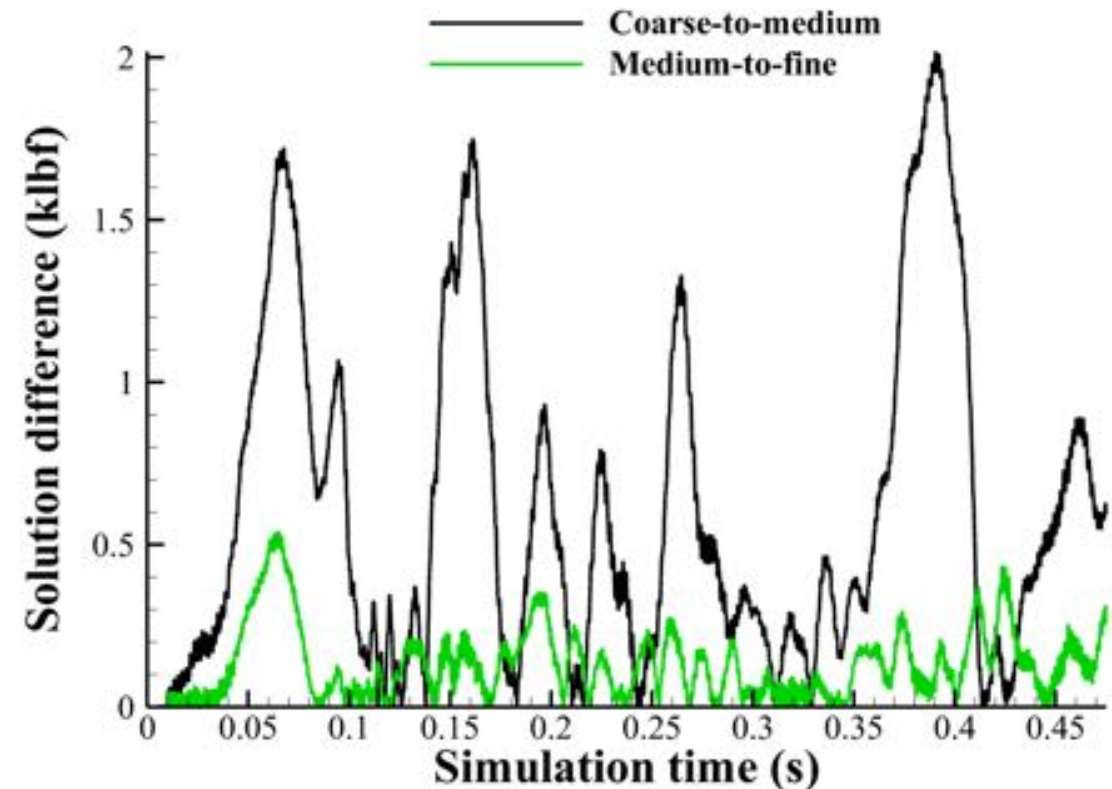
ASPIRE FSI Grid Convergence Results



- Interpolate coarse and medium pull-force time curve onto fine and use mean difference from coarse-to-medium and medium-to-fine to compute a convergence rate
- CFD and CSD time integrator are 2nd order accurate, so obtaining 3rd order convergence indicates that spatial error from high-order shock capturing scheme dominates

For the available time interval

Error Norm	Convergence Rate
L-1	2.99
L-2	3.01
L- ∞	2.57



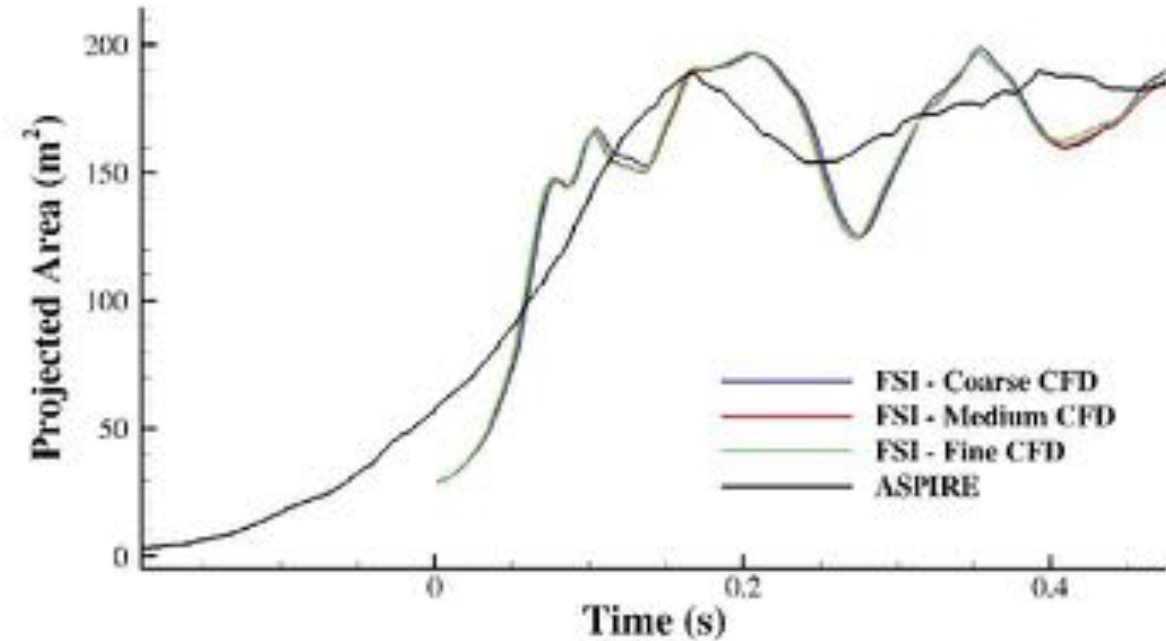
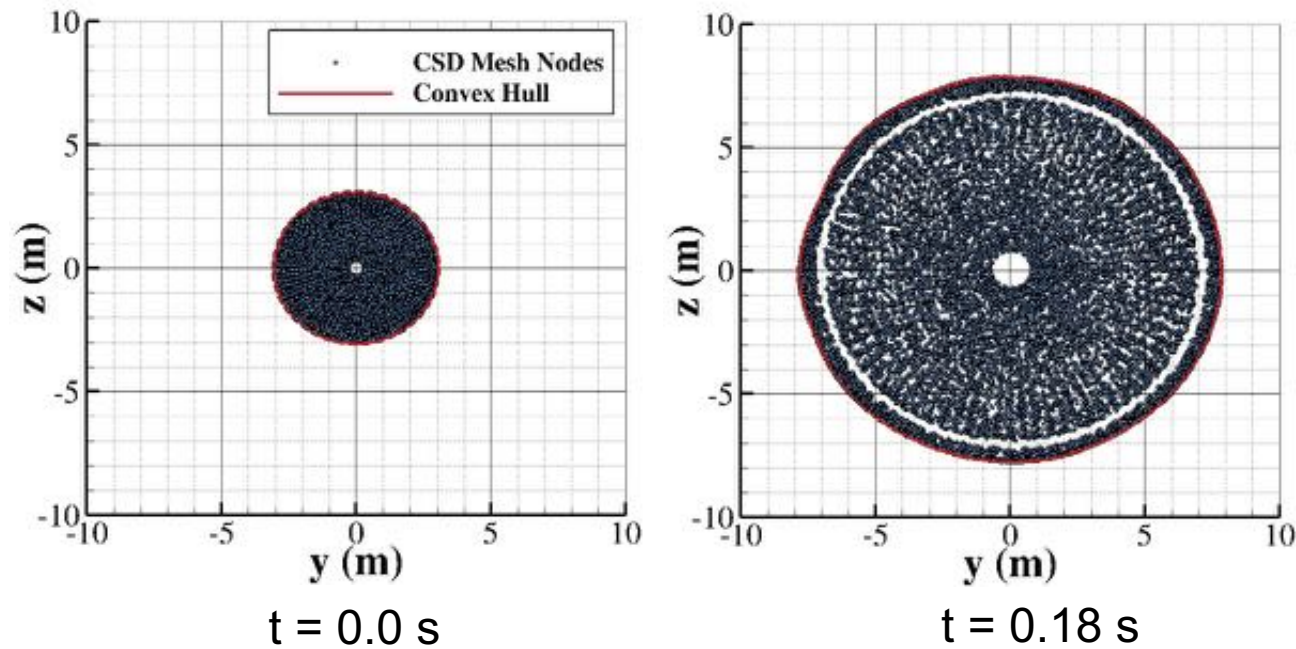
For more grid convergence metrics, please refer to [3]

[3] Boustani, J., Cadieux, F., Kenway, G. K., Barad, M. F., Kiris, C. C., and Brehm, C., "Fluid-structure interaction simulations of the ASPIRE SR01 supersonic parachute flight test," Aerospace Science and Technology, 2022, p. 107596

ASPIRE FSI Grid Convergence Results



- We can compute projected area in a similar fashion to ASPIRE test
- All 3 CFD grid resolutions predict inflation peak projected area within 1% of each other
- FSI shows faster inflation and deeper rebound than measured during ASPIRE SR01



Computational Cost of FSI Simulations



Computational Cost

CFD Grid Cells	CSD Degrees of Freedom	Number of Cascade Lake CPU Cores	Wall time (hours)	Core-hours x10 ³
Coarse (~123M)	Medium (1.26M)	1600	32	51.2
Medium (~226M)	Medium (1.26M)	960	67	64.3
Fine (~400M)	Medium (1.26M)	2400	70	168.0
Medium (~226M)	Fine (2.22M)	2400	58	139.2

- Turnaround time on coarse mesh is just over 24 hours: could enable system level studies
- Computational cost doesn't scale linearly: current bottleneck is not CFD or CSD solver themselves, but the operations required to robustly handle the large, sometimes concave, deformations of parachute for immersed boundary conditions and aero-loads: these operations scale with the number of triangles on the surface, and the number of CFD cells bounding the parachute.