



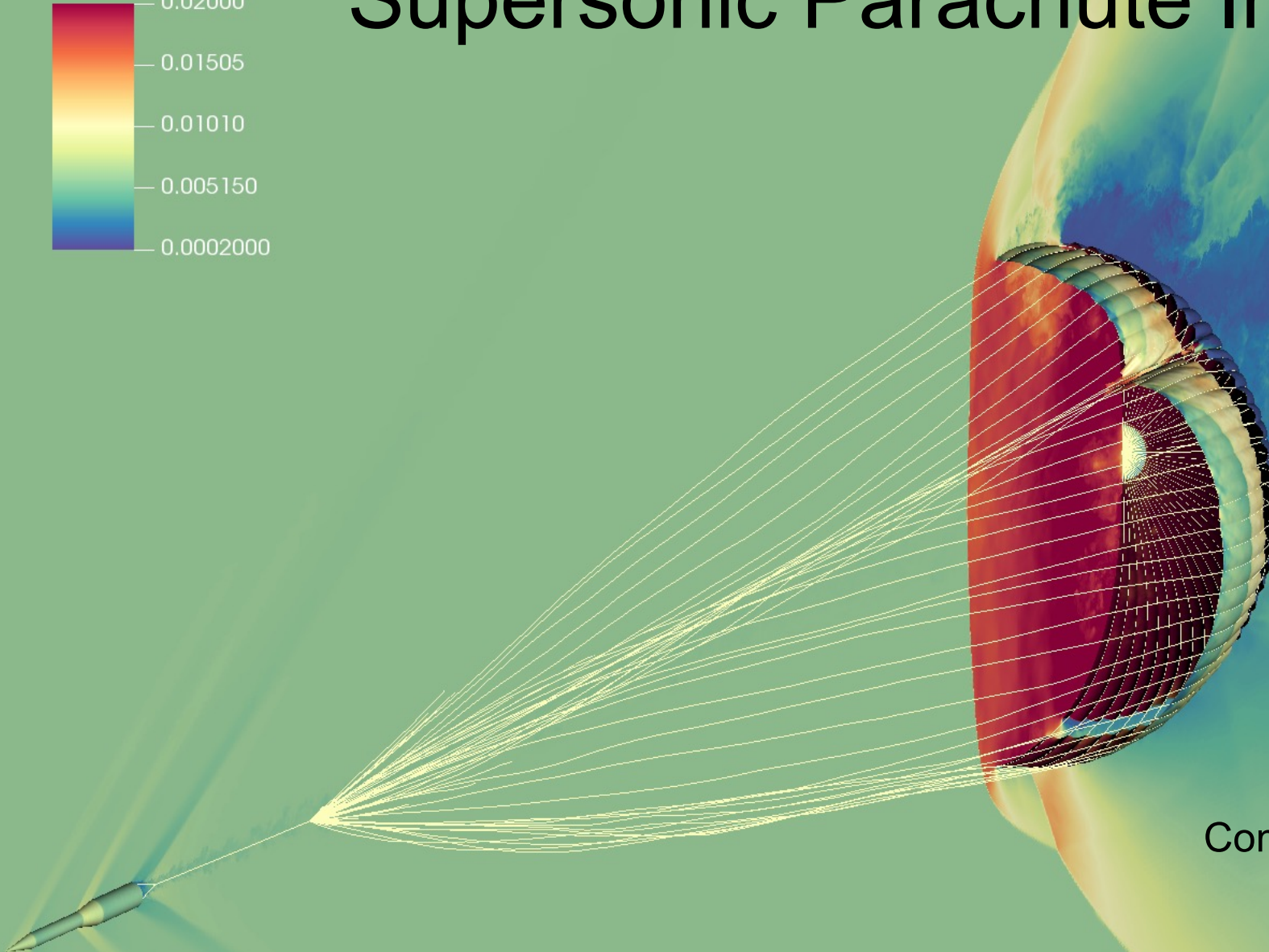
Wall-Modeled Large-Eddy Simulation of Supersonic Parachute Inflation

Time = 0.309738 s

Pseudocolor
Var: Density



0.02000
0.01505
0.01010
0.005150
0.0002000



Francois Cadieux
Michael Barad

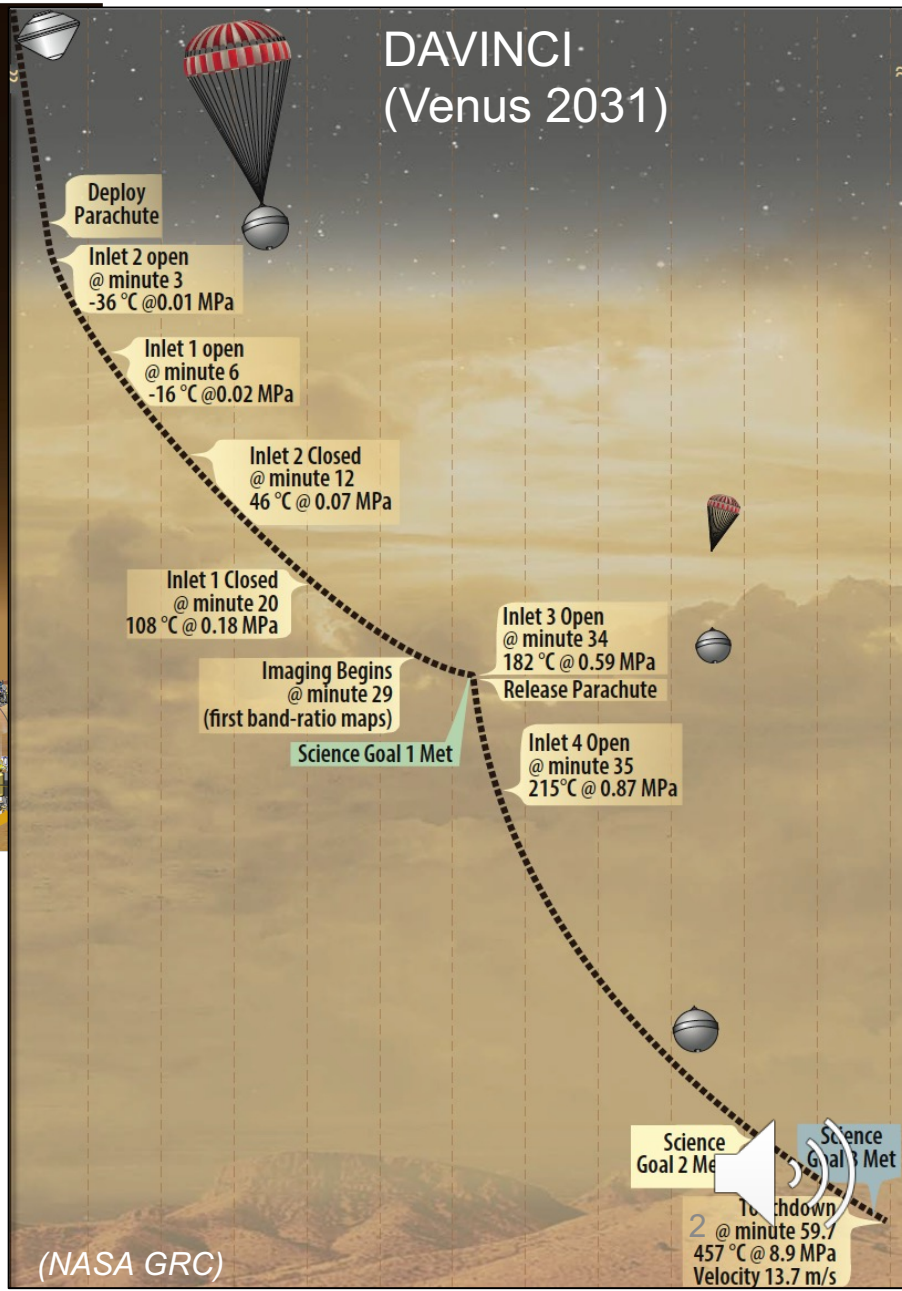
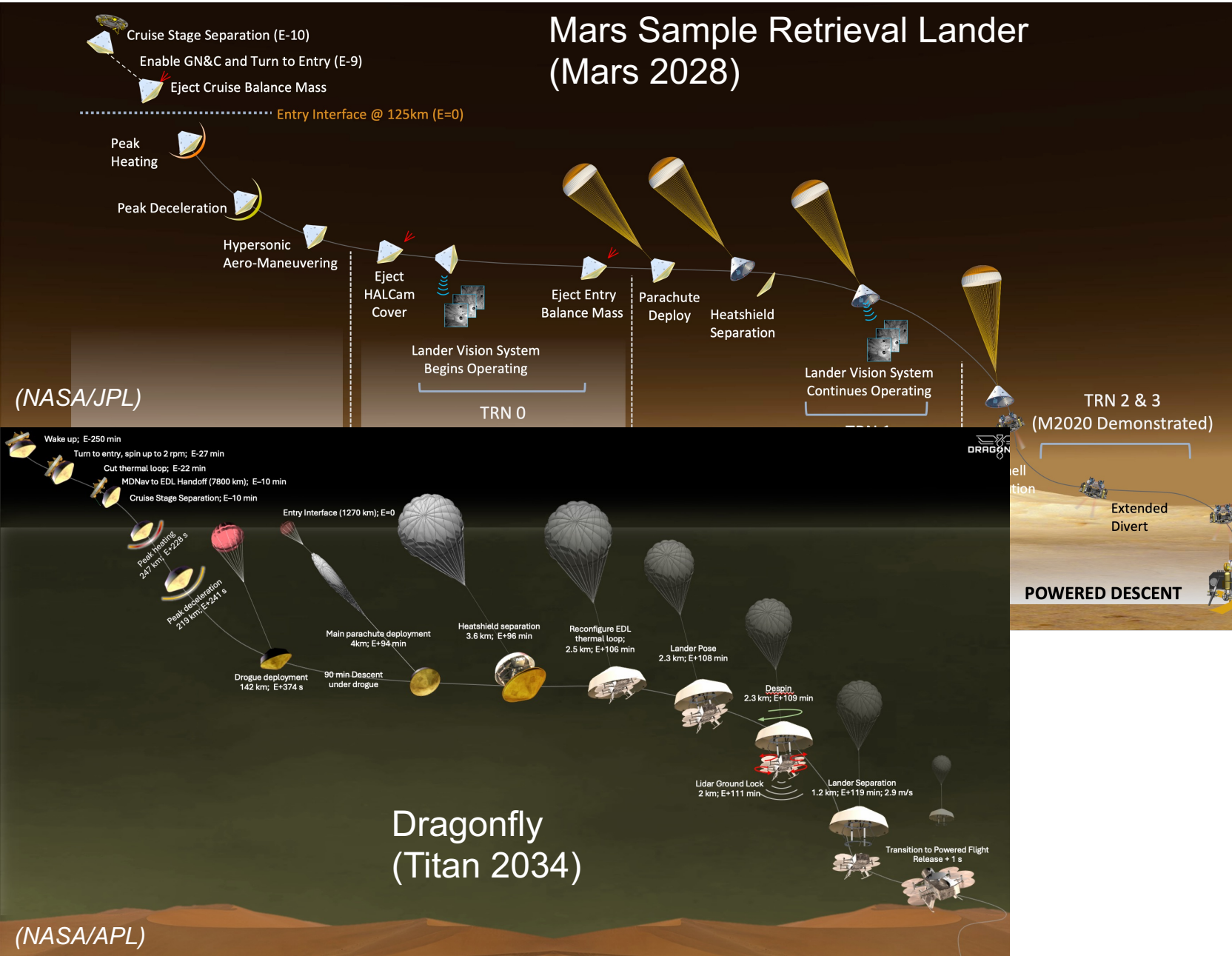
Launch, Ascent and Vehicle
Aerodynamics (LAVA) Team
Computational Aerosciences Branch
NASA Ames Research Center

Twelfth International Conference on
Computational Fluid Dynamics (ICCFD12),
Kobe, Japan, July 14-19, 2024



POC: francois.cadieux@nasa.gov

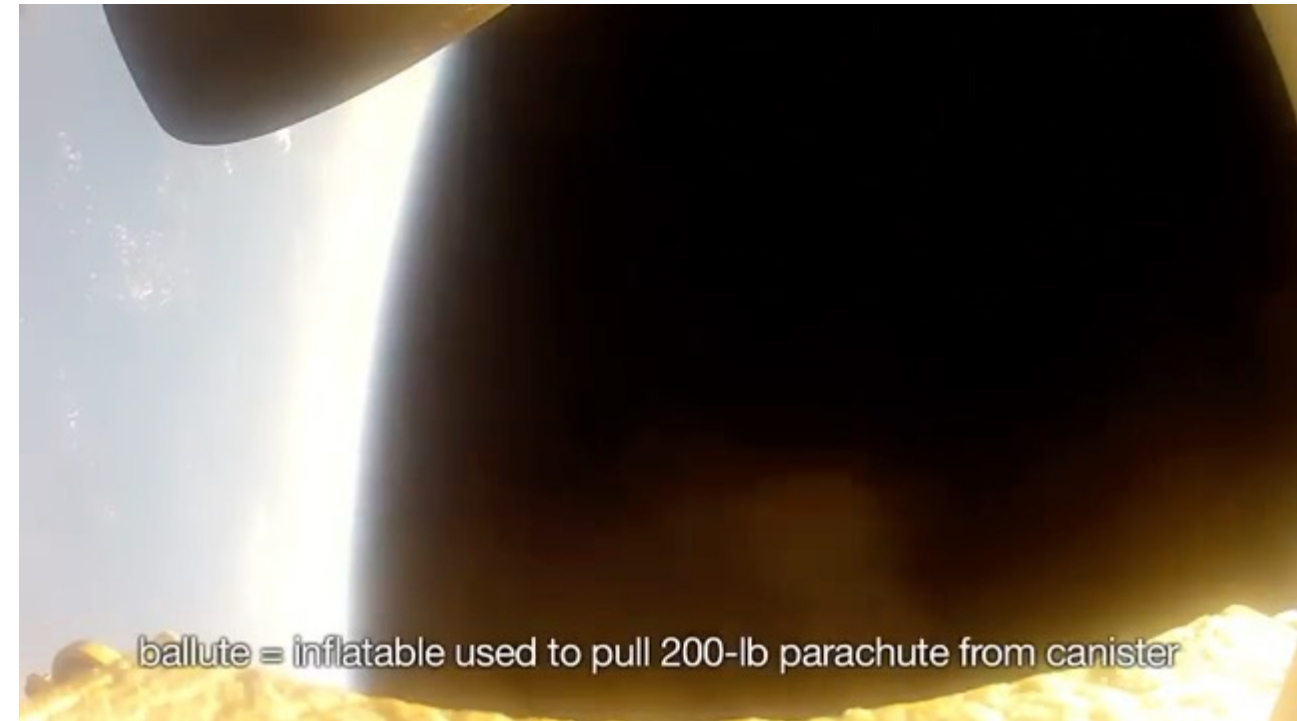
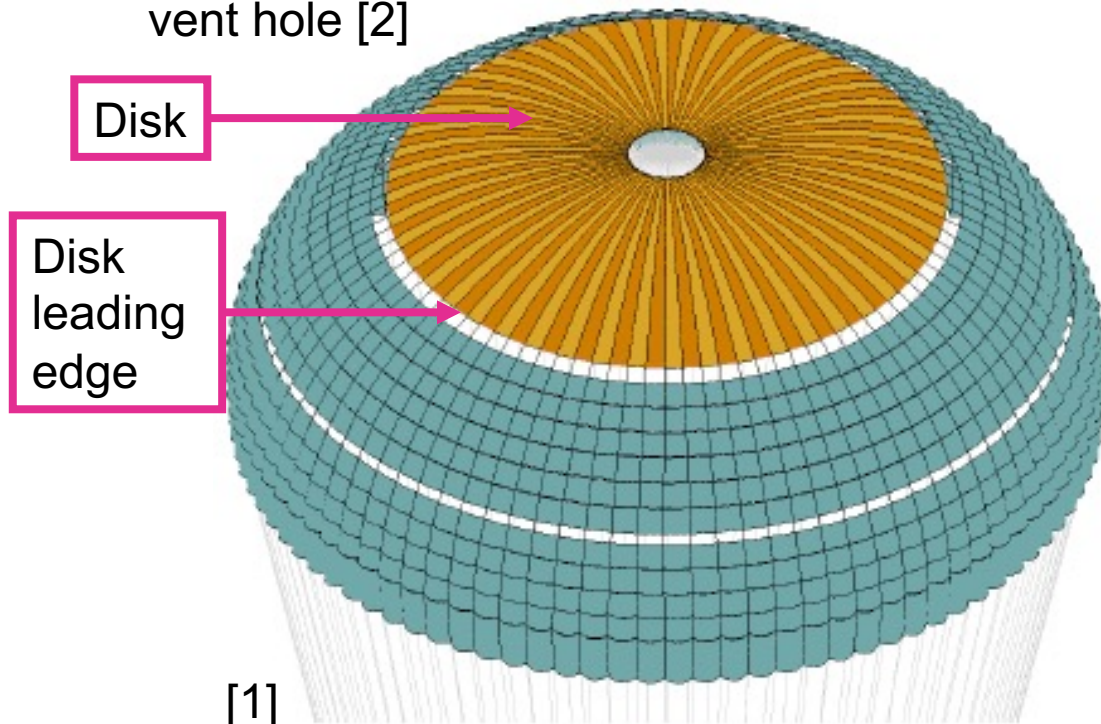
Supersonic Parachutes In Upcoming Interplanetary Missions



Motivation



- Low Density Supersonic Decelerator (LDSD) project flight tested a new parachute design called supersonic disksail (SSDS) that merges design elements of both a Ringsail parachute and a Disk-Gap-Band (DGB) parachute [1]
- The SSDS failed during inflation as soon as the disk was pulled taut with tears starting at the leading edge and propagating inward to the vent hole [2]



LDSD Flight Test Video. Credit: NASA JPL

<https://www.youtube.com/watch?v=9yRW hu0UGYw&t=74s>

- [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, AIAA# 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, AIAA# 2130



Why Simulate Supersonic Parachute Inflation?



LDSD demonstrated that the performance or potential failure modes of new parachute designs could not be reliably predicted without flight tests in upper Earth atmosphere

Investigation into root cause of LDSD failure could not reproduce the failure with available modeling tools

Fluid-structure interaction (FSI) simulations could bridge these gaps, once validated

Simplified FSI Diagram

Computational Fluid Dynamics (CFD)

Structural deformation/
velocities

Aerodynamic forces/tractions

Computational Structural Dynamics (CSD)



Problem Statement



- Validate FSI by simulating the Advanced Supersonic Parachute Inflation Research Experiments (ASPIRE) third flight test SR03
- Only consider simulating from the moment suspension lines record significant loads (line stretch) to when the system has reached stable deceleration phase (~1 second later)
- Target is to accurately predict inflation time, inflation rate, peak, trough, and rebound parachute force (loads) because these are reproducible across flights

Testing a Parachute for Mars



Jet Propulsion Laboratory
California Institute of Technology

This high-definition video was taken on Sept. 7, 2018, during the third and final test flight of the Advanced Supersonic Parachute Inflation Research Experiments (ASPIRE) campaign to certify the Mars 2020 parachute. It was the fastest inflation of this size parachute in history and created a peak load of almost 70,000 pounds of force.

Credits: NASA/JPL-Caltech

<https://www.nasa.gov/feature/jpl/third-aspire-test-confirms-mars-2020-parachute-a-go>



ASPIRE SR03 Problem Statement

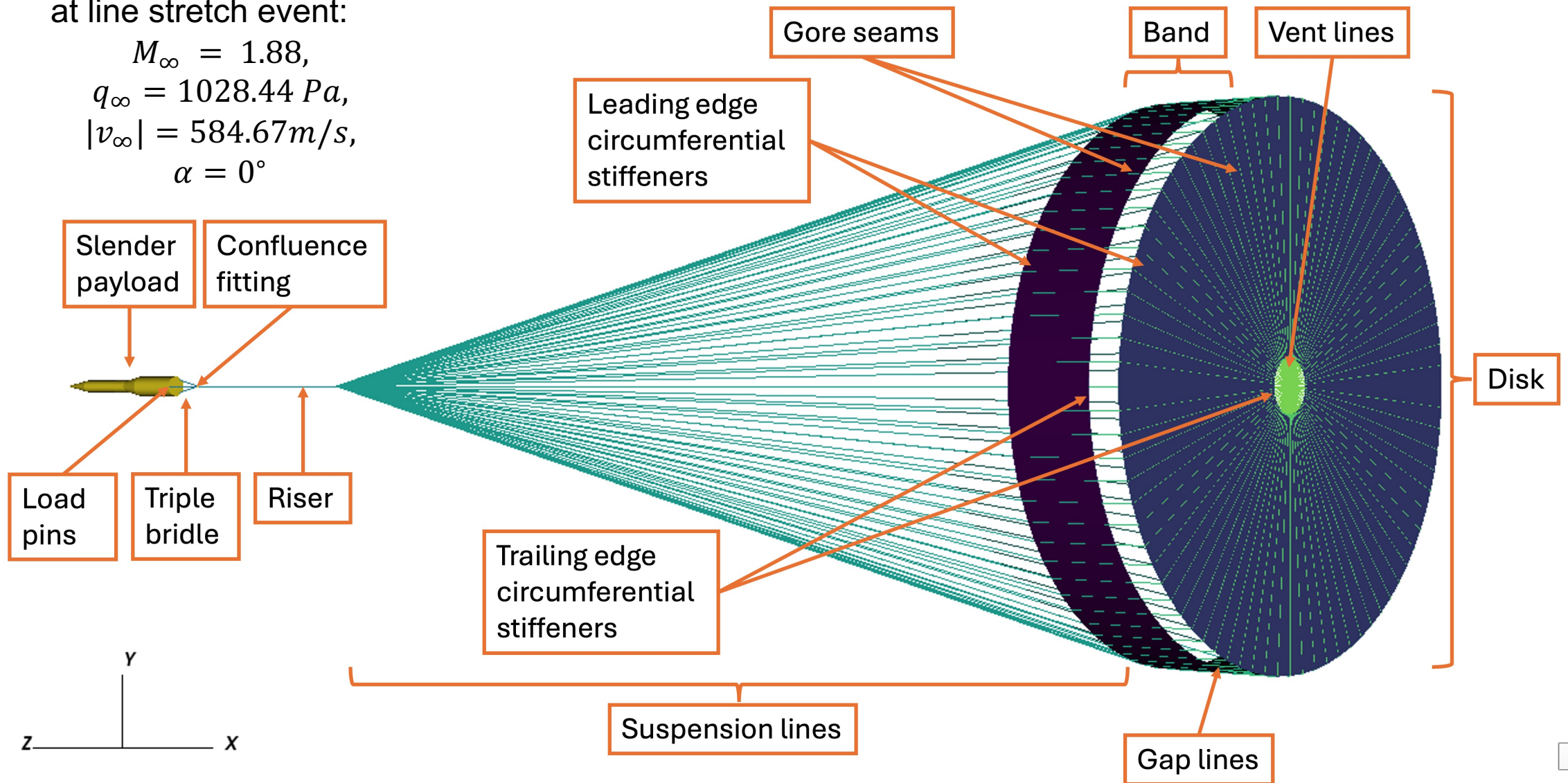
Freestream conditions
at line stretch event:

$$M_{\infty} = 1.88,$$

$$q_{\infty} = 1028.44 \text{ Pa},$$

$$|v_{\infty}| = 584.67 \text{ m/s},$$

$$\alpha = 0^{\circ}$$



Methodology: Overview



Launch, Ascent and Vehicle Aerodynamics (LAVA) FSI framework

Cartesian CFD Module

- Adaptive Mesh Refinement (AMR)
- Immersed boundary ghost cell method
- Porosity boundary condition
- Explicit Runge-Kutta time integration

Finite Element CSD Module

- Saint Venant-Kirchhoff hyperelastic model
- MITC3 shell elements for canopy fabric
- Timoshenko beams for lines
- Explicit central difference with damping

Free Flight Module

- Solves rigid body motion equations
- Coupled with aerodynamic forces from CFD and nodal forces from CSD
- Explicit Runge-Kutta time integration

Contact Mechanics Module

- Physics-based model based on momentum of fabric elements
- Solves for canopy self-contact forces that are input to CSD

For more details on the method, 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

<https://doi.org/10.1016/j.ast.2022.107596>



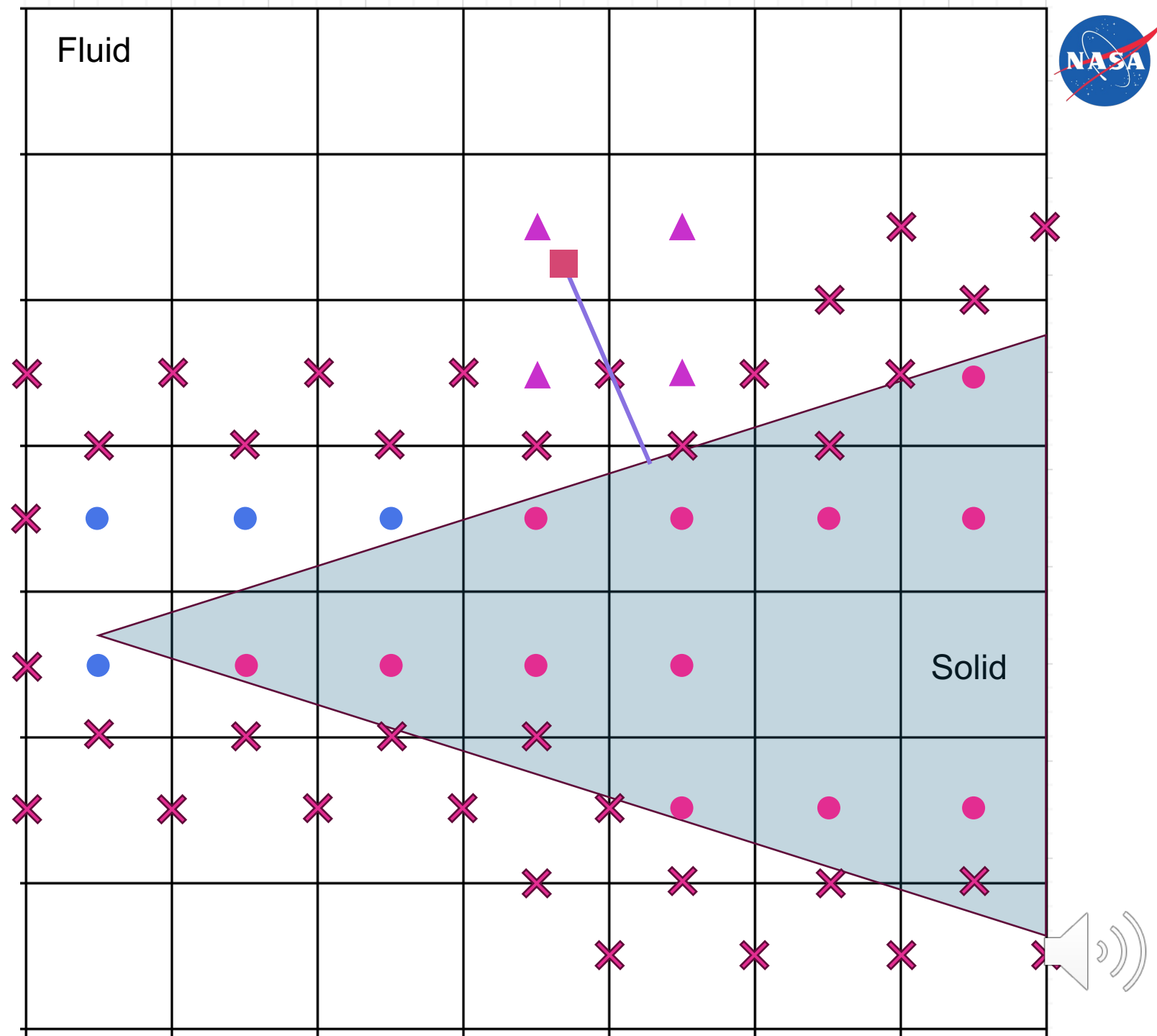
Immersed Boundary Wall-Modeled LES



- Immersed boundary ghost cell
- Immersed boundary ghost-in-fluid cell
- ✕ Face where viscous flux is corrected using wall shear stress from wall model
- Example wall model matching point* for given face center
- Vector from closest point on surface to face center extended to matching point
- ▲ Interpolation stencil points for example wall model matching point

Leverage simple algebraic wall model that approximates Musker's turbulent boundary layer profile

*Only one matching point shown

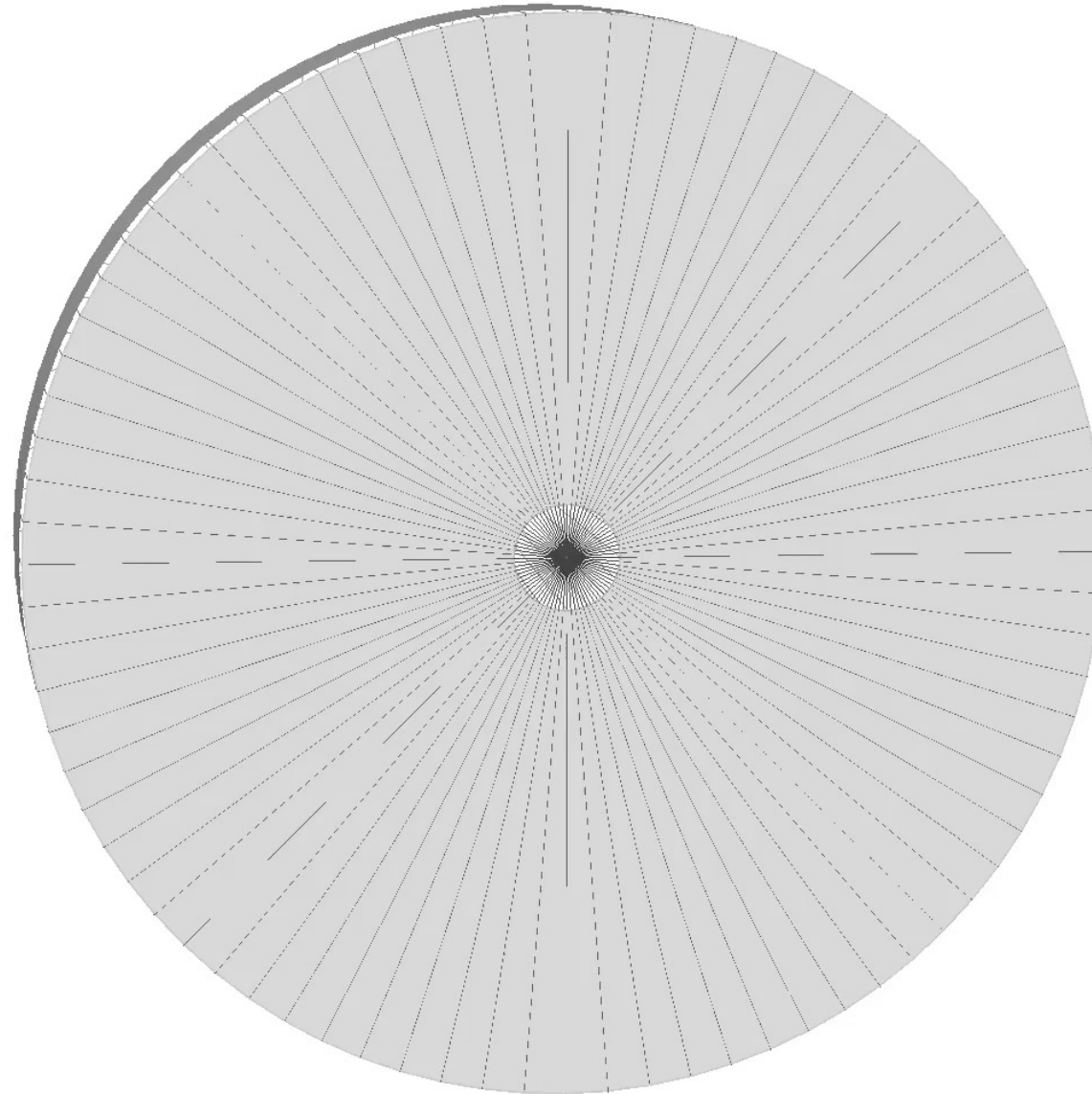


Novel Method To Get Initial Parachute Shape



Time = 0.00671424 s

- Perform structural dynamics with contact simulation of as-constructed parachute system with gravity in +x direction
- Bridle nodes attached to payload pinned in place
- Added simple line drag model with large drag constant to prevent suspension lines from bouncing back-and-forth
- Increased density of vent lines at t=7s to help fold canopy tighter



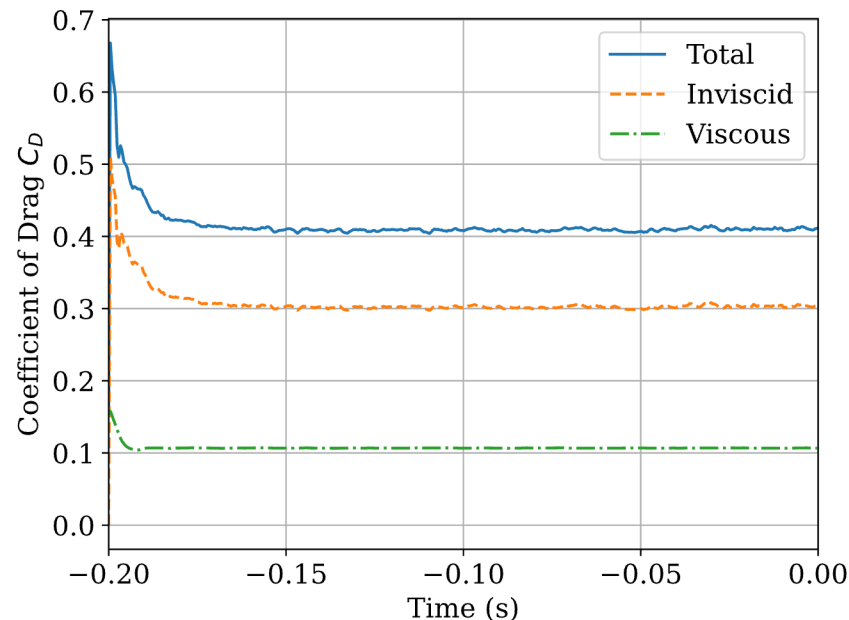
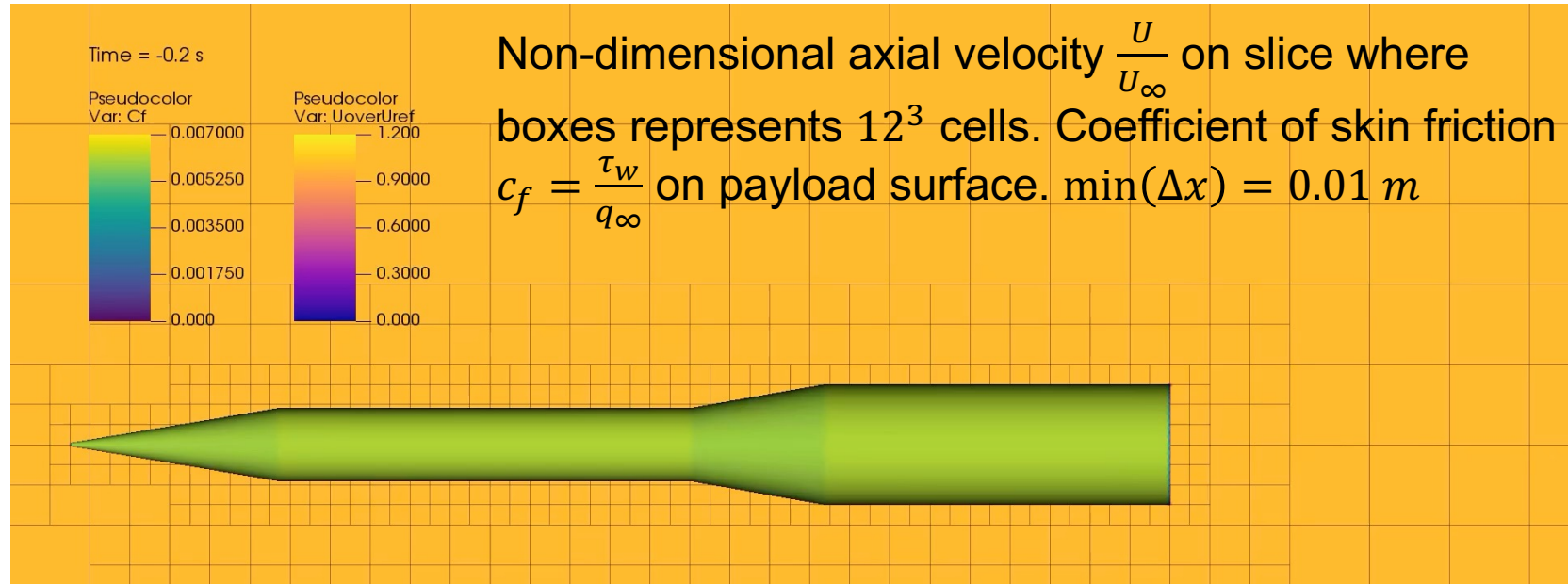
CPU Cost:
149k core-hours



Pre-FSI WMLES Of Payload



- Slender ASPIRE payload simulated for 0.2 seconds at line-stretch freestream conditions until aerodynamics load reach stationary state and wake reaches beyond parachute
- WMLES approach captures transition from laminar to turbulent boundary layer over payload, enhancing mixing in the wake
- Viscous forces represent nearly 20% of total drag on the payload, as expected from RANS simulations

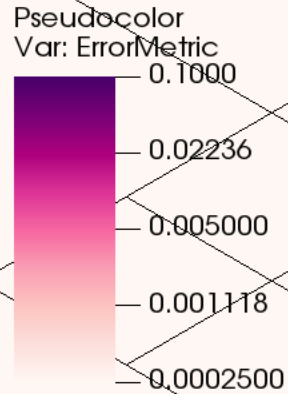


CPU Cost:
7k core-hours

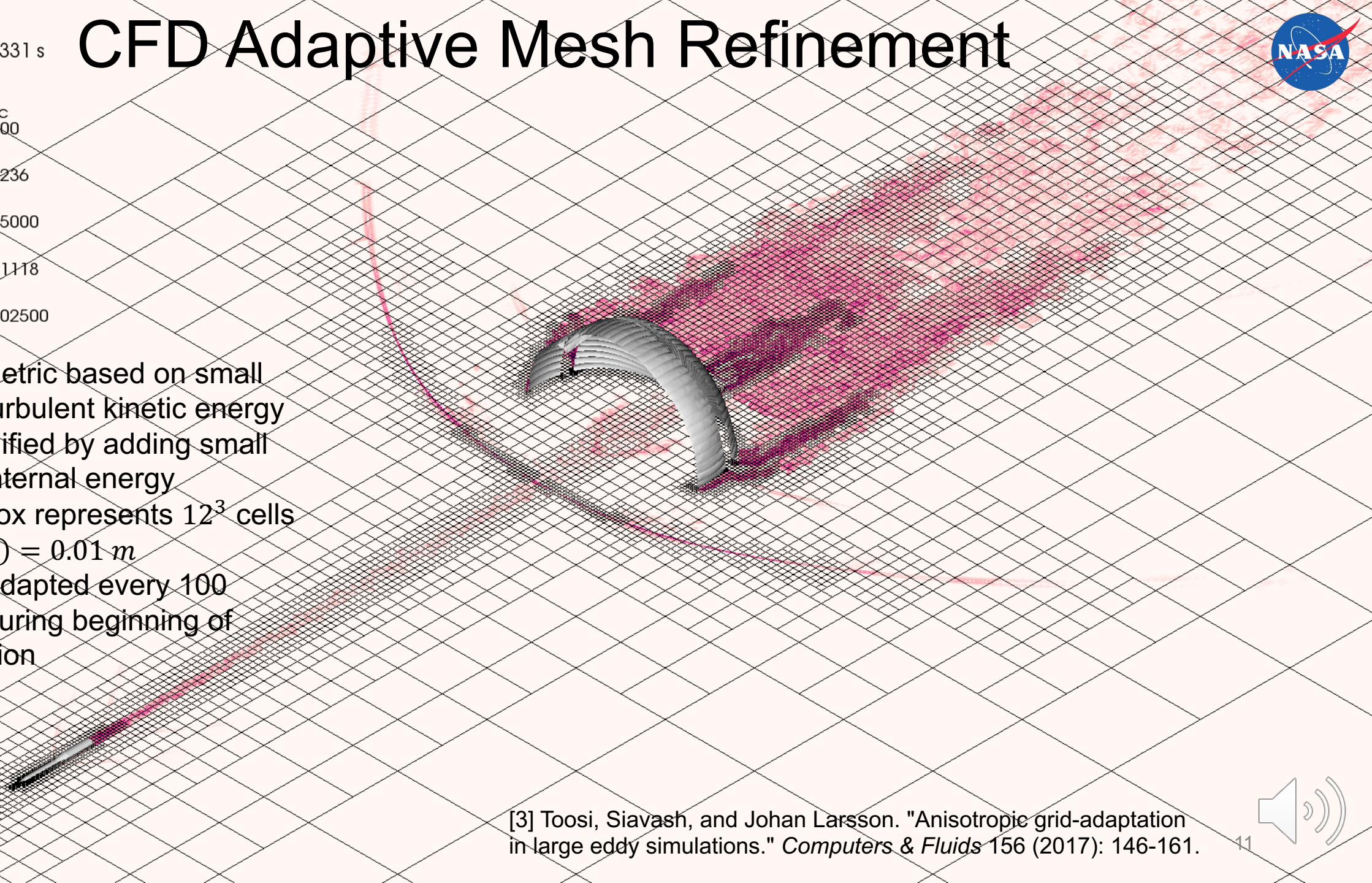


CFD Adaptive Mesh Refinement

Time = 0.449331 s



- Error metric based on small scale turbulent kinetic energy [3] modified by adding small scale internal energy
- Each box represents 12^3 cells
- $\min(\Delta x) = 0.01 \text{ m}$
- Mesh adapted every 100 steps during beginning of simulation



[3] Toosi, Siavash, and Johan Larsson. "Anisotropic grid-adaptation in large eddy simulations." *Computers & Fluids* 156 (2017): 146-161.

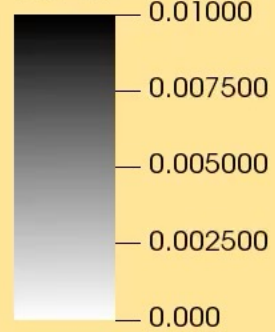


Results: FSI-WMLES Of ASPIRE SR03

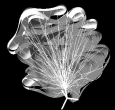
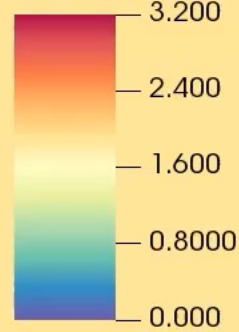


Time = -0.2 s

Pseudocolor
Var: Cf



Pseudocolor
Var: MachNumber



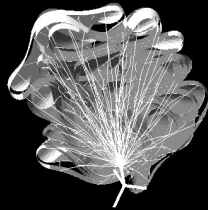
View from payload

Mach number on the slice and skin friction coefficient on the payload and canopy surface. Vent, gap, suspension, riser, and bridle lines shown in gray.

CPU Cost:
747k core-hours



Qualitative Comparison to ASPIRE SR03



Rendering of FSI parachute system meant to mimic the high-speed video from flight (right).

Testing a Parachute for Mars



Jet Propulsion Laboratory
California Institute of Technology



This high-definition video was taken on Sept. 7, 2018, during the third and final test flight of the Advanced Supersonic Parachute Inflation Research Experiments (ASPIRE) campaign to certify the Mars 2020 parachute. It was the fastest inflation of this size parachute in history and created a peak load of almost 70,000 pounds of force. **Credits: NASA/JPL-Caltech**
<https://www.nasa.gov/feature/jpl/third-aspire-test-confirms-mars-2020-parachute-a-go>

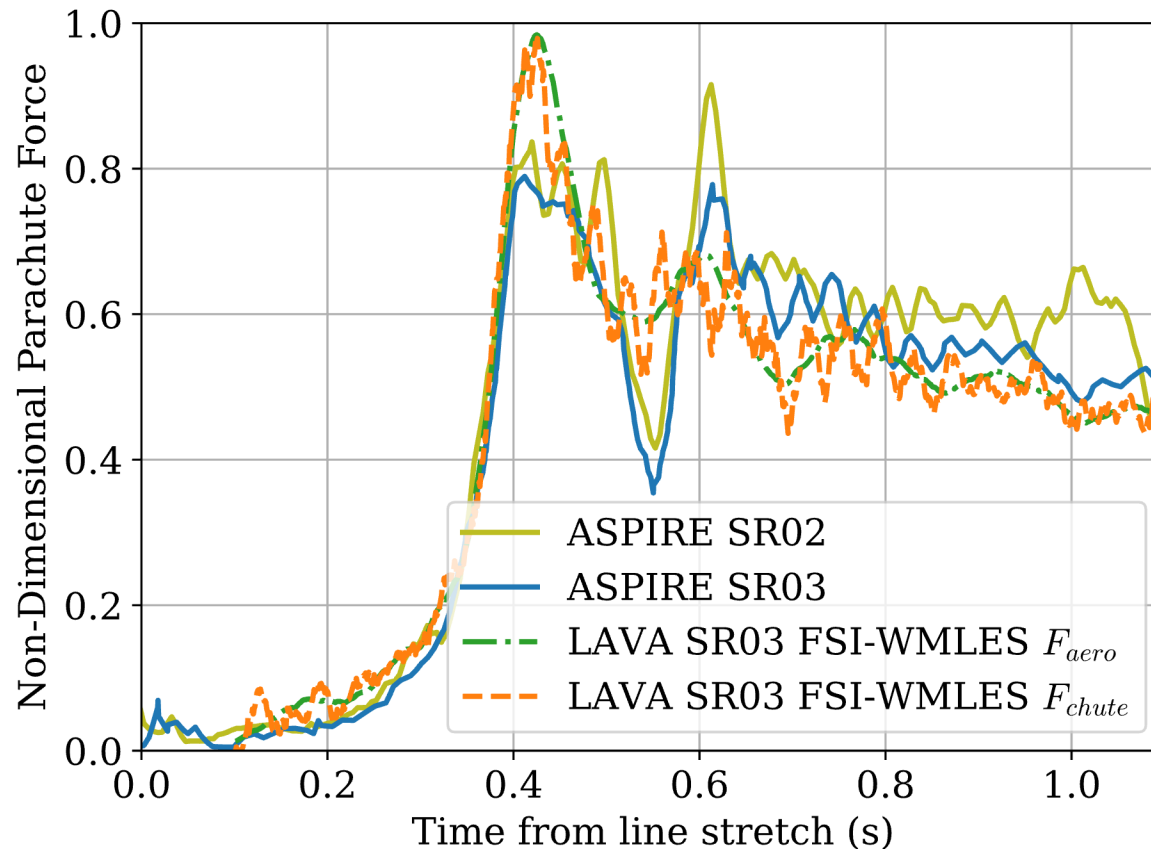


Results: Parachute Force



Parachute force (F_{chute}) is the total axial force the parachute system imparts to the payload.

Parachute aerodynamic drag (F_{aero}) is the integrated axial force over the parachute canopy in FSI.



For ASPIRE:

$$F_{chute} = F_{LP} - m_{chute}a_{payload}$$

where

F_{LP} = sum of forces measured at load pins

m_{chute} = parachute mass

$a_{payload}$ = measured payload acceleration

For FSI:

$$F_{chute} = -m_{total}a_{payload} - F_{payload,aero}$$

where

m_{total} = total mass of system

$a_{payload}$ = payload acceleration

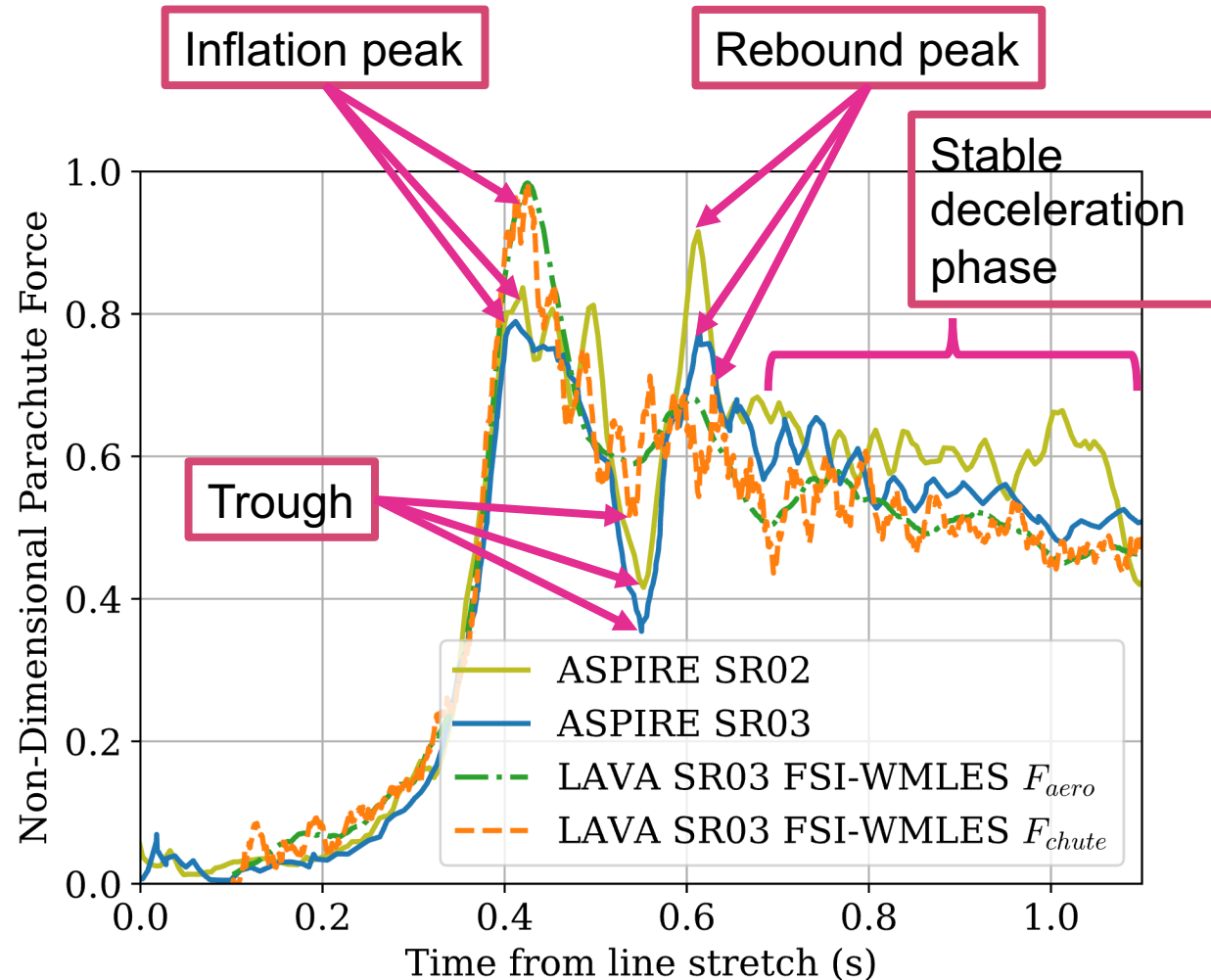
$F_{payload,aero}$ = payload aerodynamic drag

Note that the payload is decelerating so $a_{payload} < 0$ so terms $-ma_{payload} > 0$

*FSI is offset by +0.1 s and SR02 offset by -0.0375 s to remove phase shift due to different inflation times.



Results: Parachute Force



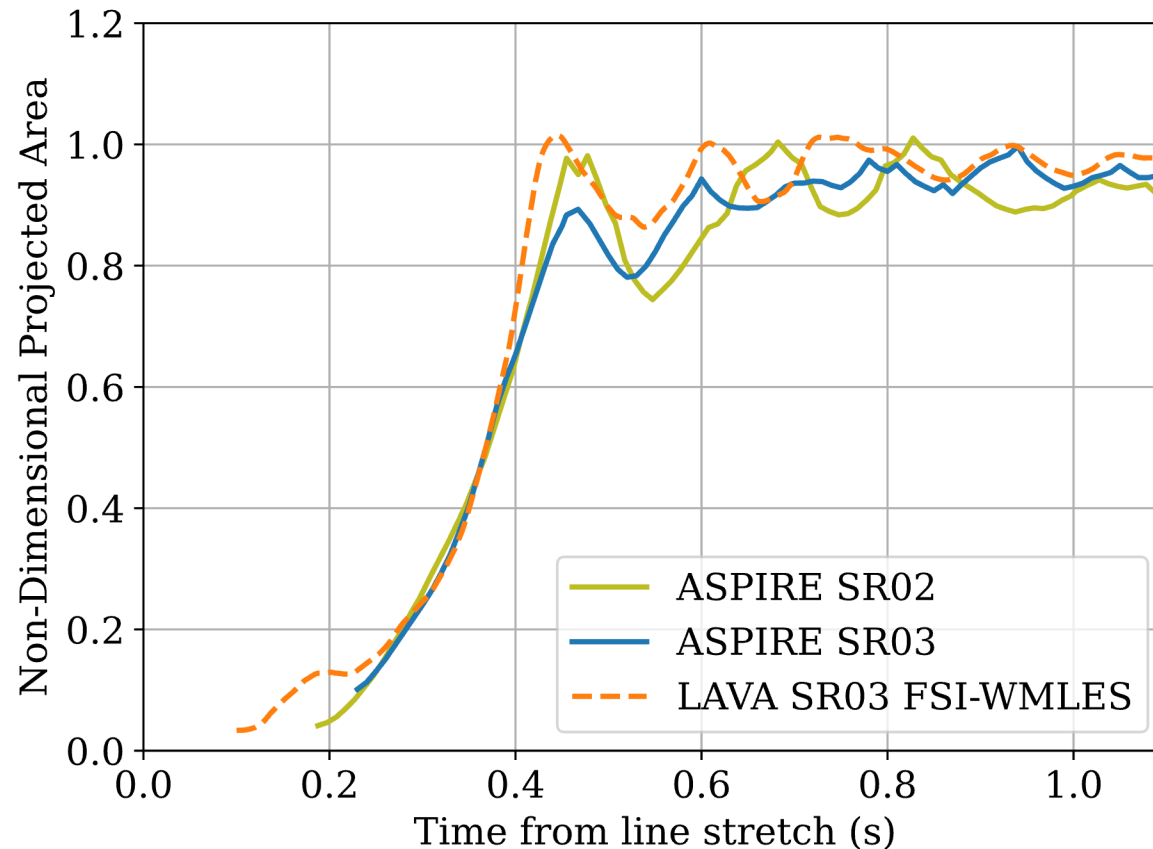
*Time offset to go from CFD time to "time from line stretch" is +0.1 s.

- Over-predicts inflation peak drag by 17%, but within family when compared to SR02 rebound peak
- Match downward slope of flight test during stable deceleration phase
- Predicts suspension line mode of ~27 Hz (~0.038 s) in close agreement with flight tests for F_{chute}

Results: Projected Area



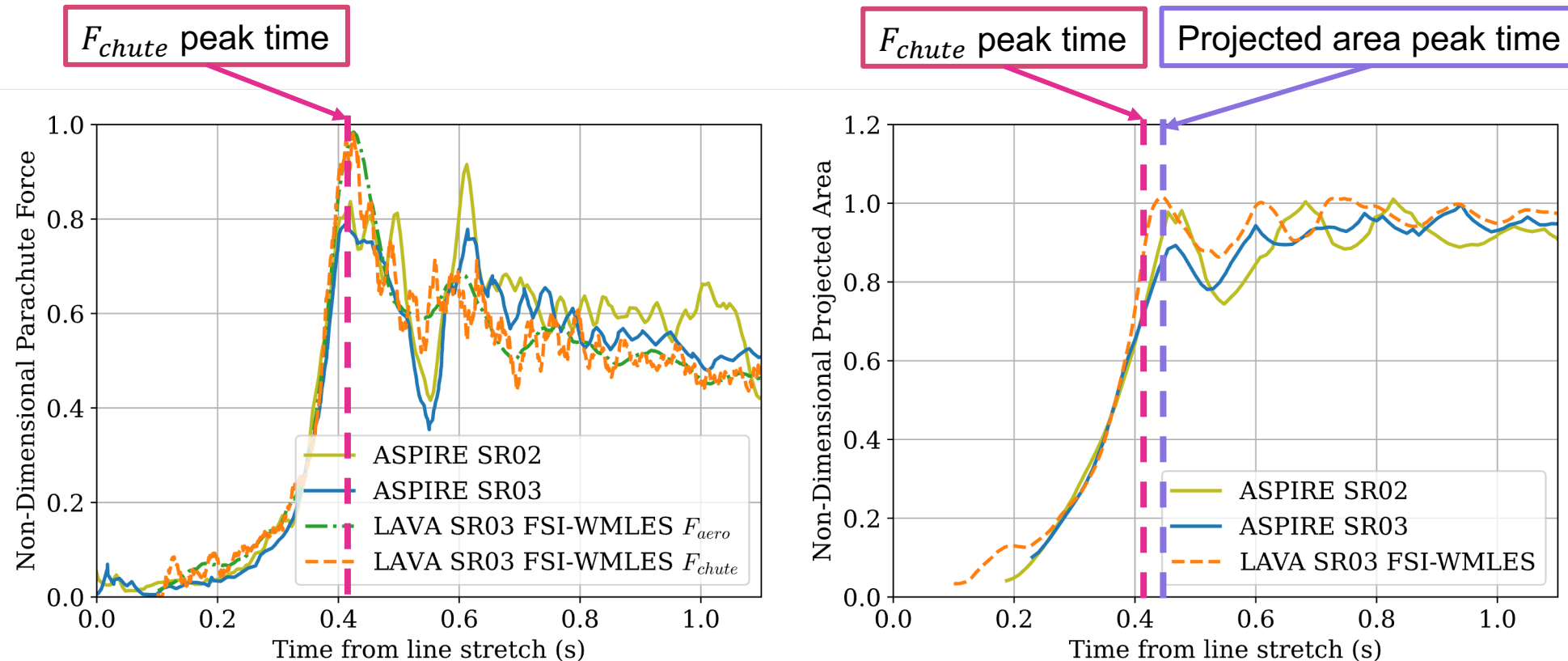
Projected area is computed using convex hull algorithm in both ASPIRE (from pictures) and FSI (from surface)



- Inflation rate matches well until 0.4s after which FSI parachute model predicts faster inflation
- Over-predicts first area peak by 12% compared to SR03, but within 5% of SR02
- Displays area “breathing” mode in good agreement with SR03

*FSI is offset by +0.1 s and SR02 offset by -0.0375 s to remove phase shift due to different inflation times.

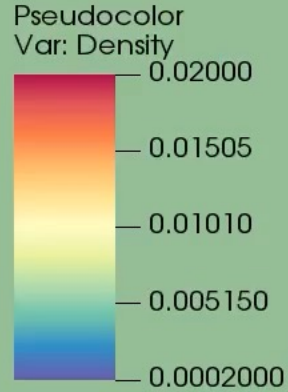
Results: Projected Area



- FSI correctly captures flight test trend where peak F_{chute} precedes first area peak
- F_{aero} closely follows the projected area curve after first peak, but does not show suspension line mode oscillations, as expected

Time = 0.00012839 s

Conclusions



- ✓ Developed novel method to obtain a more representative initial parachute shape
- ✓ Presented immersed WMLES method adapted for FSI of thin parachutes
- ✓ Performed FSI-WMLES of ASPIRE SR03 flight test and showed overall good agreement with SR02 and SR03 flight test measurements



Density on surfaces and cut plane



Time = 0.00012839 s

Future Work

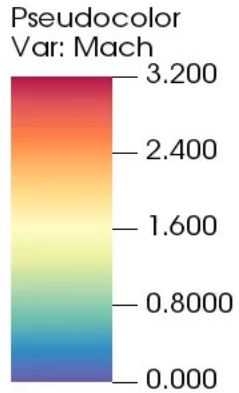
- FSI grid sensitivity study to bound discretization error
- Improve underlying structural model to better predict stress concentrations and potential material failure
- Accelerate time-to-solution by porting to GPU



Out-of-plane vorticity magnitude on cut plane and skin friction on surfaces of payload and canopy

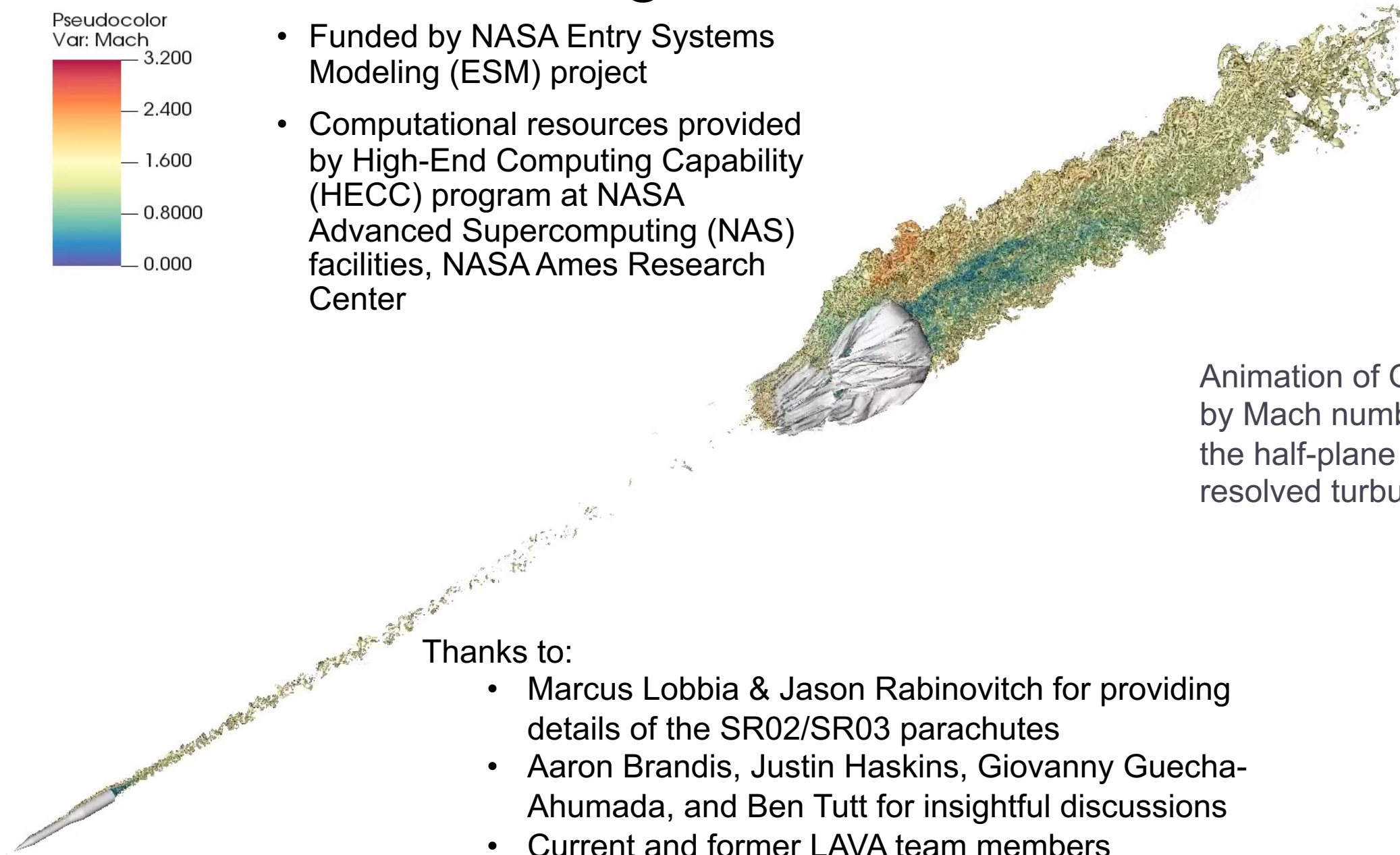


Time = 0.0973109 s



Acknowledgments

- Funded by NASA Entry Systems Modeling (ESM) project
- Computational resources provided by High-End Computing Capability (HECC) program at NASA Advanced Supercomputing (NAS) facilities, NASA Ames Research Center



Animation of Q-criterion colored by Mach number and clipped at the half-plane to highlight resolved turbulent structures

Thanks to:

- Marcus Lobbia & Jason Rabinovitch for providing details of the SR02/SR03 parachutes
- Aaron Brandis, Justin Haskins, Giovanny Guecha-Ahumada, and Ben Tutt for insightful discussions
- Current and former LAVA team members



Backup Slides

Objectives



- Develop FSI tool that can predict performance and potential failure modes of a supersonic parachute
- Validate FSI tool with available flight test data from Advanced Supersonic Parachute Inflation Research Experiments (ASPIRE)

Method Overview

- Fluid: Launch, Ascent and Vehicle Aerodynamics (LAVA) Cartesian CFD solver
- Structure: geometrically non-linear CSD solver for parachute system
- Additional models:
 - Porosity to allow some air to flow through parachute fabric
 - Contact mechanics to prevent self-intersection of parachute digital representation
 - Free flight dynamics for rigid body dynamics of payload coupled to parachute system
- For more details please refer to paper and to [3]

[3] Boustani, J., Cadieux, F., Kenway, G. K., Barad, M. F., Kiris, C. C., & Brehm, C. (2022). Fluid-structure interaction simulations of the ASPIRE SR01 supersonic parachute flight test. *Aerospace Science and Technology*, 126, 107596.

Improved Convective Flux

- $F_{j+\frac{1}{2}}^*(\mathbf{Q}_{L,j+\frac{1}{2}}, \mathbf{Q}_{R,j+\frac{1}{2}})$, where $F_{j+\frac{1}{2}}^*$ is computed using the AUSMPW+ approximate Riemann solver
- Switch from $\mathbf{Q} = [p, u, v, w, T]^T \rightarrow \tilde{\mathbf{Q}} = [\rho, u, v, w, p]^T$ to make fluxes and numerical dissipation more consistent with regards to kinetic energy and entropy preservation (KEEP)
- Mix linear and limited reconstructions based on shock Θ and grid quality Γ sensor $\zeta = \max(\Theta, \Gamma)$
- $\tilde{\mathbf{Q}}_{L,j+\frac{1}{2}}^{linear} = \tilde{\mathbf{Q}}_j + \frac{1}{2} \Delta x \frac{\partial \tilde{\mathbf{Q}}}{\partial x} |_j$
- $\tilde{\mathbf{Q}}_{L,j+\frac{1}{2}}^{limiter} = \tilde{\mathbf{Q}}_j + \frac{1}{2} \phi_j \Delta x \frac{\partial \tilde{\mathbf{Q}}}{\partial x} |_j$, where ϕ_j is the 0 to 1 output of a limiter like minmod
- $\tilde{\mathbf{Q}}_{j+\frac{1}{2}}^{central} = \frac{1}{2} \left(\tilde{\mathbf{Q}}_{L,j+\frac{1}{2}}^{linear} + \tilde{\mathbf{Q}}_{R,j+\frac{1}{2}}^{linear} \right)$
- $\tilde{\mathbf{Q}}_{L,j+\frac{1}{2}} = (1 - \zeta_{j+\frac{1}{2}}) \tilde{\mathbf{Q}}_{j+\frac{1}{2}}^{central} + \zeta_{j+\frac{1}{2}} \tilde{\mathbf{Q}}_{L,j+\frac{1}{2}}^{limiter}$
- Shock sensor $\Theta_{j+\frac{1}{2}} = \left(\frac{(\nabla \cdot \mathbf{u})_{j+\frac{1}{2}}^2}{(\nabla \cdot \mathbf{u})_{j+\frac{1}{2}}^2 + \|\nabla \times \mathbf{u}\|_{j+\frac{1}{2}}^2} \right)^{\frac{1}{2}}$ is based off the Ducros sensor
- Improvement comes from $(\tilde{\mathbf{Q}}_{L,j+\frac{1}{2}} - \tilde{\mathbf{Q}}_{R,j+\frac{1}{2}}) \rightarrow 0$, when $\zeta_{j+\frac{1}{2}} \rightarrow 0$ greatly reducing numerical dissipation in the AUSMPW+ numerical flux in turbulent regions away from shocks and grid discontinuities

Challenges In Modeling Parachutes



Parachutes...

- are typically deployed from packed state in a bag so each path to inflation is fairly unique, full of self-contact, and inherently unsteady
- go through large non-linear deformations during inflation
- are incredibly thin (e.g. ~ 76 microns)
- are made of porous woven (orthotropic) fabric
- are made of materials that are not fully characterized across range of strain in which they are used

Motivation: Why FSI?

Current State-Of-The-Art

- Empirical and low-fidelity models are used to predict peak loads and stresses in the canopy
- Wind tunnel and flight tests are used to reproduce expected environment, steady and dynamic loads and ultimately certify parachute systems for flight
- Dynamic finite element analysis is used occasionally, and FSI even more sparingly; mostly for qualitative comparisons to give insight into already known issues
- Parachutes remain one of the top risk factors for human and robotic missions

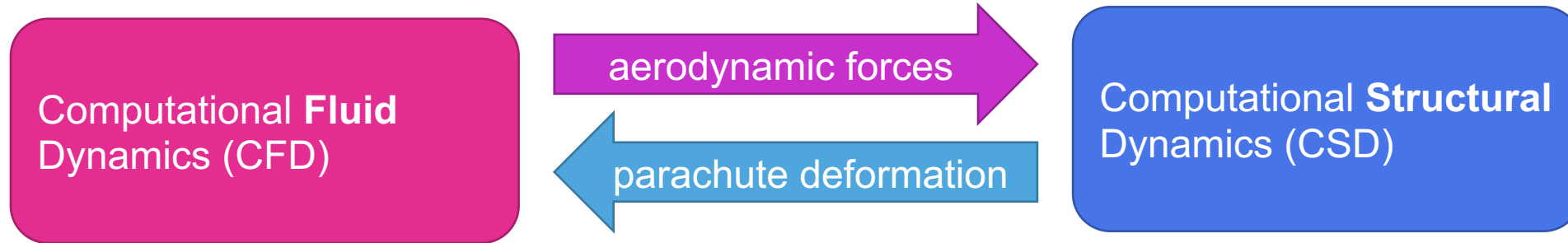
Potential For FSI

- Match atmosphere composition and transport properties and capture those effects
- Match stiffness to size ratio (limitation of wind tunnel tests)
- Provide insight into parameters not easily measurable in flight or wind tunnel test
- Conduct parametric trade-study simulations

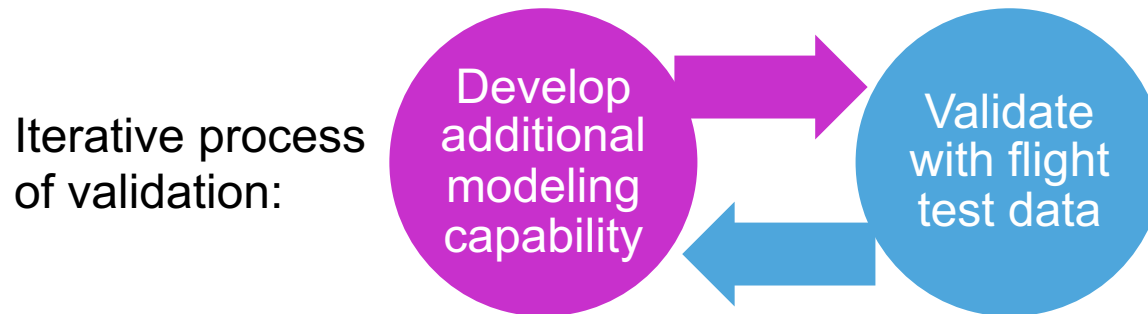
Objectives: FSI Tool Development



- Create FSI tool adapted for simulating supersonic parachute inflation using the Launch, Ascent and Vehicle Aerodynamics (LAVA) Cartesian Adaptive Mesh Refinement (AMR) module



- Validate FSI predictions with available flight test, wind tunnel, and prior mission data



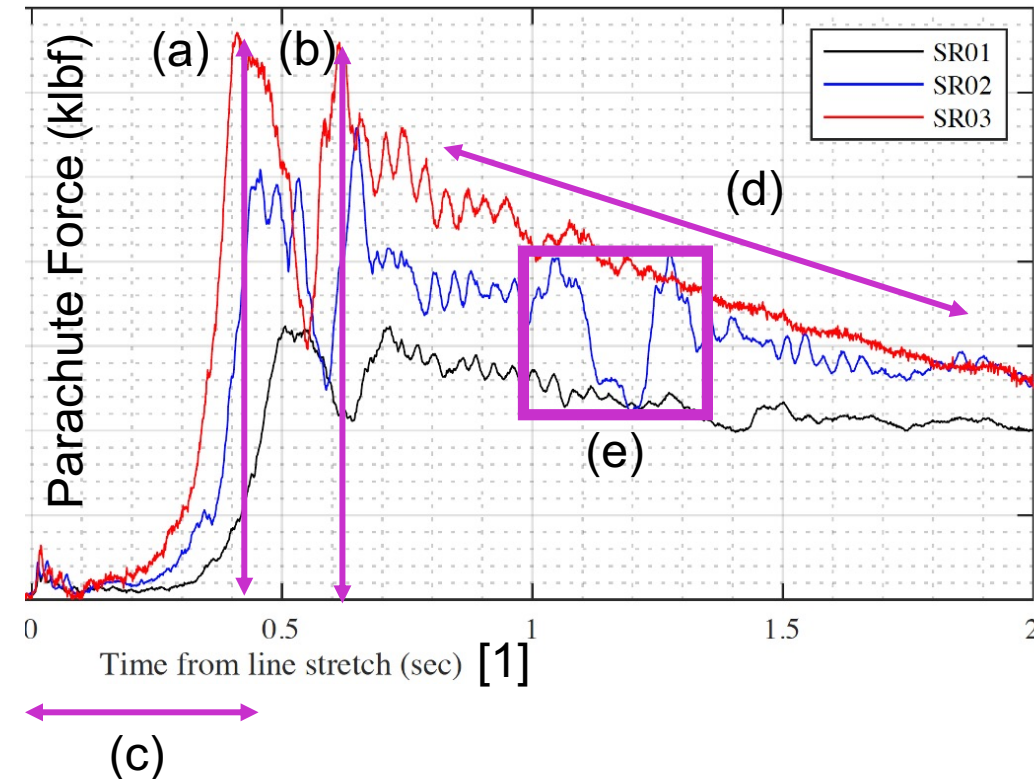
- Develop best practices and automate their implementation to reduce user burden (where possible)
- Reduce turnaround time of FSI simulations so they can be used to answer engineering questions during mission design process

Specific Goals For FSI



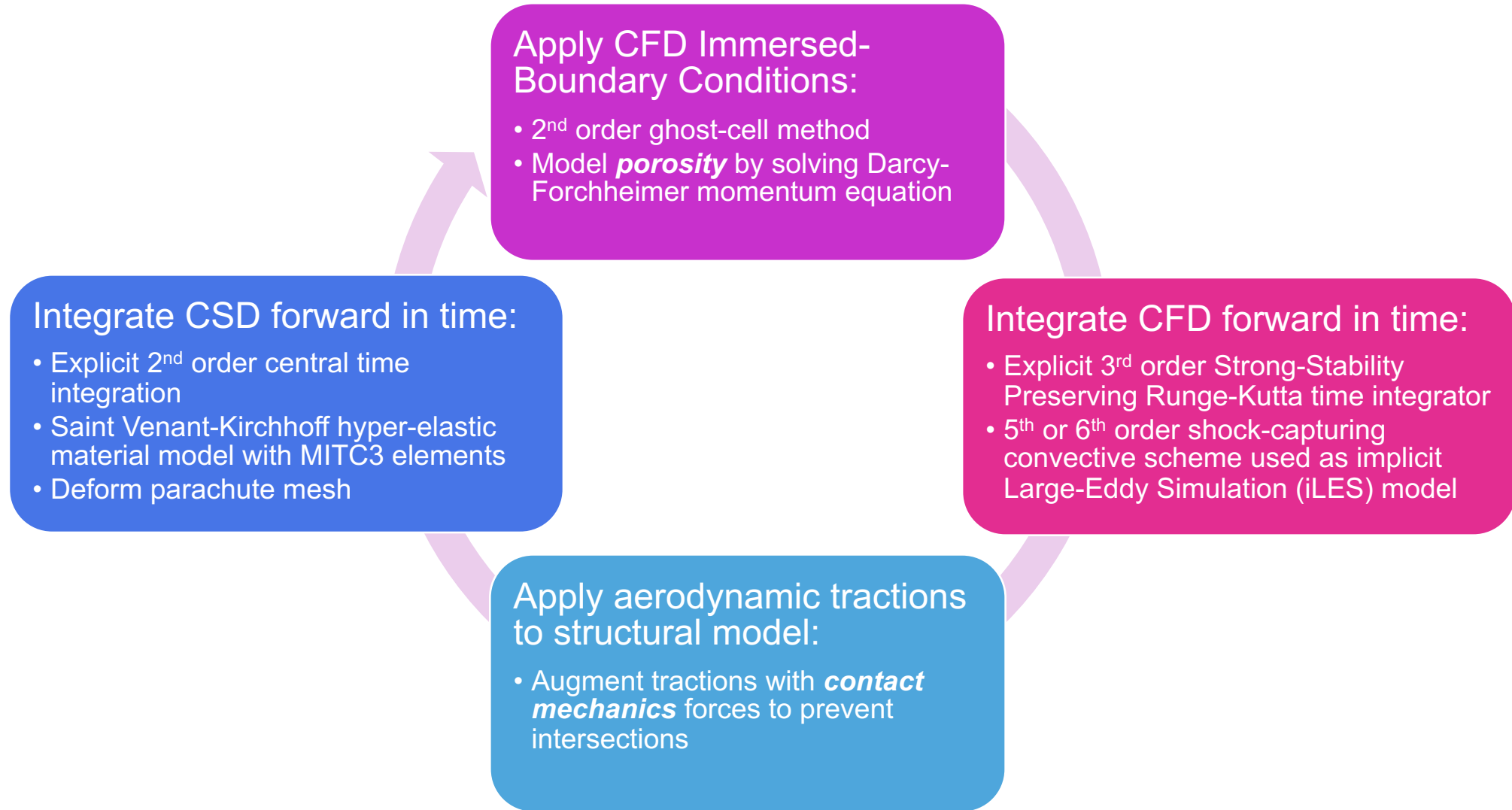
Metrics to validate in order of increasing difficulty:

- a) Peak opening loads
- b) Post-inflation dynamics (e.g. trough and rebound peak)
- c) Inflation rate and time
- d) Aerodynamic coefficients as a function of Mach, dynamic pressure, and angle of attack for “steady” descent phase
- e) Dynamic response to angle of attack changes due to wake recontact or wind gusts
- f) Detailed spatial distribution of stress magnitude in canopy fabric to predict failure (requires accurate model of woven orthotropic fabric, and gore seams)

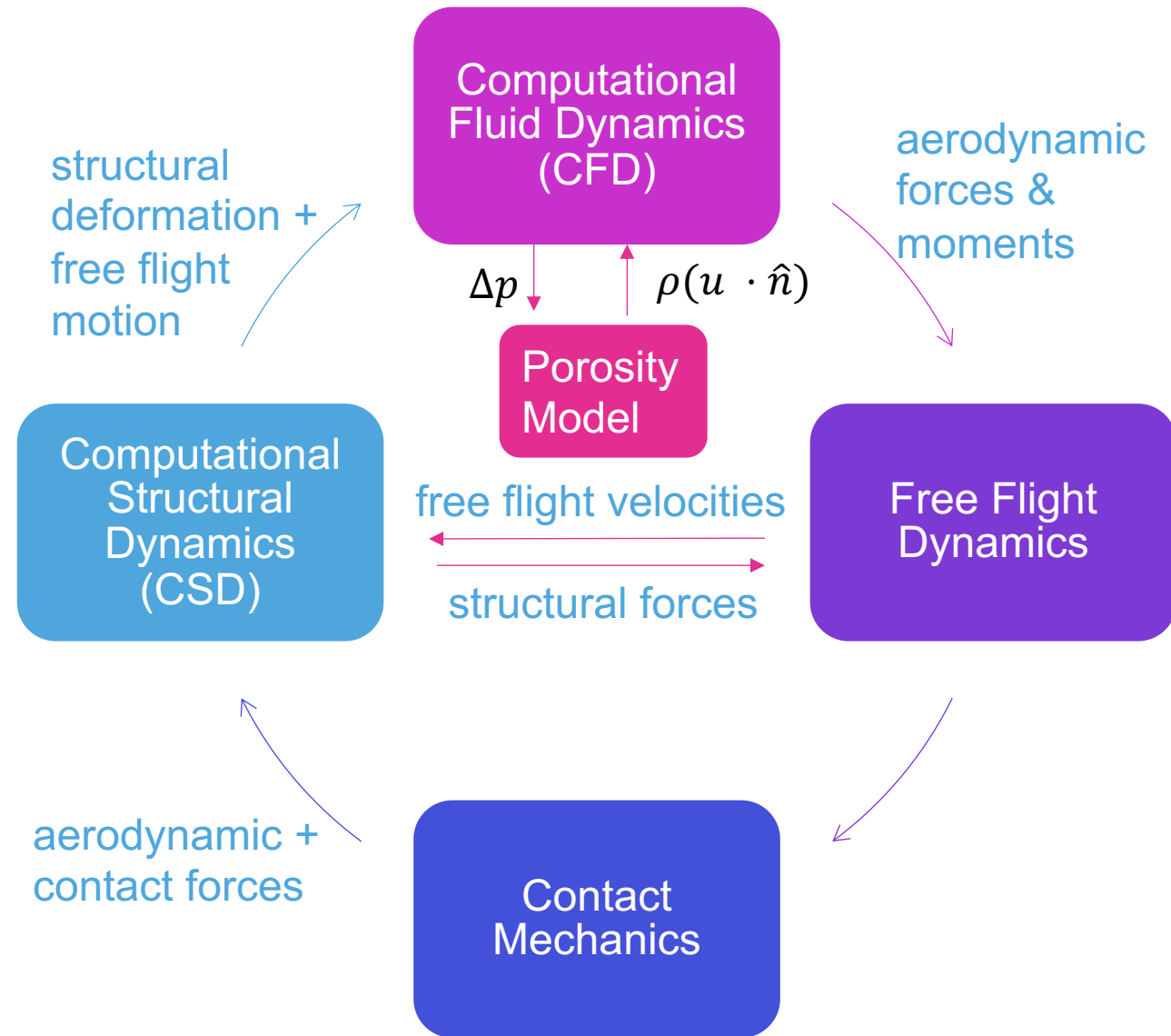


[1] Sonneveldt, Bryan S., Ian G. Clark, and Clara O'Farrell. "Summary of the Advanced Supersonic Parachute Inflation Research Experiments (ASPIRE) Sounding Rocket Tests with a Disk-Gap-Band Parachute." *AIAA Aviation 2019 Forum*. 2019.

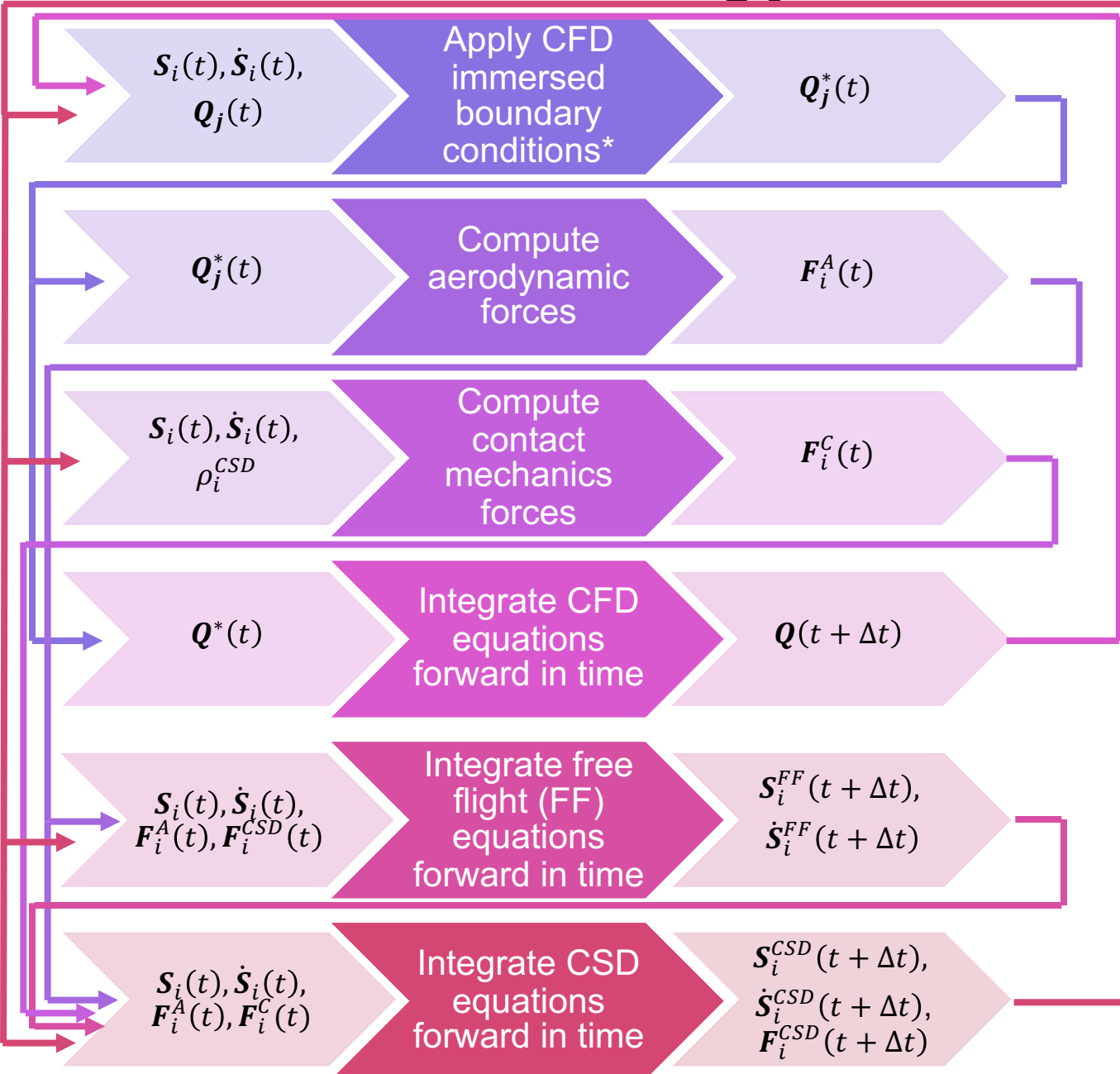
Methodology: FSI Overview



For more details on the methods, 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 <https://doi.org/10.1016/j.ast.2022.107596>



FSI Methodology



where

- $Q_j = [p, u, v, w, T]^T$ is the CFD state vector at cell j ,
- $S_i = [x, y, z]^T$ is the position of surface element i ,
- $\dot{S}_i = \left[\frac{\partial x}{\partial t}, \frac{\partial y}{\partial t}, \frac{\partial z}{\partial t} \right]^T$ is the velocity of surface element i ,
- $F_i^A = [F_x, F_y, F_z]^T$ is the aerodynamic force on surface element i ,
- ρ_i^{CSD} is the structural density of surface element i ,
- $F_i^C = [F_x, F_y, F_z]^T$ is the contact force on surface element i ,
- $F_i^{CSD} = [F_x, F_y, F_z]^T$ is the structural force on surface element i .

*including porosity to allow flow through parachute fabric

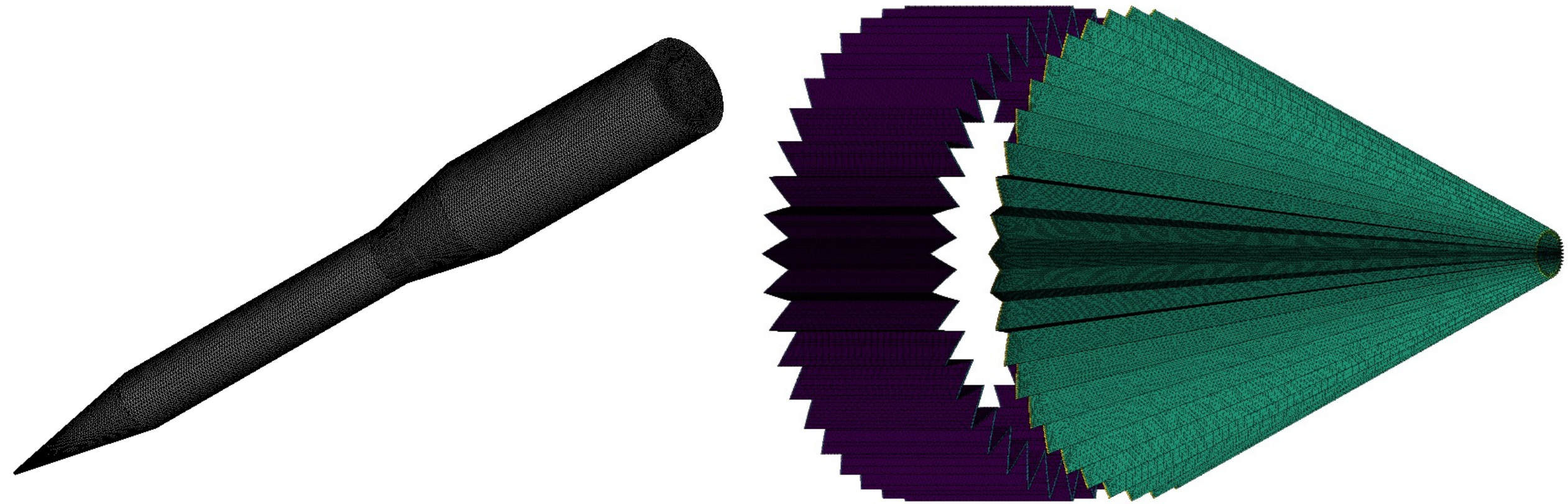
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Important Simplifying Assumptions



- Arbitrary initial parachute shape to reduce its cross-sectional area
- Gore seams (radial stiffeners) modeled as beam elements sharing same nodes as fabric elements
- Neglect viscous effects and solve Euler equations with slip boundary conditions
- Start with restrained payload (infinite mass inflation) assuming it should be fairly accurate for peak load, as well as post-inflation trough and rebound peak
- Disk and band assumed perfectly circular as opposed to each gore having straight edges
- Saint-Venant Kirkoff (SVK) hyper-elastic (linear) constitutive model for stress-strain relationship
- Isotropic material properties as opposed to orthotropic (direction-dependent, warp vs weft)
- “Can’t push on a rope” (no additional stress when under compression along line axis)
- Disregard fabric shortening due to seams (1-2% of total length)
- Neglect vent line foreshortening (vent line length is 90% of vent hole radius in reality)
- Disregard any “pre-stress” in initial parachute shape due to “folding” or “pre-inflation”
- Ignore effect of any turbulence induced by flow through canopy’s porous material

Methodology: Structural Mesh



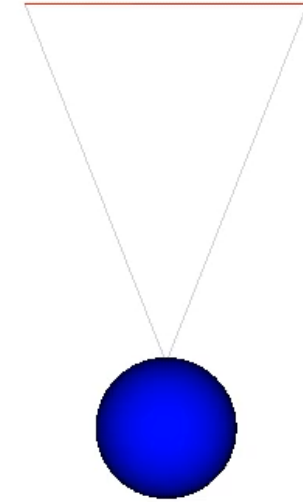
- 43,346 triangles (rigid) on payload
- Mean edge length away from nose 0.025 m

- 267,668 triangles (MITC3) on canopy surface
- Mean edge length 0.05 m on 15.62 m diameter canopy
- Min edge length at leading/trailing edge 0.025 m
- 76,954 Timoshenko beam elements for suspension lines, radials, gap and vent lines with fixed edge length of 0.05 m

Methodology: Free-Flight + FSI Motion Model



- General 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)
- Coupling between rigid body (payload) and deforming body (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 or full 6 DOF motion



Demonstration of 6 DOF free-flight
parachute-payload coupling