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Fluid-Structure Interaction Simulations of Supersonic Parachute Inflation: Model Sensitivities

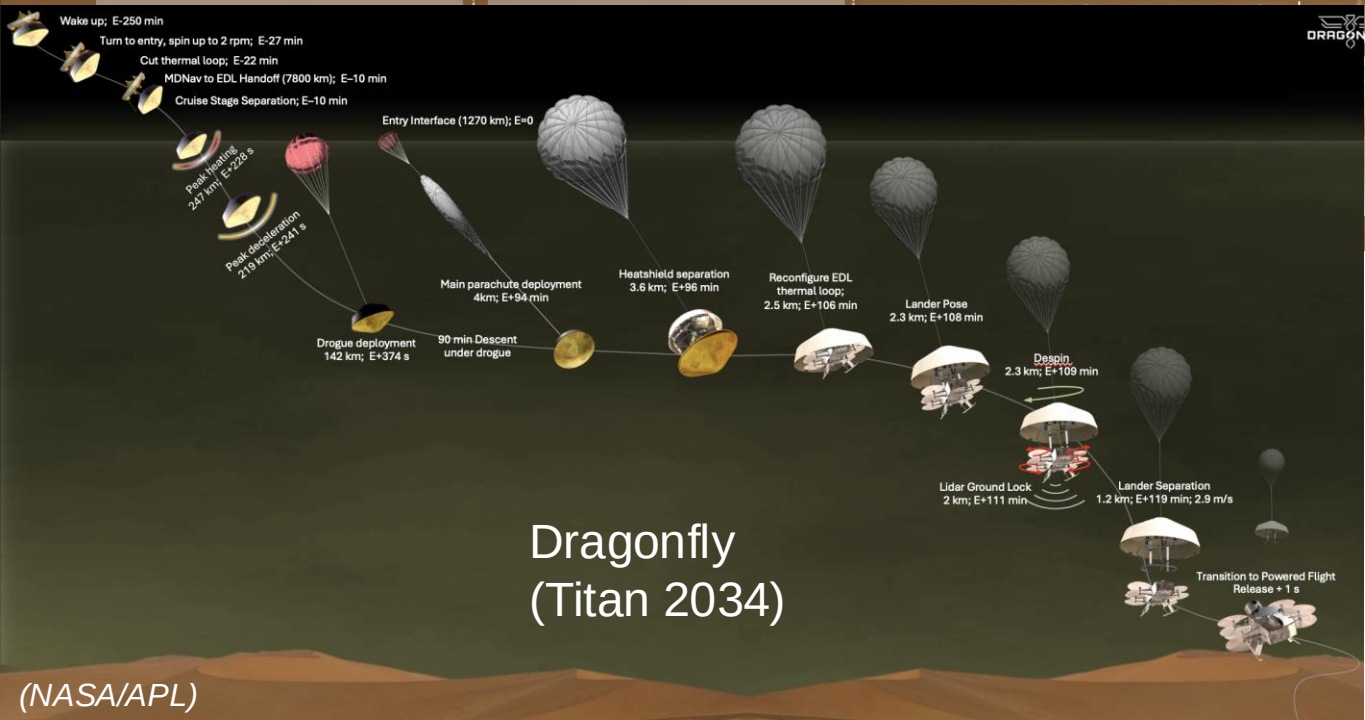
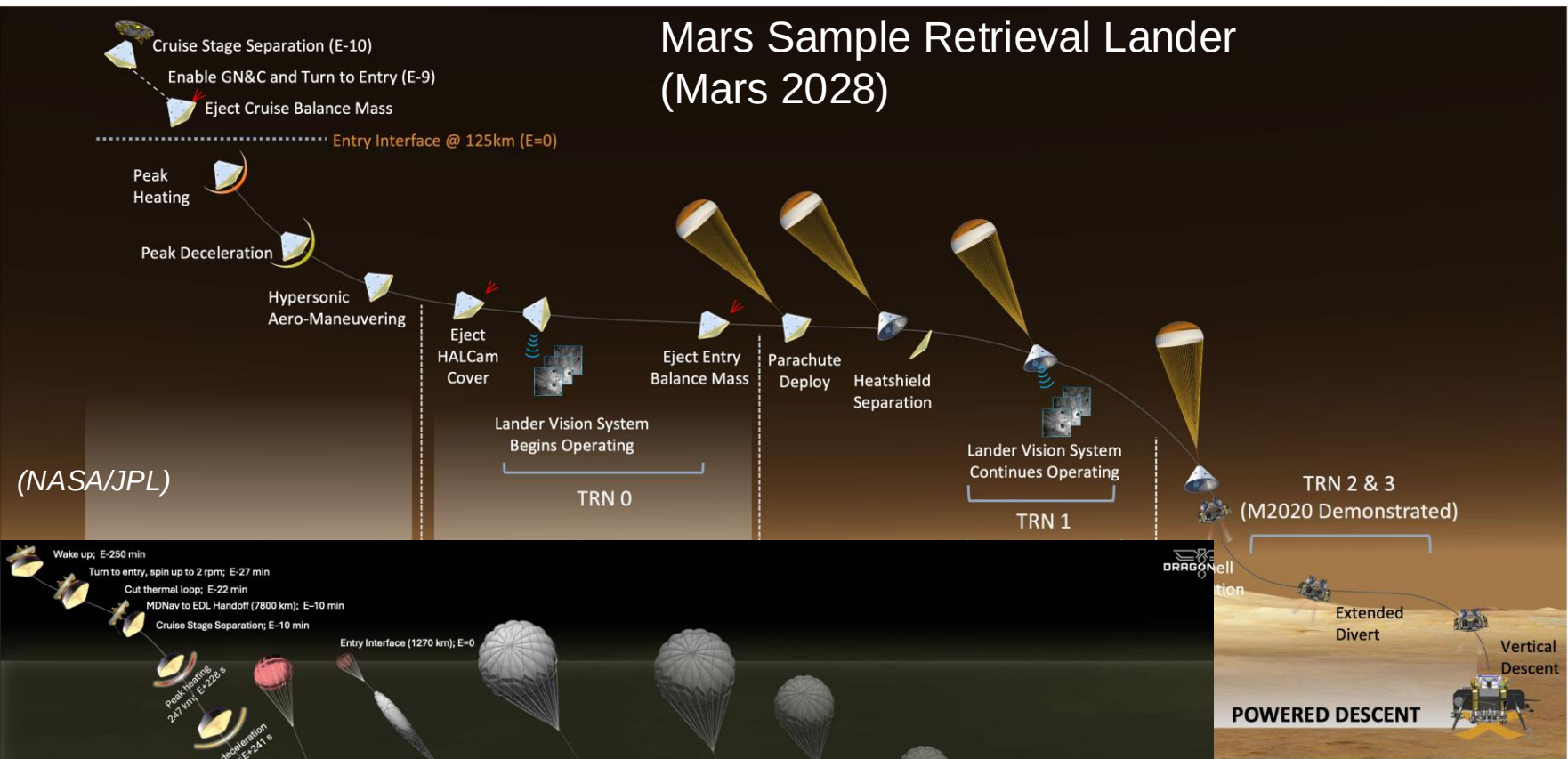
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Aerodynamics (LAVA) Team
Computational Aerosciences Branch
NASA Ames Research Center

Aerodynamic Decelerator Systems Conference,
AIAA AVIATION, Las Vegas, Jul 31 to Aug 2, 2024

POC: francois.cadieux@nasa.gov

Supersonic Parachutes In Upcoming Interplanetary Missions

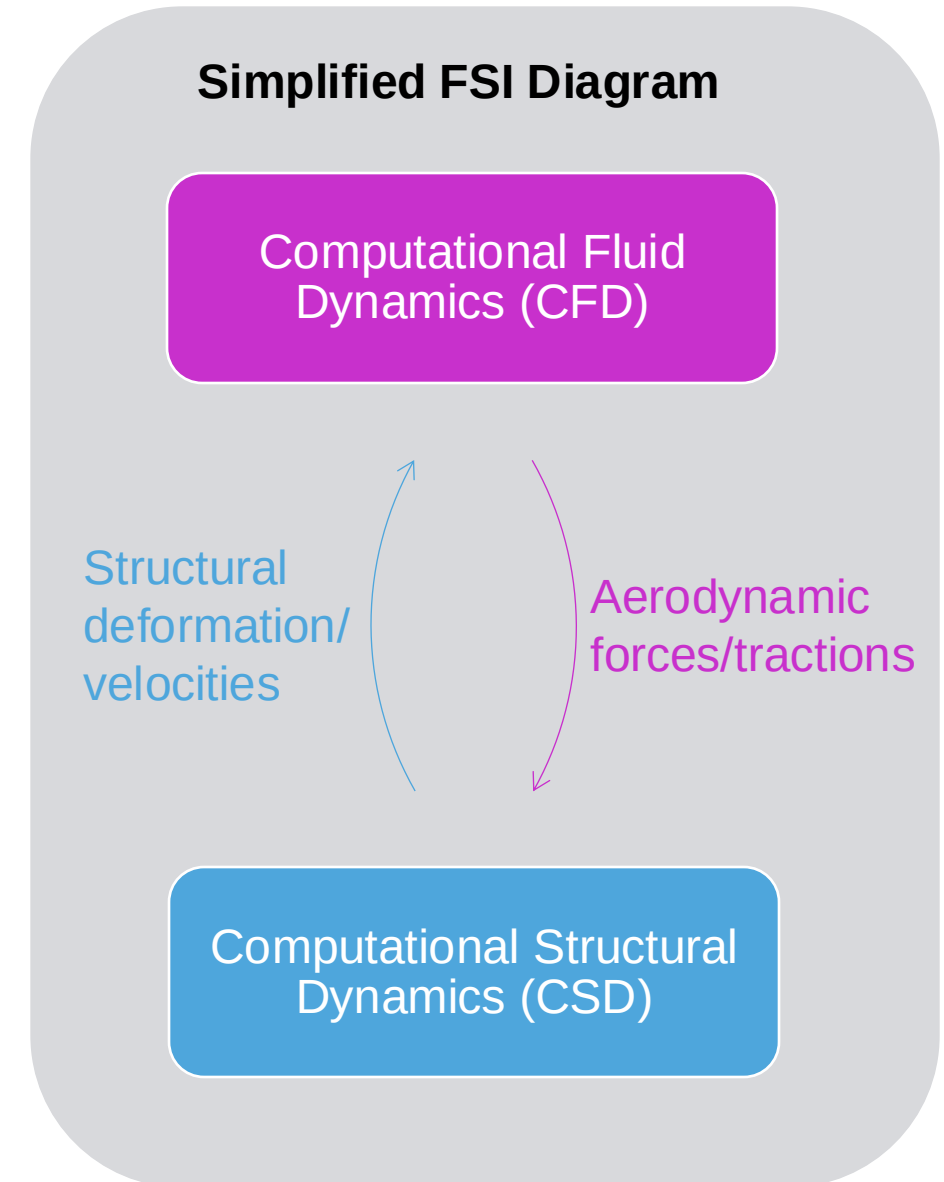


Why Simulate Supersonic Parachute Inflation?



Fluid-structure interaction (FSI) simulations, once validated, have the potential to:

- Accelerate the design of new parachute systems and mitigate risks by simulating more scenarios than can be flight tested
- Account for difference in parachute performance with blunt aeroshell versus slender payload used in flight tests
- Provide insight into parameters or phenomena not easily measured or reproduced in wind tunnel or flight tests



Problem Statement



- Continue FSI validation process by simulating the Advanced Supersonic Parachute Inflation Research Experiments (ASPIRE) third flight test SR03
- Evaluate sensitivity of FSI predictions to modeling choices focusing on:
 - Gore seams
 - Deceleration

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

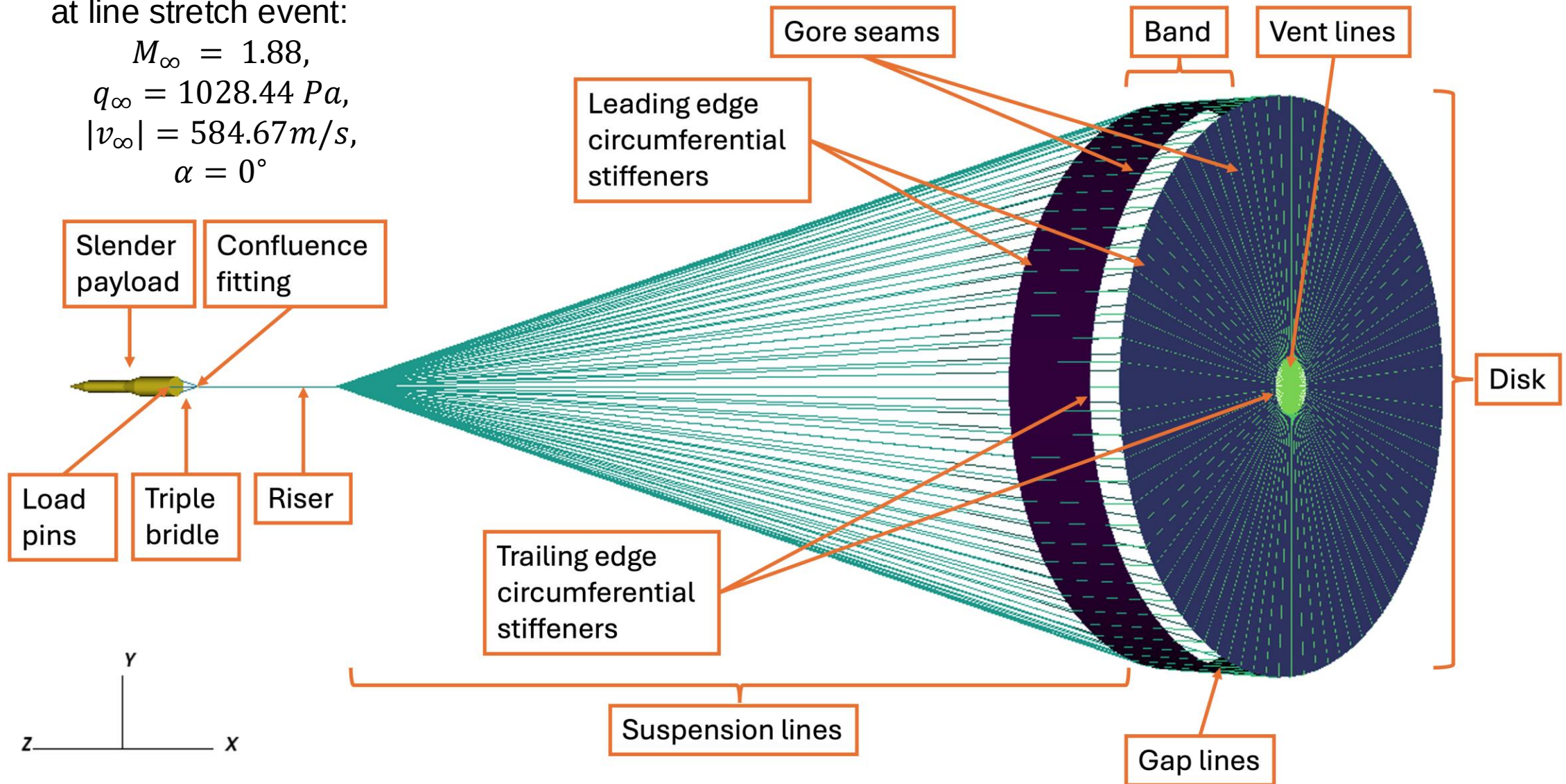
Freestream conditions
at line stretch event:

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

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

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

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



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

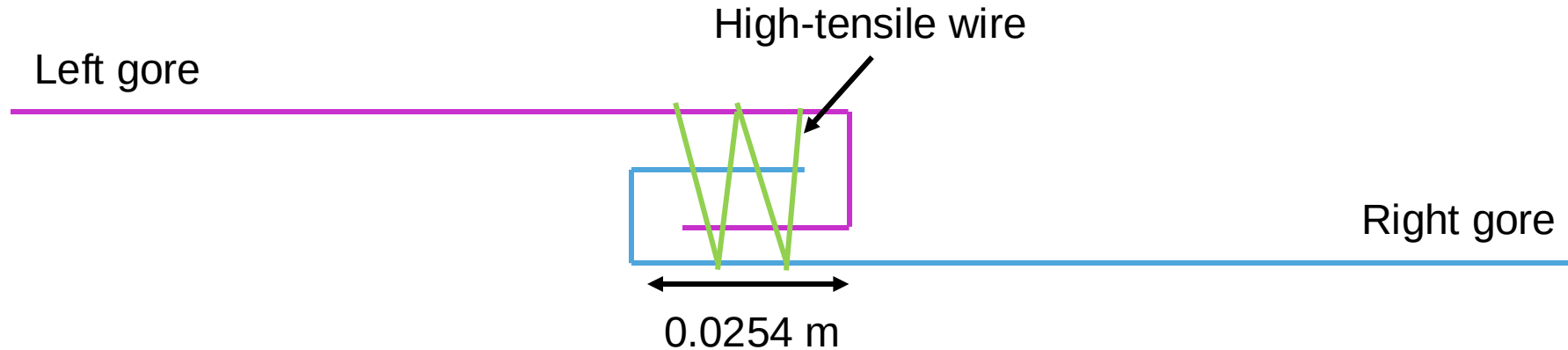
For more details on the method, please refer to: Boustani, Jonathan, et al. "Fluid-structure interaction simulations of the ASPIRE SR01 supersonic parachute flight test." *Aerospace Science and Technology* 126 (2022): 107596

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

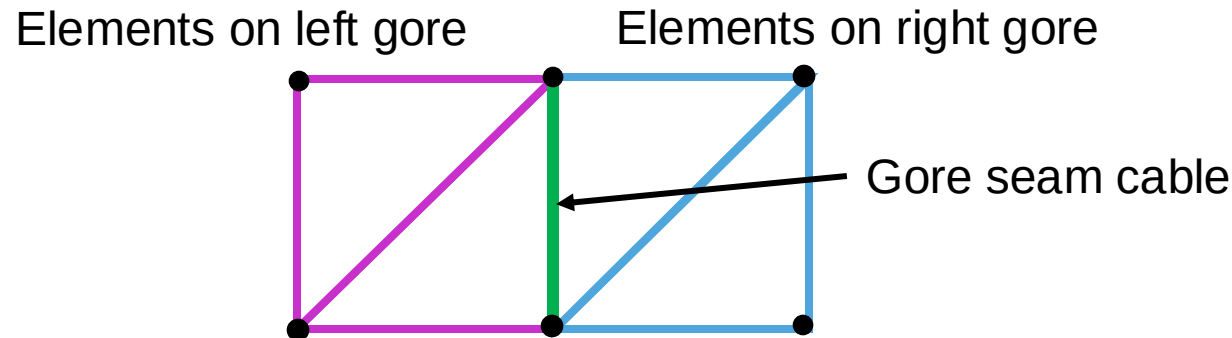
Modeling Gore Seams



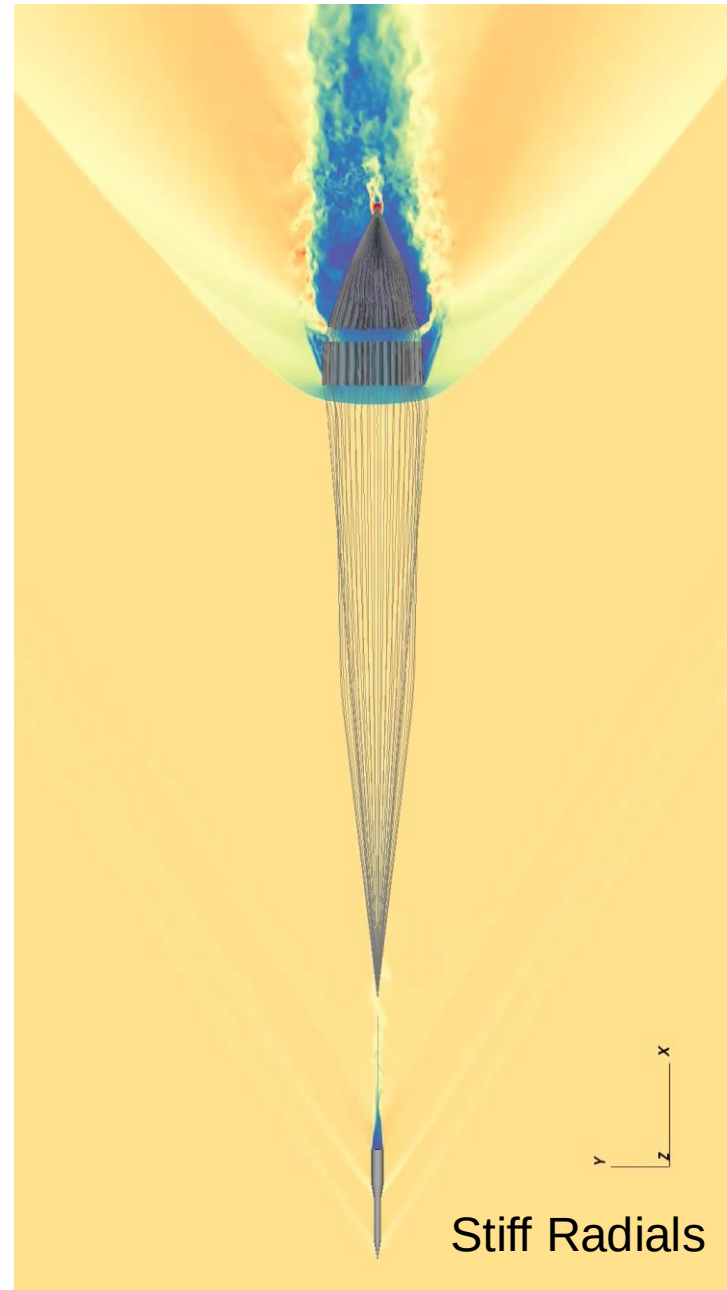
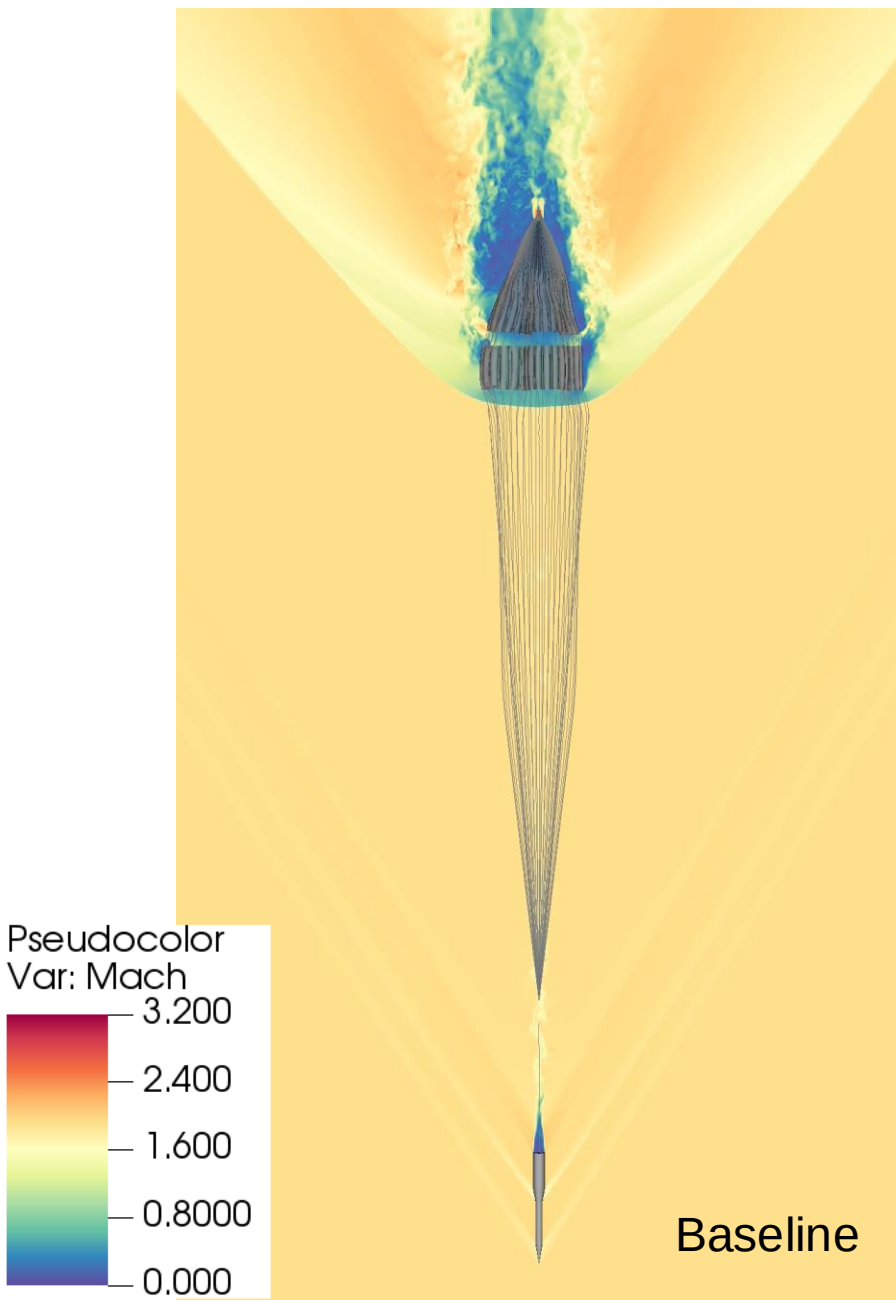
- Stitching at the gore seams implies 4 layers of canopy fabric + high tensile strength wire



- Baseline: gore seams are not modeled
- Stiff Radials: model gore seams as cables (Timoshenko beams) with a Young's modulus of 3.87×10^{10} Pa



Results: Adding Radial Gore Seams



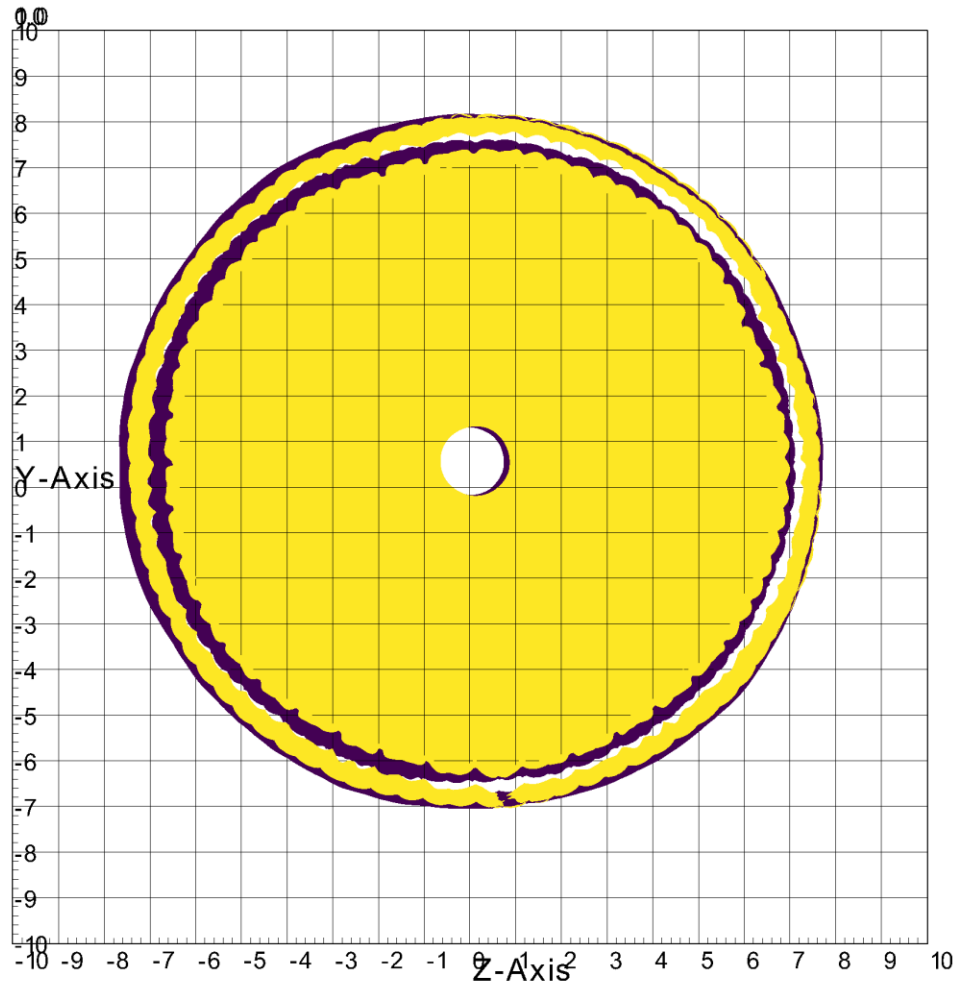
Changes the inflated
parachute shape

Adds local radius of
curvature to each gore

Restricts maximum projected
area disk can stretch to

Note: movies are not
synchronized due to slightly
different output frequency

Results: Adding Radial Gore Seams



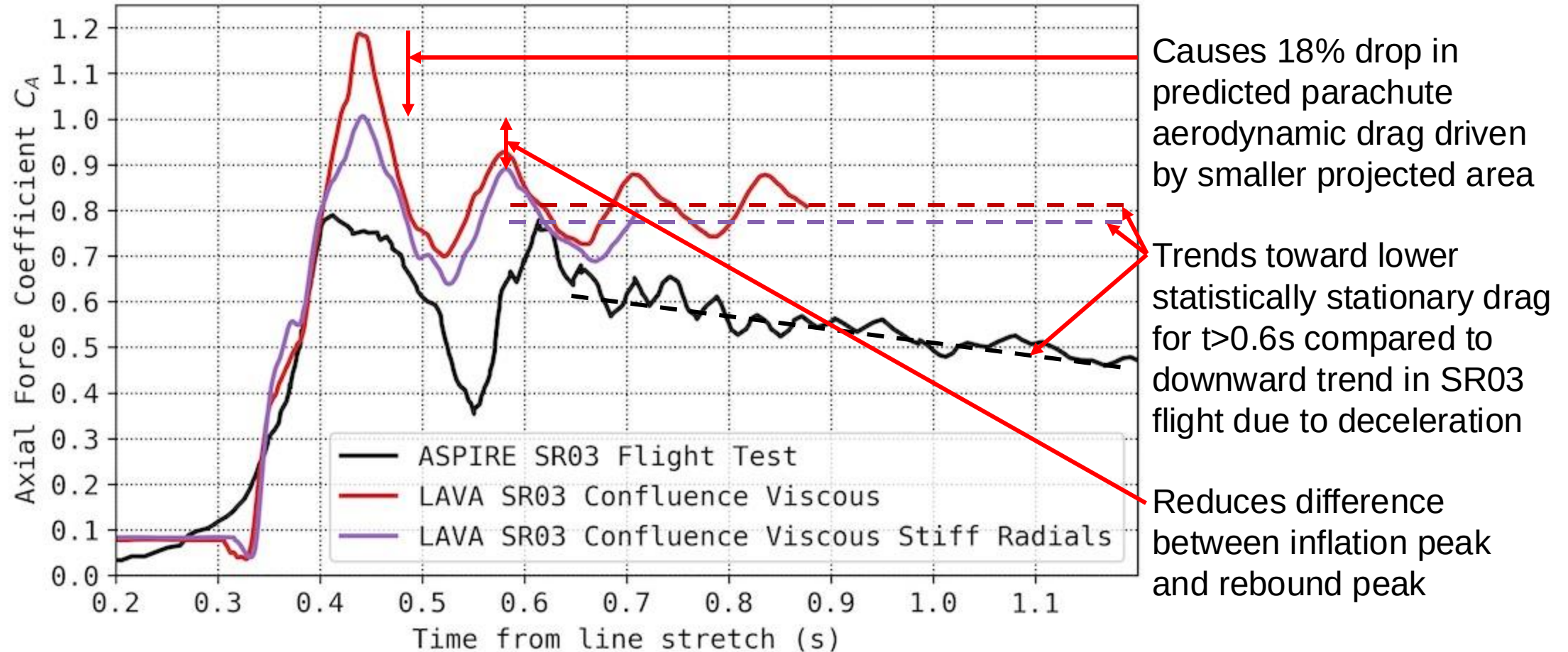
Purple: baseline (without gore seams)

Yellow: Stiff radials (with gore seams)

Disk without gore seams stretches to a larger area than disk with gore seams

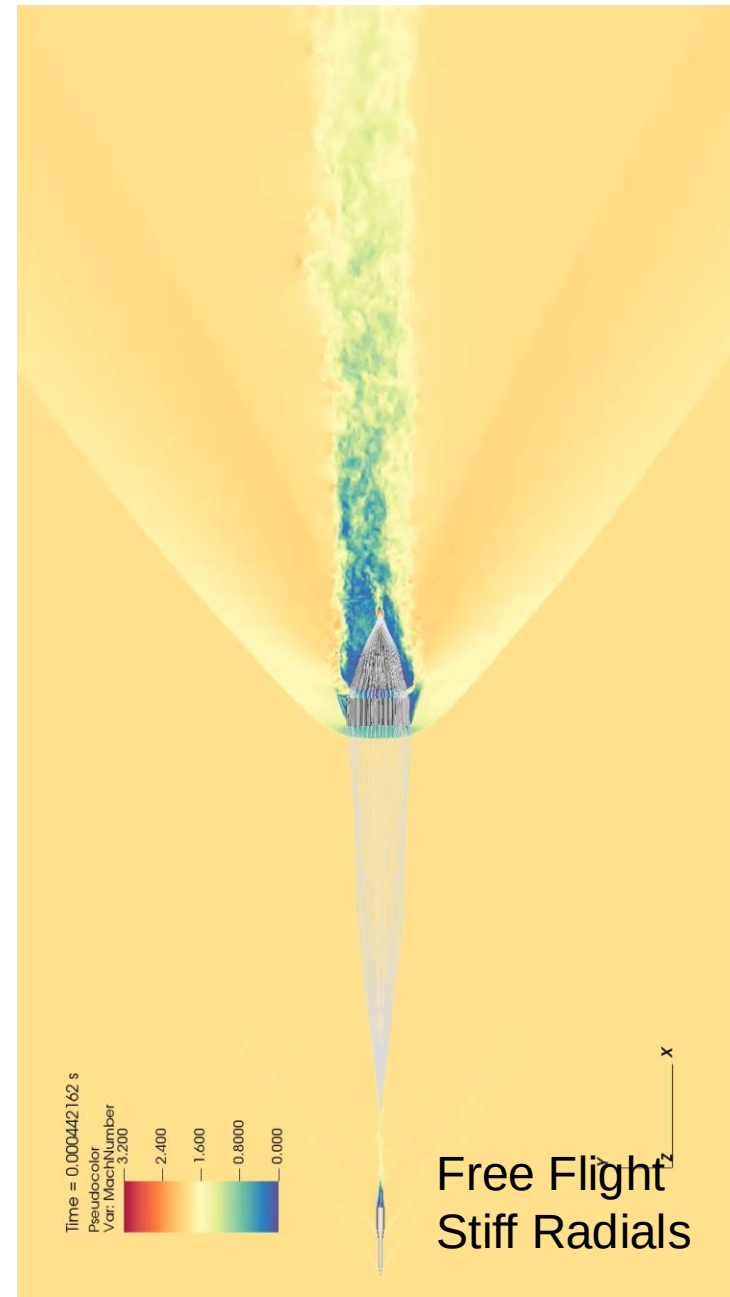
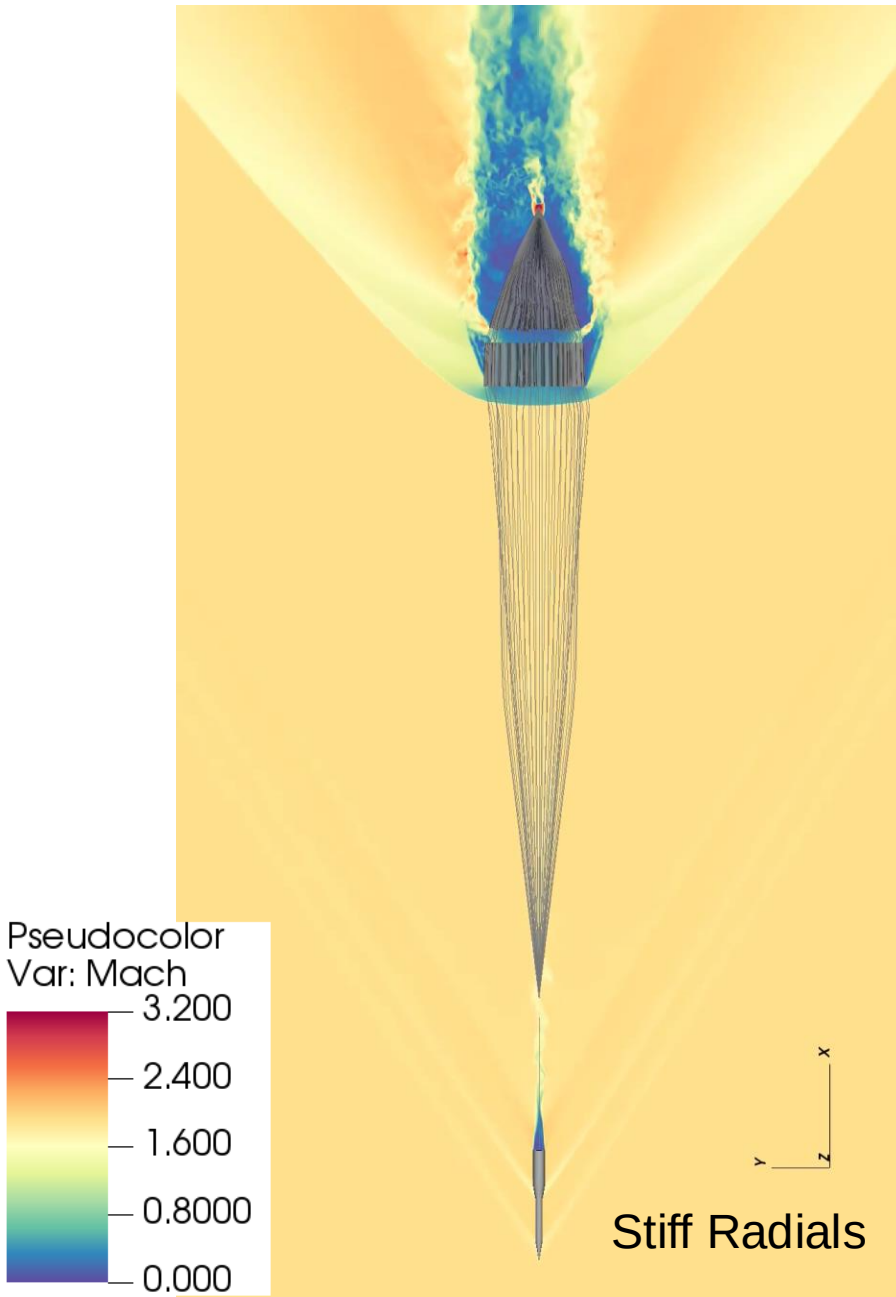
Disk is the primary drag contributor, so we expect parachute with gore seams will produce less drag

Results: Adding Radial Gore Seams



Note: FSI curves are shifted in time to take out phase difference due to different time to inflation

Results: Effect of Deceleration



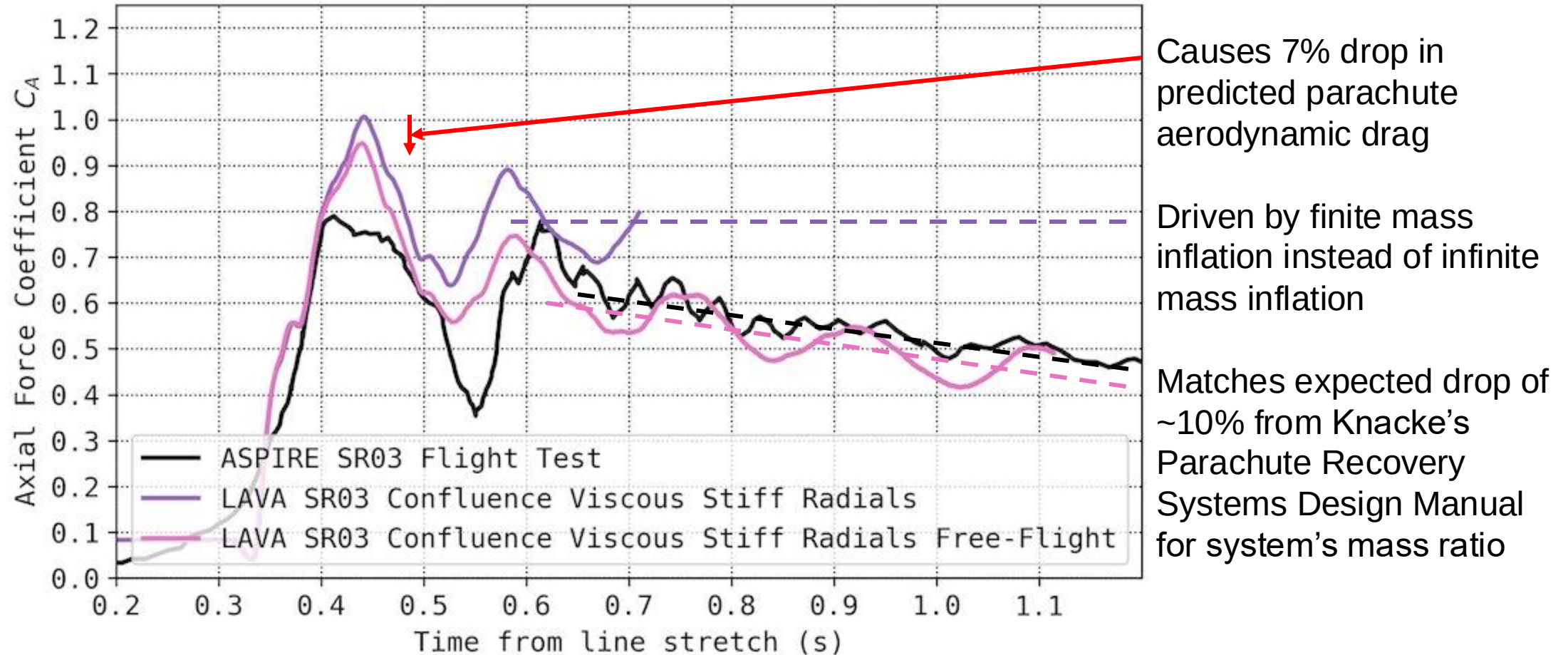
System decelerates as soon as parachute creates drag

Total (dynamic) pressure hitting canopy reduces with time due to deceleration

Bow shock strength reduces as the system decelerates

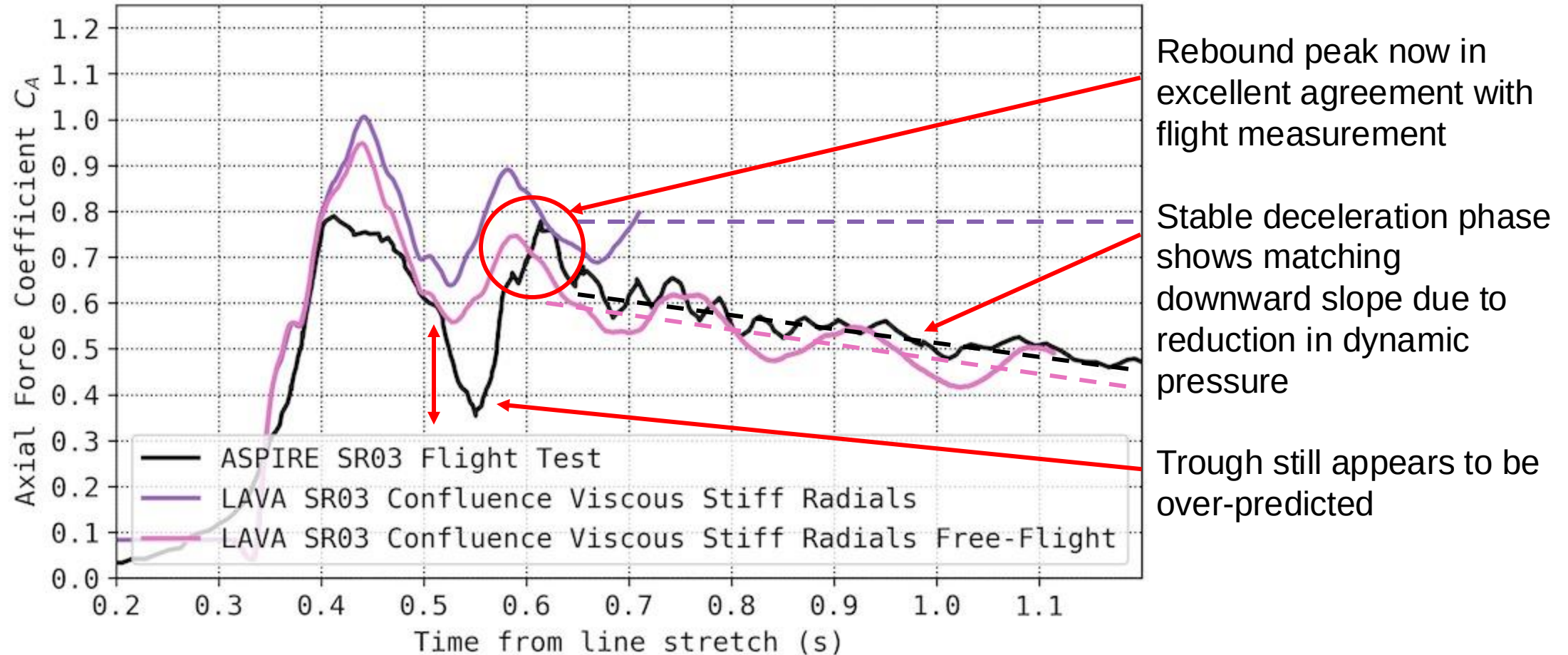
Note: movies are not synchronized due to slightly different output frequency

Results: Effect of Deceleration



Note: FSI curves are shifted in time to take out phase difference due to different time to inflation

Results: Effect of Deceleration

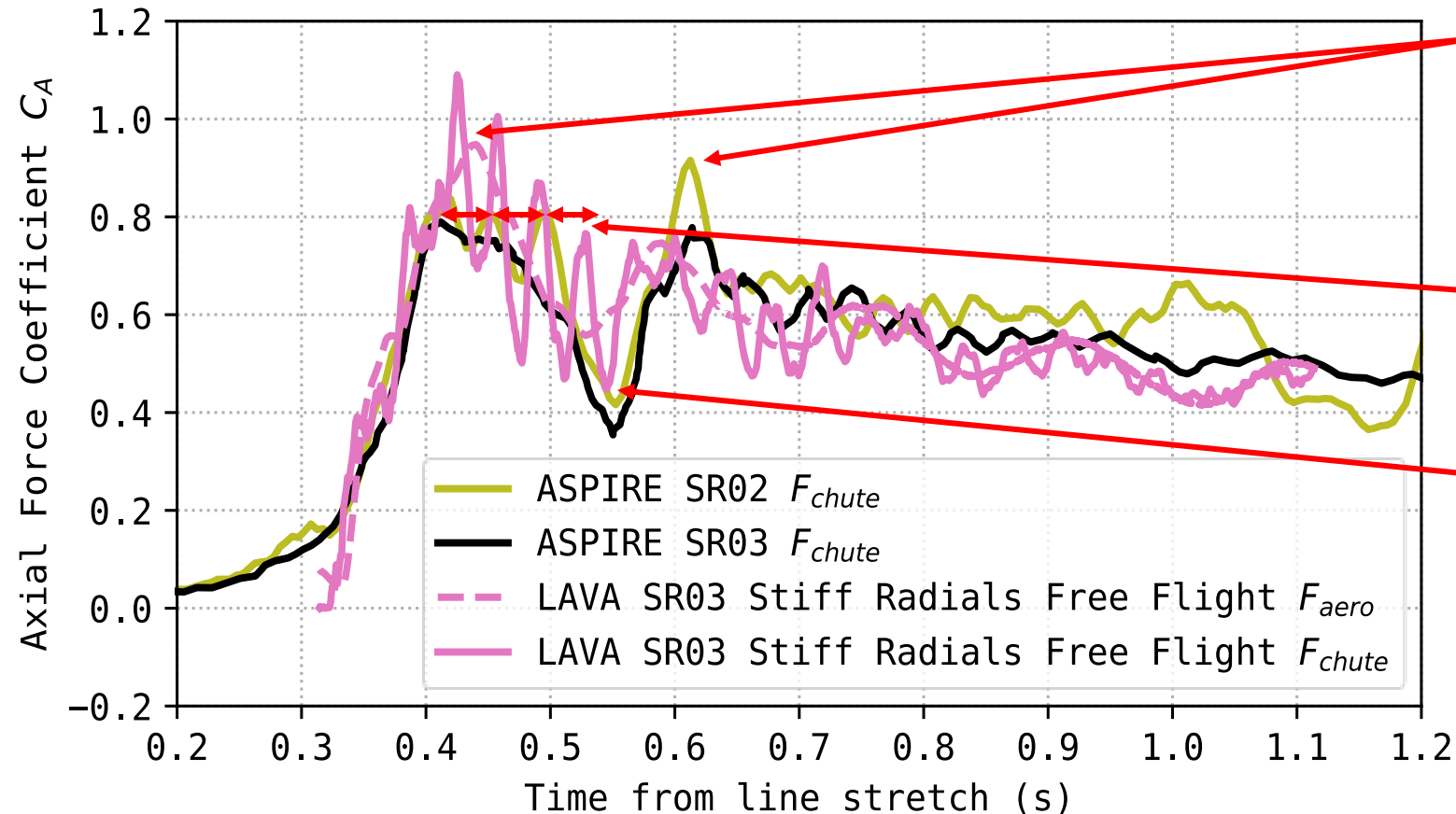


Note: FSI curves are shifted in time to take out phase difference due to different time to inflation

Results: Effect of Deceleration



Compute total axial force parachute system imparts to payload (F_{chute}) to compare to parachute aero drag (F_{aero}) and SR02 and SR03 flight test F_{chute}



Inflation peak in family with SR02 rebound peak

F_{chute} captures suspension line mode seen in SR02 immediately following F_{aero} peak

Trough in F_{chute} in good agreement with SR02 meaning it's caused by slack in the lines, not just dip in projected area

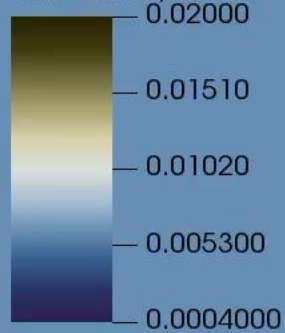
Note: FSI curves are shifted in time to take out phase difference due to different time to inflation

Conclusions

Time = 0.000442162 s

Pseudocolor

Var: Density



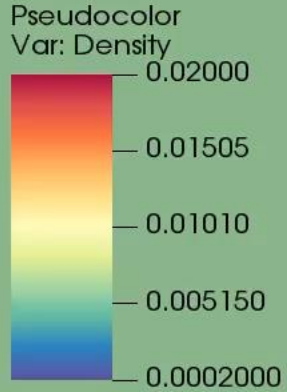
- ✓ Performed several FSI of ASPIRE SR03 flight test to assess sensitivity to modeling choices
- ✓ Modeling gore seams improved peak drag prediction by 18%
- ✓ Including deceleration further improved peak drag prediction by 7% and improved post-inflation trends

Future Work

- Improve initial parachute shape and projected area
- Refine underlying structural model to better predict stress concentrations and potential material failure
- Accelerate time-to-solution by porting to GPU

Density on surfaces and cut plane

Time = 0.00012839 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



FSI-WMLES of ASPIRE SR03
starting from new initial shape
more representative of chute at
line stretch presented at
ICCFD12 Jul 14-19, 2024

Thanks to:

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



Backup Slides

Challenges In Modeling Parachutes



Parachutes...

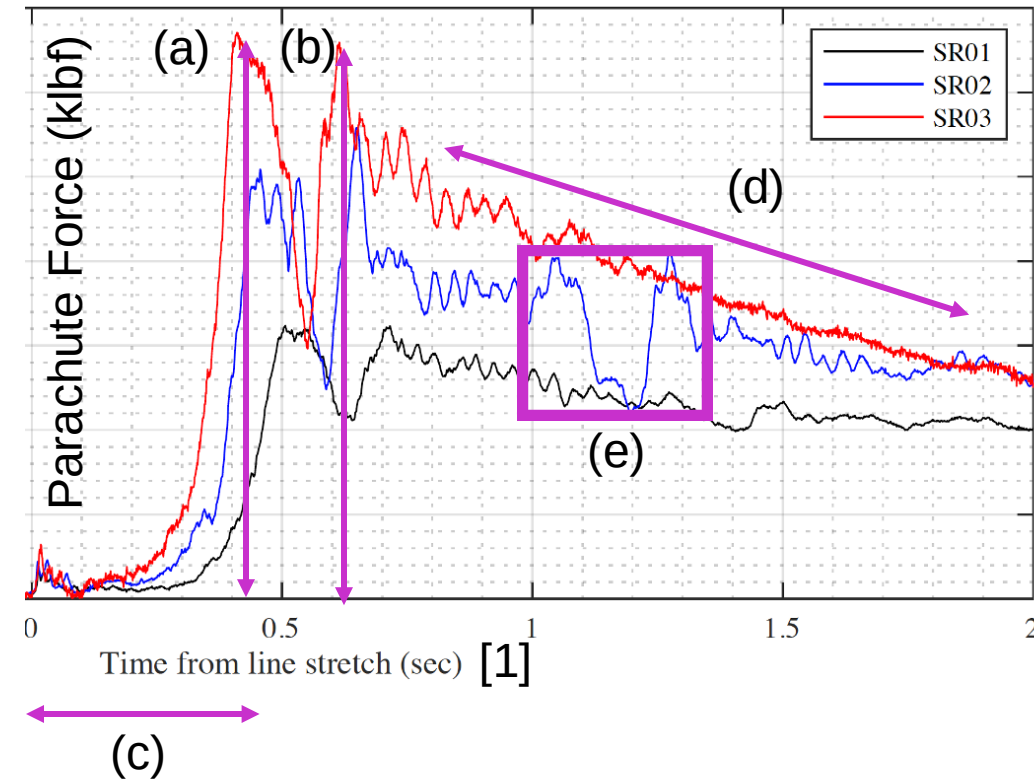
- are typically deployed from packed state in a bag so each path to inflation is fairly unique, full of self-contact, and inherently unsteady
- go through large non-linear deformations during inflation
- are incredibly thin (e.g. ~ 76 microns)
- are made of porous woven (orthotropic) fabric
- are made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

Specific Goals For FSI



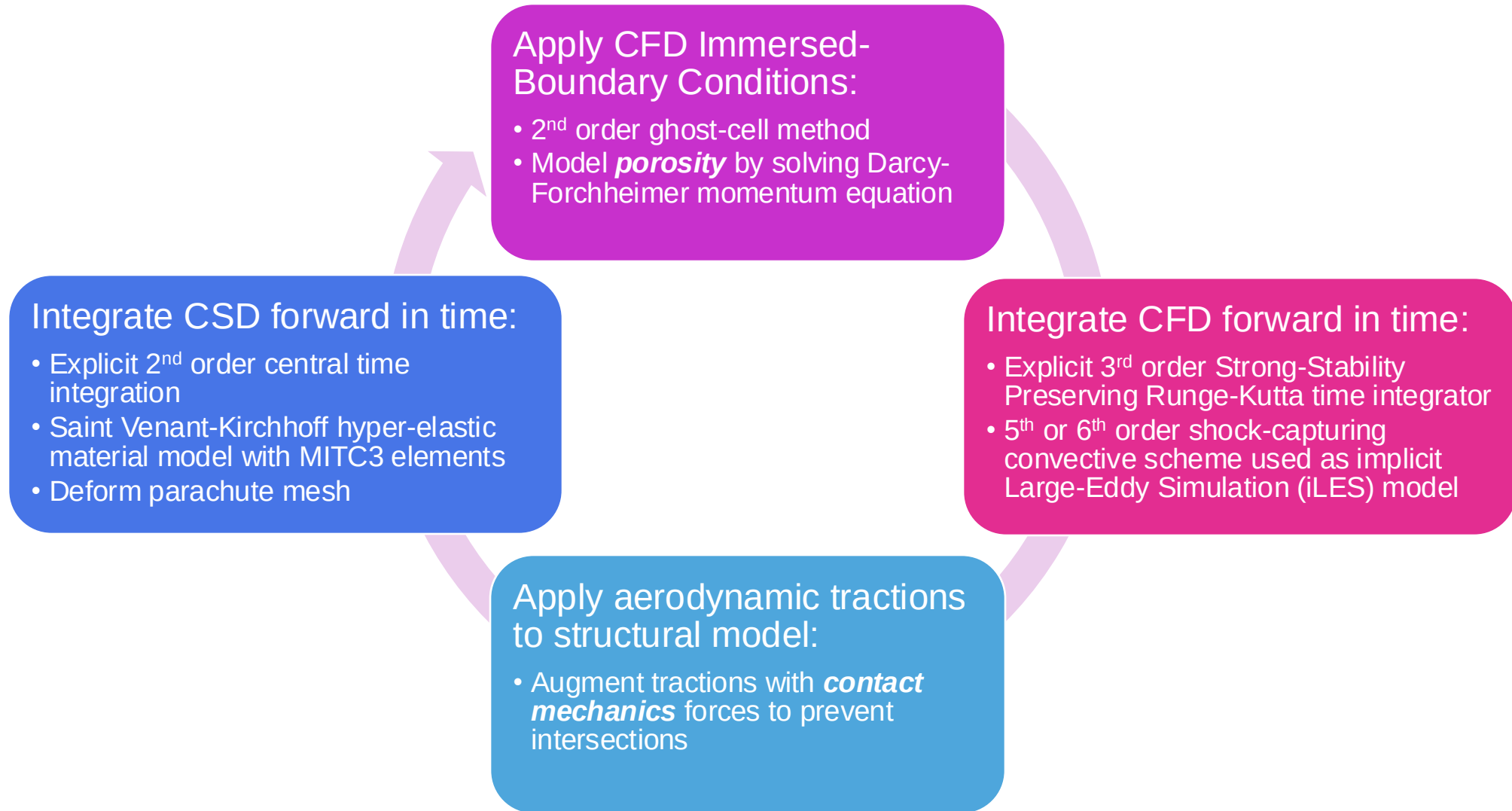
Metrics to validate in order of increasing difficulty:

- 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)



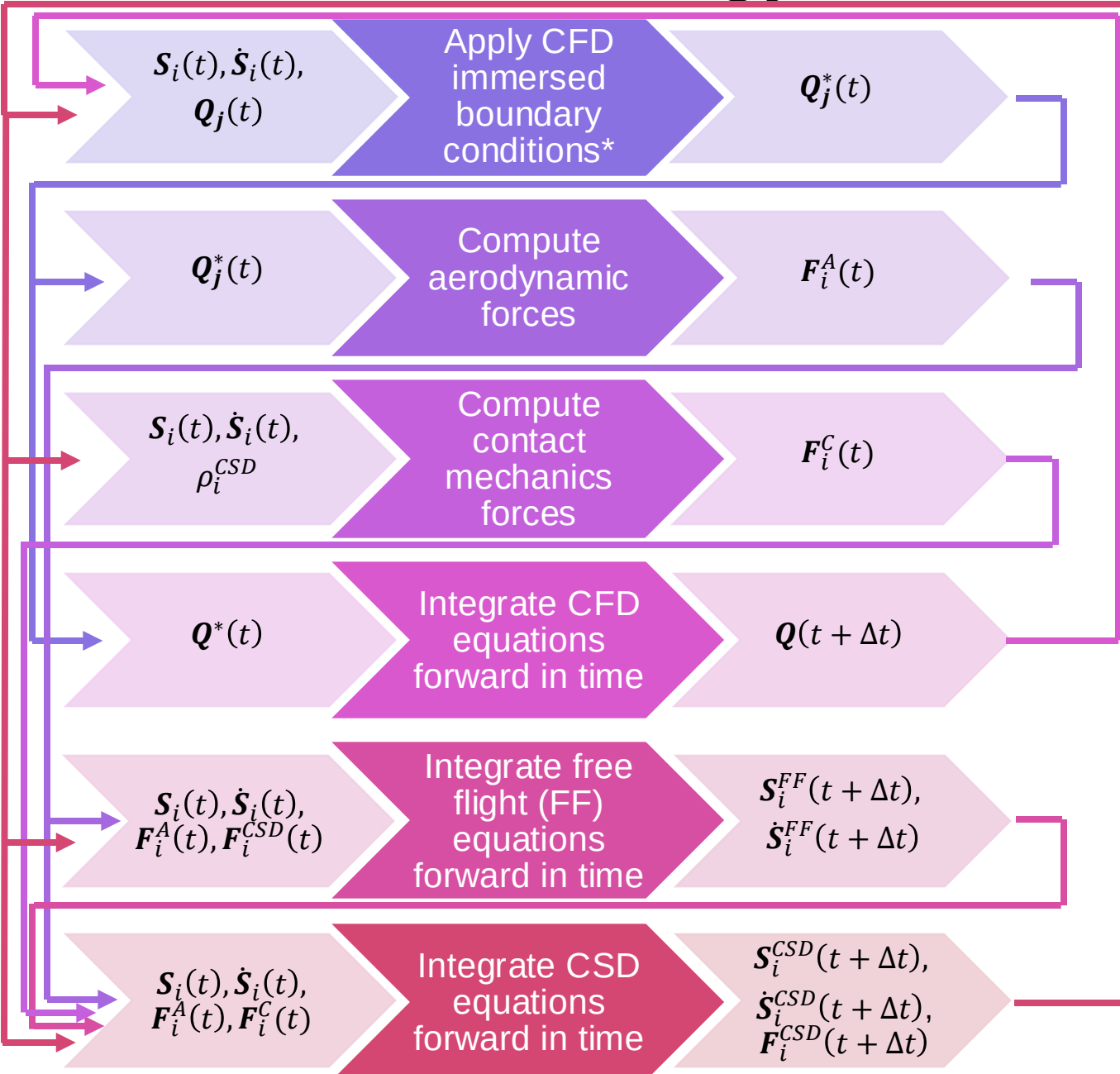
[1] Sonneveldt, Bryan S., Ian G. Clark, and Clara O'Farrell. "Summary of the Advanced Supersonic Parachute Inflation Research Experiments (ASPIRE) Sounding Rocket Tests with a Disk-Gap-Band Parachute." *AIAA Aviation 2019 Forum*. 2019.

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 .

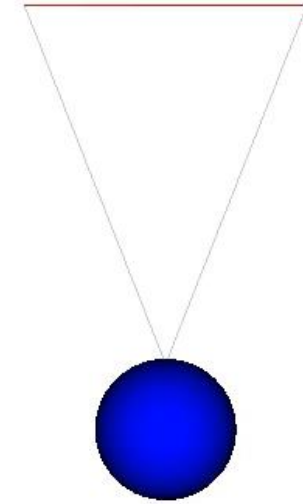
*including porosity to allow flow through parachute fabric

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>

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



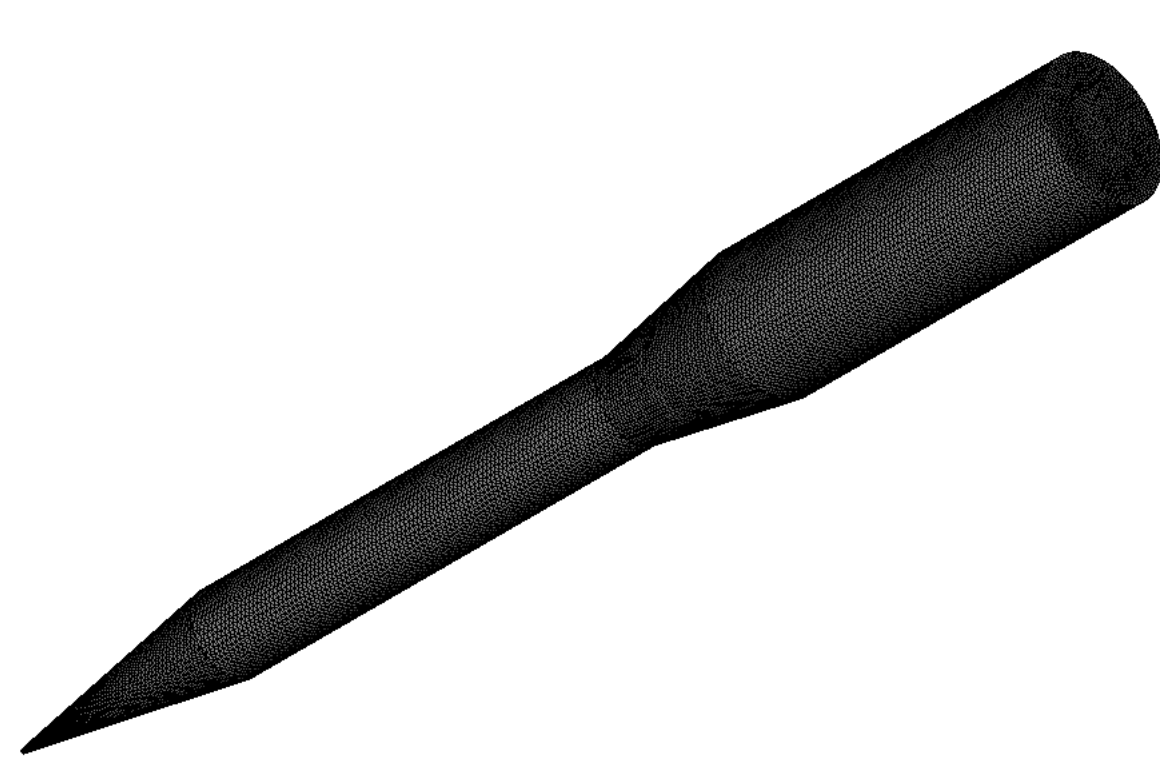
Demonstration of 6 DOF free-flight
parachute-payload coupling

Important Simplifying Assumptions

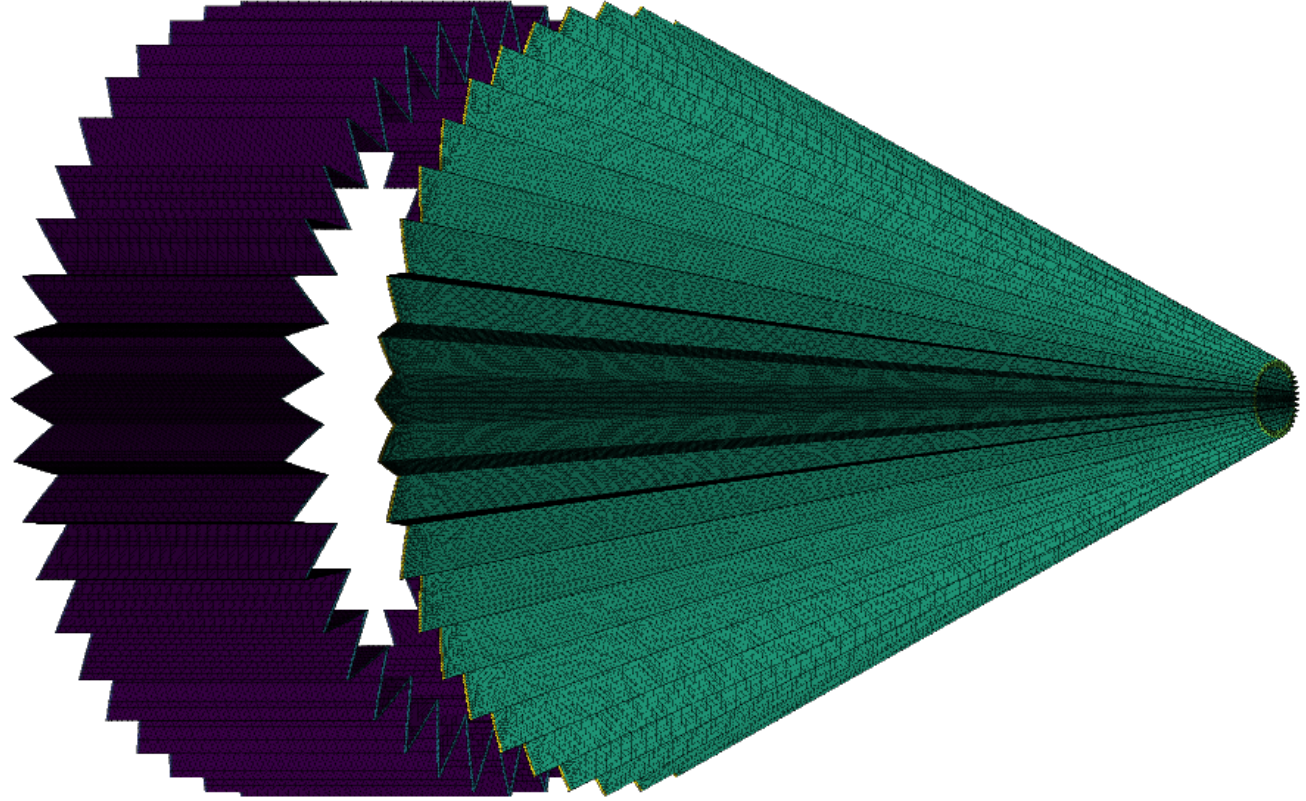


- Arbitrary initial parachute shape to reduce its cross-sectional area
- Gore seams (radial stiffeners) modeled as beam elements sharing same nodes as fabric elements
- Neglect viscous effects and solve Euler equations with slip boundary conditions
- Start with restrained payload (infinite mass inflation) 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



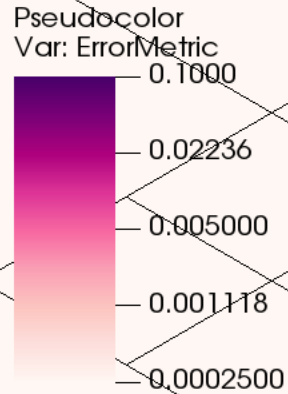
- 43,346 triangles (rigid) on payload
- Mean edge length away from nose 0.025 m



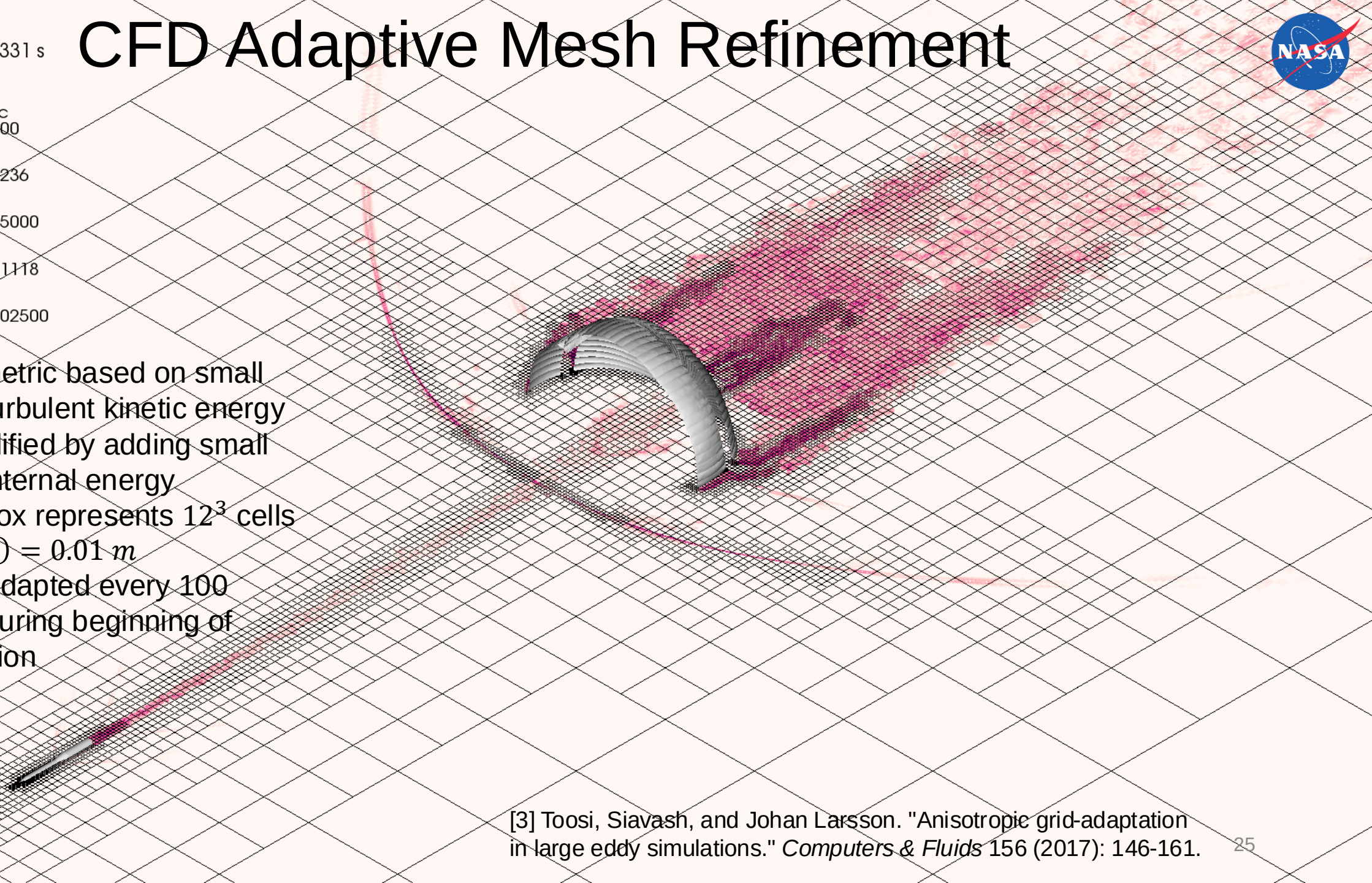
- 267,668 triangles (MITC3) on canopy surface
- Mean edge length 0.05 m on 15.62 m diameter canopy
- Min edge length at leading/trailing edge 0.025 m
- 76,954 Timoshenko beam elements for suspension lines, radials, gap and vent lines with fixed edge length of 0.05 m

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.