Fluid-Structure Interaction Parachute Simulations For Interplanetary Missions

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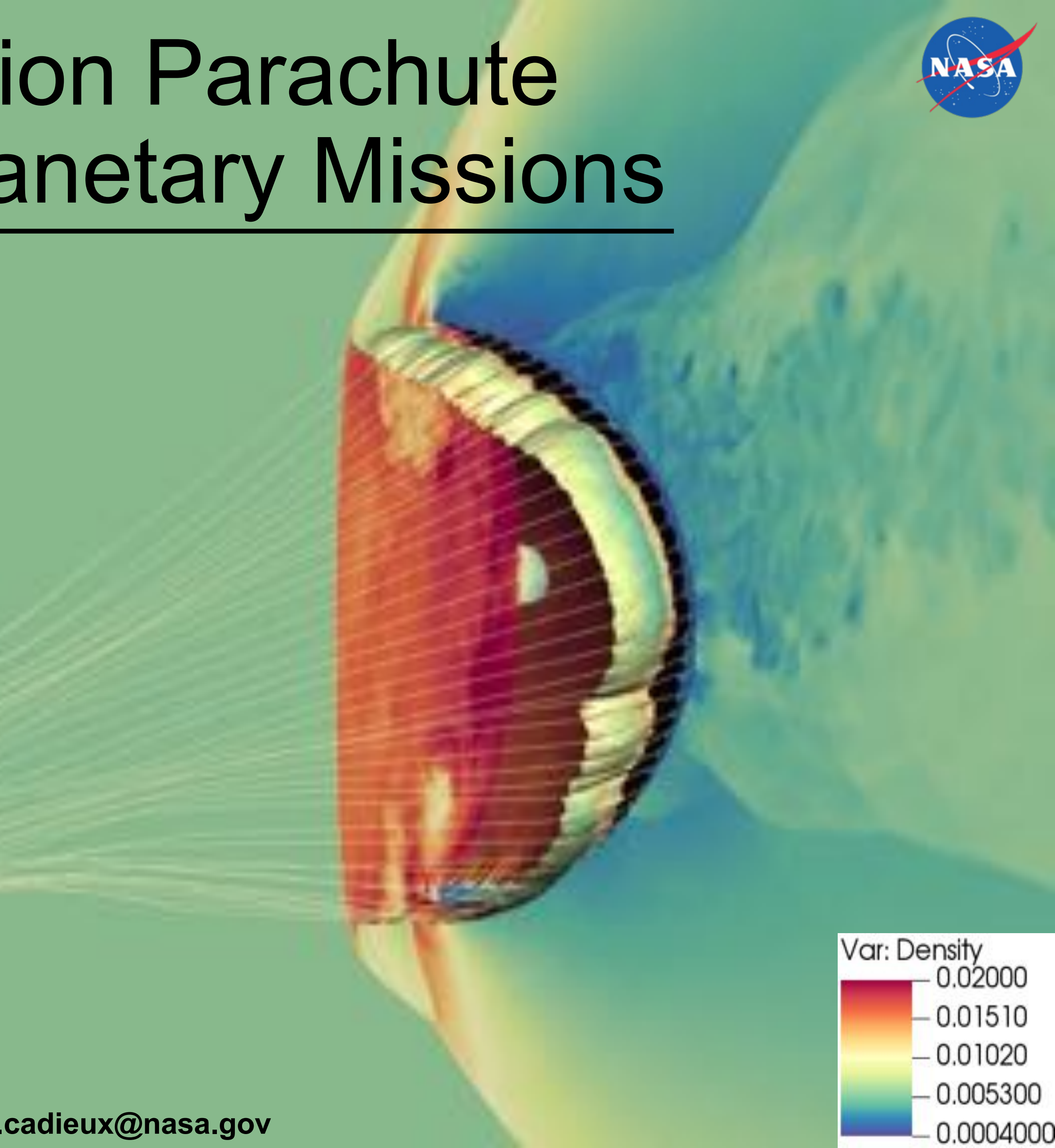

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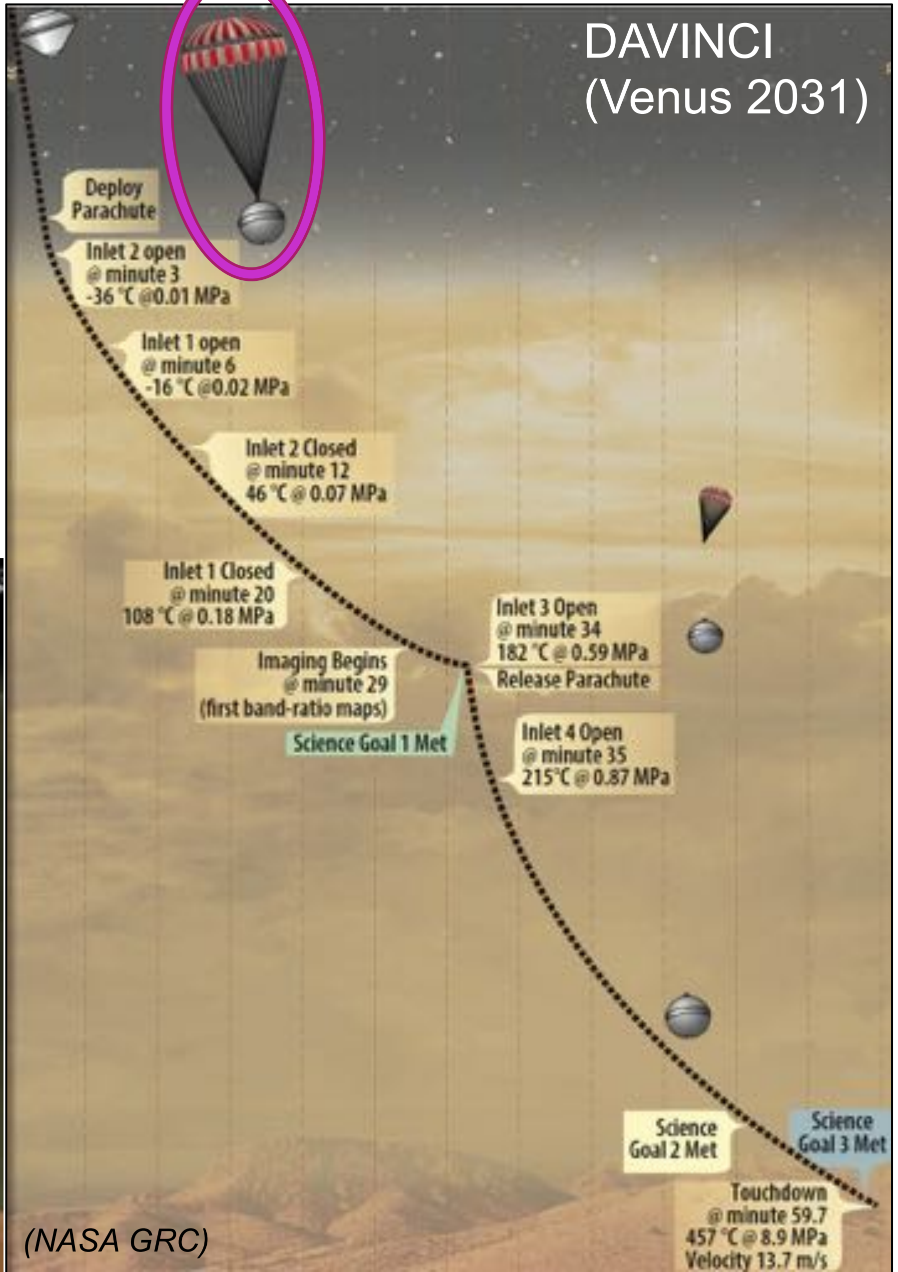
Context: Upcoming Interplanetary Missions

https://mars.nasa.gov/resources/26895/mars-sample-return-concept-illustration/

(NASA/APL)



(NASA GRC)

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

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

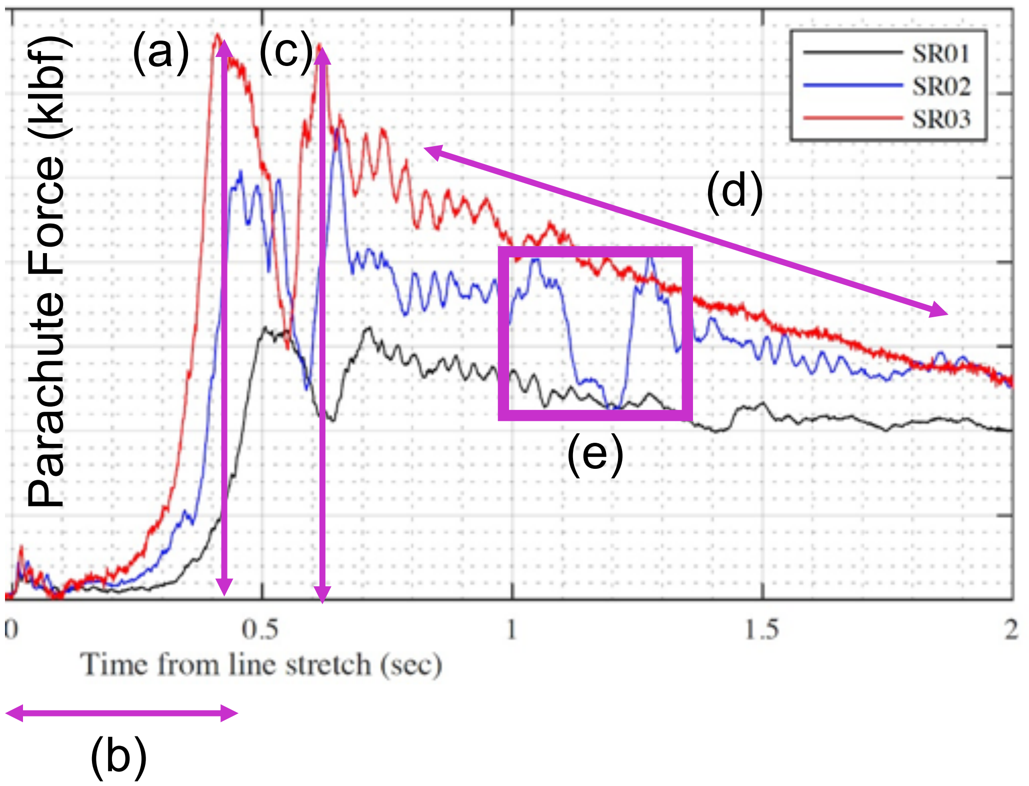
Opportunities For Parachute FSI

What are entry, descent, landing (EDL) engineers interested in predicting?

a) Peak opening loads & stresses (to predict potential failure)
b) Inflation time
c) Post-inflation dynamics (e.g. rebound peak)
d) Aerodynamic coefficients as a function of Mach, dynamic Pressure, AoA
e) Dynamic response to angle of attack changes due to wake recontact or wind gusts

What could fluid-structure interaction (FSI) simulations do better than current wind tunnel and empirical models?

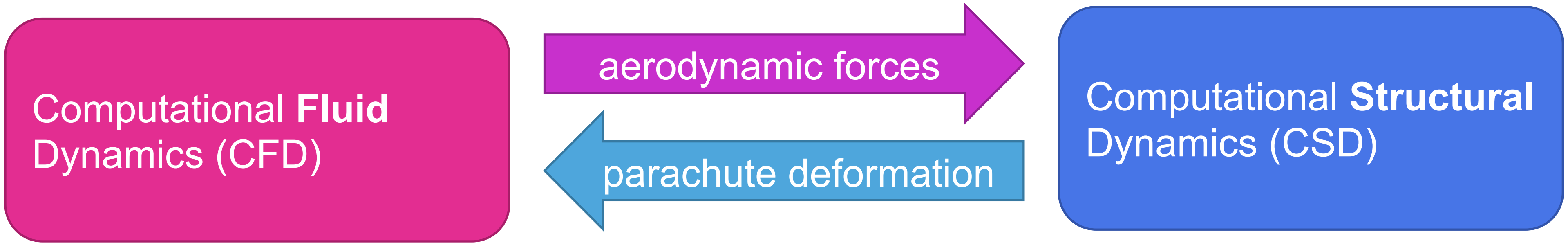
- Match atmosphere composition and transport properties
- Match stiffness to size ratio (limitation of wind tunnel tests)
- Cover larger range of scenarios, including dynamic ones (gusts, wake recontact)
- Provide insight into parameters not measurable in flight or experiment
- Conduct parametric geometry trade-study simulations



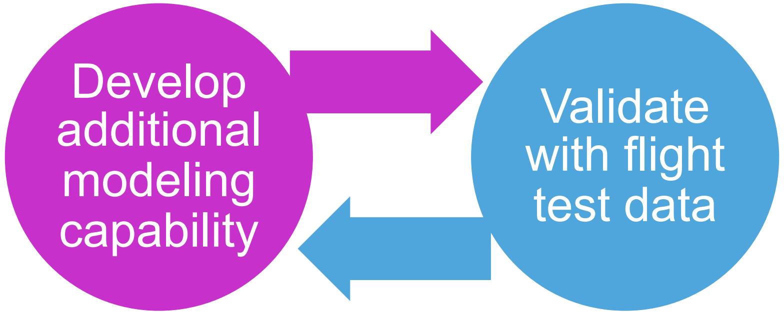
Sonneveldt, Bryan S., Ian G. Clark, and Clara O'Farrell. "Summary of the Advanced Supersonic Parachute Inflation Research Experiments (ASPIRE) Sounding Rocket Tests with a Disk-Gap-Band Parachute." *AIAA Aviation 2019 Forum*. 2019.

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

Methodology: FSI Overview

Apply CFD Immersed-Boundary Conditions:

- 2^{nd} order ghost-cell method
- Model ***porosity*** by solving Darcy-Forchheimer momentum equation

Integrate CFD forward in time:

- Explicit 3^{rd} order Strong-Stability Preserving Runge-Kutta time integrator
- 5^{th} or 6^{th} order shock-capturing convective scheme used as implicit Large-Eddy Simulation (iLES) model

Apply aerodynamic tractions to structural model:

- Augment tractions with ***contact mechanics*** forces to prevent intersections

Integrate CSD forward in time:

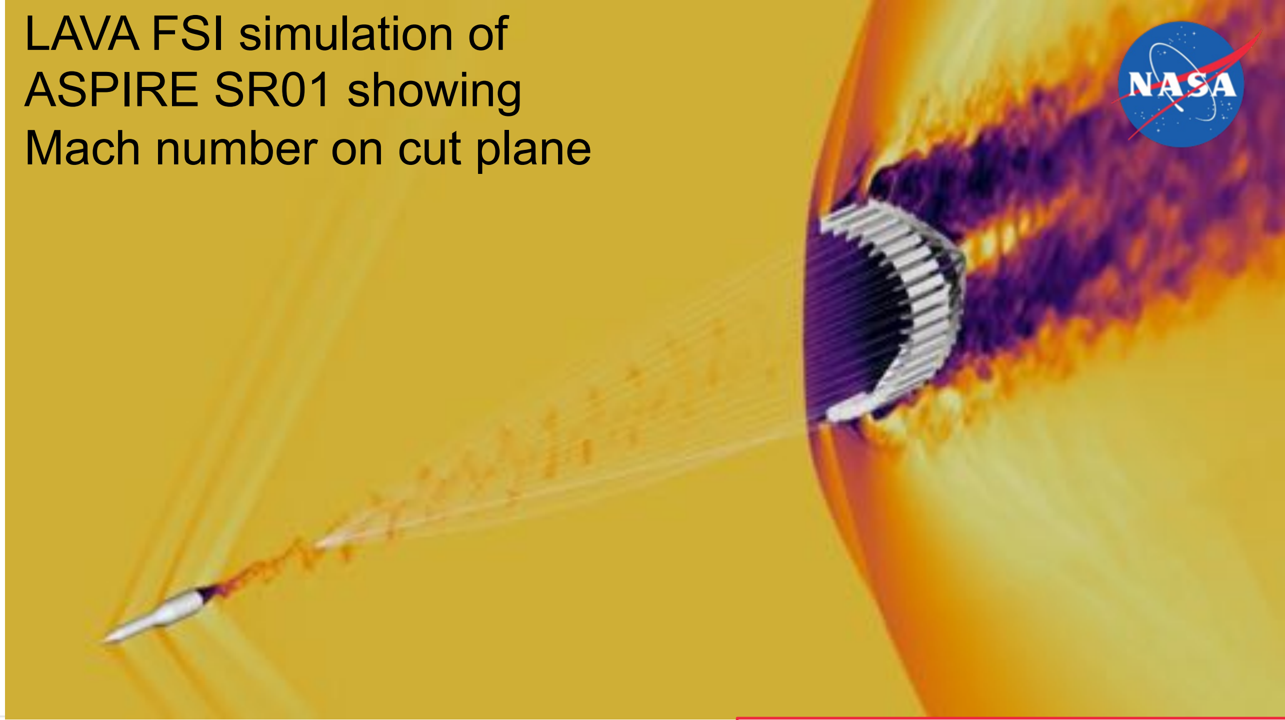
- Explicit 2^{nd} order central time integration
- Saint Venant-Kirchhoff hyper-elastic material model with MITC3 elements
- Deform parachute mesh

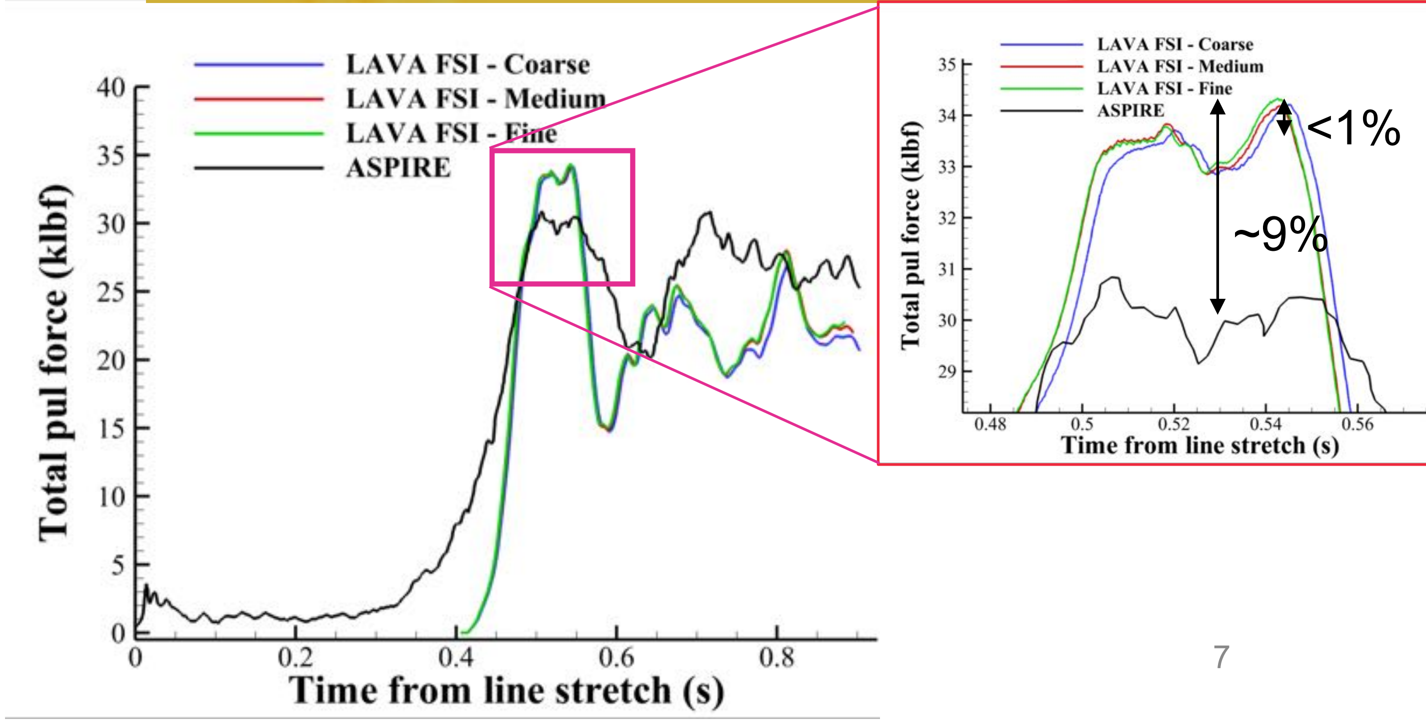
For more details on the methods, please refer to: Boustani, Jonathan, et al. "Fluid-structure interaction simulations of the ASPIRE SR01 supersonic parachute flight test." *Aerospace Science and Technology* 126 (2022): 107596 https://doi.org/10.1016/j.ast.2022.107596

Previous Work

- AMS Seminar presented 12/02/2021 by Jonathan Boustani: https://www.nas.nasa.gov/pubs/ams/2021/12-02-21.html
- LAVA team performed simulations of the ASPIRE SR01 flight with material properties derived from scarce published data on F-111 Nylon (and a lot of guess work)
- Demonstrated CFD can predict peak pull-force within 10% of measured in flight
- Investigated structural grid sensitivity and showed again less than 1% change in predicted pull-force
- 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 https://doi.org/10.1016/j.ast.2022.107596

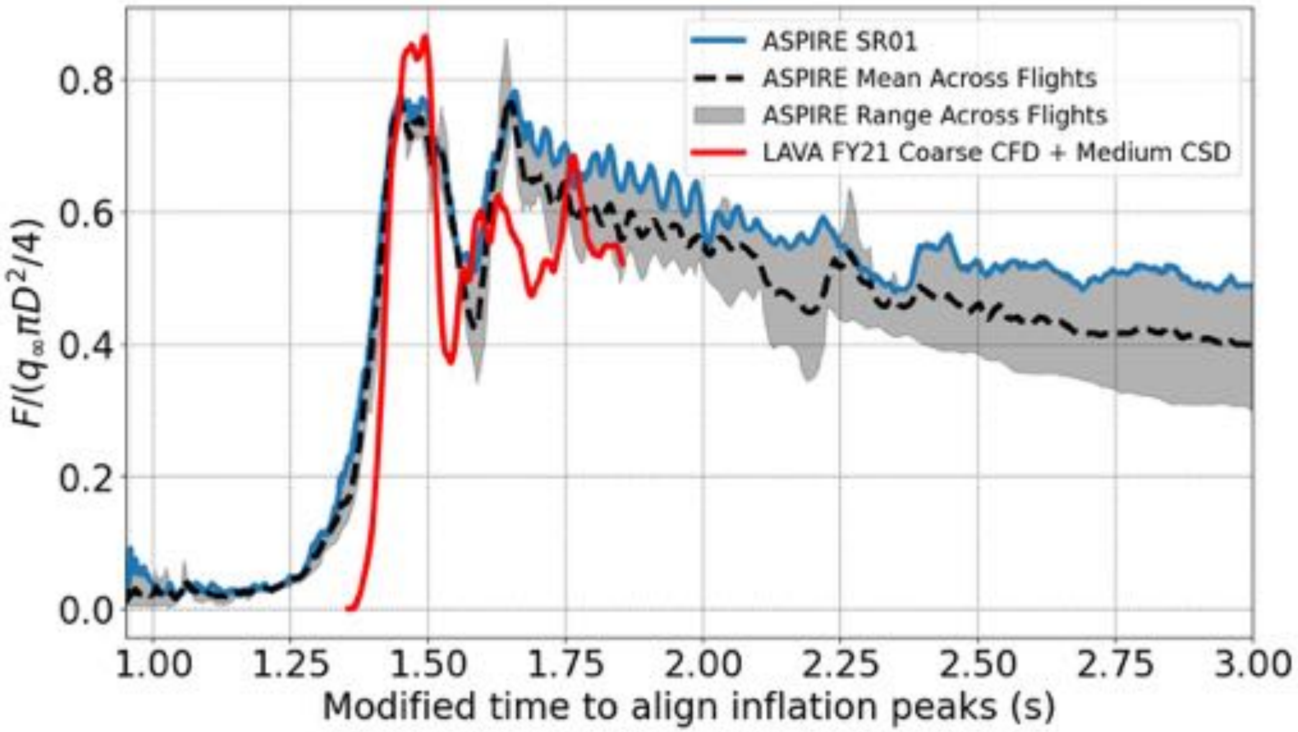
LAVA FSI simulation of ASPIRE SR01 showing Mach number on cut plane





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

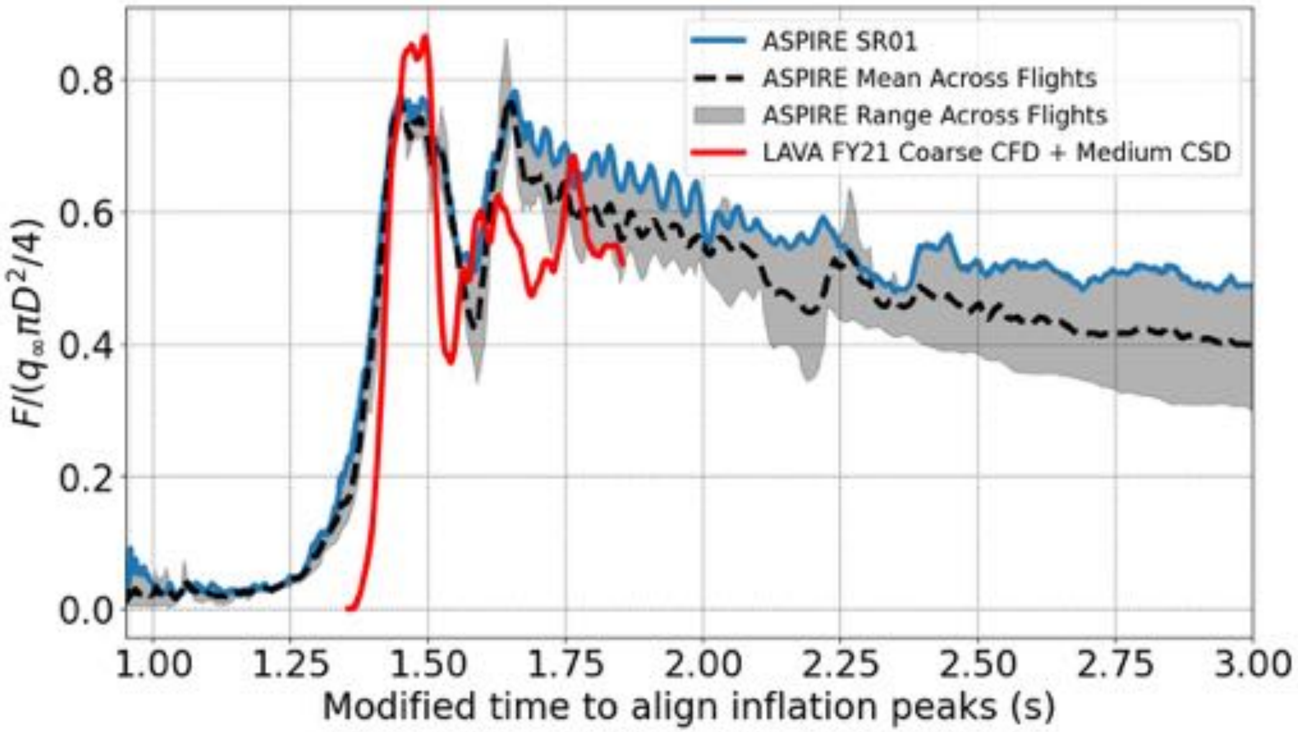


Variation in recorded pull-force across ASPIRE flights:

inflation peak ~ 3%
post-inflation trough ~ 42%
rebound peak ~ 15%
deceleration phase ~ 20%

Sources Of Modeling Error In FSI

- 10% over-prediction is expected for FSI with restrained payload due to infinite mass ratio inflation compared to finite $\mathrm{M_R} \approx 60$ from wind tunnel comparisons to flight → modeling deceleration in FSI should close this gap
- FSI predicts post-inflation trough accurately but does not capture rebound peak… why?
- Large uncertainty in material properties and as-built parachute configuration compared to FSI model
- Inflation rate (initial slope) is steeper in FSI: could it be due to our assumed initial parachute shape (cross-sectional area)?

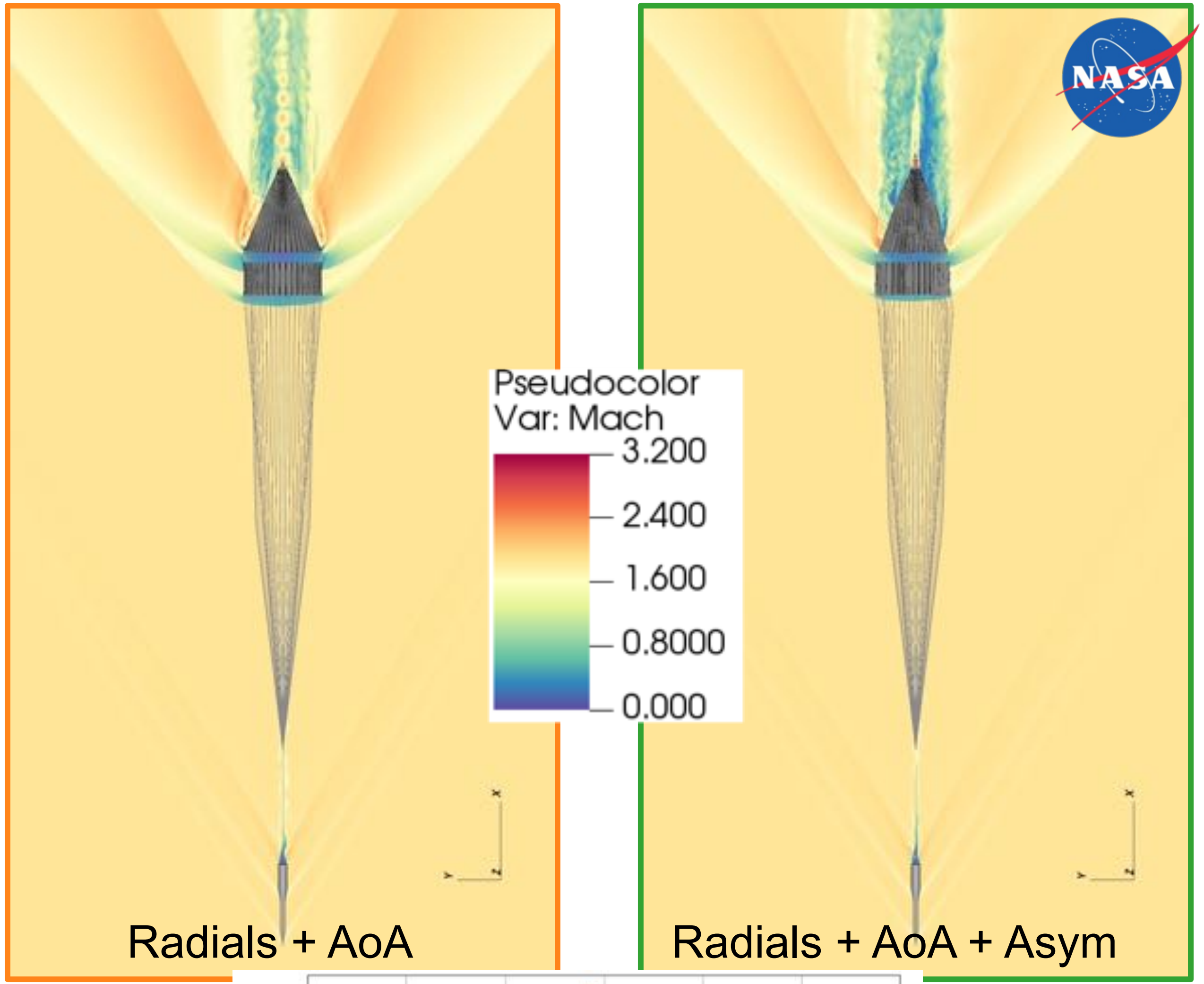


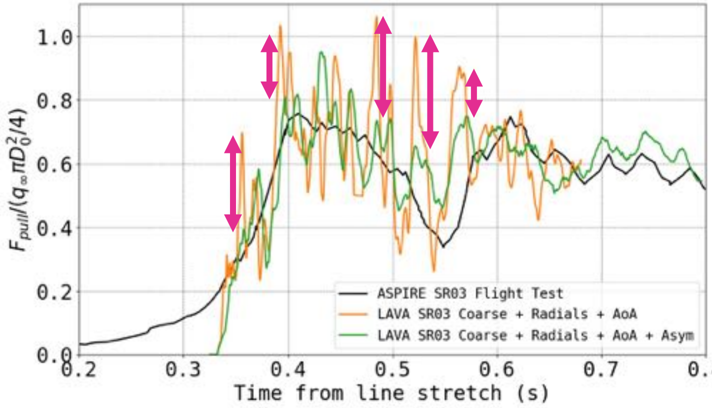
Mass ratio $\mathrm{M_R} = \frac{m_{total}}{\rho (S_0 C_D)^{\frac{3}{2}}}$ is the ratio of inertial to drag forces expressed in terms of the system mass over the mass of air ingested by the parachute at full inflation:

- $\mathrm{M_R} \rightarrow 0$: payload decelerates to terminal velocity within parachute inflation time
- $\mathrm{M_R} \rightarrow \infty$: payload does not decelerate during inflation

Recent Work

- LAVA team performed simulations of the ASPIRE SR03 flight with material properties published by J. Rabinovitch et al. https://doi.org/10.2514/6.2022-2746
- Investigated sensitivity of tension at the load pins to freestream angle of attack, asymmetry in the initial parachute shape, and the presence of radial stiffeners (gore seams) modeled as continuous suspension lines
- Found that asymmetry in the initial parachute shape is critical to reduce constructive interference of suspension line tension and transverse waves
- For more details, please refer to: Cadieux, Francois, et al. "Fluid-Structure Interaction Simulations of the ASPIRE SR03 Supersonic Parachute Flight Test." *AIAA SCITECH 2023 Forum*. 2023. https://doi.org/10.2514/6.2023-1336





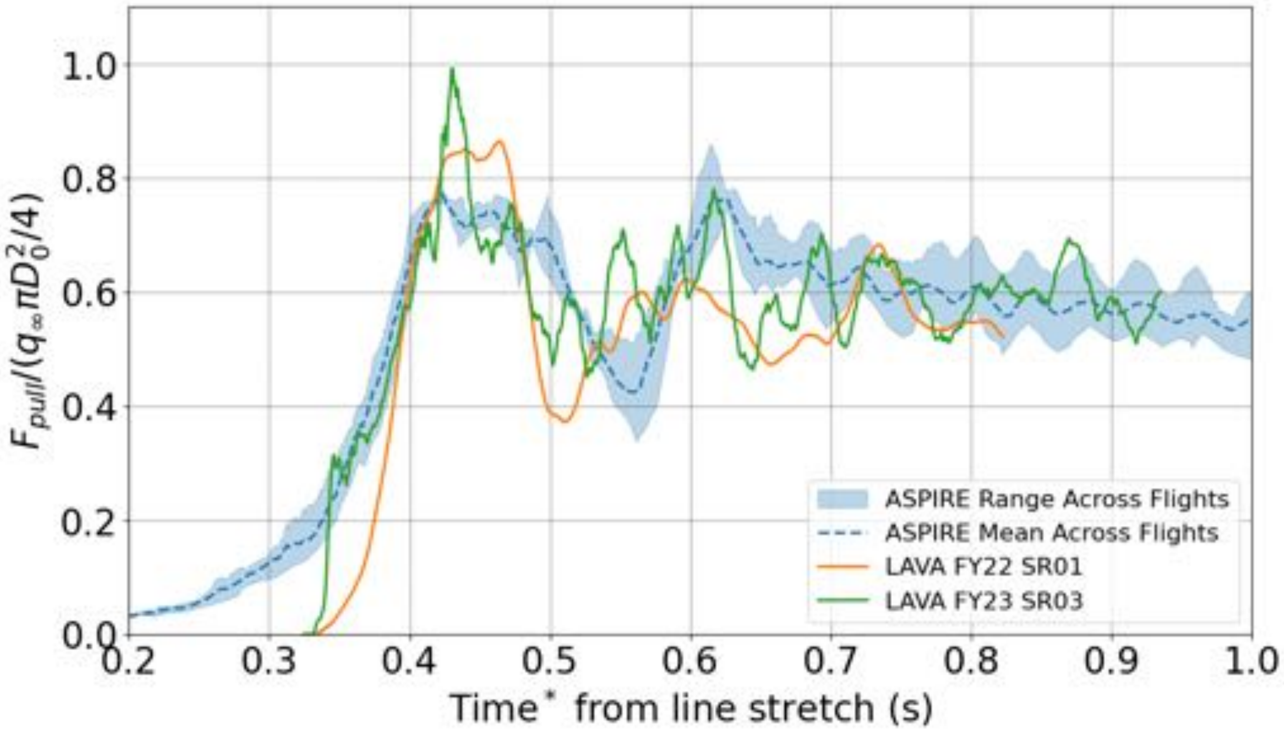
Results: From FSI of SR01 to SR03

Achievements:

- Better match to ASPIRE qualitative trend, especially during inflation
- Drop from peak to trough of 55% matches ASPIRE at 52%
- Trough and rebound peak values are within flight-to-flight variability

Remaining questions:

- Can infinite mass inflation account for ~20% overprediction in peak loads?
- What is the cause of the well-defined post-inflation trough and rebound peak in the flight test that the FSI does not quite reproduce? Is it also related to deceleration or is it modeling error?



Variation in recorded pull-force across ASPIRE flights:
inflation peak ~ 3%
post-inflation trough ~ 42%
rebound peak ~ 15%
deceleration phase ~ 20%

*Time series have been shifted to match timings of inflation peak

Ongoing: Investigating Other Modeling Errors

- Porosity of parachute fabric is known to increase significantly under strains experienced during inflation peak – could this explain why we predict larger pull-force at peak inflation, or why FSI predicts different post-inflation trough to rebound behavior?

- So far, we neglected viscous effects (Euler + slip) due to slender payload and ram drag of parachute being several orders of magnitude greater than viscous drag. Could viscous effect on canopy increase pressure in wake and thus decrease drag? Could it damp some of these oscillations in tension we observed?

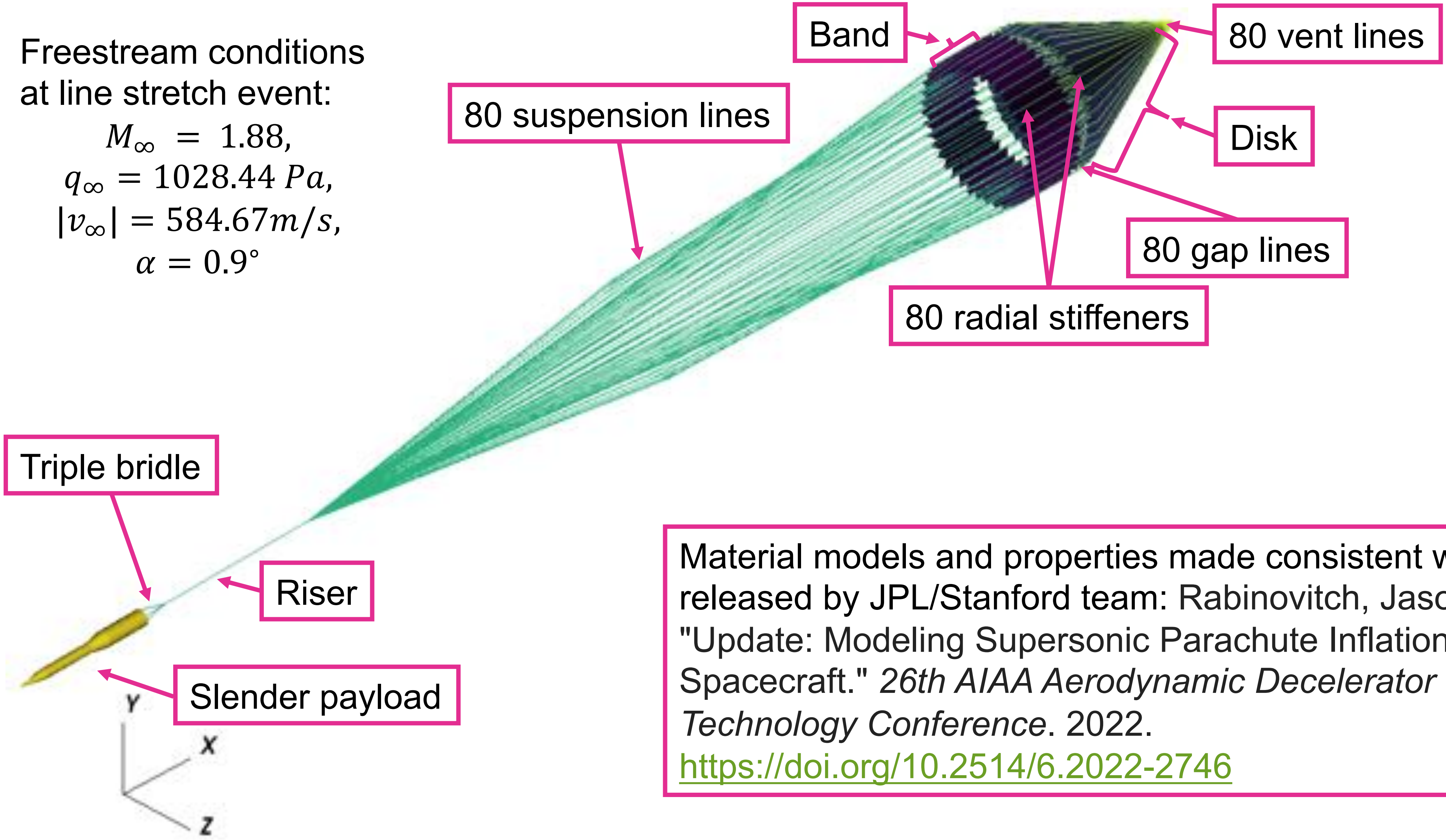
- Stiffness of many components of the parachute is calculated or estimated and carries significant uncertainty: we suspect some level of under-estimation because it’s known that more elastic suspension lines, radial and circumferential stiffeners can lead to higher loads at peak inflation, and larger oscillations

- Suspension lines do not experience drag in our current simulations, so any waves generated propagate completely undamped. Could a simple line drag model (one-way coupling from CFD to structural) provide enough drag to damp some of the oscillations observed?

ASPIRE SR03 Problem Setup

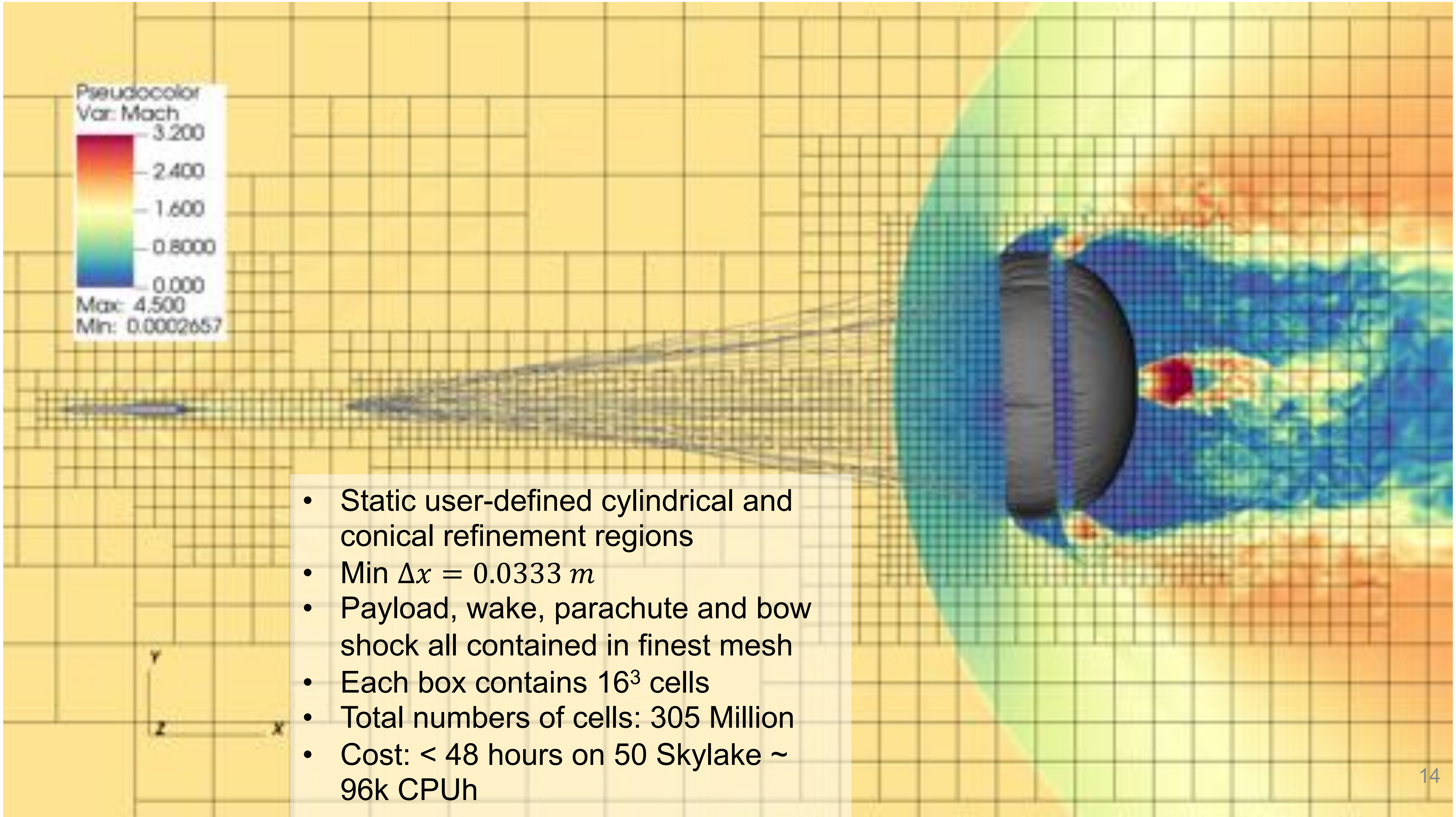
Freestream conditions at line stretch event:

$$M_\infty = 1.88,$$
$$q_\infty = 1028.44\ Pa,$$
$$|v_\infty| = 584.67 m/s,$$
$$\alpha = 0.9°$$



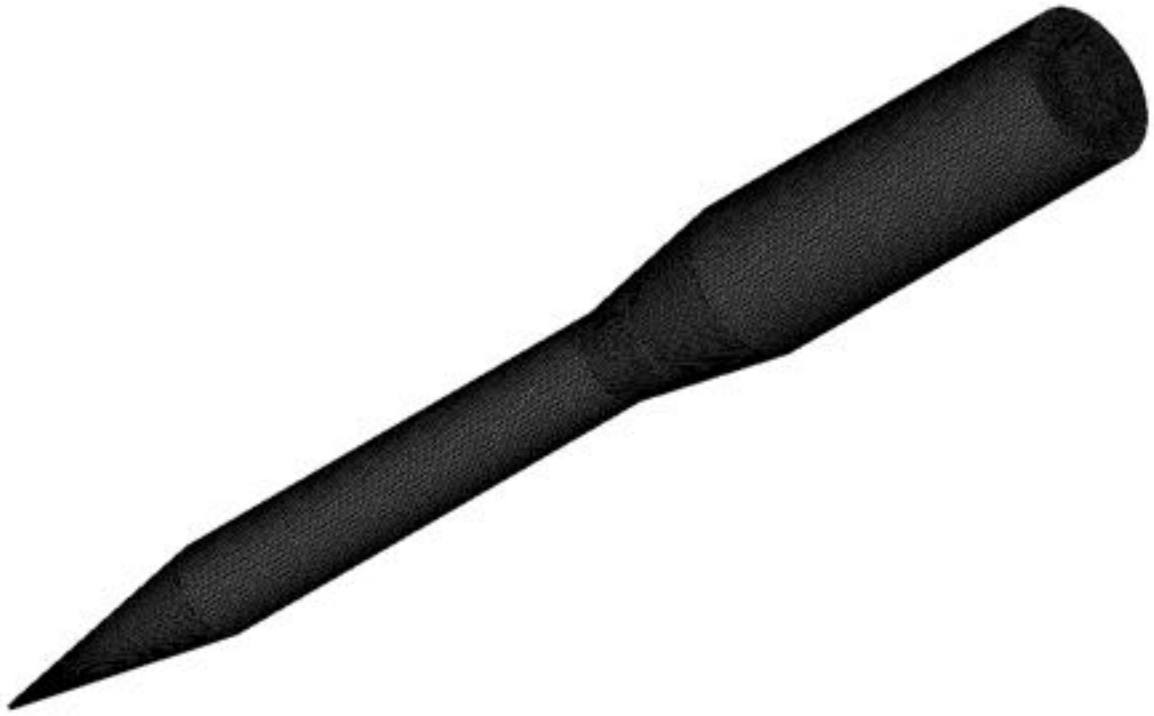
Material models and properties made consistent with those released by JPL/Stanford team: Rabinovitch, Jason, et al. "Update: Modeling Supersonic Parachute Inflations for Mars Spacecraft." *26th AIAA Aerodynamic Decelerator Systems Technology Conference*. 2022. https://doi.org/10.2514/6.2022-2746

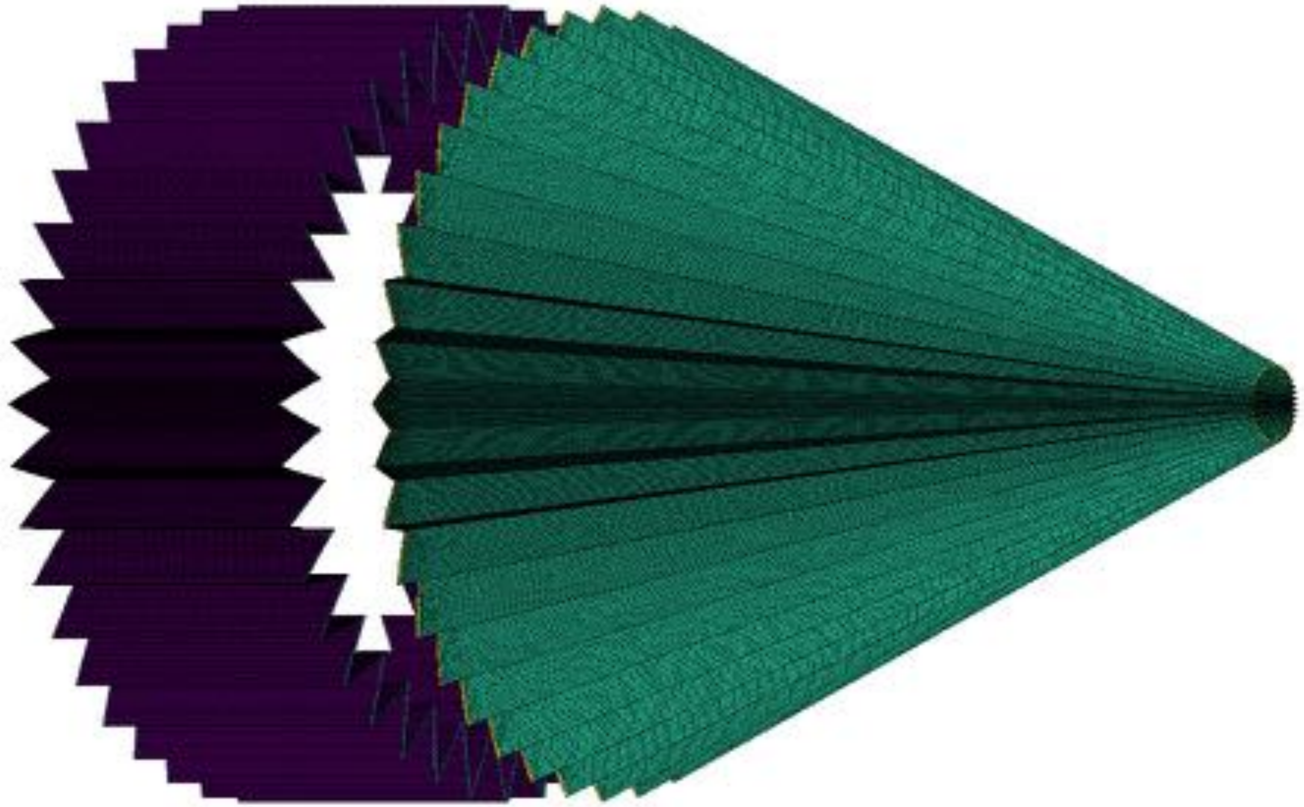
Methodology: CFD Mesh



- Static user-defined cylindrical and conical refinement regions
- Min $\Delta x = 0.0333\ m$
- Payload, wake, parachute and bow shock all contained in finest mesh
- Each box contains 16^3 cells
- Total numbers of cells: 305 Million
- Cost: < 48 hours on 50 Skylake ~ 96k CPUh

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

Initialization Procedure for FSI

1) Pre-inflate Parachute CSD + Contact

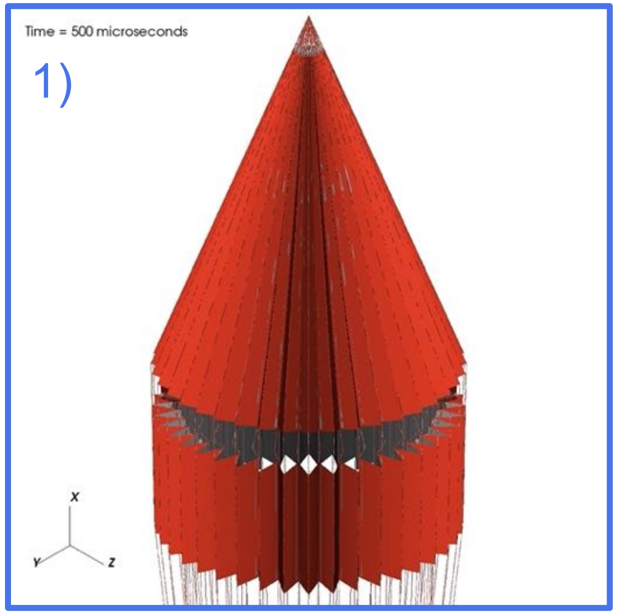
- Duration: ~0.016 s
- Purpose: improve realism of initial parachute shape

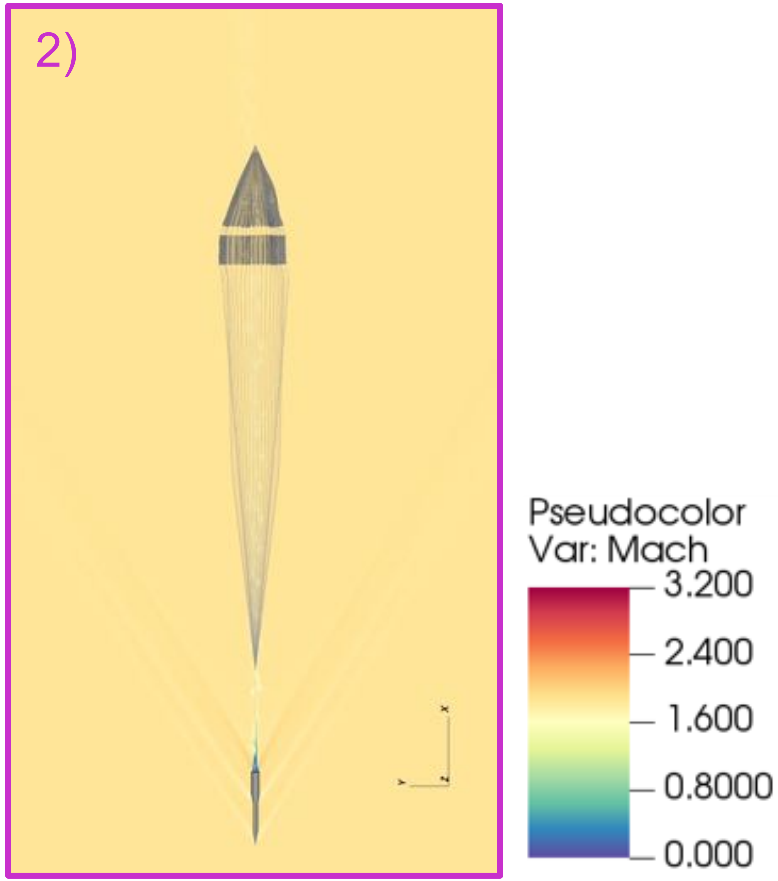
2) Payload + Rigid Parachute CFD

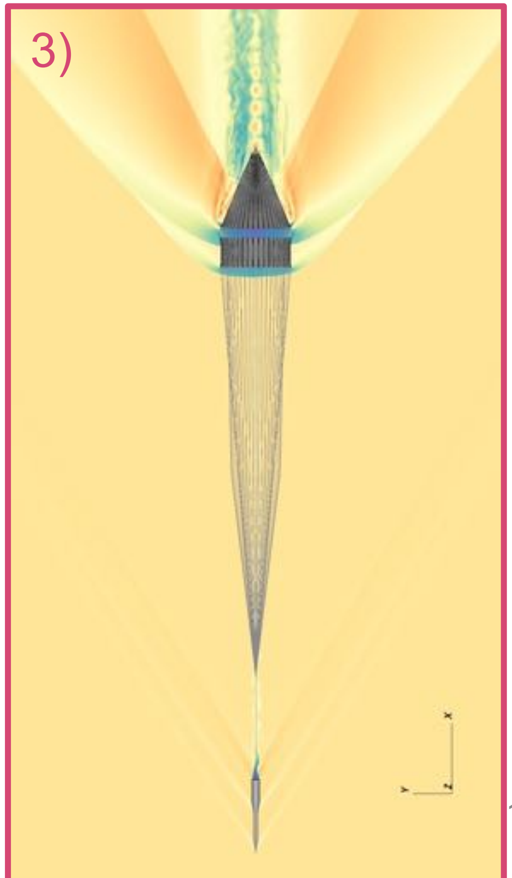
- Duration: ~0.3 s
- Purpose: establish payload wake and realistic pressure distribution over canopy

3) Coupled FSI

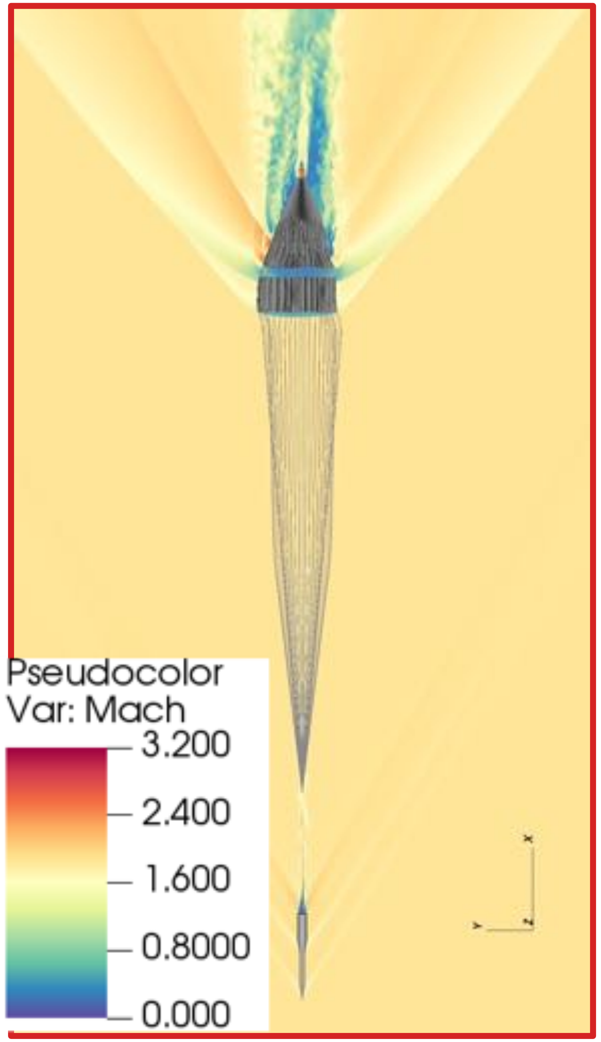
- Duration: ~0.5 s
- Purpose: Predict rise, peak, trough, and rebound peak in pull-force



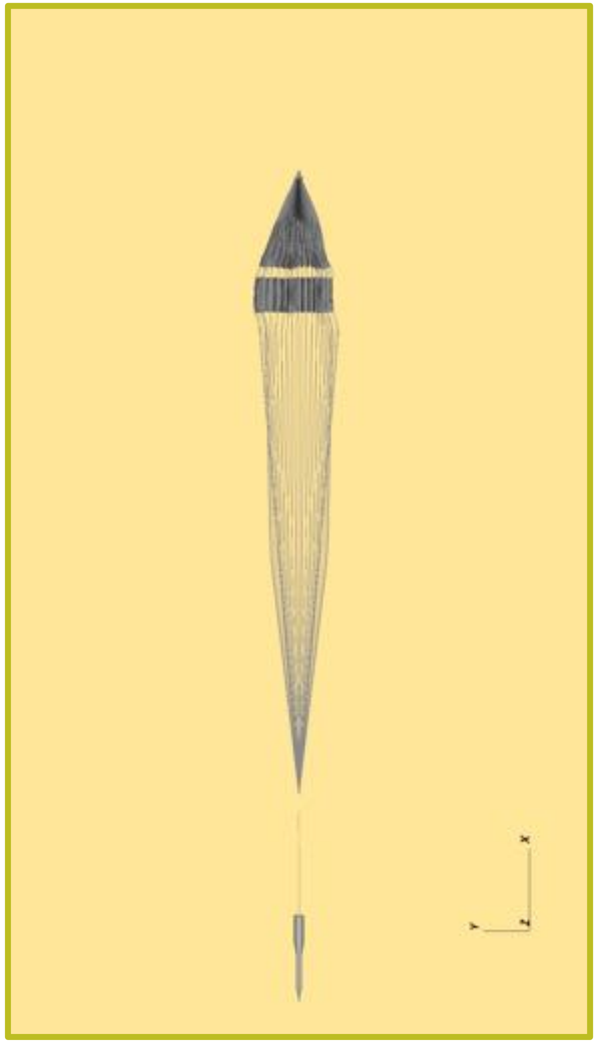




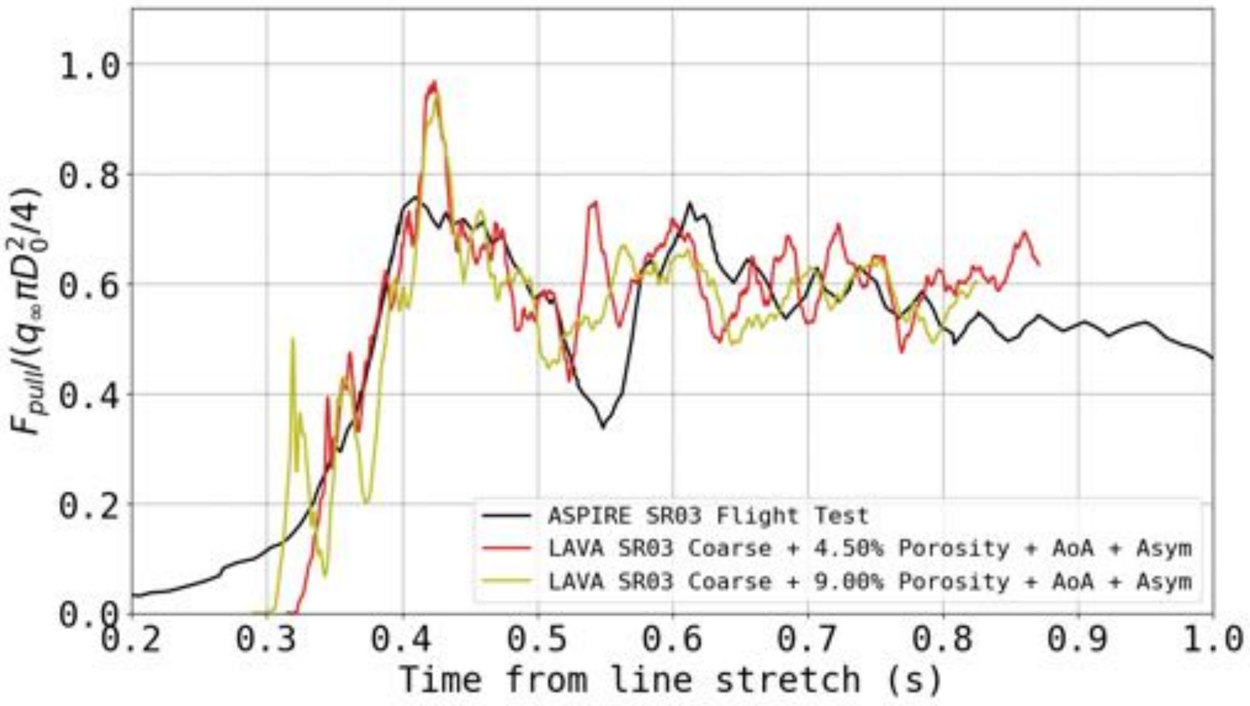
Results: Effect of Doubling Porosity



AoA + Asym

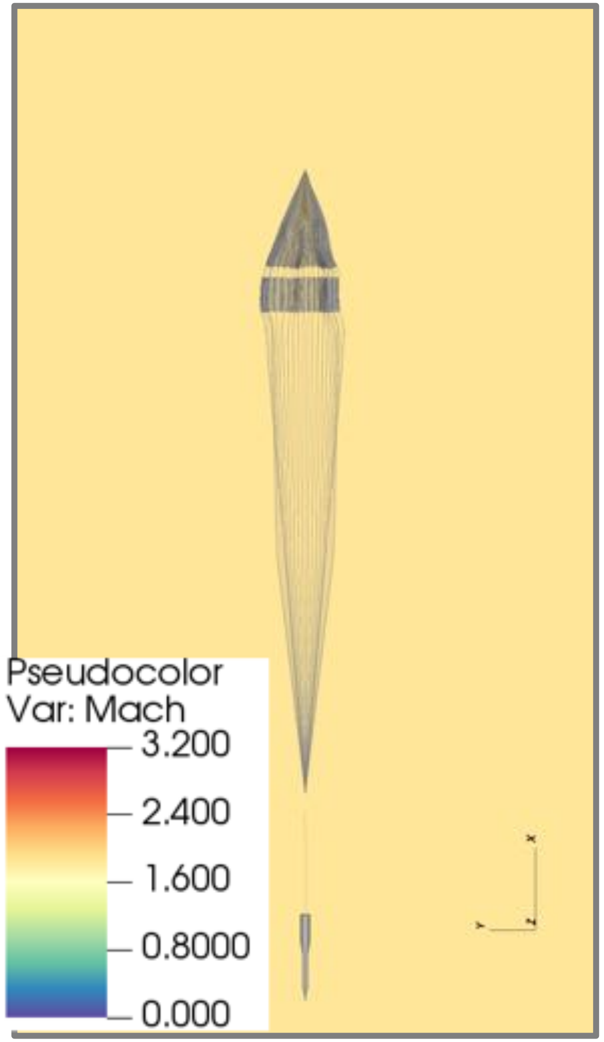


AoA + Asym + 2x Porous

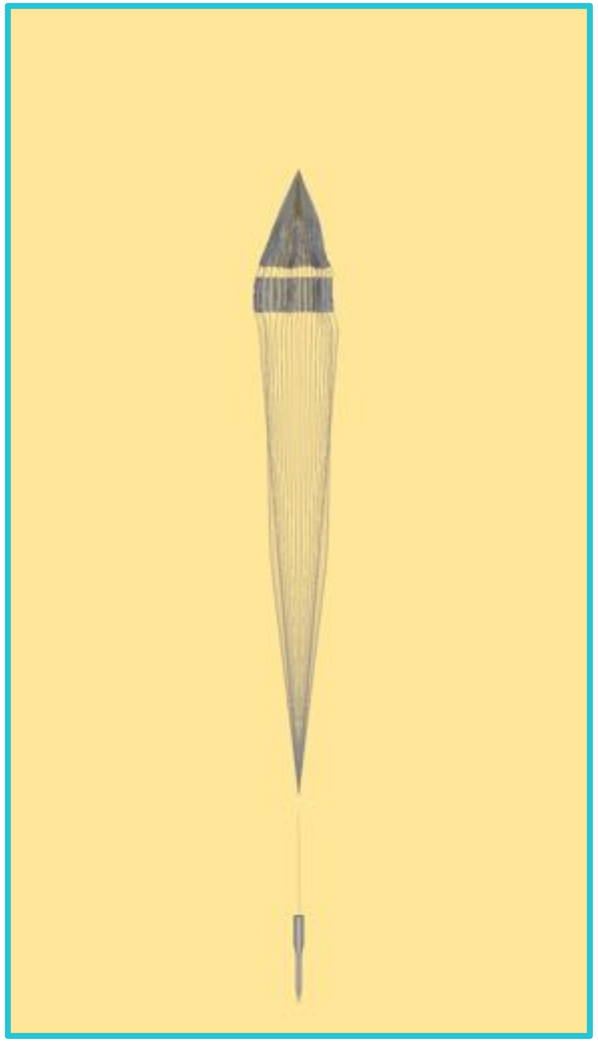


Doubling porosity causes effective cross-sectional area to be smaller and prevents bow shock from moving out of the gap. This generates larger pressure differences in the disk compared to the band and causes large oscillations in pull-force early on. It also eliminates the peak at t=0.55s.

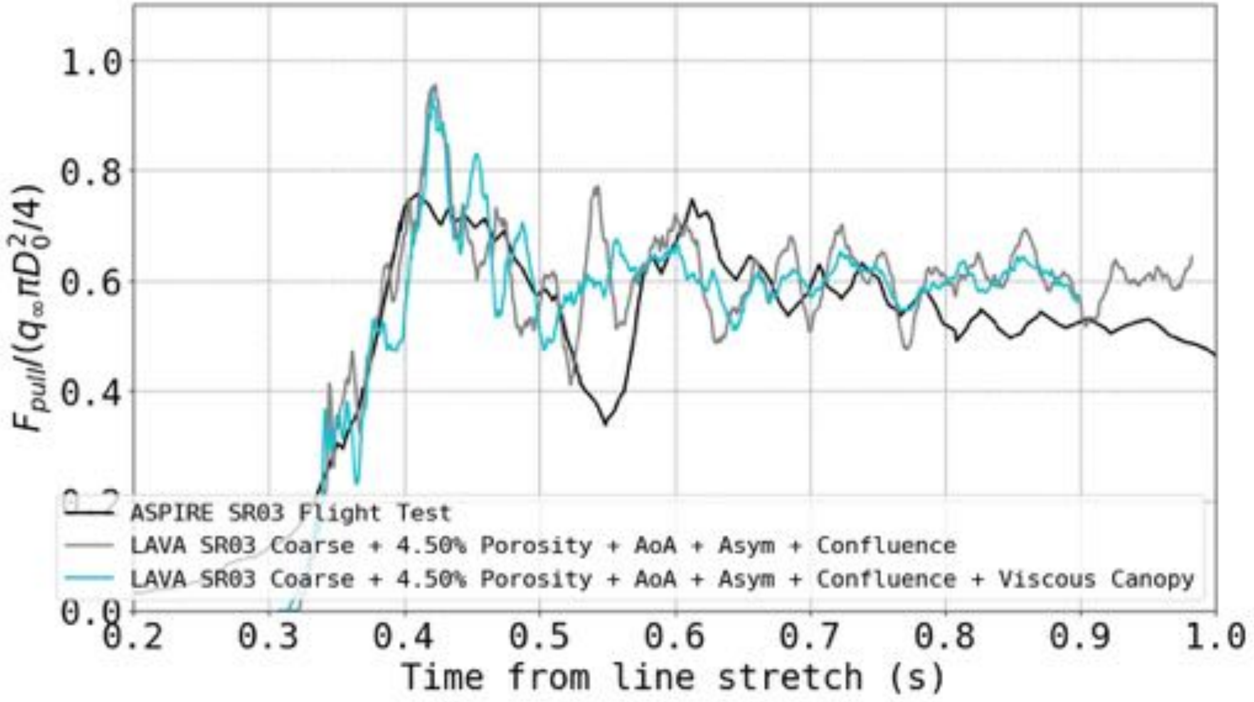
Results: Effect of Viscosity



AoA + Asym + Euler



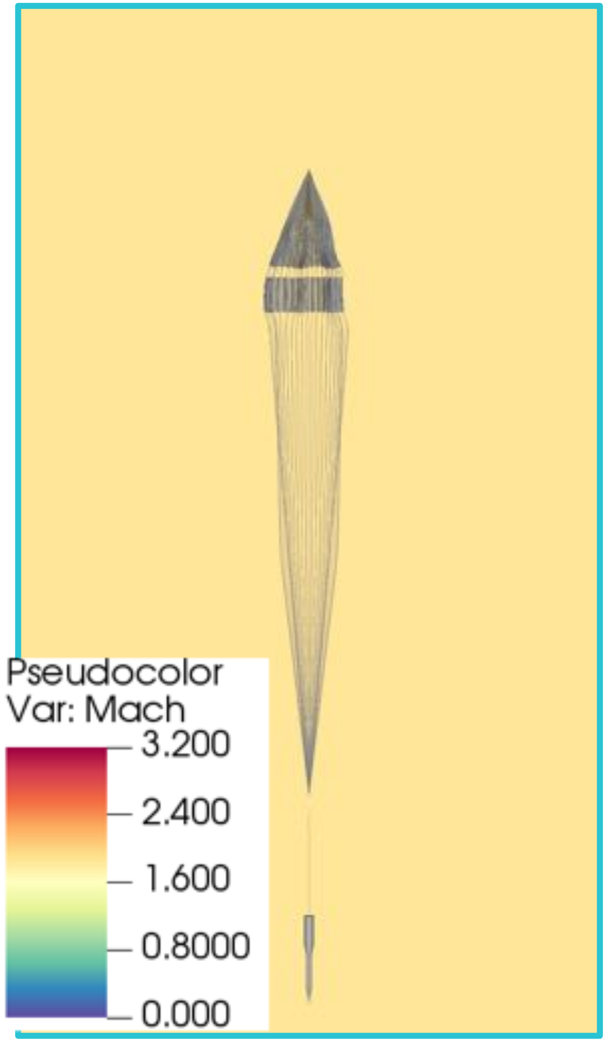
AoA + Asym + Viscous



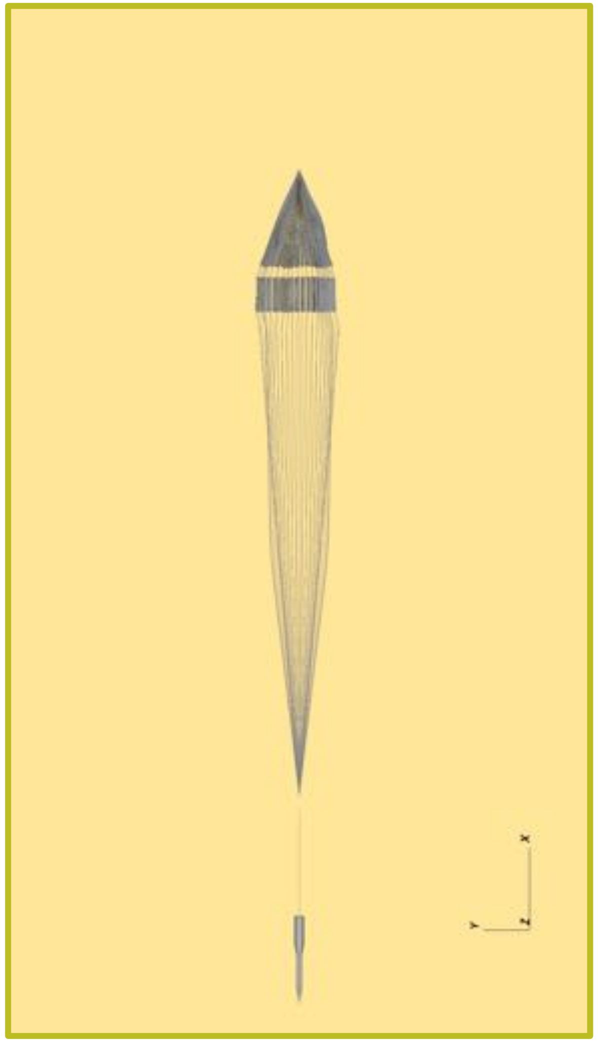
Viscous effects cause differences in the initial condition where the parachute wake is more severely separated. It also damps out the post-inflation trough and peak at t=0.55s, but introduces coherent oscillations immediately after peak.

Caveat: boundary layers are clearly over-estimated when the flow is not massively separated because no attempt made to reach $\Delta y^+ \leq 1$ resolution on the band for example.

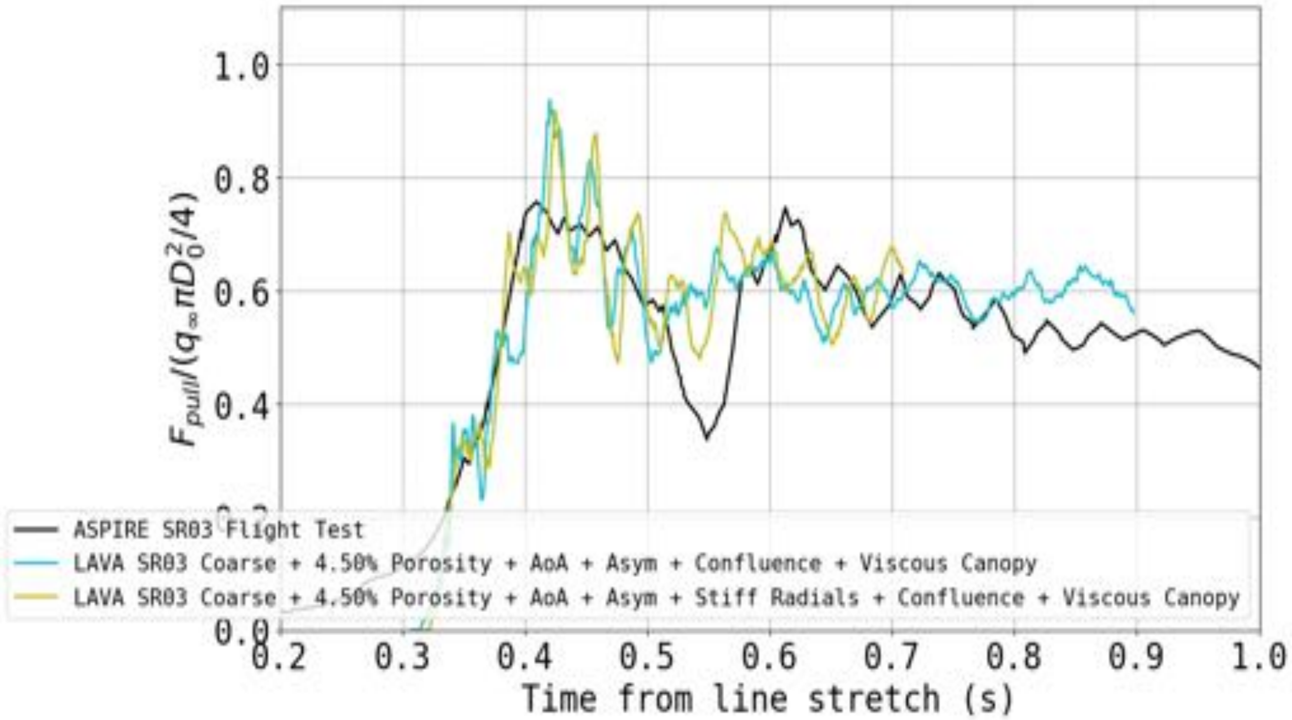
Results: Effect of Stiff Radials



AoA + Asym + Viscous



AoA + Asym + Stiff Radials + Viscous



Re-introducing radials stiffer than previously with over-estimated viscous effects does not affect peak pull-force but increases the amplitude of oscillations already present and increases post-inflation rebound peak slightly at t = 0.58s.

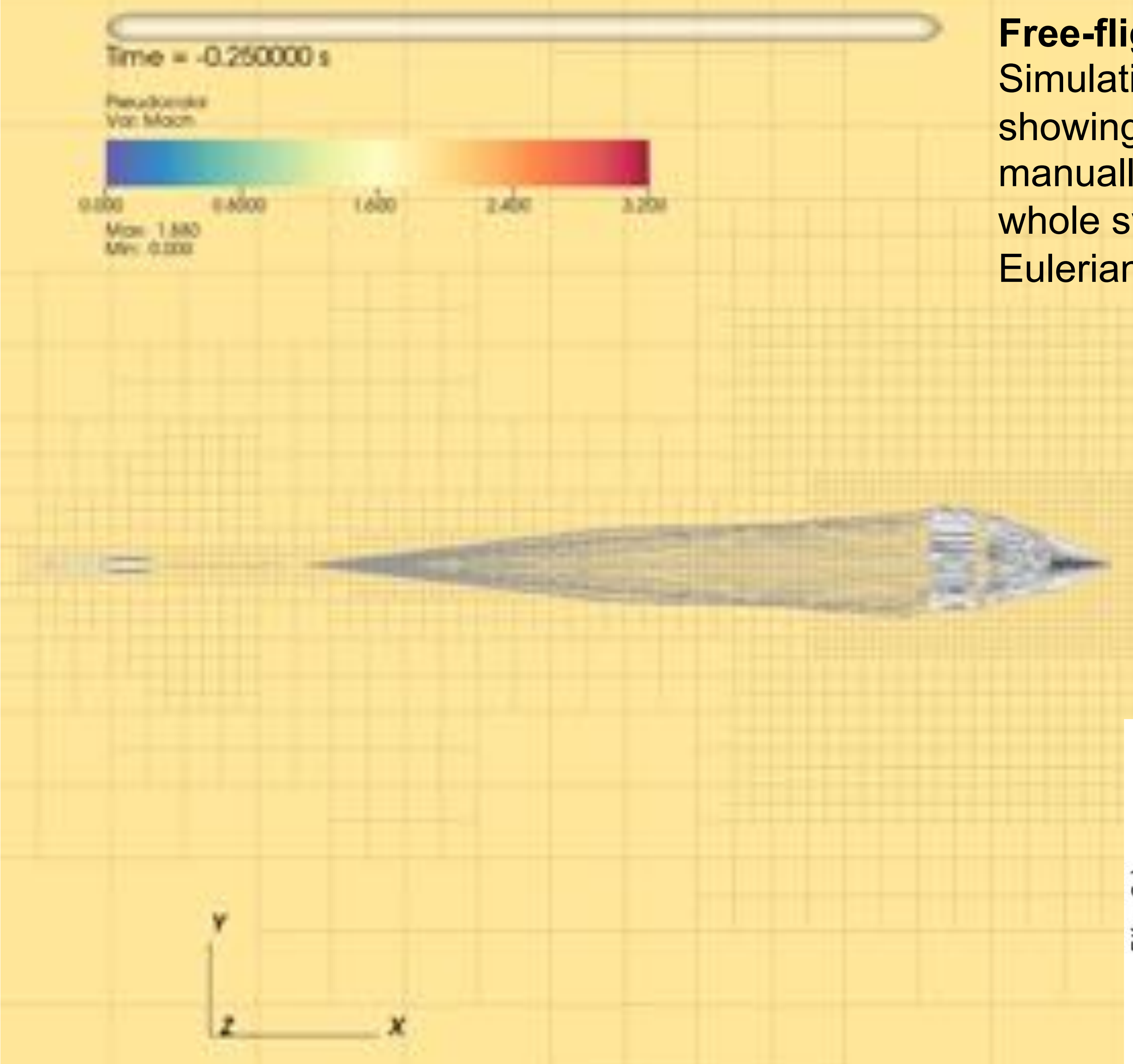
Methodology: Free-Flight + FSI Motion Model

- 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)

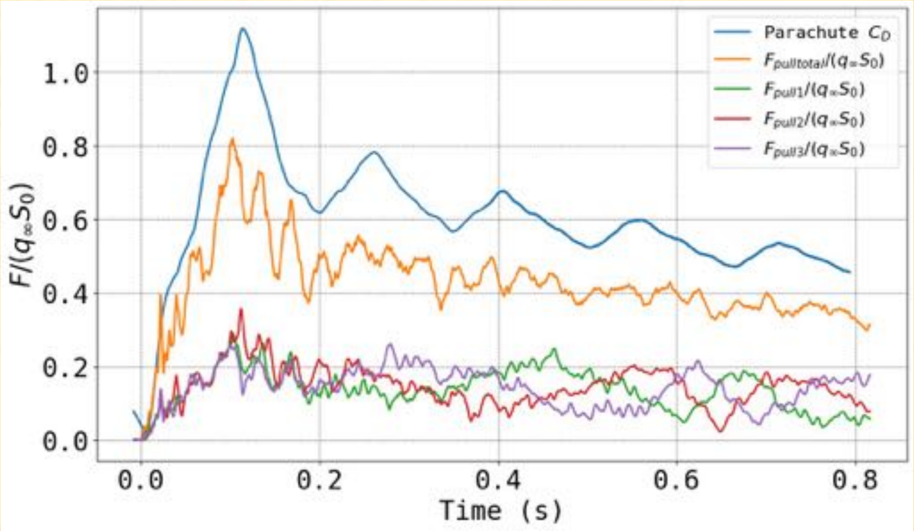
- Supports constrained formulation where inertial degrees of freedom can be “frozen” or ignored, e.g. to allow us to model only deceleration in vertical or full 6 DOF motion

Demonstration of 6 DOF free-flight parachute-payload coupling

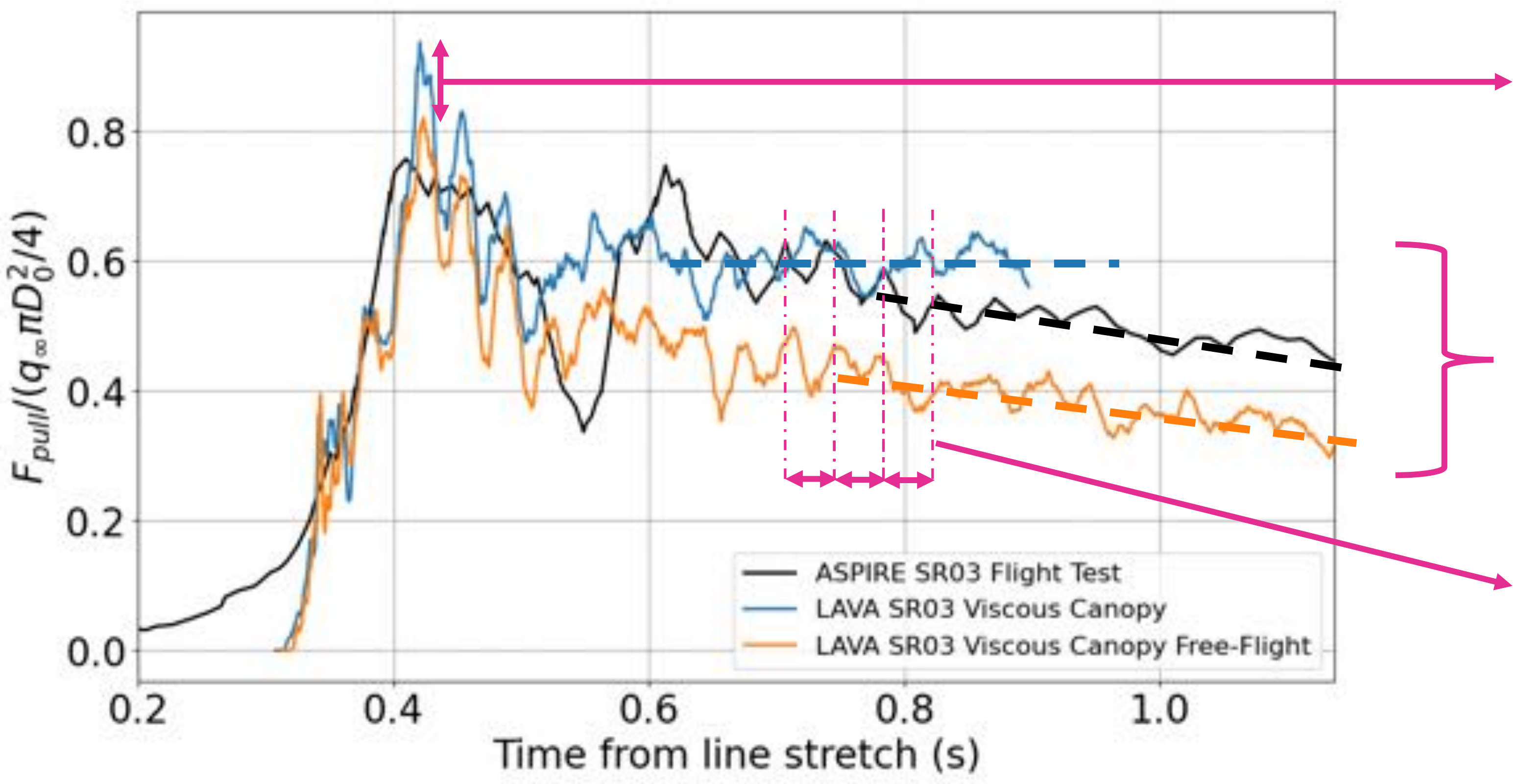


Free-flight FSI of ASPIRE SR03

Simulation with AoA + Asym + viscous canopy showing Mach number on cut plane and manually adjusted refinement regions. Notice the whole system accelerate with respect to the Eulerian Cartesian frame of reference.



Results: Effect of Acceleration



*Time offset to go from CFD time to “time from line stretch” is +0.316 s.

Effect of deceleration (finite mass inflation): 12% drop in peak load consistent with expected range of opening force factor for $R_M = 1/M_R$ ~ 0.017 [1]

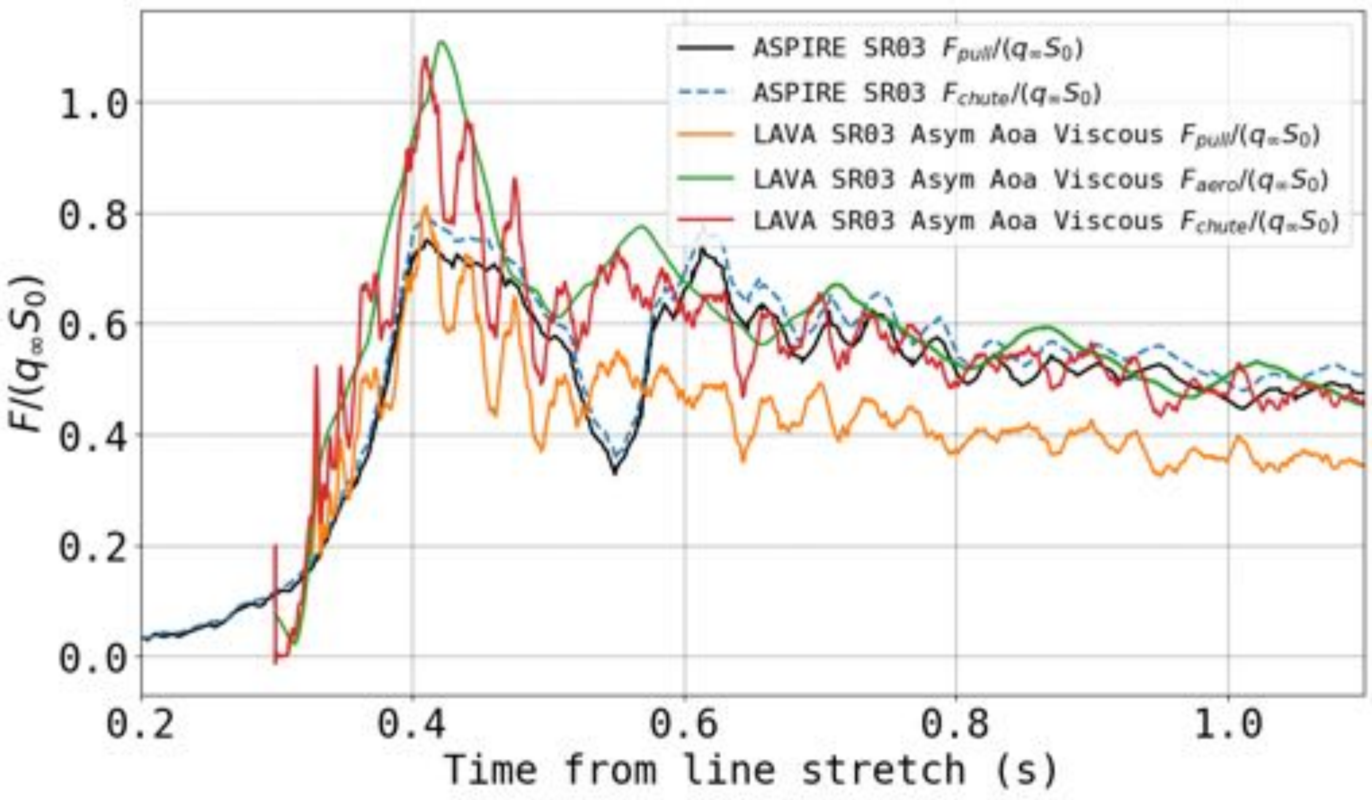
Match downward slope of flight test during stable deceleration phase instead of constant load with restrained payload

Predicts natural post-inflation “breathing” frequency of parachute of ~27 Hz (~0.038 s)

Post-inflation trough better predicted with free-flight, but no rebound peak in tension at load pins

[1] Knacke, Theo W. *Parachute recovery systems: design manual*. Para Pub., 1992. Fig 5-2 and 5-50

Results: Drag vs Pull-Force

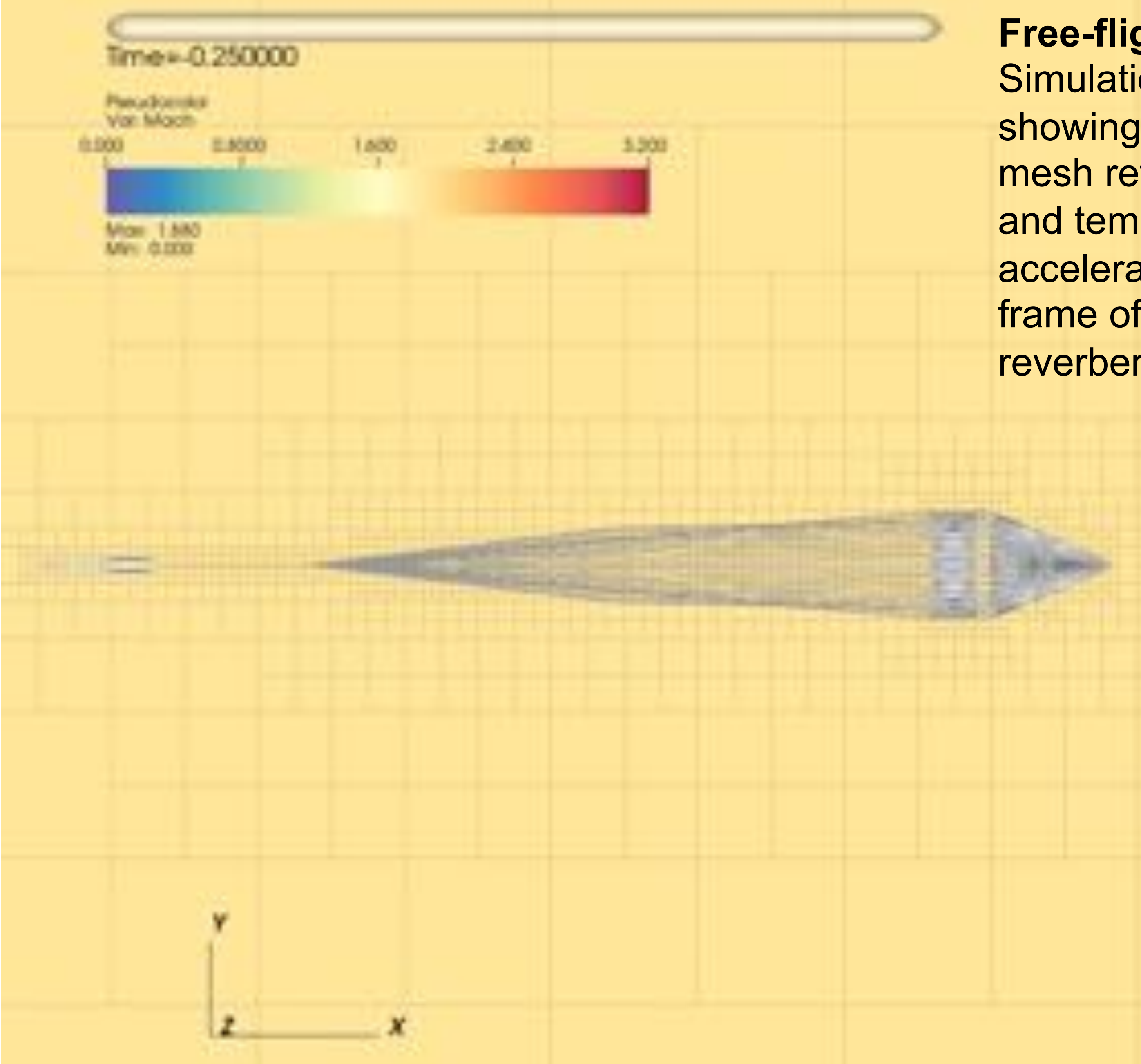


$F_{chute} = m_{system} a_{payload}$, neglecting small payload drag, where $a_{payload}$ is measured by onboard accelerometers

- Parachute aero loads do not show mid-to-high frequency oscillations, only low frequency oscillation (most likely linked to cross-sectional area) → higher frequency content in pull-force is caused by tension and transverse waves in suspension lines

- Large peak in aero drag and thus chute force felt by the payload is likely due to under-prediction of stiffness in parachute system → lack of radial stiffeners at gore seams allows parachute to stretch to larger effective cross-sectional area during inflation

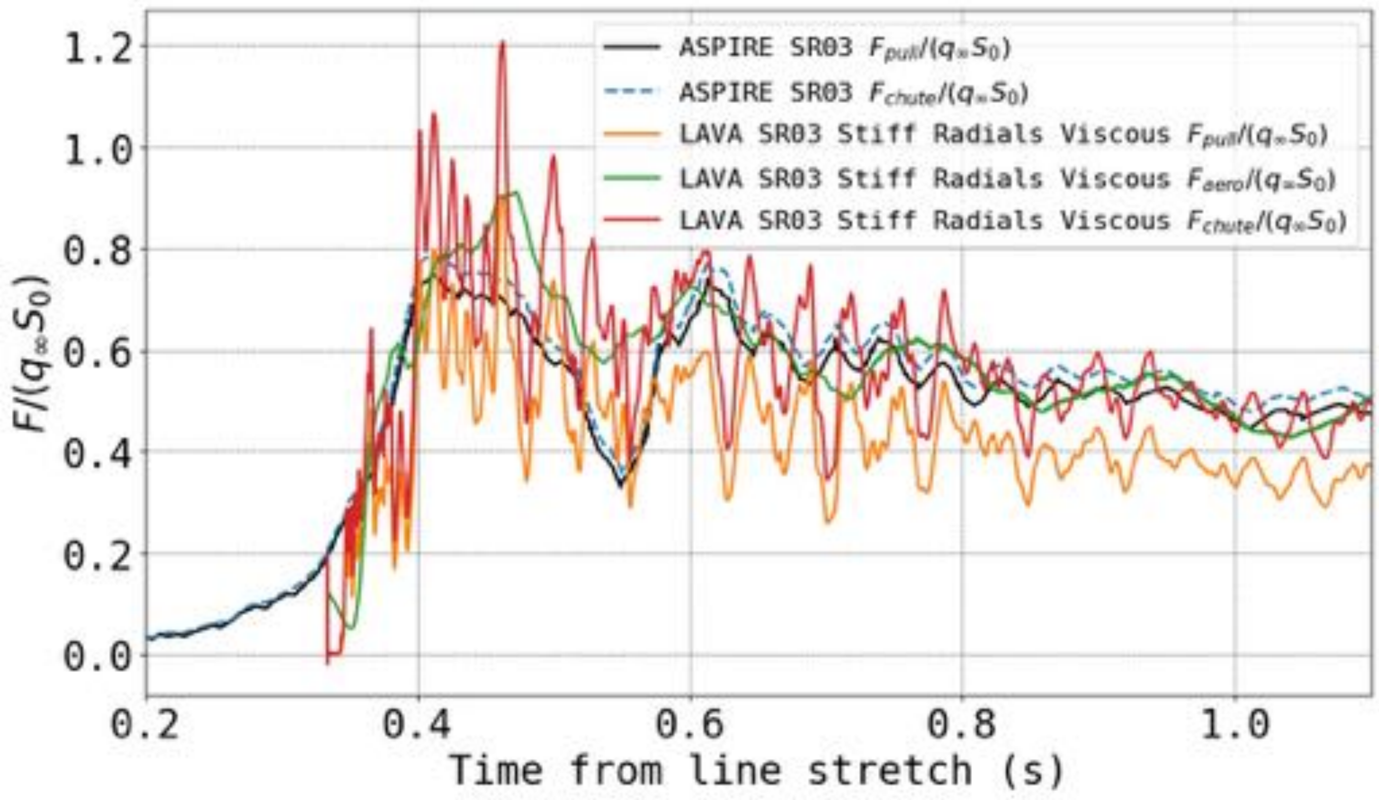
- Larger gap between F_{chute} and F_{aero} develops early on and may be due to our initial conditions and parachute shape



Free-flight FSI of ASPIRE SR03

Simulation with Stiff Radials + Viscous Canopy showing Mach number on cut plane and adaptive mesh refinement targeting Laplacian of pressure and temperature. Notice the whole system accelerate with respect to the Eulerian Cartesian frame of reference. Notice also the strong waves reverberating in the suspension lines.

Results: Effect of Stiffer Radials



$F_{chute} = m_{system} a_{payload}$, neglecting small payload drag, where $a_{payload}$ is measured by onboard accelerometers

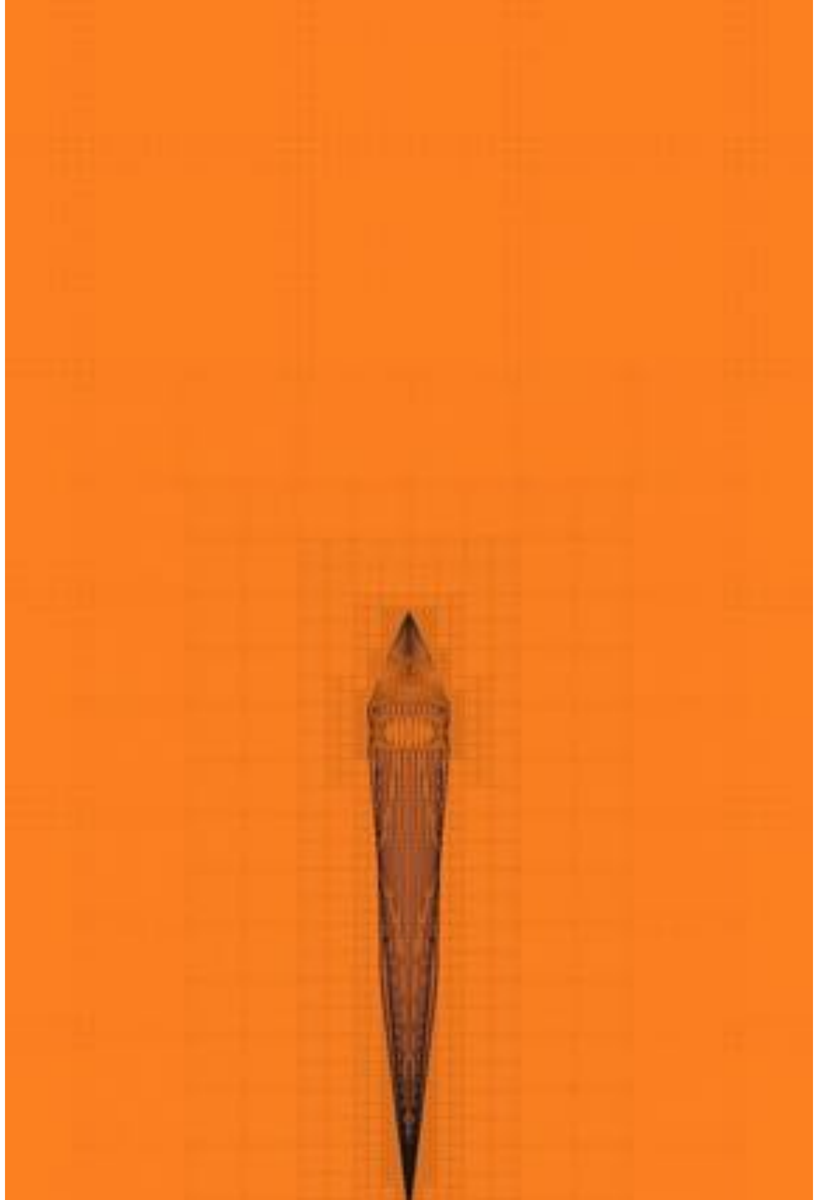
- Adds stiff radials → reduce max F_{aero} by restricting maximum cross-sectional area
- LAVA F_{aero} now follows ASPIRE F_{chute} more closely: more pronounced post-inflation trough and rebound peak than previous simulation without radials
- Removing asymmetry in initial parachute shape causes large undamped oscillations in F_{pull} due to constructive interference → will revisit with asymmetric pre-inflated chute, and possibly add line drag model to damp oscillations

Summary & Future Work

- Demonstrated capability to model ASPIRE SR03 flight test including both FSI and free-flight (6 DOF) deceleration
- Obtained better agreement with peak pull-force by modeling deceleration, but predictions are still conservative by ~8%
- Simulations predict weaker post-inflation trough and rebound, likely due to remaining under-estimation of stiffness (for certain components) and porosity

Next Steps

- Continue to investigate sources of modeling error to close out ASPIRE validation
- Further develop wall-modeled large-eddy simulation (WMLES) capability to better predict aeroshell loads and wake toward modeling upcoming interplanetary missions like Dragonfly
- Investigate how to extend capability to subsonic regime to study “steady” descent phenomena



LAVA SR03 Stiff Radials + Viscous
Log of density on surfaces and cut plane, where yellow is high and purple low, mesh shown in black

High-Priority Needs For FSI

- Relationship between strain and porosity at strains relevant to peak inflation
- Young's modulus of various parachute components and associated measurement error including strains in range relevant to peak inflation
- Simplified method to model orthotropic material (warp vs weft) using traditional or slightly augmented finite elements (e.g. MITC3)
- More wind tunnel and flight tests crafted specifically for the purpose of validating FSI predictions (e.g. better characterization of starting shape and state of parachute)

Possible Collaboration Areas

- Pathways Internship Program: happy to consider applications to work directly with us (US Citizens only) while performing thesis on a topic of relevance to parachute FSI

- Design wind tunnel test with free-to-pitch capsule and DGB parachute of various sizes (drogue vs main) to look into dynamic stability and help validate FSI predictions

- Develop a set of tests cases similar to high-lift prediction workshop that stress various aspects required for parachute FSI and build up to a case for which there is wind tunnel or flight test data available for comparison

- Time integration methods, and element formulations for structural dynamics that are stable at larger time steps and well-adapted to couple with typical Runge-Kutta schemes for CFD

Future Research Directions

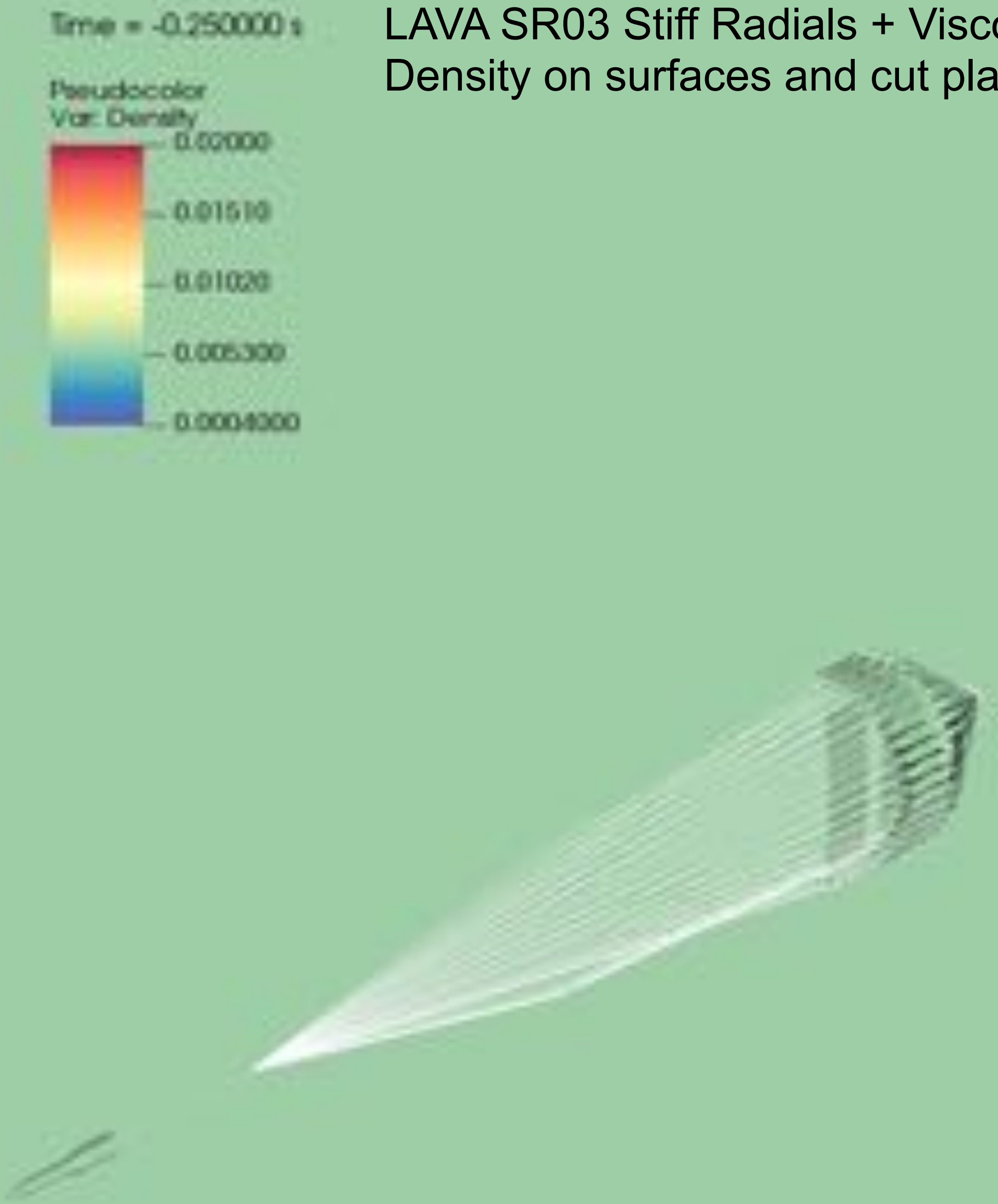
- Develop technique to record shape of parachute (relative location of various points on the canopy and the lines) as the parachute inflates to help validate FSI tools

- Develop methods and best practices to predict dynamic aero-loads over realistic capsule geometries and accurately capture the wake up to parachute location in a cost effective manner to enable dynamic stability analysis with FSI in-the-loop (e.g. wall-modeled large-eddy simulation for immersed boundary Cartesian AMR)

- If evidence arises that Saint-Venant Kirkoff (SVK) hyper-elastic material model is not representative of stress-strain relationship of individual components of parachute, we will need inexpensive constitutive models that are more accurate

- Addressing challenges of subsonic parachutes: fabric fullness, geometric porosity (modeled vs resolved), reefing, multi-canopy contact, long integration times at low Mach, line drag, wind gusts and wind shear

LAVA SR03 Stiff Radials + Viscous
Density on surfaces and cut plane



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  - Current and former LAVA members

Context: Perseverance Rover’s Descent Profile

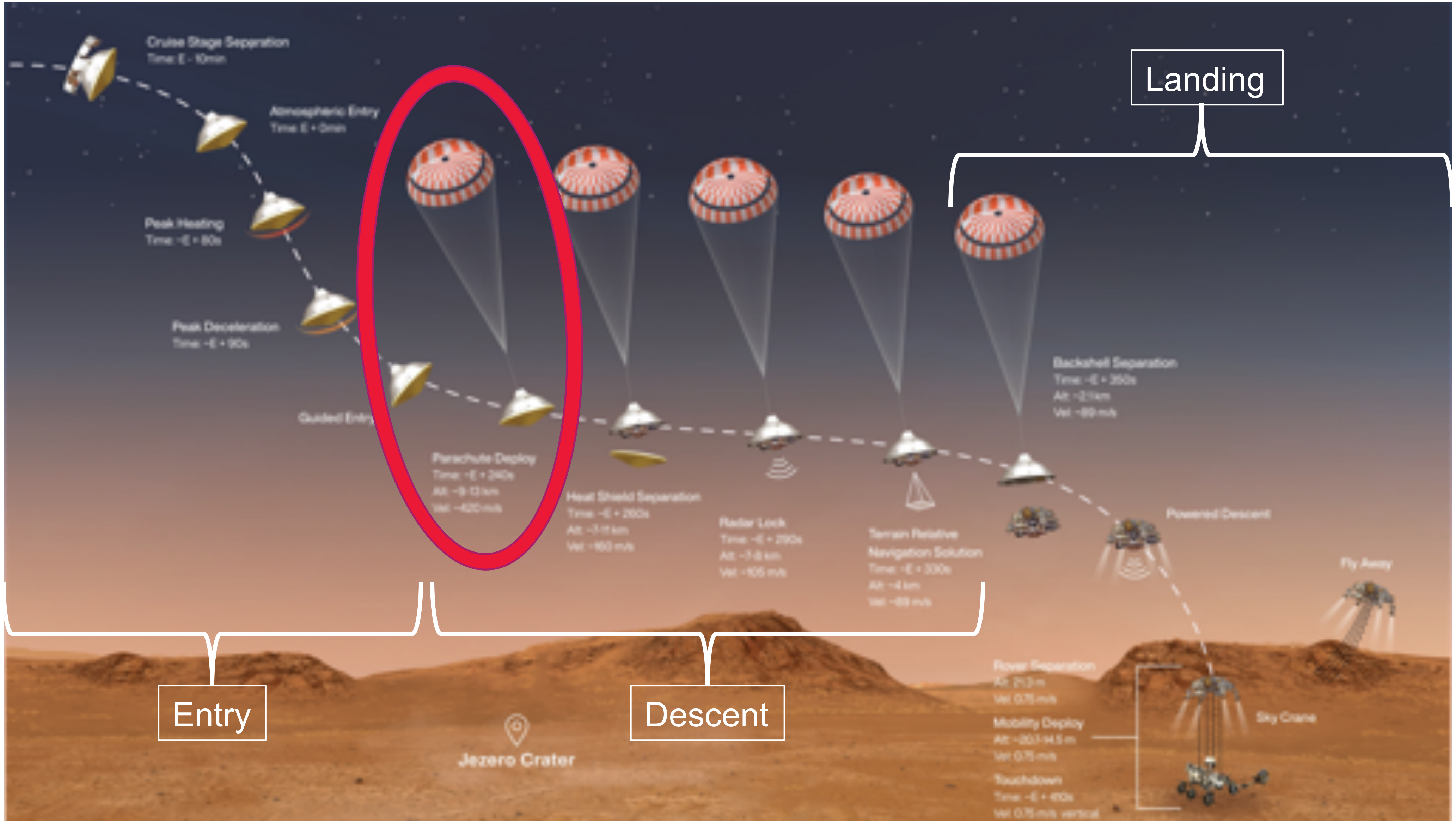
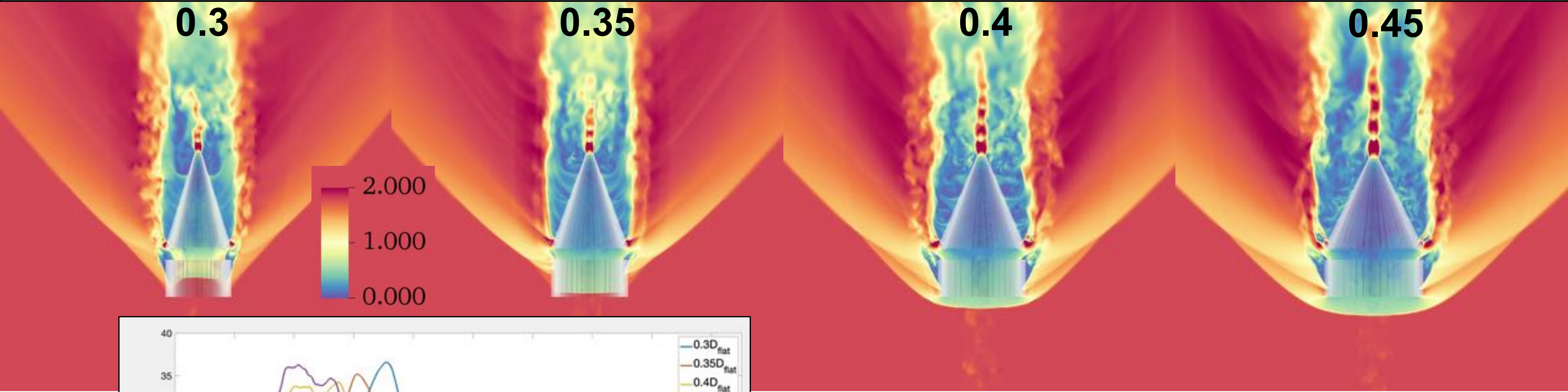
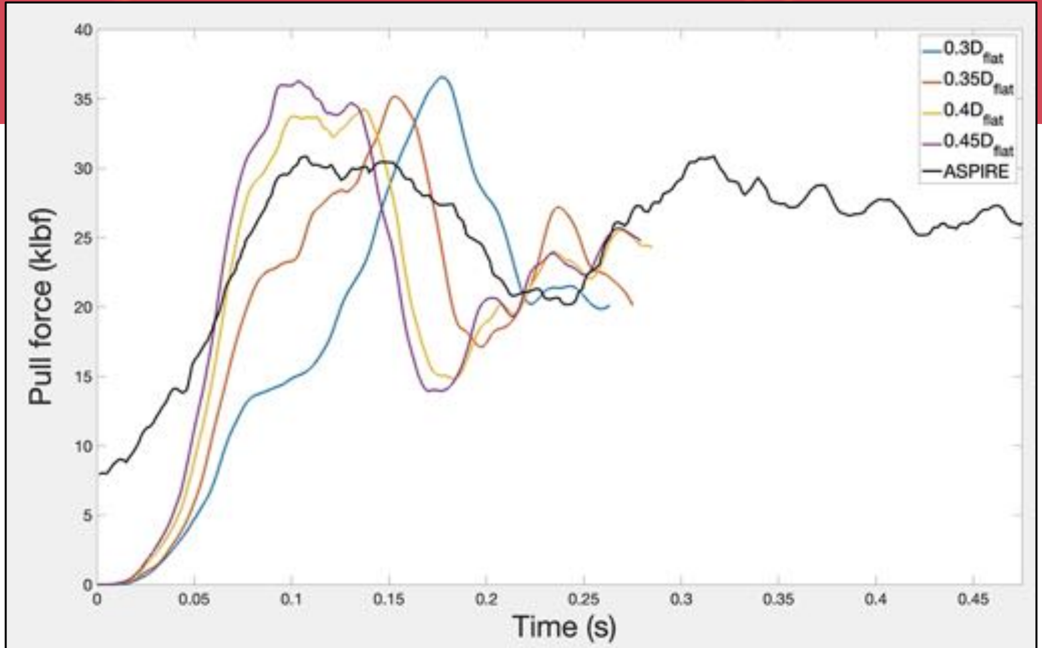


Image credit: NASA/JPL-Caltech
https://www.jpl.nasa.gov/images/pia24285-perseverance-rovers-entry-descent-and-landing-profile

Effect of Initial Parachute Diameter on SR01

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.





- Max pull-force increases if bow shock resides inside band at the start of FSI
- Smaller initial diameter cases with band outward flare move shock out of the band and recover 0.4D max pull-force
- Smaller initial diameter reduces initial inflation rate and increases inflation time as expected