

Supersonic Parachute Inflation Simulations

Francois Cadieux & Michael Barad
Computational Aerosciences Branch
NASA Ames Research Center

Mars Sample Return (2028)

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

Wake up: E-260 min

Turn to entry, spin up to 2 rpm: E-27 min

Cut thermal loop: E-22 min

MDNav to EDL Handoff (7800 km): E-10 min

Cruise Stage Separation: E-10 min

Peak heating: 2.0 km; E-120 min

Parachute deployment: 2.3 km; E-108 min

Drogue deployment: 142 km; E+37 min

Main parachute deployment: 4 km; E+94 min

Heatshield separation: 3.6 km; E+96 min

Reconfigure EDL thermal loop: 4 km; E+108 min

Lander Pose: 2.3 km; E+108 min

Descent: 2.3 km; E+109 min

Lidar Ground Lock: 2 km; E+111 min

Lander Separation: 1.2 km; E+119 min; 2.9 m/s

Transition to Powered Flight Release: +1 s

Dragonfly (Titan 2034)

DAVINCI (Venus 2031)

Deploy Parachute

Inlet 2 open
@ minute 3
-36 °C @ 0.01 MPa

Inlet 1 open
@ minute 6
-16 °C @ 0.02 MPa

Inlet 2 Closed
@ minute 12
46 °C @ 0.07 MPa

Inlet 1 Closed
@ minute 20
108 °C @ 0.18 MPa

Imaging Begins
@ minute 29
(first band-ratio maps)

Science Goal 1 Met

Inlet 3 Open
@ minute 34
182 °C @ 0.59 MPa

Release Parachute

Inlet 4 Open
@ minute 35
215 °C @ 0.87 MPa

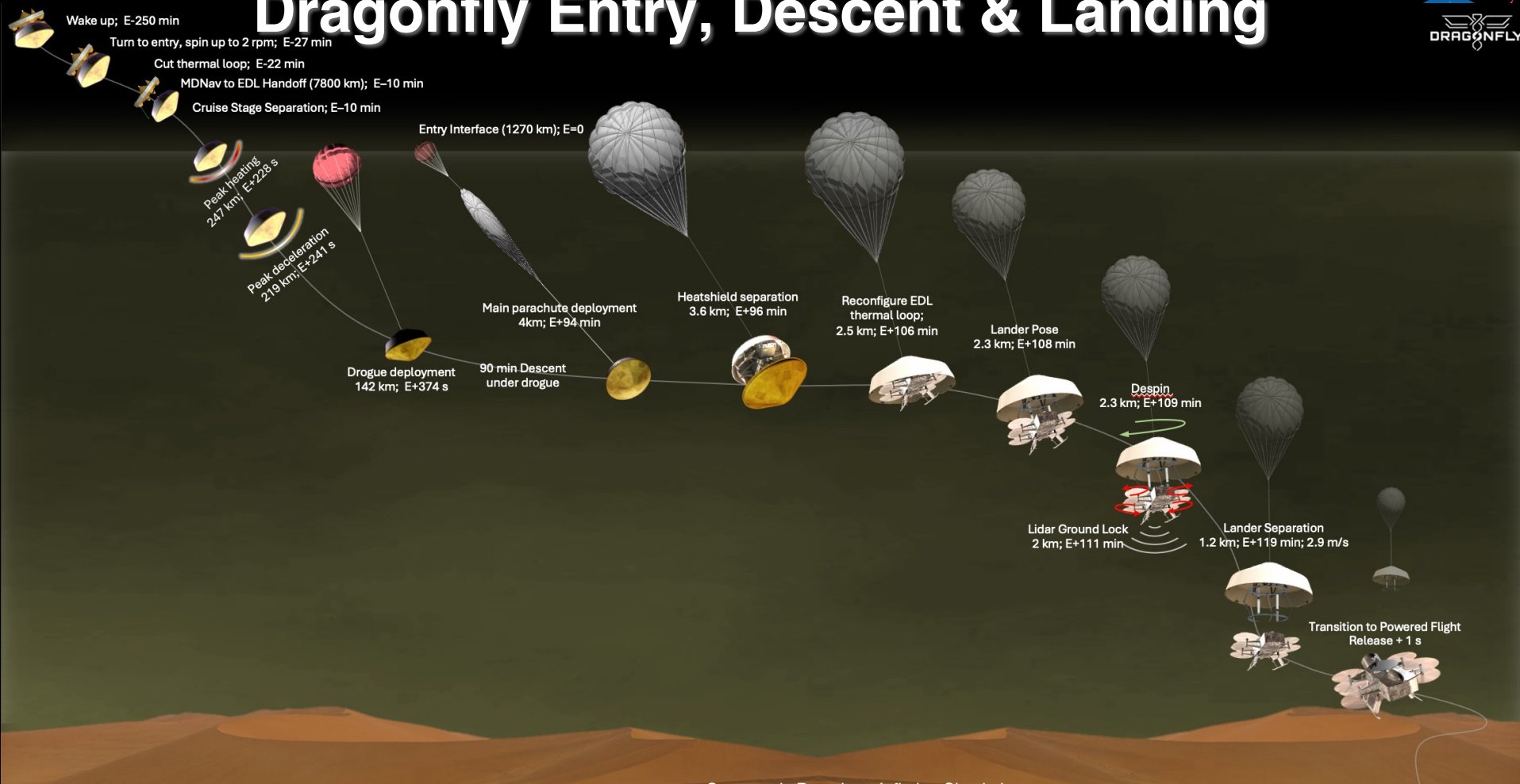
Science Goal 2 Met

Science Goal 3 Met

Touchdown
@ minute 59.7
457 °C @ 8.9 MPa
Velocity 13.7 m/s

(NASA GRC)

Dragonfly Entry, Descent & Landing





Motivation: Why HPC Simulations?

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 certify parachute systems for flight
- Dynamic finite element analysis is used occasionally, and FSI even more sparingly
- Parachutes remain one of the top risk factors for both human and robotic missions

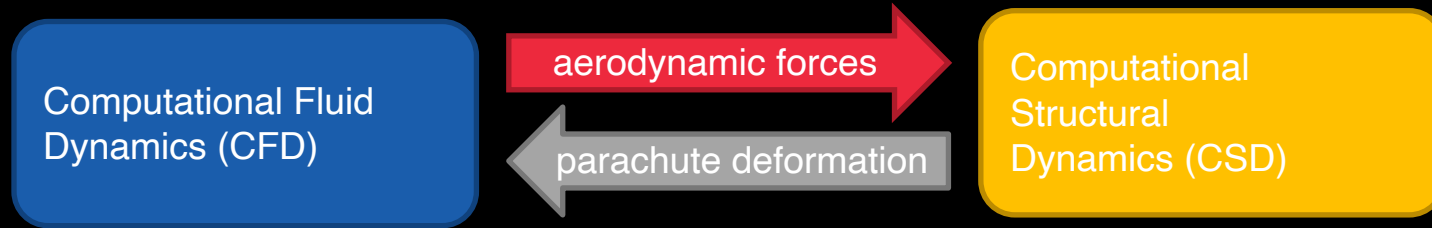
Potential For Simulations

- Provide insight into parameters not easily measurable in flight or wind tunnel test
- Overcome limitations of wind tunnel & flight tests (atmosphere composition and transport properties, stiffness to size ratio)
- Conduct more detailed parametric trade-studies
- Mitigate risks by covering more scenarios than can be tested within typical time and budgetary constraints

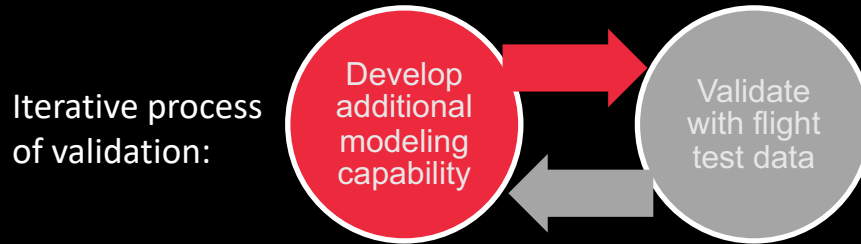
Objectives: Simulation Tool Development



- Create Fluid-Structure Interaction (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



- Reduce turnaround time of FSI simulations so they can be used to answer engineering questions during mission design process

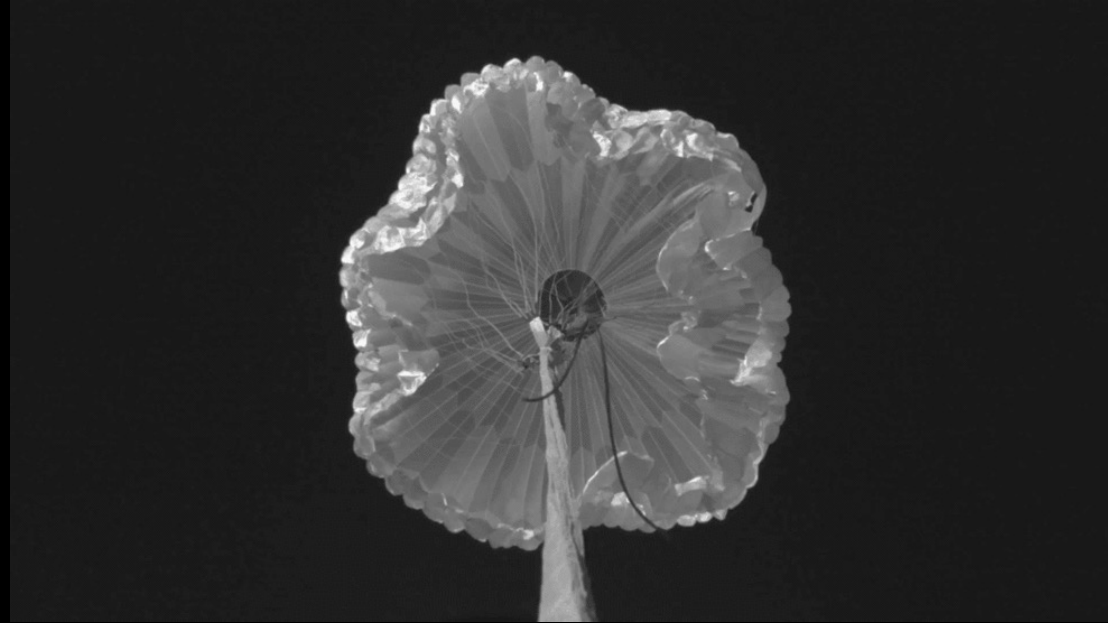
Toward Validation: ASPIRE Flight Tests



Simulating supersonic parachute inflation is extremely challenging:

- Parachutes are extremely thin (~80 microns) and made of porous, woven fibers
- Each inflation is unique, full of self-contact and inherently unsteady

So we simulate the ASPIRE flight test and compare our results to measurements taken during flight to ground our model predictions



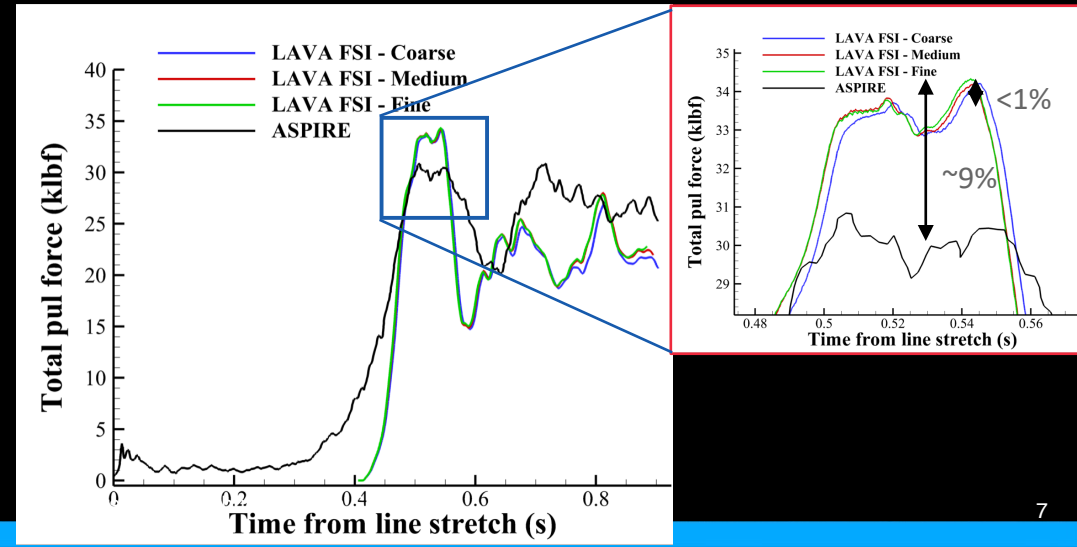
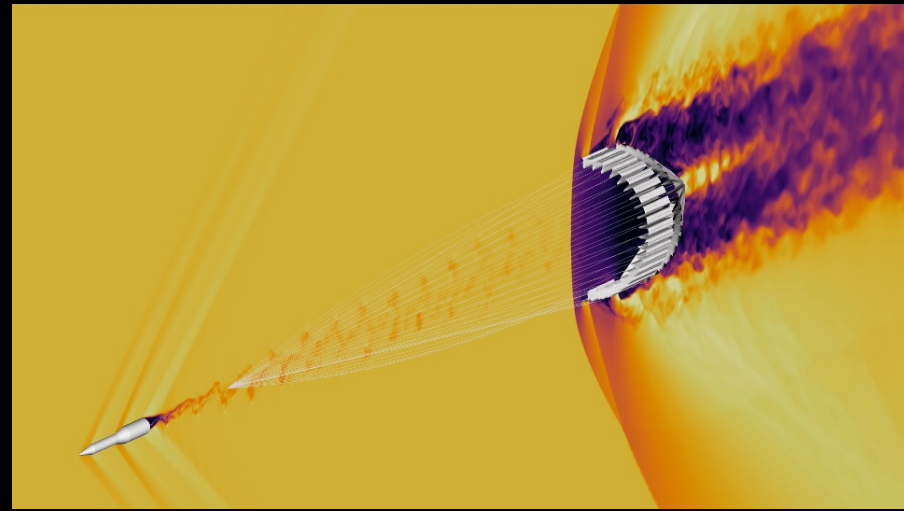
This high-definition video was taken on Sept. 7, 2018, during the third and final test flight of the Advanced Supersonic Parachute Inflation Research Experiments (ASPIRE) campaign to certify the Mars 2020 parachute. It was the fastest inflation of this size parachute in history and created a peak load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

Supersonic Parachute Inflation Simulations

Previous Work

- 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 CFD & structural grid sensitivity and showed 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>



ASPIRE SR03 Problem Setup

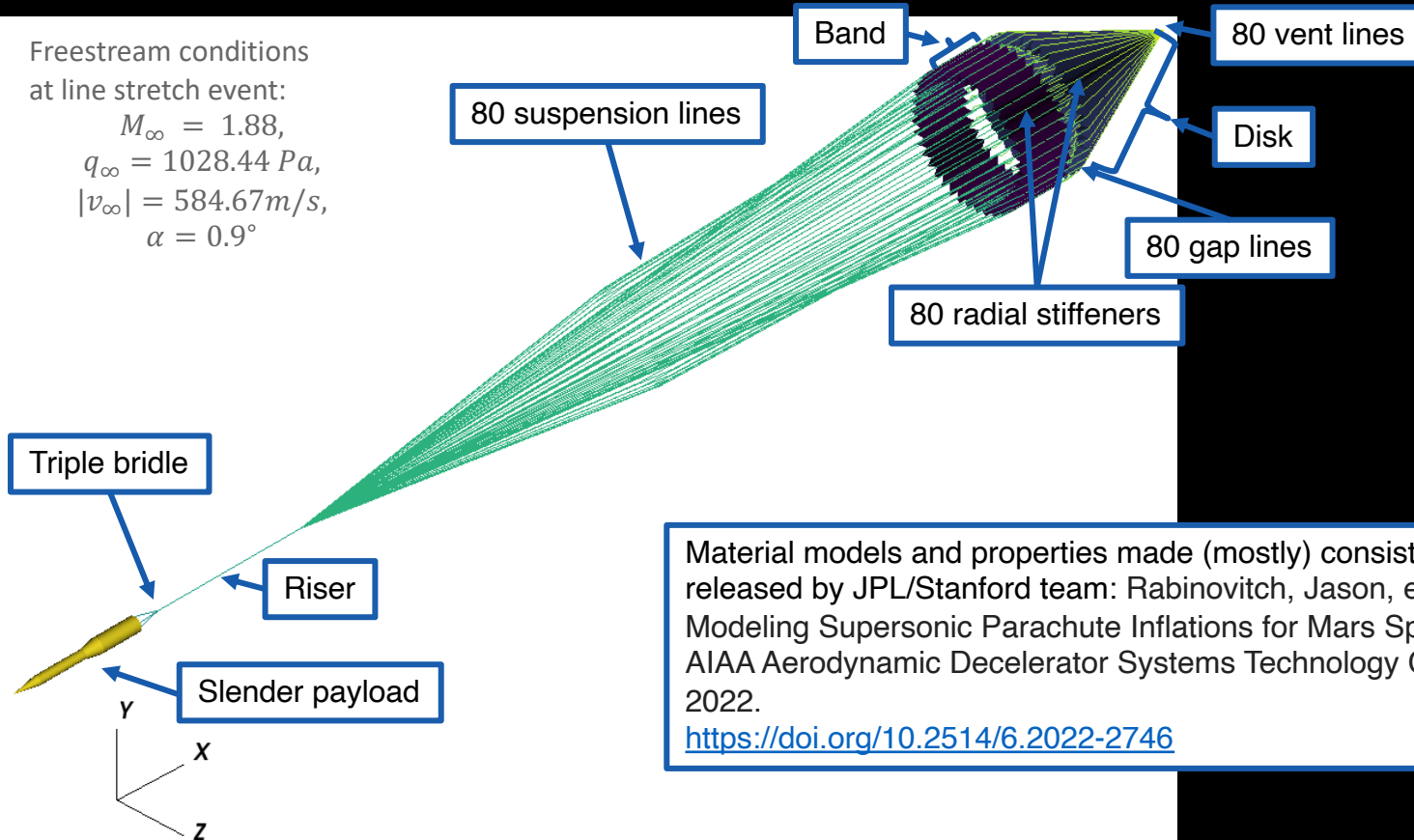
Freestream conditions
at line stretch event:

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

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

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

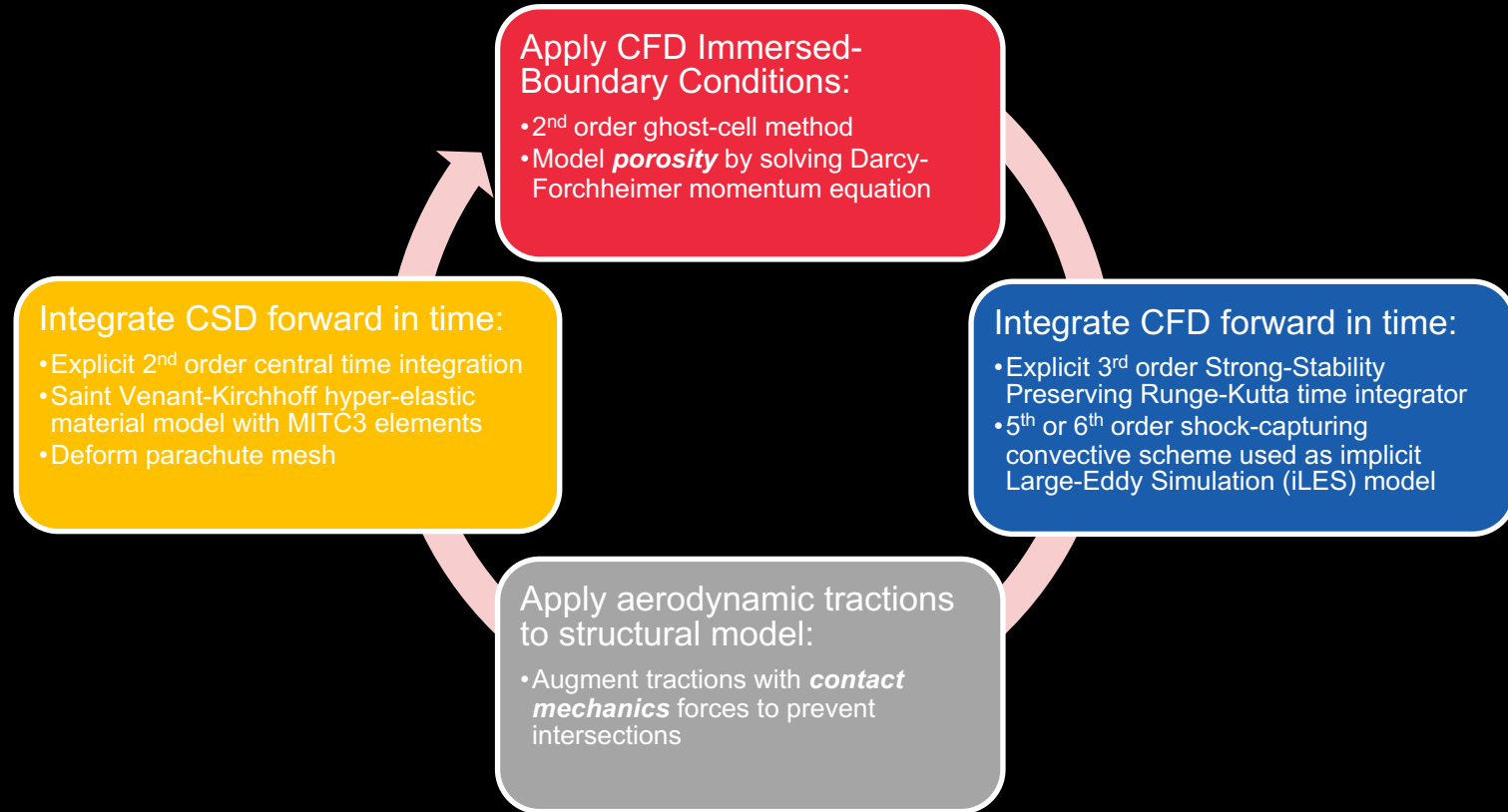
$$\alpha = 0.9^{\circ}$$



Material models and properties made (mostly) 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: FSI Overview

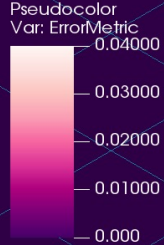


For more details on the methods, please refer to: Boustani, Jonathan, et al. "Fluid-structure interaction simulations of the ASPIRE SR01 supersonic parachute flight test." *Aerospace Science and Technology* 126 (2022): 107596 <https://doi.org/10.1016/j.ast.2022.107596>
Supersonic Parachute Inflation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

Methodology: CFD Mesh



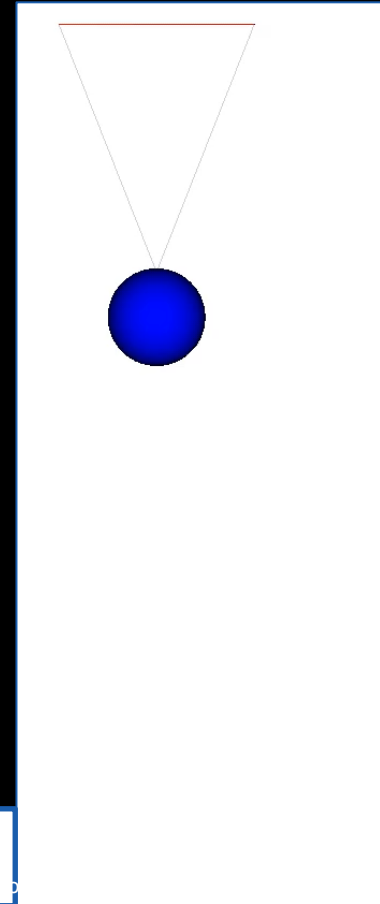
Time = 0.399167 s



- Metric-based adaptive mesh refinement (AMR)
- Min $\Delta x = 0.0333 \text{ m}$
- Payload, wake, parachute and bow shock all contained in finest mesh
- Each box contains 16^3 cells
- Total numbers of cells: ~400 Million
- Time simulated ~ 0.8 seconds
- Resources: ~ 4 days on 50 Intel Skylake ~ 192k CPUh on NASA's Electra Supercomputer
- Data generated: ~50 TB per simulation output to hybrid SSD + HDD system

Focus: Effect of Deceleration

- In previous work, we artificially kept the system at a fixed velocity
- In reality, the whole system starts decelerating the moment the parachute produces drag
- Does that deceleration have a significant impact on peak load?

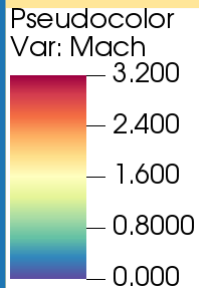


Demonstration of 6 DOF free-flight parachute-payload coupling

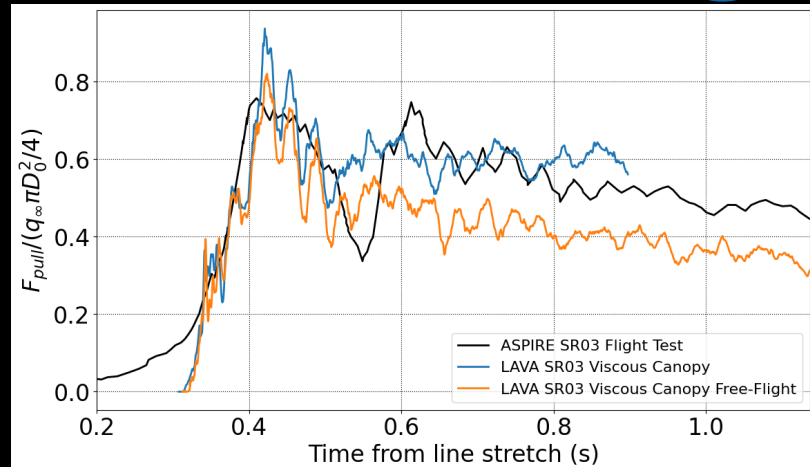
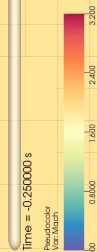
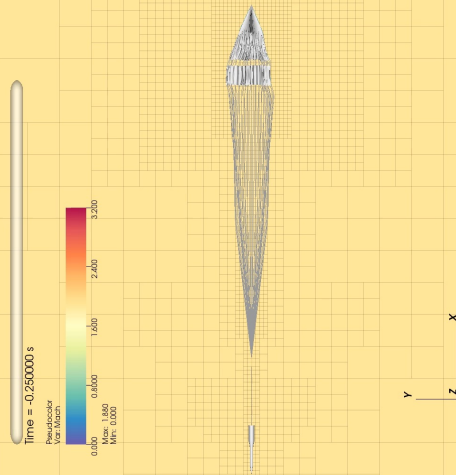
Results: Effect of Deceleration



Without Deceleration



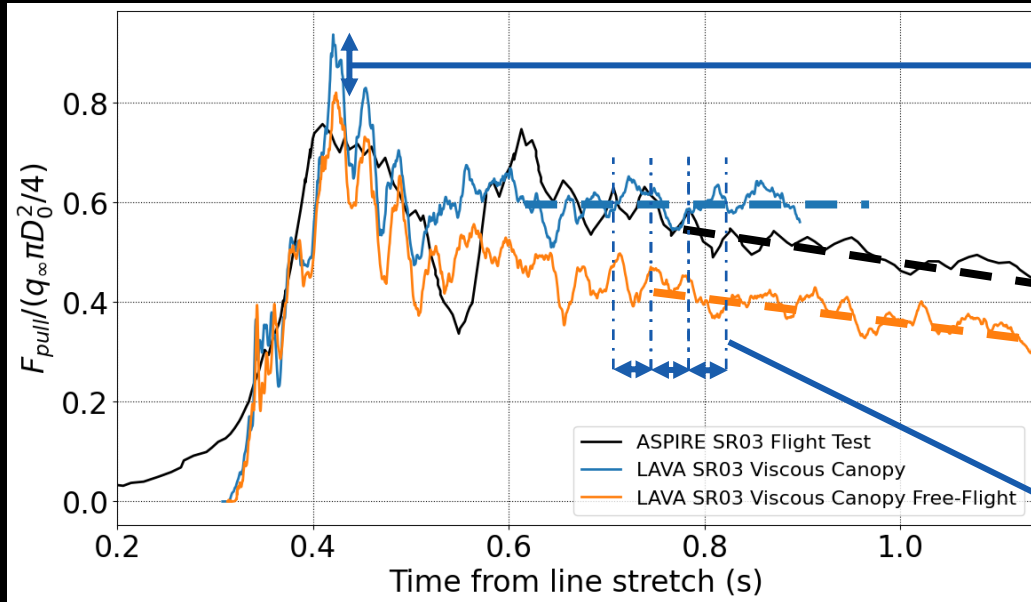
With Deceleration



Modeling deceleration decreases peak load by ~12% and changes slope of pull-force in post-inflation “steady” deceleration phase. More details on next slide.

- Each box contains 16^3 cells
- Total numbers of cells: ~400 Million
- Cost: 4 days on 50 Skylake ~ 192k CPUh

Results: Effect of Deceleration



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

Mass ratio $M_R = \frac{m_{total}}{\rho(S_0 C_D) Z}$ 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:

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

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

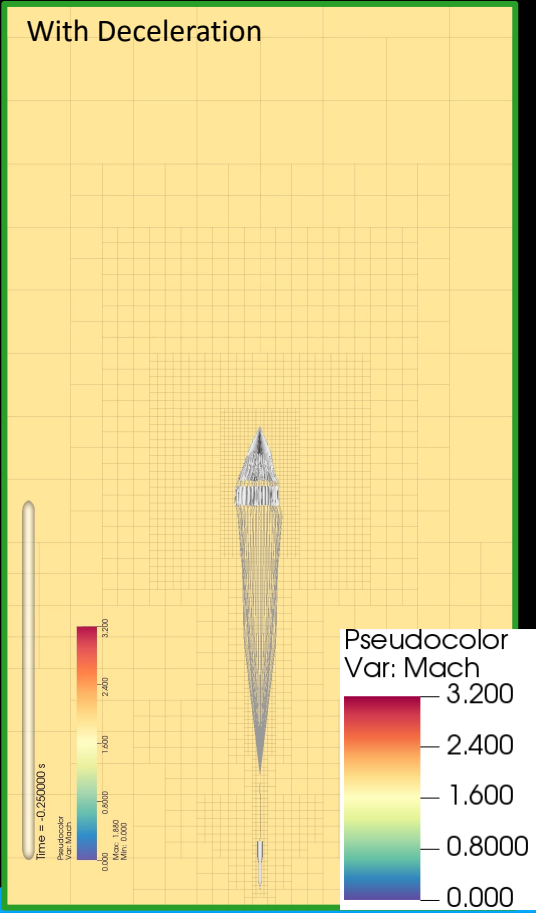
Post-inflation trough better predicted with free-flight, but no rebound peak in tension at load pins

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

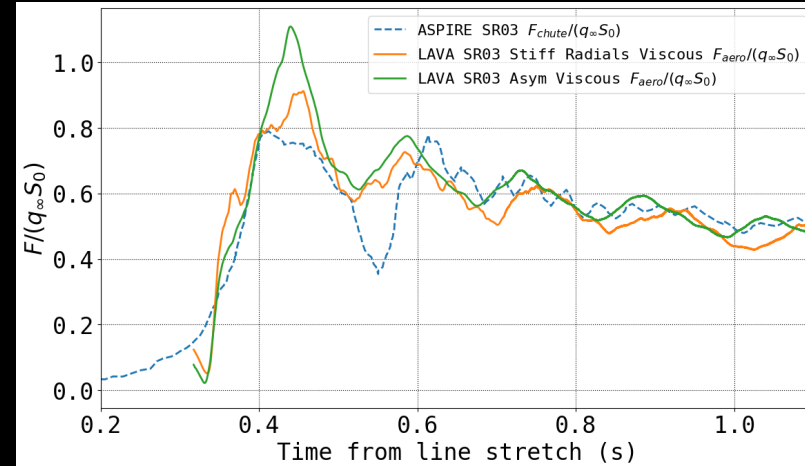
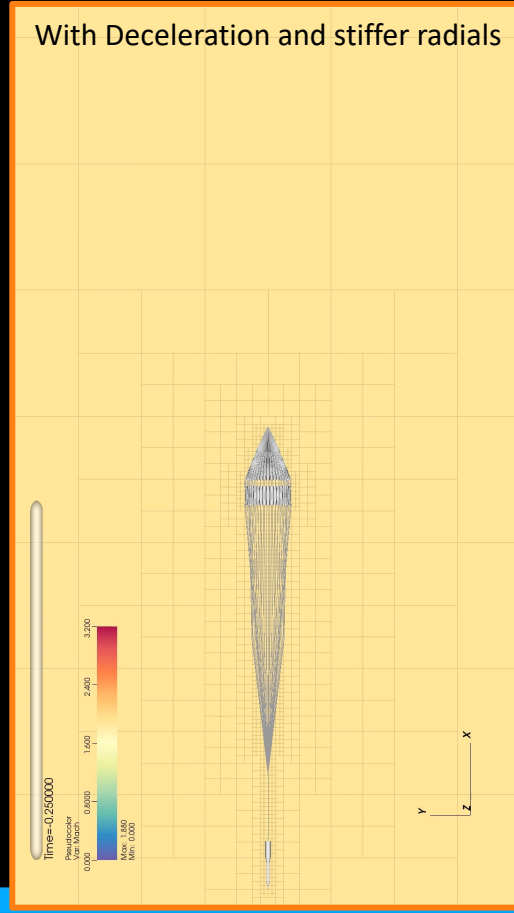
Free-Flight Results: Effect of Stiffer Radials



With Deceleration



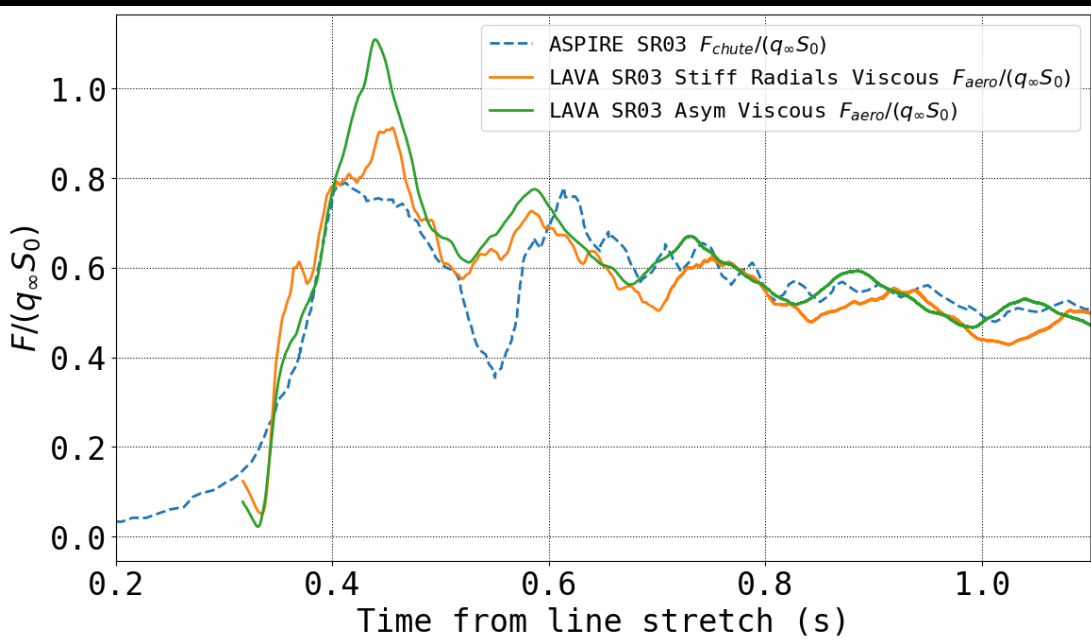
With Deceleration and stiffer radials



Modeling the stiffness of parachute's radials more accurately reduces peak parachute drag by restricting maximum canopy cross-sectional area.

- Each box contains 16^3 cells
- Total numbers of cells: ~400 Million
- Cost: 4 days on 50 Skylake ~ 192k CPUh

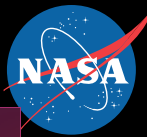
Results: Effect of Stiffer Radials



- Parachute aero loads do not show mid-to-high frequency oscillations, only low frequency oscillation (most likely linked to cross-sectional area changes) → higher frequency content in pull-force is caused by tension and transverse waves in suspension lines
- Modeling the parachute's radials more accurately reduces max F_{aero} by restricting maximum effective cross-sectional area open to flow
- Peak F_{aero} with stiff radials now within 10% of ASPIRE SR03 F_{chute}

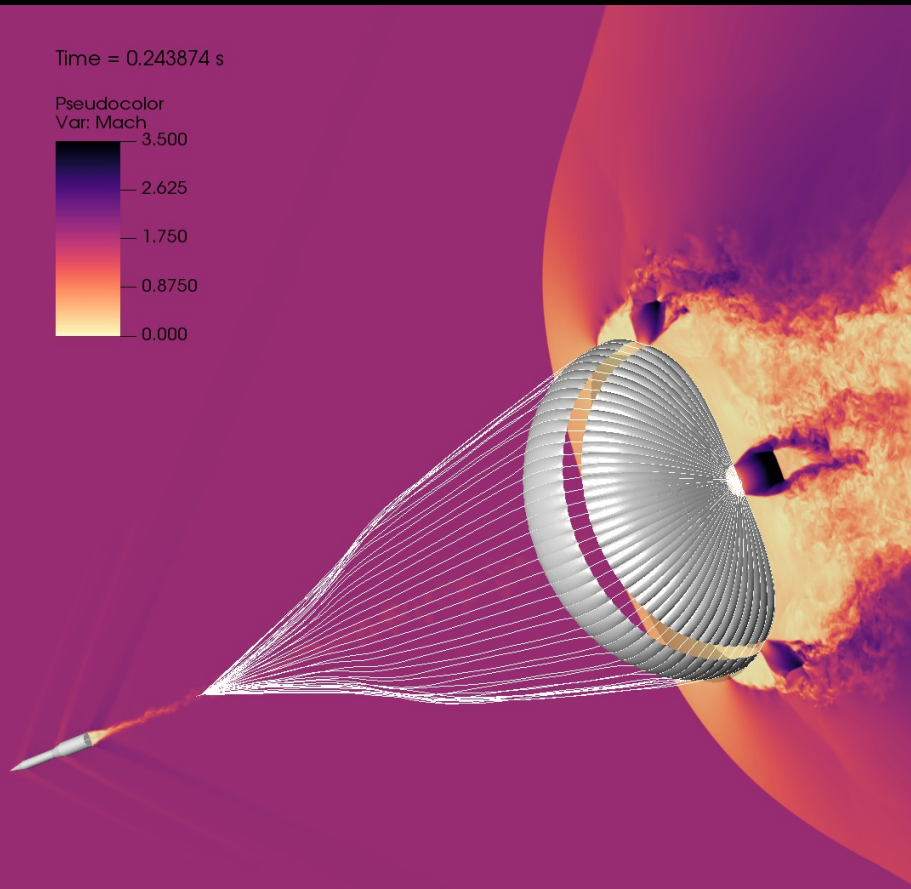
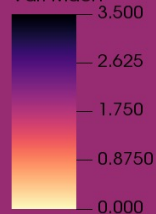
$F_{chute} = m_{system}a_{payload}$, neglecting small payload drag, where $a_{payload}$ is measured by onboard accelerometers

Summary



Time = 0.243874 s

Pseudocolor
Var: Mach

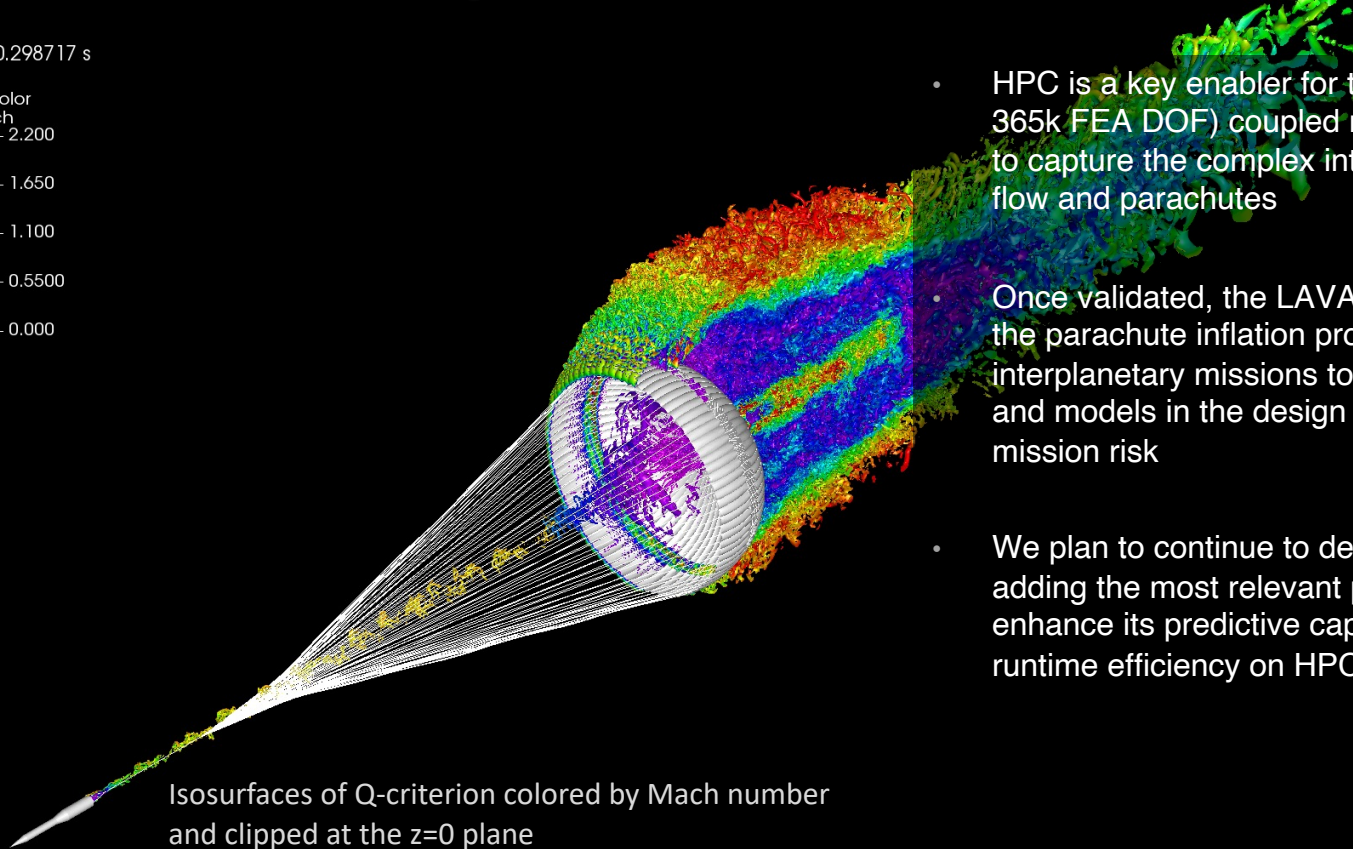
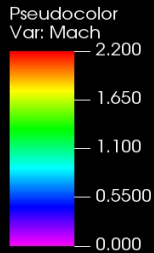


- Leveraging 50 Intel Skylake nodes on NASA's Electra Supercomputer for 4 days, we demonstrated the capability to model the ASPIRE SR03 flight test including both fluid-structure interaction and free-flight deceleration (6 degrees-of-freedom) with the Launch, Ascent, and Vehicle Aerodynamics (LAVA) software
- Including deceleration caused a 12% drop in the prediction of the force the parachute exerts on the payload (pull-force) and improved agreement with flight measurements
- Modeling the stiffness of parachute's radials more accurately reduced peak parachute drag by 20% and also improved agreement with flight measurements

Impact of HPC & Next Steps



Time = 0.298717 s



Isosurfaces of Q-criterion colored by Mach number
and clipped at the $z=0$ plane

- HPC is a key enabler for these large (400 M CFD cells + 365k FEA DOF) coupled multi-physics simulations aiming to capture the complex interactions between supersonic flow and parachutes
- Once validated, the LAVA FSI tool will be used to predict the parachute inflation process for upcoming robotic interplanetary missions to complement other data sources and models in the design process and help reduce mission risk
- We plan to continue to develop the LAVA FSI tool by adding the most relevant physics-based models to enhance its predictive capabilities and by optimizing its runtime efficiency on HPC

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

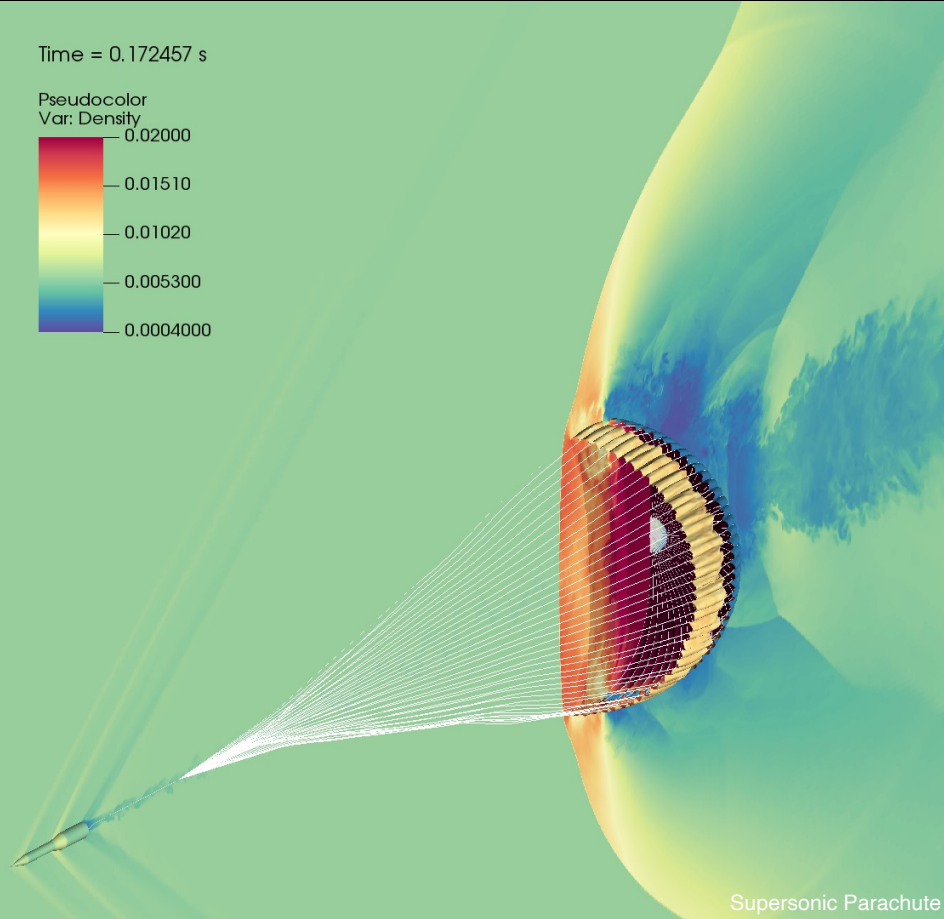
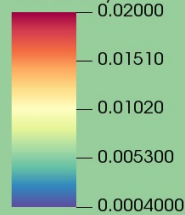
Thanks to:

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

Time = 0.172457 s

Pseudocolor

Var: Density



Supersonic Parachute Inflation Simulations