Fluid-Structure Interaction Simulations of the ASPIRE SR03 Supersonic Parachute Flight Test

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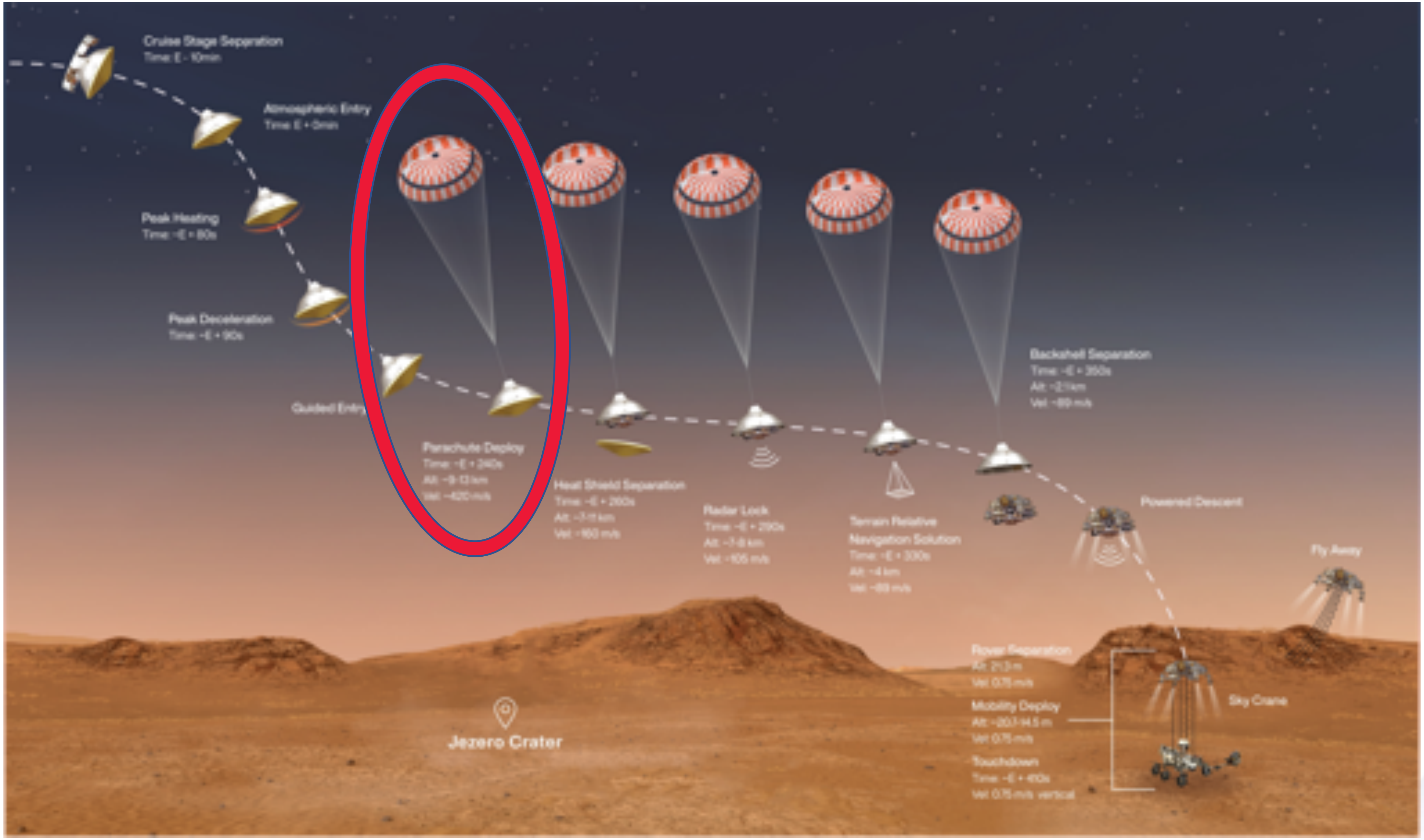
Context: Perseverance Rover’s EDL Profile



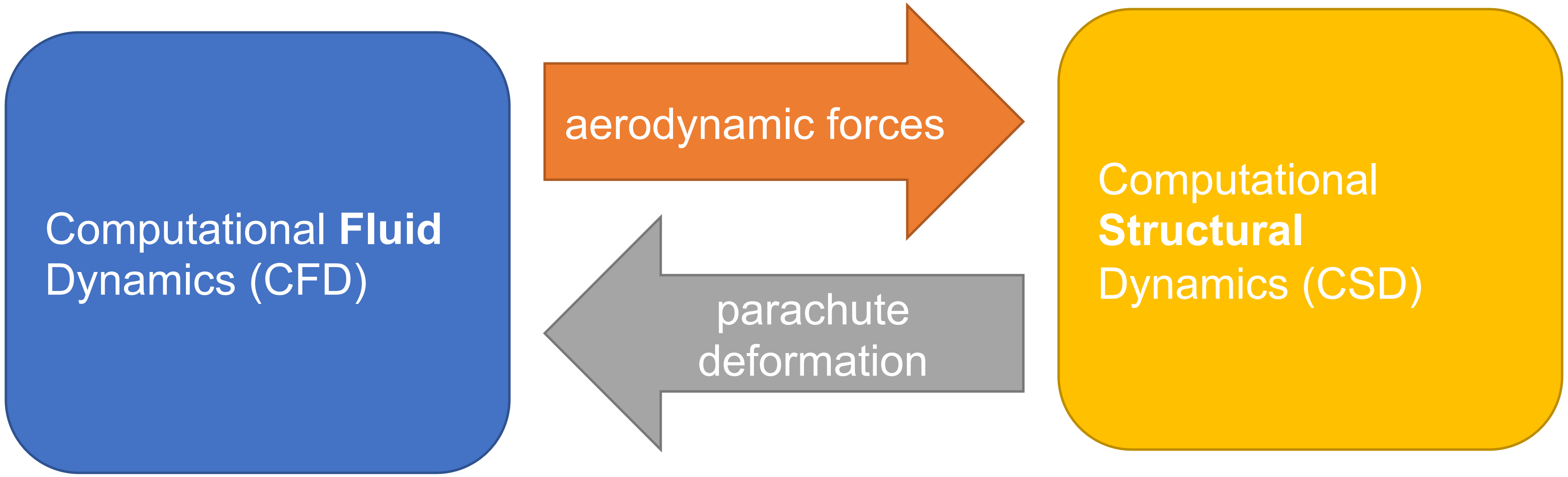
Motivation

- Any changes to state-of-the-art require costly flight test campaigns in the upper earth atmosphere to certify parachute system
- The Advanced Supersonic Parachute Inflation Research Experiments (ASPIRE) is the most recent iteration of such a campaign and its third flight (SR03) served to certify the Mars 2020 (Perseverance) parachute system
- Once validated, fluid-structure interaction (FSI) simulations could help accelerate the certification process, cover more scenarios (altitude, dynamic pressure, angle of attack, Mars vs Earth atmosphere, etc) and thus reduce overall mission cost and risk

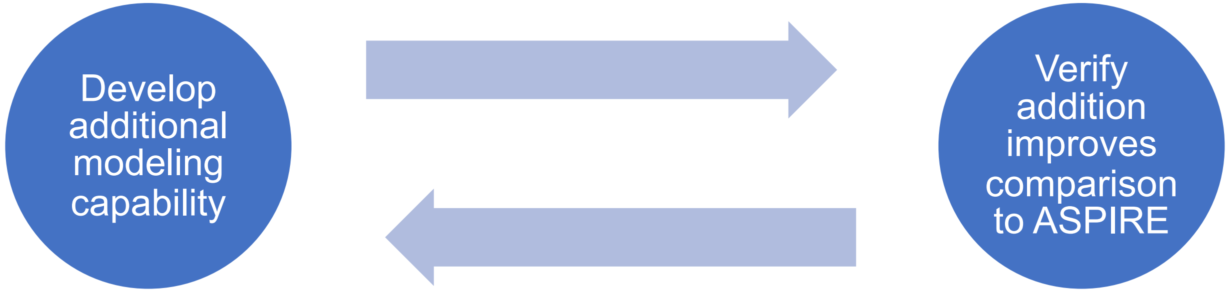
This high-definition image was taken on Sept. 7, 2018, during the third and final test flight of the ASPIRE payload. It was the fastest inflation of this size parachute in history and created a peak load of almost 70,000 pounds of force. ***Credits: NASA/JPL-Caltech***
https://www.nasa.gov/feature/jpl/third-aspire-test-confirms-mars-2020-parachute-a-go

Objectives

- Develop in-house FSI capability to simulate supersonic parachute inflation in the Launch, Ascent and Vehicle Aerodynamics framework (LAVA)



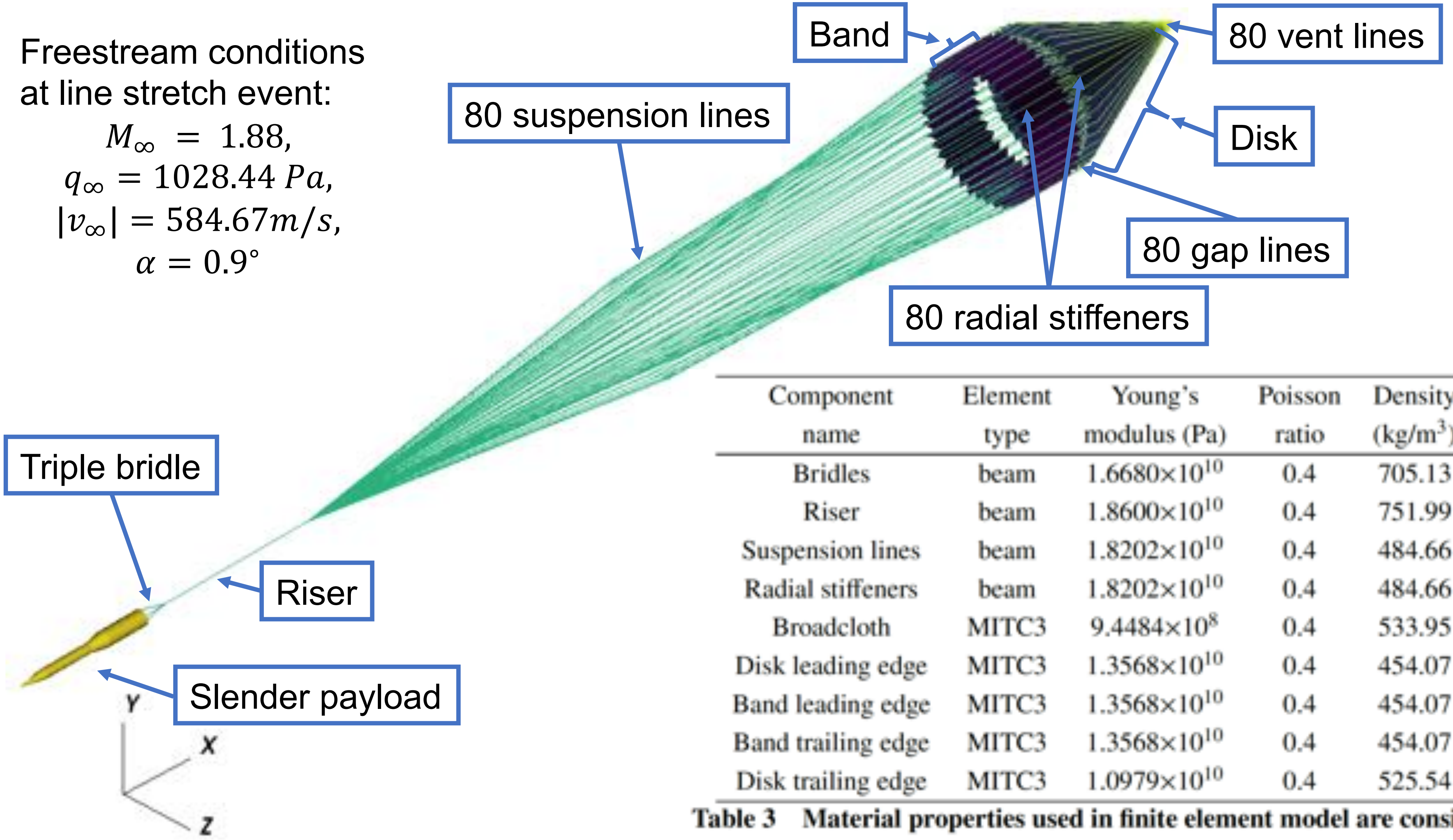
- Validate FSI predictions with ASPIRE flight test measurements



ASPIRE SR03 Problem Setup

Freestream conditions at line stretch event:

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



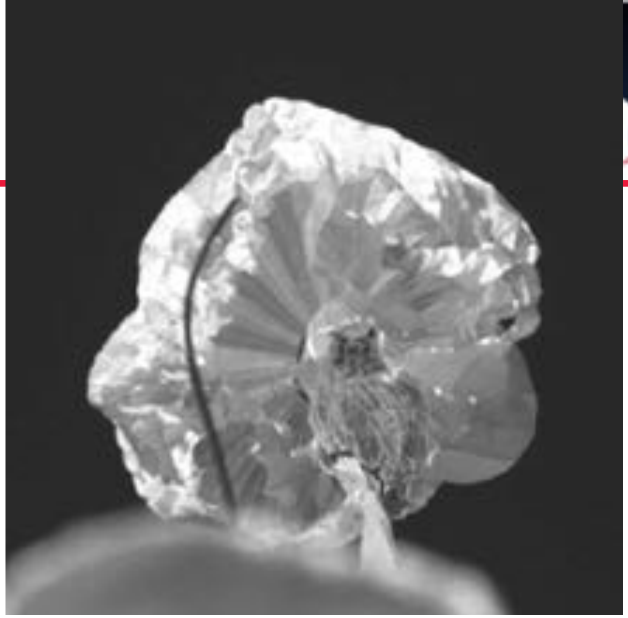
Component name	Element type	Young's modulus (Pa)	Poisson ratio	Density (kg/m^3)	Width/ Radius (m)	Thickness (m)
Bridles	beam	1.6680×10^{10}	0.4	705.13	0.01954	-
Riser	beam	1.8600×10^{10}	0.4	751.99	0.02389	-
Suspension lines	beam	1.8202×10^{10}	0.4	484.66	0.00253	-
Radial stiffeners	beam	1.8202×10^{10}	0.4	484.66	0.00253	-
Broadcloth	MITC3	9.4484×10^{8}	0.4	533.95	-	7.6200×10^{-5}
Disk leading edge	MITC3	1.3568×10^{10}	0.4	454.07	0.0254	1.0583×10^{-3}
Band leading edge	MITC3	1.3568×10^{10}	0.4	454.07	0.0254	1.0583×10^{-3}
Band trailing edge	MITC3	1.3568×10^{10}	0.4	454.07	0.0254	1.0583×10^{-3}
Disk trailing edge	MITC3	1.0979×10^{10}	0.4	525.54	0.0254	2.5400×10^{-3}

Table 3 Material properties used in finite element model are consistent with Rabinovit[illegible]a]. [8].

Cases Studied

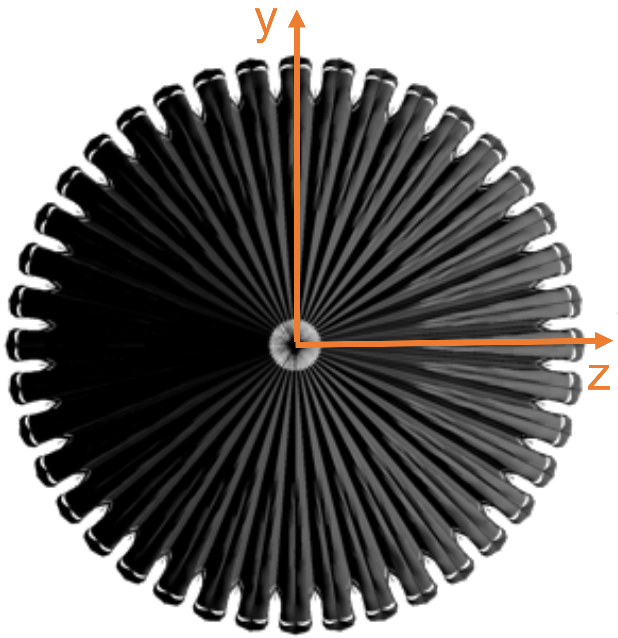
Name	α (°)	Pre-inflation	Radial stiffeners
Radials	0.0	Symmetric	Yes
Radials + AoA	0.9	Symmetric	Yes
Radials + AoA + Asym	0.9	Asymmetric	Yes
AoA + Asym	0.9	Asymmetric	No

Table 4 FSI simulation parameters.

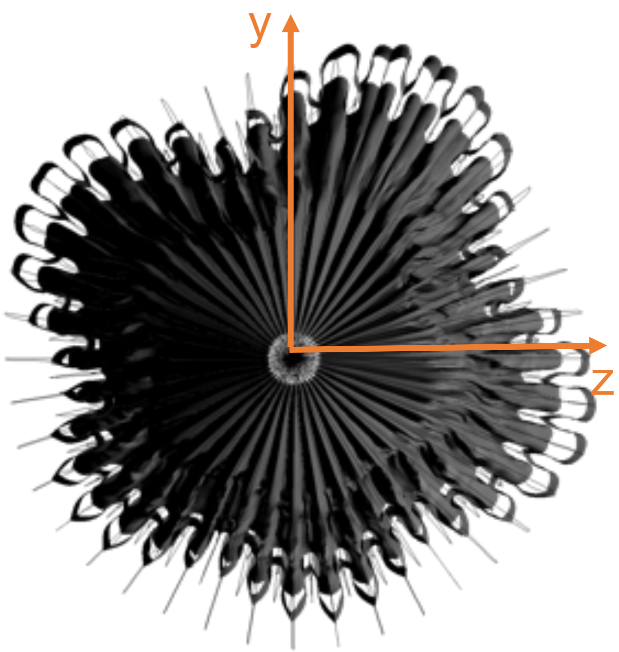


ASPIRE SR03 at t=0.25 s after line stretch
Credit: NASA/JPL-CalTech

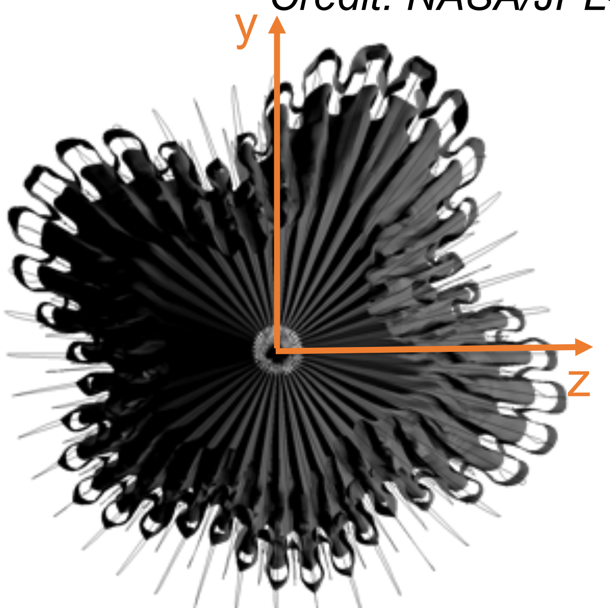
Pre-inflated canopy shape



Symmetric

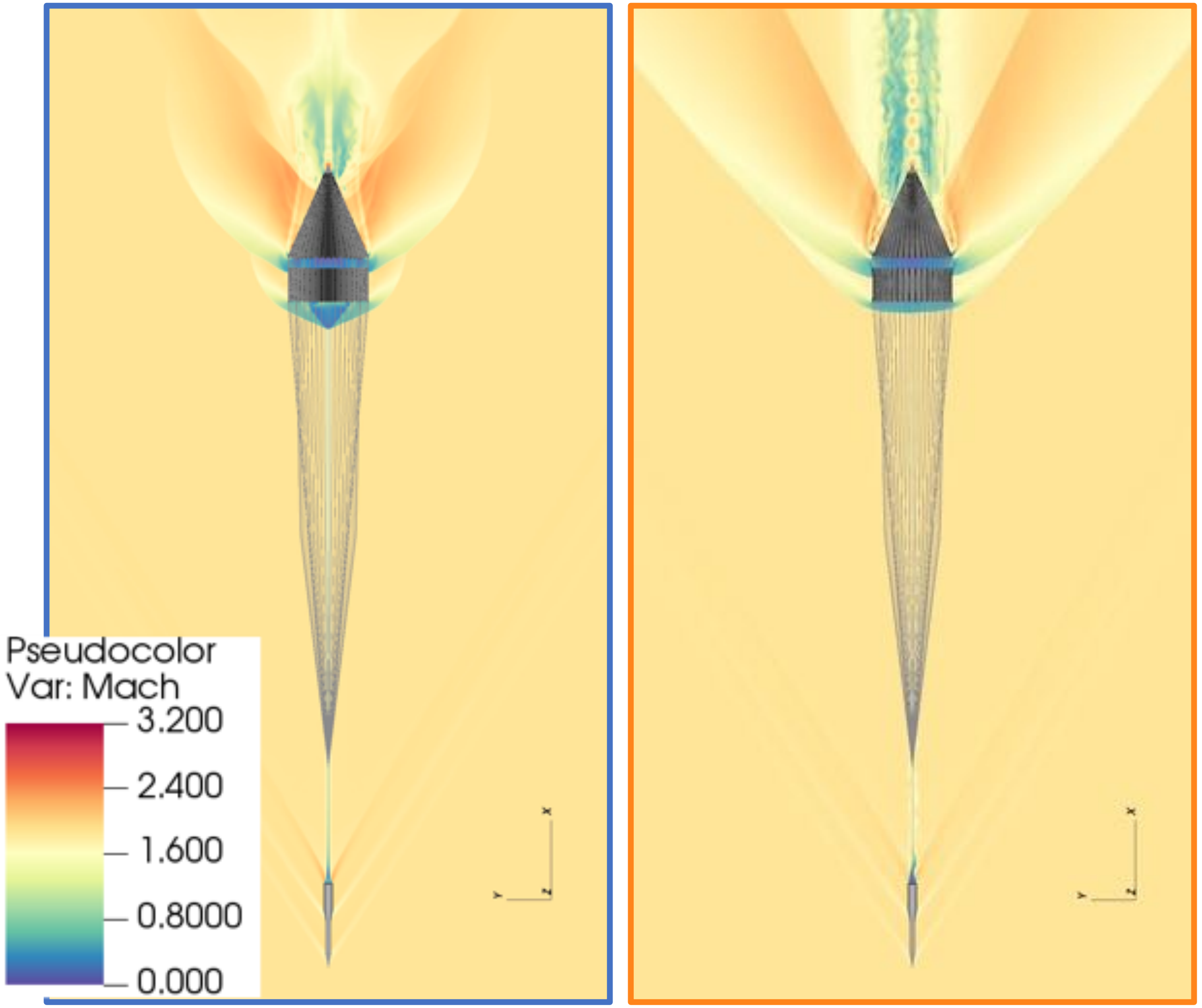


Asymmetric with radials



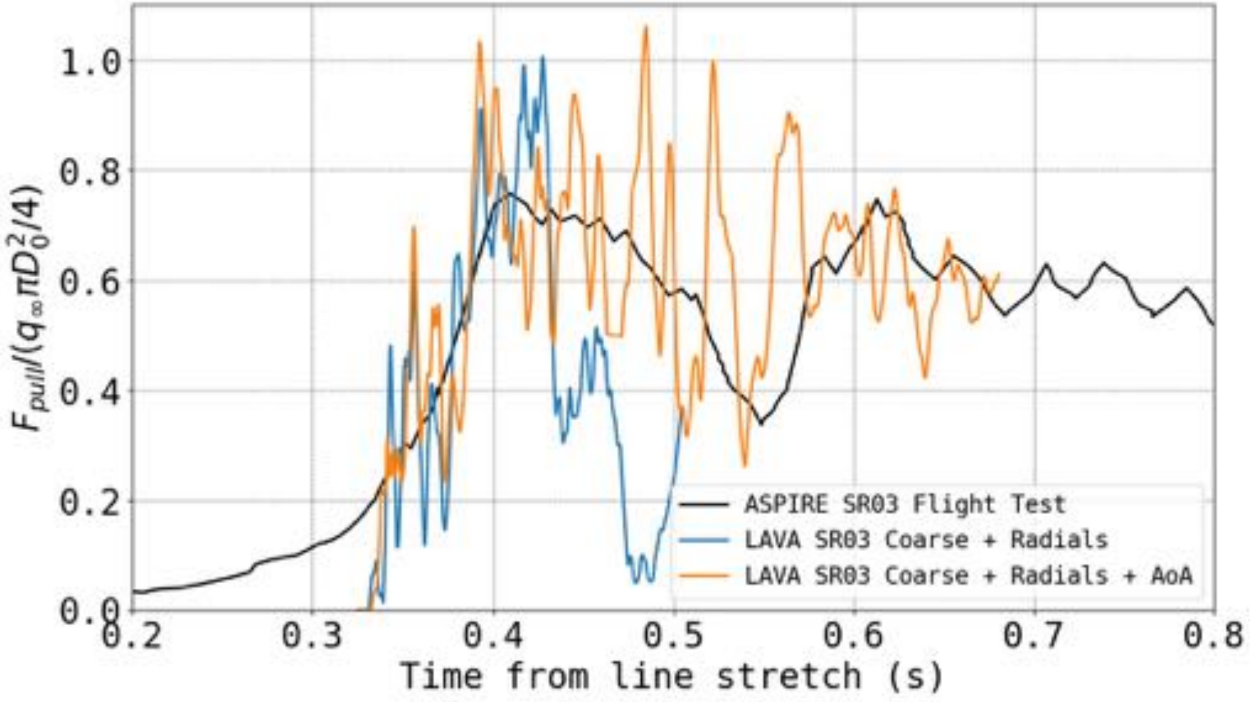
Asymmetric without radials

Results: Effect of Angle of Attack



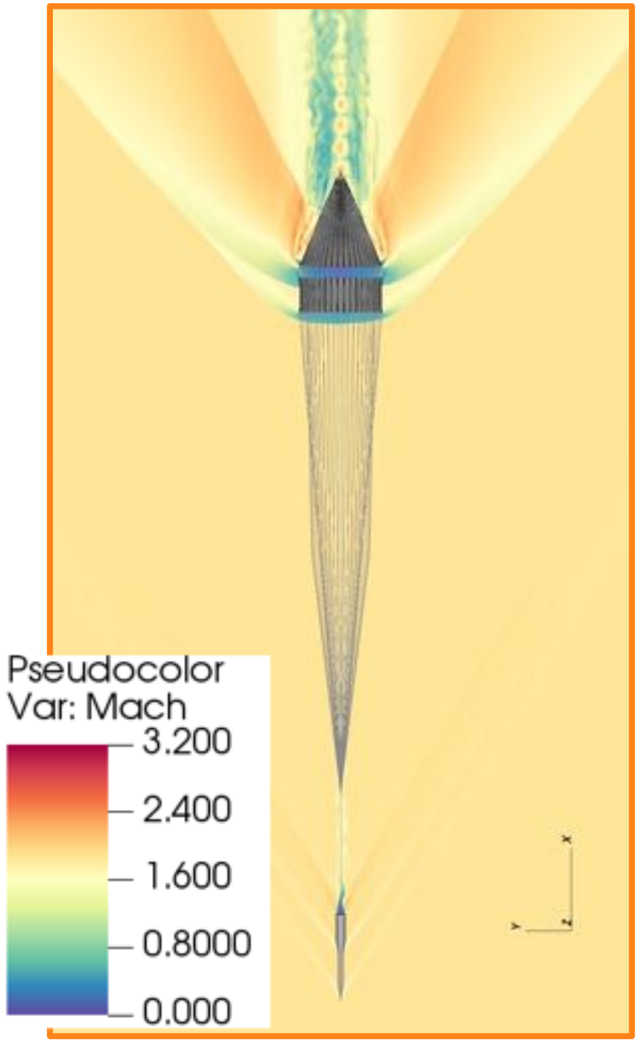
Radials

Radials + AoA

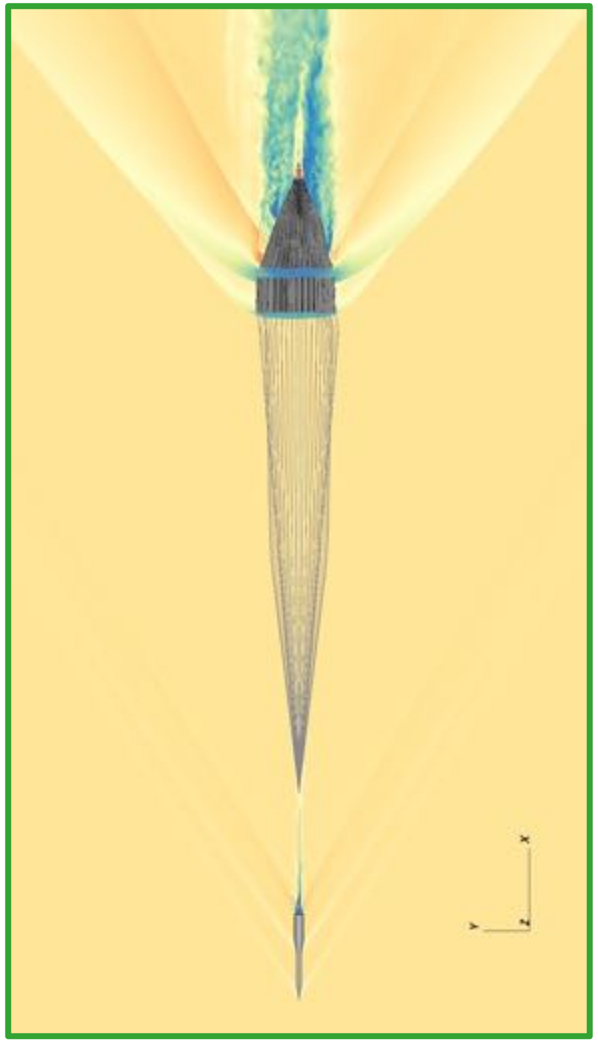


Dip down to almost zero pull force caused by quasi-2D wake bow shock interaction disappears with AoA which causes wake to break down to turbulence and bow shock to remain much flatter

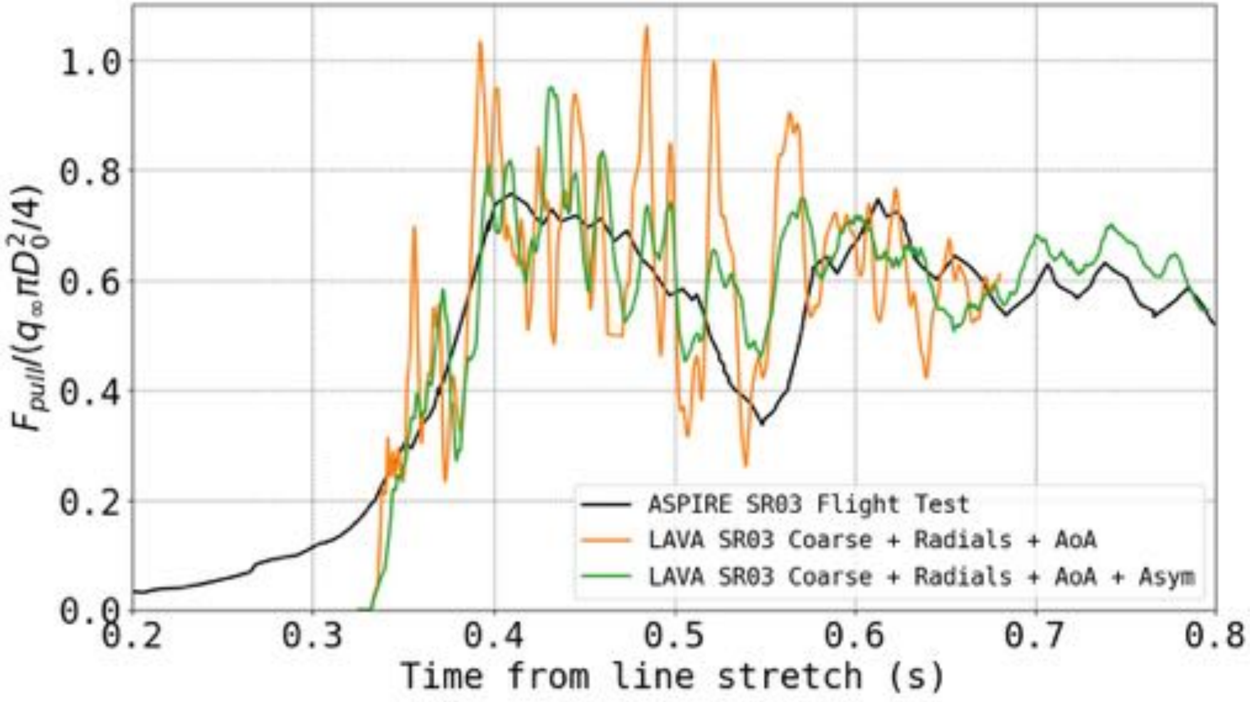
Results: Effect of Asymmetric Pre-inflation



Radials + AoA

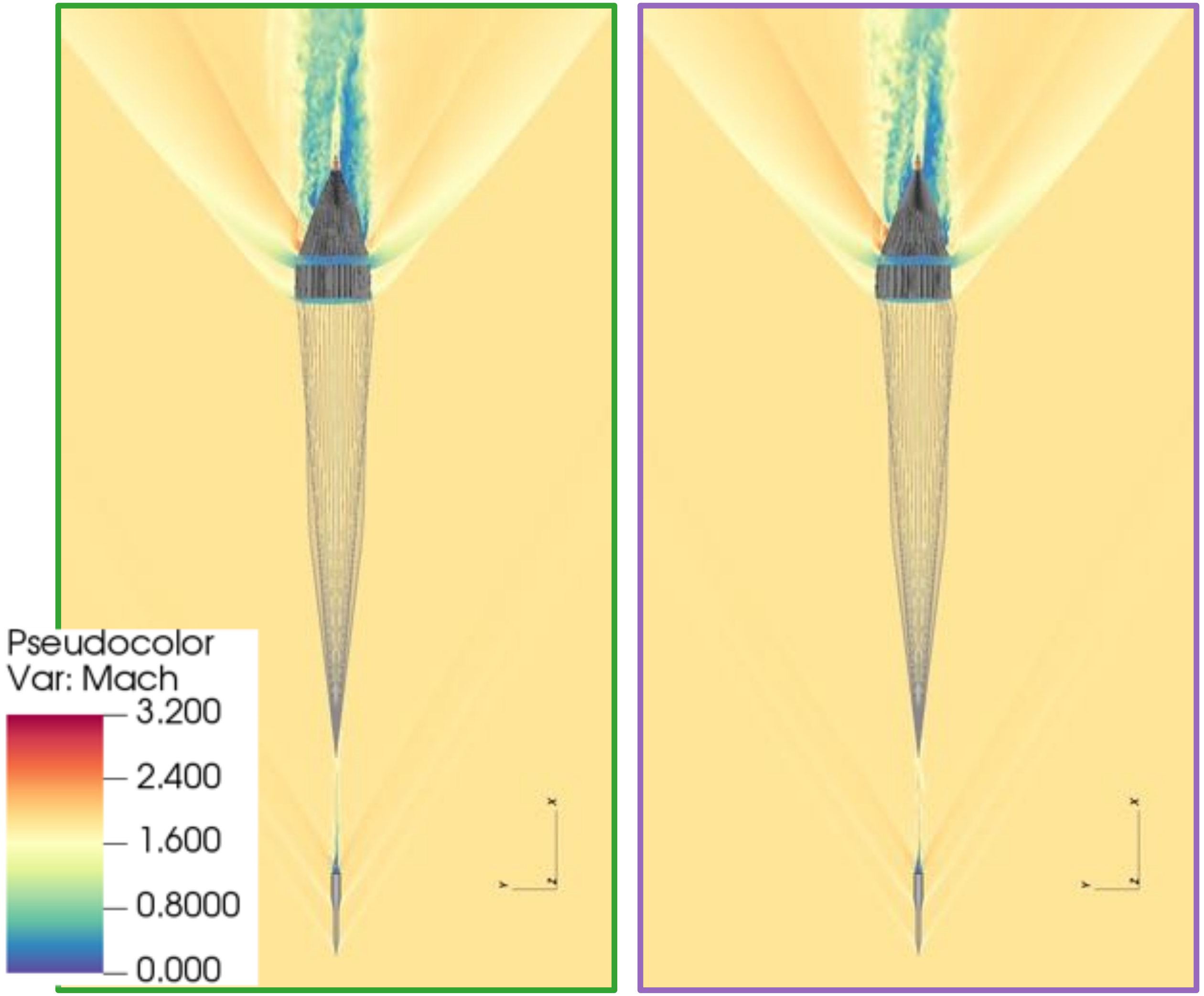


Radials + AoA + Asym



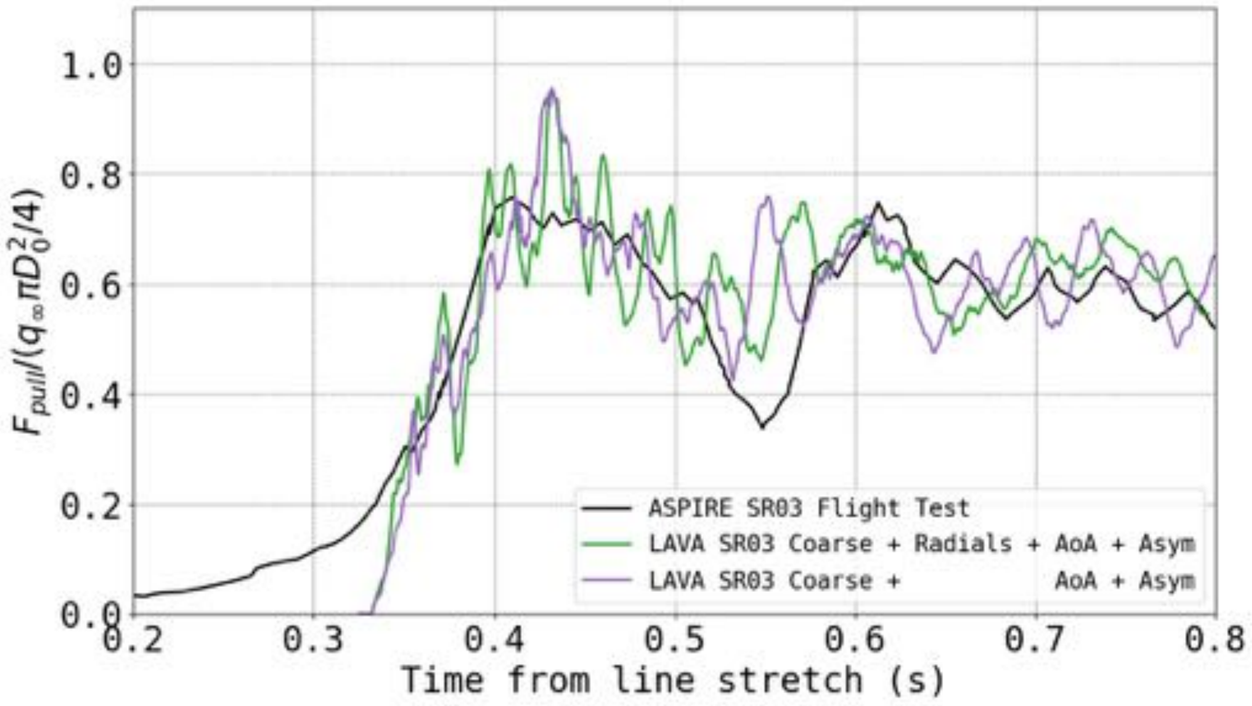
Adding asymmetry to initial parachute shape adds varying amount of slack to lines, causes uneven inflation process, and thus reduces amplitude of high-frequency oscillations caused by synchronized tension waves across radials and suspension lines.

Results: Effect of Radials



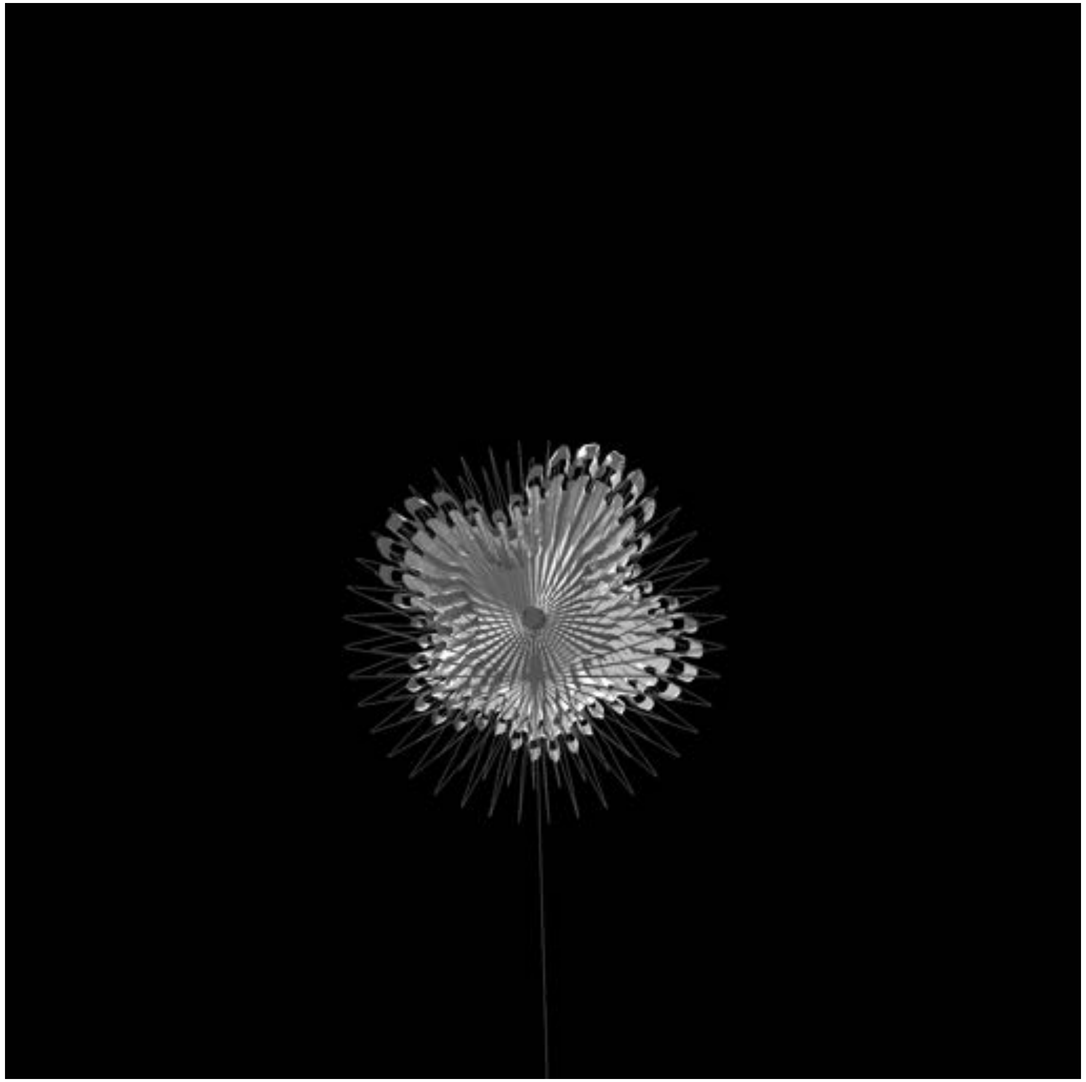
Radials + AoA + Asym

AoA + Asym



Relaxing assumption that radials act like suspension lines further damps high frequency oscillations by breaking up the possibility of standing waves, but produces very similar results.

Results: AoA + Asym



LAVA ASPIRE SR03 FSI AoA + Asym

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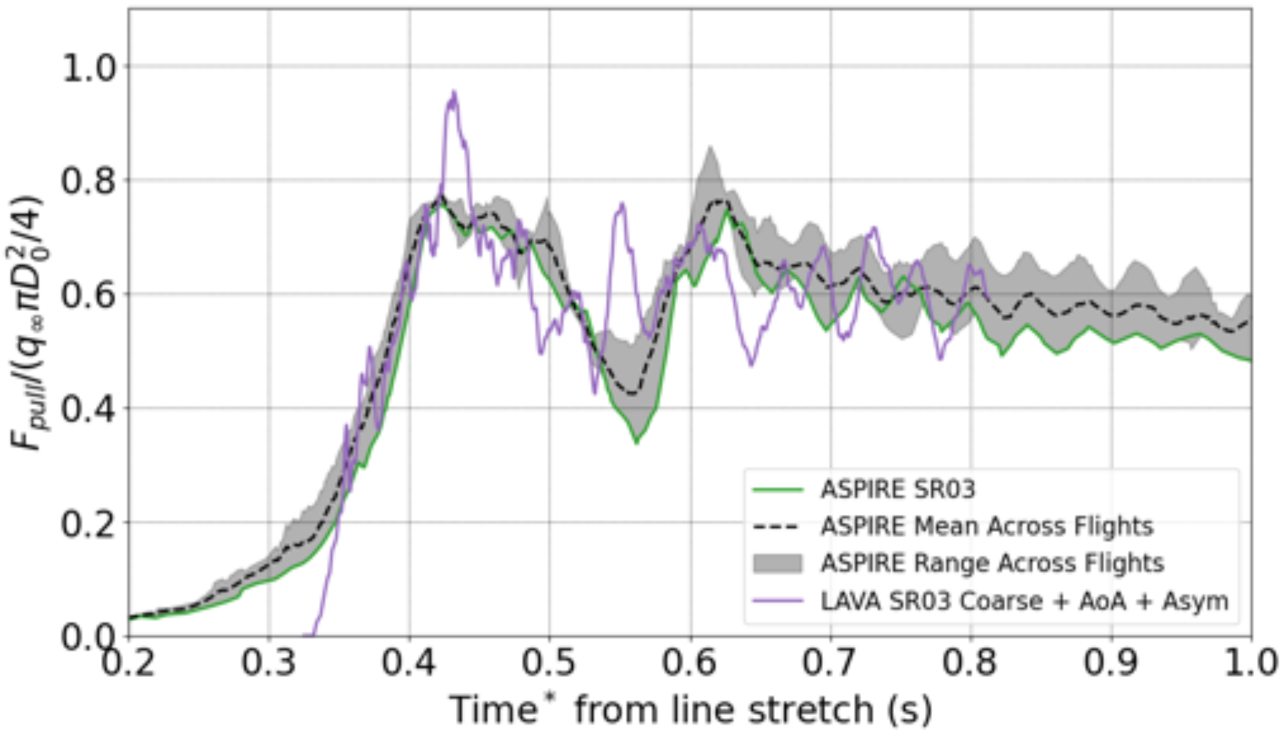
Conclusions

- Performed 4 FSI simulations of ASPIRE SR03 flight to investigate effect of angle of attack, initial parachute shape, and modeling radials as continuous suspension lines
- As expected, as we inch closer to matching flight initial conditions with angle of attack and an asymmetric parachute shape, we obtain improved agreement with flight data
- Similarly, as we relax our assumption about radial stiffeners, we obtain improved agreement



- Achievements:
  - Good match to ASPIRE qualitative trend
  - Drop from peak to trough of 55% matches ASPIRE at 52%
  - Trough and rebound peak values are within flight-to-flight variability
- To investigate in future:
  - Over-prediction of peak pull force by ~20%
  - More abrupt and earlier rebound peak at 0.55 s
  - Effect of deceleration with unrestrained payload

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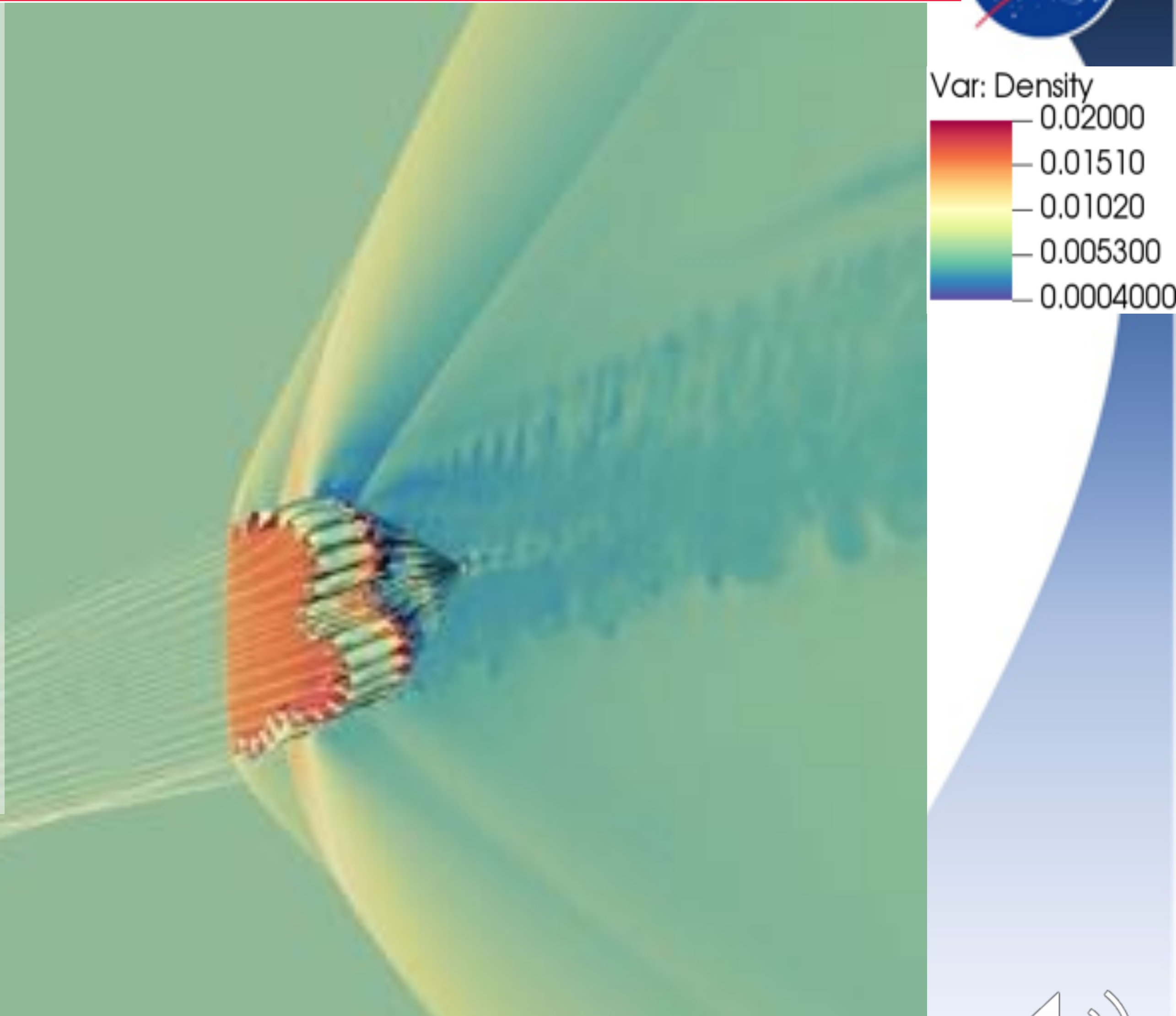
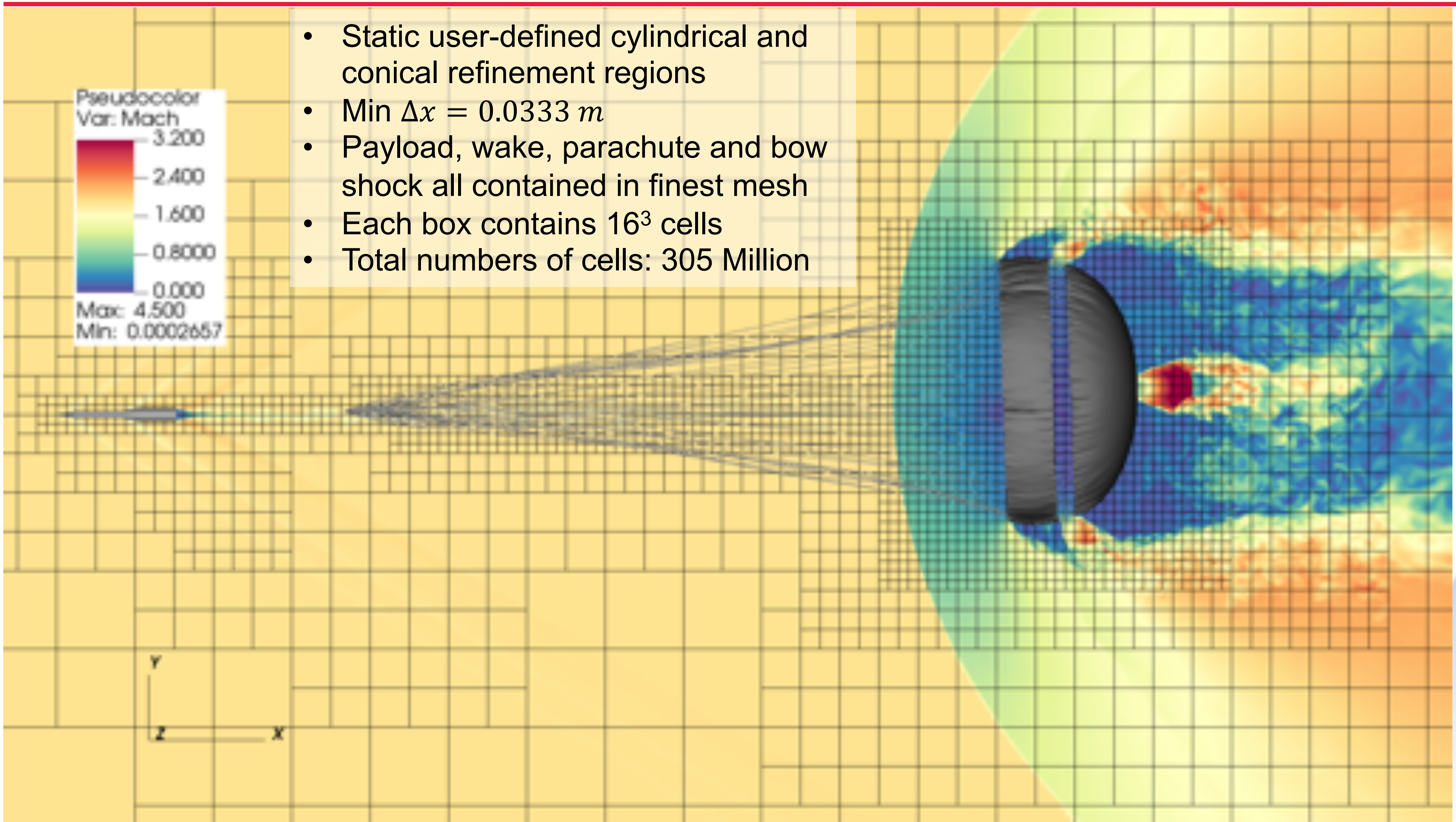
  - Marcus A. Lobbia for providing details of the SR02/SR03 parachutes
  - Michael Barnhardt and Aaron Brandis for insightful discussions and helping us focus our development efforts
  - Jonathan Boustani for developing the CSD solver in LAVA
  - Gaetan Kenway for helping to improve parallel efficiency of the CSD solver



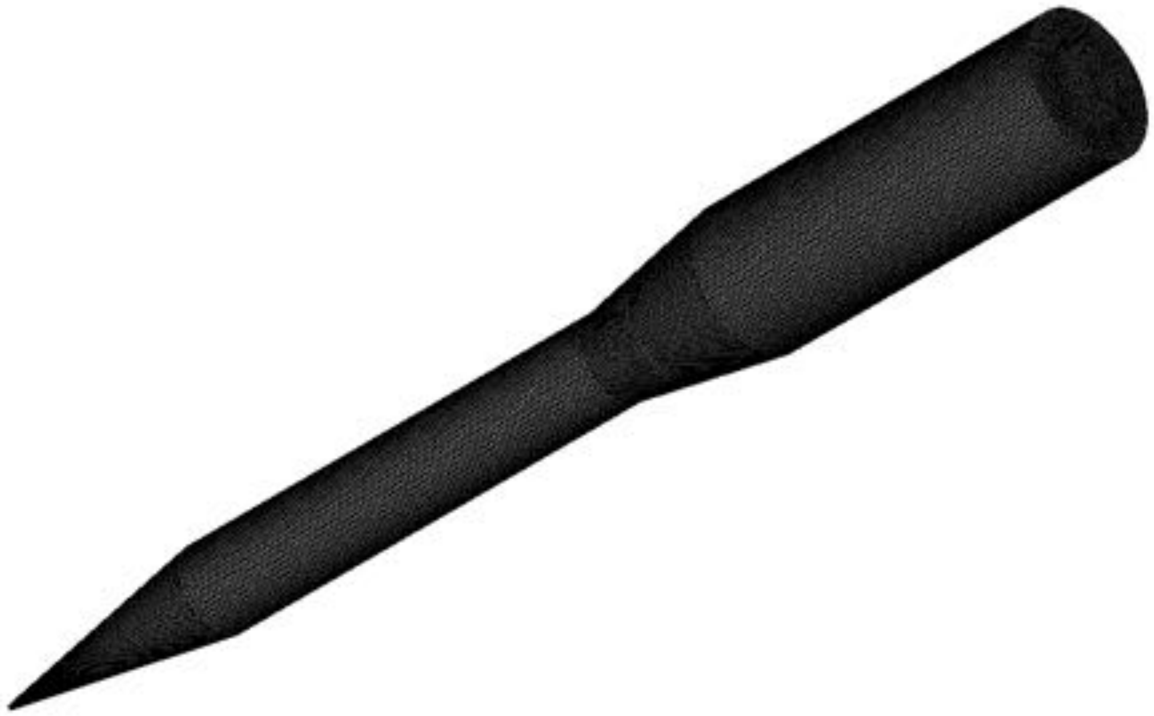
Density on the cut plane and parachute surface for AoA + Asym FSI simulation. Payload and suspension lines shown in white.

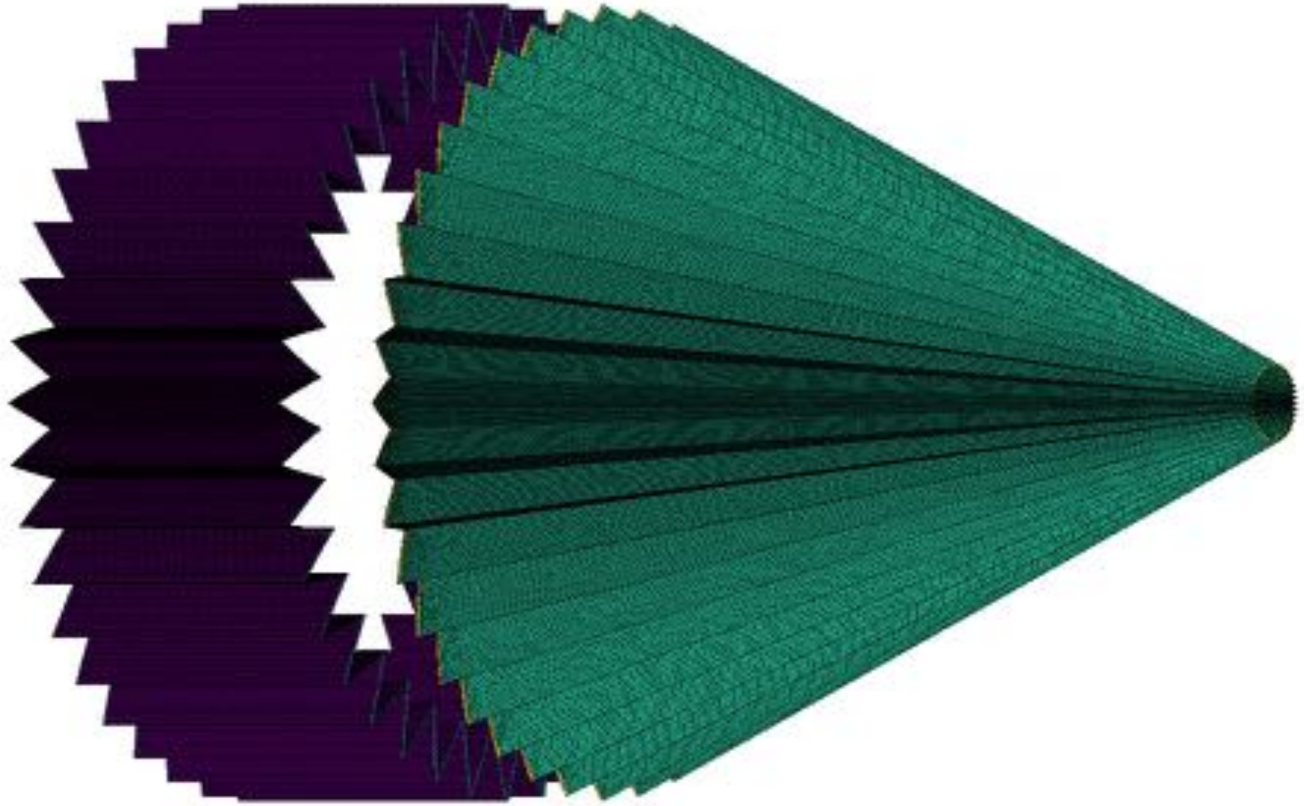
Methodology: CFD Mesh

- 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



Methodology: CSD 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
- Min edge length at leading/trailing edge 0.025 m
- 76,954 beam elements for suspension lines, radials, gap and vent lines with fixed edge length of 0.05 m