Post-Flight Quantification of LOFTID Aeroshell Deflection Using Feature Tracking

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LOFTID

- Low-Earth Orbital Flight Test of an Inflatable Decelerator (LOFTID) was a flight demonstration of Hypersonic Inflatable Aerodynamic Decelerator (HIAD) technology that launched on November 10, 2022
- After reaching low-Earth orbit, the aeroshell inflated to its full 6-meter diameter and then the vehicle successfully re-entered Earth's atmosphere and landed in the Pacific Ocean

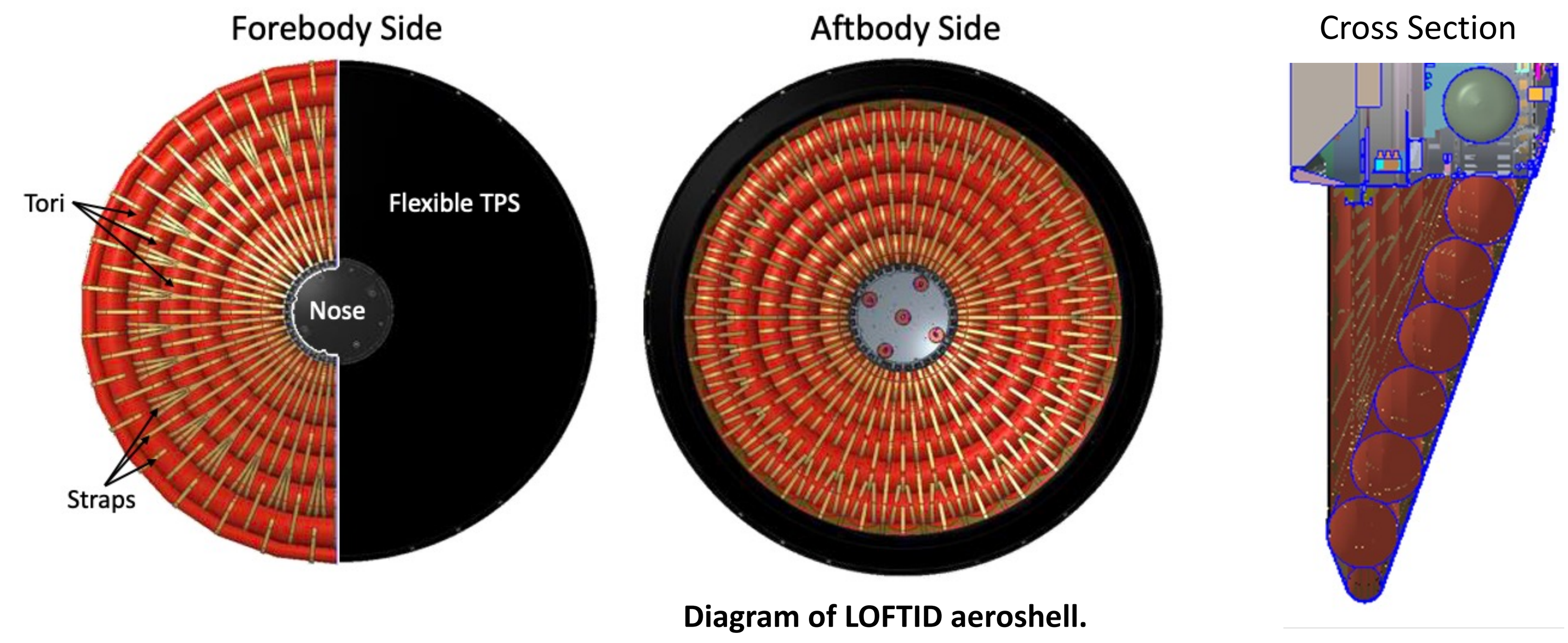
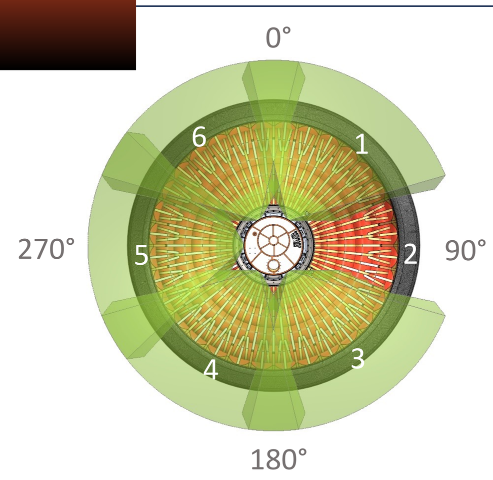


Diagram of LOFTID aeroshell.

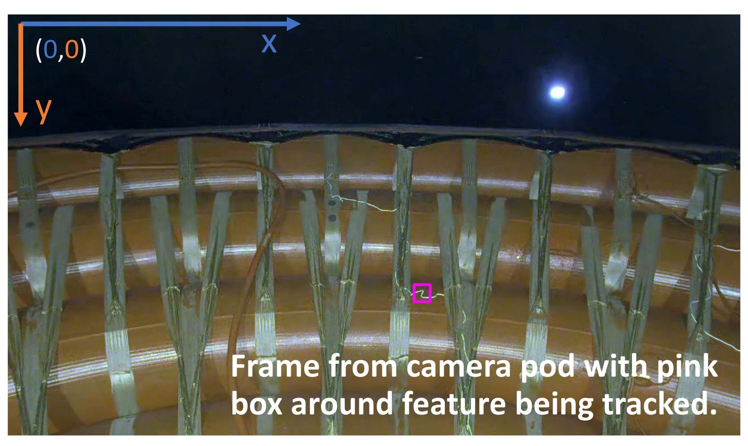
- Aeroshell is composed of 7 tori bound together by high strength straps to create a 70° half-angle sphere-cone
- Aerodynamic loading during flight resulted in the cone of the aeroshell deflecting (also observed during pre-flight static load testing)

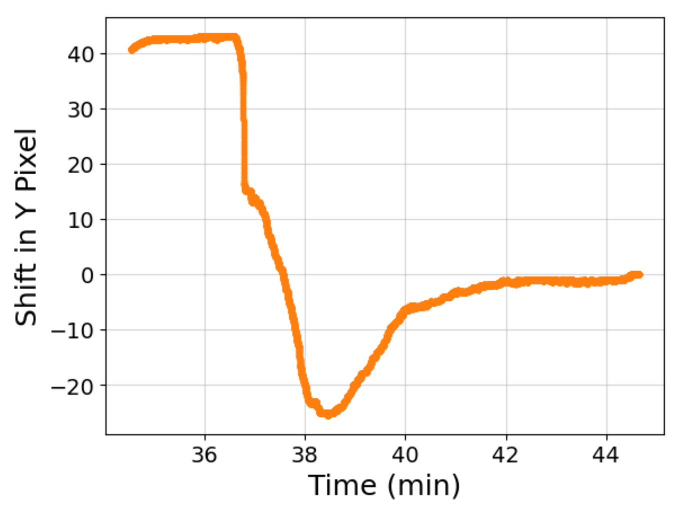
Methodology

- 6 visual cameras on center body (5 operable)
  - Field-of-view: 85.4° x 56.7°
  - Spatial resolution: <0.1"
- Computer vision algorithm
  - Implemented Discriminative Correlation Filter with Channel and Spatial Reliability tracker (CSRT) with *OpenCV*
  - User draws box around feature that is tracked throughout video
  - Chose unique thermocouple features to track in each video



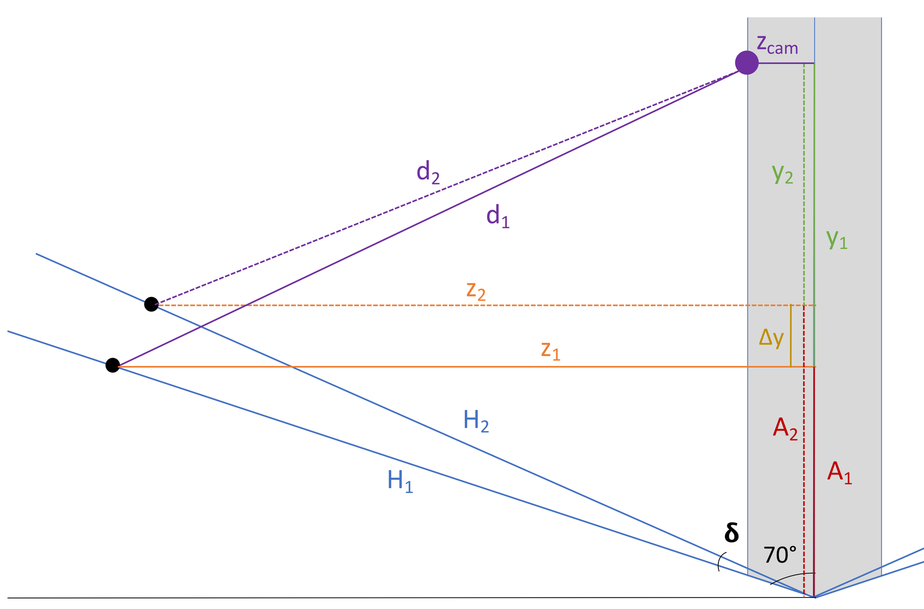
Location and field-of-view of camera pods.





Shift in y- position of feature throughout video.

- Deflection angle calculation
  - "Simple" geometry to convert shift in y-position to deflection angle
  - Assumptions: negligible movement in the x-direction, initial half-angle of aeroshell of 70°, constant linear distance between the nose of the cone and the feature ($H_1 = H_2$)



Knowns: Δy_{px}, z_{cam}, z_1, y_1

Resolution (y-direction) = $\frac{56.7°}{1080\ px} = 0.0525°/px$

At distance d, spatial resolution (s) / pixel = $d \tan(0.0525°)$

Pixel shift in y-direction = Δy_{px}

$$d_1 = \sqrt{(z_1 - z_{cam})^2 + {y_1}^2} \rightarrow s_1 = d_1 \tan(0.0525°) \approx s_2$$

$$\Delta y = \Delta y_{px} \times s_1$$

$$y_2 = y_1 - \Delta y$$

$$A_1 = \frac{z_1}{\tan 70°}$$

$$H_1 = \frac{z_1}{\sin 70°} = H_2$$

$$A_2 = A_1 + y_1 - y_2$$

$$A_2 = H_2 \cos(70° - \delta) \rightarrow \boldsymbol{\delta = 70° - \cos^{-1}\left(\frac{A_2}{H_2}\right)}$$

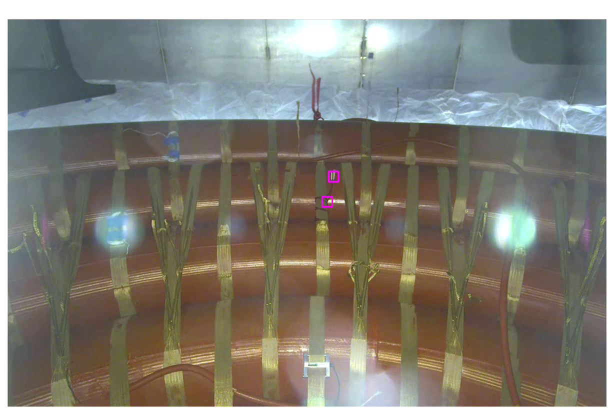
Diagram of deflection angle calculation.

Validation

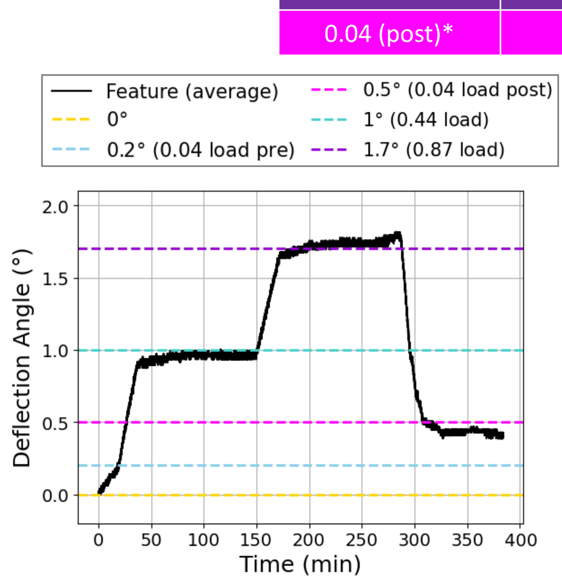
- Pre-flight static load test in May 2021
  - Deflection calculated from laser scans of the vehicle under each loading condition
- Tracked two features and averaged calculated deflection
  - Closely matches angles from laser scans

Load (Normalized)	Deflection Angle (Laser Scan)	Deflection Angle (Feature Tracking)
0	0°	0°
0.04	0.2°	N/A
0.44	1°	0.96°
0.87	1.7°	1.74°
0.04 (post)*	0.5°	0.43°

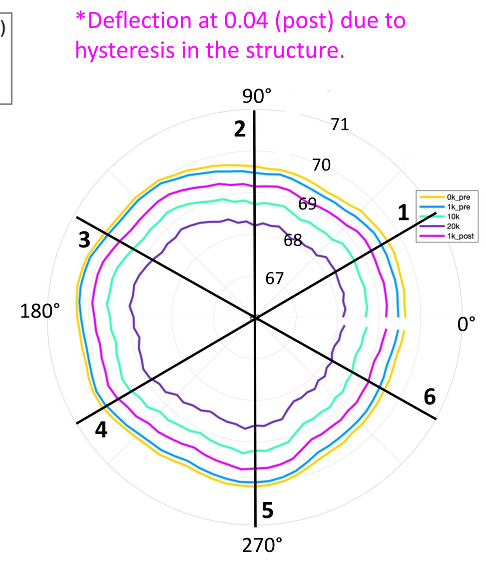
*Deflection at 0.04 (post) due to hysteresis in the structure.



Frame from camera pod during static load test with pink boxes around tracked features.



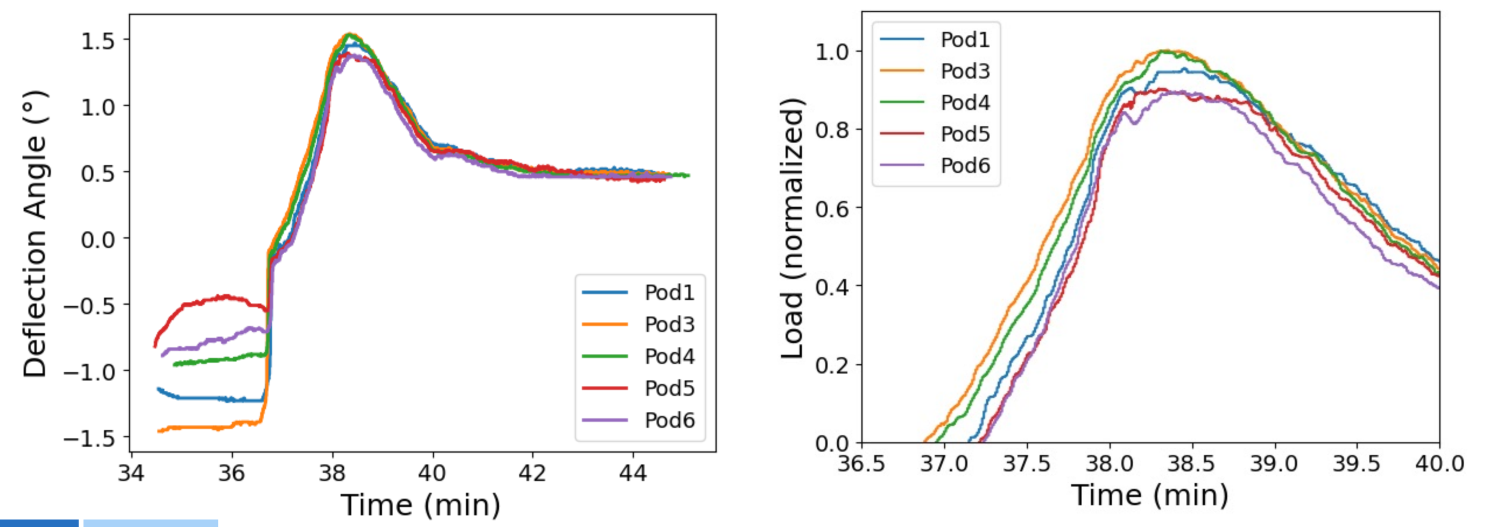
Comparison of deflections measured by laser scans and feature tracking.



Static load testing results.

Flight Video Analysis

- Tracked features from each of the 5 operable camera pods
- Forced final deflection to be 0.5° because of the expected hysteresis and the deflection measured during static load testing at low load after peak loading



Pod	Angle
Pod 1	30°
Pod 3	150°
Pod 4	210°
Pod 5	270°
Pod 6	330°

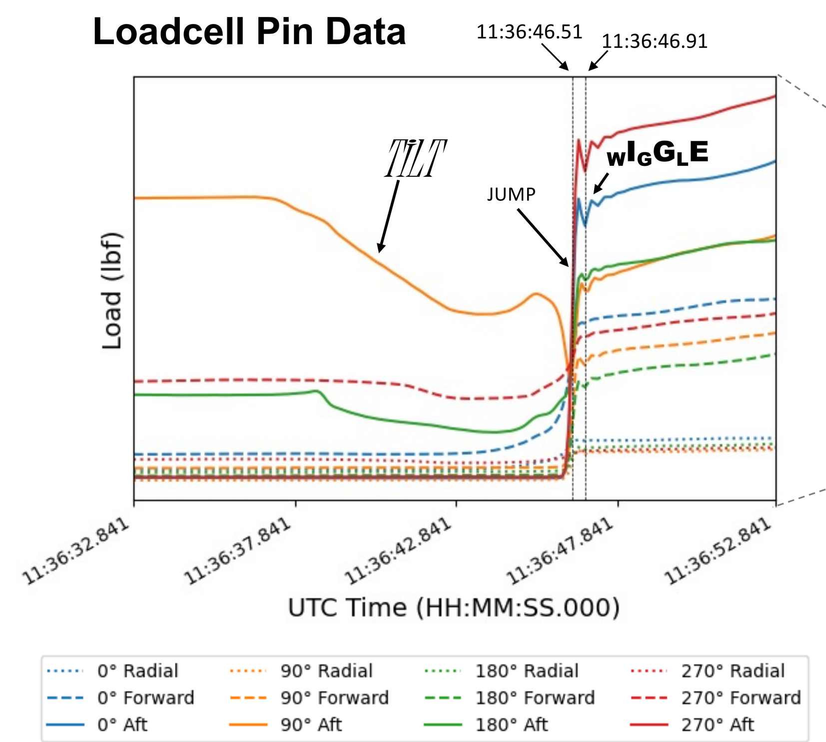
Deflection angles and loads calculated for each camera pod location.

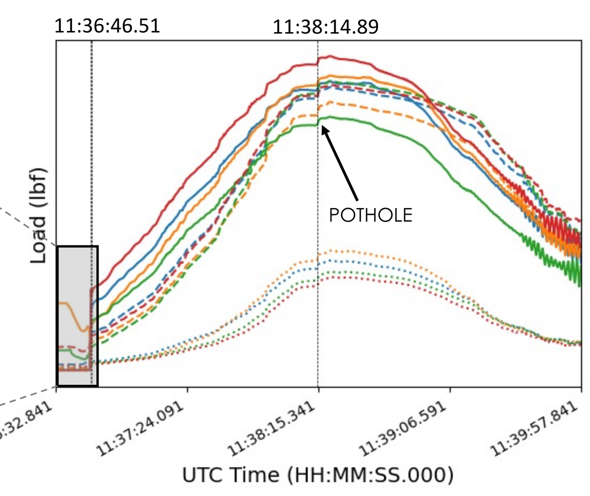
- Used static load testing to relate deflection angle to loads
- All pods showed peak 1.3-1.5° of deflection (assuming a deflection of 0.5° at the final state)

Aeroshell Events

- Events observed from feature tracking match data from loadcell pins

Loadcell Pin Data

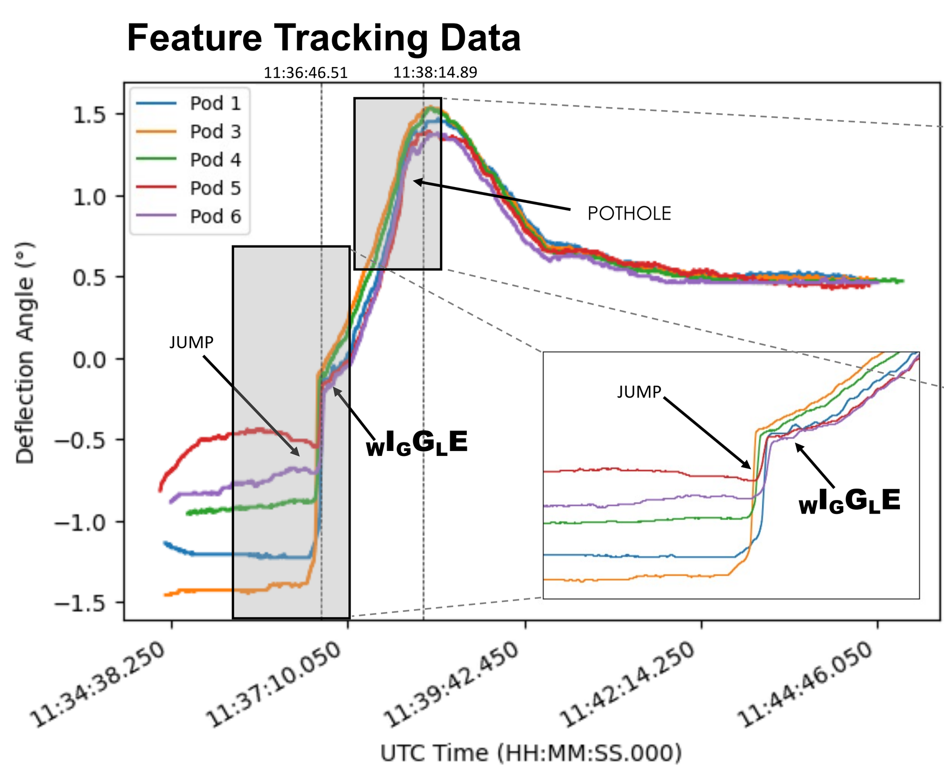


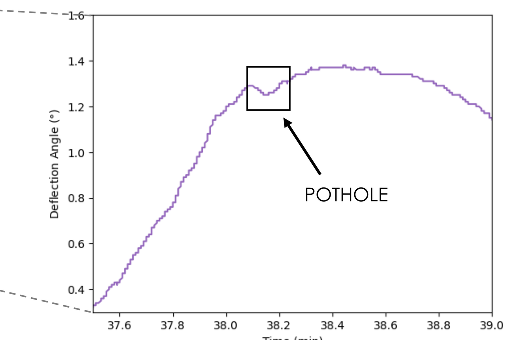


Aeroshell Events: Loadcell Pin Data

- Significant increase in load in all aft straps during the JUMP
- Small increase in load in all straps at the end of the POTHOLE
- Noticeable variation in the load in the 0° and 270° aft straps during the WIGGLE, and much lower elsewhere

Feature Tracking Data

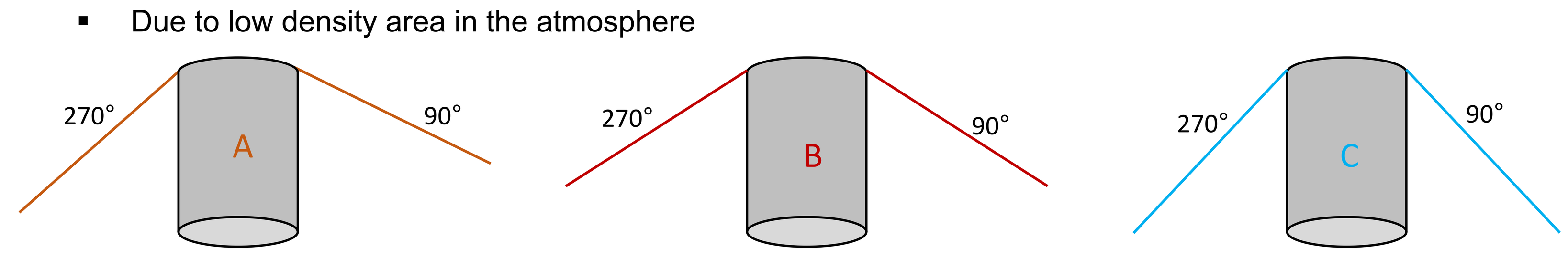




Aeroshell Events: Feature Tracking Data

- The JUMP and POTHOLE are visible in all camera pods
- WIGGLE is is visible in pods 1, 5, and 6, which are in the region of 0° and 270°

- Total load on loadcell pins before the JUMP correlates to initial deflection of aeroshell features
  - Aft – most load carried by 90° aft strap (between pods 1 and 3); pods 1 and 3 show biggest initial deflection
  - Forward – most load carried by 270° forward strap (pod 5); pod 5 shows least initial deflection
- Aeroshell event timeline
  1. Initially inflatable structure rotated with 90° tilted forward and 270° tilted aft (TILT) (A)
  2. Inflatable structure begins to rotate axially to more symmetric orientation (B)
  3. Inflatable structure has a sudden deflection in the aft direction (JUMP)
  4. Inflatable structure continues to deflect as pressure load increases towards the aft (C)
  5. Inflatable structure has small, sudden change in orientation near peak loading (POTHOLE)
     - Due to low density area in the atmosphere



- Initial tilt due to deployment in zero gravity as opposed to ground deployments done nose up in 1g
  - Implementing anchor system for future flights to ensure that the torus at the interface with the nose remains in the correct orientation

Conclusion

- A camera-based method to estimate aeroshell deflection was developed and validated on ground test data. Successful application of the tool to flight video provided aeroshell deflection and load estimates during entry. Understanding the aeroshell structural behavior has implications for trajectory estimation, aeroshell stability, and control, and will be used to inform future HIAD design.