Low Density Supersonic Decelerators (LDSD):

Reconstructed Parachute System Performance During the Second Supersonic Flight Dynamics Test

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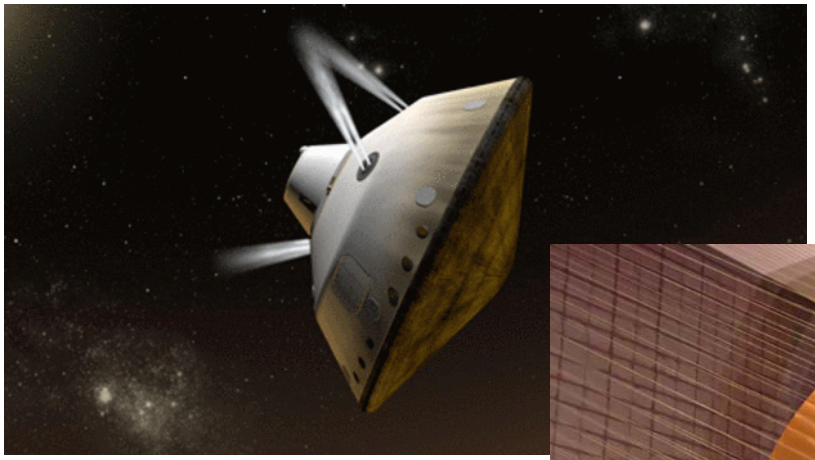
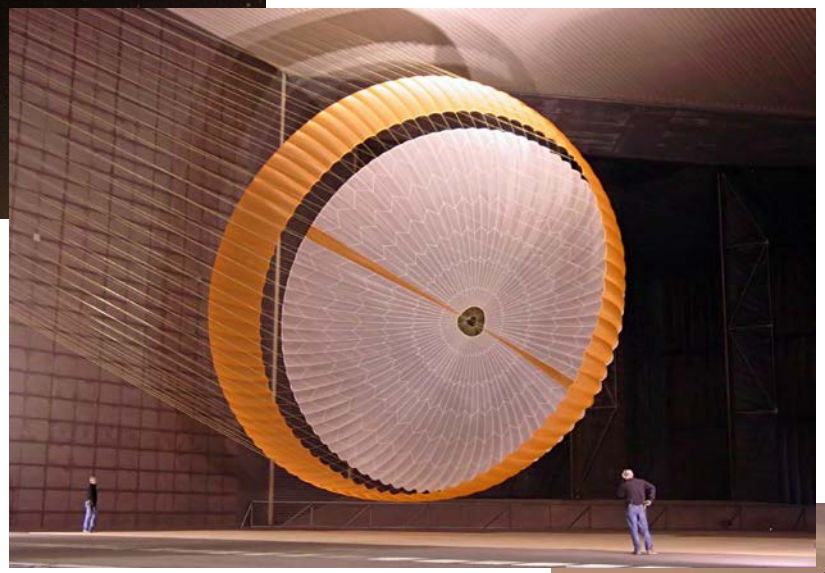
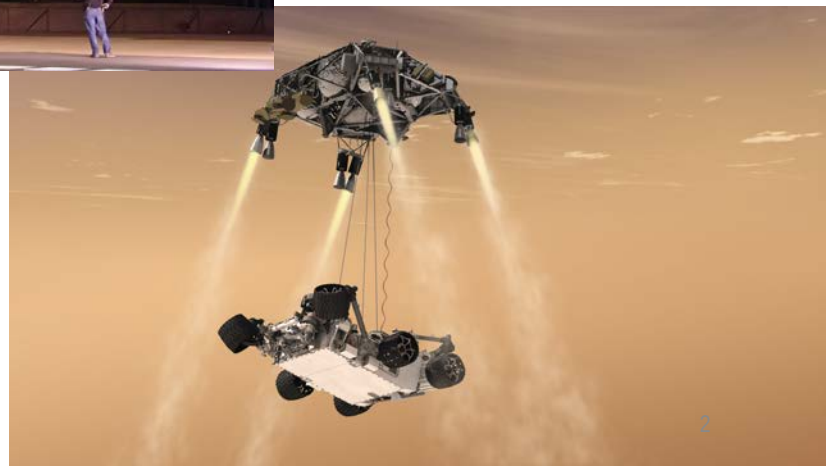
Mars Entry, Descent & Landing State of the Art

Jet Propulsion Laboratory, California Institute of Technology







Low Density Supersonic Decelerator (LDSD) Project

Jet Propulsion Laboratory, California Institute of Technology

Goal

Develop and demonstrate supersonic inflatable aerodynamic decelerators (SIADs) and parachutes on scales sufficient to prove their efficacy for future missions.

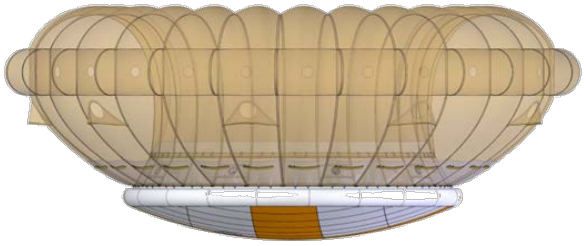
Objectives

1. Develop a 6-meter diameter, Mach 3.5 attached torus SIAD
2. Develop a 30-meter diameter or larger Mach 2 Supersonic Parachute
3. Develop an 8-meter diameter Mach 3.5 flexible ram-air isotensoid SIAD
4. Demonstrate flight performance of the parachute together with each of the two SIADs at simulated Mars atmospheric conditions

SIAD-R

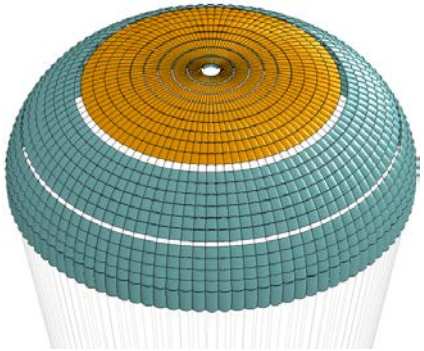
- 6 m, Mach 3.75 inflatable decelerator
- Negligible aeroelastic deformation
- 1.5x drag area of MSL

SIAD-E



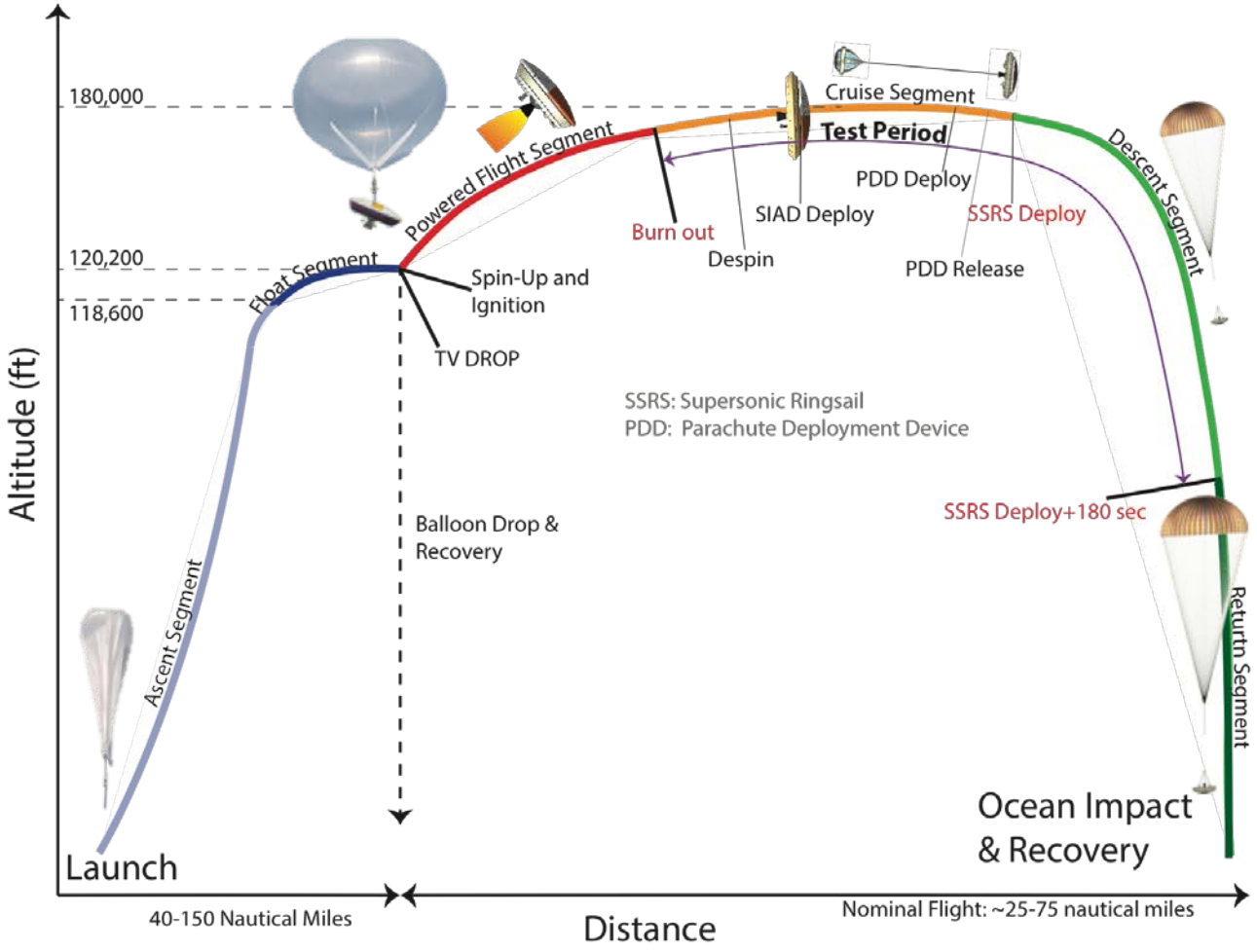
- 8 m, Mach 3.75 inflatable decelerator
- Ram-air inflated, flexible structure
- 2.25x drag area of MSL

Advanced Supersonic Parachute



- 30.5 m, Mach 2.5 parachute
- Extensible to reefing and clusters
- 2.5x drag area of MSL parachute

Supersonic Flight Dynamics Test (SFDT)

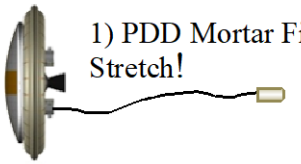


- SFDT-1: June 28th, 2014 (Clark, Adler, and Manning AIAA 2015-2100)
- SFDT-2: June 8th, 2015 (Clark and Adler 2016, IEEE Aerospace Conference Paper – in press).

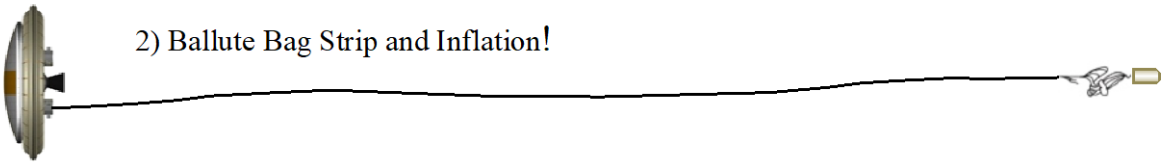
SFDT-2 Video

Parachute Decelerator System

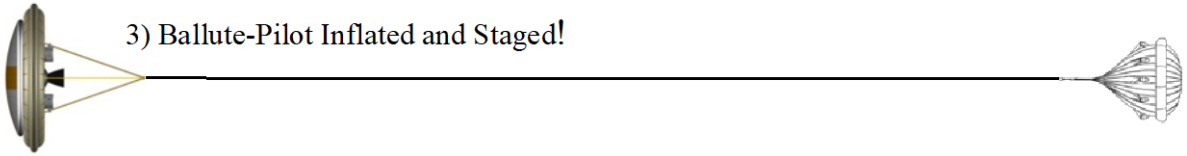
1) PDD Mortar Fire to PDD Line Stretch!



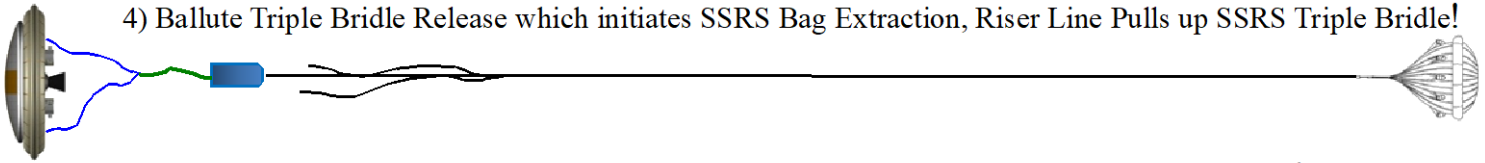
2) Ballute Bag Strip and Inflation!



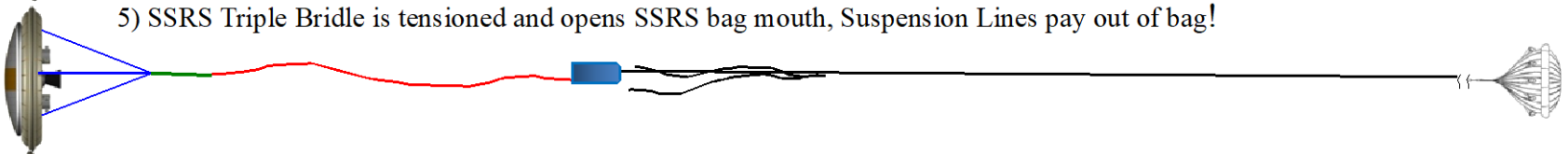
3) Ballute-Pilot Inflated and Staged!



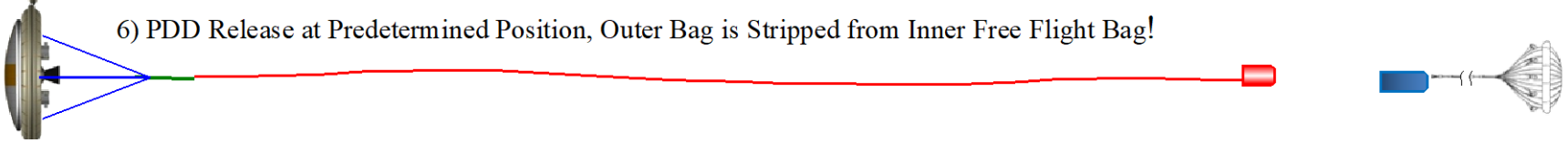
4) Ballute Triple Bridle Release which initiates SSRS Bag Extraction, Riser Line Pulls up SSRS Triple Bridle!



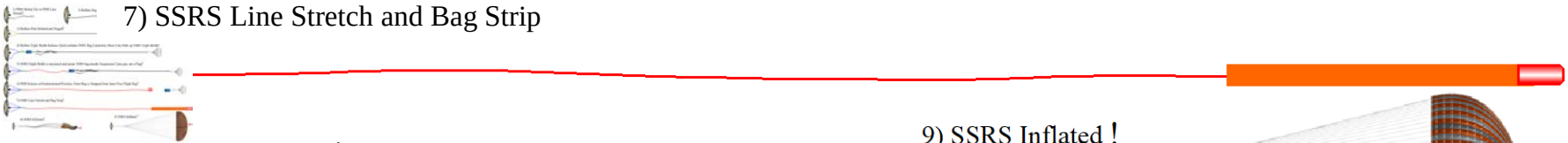
5) SSRS Triple Bridle is tensioned and opens SSRS bag mouth, Suspension Lines pay out of bag!



6) PDD Release at Predetermined Position, Outer Bag is Stripped from Inner Free Flight Bag!

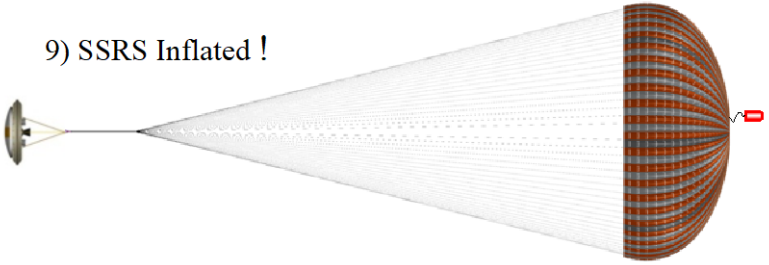


7) SSRS Line Stretch and Bag Strip



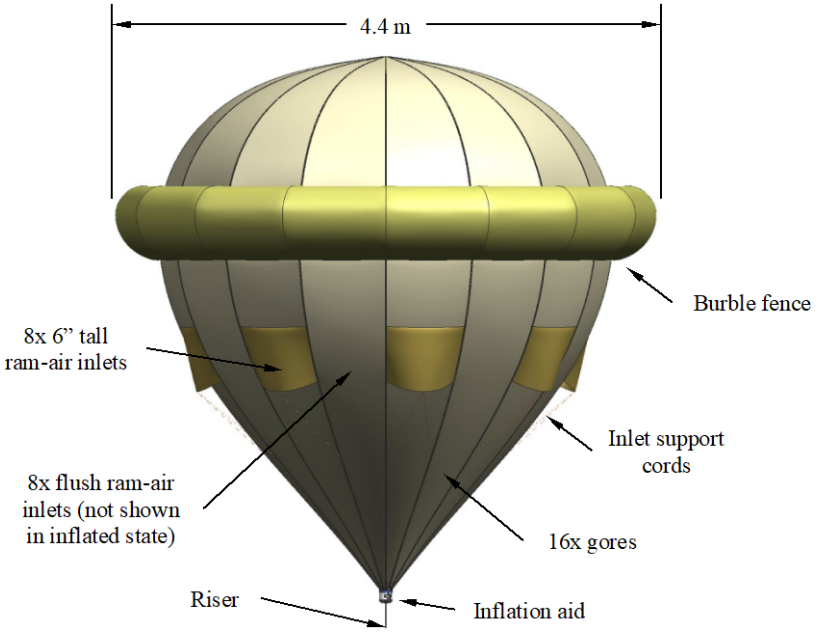
8) SSRS Inflation!

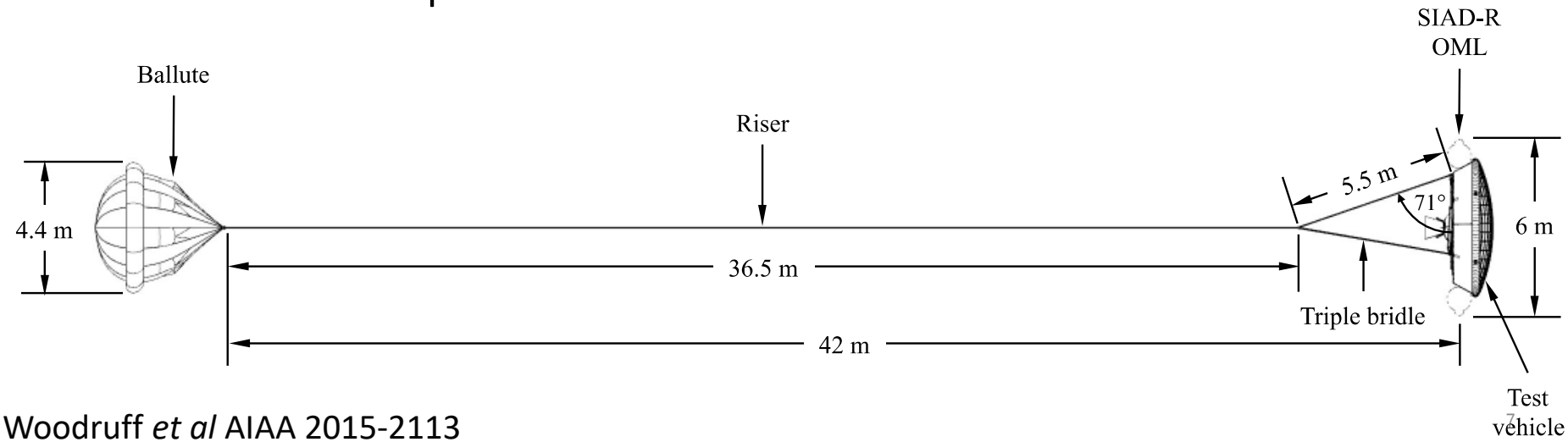
9) SSRS Inflated !



Ballute Parachute Deployment Device (PDD)

- Max. diameter = 4.4 m, 10% burble fence
- 16 gores of silicon-coated Kevlar 29, 625 lb Kevlar webbing meridians.
- Inflation initiated by gas generator Inflation Aid (IA)
- 16 inlets for ram-air inflation (8 flush-mounted, 8 “proud”)
- Attached to test vehicle (TV) via 36.5 m Kevlar riser and triple bridle.

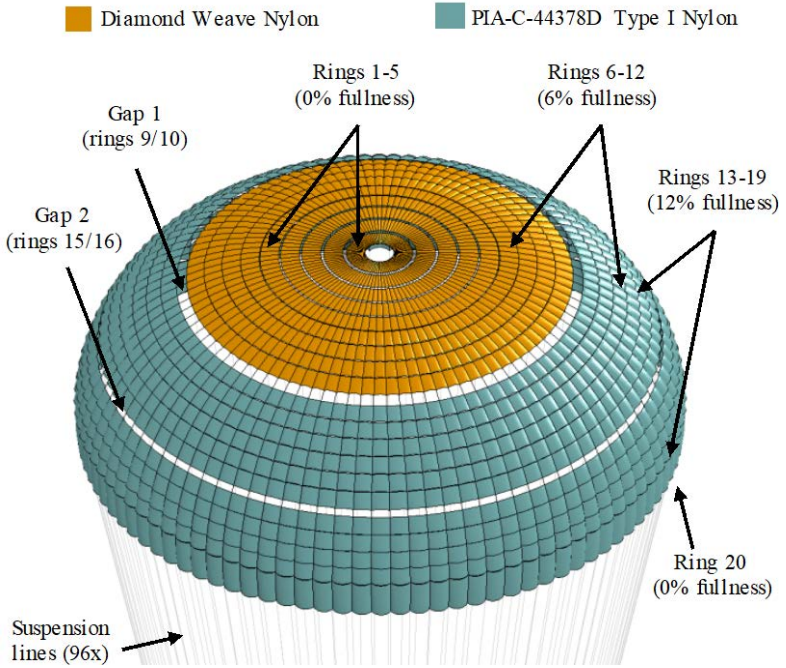


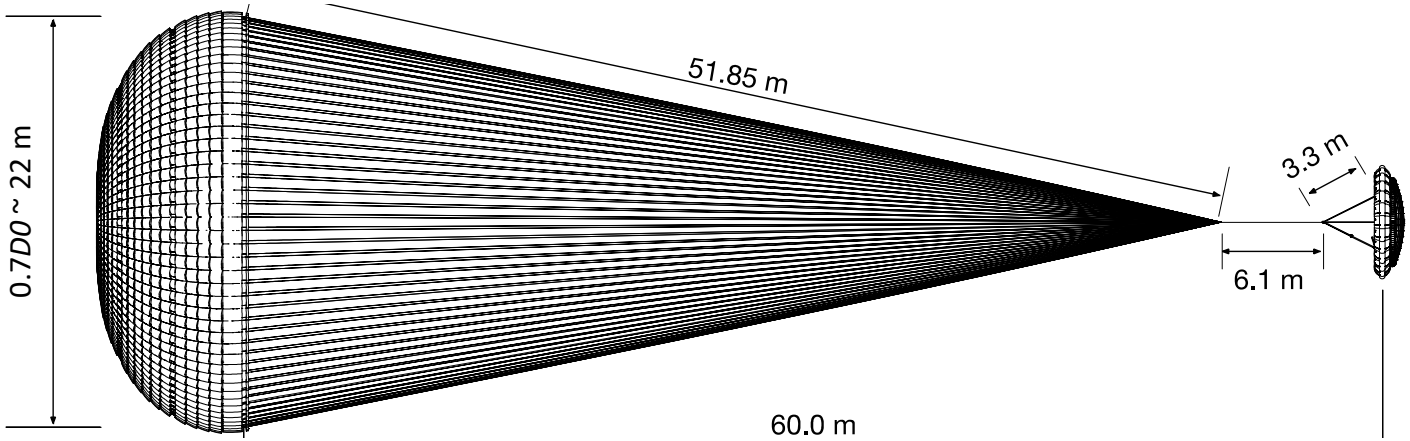


Woodruff *et al* AIAA 2015-2113

Supersonic Ringsail (SSRS) Parachute

- Nominal diameter D_0= 30.5 m
- Quarter-spherical construction
- 96 gores, 20 rings and sails, 2 gaps
- Broadcloth: Diamond Weave Nylon in crown, PIA-C-44378D Type I Nylon (F-111) elsewhere.
- Kevlar tape skeleton: radials, leading edge circumferentials (rings 1-9 only), TE circumferentials.





1.7xD_0 suspension lines, 6.1 m Kevlar riser, triple bridle.

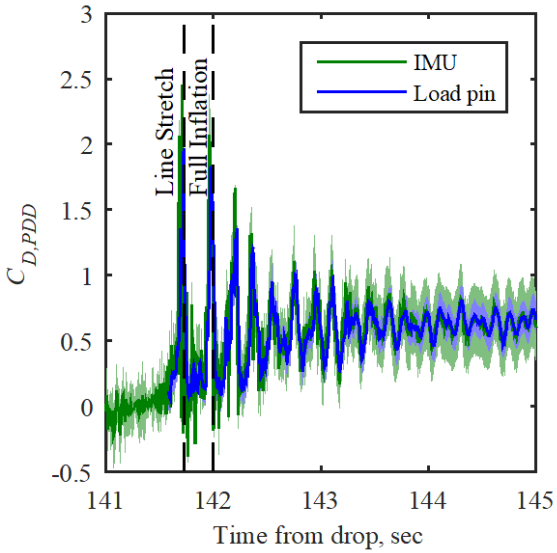
Ballute Deployment and Inflation

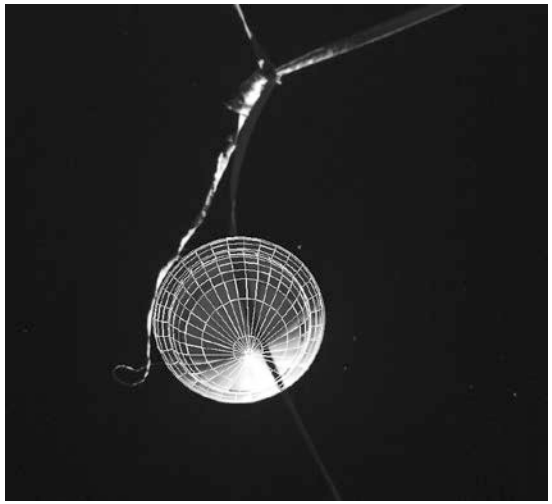
Nominal performance during deployment and inflation:

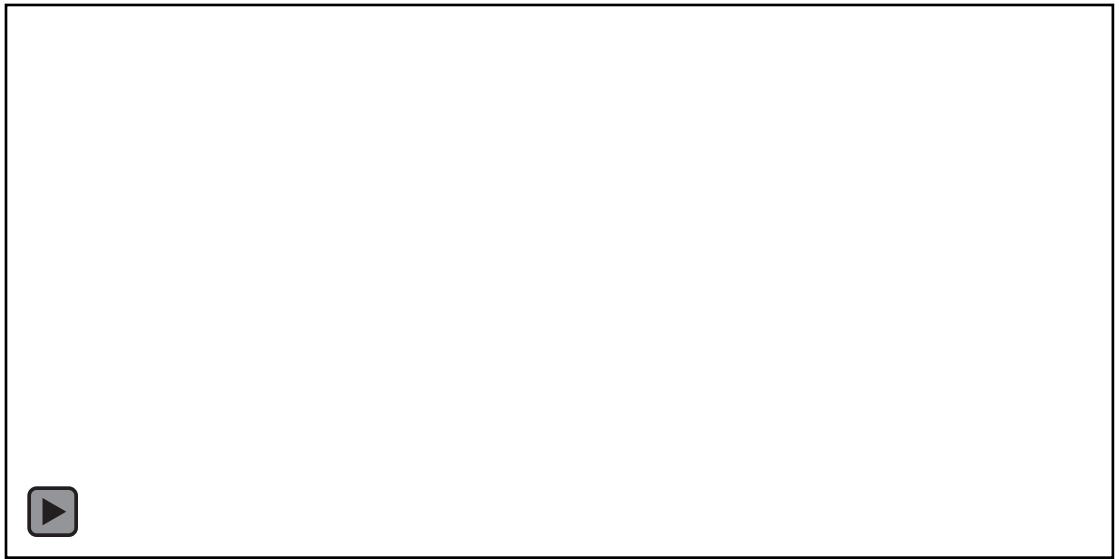
- Mortar fire:
  - M = 2.78
  - q = 493 Pa
  - Altitude 49 km
  - Muzzle velocity: 59.9 m/s (expected 57-61 m/s)
- Line-stretch 1.05 s after mortar fire
- Inflation start: ~1 s after mortar fire
- Inflation time: 0.44 s
- Inflation aid provided ~70% of internal pressure

Ballute Performance: Aerodynamics

- Ballute aerodynamic coefficients were reduced from:
  - Measured accelerations (IMU) + TV aerodatabase
  - Load cell measurements
- Ballute position wrt to TV reconstructed by fitting engineering model to footage from high-speed uplook camera
- Synchronized histories of drag coefficient and PDD position in the wake of the TV

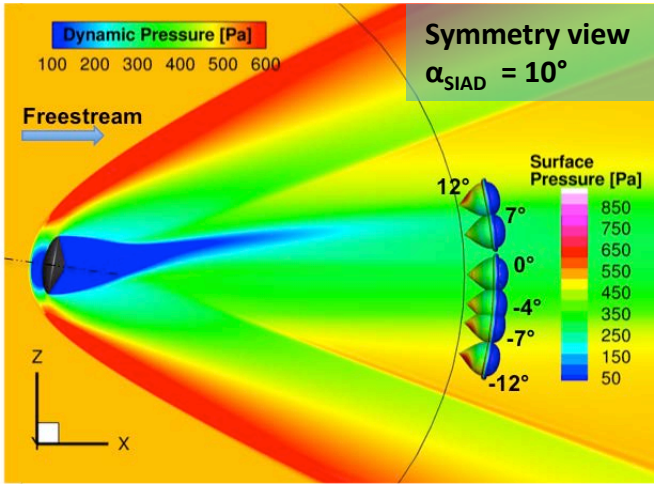


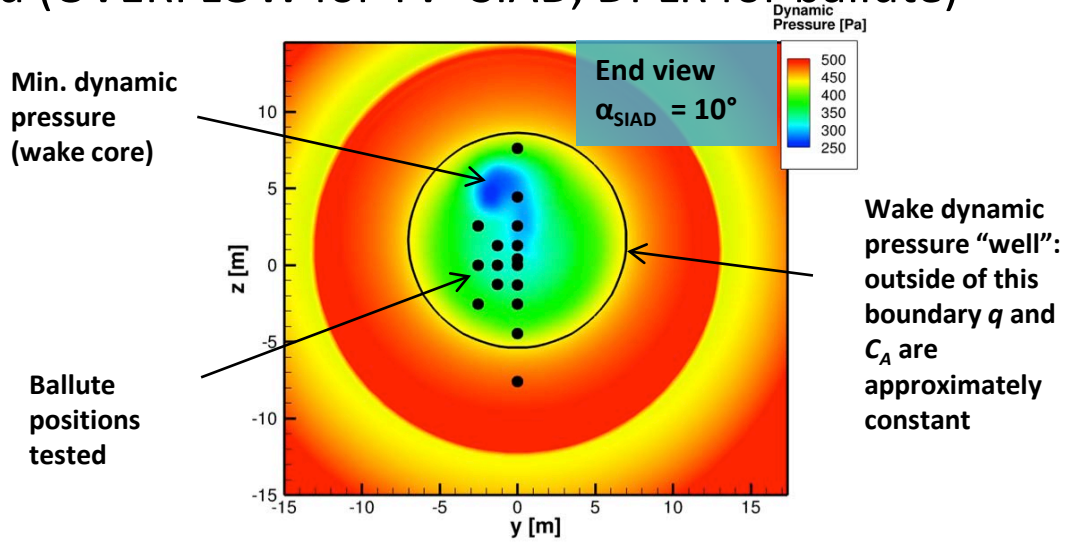




Ballute Drag Model

- Simulations at different TV angles of attack and ballute positions.
  - Two step simulation method (OVERFLOW for TV+SIAD, DPLR for ballute)

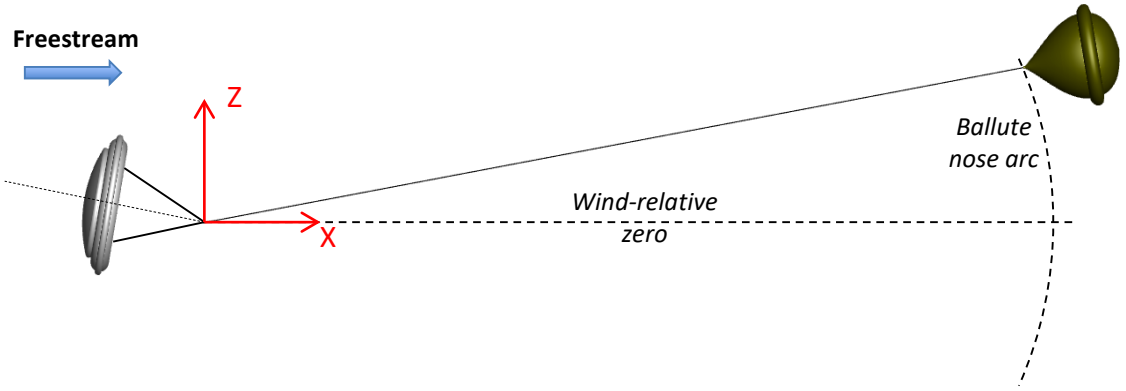


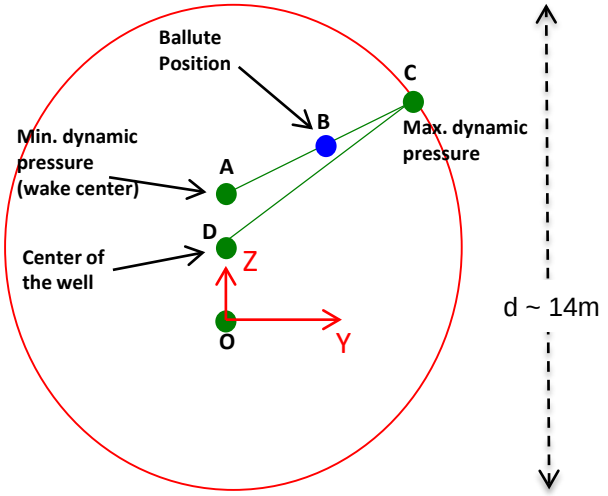


- Minimum ballute C_A occurs at the wake core
  - Value of $C_{A,min}$ depends on Mach
  - Location of wake core is a function of TV angle of attack
- Outside the well, max value of C_A is achieved:
  - Value of $C_{A,max}$ is a function of Mach
  - Diameter of the well is ~14 m at the range of Mach and angles studied

Muppidi *et al* AIAA 2015-2116

Ballute Drag Model

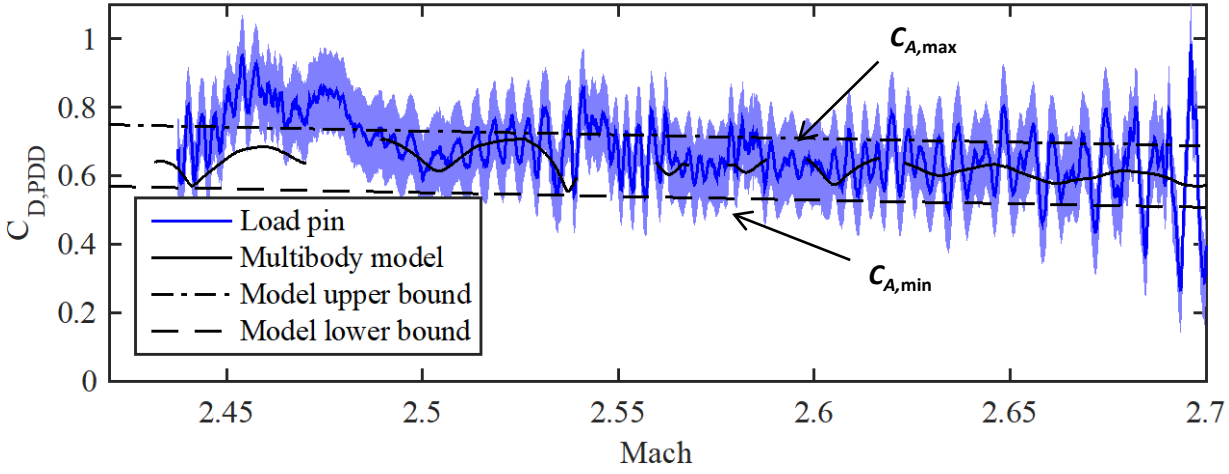




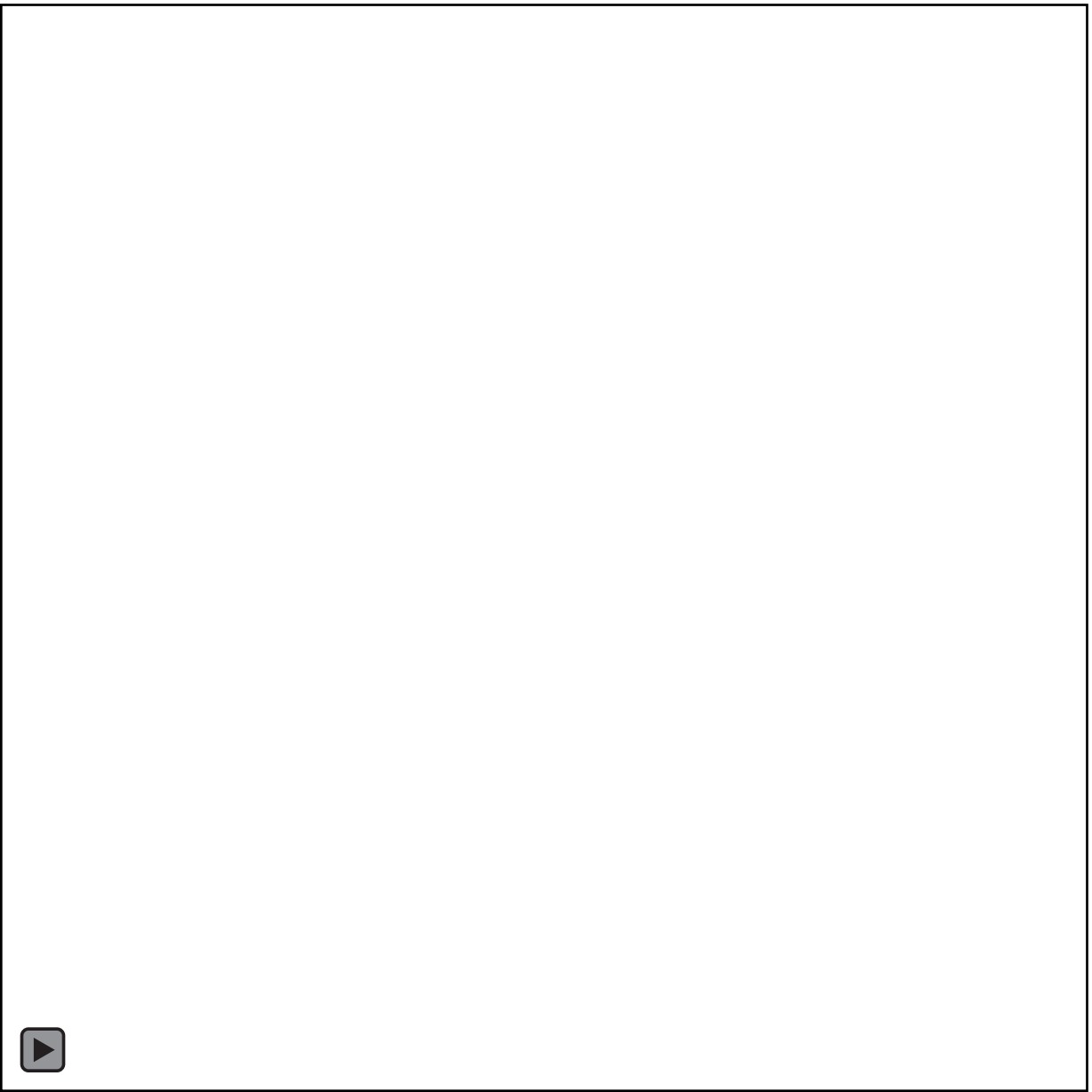
- We assume a linear variation in C_A from the minimum dynamic pressure point (A) and the edge of the dynamic pressure well (C).

$$C_{A,\text{ballute}} = C_{A,\text{min}} + (C_{A,\text{max}} - C_{A,\text{min}}) \times (AB/AC)$$

- Model agrees well with SFDT-2 flight data
- Below M = 2.5, anomaly in flight trajectory caused disagreement with model



Parachute Deployment

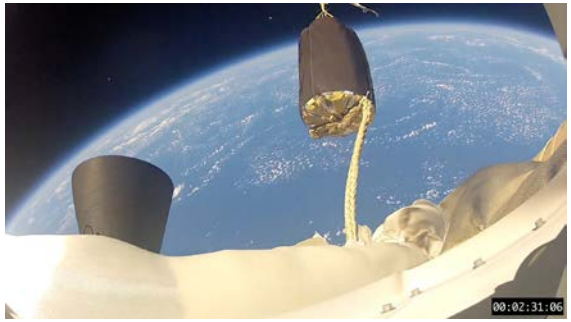


- SRRS pack extraction and deployment proceeded nominally
- Canopy inflated in 0.612 seconds
- Failure initiated just after full inflation, and propagated to the canopy vent and skirt by 0.7 s after full inflation

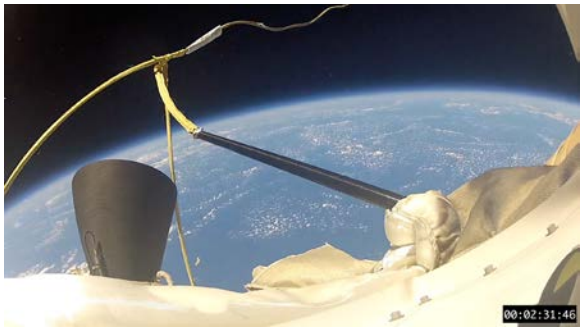
Parachute Deployment

PDD bridle cut 10 s after mortar fire

SSRS pack extracted 0.27 s after PDD cut



Triple bridle standup (0.56 s after PDD cut)



Pack mouth opened at stand-up, riser pay-out

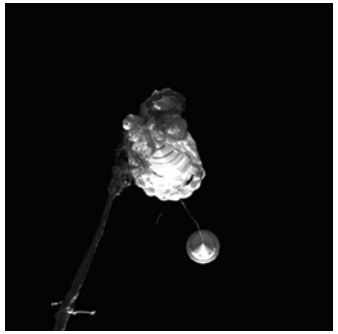
SSRS line stretch 2.18 s after PDD cut

Canopy extraction and inflation begin

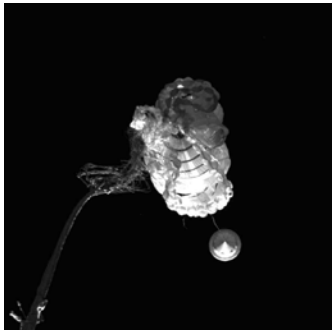
Parachute Inflation

- High speed image sequence of parachute inflation, from bag strip to the appearance of damage in the canopy (times relative to line-stretch)

0.224 s

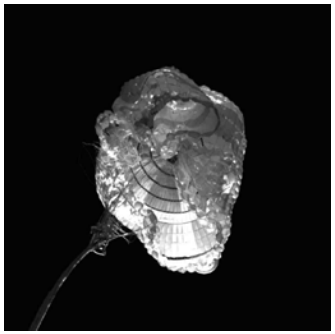


0.265 s

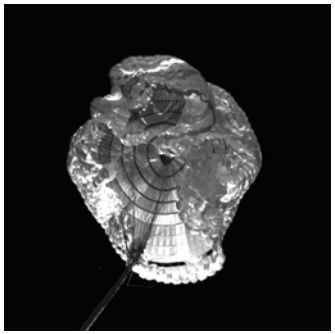


0.305 s

0.346 s

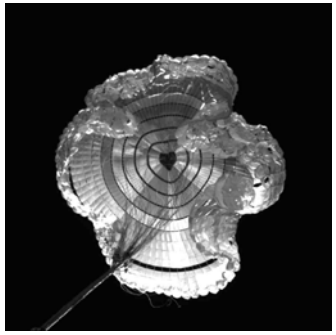


0.387 s

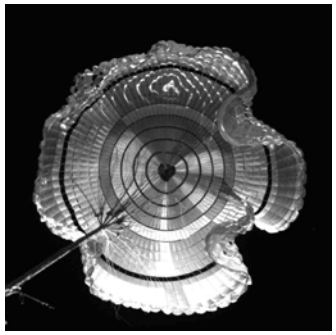


Vent is visible 0.228 s after full inflation, indicating bag strip has occurred

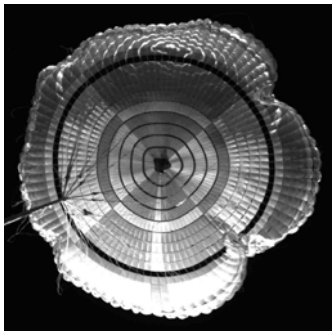
0.428 s



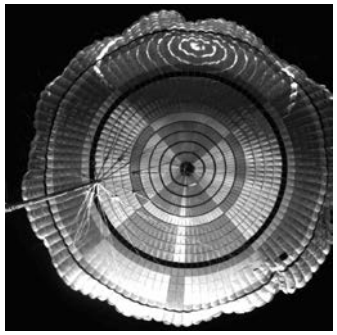
0.468 s



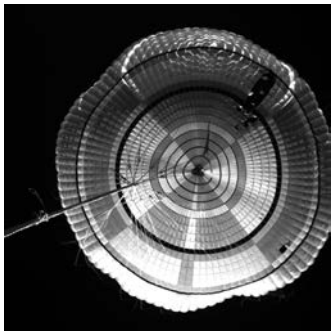
0.509 s



0.550 s



0.619 s



Damage evident just after full inflation (0.612 s after line-stretch)

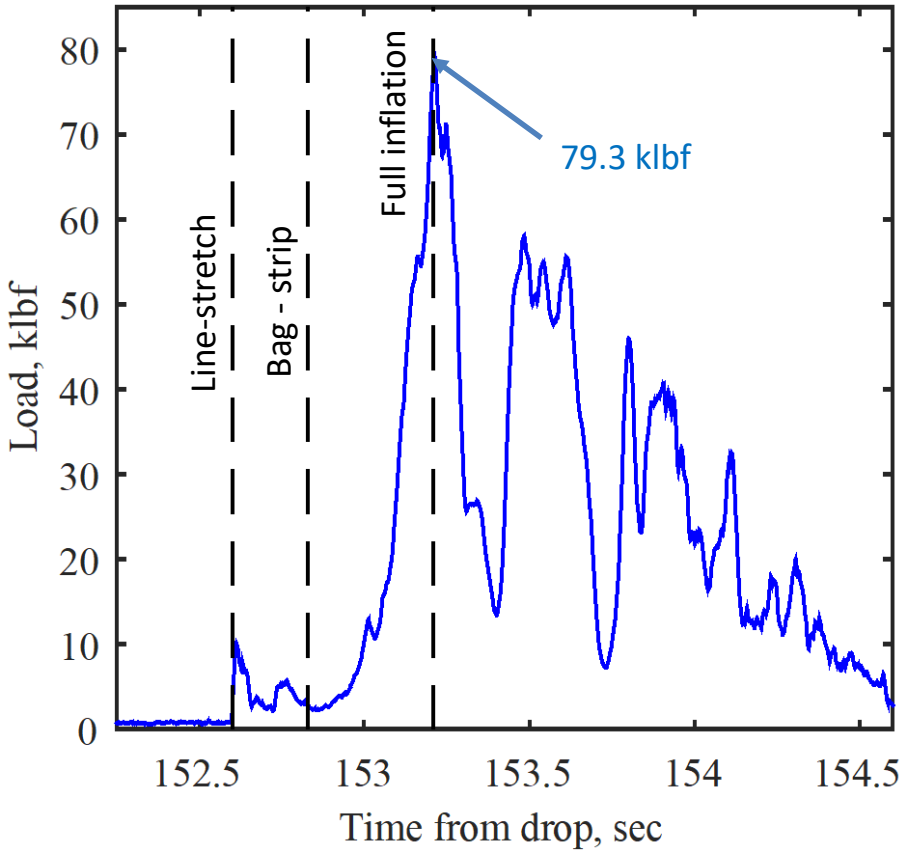
Parachute Inflation

- SSRS line-stretch was reached 2.18 s after PDD cut:
  - Mach 2.37 (Target: 2.2 to 2.5)
  - q = 602 Pa (Req't: > 240 Pa, 5%-95% Monte Carlo: 404-510 Pa)

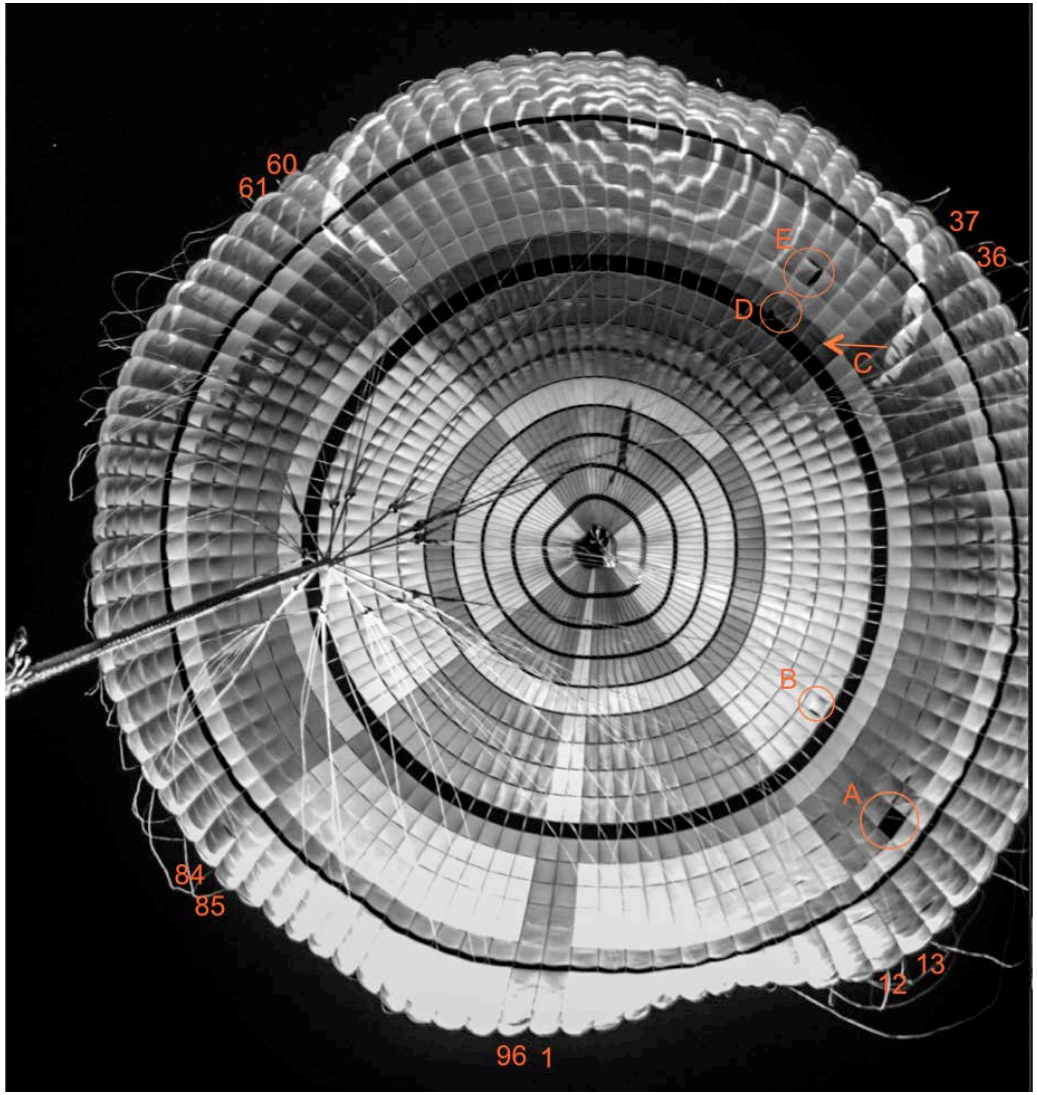
- Deployment bag was stripped by 0.228 s after line-stretch

- Load began to rise after parachute was fully out of bag

- Full inflation (time of first peak force) reached 0.612 s after line-stretch:
  - Mach 2.25
  - q = 557 Pa
  - Peak load: 79.3 klbf (352.9 kN)
  - Req't < 80 klbf
  - Canopy tested to 120 klbf



Parachute Damage Map

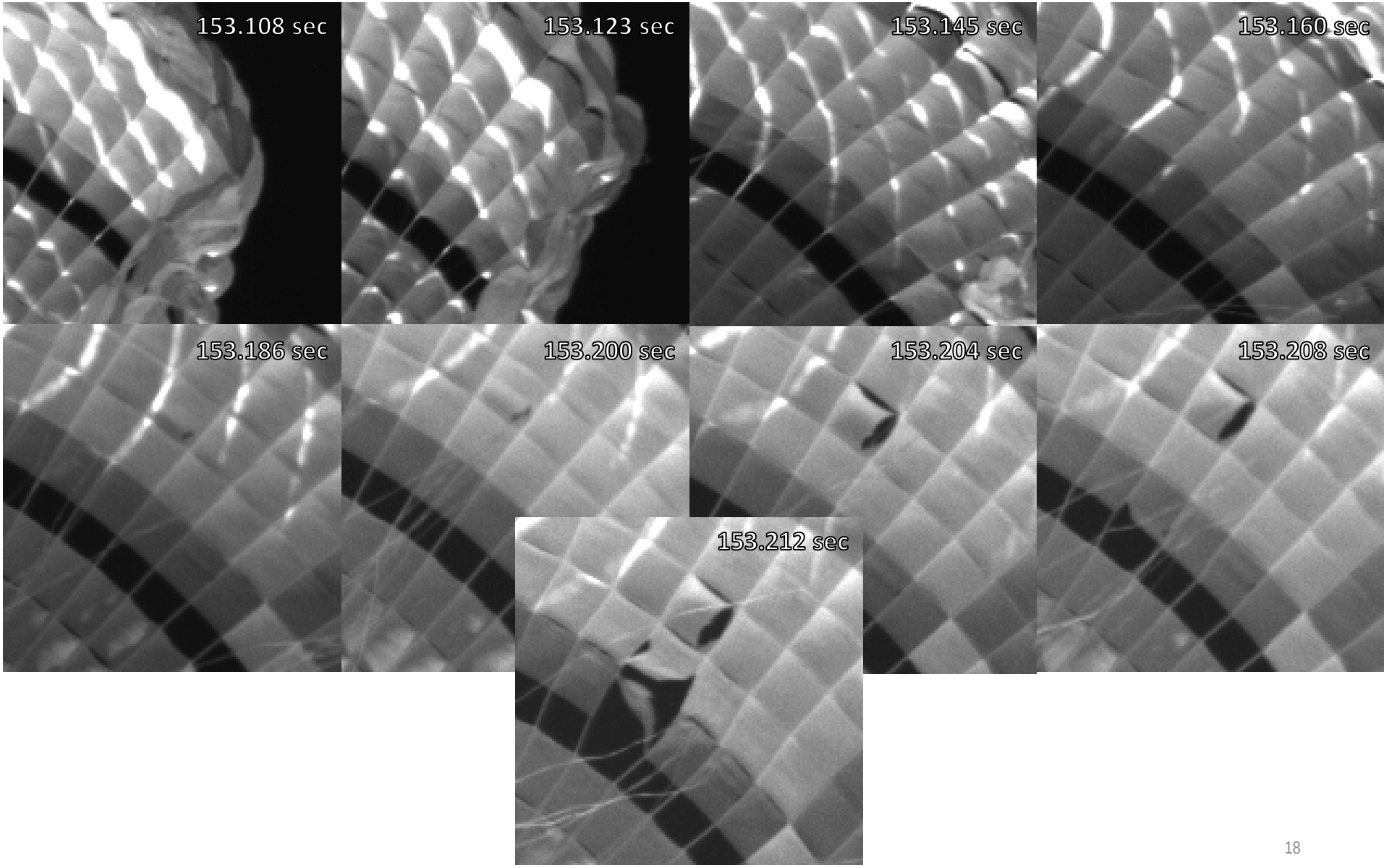


- Timing of damage during parachute inflation:

Location	Description	Time
A	Torn panel	0.560 s
B	Panel tear at main seam	0.526 s
C	Panel tear at main seam	0.534 s
D	TE tape failure	0.608 s
E	Broadcloth tear	0.508 s

- Damage at location D (gore 40, ring 10) propagated along gore and led to catastrophic failure of the canopy

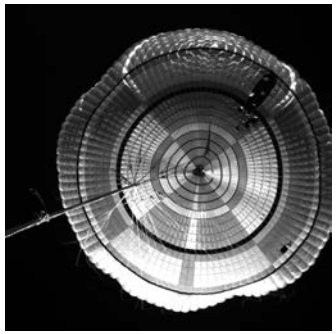
Critical Damage Progression



Parachute Failure and Damage Propagation

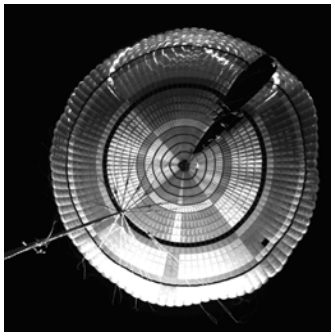
- Progression of parachute failure (times relative to line-stretch)

0.619 s

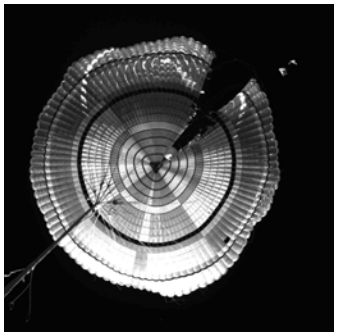


0.625 s

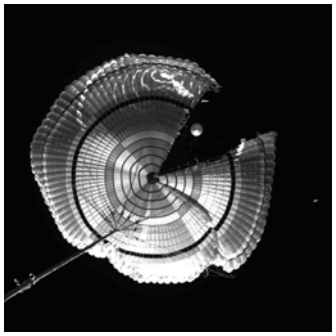
0.634 s



0.657 s

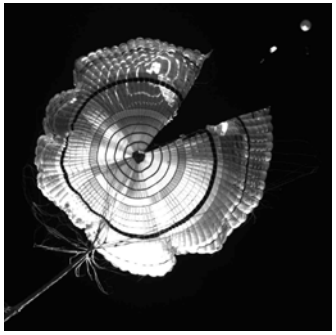


0.843 s

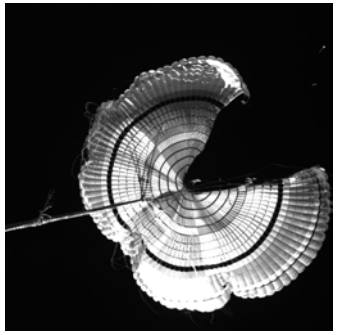


Skirt band failure at 0.656 s

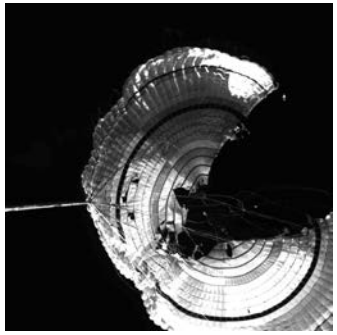
1.213 s



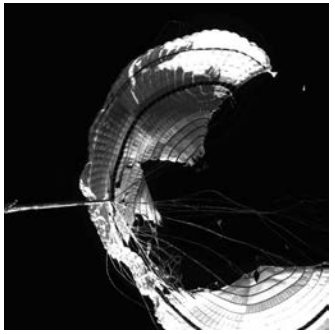
1.280 s



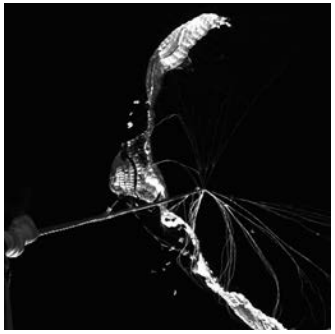
1.324 s



1.346 s



1.405 s



Parachute remains somewhat inflated until failure of the vent band

Vent band failure at 1.293 s

Parachute tears apart following the failure of the vent band

Recovery Operations

- Two vessels were dispatched to recover the vehicle, ballute, and parachute
- Ballute and parachute delivered to NSWC China Lake for inspection

Assessment of Parachute Failure

In July and August of 2015, LDSD convened a meeting of experts in the parachute community to assess the possible causes of parachute failure. Four leading hypotheses emerged:

1. Asymmetric, uncontrolled deployment led to canopy damage *prior* to inflation. Failure during inflation occurred at damaged areas.
2. Fabric and/or fluid inertia effects caused transient loads in excess of those predicted by analyses
3. Transient loading due to pressure waves during supersonic inflation resulted in regions of higher stress on the canopy
4. The strength of the Kevlar elements under dynamic loading was much lower than predicted during static testing.

Assessment of Parachute Failure

- To date, the principal cause of failure has not been identified
- LDSD undertook the following steps to determine the cause of failure, and improve the analysis of future canopy designs:

1. Carrying out dynamic strength testing of Kevlar canopy elements
2. Investigating the dynamic loads due to fabric and fluid inertia using analytical methods
3. Investigating dynamic loads on the canopy due to pressure waves using finite element methods
4. Developing instrumentation for diagnosing loads and canopy shape evolution in flight

LDSD Team at Pacific Missile Range Facility

BACKUP

INSTRUMENTATION

- Parachute instrumentation suite on SFDT-2:

Device	Manufacturer & Model	Rate	Location	Uncertainty or Field of view
IMU	NSROC GLN-MAC	400 Hz	Onboard TV	0.025 m/s^2 0.02 deg/s
PDD Load Cells (3)	Strainsert CPA-0.5-1(SS)X	1 kHz	PDD bridles	±600 N
SSRS Load Cells (3)	Strainsert CPA-0.5-1(SS)X	1 kHz	SSRS bridles	±5 kN
HS Cameras (2)	Baumer HXC40 w/ Schneider Cinegon lens	135 fps	Aft-pointed	38°x38°
HR Cameras (2)	Baumer SXC80 w/ Schneider Xenoplan lens	16 fps	Aft-pointed	48°x37°
Situational Video (2)	GoPro Hero2	30 fps	Aft-pointed	69.5°x118.2°
Stereo Video (2)	GoPro Hero4 w/ Schneider Cinegon lens	30 fps	Aft-pointed	21°x16°

- Atmosphere characterized using:
  - Meteorological balloons carrying Radiosondes (2)
  - Sounding-rocket-deployed ROBIN spheres (4)

BALLUTE INFLATION AID

- Inflation aid located at the ballute nose provides initial inflation gas
- Liquid water-methanol mixture is vaporized by sudden expansion
- Ballute and inflation aid are heated to provide sufficient enthalpy for inflation
  - Target temperature: 40 deg C at mortar fire
  - Ballute mortar tube heated to 84 deg C over 36 hours preceding flight
- At mortar fire, inflation aid temperature estimated to be 35 deg C based on thermocouple data
- The inflation gas was estimated to provide 422.6 Pa (70% of inflation *p*) assuming ideal gas behavior:

$$p = \frac{Q_{avail}}{H_{v_m}} R_m \frac{T_{sat,m}}{V_b}$$

Where Q_{avail} is the energy available for vaporization (from Kevlar, Al, methanol, water), H_{vm} is the heat of vaporization of methanol, $T_{sat,m}$ is the saturation temp for methanol, R_m is the gas constant, and V_b is the volume of the ballute

Thompson *et al* AIAA 2015-2115

METHODS

Aerodynamic forces on the PDD and SSRS were determined using two separate methods

1. Direct measurement of parachute/ballute loads at the triple bridle attachment points

$$F_{PDDx} = -F_1 \sin\theta_1 - F_2 \sin\theta_2 - F_3 \sin\theta_3$$
$$F_{PDDy} = -F_1 \cos\theta_1 \sin\phi_1 - F_2 \cos\theta_2 \sin\phi_2 - F_3 \cos\theta_3 \sin\phi_3$$
$$F_{PDDz} = -F_1 \cos\theta_1 \cos\phi_1 - F_2 \cos\theta_2 \cos\phi_2 - F_3 \cos\theta_3 \cos\phi_3$$

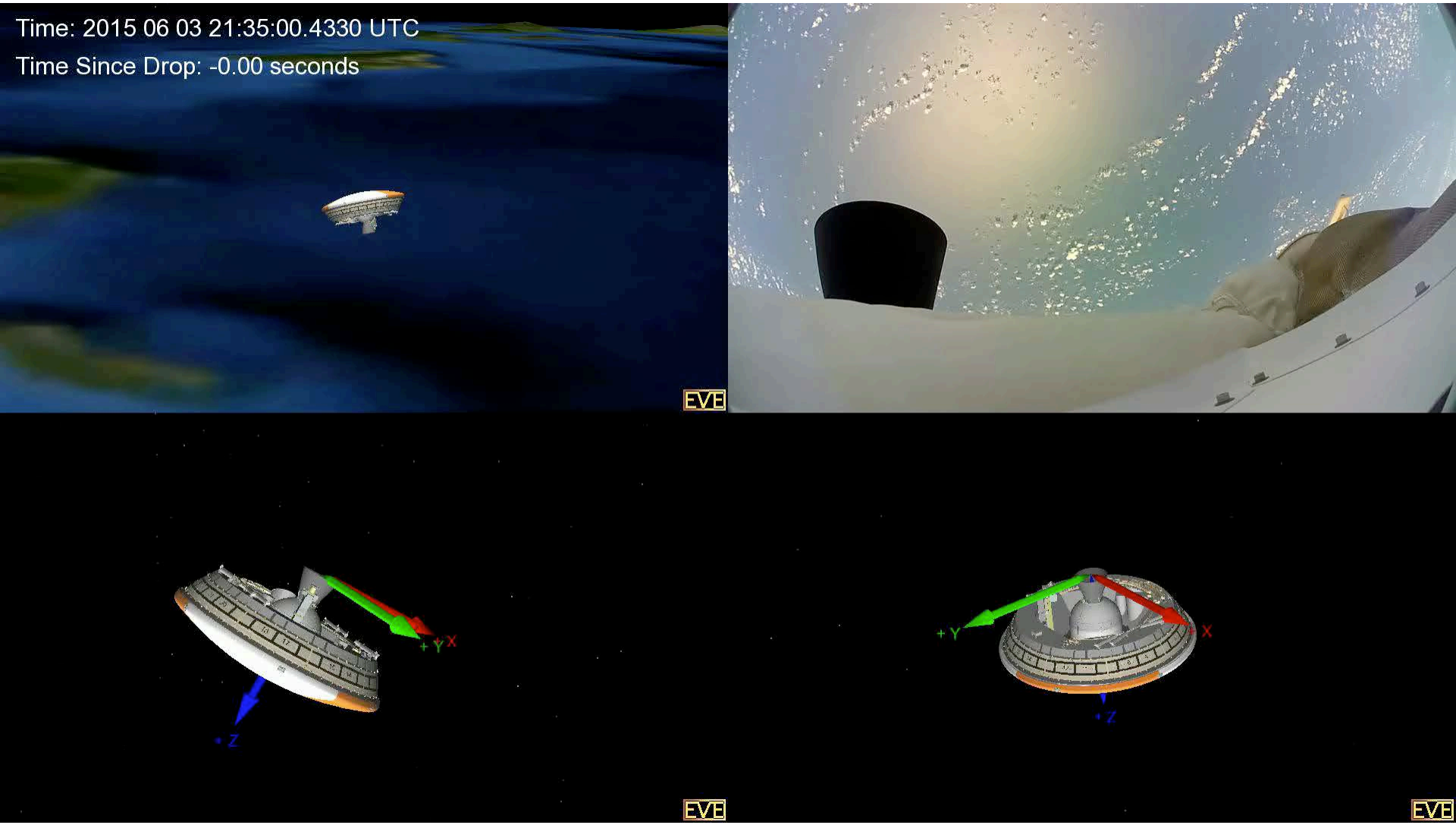
   - F_i : load cell measurements
   - θ_i : bridle leg angle from the verical
   - ϕ_i : clock angle of bridle attachment locations

2. Subtracting the contributions of the TV+SIAD from the measured accelerations:

$$F_{PDDx} = ma_x - q_1 S_S C_{AS}$$
$$F_{PDDy} = ma_y - q_1 S_S C_{YS}$$
$$F_{PDDz} = ma_z - q_1 S_S C_{NS}$$

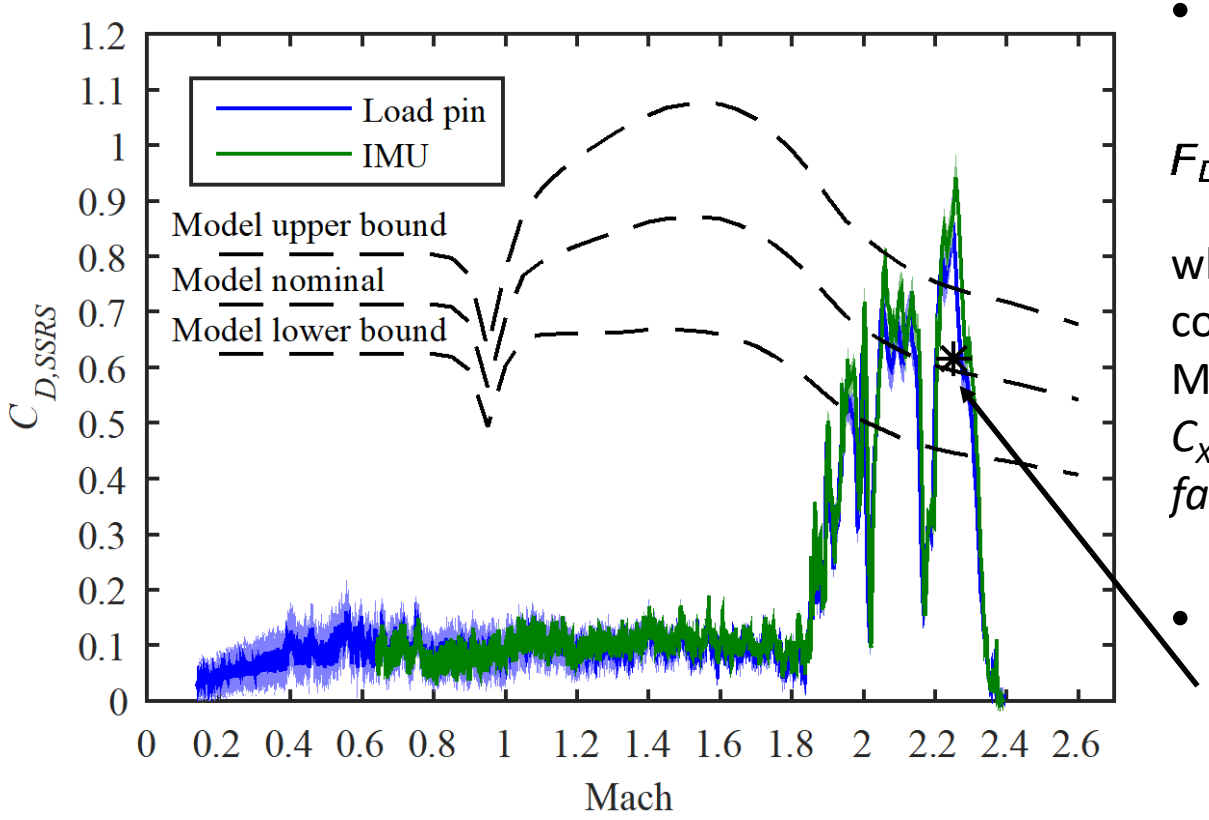
   - m : system mass
   - ai : TV accelerations
   - S : TV+SIAD reference area
   - CiS : TV+SIAD aerodynamic coeffs

A Bump in the Night



PARACHUTE AERODYNAMICS

- SSRS aerodynamic coefficients were reduced from:
  - Measured accelerations (IMU) + TV aerodatabase
  - Load cell measurements
- Prior to failure, *CD* on the order of pre-flight predictions



- Peak force at full inflation is customarily modeled using:

$$F_{D,SSRS} = qS_0C_{D,SSRS}(M_{deploy})C_X$$

where $C_{D,SSRS}$ is the drag coefficient at the deployment Mach number

C_X = 1.407 is an *opening load factor*

- Estimate $C_{D,SSRS}$ using:

$$C_{D,SSRS} \approx \frac{F_{D,SSRS}}{qS_0C_X}$$