Jet Propulsion Laboratory
California Institute of Technology

Reconstructed DGB Performance During the ASPIRE SR01& SR02 Supersonic Flight Tests

15th International Planetary Probes Workshop

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ASPIRE

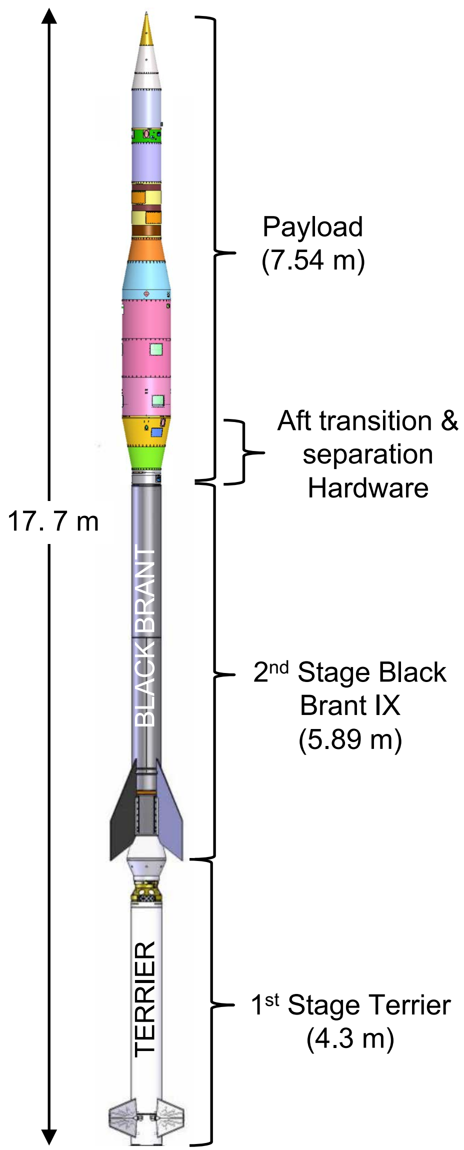
The ASPIRE Project

- **A**dvanced **S**upersonic **P**arachute **I**nflation **R**esearch **E**xperiments Project Objectives:
  - Develop testing capability for supersonic parachutes at Mars-relevant conditions.
  - Deliver 21.5m parachutes to low-density, supersonic conditions on a sounding rocket test platform
  - Acquire data sufficient to characterize flight environment, loads, and performance
- Initial flights focused on testing candidate designs for Mars2020:
  - Built-to-print Mars Science Laboratory (MSL) DGB
  - Strengthened version of MSL DGB (identical geometry, stronger materials)

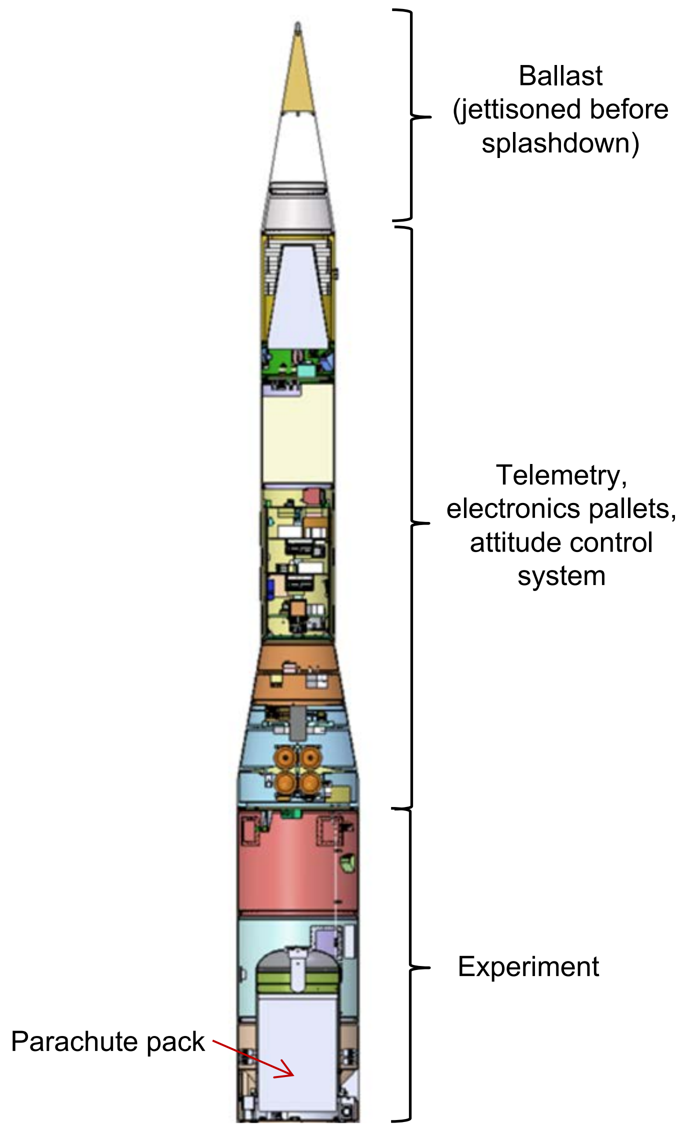
	Parachute	Load	Purpose	Test Date
SR01	MSL built-to-print	35 klbf (MSL @ Mars)	Test architecture shakeout. Ensure test approach doesn't introduce new parameters.	Oct. 4th, 2017
SR02	Strengthened	47 klbf	Incremental strength test of new design.	Mar. 31th, 2018
SR03	Strengthened	70 klbf	Strength test of new design	July 2018
SR04	Strengthened	TBD	TBD	TBD

Test Architecture

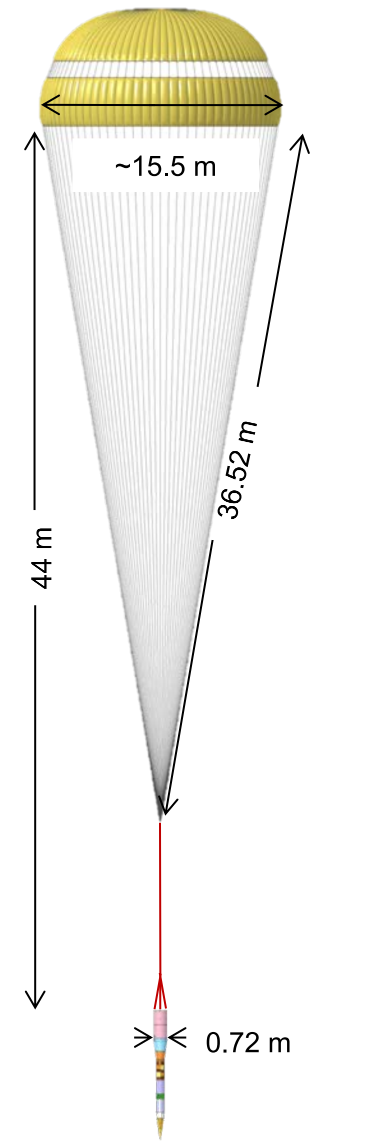
Launch Configuration



Start of Experiment Phase



Parachute Deployed Configuration



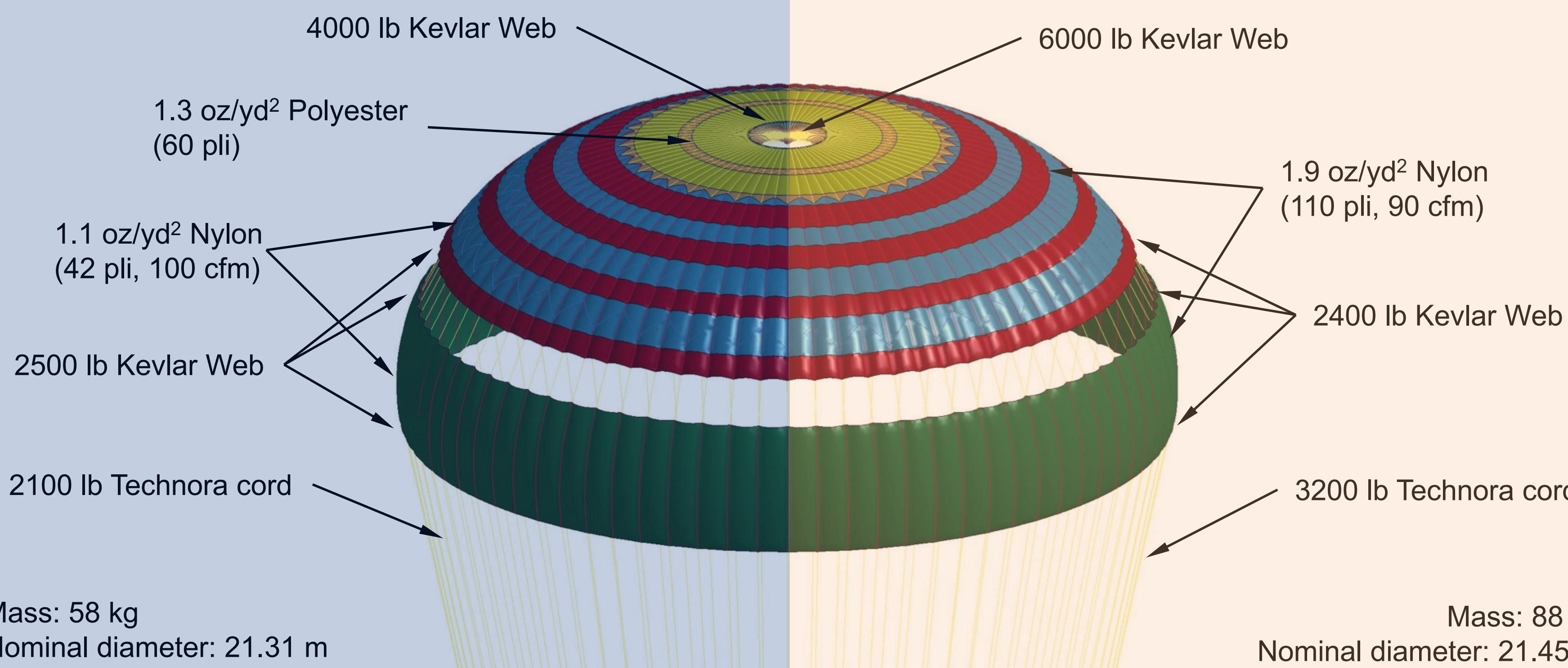
Test Articles

SR01
Target load: 35 klbf

SR02
Target load: 47 klbf

M2020 Built-to-Print

M2020 Strengthened



Mass: 58 kg
Nominal diameter: 21.31 m
Geometric porosity: 12.8%

Mass: 88 kg
Nominal diameter: 21.45 m
Geometric porosity: 12.8%

Test Conditions

SR01

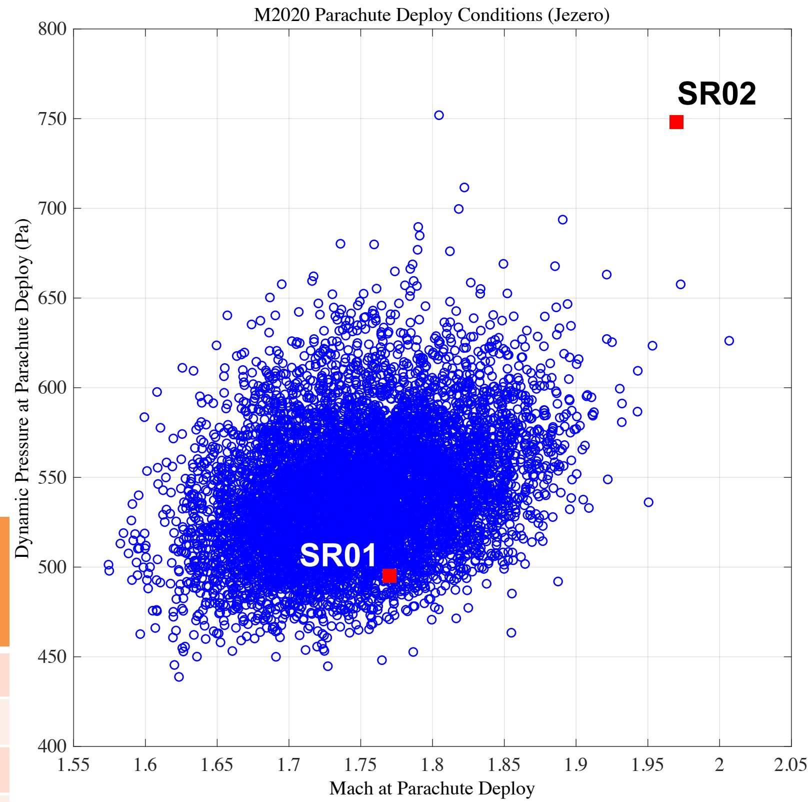
Target mortar fire conditions: Mach = 1.74 *q* = 438 Pa
Target peak load *q* = 473 Pa (MSL @ Mars)

Event	Time from launch (sec)	Mach	Dynamic pressure (Pa)	Geodetic altitude (km)	Total angle of attack (deg)
Apogee	119.04	1.19	66	51.0	2.1
Mortar Fire	161.41	1.77	453	42.4	0.5
Line Stretch	162.37	1.79	492	42.0	0.6
Peak Load	162.88	1.77	495	41.8	0.8
Mach 1.4	164.36	1.4	332	41.3	6.0 (max)
Mach 1.0	167.02	1	188	40.5	6.9 (max)

SR02

Target mortar fire conditions: Mach = 1.72 *q* = 618 Pa
Target peak load *q* = 678 Pa

Event	Time from launch (sec)	Mach	Dynamic pressure (Pa)	Geodetic altitude (km)	Total angle of attack (deg)
Apogee	123.48	1.10	33	54.8	4.0
Mortar Fire	177.59	1.97	667	40.8	1.9
Line Stretch	178.63	2.00	746	40.3	2.3
Peak Load	162.08	1.97	748	40.0	1.0
Mach 1.4	180.72	1.4	417	39.3	16.2 (max)
Mach 1.0	182.86	1	234	38.6	16.8 (max)



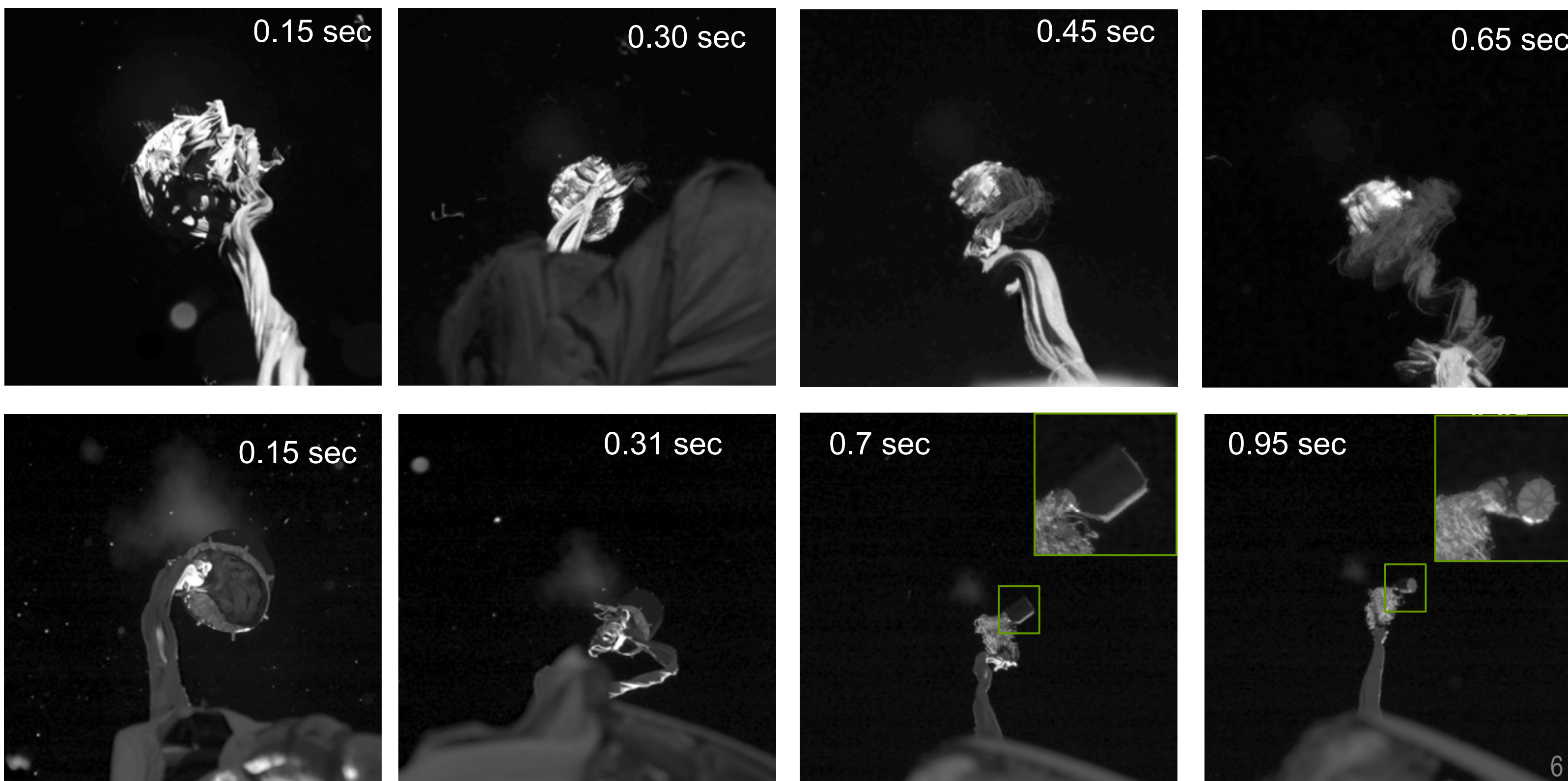
Parachute Deployment

- Lower mortar velocity on SR02
- Orderly deployment, no line entanglement
- No rotation of parachute pack on SR01; ~135° rotation on SR02

	SR01	SR02
Mortar exit velocity (flight)	48.5 m/s	46.7 m/s
Effective ground velocity (flight)	45.7 m/s	43.2 m/s
Mortar velocity (predicted)	45 m/s	44 m/s
Time to line-stretch (flight)	0.96 sec	1.04 sec
Time to line-stretch (predicted)	0.98 sec	0.98 sec

SR01

SR02



Times are from mortar fire

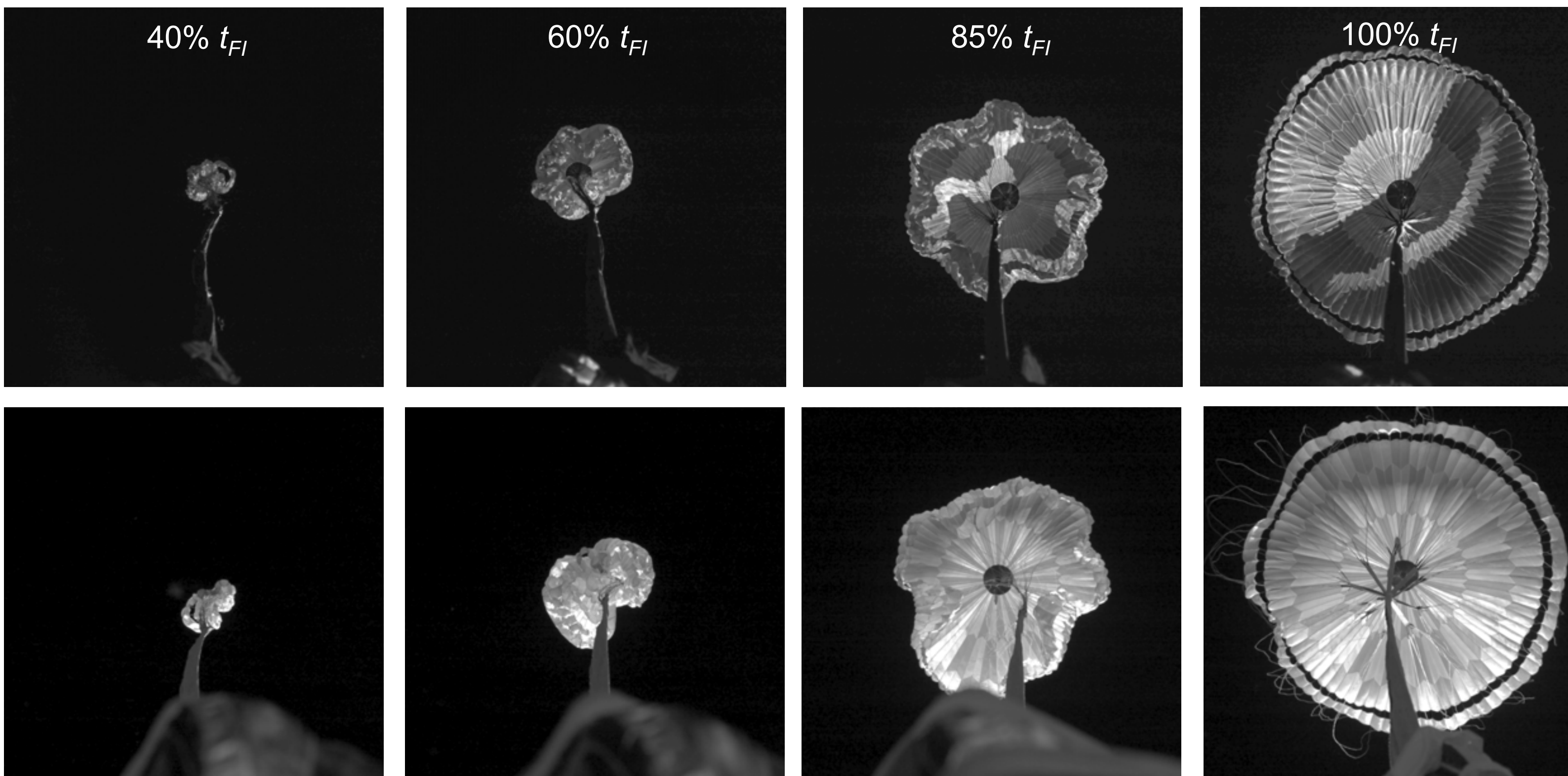
Parachute Inflation

- Inflation predicted by *inflation distance* model:
  $$\frac{L_{inf}}{D_0} = \alpha\left(\frac{\rho_c}{\rho_\infty}\right)$$
- Portion of the band leads inflation; stalls
- SR01 inflation remarkably symmetric; SR02 less so
- Vent band remains circular, suggesting symmetric radial loading
- After full area, moderate collapse. On SR01 extends to disk; less symmetric

	MSL	SR01	SR02
Inflation time (sec)	0.635	0.506	0.456
α	4.6	5.15	4.65

SR01

SR02



Peak Load

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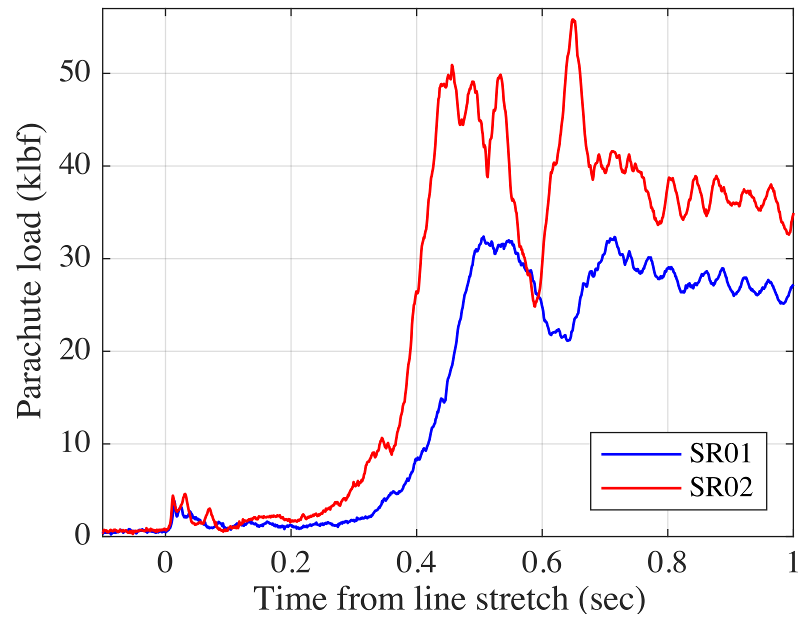
- Faster inflation & steeper load rise on SR02
- Oscillations around peak before collapse
- Partial collapse & re-inflation after peak load
- 2nd peak was larger than 1st peak on SR02
- Force oscillations were larger than projected area oscillations
- Force oscillations w/frequency ~20 Hz starting 0.7 sec after line stretch.
    - Close to system frequency due to elasticity in rigging



- Considering the conservation of momentum inside a control volume around the inflating canopy:

$$F_{peak} = k_p(2q_\infty S_p)$$

k_p = fraction of the fluid momentum converted to parachute drag

	MSL	SR01		SR02	
		1st peak	2nd peak	1st peak	2nd peak
Load (klbf)	35	32.4	32.3	50.9	55.8
k_p	0.83	0.77	0.79	0.78	0.93

Parachute Aerodynamics

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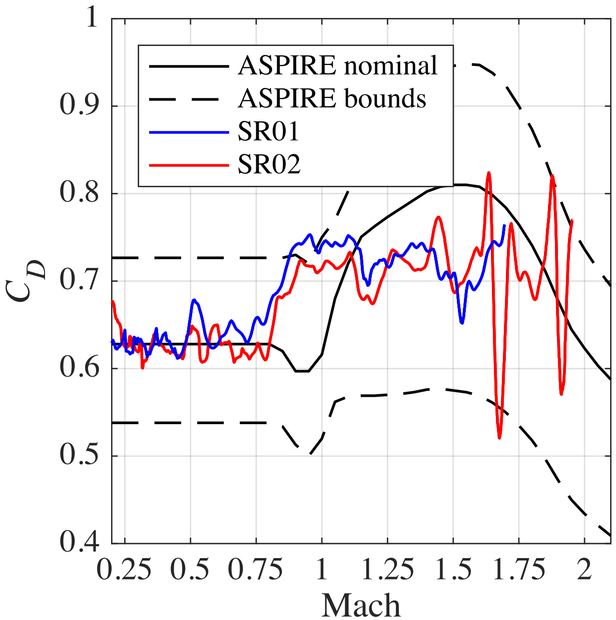
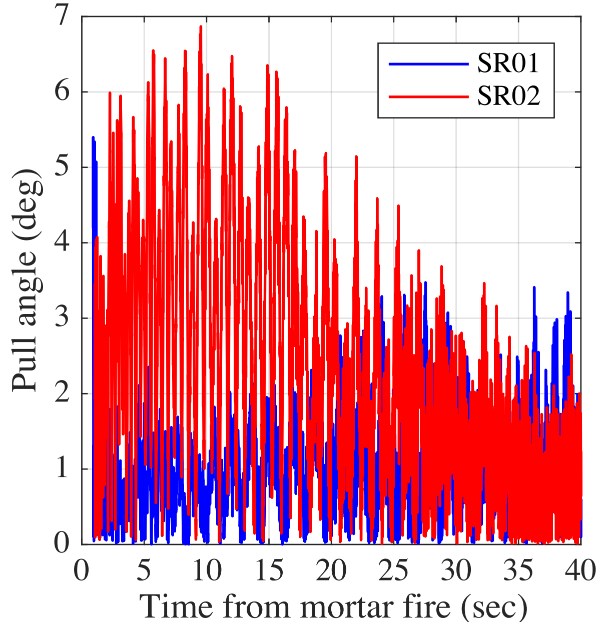
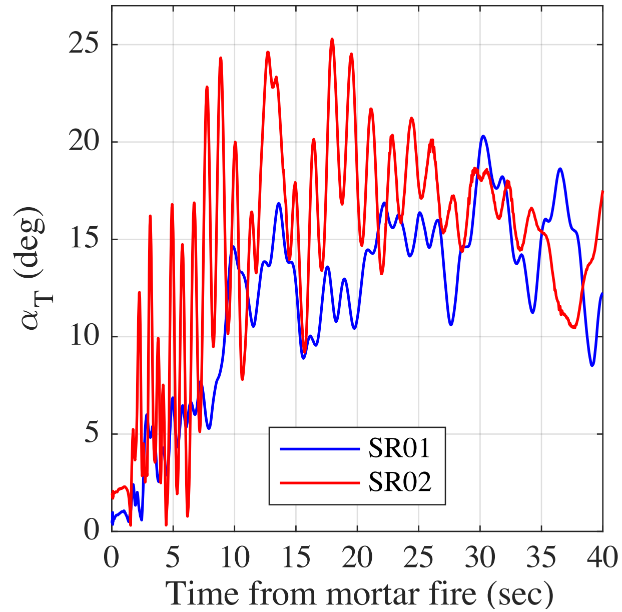






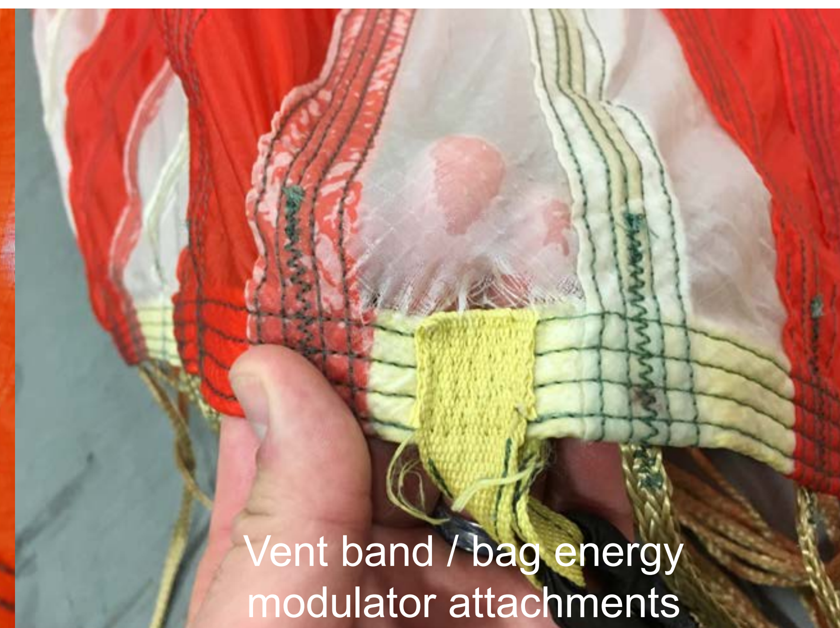
- Pre-flight C_D model based on MSL w/corrections for slender-body wake
- C_D vs Mach behavior on SR01 & SR02 very similar
- Good agreement with C_D model below M = 0.75 , but over-estimated C_D for M >1.15
- C_D remained constant in transonic region
- Parachute force vector “pull angle” larger on SR02, but remained below required 10 deg
- Wind-relative total angle of attack oscillated about 15 deg for the majority of the flight

Post-Flight Inspection

- Damage to parachute was minimal on both SR01 & SR02
- Damage on SR02 appears to be mostly deployment related & caused by interaction with the bag or friction between adjacent surfaces
- Damage was *very* minimal on SR01 & deemed recovery-related at the time. Insights from SR02 suggest some SR01 damage may be deployment related
- Some damage to vent band on SR02 at deployment bag attachment

Gore 40
band trailing edge

Gore 39
band trailing edge



Vent band / bag energy modulator attachments

Conclusions & Future Work

- SR01 & SR02 were extremely successful
- Ongoing work:
  - 3D canopy shape reconstruction from stereo videography
  - Investigate supersonic C_D: CFD with flight-like conditions & geometry
  - Static aerodynamic coefficients & parachute/payload dynamics
- SR03 launch window opens July 24:
  - Strengthened DGB canopy w/ 70 klbf target load
  - Minor changes to parachute packing & rigging

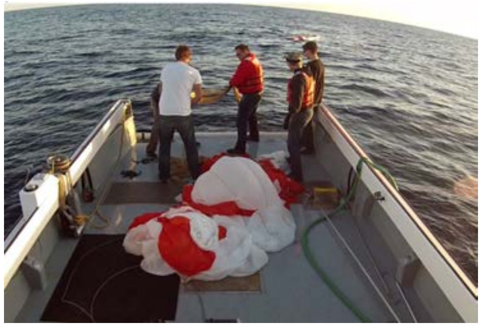


Image: Assateague Island National Seashore

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Backup

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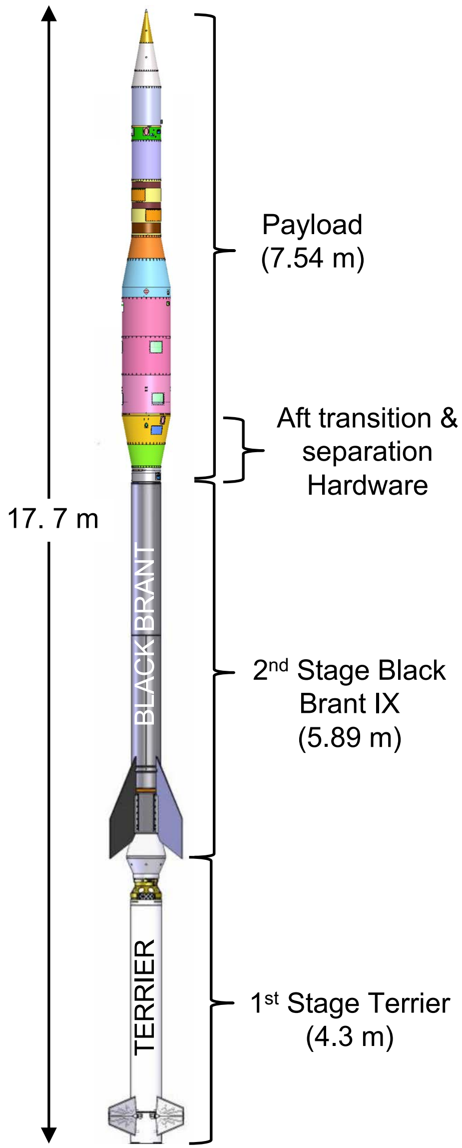
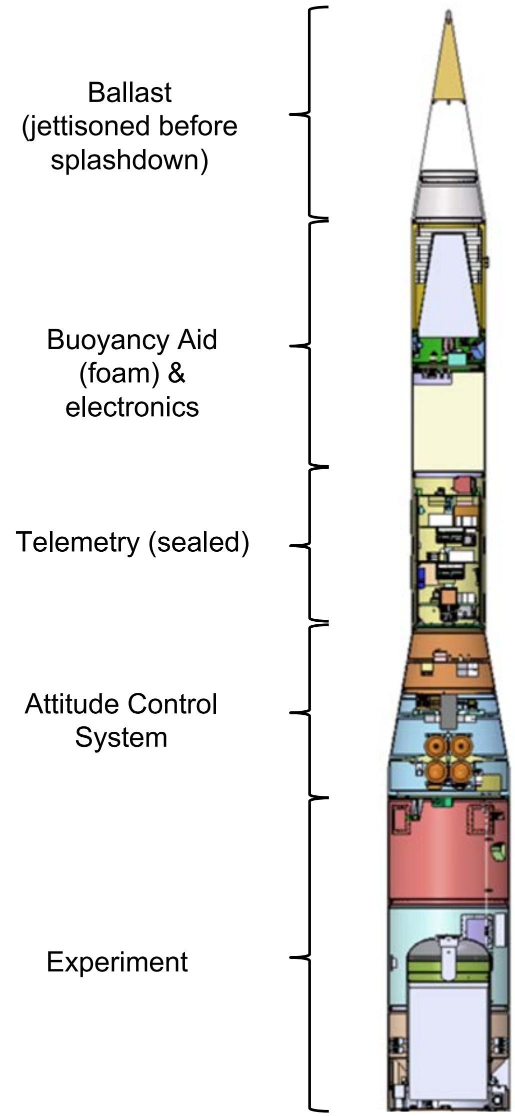
Test Architecture



- Rail-launched Terrier Black Brant
- Spin-stabilized at 4 Hz
- Yo-yo de-spin after 2nd stage burnout
- Mortar-deployed full-scale DGB
- Cold gas ACS active from payload separation to before mortar fire
- Recovery aids:
  - Foam provides buoyancy
  - Nosecone ballast (for additional mass & aerodynamic stability) is jettisoned before splashdown
- Payload mass:
  - Launch: 1268 kg
  - Post-separation: 1157 kg
  - Splashdown: 495 kg



SR01 Flight Sequence

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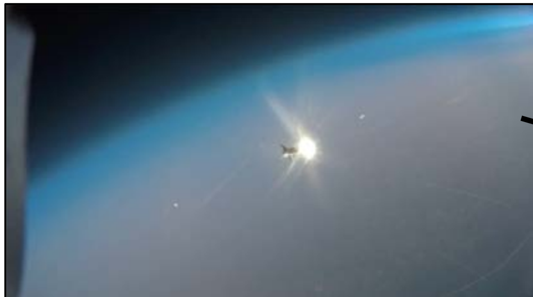
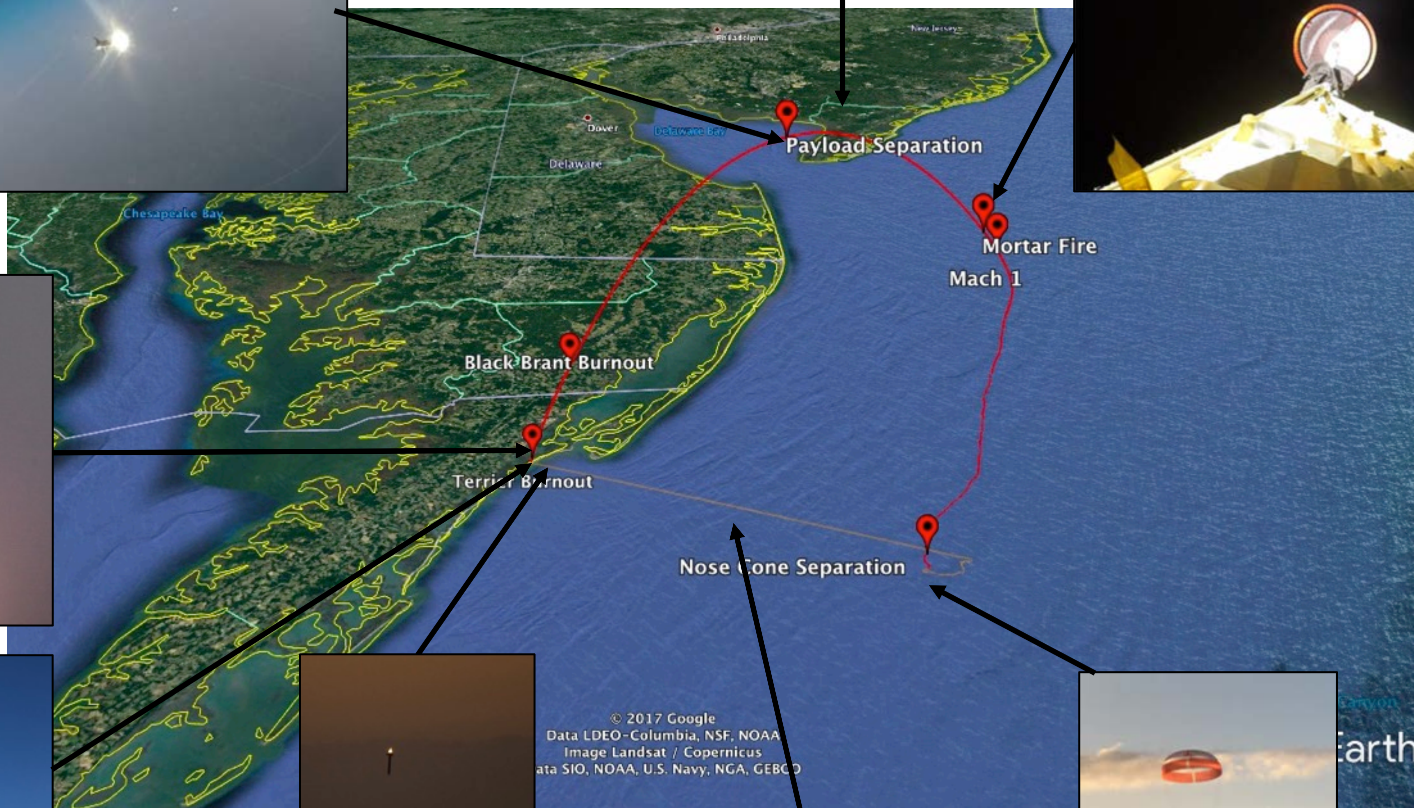
Apogee
L+119 s (51 km)

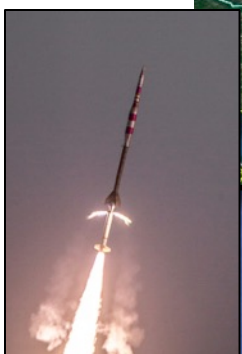




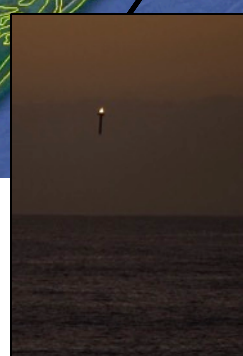
Mortar Fire
L+161 s
Alt: 42 km
q_∞: 453 Pa
Mach: 1.77

Peak Load
MF +1.47 s
q_∞: 495 Pa
Mach: 1.77

Nosecone sep.
L + ~26 min
Alt: 3 km

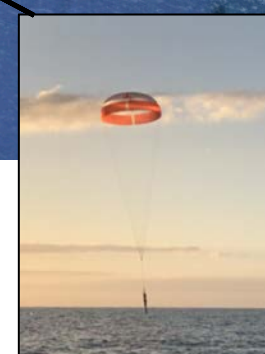


Launch 6:45 EDT.
Wallops Island, VA



1st stage burnout
L+6.2 s (1 km)

Range
55 km



Splashdown
L + ~24 min

SR01 Atmosphere

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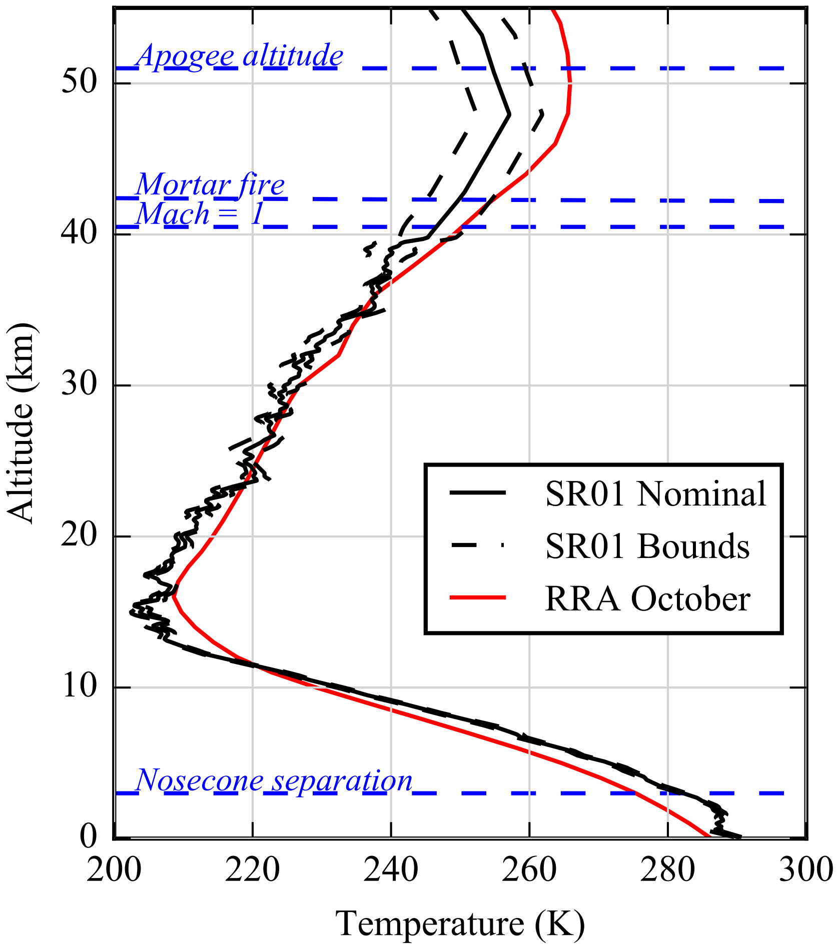
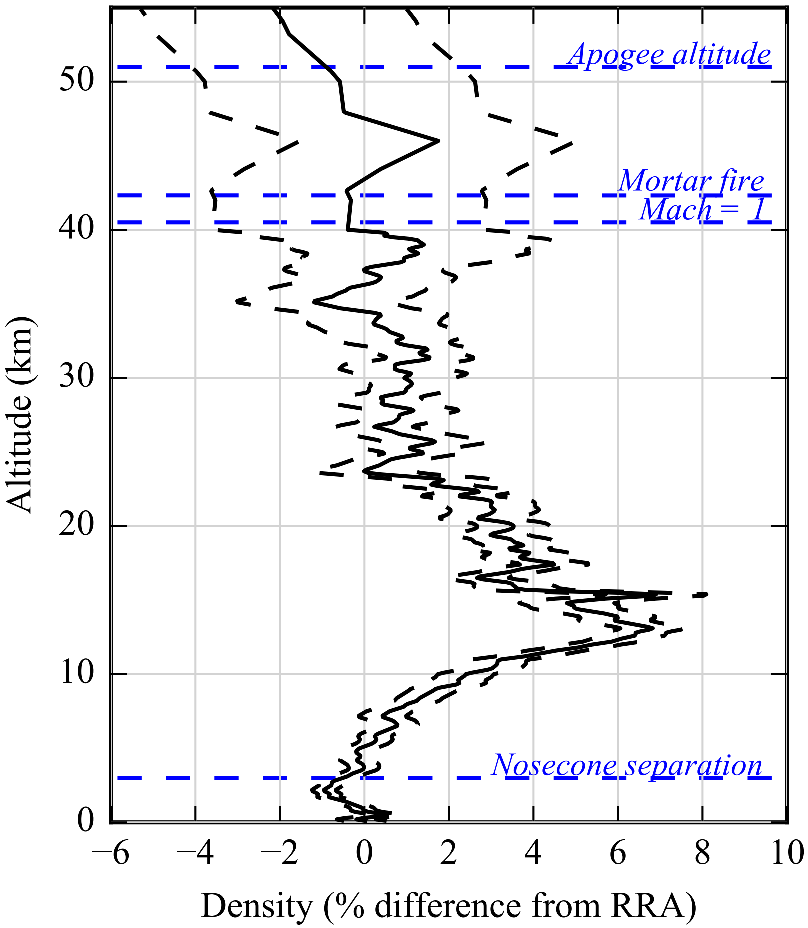
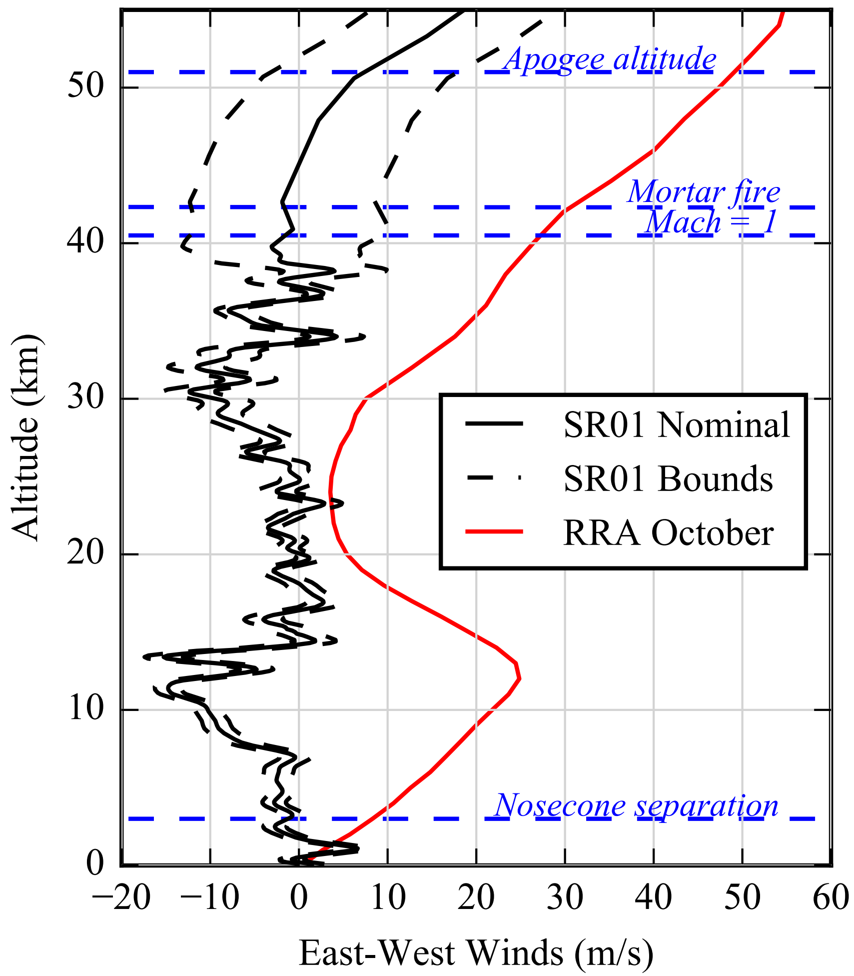
- 4x meteorological balloons carrying radiosondes:
  - He-filled 3000g latex balloon (Totex TA3000)
  - Launched at L-3 hrs, L-2:15 hrs, L-1:45 hrs, L-1 hrs, 120 minute ascent time
  - Min. burst altitude: 35 km, Max. burst altitude: 39.9 km
  - LMS-6 radiosonde: chip thermistor, capacitive humidity sensor, GPS
- GEOS-5:
  - Real-time analysis generated by GMAO @ GSFC 75 min after launch
  - Winds, density, temperature pressure from 0 to 65 km
  - Excellent agreement w/Radiosonde mean, but does not capture small-scale variations
- Below 40 km:
  - Nominal based on L-1:45 radiosonde
  - Uncertainties based on measurement error + variation among radiosondes
- Above 40 km:
  - Nominal based on GEOS
  - Uncertainties based on max. observed difference between Radiosondes & GEOS
- L-0 atmosphere was atypical for October:
  - Almost no East-West wind
  - Slightly colder (and denser) atmosphere than expected

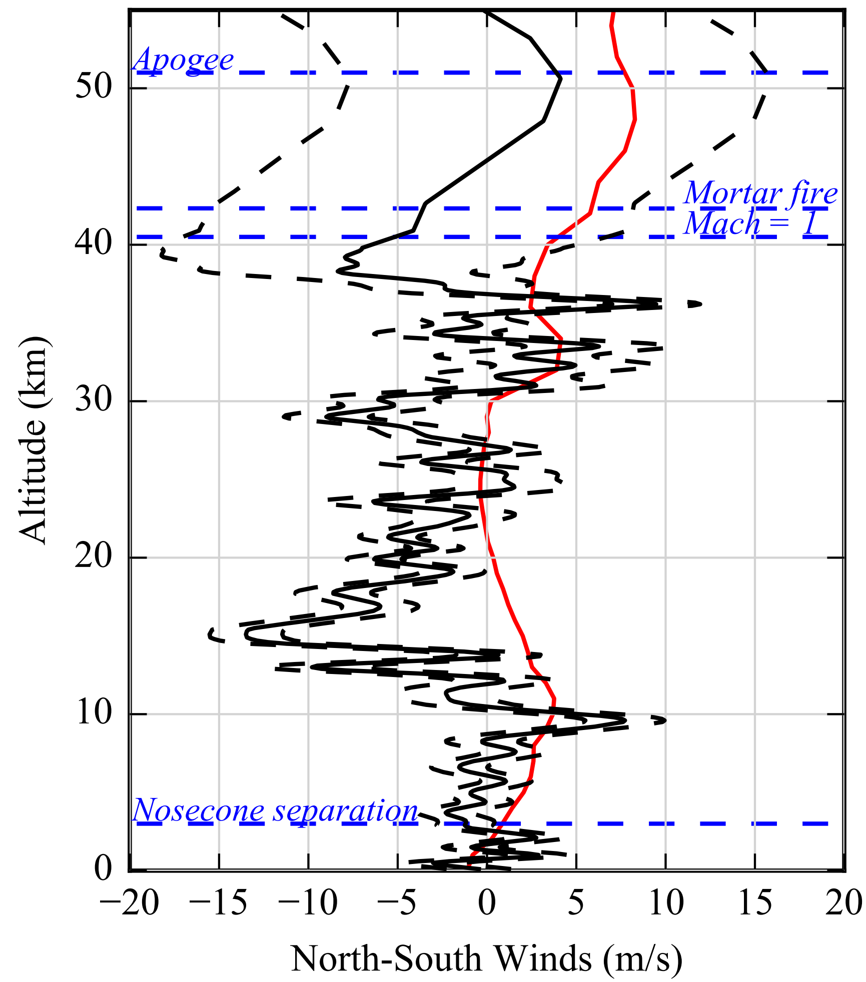
Atmosphere Reconstruction





Atmosphere Reconstruction





Parachute-Payload Dynamics

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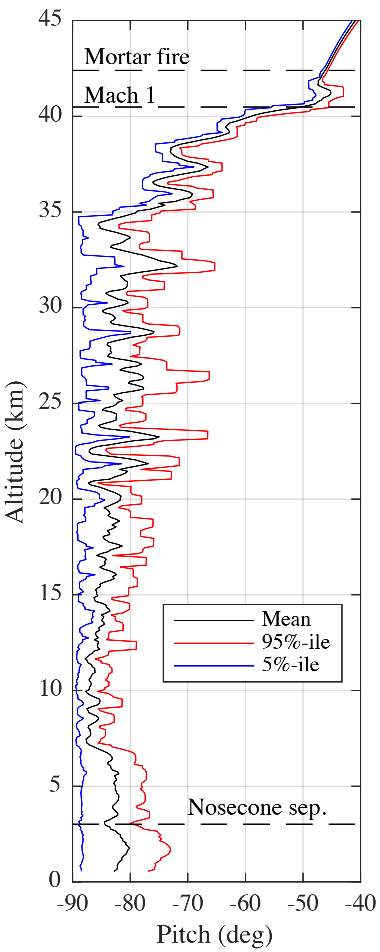
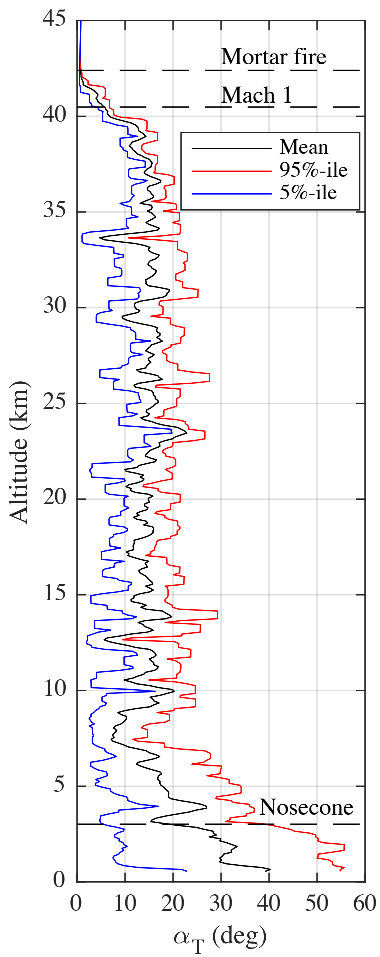
Payload attitude throughout descent

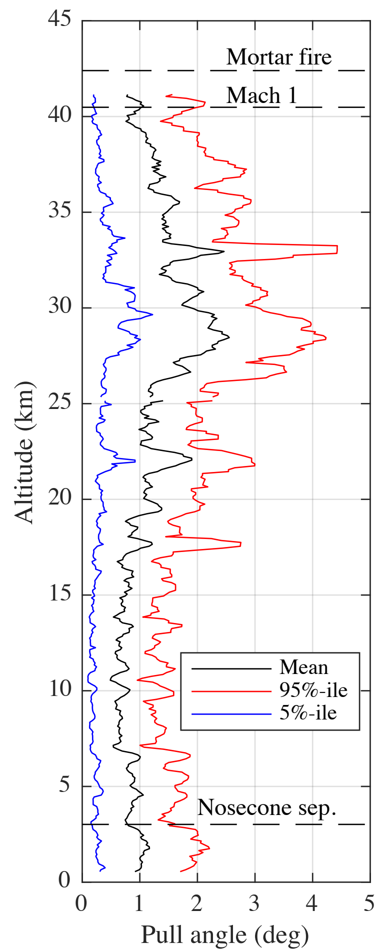
Pitch



α_T



Parachute pull angle



- Payload pitches over by ~35 km and then oscillates about vertical
- α_T increases to ~15 deg and remains constant until ~7km
- Increase in pitch and α_T below 7 km
- Pull angle remains small throughout
- System largely behaves as a rigid body

Parachute-Payload Dynamics

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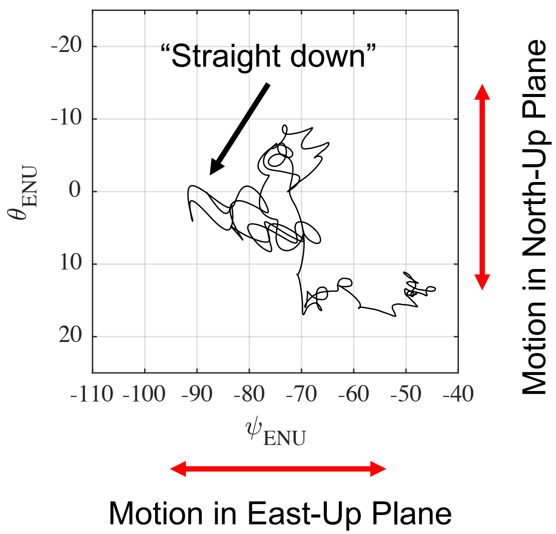
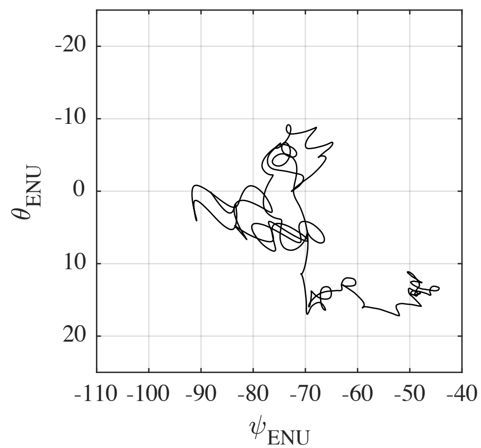
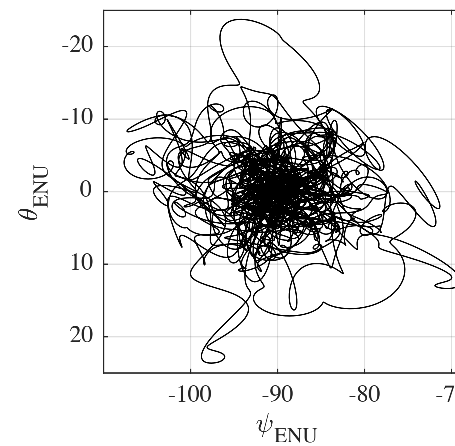
- Euler angles (pitch-yaw-roll sequence) wrt to East-North-Up frame:



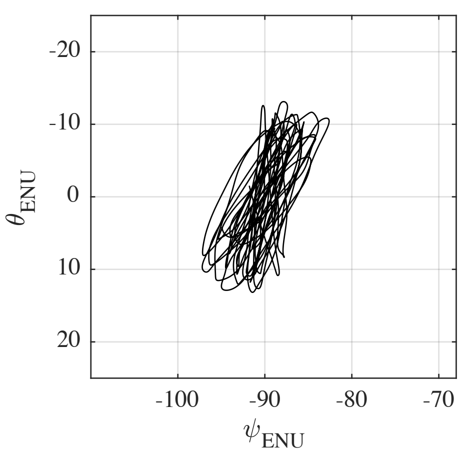
Mortar fire to 35 km:
Pitch-over motion



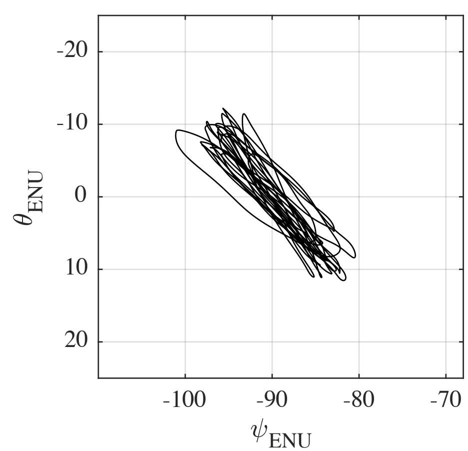
35 km to 7 km:
Chaotic motion about (-90,0)



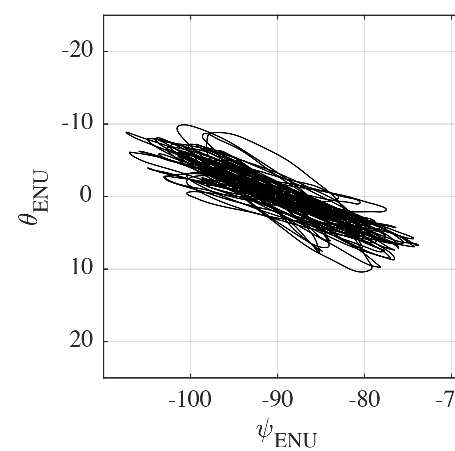
7 km to 4.5 km:
Planar pendulum motion



4.5 km to 3 km:
Planar pendulum motion



3 km to splashdown:
Nosecone drop increases amplitude



Parachute Inflation

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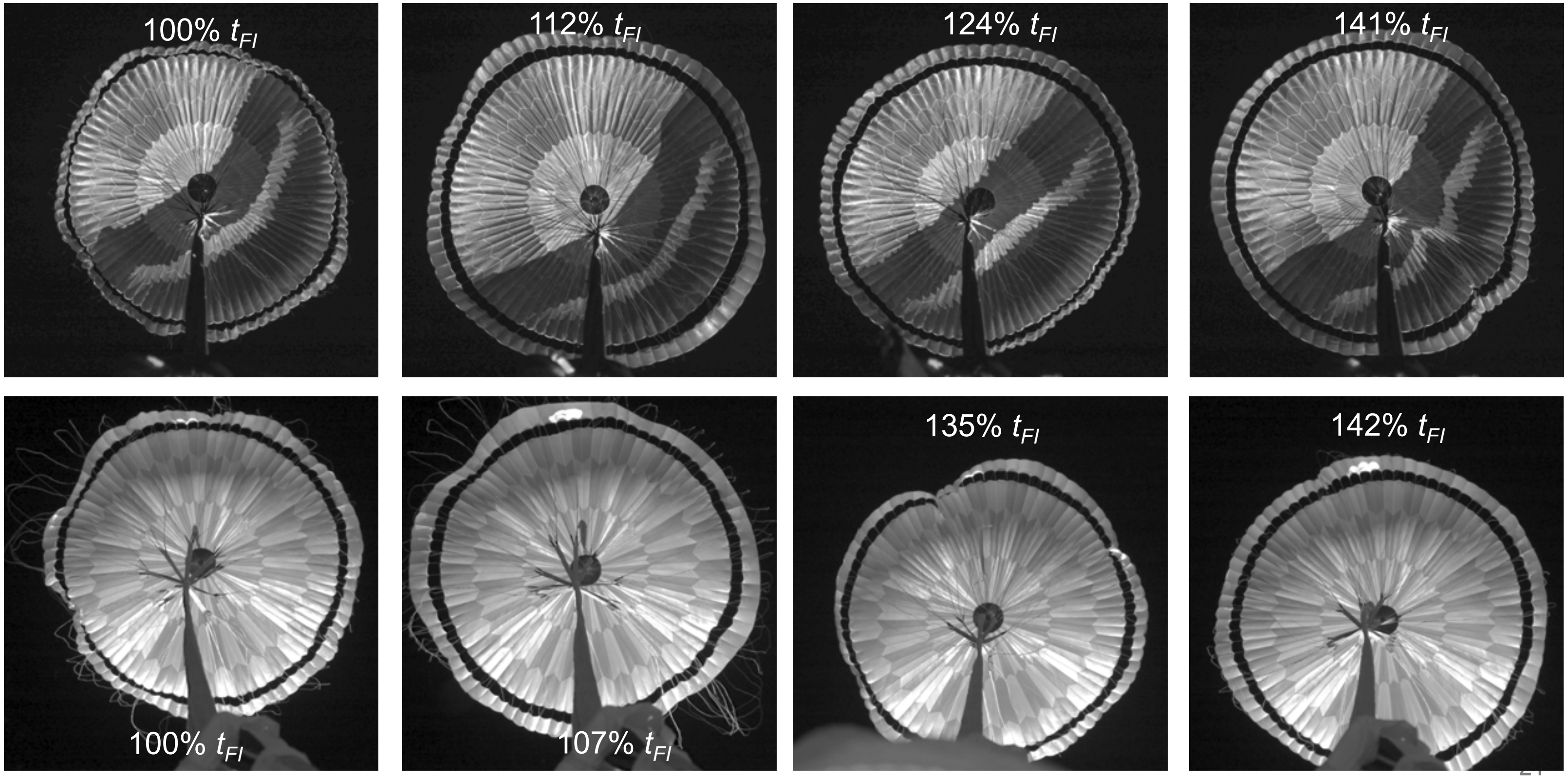
SR01

SR02



SR03: Changes to Parachute Assembly

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- Deployment bag:
  - Reduce length & mass of deployment bag energy modulators
  - Remove Teflon outer layer to reduce bag mass
  - Add Teflon tape to beckets on deployment bag
- Packing:
  - Ensure a more uniform mass distribution in bag (minimize rotation)
  - S-fold canopy to slow down inflation
- Canopy:
  - Increase number of bag/vent band attachment locations to 8 (from 4)
  - Use Nylon bag attachment cords (previously Technora)
- Riser:
  - Change dispersion keeper stitching to Nylon (from Kevlar)
- Triple bridle:
  - Use Nylon bridle legs & sabot net load elements to reduce snatch loads (previously Kevlar)