

# ASPIRE Aerodynamic Models and Flight Performance

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Southampton University, 3<sup>rd</sup> Nov 2021

(originally presented at AIAA 2019, Dallas, TX)

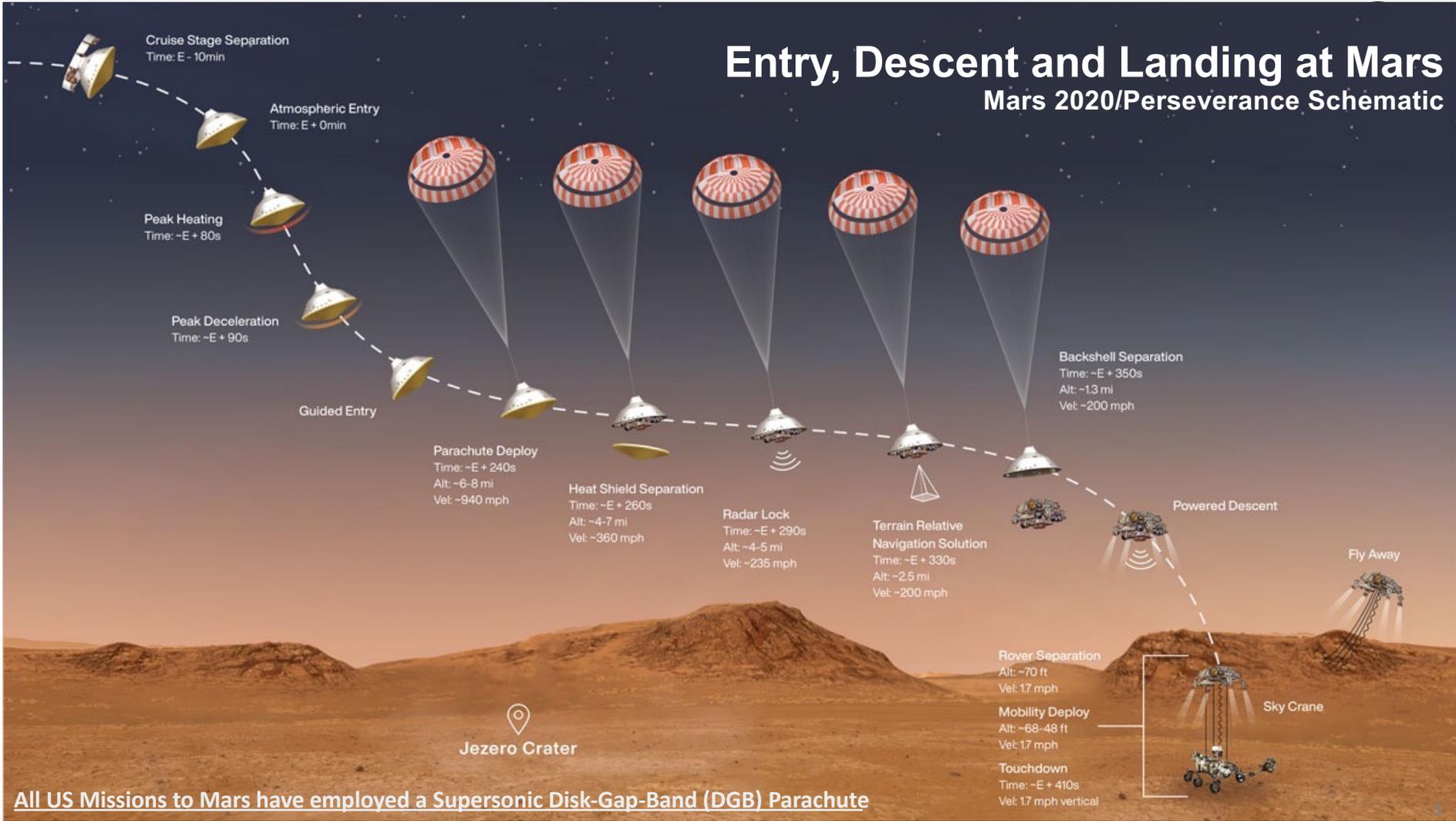
# Personal Introduction



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# Entry, Descent and Landing at Mars

## Mars 2020/Perseverance Schematic

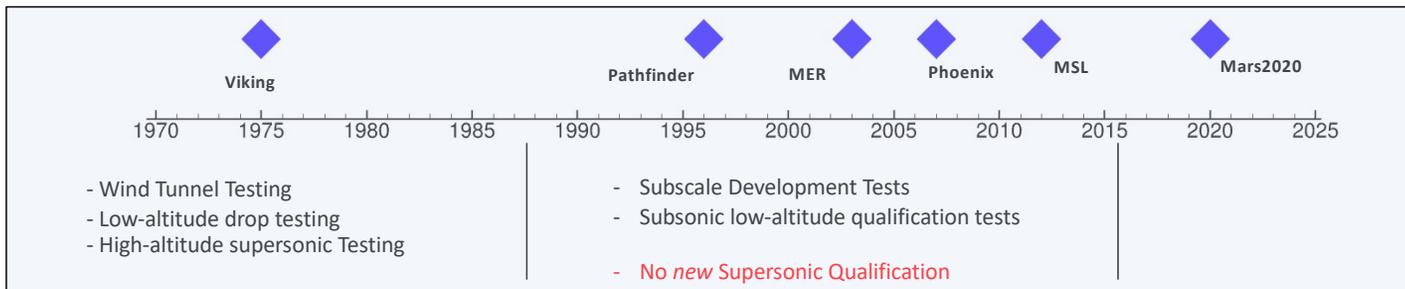


# DGB Parachutes



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- Disk-Gap-Band (DGB) parachutes have been used on all US Mars missions.
- All of the parachutes have been variants of the Viking DGB parachute.



- Since Viking era,
  - Parachute materials have changed (Dacron → Kevlar, Nylon)
  - Analysis methods have evolved
  - Parachute size and load have increased
  - Design Margins have decreased
- Relationship between subsonic testing and supersonic flight performance is not clear



# Parachute and Component Testing



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**Mortar Deploy Test**



**Sub-scale Supersonic Wind Tunnel Test**



**Full Scale Subsonic Wind Tunnel Test**

Between Mars Science Lab (MSL, 2012/2013) and Mars 2020 (2020/2021), NASA established a project to study the deployment, inflation and performance of full-scale, supersonic parachute that would eventually help land Perseverance at Mars.

# ASPIRE

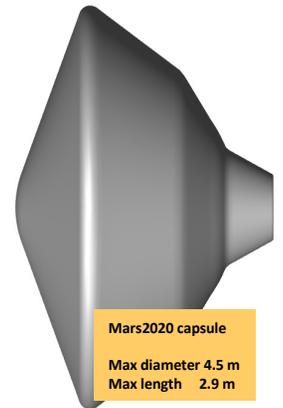


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ASPIRE\* project was launched to test full-scale parachutes at Mars relevant conditions.

- Parachutes delivered to high altitudes over Earth on a Sounding Rocket Platform
- Parachute deployed in the wake of a slender body.
- Three successful flight tests helped qualify a parachute for Mars2020 mission

ASPIRE payload  
 Max diameter 0.74 m  
 Max length 6.6 m



Mars2020 capsule  
 Max diameter 4.5 m  
 Max length 2.9 m

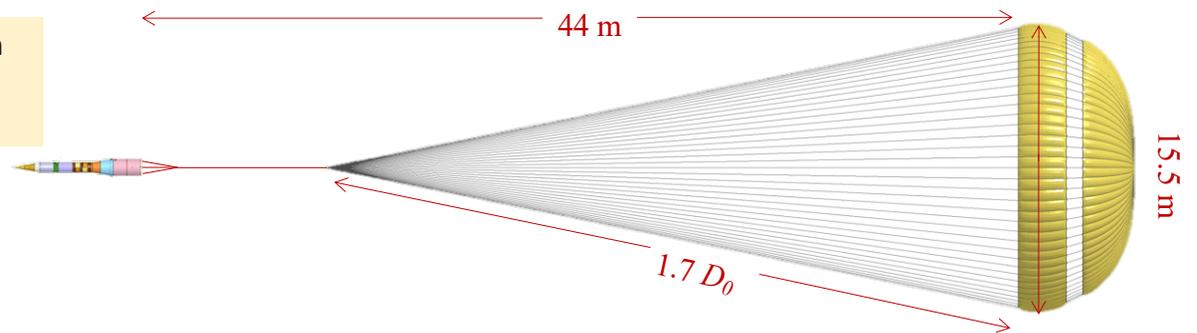
ASPIRE Disk-Gap-Band (DGB) Parachute

- Reference Diameter ( $D_0$ ) 21.5 m
- Inflated Diameter 15.5 m

*Dimensions similar to MSL parachute*

Test	Parachute	Parachute Inflation load	Inflation Mach Number	Dynamic Pressure
SR01 (Oct 2017)	MSL	32, 400 lbf	1.77	495 Pa
SR02 (Mar 2018)	Mars2020	55, 800 lbf	1.97	626 Pa
SR03 (Jul 2018)	Mars2020	67, 400 lbf	1.85	1020 Pa

When ASPIRE was launched in 2016, it had been over 40 years since NASA tested a full-scale supersonic parachute at higher altitudes.

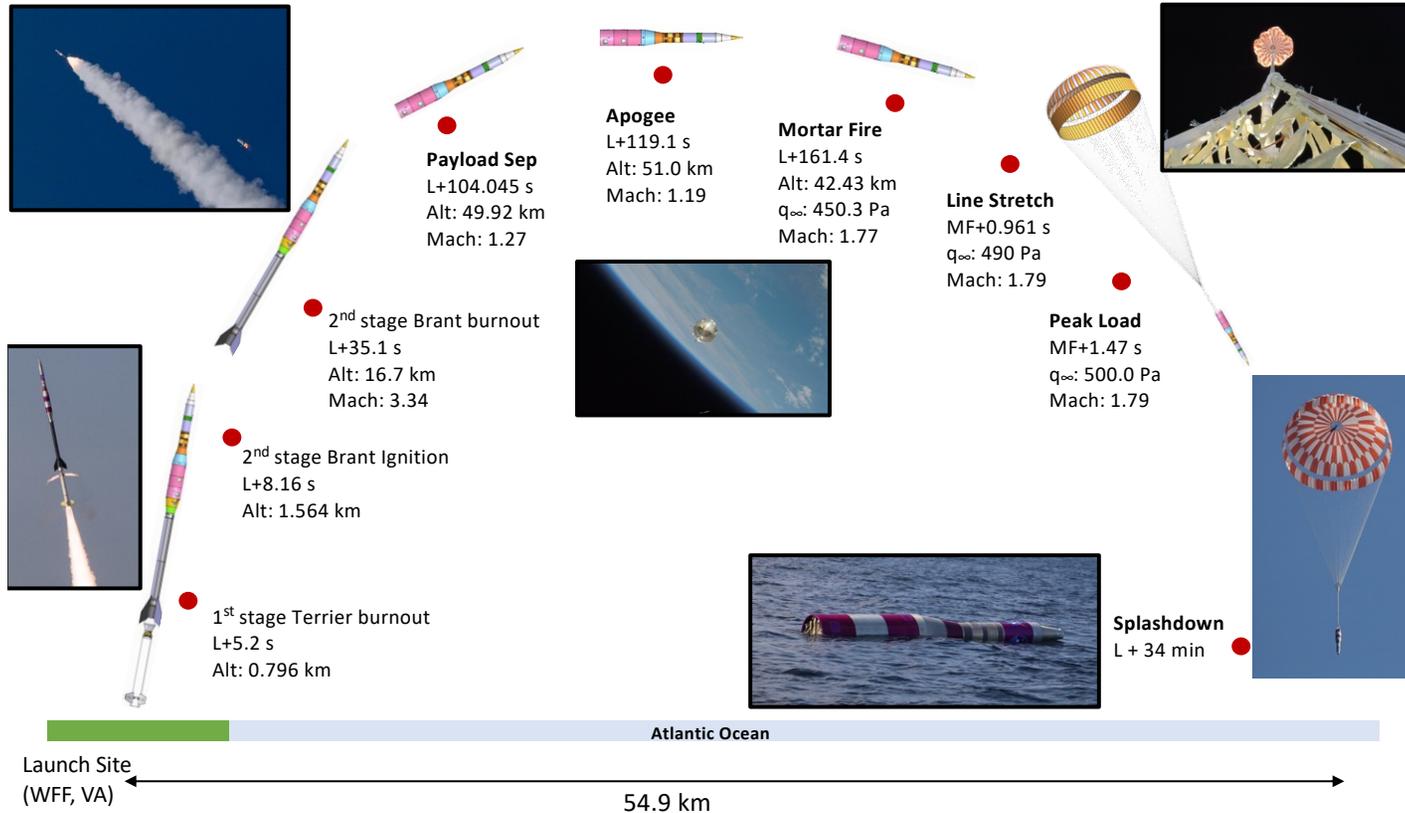


\* Advanced Supersonic Parachute Inflation Research Experiments

# ASPIRE Flight Test Schematic



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- Test Design requires models for parachute inflation, and peak and steady state loads.
- Scarce test data for similar parachutes behind slender bodies, at pertinent conditions.
- Numerical Simulations were used to help generate the parachute models.

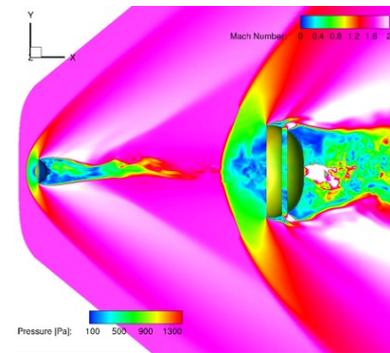
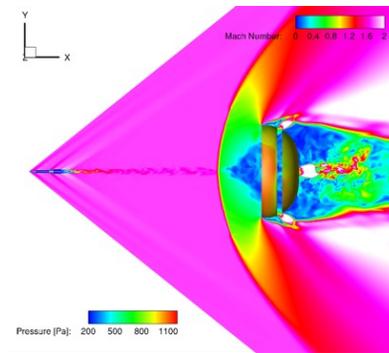
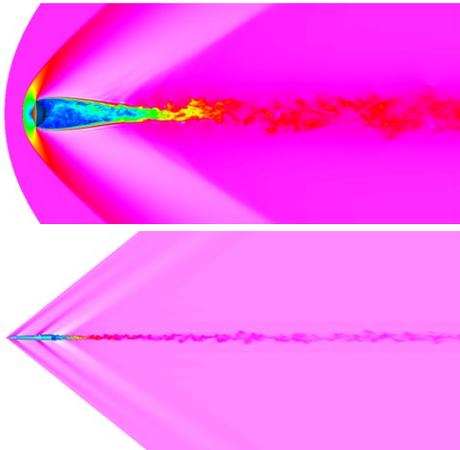
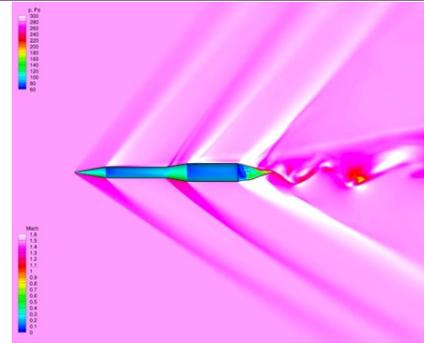
*Note: The numbers indicate actual quantities from first flight test (SR01), Oct 2017.*

# Flight Test Design: How we used CFD



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- Slender Body Simulations - to generate payload aerodynamic database.
- Wake Simulations - to explore blunt vs slender body differences, help with targeting during the flight test.
- Rigid Parachute Simulations - to investigate effect of leading body in parachute drag, generate pre-flight parachute drag model.
- Simulations in CO<sub>2</sub> - to extrapolate parachute performance over Earth and predict performance at Mars.



# Slender body Payload Aerodynamics



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- Objective: To generate a Payload Aerodynamics Database to predict flight characteristics and performance
  - This model is used from the payload separation stage to the mortar-fire leading up to parachute deploy.

- Process: CFD Simulations of flow past the payload geometry at various conditions (freestream, angle of attack)

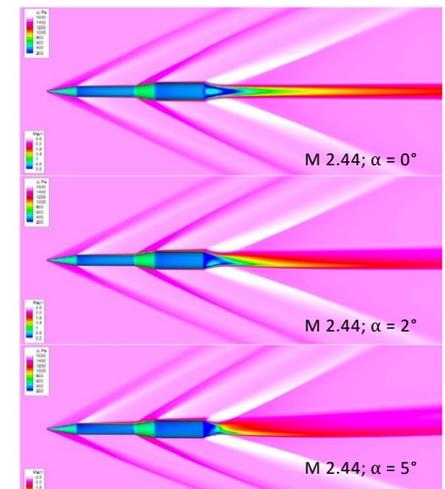
- Tools: OVERFLOW, DPLR, FUN3D

- Laminar and Turbulent flow calculations

Mach	alt, m	T, K	$\rho$ , kg/m <sup>3</sup>	V, m/s	p, Pa	q, Pa	Re/m
0.900	57848	254.9	4.330E-04	288.0	31.68	17.96	7.677E+03
1.100	55605	264.0	5.585E-04	358.2	42.32	35.84	1.198E+04
1.500	49450	271.0	1.228E-03	495.0	95.50	150.4	3.564E+04
2.444	39265	258.6	4.900E-03	787.9	363.7	1521	2.350E+05

$\alpha_T = 0, 2, 5, 10, 15, 20, 30, 45, 60, 75^\circ$

- Product(s) :
  - Tables of static aerodynamic coefficients as a function of Mach number and angle of attack
  - Uncertainties in the static aerodynamic coefficients (applied as dispersions in the flight mechanics simulations)
- Challenges:
  - Long, slender body  $\rightarrow$  significant viscous contributions (sensitivity to computational mesh and turbulent flow modeling)
  - Laminar-to-Turbulent transition criteria is not easy to implement (too many variables, not enough information on the pertinent geometry and the pertinent conditions)
- Approach:
  - Use both the laminar and turbulent flow simulations and aerodynamic behavior
  - Design a nominal based on the average ; use the differences to inform uncertainty

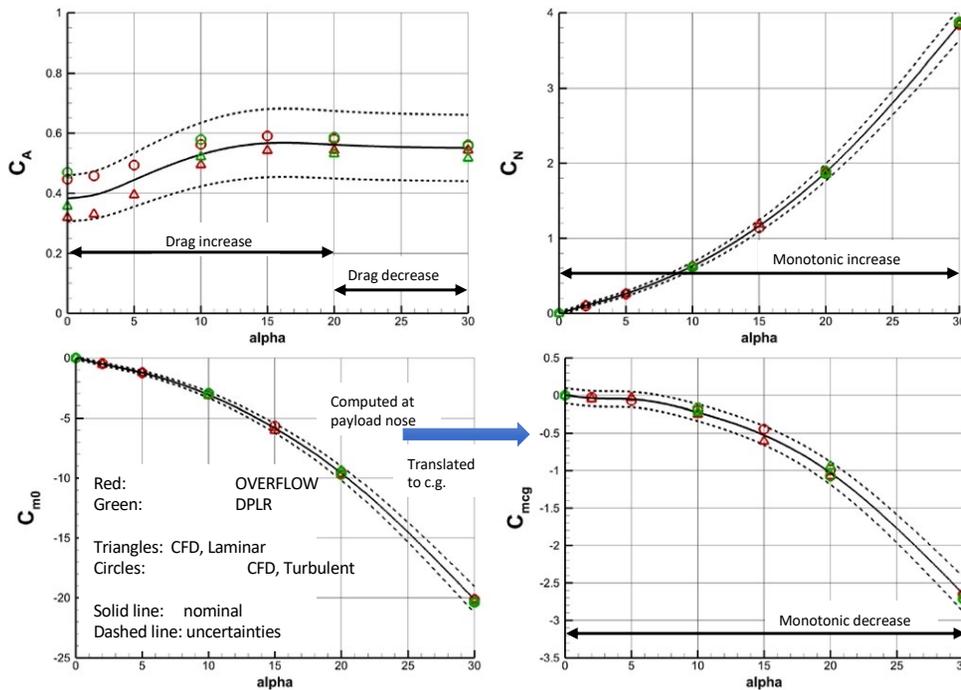


# Slender Body Payload Aerodynamic Model

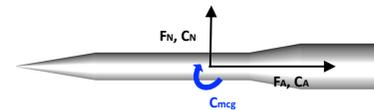


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Freestream Mach number 1.5



- Plots show variation of aerodynamic force/moment coefficients as a function of angle of attack
- In general, there is a reasonable agreement between solutions from different solvers
- There is a larger difference between laminar and turbulent flow
- Nominal curves are based on averages ; uncertainties are informed by the differences.

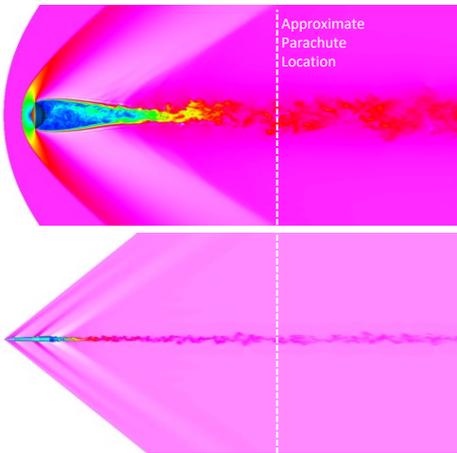


Data at multiple Mach numbers, so generated, is used by flight mechanics simulations, and to design the flight test

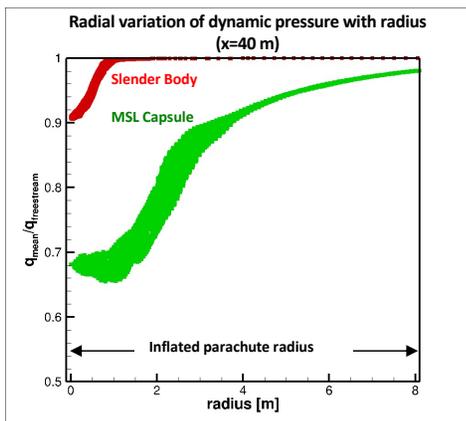
# Wake Dynamics: What wake does the parachute pack see ?



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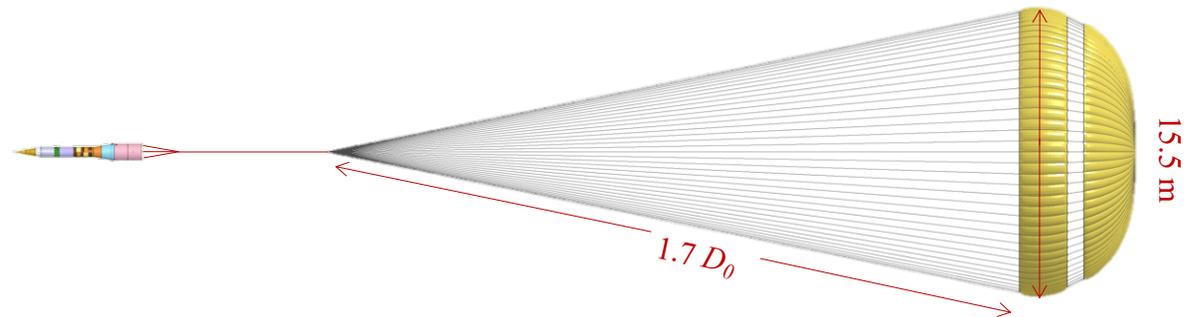
- In general, wake characteristics scale with the diameter;  $D_{MSL}/D_{ASPIRE} \sim 6$
- The wake behind the slender body closes much earlier; is thinner.
- Dynamic pressure recovery ( $q_{min}$ ) much faster behind the slender body, compared to the blunt body.
- Deficit (velocity, dynamic pressure) is larger, behind the blunt body.
- Parachute drag is directly dependent on dynamic pressure. We should expect lower drag behind a blunt body.
- Parachute inflation behind a slender body could be more stressing.



# Putting together a Parachute Drag Model



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Parameters that might affect parachute drag:

- Leading body geometry ( $D_{\text{payload}}/D_{\text{parachute}}$ )
- Trailing distance ( $L_{\text{riser}}/D_0$ )
- Parachute Fabric Permeability
- Parachute Design/Geometry

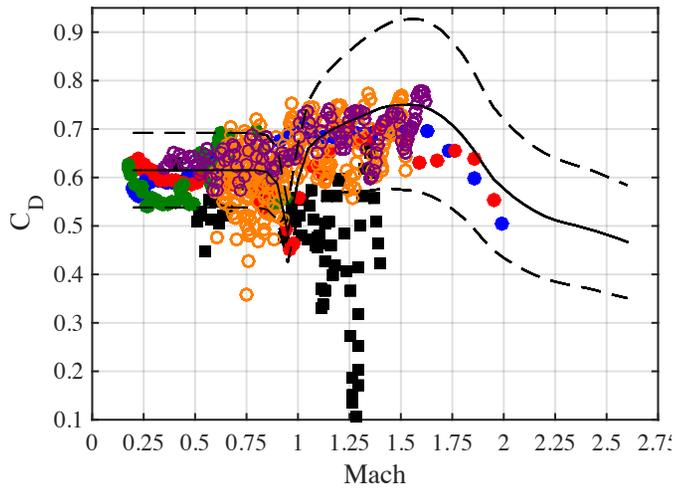
Pre-flight Parachute Performance Models had to draw on all available data and make adjustments for differences

# Putting together a Parachute Drag Model

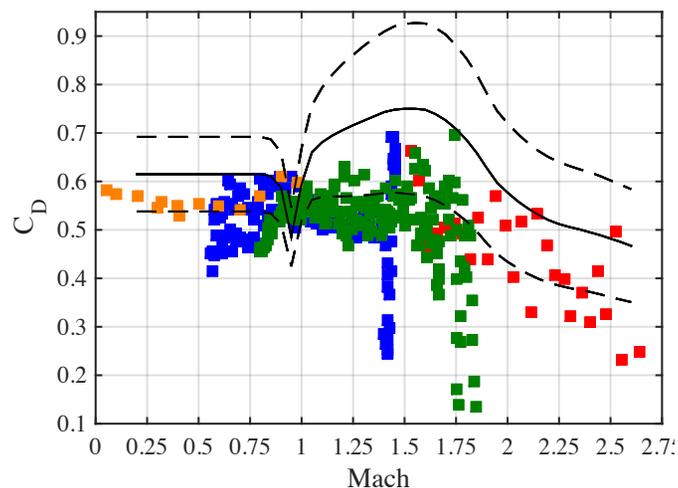


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Blunt bodies



Slender bodies



- ● ● BLDT ( $L_s = 1.7 \underline{D}_0$ )
- ○ Phoenix, MSL ( $L_s = 1.7 \underline{D}_0$ )
- PEPP ( $L_s = 1.0 \underline{D}_0$ )

— MSL model nominal

All data correspond to flight tests from PEPP, SHAPE, SPED programs ( $L_s = 1.0 \underline{D}_0$ )

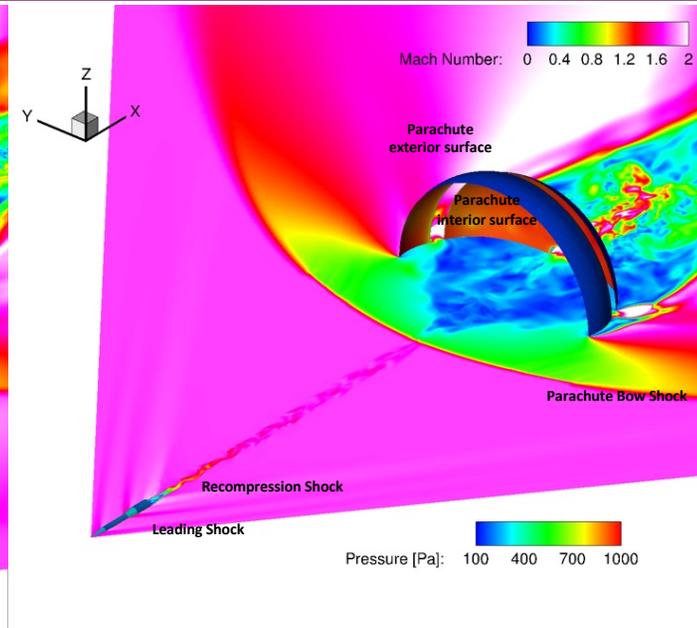
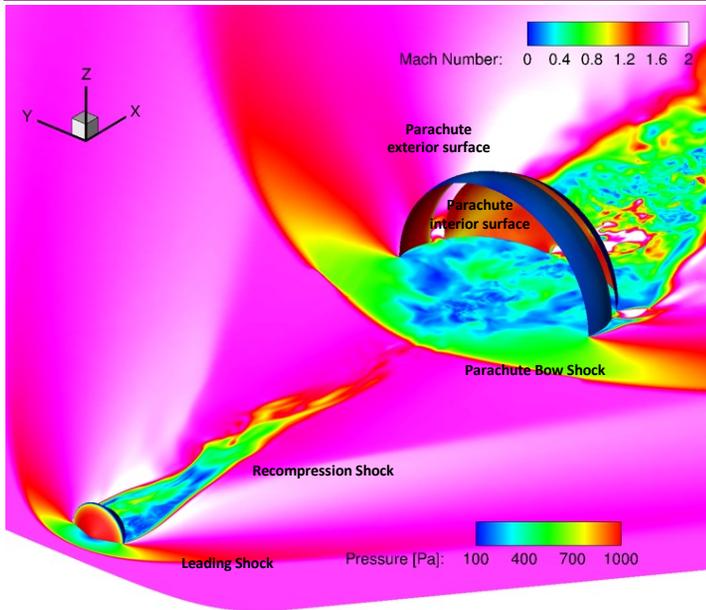
- - - MSL model high/low

Q. What is the effect of the leading body on Parachute Drag ?

# How does the leading body affect the parachute drag ?



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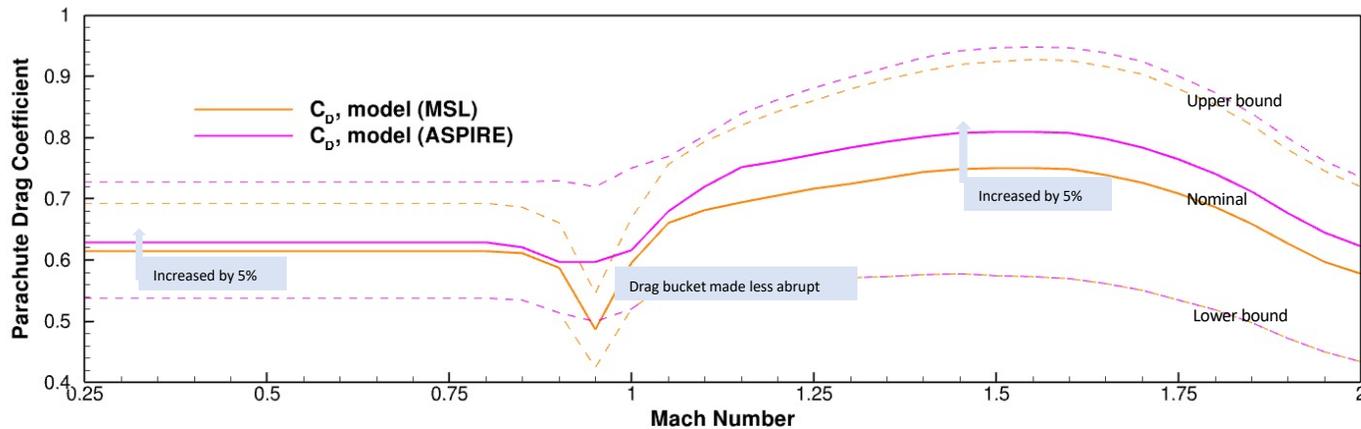
- Numerical simulations using US3D
- Mach 1.75; dyn. Pres. 538 Pa
- Parachute modeled as a rigid, impermeable, 1mm shell
- Risers and suspension lines are not modeled
- Parachute placed 45 m behind the leading body

- Unsteady flow starting at the wake of the leading body; flow acceleration through the vent and the gap.
- Interaction between the wake and the parachute shock is more apparent behind the blunt body.
- Behind the slender body, the parachute bow shock barely registers the (narrow) wake.
- Force on the parachute is unsteady; **Mean drag about 15% higher behind a slender body** (consistent with past wind tunnel studies: *Reichenau et al 1972*)

# Pre-Flight Parachute Drag Model



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- MSL parachute drag model was modified to yield the ASPIRE parachute drag model.

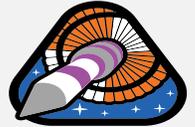
Subsonic: Increased nominal drag performance and the high margin; retained the low margin

Supersonic: Increased nominal drag performance and the high margin; retained the low margin

Transonic: reduced the steep reduction at near-sonic conditions; blended the subsonic and supersonic drag curves

- The ASPIRE drag model (and the bounds) was used in the flight mechanics simulations, and to help design the flight tests.

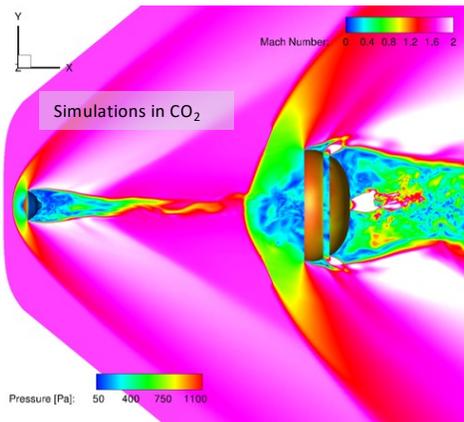
# Effect of Freestream Fluid



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Q. How representative is a parachute test in air, to the parachute performance in a CO<sub>2</sub> atmosphere.

Freestream Details				
Atmosphere	Density/Altitude	Velocity	Mach Number	Dynamic Pressure
Air, perfect gas	0.00346 (Kg/m <sup>3</sup> )	558.2 m/s	1.75	538 Pa
CO <sub>2</sub> , perfect gas	0.00605 (Kg/m <sup>3</sup> )	421.8 m/s	1.75	538 Pa



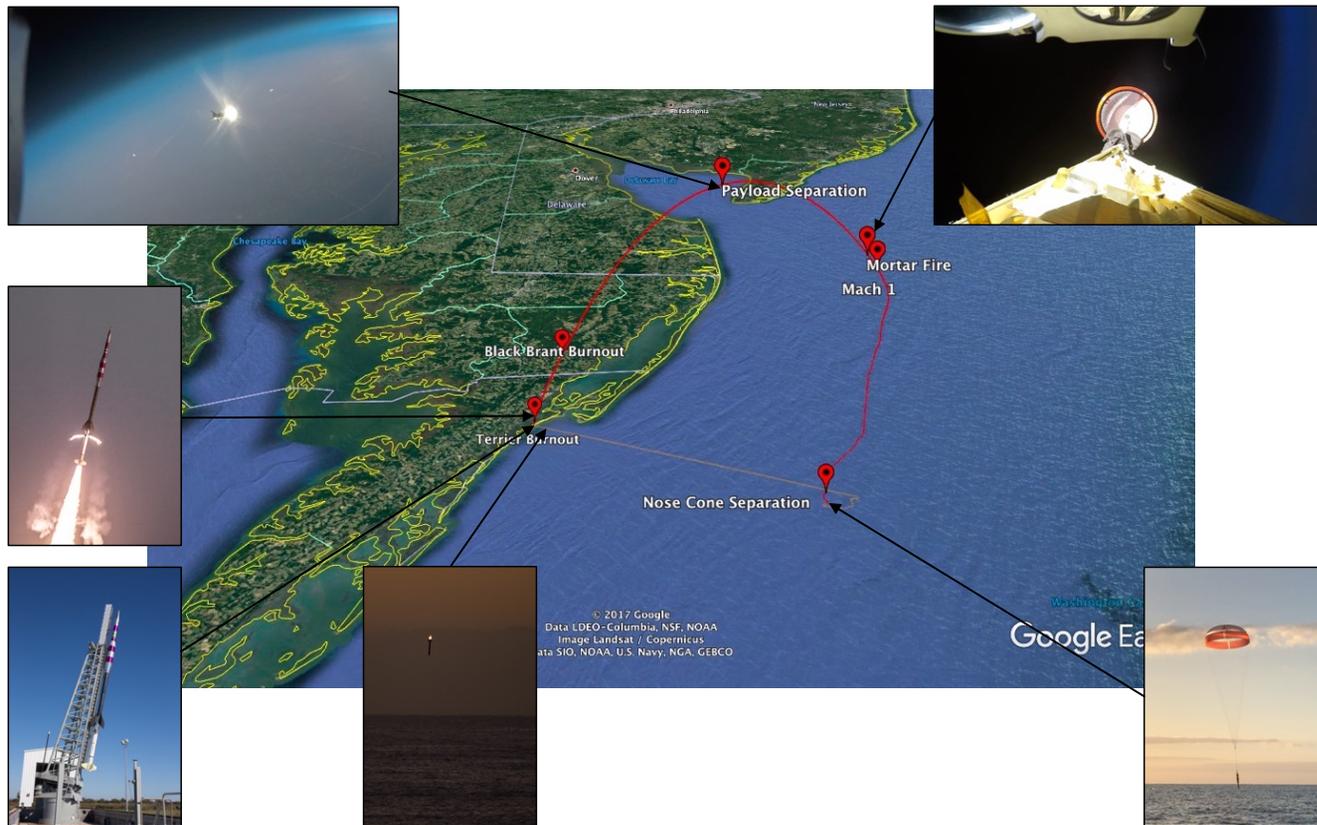
- Simulations of parachute behind the MSL capsule in air and CO<sub>2</sub> at the *same Mach number and freestream dynamic pressure*.
- The two fluids have different values for ratio of Specific Heats ( $\gamma$ ):
  - Air: 1.4
  - CO<sub>2</sub>: 1.3
- $\gamma$  affects shock standoff distance and conditions across the shock, which in turn affect pressure on the parachute, and the parachute performance.
- Simulations at M 1.75 show very similar performance in both gases (unsteadiness, and parachute drag); mean parachute drag varies by only 2%.
- $\gamma$ -effects not very significant at this Mach number (e.g. post-shock total pressure ratio is within 2.5%).

Simulations indicate that at this Mach number, a high-altitude Earth test is a good proxy for a Mars flight

# ASPIRE Flight Test - SR01 (first flight test)



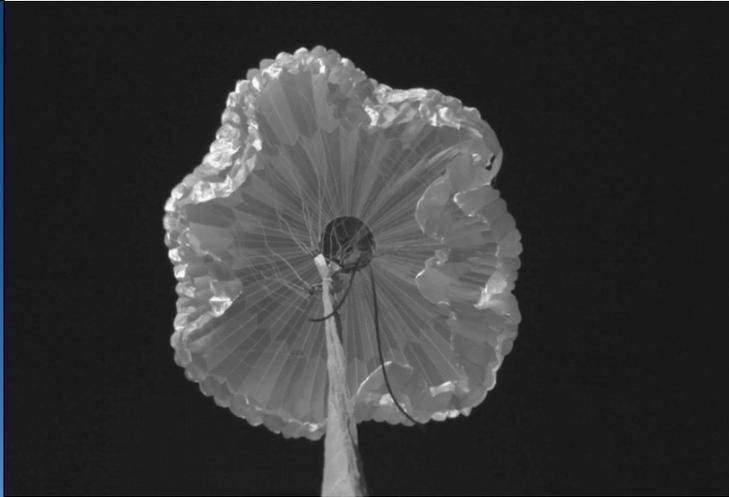
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# ASPIRE Flight Test Imagery



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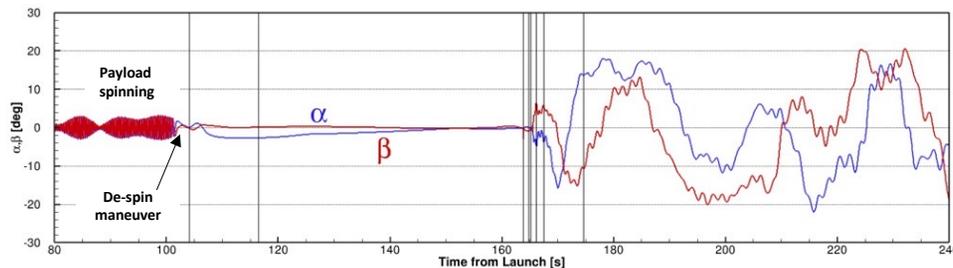
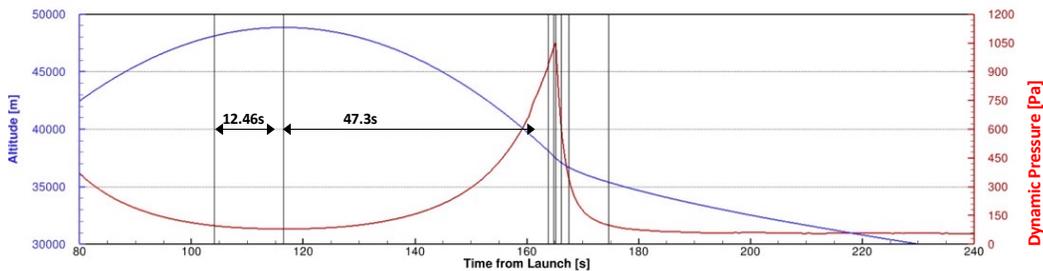
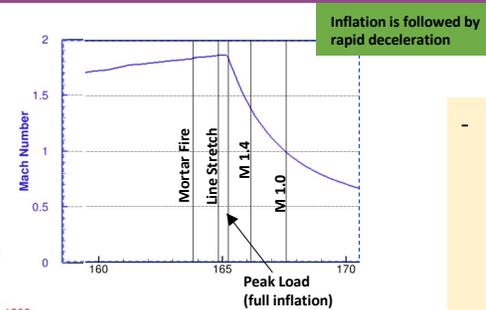
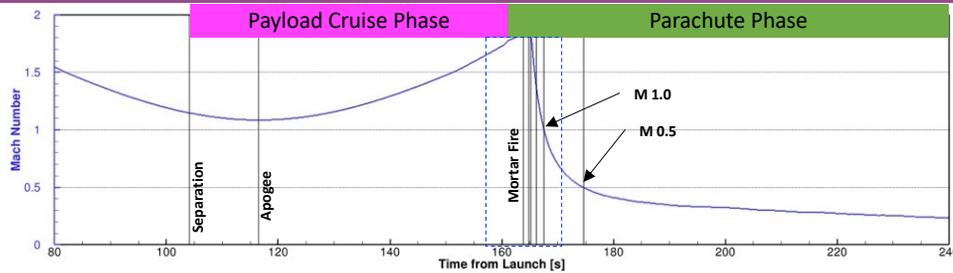


# ASPIRE Reconstruction and Reconciliation

Flight Trajectory from  
Third Flight Test



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<b>Payload Separation</b>	Altitude	48.1 km
	Dynamic Pressure	96.4 Pa
	Mach Number	1.17
	Velocity	372.5 m/s
<b>Apogee</b>	Altitude	48.85 km
	Dynamic Pressure	79.36 Pa
	Mach Number	1.11
	Velocity	354.8 m/s
<b>Mortar Fire</b>	Altitude	38.12 km
	Dynamic Pressure	931.74 Pa
	Mach Number	1.85
	Velocity	575.8 m/s
<b>Peak Parachute Load</b>	Altitude	37.46 km
	Dynamic Pressure	1020.0 Pa
	Mach Number	1.85
	Velocity	573.18 m/s

- Flight tests are followed by post-flight reconstruction (what happened during the flight ?) and post-flight reconciliation (how does it compare to what we thought would happen ?)

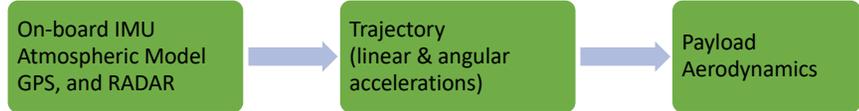
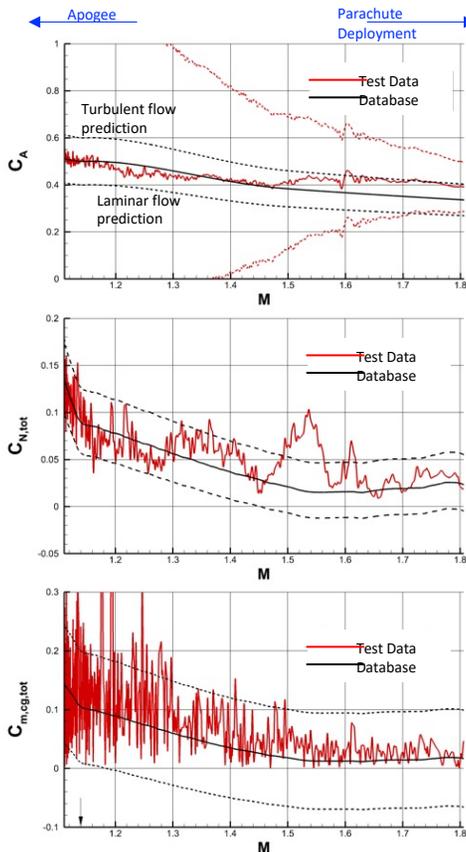
- Reconstruction and reconciliation need (a) on-board measurements, (b) GPS and radar information, and (c) atmospheric data

# Post-Flight Reconstruction - Payload Aerodynamics



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SR03 Flight data



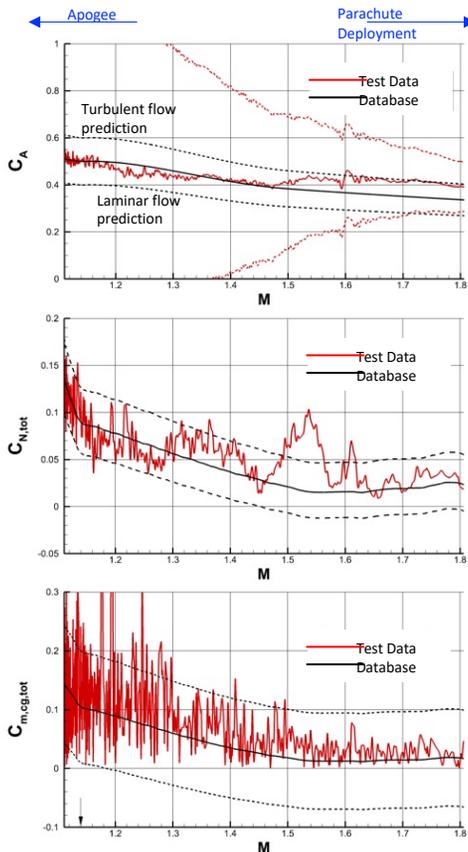
- Payload coast phase: from payload separation to parachute deploy (high altitude, low density and dynamic pressure, lower aerodynamic forces and measured accelerations)
- Challenge: Measured accelerations are of the order of the *resolution* of the IMU (sized to measure forces during parachute deployment).
- Uncertainty in reconstructing aerodynamic coefficients exceeds the coefficients themselves.
- Comparisons show:
  - *Validates design process*
  - Flight data falls within the pre-flight bounds
  - Nominal flight data compares reasonably with pre-flight predictions
  - In general, flight data closer to turbulent flow predictions than laminar flow predictions (particularly as the velocity increases).

# Post-Flight Reconstruction - Payload Aerodynamics

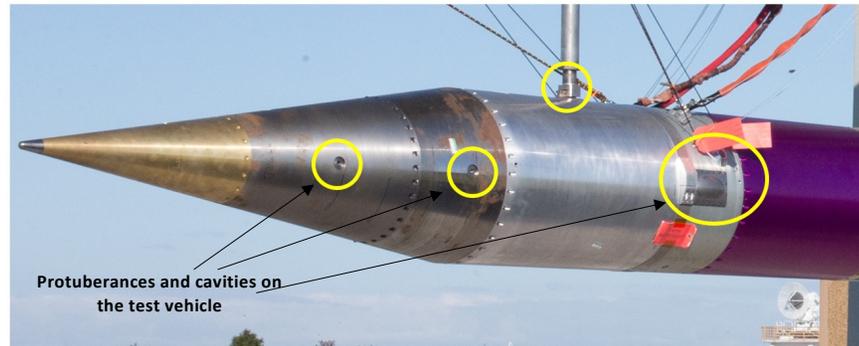


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SR03 Flight data



Pre-flight database assumes a smooth geometry ;  
Vehicle surface contains non-smooth features → flow is likely to trip



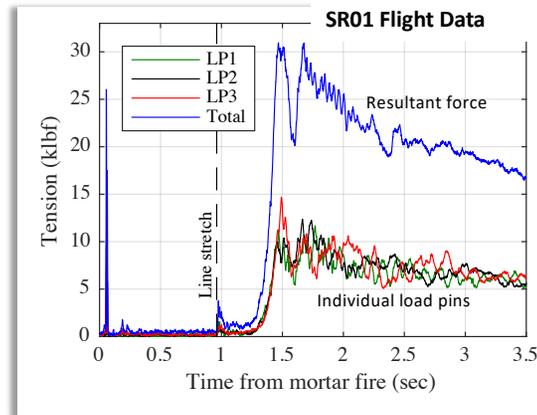
- Comparisons show:
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# Post-Flight Reconstruction - Deployment and Inflation



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- Parachute deployment and inflation are highly dynamic events
- Time(s) :
  - Mortar fire (initiation) to line stretch:  $\sim 1.0$  s
  - Line stretch to Full Inflation:  $\sim 0.5$  s
- Tension measurements from load pins  
(Parachute force = tension + payload mass x acceleration)
- Full inflation followed by a collapse/rebound and a second peak
- Peak Aerodynamic Load is a quantity of interest.



Parachute pack sailing away from the payload

Line Stretch  
(pack 45 m away)

Parachute begins to emerge from the pack

Parachute Fully Inflated  
(peak aerodynamic load)



Images from the on-board high-speed camera

# Post-Flight Reconstruction - Deployment and Inflation



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- Peak Aerodynamic Load during SR01 : 32.4 k lbf (144.07 kN)

(Pre-flight prediction 35,000 lbf)

- Inflation load indicator  $F_{peak} = k_p(2q_{\infty}S_p)$

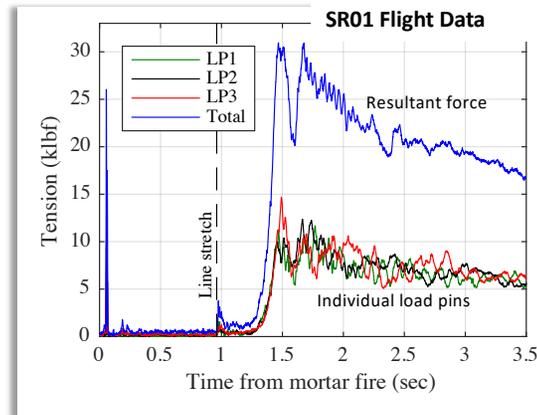
$S_p$ : Parachute Projected Area  
 $q_{\infty}$ : Freestream dyn. press.  
 $k_p$ : Inflation constant

Pre-flight range for  $k_p$   
 (informed using CFD)

0.70 - 0.90

Test	dyn. press.	Inflation Load	$k_p$
SR01	495 Pa	32,400 lbf	0.77
SR02	626 Pa	55,800 lbf	0.78
SR03	1020 Pa	67,400 lbf	0.76
MSL		35,000 lbf	0.83

$k_p$  consistent across the three flights;  
 towards the lower end of the pre-flight prediction.



Way, 2018 IEEE Aerospace Conference,  
 A Momentum-Based Indicator for Predicting the Peak  
 Opening Load of Supersonic Parachutes

Parachute pack sailing  
 away from the payload

Line Stretch  
 (pack 45 m away)

Parachute begins to  
 emerge from the pack

Parachute Fully Inflated  
 (peak aerodynamic load)

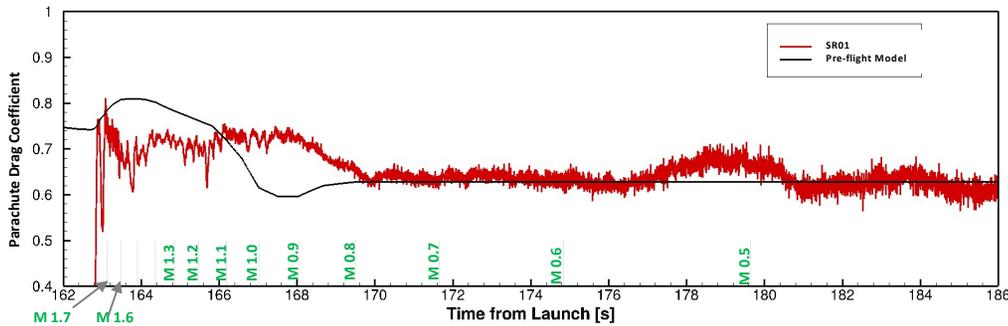


Images from the on-board high-speed camera

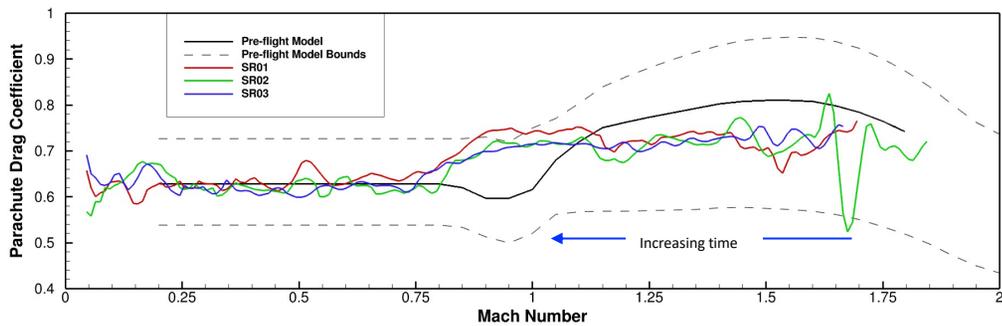
# Post-Flight Reconstruction - Parachute Drag



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- Good Agreement below Mach 0.75
- Over-prediction above Mach 1.15
- Test Data does not show a transonic drag reduction



- Consistent drag performance across three flights
- Pre-flight bounds capture all the data from three flights (about 90 min of flight data)
- Flight data indicates a near-constant subsonic drag, and a near-constant supersonic drag

Transonic Drag Decrease was not observed in any of the flight tests. Is it a blunt leading body effect ?

# ASPIRE Takeaways



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- ASPIRE project was launched to test supersonic parachutes at Mars relevant conditions first full-scale supersonic tests of parachute in over 40 years.
- ASPIRE established a framework for testing full-scale parachutes.
- Through the three flight tests, ASPIRE 'certified' a parachute for upcoming Mars2020 mission and broke records (fastest inflation, highest load for a parachute this size).
- CFD simulations help generate aerodynamic models and design the flight test; Pre-flight payload and parachute models/predictions compare well to the flight data. CFD simulations (pre- and post-test) help investigate effect of leading body on parachute performance.
- Proposed an updated parachute drag model behind slender bodies.
- Established a process to develop aerodynamic models and to design flight tests for future parachute testing.

 <p><b>ASPIRE</b> Advanced Supersonic Parachute Inflation Research Experiments</p> <p><b>ASPIRE SR01 Post-Test Report</b></p> <p>Edited By: Jan O. Clark JPL Propulsion Laboratory Chris O'Connell JPL Propulsion Laboratory Peter W. Smith JPL Propulsion Laboratory</p>	 <p><b>ASPIRE</b> Advanced Supersonic Parachute Inflation Research Experiments</p> <p><b>ASPIRE SR02 Post-Test Report</b></p> <p>Edited By: Jan O. Clark JPL Propulsion Laboratory Chris O'Connell JPL Propulsion Laboratory Peter W. Smith JPL Propulsion Laboratory</p>	 <p><b>ASPIRE</b> Advanced Supersonic Parachute Inflation Research Experiments</p> <p><b>ASPIRE SR03 Post-Test Report</b></p> <p>Edited By: Jan O. Clark JPL Propulsion Laboratory Chris O'Connell JPL Propulsion Laboratory Peter W. Smith JPL Propulsion Laboratory</p>
<p><i>Design and Test information (including flight data) extensively documented</i></p>		
<p>Advanced Supersonic Parachute Inflation Research Experiments (ASPIRE) National Aeronautics and Space Administration JPL Propulsion Laboratory California Institute of Technology Pasadena, CA 91124-3209</p>	<p>Advanced Supersonic Parachute Inflation Research Experiments (ASPIRE) National Aeronautics and Space Administration JPL Propulsion Laboratory California Institute of Technology Pasadena, CA 91124-3209</p>	<p>Advanced Supersonic Parachute Inflation Research Experiments (ASPIRE) National Aeronautics and Space Administration JPL Propulsion Laboratory California Institute of Technology Pasadena, CA 91124-3209</p>
<p>May 2013</p>	<p>November 2013</p>	<p>January 2013</p>

**ASPIRE**



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