ASPIRE Aerodynamic Models and Flight Performance

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ASPIRE

AIAA Aviation Forum, Dallas, TX, June 19th 2019

Introduction

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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.

- Wind Tunnel Testing
- Low-altitude drop testing
- High-altitude supersonic Testing

- Subscale Development Tests
- Subsonic low-altitude qualification tests

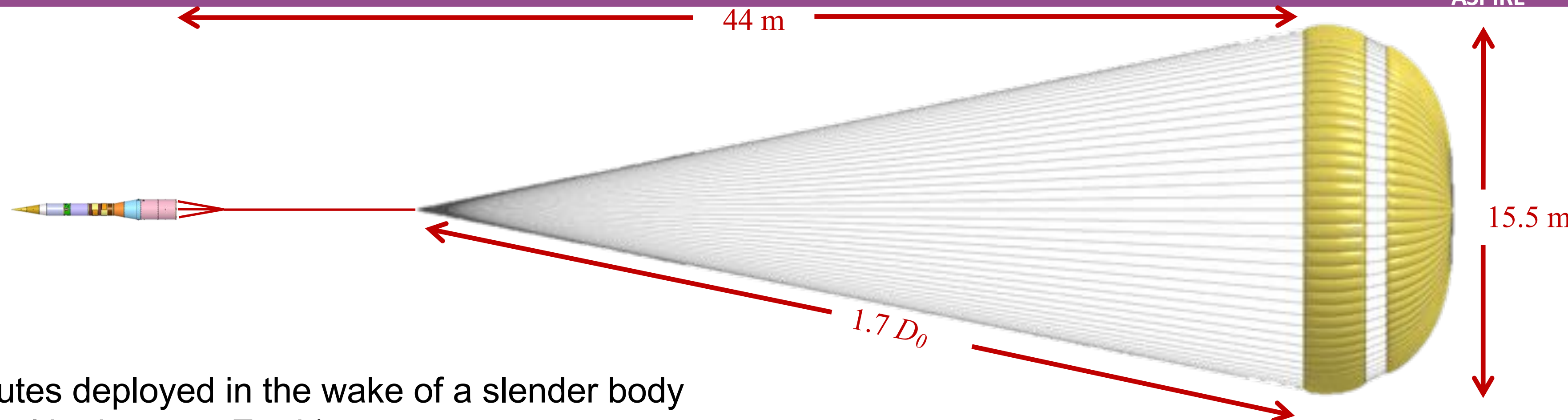
- No *new* Supersonic Qualification

- 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

MSL (2012) parachute
Inflated diameter 16 m

The Advanced Supersonic Parachute Inflation Research and Experiments (ASPIRE) project is tasked with deployment and testing of full-scale *Disk-Gap-Band* parachutes at Mars relevant conditions

ASPIRE Test Architecture



- Parachutes deployed in the wake of a slender body (at high altitudes over Earth).
- Two candidate parachutes tested (same geometry, different materials and construction).
- The parachute will be used at Mars behind a blunt body (*Mars2020, estimated entry at Mars February 2020*).

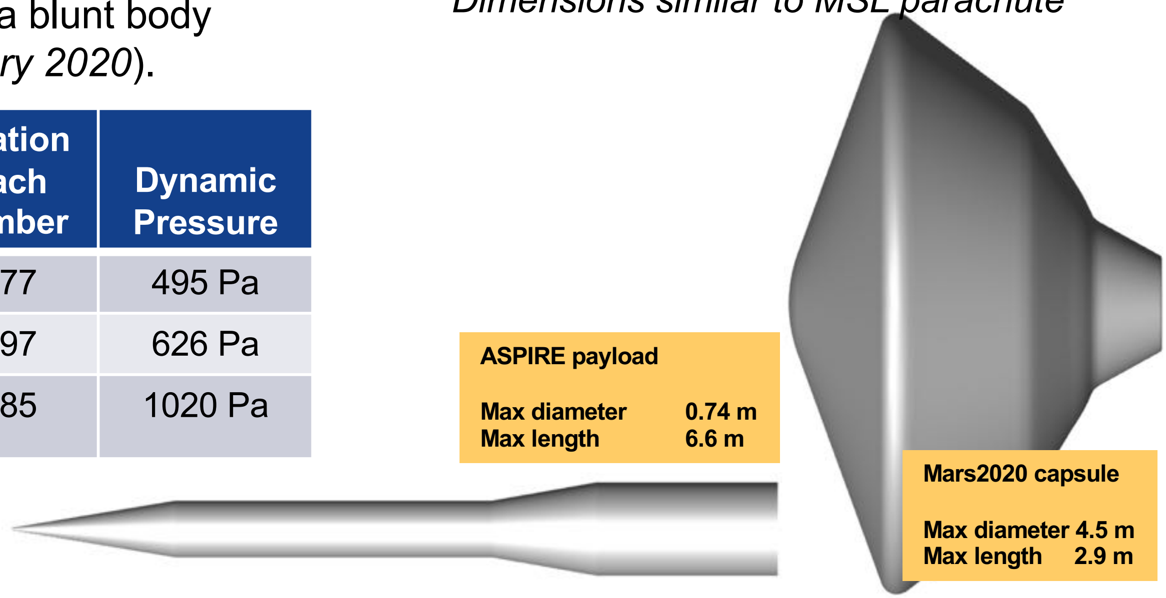
ASPIRE Disk-Gap-Band (DGB) Parachute

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

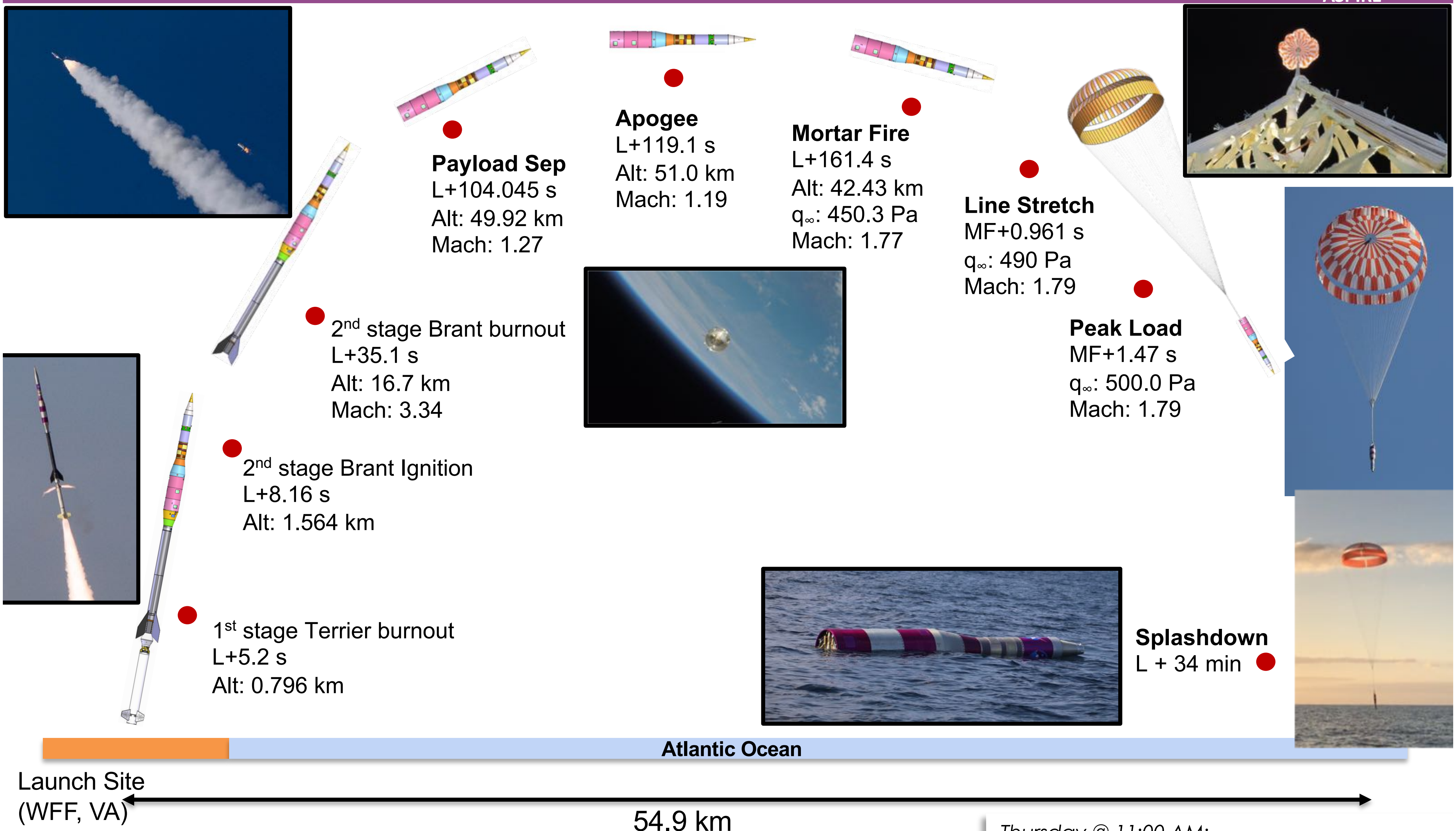
Dimensions similar to MSL parachute

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

Nominal predicted parachute load during Mars2020 entry: 35,000 lbf



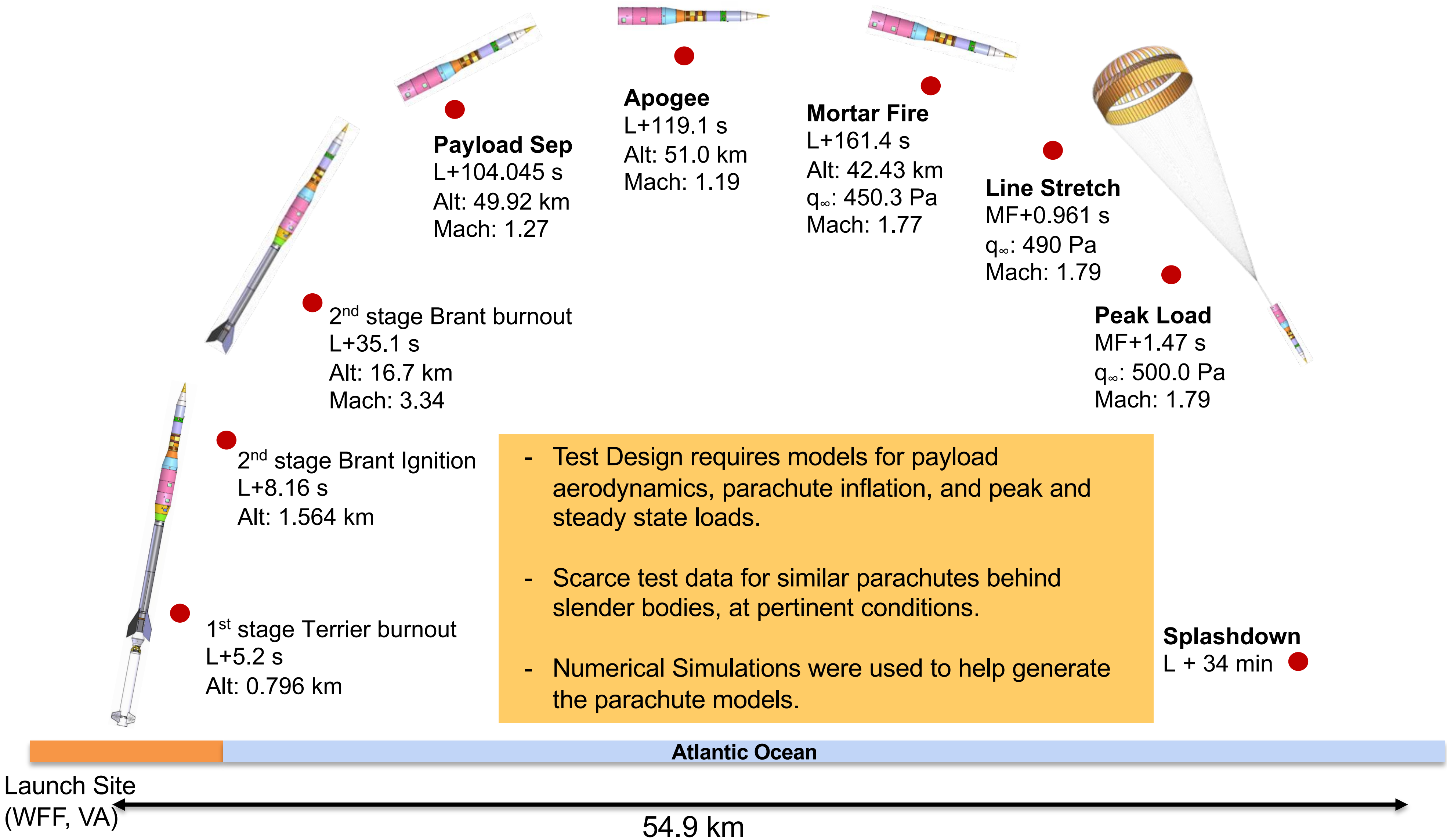
ASPIRE Flight Test



Thursday @ 11:00 AM:
211-ADS-12: Summary of ASPIRE Sounding Rocket Tests with a Disk-Gap-Band Parachute

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

ASPIRE Flight Test



- Test Design requires models for payload aerodynamics, 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.

Objective: Present the Aerodynamic Models used for flight test design, and compare performance against test data

CFD towards Flight Test Design

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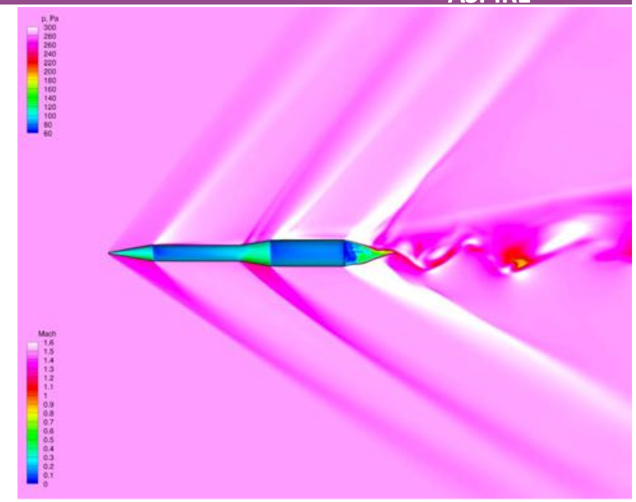
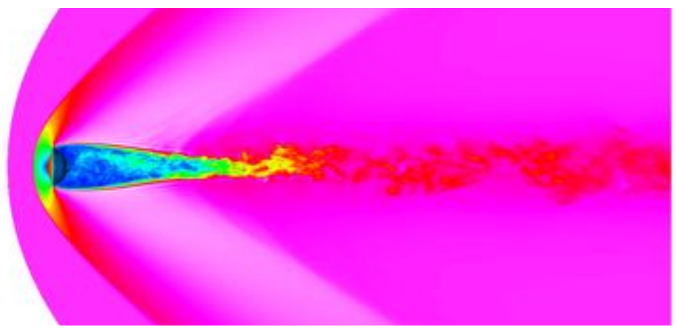
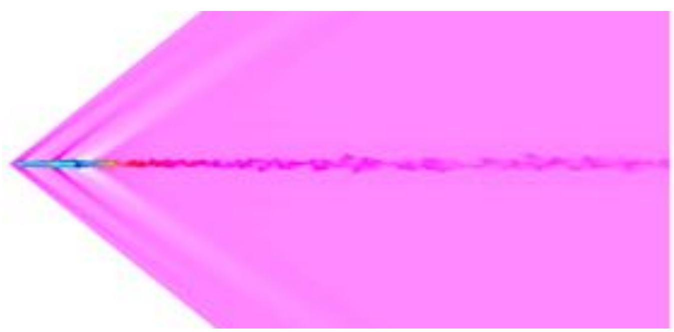
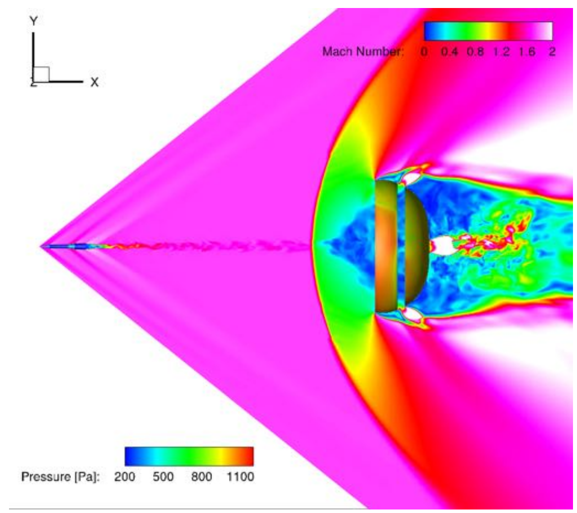
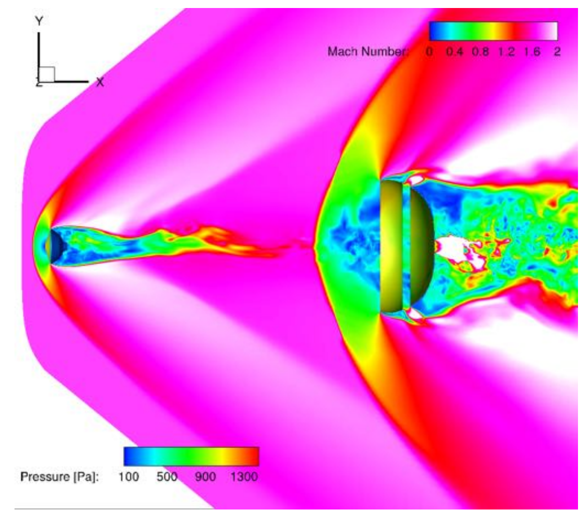
- Slender Body Simulations - to generate payload aerodynamic database.
- Wake Simulations - to explore blunt vs slender body differences, help with targeting during the flight test.
- Rigid Parachute Simulations - to investigate effect of leading body in parachute drag, generate pre-flight parachute drag model.
- Simulations in CO_2 - to extrapolate parachute performance over Earth and predict performance at Mars.





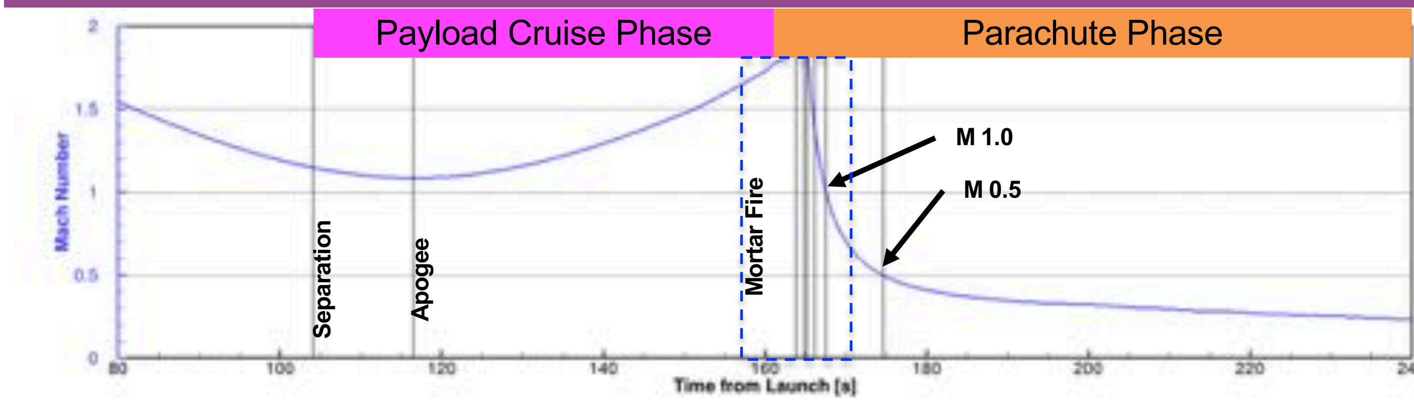


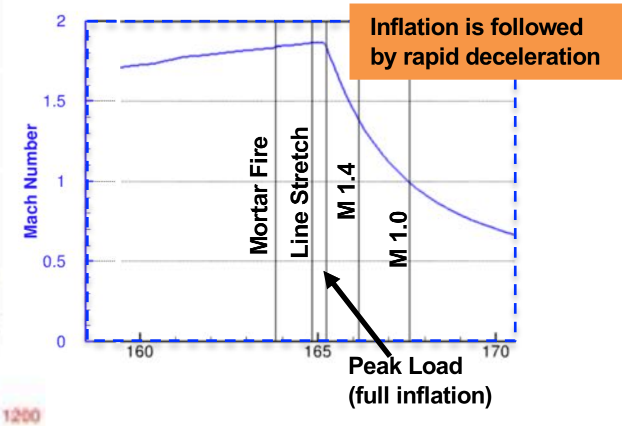


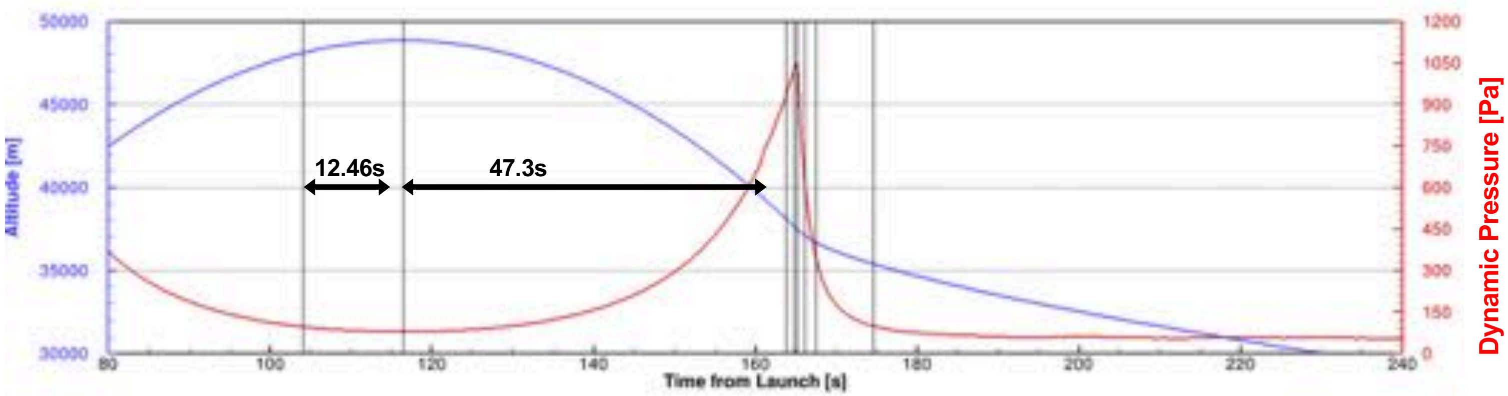


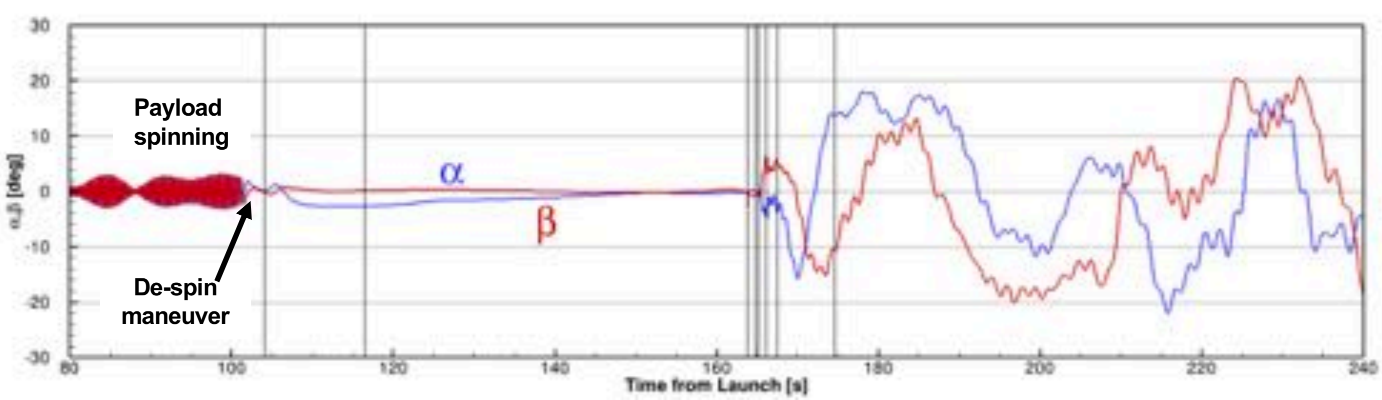
AIAA Aviation 2018: Modeling and Flight Performance of Supersonic Disk Gap Band Parachutes in Slender Body Wakes

SR03 Flight Trajectory









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

Payload Aerodynamics Models

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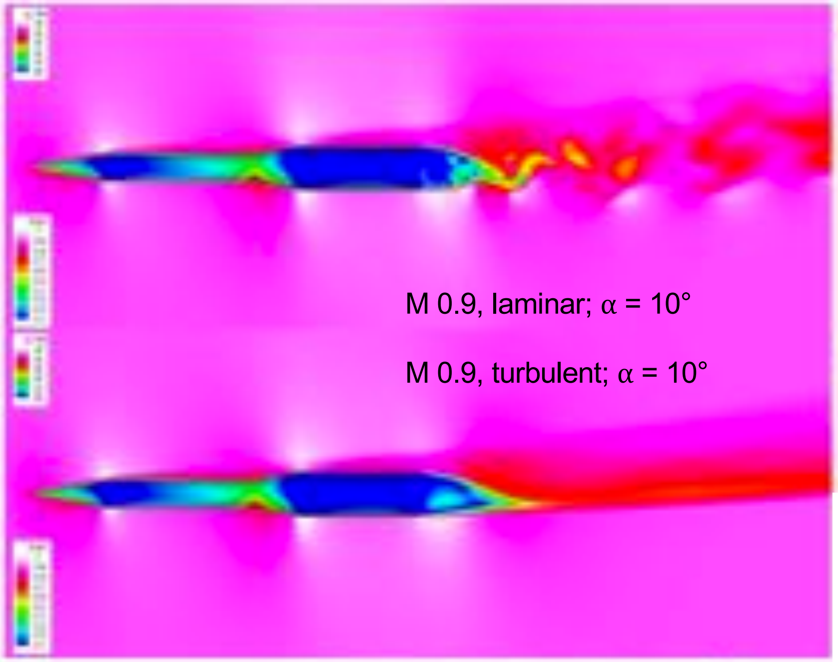
- Objective: To generate a Payload Aerodynamics Database to predict flight characteristics and performance
  - This model is used from the payload separation stage to the mortar-fire leading up to parachute deploy.
- Process: CFD Simulations of flow past the payload geometry at various conditions (freestream, angle of attack)
- Tools: OVERFLOW, DPLR, FUN3D
- Laminar and Turbulent flow calculations

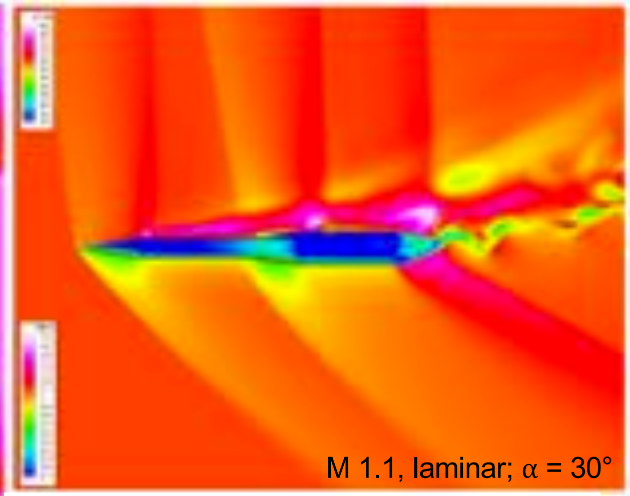
Mach	alt, m	T, K	ρ, kg/m3	V, m/s	p, Pa	q, Pa	Re/m
0.900	57848	254.9	4.330E-04	288.0	31.68	17.96	7.677E+03
1.100	55605	264.0	5.585E-04	358.2	42.32	35.84	1.198E+04
1.500	49450	271.0	1.228E-03	495.0	95.50	150.4	3.564E+04
2.444	39265	258.6	4.900E-03	787.9	363.7	1521	2.350E+05

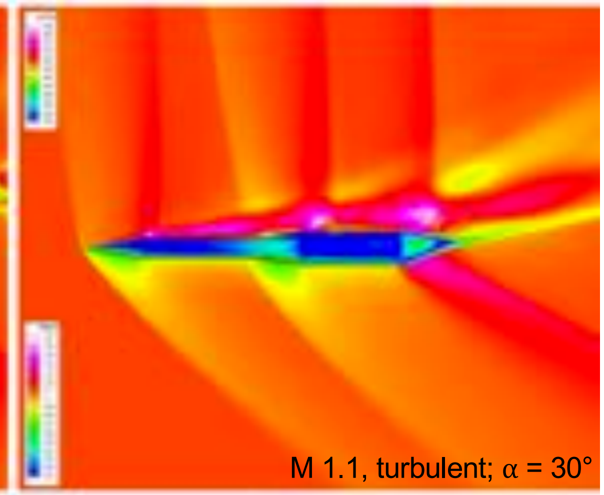
α_T = 0, 2, 5, 10, 15, 20, 30, 45, 60, 75°

- 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 → 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

Payload Flow Visualization

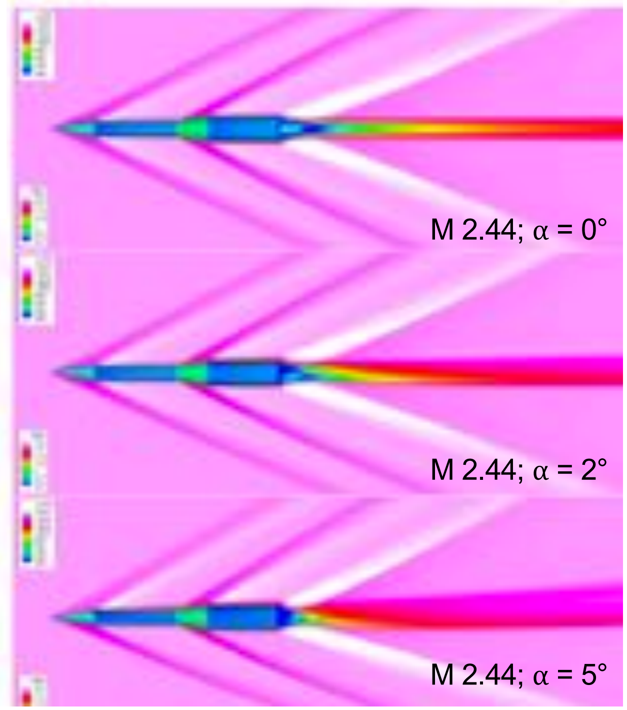


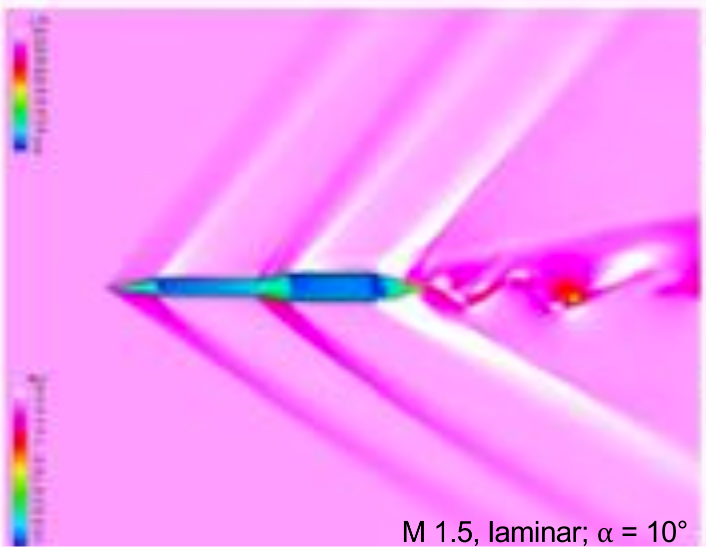


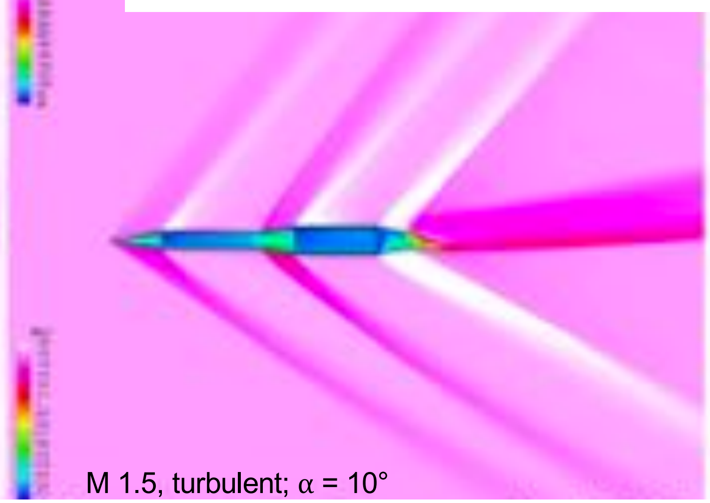


Payload length: 6.0 m
Payload diameter: 0.74 m

Flow is dominated by multiple shocks and expansions







Payload Aerodynamic Model

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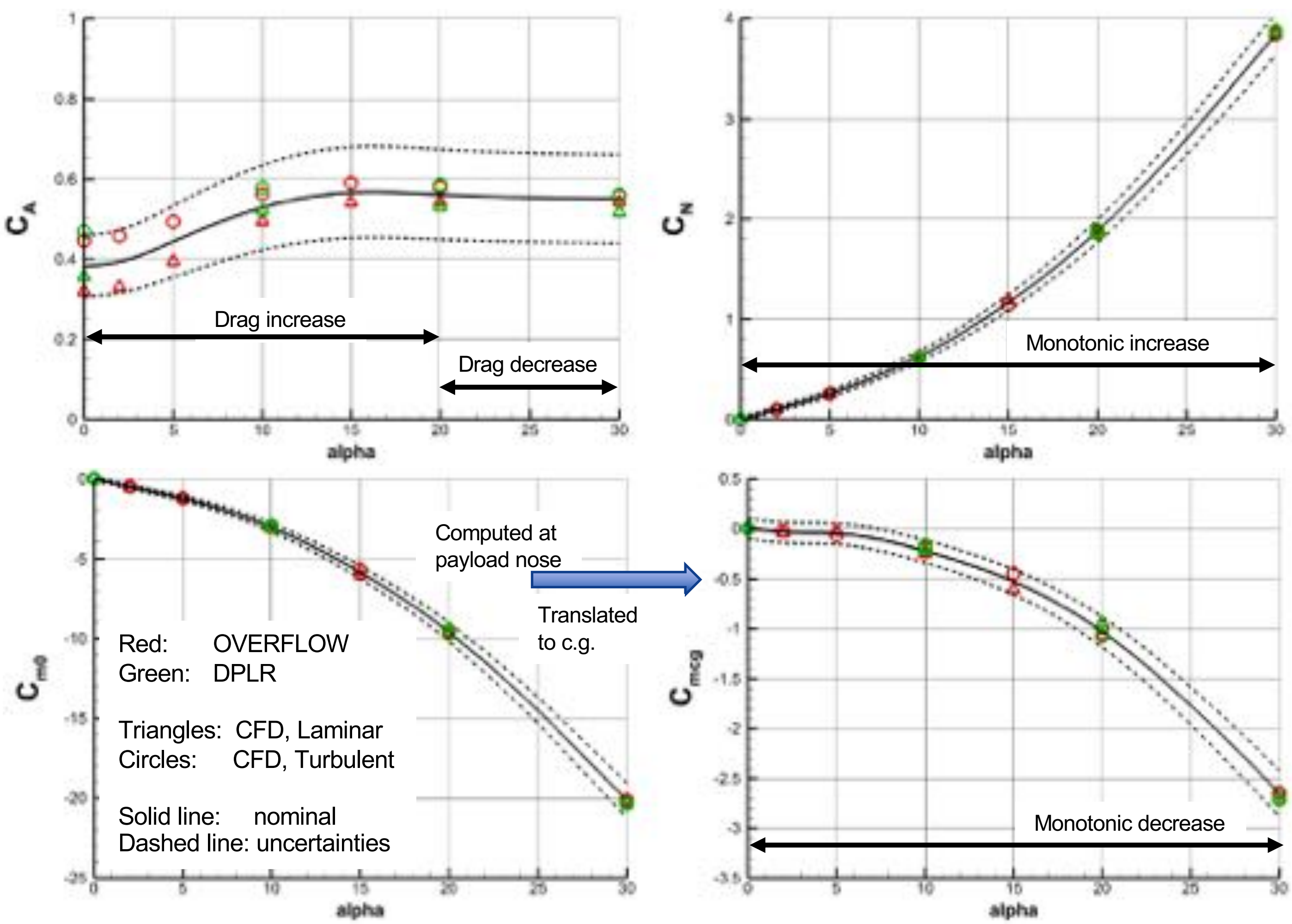
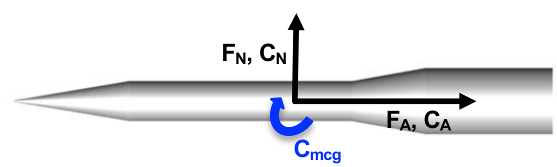
Freestream Mach number 1.5



- 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

Post-Flight Reconstruction

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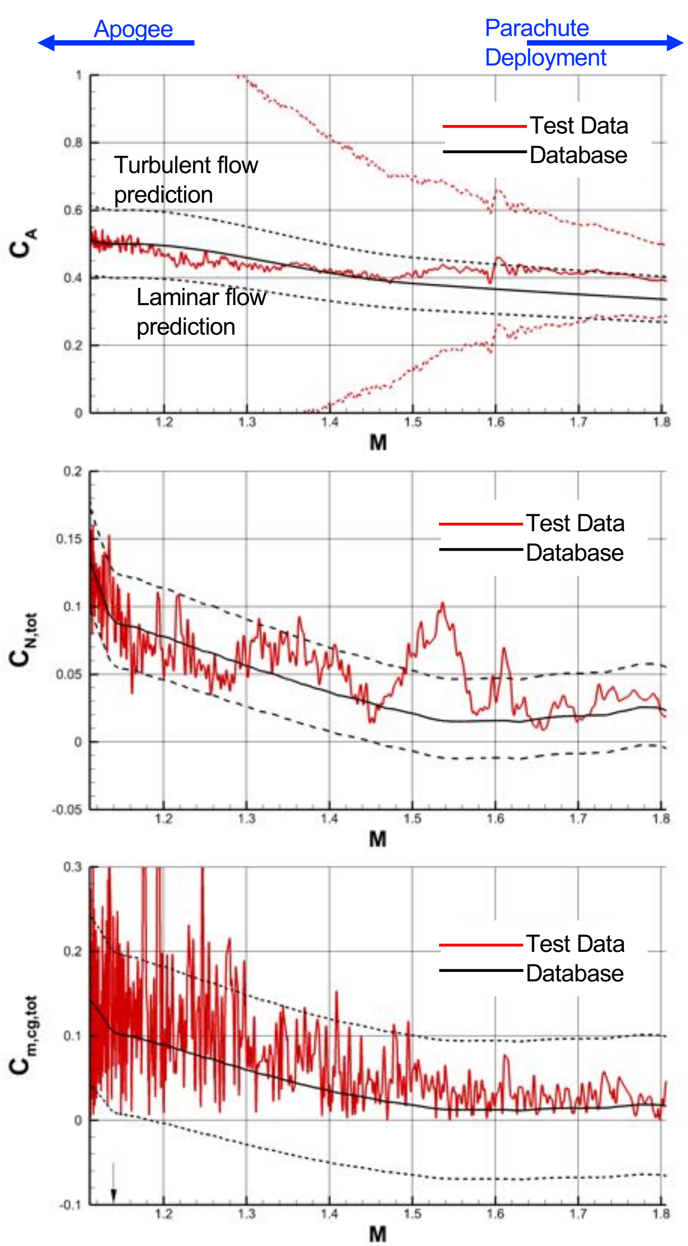
SR03 Flight data



On-board IMU
Atmospheric Model
GPS, and RADAR

→

Trajectory
(linear & angular accelerations)

→

Payload Aerodynamics

- 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:

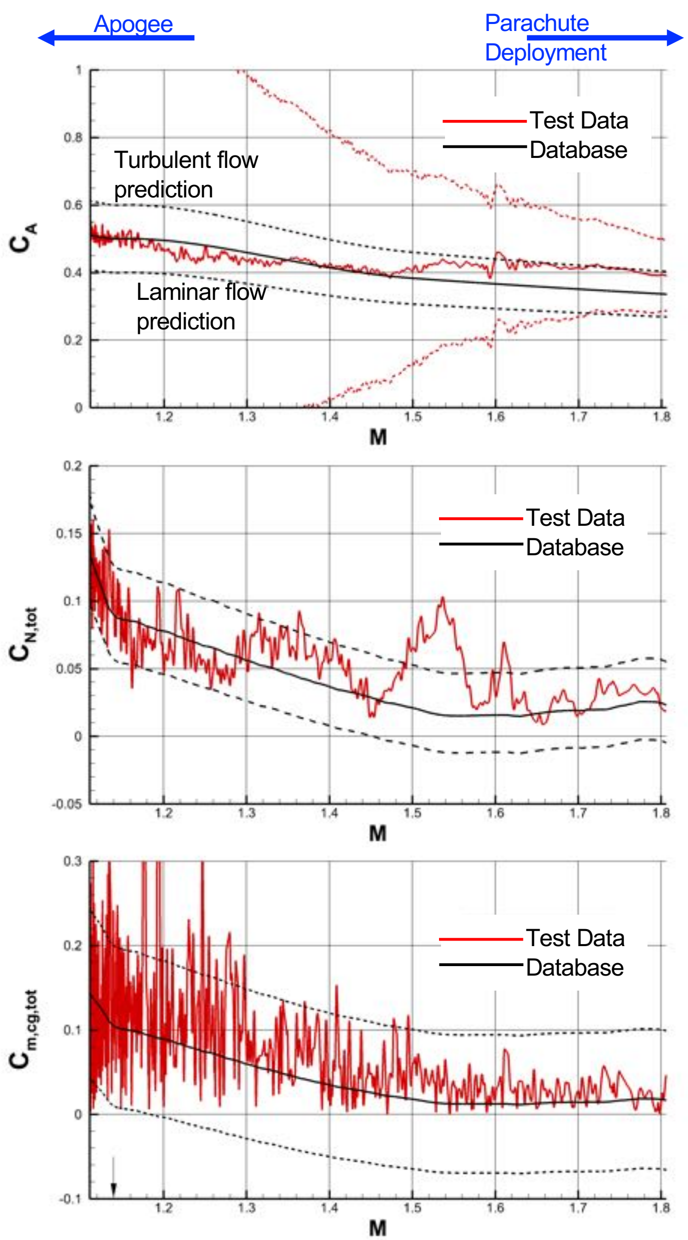
Validates design process

  - 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).

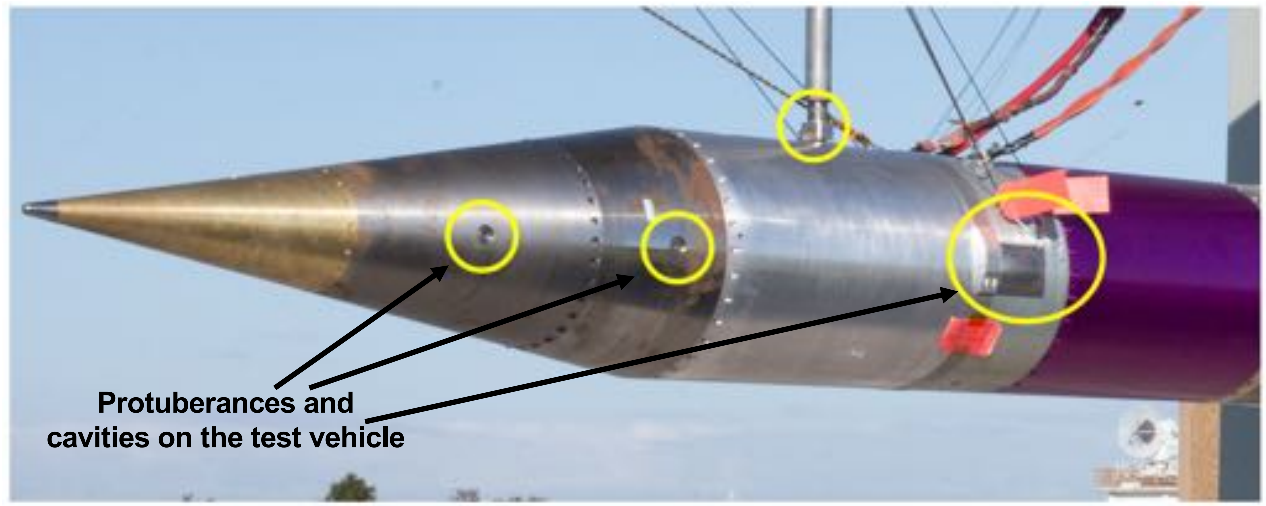
Payload Aerodynamics Reconstruction

ASPIRE

SR03 Flight data



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



- Comparisons show:
  - Flight data falls within the pre-flight bounds
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Parachute Aerodynamic Models

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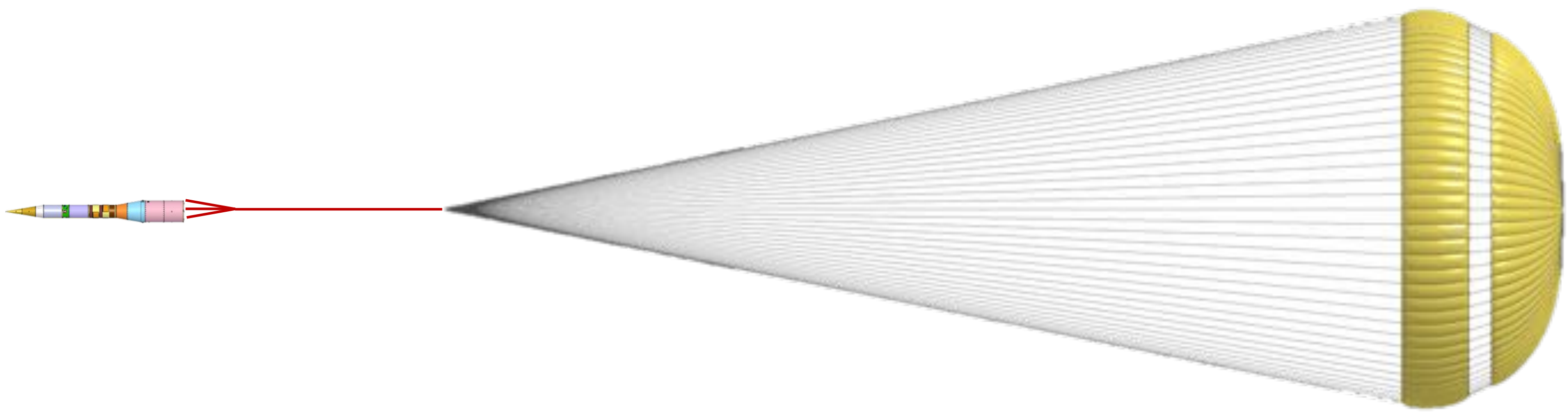
Challenges:

- Parachute performance depends on many variables
  (Mach number, geometry, leading body, fabric permeability, trailing distance etc)
- Little data on parachutes of this size and trailing distance at relevant Mach numbers behind a slender leading body

O'Farrell et al, 2017 IEEE Aerospace Conference, *Development of Models for Disk-Gap-Band Parachutes Deployed Supersonically in the Wake of a Slender Body*

Approach :

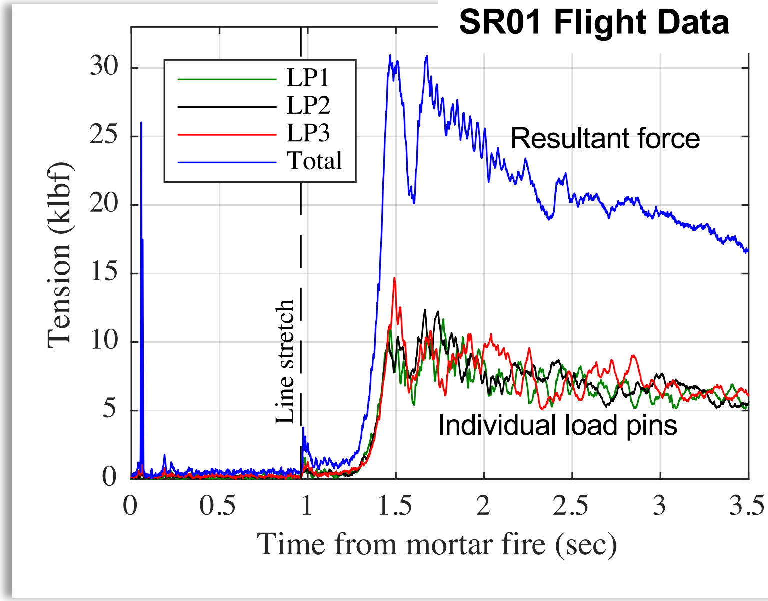
- Use models for MSL/M2020; use CFD to understand effect of leading body (blunt vs slender) & adjust



Parachute Deployment and Inflation

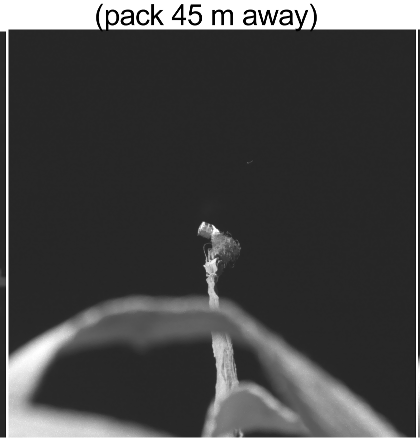
- Parachute deployment and inflation are highly dynamic events
- Time(s) :
  - Mortar fire (initiation) to line stretch: ~ 1.0 s
  - Line stretch to Full Inflation: ~ 0.5 s
- Tension measurements from load pins
  (Parachute force = tension + payload mass *x* acceleration)
- Full inflation followed by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

SR01 Flight Data

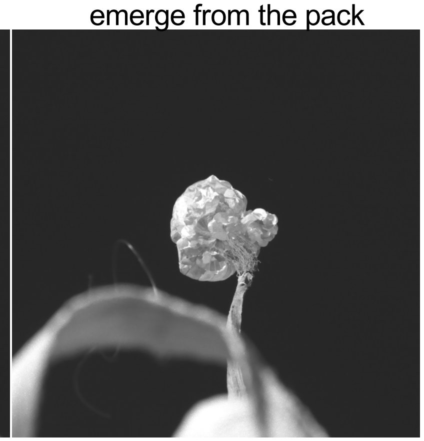


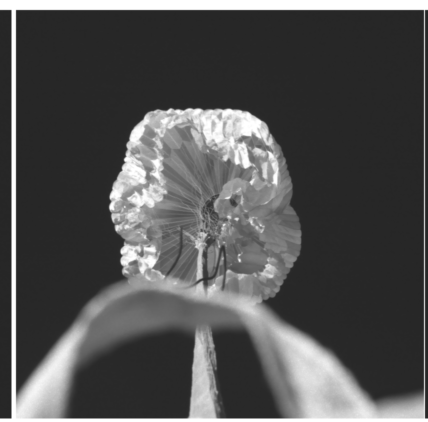
Parachute pack sailing away from the payload

Line Stretch (pack 45 m away)

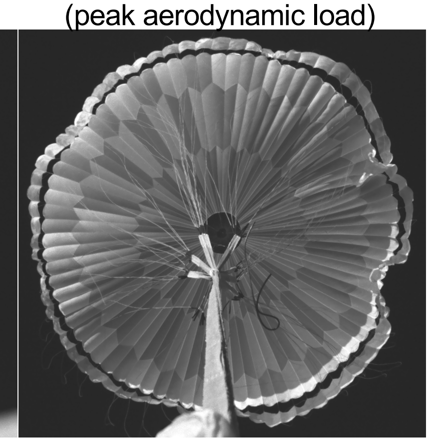


Parachute begins to emerge from the pack





Parachute Fully Inflated (peak aerodynamic load)



Images from the on-board high-speed camera

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

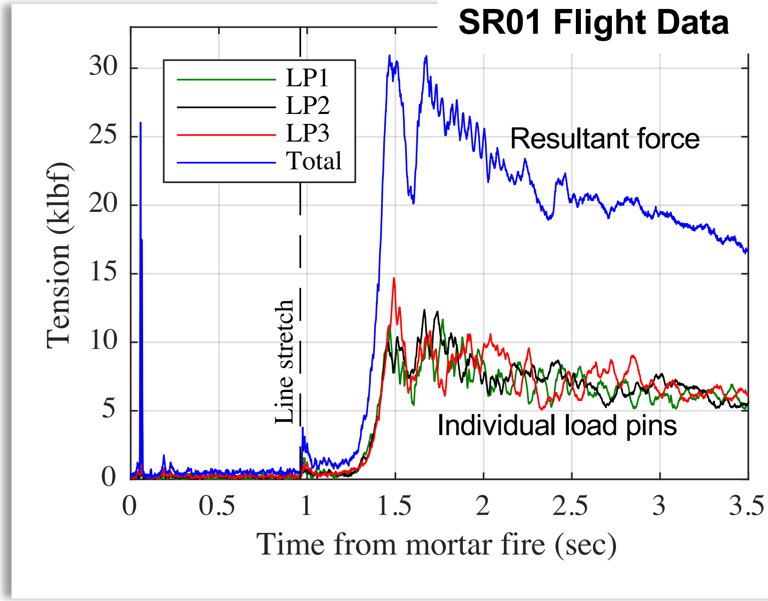
S_p: Parachute Projected Area
q_{∞}: Freestream dyn. press.
k_p: Inflation constant

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

Pre-flight range for k_p
(informed using CFD)

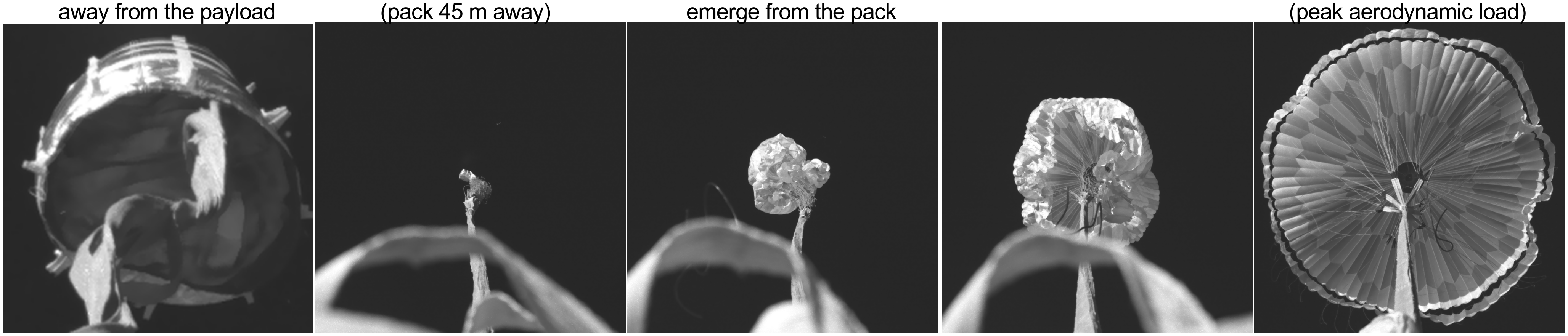
0.70 - 0.90

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

Parachute Drag Model Development

- Parachute drag model: Variation of C_d with freestream Mach number
- Very little flight test data for supersonic parachutes behind slender bodies and these conditions.
- MSL parachute drag model (behind blunt capsule) was modified to yield the ASPIRE parachute drag model.
- The modifications were informed by (limited) flight and wind tunnel tests, and numerical simulations.

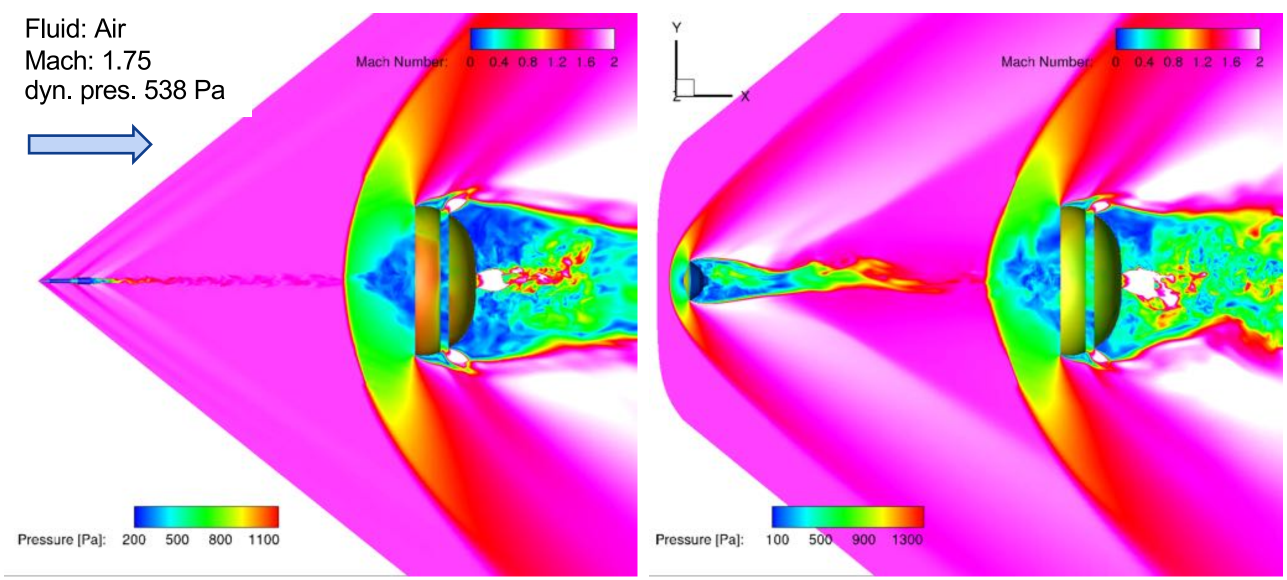
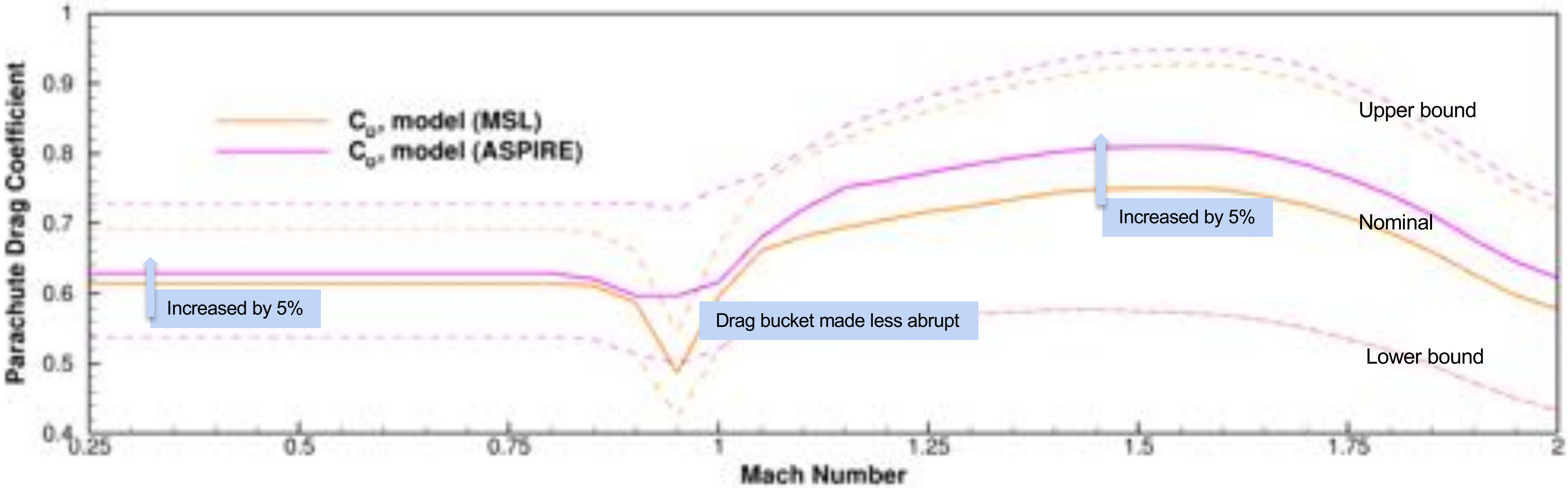


Image shows contours of Mach number on the cut-plane, contours of pressure on the leading body and parachute interior

Q. What is the effect of leading body on the drag of a rigid, simplified parachute ?

- Highly unsteady flow and aerodynamic forces
- Wake-parachute bow shock interaction stronger behind blunt body
- Mean parachute force behind the slender body is higher
- Consistent with a larger wake and deficit behind blunt body

Pre-Flight Parachute Drag Model



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

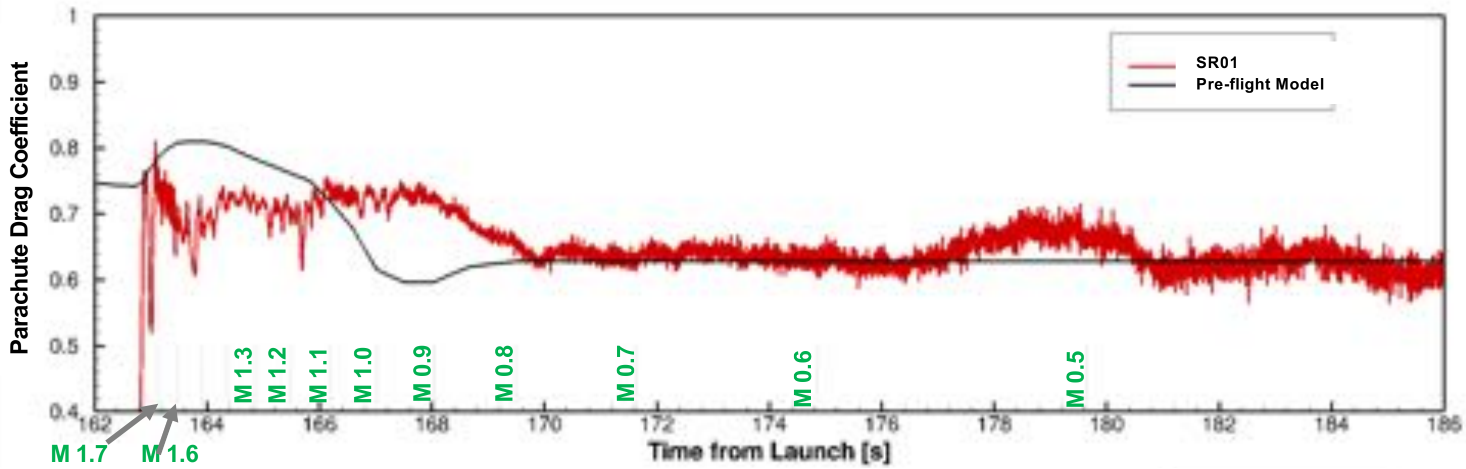
  Subsonic: Increased nominal drag performance and the high margin; retained the low margin

  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.

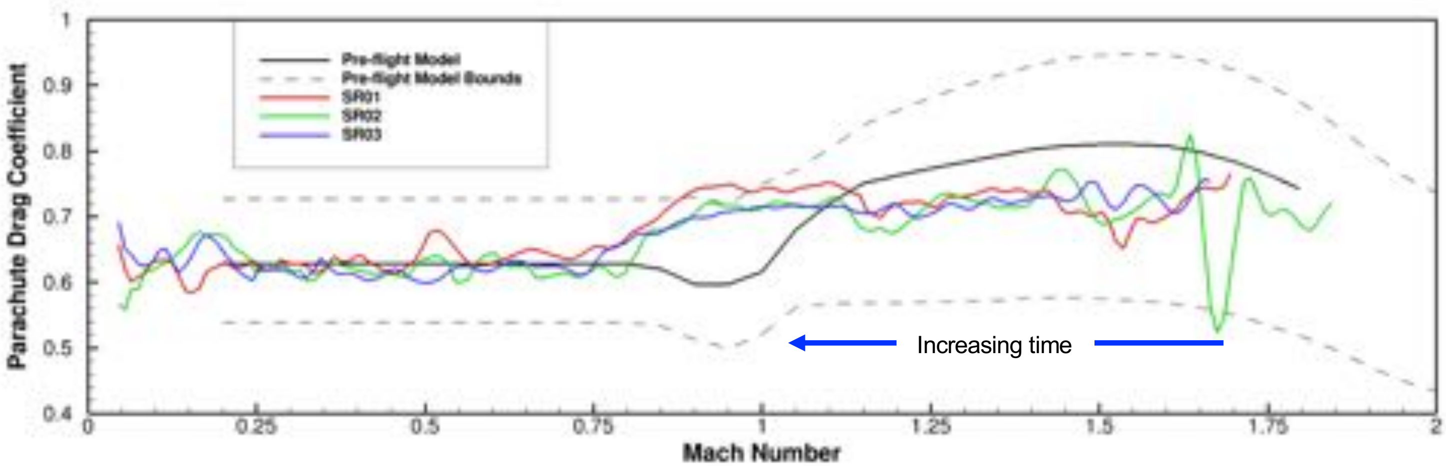
Reconstructed Parachute Drag



Good Agreement below Mach 0.75

Over-prediction above Mach 1.15

Test Data does not show a transonic drag reduction



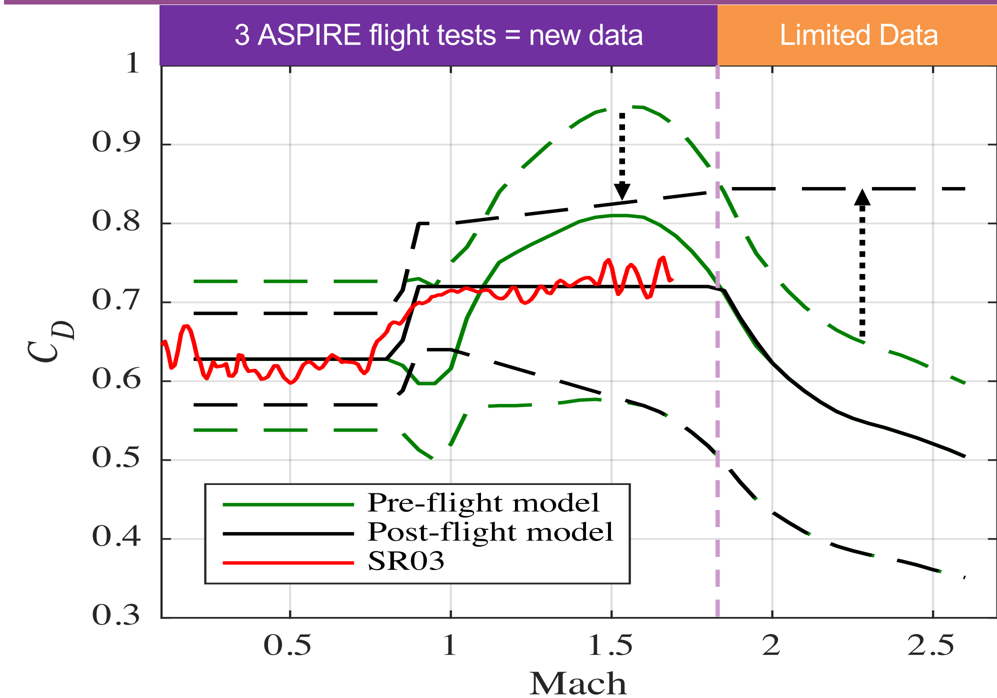
Consistent drag performance across three flights

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

Post-flight analysis indicates that the transonic drag decrease is a blunt leading body effect.

Updated Slender Body Parachute Drag Model



- M < 1.8: Takes advantage of the ASPIRE flight tests
- M > 1.8: *single* wind tunnel test + *single* flight test (shorter trailing distances; both show a reduction in parachute drag)

- Nominal Model:
  - Constant subsonic Cd (M < 0.75); unchanged from pre-flight model
  - Constant supersonic Cd (0.8 < M < 1.8); based on the flight tests
  - Revert to pre-flight Cd (M > 1.8); absence of new data

- Uncertainties:
  - Reduced subsonic uncertainty bounds (M < 0.8); based on the ASPIRE flight tests
  - Reduced supersonic uncertainty bounds (0.8 < M < 1.8)
  - Increased upper bound at higher Mach numbers ; no new data + account for possibility of near-constant drag coefficient

Conclusions

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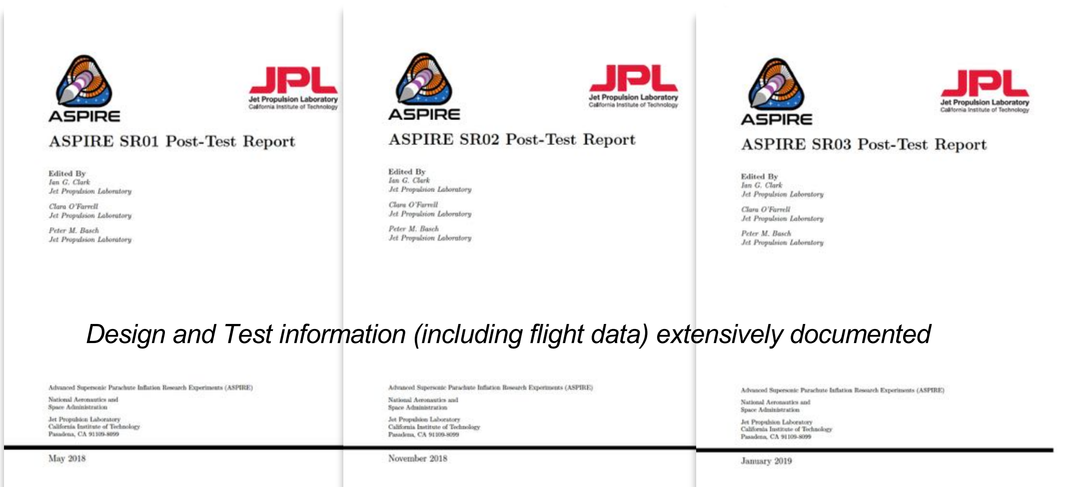
- ASPIRE project was launched to test supersonic parachutes at Mars relevant conditions
  first full-scale supersonic tests of parachute in over 40 years.
- ASPIRE established a framework for testing full-scale parachutes.
- Through the three flight tests, ASPIRE 'certified' a parachute for upcoming 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.



ASPIRE | JPL Jet Propulsion Laboratory, California Institute of Technology

ASPIRE SR01 Post-Test Report

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May 2018

ASPIRE | JPL Jet Propulsion Laboratory, California Institute of Technology

ASPIRE SR02 Post-Test Report

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ASPIRE SR03 Post-Test Report

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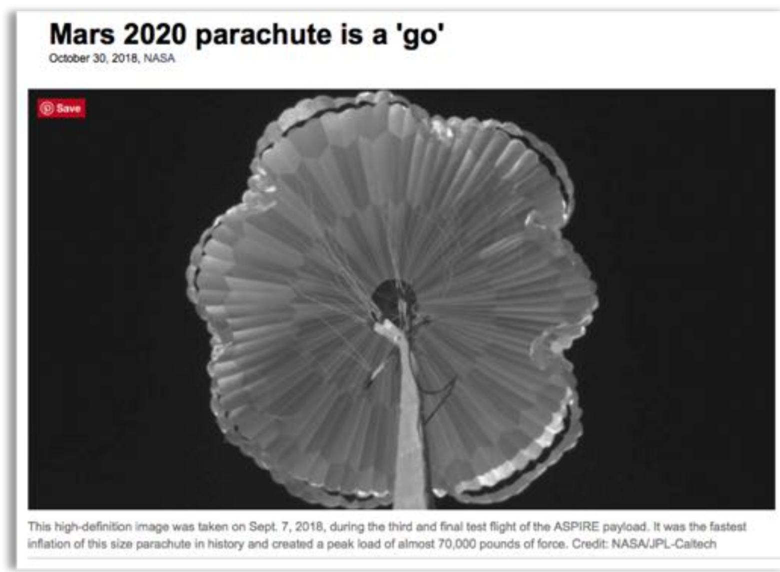
Pasadena, CA 91109-8099

January 2019

Design and Test information (including flight data) extensively documented



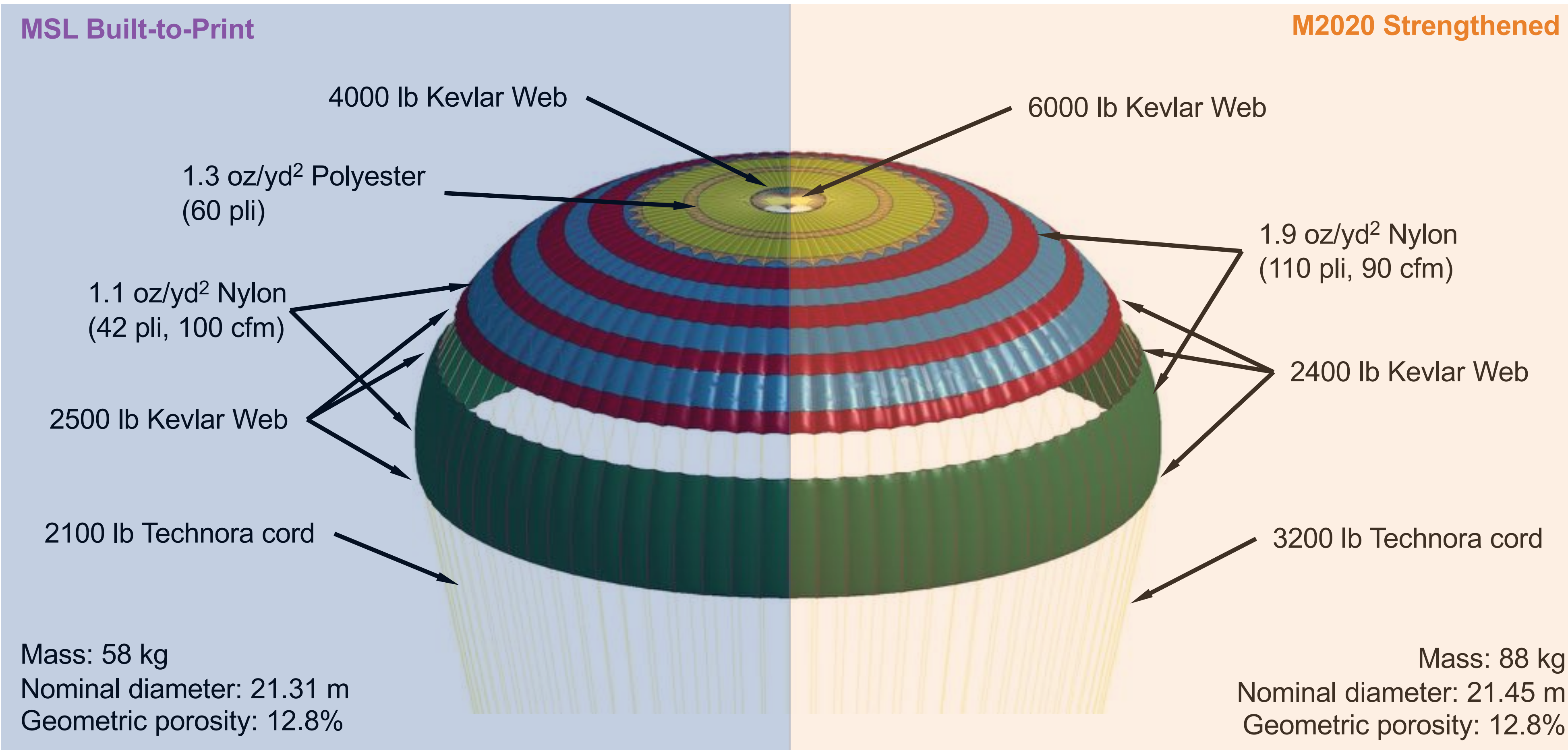
Backup

ASPIRE

Test Articles

Two candidate designs for Mars2020:

- A build-to-print 21.5-m MSL DGB (tested to 35 klbf on SR01)
- Strengthened version of MSL DGB (identical geometry, stronger materials)



Tanner, Clark, & Chen, *IEEE Aerospace 2018:* “Overview of the Mars 2020 Risk Reduction Activity”