ASPIRE Aerodynamic Models and Flight Performance

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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

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*).

**Table: Parachute Test Data**

<table>
<thead>
<tr>
<th>Test</th>
<th>Parachute</th>
<th>Parachute Inflation load</th>
<th>Inflation Mach Number</th>
<th>Dynamic Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR01 (Oct 2017)</td>
<td>MSL</td>
<td>32,400 lbf</td>
<td>1.77</td>
<td>495 Pa</td>
</tr>
<tr>
<td>SR02 (Mar 2018)</td>
<td>Mars2020</td>
<td>55,800 lbf</td>
<td>1.97</td>
<td>626 Pa</td>
</tr>
<tr>
<td>SR03 (Jul 2018)</td>
<td>Mars2020</td>
<td>67,400 lbf</td>
<td>1.85</td>
<td>1020 Pa</td>
</tr>
</tbody>
</table>

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

**Dimensions similar to MSL parachute**

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

**ASPIRE Disk-Gap-Band (DGB) Parachute**
ASPIRE Flight Test

Payload Sep
L+104.045 s
Alt: 49.92 km
Mach: 1.27

Apogee
L+119.1 s
Alt: 51.0 km
Mach: 1.19

Mortar Fire
L+161.4 s
Alt: 42.43 km
\( q_\infty: 450.3 \text{ Pa} \)
Mach: 1.77

Line Stretch
MF+0.961 s
\( q_\infty: 490 \text{ Pa} \)
Mach: 1.79

Peak Load
MF+1.47 s
\( q_\infty: 500.0 \text{ Pa} \)
Mach: 1.79

Splashdown
L + 34 min

2nd stage Brant burnout
L+35.1 s
Alt: 16.7 km
Mach: 3.34

2nd stage Brant ignition
L+8.16 s
Alt: 1.564 km

1st stage Terrier burnout
L+5.2 s
Alt: 0.796 km

Atlantic Ocean
54.9 km

Launch Site
(WFF, VA)

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

Thursday @ 11:00 AM:
211-ADS-12: Summary of ASPIRE Sounding Rocket Tests with a Disk-Gap-Band Parachute
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Mach: 3.34

**Splashdown**
L + 34 min

- 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

- 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 CO₂ - to extrapolate parachute performance over Earth and predict performance at Mars.
SR03 Flight Trajectory

**Payload Cruise Phase**
- Separation
- Apogee
- Payload spinning
- De-spin maneuver

**Parachute Phase**
- Mortar Fire
- Inflation is followed by rapid deceleration

**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

- **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**

- **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

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<table>
<thead>
<tr>
<th>Mach</th>
<th>alt, m</th>
<th>T, K</th>
<th>( p, \text{kg/m}^3 )</th>
<th>V, m/s</th>
<th>p, Pa</th>
<th>q, Pa</th>
<th>Re/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.900</td>
<td>57848</td>
<td>254.9</td>
<td>4.330E-04</td>
<td>288.0</td>
<td>31.68</td>
<td>17.96</td>
<td>7.677E+03</td>
</tr>
<tr>
<td>1.100</td>
<td>55605</td>
<td>264.0</td>
<td>5.585E-04</td>
<td>358.2</td>
<td>42.32</td>
<td>35.84</td>
<td>1.198E+04</td>
</tr>
<tr>
<td>1.500</td>
<td>49450</td>
<td>271.0</td>
<td>1.228E-03</td>
<td>495.0</td>
<td>95.50</td>
<td>150.4</td>
<td>3.564E+04</td>
</tr>
<tr>
<td>2.444</td>
<td>39265</td>
<td>258.6</td>
<td>4.900E-03</td>
<td>787.9</td>
<td>363.7</td>
<td>1521</td>
<td>2.350E+05</td>
</tr>
</tbody>
</table>

\( \alpha_{T} = 0, 2, 5, 10, 15, 20, 30, 45, 60, 75^\circ \)
Payload Flow Visualization

Payload length: 6.0 m
Payload diameter: 0.74 m

Flow is dominated by multiple shocks and expansions

M 0.9, laminar; $\alpha = 10^\circ$
M 0.9, turbulent; $\alpha = 10^\circ$

M 1.1, laminar; $\alpha = 30^\circ$
M 1.1, turbulent; $\alpha = 30^\circ$

M 1.5, laminar; $\alpha = 10^\circ$
M 1.5, turbulent; $\alpha = 10^\circ$

M 2.44; $\alpha = 0^\circ$
M 2.44; $\alpha = 2^\circ$
M 2.44; $\alpha = 5^\circ$
Payload Aerodynamic Model

- 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

- 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:
  - 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).
SR03 Flight data

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

- Comparisons show:
  - 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).
Parachute Aerodynamic Models

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

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.

Images from the on-board high-speed camera
Parachute Deployment and Inflation

- Peak Aerodynamic Load during SR01: 32.4 k lbf (144.07 kN)
  
  *(Pre-flight prediction 35,000 lbf)*

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

<table>
<thead>
<tr>
<th>Test</th>
<th>dyn. press.</th>
<th>Inflation Load</th>
<th>( k_p )</th>
</tr>
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<tbody>
<tr>
<td>SR01</td>
<td>495 Pa</td>
<td>32,400 lbf</td>
<td>0.77</td>
</tr>
<tr>
<td>SR02</td>
<td>626 Pa</td>
<td>55,800 lbf</td>
<td>0.78</td>
</tr>
<tr>
<td>SR03</td>
<td>1020 Pa</td>
<td>67,400 lbf</td>
<td>0.76</td>
</tr>
<tr>
<td>MSL</td>
<td>35,000 lbf</td>
<td></td>
<td>0.83</td>
</tr>
</tbody>
</table>

\( k_p \) 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 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.

**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

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

1. M < 1.8: Takes advantage of the ASPIRE flight tests
2. 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

• 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.

Design and Test information (including flight data) extensively documented
Backup
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)

**MSL Built-to-Print**
- 1.3 oz/yd² Polyester (60 pli)
- 1.1 oz/yd² Nylon (42 pli, 100 cfm)
- 2500 lb Kevlar Web
- 2100 lb Technora cord

**M2020 Strengthened**
- 1.9 oz/yd² Nylon (110 pli, 90 cfm)
- 2400 lb Kevlar Web
- 3200 lb Technora cord

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

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