ASPIRE Aerodynamic Models and Flight Performance

Suman Muppidi  AMA Inc., NASA Ames Research Center
Clara O’Farrell  Jet Propulsion Laboratory, California Institute of Technology
John Van Norman  AMA Inc., NASA Langley Research Center
Ian Clark  Jet Propulsion Laboratory, California Institute of Technology

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Introduction

- 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

- Wind Tunnel Testing
  - Low-altitude drop testing
  - High-altitude supersonic Testing
- Subscale Development Tests
- Subsonic low-altitude qualification tests
- No new Supersonic Qualification
• 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).

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

<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>

Dimensions similar to MSL parachute

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

**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 Flight Test

1st stage Terrier burnout
L + 5.2 s
Alt: 0.796 km
Mach: 1.27

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

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

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

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∞: 450.3 Pa
Mach: 1.77

Line Stretch
MF + 0.961 s
q∞: 490 Pa
Mach: 1.79

Peak Load
MF + 1.47 s
q∞: 500.0 Pa
Mach: 1.79

Splashdown
L + 34 min

Atlantic Ocean
54.9 km

Launch Site
(WFF, VA)

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.
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
- Payload spinning
- De-spin maneuver

Parachute Phase
- Separation
- Apogee
- Mortar Fire

Altitude and Dynamic Pressure

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

Inflation is followed by rapid deceleration
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

<table>
<thead>
<tr>
<th>Mach</th>
<th>alt, m</th>
<th>T, K</th>
<th>$\rho$, 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>4.33E-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>5.58E-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>1.22E-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>4.90E-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).
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
- 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

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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>
</thead>
<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></td>
<td>35,000 lbf</td>
<td>0.83</td>
</tr>
</tbody>
</table>

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

Images from the on-board high-speed camera

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
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

- 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**
- 4000 lb Kevlar Web
- 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**
- 6000 lb Kevlar Web
- 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%