Parachute Decelerator System Performance During the Low Density Supersonic Decelerator Program’s First Supersonic Flight Dynamics Test

John C. Gallon\textsuperscript{1}, Ian G. Clark\textsuperscript{2}

\textit{Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA 91109, USA}

\textit{and}

Allen Witkowski\textsuperscript{3}

\textit{Pioneer Aerospace Corporation, South Windsor, CT 06074, USA}

During the first Supersonic Flight Dynamics Test (SFDT-1) for NASA’s Low Density Supersonic Decelerator (LDSD) Program, the Parachute Decelerator System (PDS) was successfully tested. The main parachute in the PDS was a 30.5-meter supersonic Disksail parachute. The term Disksail is derived from the canopy’s constructional geometry, as it combined the aspects of a ringsail and a flat circular round (disk) canopy. The crown area of the canopy contained the disk feature, as a large flat circular disk that extended from the canopy’s vent down to the upper gap. From this upper gap to the skirt-band the canopy was constructed with characteristics of sails seen in a ringsail. There was a second lower gap present in this sail region. The canopy maintained a nearly 10x forebody diameter trailing distance with 1.7 Do suspension line lengths. During the test, the parachute was deployed at the targeted Mach and dynamic pressure. Although the supersonic Disksail parachute experienced an anomaly during the inflation process, the system was tested successfully in the environment it was designed to operate within. The nature of the failure seen originated in the disk portion of the canopy. High-speed and high-resolution imagery of the anomaly was captured and has been used to aid in the forensics of the failure cause. In addition to the imagery, an inertial measurement unit (IMU) recorded test vehicle dynamics and loadcells captured the bridle termination forces. In reviewing the imagery and load data a number of hypothesizes have been generated in an attempt to explain the cause of the anomaly.

Nomenclature

\begin{tabular}{ll}
\texttt{BLDT} & Balloon-Launched Decelerator Test \\
\texttt{Do} & Nominal Parachute Diameter \\
\texttt{DGB} & Disk-Gap-Band \\
\texttt{IMU} & Inertial Measurement Unit \\
\texttt{JPL} & Jet Propulsion Laboratory \\
\texttt{LDSD} & Low Density Supersonic Decelerator \\
\texttt{NAWCWD} & Naval Air Warfare Center Weapons Division \\
\texttt{NFAC} & National Full-Scale Aerodynamics Complex \\
\texttt{SFDT} & Supersonic Flight Dynamics Test (“- number” suffix indicates which SFDT test) \\
\texttt{SNORT} & Supersonic Naval Ordnance Research Tracks \\
\texttt{SSRS} & Supersonic Ringsail \\
\texttt{SSDS} & Supersonic Disksail \\
\texttt{PAC} & Pioneer Aerospace Corporation \\
\texttt{PDD} & Parachute Deployment Device \\
\end{tabular}

\textsuperscript{1} LDSD Parachute Cognizant Engineer, AIAA Member, john.c.gallon@jpl.nasa.gov
\textsuperscript{2} LDSD Principal Investigator, AIAA Member, ian.g.clark@jpl.nasa.gov
\textsuperscript{3} Director of Engineering Operations, AIAA Associate Fellow, al.witkowski@zodiacaerospace.com
I. Introduction

The Low Density Supersonic Decelerator (LDSD) project has undertaken the task of developing a large Supersonic Parachute to provide improved capabilities for future Mars landed missions. NASA has identified the need for a new parachute system to support an increase in payload mass, target higher altitude landing sites, and improve landing accuracy. As Mars-bound spacecraft continue to get larger and the possibility of future manned missions arises, the state of the art in low density supersonic parachutes must also advance. To date, all seven of the successful Mars landings have employed disk-gap-band (DGB) parachutes, which were based on a design that was developed in the 1960’s and 1970’s for the Viking Mars mission. While the success of the MSL parachute expands the DGB flight proven size envelope, it still falls short of the necessary drag performance expected to be required by future missions. To increase the parachute diameter requires a new parachute qualification and, to that end, the LDSD project is continuing the process of developing and flight-testing these supersonic parachutes. The first supersonic test of the proposed next generation supersonic parachute for Mars was successfully tested on June 28th, 2014 in the Supersonic Flight Dynamics Test #1(SFDT-1).

Figure 1: Overview of the LDSD Supersonic Flight Test Architecture
Figure 1 shows an overview of the SFDT. In this test, a large helium balloon is used to hoist a 4.7 m diameter blunt body test vehicle (TV) to an altitude of over 36 km. The test vehicle is released from the balloon, spun-up for stability, and a Star-48 solid rocket motor ignites. The motor accelerates the test vehicle to speeds over Mach 4 at an altitude of 50 km. Upon burn-out, the vehicle is de-spun and the primary test phase begins. Shortly thereafter, the first of the technologies, a Supersonic Inflatable Aerodynamic Decelerator (SIAD) is deployed. Later in the flight, the Parachute Deployment Device (PDD) is mortar fired, inflated, and subsequently used as a pilot device to extract and deploy the large supersonic parachute from the test vehicle. The parachute decelerates the vehicle to subsonic conditions and the vehicle descends to the ocean for recovery.

SFDT-1 was conducted with a balloon launch from the Pacific Missile Range Facility (PMRF) on Kauai, Hawaii. The test successfully demonstrated all aspects of the integration and test, balloon launch, balloon operation, test vehicle operation, test vehicle flight, and recovery. The parachute was deployed within the desired operational envelope and succeeded in becoming fully inflated; however, in the midst of parachute inflation, at least three large tears were observed in the disk portion of the Supersonic Disksail (SSDS). The tears propagated radially until the parachute suffered significant failure at the moment of full inflation. The test infrastructure included first-of-a-kind imaging that allowed the team to observe the supersonic parachute inflation dynamics at levels of detail never before observed. This paper provides documentation of the results of the supersonic parachute test only. It does not include balloon launch and float, flight and performance of the test vehicle, or the performance of the other technologies tested, such as the SIAD or the PDD.

II. Disksail Parachute

The parachute tested on SFDT-1 was a 96 gore, 30.5 m D₀ Supersonic Disksail, as shown in Figure 2. The Disksail parachute merges design elements of both a Ringsail parachute and a Disk-Gap-Band (DGB) parachute. The design began with a 22 panel, 96-gore design for a 33.5 m D₀ Ringsail parachute tested as part of the 2004 Subsonic Parachute Technology Task (SPTT). The smaller Disksail design reduces the base number of panels to 20 and subsequently replaces the upper 9 panels of the crown with a flat circular disk. The remaining 11 panels constitute sails of increasing fullness, with panels 10-12 having 6% fullness and panels 13-19 having 12% fullness. Panel 20 contains zero fullness, as per typical Ringsail design. Two gaps are present, one large gap at the edge of the disk and another shorter gap between the 15th and 16th panels. The parachute had an as designed geometric porosity of 13.69%, though the as-built geometric porosity of the canopy tested was estimated as 13.06%.
Figure 2: Supersonic Disksail Parachute

Construction of the parachute utilized Kevlar for the radial and circumferential skeleton. The circumferentials were made from PIA-T-87130, Ty I, Cl 2 Kevlar tape, at the trailing edge of each of the sails. The leading edge of the disk portion of the canopy included a PIA-C-87130, Ty I, Cl 3 Kevlar Tape. The radial tapes and skirt band were constructed from PIA-T-87130, TVI, Cl 6 Kevlar tape. The 96 suspension lines and 48 vent lines were each PAC PN 12518-1, 2100 lbf Technora cord. The vent band was a PIA-W-4088, Ty VII, Cl 1A Nylon webbing.

Sail panels of the parachute were made from 1.2 oz/yd² PIA-C-44378 Ty I (aka F-111) ripstop Nylon with a minimum specified strength of 45 lbf/in. The disk is constructed predominantly of PIA-C-44378 with the exception of a region near the vent, which was constructed from PAC PN 12220-1, 1.9 oz/yd² Diamond Weave ripstop Nylon, which has a minimum specified strength of 80 lbf/in in the warp direction and 85 lbf/in in the fill direction. Low or zero-permeability materials were intentionally selected for parachute construction. The nominal permeability of PIA-C-44378 is 0-5 cfm while the Diamond Weave permeability is 20-50 cfm. Because of this, the total porosity, including the effects of material permeability, of the Disksail should be very close to the geometric porosity.
Table 1: SSDS As-Designed and Primary As-Measured Geometric Properties

<table>
<thead>
<tr>
<th>Item</th>
<th>Relative Design Value</th>
<th>Dimensional Design Value</th>
<th>As-Measured Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Diameter, $D_0$</td>
<td>$D_0$</td>
<td>30.5 m</td>
<td>30.407 m</td>
</tr>
<tr>
<td>Geometric Porosity</td>
<td>13.69% $S_0$</td>
<td>100.021 m²</td>
<td>13.06% $S_0$</td>
</tr>
<tr>
<td>Total Area, $S_0$</td>
<td>$(\pi/4)D_0^2$</td>
<td>730.617 m²</td>
<td>726.149 m²</td>
</tr>
<tr>
<td>Disk Area</td>
<td></td>
<td>163.925 m²</td>
<td></td>
</tr>
<tr>
<td>Disk Diameter</td>
<td></td>
<td>14.447 m</td>
<td></td>
</tr>
<tr>
<td>Ring 10-19 Height</td>
<td></td>
<td>0.635 m</td>
<td></td>
</tr>
<tr>
<td>1st Gap Height</td>
<td></td>
<td>0.422 m</td>
<td></td>
</tr>
<tr>
<td>2nd Gap Height</td>
<td></td>
<td>0.635 m</td>
<td></td>
</tr>
<tr>
<td>Vent Area</td>
<td>0.4% $S_0$</td>
<td>1.993 m²</td>
<td></td>
</tr>
<tr>
<td>Vent Diameter</td>
<td></td>
<td>1.593 m</td>
<td></td>
</tr>
<tr>
<td>Number of Suspension Lines</td>
<td></td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>Length of Suspension Lines</td>
<td>1.7$D_0$</td>
<td>51.85 m</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3: Dimension of the Deployed SSDS Configuration

The parachute was packed in a two-stage deployment bag. The canopy and approximately 8m of suspension lines were packed into an inner bag and the remainder of the suspension lines were packed into the outer bag. The achieved density of the pack was calculated as 552.6 kg/m³ (34.5 lbm/ft³). After deployment, the inner bag remained attached to the parachute vent lines while the outer bag remained with the ballute. Figure 4 illustrates the deployment process.
This paper will discuss the results of the test starting from the PDD triple bridle release through the SSDS inflation and resultant state thereafter. For additional details on the PDD performance and pack parachute extraction and deployment see references 4 and 5.

**III. Deployment**

The supersonic parachute deployment starts with PDD triple bridle release, which initiates the SSDS bag extraction as illustrated in Figure 4. This pyrotechnic event happened 166.57 seconds after the TV was dropped away from the balloon. The PDD bridle is released via three pyrotechnic cutters at the test vehicle interface, which severs the structural connection of the ballute to the vehicle. It is the event that marks the start of the parachute deployment. At this point the structural load path from the ballute switches from the test vehicle to the SSDS parachute pack, which results in the extraction of the pack from the test vehicle. At the moment of PDD bridle cut, the ballute was in a stable flight behind the test vehicle with a measured drag force of approximately 4,862 N (1,093 lbs). Reconstruction times of the test events for the parachute deployment are referenced from the instance of test vehicle drop from the balloon. The PDD bridle load pins indicated that all three bridles legs were cut simultaneously. This resulted in the ballute’s drag force very quickly transferring to the parachute pack, and the parachute pack was out of the parachute can 0.27 seconds after PDD bridle cut as shown in Figure 6.

The parachute triple bridle, which was stowed on the aft deck of the TV, was deployed through the break ties and thermal insulation as expected (Figure 7). The bridle stiffeners successfully supported the triple bridle. The only bridle contact observed was during deployment, when bridle leg 1 impacted the top of the STAR-48 nozzle. This impact was not unexpected, as ground testing with the rigging deployment indicated that due to the deployment dynamics an impact was probable. The triple bridle included carbon-fiber stiffeners that ran in parallel to the structural bridles from the TV bridle connection to the confluence point of the bridles. These stiffeners were intended to mitigate the dynamics of the bridle legs during deployment to reduce the risk of snagging or tangling with hardware on the aft-deck. In addition, once deployed, the stiffeners were designed to reduce the possibility of the triple bridle falling back toward the hot Star-48 rocket motor before the parachute had a chance to inflate and support the bridles in an upright position. Although the stiffeners increased the rigidity of the bridles, they were still
flexible enough to flex as required during deployment. No damage was observed to the bridle or stiffeners during the deployment process. Although one of the bridles impacted the rocket motor, the outer sheathing of the bridle and the dynamic mode modification provided by the stiffeners resulted in no damage to the bridle from either contacting the hot rocket motor nozzle or abrasion damage from the impact. Once the triple bridle has stood up and the stiffeners are in their upright position, the back of the parachute pack is allowed to open up via the breaking of a strong break-tie and then the severing of the pack mouth restraint tie via redundant lanyard activated cut-knives. The parachute pack mouth was cut open as expected by the triple bridle snatch 0.62 seconds after PDD bridle cut as shown in the sequence of images in Figure 8.

The suspension lines deployed cleanly from the parachute deployment bag without any observed dumping or tangling. The deployment bag was packed so that 52 meters from the test vehicle the outer deployment bag would strip of the inner bag and fly away with the ballute, leaving the inner bag to fly free with momentum, mimicking the deployment dynamics of a mortar fired. Visual examination of the high-resolution images indicates that the outer parachute deployment bag was successfully separated from the inner deployment bag. There is no data to show exactly when the outer deployment bag separated, but one of the high-resolution images seems to show the white surface of the inner deployment bag exposed as expected (Figure 9). The deployment reconstruction indicates that the ballute separation should have occurred 0.16 s before line stretch, so this is plausible evidence. Later images clearly show the outer bag completely separated behind the canopy. Additional information on the deployment reconstruction can be found in reference 5.

The parachute pack reached line stretch 2.06 seconds after PDD bridle cut. The dynamics of the parachute deployment cannot be accurately modeled with analytical methods, so a numerically integrated model is utilized to reconstruct the parachute pack velocity relative to the test vehicle during deployment. The vehicle trajectory at PDD bridle cut is used as an input to the reconstruction model. A summary of the reconstruction model results is in Table 2.

The axial parachute loads recorded at the vehicle interface indicate the canopy extraction time, as shown in Figure 5. The axial load clearly indicates a region of higher force, which is attributed to the increased momentum transfer during canopy extraction due to the change in linear density deploying from suspension lines to canopy. The load reaches a minimum around 168.9 seconds before increasing again from aerodynamic loading. This possibly indicates that the canopy was fully extracted prior to inflation, as the momentum transfer would have stopped once the canopy was fully stretched. Additionally, the bag strip ratio (defined as canopy extraction time from line stretch divided by the full inflation time from line stretch) for the deployment was 0.37. This is in the neighborhood of prior successful supersonic parachute deployments conducted in the 1960’s and 70’s.

<table>
<thead>
<tr>
<th>Event</th>
<th>Observed</th>
<th>Reconstructed</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDD Bridle Cut</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>SSDS Pack out of Can</td>
<td>0.27</td>
<td>0.27</td>
</tr>
<tr>
<td>SSDS Pack Mouth Open</td>
<td>0.62</td>
<td>0.64</td>
</tr>
<tr>
<td>Ballute Separation (52 m)</td>
<td>n/a</td>
<td>1.96</td>
</tr>
<tr>
<td>SSDS Line Stretch</td>
<td>2.06</td>
<td>2.12</td>
</tr>
<tr>
<td>SSDS Bag Strip</td>
<td>2.30</td>
<td>2.42</td>
</tr>
</tbody>
</table>
Figure 5: Axial parachute force on the test vehicle during canopy extraction. Note that line stretch load spike is around 168.63 seconds after drop.
Figure 6: Image sequence showing parachute pack extraction. Top: Ballute load transferred to parachute pack after ballute bridle cut. Middle: Bottom of the parachute pack is visible as the pack exits the can. Bottom: A portion of the single riser is visible just prior to triple bridle standup.
Figure 7: Image sequence from situational camera showing parachute bridle standup. Top: Confluence point being lifted off the top deck. Bridles are just visible emerging from the insulation. Middle: Parachute triple bridle during deployment. Note the impact of bridle leg 1 with the rocket nozzle. Bottom: The parachute triple bridle after deployment supported by the bridle stiffeners.
Figure 8: Image sequence from up look camera showing parachute bridle standup. Top: Pack mouth structural tie has broken and the single riser is releasing from the bottom of the pack. The cut knives have not actuated yet. Middle: Single riser has actuated pack mouth cut knives and pack mouth is open. Bottom: Clear view of open parachute deployment bag with lines paying out as expected.
Figure 9: Image of best evidence of outer bag strip prior to parachute line stretch. The white surface of the inner bag is barely visible. The lower image highlights the surface of the inner bag. The bright object just to the right of the inner bag is likely reflection from the aluminized surface of the outer bag flaps as it is pulled away.

IV. Parachute Inflation

As previously discussed, the ballute separates from the parachute pack prior to line stretch, such that the canopy is extracted by its own inertia. The parachute canopy and a short length of suspension lines are packed in the inner deployment bag, which is then packed with the remaining suspension lines into the outer deployment bag. When the parachute pack reaches the end of the outer bag suspension lines, the outer bag is pulled away by the ballute and the inner bag is left flying with its own inertia. In this sense, the canopy extraction is the same as with a mortar-deployed parachute. For more information on this mortar extensibility refer to reference 6.

Prior to line stretch, the suspension lines appear relatively orderly. The snatch force of line stretch excited a transverse wave in the lines that caused the suspension lines to become more disorganized. Line stretch also caused a noticeable amount of canopy rebound, which is not unexpected from this type of system. Figure 10 shows the
canopy and suspension lines at bag strip. The canopy appears to deploy cleanly from the inner deployment bag, and the outer deployment bag is visible and attached to the ballute behind the canopy.

**Table 3: Test vehicle environmental conditions during parachute events**

<table>
<thead>
<tr>
<th>Event</th>
<th>Time from Drop (s)</th>
<th>Mach Number</th>
<th>Dynamic Pressure (Pa)</th>
<th>Geodetic Altitude (km)</th>
<th>Mars Eq Alt (km)</th>
<th>WR FPA (deg)</th>
<th>Total Angle of Attack (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VT2 Detection</td>
<td>161.41</td>
<td>2.73</td>
<td>426</td>
<td>50.05</td>
<td>15.17</td>
<td>-27.2</td>
<td>1.6</td>
</tr>
<tr>
<td>PDD Mortar</td>
<td>161.59</td>
<td>2.73</td>
<td>430</td>
<td>49.98</td>
<td>14.92</td>
<td>-27.3</td>
<td>1.7</td>
</tr>
<tr>
<td>Bridle Cut</td>
<td>166.57</td>
<td>2.60</td>
<td>508</td>
<td>47.92</td>
<td>11.84</td>
<td>-30.1</td>
<td>7.6</td>
</tr>
<tr>
<td>Line Stretch</td>
<td>168.63</td>
<td>2.54</td>
<td>545</td>
<td>47.05</td>
<td>9.59</td>
<td>-31.3</td>
<td>11.2</td>
</tr>
<tr>
<td>Full Inflation</td>
<td>169.30</td>
<td>2.45</td>
<td>526</td>
<td>46.77</td>
<td>10.08</td>
<td>-31.8</td>
<td>3.2</td>
</tr>
</tbody>
</table>

The environment conditions at parachute inflation are shown Table 3. These conditions were within the pre-flight Monte Carlo predictions as well as the design specification of the parachute. The evolution of the parachute during the inflation process to the inflated state can be seen in Figure 11. As shown in these figures, the parachute experienced an anomaly during the inflation process. Visual indications from the video show initial parachute damage was seen prior to the full-inflated state. A plot of the canopy load during inflation is shown in Figure 18. The peak measured load was 57,588 lbf.

In review of the high-speed video, initial damage was seen at 169.08 seconds after drop. This was 0.45 seconds after line stretch and 0.2 seconds after predicted bag strip. The image frame seen in Figure 12, shows the location of the initial failure. Initial failure appeared to occur in the disk area closer to the disk leading edge, as opposed to the trailing edge near the vent area. This failure can be seen through the sail gaps as black areas, which indicates the witnessing of the black of the sky rather than the disk broadcloth, indicating the disk broadcloth has ripped in those areas. Subsequent high-speed video frames, shown in Figure 13 and Figure 14, show a growth of the failure region and indicate that the failure began in the region of gore 95. The failure appears to propagate toward the vent as well as toward the leading edge of the disk. During the initial inflation process, two additional failures of the broadcloth can be observed. The first of these can be seen to start as windowing in the fabric in Figure 12 and the second began around 169.14 seconds after drop. It is unclear if the first failure contributes to the next two. Hypotheses of the failures will be discussed later in this paper. High-speed video also indicates that there were some suspension lines that tangled during inflation. This can be seen at 169.11 seconds after drop, as shown in Figure 15. Of note are the two sections of canopy skirt connected just below the vent in the image. The entanglement lasted a few hundreds of a second and there is no visual damage to these lines from the in-flight video. At the point of fullest inflation, high-resolution images indicate that all suspension lines are still attached at the skirt band, indicating that the tangle of suspension lines worked itself out rather than failing a suspension line in the process of letting loose. In addition, there was not any visual damage to the length of the suspension lines, or knots seen post test, indicating that this observed tangling was part of the process of the lines organizing themselves during inflation and sliding past each other as they separate. There was however a failed suspension line that was in the same area of the tangling noted in the post-test inspection. The failed suspension line did so in the termination connection at the skirt of the canopy. It is unclear at what point this line failed, but the line tangling may have contributed to the ultimate failure of this line. In the same area of line entanglement, there is also observed an unfolding hesitation of the lower sail area of the canopy. This area is indicated in Figure 15, where bunching of canopy material on the right side of the image is seen. Similar to the line entanglement, this area eventually works itself free, but during the process there is an inflated pocket, which highlights the hesitation area. In tracing the skirt path, there is no indication of skirt inversion of the canopy. This indicates that the hesitation is likely not to be an inversion, but rather the un-stowing of the canopy from its canopy-stretched state. After the hesitation has released and inflated, there are no visual indications of damage to any of the sails in this area. This indicates that, although there was a hesitated inflation behavior of the canopy in this region, no apparent damage was caused either by friction or snags.
Figure 10: Image showing the canopy near bag strip. The canopy is likely completely deployed at this point. There is slack in the suspension lines from the canopy rebound. Note the outer deployment bag attached to the ballute.
Figure 11: Image sequence during canopy inflation. Note that the time reference is arbitrary.
Figure 12: High speed video image showing initial canopy damage
Figure 13: High speed video image showing propagation of canopy damage
Figure 14: High speed video image showing propagation of canopy damage
Figure 15: High speed video image showing suspension line tangling during inflation
To further understand the inflation process, skirt tracking from the high-speed video was done of each of the 96 suspension line to skirt attachment points. Figure 16 shows the last frame of the inflation process that the tracking was performed. Working backwards from this frame and tracing the suspension line / skirt points in each frame, a trace of the skirt can be generated. Centering this trace about mean area of the skirt opening results in Figure 17. Using this skirt trace, the evolution of the parachute's skirt area can be observed. When overlaying this area with the load history one can see a similarity in the area verses the load as indicated in Figure 18. In this figure, the area of the canopy is measured from photographs and normalized by fully inflated parachute projected area. Traditionally application of a 4th order function agrees the best for supersonic inflations. Even with the failure of the parachute, one can see that a 4th order fit matches quite well with the rise in loads.
Figure 17: Evolution of the canopy’s skirt size and shape during the inflation process. Contour rings are centered at the mean of the enclosed area.
Figure 18: Normalized parachute inflation loads plotted with normalized parachute projected area

V. Aerodynamic Performance
The coordinate system used for the aerodynamic analysis can be seen in Figure 19. The origin of this coordinate system is located at the nose of the vehicle. The primary axes are labeled according to traditional aircraft flight mechanics.
The total parachute force coefficient $C_{tot}$ was calculated using:

$$ C_{tot} = \frac{F_{SSDS}}{4SSDS} \quad (1) $$

where $F_{SSDS}$ is the magnitude of the parachute force acting on the test vehicle, and $SSDS = 730.6 \text{ m}^2$ is the SSDS reference area. The force exerted by the parachute ($F_{SSDS}$) was calculated by two independent methods: 1) from the triple-bridle load pin measurements and 2) from the IMU on board the test vehicle.

For the first measurement method, the triple bridle geometry was assumed to be a ridged structure and no slacking existed in the bridle lines. The second assumption of no slacking was assumed to be an accurate assumption as both visual inspection of the lines indicated they stayed rigid during critical loading as well as positive load in the loadcells was also seen. Given the above assumptions, $F_{SSDS}$ was calculated as follows:

$$ F_{SSDS_x} = -F_1 \sin \theta_1 - F_2 \sin \theta_2 - F_3 \sin \theta_3 \quad (2) $$
$$ F_{SSDS_y} = -F_1 \cos \theta_1 \sin \phi_1 - F_2 \cos \theta_2 \sin \phi_2 - F_3 \cos \theta_3 \sin \phi_3 \quad (3) $$
$$ F_{SSDS_z} = -F_1 \cos \theta_1 \cos \phi_1 - F_2 \cos \theta_2 \cos \phi_2 - F_3 \cos \theta_3 \cos \phi_3 \quad (4) $$

where $F_1$, $F_2$ and $F_3$ are the load pins measurements; $\theta_1 = \theta_2 = \theta_3 = 60.149^\circ$ which is the angle between each of the triple bridle legs and the y-z plane; and $\phi_1 = \frac{\pi}{3}$, $\phi_2 = \pi$, $\phi_3 = -\frac{\pi}{3}$ are the angels between the +z-axis and each of the three triple bridle attachment points.

For the second measurement method, $F_{SSDS}$ was computed by determining the total force on the test vehicle using the vehicle mass and accelerometer data, then subtracting from it the aerodynamic contributions from the test vehicle with the SIAD-R deployed. The aerodynamic force on the test vehicle was determined using the reconstructed Mach number, dynamic pressure, aerodynamic angles and the test vehicle aerodynamic database. $F_{SSDS}$ was then determined from:

$$ F_{SSDS_x} = -F_1 \sin \theta_1 - F_2 \sin \theta_2 - F_3 \sin \theta_3 \quad (2) $$
$$ F_{SSDS_y} = -F_1 \cos \theta_1 \sin \phi_1 - F_2 \cos \theta_2 \sin \phi_2 - F_3 \cos \theta_3 \sin \phi_3 \quad (3) $$
$$ F_{SSDS_z} = -F_1 \cos \theta_1 \cos \phi_1 - F_2 \cos \theta_2 \cos \phi_2 - F_3 \cos \theta_3 \cos \phi_3 \quad (4) $
\[ F_{SSDS_y} = ma_y - qS_{SIAD}C_{YS} \]  
\[ F_{SSDS_z} = ma_z - qS_{SIAD}C_{NS} \]

where \( m \) is the mass of the vehicle, \( S_{SIAD} = 28.27m^2 \) is the SIAD-R reference area, and \( C_{NS} \), \( C_{YS} \), and \( C_{AS} \) are the aerodynamic force coefficients for the vehicle with a SIAD-R inflated. The parachute drag force \( (F_D) \) was calculated by projecting \( F_{SSDS} \) onto the wind-relative anti-velocity vector, and the parachute drag coefficient was computed as:

\[ C_D = \frac{F_D}{\frac{1}{2} \rho SSDS} \]  

The time histories of \( C_{tot} \) from 168 to 171 seconds after drop are shown in Figure 20. The initial peak in \( C_{tot} \) corresponds to line stretch. Following line-stretch, \( C_{tot} \) rose rapidly to a peak values of 0.67, which corresponds to full inflation. Subsequently, \( C_{tot} \) decreased to below 0.1, due to the damage to the canopy. The time histories of the parachute drag coefficient, which follow \( C_{tot} \) very closely, are shown in Figure 20.

The extended time histories of \( C_{tot} \) and \( C_D \) into the subsonic regime are shown in Figure 21. Following full inflation, \( C_{tot} \) rapidly decreased to approximately 0.06, due to canopy damage. Over the following 10 seconds, \( C_{tot} \) and \( C_D \) slowly increased until achieving an average value of approximately 0.1, 180 seconds after drop. Both \( C_{tot} \) and \( C_D \) remained approximately constant for the remainder of the flight.

During the supersonic phase of the parachute flight the load pin and accelerometer results were in good qualitative agreement, and both values agreed within three standard deviations. However, due to the large measurement uncertainties associated with the load pins, the uncertainties in the values of \( C_{tot} \) and \( C_D \) obtained from these measurements were on average five times larger than the uncertainties in the accelerometer results. In the subsonic phase, however, the results obtained from the accelerometer values fell below those obtained from the load pin measurements. By 210 seconds after drop, the accelerometer results were approximately 25% lower than the load pin results.

![Figure 20: C_{tot} vs Time and C_D vs Time](image-url)
Figure 21: Extended $C_{tot}$ and $C_D$ Time Histories

VI. Failure Assessment

At the time of this report, investigation into root causes of the parachute is ongoing. However, a leading hypothesis has emerged and is associated with asymmetric loading of the canopy in the disk area resulted in circumferential loads that exceeded the structural capability of the material present. The nature of the failure indicates that the broadcloth was pulled apart between the radial kevlar tapes. The construction of the disk region was such that there was no circumferential skeletal structure in the parachute and therefore once the initial failure started, there was nothing to keep the ripping of the fabric in the radial direction from propagating. There was a
single leading edge reinforcement tape on the disk, however it was inadequate to stop the propagation of the failure as the tear moved radially downward toward the upper gap. The failure continued through the gap and continued through the sails, which did have trailing edge reinforcements, however again these tapes did not provide adequate rip-stop strength to stop the propagation of the tear.

Structural analysis of the Disksail showed adequate strength margins in the disk region, however this analysis assumed a fully inflated parachute with uniform loading. The analysis did not consider asymmetric loads during inflation, but rather added an asymmetric/dynamic load factor to the fully inflated configuration to account for assumed loads that would be seen during inflation. These load factors have been found to be of inadequate margin for the Disksail design after the SFDT-1 test. Contributions to the asymmetric loading have been theorized to be attributed to five main reasons.

1. The selection of combining a flat disk with quarter-sphere Ringsail geometry resulted in stress concentrations in the disk area. During the inflation process, with the asymmetric loading, the shoulders of the Ringsail portion caused excessive loads in the disk region. This could be amplified by the visual indications of pressure loops seen to inflate. The pressure in these loops would result in circumferential loads in the area that the failures were initially seen. Noting that principle pressure vessel stresses are proportional to the product of pressure and local radius of curvature, loading in the shoulder regions of the canopy would help pull the disk portion flat and significantly increase the local radius of curvature of the disk. Even in the presence of relatively low pressure, this could lead to significant stress in the disk.

2. The combination of a rapid inflation and a solid crown area resulted in crown pressurization higher than expected. Due to the lack of distributed geometric porosity, as is present in traditional Ringsail canopies, the disk did not allow for venting of high-pressure pockets in the canopy during inflation.

3. The inflation process was faster than predicted. Full inflation occurred in approximately 0.7 seconds, which is faster than the preflight estimates of about 1 second, based on prior supersonic DGB inflations. Due to this fast inflation, there could have been inertial loads of the rapidly expanding canopy that would result in tensile forces of the non-expanding fabric areas.

4. During inflation there appears to be a nondeterministic amount of non-planarity of skirt around the time of the initial failure. Due to the rapid inflation process, it is theorized that non-planarity of the skirt would result in some of the radials to be pulled downward toward the test vehicle, resulting in higher loading further up in the canopy.

5. This was the largest canopy ever attempted to be inflated in this environment and there remains some questions about scaling of supersonic parachute inflation.

None of these hypotheses have been proven to fully contribute to the failure of the canopy and there may be an alternative cause that has not been discussed. Or it may be that a combination of the above causes, when combined resulted in the failure observed.

The results of SFDT-1 have been compared to the videos of past supersonic low-density inflations. In looking at footage from PEPP, SPED, SHAPE, and BLDT inflations, the SFDT-1 inflation process does not look out of family. In particular the asymmetric inflation process and the formation of lobes can be seen in many of the past supersonic inflations. This indicates that the asymmetric inflation observed in SFDT-1, though likely a contributing factor, was not the only factor leading to the failure. That is, that the inflation observed is what is to be expected in a supersonic, low-density inflation. Never before has the inflation process been so well videoed. As of the time of this paper’s publication, the dominant contributor to the failure of the parachute was a parachute geometry and configuration that was not adequately robust to a typical supersonic parachute configuration. More specifically, the presence of a flat disk on an otherwise hemispherical geometry is felt to have led to stress states beyond the capabilities of the disk’s broadcloth Nylon where the initial failures were seen.

VII. Recovery

After descending from the testing environment, the TV with a majority of the parachute landed in the Pacific Ocean in the waters controlled by the Pacific Missile Range Facility. Using GPS trackers, recovery boats were vectored in to the splash-down location to start the recovery effort. Recovery personnel arrived approximately 1.5 hours after expected splash down. Upon arrival of the TV, the parachute was not visible, as it had sunk. Navy EOD divers secured the TV and disconnected the triple bridle, freeing the parachute, but not before attaching a boat’s mooring line to one of the parachute bridle legs so that it could be towed away from the TV and allowed to surface.
Figure 22: Navy EOD divers disconnecting the parachute from the TV. The triple bridle can be seen collapsed with its confluence point hanging off the right side of the vehicle in the image.

Figure 23: The parachute underwater as it is being towed to the surface
Figure 24: The parachute being pulled aboard

Figure 25: Recovery personnel pulling the parachute aboard
Once the TV was secured aboard, the parachute was then extracted from the water. Initially the recovery vessel’s ship crane was used to pull the parachute in, however, once the canopy started to emerge from the water, recovery personnel themselves pulled the parachute from the water as shown in Figure 22 and Figure 23. Care was taken to not do further damage to the canopy than had already been experienced from flight. Once the parachute was on board, it was hosed down with fresh water to rinse as much salt water from the canopy. Once it was rinsed, it was place in a large container. Fresh water was added to the container and allowed to soak using the boat’s natural rocking to agitate the water surrounding the boat. The container’s water was drained and replenished with fresh water. This process was repeated until the salinity of the water reached a level of 0.2% or lower. This process took place during the return of the recovery vessel to Kauai. Once at dock, the water was drained and the container was transported back to PMRF where it was laid out on a highbay floor for drying and inspection.

VIII. Post-Test Inspection

Initial parachute inspection was done at PMRF. After the parachute was adequately dried, it was sent to the Naval Air Warfare Center Weapons Division (NAWCWD) in China Lake CA for detailed inspection and assessment. Post-test inspection and assessment of the parachute provided limited information of the parachute’s initial failure cause. The majority of the fabric that was in the disk (and elsewhere) was badly torn, frayed and knotted from the 20-30 minute descent to the ocean. Post-test inspectors of the parachute attempted to untangle the remains of the parachute, however it was quickly assessed that the usefulness of the effort to uncover any substantial information about the parachute did not justify the labor and time to do so. Some notable results however were as follows:

1. The majority of the radials remained structurally connected at both the vent and suspension lines.
2. The deployment inner bag was partially ripped off of the vent and was found knotted inside part of the canopy broadcloth.
3. Although the vent area was badly abused, only six of the 48 vent lines were disconnected on one side of the band and the vent band overwrap was still intact.
4. About 1/8th of the pocketbands had disconnected from one end where they were attached to the skirt band.
5. The skirt band broke at gore #96. This failure was seen in the high speed video.
6. Many of the radial to skirt band stitches were failed. It is assumed this happened during the high dynamics during inflation and rebound induced by the failure, as well as during the long descent. However, only a few radials actually totally broke free from the skirt band.
7. The Braided Riser Bridle was in good shape other than the damage resulting from the recovery efforts.
8. There were no concrete signs of either bag-burn or aerothermal heating damage. There were areas that showed nylon thermal damage, but they were attributed to either the high force of knotting action or violent flagging during descent.

Post-test inspection results indicated no apparent indications of the failure cause of the parachute. Either the evidence was so badly damaged during descent, or there was no real evidence that there was anything off-nominal with the deployment and inflation outside of the theories hypothesized in the Failure Assessment section.
IX. Summary

The first supersonic test of the proposed next generation supersonic parachute for Mars was successfully tested on June 28th, 2014 in the Supersonic Flight Dynamics Test #1(SFDT-1). The parachute configuration that was tested was a Disksail, which consisted of a crown area with features of a flat circular round canopy (disk) and a shoulder to skirt configuration that resembled a ringsail canopy. The parachute was successfully deployed at the targeted aerodynamic environment and full inflation was seen at Mach 2.45 with a dynamic pressure of 526 Pa. During the inflation process, large tears developed in the disk area of the canopy, which propagated radial up and down the canopy toward the vent and skirt. There were significant tears in the canopy at full inflation, however the canopy still generated a measured peak inflation load of 57,588 lbf. Shortly after full inflation, the supersonic flow continued to tear the parachute apart to the point that the drag area was significantly reduced to less than 1/6th that seen originally. The parachute trailing the test vehicle splashed down in the Pacific Ocean and was recovered. Imagery of the parachute was fully recovered as well and provided the highest resolution and frame rate ever recorded of a supersonic parachute. In review of the imagery and dynamic load/acceleration data, many theories have been formulated as of the cause of the initial failure. Leading hypothesizes point to the mismatch of the flat disk geometry attached to the top of a quarter-spherical ringsail. Although static analysis of the fully inflated canopy resulted in positive structural margins, it is postulated that the asymmetries and dynamic loads seen during the inflation process were greater than those assumed in the pre-flight analysis. Post inspection of the canopy resulted in limited insight to the failure cause of the canopy due to the tearing, fraying and knotting of the failed canopy as it descended to the Pacific Ocean below. Due to the abundant imagery and load/acceleration data that was captured, there has been a significant increase in knowledge and understanding of supersonic inflations of large parachutes. This knowledge will be used to inform future designs of large supersonic parachute for future SFDT flights as well as future flights for Mars applications.

X. Acknowledgement

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.
References