Rigging Test Bed Development for Validation of Multi-Stage Decelerator Extractions

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The Low Density Supersonic Decelerator project is developing new decelerator systems for Mars entry which would include testing with a Supersonic Flight Dynamics Test Vehicle. One of the decelerator systems being developed is a large supersonic ringsail parachute. Due to the configuration of the vehicle it is not possible to deploy the parachute with a mortar which would be the preferred method for a spacecraft in a supersonic flow. Alternatively, a multi-stage extraction process using a ballute as a pilot is being developed for the test vehicle. The Rigging Test Bed is a test venue being constructed to perform verification and validation of this extraction process. The test bed consists of a long pneumatic piston device capable of providing a constant force simulating the ballute drag force during the extraction events. The extraction tests will take place both inside a high-bay for frequent tests of individual extraction stages and outdoors using a mobile hydraulic crane for complete deployment tests from initial pack pull out to canopy extraction. These tests will measure line tensions and use photogrammetry to track motion of the elements involved. The resulting data will be used to verify packing and rigging as well, as validate models and identify potential failure modes in order to finalize the design of the extraction system.

Nomenclature

D_O	=	parachute nominal diameter
LDSD	=	Low Density Supersonic Decelerator
MAWP	=	maximum allowable working pressure
PDD	=	Parachute Deployment Device
PDS	=	Parachute Decelerator System
RTB	=	Rigging Test Bed
SSRS	=	Supersonic Ringsail
JPL	=	Jet Propulsion Laboratory
SFDTV	=	Supersonic Flight Dynamics Test Vehicle
SIAD	=	Supersonic Inflatable Aerodynamic Decelerator
V&V	=	verification and validation

I. Introduction

The Rigging Test Bed (RTB) was initiated to provide a test capability in which the uncertainties associated with the unique Low Density Supersonic Decelerator (LDSD) test flight deployment architecture could be explored to aid in risk mitigation. The objective is to conduct multiple parachute deployment tests, not including inflation, under representative flight conditions using full scale hardware.

This paper will discuss the development of the RTB to meet the challenges of LDSD. It is designed to be highly adaptable by operating at a wide range of forces and extraction distances. With minor tailoring, it can be leveraged to test a variety of parachute systems either in segments or end to end (from pack extraction to just prior to canopy inflation).

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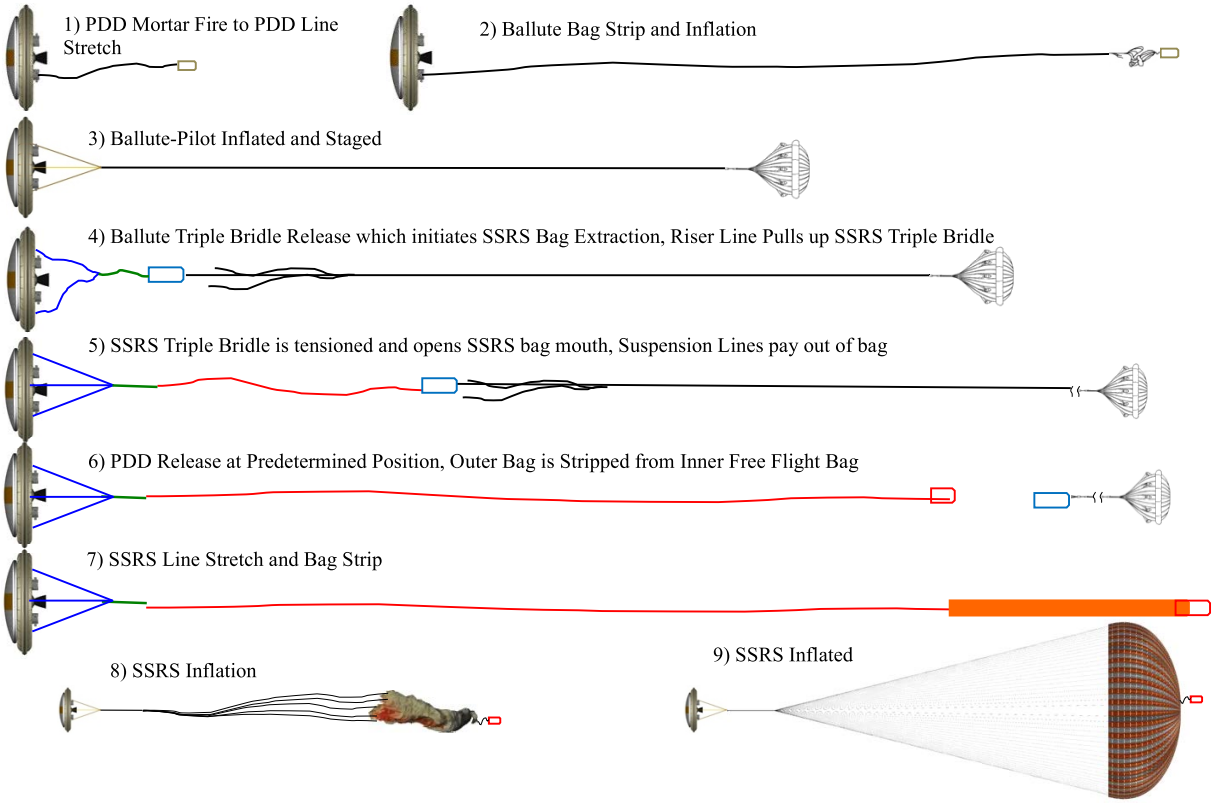
II. LDSD Staged Parachute System

The LDSD project is focused on technology development and demonstration for future Mars exploration missions. Several new techniques for Mars are expected to be explored including the vehicle forebody shape, a torus shaped Supersonic Inflatable Aerodynamic Decelerator (SIAD), and a planned 33.5 m nominal diameter Super Sonic Ring Sail (SSRS) parachute. These elements are planned to be tested on a Supersonic Flight Dynamics Test Vehicle (SFDTV) that would be dropped from a high altitude balloon and accelerated using a center mounted rocket engine to supersonic velocities. This would achieve test conditions like those experienced at Mars in a manner similar to the Balloon Launched Decelerator Tests (BLDT) that were conducted in 1972 to qualify the decelerator system used on the NASA Viking Landers. During the test flights, once the vehicle has achieved the desired altitude and speed the SIAD will deploy first around the shoulder of the forebody and remain attached to the vehicle. It is then followed by the SSRS deployment.

Parachutes on Mars vehicles are typically deployed by a mortar that is positioned on the vehicle's central axis, which deploys the parachute quickly and prevents mortar thrust loads from causing the vehicle to tumble. Velocity of the parachute relative to the vehicle starts high as it leaves the mortar and decays as it moves away. When the canopy extracts from the bag after line stretch the velocities have decreased such that friction burning doesn't occur.

The center-mounted motor on the SFDTV prevents use of a centrally mounted parachute mortar. This prompted selection of a modified pilot deployment where a small mortar is fired to deploy a ballute capable of extracting the SSRS without upsetting vehicle flight dynamics. Pilot deployments, however, start at zero relative velocity to the vehicle and accelerate away. This poses a challenge to the system since tension in the parachute suspension lines and triple bridle during the deployment process is principally generated by the mass flow of suspension lines coming out of the deployment bag. Slow bag velocities at the start of the parachute deployment process result in low tension in the parachute suspension lines and triple bridle. Since the SIAD is decelerating the vehicle through this extraction process, the low tension could lead to lines piling up against the back of the vehicle as they are extracted. Simply using a larger ballute to generate speed and tension is the suspension lines carries the risk of generating very large bag strip velocities which could damage the canopy. High bag strip velocities would also violate one of the SFDT test requirements that the pilot deployment be designed to produce a mortar like deployment of the canopy[1].

To overcome these challenges a staged deployment has been developed, detailed in Figure .



III. Rigging Test Bed

The basic strategy for the RTB is to simulate the deployment of the parachute system on the decelerating vehicle by applying a force to the parachute pack and extracting the chute vertically against gravity from a stationary vehicle on the ground as shown in Figure 2. RTB Concept. This will be performed by applying tension to a rope and routing the rope over a pulley suspended above the vehicle. The extracted SSRS prior to inflation with all of its lines and rigging stretches approximately 260 ft (80 m) behind the vehicle. Due to the length of the SSRS, a structure 300 ft (90 m) tall would be required to perform a vertical end to end test.

The decelerating vehicle in flight reduces the relative acceleration of the parachute away from the vehicle. In the majority of cases, the vehicle deceleration is within 1-1.5 g's. Orienting the test bed vertically enables the use of gravity to simulate a 1 g vehicle deceleration and better approximate the dynamics of the parachute relative to the vehicle.

The required force to be applied matches the expected ballute extraction force in flight, which may be as high as 2500 lbf (11.1 kN). However, the inflight extraction may not always be straight back from the vehicle. Flight dynamics of the ballute and vehicle could cause the two to oscillate relative to each other. To approximate these dynamics the RTB is required to hold the mockup at an angle up to 30 degrees from horizontal to envelope the expected range of oscillation in the flight tests.

The testing conducted in the RTB mitigates a number of risks in the deployment sequence. The dynamic tests will investigate successful triggering of the sequential stages, interferences between nested extraction components, tension forces and slacking in parachute rigging, interferences between the parachute and vehicle during extraction, field of views for cameras installed on the flight vehicle, and velocity profiles of the parachute pack for comparison to analytical models. The validation of analytical models is of critical concern, as these models are the only means available to assess the expected flight dynamics.

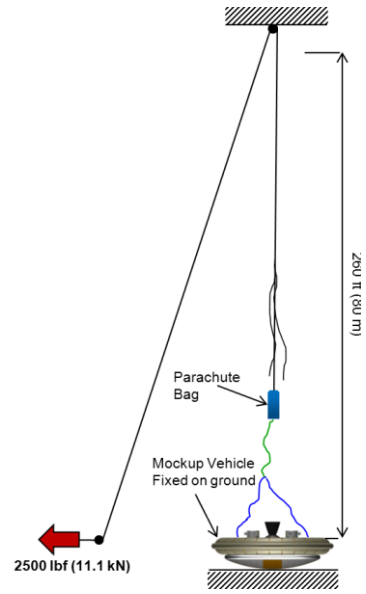


Figure 2. RTB Concept.

A. Two Test Locations

There are no facilities at JPL tall enough to support a 300 ft (90 m) end to end test of parachute extraction. A mobile hydraulic boom crane was selected to provide a support for these tests. The crane has the advantage of being a very quick method of placing a pulley point at variable heights without the complexity of erecting a new test structure. Unfortunately renting a large crane for dozens of tests would be prohibitively expensive.

To reduce the number of end-to-end tests required a segmented test campaign was developed. Using existing high bay facilities at JPL the extraction could be tested in 40 ft (12 m) segments independently. Once each segment has completed its individual evaluation the test setup would be moved to a new location where the mobile crane can be brought in. The requirement to test in two locations drove the hardware design of the test bed to be portable and highly adaptable.

B. Force Device

The key mechanism of the rigging test bed is a constant force device capable of simulating the extraction loads the parachute pack would experience in flight. Many concepts were considered for this device. One of the design drivers was the inertia of the force system. For example, spinning up a large motor to pull the line would have a large rotational inertia. The ballute being developed for flight tests weighs on the order of 30 lbm (15 kg) compared to the parachute pack's 300 lbm (150 kg). Dynamic events where fabric or lines snag could slow down or stall the deployment driven by the ballute. A large motor would power through likely tearing snags and making it more difficult to understand the failure mode.

The solution selected was to design a pneumatic cylinder shown in Figure 3. Force Device schematic. Inside the cylinder a piston head would be driven from a large compressed air tank. A rope connected to the back of the piston would feed out a small port on the end of the cylinder and run over pulleys to the test article. In this approach, the mass of the piston head and rope can be kept on the same order as the ballute to approximate the ballute's inertia. This enables examination of flight like snags, as mentioned previously.

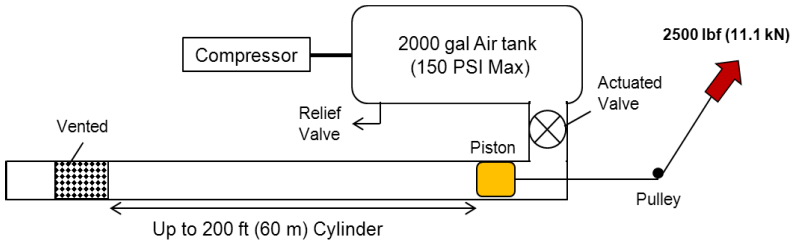


Figure 3. Force Device schematic.

The force is also easily adjusted by changing the pressure of the compressed air. In expected flight conditions, there is a wide range of possible dynamic pressures that significantly affect the drag force on the ballute that drives the extraction. The test bed is capable of dialing in to any of these expected forces and it can be kept reasonably constant by ensuring the tank is large enough relative to the volume of the cylinder. A vent section is included near the end of the pipe to bleed the system and effectively stop the tension in the rope. This allows the system to be stopped once it has pulled for a certain distance.

The force expected from the ballute could be as high as 2500 lbf (11.1 kN). The force device needs to be capable of significantly higher force to make up for any friction losses in the system and to provide flexibility as the flight design further develops. Additionally it was decided that the system should have a maximum allowable working pressure (MAWP) of 150 psi (1030 kPa) to make commonly available pressure hardware suitable.

Due to the need to pull different distances at different locations, the cylinder would need to be mobile and easily reconfigurable. For this reason welded or cemented pipe was ruled out. An aluminum quick connect piping system was selected which has a 6.6 in (168 mm) diameter. The large cross section allows the piston to achieve high forces at modest pressures. At 80 psi (550 kPa) the piston will produce the required 2500 lbf (11.1 kN) and have almost 90% margin to the MAWP.

To match potential flight cases, for the testing it was decided that 25% variation in force, and thereby pressure, from start to finish of a test would be acceptable. A commercially available 2000 gal (7500 L) air tank was chosen based on the volume of the selected pipe size.

C. Configuration

The setup of the RTB centers around a mockup of the vehicle weighted down to keep it stationary during dynamic testing. The mockup for LDSD consists of a welded steel frame which is equipped with wood and foam stand-ins to represent the vehicle geometry. The base of the mockup is an adjustable angle fixture. This enables holding the vehicle at angles relative to the extraction path to investigate the effects of vehicle oscillation during the SSRS deployment.

The mockup is placed under the crane and then the pneumatic force device is placed to the side. The force device is also weighted down to react any dynamic loads. A vectran rope is run from the piston through a pulley at the cylinder and a pulley on the crane to the test article mounted to the mockup.

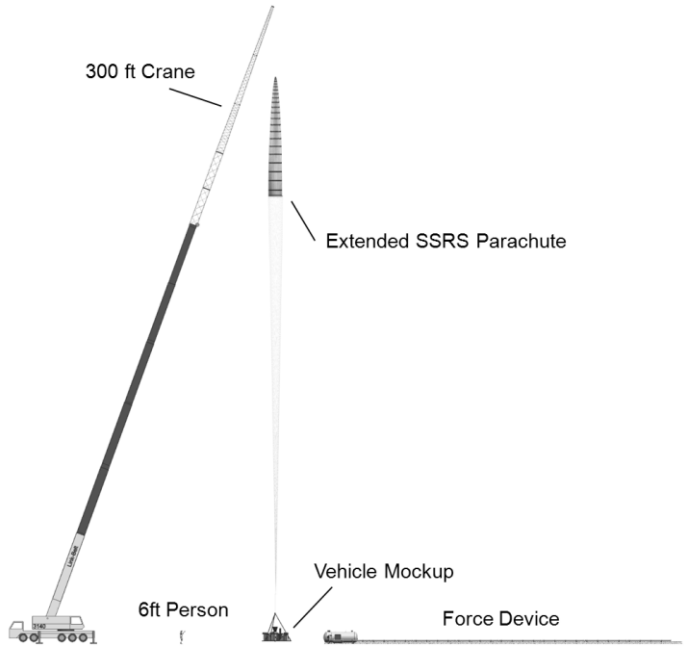


Figure 4. Rigging Test Bed Configuration.

D. Data Gathering

The test bed contains a combination of sensors and cameras for collecting data. Load cells are positioned to measure tension on the test article. Four high speed cameras will be used for photogrammetry to track the pack and its rigging during the deployment. An accelerometer will also be placed on the pack to capture its motion. Pressure transducers will be placed on the force device to monitor its performance through the test.

Two load cells are placed at the base of each bridle in series. A 2,000 lbf (8.9 kN) load cell is positioned first in the path to accurately measure the line tension forces through standup expected to be on the order of 100 lbf (0.44 kN). However, at the conclusion of the test the article will quickly snatch against the mockup creating high transient loads on the order of 10,000 lbf (44 kN). The fixture, which the bridle connects to, shorts loads above 2,000 lbf (8.9 kN) to a 50,000 lbf (220 kN) load washer that does not have the fidelity to measure the lower tension loads. In this way, the full force profile on the bridles will be captured without risk of damaging the 2,000 lbf (8.9 kN) load cell.

A wireless load cell and wireless 3-axis accelerometer will be placed at the linkage between the pack and the rope to the force device. These two sensors will capture the force driving the extraction and integration of the acceleration data will provide a secondary data set for the position and velocity profiles of the pack. Photogrammetry will be used to capture the primary velocity and position measurements.

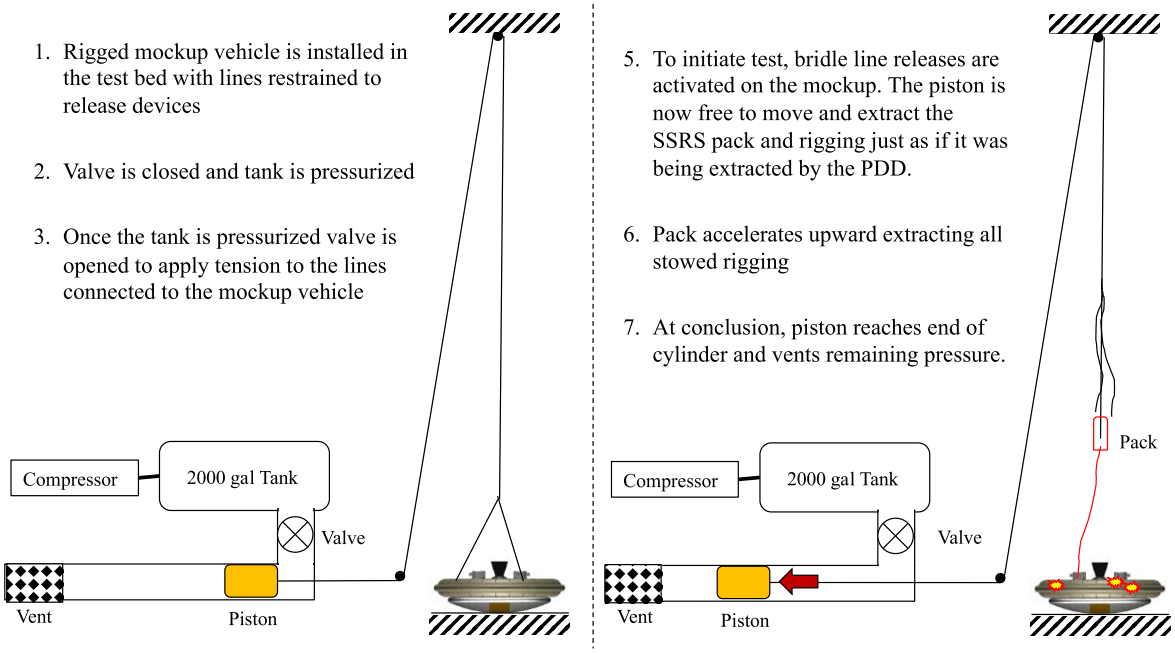
All data and video is time synched through a data acquisition (DAQ) system setup away from the vehicle. This enables the various data sets to be combined together and checked against the analytical flight models being developed.

E. Operation

At the start the vehicle mockup is placed at the center of the test bed with the parachute test article installed. The DAQ system is linked up and checked out. Electro-mechanical solenoid releases are used restrain the staged ballute lines to the mockup. Meanwhile, the air tank is pressurized to the correct gauge pressure for the desired extraction force while all the tank isolation valves are closed.

When this setup is complete, the area is cleared of personnel. The main tank valve is actuated open; this pressurizes the cylinder up to the piston and tensions the staged lines, which are restrained by the solenoid releases. Once completely open the test hardware is static but under load. The DAQ system is used to simultaneously actuate the solenoid releases and initiate logging of data products. Once the solenoids are released, the lazy leg tensions and the SSRS pack begins its extraction.

The pneumatic device accelerates the test article upward until the piston travels past the vented section. At this point the force on the piston drops off and the piston is captured and brought to rest by crushable honeycomb at the



end of the cylinder. The test article then snatches against the mockup and is restrained from falling by cam cleats located near the end of the pneumatic cylinder. The cleats allow the line to feed in one direction enabling the test to be performed without the test bed actively providing any time critical functions once the article is released. Once the test article comes to rest and the air system has vented the crane can be lowered to bring the test article down. At this point visual inspection would begin of the article and mockup. Once completed the test bed is ready for reset.

IV. Highly Adaptable Test Facility

The architecture and large force capability make the Rigging Test Bed capable of many different test runs. The RTB has been developed in parallel with the LDSD SSRS. The natural development and evolution of the hardware for the SSRS has created minimal ripples for the RTB. With the exception of drawing from a shared pool of personnel the efforts have been largely independent. This is possible because there are very few interfaces between the two efforts.

The RTB hardware is designed to operate in multiple locations at multiple pull distances. As line geometry and lengths evolve for the rigging of the parachute the RTB is already capable of craning to multiple heights and adding quick connect pipe sections for longer pull distances. The tune-ability of the applied force allows pulling at the full spectrum of flight-like loads. Alternatively, a lower force may be used to achieve appropriate velocity when examining individual stages after removing massive components (such as a packed canopy).

Many different approaches were considered in the SSRS deployment sequence to preserve tension in the lines and achieve desired canopy extraction velocities. Each approach called for different stage transitions each of which were evaluated for testability and were found to be workable within the existing test bed design.

The limiting factor for a segmented test was usually found to be decelerating the test article prior to it impacting the crane or ceiling above the test bed. The seemingly straightforward approach to this problem would be to let it simply snatch against the stationary mockup. However, it is not possible to anchor the mockup into the ground at either of the proposed test locations. Counterweight is being used to hold the mockup, and sufficient weight to restrain the snatch event cannot be readily accommodated. The favored solution to this was the proposal of adding a coiled segment of low stiffness line, such as nylon, that would be extracted at the end of the segmented test. As it is pulled out, it also stretches absorbing energy and decelerating the moving test article to the point where it could acceptably snatch against the mockup. Similarly, a length of rip stitch could be used to the same effect.

V. Approximation of Flight

The RTB provides a suitable test facility for developing the parachute deployment system for the LDSD project. It is not, however, a perfect replication of the expected flight conditions. Some advantages and disadvantages of the RTB compared to the LDSD flight deployment are listed below. These may be found when using this approach to test similar systems.

A. Disadvantages

- There is no representation of the flow and pressure environment expected behind the vehicle at altitude under expected test conditions. This creates higher drag forces experienced by the article in the denser atmosphere and an absence of dynamic effects from the turbulent wake.
- Gravity is used to simulate the deceleration of the vehicle providing no control to explore extraction cases where the vehicle is decelerating faster or slower than 1 g.
- There is limited ability to test the effect of vehicle attitude and dynamics since the vehicle mockup can only be held statically at fixed angles with no rotation.
- When testing in segments, some modifications may need to be made to the test article to aid in deceleration of the article at end of the test and reduce loads going into the mockup vehicle.

B. Advantages

- The test article and vehicle interactions are evaluated at full scale.
- The test bed provides reasonable approximation of extraction force and velocities seen in flight with easy adjustment to explore lower probability flight cases.
- The test bed provides reasonable approximation of the inertia of the pilot device to better examine snag behaviors.
- Setup permits rapid modification and re-test of test article and vehicle mockup at a fraction of the cost of flight tests or aircraft drop tests.
- Ability to isolate extraction segments for individual testing to differentiate any observed failure modes.
- The test bed is able to produce greater fidelity than “static” pull tests.
- Provides data that can be readily used to validate computational models of the deployment.
- Provides suitable venue not just for development of the parachute but much of the related vehicle hardware as well which interacts with the deployment event. On the SFDTV there are many cameras positioned to observe the decelerators and the test bed provides a way to check field of views and operations prior to any flights while observing the SSRS in its full range of motion.

VI. Conclusion

A dynamics test bed for parachute extraction events is a versatile tool in the development of parachute decelerator systems. The unique architecture being proposed by LDSD drove the need to develop a facility where the extraction events could be thoroughly tested before the proposed test flights. It was determined that a pneumatic cylinder could be a simple mechanism to apply constant loads in a controlled way while preserving the inertia of the extraction system. This mechanism can be used to load the test articles in various configurations without much modification to the pneumatic system making it very flexible to an evolving design. This facility will be used heavily to finalize the development of the LDSD extraction system.

As with many efforts, the development of this facility was born of necessity. However having this facility available at the onset of a development may provide an invaluable sandbox for exploring new ideas. In this way, the investment in the facility and testing techniques can be used to benefit many future projects. It can be an effective laboratory space for experimenting with many dynamic events, not just those encountered in parachute development.

Acknowledgments

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References

1. Gallon, J., Clark, I., Rivellini, T., Adams, D., Witkowski, A., "Low Density Supersonic Decelerator Parachute Decelerator System," 22nd AIAA Aerodynamic Decelerator Systems Conference, March 2013.
2. Speelman III, R. J., "Parachute Deployment Process Evaluation Using a Simple Dynamic Testing Technique," 5th AIAA Aerodynamic Decelerator Systems Conference, November 1975.