V&V on a NASA Technology Demonstration Project: Low Density Supersonic Decelerator

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Abstract— **Given their smaller budgets, but higher allowed risk posture, technology demonstration missions face different Verification and Validation (V&V) challenges than typical NASA missions. Despite these challenges, the Low Density Supersonic Decelerator (LDSD) project, managed by NASA's Jet Propulsion Laboratory (JPL), has been extremely successful in testing new supersonic atmospheric decelerator technologies. A contribution to the project's success is the unique V&V program that emphasized efficiency and flexibility. This paper will provide an overview of LDSD test objectives, Supersonic Flight Dynamics Tests (SFDT) performed so far, unique requirements structure and V&V processes implemented. The paper will focus on the V&V of the SFDT test architecture. Furthermore, lessons learned will also be presented at the end of the paper to aid future technology demonstration projects.**

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1. PROJECT OVERVIEW

Current atmospheric deceleration technology used for planetary entry dates back to NASA's Viking program. Though successfully utilized on past projects, new atmospheric deceleration technologies are needed to land larger payloads on the surface of Mars.

LDSD is funded by NASA's Space Technology Mission Directorate (STMD) to develop, test and qualify new supersonic atmospheric decelerator technologies for future missions. LDSD is developing three atmospheric drag devices. Two of the devices are donut-shaped pressure vessels that inflate around the entry vehicle called Supersonic Inflatable Aerodynamic Decelerators (SIAD). The SIAD has two configurations: 1) Robotic Class (SIAD-R) which is 6m in diameter and 2) Exploration Class (SIAD-E) which is 8m in diameter. The third device is a 33.5m diameter parachute, the largest supersonic parachute ever developed. [1]

As a technology demonstration project, LDSD is fundamentally different from many NASA flight missions in various aspects. Unlike typical NASA projects (e.g. Mars Science Laboratory) where success of the project is dependent on a single flight, a single ground or flight test success for LDSD is insufficient. Instead, LDSD requires multiple complex ground and flight test successes in order to qualify the decelerator technologies for future flight use.

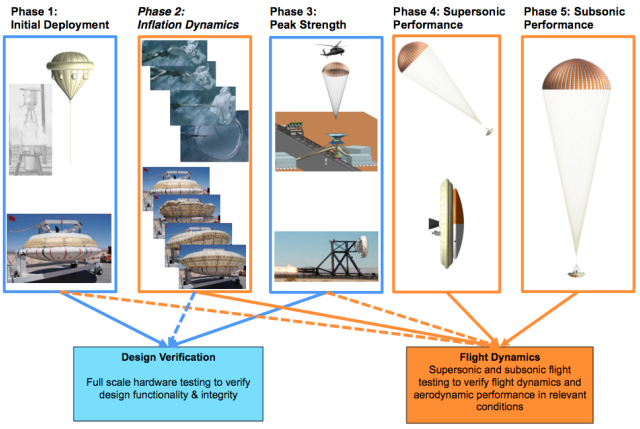

Figure 1 – LDSD Five Pillars of Testing [1]

To qualify the decelerators, five phases of each drag device needed to be tested (as shown in Figure 1) [1]:

1. Initial Deployment – mechanical performance when the decelerator is released from stowage and deployment forces are applied.

2. Inflation Dynamics – shape evolution of the decelerator after initial deployment.

3. Peak Strength – structural integrity of the decelerator under its flight load and temperature conditions.

4. Supersonic Performance – aerodynamic performance of the decelerator under expected Mach speeds and wake conditions at Mach numbers greater than 1.

978-1-4673-7676-1/16/$31.00 ©2016 IEEE

5. Subsonic Performance – aerodynamic performance of the decelerator under expected Mach speeds and wake conditions at Mach numbers less than 1.

To validate the decelerators' initial deployment phase, ground based deployment tests were conducted. For the parachute, the mortar used to fire the ballute (a pilot balloon parachute) to extract the parachute from stowage underwent ground testing to verify the mortar's capability to fire the ballute at the required speeds. For the SIAD, the gas generators used to deploy the SIAD were tested under static conditions with the SIAD integrated to a test vehicle. Photogrammetry analyses were performed to compare the post-inflated SIAD to expected dimensions.

To validate the decelerators' inflation dynamics, a mixture of analyses and tests were conducted. For the parachute, a historical analysis of past supersonic parachutes (e.g. Viking missions) was done to convince the team that LDSD's parachute would withstand supersonic inflation. For the SIAD, the inflation dynamics were verified through a rocket sled test at the Supersonic Naval Ordnance Research Track (SNORT) located at China Lake, CA. The SIAD was strapped to a rocket sled, accelerated to the desired test conditions and then inflated. High-speed imagery was taken to evaluate the SIAD's inflation dynamics. This test was referred to as the SIAD Design Verification (SDV) test. [2]

To validate the decelerators' deployed structural integrity, the same rockets sleds at the SNORT were used. For the parachute, a Parachute Design Verification (PDV) test is conducted. During a PDV test, the parachute is dropped from a helicopter and pulled down by a rocket sled on the ground through a pulley system to its desired load conditions. Both the SIAD's inflation dynamic performance and deployed structural integrity are tested during the SDV concurrently. The SIAD is strapped to a rocket sled, accelerated to the desired load conditions and then inflated. Internal pressure measurements and high-speed imagery were taken to characterize the deployed SIAD structural integrity. [2] [3]

To validate the decelerators' supersonic and subsonic performance a SFDT was performed at the Pacific Missile Range Facility in Kauai, Hawaii. The SFDT goal was to deploy and inflate the decelerators under similar supersonic atmospheric entry conditions to those expected when landing on Mars. This meant a low-density atmospheric environment and supersonic speeds up to up to Mach 4. The SFDT was accomplished by raising a test vehicle equipped with a SIAD and parachute to approximately 120,000 ft using a scientific balloon. Upon reaching altitude, the vehicle is dropped, an attached STAR-48 rocket motor is lit, and the vehicle is propelled to 180,000 ft at Mach 4 where the technologies are tested. Subsonic performance is validated after the supersonic inflation and the vehicle is decelerated to subsonic speeds. Figure 2 illustrates the SFDT concept of operations. [1]

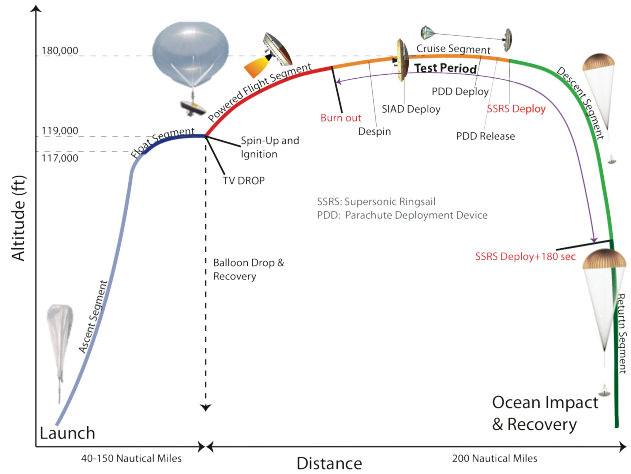

Figure 2 – SFDT Concept of Operations [1]

2. Test Flight Overview

In June 2014, the first SFDT flight (SFDT-1) took place. The flight was a shakeout test with a goal to verify the SFDT test architecture. Per SFDT-1 test plan, the minimum success criteria for SFDT-1 were:

1. Launch with a STAR-48 on a balloon from the Pacific Missile Range Facility (PMRF) on the Island of Kauai to float altitude.

2. Conduct a powered flight, demonstrating the ability to target test Mach and dynamic pressure requirements.

3. Collect sufficient real-time telemetry from the test vehicle to assess flight objective and to demonstrate the operation of all RF (radio frequency) links.

4. Recover the balloon envelope from the ocean for disposal

Additional goals for SFDT-1 were:

- Deploy and collect data on SIAD-R operation and dynamics.

- Deploy and collect data on the parachute operation and dynamics.

- Retrieve Fly camera mast assembly and other SIAD and parachute sensors.

- Recover the test vehicle or flight image recorder from the ocean.

During the test, the vehicle was successfully lifted to 120,000 ft, dropped, spun up after release, fired its STAR-48 rocket motor, and despun after accelerating to the required test conditions. The vehicle successfully deployed

and tested its 6m diameter SIAD and 33.5m diameter parachute. The SIAD successfully inflated and maintained inflation through the supersonic period. The parachute was successfully extracted from stowage and inflated, but failed before fully inflated. Though the parachute did not survive inflation, SFDT-1 met all of its success criteria and the SFDT test architecture was successfully validated for the first time.

In June 2015, the second SFDT flight (SFDT-2) took place at PMRF. With the successful demonstration of SFDT-1 as a shakeout test, the follow on flight SFDT-2 success criteria was to validate the technologies. Per SFDT-2 test plan, the minimum success criteria for SFDT-2 were:

1. Deliver a flight-like 30m diameter or larger supersonic parachute to the required test conditions at line stretch, behind a 6m diameter forebody.

2. Collect real-time telemetry from the test vehicle or recover data from the on-board recorder, and collect coincident high-altitude atmospheric data. These data sets will allow for the reconstruction of the trajectory and determine the deployment conditions, total force, and flight dynamics of the parachute through three minutes after ballute mortar fire.

3. Collect both high-speed and high-resolution video over the three minutes following ballute deployment. This require recovery of the flight image recorder, to observe and measure deployment, inflation and supersonic operation of the parachute, and to diagnose any damage to the parachute.

4. Recover the balloon envelope from the ocean for disposal.

Additional goals for SFDT-2 were:

- Collect data on SIAD-R operation and dynamics.

- Maintain general parachute integrity through three minutes after mortar fire.

- Recover and return the test vehicle and parachute.

During the test, the vehicle was successfully delivered to its test conditions similar to SFDT-1. The 6m SIAD inflated and maintained inflation during the supersonic period. The parachute was extracted and inflated for a brief moment until it experienced a structural failure. Despite the parachute failure, the project still met its minimum success criteria.

Although the SFDT test architecture was successfully verified and validated for SFDT-1 and SFDT-2, project objectives have not been met yet. Additional SFDTs are required to qualify the parachute. Currently the project is planning a SFDT-3 for the summer of 2017.

3. REQUIREMENTS

Since the goal of the LDSD project is develop, test and qualify new supersonic atmospheric decelerators for future missions, the project's requirements structure is different from traditional NASA missions. In total, LDSD had approximately 700 requirements, which was significantly less compared to Class A NASA missions that have around 6000 requirements. Level 1 project requirements levied by NASA include the following:

1. Robotic Class (SIAD-R) Technology Application – For a 4200 kg, 4.7 m diameter entry vehicle, the LDSD system shall be capable of increasing the 99% low dispersed altitude at Mach 0.5 by 2 km as compared to an equivalent entry mass utilizing MSL technology at Mars.

2. Exploration Class (SIAD-E) Technology Application – for a 5825 kg, 4.7 m diameter entry vehicle, the LDSD system shall be capable of increasing 99% low dispersed altitude at Mach 0.5 by 2 km as compared to an equivalent entry mass utilizing MSL technology at Mars

3. Project Documentation – The project shall document and archive all data relevant to the design, production, and qualification of future LDSD applications.

From Level 1 requirements, Level 2, Level 3 and Level 4 requirements modules were derived. In Figure 3, at Level 2, two requirements modules called Capability and SFDT Test were created to separate out the design of the decelerators and the SFDT test architecture.

At Level 3, performance, accommodation, measurement and safety requirements are defined for the SIAD-R, SIAD-E and Parachute requirement modules. For the flight test architecture, the requirements were distinguished into Flight System and Launch Services. The Launch Services module contains the interface, performance capability, operations and safety requirements necessary to launch the test vehicle. The Flight System module contains the test vehicle properties, performance capability, instrumentation, vehicle control and safety requirements.

At Level 4, performance, interface, instrumentation and safety requirements are refined at the component level for both the decelerators and the SFDT test vehicle. Furthermore, the interface, instrumentation, performance capability and safety requirements are defined at Level 4 for the PDV and SDV ground test architectures. Note that the Level 4 PDV and SDV requirements were derived directly from Level 2 Capability requirements.

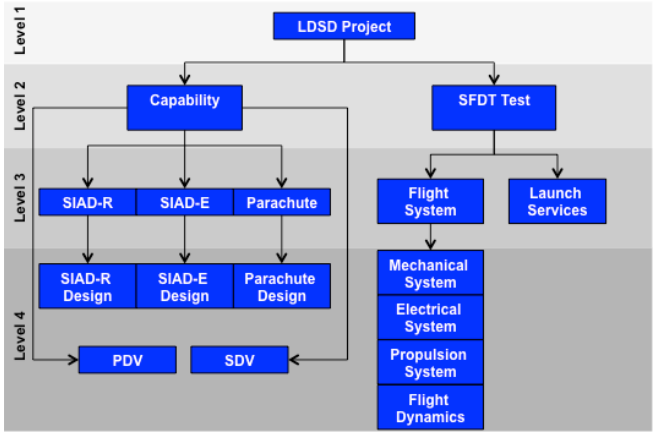

Figure 3 – LDSD Requirement Structure

4. V&V Approach and Practices

Requirement Classification

Project requirements were classified into three types: 1) Scientific Integrity, 2) Flight Worthiness, and 3) Safety Critical. Classifying the requirements into these types allowed the Project V&V Engineer (PVE) and requirement owners to prioritize verification activities and allow for a flexible V&V standard.

1. Safety Critical – Requirements that affect the safety of personnel. These requirements are subjected to strict V&V processes and standards. (e.g. RF transmit inhibit requirement)

2. Flight Worthiness – Requirements that affect the test vehicle's ability to avoid catastrophic failure or complete loss of data products. It is at the discretion of the PVE and requirements owners to agree on the verification rigor of these requirements. (e.g. Mass properties requirement)

3. Scientific Integrity – Requirements that affect the quality of the final test data set. It is at the discretion of the PVE and requirements owners to agree on the verification rigor of these requirements. (e.g. Camera resolution requirement)

V&V Schedule and Tracking

LDSD did not impose structured deadlines on when requirements were to be verified. It was left to the PVE to consistently meet with requirements owners to identify expected closure dates and manage schedule slips as they occurred. It was critical to be flexible in managing changing closure dates as requirements owners were technical leads that often had to respond immediately to issues that came up during the system integration and tests. Often, the PVE would contribute by executing the necessary test or analysis to verify the requirement when the requirement owner was occupied. Having a PVE who understood the system well enough to contribute technically was extremely beneficial when trying to meet deadlines.

LDSD project requirements were captured in revision-controlled project documents. The Project System Engineer (PSE) is responsible for maintaining and updating the documents throughout the project life cycle. For V&V tracking, the requirements were imported into a tool called DOORS. (Dynamic Object Oriented Requirements System). The tool is used solely by the PVE to track and manage the ongoing V&V process. Attributes such as verification methodology, approach, closure evidence and closure status were populated for each requirement and for each test. Closure evidences were only linked to in DOORS; the documents were actually stored within JPL's electronic library service.

Unlike Class A NASA missions where requirement burndown charts are generated to see if the project is on track to meeting its launch date, burndown charts were not required by LDSD project management. Deadlines for requirements closures were never formally established. Therefore burndown charts were neither practical nor useful for LDSD. Instead, weekly simple open/close V&V status logistics plots were generated to identify the number of requirements that were still open and areas of concern. Figure 4 shows an example of the V&V logistics graphs that were generated.

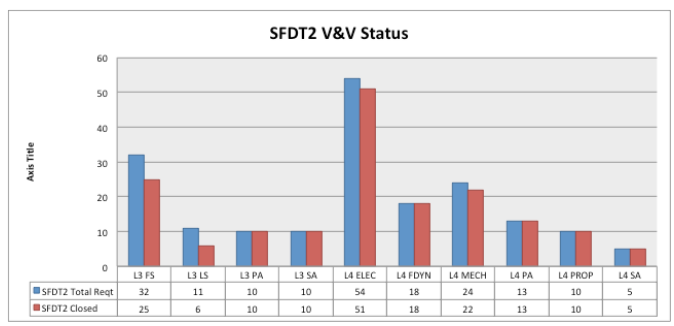

Figure 4 – LDSD V&V Logistics Example

Requirement V&V Closure Process

A standard V&V documentation rigor was not applied to all requirement verification on LDSD. It was up to the PVE and requirement owners to agree on the documentation required to verify each requirement based on requirement classification. Example verification documentation ranged from 200-page safety compliance reports to simple email correspondences confirming the execution of planned tests. It was important that the PVE not only managed and tracked the V&V process but was involved in all areas of testing and analysis that were performed. Including the PVE in verification activities allowed requirement owners to quickly submit accurate verification evidences without being burdened by a heavy documentation process. In many cases, the PVE actively contributed by executing subsystem or system level tests and producing the closure documentation.

For the SFDT flight requirements, final V&V closure required an approval from PVE, the Flight System Engineer (FSE) and the requirement owner. Having the FSE review the closure evidence was a simple way to ensure that the tests and analyses performed were adequate from a flight system perspective. This added approval step ensured that nothing was missed from validating the test vehicle design.

Parameter and System Level Phasing V&V

Aside from the verification activities associated with closing out requirements, numerous other verification activities were performed to validate the SFDT test vehicle. One such activity that was performed was device parameter verification. The PVE was responsible for managing and executing parameter verification activities for nine flight devices. These included the flight computer, the multi-functional timers used to fire the pyros on board, the GPS receiver, and the S-band transmitters. Device parameters were verified by either parameter file inspection or parameter functionality tests.

Phasing verification activities were also executed to confirm that devices were connected appropriately. An example is the pyrotechnic phasing test done on the vehicle to confirm that all pyro firing lines were appropriately connected throughout the vehicle. The test involves executing a pyrotechnic firing sequence and confirming that the firing signals reach their intended pyro. For example, if the onboard flight computer sent a signal to Pyro A, its expected that the signal would travel through the pyro harness bundle and fire Pyro A not Pyro B. The off-nominal case is when Pyro B fires when a firing signal was intended for Pyro A. The phasing tests are specifically designed to avoid these 'mix-ups'.

Operations V&V

The same Electrical Ground Support Equipment (EGSE) units used at the subsystem and system level integration were ultimately used for flight operations. The EGSE units were initially used to test the avionics pallet at the subsystem level (both of which were developed by NASA's Wallops Flight Facility). After integrating the avionics pallet to the test vehicle, the same EGSE units were shipped to JPL to support vehicle level system tests. Finally, the same EGSE units were used to during flight operations at PMRF. Normally, on a NASA mission, the equipment used for operations had to be verified separately from the system integration EGSE through numerous hardware-in-the-loop operations tests. By using the same EGSE, additional operational testing was not required, allowing the project to meet its launch period.

Post Shakedown Flight V&V

After SFDT-1, the PVE worked with requirement owners to identify which requirements needed to be verified again for SFDT-2. The requirements that were selected for re-verification can be summarized in the following categories:

1. Design Changes – requirements that were affected by design changes between SFDT-1 and SFDT-2 (e.g. Added science cameras for SFDT-2).

2. Workmanship – requirements that are impacted by mechanical and electrical workmanship (e.g. Mass properties changes between vehicles).

3. Failed Requirements – requirements that failed during SFDT1 flight.

4. Extra Credit Requirements – requirements that requirement owners wanted to re-verify and tracked by the PVE.

Requirements that were not selected for re-verification can be summarized in the following categories:

1. One-off Analysis – requirements that were verified by an analysis that is applicable to both flights (e.g. Aerothermodynamic analysis of the SIAD).

2. One-off Tests – requirements that were verified by a test that do not need to be repeated for SFDT-2 (e.g. impact testing of data storage unit).

3. System level Protoflight Tests – requirements that were related with protoflight certifications (e.g. SFDT test vehicle electromagnetic interference and compatibility tests).

At the end, around 150 SFDT Test requirements were identified for SFDT-2 compared to 500 SFDT Test requirements that were verified for SFDT-1.

5. LESSONS LEARNED AND CONCLUSION

Many lessons were learned during SFDT-1 and SFDT-2 test campaign. The following are major V&V lessons learned thus far:

1. On a technology demonstration project, the more involved the PVE is in all verification activities, the easier it is for the project to track and close verification items. On LDSD, the PVE assisted requirements owners by contributing or leading various system testing (e.g. pyrotechnic phasing). Since the PVE had a direct knowledge to the test method and results, the PVE was able to track and verify requirements with confidence.

2. During the early development phase of a technology demonstration project, V&V process and planning needs to be considered. During SFDT-1, it was discovered that some requirements were hard to verify based on the requirement wording. This resulted last minute requirement changes leading up to SFDT-1 launch.

3. By classifying the requirements into categories, the verification rigor can be tuned for each category allowing

more prioritization on how and when requirements are verified.

4. Identify requirements that need to be re-verified early and revisit these requirements on a bi-weekly basis and between each flight. It was important for the PVE and requirements owners to scrub through their requirements and understand why or why not certain requirements had to be verified. It was imperative to not miss any critical requirements (e.g workmanship types) that needed to be verified for a test flight

5. Aside from requirement verification, other verification activities such as parameter and phasing verification are important to ensure the success of the qualification tests. During system integration and testing, an actual system phasing issue was discovered. This serves as a reminder that additional verification activities are important besides activities needed for requirement verification.

6. Simple V&V logistics were sufficient for V&V management on a technology demonstration project. Not generating traditional burndown metrics saved time. Creating burndown metrics would've added unnecessary burden on the system engineering team.

Verification and Validation on a technology demonstration project was a unique system engineering challenge. In order to meet the project's aggressive delivery schedule and deliver functional tests, a flexible and efficient V&V process was developed. Furthermore, LDSD posed an additional challenge being that the project required multiple tests where other NASA projects fly only once. In order to achieve success for multiple flights, engineers on the project had to scrub through requirements and define re-verification criteria. It is with great hope that the practices and lessons learned presented in this paper will help future technology demonstration projects.

ACKNOWLEDGEMENTS

The project was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The authors would like to thank the entire LDSD team across the participating government facilities and industrial contractors for helping to advance these technologies for the next generation of Mars landers. The authors would also like to thanks Jessica Samuels on her V&V guidance and contributions to the LDSD V&V program. Lastly, the authors would also like to thank Michael Kilzer and Danny Wernicke for their contributions to the paper.

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BIOGRAPHY

Michael Murry *received his B.S and M.S. in Aerospace Engineering Sciences from the University of Colorado, Boulder in 2013. After graduation, he started working at JPL as a SMAP Instrument Test Engineer. Afterwards he joined LDSD as the Lead V&V Engineer for SFDT-1 and SFDT-2 test campaign. He currently still works on LDSD while supporting Fault Protection Testing on Insight.*

Thomas Randolph *received his B.S. in Aerospace Engineering from USC in 1989 and his M.S. in Mechanical & Aerospace Engineering from Princeton in 1994. From 1992 until 2008, he worked on the development and flight of spacecraft electric propulsion systems at Loral and JPL. Starting in 2008, he has been a systems engineer at JPL for spacecraft system concept development and as the Project Systems Engineer on LDSD through the second SFDT flight in 2015. Tom is now the supervisor for JPL's Project Systems Engineering group.*