

Resurrected DSCOVR Propulsion System – Challenges and Lessons Learned

Apurva P. Varia¹ and Ashley R. Scroggins²
NASA Goddard Space Flight Center, Greenbelt, MD 20771

The Deep Space Climate Observatory (DSCOVR), formerly known as Triana, is a unique mission, not because of its objectives but because of how long it was in storage before launch. The Triana spacecraft was built in the late 90s and later renamed as DSCOVR, but the project was canceled before the spacecraft was launched. The nearly-complete spacecraft was put in controlled storage for 10 years, until the National Oceanic and Atmospheric Administration (NOAA) provided funding for the National Aeronautics and Space Administration (NASA) to refurbish the spacecraft. On February 11, 2015, DSCOVR was launched on a Falcon 9 v1.1 from launch complex 40 at Cape Canaveral Air Force Station. This paper describes the DSCOVR propulsion system, which utilizes ten 4.5 N thrusters in blowdown mode to perform Midcourse Correction (MCC) maneuvers, Lissajous Orbit Insertion (LOI) at Lagrangian point L1, momentum unloading maneuvers, and station keeping delta-v maneuvers at L1. This paper also describes the testing that was performed, including subsystem-level and spacecraft-level tests, to verify the propulsion system's integrity for flight. Finally, this paper concludes with a discussion of the challenges and lessons learned during this unique mission, including replacement of a bent thruster and installation of an auxiliary heater over existing propellant line heaters.

Nomenclature

<i>ACE</i>	=	Advanced Composition Explorers
<i>ADP</i>	=	Acceptance Data Package
<i>DMP</i>	=	DSCOVR Manifold Panel
<i>DSCOVR</i>	=	Deep Space Climate Observatory
<i>DTM</i>	=	Dual Thruster Module
<i>EGSE</i>	=	Electrical Ground Support Equipment
<i>FDM</i>	=	Fill and Drain Module
<i>FDV</i>	=	Fill and Drain Valve
<i>GSE</i>	=	Ground Support Equipment
<i>GSFC</i>	=	Goddard Space Flight Center
<i>ICD</i>	=	Interface Control Document
<i>ITOS</i>	=	Integrated Test and Operations System
<i>L1</i>	=	First Lagrangian Point
<i>LOI</i>	=	Lissajous Orbit Insertion
<i>MCC</i>	=	Midcourse Correction
<i>MDP</i>	=	Maximum Design Pressure
<i>MEOP</i>	=	Maximum Expected Operating Pressure
<i>MLI</i>	=	Multilayer Insulation
<i>NOAA</i>	=	National Oceanic and Atmospheric Administration
<i>NASA</i>	=	National Aeronautics and Space Administration
<i>PCM</i>	=	Propellant Control Module
<i>PM</i>	=	Propulsion Module
<i>PN</i>	=	Power Node
<i>RGA</i>	=	Residual Gas Analyzer
<i>S/C</i>	=	Spacecraft
<i>SMEX</i>	=	Small Explorer

¹ Propulsion Engineer, NASA Goddard Space Flight Center Propulsion Branch, Mail Stop 597, AIAA Member.

² Propulsion Engineer, NASA Goddard Space Flight Center Propulsion Branch, Mail Stop 597, AIAA Member.

TC = Temperature Controller
UHUB = Utility HUB

I. Introduction

How often is a project repurposed after many years of operation or after a hiatus? For missions in flight, a new objective can be chosen if the spacecraft remains functional after the primary mission is complete. However, this kind of change is a rare occurrence prior to launch. One example is the Triana mission, which was mothballed for many years and resurrected as the Deep Space Climate Observatory (DSCOVR), with the priorities of the original objectives reversed.

DSCOVR is supported by the National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), and the United States Air Force. The mission's primary objective is to provide advanced warning of solar storms and other extreme solar events. This warning will allow utility companies and satellite operators to take action and avoid damage to critical components. Millions of people depend on modern equipment that could be greatly affected by solar events. The secondary objective of the DSCOVR mission is to provide a continuous view of Earth for observing and tracking changes in the ozone, effects of aerosol usage, and information about cloud cover. Figure 1 shows DSCOVR on +X side, and Figure 2 shows DSCOVR on -X side.

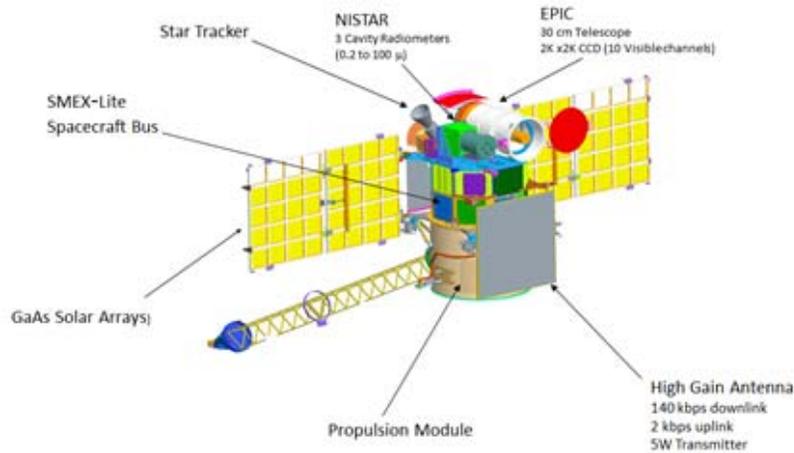


Figure 1. Deep Space Climate Observatory on +X Side

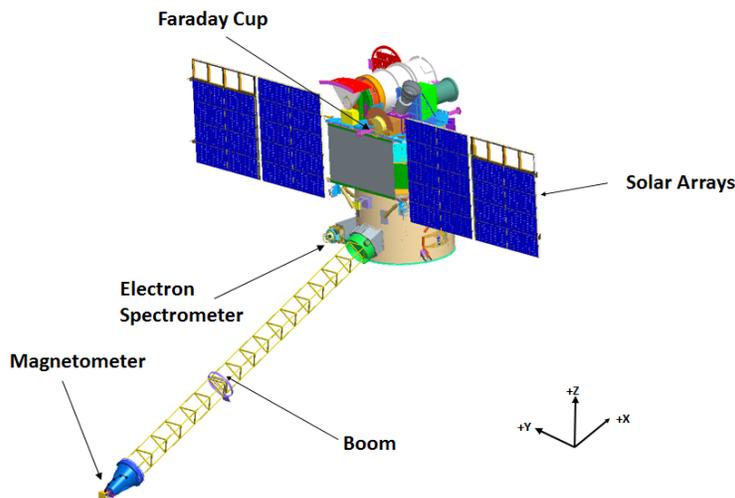


Figure 2. Deep Space Climate Observatory on -X Side

In the late 1990s, Triana was primarily designed to provide a continuous view of the Earth in order to observe changes in the atmosphere and effects of modern life. Additionally, Triana would provide advanced warning of coronal mass ejections toward Earth. To meet these objectives, the spacecraft consisted of a Small Explorer (SMEX)-lite module and a propulsion module (PM). The SMEX-lite module includes the avionics box, four reaction wheels, gyro, star tracker, and structure. The propulsion module includes the propulsion components. Triana was originally to be launched on a Space Shuttle.

The Triana project was canceled in 2001 after completion of environmental testing. The spacecraft was placed in a GN2-purged storage box in a controlled cleanroom environment after the project was canceled. The controlled cleanroom has temperature and humidity sensors. On occasion, the spacecraft was taken out of its box and checked inside the cleanroom. Because it was not known whether the spacecraft would eventually fly, some parts were taken and used for other projects.

NOAA requested that NASA evaluate whether the Triana spacecraft could replace the space weather data coming from the Advanced Composition Explorer (ACE). ACE launched on August 25, 1997, and its instruments are beginning to show signs of degradation. Replacing ACE with DSCOVR would maintain operations as the spacecraft continues to age. Approval was given to remove DSCOVR from storage, with the expectation that the satellite would be refurbished with minimal effort. DSCOVR was taken out of storage in 2012, making this the first in-house spacecraft NASA Goddard Space Flight Center (GSFC) has refurbished after long-duration storage.

This paper describes the propulsion system and the testing performed to verify its integrity for flight. This paper also describes the challenges and lessons learned during refurbishment, testing, launch, and early flight operations.

II. Propulsion System Overview

A. Propulsion System

The DSCOVR propulsion system is a monopropellant blowdown system that consists of ten 4.5 N thrusters, one 0.71 m spherical tank with 145 kg of hydrazine, two fill and drain valves (FDV), and Propellant Control Module (PCM) which includes one latch valve, two pressure transducers, one filter, and one orifice. Tubing sizes are 1/4 and 3/8 inch. The fluid schematic is shown in Figure 3

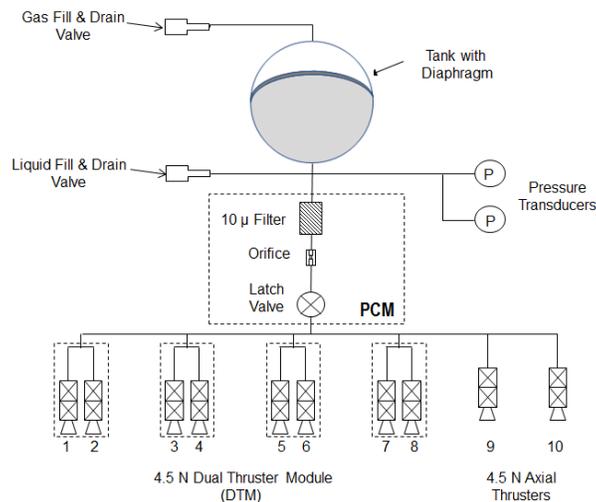


Figure 3. DSCOVR Propulsion Schematic

The DSCOVR propulsion system is required to:

- Provide propellant for five years of operation
- Correct excessive tip-off rates after launch vehicle separation if needed
- Provide thrust for Midcourse Correction (MCC) maneuvers and Lissajous Orbit Insertion at L1
- Reduce the momentum built up in the reaction wheels every 30 to 40 days

- Provide stationkeeping maneuvers at L1
- Maintain propulsion system temperatures between 10°C and 50°C.

The Triana project was given a short timetable – approximately 2 years - to build the observatory. Because of the long lead time required for new propulsion components, several spare components were used from other projects. For instance, instead of procuring a new fuel tank, the spare fuel tank from the CASSINI project was transferred to the Triana project. This propellant tank was manufactured by Pressure Systems, Inc. (now ATK).

The thrusters were manufactured by Kasier Marquardt (now Moog). Eight of the 4.5 N thrusters were manufactured as dual thruster modules (DTM) with the nozzles oriented 45 degrees opposite each other in the Z direction. The DTM contains two 4.5 N thrusters, a connector, and temperature controller. The DTMs provide attitude control during delta-V, momentum unloading, and contingency delta-V burns in +Z, -Z, +X, and -X directions. Two 4.5 N thrusters are mounted on the aft end of DSCOVR to provide thrust in the +Z direction. These axial thrusters are more efficient for delta-V burns and stationkeeping at L1.

Two FDVs were provided by the Cassini project. A 1/4 inch valve for the gas side and a 3/8 inch valve for the liquid side. These valves were manufactured by OEA Aerospace (now Cobham Life Support).

The pressure transducers were provided by the Near Earth Asteroid Rendezvous (NEAR) project. The transducers were manufactured by Paine Corporation (now Paine Electronics). Each transducer has a full scale of 0-500 psia. The second pressure transducer was added late in the Triana project to satisfy fault tolerance requirements from Shuttle safety. The pressure transducers are wired to the Safety Inhibit Unit to preclude overheating in the PCM.

The 1/4 inch latch valve was manufactured by VACCO. The valve remains magnetically latched in position until it is commanded to change states. The function of the latch valve is two-fold. The latch valve is one of three mechanical inhibits required by Range Safety AFSPCMAN 91-710 Volume 3. Also, the latch valve isolates the entire thruster manifold if any of the thrusters leak.

B. Mechanical Design

As shown in Figure 4, the propulsion components and lines are mounted inside an aluminum cylindrical structure that interfaces with the SMEX bus. Each DTM is mounted on brackets at the top of the cylindrical structure. Two axial thrusters are mounted on the bottom of the deck. The locations of all 10 thrusters are shown in Figure 4 and Figure 5. The propellant lines are supported by standoffs which are bonded to the deck and structure. The PCM is mounted on a plate, which is mounted onto the deck inside the cylinder as shown in Figure 6.

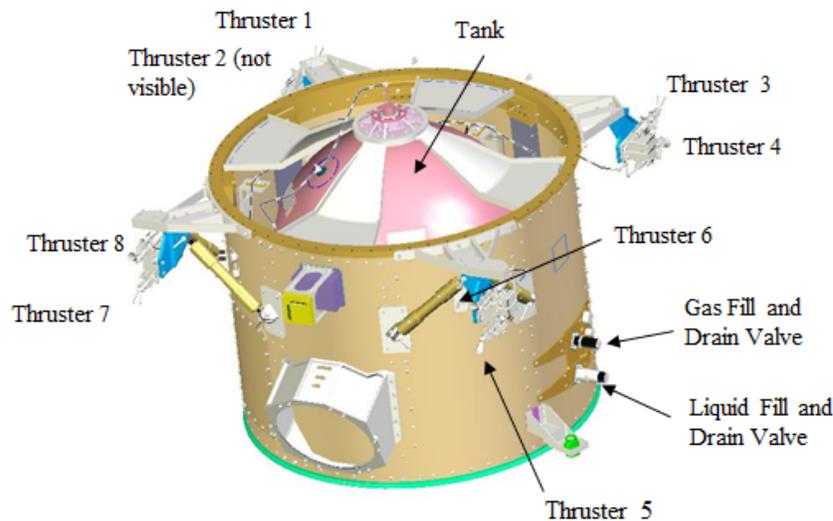


Figure 4. Propulsion Module

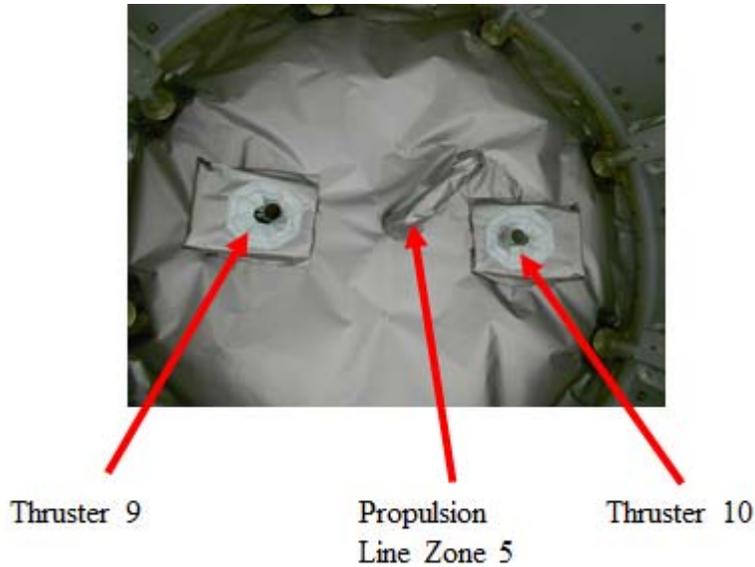


Figure 5. Axial Thrusters and Prop Line Zone 5

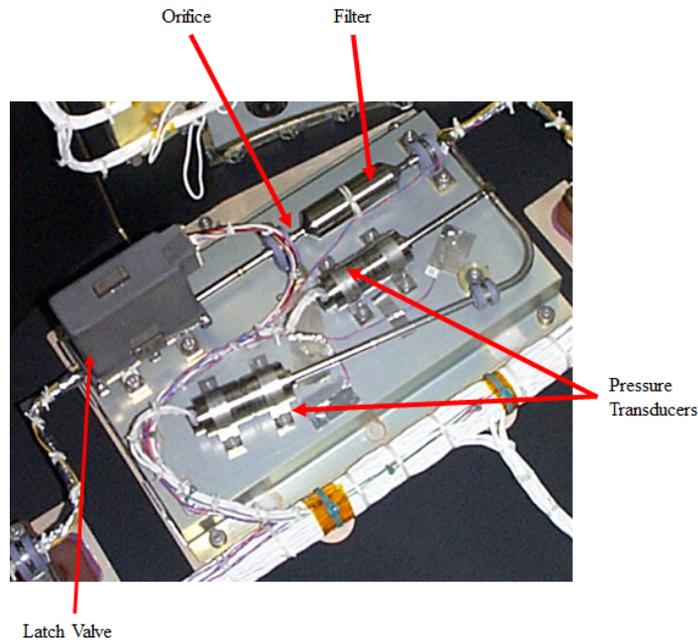


Figure 6. Propulsion Control Module

C. Electrical Design

As shown in Figure 7, the thrusters, latch valve, and pressure transducers receive power from the Power Node (PN) electrical box via the Utility HUB (UHUB) electrical box. The PN also provides power to the line heaters, tank heaters, and thruster valve and catalyst bed heaters. When a command to fire a thruster is received in the UHUB, the UHUB switches the power to the thrusters. Upon completion of firing, the UHUB removes power from the thruster valve, which in turn closes it. Likewise, the latch valve is actuated and the pressure transducers are turned on when a command is received in the UHUB to turn on these components. In addition, the UHUB receives analog data for the latch valve position, tank pressure, and propulsion module temperatures (propellant lines, PCM, FDV, tank, thruster valves).

Triana Propulsion Electrical Interface Diagram

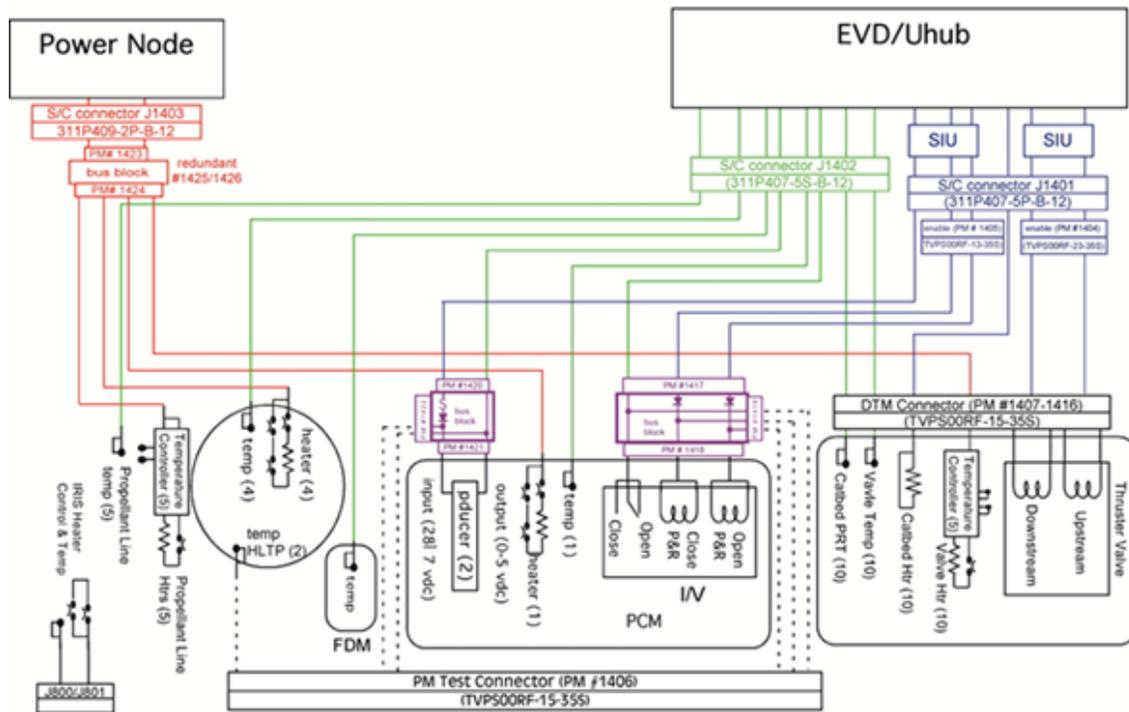


Figure 7. Propulsion Electrical Interface Schematic

D. Thermal Design

All components in contact with the propellant have redundant heater circuits to ensure the propellant temperature is above 10°C. (Hydrazine will freeze if the bulk liquid temperature drops below 2°C.) A minimum operating temperature of 10°C was chosen to account for temperature variations within the system and to allow for some margin above the freezing point of hydrazine. All heater circuits are active whenever heater bus power is applied. In order to satisfy the Shuttle requirement for two fault tolerance, each heater circuit has three separate thermal control devices to prevent thermal runaway. For example, the tank heater and PCM heater have three redundant mechanical thermostats. The line heaters and thruster valve heaters have two separate temperature controllers and one over-temp thermostat. The line heaters are grouped in five zones, resulting in five redundant heater circuits. Table 1 shows the setpoints for the flight thermostats and temperature controllers.

Table 1. Setpoints for Thermal Components

Heater Circuit	Primary Setpoints
Tank	15°C ON/ 20°C OFF
PCM	10°C ON/ 20°C OFF
Propulsion Zone 5 Auxiliary	10°C ON/ 15°C OFF
Propulsion Line (Five Zones)	18.0°C ON/ 19.6°C OFF
Thrusters	18.0°C ON/ 19.6°C OFF

As mentioned above, the Temperature Controller (TC) is one of three separate thermal devices that regulate heat and prevent thermal runaway. The Translogic Inc. Dual Trip TC is equivalent to two mechanical thermostats. The TC uses two thermistor temperature inputs that are continuously validated by two active circuits which in turn control the heaters. The primary purpose of the TC is to maintain the temperature of the propellant lines within the defined limits. The controller has two features:

1. Cycle heater power ON and OFF based on the feedback from dedicated thermistors (resistance measurements)
2. Check the thermistor readings to look for shorts (low resistance) or open readings (high resistance)

The controller has setpoints as specified in Table 1 to cycle the heaters. Power is not applied to the heaters until both the “switches” in the TC close. The result of this configuration is that the TC will control about the lowest – primary – setpoint and therefore use the lowest overall power. The TC also evaluates the thermistor resistances. If the values are outside the operating range (< -49°C or > 29.5°C), the TC will not operate, resulting in a fail safe. The digital logic utilizes an “AND” gate that requires both the resistance/temperature to be within the required control range and within the overall allowable range. If either of these conditions is not true, the TC will not operate. In addition, there is a high temperature mechanical thermostat with a setpoint of 28.9°C on the return leg of each heater. This thermostat is set to prevent overheating and was necessary to meet the Triana dual-fault tolerant requirement for the Space Shuttle.

All components are covered by multi-layer insulation (MLI) blankets to minimize heat loss, thus reducing the required heater power to maintain the minimum temperature. All MLI is grounded to the structure to eliminate floating charge over the blankets.

III. Propulsion System Testing

The PM was fully built and tested during the Triana project lifetime. The Triana team was given a shortened schedule to build the PM. PM integration and testing took place in 1999 and 2000, followed by spacecraft-level environmental testing in 2001. The PCM was assembled separately; the latch valve, pressure transducers, and filter were installed in place on the PCM plate, and the interconnecting manifold tubing was welded to the components. The PCM was installed into the PM structure on the lower deck after completion. The FDVs were installed on the PM structure, and the thrusters were installed and aligned before the interconnecting manifolds of stainless steel tubing were welded together in place. All welds were x-rayed after completion. After manifold proof and leak testing, thermal hardware was installed on the lines and PCM. Finally, the fuel tank, with its thermal hardware already installed, was integrated and welded into the system. Once complete, the PM underwent a test program that included a system proof and leak test at 675 psia (1.5 x maximum design pressure), and component and system-level functional and leak testing. Typically, a propulsion system is tested at a maximum expected operating pressure (MEOP) that is based on tank design. However, the propulsion system was designed to satisfy the requirements which envelopes all worse-case hot orbit and abort conditions. For all testing, the tank’s maximum design pressure (MDP) is 450 psia at 58°C. All analyses for blowdown and propellant budget use the system MEOP which is 400 psia at 40°C.

When the DSCOVr project began, the Propulsion Team determined that functional, leak, and command verification testing should be repeated on the propulsion module to verify the integrity of the system. Because there were no indications that anything had changed in the system and because the tank is cycle-limited, proof testing was

unnecessary. Discussions about a proof test were re-opened after the bent thruster issue addressed later in this paper, but ultimately the decision was to test the repair weld to MDP and write a waiver for not performing a proof test of the rework. The waiver was approved by Range Safety. Descriptions of the testing performed on the DSCOVER propulsion system are below.

A. Functional and leak testing

The DSCOVER functional and leak testing procedure was based on the Triana testing procedure and incorporated lessons learned from other in-house propulsion systems built by the GSFC Propulsion Branch. This test was performed three times: 1) after the observatory was removed from storage, 2) after observatory-level environmental testing, and 3) at the launch site prior to propellant loading. Initial testing was performed in two parts, as the first dolly used to support the spacecraft did not allow access to the axial thrusters. Functional and leakage testing of the axial thrusters was performed separately at a later date. A special partial test was also added to check the repaired thruster module after welding. Important dates from the integration and test schedule are shown below.

- January 2012 – DSCOVER spacecraft removed from storage
- August 2012 – Functional and leak testing, not including axial thrusters
- January 2013 – Functional and leak testing, axial thrusters only
- May 2013 – Bent thruster repair
- August 2013 – Functional and leak test on repaired thrusters only
- August 2013 – Reintegration of the PM with the SMEX bus
- December 2013 through May 2014 – Spacecraft-level environmental testing
- July 2014 – Post-environments propulsion functional and leak testing
- December 2014 – Pre-fueling functional and leak testing

The functional and leak test procedure follows the timeline shown in Figure 8. Functional and Leak Testing Timeline

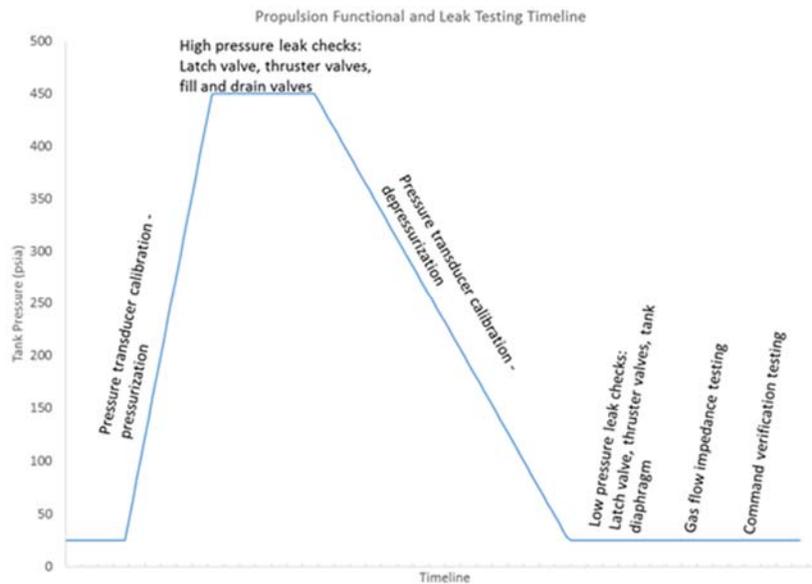


Figure 8. Functional and Leak Testing Timeline

Note, however, that for the final functional and leak test prior to propellant loading, the low pressure valve and diaphragm leakage testing was performed prior to pressurization. This rearrangement was utilized to take advantage of available schedule time but avoid facility restrictions of performing high pressure testing during normal business hours. The included tests are described below.

- Pressure transducer calibration – Telemetry readings are taken approximately every 25 psid from pad pressure (25 psia) to MDP (450 psia) and compared to analog pressure gauge readings.

- Valve seat internal leakage testing – The fill and drain valve primary seats, secondary caps, and secondary O-ring seals are tested for helium leakage at MDP. A modified cap is used to isolate potential O-ring leakage when the primary seat is open and the AN cap is installed. This special test is described in detail in the Lessons Learned section of this paper. The latch valve seat, upstream and downstream thruster valve seats are tested for helium leakage at MDP and at pad pressure.
- Gas flow impedance testing – The gas flow rate through each thruster is measured at a known pressure differential. Note that during the initial DSCOVER functional and leak test, gas flow impedance testing was not performed. The risk of not performing this test, which results in information-only data, was accepted. After the bent thruster replacement was completed, this test was included in the sequence as an additional verification of the health of the thrusters.
- Diaphragm leakage testing – The helium leakage rate across the tank diaphragm is measured with the diaphragm bottomed out on the fuel side of the tank and the gas side of the tank filled with helium.

Major constraints for the functional and leakage testing are as follows.

- Maintain tank surface temperature below 35°C. Pressurization to MDP causes the tank temperature to rise, so this constraint results in a lengthy pressurization process.
- Maintain tank surface temperature above the ambient dew point temperature with a margin of 5°C. Depressurization from MDP to pad pressure causes the tank temperature to drop, so this constraint results in a lengthy depressurization process. This constraint is also highly dependent on the testing environment. For example, performing the test in a hot, humid location during the summer months, in a less-than-ideal clean tent, extends the duration of depressurization much further than performing the test in the drier winter months.
- Verify that test gases entering the propulsion system has a dew point less than -51°C. Dew point is checked at the point of use prior to connecting to the propulsion system to check that both the supply gas and the ground support equipment (GSE) are sufficiently dry.
- Maintain less than 50 psid across the tank diaphragm from the gas side to the liquid side to avoid damaging the elastomeric diaphragm.
- Maintain less than 1 psid across the tank diaphragm from the liquid side to the gas side. The diaphragm in the DSCOVER tank is not fully reversible, so pressure differences in the reverse direction could have adverse effects on the diaphragm.

The equipment setup for the functional and leak test is shown in Figure 9.

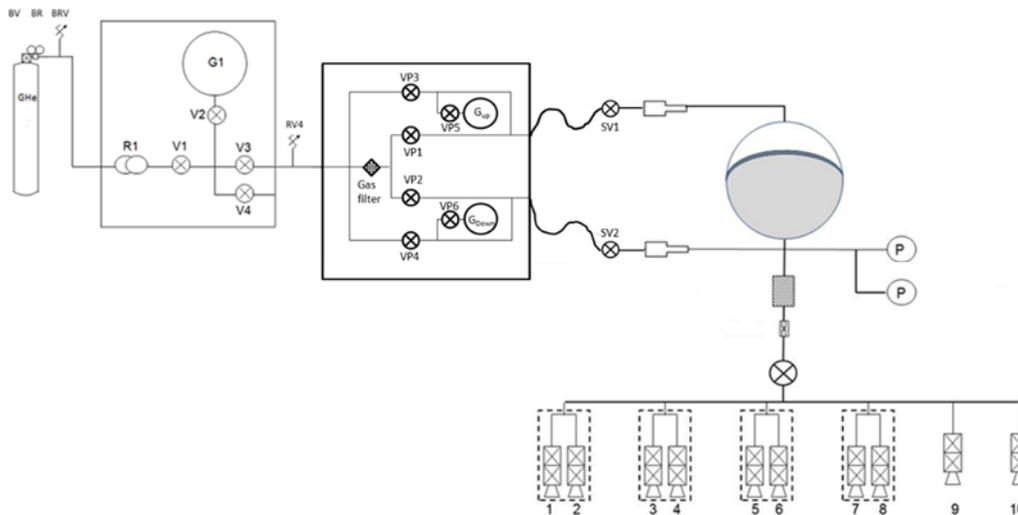


Figure 9. Functional and Leak Testing Equipment Setup

The pressurization panel used for testing has been used for previous missions built in-house. Gauge calibration was kept up-to-date for DSCOVER work. The test setup includes a smaller manifold panel, the DSCOVER Manifold Panel (DMP) that is used to direct helium into the gas or liquid side of the tank, or both, as needed for testing. The DMP also includes gauges to read the pressure on each side of the diaphragm. A 0.5 micron gas filter is built into the DMP. By opening VP1 and VP2, with VP3 and VP4 closed, the helium will flow through the filter before entering

the flight system for pressurization. However, the filter creates a large pressure drop. For depressurization, VP3 and VP4 are opened and VP1 and VP2 are closed, allowing the gas flowing out of the flight system to bypass the filter so depressurization can occur faster.

An electrical ground support equipment (EGSE) panel was built for DSCOVOR propulsion to actuate the flight component during testing. This panel, shown in Figure 10, accesses the propulsion components through the propulsion test connector and the thruster enable connector, located next to the fill and drain valves. The EGSE capabilities are as follows.

- Actuate upstream, downstream, or both thruster valve seats on any of the 10 thrusters. The thruster valve seats can be actuated using adjustable voltage, which allows the user to reduce to hold-open voltage to protect the valve coils.
- Actuate primary or redundant coils for the latch valve to open or close the valve.
- Read latch valve status without powering the valve. This was an important safety control for use during propellant loading so that the state of the latch valve could be verified without the possibility of inadvertently opening the valve and allowing hydrazine to flow into the thruster manifolds.
- Power both pressure transducers at nominal voltage.
- Display tank pressure readings in psia and in volts from both the primary and redundant pressure transducers.
- Display thruster valve coil current upon actuation.
- Display temperature readings for the propellant tank from two GSE thermistors, one located on the gas side of the tank and the other located on the propellant side of the tank.
- Allow for electrical traces of the thruster valves and latch valve using a current probe.



Figure 10. EGSE Panel

B. Command Verification Testing

Command verification testing was performed as part of re-integrating the SMEX bus and the propulsion module, prior to shipping to the launch site, and in conjunction with the post-shipping functional and leak tests at the launch site prior to propellant loading. This test verifies the integrity of the electrical command paths for each component. The first test included capturing electrical traces for valve seat opening and closing to verify response time requirements after integration. The testing performed post-environments and post-shipping commanded valve seat opening and closing using spacecraft ground commands. This testing requires that the thruster and latch valve enable plugs are installed. Command verification testing includes the following events.

- Tank pressure is monitored using spacecraft telemetry and strip charts. Command verification testing is only performed at pad pressure and does not include pressurization or depressurization. However, the pad pressure in the system is monitored to verify no significant, unexpected changes.
- Latch valve commands are verified by sending manual commands to open and close the latch valve. Both the primary and redundant coils are used, and the latch valve opening and closing commands are repeated using propulsion power bus A only, propulsion power bus B only, and both propulsion power buses,

which is the nominal configuration during flight. Latch valve actuations are verified through spacecraft telemetry and an acoustic check.

- Thruster valve commands are verified by sending manual commands to fire each thruster for 50 ms. These commands are sent from the ground to the UHUB via the 1553 bus. The UHUB switches the appropriate relays to send power to both the upstream and downstream thruster valve seats simultaneously for 50 ms, and then removes power from the thruster valves to close them. Before sending each command, an inflatable nitrile nozzle cover is installed on each thruster. When the command is sent to actuate the thruster, the cover is disturbed by the gaseous helium flowing out of the system, allowing the test conductor to verify correct thruster actuation. Because covers are installed on all 10 thrusters during the entire test, the team can verify that only the correct thruster has fired.

C. Environmental Testing

Environmental tests were repeated on the Observatory. The change in launch vehicle from the Space Shuttle to a SpaceX Falcon 9 rocket also meant that the spacecraft needed to be tested with different dynamic loads than it had seen previously. The environmental testing program included electromagnetic interference and compatibility, thermal vacuum and balance, acoustics, vibration, and separation/shock testing, in the order listed. This order is atypical for most spacecraft. Thermal vacuum testing was completed before vibration testing because of hardware availability and analysis results constraints from the launch vehicle provider. Four cycles for thermal vacuum testing were completed, followed by thermal balance testing in order to minimize chamber break time. Additional changes to the order of planned testing were necessitated by facility availability and schedule coordination with other in-house projects.

For vibration testing, a fluid in the propellant tank or mass simulator for the propellant was not necessary to simulate propellant mass. Instead, the helium previously in the system was replaced with argon at a pad pressure of 30 psia because the cryopumps in the thermal vacuum chamber cannot process helium. Special propulsion command testing performed during thermal vacuum and balance testing pulsed each thruster, thus releasing some gas into the chamber. The following tests were performed at both hot and cold plateaus:

- Both pressure transducers were powered to verify tank pressures and to meet the requirement for continuous powered usage before flight.
- Each of the catalyst bed primary and redundant heaters was powered on until the catalyst beds reached the desired minimum temperature for thruster firing. There is a high risk of catalyst poisoning if the catbed heaters are turned on in air, so this test can only be performed in a vacuum environment. This test also allowed for verification of the catalyst bed safing script that closes the latch valve in the event that unexpected temperature rises are seen in the catalyst beds, indicating a possible thruster leak during flight. In addition, the catalyst temperature rates were characterized at both nominal and low bus voltages.
- Each thruster was actuated for 50 ms. Thruster actuations allowed some argon gas to flow into the chamber, which was read by the Residual Gas Analyzer (RGA). The RGA provides an alert if any gas is introduced into the chamber, so the RGA notification that argon was released provided verification that a thruster had fired. In addition, a second verification was provided by the chamber pressure monitoring system, which alerted operators of the rise in pressure after a thruster firing.

D. Fill and Drain Valve O-Rings

After DSCOVER was taken out of extended storage, the shelf life of all parts on the PM and whether there was any concern about materials' age needed to be determined. The Propulsion Team then needed to determine whether special tests needed to be performed to verify the integrity of these materials. The FDVs contain O-rings made of kalrez, which act as secondary seals when the primary valve seat is open. The caps and the primary seat remained fully closed and torqued during storage, so the integrity of the O-rings after opening the valves and decompressing the seals was unknown. Leakage across the O-rings would be a safety concern during fueling operations.

The Propulsion Team held several conversations with the vendor who now holds the design for the FDVs on the DSCOVER spacecraft. Ultimately, the exact age of these specific O-rings could not be determined, but documentation and papers that were found indicated a possible shelf life of 15-20 years, which was a concern because of the age of the spacecraft.

In order to determine the integrity of the O-rings, a special test was included in the propulsion functional and leak test sequence. Propulsion technicians installed a test port in external caps that fit the fill and drain valves. The special test caps are shown in Figure 11. During testing, the secondary AN cap was installed on each FDV, and the primary valve seat on each valve was opened. The test caps were torqued onto the fill and drain valves, and a helium leak detector was installed on the test port located in each cap. These caps isolated the secondary cap and seals in order to check for leakage through the O-rings.

Each time propulsion functional and leak testing was completed, this special test was performed. The O-ring seals did not show any leakage, so the integrity of the seals was intact.



Figure 11. Special Test Caps

IV. Launch Activities and Early Operations

A team contracted from Jacobs loaded DSCOVR with 145 kg of hydrazine at Astrotech Space Operations on January 11, 2015. The propellant lines downstream of the latch valve had been filled with 25 psia of helium after the final functional and leak test in December 2014. The latch valve was closed at the end of testing, so after loading the propellant lines were wet to the latch valve and dry between the latch valve and thrusters. The tank was pressurized to 354 psia at 22°C with helium. The system was monitored for 24 hours for any hydrazine decomposition and leaks.

On February 11, 2015 at 6:04 PM EST, DSCOVR was launched on a Falcon 9 v1.1 from launch complex 40 at Cape Canaveral Air Force Station. DSCOVR separation occurred approximately 36 minutes after launch. Approximately 3 hours after launch, the propulsion power buses were turned on. Pressure transducer #2 was turned on first to verify tank pressure. Then, pressure transducer #2 was turned off and pressure transducer #1 was turned on. The tank pressure reading was nominal.

Propulsion checkout occurred approximately 16 hours after launch. The propulsion checkout serves three purposes. The first objective is to open the latch valve to prime propellant lines with fuel. The second objective is to purge helium from the lines by pulsing each thruster for 50 ms. The third objective is to verify each thruster works as expected by observing spacecraft momentum changes in the X, Y, and Z directions in response to each thruster pulse. The nominal plan included only one pulse per thruster. However, during the checkout process, three of the ten thrusters fired but did not produce enough change in spacecraft momentum to determine their performance. The team concluded that helium was still in these propellant lines. After several 50 ms pulses, these three thrusters imparted the expected torques on the DSCOVR spacecraft.

The first planned thruster maneuver was the MCC burn, which was designed to correct any launch dispersion in the spacecraft trajectory. Since the Falcon 9 trajectory resulted in a low launch dispersion, the MCC #1 burn only required a burn duration of 37 seconds (0.4895 m/s). The maneuver was performed successfully 32 hours after launch. The original maneuver plan used Thrusters 1, 2, 3, and 4 for -X delta-V direction and Thrusters 1 through 8 for attitude control because of concern about thruster plume heating the spacecraft boom. The MCC #1 maneuver was actually performed using Thrusters 9 and 10 for +Z delta-V direction and Thrusters 1 through 8 for attitude control. Plume analysis completed prior to the burn concluded that heating on the boom was not a concern. MCC #2 was performed on April 28, 2015, as a +Z maneuver with a burn duration of 3.1 minutes (about 2.449 m/s).

Momentum unloading is performed every 30 to 40 days to reduce the momentum built up in the reaction wheels. As of June 8th 2015, five momentum unloading maneuvers have been performed. These thruster burns used thrusters 1 through 8 in pulse mode, and the burn duration for each maneuver was approximately 45 seconds.

On June 7, 2015 (115 days after launch), the Lissajous Orbit Insertion (LOI) burn placed DSCOVR in orbit at the Sun-Earth L1 Lagrangian point. The burn consisted of two segments: one burn approximately 4 hours long (152.4 m/s) and a second burn approximately 35 minutes long (13.9 m/s). The burn was performed in two segments so the Flight Dynamics team could re-calibrate the second segment based on the information from the first segment. The thruster configuration used Thrusters 9 and 10 for +Z delta-V and the Thrusters 1 through 8 as needed for attitude control.

V. Issues and Lesson Learned

Since the propulsion system was already built and tested in the 1990s, many challenges arose when refurbishing the system for use as described below.

1. Missing Documentation

The Thruster Acceptance Data Package (ADP) and UHUB Interface Control Documents (ICD) were missing. The thruster vendor was contacted for a copy of the Thruster ADPs. Fortunately, a copy was found for each of the 10 thrusters. The UHUB ICD is an electrical drawing of the UHUB, which is the electronic box that provides power to and receives telemetry from the propulsion components. Unfortunately, the latest version of the UHUB ICD was not found. Instead, other documents were used to understand the grounding of the pressure transducers as explained in Section V.3. Several other documents not related to the propulsion system were missing too. The original database containing the electronic Triana files was erased because of a hardware malfunction. The lesson learned from these issues is to keep all important documentation, even if the project is shut down and place electronic copies in well-protected and backed-up databases.

2. FDV Seals

Even though the pressure in the tank remained stable for many years in storage, the seals in the fill and drain valves needed to be checked for loss of elastomeric properties. This required a special test to check the leakage of the O-rings in the fill and drain valves, which is described in Section III.D.

3. Pressure Transducer Readings

During functional testing, the pressure transducers readings were slightly different from each other. An initial investigation determined that the pressure transducers were grounded to different points on the spacecraft. The spacecraft drawings did not show the grounding path for one of the transducers. After several months of work and investigation, a ground wire to the chassis was noticed in a recent spacecraft picture. This wire was not shown in any spacecraft drawing. The ground wire for one of the pressure transducers was wired to connector P1421 (reference Figure 7), whereas the ground wire for the other pressure transducer is wired to the UHUB circuit board. As a result, two ground locations created the difference in the pressure transducer readings by a few psi.

4. Bent Thruster

In April 2013, while a Propulsion Team member was labeling pictures of the propulsion module with desired thermocouple locations for thermal vacuum testing, the nozzle for Thruster 4 appeared to be pointing in a different direction than its counterparts on the other DTM; Thruster 4 should have been pointing downward. Figure 12 shows the bent thruster at the bottom. Inspection of the thruster showed that it was bent at the thermal standoff near the bracket, behind the high temperature blanket on the module. The nozzle of Thruster 4 also had a slight dent at the top.

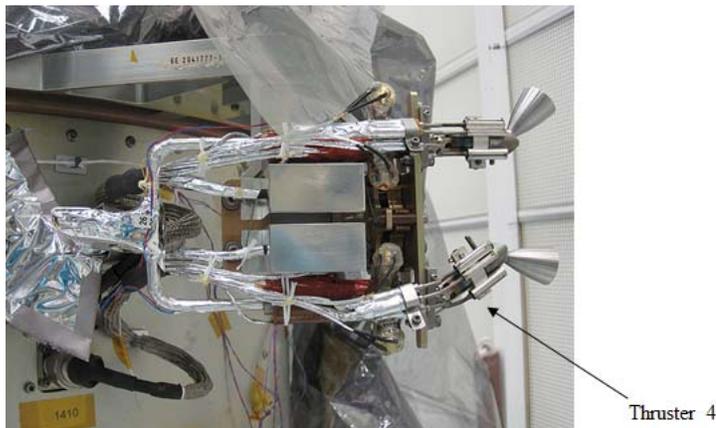


Figure 12. Bent Thruster

The Propulsion Team met immediately with the DSCOVER failure review board to discuss their findings. The other nine thrusters were checked for visible damage, and none was found. The team investigated all paperwork and pictures to try to determine what had happened. An official Mishap Investigation Board was formed as well and completed an official investigation of paperwork, pictures, and interviews with personnel.

A plan with two options was presented to the DSCOVER failure board review. The first option was to replace the DTM with the damaged thruster with the spare DTM. This effort was less invasive because it replaced the damaged hardware with a complete spare module and did not require extensive work such as removing the damaged thruster

and rewiring the harness. The second option was to remove the damaged parts downstream of the thruster valves. This effort would not require breaking the integrity of the propulsion system because the thrust chambers are bolted to the thruster valves. However, replacing the parts downstream of the thruster valves would have a risk of changing the thruster characteristics such as thrust level and catalyst heater profile. The failure review board concurred with the first option to replace the damaged DTM with the spare DTM. Because of schedule constraints for reintegrating the PM with the SMEX-lite bus, project management gave the Propulsion Team one month to complete the rework.

The spare DTM was removed from propulsion storage, and its condition was fully verified to be acceptable for flight use. Procedures were written for the rework and evaluated by the propulsion branch. The damaged DTM was cut out of the system and replaced in May 2013. The Propulsion Team was able to install the spare DTM with only one cut and one weld. The new weld was inspected by x-ray and found to be free of any defects.

The completed rework was followed by a functional and leak test at tank MDP for those two thrusters only in August 2013. Range Safety requires proof testing of all propulsion systems. However, the manifold containing the repair could not be tested to the manifold proof pressure or tank proof pressure because it would have reduce the number of proof cycles of the tank. Instead, Range Safety approved the waiver with the following conditions: 1) pressurize the system to MDP and perform a leak test and 2) the lines downstream of the latch valve will be free of propellant until after spacecraft separation from the launch vehicle.

The official Mishap Investigation Board presented their final report in July 2013. The board could not determine when the damage occurred and did not find a specific root cause. The board presented three recommendations, which are also lessons learned:

- Track the removal and installation of the thruster covers in a log.
- Keep more consistent photographic evidence of the state of the spacecraft before and after major events.
- Define visual inspection requirements for the subsystem. A full visual inspection of the spacecraft, with all covers removed, was not performed after DSCOVER was taken out of storage. A more detailed inspection may have provided earlier evidence of thruster damage, allowing for more room in the schedule to replace it.
- Perform an alignment check at the beginning of the project (January 2012)

5. *Plume Impingement*

In 2014, an independent analysis of plume impingement on the magnetometer boom was performed by the GSFC Propulsion Branch. The original plume analysis was performed by the Contamination Control Branch for Triana in 1999. The updated analysis showed that heating imparted by Thrusters 5 and 7 on the deployed boom was 6070 W/m^2 . (This is much higher than the 880 W/m^2 shown in the 1999 analysis.) Figure 13 shows DSCOVER with the deployed boom. There were three differences between the two analyses that contributed to the discrepancy in the results. First, the original analysis used a simplified model of the boom geometry that only included the three longerons that run down the length of the boom. It did not include any of the cross-pieces. Figure 14 shows the structure of the boom. Second, the clocking of the boom was changed from Triana to DSCOVER, which impacted the distances between the longerons and the thrusters. Third, the plume models treat the spreading of the plume differently, resulting in different results at the angles of interest for the boom. The thermal analysis showed that the 6070 W/m^2 heat flux would cause parts of the boom to exceed their 70°C temperature limit. Because of this concern, the GSFC Propulsion Branch conducted additional analyses using a more accurate plume modeling approach and a refined model of the boom. At the same time, the Contamination Control Branch updated their analysis to correct the clocking of the boom. The updated results showed good agreement of 1200 and 1400 W/m^2 heat flux on the boom longerons for the Propulsion Branch and Contamination Control Branch analyses, respectively. However, the maximum heat flux from the Propulsion Branch analysis was not on the longerons but on the battens that were not included in the Contamination Control Branch's analysis. This maximum heat flux was 2800 W/m^2 and still posed a concern for exceeding the temperature limit of 70°C . Therefore, testing was conducted by the boom vendor on spare boom material to show that the boom could tolerate a temperature of 102°C . With this new temperature limit, Thrusters 5 and 7 can be used without overheating the boom, although some on-time/off-time restrictions are needed in certain thruster failure scenarios. The lesson learned is to re-verify the assumptions of original analyses at the beginning of a refurbishment project like DSCOVER.

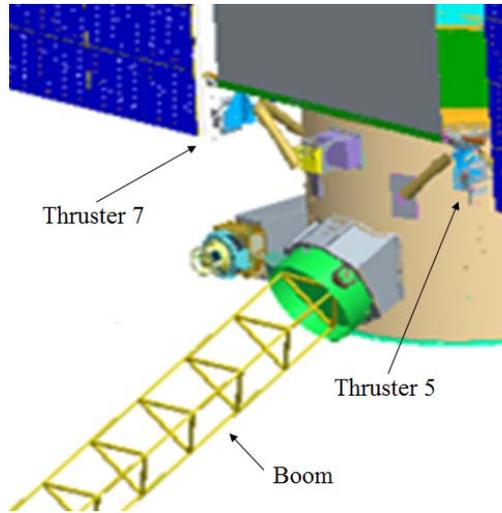


Figure 13. DSCOVR with the Deployed Boom

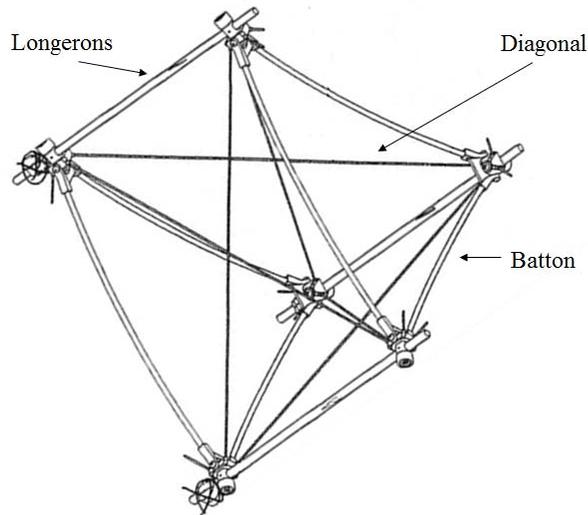


Figure 14. Structure of the Boom

6. Propulsion Line 5 Heater

During thermal vacuum and balance testing, one propulsion line zone temperature dropped as low as 1.9°C, which is below the freezing point of hydrazine (2°C). Zone 5 is located on the aft end of the spacecraft, between the two axial thrusters, as shown in Figure 5. This thermal zone overall was cooler than expected during testing, and a review of the data showed that similar behavior was seen in this zone during Triana thermal vacuum and balance testing. Additionally, the original thermal design assumed solar heating affected the axial thrusters and this propellant line. The retesting profile assumed no solar heating on the aft end of the spacecraft, which is more flight-like.

The DSCOVR Thermal Team determined that an auxiliary heater and thermostats should be installed on this propulsion line to prevent freezing any hydrazine in that line. The setpoints of the new thermostats are 10°C ON/15°C OFF. Because of the maturity of the spacecraft and accessibility issues with electrical harnessing, the auxiliary heater and thermostats needed to be installed over the existing thermal hardware. This plan is unusual for spacecraft and carried a risk of damaging the existing thermal hardware, which was still expected to be used in flight. The propulsion team created a mockup tube of the same dimensions as the flight tube for the Thermal Team to use in their testing. Thermal hardware was installed on the mockup tube to verify that installing thermostats over the older thermal hardware would not damage the existing heater. The mockup also verified the size of the thermostat saddles that would

be needed for installation. The DSCOVER Mechanical Team performed a structural analysis of the design and concluded it was acceptable for flight.

After this plan was approved for flight, the blanketing over line zone 5 was opened and removed, and the new thermostats and line heater were installed. The wiring for the auxiliary heater was spliced into existing hardware. A special powered test during a Comprehensive Performance Test for the spacecraft verified that the heater cycled appropriately by cooling that specific location on the spacecraft. Finally, the blanketing was re-installed on the thermal zone in preparation for flight. Post-launch, the auxiliary heater is performing nominally.

7. Command Verification Testing

During command verification testing at the launch site, a Propulsion EGSE connector was connected to DSCOVER in anticipation of later use. When the command was sent from the Integration and Testing Operation Software (ITOS) workstation to close the latch valve, the latch valve did not respond. The latch valve was successfully commanded closed only after the EGSE connector was disconnected from the spacecraft. The conclusion of the investigation was that the diodes inside the solid state relays in the Propulsion EGSE cards allowed the voltage being supplied to close the latch valve to be fed back into the EGSE power supply. The lesson learned from this issue is to fully understand the electrical testing configuration with flight hardware and potential issues with equipment. In addition, previous command verification tests did not include the EGSE connected to the spacecraft. Testing configurations should be consistent each time they are performed, unless there is a technical reason to change the test setup.

VI. Conclusion

Despite unique challenges posed by a resurrected spacecraft, the DSCOVER propulsion system was successfully refurbished and tested by the GSFC Propulsion Team. DSCOVER is currently on its journey to L1; the propulsion system is performing nominally and showing no signs of degradation, even after 10 years in storage.

Acknowledgments

The success of this mission is dependent on a great team and hard work. The authors recognize and thank the members of the DSCOVER Propulsion Team: Caitlin Bacha, Hal Baesch, Kyle Bentley, Mark Fiebig, Scott Glubke, Rich Luquette, Steve Graham, Steve McKim, Alison Rao, Steve M. Smith, Mark Underdown, and Mike Wilks. Special recognition is given to the liaisons to the propulsion group: Gary Meadows (Systems Engineering), Carmen Parkinson (Systems Engineering), Shirley Dion (Safety), Steve Leiter (Safety), Anyim Nwagu (Safety), Steven Himes (Quality Assurance), Milton Cowperthwaite (Quality Assurance), Mark Noteware (Quality Assurance), John Hawk (Thermal), Giulio Rosanova (Mechanical), Eduardo Rodriguez (Mechanical), and the Jacobs fueling team.