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EARLY MISSION MANEUVER OPERATIONS FOR THE DEEP SPACE CLIMATE OBSERVATORY SUN-EARTH L1 LIBRATION POINT MISSION

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The Deep Space Climate Observatory mission launched on February 11, 2015, and inserted onto a transfer trajectory toward a Lissajous orbit around the Sun-Earth L1 libration point. This paper presents an overview of the baseline transfer orbit and early mission maneuver operations leading up to the start of nominal science orbit operations. In particular, the analysis and performance of the spacecraft insertion, mid-course correction maneuvers, and the deep-space Lissajous orbit insertion maneuvers are discussed, comparing the baseline orbit with actual mission results and highlighting mission and operations constraints.

INTRODUCTION

The Deep Space Climate Observatory (DSCOVR) was recently launched on a SpaceX Falcon 9 v1.1 launch vehicle from the Eastern Test Range on February 11, 2015, and injected into a 115-day transfer trajectory to the Sun-Earth collinear point L1, located 1.5 million km from the Earth toward the Sun. Specifically, the destination is an L1 Lissajous orbit of dimensions nearly identical to those of NASA's presently operational Advanced Composition Explorer (ACE) mission.[1] Following a period of calibration, DSCOVR is intended to relieve ACE of its current support of NOAA's Real-Time Solar Wind (RTSW) solar weather monitoring program. A joint effort of NASA, NOAA, and the USAF, the DSCOVR mission is a resurrection of NASA's Triana mission that was placed on hold in 2001.[2] The DSCOVR spacecraft is in fact the re-furbished Triana spacecraft, refitted for launch on a two-stage Falcon 9 expendable launch vehicle. (Triana had been fitted for launch from a Space Shuttle with an attached transfer injection motor.) NOAA took over responsibility for DSCOVR flight operations in late July 2015 from a NASA Goddard Space Flight Center (GSFC) launch and operations team. DSCOVR is the first mission operated by NOAA to fly in a libration point orbit (LPO).

DSCOVR was launched by a SpaceX Falcon 9 launch vehicle onto a short coast in low-Earth orbit (LEO) followed by a second-stage launch vehicle transfer-trajectory insertion (TTI) burn. During the transfer, mid-course correction (MCC) maneuvers were completed to ensure DSCOVR would arrive at the correct location in the L1 region. Upon its arrival at the L1 region on June 7, 2015, DSCOVR performed its Lissajous Orbit Insertion (LOI) maneuver to place it on its Class-2 Lissajous orbit. Following the LOI maneuver, an LOI-correction (LOI-c) maneuver was executed to correct the LOI maneuver errors and fine-tune the Lissajous orbit. Figure 1 depicts the Earth-to-

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L1 transfer trajectory and one revolution in the mission Lissajous orbit, from the perspective of the North Ecliptic Pole. The figure includes the lunar orbit trace and pointers to locations of the major maneuvers. The LOI maneuver established a 160,538 km (out of the ecliptic plane) by 281,476 km (projected into the ecliptic plane) Lissajous orbit about L1 in the Sun-Earth system.

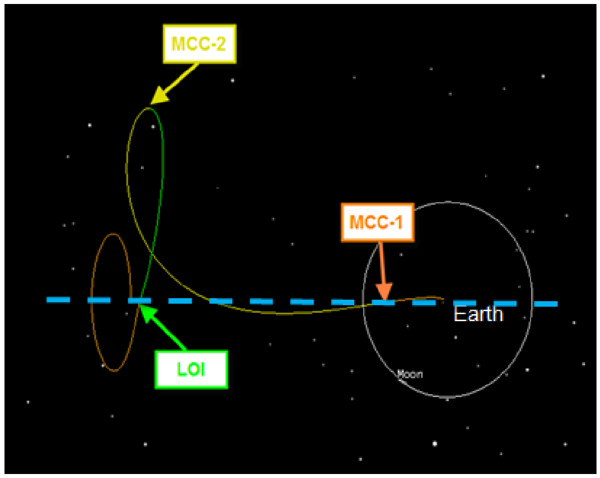

Figure 1. Trajectory and Maneuvers Overview as Viewed in RLP XY Plane.

As of this writing, DSCOVR stationkeeping maneuvers are planned for every 30 to 90 days to maintain the Lissajous orbit, starting in late July 2015. After approximately 3.5 years in the mission orbit, SEZ (solar exclusion zone) avoidance maneuvers can be used to freeze the phase of the Lissajous to ensure that the orbit does not violate the minimum 4° SEV (Sun-Earth-Vehicle) angle requirement.[3] The SEV angle, with Earth as the vertex, measures the angular distance between the Sun and the DSCOVR spacecraft as seen from Earth. The 4° minimum angle requirement ensures that the spacecraft does not travel too close to the Earth-Sun line, which could impact communications with the spacecraft.

This paper provides a comprehensive review of the DSCOVR transfer trajectory and early orbit maneuver operations. The nominal trajectory and the maneuver design process and operational results for the four early-mission maneuvers (MCC-1, MCC-2, LOI, and LOI-c) are presented, with insight into the vehicle constraints that affected maneuver planning. For DSCOVR, the propulsion, attitude control, thermal, power, and communications systems all had constraints and idiosyncrasies that affected the planning options for one or more of these early orbit maneuvers. Inter-subsystem communication and planning allowed these constraints to be identified and accommodated, leading to very successful completions of these maneuvers and fuel savings that will extend the operational life of the mission.

SPACECRAFT OVERVIEW

DSCOVR is depicted with a number of its instruments in Figure 2. This three-axis stabilized spacecraft has a SMEX-Lite bus about 1 meter wide and 1.8 meters tall (including the top-deck mounted science instruments), roughly the size of an average refrigerator. Its deployed solar arrays extend two meters to each side. DSCOVR's mass at launch was approximately 573 kg, including a fuel load of 145 kg.

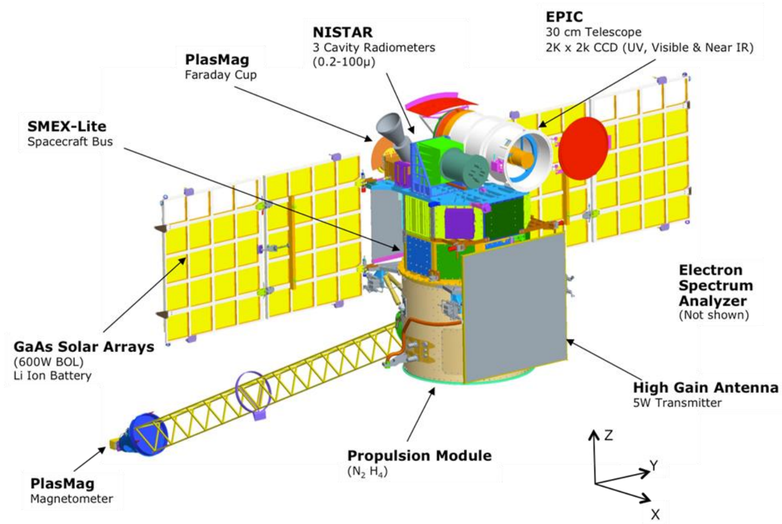

Figure 2. DSCOVR Spacecraft and Science Instruments.

DSCOVR has a mono-propellant hydrazine blowdown propulsion system with a single 28 inch diameter fuel tank with a diaphragm separating the fuel and the gaseous nitrogen pressurant. The mounting arrangement, locations, and orientations of the ten 4.45 N thrusters are indicated in Figure 3.

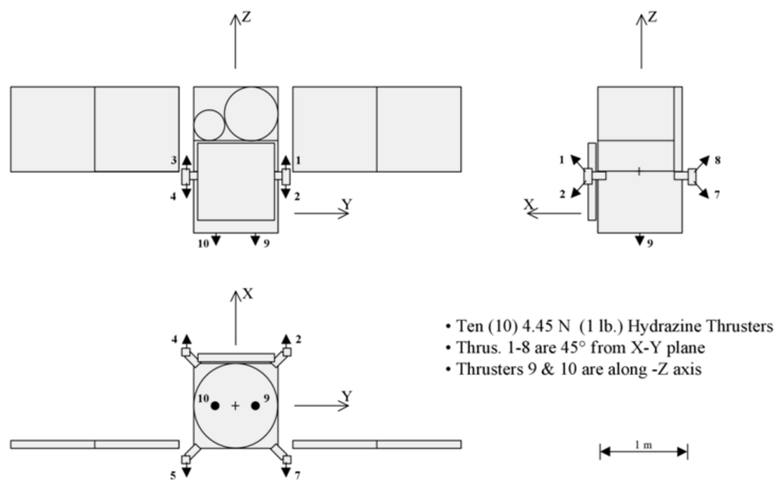

Figure 3. Schematic of Thruster Locations and Orientations.

Thrusters 9 and 10, mounted on the –Z (bottom) deck, apply thrust in the body +Z direction, and are used only for imparting ΔV. Only thrusters 1 through 8—canted to the body XY plane by 45 degrees—are used for attitude control during orbit maneuvers. However, there are also orbit maneuver modes where sub-sets of these eight thrusters can be used to impart ΔV. The +X thruster set is formed by the thruster quartet 5, 6, 7, and 8. The –X thruster set is formed by thrusters 1, 2, 3, and 4. Finally, the –Z thruster set is formed by thrusters 1, 3, 6, and 8.[4]

LAUNCH AND TRANSFER TRAJECTORY

The DSCOVR spacecraft was launched on a SpaceX Falcon 9 launch vehicle on February 11, 2015. The Falcon 9 second stage performed two separate burns. The first burn established a short coast low-Earth parking orbit and the second burn, known as the transfer trajectory insertion (TTI), inserted the DSCOVR satellite directly onto its transfer trajectory to L1.

Design and Analysis for the Launch Vehicle Second Stage Maneuvers

The launch and transfer trajectory analysis for DSCOVR was a collaboration between the Flight Dynamics (FD) team at Goddard Space Flight Center (GSFC) and SpaceX. Approximately sixty days of launch opportunities were analyzed between January 12, 2015 and March 12, 2015, with some blackouts due to the location of the moon. For each launch opportunity, SpaceX provided the GSFC FD team with Second Engine Cut-Off 1 (SECO-1) states to use as initial state vectors for the nominal trajectory analysis. SECO-1 is a state vector that represents the injection of the upper stage stack (Falcon 9 Second Stage with the DSCOVR payload) into a nominal 185 km altitude, 37° inclination low-Earth parking orbit, nominally set to occur 517.2 seconds after launch. The inclination of the parking orbit went through three cycles of change to iterate on favorable coast times before the TTI maneuver (a coast time of greater than 10 minutes was desired by SpaceX) and to avoid range safety concerns.

The GSFC FD team used the SECO-1 states to compute the impulsive TTI maneuver of approximately 3.2 km/s necessary to achieve the nominal transfer trajectory and mission orbit at the Sun-Earth L1 libration point. Using this data, SpaceX generated corresponding trajectories modeling finite maneuvers and provided updated SECO-1, SECO-2, and target interface point (TIP) states to the GSFC FD team. SECO-2 is the state vector immediately after TTI and TIP is the state vector at TTI+10 minutes. The GSFC FD team then propagated the new SECO-1 and TIP states to confirm convergence and compared the TTI, TIP, and C3 values to the expected values based on the GSFC impulsive maneuver models. The GSFC FD team also used the TIP states from SpaceX to calculate the impulsive spacecraft maneuver that would be required to correct these baseline trajectories. The correction maneuvers at L+24 hours were approximately 7 cm/s or less for each launch case, indicating that the GSFC and SpaceX trajectories showed great consistency.

Launch Results

The launch vehicle insertion errors were very small, inserting the DSCOVR spacecraft on a transfer trajectory within 0.2σ of the target orbital energy value. The required mid-course correction (MCC) maneuvers were therefore small as well, which provided a significant fuel savings that will allow the mission life to be extended past the original predictions. The sections that follow discuss the planning and execution of the MCC maneuvers, including the effects of spacecraft vehicle constraints on the implementation of the maneuvers.

MID-COURSE CORRECTION MANEUVER (MCC-1)

Mid-course corrections are stochastic maneuvers designed to correct for a potential range of statistical dispersions and place the spacecraft back on a nominal transfer trajectory toward L1. Overall, the goal of the mid-course correction maneuvers for DSCOVR was to provide fine-tuning of the transfer trajectory to ensure that the trajectory crosses the rotating libration point (RLP) frame[5] XZ-plane at the desired coordinates for proper execution of the LOI maneuver. The RLP X-axis points along the vector between the primary bodies of the libration point system: the Sun and the Earth/Moon barycenter. The RLP Z-axis points along the angular momentum vector of the system, toward the north ecliptic pole, and the Y-axis completes the right-handed system. The RLP XZ-plane is depicted as a dotted blue line in Figure 1.

The DSCOVR MCC-1 maneuver was executed on February 12, 2015, approximately 31 hours after launch (L+31), as the first of two MCC maneuvers to correct for the Falcon 9 launch vehicle injection error. Because of the small injection error, MCC-1 was a relatively small maneuver, approximately 0.5 m/ s (36.5 seconds of burn duration) in the out-of-plane direction (towards the RLP +Z axis).

Design and Analysis for the MCC-1 Maneuver

For trajectories to deep space or libration point orbits, it is critical that course correction maneuvers are executed in a timely fashion, often early in the mission, as the ΔV and fuel costs to correct for trajectory errors increase exponentially with elapsed time.[6] The DSCOVR team prepared to execute the first MCC maneuver as quickly as possible after receiving the required orbit determination (OD) data to determine the outbound trajectory; the baseline plan was to execute MCC-1 at L+31 hours, and perhaps even earlier in the case of very large injection errors from the launch vehicle.

The Falcon 9 TTI burn was designed to deliver DSCOVR directly onto the nominal transfer trajectory, with deviations no larger than ±4 m/s, 3σ. Because of the stochastic nature of MCC maneuvers, mission planners conducted analyses before launch that addressed the wide range of possible trajectories within a specified statistical range from the launch vehicle injection. SpaceX provided the DSCOVR Maneuver Team with the results of a Monte Carlo analysis that included 514 launch vehicle dispersion cases for each possible launch date. These TIP states represented a range of possible, representative scenarios that the DSCOVR spacecraft had to be capable of recovering from using one or more MCC maneuvers in order to reach its Sun-Earth L1 Lissajous orbit.

The MCC targeting algorithm consists of several differential correction schemes. The first two differential correctors use an impulsive maneuver model to target the nominal trajectory C3 value at a specified epoch and then target the desired crossing point where the spacecraft trajectory intercepts the RLP XZ-plane before it enters the Lissajous orbit. The results from this impulsive maneuver solution are used to compute an initial approximation for the finite maneuver. Then the algorithm runs another set of differential correctors to refine the finite maneuver solution to achieve the desired RLP XZ-plane crossing position within 0.1 km tolerance, which is below the noise level of the orbit determination solutions for the mission. These differential correction schemes are developed to be robust enough to converge for the full range of reasonably expected input states without manual tuning of the differential corrector. Automatic, rapid convergence was important for both hands-off pre-launch mission analyses and for real-time spacecraft operations due to the short timeframe for MCC-1 maneuver planning and analysis on the day of launch.

The Monte Carlo TIP states received from SpaceX were used as input states for an MCC-1 targeting study to characterize the expected attributes of a potential MCC-1 maneuver conducted at L+31 hours. Figure 4 displays the computed MCC-1 ΔV magnitude for each of the 514 TIP states for a given launch day, as a function of the TIP C3 energy. The left and right "branches" of the V-shape in this plot correspond to TTI underburns and overburns, respectively. That is, a perfect TTI from launch requires no MCC (0 ΔV), whereas a TTI underburn requires additional energy to achieve a transfer to the Lissajous orbit and a TTI overburn requires energy to be removed via the MCC-1 ΔV. The median MCC-1 ΔV estimate was 5.62 m/s (i.e., based on the data set, a 50% probability existed that the necessary MCC-1 ΔV would be less than 5.62 m/s and an equal probability existed that it would be greater). The maximum MCC-1 ΔV from the sample states was 26.05 m/s to correct for an underburn.

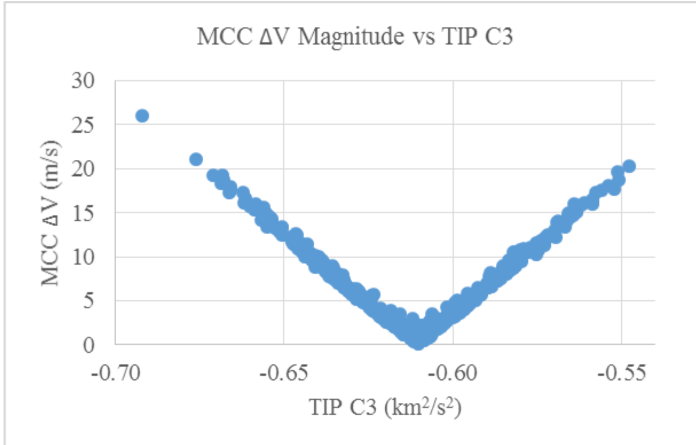

Figure 4. MCC-1 Computed ΔV Magnitude based on SpaceX TIP States.

Figure 5 shows the range of fuel usage and maneuver durations corresponding to the MCC-1 ΔV values in Figure 4. These values were used to set the fuel budget allocation for MCC-1, which informed the predictions for the total mission lifetime. This data was also available on the day of launch as an early indicator for a launch anomaly. If the solution computed for MCC-1 required more fuel than the expected range shown here, that would indicate that the launch vehicle error was outside the 3σ range. The DSCOVR maneuver planning team would then compute alternative maneuver plans, executing MCC-1 earlier than the nominal L+31 hour mark to save fuel.

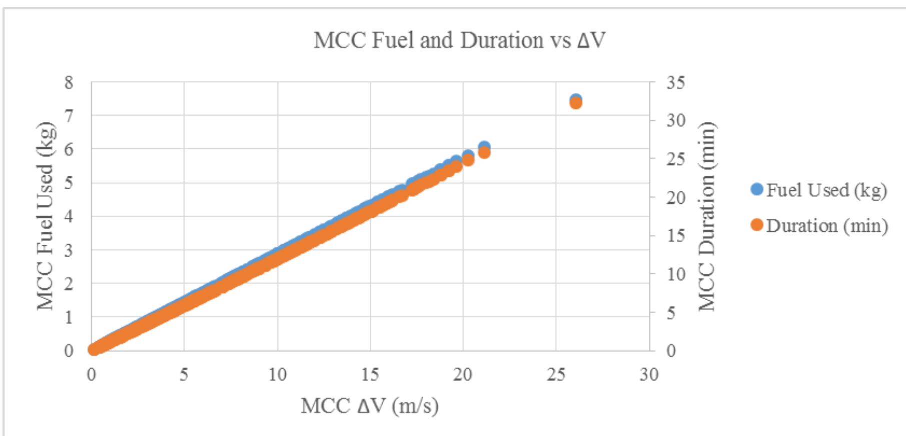

Figure 5. MCC-1 Fuel Usage and Burn Duration.

Various DSCOVR spacecraft constraints were taken into account in the MCC-1 analysis, most importantly to ensure that the maneuver would not place the spacecraft into a power-negative attitude for too long. In many of the MCC-1 Monte Carlo cases, the maneuver requires a significant slew away from the spacecraft's nominal pointing attitude in order to align the thrust direction of the spacecraft's +Z thrusters with the required ΔV direction, bringing the solar panels nearly normal to the Sun. The MCC-1 burn durations as a function of the Sun-to-solar-array-normal angle during the maneuver, together with the 40% DoD (depth of discharge) limit for the spacecraft appear in Figure 6. Fortunately, these results show that the MCC-1 maneuver could be implemented in a single segment without exceeding this power constraint. If the power constraint were violated, then the MCC-1 maneuver would have been segmented into a series of burns separated by a recharge time.

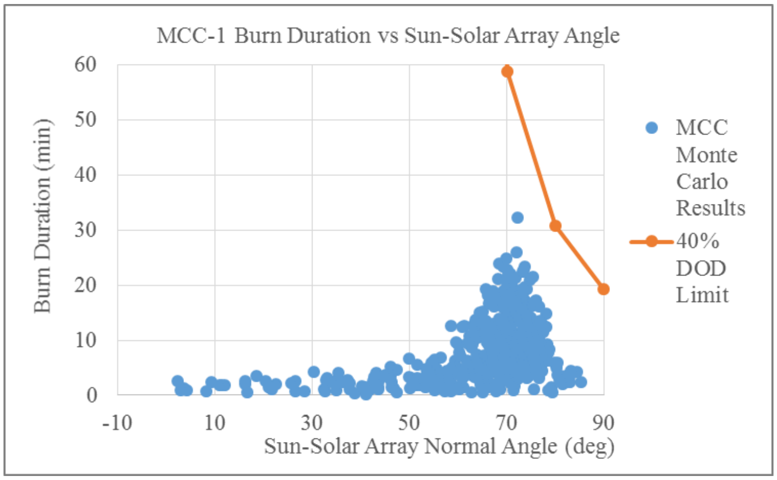

Figure 6. MCC-1 Power Limit.

Since the MCC-1 maneuver was the first maneuver executed, it was necessary to properly study the potential errors in the DSCOVR attitude control and propulsion systems and assess their impact on the MCC-1 maneuver effectiveness; that is, determine the effect of MCC-1 maneuver execution on the design of the subsequent MCC-2 maneuver. Before flight, the propulsion and attitude control teams provided a range of probable deviations which were employed to model execution errors in the MCC-1 maneuver. These results were used to characterize the properties of the MCC-2 burn. This analysis assumed that MCC-2 would be executed at L+17 days in order to allow a full OD arc of at least 14 days between MCC-1 and MCC-2. The MCC-1 maneuver analysis focused on launch vehicle TTI 3σ overburn (+3.2 m/s) and 3σ underburn (–4.1 m/s) cases. The MCC-1 maneuver was modeled at L+31 hours, with the following ranges of MCC-1 errors applied in all possible combinations:

- MCC-1 pointing angle error: 0 to 5° in 1° increments
- MCC-1 error direction ("clock angle" of the pointing error): 0 to 315° in 45° increments
- MCC-1 magnitude error: 0%, –3%, and 3% (applied as a total burn duration error)

The pointing angle error and the clock angle of the pointing error are equal to the elevation and azimuth of the achieved thrust vector with respect to the planned thrust vector. Combining the above effects, a total of 144 combinations were examined to assess the effects of errors in the MCC-1 execution for a given launch scenario. The effects of MCC-1 execution errors on MCC-2 appear in Figure 7. The left half of Figure 7 displays the results when no MCC-1 magnitude error is applied. The different series in this plot represent the range of clock angles at which the pointing angle error was applied, as well as the TTI underburn and overburn data sets. On the right, Figure 7 shows the results when the ±3% MCC-1 magnitude errors as well the pointing angle errors are applied. Given the large uncertainty in the maneuver pointing accuracy in the attitude control system before it was used for the first time on-orbit, as well as the uncertainty in the propulsion system efficiency, these results allowed DSCOVR mission planners to set a bound on the expected ΔV budget for the MCC-2 maneuver that would follow MCC-1.

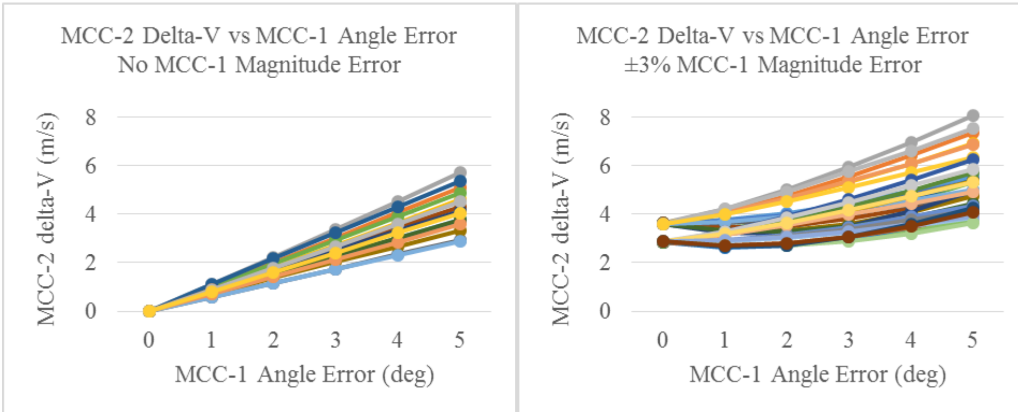

Figure 7. MCC-2 Cost Based on MCC-1 Error Analysis.

Figure 8 presents results from the same analysis as Figure 7, but uses a polar plot to depict the clock angle of the error in a more intuitive way. Another investigation in the MCC-1 maneuver error study focuses on the combinatorial effects of two or more error sources. It is apparent in Figure 8 that MCC-1 clock-angle error and magnitude error are coupled in their ramifications for the subsequent MCC-2 ΔV necessary to target the vehicle to LOI. In the absence of MCC-1 magnitude error, the resulting MCC-2 ΔV depends primarily on the pointing error of the MCC-1 maneuver; a small dependency exists on the MCC-1 clock error in that, if the clock angle of the pointing error is near 90° or 270°, a larger MCC-2 ΔV is required. This characteristic is depicted in the left plot in Figure 8. However, when a 3% MCC-1 underburn is applied, as shown in the right of Figure 8, it is clear that MCC-1 pointing error direction and magnitude are coupled in their effects on the subsequent MCC-2 ΔV. Costs for MCC-2 are much higher when the MCC-1 pointing error has a clock angle between 45° and 90° as compared to 225° and 270°. As expected, magnitude errors in MCC-1 will result in a larger MCC-2 with a larger requisite ΔV, which is represented by the differing radii between the left and right plots. Because of the bias from clock angle error, a slight pointing angle error corresponding to a clock angle near 270° has negligible effect on the MCC-2 ΔV for an MCC-1 underburn, but a significant effect when the pointing error has a clock angle near 90°. The opposite effect occurs for an MCC-1 overburn.

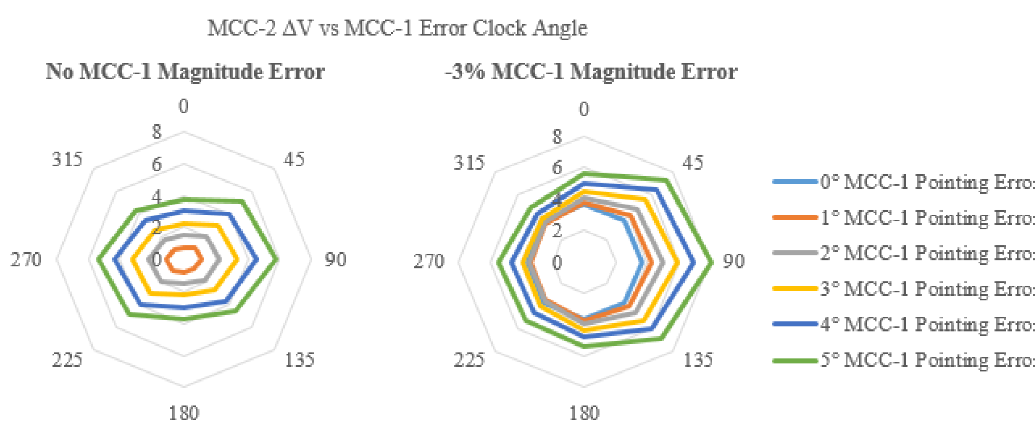

Figure 8. Polar Plot of MCC-2 Cost based on MCC-1 Error Analysis.

MCC-1 Results

The transfer trajectory insertion by the SpaceX Falcon 9 was excellent, placing the vehicle within 0.2σ of the intended target orbital energy value. The insertion error from the launch vehicle was in the out-of-plane direction (towards the +Z RLP direction), requiring an MCC-1 ΔV vector nearly perpendicular to the ecliptic plane. The MCC-1 maneuver, executed at 13 February 2015, 0700 UTC, was relatively small, with a planned ΔV of 0.503 m/s and a total burn time of 36.4 seconds, consuming 0.150 kg of hydrazine. The ΔV mode efficiency (the ratio of time firing the ΔV thrusters versus the total time to complete the maneuver, including time spent performing attitude control thruster firing) was 87.39%, which was close to the expected 87.63%. As a result of the excellent launch vehicle performance, it would have been possible for mission planners to postpone the MCC-1 maneuver for several weeks without violating the available fuel budget. However, the MCC-1 maneuver was executed as planned at L+31 hours to exercise the spacecraft propulsion system and to avoid changing the staffing and ground tracking plans. Actual results for MCC-1 are summarized in Table 1.

Reconstruction of the spacecraft telemetry showed that pointing errors during the MCC-1 maneuver were under 0.2°, well below the 5° pointing requirement. Calibration of the maneuver based on ground-based Doppler tracking data during the maneuver (using the NASA GSFC Delta-V Along Line Of Sight, or DVALOS, tool) revealed that the maneuver was approximately 2.2% cold, achieving 0.490 m/ s ΔV, compared to the planned 0.503 m/ s ΔV. This variation in spacecraft propulsion performance was within expectations, as MCC-1 was the first DSCOVR maneuver and employed an un-calibrated propulsion system. Because the pointing error was small, the scale factor error was the primary source of error for MCC-1. The maneuver error and orbit state uncertainty errors necessitated a second mid-course correction maneuver, MCC-2. Without incorporating MCC-2 into the transfer trajectory, DSCOVR would have missed its intended target on the RLP XZ-plane by 7675 km. The MCC-1 cold performance was accounted for in the thrust and I_{sp} scale factor modeling for MCC-2.

Table 1. MCC-1 Maneuver Operational Results.

Burn Start / End on Feb 13, 2015	07:00:00.000 to 07:00:36.429 UTC	
Thruster Configuration	+Z axis thrusters (9, 10)	
Maneuver Attributes	**Planned**	**Observed**
ΔV (m/s)	0.503	0.490
Total Burn Time (s)	36.4	36.5
ΔV Mode Efficiency	87.63%	87.39%
Fuel Use Estimation (kg)	0.149	0.150
Thrust Scale Factor	1.000	0.978

MID COURSE CORRECTON MANEUVER #2 (MCC-2)

The DSCOVR MCC-2 maneuver was executed on April 27, 2015, as the second of two MCC maneuvers to correct for the Falcon 9 launch vehicle injection errors and maneuver errors from the MCC-1 maneuver executed on February 13.

Design and Analysis for the MCC-2 Maneuver

The goal of the second mid-course correction maneuver (MCC-2) for DSCOVR was to continue to fine-tune the transfer trajectory and correct for MCC-1 maneuver execution errors. The MCC-2 maneuver further ensures that the transfer trajectory crosses the XZ-plane of the RLP frame at the desired coordinates, so that the spacecraft would be at the nominal position prior to executing the LOI maneuver. Mission planners expected to conduct MCC-2 approximately L+17 days after MCC-1 to allow a full OD arc of 14 days between the two maneuvers. However, since the SpaceX Falcon-9 launch vehicle injection error was small and the resulting MCC-1 maneuver was also small as a consequence, mission planners decided to postpone the MCC-2 maneuver until approximately L+10 weeks to allow the deviation from the nominal trajectory to continue to grow until the MCC-2 burn would require at least 2 m/s and 2 to 3 minutes of burn duration. The motivation for this decision was to gather substantially more maneuver propulsion system calibration data with the goal of providing a better thrust and I_{sp} calibrated scale factor in preparation for the large LOI maneuver in early June 2015.

Maneuver targeting for the MCC-2 maneuver was initially conducted in a similar fashion as the MCC-1 maneuver, allowing the targeter to vary all three components of the thrust vector to determine a solution. However, while the burn plan analysis indicated no issues with spacecraft power or thermal constraints, another constraint affected the viability of the maneuver plan. The MCC-2 solution placed the spacecraft into a ΔV attitude that violated communications constraints by placing the Low-Gain Antenna (LGA) into a null region, where the communication link with the ground antenna would not be closed. As a result, the maneuver targeting for MCC-2 was customized by constraining the cross-track component of the maneuver to be zero, forcing the targeter to calculate a solution that did not violate the communication constraint. The final MCC-2 plan was for a 3-minute long maneuver of 2.5 m/s ΔV.

Similar to the MCC-1 execution error analysis, an MCC-2 error analysis was performed. While the MCC-1 error analysis focused on the effect of MCC-1 errors on the fuel budget for MCC-2, the focus of the MCC-2 error analysis was to characterize the probable coordinates of the RLP XZ-plane crossing with respect to the target location. Figure 9 shows the nominal target for the RLP XZ-plane crossing along with results of the MCC-2 error study and the pre- and post-MCC-2 actual results. As noted previously, if no MCC-2 maneuver had been performed, then the XZ-plane crossing would have been approximately 7675 km away from the target. This error would have been primarily in the X-component of the intercept, with the miss distance constituting about 9% of the amplitude of the Lissajous orbit oscillation in the RLP X-axis direction and therefore would have affected the shape of the Lissajous orbit significantly. Analyzing a range of potential MCC-2 maneuver errors, with thrust model variations from 0% to 5% (positive or negative) in 1% increments, pointing angle errors from 0° to 5° in 1° increments, and pointing clock angle values from 0° to 315° in 45° increments, a distribution of possible XZ-plane crossing coordinates was computed. This selection of 528 cases creates the pattern of blue dots seen in Figure 9. The cases with the largest error in the XZ-plane crossing coordinates with respect to the nominal target correspond to cases with the largest values of pointing angle error; the thrust model variations had relatively little effect. The results of this study showed that all probable MCC-2 results were acceptable and the likelihood of requiring an MCC-3 maneuver was therefore low. Any result within the observed range of MCC-2 errors would have a negligible impact on the LOI maneuver and the subsequent shape of the Lissajous orbit. The actual post-MCC-2 result is also indicated in the figure; the actual XZ-plane crossing was about 80 km away from the target.

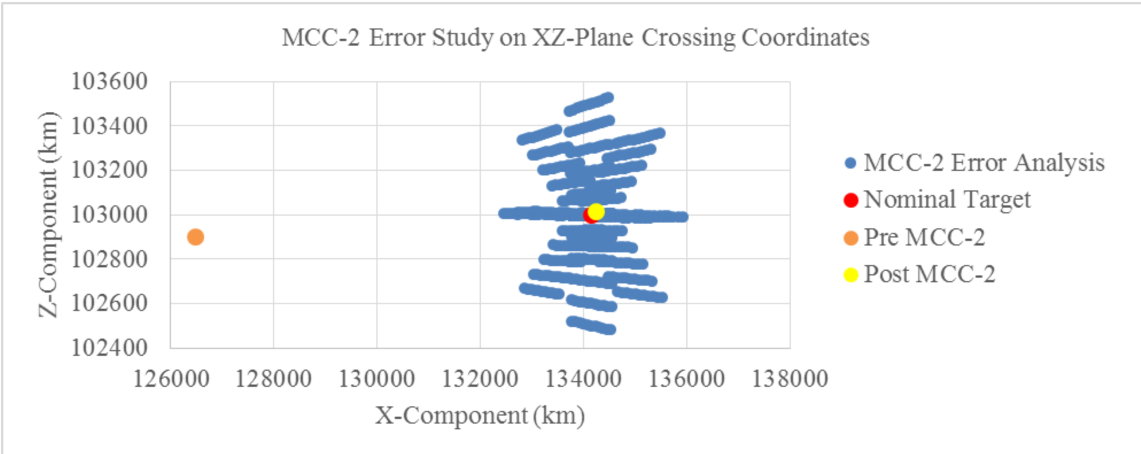

Figure 9. RLP XZ-Plane Crossing Coordinates.

MCC-2 Results

The MCC-2 maneuver, executed on 27 April 2015, 1500 UTC, was small, even after postponing the maneuver until L+10 weeks. The planned ΔV was 2.495 m/ s with a total burn time using the +Z thruster set of 3.09 minutes, consuming 0.779 kg of hydrazine. The ΔV mode efficiency was 84.83%, which was close to the expected 84.45%.

Once again, reconstruction using downlinked spacecraft telemetry showed that the pointing angle error was below 0.2°. Calibration of MCC-2 revealed that the maneuver was approximately 4.9% hotter than expected, achieving 2.619 m/ s ΔV, compared to the planned 2.495 m/ s ΔV. It is expected for thrust scale factor to increase as a function of burn duration, and MCC-2 was about five times longer than MCC-1. However, a variation of almost 5% in spacecraft propulsion performance was somewhat unexpected, as MCC-2 was the second DSCOVR maneuver, employing a previous calibration data point, albeit based on a very short duration MCC-1 maneuver. Post-MCC-2 maneuver analysis revealed that the resulting XZ-plane crossing on June 7 was only approximately 80 km away from the targeted position. Actual results for MCC-2 are summarized in Table 2.

Table 2. MCC-2 Maneuver Operational Results.

Burn Start / End on Apr 27, 2015	15:00:00.000 to 15:03:06.451 UTC	
Thruster Configuration	+Z axis thrusters (9, 10)	
Maneuver Attributes	**Planned**	**Observed**
ΔV (m/s)	2.495	2.619
Total Burn Time (min)	3.11	3.09

ΔV Mode Efficiency	84.45%	84.83%
Fuel Use Estimation (kg)	0.782	0.779
Thrust Scale Factor	0.978	1.026

LIBRATION ORBIT INSERTION (LOI)

The Libration Orbit Insertion (LOI) maneuvers were two deterministic maneuvers executed on June 7, 2015, to place the DSCOVR spacecraft onto its mission design Lissajous. The LOI maneuvers established a 160,538 km by 281,476 km Lissajous orbit about L1 in the Sun-Earth system. The combined DSCOVR LOI maneuver was large, imparting approximately 167 m/ s in ΔV and consuming 49.7 kg of fuel, over one third of the total mission fuel mass. However, unlike the MCC-1 and MCC-2 maneuvers, the LOI maneuver was deterministic and not statistical; a large ΔV was expected.

Design and Analysis for the LOI Maneuver

The purpose of a LOI maneuver is to place a libration point orbiter onto its intended Lissajous or halo orbit in the vicinity of L1 or L2 by modifying the spacecraft's orbital energy, in this case reducing the orbital energy to achieve the required Lissajous orbit velocity. Subsequent station-keeping maneuvers follow LOI to continue to balance the orbital energy to prevent it from falling back to the vicinity of the Earth or escaping into a heliocentric orbit around the Sun.

Approximately 40 days after the completion of the MCC-2 burn, the DSCOVR spacecraft was en route to intercept the L1 XZ-plane at 7 June 2015 15:19 UTC after its 115 day transfer trajectory. Analysis indicated that the optimal time (based on ΔV and fuel considerations) to perform the LOI maneuver was within 24 hours of crossing the XZ plane.

The LOI maneuver targeting algorithm is based on targeting three components of the RLP position and velocity state on the first RLP XZ-plane crossing following LOI, after about three months. These coordinates, targeted on the far side of the Lissajous orbit (the Sun side), are the X and Z components of the position (–70,401 km and –134,253 km with tolerances of 0.1 km) and the X component of the velocity (0 mm/s with a tolerance of 5 mm/s). The zero value for the X component of the velocity ensures a perpendicular XZ-plane crossing, so that the spacecraft is not tending toward the Earth or toward the Sun as it crosses the plane. For a Lissajous orbit, unlike a halo orbit, the out-of-plane oscillation (in the RLP Z direction) is at a different frequency than the in-plane oscillation (in the RLP XY plane), and so the Z component of the velocity will not necessarily be zero at the XZ-plane crossings. For simplicity for the DSCOVR mission, this is still referred to as a perpendicular plane crossing.

The LOI maneuver targeting algorithm first conducts an impulsive maneuver differential correction scheme, varying the three components of the velocity vector in the RLP frame. These impulsive results are then used to seed a finite burn differential corrector, which varies the burn duration, azimuth, and elevation to achieve the Sun-side perpendicular XZ-plane crossing discussed previously. Upon convergence, an additional differential corrector re-targets the burn duration by propagating to additional future XZ-plane crossings and adjusting the burn duration to achieve perpendicular plane crossings (RLP $V_x = 0$ mm/s with a tolerance of 5 mm/s).

Originally, the LOI maneuver was planned as a single maneuver, with one burn dedicated to achieving the required ΔV necessary to place the spacecraft onto the nominal Lissajous. Initial analysis, based on the latest OD data available from NASA GSFC Flight Dynamics Facility (FDF) at the time, showed that a LOI maneuver beginning at 7 Jun 2015, 1340 UTC would have the characteristics listed in Table 3.

Table 3. Nominal Single-Segment LOI.

LOI Burn Start Epoch (UTCG)	LOI Burn End Epoch (UTCG)	LOI ΔV Cost (m/s)	LOI Fuel Cost (kg)	LOI Burn Duration (hr)
7 Jun 2015 13:40:00.000	7 Jun 2015 18:10:27.180	166.36	49.74	4.51

Due to the realities of spacecraft operations, it was necessary to investigate the potential costs associated with a delay in the LOI maneuver execution. Initial analysis modeled a single LOI maneuver was conducted at one day increments after 7 June 2015, 1340 UTC. For maneuvers occurring within 4 to 5 days, it was observed that there is relatively little impact to the post-LOI maneuver Lissajous geometry. However, for maneuvers postponed 7 days after June 7 or later, considerable distortion of the Lissajous orbit occurs. As a result, a sizable LOI correction burn would be required to re-align the spacecraft velocity at the first XZ-plane crossing on the Sun-side of the Lissajous orbit, adding significant cost to the LOI maneuver. The trend for fuel costs as a function of LOI delay appears in Figure 10.

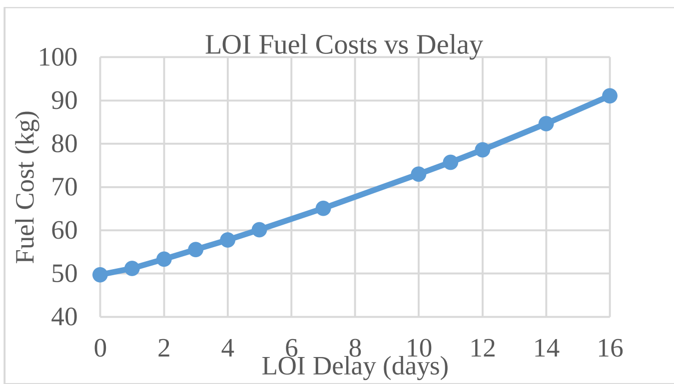

Figure 10. LOI Fuel Costs vs. Delays.

As noted previously, DSCOVR mission planners ultimately decided to divide the LOI maneuver into two segments. The first segment, starting at 7 June 2015, 1340 UTC, was designed to impart the first 90% of the total burn duration required for the LOI maneuver, with the second segment executed approximately 6 hours later to achieve the remaining 10% of the maneuver. The initial impetus for LOI segmentation analysis was potential spacecraft thermal constraints. However, substantial analysis by the DSCOVR thermal team revealed that a single, 4.5-hour long LOI burn would not present any thermal hazards to the spacecraft. Ultimately the LOI segmentation approach was pursued for a different reason: the large fluctuations in the maneuver calibration results from MCC-1 to MCC-2 presented a concern that executing a single-segment LOI maneuver would result in errors that would necessitate a large LOI correction maneuver. The thrust and I_{sp} scale factor computed after MCC-1 was 0.978 and the scale factor computed after MCC-2 was 1.026, a 4.9% difference. Based on past mission experience, thrust scale factor is expected to be a function of burn duration. The relatively short durations of MCC-1 and MCC-2 did not provide sufficient characterization of the thrust scale factor trend to indicate what the thrust scale factor would be for LOI, which is two orders of magnitude longer than either MCC maneuver. If an error of 5% were applied to the thrust and I_{sp} scale factor for LOI, the consequent ΔV error would be about 8 m/s.

Initially, mission planners assessed the operational feasibility and costs associated with a wide-range of potential segmentation options, ranging from 50/50 to 92/08, and with various intra-segment durations ranging from 4 to 48 hours. It was observed through both impulsive and finite burn analysis that the various segmenting options and intra-segment burn durations caused relatively limited differences in terms of ΔV and fuel costs as long as the intra-segment duration was kept below 12 hours, as noted in Figure 11.

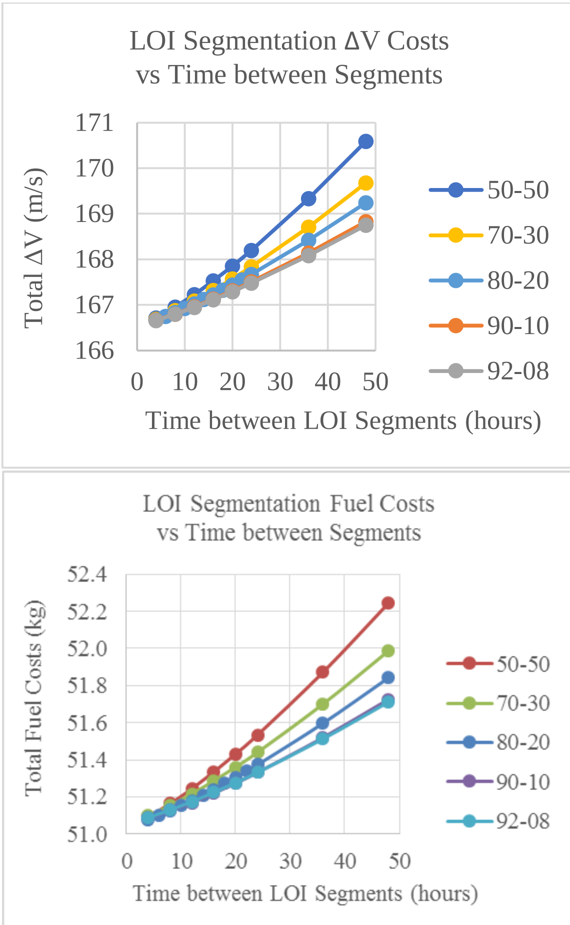

Figure 11. LOI Segmentation Cost vs. Time Between Segments.

Ultimately, it was decided to use the 90/10 LOI segmentation option, not for the minimal fuel savings associated with it compared to other segmentation options, but because the 90/10 split provided one of the longest Segment 1 burn durations, providing for better recoverability in case the Segment 2 burn could not be executed on time due to any sort of spacecraft anomaly. At the same time, the second segment needed to be long enough so that it would be appropriate to use the I_{sp} and thrust scale factor computed from LOI Segment 1 in the planning of Segment 2. A six hour break between the two segments was chosen because it was the shortest reasonable amount of time that the spacecraft operations team could complete all required activities for Segment 2 replanning. While this complicated the maneuver operations, it was deemed necessary and appropriate to provide an effective LOI maneuver, drive maneuver errors down below 1%, reduce the LOI-c maneuver that would follow approximately 3 weeks later, and reduce the early stationkeeping maneuver costs as well. Overall, the LOI segmented approach would assist with a more accurate maneuver insertion into the nominal DSCOVR Lissajous orbit, ensuring a more stable Lissajous orbit and aiding in the subsequent orbit determination.

LOI maneuver error studies illustrate the rationale for the LOI segmentation. The baseline cost of executing LOI as a single segment, with no accounting for errors in the maneuver scale factor, is 166.4 m/s, as shown in Figure 12. If that single segment has a 5% cold or 5% hot error, the required LOI-c maneuver executed 3 weeks after LOI costs 17.9 m/s or 18.0 m/s, respectively. The total ΔV costs in these scenarios go up to 175.9 m/s and 192.6 m/s, a significant impact to the DSCOVR fuel budget and mission lifetime. The total baseline cost of the 90/10 segmentation strategy is not appreciably different from the single segment cost, remaining at 166.4 m/s. The advantage of implementing a 90/10 segmented LOI maneuver option is apparent when modeling a 5% hot or cold burn for the first segment and compensating for that error in the modeling and re-planning for the second segment. To compensate for the underburn or overburn of the first segment, the maneuver model is updated with the most accurate estimate of the spacecraft state and maneuver scale factors. For a first segment underburn of 5%, the second segment is re-planned to be longer, so that the total ΔV for the two maneuver segments is barely changed from the baseline. Likewise if there is a first-segment overburn of 5%, the second segment is replanned and becomes shorter, and the overall ΔV cost is not affected. For the 90/10 segmentation cases shown in Figure 12, the second segment of the LOI maneuver is executed 6 hours after the first segment. This analysis assumes that there is no error in the thrust and I_{sp} scale factor modeling in the second segment maneuver as a result of the maneuver calibration of the first segment.

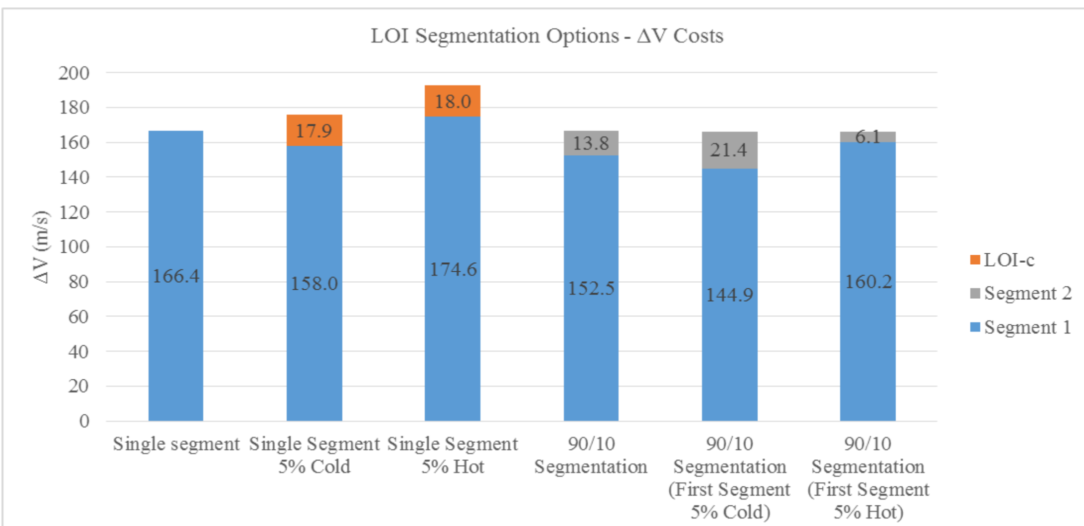

Figure 12. LOI Segmentation Costs.

Figure 13 shows the same analysis as Figure 12, but presents the fuel cost of each maneuver instead of the ΔV cost. Again, in the single-segment cases, the LOI-c burn is executed 3 weeks after LOI, and in the 90/10 segmentation cases, the first segment is 90% of the nominal LOI maneuver and the second segment is re-planned and executed within 6 hours after Segment 1. The LOI-c fuel costs when there are 5% errors in a single segment LOI approach add about 5 kg to the total insertion cost, while the 90/10 segmentation is more robust and allows maneuver planners to recover from errors quickly and at low cost.

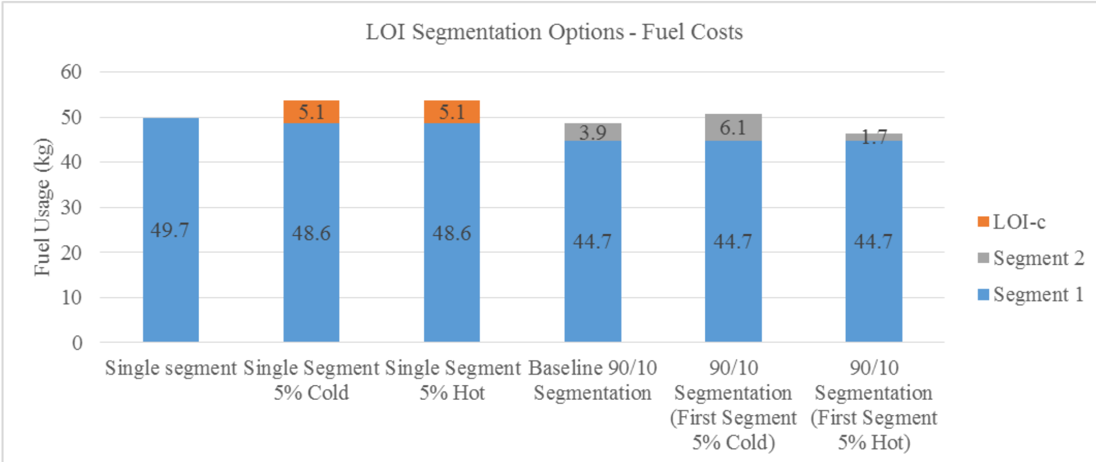

Figure 13. LOI Segmentation Fuel Costs.

The total costs of each approach, in terms of ΔV and fuel, are shown in Table 4. Overall, comparing the costs of the 90/10 segmented LOI maneuver with the costs of a single-segment LOI maneuvers, considering the possible outcomes with a 5% hot or cold error in the first maneuver, the segmentation provides a significant potential fuel savings of up to 3 kg for a cold maneuver and up to 7 kg in fuel savings for a hot maneuver.

Table 4. Single-Segment vs. Segmented LOI Costs.

LOI Maneuver Type	Total ΔV Cost (m/s)	Total Fuel Cost (kg)
Single segment LOI	166.4	49.7
Single segment LOI maneuver 5% cold plus LOI-c Cost	175.9	53.7
Single segment LOI maneuver 5% hot plus LOI-c Cost	192.6	53.7
Baseline 90/10 Segmentation	166.4	48.6
90/10 Segmentation (First segment 5% Cold)	166.3	50.8
90/10 Segmentation (First segment 5% Hot)	166.3	46.4

As noted previously, there are significant operational constraints and considerations that have be taken into account to effectively execute all DSCOVR maneuvers. Fortunately, the nominal maneuver attitude for LOI satisfied all spacecraft constraints for power, thermal, and communications.

LOI Results

The DSCOVR LOI maneuver was executed on 7 June 2015, with the first segment beginning at 1340 UTC. Segment 1 was completed at 1733 UTC, for a burn duration of 3 hours and 55 minutes, achieving a 148.6 m/s of ΔV and consuming 44.41 kg of hydrazine. Segment 2 began at 2330 UTC and ended 8 June 2015, 0005 UTC, for a maneuver duration of 35.6 minutes and achieving 18.3 m/s ΔV while consuming 5.3 kg of hydrazine. Total ΔV for both maneuver segments was

166.9 m/s, which represents a successful LOI maneuver sequence achieving the required ΔV to place the DSCOVR spacecraft onto its Lissajous orbit.

The LOI segmentation operations concept is shown in Figure 14. During the 6 hour intra-maneuver period, the maneuver team reconstructed the first segment maneuver using telemetry received from the spacecraft (temperature, pressure, and thruster on-times), received Doppler residual O-C data (observed residuals minus the residuals computed based on a nominal, no-burn ephemeris) from the GSFC FDF, and used NASA's DVALOS software to conduct maneuver calibration on the first segment to re-compute the thrust and I_{sp} scale factor. This updated scale factor was then used to re-plan the second maneuver segment to impart the total ΔV required for the LOI maneuver. After the final replanning of the second segment burn, updated slew planning and standard spacecraft maneuvering operation sequences were conducted to execute the second segment burn.

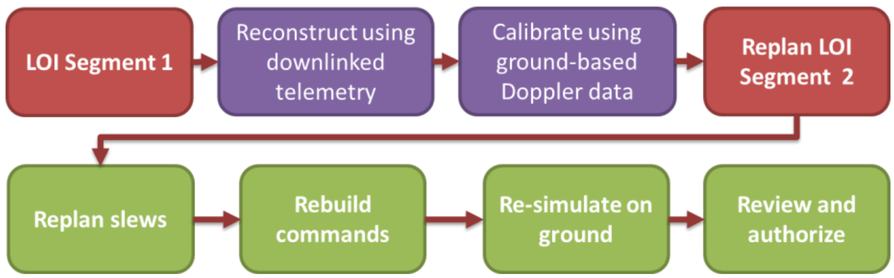

Figure 14. LOI Segmentation Operations Concept.

The Segment 1 reconstruction and calibration using the DVALOS utility revealed an approximate 2.5% Segment 1 underburn. The maneuver team re-planned the Segment 2 maneuver accounting for the Segment 1 underburn and incorporating the newly computed thrust scale factor derived from the DVALOS calculations. The resulting maneuver plan called for a longer Segment 2 burn duration than the baseline prediction to provide the additional ΔV necessary to recover from the first segment underburn.

The Segment 2 maneuver plan was computed by adjusting only the burn duration, and not the maneuver attitude. The same maneuver attitude was used for Segment 1 and Segment 2 to simplify the maneuver planning process and reduce the number of verification steps completed by other spacecraft subsystem elements. Using the same maneuver attitude for both maneuvers minimizes the workload during the intra-segment timeframe for the slew planning team as well as the thermal, power, and communications teams who must approve the maneuver plan. Analysis completed prior to LOI showed that using the same attitude for both maneuver segments had negligible impact on the effectiveness of the LOI maneuver.

Upon completion of the Segment 2 burn at 8 June 2015, 0005 UTC, maneuver reconstruction and calibration was conducted once again by the maneuver planning team. Segment 2 reconstruction and calibration revealed a 0.7% overburn on the 18.2 m/s maneuver, for a total computed LOI error of 0.13 m/s. If the full 2.5% error had been imparted to a single-segment LOI maneuver of 166 m/s (with no correction planned for 3 weeks), the error would have been 4.2 m/s. Breaking the LOI maneuver into two segments and re-planning the second segment within 6 hours of the first segment reduced the total insertion maneuver error from 4.2 m/s to 0.13 m/s for a 97% reduction. Table 5 summarizes the planned and achieved results from the two LOI maneuver segments.

Table 5. LOI Maneuver Operational Results.

	Segment 1	**Segment 2**

Burn Start / End on 7 June 2015	13:40:00.000 to 17:33:43.907 UTC		23:30:00 to 8 June 00:05:37.875 UTC	
Thruster Configuration	+Z axis thrusters (9, 10)		+Z axis thrusters (9, 10)	
Maneuver Attributes	**Planned**	**Observed**	**Planned**	**Observed**
ΔV (m/s)	152.442	148.579	18.175	18.301
Total Burn Time (mins)	235.10	233.73	35.48	35.63
ΔV Mode Efficiency	84.24%	84.74%	84.52%	84.17%
Fuel Use Estimation (kg)	44.658	44.410	5.306	5.313
Thrust Scale Factor	1.026	0.9997	0.9997	1.0066

LOI CORRECTION (LOI-C)

LOI-c is a stochastic correction maneuver to correct for the LOI maneuver error. This stochastic correction burn provides a final fine-tuning of the Lissajous trajectory per the desired baseline design before commencing regular orbit maintenance maneuvers. The LOI-c maneuver was executed on 30 June 2015, 0100 UTC, to correct the small trajectory errors after the LOI maneuvers conducted on 7 June. These errors arise from the inherent spacecraft ΔV pointing inaccuracies, maneuver calibration inaccuracies, and OD state errors. The magnitude of the LOI-c maneuver was approximately 0.9 m/s.

Design and Analysis for the LOI-c Maneuver

The cost to correct the LOI maneuver errors increases with elapsed time, so it is necessary to complete the LOI-c maneuver as soon as possible. However, GSFC FDF personnel determined that at least three weeks of tracking data is required to provide an accurate estimate of the spacecraft state after breaking the OD arc for LOI. Taking into account operational considerations as well as DSN support availability, the LOI-c date was set for 30 June.

There are several LOI-c maneuver targeting options available to the maneuver planners to execute an effective LOI-c maneuver. These options are analogous to the various stationkeeping strategies available for DSCOVR, as discussed in Reference 3. The purpose of each of these options is to add or remove energy from the orbit, with thrust generally aligned with the X or Y axis of the RLP frame. The goal of the differential corrector is to compute a perpendicular XZ-plane crossing two to four XZ-plane crossings into the future (with RLP Vx = 0 mm/s with a tolerance of 5 mm/s). A maneuver that provides a perpendicular plane crossing after four plane crossings (or two orbits, because the vehicle crosses in both the +Y and –Y directions for each orbit) will be more stable about the libration point than a maneuver that is computed by propagating only two plane crossings (or one orbit) into the future. The differences in the maneuver magnitude are very small when computing different numbers of plane crossings, but the precision gained by targeting farther along the trajectory ultimately reduces long-term fuel costs.

Four options are examined as control techniques for the LOI-c maneuver:

1. RLP L1 X-Axis Control – The thrust vector is along the RLP X axis and the ΔV is executed using the –X thruster set. This option requires only a small slew to place the spacecraft into the required ΔV attitude, using the LGA for communications. Costs: 0.93 m/s, 0.45 kg fuel.
2. RLP L1 Y-Axis Control – The thrust vector is along the RLP Y axis and the ΔV is executed using the +Z thruster set. This option requires using the LGA for communication. Costs: 1.39 m/s, 0.40 kg fuel.
3. RLP L1 Y-Axis Control Variant – The thrust vector is similar to the RLP Y axis direction, but rotated within the ecliptic plane such that the spacecraft X axis points directly toward Earth and the ΔV is executed using the +Z thruster set. This option allows use of the high gain antenna (HGA) which provides higher data rates during the maneuver, however, it is the most expensive. Costs: 1.77 m/s, 0.51 kg fuel.
4. RLP X-Axis Control Variant – The thrust vector is similar to the RLP X axis direction, but rotated within the ecliptic plane such that the spacecraft X axis points directly toward Earth and the ΔV is executed using the –X thruster set. This aligns with the spacecraft's nominal science attitude and therefore does not require the spacecraft to slew. This option allows use of the HGA and is among the cheapest. Costs: 0.86 m/s, 0.42 kg fuel.

Option 4 was selected for the LOI-c maneuver due to its operational simplicity in not requiring a slew, along with being inexpensive in terms of fuel usage. In addition, this option allows mission operators to conduct a small maneuver using the –X-axis thrusters for the first time; the +Z thruster set was used for all previous maneuvers.

LOI-c Results

The LOI-c maneuver was conducted on 30 June 2015, 0100 UTC, using the –X thruster set (thrusters 1, 2, 3, 4) – the first time these thrusters were used in ΔV mode during DSCOVR operations. The total burn duration was 1 minute, 36 seconds, consuming 0.428 kg of hydrazine and achieving 0.856 m/s ΔV, compared to the planned 0.861 m/s ΔV. The LOI-c maneuver was successful in correcting the Lissajous orbit back to the nominal design parameters by applying thrust in the sunward direction, adding energy to the orbit. After completion of the LOI-c maneuver, reconstruction and calibration revealed a very small underburn of approximately 0.48%.

Since the spacecraft was kept in the Earth-pointing science attitude during LOI-c, no slew was required and HGA communication was maintained throughout the maneuver. Because the thrust was along the spacecraft X axis, which points directly toward the Earth in the nominal science attitude, the entire planned ΔV was along the line of sight from the spacecraft to Earth. Reconstruction of the onboard telemetry revealed an off-pointing angle during the maneuver of approximately 3.6° due to expected limitations of the attitude control system when executing a ΔV using the ±X thruster sets. This off-pointing resulted in an unplanned ΔV component perpendicular to the line of sight from the spacecraft to the Earth of approximately 5.4 cm/s. The maneuver costs for the first DSCOVR stationkeeping maneuver, scheduled for late July as of this writing, are still under analysis, but initial results show that this maneuver will be quite small. Actual results for LOI-c are summarized in Table 6.

Table 6. LOI-c Maneuver Operational Results.

Burn Start / End on 30 June, 2015	01:00:00.000 to 01:01:36.233 UTC
Thruster Configuration	-X axis thrusters (1, 2, 3, 4)

Maneuver Attributes	Planned	Observed
ΔV (m/s)	0.861	0.856
Total Burn Time (min)	1.57	1.60
ΔV Mode Efficiency	66.63%	65.61%
Fuel Use Estimation (kg)	0.415	0.428
Thrust Scale Factor	1.000	0.995

EARLY OPERATIONS SUMMARY AND CONCLUSIONS

A major driver for the success of DSCOVR early operations was the excellent Falcon-9 launch vehicle performance with the resulting 0.2σ injection error. As a result, both stochastic MCC-1 and MCC-2 maneuvers were relatively small, requiring only 0.93 kg of hydrazine. The low fuel costs of the MCC maneuvers ensures that these fuel savings will be available for extended mission operations for additional years of Lissajous orbit maintenance.

Detailed communication and planning between the maneuver planning team and other spacecraft subsystems was a necessity for this mission to ensure that the maneuvers did not violate any of the overlapping constraints imposed by the power, thermal, and communications systems. Maneuver error analyses ensured the entire mission operations team was prepared for a wide variety of possible maneuver scenarios. The maneuver planning software that was developed for DSCOVR was used for both analysis and operations, resulting in a well-designed ground system that was automated where appropriate to allow a relaxed operations tempo.

The LOI 90/10 segmentation approach was extremely successful in placing the spacecraft onto its planned Lissajous orbit. The value of the segmentation strategy was proven when the second segment was able to compensate for the first segment underburn, reducing total insertion errors by 97%. The 2.5% underburn error in the first segment could have affected the entire LOI maneuver, with no opportunity to correct the error until the LOI-c maneuver three weeks later, if not for the segmentation strategy. Reconstruction, calibration, and re-planning of the second segment to correct for the first segment underburn allowed the majority of the error to be removed within 6 hours, reducing the cost of the LOI-c maneuver significantly.

The LOI-c maneuver allowed the NASA operations team to exercise the –X thruster set for the first time and characterize the expected pointing error when using this thruster set before the handover to NOAA. Going forward, NOAA stationkeeping maneuver planners will have the same four maneuver options presented in the discussion of the LOI-c maneuver. The four early-orbit maneuvers (MCC-1, MCC-2, LOI, and LOI-c) tested thruster sets aligned with the X and Z spacecraft body axes, removing uncertainty about the propulsion and attitude control system performance, and establishing DSCOVR in a safe Lissajous orbit about L1 that can be maintained for many years to come.

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