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GUIDANCE AND CONTROL CHALLENGES TO THE MESSENGER SPACECRAFT IN ACHIEVING AND OPERATING FROM ORBIT AT MERCURY

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Next to the launch of the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft, the Mercury orbit insertion (MOI) maneuver was the most critical activity of the mission. The MOI maneuver was the largest of the mission by nearly a factor of three and required extensive planning and simulation to ensure insertion into the desired science orbit. The criticality of the MOI maneuver also prompted a unique fault management schema. Once in orbit about Mercury, a series of orbit-correction maneuvers was required in the year-long primary mission to ensure that the orbit continued to meet the science requirements. These maneuvers capitalized on the flexibility in the guidance and control (G&C) system, as they required operational strategies unforeseen at the time the G&C software was designed.

INTRODUCTION

On 18 March 2011, the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft became the first probe to successfully achieve orbit about Mercury. As part of NASA's Discovery Program, MESSENGER is the first spacecraft to closely observe the planet Mercury since the Mariner 10 flybys of the mid-1970s. The spacecraft, which was launched in August 2004, successfully completed an Earth flyby, two Venus flybys, and three Mercury flybys, as well as a series of deep-space maneuvers (DSMs), before performing the Mercury orbit insertion (MOI) maneuver to be captured into orbit.[1] During the year-long primary orbital mission, the diverse suite of miniaturized science instruments onboard the spacecraft are being used to globally characterize the planet.[2] The long interplanetary cruise phase of the mission helped to ready the team for MOI and orbital operations. However, despite the team's detailed plans and preparation, several changes to the expected modes of operation became necessary as the orbital operations phase unfolded.

The MESSENGER spacecraft is a three-axis-stabilized spacecraft that primarily uses reaction wheels to maintain attitude control.[3] The guidance and control (G&C) system's sensor suite consists of star trackers, digital Sun sensors, and an inertial measurement unit, which contains four accelerometers and four gyroscopes. During nominal operations, attitude determination and control are achieved through the combination of four reaction wheels, one star tracker, and four gyroscopes. Solar panels provide electric power to the spacecraft, and a heat-resistant and reflective sunshade protects the spacecraft from the extreme thermal

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conditions encountered close to the Sun. The Sun keep-in (SKI) constraint included in the G&C software ensures that the spacecraft's sunshade sufficiently shields the spacecraft and science instruments from the Sun by allowing only small deviations from direct Sun pointing in rotations around the spacecraft *x*- and *z*-axes. In Figure 1, which shows the spacecraft body axes and selected component locations, this constraint translates to aligning the −*y*-axis with the Sun line.

In addition to reaction wheels, the G&C system's actuator suite includes thrusters, which are used primarily for angular momentum management and for trajectory control; they can also be used as a backup for attitude control in the event of multiple wheel failures. The MESSENGER propulsion system (MPS), shown in Figure 2, was designed and built by Aerojet and consists of four propellant tanks and 17 thrusters.[4] The MPS includes one bi-propellant engine, the large velocity adjust (LVA) thruster, which provides about 680 N of thrust. In addition to the LVA, the MPS includes two sets of monopropellant thrusters: twelve 4.4-N thrusters and four 22-N thrusters. Eight of the 4.4-N thrusters, designated A1-4 and B1-4, are used to execute small velocity changes orthogonal to the Sun line and to provide attitude control for all other maneuvers. The remaining 4.4-N thrusters, designated S1-2 and P1-2, are used for small velocity changes in the sunward or anti-sunward direction. The four 22-N thrusters provide medium velocity changes orthogonal to the Sun line and also provide attitude control when using the LVA. The two main fuel tanks, which contain hydrazine (N_2H_4), and the oxidizer tank, which contains nitrous tetroxide (NTO, or N_2O_4), are mounted along the spacecraft *y*-axis. The tank centered at the origin of the *x*-*y*-*z* coordinate frame is the oxidizer tank. These three propellant tanks are pressure regulated by a helium pressurization system and contain two ring baffles each but do not have diaphragms. Since the tanks do not include diaphragms, a fourth tank, the auxiliary tank, is used to conduct a short "settling burn" before any propellant is drawn from the main fuel tanks and oxidizer tank to ensure that there is propellant settled at the outlet end of the tanks. The auxiliary tank contains a diaphragm but it is not pressure regulated, and due to its small volume it must be refilled from the main fuel tanks. The auxiliary tank can also be used for any small velocity change (ΔV) or momentum off-loading maneuvers.

The G&C software recognizes three types of propulsive maneuvers: Mode-1, Mode-2, and Mode-3, which in general are defined by the thrusters that can be used and the tanks that supply propellant. Mode-1 maneuvers are used for small ΔV and momentum off-loading maneuvers and can use either the 4.4-N or the 22-N thrusters, with fuel supplied by the auxiliary tank operating in blow-down mode. The G&C software breaks a Mode-1 maneuver into two segments: main and tweak. During the main segment, ΔV is imparted to the spacecraft. The tweak segment, which is the final segment, begins when the thrusters being used for ΔV are disabled and the thrusters being used for attitude control continue firing to allow structural excitations and propellant slosh to damp out prior to returning control to the reaction wheels. Mode-2 maneuvers are used for medium ΔV maneuvers and can use the 4.4-N and 22-N thrusters. The G&C software breaks a Mode-2 maneuver into three segments: settle, main, and tweak. The settle segment executes a "settling burn" with fuel from the auxiliary tank used in blow-down mode, which prepares the main fuel tanks for the main segment. During the Mode-2 main segment, the thrusters are pressure-fed from the main fuel tanks and the majority of the target ΔV is imparted to the spacecraft. Additionally, at the beginning of the main segment the auxiliary tank is refilled from one of the main fuel tanks. In a closed-loop controlled maneuver, the main segment will continue until the target ΔV has been reached or the maneuver reaches a duration limit. The tweak segment follows, using fuel supplied by the auxiliary tank. Mode-3 maneuvers are used for large ΔV maneuvers and use the LVA thruster. The G&C software breaks a Mode-3 maneuver into five segments: settle, refill, main, trim, and tweak. The Mode-3 settle and tweak segments are the same as in a Mode-2 maneuver; however, the auxiliary tank is refilled in a separate segment in a Mode-3 maneuver. A separate refill segment is required since during the main segment the main fuel tanks would not be able to support the flow rate required to simultaneously fire the LVA, fire the C-thrusters as necessary for attitude control, while also refilling the auxiliary tank. In the Mode-3 main segment, the LVA fires for an integral number of seconds using propellant from the oxidizer and main fuel tanks. At a predetermined time (in an open-loop controlled maneuver) or when a percentage of total ΔV is reached as determined from accelerometer data (in a closed-loop controlled maneuver) the G&C system transitions to the trim segment, which uses the monopropellant thrusters drawing fuel from the main fuel tanks to complete the desired ΔV.

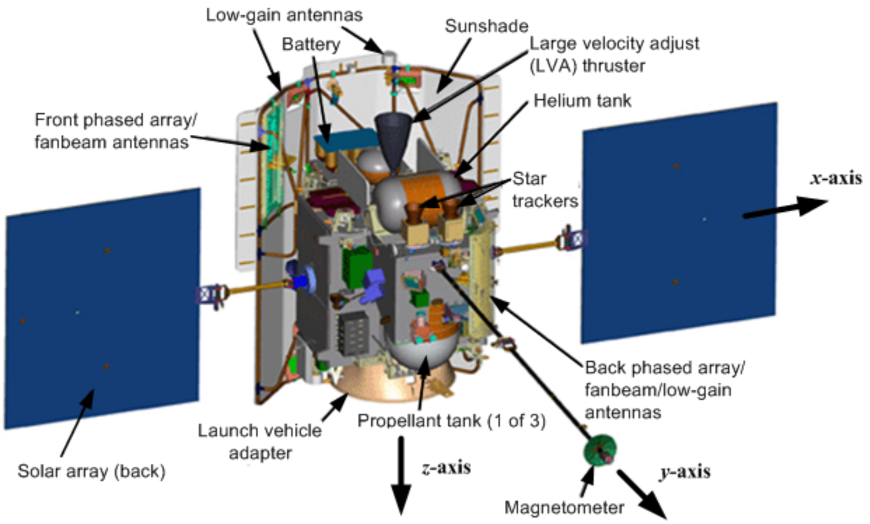

Figure 1. MESSENGER Spacecraft Components and Body-Axis Convention.

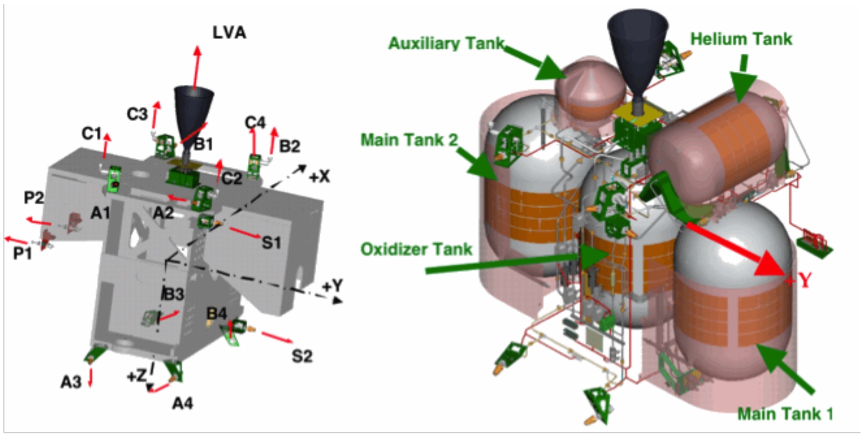

Figure 2. MESSENGER Propulsion System Thruster Location, Thruster Direction, and Tank Layout.

MERCURY ORBIT INSERTION

MESSENGER's MOI maneuver was executed on 18 March 2011. The MOI maneuver imparted 862 m/s of ΔV, which allowed the MESSENGER spacecraft to be captured into a 12-hr, high-inclination orbit about Mercury. The orbital parameters for MESSENGER's orbit are given in Table 1. This single event consumed 185.56 kg of propellant, of which 101.83 kg was hydrazine and 83.73 kg was oxidizer. In terms of percentages of mass at the start of MOI, the burn consumed about 64% of the available hydrazine and 92% of the available oxidizer. The maneuver represented 39.4% of the total mission ΔV and was the largest burn of the mission by nearly a factor of three. Next to launch of the spacecraft, the MOI maneuver was the most carefully planned event of the mission. Recovery scenarios for a partial or no-burn MOI were generally not feasible due to increased mission duration, cost, and/or complexity.[5] As a result of the dearth of attractive recovery options, many elements of the burn design were rooted in a "go for broke" operational philosophy. Additionally, because MESSENGER is a Discovery-class mission and has only selective redundancy, certain faults were irrecoverable. The LVA thruster and the IMU are notable single-string hardware elements. Extensive simulations were performed to ensure that the maneuver design was robust to selective faults and to fully understand the sensitivity of the science orbit metrics to maneuver performance. The MOI maneuver was additionally complicated by the need to slew the spacecraft 30° during the maneuver to ensure that the thrust vector remained directed against the Mercury-relative velocity vector, thereby minimizing the required propellant for the maneuver. Despite the possible implementation complications, MOI exhibited excellent performance, and the resultant orbit met all of the science team goals without the need for a cleanup maneuver.

Table 1. Mercury Orbital Parameters for MESSENGER.
The * Symbol Denotes Values Provided with Respect to Mercury True Equator.

	Post-MOI Target	**Estimated Value ($\pm 3\sigma$)**	**Deviation**	**Science Requirement**
Periapsis Altitude (km)	200	206.77	6.77	125–225
Orbital Period (s)	43195.5	43456.9	261.4	43196 ± 600
Eccentricity	0.740	0.740 ± 10^{-4}	0.00038	–
Inclination* (°)	82.5	$82.52 \pm 5\times10^{-3}$	0.0219	82.5 ± 1.0
Argument of Periapsis* (°)	119.13	$119.16 \pm 3\times10^{-3}$	0.034	–
Periapsis Latitude* (°)	60	59.976	–0.024	54–61

Critical Design Elements

The mission mass constraints at launch led to a propulsion system design for MESSENGER that did not include propellant management devices in the main fuel and oxidizer tanks; this design complicated the operational sequence required to fire the LVA. Before LVA ignition, propellant had to be settled by firing smaller monopropellant thrusters with hydrazine supplied by the auxiliary fuel tank, which contains a diaphragm (settle segment). Once propellant settling was complete, the auxiliary tank was refilled with hydrazine from one of the two main fuel tanks (refill segment). Next, the main segment of the maneuver was accomplished with the LVA, during which time the drawing of hydrazine alternated between the main fuel tanks to control the location of the center of mass (CM). When the maneuver was nearly complete as determined by the onboard estimate of the achieved ΔV, the spacecraft autonomously disabled the LVA and transitioned to smaller monopropellant thrusters to help ensure precision in the maneuver magnitude (trim segment). Finally, when the desired ΔV magnitude was achieved, the spacecraft disabled the ΔV thrusters but left the attitude control thrusters enabled for about 30 s to allow structural excitations and propellant slosh to damp out prior to returning control to the reaction wheels (tweak segment). This sequence of events, which is recognized by the G&C software as a Mode-3 propulsive maneuver sequence, had been used for seven burns during the cruise phase and was thoroughly proven prior to MOI. All burn segments executed flawlessly at MOI, despite the complexity required to manage the propellant. Additionally, the CM control worked as expected, and the CM remained very close to the LVA thrust axis, ensuring sufficient attitude control margin.

An additional element at MOI that required careful testing was the implementation of the powered turn, also called turn-while-burning. By changing the inertial orientation of the thrust vector during the insertion burn, the thrust could remain directed against the Mercury-relative velocity vector, allowing the propellant consumption (and execution duration) to be reduced when compared to a fixed-direction burn. The maneuver was designed such that nearly all of the turn was executed around the Sun line, a requirement to ensure SKI compliance. The slew rate required to implement the powered turn was about 0.04°/s and was well within the capabilities of the attitude control thrusters. Figure 3 shows the MESSENGER trajectory around the MOI maneuver as viewed from the Sun; in this graphic, the green trajectory is the pre-MOI heliocentric trajectory, the light blue represents the trajectory during the MOI maneuver, and the dark blue portion shows the resultant MESSENGER orbit about Mercury. This light blue arc highlights the turn that was necessary to maximize the efficiency of the insertion maneuver. To reduce risk, the onboard software did not integrate the MESSENGER trajectory in real-time; instead, the desired planet-relative velocity direction was pre-computed on the ground and was uploaded to the G&C software as a function of the maneuver magnitude. As the onboard software integrated the accelerometer measurements, the direction of the attitude command changed accordingly to maintain (approximately) the thrust vector against the planet-

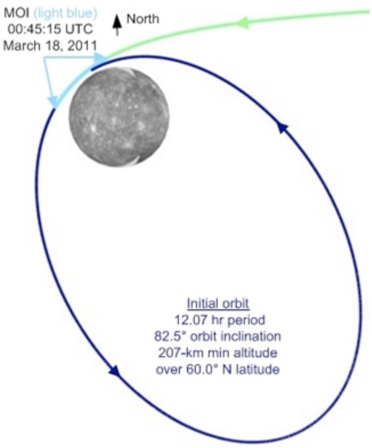

Figure 3. MESSENGER MOI Trajectory as Viewed from the Sun.

relative velocity. In this way, the onboard software controlled the ΔV directly, and the spacecraft trajectory implicitly. A critical assumption to the software design approach described above is that the acceleration performance of the burn was known to ground planners in advance of the burn. At that point in the mission, all the thrusters had been used multiple times, and their performance was well characterized. The implementation of the powered turn was flight tested at two prior DSMs to ensure that all hardware and software performed as expected. These successful tests provided confidence in the validity of the MOI design. The MOI powered turn worked as designed, and both the turn arc and resultant ΔV were within 10 cm/s of the target values, as determined by the onboard accelerometers. Post-burn reconstructions from navigators revealed ΔV errors about 5 times larger, which is likely due to small uncompensated accelerometer scale factors (~300 ppm) and accelerometer alignment errors (~50 arcseconds).

Simulations and Maneuver Performance

A great deal of effort was devoted to demonstrating through simulation that the MESSENGER orbit about Mercury would meet the science requirements shown in Table 1. Although science requirements were imposed on several of the orbit parameters, the requirement on the orbital period was by far the most challenging to meet. Extensive Monte Carlo simulations revealed that the period requirement was strongly influenced by both the effective thrust from the spacecraft and the trajectory arrival conditions. Typically, these arrival conditions are defined in terms of the coordinates in the B-plane, or hyperbolic impact-plane.[6] The B-plane is the plane normal to the incoming asymptote of the hyperbolic flyby trajectory that intersects the center of the target body (i.e., Mercury). The reference vector normal to the B-plane, the *S*-axis, lies along the incoming asymptote. For MESSENGER planetary encounters, the *T*-axis is parallel to the line of intersection between the B-plane and the Earth Mean Ecliptic plane of 1.5 January 2000 (and is positive in the direction of decreasing right ascension). The *R*-axis (positive toward the south ecliptic pole) completes the orthogonal, right-handed *T-R-S* Cartesian coordinate axes. Mission designers selected a target in this plane (values for the *T* and *R* coordinates, referred to as B•T and B•R) that defined the desired trajectory arrival conditions. For MOI, the coordinate frame was set up such that (generally speaking) B•R errors represented arrival altitude errors and B•T errors represented errors out of the desired orbit plane about Mercury.

The strong correlation between the periapsis altitude, orbital period and inclination, and the B-plane arrival conditions is shown in Figure 4. While the performance in altitude and inclination were well within their respective requirements for the science orbit, the three-standard-deviation (3-σ) error in orbital period shown in Table 1 was a substantial portion of the maximum allowable orbital period error of 600 s. Although the performance demonstrated in the Monte Carlo study shown in Figure 4 was deemed satisfactory, simulations for burns during which the accelerometers were assumed to have failed (and the burn was instead terminated on the basis of ground estimates of the required maneuver duration) violated the orbital period requirement 30% of the time. The MESSENGER team investigated a possible two-burn strategy that allowed for a cleanup maneuver, mostly to ensure the satisfaction of the orbital period constraint in the event of accelerometer issues. However, this strategy resulted in an overly complicated operational implementation. In the end, the team elected to trust the accelerometers and used the single-burn approach. In retrospect, this was a good decision since all of the orbit parameter requirements were met with a direct insertion into the science orbit.

The aforementioned powered turn strategy required accuracy in the ground assumptions used for the maneuver design, since the G&C software does not integrate MESSENGER's trajectory onboard. Despite this shortcoming, extensive study via Monte Carlo simulations revealed that relying on accurate ground information is a robust strategy if the ground estimates of the engine performance (which is strongly influenced by the CM location) and inbound trajectory are accurate. Although these were reasonable assumptions at that point in the mission given the experience of the flight team, Monte Carlo studies of maneuver performance in the face of wide variation in arrival conditions and engine performance were undertaken. Although the LVA performance was well characterized prior to MOI, effective thrust performance could change markedly because of changes in the CM. Figure 5 shows the location of the CM (indicated by the vector **r**) in the spacecraft *x-y* plane. As the CM moves away from the LVA thrust axis (which pierces the *x-y* plane at approximately [0–10] mm), the LVA imparts a torque on the spacecraft that must be countered with attitude-control thruster firings. These attitude-control firings are done with thrusters that impart ΔV in the same direction as the LVA; therefore, a large CM offset can greatly increase the effective thrust. Such performance would cause the maneuver to complete too quickly, resulting in a shorter orbital period. Because of this sensitivity, the propellant depletion was carefully managed to ensure that the CM remained within about 5 mm of the LVA thrust axis. Taken from a 1,000-case set of Monte Carlo simulations of MOI, the correlation between the CM location and the orbital period are shown in the right-hand graphics in Figure 5. As the CM moves away from the center of the figure, the attitude control thrusters must pulse more frequently, leading to higher effective thrust, a shorter maneuver, and a shorter orbital period.

The MOI Monte Carlo simulations shown in Figure 4 used the expected B-plane delivery statistics on the basis of the best estimate of the orbit determination uncertainty prior to MOI. The actual arrival conditions (as determined by post-MOI reconstruction) were −2 km and −8 km in the B•T and B•R directions

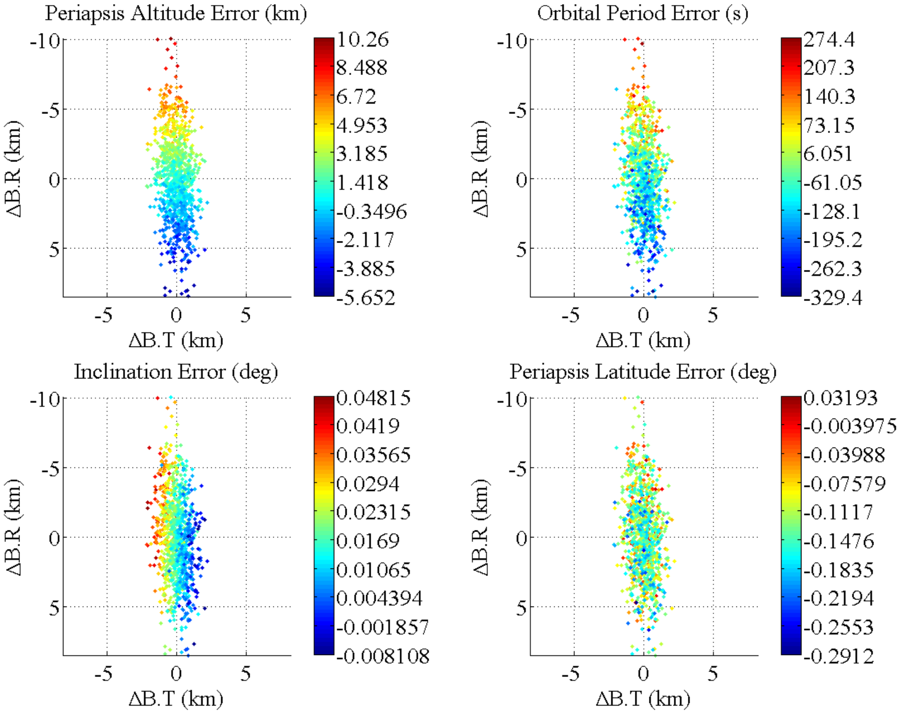

Figure 4. Monte Carlo Simulations Showing Terminal Orbit Errors as Functions of B-plane Arrival Conditions.

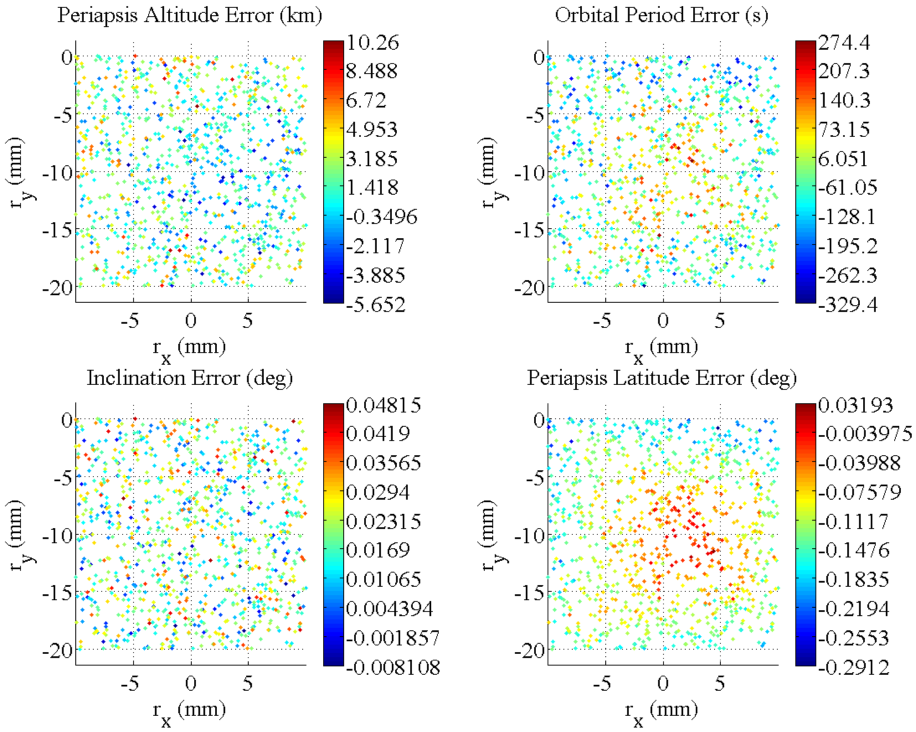

Figure 5. Monte Carlo Simulations Showing Terminal Orbit Errors as Functions of CM Offset from the Spacecraft z-axis.

respectively, and were near the limits of the arrival errors assumed in the Monte Carlo analysis. These errors were larger than expected, as prior MESSENGER flybys used solar sailing to reduce the arrival errors[7], and similar B-plane delivery accuracy was expected at MOI. The larger arrival errors at MOI were chiefly the result of unexpected sensitivity of the B-plane solution, due in part to inconsistencies between concurrent orbit determination solutions from radiometric fit arcs of different lengths. The orbit determination was also affected somewhat by the varying fidelity of the solar panel angles modeled in the navigation software. Although the arrival errors were larger than expected, they were within the parametric variations of the Monte Carlo simulations, and the burn design proved to be robust to these errors, as predicted by the pre-MOI studies. Nonetheless, the B-plane arrival conditions were the dominant source of altitude and period error in the resultant orbit about Mercury, as shown in Table 1.

Fault Management Scheme

After the launch of the MESSENGER spacecraft, MOI was the most critical activity of the mission. In a manner similar to preparing for the launch of a space mission, the MESSENGER team engaged in a series of reviews and performed verification and in-flight demonstration activities over a span of three years prior to this critical event. In parallel with these preparations, the MESSENGER team prepared for and executed five DSMs and three flybys of Mercury and developed the detailed plans for operations in-orbit around the planet. Foremost in the preparations for MOI was the team's determination to minimize the overall risk to successfully placing MESSENGER in orbit around Mercury.

The general fault management goal for MOI was to ensure spacecraft insertion into Mercury orbit. Therefore any autonomous actions that would disrupt or terminate the maneuver should be inhibited, and any autonomous action that could continue the maneuver under anomalous conditions should be exercised. However, since the primary mission had not yet started, sufficient autonomy should remain enabled to protect the spacecraft subsystems and instruments so they could complete scientific measurements from orbit.

The fault management system for the MESSENGER spacecraft is robust and provides the capability to switch between redundant units upon detection of a component fault in a large majority of situations. However, upon detection of major systematic faults, similar to many planetary missions, the general response of the fault management system is to isolate the fault, place the spacecraft in a safe and stable configuration, and wait for engineers on the ground to evaluate and correct the fault. Given this design architecture, the command execution software and part of the flight electronics were not designed to continue executing commands during a major fault or to recover and pick up execution of a critical command sequence upon detection of a major fault. Under this design constraint, the team had to develop a MOI-unique fault management schema to cover the period of time before, during, and after the MOI maneuver sequence. This schema involved a progressive sequence of both ground-initiated and automatic flight sequences to disable, delay, replace, and/or augment the detection and response for a variety of faults on the system.

One of the key driving functions for the definition of the fault management schema was the knowledge of the mission state as a function of the amount of ΔV that would be imparted during the maneuver. Reviewing the resulting trajectories revealed three distinct outcomes. First, if less than 50% of the total ΔV was imparted to the spacecraft, the spacecraft would not achieve Mercury orbit but would be left in heliocentric orbit with sufficient on-board propellant to attempt a future insertion many years and additional Mercury gravitational assists later. Second, if more than 70% of the total ΔV was imparted, the spacecraft would attain orbit about Mercury but would require a series of in-orbit maneuvers to reach an orbit capable of meeting scientific objectives. And last, if anywhere between 50 and 70% of the total ΔV was imparted, the spacecraft would be stranded in a heliocentric orbit, never able to complete the primary objectives of the mission. Given these potential outcomes, it was necessary to ensure that once the MOI maneuver sequence was started, it continued under all circumstances, until at least 70% of the target ΔV was imparted to the spacecraft.

In addition to the constraints on system design and the complications of astrodynamics, there were operational considerations that added to the definition of the MOI-unique fault management approach. Depending on the type of fault, the system can respond by demoting the spacecraft into one of two safe configurations, each of which requires real-time ground commands and command verifications to promote the system back into normal operational mode, a state required to execute any command sequence. During the 6.6 years of interplanetary cruise between launch and Mercury orbit insertion, the operations team had several opportunities to refine both the sequence of commands and the amount of time required to promote the spacecraft back to operational mode. From this experience, the operations team was able to reduce the promotion sequence to the absolute minimum, ensuring recovery within 24 hours without risk, and in less time with increased maneuver execution risk.

Given these constraints, the fault management approach for MOI was broken into four distinctive operational periods: 1 week prior to MOI, 24 hours prior to MOI, 5 minutes prior to the start of MOI, and approximately 10 minutes after the start of MOI. One week prior to MOI, continuous coverage of the spacecraft from the Deep Space Network (DSN) was initiated to ensure that any faults could be evaluated and mitigated. This action also provided ample access to the spacecraft for pre-maneuver component checkout.

Twenty-four hours prior to MOI, the system entered the "demotion exclusion window." During this period of time, any fault monitor, other than an autonomous processor reset – a condition that cannot be disabled – was either disabled or its action changed so that the system could not be demoted. Although system-state demotions were precluded, component-level redundant-unit changes were permitted for both MOI-critical and non-critical units. During this period of time, the spacecraft, which was once completely autonomous and robust to all manner of failures, became potentially reliant on ground intervention. To ensure that this critical link with the ground was maintained, redundant DSN support was provided throughout the demotion exclusion window and round-the-clock engineering staffing was maintained.

Five minutes prior to starting the MOI sequence, almost all on-board autonomy that could prematurely terminate the maneuver was disabled. Only three events at that point could terminate the maneuver. The first was a spontaneous flight computer re-boot, a condition that cannot be disabled. The second was loss of initial maneuver attitude; the assumption was that it is better not to start a maneuver at the wrong attitude and recover at a later date then to execute a major maneuver in an incorrect attitude and potentially impact the planet. The third was uncontrolled momentum accumulation, e.g., as a result of unforeseen dynamic instability; the decision under such an event was to terminate the maneuver and recover the spacecraft later. In addition to these spacecraft autonomy rules, all component-level fault protection associated with non-MOI-critical equipment remained enabled. This action ensured that any faults in these units would be mitigated and would allow for their future use during orbital science operations.

At a pre-determined point during the command sequence execution, approximately 10 minutes after starting MOI, additional autonomous actions were enabled. The time of re-enabling was based on analysis of potential best- and worst-case propulsion system performance estimates. These additional autonomous actions would terminate the burn either due to significant under-performance of the propulsion system and/or failure of the accelerometers. Terminating the burn under these conditions prevented a seriously underperforming maneuver from further wasting precious propellant that could possibly be used later in the mission for another attempt at orbit insertion. It also prevented any substantial overburn, which would both waste propellant and place the spacecraft in a very close orbit around the planet.

At the completion of the MOI sequence and following establishment of ground contact with the spacecraft, all disabled and/or altered autonomy rules were re-enabled, restoring the full on-board fault management system and allowing the system to take any appropriate actions in response to ambient conditions. In the end, the MOI sequence executed nominally, placing the spacecraft nearly perfectly into the designed science-observing orbit, without tripping any fault conditions.

COMMISSIONING PHASE

Although all MESSENGER instruments and components were thoroughly checked during the three flybys of Mercury, which served as trial runs for orbital operations, MESSENGER was the first spacecraft ever to orbit the closet planet to the Sun. To ensure that the spacecraft and instruments were operating properly in this unverified and challenging environment, a 17-day commissioning phase followed MOI. This period of 17 days provided sufficient time for spacecraft system checkout and characterization and instrument turn-on and calibration. It also ensured a stable post-MOI orbit determination from which to commence mission science operations on 4 April 2011.

ORBIT-CORRECTION MANEUVERS

MESSENGER's orbit about Mercury is strongly perturbed by solar gravity, Mercury's gravity field, and solar radiation pressure. To ensure that the orbit continues to meet the mission's science requirements, a series of orbit-correction maneuvers (OCMs) are used.[8] The OCMs performed in the primary mission kept the orbital periapsis near 200-km altitude and the orbital period near 12 hours. Originally, it was planned that these maneuvers would be executed in pairs (a periapsis-lowering maneuver at apoapsis, followed by an orbital period correction at periapsis on the subsequent orbit). A modified primary mission OCM schedule reduced the operational complexity by alternating between the periapsis-lowering maneuver at apoapsis (odd-numbered OCMs) and an orbital period correction at periapsis (even-numbered OCMs) 44 days later. The maneuver sequencing and contingency planning were greatly simplified by this modified approach. Additionally, separating the maneuvers also reduced the mission risk, as the OCMs relied on unproven implementation strategies that were employed when the main fuel tanks had very low fill levels. These maneuvers capitalized on the flexibility in the G&C system, as they required operational strategies unforeseen at the time the software was designed. This flexibility has allowed for successful execution of all five OCMs in the primary mission, despite complex maneuver execution sequences.

Because the MPS fuel and oxidizer tanks do not contain propellant management devices, at very low fill fractions care must be taken when operating the system to minimize the amount of propellant that can be trapped on the tank baffles and the chances of gas ingestion. For instance, high impulse at low fill fractions can create a fluid geyser capable of reaching above the tank baffles, resulting in the trapping of liquid above the baffles (i.e., the tank end opposite to the outlet), as well as propellant sloshing, which can move fluid away from the tank outlets and cause gas ingestion. Prior to MOI, Donald E. Jaekle of PMD Technology performed low-gravity fluid dynamics analyses to determine a set of guidelines for operating the MPS after the MOI maneuver. The post-MOI MPS operation guidelines have dictated the operation of the MPS throughout the primary orbital mission. The guidelines cover both Mode-2 and Mode-3 maneuvers and dictate the durations of maneuver segments, the propellant sources, and the prescribed thruster selection during each segment. The guidelines do not include tweak segment specifications, since firing thrusters purely for attitude control does not present propellant management difficulties.

According to the post-MOI MPS operational guidelines, the LVA thruster cannot be operated unless there is at least 8 kg of usable fuel in each main fuel tank. The 8-kg fuel limit can be referred to as the "minimum-per-tank fuel load limit," and each main fuel tank met this limit throughout the primary mission. The minimum-per-tank fuel load limit is a sum of the 3.6 kg that could possibly be attached to the baffles during the settling portions of a maneuver and the 4.4 kg of propellant that has to be present at the tank outlet to prevent gas ingestion. If both main fuel tanks meet the minimum-per-tank fuel load limit, the post-MOI MPS operational guidelines dictate a specific Mode-3 maneuver sequence, which is outlined in Table 2. The settle and refill segments in Table 2 draw liquid below the baffles and into a pool at the tank outlets. The main segment minimum duration of 12 s sufficiently dampens the propellant acceleration caused by LVA ignition so that the transition to C-thruster firing in the trim segment will not form a large geyser. As an added benefit, the main segment allows the majority of liquid to move from above all baffles, from below the upper baffle in the main fuel tanks, and from below both baffles in the oxidizer tank. After the main segment is complete, the trim segment must use the thruster pairs of C1 and C4 or C2 and C3 and last at least 61 s, which serves to keep the propellant settled after the large thrust from the LVA is removed. The sequence as a whole reduces the chance of gas ingestion during the maneuver and the trapping of liquid on tank baffles, thereby maximizing the amount of propellant and oxidizer available for future maneuvers.

Table 2. Nominal Post-MOI LVA Maneuver Sequence.

Segment Order	Segment Type	Thruster(s)	Minimum Duration (s)	Propellant Source
1	Settle	A1, A2, B1, B2	60	Auxiliary Tank
2	Refill	C1 and C4 or C2 and C3	23	Main Tanks
3	Main	LVA	12	Main Tanks
4	Trim	C1 and C4 or C2 and C3	61	Main Tanks

Smaller velocity changes were required for the even-numbered OCMs of the primary mission, sufficiently small that using the LVA for ΔV while adhering to the minimum LVA duration of 12 s would not be possible or would require an inefficient burn attitude that would negate any LVA efficiency gains. In addition, if operating the LVA is deemed too risky or the oxidizer tank has been depleted, the ΔV can be achieved with the monopropellant 22-N thrusters, albeit less efficiently. Therefore, the low-gravity fluid dynamics analyses performed prior to the orbit phase also produced post-MOI MPS operational guidelines for Mode-2 maneuvers; a nominal sequence including a final trim segment and a sequence with no trim. The nominal Mode-2 maneuver sequence is shown in Table 3. The settle segment in Table 3 is the same as the Mode-3 settle segment in Table 2 and settles the propellant in the main fuel tanks by firing the specified 4-N thrusters in blow-down mode using the auxiliary tank as the source tank. Additionally, the main segment is almost identical to the Mode-3 refill segment in Table 2, except that a longer main-segment duration of 35 s is required. The G&C software recognizes the settle and main segments of the Mode-2 maneuver sequence in Table 3 under the same names, but the trim segment, which must last at least 50 s, is implemented through a mid-maneuver parameter block load.

Table 3. Nominal Post-MOI Mode-2 Maneuver Sequence with Main Fuel Tank Fill Fraction Greater than the Minimum-per-Tank Fuel Load Limit.

Segment Order	Segment Type	Thruster(s)	Minimum Duration (s)	Propellant Source
1	Settle	A1, A2, B1, B2	60	Auxiliary Tank
2	Main	C1 and C4 or C2 and C3	35	Main Tanks

3	Trim	A1, A2, B1, B2	50	Main Tanks

Under the post-MOI MPS operational guidelines, Mode-2 maneuvers can also be executed without a trim segment, but only if the main segment has duration of at least 67 s. This requirement means that the desired ΔV has to be sufficiently large to require the firing of two 22-N thrusters for at least 67 s. The post-MOI no-trim maneuver sequence with the main fuel tank fill fraction greater than the minimum-per-tank fuel load limit is shown in Table 4.

Table 4. Post-MOI No-trim Mode-2 Maneuver Sequence with Main Fuel Tank Fill Fraction Greater than the Minimum-per-Tank Fuel Load Limit.

Segment Order	Segment Type	Thruster(s)	Minimum Duration (s)	Propellant Source
1	Settle	A1, A2, B1, B2	60	Auxiliary Tank
2	Main	C1 and C4 or C2 and C3	67	Main Tanks

During the primary orbital mission, OCM-1 and OCM-3 were performed as Mode-3 (LVA) maneuvers, and OCM-2, OCM-4, and OCM-5 were performed as Mode-2 maneuvers. The odd-numbered OCMs were performed at apoapsis to lower periapsis altitude, whereas the even-numbered OCMs were performed at periapsis to adjust the orbital period to 12 hours. A secondary consequence of lowering periapsis altitude is a reduction in the 12-hr orbital period. OCM-1 was executed 89 days (approximately one Mercury year) after MOI, and subsequent OCMs were performed 44 days apart. The design cycle for each OCM began approximately 5 weeks before maneuver execution, which allowed two iterations of the maneuver design: a preliminary ΔV target and a final ΔV target based on updated navigation tracking data. For each OCM, both a nominal maneuver sequence and a no-burn contingency sequence were designed. No-burn contingency sequences were planned to execute approximately 24 hours after a no-burn (zero ΔV imparted) at the primary maneuver opportunity and targeted the same orbital change as the nominal maneuver sequence. The time between the prime and contingency maneuver opportunities equates to two orbits about Mercury, which would allow the operations teams to assess spacecraft health and safety prior to activating a no-burn contingency sequence. All of the OCMs were performed closed-loop, meaning that accelerometer data were used in real-time to determine the maneuver cut-off as well as to adjust the commanded attitude to reduce ΔV errors.

OCM-1

After the nominal execution of MOI, both main fuel tank fill fractions were well above the minimum-per-tank fuel load limit prior to the first planned OCM. Therefore, for the first OCM the nominal sequence (OCM-1) followed the nominal post-MOI LVA maneuver sequence in Table 2, and the no-burn contingency sequence (OCM-1C1) followed the nominal post-MOI no-trim Mode-2 sequence in Table 4. OCM-1C1 was designed as a Mode-2 maneuver under the assumption that if the OCM-1 sequence failed to pass initiation checks related to tank pressures and/or LVA health, then another attempt to operate the LVA 24 hours later presented unacceptable risk. In particular, a Mode-3 OCM-1C1 would be the first post-MOI LVA use, and the maneuver would be executed after only one Mercury year of thermal environment characterization and a mere 24 hours after failure to initiate OCM-1. Additionally, the desired OCM-1C1 ΔV could be adequately achieved without the use of the LVA. Simultaneously designing two maneuver sequences of different modes increased workloads since the two sequences did not have many similarities, but the choice markedly reduced mission risk.

Although the OCM-1C1 sequence was prepared, its activation was not necessary since OCM-1 was successfully executed on 15 June 2011, imparting a total ΔV of 27.87 m/s, which lowered periapsis altitude from 505.27 km to 200.61 km (610 m above target) and decreased orbital period from 12:04:15 to 11:48:02. The G&C system performed exceptionally well, resulting in a ΔV magnitude error of –0.0058% and a ΔV pointing error of 0.0258°, both of which are within the expected errors for a Mode-3 maneuver.

The OCM-1 sequence was a single-component, fixed-direction, Mode-3, and closed-loop burn and used the segment durations, fuel tank switching scheme, and thruster selections outlined in Table 5.

Table 5. OCM-1 Sequence. Attitude Control Thrusters are On-Pulsed as Needed.

Maneuver Segment	Designed Duration (s)	Achieved Duration (s)	ΔV Thrusters	Attitude Control Thrusters	Fuel Tanks
Settle	60	60	A1, A2, B1, B2 (continuous)	A3, A4, B3, B4, C2, C3	Auxiliary Tank
Refill	23	23	C1, C4 (off-pulse)	A3, A4, B3, B4, C2, C3	Fuel Tank 1
Main	15	15	LVA (continuous)	A1, A2, B1, B2, C1-4	Balance portion (12 s) with FT2, then alternation every 20 s
Trim	74	75.6	C1, C4 (off-pulse)	A1, A2, B1, B2, C2, C3	Continue to alternate on 20-s centers
Tweak	30	30	None	A1-4, B1-4	Auxiliary Tank

The post-MOI LVA maneuver sequence in Table 2 presents implementation issues for Mode-3 maneuvers, since the settle and refill segments use different thruster sets for ΔV. The G&C software provides two different thruster sets for ΔV in the settle and refill segments, one set for the settle segment and one set for the refill segment, but only one set for attitude control during both segments. In past maneuvers, the settle segment has always been performed using the A1, A2, B1, and B2 thrusters for ΔV, but a refill segment using the C1 and C4 thrusters for ΔV was a first use at OCM-1. If using the post-MOI LVA maneuver sequence guidelines and the G&C software "as designed," one set of thrusters must be capable of controlling both the A1, A2, B1, and B2 thrusters, and, the C1 and C4 thrusters. To control all of the aforementioned thrusters with the G&C software "as designed," the following thrusters must be available for both the settle and refill segments: A3, A4, B3, B4, C2, and C3. Having only one set of thrusters for both the settle and refill segments presents two issues. First, if a 22-N C-thruster were to fire to control attitude during the settle segment, which uses 4-N A/B thrusters for ΔV, an undesirable attitude transient would result. But, since the control law should never fire a thruster unless it helps improve attitude errors, the control law will correctly favor the A/B thrusters over the C thrusters during this time for attitude control (the A/B thrusters have control deadbands that are ~5 times smaller than for the C thrusters). The second issue in using the same thruster set is that during the refill segment the A3, A4, B3, and B4 thrusters will oppose the desired ΔV direction when they are used for attitude control. This opposition introduces a minor inefficiency in the maneuver execution, but since the refill segment is short and since the principal attitude control will come from C2 and C3 during this time, this issue is not major. To eliminate these two issues, an alternate approach is a mid-maneuver parameter load; set the attitude control thrusters for the settle segment to be A3, A4, B3, and B4 before the start of the maneuver, and then at the start of the refill segment, set the attitude control thrusters to be A1, A2, B1, B2, C2, and C3. The mid-maneuver parameter load was considered but ultimately not implemented for OCM-1, on the basis of the very unlikely chance that a C thruster would fire during the settle segment and only minor inefficiencies would result from the inclusion of A3, A4, B3, and B4 in the attitude control thruster set for the refill segment.

As shown by the "designed duration" and "achieved duration" columns in Table 5, the OCM-1 segment durations met the post-MOI LVA maneuver sequence requirements set forth in Table 2. Additionally, the achieved durations indicate accurate modeling of propulsion system pressures prior to and during the burn. Accurate propulsion system modeling is evidenced by the durations achieved for main and trim segments. In particular, the LVA portion of the maneuver transitioned into the trim segment after 15 s, as expected, and the trim segment lasted only 1.6 s longer than the expected duration.

At the start of OCM-1, the main fuel tank fill levels were within 0.2 kg of each other, with main fuel tank 1 (FT1) having the most hydrazine at a mass of 23.56 kg, and the oxidizer tank contained 7.73 kg of

NTO. To keep a constant center of mass throughout the maneuver and end the maneuver with balanced main fuel tanks, the auxiliary tank was refilled from FT1 during the refill segment, and during the first 12 s of the main segment hydrazine was drawn from main fuel tank 2 (FT2) in order to balance the tanks following the auxiliary tank refill. The beginning portion of a Mode-3 main segment in which a specific fuel tank is specified to feed hydrazine to the LVA for a set duration is referred to as the "balance" portion of the main segment and is controlled by settable Mode-3 parameters. After completion of the balance portion of the main segment, fuel tank alternations began, switching between main fuel tanks every 20 s. The maneuver consumed a total mass of 6.23 kg (4.71 kg hydrazine and 1.52 kg NTO). The tank-switching scheme kept a nearly constant center of mass throughout the maneuver, left the main fuel tank levels within 0.12 kg of each other at the end of the maneuver, and left the main fuel tank fill fractions well above the minimum-per-tank fuel load limit.

OCM-2

For the first orbit-correction maneuver to adjust the orbital period back to 12 hours, the nominal sequence (OCM-2) and no-burn contingency sequence (OCM-2C1) followed the post-MOI Mode-2 maneuver sequence guidelines in Table 3, which include a trim segment as well as minimum segment durations. The G&C software "as designed" does not provide a trim segment for Mode-2 maneuvers, so to end the main segment after a desired duration and force a trim segment, mid-maneuver parameter loads must be used. Prior to OCM-2, re-loading parameters mid-maneuver to force a Mode-2 trim segment had never before been implemented.

The mechanism for forcing a Mode-2 trim segment is the re-loading of the two parameter blocks that define the thrusters to be used for each segment of the burn: the CLUST parameter block, which defines the attitude control thrusters, and the DVG0 parameter block, which defines the ΔV thrusters. Prior to the start of the maneuver these blocks are loaded with values that specify the thruster selections for the Mode-2 segments that are recognized by the G&C software: settle, main, and tweak. To force a trim segment, at some time after the start of the main segment the values within CLUST and DVG0 that specify the main segment thruster selections are modified to reflect the trim segment thruster selections. Then, 1 s before the desired trim segment start time within the G&C-software-recognized main burn, the modified CLUST and DVG0 parameter blocks are loaded, and the trim segment begins 1 s later (this process is handled by the 1 Hz G&C software task). At this point, the G&C software still considers the maneuver progression to be within the main segment, but the trim segment thruster selections are now being used. Hereafter, the portion of the main segment that is using trim segment thruster selections in a Mode-2 maneuver will be referred to as the trim segment.

The execution of OCM-2 contained some operational surprises, which will be discussed below, but ultimately the maneuver was successfully executed. OCM-2, completed on 26 July 2011, imparted a total ΔV of 4.08 m/s, which increased the orbital period from 11:48:02 to 12:00:01 (1 s above target) and decreased periapsis altitude by only 30 m (periapsis altitude was to be effectively unchanged). The G&C system performed well, resulting in a ΔV magnitude error of 0.0452% and a ΔV pointing error of 0.6766°, both of which are within the expected errors for a Mode-2 maneuver. The OCM-2 sequence was a single component, fixed-direction, Mode-2, and closed-loop burn and used the segment durations, fuel tank switching scheme, and thruster selections outlined in Table 6.

Table 6. OCM-2 Sequence. Attitude Control Thrusters are On-Pulsed as Needed.

Maneuver Segment	Designed Duration (s)	Achieved Duration (s)	ΔV Thrusters	Attitude Control Thrusters	Fuel Tanks
Settle	60	60	A1, A2, B1, B2 (continuous)	A3, A4, B3, B4	Auxiliary Tank
Main	34	32	C1, C4 (off-pulse)	A1-4, B1-4	Balance portion (15 s) with FT2, then alternation every 20 s

Trim	63	95.54	A1, A2, B1, B2 (continuous)	A3, A4, B3, B4	Continue to alternate on 20-s centers
Tweak	30	30	None	A1-4, B1-4	Auxiliary Tank

Although the maneuver imparted the desired ΔV, the achieved durations for the main and trim segments were off nominal. First, it should be noted that the main segment designed duration of 34 s is 1 s below the minimum main segment duration in Table 3. Monte Carlo simulations that were performed using the most up-to-date prediction of propulsion system pressures showed that for a main segment with a duration of 35 s, the worst-case trim segment duration would be 33 s, well below the minimum trim segment duration of 50 s in Table 3, whereas for a main segment with a duration of 34 s, the worst-case trim duration would be 58 s. Therefore, the final maneuver design used a 34-s duration main segment, with the assumption that executing the main segment 1 s short of the minimum main segment duration would be less adverse than executing the trim segment 17 s short of the minimum trim segment duration. As seen in Table 6, however, the achieved main segment was even shorter, 2 s short of the desired duration, which increased the trim segment duration above the desired duration by almost 33 s. In fact, the maneuver completed less than 3 s before it would have been cut off by the on-board timer. At fault for the shorter-than-expected main segment is an inexplicable 2-s delay in Mode-2 maneuvers, in combination with the mechanism used to force a Mode-2 trim segment. The precise cause for the 2-s delay has not yet been ascertained.

The 2-s delay was discovered during a review of the final OCM-2 sequence hardware simulations. The delay is from the time that the “do burn” command is sent to the time that the propulsion state changes to “settle” and the fire delay begins (before any thruster firings begin there is always a 10-s fire delay). The sequence was designed as if there were no delay after the “do burn” command, as seen in Mode-3 maneuver flight telemetry (the “do burn” command is handled by the 50 Hz G&C software task). When the G&C software is used “as designed” the segment transitions occur relative to the “do burn” command, not at an absolute time. Therefore, if a Mode-2 trim segment is forced by parameter loads that are not tied to the “do burn” command, but to an absolute time, and there are delays in the system that are not fully incorporated, then when the modified parameters blocks take effect they will be relative to the incorrect time. For instance, in the final OCM-2 sequence, the modified CLUST and DVG0 blocks were sequenced so that they would take effect 104 s after the “do burn” command was sent, the 104 s coming from a sum of the 10-s fire delay that begins at the “do burn” command, a settle segment duration of 60 s, and a main segment duration of 34 s. But in the hardware simulation of the final OCM-2 sequence, instead of a main segment duration of 34 s, the main segment had a duration of 32 s because the first thruster firings occurred 2 s later than anticipated. All of the relative timing was maintained, but the re-load of CLUST and DVG0 occurred at the same absolute time.

When the 2-s delay was discovered, and simple sequencing fixes to eliminate it were proven ineffective, it was already late in the planning process, leaving only 1–2 days to build and upload a new maneuver sequence. Therefore, Monte Carlo simulations were run to determine if a 32-s main burn would result in a significant underburn, which would prompt a last-minute sequence re-build. But, in the majority of cases (which also happened to be the cases with the most realistic initial conditions and parameter variations), even if the main segment were cut off 2 s early, the maneuver would still achieve the desired ΔV prior to being terminated by the maneuver duration timer. This decision proved to be prudent, as OCM-2 successfully altered the spacecraft’s orbital trajectory without the need for a cleanup maneuver. Additionally, since the segment durations in the post-MOI MPS operational guidelines in Tables 2–4 contain some conservatism, it can be reasonably assured that executing the main segment for 3 s less than what the guidelines dictate did not markedly increase the amount of unusable propellant in the system.

At the start of OCM-2, the main fuel tank levels were within 0.12 kg of each other, with FT2 having the most propellant at a mass of 20.92 kg. The balance portion of the main segment lasted 15 s, during which FT2 was used to draw hydrazine to the thrusters and to refill the auxiliary tank. Next, fuel tank alternations began, switching between main fuel tanks every 20 s. The maneuver consumed a total mass of 1.92 kg, all of which was hydrazine. The tank-switching scheme kept a nearly constant center of mass throughout the maneuver, left the main fuel tank levels within 0.44 kg of each other at the end of the maneuver, and left the main fuel tank fill fractions well above the minimum-per-tank fuel load limit.

OCM-3

The third orbit-correction maneuver (OCM-3), which was the second maneuver to lower periapsis altitude back to 200 km, was very similar to OCM-1, including the similarity of using the LVA to achieve the majority of the ΔV. Aside from the ΔV target and the start time of the maneuver, the only notable differences between the OCM-1 and OCM-3 maneuver designs were the duration of the main segment, the duration of the trim segment, and the fuel tank switching scheme, as outlined in Table 7. Both were single-component, fixed-direction, Mode-3, and closed-loop burns. OCM-3, successfully executed on 7 September 2011, imparted a total ΔV of 24.95 m/s, which lowered periapsis altitude from 470.23 km to 200.55 km (550 m above target) and decreased the orbital period from 12:00:01 to 11:45:41. The G&C system performed exceptionally well, resulting in a ΔV magnitude error of –0.0357% and a ΔV pointing error of 0.0132°, both of which are within the expected errors for a Mode-3 maneuver.

Table 7. OCM-3 Sequence. Attitude Control Thrusters are On-Pulsed as Needed.

Maneuver Segment	Designed Duration (s)	Achieved Duration (s)	ΔV Thrusters	Attitude Control Thrusters	Fuel Tanks
Settle	60	60	A1, A2, B1, B2 (continuous)	A3, A4, B3, B4, C2, C3	Auxiliary Tank
Refill	23	23	C1, C4 (off-pulse)	A3, A4, B3, B4, C2, C3	Fuel Tank 1
Main	12	13	LVA (continuous)	A1, A2, B1, B2, C1-4	Balance portion (5 s) with FT1, then alternation every 20 s
Trim	76.8	69.5	C1, C4 (off-pulse)	A1, A2, B1, B2, C2, C3	Continue to alternate on 20-s centers
Tweak	30	30	None	A1-4, B1-4	Auxiliary Tank

As evidenced by the achieved durations for the main and trim segments, the observed effective thrust of the LVA during the main burn was a bit lower than expected. More specifically, the G&C software fired the LVA for 1 s longer than the designed main segment duration because the additional firing time was required to meet the ΔV threshold that would initiate transition to the trim segment. The increased main segment duration decreased the amount of ΔV required of the C1 and C4 thrusters during the trim segment to achieve the total ΔV, which in turn reduced the trim segment duration. High-rate (100-Hz) accelerometer data were recorded during the execution of OCM-3 and were used to reconstruct the spacecraft accelerations during the maneuver. The maneuver reconstruction shows an approximately 75-N reduction in effective thrust about 5 s into the firing of the LVA from the steady-state value of about 700 N. The thrust quickly returned to steady state after about 1.5 s. Before OCM-3, the oxidizer tank contained 6.21 kg of NTO, 4.06 kg of which could possibility be unusable (trapped on tank baffles), and the maneuver consumed 1.32 kg of NTO. It cannot be fully demonstrated, but it is most likely that the temporary drop in thrust was due to gas ingestion originating from the oxidizer tank. Since the decrease in thrust was short, the gas ingestion could either be from an oxidizer droplet falling from the tank baffles and impacting the fluid pool at the tank outlet, or from temporary exposure of the tank outlet due to propellant sloshing. OCM-3 was executed nominally even with possible gas ingestion, but since the chances of more severe gas ingestion increase as the oxidizer tank continues to be depleted, any additional use of the LVA after OCM-3 deserves increased scrutiny, and the chance of gas ingestion must be considered in the design of the maneuver.

At the start of OCM-3, the main fuel tank levels were within 0.44 kg of each other; FT1 had the most propellant at a mass of 20.07 kg. Since FT1 had a higher fill fraction than FT2, the auxiliary tank was refilled from FT1 during the refill segment. In addition, the balance portion of the main segment used FT1 and lasted 5 s. After completion of the balance portion of the main segment, fuel tank alternations began, switching between main fuel tanks every 20 s. The maneuver consumed a total mass of 5.65 kg, of which 4.33 kg was hydrazine and 1.32 kg was NTO. The tank-switching scheme kept a nearly constant center of mass throughout the maneuver, left the main fuel tank levels within 0.17 kg of each other at the end of the maneuver, and left the main fuel tank fill fractions above the minimum-per-tank fuel load limit.

OCM-4

The fourth orbit-correction maneuver (OCM-4), which was the second maneuver to adjust the orbital period back to 12 hours, was very similar to OCM-2. The designed burn segment durations and thruster selections were identical, as outlined in Table 8. Aside from the ΔV target, start time of the maneuver, and the fuel tank switching scheme, there was one major difference between the OCM-2 and OCM-4 sequences; in the OCM-4 sequence, the 2-s delay in Mode-2 maneuvers was incorporated in the re-load of CLUST and DVG0 to force a trim segment, which resulted in an achieved main segment duration of 34 s. OCM-4 was a single-component, fixed-direction, Mode-2, and closed-loop burn, which was successfully executed on 24 October 2011. OCM-4 imparted a total ΔV of 4.16 m/s, which increased the orbital period from 11:45:41 to 11:59:57 (3 s below target) and decreased the periapsis altitude by only 36 m (periapsis altitude was to be effectively unchanged). The G&C system performed well, resulting in a ΔV magnitude error of 0.0329% and a ΔV pointing error of 0.5461°, both of which are within the expected errors for a Mode-2 maneuver.

Table 8. OCM-4 Sequence. Attitude Control Thrusters are On-Pulsed as Needed.

Maneuver Segment	Designed Duration (s)	Achieved Duration (s)	ΔV Thrusters	Attitude Control Thrusters	Fuel Tanks
Settle	60	60	A1, A2, B1, B2 (continuous)	A3, A4, B3, B4	Auxiliary Tank
Main	34	34	C1, C4 (off-pulse)	A1-4, B1-4	Balance portion (5 s) with FT1, then alternation every 20 s
Trim	63	65.30	A1, A2, B1, B2 (continuous)	A3, A4, B3, B4	Continue to alternate on 20-s centers
Tweak	30	30	None	A1-4, B1-4	Auxiliary Tank

As shown by the designed duration and achieved duration columns in Table 8, the OCM-4 segment durations met all of the post-MOI Mode-2 burn sequence guidelines in Table 3, except for the main segment duration. Similarly to OCM-2, analyses showed that a main segment of duration 34 s would guarantee that the minimum trim segment duration in Table 3 would be met, but a main segment of duration 35 s could result in a trim segment duration much more than 1 s short of the allowable minimum trim segment duration.

At the start of OCM-4, the main fuel tank levels were within 0.17 kg of each other; FT1 had the most hydrazine at a mass of 17.84 kg. The balance portion of the main segment lasted 5 s, during which FT1 was used to draw hydrazine to the thrusters and to refill the auxiliary tank. Next, fuel tank alternations began, switching between main fuel tanks every 20 s. The maneuver consumed a total mass of 1.80 kg, all of which was hydrazine. The tank-switching scheme kept a nearly constant center of mass throughout the maneuver, left the main fuel tank fill fractions above the minimum-per-tank fuel load limit, but left the main fuel tank levels within 0.97 kg of each other at the end of the maneuver. The larger than expected discrepancy between final main tank fill fractions was due to the autonomous activation of a secondary tank heater just prior to the maneuver, an action that increased the pressure in FT2 about 68.95-kPa (10-psi) higher than the expected value. A longer balance time would have reduced the final main tank fill fraction discrepancy.

OCM-5

The fifth orbit-correction maneuver (OCM-5), which was the third maneuver to lower periapsis altitude back to 200 km, was the final maneuver included in MESSENGER's primary mission OCM plan (OCM-6, currently scheduled for 3 March 2012, is within the year-long primary mission but would not be included in the operational plan without an extended mission, which will begin on 18 March 2012). The primary mission OCMs that were used to lower periapsis altitude required higher ΔV than those that adjusted orbital period. Due to the higher required ΔV, the odd-numbered OCMs were planned to be Mode-3 maneuvers.

Thus, OCM-5 was originally planned to be a Mode-3 maneuver. But, because of the apparent gas ingestion from the oxidizer tank during OCM-3, if OCM-5 were to be executed as a Mode-3 maneuver there would be an increased chance of gas ingestion, and thus erratic LVA behavior, during the maneuver. Therefore, it was decided to execute OCM-5 as a Mode-2 maneuver to assure the lowest possible risk for the completion of the primary mission. In addition, deferring final use of the LVA to a maneuver within the extended mission allows for additional time to design a maneuver sequence that will be robust to the possibility of complete oxidizer depletion during the maneuver.

Designing OCM-5 as a Mode-2 maneuver greatly simplified the maneuver design since the ΔV target was sufficiently large to permit use of the post-MOI no-trim Mode-2 maneuver sequence guidelines in Table 4. In addition, fuel tank switching was not implemented in the OCM-5 sequence, which further simplified the design. At the start of OCM-5, the main fuel tanks had 17.20 kg and 16.23 kg of hydrazine, respectively, the pressure in FT2 was about 27.58-kPa (4-psi) higher than in FT1, and the maneuver was predicted to consume about 6 kg of hydrazine. Taking the main fuel tank masses and the expected mass decrement into account, it was decided to draw hydrazine to the thrusters and to refill the auxiliary tank during the main segment entirely from FT1. If tank switching were to occur, the large pressure difference between the main fuel tanks would have increased the chance of fuel transfer between the tanks, an undesirable outcome since fuel transfer between tanks is not easily modeled and considerable effort is devoted to tracking the amount of usable propellant in the system. In addition, OCM-5 presented an opportunity to bring FT1 to just above the minimum-per-tank fuel load limit (8 kg of usable hydrazine), while testing the ability to perform managed tank depletion (and thus demonstrate nominal maneuver performance and attitude control with up to 5 kg of mass discrepancy between the main fuel tanks).

OCM-5 was a single-component, fixed-direction, Mode-2, and closed-loop burn that used the segment durations, thrusters, and fuel tanks outlined in Table 9. The maneuver was successfully executed on 5 December 2011, imparting a total ΔV of 22.22 m/s, which lowered periapsis altitude from 441.38 km to 200.43 km (430 m above target) and decreased the orbital period from 11:59:57 to 11:47:10. The G&C system performed exceptionally well, resulting in a ΔV magnitude error of 0.039% and a ΔV pointing error of 0.028°, both of which are well within the expected errors for a Mode-2 maneuver.

OCM-5 consumed a total mass of 6.06 kg, all of which was hydrazine. The final masses at the end of OCM-5, including the current estimate of masses considered to be usable (not trapped on baffles), are shown in Table 10. Since a major consideration in the design of future maneuvers will be the most efficient utilization of the ΔV capability remaining on the spacecraft, the OCM-5 mass end states will have an important influence on the design of all future maneuver sequences.

Table 9. OCM-5 Sequence. Attitude Control Thrusters are On-Pulsed as Needed.

Maneuver Segment	Designed Duration (s)	Achieved Duration (s)	ΔV Thrusters	Attitude Control Thrusters	Fuel Tanks
Settle	60	60	A1, A2, B1, B2 (continuous)	A3, A4, B3, B4	Auxiliary Tank
Main	226.8	231.22	C1, C4 (off-pulse)	A1-4, B1-4	Fuel Tank 1
Tweak	30	30	None	A1-4, B1-4	Auxiliary Tank

Table 10. OCM-5 Mass Tracking Summary.

	Auxiliary Tank (kg)	Fuel Tank 1 (kg)	Fuel Tank 2 (kg)	Oxidizer Tank (kg)
OCM-5 Starting Mass	10.54	17.20	16.23	4.89
Mass Added/Consumed for OCM-5	−0.13	−5.93	0.00	0.00
Ending Mass	10.41	11.27	16.23	4.89

Unusable Propellant Estimate	−0.93	−2.46	−2.46	−4.06
Usable Mass	9.48	8.81	13.77	0.83

CONCLUSIONS

The MOI maneuver was near perfectly executed as a result of careful planning, extensive simulation, and the MESSENGER team's rich experience in operating the spacecraft. The carefully designed MOI-unique fault management schema sharply reduced mission risk, ensuring the best chance of spacecraft insertion into orbit about Mercury. Once MESSENGER was in orbit about Mercury, the G&C system exhibited flexibility in its ability to successfully execute all five OCMs of the primary mission despite a need for operational strategies unforeseen at the time the software was designed. Thus far, the team's experience and the spacecraft's flexibility have allowed science data collection to continue uninterrupted since shortly after MOI. The successful execution of MOI and the primary mission OCMs has left the MESSENGER mission with sufficient ΔV capability to continue making science observations of the innermost planet well past the end of the primary mission on 18 March 2012.

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