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THE FIRST THREE MANEUVERS DURING MESSENGER'S LOW-ALTITUDE SCIENCE CAMPAIGN

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Periapsis-raising orbit-correction maneuvers (OCMs) are required during the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft's second extended mission (XM2) to delay Mercury surface impact and to maximize the time that the spacecraft spends at altitudes as low as 15 km. The first OCM of XM2 was implemented to ensure that fuel remaining in main fuel tank 2 (FT2) would be accessible in the future. The second OCM depleted the fuel remaining in FT2 and demonstrated the use of helium gas pressurant as a propellant. A specialized autonomy scheme was developed to detect and respond to prolonged gas ingestion. Performance of the first three OCMs facilitated an extension of MESSENGER operations several weeks past the projected XM2 surface impact date of 28 March 2015. The ability to impart velocity change (ΔV) using pressurization gas has increased the mission's ΔV capability.

INTRODUCTION

As part of NASA's Discovery Program, the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft became the first probe to orbit the planet Mercury on 18 March 2011 UTC. During a primary orbital phase of one Earth year, MESSENGER performed the first complete reconnaissance of the geochemistry, geophysics, geologic history, atmosphere, magnetosphere, and plasma environment of the solar system's innermost planet. Six orbit-correction maneuvers (OCMs) were performed during the primary mission to keep the periapsis near 200-km altitude and the orbital period near 12 hours.[1,2] MESSENGER's first extended mission began on 18 March 2012 and included two OCMs that reduced the orbital period from 11.6 to 8 hours to allow for more observing time at low altitudes.[3] The pair of OCMs in April 2012 was designed to maximize use of the bipropellant propulsion system by depleting the usable oxidizer at the first OCM and completing the orbital period adjustment using only monopropellant thrusters at the second OCM.[4]

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Successful execution of the April 2012 OCMs guaranteed a remaining velocity change (ΔV) capability that could postpone Mercury surface impact until at least March 2015. A second extended mission (XM2) began on 18 March 2013 to take advantage of the substantial opportunity for additional scientific observation of Mercury. Without periapsis-raising maneuvers during XM2, solar gravity perturbations would continually reduce the periapsis altitude, leading to Mercury surface impact in August 2014. Therefore, a series of OCMs was planned as part of XM2 serving to delay Mercury surface impact while also providing opportunities for low-altitude flyover observations as low as 15 km above Mercury's surface.[5] The first two OCMs of XM2 (OCM-9 and OCM-10) were designed to continue to maximize use of the MESSENGER propulsion system (MPS) by following specialized operational guidelines. Additional OCMs are using the remaining propellant allotted for ΔV to extend mission lifetime. Propellant margin is required through the end of mission so that angular momentum can be managed by performing regular momentum-offloading maneuvers.

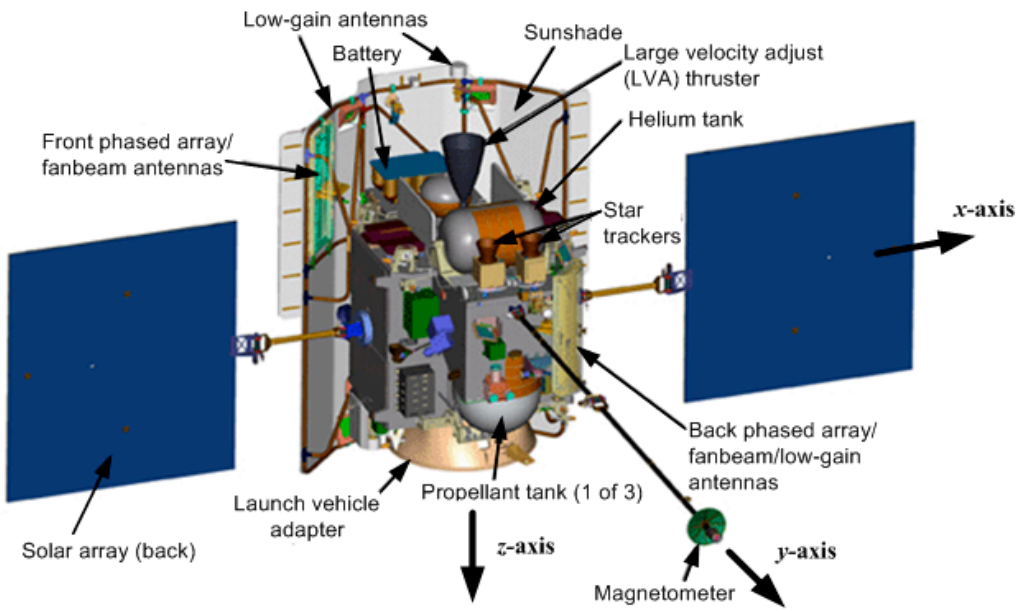

Figure 1. MESSENGER Spacecraft Components and Body-Axis Convention.

The MESSENGER spacecraft is three-axis stabilized and uses reaction wheels as the primary means of maintaining attitude control.[6] In addition, the actuator suite includes thrusters, which are used for angular momentum management and trajectory control and can also be used as a backup for attitude control in the event of multiple wheel failures. The sensor suite is composed 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 conditions close to the Sun. The guidance and control (G&C) software ensures that the sunshade sufficiently shields the spacecraft and science instruments from the Sun by allowing only small deviations from direct Sun pointing in rotations about the x- and z-axes (see Figure 1 for the definition of spacecraft body axes and locations of selected spacecraft components). This constraint translates to aligning the $-y$-axis with the Sun line.

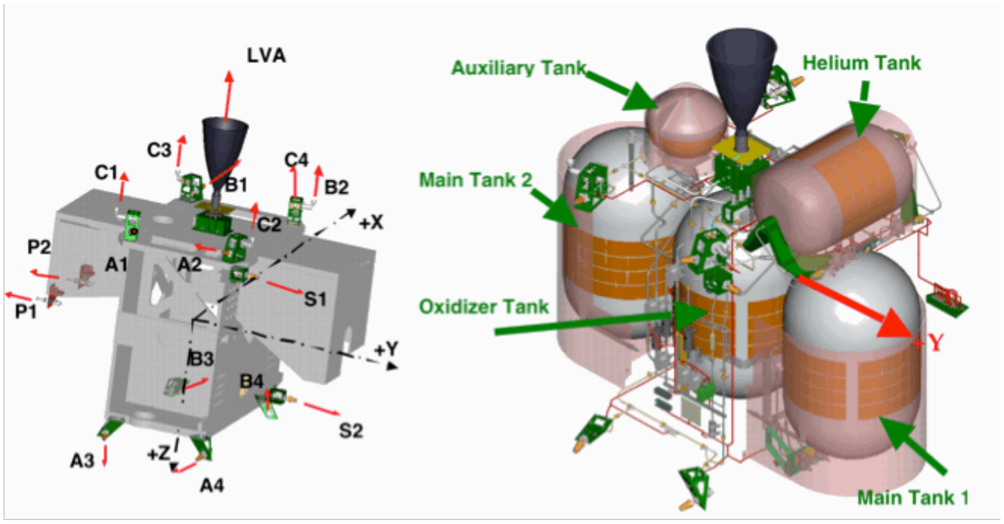

Figure 2. MESSENGER Propulsion System (MPS) Thruster Locations, Thruster Directions, and Tank Layout.

The MPS, shown in Figure 2, was designed and built by Aerojet and consists of four propellant tanks and 17 thrusters.[7] The MPS includes one bipropellant engine, which provided ~680 N of thrust at the final bipropellant maneuver in April 2012, and two sets of monopropellant thrusters, including 12 4.4-N thrusters (thrusters A1–A4, B1–B4, S1–S2, P1–P2) and four 22-N thrusters (thrusters C1–C4). The two main fuel tanks and oxidizer tanks are pressure regulated by a helium pressurization system and contain two ring baffles each but do not have diaphragms. The fourth tank, the auxiliary tank, contains a diaphragm but is not pressure regulated. To date the MPS has been used to execute successfully a total of eleven OCMs, with eight (notionally) remaining before the end of the mission. The oxidizer tank and main fuel tank 1 (FT1) were depleted during the April 2012 OCMs. The first two OCMs of XM2 were designed with a complex set of MPS operational guidelines in mind. At very low fill fractions care is needed when operating the system since no propellant management devices were incorporated in either the fuel or oxidizer tanks to save mass. The MPS operational guidelines used throughout the primary and extended missions are designed to minimize the amount of propellant trapped on the tank baffles and the chance of gas ingestion.[8]

Table 1. MPS Operational Guidelines for Main Fuel Tank Masses Below the Minimum Per Tank Fuel Load Limit of 7.35 kg.

Segment Order	Segment Type	Thrusters	Minimum Duration (s)	Propellant Source
1	Settle	A1, A2, B1, B2	60	Auxiliary Tank
2	Main	C1 and C4 or C2 and C3	35	First 40 s: Auxiliary Tank After 40 s: Main Tanks
3	Trim	A1, A2, B1, B2	50	If Main Burn < 40 s: Auxiliary Tank If Main Burn > 40 s: Main Tanks

OCM-9 DESIGN AND RESULTS

OCM-9 was a monopropellant periapsis-raising maneuver that was executed successfully on 17 June 2014 to target a 25-km periapsis altitude on 13 September 2014. Although OCM-9 was performed using fuel only from the auxiliary tank (which contains a propellant management device), a specialized set of MPS operational guidelines, shown in Table 1, was used so that fuel in main fuel tank 2 (FT2) could be accessed at a later time. The fuel in FT1 was exhausted at OCM-8; ~0.576 kg remains, and none of that total is considered usable. A specialized set of MPS operational guidelines was required for the OCM-9 design because the FT2 mass at the time of the maneuver was estimated to be 5.2 kg; main fuel tank masses of <7.35 kg are considered low fill-fractions. The settle segment is designed to draw as much liquid as possible below the main fuel tank baffles and into a pool at the tank outlets. The settle segment minimum duration of 60 s is recommended on the basis of the lower thrust provided by the A- and B-thrusters (4.4-N nominally) and their 15° cant angle. The main segment provides the majority of ΔV, can use only two of the C-thrusters, and must last for at least 35 s to ensure that a propellant geyser will not form after C-thruster shutdown that would deposit liquid above the tank baffles. The trim segment provides a "soft landing" for the geyser so that the change in acceleration caused by the two C-thrusters shutting off would not cause the geyser to rise above the bottom baffle. The tweak segment, which is not included in Table 1, is the final segment of all MESSENGER maneuvers. The tweak 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 before returning control to the reaction wheels.

Table 2. OCM-9 Maneuver Sequence. Attitude Control Thrusters Are 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	54	54	C1, C4 (off-pulsed for control)	A1–A4, B1–B4	Auxiliary Tank
Trim	60.2	76	A1, A2, B1, B2 (continuous)	A3, A4, B3, B4	Auxiliary Tank
Tweak	30	30	None	A1–A4, B1–B4	Auxiliary Tank

OCM-9 was executed using the segment durations and thruster selections outlined in Table 2. A series of mid-burn parameter loads was used to force the settle and main segments to last precisely 60 s and 54 s, respectively, and to ensure that the trim segment would last at least 50 s. The thruster selections for ΔV and attitude control differentiated the three segments, because the entire maneuver used the auxiliary tank. An additional mid-burn parameter load was required 50 s into the trim segment to change from open-loop control to closed-loop control, thereby ensuring a minimum trim duration of 50 s. The decision to begin the maneuver in open-loop control and end in closed-loop control was based on the assumption that the starting fuel feed pressure to the thrusters could vary around the predicted starting pressure; the auxiliary tank is not pressure regulated and varies seasonally as it undergoes different thermal conditions. For instance, if the starting fuel feed pressure was higher than predicted, an increased percentage of total ΔV would be imparted during the main segment, reducing the amount of ΔV (and the duration of thruster firing) needed in the trim segment. Implementing the maneuver using this method increased the chances of an over-burn but was deemed an acceptable risk because the negative effects of an over-burn were weighted lower than mismanagement of the remaining propellant in the main fuel tanks. An over-burn of a periapsis-raising maneuver does not increase the chances of impacting the planet, and the science observation plans after OCM-9 were designed to be adaptable to a wide range of achieved periapsis altitudes.

Late in the OCM-9 design cycle, the predicted fuel feed pressure dropped to a level that would have required a longer trim segment to complete the desired ΔV. Because the trim segment uses the

A- and B-thrusters to impart ΔV, lengthening the duration would have consumed a substantial amount of additional propellant. A mission design analysis was performed to determine whether the range of expected under-burn percentages (if no change were made to the burn cutoff time) would have a substantial effect on the low-altitude target of 25-km periapsis altitude on 13 September 2014. The analysis indicated that the low-altitude target would vary by <1 km. No change was made to the sequence as a result of this analysis, because the low-altitude target difference was minimal and because lengthening the burn cutoff time would have substantially increased propellant consumption.

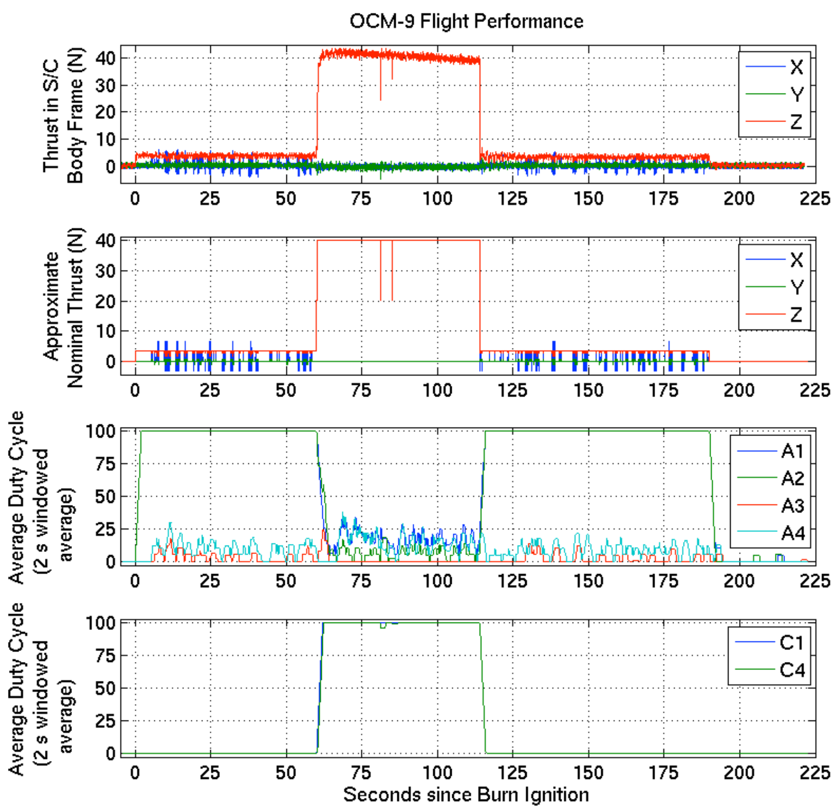

Figure 3. OCM-9 Flight Performance Showing Thrust in the Spacecraft (S/C) Body Frame, Approximate Nominal Thrust Assuming Constant Pressure and Thruster Duty Cycling, and Moving Averages of A- and C-Thruster Duty Cycles.

Flight Performance

In line with expected performance, OCM-9 imparted a total ΔV of 5.0299 m/s (1.63% under-burn, 0.36° pointing error), which raised the periapsis altitude to 155.04 km (552 m lower than the target value) and consumed ~1.87 kg of hydrazine. As expected, the maneuver was terminated by the burn timer 76 s into the trim segment, resulting in an under-burn. Thrust and thruster duty cycles during OCM-9 are shown in Figure 3. B-thruster duty-cycle values are not shown in Figure 3 because they can be inferred from the A-thruster duty cycles; when the A- and B-thrusters are used for ΔV, they are fired in a continuous fashion, and when used for attitude control, they fire in coupled pairs to reduce residual ΔV. The thruster duty cycles during the maneuver indicate a favorable center of mass position and a well-controlled maneuver. Imparted thrust in the spacecraft body frame was consistent throughout all segments; all variations in thrust levels can be attributed to decreasing fuel feed pressure during the maneuver (the auxiliary tank is not pressure regulated) and duty cycling of the thrusters for attitude control.

OCM-10 DESIGN AND RESULTS

OCM-10, executed on 12 September 2014, was designed to target a 25-km altitude on 24 October 2014. OCM-10 was originally scheduled for 13 September 2014 (a Saturday) but was moved one day earlier into the standard workweek. To delay Mercury surface impact to at least March 2015, the usable fuel in FT2 (estimated at 2.74 kg) was required to supply a substantial portion of the ΔV at OCM-10. The primary risk of pursuing fuel from FT2 was that pressurant (helium gas) could be ingested into the fuel manifold and that this pressurant would reach the thrusters and possibly the auxiliary tank. The probability of this outcome increases the longer FT2 is accessed. To minimize the risk of gas ingestion and to ensure successful execution of OCM-10, special onboard fault protection was used. In addition, the maneuver itself used a carefully selected G&C design.

Table 3. OCM-10 Maneuver Sequence. Attitude Control Thrusters Are Pulsed as Needed.

Maneuver Segment	Designed Duration (s)	Achieved Duration (s)	ΔV Thrusters	Attitude Control Thrusters	Fuel Tanks
Settle 1	60	59	A1, A2, B1, B2 (continuous)	A3, A4, B3, B4	Auxiliary Tank
Settle 2	36	36	C1, C4 (off-pulsed for control)	A1–A4, B1–B4	Auxiliary Tank
Main	30	30	C1–C4 (off-pulsed for control)	A1–A4, B1–B4	Fuel Tank 2
Trim (if necessary)	<49	9.1	C1–C4 (off-pulsed for control)	A1–A4, B1–B4	Auxiliary Tank
Tweak	30	30	None	A1–A4, B1–B4	Auxiliary Tank

OCM-10 was executed using the segment durations and thruster selections outlined in Table 3. The maneuver sequence follows the MPS operational guidelines shown in Table 1 with a few exceptions. During the design of OCM-10, it was assumed that OCM-10 would be the final maneuver to use either of the main fuel tanks. Therefore, after the second settle segment, all four C-thrusters could be used to provide ΔV more efficiently, and an inefficient trim segment using A- and B-thrusters only was unnecessary; both are departures from the MPS operational guidelines shown in Table 1. A series of mid-burn parameter loads was used to force the settle segments to last precisely 60 s and 36 s, respectively, and to change thruster selections. For the first settle segment, a 2-s burn ignition delay was seen in flight, although a 1-s burn ignition had been assumed for the command sequence. Fuel tank management was controlled via the command sequence such that FT2 would be open for no longer than 30 s. A main-segment duration of 30 s was the estimated maximum duration that fuel could be supplied to the four C-thrusters drawing fuel from FT2 given that 2.74 kg of usable fuel remained in FT2. If the ΔV target was not achieved after accessing FT2 for 30 s, the four C-thrusters would continue to be used but would draw fuel instead from the auxiliary tank for a maximum duration of 49 s.

Fault Protection

Gas ingestion will lead to a drop in thrust, which will have a transient effect on the attitude control. Cold-gas performance at the expected FT2 regulated pressure at OCM-10 was predicted to provide a substantial fraction (~40%) of the nominal thrust. This thrust level will make the attitude control response sluggish (because control torques will be reduced to 40% of typical values) but will not affect the stability or steady-state performance of the attitude controller. However, the thruster control law used for MESSENGER was designed to be robust to intermittent thrust degradation and failed thrusters. Once FT2 is closed, hydrazine will be supplied to the thrusters from the auxiliary tank, restoring the nominal thruster force and torque. Because the maneuver is designed to terminate with use of the auxiliary tank, any drop in thrust due to gas ingestion from FT2 is guaranteed to be a transient condition, and the nominal torque authority will be restored to the attitude control system. To ensure that OCM-10 would achieve the target ΔV despite a possible prolonged reduction in thrust, the maneuver relied on the accelerometers to determine the thruster cutoff time. If the target ΔV has not been achieved by the maneuver timeout, the maneuver would be cut off. A Monte Carlo analysis of off-nominal cases was performed to select the timeout parameter such that the G&C system could complete the maneuver despite a possibly lengthy thrust drop. Although cold-gas performance was predicted to provide 40% of the nominal thrust, a conservative value of 10% was used in the analyses. From the results of the Monte Carlo analysis, a burn cutoff time of 175 s was selected, which provided ~12% margin during segments that used all four C-thrusters for ΔV.

Two new autonomy rules were developed for OCM-10 to reduce the time that FT2 is open if hydrazine is no longer available and gas ingestion is detected. The first rule was designed to monitor the pressure in FT2 for a substantial pressure drop below the tank regulation point of 280 psi. Such a pressure drop would indicate that the manifold had been emptied of hydrazine because the flow rate of helium into the tank across the regulator into the fuel tank is much less than the expected outflow of helium to the four C-thrusters, which will be used during the FT2 segment (the main segment in Table 3). A second fault protection rule was designed to monitor all abort conditions from the G&C software. The principal abort condition of concern is the check that monitors the attitude error (both commanded and estimated). The response of both fault protection rules is to close FT2, shutting off the flow of gas and restoring hydrazine to the thrusters via the auxiliary tank. The first rule will allow the maneuver to continue uninterrupted despite gas ingestion. The second rule responds only if the G&C high-fidelity checks detect a condition that requires aborting the burn, and this rule will ensure that FT2 is closed to prevent the risk of pushing an appreciable amount of gas into the auxiliary tank. If G&C were to abort the burn due to gas ingestion, because the gas ingestion is detected indirectly via the attitude-error check, then an OCM-10 cleanup maneuver would be required to complete the desired trajectory change. A Monte Carlo analysis of gas-ingestion scenarios was performed to inform the choice of the attitude-error abort check limit. In addition, the analyses confirmed that the level of protection afforded by the onboard fault protection and G&C maneuver design was sufficient to reduce risk at OCM-10.

Table 4. OCM-10 Monte Carlo Scenarios.

Scenario Name	Description
Nominal	1-Hz profiles of expected thrust and specific impulse used in lieu of pressure-dependent thrust and specific impulse variation.
Cold-Gas Thrust	3 s into main segment (the FT2 segment), thrust drops to 10% of nominal thrust. Returns to 100% of nominal thrust 5 s after sequenced switch to auxiliary tank. Models FT2 hydrazine depletion 3 s into main segment and subsequent cold-gas thrust for remainder of main segment and transfer of helium gas to auxiliary tank.
Wide Pressure Variation	5% variation around expected tank pressures that are used to determine pressure-dependent thrust and specific impulse variation. Typical tank pressure variation is 2.5% around expected tank pressures.
Fuel Blob	At beginning of main segment (the FT2 segment), all thrusters except C3 and C4 reduce to 25% thrust. At sequenced switch to auxiliary tank, all thrusters return to 100% thrust. Models a "fuel blob" scenario in which only the C3 and C4 thrusters are supplied hydrazine while all other thrusters are operating on helium gas.

Monte Carlo Analysis

Four scenarios, described in Table 4, were considered to confirm that the fault protection scheme would be sufficient for ensuring attitude stability and satisfactory ΔV performance at OCM-10. Monte Carlo simulations were run for each of these scenarios. The four scenarios included the same parametric variations used for all maneuvers since Mercury orbit insertion, including, but not limited to, sensor alignments, sensor noise, sensor latencies, actuator alignments, thruster impingements, and initial reaction wheel speeds. As is standard for all maneuvers, tank pressures, centers of mass, tank masses, and inertias are varied around expected initial conditions. Any departures from the standard variation schemes are noted in Table 4. Each Monte Carlo scenario consisted of 1,000 cases.

Despite substantial differences among initial conditions and thrust levels in the OCM-10 Monte Carlo scenarios, each set of simulations had comparable commanded and estimated attitude-error distributions, demonstrating the robustness of the thruster control law. In all four scenarios, the maximum commanded attitude error stayed below 0.55° with a mean of ~0.48°. In a like manner, the maximum estimated attitude error stayed below 2.55° with means from 1.11° to 1.3°. On the basis of the Monte Carlo analyses, the attitude-error abort check limit was selected to be 5° for OCM-10. This value was sufficiently large to avoid aborting a well-controlled maneuver while also providing protection against attitude errors that could expose thermally susceptible parts of the spacecraft and science instruments to the Sun. Furthermore, an attitude-error abort check limit of 5° has been used successfully during past OCMs.

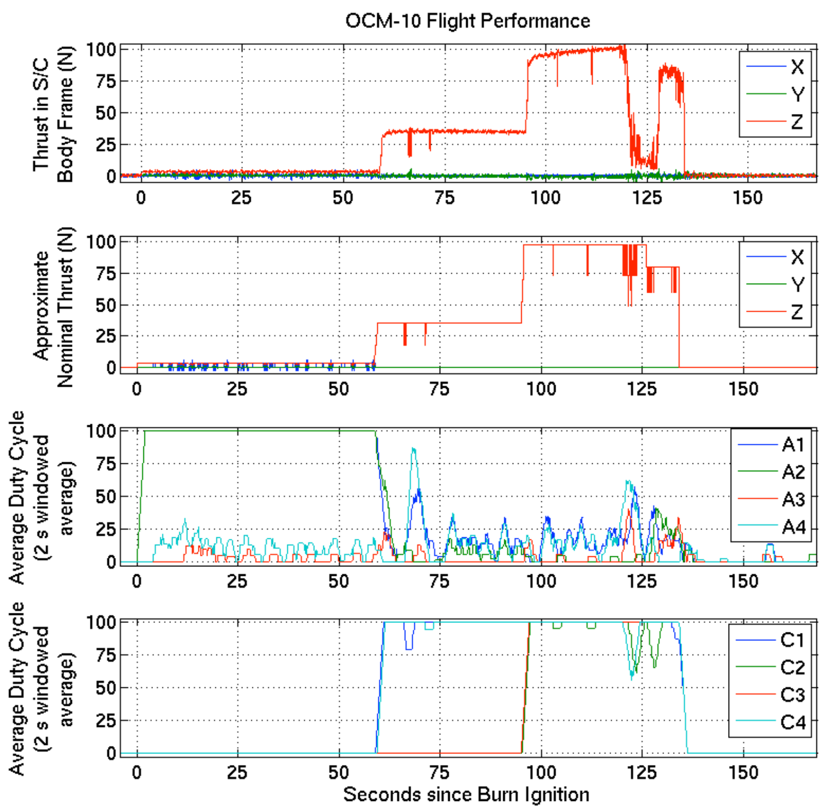

Figure 4. OCM-10 Flight Performance Showing Thrust in the Spacecraft (S/C) Body Frame, Approximate Nominal Thrust Assuming Constant Pressure and Thruster Duty Cycling, and Moving Averages of A- and C-Thruster Duty Cycles.

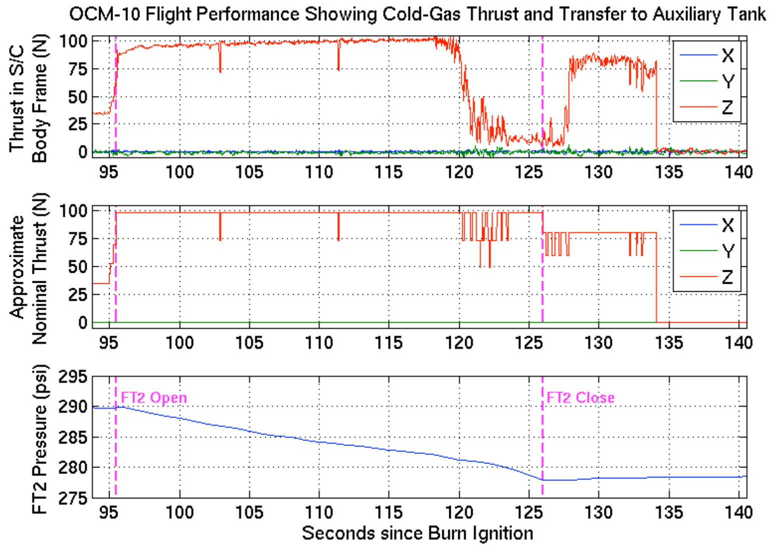

Figure 5. OCM-10 Flight Performance Showing Thrust in the Spacecraft (S/C) Body Frame (Cold-Gas Thrust and Helium Gas Transfer to Auxiliary Tank Is Apparent), Approximate Nominal Thrust Assuming Constant Pressure and Thruster Duty Cycling, and FT2 Pressure. Times of FT2 Latch Valve Open and Close Are Noted in Magenta.

Flight Performance

OCM-10 imparted a total ΔV of 8.5702 m/s (0.02% under-burn, 0.09° pointing error), which raised the periapsis altitude to 93.62 km (37 m lower than target value) and consumed ~2.16 kg of hydrazine. As evidenced by the fact that the total hydrazine consumption was less than the assumed maximum usable hydrazine remaining in FT2 (2.76 kg) and by the imparted thrust shown in the top plot of Figures 4 and 5, the MPS pushed helium gas through the thrusters and transferred gas to the auxiliary tank. At ~119 s from burn ignition (t_0 + 119 s, and 23 s into the FT2 segment), the imparted thrust began to drop, the A- and B-thruster duty cycles increased (A- and B-thrusters were on-pulsed for attitude control), and the C-thruster duty cycles decreased (C-thrusters were off-pulsed for attitude control), indicating a sluggish attitude control response. It is believed that only gaseous helium was supplied to the C-thrusters for the 2 s before the sequenced switch to the auxiliary tank (at t_0 + 126 s), as by this time thrust had reached a steady state and the C-thrusters were not off pulsing. If correct, the thrust level for the C-thrusters was reduced to 10% of the nominal thrust when operating with helium as the propellant. Nominal thrust levels were not recovered until 2 s after the sequenced switch to the auxiliary tank. This outcome is believed to be because helium gas was transferred to the auxiliary tank during the FT2 segment and the first 2 s of operation purged this gas from the tank. Nominal thrust levels for the C-thrusters throughout the remainder of the maneuver suggest that the majority of helium gas transferred to the auxiliary tank was expelled before burn completion.

Although the attitude control response was sluggish while helium gas flowed through the thrusters, robustness of the thruster control law ensured that attitude errors during the maneuver did not exceed 1.25°, which was well below the attitude-error abort check limit of 5° and therefore did not trip the second autonomy rule that was monitoring for abort conditions throughout the maneuver. The conservatism in the helium gas thrust levels used in Monte Carlo analyses proved to be a prudent decision because the measured cold-gas thrust was ~10% of nominal thrust, not 40% of nominal thrust as predicted. The autonomy rule that was designed to switch to the auxiliary tank once FT2 depletion was detected never fired even though the tank was depleted of usable hydrazine. The pressure-dependent rule was designed to fire if the pressure of FT2 (PFT2) dropped to 270 psi, which is 10 psi below the tank regulation point of 280 psi. The bottom plot of Figure 5 shows PFT2 throughout the main and trim segments of the maneuver. When FT2 is opened and the main segment begins, PFT2 is ~290 psi. Contrary to predictions, PFT2 did not drop to <270 psi during tank depletion, as the flow-rate of helium gas out of FT2 was much less than expected. Although the pressure-dependent rule did not fire, the trim segment was sufficiently long to ensure that the target ΔV was achieved. An additional 9.1 s of four C-thruster firing was required to complete the maneuver.

Table 5. OCM-11 Maneuver Sequence. Attitude Control Thrusters Are Pulsed as Needed.

Maneuver Segment	Designed Duration (s)	Achieved Duration (s)	ΔV Thrusters	Attitude Control Thrusters	Fuel Tanks
Main	148.7	149.88	C1–C4 (off-pulsed for control)	A1–A4, B1–B4	Auxiliary Tank
Tweak	30	30	None	A1–A4, B1–B4	Auxiliary Tank

OCM-11 DESIGN AND RESULTS

OCM-11, executed on 24 October 2014, was designed to target a 25-km altitude on 21 January 2015 and was the third maneuver of XM2. OCM-11 was the most straightforward maneuver of XM2 because it used only the auxiliary tank, a single set of ΔV thrusters, and a single set of attitude control thrusters. The segment durations and thruster selections are outlined in Table 5. The MPS operational guidelines in Table 1 were not followed in the design of OCM-11 because both main fuel tanks were considered depleted after OCM-10. Any future attempts to access the main fuel tanks will be to access hydrazine previously categorized as unusable and/or to deliberately use helium gas to impart ΔV. Although the OCM-11 implementation was straightforward, the maneuver timeout selection was padded to ensure that the target ΔV would still be achieved even in the presence of helium gas bubbles that might remain in the auxiliary tank after OCM-10. Monte Carlo analyses were used to help select the appropriate timeout value and to ensure that the maneuver design was sufficient to maintain attitude stability.

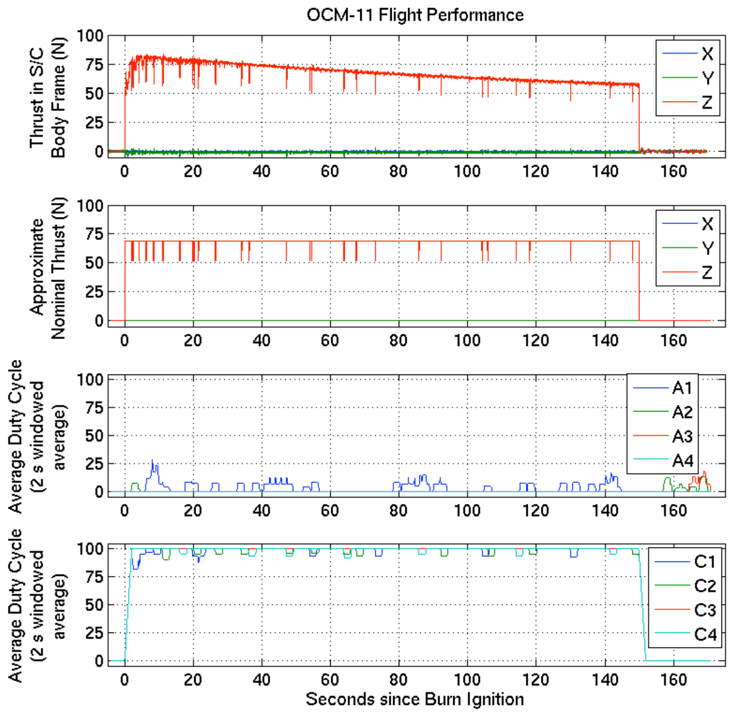

Figure 6. OCM-11 Flight Performance Showing Thrust in the Spacecraft (S/C) Body Frame, Approximate Nominal Thrust Assuming Constant Pressure and Thruster Duty Cycling, and Moving Averages of A- and C-Thruster Duty Cycles.

Flight Performance

OCM-11 imparted a total ΔV of 19.3683 m/s (0.01% over-burn, 0.06° pointing error), which raised the periapsis altitude to 184.38 km (554 m lower than target value) and consumed ~4.24 kg of hydrazine. The thrust and thruster duty cycles during OCM-11 are shown in Figure 6. There was a slight increase in A- and B-thruster duty cycling and a slight decrease in C-thruster duty cycling during the first 20 s of the maneuver. This behavior combined with the slightly prolonged C-thruster rise time could be indicative of helium gas bubbles in the auxiliary tank at the beginning of the maneuver. The thrust levels and thruster duty cycles quickly returned to expected values, which could indicate that all remaining helium gas bubbles were expelled from the auxiliary tank. However, to maintain conservatism in the design of all post-OCM-10 maneuvers, the presence of helium gas bubbles must continue to be considered. There is little doubt that helium gas was transferred to the auxiliary tank during OCM-10 on the basis of the high-rate accelerometer data collected during the maneuver, but it cannot be proven with certainty that all helium gas has been expelled from the auxiliary tank since the initial transfer.

CONCLUSION

The first three maneuvers of XM2 successfully delayed Mercury surface impact and provided valuable science observations at altitudes as low as 25 km above the surface. In addition to ensuring that the science objectives of XM2 would be met, the performance of OCM-9, OCM-10, and OCM-11 facilitated an extension of MESSENGER operations several weeks past the projected XM2 surface impact date of 28 March 2015. OCM-10 flight performance demonstrated that the MESSENGER maneuver design and execution process is robust to intermittent thrust degradation due to ingestion of helium gas by the thrusters. The performance at OCM-10 suggests that a more substantial and dedicated use of helium could be planned to provide the necessary ΔV to further delay Mercury surface impact. Additionally, the fault protection developed for OCM-10 can be reused in future maneuvers to permit subsequent attempts to access hydrazine previously deemed unusable. OCM-12, scheduled for 21 January 2015 and designed to target a 15-km minimum altitude on 1 March 2015, was originally intended to be the final MESSENGER maneuver before a surface impact date of 28 March 2015. The revised XM2 reference trajectory calls for seven (notional) additional OCMs past OCM-12, some of which will use helium gas as the sole source of propellant. Maintaining MESSENGER operations until the revised surface impact date of 30 April 2015 will depend on flight performance of subsequent OCMs and the team's application of lessons learned during the implementation of OCM-9, OCM-10, and OCM-11.

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